THEORY DEPARTMENT FIVE-YEAR PLAN*

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THEORY DEPARTMENT 5 YEAR PLANNING DOCUMENT

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I. INTRODUCTION AND OVERVIEW

The PPPL Theory Department's primary mission is to advance the scientific understanding needed to establish fusion as an attractive, technically feasible energy option. The goals articulated by the Fusion Energy Sciences Advisory Committee (FESAC) in the panel report entitled, "Scientific Challenges, Opportunities and Priorities for the U. S. Fusion Energy Sciences Program", (April 2005), provide a clear vision for achieving this mission. Predicting the properties of high-temperature magnetically-confined plasmas is a scientific grand challenge, which depends on the integration of many complex physics phenomena that cannot be reliably deduced from empirical scaling and extrapolation alone. This requires the application of state-of-the-art theoretical and computational tools to the interpretation of experimental results. Increasingly powerful computational resources have stimulated progress, and the PPPL theory effort continues to be at the forefront of innovation in the field. This is evident in the leadership, by members of the Theory Department, of two of the current national SciDAC, DOE's Scientific Discovery through Advanced Computing, programs.

The research areas addressed by the Theory Department impact plasma science issues of importance to all of the major national and international magnetic confinement experiments as well as the design and operation of many proposed future devices. In the magnetic fusion energy (MFE) research area, key topics addressed at PPPL include: (1) turbulence-driven as well as classical transport in the presence of sheared magnetic topology and plasma flow; (2) dynamical interplay between the evolution of large-scale MHD systems and small-scale dissipation mechanisms; (3) wave-particle interactions influenced by energetic particle dynamics and their impact on alpha-particle physics in present-day experiments and future ignited plasmas; and (4) plasma boundary physics with emphasis on a realistic depiction of the transport of neutrals which is needed to assess the properties of advanced divertor configurations.

In carrying out its research mission, the PPPL theory program has a strong history of producing seminal theories and reliable codes which have demonstrably benefited the fusion energy sciences program. These efforts have and will continue to place emphasis on sustaining productive research collaborations as well as developing new partnerships with the theory community and with experimental programs. Along with its strong commitment to education, the PPPL theory program strives to provide a stimulating research environment, which can generate and sustain the intellectual vitality essential for the excellence of the plasma sciences.

Achieving the goals targeted by the Theory Department will require continued advances in analytical capabilities and advanced computational codes together with the active applications of the best existing theoretical tools for interpretation and design. Key contributions from the areas highlighted in this planning document are reminders of the lead role that theory can play in the fusion program and serve to underscore the fact that many of the advances in the field have resulted from an improved understanding of the basic mechanisms involved in toroidal confinement and not only from the development of empirical rules for confinement scaling. For example, theoretical predictions of improved

local thermal confinement in regions of reversed magnetic shear were subsequently borne out in experimental studies in TFTR, DIII-D, JET and other major tokamaks. Another prominent example is the observation of the theoretically-predicted presence of unstable toroidal Alfvén eigenmodes (TAEs) driven by energetic particles in the TFTR, DIII-D and JET experiments. The continuing improvements in operating regimes and in diagnostic techniques, applied to magnetically confined plasmas, should enable more realistic comparisons of experimental results with theoretical models. As more reliable physics-based models emerge, it is expected that the pace of breakthroughs will be accelerated by more efficient acquisition of key results from experimental facilities.

Theoretical activities at PPPL range from the initial formulation of promising new theoretical approaches and ideas for innovative confinement configurations, to the high-impact applications directly benefiting experimental projects. Fundamental studies of the properties of plasma form a base for the applied studies to build upon and also provide recognition and an opportunity to interact and share ideas with scientists in other related disciplines. The more applied theoretical studies form the physics basis for interpreting data from experiments and also for developing new MFE and non-MFE plasma concepts.

Organization: In order to ensure effective communication and enhanced productivity, the Theory Department has an active Steering Committee chaired by J. Manickam, Head of the Theory Department, and includes R. Davidson, Deputy Head of the Theory Department, for *Inertial Fusion Energy (IFE)* and *Non-MFE Plasma Sciences*, S. C. Jardin for MHD, T. S. Hahm for *Analytic Theory and Edge Physics*, W. Lee for *Turbulent Transport*, N. Gorelenkov for *Energetic Particle Physics*, E. Valeo for *Laser-Plasma Interactions,* and W. Tang, Chief Scientist of PPPL. In addition to these topical areas the major projects at PPPL are also represented, by A. Reiman for *Stellarators* and J. Manickam for *Spherical Torus Systems*. N. Fisch represents *Academic Affairs,* and J. Johnson *Space Plasma Research.* Members of the Steering Committee are responsible for planning research activities, which are described in the annual Theory Field Work Proposal and five-year plans, such as this document. They are also responsible for staff evaluations and assure scientific progress towards the goals. Department scientists also serve as Science Focus Group (SFG) leaders, a task shared with experimentalists. At the present time, two of five SFG leaders are theoreticians, W. Park for MHD and N. Gorelenkov for energetic particle physics. The mission of the SFGs is to provide cross-connections between the different Laboratory scientific departments; NSTX, NCSX, ITER, Plasma Science and Technology, and Theory. In addition to strong collaborations with experimental projects within PPPL, the Theory Department has actively developed productive national and international partnerships with theorists and theory groups, with experimentalists and experimental groups, and with the advanced scientific computing community.

Research in the PPPL Theory Department is guided by national priorities, as articulated in the Priorities Panel report to FESAC and by the needs of on-site projects and off-site collaborations. PPPL expects to maintain strong theoretical programs in each of the following areas:

Fundamental Plasma Theory: Scientists at PPPL have a long and productive history of developing the fundamental foundations of plasma science. It is currently active in advancing the basic theory of plasma turbulence and in developing new formulations to allow efficient computation of the evolution of both microscopic and macroscopic properties of plasmas. A better understanding of such fundamental processes has application to interpretation of key phenomena in both laboratory and natural plasmas.

Macroscopic Stability: The FESAC report identifies three scientific questions relating to macroscopic plasma physics.
T1. How does magnetic field structure impact upon fusion plasma confinement?
T2. What limits the maximum pressure that can be achieved in laboratory plasmas?
T3. How can external control and plasma self-organization be used to improve fusion performance?
PPPL has made important contributions in each of these areas and will continue to do so. With regard to *T1,* PPPL has been at the forefront of investigating the role of magnetic structure starting as far back as 1983, with the design of the Princeton Beta Experiment, PBX, which exploited changes in the magnetic curvature to exploit access to second stability against ballooning modes. More recent examples include the National Spherical Torus Experiment, NSTX, which takes advantage of very low aspect ratio, and the design of the National Compact Stellarator Experiment, NCSX. The NCSX design highlights the use of magnetic structure to improve confinement and stability, to disruptions, by using a sophisticated combination of external coils and internal currents. In effect NCSX will address all three of the scientific questions. Important contributions have also been made to design studies relating to ITER, TPX, ARIES, and KSTAR. With regard to *T2,* the department has played an important role in advancing the understanding of the role of instabilities in experiment. This was enabled by the development of codes and comparison of theory with experiment. The study was enabled by codes such as M3D, PEST, TSC AND VACUUM, which are now recognized as standards in the field. Analysis of experimental discharges on many devices has identified the role of ideal and resistive instabilities such as axisymmetric modes, internal and external kinks, sawteeth, infernal modes, ballooning modes and resistive wall modes, RWMs, in setting the beta limits, Recent applications to NSTX discharges have revealed the role of rotation in reducing the growth-rate of internal modes. In addition, using M3D, simulations of complete sawtooth cycles are improving the understanding of this ubiquitous mode. The PEST-III code is a unique tool for determining a stability parameter, D', which is critical for determining the growth and saturation of neoclassical tearing modes. The VACUUM code is an integral component of many codes used for the study of RWMs and external kinks. Recent studies are increasingly focusing on nonlinear effects, using M3D. With regard to *T3,* the design of NCSX, as previously mentioned, represent a result where external control plays a critical component. In addition, studies of field-reversed-configurations have revealed that kinetic effects can lead to nonlinear saturation of n=1 tilt instabilities, effectively a self-organized mechanism. This work played a critical role in the design of MRX-FRC. In the past the group contributed significantly to the design of TPX, an experiment designed specifically to reach high beta by controlling instabilities and to operate at near steady-state, relying on self-organized bootstrap currents. The methods and codes used for that design are currently being employed to identify favorable operating scenarios in a variety of devices, including NSTX,

DIII-D and ITER. It is notable that the TPX design was largely adopted by the Korean group for KSTAR and will be tested when that machine becomes operational.

Turbulence and Transport: The FESAC report identifies three scientific questions relating to multi-scale transport physics.
T4. How does turbulence cause heat, particles and momentum to escape from plasmas?
T5. How are electromagnetic fields and mass flows generated in plasmas?
T6. How do magnetic fields in plasmas reconnect and dissipate their energy?

With regard to question T4, the PPPL Theory Department has been a leader in producing seminal contributions both to innovative and powerful computational methods and to conceptual and analytic theoretical advances. In addition to successful development and applications of comprehensive kinetic micro-stability eigenmode codes such as FULL, there have been significant contributions from the Department to advancing initial value codes such as GS2. These tools have been extensively applied to realistic assessments of linear thresholds for the onset of prominent linear microinstabilities and associated quasi-linear estimates of anomalous heat, particle, and momentum transport. The PPPL Theory Department is internationally recognized for contributions to the development and applications of nonlinear gyro-kinetic particle codes and the rigorous theoretical formulations on which they are based. Taken collectively, the productive contributions from the gyrokinetic simulation (GTC) team, the gyrofluid group, and the analytic theorists in the 90's led to a new paradigm for the interpretation of microturbulence in magnetic confinement devices. This effort is part of a multi-institutional collaboration. The picture, which emerged, was of a self-regulating two-component system consisting of microturbulence that produced heat, particle and momentum transport, and the zonal flows which are generated by this turbulence and serve in turn to regulate the turbulence. These developments have led to a robust conceptual building block and a widely used computational methodology in the theory community. Moreover, detailed diagnostics for nonlinear simulations and clear characterization of zonal flow properties have significantly influenced the experimental community to measure zonal flows to gain deeper understanding of turbulence driven transport. In this sense, it is now somewhat artificial to discuss the issue in question T4 alone without a consideration of that in question T5. While the traditional linear and nonlinear codes calculate the rates at which the non-axisymmetric parts of electromagnetic fields (crudely termed turbulence) get generated from the radial gradients associated with free energy in the pressure and plasma current, the PPPL Theory Department has led the way to systematically calculating, analyzing, and interpreting the turbulent generation of the axisymmetric part of the mesoscale radial electric field ("zonal flow" is its associated ExB flow) which evolves on a time scale between turbulent time scale and transport time scale. On the other hand, macroscopic mean mass flow can be generated via external torque associated with unbalanced neutral beam injection, orbit loss, and diamagnetism associated with the radial pressure gradient. It is evolving in the transport time scale and related to the mean ExB flow through the radial force balance relation. Experimental observation of spontaneous macroscopic scale toroidal rotation indicates a need for better understanding of flow generation mechanism so that it can be utilized for transport reduction in the future devices.

To address the neoclassical physics issues including the relation between the mass flow and the radial electric field, the GTC-Neo code has been developed to provide realistic estimates of the irreducible minimum (neoclassical) transport level of heat, particle and momentum, and the generation of self-consistent electric field, These important new results are currently being compared to experimental results from NSTX and DIII-D to help address outstanding unresolved issues about the "irreducible minimum" level of transport in toroidal systems .

Waves and Energetic Particles: The FESAC report identifies two scientific questions relating to waves and energetic particles physics.
T11. How do electromagnetic waves interact with plasma?
T12. How do high-energy particles interact with plasma?
The Theory Department has played a pioneering role in the analysis and modeling of energetic particle-excited modes. The NOVA suite of codes are widely used to match the experimental measurements on several machines, including NSTX, DIII-D, JET and JT60-U as well as on TFTR previously. These codes address linear physics, most recently with the improvements of the hybrid version of M3D. They are now able to begin addressing non-linear regimes as well. The damping mechanisms predicted by theory are being compared with experimental results. Experimentally relevant regimes for which the energetic particle velocity exceeds the Alfvén velocity are being modeled. Plans are in place to study the particle transport caused by energetic particle induced modes. The goal is to simulate the evolution of the energetic particle distribution in a nonlinear system, which can be used to predict alpha-particle transport in a burning tokamak experiment;

Plasma-boundary Interfaces: The FESAC report identifies one scientific question relating to multi-phase boundary physics.
T10. How can a 100-million-degree burning plasma be interfaced to its room temperature surroundings?

PPPL began exploring the possibility of using poloidal divertors to address this question with the PDX device. Modeling of poloidally diverted plasmas led to the successful prediction of the high recycling regime in which the plasma temperature is substantially reduced as it flows along open field lines towards the divertor target. PPPL's DEGAS 2 neutral transport code grew out of these initial modeling efforts, providing a fast and flexible tool for analyzing experiments targeted at question T10 and for evaluating proposed approaches to answering it. DEGAS 2 has most recently been a key component in the analysis of Gas Puff Imaging turbulence visualization experiments, allowing the underlying turbulent plasma structures to be inferred from the recorded GPI images. The discovery of the "supershot" and "lithium aided supershot" regimes on TFTR illustrated the tremendous extent to which core plasma performance can depend on the state of the vacuum vessel walls. A variety of subsequent theoretical and experimental efforts have attempted to use this connection to provide a truly satisfactory solution to question T10. In particular, the department has examined novel uses of lithium as a plasma facing material.

Tokamak Theory: While much progress has been made in understanding the tokamak configuration, there remains much work to be done before a robust first-principles-based

predictive capability is available. The gyrokinetic and gyrofluid models of the tokamak have had considerable success in their qualitative predictions, but need to be enhanced to achieve better quantitative agreement with experiments. Prospects for a more realistic description of electron physics and electromagnetic effects have been greatly enhanced by the advances in the needed mathematical formalism, together with the availability of increasingly powerful massively parallel computational resources. The advanced tokamak holds the promise of leading to an attractive reactor design, but major challenges remain in developing a better theoretical understanding of such features as the conditions for transport barrier formation, and for feedback stabilization of dangerous MHD modes. Also under investigation are important burning plasma physics issues, including the possible impact of energetic-particle-driven MHD modes, such as toroidal Alfvén eigenmodes (TAE). This workscope is particularly important for the Theory Department's productive collaborations on national (DIII-D, C-MOD) and international (JET, JT-60U, ASDEX, KSTAR) tokamak projects and for future major international collaborations on ITER.

ITER: Researchers in the Theory Department are co-authors of the Tokamak Physics Basis document, which describes the present understanding of ITER relevant physics and helps identify needed research thrusts. The Department is engaged in ITPA High Priority Research tasks, such as: RWM modeling, disruption mitigation, advancing the understanding on high-n Alfvén eigenmodes, and turbulence simulations.

Theory of Alternate Confinement Configurations: A portion of the theoretical analysis of confinement systems at PPPL is focused on promising confinement configurations that are alternatives to tokamaks.

NSTX: With the on-site presence of the National Spherical Torus Experiment, (NSTX), spherical torus physics is a key area of concentration. Many of the attractive features of the ST were identified theoretically as part of the NSTX design process, including regimes of high performance and regimes where very little external current drive would be required to sustain the configuration. The department is also active in comparing experimental results from NSTX with theoretical models. Some recent examples include: The reduction of growth-rate of the internal 1/1 mode due to high rotation, leading to either delayed and smaller crashes or saturation; Identification of compressional and global Alfvén modes; Predictions of radial electric field and poloidal rotation profiles using neoclassical transport theory; and, modeling of gas puff imaging diagnostics, GPI. It should be noted that the PPPL Theory contributions are a part of the efforts of a large multi-national, multi-institutional theory team, which in combination address the theory and modeling needs of NSTX.

NCSX: There is now also great interest in advanced stellarator configurations. Theoretical studies have identified attractive new configurations such as the compact quasi-axisymmetric stellarator. These innovative designs, which are expected to provide compact configurations with high power density and good confinement, while at the same time providing a path to possible disruption-free operation, have led to the establishment of the National Compact Stellarator Experiment (NCSX) at PPPL. While the machine's construction progresses, the Department is engaged in collaborations with other stellarator

projects, including: QPS at ORNL, QHS at Wisconsin, CNT at Columbia, CTH at Auburn, TJ-II in Spain, LHD and Heliotron-J in Japan and the W7-AS/W7-X program in Germany. A recent example of comparison with experiments was a study correlating the observed beta-limit on W7-AS with a predicted loss of good flux surfaces over a substantial fraction of the plasma cross-section.

FRC: Studies of innovative confinement concepts such as the Field Reversed Configuration (FRC) are actively pursued. A 3D nonlinear hybrid and MHD simulation code called HYM, developed at the Princeton Plasma Physics Laboratory, has been used to study the relative roles of various competing kinetic effects on linear stability behavior, and has demonstrated that the n=1 tilt instability can saturate nonlinearly in highly kinetic FRCs. Three-dimensional MHD simulations of counter-helicity spheromak merging and FRC formation have been completed, and show very good agreement with results from the SSX-FRC experiment. These and other studies, described in section III.D, have provided the theoretical basis for the proposed ion-beam stabilized device, MRX-FRC.

Advanced Scientific Computing: This is an integral part of the research program in the Theory Department and has been an area where PPPL has continued to provide the national leadership and technical progress essential for the effective development and deployment of advanced computing capabilities required to deal with problems of extraordinary complexity encountered in the plasma sciences. It basically requires productive coupling between conceptual physics insights with new approaches from computer science and applied mathematics to address outstanding issues facing fusion energy research. PPPL's activities in this area respond to the charge from the Office of Fusion Energy Sciences to work with the national fusion community to develop an appropriate vision for advanced computing and implement the associated plan within the Plasmas Science Advanced Scientific Computing Institute (PSACI). The PSACI with its distinguished Program Advisory Committee has the key role of coordinating the research activities of the Fusion Energy Science projects within DOE's Scientific Discovery through Advanced Computing (SciDAC) Program. This includes three Fusion Energy Science (FES) SciDAC Centers in the key areas of Gyrokinetic Particle Simulation of Turbulence, Extended MHD Modeling, and Simulation of Wave-Particle Interactions – the first two of which are led by principal investigators from PPPL. This FES SciDAC portfolio has recently been expanded to include two SciDAC Fusion Simulation Project (FSP) Proto-type or Pilot Centers on the integrated simulation of the plasma edge/boundary region and the integrated simulation of wave interactions with MHD. PPPL is involved as a major partner in both of these new programs. More general technical progress at PPPL in the advanced computing area has entailed close collaboration between the Theory Department and the Computational Physics Group (CPPG) staff and includes the introduction of new physics capabilities and the conversion and optimization of several major PPPL codes to effectively utilize massively parallel computers. Associated activities have involved the introduction of new algorithms and computational techniques, and also the application of state-of-the-art visualization tools. Overall, the PPPL advanced scientific computing efforts in the “capability computing” area have clearly demonstrated the effective utilization of FES codes on the most powerful supercomputing platforms located, for example, at the National Energy Research Supercomputing Center (NERSC) at Berkeley, the new Leadership Class Computing Facility at Oak Ridge National Laboratory

(ORNL), and at the Earth Simulator Center in Japan. PPPL has also made highly-valued contributions to progress on important "capacity computing" issues by examining the cost-effective utilization of commodity clusters dedicated to key FES applications.

Collaborations: One of the important goals of the PPPL Theory Department is to sustain and improve the productive collaborations between PPPL and other national plasma science programs, including those at General Atomics (GA), Massachusetts Institute of Technology (MIT), University of Texas Institute of Fusion Studies (IFS), Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Los Alamos National Laboratory (LANL); international institutions such as the Japan Atomic Energy Research Institute (JAERI), the Joint European Torus (JET), and NIF in Japan, Max Planck Institute in Germany, Culham Laboratory in the United Kingdom, Cadarache Laboratory in France, the Ecole Polytechnic Federal of Lausanne Switzerland, Frascati Italy; and with individual scientists from university programs such as the University of California at San Diego, Los Angeles, and Irvine, University of Maryland, New York University, Swarthmore College, Columbia University, University of Colorado, University of Rochester, Lehigh University, St. Michael's College, and Cornell University. With the broader focus on innovative confinement concepts, collaborative linkages are being further strengthened with the international stellarator community and with national initiatives on stellarators, STs, RFP's. and FRC's. PPPL is also actively involved with many of the above institutions as part of the national computational project which it leads – the Plasma Science Advanced Computing Institute (PSACI). The SciDAC projects also represent strong multi-institutional collaborations. Details of collaborations in the different topical areas are described in the following chapters.

Non-MFE Plasma Theory: Recognizing that achieving the goal of producing an efficient energy-producing magnetically confined fusion plasma system is still decades away, the PPPL theory research efforts make significant contributions to other applications of plasma science and to inertial fusion. These non-MFE applications have continued to grow -- especially in the accelerator physics, heavy ion fusion and high energy density physics, laser-plasma-interactions, and space physics areas. Plasma-based accelerators are expected to enable much more cost-effective and compact high-energy particle accelerators. Space and solar physics are increasingly vibrant scientific arenas with the wealth of new data from satellite observations that need interpretation. Extensions of theoretical models developed in fusion studies of energetic particle have already had significant impact in the magnetospheric physics area. Other key applications, such as the development of plasma thrusters, plasma display panels, and advanced diagnostics to monitor the manufacture of fibers, are important spin-offs of the Theory Department's plasma science and fusion research.

Education: Finally, motivated by the urgent need to attract, train and assimilate the best and brightest young talent into the field, the Theory Department actively participates in Princeton University's Department of Astrophysical Sciences Program in Plasma Physics. In addition to those serving on the faculty and associated faculty, many members of the Theory Department have served as thesis research advisors. This has been a mutually

beneficial relationship in that the Laboratory provides an exciting array of frontier research opportunities, while Princeton University provides a steady source of extraordinarily well-qualified and energetic students. The teaching program also provides opportunities for the PPPL Theory staff to interact with faculty and students in other departments at Princeton University.

Honors: The Theory Department is fortunate to have a highly capable and well-recognized staff. Twenty scientists have been recognized as APS Fellows. Department scientists have won several awards over the years. In the past five years the awards include: Nat Fisch received the E. O. Lawrence medal; Frank Cheng received the APS award for Excellence in Plasma Physics Research; Ron Davidson received the Particle Accelerator Science and Technology Award; Hong Qin received the Presidential Early Career award for Scientists and Engineers; John Krommes, Doug McCune and Alan Reiman were recognized as Distinguished Lab Fellows.

Staffing and Budget

The Theory Department has a staff of thirty research scientists, seven computational scientists, one administrative assistant, and shares a project control officer with other PPPL departments. The thirty-seven scientists have a wide range of expertise. The distribution in FTEs, Full Time Equivalents, of their primary area of interest is as follows: in the MFE area: 32; accelerator physics and IFE: 3; and space plasma: 2. Within the MFE area the distribution of effort is: macroscopic stability: 12; transport and turbulence: 13; wave-particle interactions: 3; edge physics: 2; teaching: 1 and management: 1. The distribution includes both research and computational scientists. The computational scientists are distributed as follows. Three are working to develop, maintain and run the plasma simulation code, TRANSP and are associated with the transport modeling effort; two work with MHD codes; one is mostly working with the turbulence simulation code, GTC, but also helps the rest of the department with parallelization and leadership-class computing; and, one is a visualization expert, who provides support to all the large codes.

Funding for the members of the Theory Department is drawn from multiple sources. Individuals are frequently assigned to more than one cost center. A broad overview of these assignments, rounded to integer values follows. The largest source of funding is the Theory Team in the Research Division of the Office of Fusion Energy Sciences, which supports approximately 20 FTEs. MFE-related projects, NSTX and NCSX together support 4 FTEs. Innovative confinement concepts support 1 FTE. Off-site collaborations support 4 FTEs. Accelerator physics and IFE supports 3 FTEs. Academic Affairs supports about 1 FTE. Support for management is 1 FTE. The space plasma group, 2 FTEs, is funded by NASA and NSF. Details of the distribution by funding source and topical area are presented in Appendix A, in tabular form.

The budget for direct Theory funding primarily supports the existing staff. The main topical areas are: tokamak theory, alternates theory, scientific computing and SciDAC grants. The

requests, in units of $K, are: tokamak theory: $2,401 K; alternates theory $1698K, ICC (FRC): $208 K; scientific computing: $2,046 K; and SciDAC grants represent $1,665K. Together, these add up to $8,018 K. Our baseline budget request is for this amount, with projections for the out years based on an inflation rate of 3.0% per year. These figures are based on the Field Work Proposal submitted in February 2005, augmented by the budget requests which were recently approved in the FSP-SciDAC proposals for; integration of RF and MHD; and edge-core turbulence simulations.

It is important to recognize that the funding for tokamaks and alternates theory represent the bedrock of the Department's budget, both in terms of resources, but equally important as the progenitor of the seminal research activities which are more application-oriented. Reduction of the budget, for direct Theory funding, would severely hamper the 'seed-corn' activities, which fuel future scientific advances.

In order to keep pace with the rapidly changing computing environment, and to ensure the continued vitality of theoretical research in the fusion program, through collaborations and education, incremental requests are included for three categories, computer hardware, incoming-collaborations, and post-doctoral research associates.

The substantial computational resources available for theoretical research fall into two categories: supercomputing facilities at remote sites, and several local computational clusters including, 211 dual-processor nodes, and two SGI-Altix symmetric multi-processors, SMPs, (one of which has 16 nodes, the other has six). The aggregate resources are comparable, and represent about 3 million CPU-hours/year each. The remote sites are preferentially used for very large scale computations which require as many as thousands of processors, GTC simulations of full-scale tokamaks are an example. Much of the capacity computing is done on the local clusters. The PPPL clusters have been facilitated by combining multiple sources of funding, specific OFES grants, matching funds from Princeton University, and Theory and PPPL project funds. As a result, the owner and user community is large. The clusters meet multiple requirements: between-shot data analysis, machine design computations, mid-scale simulations of turbulence, MHD simulations, RF heating and diagnostic simulations, etc. The bulk of the local computational capability is at least three years old and is becoming obsolete, and is in immediate need of replacement. A modest step has been taken in this direction by the purchase of 24 dual-CPU-64-bit AMD Opteron workstations with high-speed, low-latency Infiniband interconnect, the purchase of the second 6-processor SMP, and a memory upgrade of our existing 16-processor SMP has been made possible by combining Theory and NSTX funds. In addition to purchasing compute nodes, PPPL has invested substantial project funds and manpower in evaluating, purchasing and deploying the necessary supporting infrastructure: networking, multi-terabyte file servers, and two automated tape libraries. As a result of the past three years of activities, the PPPL computer support group has gained valuable expertise in the deployment and operation of a substantial scientific computational center and is now capable of supporting growth and a wider user base. In order to provide for a continuing refurbishment of capability, which is now significantly overdue, incremental funds of $350K/year are required. This would enable the replacement of approximately 50 dual-processor nodes/year, with a fast interconnect capability.

As the program moves into the burning plasma era, it is increasingly important that national and international efforts become more collaborative and integrated. The Theory Department has a long history of successful collaborations, which have benefited the fusion program. In recent years, budgetary constraints have limited the opportunity to sustain incoming collaborations. Designated funds for such activities will enable a predictable collaboration program and is intended to support visitors coming to PPPL for collaborative research. The requested incremental funding is $100 K/year.

The fusion theory program is increasingly invested in advanced computing, which is a rapidly changing field. Young scientists with strong computational skills are required who can be trained to become leaders in the future. It is proposed to institute a vigorous postdoctoral program. Over the next five years, incremental funds are requested as follows: for FY2006: $198K and starting in FY2007: $389K.

A summary of the budget request for the direct theory funding, for the period FY06-10, is presented in Appendix B.

II. SCIENTIFIC AREAS

This chapter provides details of the Theory Department's activities, identified by scientific topical areas: macroscopic stability; transport and turbulence; wave-particle interactions; multi-phase, i.e. boundary, physics; and non-fusion basic plasma science. With the increased sophistication of the theoretical models, the boundaries between these topical areas become less distinct, and the research activities overlap. For example, there is an overlap between macroscopic stability and wave-particle interaction physics, because they both address the interaction of energetic particles with MHD waves. This topic is in fact addressed in both sections. However in the macroscopic stability section, the focus is on modeling low-n low-frequency modes, using an initial value approach, whereas, in the wave-particle section, the focus is more on medium to high-n, using more efficient eigenvalue codes, which can model high-frequency as well. Another example is the modeling of Li walls, which can have a major impact on macroscopic stability as well as confinement, by altering edge boundary conditions.

In the following sections, each of the topical areas is addressed, starting with a review of the relevant scientific questions, identified in the FESAC Priorities Panel report, a description of the physics issues, the Department's accomplishments to provide the background and a work-plan with goals and milestones. A note about the milestones; the pace of progress in research is hard to predict with accuracy, but it is important to establish timelines, which is done. Wherever possible specific dates are given. In many cases a range of dates is specified, the first date is the estimate of when that particular activity will commence, and the latter the estimate for completion. In some instances, the activity will continue beyond the specified date of completion. This refers to activities involving support for analysis of experiments. These milestones are intended to give an overview of future activities, as Field Work Proposals are developed, each year, specific milestones will be identified.

A. Macroscopic Stability

The FESAC Priorities Committee report identifies several scientific questions relating to macroscopic plasma physics. These are: (T1) How does magnetic field structure impact upon fusion plasma confinement? (T2) What limits the maximum pressure that can be achieved in laboratory plasmas? (T3) How can external control and plasma self-organization be used to improve fusion performance? (T5) How are electromagnetic fields and mass flows generated in plasmas? (T6) How do magnetic fields in plasmas reconnect and dissipate their energy? (T12) How do high energy particles interact with plasma? In order to address these, we need to both develop improved mathematical models (closures) that describe the macroscopic dynamics of high-temperature magnetized plasma and to develop advanced numerical techniques for solving both existing and improved models and use these to perform critical comparisons with experiments and make predictions. This section describes the recent accomplishments and planned activities related to these issues.

A.1 Overview

It is hard to overstate the importance of macroscopic dynamics in tokamak fusion research. The operational space of tokamaks is largely set by non-linear global stability thresholds. These include the instabilities that set current limits, pressure limits, density limits, and limits on the cross-sectional shaping. High performance burning plasma tokamak discharges must necessarily operate near these stability boundaries, but cannot exceed them. It is therefore essential that we develop a quantitative understanding of the detailed mechanisms that set these operational limits and how they scale with size and plasma parameters from the present generation of tokamaks to those of the ITER class.

The high-energy alpha particles present in a burning-plasma will have significant effects on the global dynamics. These particles, created in the DT fusion reaction with a birth-energy of 3.52 MeV, are expected to have a stabilizing effect on the internal kink mode, which can, paradoxically lead to large central disturbances (or giant sawteeth). The alpha particles can also resonantly excite shear Alfven waves, such as toroidal Alfven eigenmodes (TAE) or Energetic Particle Modes (EPM, e.g., fishbones). These alpha-driven modes can lead to anomalous alpha particle loss, degradation of alpha particle heating, or more seriously, damage in the reactor wall. Therefore, alpha particle physics is a key and essential component for understanding the macroscopic dynamics of a burning plasma experiment such as ITER.

The PPPL Theory Department is actively involved in pioneering new computational tools for the analysis and optimization of the stability properties of a number of magnetically confined configurations. The same basic macroscopic fluid equations describe the stability properties of all devices. However, each configuration allows different simplifying approximations to be made that may not apply to the others. For example, for analysis of a tokamak, it is usually sufficiently accurate to treat the underlying equilibrium configuration and domain boundary as axisymmetric and to treat the ratio of the ion Larmor radius to the system size as a small parameter. These simplifications are not possible for stellarators (non axisymmetric), and are not always valid for the spherical torus (ST) or FRC (large Larmor radii) configurations. In this section we describe some of the macroscopic stability activities

that are of general applicability to a number of configurations, as well as the tokamak specific items. Additional tools and applications for STs, stellarators, and FRCs are described in later sections, III.B, III.C and III.D.

The dominant theme in the near term tokamak research is to strengthen the physics basis for the International Thermonuclear Engineering Reactor (ITER), that is scheduled to begin operation in the next decade (see www.iter.org). The critical topics as listed by the International Toroidal Physics Activity (ITPA) topical physics group on MHD, Disruption and Control are listed here and described more in the subsequent sections:

- Beta limiting MHD modes and their active control. This includes sawtooth oscillations, tearing and neoclassical tearing modes (NTM), and resistive wall modes (RWM).
- Edge MHD stability and the behavior of Edge Localized Modes (ELMs).
- Fast-ion driven instabilities.
- The prediction, avoidance, and mitigation of disruptions and vertical displacement events. This includes calculating forces due to halo currents during disruptions, and the prediction, avoidance, and mitigation of large runaway populations during disruptions.
- Control issues in standard and advanced scenarios: shape, position, and performance.

We also describe macroscopic-stability research activities underway and planned that are not directly tied to the ITPA activities, but are of a more fundamental or exploratory nature. These are in the area of the MHD properties of tokamaks and STs with close fitting lithium walls, fundamental reconnection physics, and the physics of co-axial helicity injection. A high level chart describing the major research thrusts is shown in Fig. A.1

A.2 Beta limiting MHD modes:

A.2.1 Ideal MHD

Ideal MHD theory and computations are now quite mature for tokamaks. The PEST I/II codes have been the community standard for evaluating linear ideal MHD stability in axisymmetric devices for some years. We continue to support the use of these codes to benchmark and validate newer codes, and to apply them to new problems for which they are well suited. Applications include continuing efforts to understand and optimize the current and pressure limits of toroidal devices, and their sensitivity to plasma shaping and profiles. Detailed benchmarking of these codes against high-beta experimental results in NSTX and other devices provides an excellent test of the relevance of ideal MHD theory to fusion-relevant plasmas.

An active area of emphasis area for tokamaks is to better understand the role of ideal MHD in the transport barrier in reversed-shear discharges, and the role of current on the open field lines (halo currents) in providing stability to diverted discharges, and the role of moderate-n ideal MHD modes in ELMs. An ideal MHD description is typically also used as the plasma model in the resistive wall mode studies.

Another area of emphasis is the effect of rotation on ideal MHD modes. This is especially important in STs, such as NSTX, where rotation velocities exist that are a substantial

fraction of the Alfvén velocity. This can presently be computed with the nonlinear M3D code, as described in Sec. A.2.4.

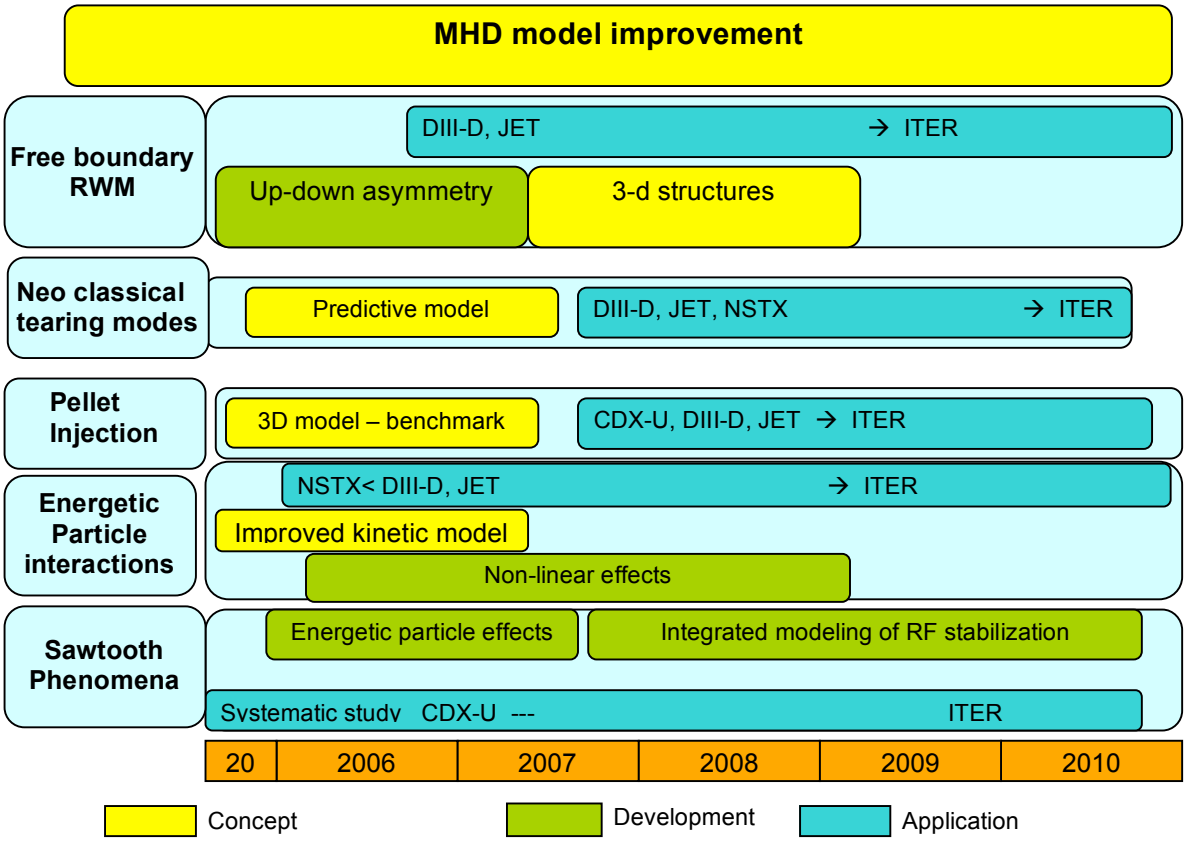

Figure A.1 A high level schematic describing the research thrusts, development and applications in the macroscopic stability area with approximate time-lines.

A.2.2 Two-Fluid Extended-MHD

Two-fluid Extended-MHD models utilize fluid-like equations for the electrons and the ions where the difference in their relative velocity and the anisotropy and off-diagonal terms in the pressure tensor are accounted for. There is not presently a universally agreed-upon unique form for the two-fluid equations in a fusion plasma. The theoretical challenge is to define the ion and electron stress tensors and heat fluxes in a way to include finite (ion) Larmor radius (FLR) effects (which lead to gyroviscosity) and the effect of long collision lengths parallel to the magnetic field, including magnetic particle trapping (important in neoclassical effects). Defining appropriate closure relations and testing their regions of validity is an important long-term activity that we participate in as part of the Center for Extended Magnetohydrodynamic Modeling (CEMM) SciDAC activity.

The M3D code now has a particular two-fluid model implemented for including the ion-gyroviscous contributions to the ion stress tensor, and for taking into account the difference in the ion and electron fluid velocities.[1,2] These extensions account for several important physical effects, including the "omega-star" stabilization of ideal and resistive MHD modes,

and the Hall term in Ohm's law, which can greatly speed-up magnetic reconnection. This capability has enabled a whole new class of simulations that seek to explain recent experimental phenomena that cannot be explained by resistive MHD alone. For example, without these terms, we do not see saturation of the internal kink mode under co-injection in NSTX simulations, whereas it does occur with the two-fluid terms included (and also in the experiments). [3]

The "two-fluid" terms are also essential for determining the trigger and the crash time for the sawtooth, and to explain many of the global stability properties of stellarators. [4] We note here that an in-depth study of these important phenomena will take many years because of the need to perform many cross-checks, including analytic, cross-code, and experimental comparisons. A program to accomplish this is being carried out through the CEMM project. As part of this activity, the present M3D two-fluid model [2] is in the process of being compared with other models to clarify its regime of validity. Numerical resolution and stability requirements also need to be clarified, and new approaches that offer greater numerical efficiency are being examined [5-7].

A.2.3 Kinetic Extended-MHD

To model the nonlinear interaction of ions with MHD waves and to include large gyro-orbit and neoclassical effects self-consistently, we have developed hybrid methods, where either an energetic ion component or the whole ion population are modeled using the gyrokinetic or drift kinetic equations. In the methods implemented in M3D so far, the ion fluid velocity is calculated by solving the momentum equation, and the calculated ion fluid velocity is used in the Ohm's law. The ion pressure tensor is taken to be in the Chew-Goldberger-Low form and the gyroviscous part of the stress tensor is calculated from the particles. Hot particle populations, for example fusion-produced alpha particles or injected neutral beam ions, can be simulated by combining a gyrokinetic hot particle population with a fluid model for the background. [1] This represents a unique capability for studying the nonlinear development of energetic particle modes in shaped geometry, of arbitrary aspect ratio fusion devices. It is thus applicable to interpret results from NSTX and present-day tokamak and stellarator experiments, as well as for assessing the effects of energetic particle modes in a burning plasma.

We also have linear codes that calculate the self-consistent interaction of energetic-ion populations with MHD modes: NOVA-K (and NOVA-KN is the non-perturbative version) for modes with low to medium toroidal mode numbers (n), and HINST for high-n modes. These are described more fully in Section C. The linear codes are much more computationally efficient than the nonlinear code, and make computational parameter scans possible. Also, the use of the linear codes to benchmark the nonlinear code was an essential element in its development.

A.2.4 Sawtooth Phenomena and the Current Hole

The sawtooth instability, present when the current in the tokamak peaks sufficiently so that the central safety-factor falls below the stability criteria, is a concern for the next generation of inductively-driven burning plasma experiments: including ITER. These modes introduce an intrinsic non-axisymmetric nonlinearity into the device that can interact with other modes

to degrade confinement, shed energetic particles, or induce a disruption. Our nonlinear codes have been used to model the sawtooth in a variety of devices and have had considerable success in reproducing many qualitative features such as the stabilizing effects of rotation and the existence of metastable states.[8] (See Fig A.2)

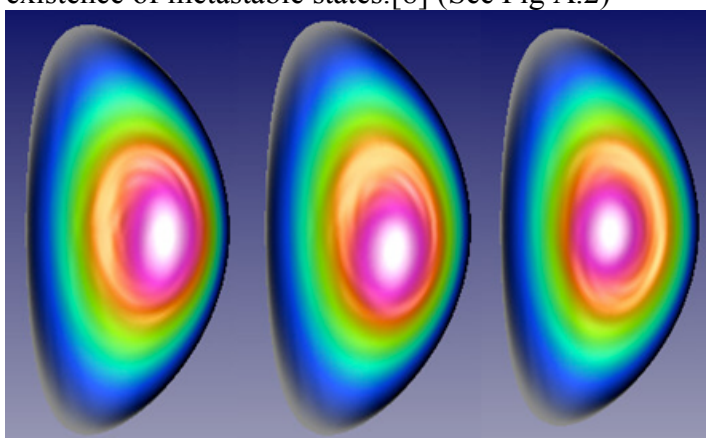

Figure A.2. Sequence of figures from a time-dependent 2-fluid M3D simulation of a long-lived saturated n=1 mode in NSTX with co-injection.

A phenomena closely related to the sawtooth is the "current hole". (Fig. A.3) This occurs when the toroidal current in the tokamak is increased faster than the natural skin time, causing the negative induced electric field to attempt to reverse the sign of the central current density. Once the central current density starts to reverse, a form of axisymmetric reconnection occurs that effectively clamps the central density at zero. The same codes we developed to study the sawtooth have been used in the last few years to model and explain the current hole, with particular emphasis on the Joint European Torus (JET) experiment, where excellent diagnostic measurements were available [9,11].

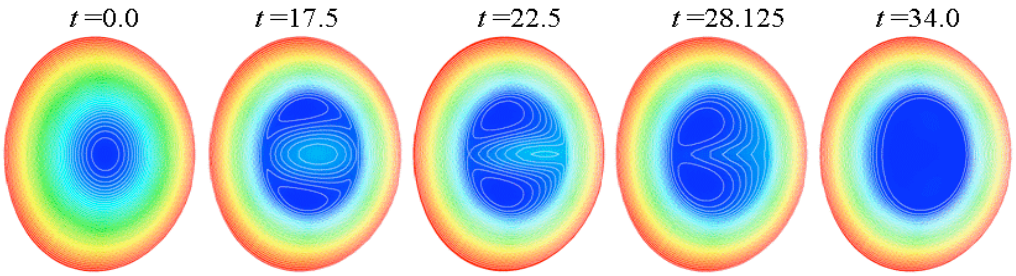

Figure A.3 Sequence of flux surface plots in a current-hole reconnection simulation.

We have also recently had success in modeling the sawtooth phenomena in a small device, CDX-U, ($S \sim 10^4$) using the actual physical parameters of that device (Fig. A.4). This modeling needs to be extended to larger devices where "two-fluid" effects are of greater importance, and eventually to the burning plasma regime. A fully predictive model should predict not only what the period is, but how the mode interacts with other modes and an energetic particle population.

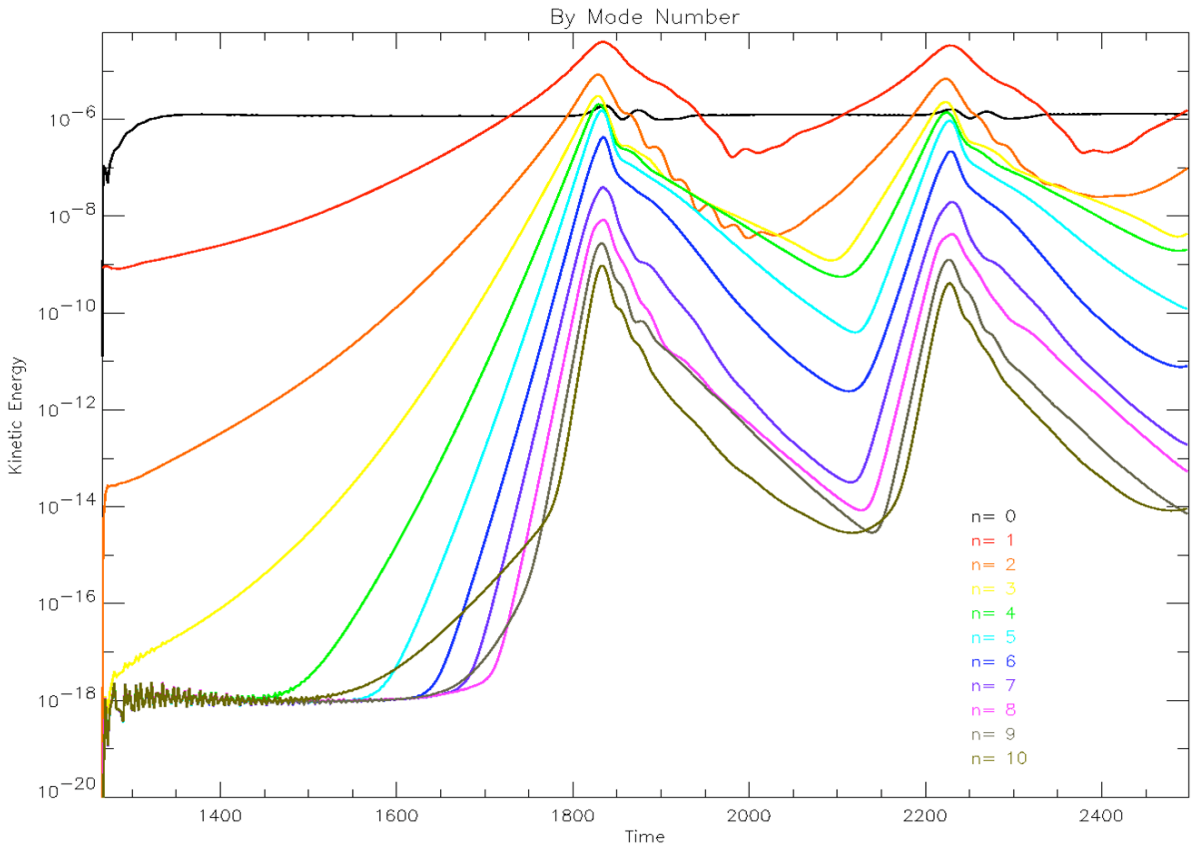

Figure A.4. Result from M3D simulation of sawtooth simulation for CDX-U. K.E. of each of the first 10 toroidal harmonics is plotted. Simulation period agrees with experimental period to within 25%.

High-Level Milestones:

- Complete and publish CDX-U simulation results.***(2006)***
- Extend the CDX-U work to larger, higher temperature tokamaks ***(2008).***
- Incorporate energetic particle effects into the predictive sawtooth modeling for a burning plasma ***(2010).***

A.2.5 Neoclassical Tearing Modes

The Neoclassical Tearing Mode (NTM) is observed to set the pressure limits in many long-pulse discharges. One of the major thrusts of the nonlinear MHD effort is to include sufficient physics to simulate the NTM and to differentiate between the competing mechanisms, for which neoclassical closures for the ion and electron viscous stress tensors are essential. We are presently collaborating with the ORNL theory group in interfacing the neoclassical closures developed at ORNL with the M3D code. The goal of this work is to extend the scaling of the NTM threshold to large devices and investigate relative changes in the importance of the different threshold mechanisms. This model will form the basis for subsequent modeling of RF control on the NTM.

Another issue is whether the plasma can generate a seed island of sufficient width to exceed the NTM threshold. A wide range of mechanisms have been observed as precursors to NTMs, including the sudden onset of the internal kink, coupling to magnetic field errors, coupling to the magnetic perturbation of an Edge Localized Mode (ELM), and transition from resistive tearing to neoclassical tearing. These coupling issues relate this effort to the sawtooth modeling efforts. Another, related issue is to better explain the cause and effects of island rotation.

The NTM problem is challenging because of the very slow growth rates, necessitating long run times for the M3D code. The 3D equilibrium code PIES code potentially provides a complementary approach to studying NTMs. Because the mode grows on a resistive time scale, radial force balance is maintained, and the dynamical nonlinear evolution could in principle be described by Faraday's law, and a three-dimensional equilibrium code with the correct constraints. A plan for addressing this with the PIES code is discussed in Section C.

High-Level Milestone:
Develop a predictive model of neoclassical tearing modes in tokamaks and STs together with researchers at ORNL ***(2008).***

A.3. Edge MHD Stability and the Behavior of ELMs
The long-term goal of this work is to understand the origin and dynamics of the edge localized modes, to make contact with the theory to the experimental characterization of (Type I-V), and to understand under what conditions a burning plasma can access small ELM regimes.

A.3.1 Linear Analysis:
Detailed comparison of the results of linear ideal MHD analysis and experimental results show a good correlation between the stability criteria for intermediate-n ideal peeling/ballooning MHD mode stability and Edge Localized Mode (ELM) activity in experiments. Recent efforts include, a resistive plasma, and a simulation domain that extends to the separatrix. [12] These calculations can provide indications of what the critical gradients are, as a function of edge current density, for edge-localized MHD modes, and what the height of the H-mode pedestal is. Among the items that need to be determined are the width of the region over which the plasma pressure profile can assume the critical value, and the nature of the trigger mechanism for the ELM.

A.3.2 Nonlinear Physics of ELMs and Nonlinear Evolution of Free Boundary Modes:
The M3D code has recently been extended to be able to model free-boundary modes, where a vacuum region surrounds the plasma, which is in turn surrounded by a conducting wall. [13] The primary applications of this extension are to ELMs and resistive wall modes (RWMs), although it also provides a more realistic description of primarily internal modes, and the onset of plasma disruptions. The goal is to make closer contact with the ELM cycles observed in experiments, and to identify under what conditions the different ELM types will occur, i.e., Type-I, Type-II, etc.

High-Level Milestone:

- Support the nonlinear study of free boundary modes in tokamaks and stellarators by researchers at NYU and MIT (***2006/10).***

A.4 Energetic Particle Modes

We plan to further investigate resonant destabilization of discrete and continuum Alfven modes by energetic particles such as fusion alphas or beam-injected ions. [14-15] This effort includes toroidal Alfven eigenmodes (TAE), "fishbones", and energetic particle modes.

Current emphasis is on including more realistic models that take into account realistic geometry, non-Maxwellian background distribution functions, improved damping models, and self-consistent mode structure, (see Fig. A.5), so that the energetic particles are included non-perturbatively [16-18]. Interest is in conventional and reversed-shear plasmas, as well as in STs and stellarators [19]. The long-term goal is to provide quantitative reliable predictions of the amplitude saturation of collective modes and consequences for ITER, such as alpha particle transport and its effect on plasma burning.

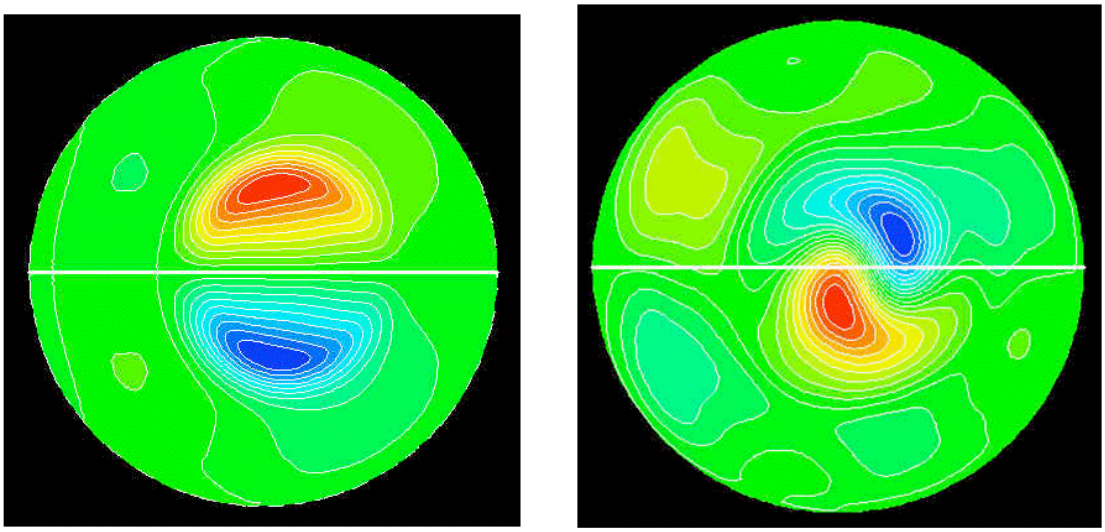

Figure A.5. Change in the unstable eigenfunction when going from an ideal instability (left) to a fishbone instability (right) driven by energetic particles.

High-Level Milestones:

- Perform nonlinear hybrid simulations of beam-driven MHD modes in NSTX and relate to experimental results ***(2006).***
- Perform nonlinear hybrid simulations of alpha-driven MHD modes in ITER ***(2008).***
- Explore integrated simulations of fast ion driven modes where their effect on the background profiles is calculated self-consistently as part of an integrated plasma model. ***(2010).***

A.5 Prediction of the Cause and Effect of Disruptions

The highest performance discharges in tokamaks are often terminated by a major disruption. This event causes rapid loss of thermal energy during the thermal quench phase and then loss of current during the current quench phase. The current quench phase also produces

large electric fields that can accelerate substantial populations of electrons to the runaway regime by way of the avalanche process. In reactor scale devices, structural, divertor tile, and first wall damage caused by disruptions are major concerns.

A.5.1 Physics of the Disruption

For the tokamak to succeed as the embodiment of a fusion power plant, we will need a much better understanding of the mechanisms that lead to major disruptions. MHD simulations have been used to identify the mechanism of a particular type of high-beta disruption in the Tokamak Fusion Test Reactor (TFTR): a localized moderate-n ballooning mode nonlinearly destabilized by an internal kink. Further studies with more resolution and improved physics models will be carried out to produce accurate criterion for such instabilities, which may shed light on ways to control or avoid them. Other disruption mechanisms need to be studied, such as the overlap of islands, and the coupling of sawteeth modes with NTMs and ELMs. These studies will necessitate many different nonlinear code runs with a credible physics model to build up a better understanding of the different sequences of events that lead to disruptions, their statistics, and their dependence on tokamak operating parameters. Another related thrust is to understand the difference in disruption mechanisms between tokamaks, current-carrying stellarators, and spherical tori. Of particular interest is to understand how externally-generated rotational transform provides disruption protection in stellarators.

A.5.2 Disruption Forces

We have developed a detailed axisymmetric model of disrupting tokamaks with the TSC code. This includes a model of the thermal quench, current quench, halo currents, runaway electron generation, and the surrounding coils and structure. We have used this to study disruption prevention and mitigation techniques in tokamaks [20-22]. There is a continuing need to apply these tools to ITER in order to evaluate specific mitigation techniques, such as massive impurity injection and massive gas injection by way of supersonic gas jets, extending previous “killer pellet” injection simulations. There is also a need to calculate the vessel forces due to the non-axisymmetric nature of the disrupting plasma. These non-axisymmetric halo currents have been identified by the ITPA as a critical item affecting the design of ITER. The vacuum and resistive wall additions to the nonlinear code M3D have enabled it to address these issues. We are also providing technical support to researchers at NYU and in Europe who are using the M3D code to study these [13].

A.6 Control Issues

A tokamak fusion Power Plant will require many control systems. The PPPL Theory Department has been closely involved in several design studies for next generation burning plasma experiments and tokamak Power Plants where we have contributed to the design and evaluation of the control systems. [23-26]. Here we discuss some of the ongoing and planned activities.

A.6.1 Profile and Shape Control

The Tokamak Simulation Code (TSC) is a widely used tool for predicting the axisymmetric evolution of tokamaks and spherical torii. It solves for the transport-timescale evolution of the plasma parameters as well as the poloidal field coil currents and their associated control

systems and vessel currents. It was chosen by the ITER project as the standard code for projecting Volt-second requirements, plasma evolution, plasma shape control and several other functions. (However when the US dropped out of ITER, the project transitioned to using the DINA code. Now that we are back in the ITER framework, TSC is again being used, but more by the U.S. ITER team to verify and extend some of the DINA calculations) We plan to keep developing TSC and to continue to perform new calibrations as available, and to use it to design new experiments and to help optimize existing experiments as required. Recent applications of TSC include the study of tokamak startup by bootstrap overdrive [27], a study of methods to prevent the production of runaway electrons in disrupting tokamaks [21], a study of current spike behavior and its effect on plasma control during a disruption [22], and a study to design a shape control system for the new Korean Tokamak KSTAR [28]. Present applications include optimizing the CHI experiments on NSTX (see section A.9.1) and comparison of integrated modeling calculations with experimental data on DIII and NSTX). Future development will concentrate on incorporating better current-drive modules, a closer coupling with the TRANSP and pTRANSP codes, and incorporation of a more modern graphics package. We are providing technical support for the usage of TSC by the PPPL experimental and engineering departments as well as users outside of PPPL.

A.6.2 The Physics of Pellet Fueling

Injecting small pellets of frozen hydrogen into a tokamak is known to be a viable method of fueling. Early work by Parks, et al., gives a fairly accurate expression for the ablation rate for such pellets once they contact the high temperature plasma in the tokamak. However, it is known from many experiments that the resulting density profile measured after the pellet has ablated is not consistent with what one would infer by assuming that the ablated material remains on the flux surfaces where the ablation occurred. The subsequent "anomalous" redistribution of mass is believed to be due to MHD processes.

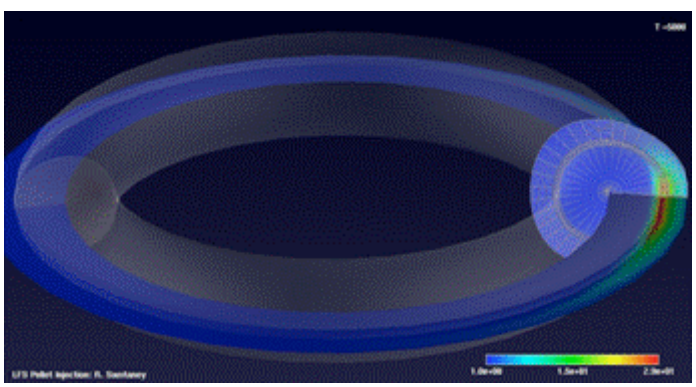

Figure A.6. AMR calculation of outside launch pellet injection.

This mass redistribution is most dramatic in experiments that compare density profiles resulting from "outside launch" and "inside launch", referring to whether the pellet is injected from the exterior, low-field side of the torus, or the interior, high-field side. It has been clearly demonstrated that pellets injected from the inside are more effective in fueling the center of the plasma. Near vertical launch is also an attractive option for next-generation experiments.

In an initial attempt to model this mass redistribution, the M3D code has been used to model the evolution of a localized "density blob" in a tokamak, and has verified that MHD effects cause the localized density perturbation to displace towards the low-field side of the plasma. [29]. Impurity pellets have also been shown to induce disruptions within this model. [30]

However, this simulation did not have a pellet ablation model, did not follow the pellet trajectory, used single-fluid resistive MHD, and the resolution was fairly coarse.
We are extending this modeling in several ways with a new Adaptive Mesh Refinement (AMR) MHD code AMRMHD (see Fig A.6), developed in conjunction with the applied math group at Lawrence Berkeley National Laboratory (LBNL).[31] The model being developed has two-fluid physics, the Parks pellet ablation model, anisotropic heat conduction, and adaptive zoning to allow accurate modeling of the expected range of space scales.

High-Level Milestone:

- Develop a realistic 3D model of pellet injection into a tokamak based on the AMR technique, publish this (will be presented as an APS invited talk) ***(2006)***
- Compare inside and outside pellet simulations with JET data using the AMR code. ***(2008)***
- Project pellet injection simulations to ITER ***(2010)***

A.6.3 Resistive Wall Mode Control

We are performing both linear [32-34] and non-linear [35] analysis of the resistive wall mode and its active feedback stabilization For the linear analysis, we have modified the VACUUM code to contain a resistive shell and feedback coils. This has been interfaced both to the DCON ideal MHD stability codes to allow the computation of resistive wall modes and feedback with these stability codes. This also facilitates the interpretation of Mirnov loop signals and eddy currents induced by instabilities. [38] The active feedback analysis is guided by the circuit equations formulation for kink-mode feedback.

A major thrust of both the DIII-D and NSTX experimental programs is to demonstrate feedback stabilization of the resistive wall mode at high-beta. Together with colleagues in the Theory Division at General Atomics, we have developed a unique linear tool for analyzing these experiments using an eigenmode approach, and incorporating feedback at a fundamental level so that its effect on the plasma eigenfunction can be calculated self-consistently.[33,34] This code differs from the VALEN approach, where the structure of the eigenfunction is assumed to be independent of the applied feedback. This code is now in the process of being upgraded to include plasma rotation.

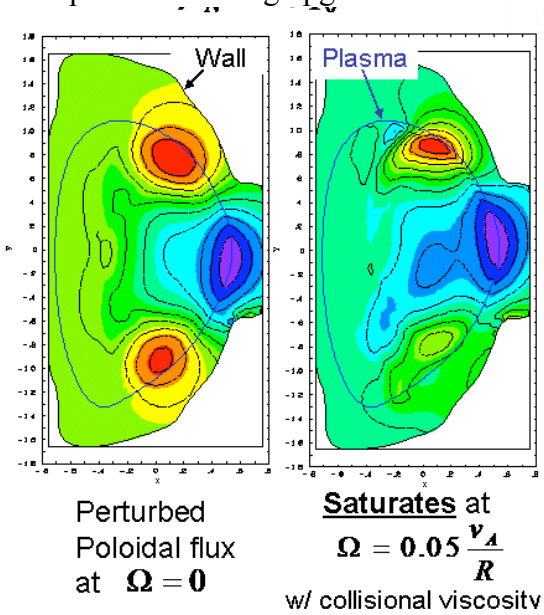

Figure A.7. Nonlinear M3D simulaton of an RWM.

For the nonlinear analysis, we will continue to use the nonlinear Extended-MHD code M3D (and possibly the 3D iterative equilibrium code PIES) to investigate nonlinear physics associated with the resistive walls and free- surface motion of the plasma/vacuum interface. Nonlinear simulations have begun, (see Fig. A.7), including models for the resistive wall and for plasma flow damping. [35] These will

continue, and are expected to provide essential information on resistive wall modes and mode locking. This information will be compared with experimental, [36, 37] linear numerical results and analytical results to learn when to expect detrimental MHD activity and how to avoid it.

These simulations will be extended to include magnetic feedback, which will be modeled with time-dependent magnetic fields applied from realistic coil configurations. Nonlinear simulations will provide information on the effectiveness of feedback schemes for activity coupling to realistic plasma/resistive wall systems.

The application of the M3D code to this problem has required the development of non-ideal boundary conditions. These consist of two pieces: (1) the resistive wall and external vacuum region, and (2) the internal vacuum region between the magnetic separatrix and the wall. The resistive wall and external vacuum are incorporated as a boundary condition, which is applied to the magnetic vector potential in M3D. The thin-shell approximation relates the evolution of the normal magnetic field to the jump in its normal derivative inside and outside the wall. The interior numerical solution is coupled through this normal derivative inside the wall, and the exterior solution is determined by a Green's function treatment of the outer vacuum. This is presently being done with the GRIN code, but we will transition to using the VACUUM code, which has improved capabilities and better support. The technique we are using for simulating the internal vacuum region is to represent it as a plasma, with a large resistivity thereby suppressing current within this region.

The present VACUUM and resistive wall analysis used in the linear codes and to be incorporated into the nonlinear codes assumes an axisymmetric wall. This assumption eventually has to be removed in order to quantitatively assess the effect of ports and other non-axisymmetric structures, and work has begun on generalizing this approach.

High-Level Milestones:

- Extend the VACUUM code to be fully up-down asymmetric capable, and incorporate the same vacuum code in M3D that is used in the linear codes ***(2006).***
- Perform a study on NSTX, similar to what was done on DIII-D, of RWM feedback as a function of the geometry and placement of the coil system. ***(2007)***
- Extend the vacuum treatment to allow for 3D structures ***(2007-2008).***

A.6.4 Internal Mode Control

It has been demonstrated experimentally that both the sawtooth and the NTM can be controlled by the application of RF heating and current drive. Our goal is to develop theoretical models of this stabilization and to use these models and simulations to interpret and extend the region of applicability of the experiments.

It has been demonstrated on JET and other tokamaks that application of ICRH near the q=1 resonant surface can delay or completely stabilize the sawtooth. It is proposed to study this phenomenon from a fundamental level. There are now RF absorption codes that can accurately calculate the absorption of RF waves in fully 3D geometry and the resulting

modification of the distribution function. We plan to couple these with the nonlinear 3D Hybrid/MHD code to assess the relative importance of current drive, plasma pressure modification, and energetic particles in controlling this mode. This modeling should be of direct benefit to ITER, to provide the flexibility to control the sawtooth if it becomes necessary.

Where NTMs cannot be avoided, active stabilization is required. Both lower hybrid wave and electron-cyclotron emission current drive have been proposed and tested experimentally as mechanisms for stabilizing tearing modes through the generation of current and pressure in the vicinity of an unstable island. We propose implementing existing fluid-like models of RF-driven current in M3D to investigate the feedback stabilization of NTMs as part of the SWIM-FSP collaboration.

High-Level Milestone

- Produce a publication on the physics of RF inducement of sawteeth (with SWIM colleagues) ***(2008).***
- Produce a publication on the physics of RF stabilization of the NTM (with SWIM colleagues) ***(2010)***

A.6.5 Equilibrium Reconstruction

We have recently resolved the long-standing problem of equilibrium reconstruction in an environment where substantial eddy currents exist. A special numerical code Cbc2e was written and a new technology of calibrating tokamaks was tested on the CDX-U device, which uses the time history in equilibrium reconstruction. This approach gives rigorous interpretation to the magnetic measurements and is especially important for devices where the decay time of the eddy currents in the conducting structures is comparable with the plasma current ramp-up time.

A.6.6 Real-Time Forecasting for Tokamak Discharges

The code system ASTRA-ESC-DCON-BALLOON is under development, linking transport simulations, free boundary equilibrium reconstruction, and low and high n-stability. The system is a prototype for a system for real time forecasting (RTF) of tokamak discharges. RTF would extend the current EFIT approach, presently restricted to equilibrium reconstruction, to more sophisticated plasmas models, which evolve consistent with the real time data flow from the experiment. RTF is envisioned as a software package, which arranges the communications and control of an open system of codes, working with imperfect data and models and with a large number of control parameters. At present, the four code system has shown its functionality and it will be extended in the future. Future applications include the use of this technique for real-time disruption prediction so that disruption mitigation measures, (e.g., killer pellet) could be invoked.

A.7 The Li-Wall Concept

A new theoretical assessment and interpretation of basic technology data obtained by the University of Illinois and the T11 tokamak team indicate that the unique pumping properties of lithium make it feasible to have a close fitting stabilizing “lithium wall” right at the plasma boundary. Such a first wall is compatible with high plasma edge temperatures, and is predicted to give access to stable high-beta regimes (10% or greater in tokamaks, 40-50%

in STs). [39] The high beta would allow the use of lower magnetic fields for the same fusion power density, which when combined with the high plasma temperature would increase the importance of Finite Larmor Radius (FLR) effects, further contributing to stability at high beta. This low-recycling, high edge temperature, wall-stabilized plasma has many attractive features,[40,41] and we expect to continue to explore its properties, to support the new experiment, LTX at PPPL, and to propose further experimental tests [42] of this configuration.

A.8 Reconnection Physics

We continue to seek a better understanding of basic magnetic reconnection and to identify the common features and differences between reconnection physics occurring in simple laboratory plasmas, high-temperature fusion devices, near space, the sun, and in galactic dynamics. The present focus is in the cross - coupling of macro and micro scales, including the generation of turbulence and associated anomalous resistivity and viscosity, which results as a consequence of the magnetic reconnection. [43-49]

A.8.1 Reconnection in the Extended MHD Model

We continue to investigate model problems with more complete extended MHD equations to understand the role and importance of the different terms, such as the Hall term, electron pressure gradient, neoclassical terms, and electron inertia in the generalized Ohm's law, of the gyroviscous and neoclassical terms in the momentum equation, and of three-dimensional effects and intermittency in the reconnection region.

A.8.2 MRX Modeling

We are performing high-resolution numerical simulations of the 2-D Hall-MHD equations and comparing these to MRX data. [50] We are also incorporating two-fluid effects in the simulations of reconnection in tokamaks to quantify their effects there. We will begin exploring fully 3D reconnection with the goal of identifying the secondary instabilities that lead to anomalous resistivity, viscosity, energy and particle transport, and understand the differences with the 2D system. This work should help to bridge the gap between the MRX results and resistive MHD (the growth of neoclassical tearing modes and the sawtooth periods) observed in high-temperature tokamaks, as well as with solar-flare rates and other astrophysical phenomena.

A.9 Relaxation Physics and Self-Organization

It is well known that certain plasma confinement configurations such as the spheromak or a spherical torus undergoing CHI relaxation exhibit some degree of self-organization. The detailed modeling of these experiments with extended-MHD codes provides insight into the relaxation process, provides experimental guidance, and may provide a useful design tool for the design of future devices.

A.9.1 CHI Physics:

NSTX is unique among the large toroidal fusion devices in its ability to bias the central and outer parts of the vacuum vessel in order to draw large currents to study the physics of Coaxial Helicity Injection (CHI). The CHI experiments are key to the mission of the

Spherical Torus (ST) in that their demonstrated success would allow the next generation of STs to be designed without a central solenoid, thus allowing the ST to reach its full potential as a compact and attractive confinement configuration. We have developed specialized equilibrium reconstruction codes (based on ESC) and specialized axisymmetric evolution codes (based on TSC) to support these experiments. The existing experiments can be explained by these 2D models, and we will continue to use these to support new experimental campaigns aimed at optimizing the amount of closed flux and at "handing off" a CHI-produced plasma to be amplified by the OH system. If experimental results warrant it, we will extend these simulation and interpretation studies to 3D using the M3D code, which now has a vacuum mesh and conducting-wall boundary conditions implemented.

A.10 Relation to the CEMM SciDAC and SWIM Fusion Simulation Project

This group is partially funded by the SciDAC proposal Center for Extended MHD Modeling (CEMM) and the Fusion Simulation project Simulation of Wave Interaction with MHD (SWIM).

PPPL is the lead institution for CEMM. (see http://w3.pppl.gov/CEMM) The PPPL-specific work will concentrate on the M3D applications involving sawtooth and energetic particle modes, on M3D code improvements involving the higher order C^1 elements, and on the integration work with the Wave-Plasma SciDAC Center. With the SAPP funding, we will also perform the Adaptive Mesh Refinement work (together with Lawrence Berkeley Laboratory and the SciDAC APDEC), and on developing advanced data transfer and graphics for all the codes.

Within SWIM (see http://www.cswim.org), PPPL is responsible for managing the "Fast MHD" campaign where the effect of RF on the sawtooth will be simulated, and will implement the SWIM closures into the M3D hybrid option, and pursue applications. The CPPG group will take the lead for the SWIM evolving-equilibrium-code suite, data management, code monitoring functions and will provide additional computer science support as needed.

Related topics: This section has addressed only some of the issues related to macroscopic stability, with particular emphasis on tokamak applications. In later sections, the topic of macroscopic stability is revisited with different emphases. The interactions of energetic particles with MHD are treated with greater detail in Section II.C. Collaborative activities, with an emphasis on modeling experiments, are summarized in Section III.A. Macroscopic stability issues, which are relevant to the ST operating regime, high plasma rotation, high-b, and low aspect-ratio, with particular emphasis on NSTX experiments are described in Section III.B. Macroscopic stability of non-axisymmetric devices, with emphasis on NCSX, is addressed in Section III.C. The physics of kinetically dominated MHD, as observed in field reversed configurations, FRCs, is the subject of Section III.D

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B. Turbulence and Transport

Multiscale transport physics deals with spatial scales from the ion gyroradius to the device size with mesoscale physics in between. It also has to include temporal scales ranging from fast electron motion along the magnetic field line to the much slower transport time scale. Therefore, this area of research is challenging both theoretically and computationally. The primary purposes here, as stated in the 2005 FESAC report, are to understand 1) turbulence-generated heat, particle and momentum loss, 2) the origins of and the methods to control large scale currents and flows in fusion devices, and 3) magnetic reconnection and the associated energy dissipation. Progress in understanding key transport physics issues associated with accessing and maintaining enhanced confinement regimes will be pursued, including, further development of nonlinear simulations, comprehensive turbulence diagnostics, analytical theories, and comparisons to experiments. It must be appreciated that the time scale for advances in basic physics is difficult to predict, but certain milestones can be laid out to measure progress, as shown below. Nevertheless, over a period of five years, one can expect significantly improved understanding of a variety of fundamental nonlinear processes of relevance to plasma physics in general and to tokamaks in particular. The approaches taken are based on both simulation and theory. On the simulation front, PPPL has been a leader in using gyrokinetic particle codes on massively parallel computers to investigate microturbulence for the past decade. Significant achievements include the successful comparison of k-spectra from ion temperature gradient (ITG) turbulence simulations with the experimental measurements; elucidation of zonal flow properties in toroidal geometry; and the role of turbulence spreading in determining confinement scalings. PPPL is now the lead institution for the DoE Office of Fusion Energy Science's SciDAC grant, "Center for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas" in collaboration with six other universities. In addition, PPPL has just received a three-year grant to pursue a multiscale mathematics research project sponsored by the DoE Office of Advanced Scientific Computing Research, entitled "Multiscale Gyrokinetic Particle Simulation of Magnetized Plasmas." These activities are expected to expedite the PPPL turbulence effort in the future. On the theoretical front, we will continue to assist the simulation effort by interpreting the numerical results and to develop new theories for predicting future experimental trends. Our five-year plan is summarized below in sections B.1 – B.6.

B.1. Ion Thermal Transport and Physics of Zonal Flows

Nonlinear simulations of toroidal Ion Temperature Gradient (ITG) driven turbulence have in the past significantly contributed to our understanding of the characteristics of turbulence responsible for anomalous heat transport in tokamaks, and to progress toward quantitative prediction of transport. Following the pioneering work on gyrokinetic particle simulation [1] and the rigorous nonlinear gyrokinetic formulations [2-3] in the 80's, close interactions within the gyrokinetic particle simulation team [4], the gyrofluid simulation team [5], and analytic theorists in the 90's [6] led to a new paradigm of microturbulence in magnetic confinement devices. The model that emerged is one of a self-regulating two component system consisting of microturbulence, which can cause radial transport, and the zonal flows, which can be generated by the turbulence and regulate the turbulence in return. Detailed

diagnostics for nonlinear simulations and characterization of zonal flow properties [7] have significantly influenced the experimental community to measure zonal flows to gain deeper understanding of turbulence driven transport.

Computationally, the primary tool to study micro-turbulence is the global gyrokinetic toroidal code (GTC). The simulations using GTC are free from the subtleties of local turbulence assumptions employed in simplified flux-tube codes and can straightforwardly address the possible importance of non-local physics phenomena in determining transport scalings. In particular, the deviation from gyro-Bohm scaling observed for a modest system size [8] appears to be related to radial spreading of turbulence into the linearly stable zone [9] which has been ubiquitously observed in global gyrokinetic simulations [8-11]. The flux tube codes are also valuable, particularly when local, and faster, solutions are needed, such as in large parameter scans.

The issue of particle noise has been a topic of research ever since the invention of Particle-In-Cell (PIC) simulation, nearly forty years ago. Since then, a lot of progress has been made in understanding the nature of particle noise and methods to remedy it have been identified. Recently, with the requirement of longer time simulations, needed to understand transport scaling trends, particle noise has resurfaced as an issue. As in the past, the best ways to deal with the issue are: use convergence tests to assure that the number of particles used is adequate; bench marking with other particle codes; bench marking with other kinetic simulation codes; and comparisons with theoretical predictions. We plan to adopt all these methods in the future.

Milestones and Deliverables

Simulations: Full torus gyrokinetic global particle simulations based on GTC have been focused on the role of turbulence spreading in influencing confinement scalings. This study will be continued, in collaboration with the University of California, San Diego and with the University of California, Irvine (FY06-07). An additional focus is on edge-core coupling, this is also addressed in Section D.

Code development: In order to facilitate team coding and to improve the parallelization, scalability and efficiency on massively parallel computers it is necessary to develop a modularized object-oriented version of the global GK code (GTC). This will be done in collaboration with UC-Irvine, UCLA, and U. Colorado. We also plan to develop comprehensive diagnostics and visualization for turbulence characteristics and spectral transfers in order to advance the fundamental understanding of the nonlinear, non-local behavior of turbulence with zonal flows, and for more detailed comparisons with experiments as part of the SCIDAC turbulence transport simulation activity. (FY06-09).

Our global gyrokinetic simulation results from the GTC code are being analyzed by the ORNL and UC-Davis team using a comprehensive diagnostic package, and this will be continued (FY06-10).

Model improvements: Building upon recent success using a four-dimensional center manifold [12], a quantitative, self-consistent analytical statistical theory of self-generated shear-flow causing suppression of turbulence will be pursued (FY06).
The role of velocity-space nonlinearity in influencing the long-term behavior of ITG turbulence [13] will be studied further (FY06-08).

B.2. Electron thermal transport and particle transport

Full kinetic descriptions of electron dynamics have become standard in some local and wedge gyrokinetic particle and continuum simulations and are being developed for global gyrokinetic particle-in-cell simulations. However, compared to the understanding of ion thermal transport and electrostatic turbulence, the magnetic fusion community has much less of an understanding of electron thermal transport, particle transport, toroidal angular momentum transport and electromagnetic turbulence. For instance the zonal flow behavior in the presence of trapped electron dynamics, appear to be qualitatively different [14] based on nonlinear simulations, which have been carried out during the past few years with fully kinetic electron dynamics. Much more research is needed to fully understand these results and to integrate them into predictions of tokamak performance. With these uncertainties, the possible relevance of radially elongated streamers generated by ETG turbulence is being studied via the gyrokinetic continuum code in collaboration with IPP-Garching and the University of Maryland [15]. In parallel it is being addressed using GTC, in collaboration with the University of California at Irvine. The initial results with GTC show a rather low level of electron thermal transport with toroidal mode coupling as a possible explanation for the observed nonlinear saturation [14], and further detailed studies will be carried out in terms of particle convergence tests and bench marking with other particle codes in an effort to obtain a better understanding. Theoretical methods will also be pursued.

We are also in the process of implementing electron dynamics in GTC using the split-weight scheme [16], which depends crucially on the use of the PETSc toolkit [17] with a finite element interface [18]. The nonlinear consequences of trapped electrons, including the role of short radial scale zonal flows observed in simulations [14] are being investigated. Currently, the electromagnetic effects are being included in a simple geometry GTC code.

Milestones and Deliverables

Noise in ETG turbulence: In collaboration with University of California at Irvine, we will study the role of radially elongated streamers in ETG turbulence and examine the role of particle noise in the coming year, which includes particle convergence tests and benchmarking with other particle codes (FY06).

Benchmarking: Following the benchmarking of GTC with GYRO and PG3EQ on ion thermal transport, nonlinear simulations addressing electron thermal and particle transport will be benchmarked against the GT3D code of JAERI, Japan, and the GEM code of the University of Colorado. The general geometry version of the GTC code [11] will be used for applications to NSTX, JT-60U, JET, and ITER (FY06-08).

Improved electron dynamics: We will port all new algorithms relating to more realistic kinetic electron dynamics, developed in simple geometry, to the general geometry version of GTC code. The resulting code will be used for studying NSTX plasmas and, with proper parallelization and optimization, to investigate burning plasma physics for ITER (FY07-09).

Role of shear: Studies of the role of trapped electron precession shear in suppressing trapped electron driven turbulence will be carried out (FY07).

B.3. Neoclassical Physics and Pathways to Integrated Simulations

Neoclassical physics in shaped plasmas has recently been under investigation using the GTC-Neo code [19]. The linkage between the turbulence code, GTC, and GTC-Neo will be a crucial step toward a more comprehensive integrated simulation of tokamak confinement. With our recent progress in simulating turbulence in the long term steady state [13] and expected implementation of the electromagnetic effects in GTC, it will be possible to design a pathway to an integrated simulation of steady state transport. However, even with the most advanced computing resources, it is not feasible to carry out integrated simulation in time using "first principles simulations." Reduced models to bridge the time domain are still needed along with other novel ideas.

The traditional multi-region treatment (e.g., using the pedestal temperature for a boundary condition for core transport simulation) of tokamak confinement can be improved by considering the effect of turbulence spreading. As shown in Fig B.1, a recent GTC simulation indicates that the core turbulence level, which is predicted to be negligible from a local simulation, can be enhanced to a significant level of experimental relevance due to turbulence spreading from the more strongly turbulent edge [20].

Milestones and Deliverables:

Plasma geometry: Neoclassical physics (especially accurate calculation of ion thermal transport, radial electric field and bootstrap current) in tokamaks, spherical tori, and stellarators will be studied using the particle-in-cell GTC-Neo code. This is a long term project, which involves extensive changes in the code for progressively more complicated geometries culminating in shaped cross-section non-axisymmetric capability (FY06-10).

Comparison with Experiment: The macroscopic ExB flows will be included in gyrokinetic particle simulation of shaped plasmas to study the transition to enhanced confinement regimes, and the simulation results will be compared with the experimental results (FY06-08). (See the tokamak projects section in Sec. III for details)

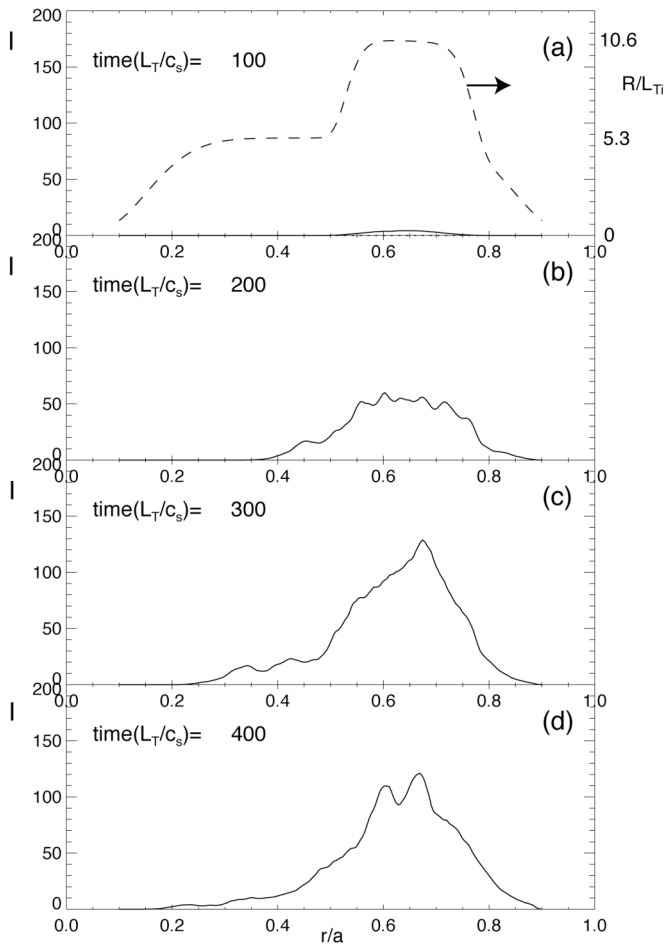

Fig. B.1 Spatio-temporal evolution of turbulence intensity from a GTC simulation exhibiting significant turbulence spreading from the strongly unstable edge region to the core region, which is within the Dimits shift regime (i.e., dominated by self-generated zonal flows which locally reduce the transport to a negligible value) [20].

Integrated simulation: Building on the success of gyrokinetic codes developed for core turbulence, kinetic edge turbulence code development has been initiated under the sponsorship of the Center for Plasma Edge Simulation (CPES) in collaboration with NYU and other institutions, in which the interaction with the DEGAS 2 neutral code (FY05-FY08) and with the GPSC/GTC team on diverted tokamak geometry for studying L-H transition physics will be explored. See also section II.D (FY07-10).

Nonlinear studies: Turbulent transport in stellarators and spherical tori are being studied by linear stability analyses using the FULL code, which has been extended to alternate concept geometry, and by continuum gyrokinetic calculations in collaboration with the University of Maryland. These will be extended to the nonlinear gyrokinetic global particle-in-cell simulations in spherical tori (FY06-08), and stellarators (FY08-10).

Transport time scales using PIC codes: Following algorithm development for the integration between gyrokinetic particle microturbulence simulations and transport time scale simulations involving transport modeling codes and an MHD equilibrium code

(FY07), we will initiate microturbulence simulations on the transport time scale on massively parallel computers (FY08-10). This involves the use of gyrokinetic particle codes to simulate steady state micorturbulence as an initial value problem, the use of transport modeling codes to predict the profile evolution and the use of an MHD equilibrium code to calculate the new magnetic topology before starting the next cycle of microturbulence simulation.

Integrated transport simulation using continuum codes: After testing the local gyrokinetic version of the GLF-23 model, and its interaction with transport codes, we plan to explore the possible coupling of the nonlinear GS2 code with transport codes to provide a fully integrated simulation of core tokamak profiles. Techniques have been proposed to stabilize the iteration between the nonlinear turbulence code and the long-time-scale transport code. To make this more tractable, we are exploring the use of sub-grid models in GS2. This research will be carried out in collaboration with the University of Maryland and other institutions (FY06-08).

B.4. Analytic Theory of Microturbulence

On the analytic front, besides the work on turbulence spreading [9,10,20] and zonal flow induced upshift of the ITG linear threshold [12] mentioned earlier, review articles on the long term outstanding plasma turbulence issues have been published and are currently in preparation. Recent examples include a review on the statistical description of magnetized plasma turbulence with an emphasis on conceptual foundations and methodology [21], a review on transport barrier theories and simulations with an emphasis on the common physics element and comparisons to experiments [22], and a comprehensive review article of zonal flow phenomena in plasmas including the status of theory, numerical simulation and experiments as well as directions for progress in future research [23]. This article has been written in collaboration with University of California, San Diego, Kyushu University, Japan, and National Institute for Fusion Sciences, Japan. In addition, a significant advance in the analytic formalism addresses the analysis of possible interactions between convective cells and the key topic of zonal flow dynamics [24]. Progress in an analytic elucidation of transport reduction due to zonal-flow-induced random shearing has also been achieved [23].

Milestones and Deliverables:

Nonlinear gyrokinetic theory: A review article on foundations of nonlinear gyrokinetic theory in collaboration with St. Michael's college will be finished and submitted for publication [FY 06].

Edge turbulence: The development of a theoretical model for coherent structures in edge turbulence for use in comparisons with the GPI (gas puff imaging) data from NSTX and C-Mod, the inclusion of the zonal flow intensity in a simple analytic theory of turbulence spreading (in collaboration with UCSD, and UCI) and the extension of nonlinear gyrokinetic equations to high fluctuation amplitudes and steep gradient edge regions will be carried out for FY07-08.

ITG analysis: Theoretical analysis of the effects of the velocity space nonlinearity on ITG generated zonal flow and transport will be initiated, following the availability of comprehensive diagnostics [FY07].

B.5. Center for Gyrokinetic Particle Simulation of Turbulent Transport in Burning Plasmas

The center is supported by the Scientific Discovery through Advanced Computing Partnership (SciDAC) of the DoE Office of Science, for which PPPL is the lead institution in a seven party consortium. The primary purpose of the Center is to develop simulation capabilities for ITER plasmas in collaborations with the partners in applied mathematics and computer sciences communities. For the past year, PPPL has carried out: the optimization of GTC on vector-parallel computers [26]; its extension to general geometry [11]; its interface with the field solve [18]; the study of trapped electron effects on zonal flow dynamics [16] and the 3D visualization of ITG turbulence (see for example, Fig. B.2). Moreover, Many of the milestones associated with the Center activities have already been mentioned in the previous sections. Briefly, in FY06, we plan to investigate trapped electron effects in general geometry and the electromagnetic simulations of microturbulence will be carried out in FY07.

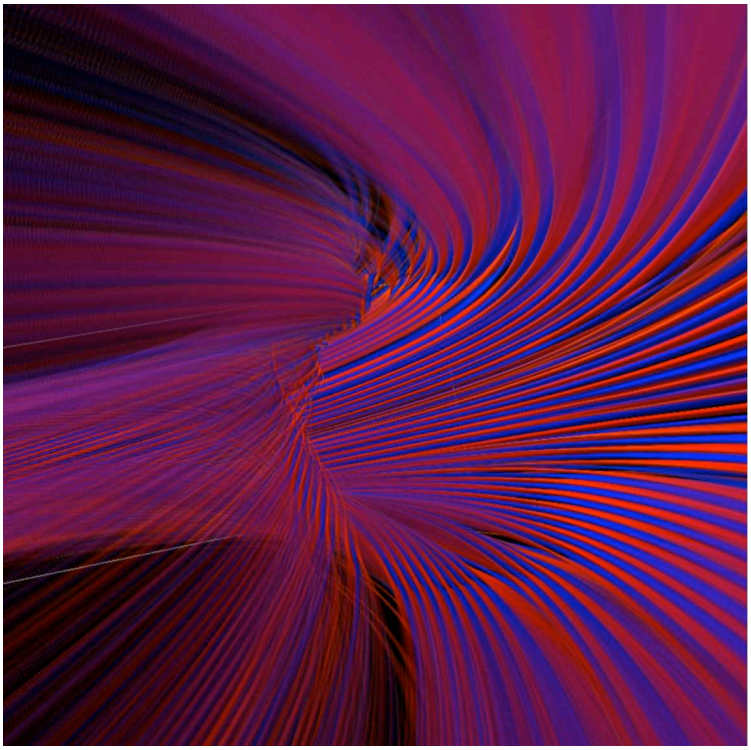

Fig. B.2 Three-dimensional view of the perturbed electrostatic potential due to ITG turbulence, viewed as flux tubes, aligned with the magnetic field lines.

B.6. Multiscale Gyrokinetic Particle Simulation of Magnetized Plasmas

This project for Multiscale Mathematics Research and Education (MMRE) is supported by the Office of Advanced Scientific Computing Research of the Office of Science in support SciDAC. PPPL is the lead institution in partnership with Columbia University. The primary purpose is the development of multiscale gyrokinetic particle codes by integrating, to the extent possible, high frequency ion cyclotron physics, medium frequency mesoscale turbulence transport and low frequency MHD modes. The algorithms design for the mesh refinement of the field solves and for the high frequency gyro-motion will be the focus for the first year (FY06). Simulations of kinetic internal kink modes and ion cyclotron waves will be conducted in FY07. In FY08, wave heating physics and the resulting MHD profile effects will be investigated.

In summary, PPPL has an ambitious but well planned program for turbulence transport studies for the next five years and the milestones are schematically described in Fig. B.3.

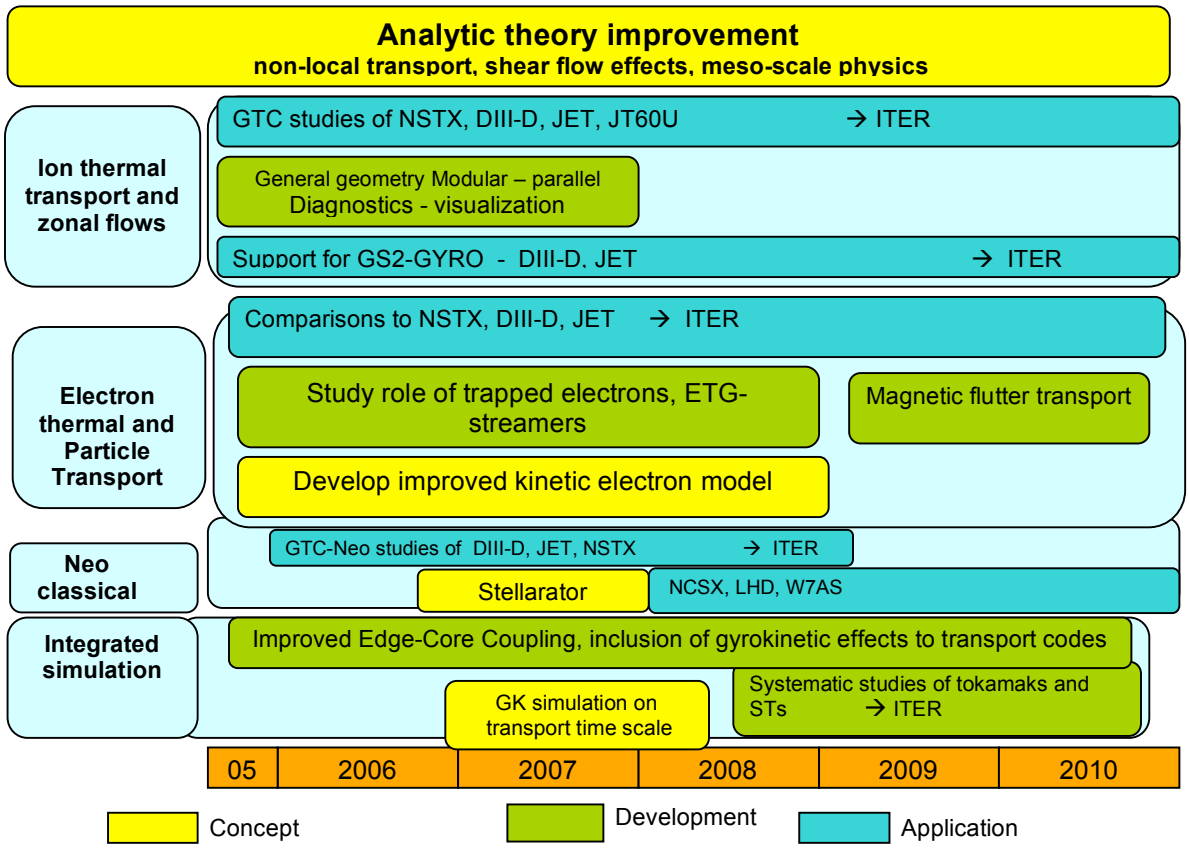

Figure B.3. A high level schematic, describing the research thrusts, development activities and applications in the turbulence and transport area with approximate time-lines.

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C. Wave-Particle Interaction/Energetic Particle Physics

The FESAC Priorities Panel report identifies two scientific questions relating to waves and energetic particles physics.
T11. How do electromagnetic waves interact with plasma?
T12. How do high-energy particles interact with plasma?

Our past theoretical efforts in the area of wave-particle interactions have been designed to understand the stability properties and confinement of fast particles in toroidal magnetic confinement devices. Our work is well aligned with the FESAC goals in this area. Our approach is to first emphasize efforts to improve our understanding and provide numerical tools for the analysis of present day experiments, and to predict the dynamics of energetic particle-excited modes in advanced regimes of operation with high pressure, inverted magnetic shear, and strong flow. The next step aims at burning plasmas, where Alfvén-mode-driven alpha particle transport will be of critical importance. In order to do this, we need to identify the character of Alfvén turbulence and the evolution of the energetic particle distribution in a nonlinear system.

The topic of wave particle interaction will be addressed using the perturbative hybrid MHD/kinetic models, which are used in the NOVA family codes. Another approach is to use full wave RF-wave codes, such as TORIC and AORSA. They can also account for the physics associated with kinetic effects, such as FLR and finite w/w_c effects. The two approaches are complementary.

Our work in this area is also complementary to the activities described in the Macroscopic Stability section, The difference is that here, the emphasis is on the effects due to super thermal species, such as instabilities driven by fast ions. These instabilities are like cavity modes of the plasma or energetic particle modes and primarily result in the redistribution of fast ions in the phase space.

The theory of energetic particle instabilities was initiated at PPPL in the 1980s. This area of research has now been established as a new sub-field of plasma physics, in addition to the traditional disciplines, such as fluid global MHD, kinetic theory of microinstabilities, turbulence and transport. At PPPL we have established a basic modeling framework for energetic particle physics based on an approach where a kinetic treatment of the particles is combined with fluid (MHD) equations into kinetic-fluid equations. PPPL's energetic particle physics group is now recognized as one of the world-leader, and its expertise in energetic particle physics is being used in many collaborative experimental and theoretical activities within the fusion community, and is also expanding into related non-fusion plasma physics fields such as space plasma physics.

Several key research areas are under investigation at PPPL and through collaborative activities with other institutions

1. *Single-particle orbits* in toroidal confinement devices including systems with strong magnetic shear and gradients (with ion gyroradii on the order of magnetic field shear

and gradient scale size). The goal is to understand particle transport due to (1) toroidal field ripple and collision including vacuum field and separatrix, and (2) MHD modes such as tearing modes, internal and external kinks, etc. We need to be able to control particle transport in advanced tokamak operation as well as in other magnetic fusion devices.

2. *Collective fast ion/alpha-driven instabilities* (TAEs, fishbones, kinetic ballooning modes, sawtooth stabilization and fishbones, bursting modes, compressional and global Alfvén eigenmodes (CAEs and GAEs) etc.) and their nonlinear behavior. The goal is to model (1) the interaction of fast ions with the $n=1$ internal kink mode related to sawtooth stabilization and fishbone excitation; (2) fast ion/alpha-driven shear-Alfvén type modes (TAE, RTAE, KTAE, EAE, NAE, RSAE, HAE, etc.); (3) fast-ion-driven CAE and GAE modes has been observed in NSTX to show very rich sub-ion cyclotron fluctuations, and (5) control of fast ion/alpha-driven instabilities by varying $q(r)$, $n(r)$, and $T(r)$ profiles.
3. *Fast ion/alpha transport.* The goal is to understand fast ion/alpha transport due to fast ion/alpha-driven instabilities such as fishbones, TAE type modes, and other bursting modes.
4. *Particle interaction with EM wave field.* The goal is to understand fast ion/alpha loss due to Alfvén and ion cyclotron waves and their effects on thermal plasma heating and current drive, Helium ash removal based on the idea of bucket transport by frequency chirping RF waves, as well as alpha channeling.
5. In the long term, *integration* of energetic/alpha particle physics with global plasma stability and confinement, auxiliary heating and current drive in burning plasmas is required.

To properly address the key research areas outlined above, we use analytical theory, numerical simulations and code development based on sound theoretical models. These include:

1. Single-particle dynamics. The ORBIT code for studying fast ion orbit loss due to TF ripple and vacuum field including separatrix, particle interaction with RF wave field, and stochastic particle orbit theory.
2. A kinetic-MHD model, which is the foundation for the present NOVA-K, and M3D-K codes.
3. A hybrid model (fluid electrons and particle ions), which is the foundation for the HYM code.
4. A kinetic-fluid model for high beta plasmas including plasma flow and large ion gyro-orbit physics for general 3D magnetic confinement systems. This is the foundation for improving the NOVA-K and M3D-K codes.
5. Linear theory, quasi-linear theory, mode-mode coupling theory, and nonlinear theories involving wave-particle interactions.
6. A particle simulation model, which follows the full ion orbit and uses guiding-center electron dynamics.
7. Full wave simulations using the TORIC code, after including kinetic background and energetic particle FLR effects, non-Maxwellian distribution functions, and ω/ω_c effects. With these capabilities, CAE and GAE high-frequency instabilities in NSTX will be addressed and benchmarked with analytic theory and NOVA calculations.

C.1. Highlights of Accomplishments

Summarized below are highlights of theoretical accomplishments in the wave-particle interaction/energetic particle physics area. Analysis of experimental data in collaboration with major tokamak experiments resulted in the discovery of the toroidicity-induced Alfvén eigenmode (TAE) [1-2]. The TAE class of modes can exist for all toroidal mode numbers in all toroidal magnetic confinement devices and are manifest in various forms, such as core-localized modes, EAE, NAE, RTAE, etc. They are expected to be destabilized by energetic particles, and can cause large energetic particle loss. Theoretical predictions and experimental measurement of TAEs have been confirmed in fast ion (and alpha) experiments in TFTR, JT-60U, DIII-D, and JET [3]. Explanation of the observed high frequency "fishbone" instability in high H-minority beta JET discharges as being excited by the energetic trapped ions. In such strongly-driven plasmas two branches have been shown to exist, making use of the kinetic nonperturbative code NOVA-KN, which was modified to include the finite-orbit-width effects of fast ions [4]. A theory of coupling among TAE modes, resonant-TAE (RTAE) modes, and kinetic ballooning modes in the presence of energetic particles was developed. The theory successfully explains the experimental observation of the transition of the TAE mode to the beta-induced Alfvén eigenmode (BAE) in DIII-D neutral beam injection experiments [5]. Studies of TAE stability in burning plasma devices have been continued with an emphasis on ITER. In addition to alpha particles, the planned Negative ion Neutral Beam Injection, NNBI, in ITER, which will be at 1MeV energy, can drive TAEs strongly unstable. Figure C.1 shows the results of the stability calculations for ITER normal shear plasma, which show that the predicted range of unstable modes is shifted towards high-n, as expected [6].

In addition, in collaboration with H. Berk of IFS, we have developed a model of quasilinear alpha-particle diffusion driven by multiple Alfvén instabilities and have studied the associated alpha transport [6]. The study showed that in a nominal ITER plasma at ion temperature above 24keV strong alpha particle losses above 5% of the confined alphas are expected.

With regard to NSTX, TAE modes have been observed in NSTX even for modest NBI power. Because of the low aspect ratio, the toroidal coupling effect is strong, and the Alfvén continuum gap is wide open across the minor radius and a broad spectrum of TAEs can exist for each toroidal mode number n. A variety of modes in the frequency range from 20 to 150 kHz with toroidal mode numbers from n=1 to n=6 are commonly seen in beam-heated discharges. In addition to the more commonly observed quasi-continuous TAEs, bursting TAEs are also observed. These bursting modes are associated with fast neutron drops, H_a micro-bursts, and 5 - 10 % fast ions hitting the wall. The bursting fluctuation is dominated by a single-frequency mode with mode growth and decay times approximately 50 - 100 ms. TAEs for n=1-5 modes computed by the NOVA/NOVA-K code with TRANSP profiles are consistent with the observed mode frequencies when the frequency Doppler-shift effects due to the significant plasma toroidal rotation velocity is taken into account.

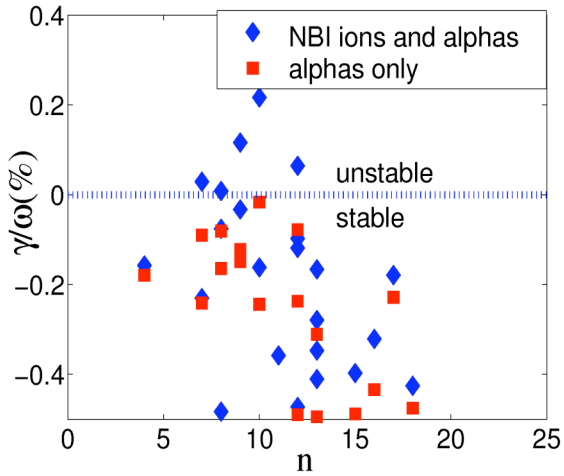

Fig.C.1. NOVA-K calculated growth rates of TAE modes for different toroidal mode numbers using the standard, positive shear, ITER configuration. Red squares correspond to the case where the drive for the mode, is due to alpha particles only, whereas the blue diamonds correspond to the case where both beam ions and alphas contribute to the drive. Note that the unstable mode numbers range from n=7 to 13 and that for each n several eigenmodes are found in the simulations.

Furthermore, similarity experiments on NSTX and DIII-D have been used to validate the theoretical prediction of finite-Larmor-radius scaling for the most unstable TAE toroidal mode number [7]. The NOVA-K code has been used in the analysis, which showed general agreement between the theory and experiments, with the exception of the case of the low-n mode, including n=1, for which the code seems to underestimate damping. But for high-n modes the numerical simulations show rather good agreement, which helps to validate the numerical tool for simulations of the fast-ion effects in burning plasmas.

We have developed a theory of Alfvén ion cyclotron instability (ACI) to model ion cyclotron emissions (ICE) observed in TFR, TFTR and JET plasmas. The ACI is excited as a result of an interaction of compressional Alfvén eigenmodes with fusion product ions [8]. Another development is a theory of "alpha channeling", which can potentially transfer alpha particle energy directly into thermal ions, instead of collisionally heating electrons. This can be achieved by amplifying plasma waves, which are then absorbed by thermal ions. Channeling of alpha energy to thermal ions could accomplish more useful functions than mere electron heating, such as improving the reactivity of a fusion reactor or driving current [9]. We are developing stochastic diffusion theories of energetic ions transport in the presence of a rippled magnetic field as well as in the presence of MHD perturbations such as TAE modes and kinks. Another development is a model of nonlinear saturation of high-n TAE modes via the ion Compton scattering process. The nonlinear saturation occurs when unstable TAE modes transfer their energy to linearly stable TAE modes.

A theory of the kinetic ballooning mode (KBM) in low-aspect-ratio toroidal plasmas shows stabilization of KBMs by the parallel electric field due to the combined effects of finite ion Larmor radii and trapped electron dynamics [10].

Using the M3D hybrid code [11-12] the alpha-particles are found to be strongly stabilizing for the internal kink using the ITER-FEAT parameters and profiles with the central safety factor q(0) close to unity. This confirms previous models. A new result is that the elongation of the plasma boundary shape is found to decrease the stabilization by a factor of two as compared to cases with circular shape, Fig. C.2.

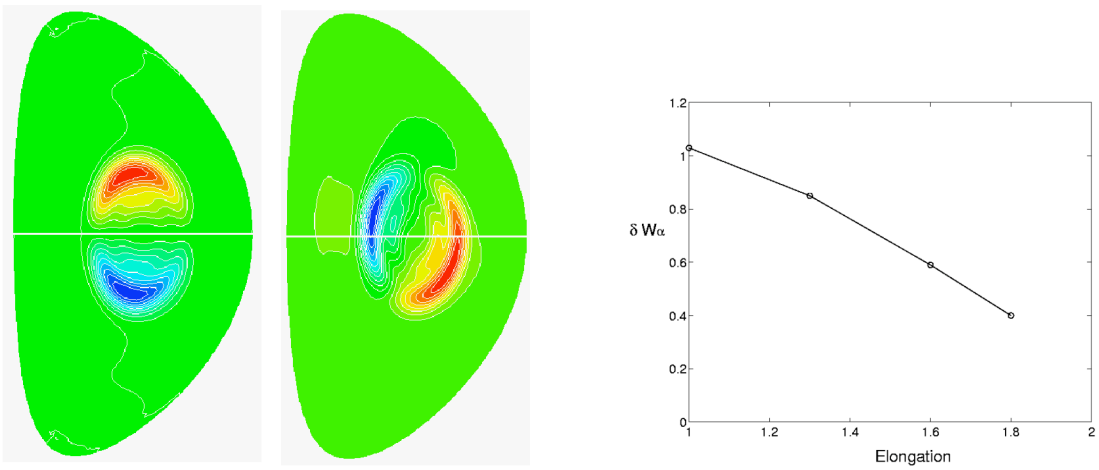

Figure C.2. The linear structure of the 1/1 mode is shown, on the left, without and with a-particles. Note that as a result of the □-particles, the growth-rate is reduced, not shown, and the symmetry is broken as the mode rotates slowly. The effect of changing the elongation is shown on the right. The potential energy, dW_a, associated with the a-particles, decreases by more than a factor of two, as the elongation is increased from 1 to 1.8.

We have developed a theory of Compressional and Global Alfvén eigenmodes (CAE and GAE) to explain the sub-ion-cyclotron fluctuations observed in NSTX, which are destabilized by free energy in the neutral beam ion velocity space anisotropy [13-15]. The HYM code successfully predicted GAEs, which was later confirmed by the experimental observations. Measurements of the polarization of GAE and CAE confirmed theoretical predictions of the CAE/GAE dispersion relation [7]. Figure C.3. shows results of HYM modeling of GAE mode structure in terms of plasma perturbed velocity, [Fig.C.3(a)]. That should be compared with the results of NOVA modeling of the plasma displacement, [Fig. C.3(b)]. Both codes show strongly core localized modes below the minimum of the shear Alfvén continuum.

We have also developed a theory of stochastic heating of thermal ions by multiple CAE/GAEs with frequency below ion cyclotron frequency [16] and a theory of generation of plasma rotation in a tokamak by ion cyclotron absorption of fast Alfvén waves.

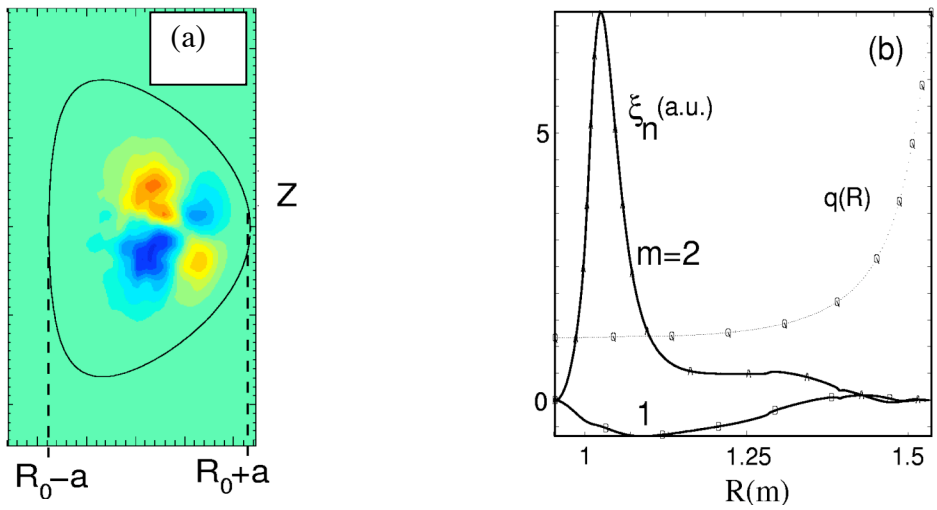

Fig.C.3. GAE mode structure in terms of the perturbed plasma velocity as obtained in HYM (a) and in NOVA (b) modeling, shown as the plasma displacement.

These physics accomplishments were achieved through a coordinated effort to develop the spectrum of codes described earlier. Here we highlight some of the key features in this area. We have developed equilibrium codes including ripple and vacuum field for tokamaks, stellarators, and low-aspect-ratio toroidal devices such as NSTX. A new equilibrium code, TKIN, which provides input for the HYM code, has been developed for two-component plasmas [17]: MHD fluid and energetic (large Larmor radius) ions with anisotropic pressure. The calculated self-consistent NSTX equilibrium including the fast ion current shows that contribution of beam ions with E=80keV, and density ~3% is comparable to that of background plasma, and the equilibrium profiles are significantly modified on low-field side.

The particle orbit following code, ORBIT, which can efficiently follow energetic particle orbits in the presence of complex magnetic perturbations has been extended to include a □f scheme to study quasi-linear energetic particle interaction with MHD waves in tokamaks. In particular, we have shown that TAE modes are capable of inducing ripple trapping of high energy particles in tokamaks, causing intense localized particle loss such as observed in TFTR during RF heating.

With regard to the NOVA family of codes a non-perturbative code, NOVA-KN was developed for studying all types of TAE modes, sawtooth stabilization, fishbones, and kinetic ballooning modes in tokamaks [4]. The perturbative NOVA-K code is now widely used for prediction of TAE stability properties in large tokamaks such as TFTR at PPPL, DIII-D at General Atomics, and the JT-60U tokamak in Japan.

We have developed a high-toroidal-mode number, kinetic-MHD stability code, HINST, for studying energetic-particle-related physics such as TAE instabilities and kinetic ballooning modes in tokamaks [5]. This is relevant to ITER, because of its large size and thus smaller pressure gradient, where it is expected that kinetic-MHD instabilities with high toroidal

mode numbers will be important in determining the energetic particle transport behavior. The HINST code will be extended to stellarator geometry.

Finally, the M3D-K code, a nonlinear global kinetic-MHD simulation code, based on the kinetic-MHD model that includes energetic gyrokinetic ion effects of finite orbit width, Larmor radius and wave-particle resonances has been significantly improved [12]. This large-scale nonlinear simulation code is an important tool for studying fast-particle-driven MHD modes and associated fast ion transport. Simulations of internal kink modes, fishbones and TAEs have been performed using the M3D-K code. Wave-particle trapping was identified as the dominant saturation mechanism for energetic-particle-driven TAEs. Recently, the M3D code has been extended to use an unstructured mesh, which enables simulations of NSTX plasmas and runs on massively parallel computers.

We have actively participated in collaborative joint experimental-theoretical programs on applications of fast particle physics in tokamaks. Some of the joint experimental-theoretical activities are summarized below.

The study of TAE instabilities driven by NBI ions started with observations on DIII-D and TFTR. Subsequently TAE modes driven by ICRF minority ions and alphas, were observed in TFTR dT operations, We have collaborated with the Japanese Fusion Program to study TAE instabilities driven by ICRF minority ions and for the 500 keV Negative Ion Neutral Beam program at JT-60U. HINST and NOVA-K codes have been employed to study JT-60U experimental results on TAE modes. Experiments have been performed in regimes relevant to ITER in terms of V_{beam}/V_A and volume averaged fast ion pressure. In particular, a variety of TAE modes were observed: gradual frequency chirping modes with frequency chirping time scale of a few hundred milliseconds, and bursting modes (called Abrupt Large-Amplitude Events ALEs) that lasts over a few milliseconds. Fast ion radial redistribution was also observed. The gradual frequency chirping modes have been modeled successfully as RTAEs. Based on the theoretical study of the excitation of TAE type modes, three physical mechanisms were identified. First is the slowly evolving q profile, which leads to the radial shift of the mode location and its subsequent change in the frequency. The second one is the change in the fast-particle pressure profile as a result of increased plasma density and broadening of the beam deposition profile. The position of the strongest fast-particle pressure gradient is shifted radially and, thus, it leads to the slow movement of resonant TAE modes (RTAEs) in the radial direction, and slow frequency chirping within 100-200 msec. The NOVA-K modeling of the TAE frequency has also enabled the measurement of safety factor profile evolution within the q=1 surface before and after the sawtooth crash in JT-60U ICRF plasmas. The bursting modes are due to the change of the strong fast particle drive in phase space within a very short period, 3 - 5 msec. Alfvén eigenmodes (AEs) with a large and rapid frequency sweeping as q_{min} decreases, and the saturation of frequency sweeping were observed in reversed shear (RS) plasmas in JT-60U NNB experiments. The rapid frequency sweeping AEs are consistent with the theory of shear Alfvén eigenmodes near the zero shear region of RS plasmas and is called the reverse-shear-induced AEs (RSAEs). The observed large RSAE frequency sweeping can be explained by the change of q-profile and q_{min}. The saturation of the large frequency sweeping can also be explained by the transition from RSAE to TAE. The AE fluctuation

amplitude is maximum around this transition, e.g., $2.4 < q_{min} < 2.7$ for the n=1 mode. The results suggest that in advanced tokamak operating regime in burning plasma devices, it would be advisable to operate RS plasmas outside of the transition region to avoid serious fast ion losses due to large-amplitude AEs. A collaboration with Dr. N. Nakajima of NIFS, Japan to modify the HINST code for (LHD and NCSX) stellarator plasmas was initiated. Presently, the HINST code can read numerical LHD equilibrium output files, and ideal ballooning mode analysis has been benchmarked with the NIFS code for LHD and tokamak conditions. We have extensive collaborations with the European Fusion Program, particularly for the DT operation and alpha channeling experiments in the Joint European Tokamak (JET).

Recent experiments in JET have provided evidence of sawtooth stabilization by fast ions, arising from deuterium Neutral Beam Injection, and were studied using the NOVA-K code [18]. The beam-ion term is found to be sufficiently stabilizing to reproduce the observed sawtooth periods, in agreement with experimental results. The stability of TAEs in DIII-D was analyzed using the nonperturbative HINST code. In this case because of the strong drive by the beam ions the stability analysis of TAEs must be treated non-perturbatively and the TAE frequency lies in the Alfvén continuum. Good agreement between the experimental results and the HINST calculation were achieved. We have also collaborated with the NSTX and DIII-D experimental teams in a series of similarity experiments on both low and high frequency mode instabilities, with favorable comparisons of theory and experiment. This has provided validation of the theory and the numerical tools that were used.

The research on RF wave modeling is accomplished in support of the MIT and ORNL efforts, where the TORIC and AORSA codes were developed. The focus of the Department's efforts is to enhance the physics models that are implemented in those codes, by developing improved theoretical models for treating the thermal plasma and fast ion distribution functions and exploring innovative, compact representations, which can replace the fourier representation presently in use. In addition to these theoretical efforts, the department is also involved in numerical modeling and code benchmarking.

We collaborate with experimentalists on applications in stellarators such as NCSX and innovative confinement devices such as NSTX, FRCs, etc. We also collaborate with several theoreticians at other fusion research groups and universities engaged in energetic particle physics most notably with IFS.

C.2. Proposed Research and Milestones

In this section we outline several critical research areas to be addressed over the next five years. These are broadly divided into four categories, the study of energetic-particle driven instabilities, code developments required to advance nonlinear simulations and address challenging new regimes and geometry, issues specific to burning plasmas and collaboration with experiments. Associated milestones are identified. A global roadmap of the proposed activities is shown in Fig. C.4

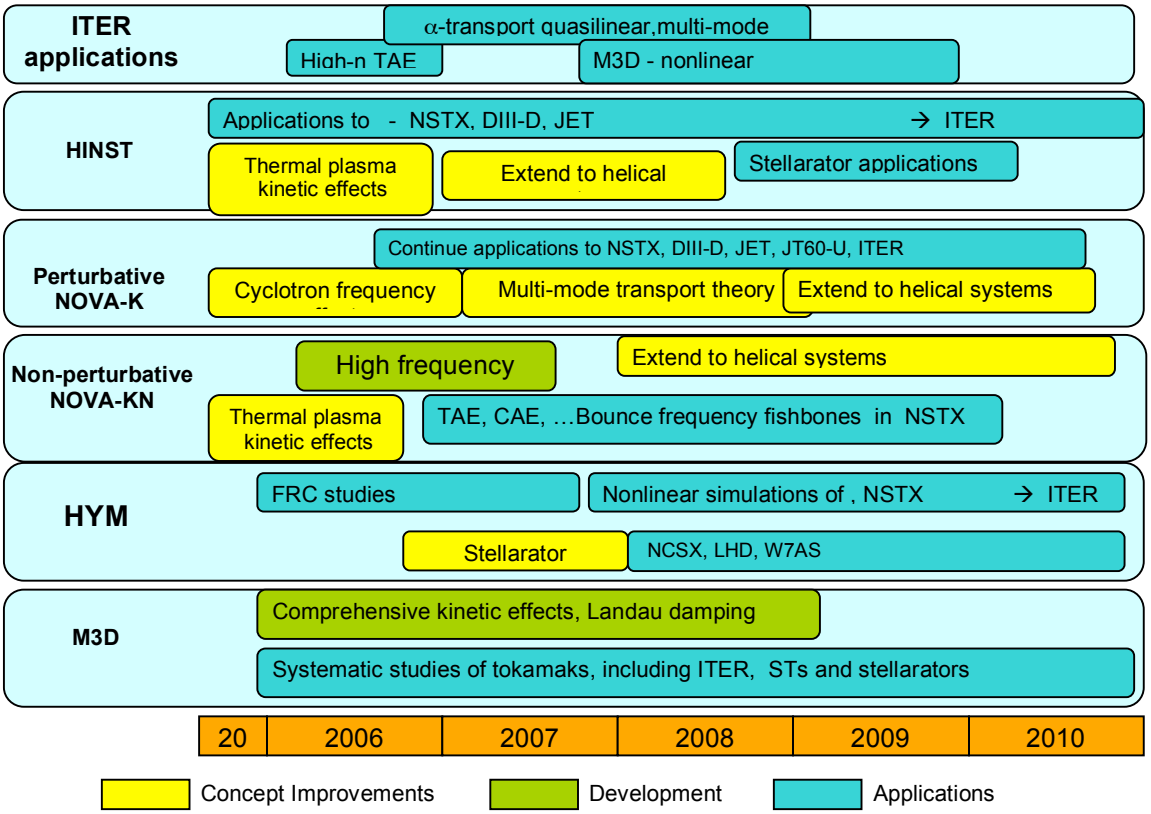

Figure C.4. A roadmap of activities in the energetic-particle wave interaction area. It includes conceptual improvements, specific code developments and applications.

Fast Particle Driven Instabilities

Research in this area will include improvement of the NOVA-K codes (both perturbative and non-perturbative versions), which are based on a kinetic-fluid model to include thermal and fast particle kinetic physics for tokamaks; extend the present NOVA-K and HINST codes to enable stellarator applications; improve the NOVA-K code to include the effects of plasma flow and pressure anisotropy for both tokamaks and stellarators; improvement of the high-n TAE stability code, HINST, to couple with numerical equilibria and to include thermal particle kinetic effects in stellarators; analyze TAE modes and high frequency compressional and global Alfvén eigenmodes (CAE and GAE) in NSTX, including kinetic effects due to both, thermal plasma and energetic particles; and improve the plasma model in TORIC to account for non-Maxwellian distribution functions of background species and energetic ions. This will allow for proper analysis of short wavelength phenomena and, in particular, for CAE/GAE stability studies in NSTX.

Milestones

1. Extend and apply the kinetic perturbative NOVA-K code to include contribution from finite cyclotron frequency harmonics and wave-particle interactions (2006-2007). Benchmark the TORIC/AORSA codes with NOVA-K results on CAE excitation in NSTX (2006-2007).
2. Formulate full wave equations for TORIC to include the non-Maxwellian

distribution functions of plasma species and effects associated with short wavelength modes (such as Lower Hybrid waves) (2006-2007).

3. Extend and apply the non-perturbative version of the NOVA-KN code to include thermal plasma kinetic effects, include high bounce frequency resonances (2006), and thermal ion kinetic effects (2006-2007).
4. Develop massively parallel versions of the nonlinear simulation codes, M3D-K and HYM, to study fast-particle-driven instabilities in tokamaks (2006-2007)
5. Extend the HINST code for helical devices (LHD and NCSX) for studying high-n kinetic ballooning modes and TAE type modes (2006-2008).
6. Extend the NOVA family of codes to study global modes in helical devices. (2008-2010)

Simulations:

Research in this area: Study the nonlinear interaction of energetic particles with MHD modes such as TAE and fishbone modes and associated energetic particle transport by integrating theory into the linear NOVA codes with appropriate resonance calculations; Use the quasi-linear ORBIT code for fast ion transport studies; Study fast ion physics experiments using the existing M3D-K code; Develop an improved three-dimensional nonlinear kinetic-fluid simulation code that incorporates the kinetic effects of both fast ions and thermal plasmas for axisymmetric toroidal devices. This code will serve as the foundation for studying the integration physics of alpha particles and thermal plasmas in burning plasmas; Develop a kinetic-fluid simulation code for systems with large particle gyro-orbits such as NSTX or FRC devices; Develop a global kinetic-fluid simulation code for stellarators.

Milestones

1. Introduce a reduced theoretical model into the NOVA codes to study transport in the multi-mode resonance overlapping regimes (2006-2008).
2. Study CAE and GAE modes with the HYM code to determine instability properties including the saturation mechanism (2006-2007).
3. Study fast particle transport due to the stochastic interaction between fast particles and fast-ion-driven MHD modes such as TAEs, sawteeth and fishbones, and other MHD modes (2007-2009).

Integration of Alpha and Thermal Plasma Physics in Burning Plasmas:

Research in this area: Study alpha-driven instabilities and alpha transport. Study the effect of alpha heating of thermal plasmas on instabilities and examine possibilities of profile control, with emphasis on helium ash removal.

Identify the impact of nonlinear interactions of alpha particles with thermal plasmas that can affect global MHD stability and confinement, plasma heating, and bootstrap current development.

Milestones

1. Determine detailed linear stability properties of Toroidal Alfvén Eigenmodes (TAEs) in the presence of energetic alpha particles and high energy neutral beams for discharges representing the three main operating modes of ITER. The study will address toroidal mode numbers, n, in the range, unity to fifteen. (2006-2007)
2. Apply quasilinear alpha particle transport theory to ITER for different scenarios.(2007-2008)

3. Perform nonlinear studies of AEs in ITER using M3D. (2007)

***Joint Theory-Experiment Programs**:*
Research in this area: Participate in the NSTX research programs on fast particle physics and RF physics; Collaborate with the JT-60U group to study TAE stability, RSAE modes, bursting TAEs, fishbone modes, and sawtooth stabilization for 500 keV N-NBI and ICRF experiments in JT-60U, including plasma flow effects; Collaborate with the JET group to study alpha particle physics and n=1 modes; Collaborate with the LHD/NIFS group and other stellarator groups to study fast particle physics and RF physics; Collaborate with other domestic fusion research groups such as DIII-D, IFS, and MIT on wave-particle interaction physics. Collaborate with the C-Mod experiment on active TAE excitation experiments to test our models of continuum damping, and other linear damping mechanisms, such as collisional damping due to trapped electrons.

Milestones.

1. Study stochastic heating in NSTX due to fast-ion-driven CAEs using a quasi-linear modeling code and HYM (2007-2009).
2. Perform nonlinear simulation with HYM of NSTX, including several mode numbers and, two-fluid, and kinetic thermal ion effects (2007-2010).
3. Investigate ripple transport on NSTX including large gyro orbit effects (2006-2008).
4. Study energetic-particle-driven MHD instabilities such as TAE, CAE, and fishbones in NSTX and other devices such as DIII-D and JET, using analytical theory, modeling as well as simulation codes and compare with present-day experimental results (2006-2010).

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D. Multi-Phase Interfaces

The FESAC Priorities Panel report identifies one high-level scientific question relating to mult-phase interfaces.
T10. How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings? (FESAC Priorities Panel Report)

The topic of "multi-phase interfaces" encompasses not only plasma-material interactions, but also the consequences of those interactions for the adjacent confined plasma. One of the main challenges for multi-phase interface science is to understand the strong connection between the state of the material surface and core plasma performance. So, developing a truly predictive capability in this region will require models of turbulence and transport in the core and edge plasmas, as well as a more comprehensive description of the surrounding materials than we have presently. The research efforts discussed below attempt to make progress on both of these fronts. This program has been adapted to address goals outlined in the FESAC Priorities Panel Report; those goals and the constituent activities will be identified in each of the following sections.

First, we will discuss turbulence related research in Sec. D.1. Second, we will examine our efforts to better understand recycling, fueling, and plasma-material interactions in Sec. D.2. In both thrusts, the role of neutral particles will be studied with the DEGAS 2 Monte Carlo neutral transport code developed at PPPL. Tools for addressing other aspects of the problems, including plasma turbulence and transport, will be provided by or developed in conjunction with collaborators. Finally, Sec. D.3 lists possible approaches to building for DEGAS 2 the neutral transport simulation tools that will be needed for the NCSX stellarator. Milestones are summarized in Sec. D.4.

D.1 Edge and Scrape-Off Layer Plasma Turbulence and Transport

Plasma performance in high-confinement regimes, such as H-mode, is driven by the physics of the outer 10% or so of the confined plasma, a region in which the impact of the nearby plasma interactions with material surfaces can be directly felt. Experimental studies of the plasma turbulence in these regions have progressed substantially over the last few years, but need further development and improved analysis. The same is true of our ability to simulate edge plasma turbulence and transport. In this section, we will discuss research directed at simulating neutral particle behavior in turbulence visualization experiments and describe plans for the development of a plasma kinetic code capable of simulating plasma turbulence and transport in the tokamak edge and scrape-off layer.

This work contributes to two of the goals described in the FESAC Priorities Panel report:

Predict the expected magnetohydrodynamic stability and plasma parameters for the ITER H-mode edge pedestal with high confidence (p. 66).

Identify the underlying driving mechanisms for mass flow and cross-field transport in the scrape-off-layer plasma, in H-mode attached and detached plasma. (p. 68).

Note that these goals overlap somewhat with two in the Multi-scale Transport Physics section of the FESAC Priorities Panel report (p. 40).

D.1.1 Gas Puff Imaging

The "gas puff imaging" (GPI) diagnostic permits edge plasma turbulence to be directly visualized [1]. The resulting data aid in understanding the physical mechanisms involved and provide data for testing turbulence simulation codes. As such, this work contributes directly to the FESAC Priorities Panel research activities to "compare computer simulations and experimental data over a wide range of plasma parameters to confirm physics understanding" and "measure the characteristics of edge fluctuations at select regions of the scrape-off layer to identify the fundamental transport processes" (both p. 67).

A fast camera is used to view the fluctuating emissions associated with a gas puff into the plasma edge. By orienting the camera to view along a field line, high time and spatial resolution images of the plasma turbulence perpendicular to the field are obtained. Theory predicts the turbulent structures to be highly elongated along the magnetic field, but with much smaller length scales in the perpendicular directions. The geometry of the GPI diagnostic allows that smaller scale structure to be isolated.

Figure D.1 illustrates the physical relationships between the principal elements of the GPI diagnostic as installed on NSTX; the configuration on other devices is qualitatively similar. The gas is introduced through a manifold at the outer edge of the plasma, just above the midplane. As the gas cloud (shown in yellow) enters the plasma, electrons excite the atoms, generating photons (the blue disk represents an isosurface of a visible light helium line). The camera (red lines) is oriented so that it views that emission parallel to the field line (field line path indicated by the red dots).

To obtain from the camera images the desired detailed description of the plasma turbulence, the light emission must be related to the plasma parameters. This relationship consists of the electron density and temperature dependence of the atom excitation rate and the neutral density profile. The objective of modeling these experiments with DEGAS 2 is to provide both pieces of information, as well as to yield insight into the operation of the diagnostic (e.g., via visualizations such as in Fig. D.1). The experiments also provide an opportunity to test DEGAS 2 or, equivalently, to validate the physics underlying the GPI diagnostic.

Initial simulations of GPI on Alcator C-Mod performed with deuterium gas puffs showed that a significant fraction of the observed emission was associated with the breakup of the molecules and not coming directly from atoms. Since this complicated interpretation of the experiment, helium has been preferentially used during subsequent dedicated NSTX experiments.

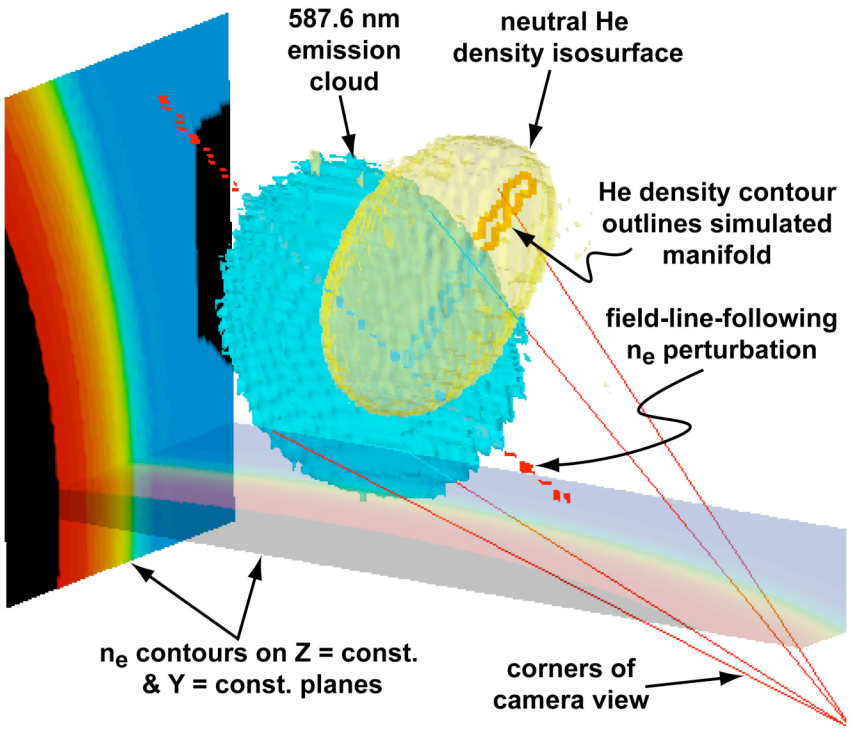

Figure D.1. The physical objects in gas puff imaging experiments are represented in this visualization based on a 3-D DEGAS 2 simulation.

Two-dimensional DEGAS 2 simulations [2] showed that the spatial structures in plasma parameters were reflected in the spatial structure of the emission pattern, suggesting that a wavenumber analysis would yield qualitatively the same spectrum in both cases. Three-dimensional DEGAS 2 simulations of NSTX GPI experiments were subsequently developed [3]. A key component of these simulations was the emulation of the camera view in which the view of each of the thousands of camera pixels was individually computed. Initial 3-D steady-state simulations yielded emission clouds tilted relative to those obtained from a time average of the experimental results from 2003 NSTX experiments [3]. Analogous simulations of 2004 NSTX experiments resulted in much better agreement.

An effective 2-D neutral density can be derived from DEGAS 2's 3-D density profile [3]. These effective neutral densities, from both the 2003 and 2004 NSTX runs, have been used by collaborators at Lodestar Research Corporation to infer, with a few plausible assumptions, the underlying 2-D, time-dependent structure of the plasma density and temperature.

D.1.1.1 Future Work on Gas Puff Imaging

Stewart Zweben has proposed hardware improvements and additional applications for the GPI technique. For the most part, the neutral particle behavior in these experiments can be simulated with the DEGAS 2 model described above (2006). Future GPI experiments performed on Alcator C-Mod can be modeled as well.

One of the proposed objectives that may require additional development and study is the usage of two separate neutral emission lines to permit the electron density and temperature to be directly inferred from the images. Zweben is also considering using a supersonic gas nozzle to provide a more tightly focused neutral gas cloud. Modeling the penetration and behavior of the resulting gas cloud will leverage off of the modeling of the NSTX supersonic gas injector (SGI; see Sec. D.2.2). Unlike the use of SGI for fueling, the application to GPI is purposely non-perturbative. In this case, the "low flow" assumptions associated with the simplest application of DEGAS 2 (again, these are discussed below) are likely to be valid. Preliminary efforts at visualizing turbulence around the NSTX X-point have already been made. However, the geometrical and physics complexity of this region is vastly greater than at midplane, and interpreting the resulting images is correspondingly more difficult. While DEGAS 2 modeling of future X-point GPI experiments is possible, the experimental approach will need to be refined to facilitate interpretation and model construction.

The result of this and related work should be a more accurate characterization of turbulent plasma transport in the edge region. This will provide useful validation data for proposed models of the multi-phase interactions at the edge of magnetic confinement fusion devices. The development of such a model is discussed in the next subsection.

D.1.2 Simulations of Plasma Turbulence and Transport

An integrated kinetic plasma turbulence and transport code will be built by the Center for Plasma Edge Simulation (CPES), a DOE-funded Scientific Discovery through Advanced Computing Fusion Simulation Prototype Center (C. S. Chang, NYU – PI). Chang's existing XGC neoclassical plasma and neutral particle transport code, which has already demonstrated edge pedestal behavior similar to that seen experimentally [4], will be extended to include turbulence. The proposed modifications would permit detailed simulation of pedestal behavior, including investigation of the L-H transition and would be ideal for comparison with GPI data. The Center also involves members of the Center for Gyrokinetic Particle Simulation SciDAC project, which focuses on core plasma turbulence simulation, so as to facilitate an eventual coupling of the core and edge plasma simulation capabilities, resulting in a whole device model. The CPES project is specifically intended to be aligned with multiple activities described in the FESAC Priorities Panel report, including "develop testable pedestal simulation codes that incorporate the relevant spectrum of physical processes (e.g., topology, magnetohydrodynamic stability, flows, transport, and atomic physics) and span the range of plasma parameters relevant to ITER" (p. 66) and "develop an integrated computational model that includes the pedestal and the scrape-off layer (e.g., kinetic pedestal model coupled to fluid scrape-off layer model)" (p. 69).

The 2-D Monte Carlo neutral transport routine currently used in XGC will be replaced with the more comprehensive model represented by DEGAS 2 (2006-2008). The geometry used in XGC will be transformed into the format used internally by DEGAS 2. Since XGC is a time-dependent code, at least the core tracking routines of DEGAS 2 will need to be made time-dependent so that neutral trajectories can be followed for specified time intervals. The input from XGC to the DEGAS 2 neutral tracking subroutine will produce a kinetic description of an

ion striking a material surface. In return, DEGAS 2 will provide information on plasma sources and sinks due to the neutral particles.

Careful verification of the methods used in XGC and DEGAS 2, as well as the approach to coupling them, will be required to ensure that the plasma and neutral equations are being solved correctly and accurately. First, the techniques for ensuring software quality employed in the development of DEGAS 2 will be carried over to this task. Second, CPES mathematicians from the NYU Courant Institute of Mathematical Sciences will generate useful test cases with known exact solutions (2006-2008).

Developing a true predictive capability in the plasma boundary region may require more detailed models and data for the atomic and molecular physics processes and for the plasma material interactions (PMI) used in DEGAS 2. In particular, the PMI models incorporated into DEGAS 2 are roughly twenty years old and neglect modification of material properties due to the bombardment by plasma fluxes. This can result in changes in structure from erosion and redeposition, and in composition (particularly via hydrogen implantation). Furthermore, the reactions and data used for the dissociation and ionization of hydrogen molecules are out of data relative to the current state-of-the-art treatments employed in other neutral transport codes. Together with members of the CPES associated with the Oak Ridge National Laboratory Controlled Fusion Atomic Data Center, we will develop improved models and data for both PMI and the atomic and molecular processes (2006-2009).

D.2 Recycling Behavior, Fueling, and Plasma-Material Interactions

The intermittent, turbulent plasma structures seen in the GPI movies may result in a greater degree of plasma interaction with the main chamber wall than is expected from the standard theory of divertor operation. These interactions need to be characterized experimentally and studied theoretically so that future devices, such as ITER, can be designed to account for them. Two of the FESAC Priorities Panel goals are associated with these concerns.

Identify the underlying driving mechanisms for mass flow and cross-field transport in the scrape-off-layer plasma, in H-mode attached and detached plasmas (p. 68).

Resolve the key boundary-physics processes governing selection of plasma facing components for ITER. This is a time-sensitive issue relevant to the success of ITER (p. 70).

In this subsection, we will describe modeling of NSTX experiments targeting these goals. We will also cover related modeling and theoretical investigations examining the efficacy of an advanced fueling technique and of lithium coatings and layers as plasma facing materials. These efforts will contribute to the above FESAC Priorities Panel goals as well as to two others:

The ten-year goal is to develop the plasma technologies required to support U.S. contributions to ITER (p. 94).

Complete the evaluation of candidate plasma-facing materials and technologies for high-power, long-pulse fusion experiments (p. 71).

D.2.1 Poloidal Variation of Recycling in NSTX

Detailed DEGAS 2 modeling of plasma-wall interactions and neutral transport in NSTX will lead to an improved understanding of the location and relative strength of particle recycling sources and the corresponding contributions to core fueling. The associated FESAC Priorities Panel research activities are to "use numerical simulation (interpretive and predictive) to relate measured profiles to the underlying physics of particle and energy transport (p. 69) and to "characterize plasma-wall interactions (e.g., particle and energy fluxes, sputtering rates, and erosion / redeposition profiles) and material migration in H-mode plasmas by means of focused measurements in devices with carbon and metallic walls (p. 70)."

The inputs required for the DEGAS 2 model consist of a description of the neutral sources (whether due to recycling or externally introduced, such as a gas puff) and the plasma parameters throughout the region of interest. A variety of calibrated, filtered cameras provide quantitative information on particle fluxes leaving plasma-facing surfaces in NSTX. Langmuir probes embedded in the divertor target plates and in tiles at other poloidal locations will give plasma fluxes to these surfaces. Midplane profiles of the electron density and temperature will come from the Thomson scattering system and the fast reciprocating probe. Neutral pressure gauges at midplane and in the divertors will yield constraints on the finished DEGAS 2 model. The Langmuir probes will provide a starting point for the recycling sources. Since the probes do not completely cover the poloidal cross section, additional sources may need to be postulated and calibrated using the camera and neutral pressure data. The UEDGE code can be used to develop a model for the plasma consistent with the available measurements. If a UEDGE run for a particular discharge of interest is not available, a simpler (2-point) but less accurate model can be developed using data from Thomson scattering, the midplane reciprocating probe, and target Langmuir probes.

That the boron-coated graphite tiles in NSTX probably serve as a net sink of particles further complicates this modeling. A poloidally varying absorption coefficient can be incorporated into the DEGAS 2 simulations to account for this behavior. Since the other sources of particles in the vacuum vessel, e.g., due to neutral beam injection or gas puffing, are known, we can invoke particle balance to infer the overall strength of this wall absorption.

The ideal end result of this modeling would be quantitative estimates of the plasma particle flows to the main chamber walls and the extent to which particles recycled there result in fueling of the core plasma. Second, we should be able to compare these flows and recycling with that occurring at the divertor targets (2005-2007).

D.2.2 Modeling of Supersonic Gas Injector Operation

Finite limits for the ITER on-site and in-vessel tritium inventory motivate the search for efficient fueling techniques. One such technique, supersonic gas injection, is being tested on the NSTX and CDX-U devices, corresponding to the FESAC Priorities Panel research activity to "use experimental run time, diagnostic and facility support on existing tokamaks to develop and deploy the specific magnet, heating and current drive, and fueling technologies."

A series of preliminary DEGAS 2 simulations were carried out [5] to evaluate the impact of supersonic velocities on gas particles' penetration into the core plasma. In these 2-D runs, derived from two of existing GPI simulations, the standard assumption of a gas puff with a room temperature thermal velocity distribution was replaced with one in which the gas particles had a directed velocity increment of 2.2 km/s and a decreased gas temperature of 50 K. The simulations effectively assumed a very low gas flow rate since the impact of the gas on the plasma was not taken into account and collisions between gas particles were ignored. The gas' directed velocity did not significantly increase penetration relative to that obtained with a thermal gas puff. However, the neutral densities and resulting ion source were more focused than those obtained with the thermal gas puff. For this reason, supersonic gas injector (SGI) fueling may be more efficient.

The NSTX supersonic gas injector was installed during 2004 [5] and initial experimental tests have been performed. We envision carrying out DEGAS 2 simulations of these NSTX experiments as was done previously (i.e., strictly valid only in the low gas flow limit), but using the specific equilibrium and plasma profiles from the shot of interest and the velocity distribution of the gas particles obtained from test stand measurements of the supersonic gas injector [5]. The initial plan (2006-2007) is to make qualitative comparisons between the 2-D simulations and the available experimental camera images of the gas plumes. If more detailed and quantitative comparisons are warranted, 3-D simulations can be done in which the camera view is directly emulated. An opportunity also exists for making connections with MHD and gas dynamic simulations of SGI operation and fueling in collaboration with Samtaney and Jardin.

The DEGAS 2 simulations will provide an unambiguous value for the SGI's fueling efficiency. Its variation with the radial location of the injector and with discharge type (e.g., L-mode vs. H-mode) can be examined. In addition, the simulations will allow the fractional contribution of Balmer-a photons from the dissociation of D_2 to the total number to be estimated.

D.2.3 Modeling of Lithium Coatings

Interest in lithium as a plasma facing material is the result of two potential benefits. First, as was demonstrated in the 'lithium aided supershot" regime on TFTR, the ability of lithium to absorb impinging hydrogen atoms alters the plasma's "boundary condition" and leads, potentially, to dramatic improvements in core plasma performance. Second, liquid plasma facing surfaces (such as molten lithium) are less susceptible to erosion than solid surfaces and can handle very high heat loads. This interest is embodied in the FESAC Priorities Panel research activity to "pursue development of suitable new technologies for long-pulse, high-power fusion experiments through research at dedicated plasma-facing component test facilities" (p.72).

Experiments on NSTX will investigate the effectiveness of lithium coatings, deposited via lithium pellet injection or in situ evaporation, in controlling fuel recycling. The subsequent installation of a liquid lithium surface module will allow the efficacy of a liquid lithium surface as a plasma facing material in a spherical torus to be tested. Modeling these various experiments with DEGAS 2 will facilitate their interpretation and help to elucidate the underlying physics. The machinery for handling physical sputtering required for this work will

be added to DEGAS 2 (2006-2007). Once completed, the relevant surface and atomic physics data for lithium can be incorporated. Generation and collection of such data are currently being undertaken by participants in the Plasma Facing Components (PFC) program, such as the PMI group at the University of Illinois Urbana-Champaign.

D.2.4. Plasma Interaction with Lithium Walls

The power handling capabilities of conventional plasma facing components have been stressed by plasma science research devices (like JET, TFTR, JT-60), and a uniformly acceptable plasma facing component solution for ITER has not been identified. In contrast, using lithium to line the walls of the device (a "LiWall" [6]) provides the opportunity for handling reactor-scale power loads. Instead of concentrating power deposition at the divertor plates, LiWalls rely on classical, distributed power extraction from a large surface area surrounding the plasma. Compatible with high plasma edge temperature, LiWalls suggest new confinement regimes, and plasma stabilization by conducting walls right at the plasma boundary, relevant to power reactor fusion performance. Because of profound differences with the conventional approach, the LiWall represents a separate, unique concept of the magnetic fusion reactor and the approach to its development [6].

A new experimental program on the Lithium Tokamak Experiment (LTX), being proposed for the next four years, will be the first step in the US towards investigating this concept, studying plasma interaction with a large liquid (or molten) lithium surface (on the surface of an explosively bonded stainless steel and copper sandwich wall structure). One of the goals of the theory and experiment will be the determination of the characteristic scale lengths and alignment requirements for the plasma-wall surface. A theory and a special (Cbc2e) code have been developed for calibrating tokamaks for equilibrium reconstruction in the presence of conducting structures near the plasma. Another code (ESC) will be used for studies of plasma control and its alignment with the wall surface.

Recently, the development of a new theory and the code, Cbebm, for liquid lithium MHD was initiated by experimental discovery on CDX-U of extraordinary heat transfer from a localized (more than 40 MW/m^2) e-beam power deposition to the surface of the liquid lithium tray. The theory of Marangoni flow, generated by the temperature dependence of the surface tension of liquid lithium, was created as an explanation of the heat transfer by the fluid convection (Fig. D.2). This, so far unknown, property of LiWalls to be insensitive to the localized power deposition may open additional opportunities for the fusion program.

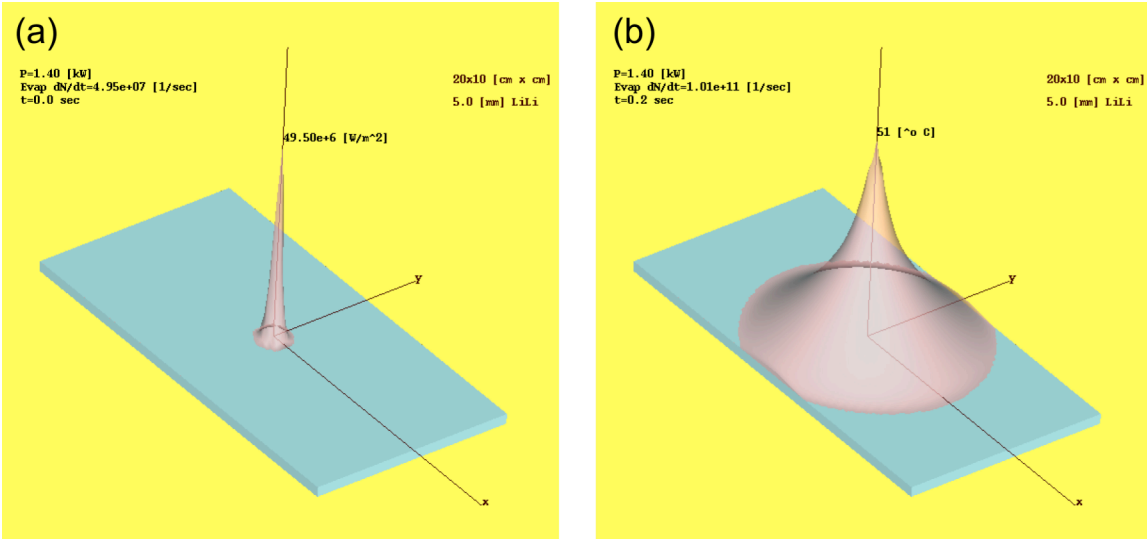

Figure D.2(a) Power deposition profile (50 MW/m^2 in peak) in a 6 mm e-beam spot in CDX-U liquid lithium tray. (b) The Marangoni convection delivers the heat to the edges of the tray in a fraction of second and limits the temperature rise at a low level (50° C here).

D.3 Approaches to Neutral Transport for NCSX

As the FESAC Priorities Panel report notes (e.g., on p. 68), the study of non-axisymmetric plasma devices will provide insight into the analogous physical processes occurring in tokamaks. Such considerations provide some of the motivation for the proposed NCSX project (see Sec. III.C for further details). The capability for simulating neutral transport in NCSX needs to be developed to aid in the design of NCSX and in the interpretation of subsequent experiments. The task of specifying these potentially complex geometries is facilitated by the existence of compact numerical descriptions of the magnetic surfaces and vacuum vessel in terms of Fourier harmonics. The translation of this information into a format suitable for input to DEGAS 2 should be straightforward (2006-2007).

Potential applications of this DEGAS 2 model for the neutral transport would be as part of a comprehensive core transport analysis code and in conjunction with a predictive edge plasma transport code. The objective of the former is to create the functional equivalent of TRANSP for NCSX. Such a code would require estimates of the plasma particle, momentum, and energy sources in the core due to neutral atoms and molecules resulting from the plasma-wall interaction. Given adequate diagnostic signals and at least a simple model for the edge plasma, the requisite DEGAS 2 model could be developed. The target date for the TRANSP-like code is 2009, although development needs and nearer term applications may require more rapid progress on the DEGAS 2 model (2007-2008).

Predictive simulations of edge plasma transport in stellarators are hampered by the occurrence of island structures and / or stochastic field lines. The increase in complexity is sufficiently great that the W7-X group has mounted a roughly 30-man year effort to develop a suitable edge plasma transport code (BoRiS). Colleagues at Lawrence Livermore National Laboratory are considering its application to NCSX. Additional development effort at PPPL will be needed to

couple this work to DEGAS 2. The computational demands of such a coupled plasma –neutral transport code will be substantial. To be practical, both codes will need to be run on multiprocessor machines. Previous research has indicated a need for going beyond the obvious parallelization opportunities and parallelizing the coupling algorithm itself (2009).

D.4 Summary of High-Level Milestones

- Simulations of Gas Puff Imaging Experiments **(2006)**.
- Replace neutral transport module in XGC with one derived from DEGAS 2 **(2006-2008)**.
- Improved data for atomic and molecular physics and for plasma material interactions **(2006-2009)**.
- Studies of poloidal distribution of recycling in NSTX **(2005-2007)**.
- Model supersonic gas injector behavior **(2006-2007)**.
- Incorporate sputtering sources and lithium atomic and surface physics data into DEGAS 2 **(2006-2007)**.
- Simulate lithium coating and liquid lithium module experiments on NSTX **(2007-2008)**.
- Develop tool for creating 3-D DEGAS 2 stellarator geometries and plasmas **(2006-2007)**.
- Develop neutral transport module suitable for inclusion in NCSX core transport code analysis **(2007-2008)**.

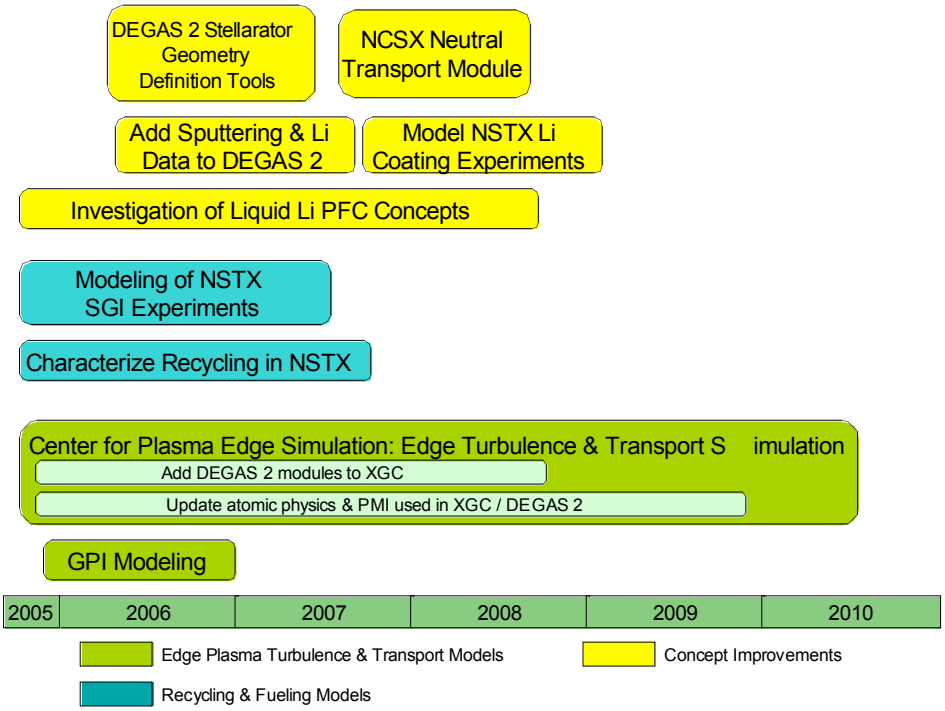

Figure D.3 Schematic representation of multi-phase interface tasks outlined in text.

D.5 References

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E. Plasma Science Applications

As discussed in the FESAC Priorities Panel Report, *Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program* (April, 2005), the principles of plasma physics apply from spatial scales of microns in fusion plasmas and industrial-processing plasmas to millions of light years in extra-galactic structures, and from time scales of a billionth of a second in inertially confined laboratory fusion plasmas, to billions of years in galaxies. Understanding how plasma, electromagnetic fields, and other states of matter interact and organize is crucial to understanding the universe and to discovering methods for generating fusion energy. The Theory Department's five-year goal in the plasma science applications area can be summarized as follows.

Five-Year Plasma Science Applications Goal: *Advance the forefront of plasma science across a broad range of applications, synergistically with the development of fusion science.*

This section provides a brief overview of topical activities in plasma science applications at PPPL, and Sec. III.E provides a more detailed description of programmatic milestones and plans, particularly in ion-beam-driven high energy density physics and fusion, and in space plasma physics.

E.1 Nonneutral Plasmas and Accelerator Physics

A nonneutral plasma is a many-body collection of charged particles in which there is not overall charge neutrality. Such systems are characterized by intense self-electric fields and, in high-current configurations, by intense self-magnetic fields. Nonneutral plasmas, like electrically neutral plasmas, exhibit a broad range of collective properties, such as plasma waves and instabilities. The intense self-fields in a nonneutral plasma can have a large influence on detailed plasma equilibrium, stability, and confinement properties, as well as on the nonlinear dynamics of the system.

The many practical applications of nonneutral plasmas include: improved atomic clocks; the development of positron and antiproton ion sources; antimatter plasmas; coherent electromagnetic radiation generation by energetic electrons interacting with applied magnetic field structures, including free electron lasers, cyclotron masers, and magnetrons; intense nonneutral electron and ion flow in high-voltage diodes; high-intensity charged particle beams propagating in periodic-focusing accelerators, such as those envisioned for ion-beam-driven high energy density physics and fusion, tritium production, spallation neutron sources, and high energy physics and nuclear physics applications; and the measurement of background neutral pressure and electron collision cross sections with neutral atoms and molecules.

Theoretical research on nonneutral plasmas and high-intensity accelerators at the Princeton Plasma Physics Laboratory (PPPL) focuses on two areas: (1) fundamental theoretical studies of one-component nonneutral plasmas confined in a Paul trap configuration, used to simulate experimentally intense charged particle beam propagation over large distances; and (2) analytical and numerical studies of the nonlinear dynamics and collective processes in

intense charged particle beams propagating in periodic focusing accelerators and transport systems. Particular emphasis is placed on a determination of the class of beam distributions that can propagate quiescently over large distances; and the development and application of nonlinear multispecies 3D perturbative simulation techniques using the Beam Equilibrium, Stability and Transport (BEST) code for investigation of nonlinear collective processes in intense beam propagation.

Specific applications to ion-beam-driven high energy density physics and fusion are described in Sec. III.E.1.

Recent related publications:

Recent scientific publications in the nonneutral plasma and nonlinear beam dynamics areas can be found at the website: http://nonneutral.pppl.gov. The reader is also referred to:

Physics of Nonneutral Plasmas, R. C. Davidson, (World Scientific & Imperial College Press, 2001).

Physics of Intense Charged Particle Beams in High Energy Accelerators, R. C. Davidson and H Qin, (World Scientific & Imperial College Press, 2001).

E.2 Innovative Concept Development

The PPPL Theory Department explores and develops new ideas, both in fusion and in broader areas of plasma science. Some of these explorations have led to entirely new areas of research. In many instances, the principal research in these innovative areas has been carried out by PhD students in Princeton University's Program in Plasma Physics.

Current examples of research in this category include:

1. Investigations of fundamental plasma physics including current generation in dense plasma, such as Fermi-degenerate plasma.
2. Methods of manipulating particles in plasma, including one-way magnetic wells.
3. Conceptual improvements to fusion methodologies, including alpha channeling in mirror machine and other open or closed magnetic field geometries.
4. Fundamental scientific investigations of wave-particle interactions in plasma, including Landau damping at high field intensities and short time durations.

Earlier research in this category includes investigations of:

1. Enhancement of reaction rates in fusion plasma through the use of spin-polarized nuclear fuel.
2. Physics of muon-catalyzed fusion.
3. The transition of particle motion from regular to stochastic phase-space trajectories.
4. Development of general methods to describe the evolution of solitary waves.

E.3 Space Plasma Physics

The purpose of PPPL's space plasma physics program, supported primarily by the National Aeronautics and Space Administration and the National Science Foundation, is to investigate low- frequency collective plasma and wave phenomena and associated transfer processes of mass, momentum, and energy in space plasmas. The Earth's magnetosphere and solar atmosphere have been the principal areas of research in space plasma physics. The primary goal is to understand solar activity (such as the solar wind, coronal mass ejection, solar flares, and prominence eruption) and how these solar activities affect the plasma dynamics, waves and instabilities (such as substorms and storms) in the magnetosphere and the ionosphere.

The magnetosphere is formed by the interaction of the geomagnetic field with the solar wind, a supersonic flow of plasma streaming away from the sun at 300 to 800 km/s. At the outer magnetospheric boundary, interaction of solar wind particles with the Earth's magnetic field sets up a boundary current layer, the magnetopause, which prevents direct penetration of solar wind particles into the magnetosphere with only a few percent penetrating the magnetopause. As the solar wind passes by the Earth, it pulls the Earth's magnetic field with it to form the magnetotail, which extends at least 200 R_E in the anti-sunward direction with a cross section of 50 to 60 R_E in diameter. Plasmas from both the solar wind and the ionosphere are energized and stored in the plasma sheet, a storage region near the center of the magnetotail. Dramatic changes in the magnetospheric environment in the form of substorms and storms can occur when coronal mass ejection or solar flare effluents arrive at Earth's orbit. Precipitating particle fluxes can change rapidly in response to quick variations in the magnetotail plasma sheet and the magnetopause boundary layer source regions.

Coupling between solar activities and the magnetospheric boundary determines how and where energy, momentum and particles are transported into the magnetosphere, which subsequently affects the magnetospheric dynamics. The dynamics of plasmas, magnetic field and electromagnetic waves in the magnetosphere determines how particle and energy are dissipated in the ionosphere. The ionospheric dynamics then determines how particles and energy are fed back to the magnetosphere. Understanding of these highly nonlinear coupling processes is fundamental in determining the dynamics of the geospace environment.

The plasma transport processes usually involve multiscale coupling phenomena in which particle kinetic physics involving small spatial and fast temporal scales (for example, finite Larmor radii, trapped particle dynamics in a nonuniform magnetic field, and wave-particle resonances) can strongly affect the global plasma structure and long-time behavior of magnetohydrodynamic phenomena. Critical space phenomena also involve global coupling among regions with several orders of magnitude difference in plasma collisionality and plasma beta. These areas of basic plasma physics are only now beginning to be pursued.

In the past five years we have carried out research in space plasma physics related to the magnetosphere, ionosphere and solar atmosphere. Highlights of key accomplishments, and future plans and milestones are summarized in Section III.E.4. It is planned to continue actively pursuing these areas of research during the next five-year period.

III. PROGRAMMATIC AREAS

In this chapter, we describe the activities which emphasize programmatic needs. This includes magnetic fusion, non-magnetic fusion, space plasma physics and the activities of the computational plasma physics group, CPPG. The MFE area includes: Tokamaks including ITER; Spherical tokamaks, in particular NSTX; Stellarators with an emphasis on NCSX; and field reversed configurations. The non-MFE area includes; Ion-beam driven high-energy physics; laser-plasma systems; and, plasma thrusters.

The work in the MFE areas and by CPPG is supported jointly by funding from the Theory Team at OFES, collaborations and experimental projects. The FRC work is an exception. This is supported by the Innovative Confinement Concepts group, which also supports the high-energy density physics. The work on thrusters and space-plasma physics is supported by other agencies, NSF and NASA. The laser-plasma physics is done under a contract with LLNL.

A. Tokamak Collaborations and Project Areas

Tokamak collaborations

A.1. Progress and Highlights

The PPPL theory group has a long history of advancing the understanding of the physics of tokamaks and continues this activity through NSTX (see Section B) and through strong collaborations with off-site facilities. The scope of recent collaborations includes: linear instability and nonlinear turbulence analysis for microinstabilities, study of the propagation of microwaves (for reflectometry diagnostics) in the presence of this kind of turbulence, study of Alfvén eigenmodes of several varieties, MHD studies of resistive wall modes, simulation of neutral transport in divertor geometry, and study of lithium wall regimes .

In the period 2001-2005, radially-local linear and quasilinear microinstabiity calculations by the FULL code have been carried out, for instabilities such as the ion temperature gradient (ITG) mode and the trapped-electron mode (TEM) for the JT-60U tokamak, in collaboration with the Japan Atomic Energy Research Institute (JAERI), the JET tokamak, in collaboration with the European Fusion Development Agreement (EFDA), and other tokamaks. In addition, the PPPL Theory Department has played a role of providing theoretical interpretation/assessment of fluctuation/confinement related experiments, such as the identification/classification of measured fluctuations and their behavior under the influence of **E**x**B** shear. These include JET, JT-60U, DIII-D at GA, and C-Mod at MIT, (and also through the ITPA Transport Physics Topical Group). The propagation of reflectometry diagnostic microwaves in this kind of ITG turbulence has been calculated for the JT-60U and DIII-D tokamaks, in a single poloidal plane (2D).

Energetic particle physics issues need to be understood to insure the successful operation of a fusion reactor. The PPPL Theory Department has actively participated in collaborative joint experimental-theoretical programs on applications of fast particle physics in tokamaks. Some of the joint experimental-theoretical activities are: collaborations with the the JT-60U group to study TAE instabilities driven by ICRF minority ions and with the 500 KeV Negative Ion Neutral Beam program at JT-60U, using the HINST and NOVA-K codes; studies of Alfvén eigenmodes (AEs) with large and rapid frequency sweeping as q_{min} decreases and with saturation of frequency sweeping, as observed in reversed shear (RS) plasmas in JT-60U negative neutral beam experiments; a theoretical model for the interpretation of the observed sawtooth period behavior, for recent experiments in JET which have provided evidence of sawtooth stabilization by fast ions arising from deuterium NBI, using a sawtooth period model developed to predict the sawtooth period in ITER; and analysis of the stability of TAE modes, using the HINST code, for DIII-D experiments, including collaboration with the NSTX and DIII-D experimental teams in series of similarity experiments on both low and high frequency mode instabilities.

In collaboration with the JET group and with the Institute for Fusion Studies (IFS) at the University of Texas at Austin, the perturbative NOVA-K code was used to calculate the

damping rate of n=1 toroidal Alfvén eigenmodes (TAE modes) in JET and the results were compared with the experimental measurement. It was found that the calculated damping rates were too small to account for the measured damping rates. This discrepancy motivated recent work using a non-perturbative kinetic model. The damping of TAE modes in JET plasmas was investigated by using a reduced kinetic model. Typically no significant damping was found to occur near the center of the plasma due to mode conversion to kinetic Alfvén waves. In contrast, continuum damping from resonance near the plasma edge may be significant, and may give rise to damping rates that are compatible with the experimental observations.

Collaborative MHD research for the past five years has included applications in support of the DIII-D device at General Atomics. We have modified the VACUUM code to simulate the feedback stabilization of the resistive wall mode (RWM) using the error correcting C-coils and the recent and more effective internal I-coils. A novel approach was developed where the plasma-resistive wall interaction was cast in a self-adjoint form encompassing the full spectrum of plasma and wall modes. A set of circuit equations, which comprises the eigenmodes of this system together with the feedback elements and sensor loops, completed the model. The internal loops with the sensors oriented to measure the poloidal magnetic perturbations were found to be more effective in controlling the RWM and could increase the achievable beta in DIII-D to near the ideal wall limit. Another benefit offered by the VACUUM code is the ability to simulate the Mirnov loops signals in tokamaks and this was used to substantiate the magnitude and phase measurements of the loops in DIII-D.

Resistive wall mode studies have largely addressed the situation, where there is substantial plasma rotation, which has a strong stabilizing influence. This rotation is largely a consequence of intense unbalanced neutral beam injection. This model is inconsistent with the present design of ITER, where plasma rotation is likely to be small, if present. In order to facilitate the study of the low rotation regime, the DIII-D program plans to reorient an NBI beam to provide balanced injection. Theoretically this regime can be studied using a simple extended MHD model, which can determine the effect of kinetic trapped ions as they interact with the plasma perturbation, using a δW approach [18]. This model has been implemented in a post-processor for the PEST-1 code, in collaboration with the University of Rochester. The extended δW_k can be determined for multiple species, including ions, electrons and the energetic a-particles, through the perturbed perpendicular pressure, which is computed by PEST. Computations using standard ITER equilibrium profiles, indicates a significant reduction in the growth-rate of kink modes, which are responsible for RWMs.

For equilibrium reconstruction on JET, the ESC code with its equilibrium reconstruction capabilities was linked to the JET database of raw magnetic signals as well as the MSE measurement data. For the first time, the equilibrium reconstruction was performed for current-hole discharges. Development of the ASTRA-ESC-DCON-BALLOON code system, in collaboration with IPP-Garching and with Los Alamos National Laboratory, created an integrated system of transport, equilibrium and stability codes.

The work described in this and the following paragraph addresses question T10 of the FESAC Priority Panel report "How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?"

Initial DEGAS 2 simulations of the neutral transport behavior in Alcator C-Mod divertor baffling experiments were based on a traditional interpretation of divertor operation and an analytic description of the plasma parameter variation. These simulations yielded neutral pressures and Balmer-alpha emission rates much smaller than those observed. Subsequent DEGAS 2 runs confirmed the contention that explaining the discrepancy would require additional physics, such as detailed modeling of the recombining plasma in the divertor's private flux region and the inclusion of 3D details of the C-Mod divertor substructure. MIT later designed and carried out experiments to measure gas flows through the divertor substructure that could be used to validate DEGAS 2 for simulating such gas flows. Three-dimensional DEGAS 2 simulations of two of the MIT experiments were carried out.

The theory of lithium wall regimes was advanced in collaboration with the University of California, San Diego and the Max-Planck Institute for Plasma Physics, Garching, Germany. A transport model for the low recycling regime was implemented in the ASTRA code and it was shown that the ITER plasma could reach ignition if a partial lithium wall were to be implemented in ITER. The concept of the ignited spherical tokamak (IST) was developed as a step towards reactor development. Based on the lithium wall regime, the IST, at least theoretically, is capable not only of ignition for conventional DT plasmas, but also for DD plasmas as well.

A.2. Challenges and deliverables

Major efforts for turbulence and anomalous transport calculations in the PPPL Theory Department are centered on the gyrokinetic toroidal code (GTC), in collaboration with the University of California, Irvine. To address the turbulent transport of real tokamaks, a general axisymmetric geometry capability is being developed for GTC with a number of enhanced and extended features. The general geometry GTC is interfaced with TRANSP for experimental plasma profiles and with the JSOLVER, QSOLVER and ESC codes for numerical MHD equilibria, which makes it consistent and compatible with the GTC-Neo code, which calculates neoclassical transport quantities for tokamak experiments. The general-geometry GTC also includes a systematic treatment of plasma rotation, with a shifted Maxwellian background distribution and a consistent equilibrium **E**x**B** flow which can be calculated from GTC-Neo, using an input experimental profile of toroidal rotation velocity. Linear and nonlinear ITG benchmarks have been performed to validate the code. Initial application of the code to a DIII-D-sized shaped plasma has obtained interesting results with regard to nonlinear dynamics of ITG turbulence spreading and associated energy cascading to the longer wavelength (low-n) modes (see Fig. A.1).

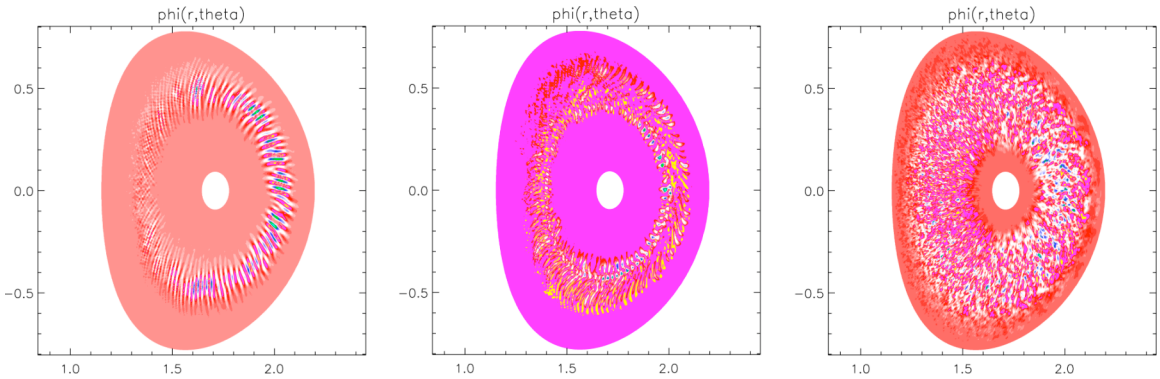

Figure A.1. Contour plots of electric potential at three times on a poloidal plane, from a simulation of a shaped plasma with typical DIII-D parameters.

This new capability is ready for use to investigate electrostatic turbulence in tokamak experiments, including both ion and electron dynamics. The numerical investigation will pay attention to both the turbulent transport level and to the associated nonlinear physics of experimental plasmas. In year 05-06, we will investigate electrostatic turbulence of JT-60U and DIII-D plasmas with focus on global ITG turbulence spreading and associated transport nonlocality. We also plan to include simple like- and unlike-particle collisions in such simulations, to address the important physics issues associated with particle trapping and detrapping, and with collisional zonal flow damping. In year 06-07 our investigation will focus on collisionless and collisional trapped electron modes in tokamak experiments, along with electron effects on ITG modes. Physics issues will include collisionless trapped electron mode (CTEM) driven transport of energy, particles and momentum. The Alfvénic ITG (or kinetic ballooning) mode turbulence in tokamak experiments will be studied in year 07-08, as such an electromagnetic (EM) simulation capability and the necessary computer resources become available. The EM turbulence investigation will continue in year 08-09. Experimentally derived cases will be used throughout these years for these efforts. The direct simulation of internal transport barrier dynamics of experiments will be conducted in the last 2 years of this 5-year plan. All investigations mentioned above will be extended to ITER-sized and ITER-parameter-relevant plasmas. A thrust will be proposing experiments to clarify the role of turbulence spreading in tokamaks such as C-Mod, NSTX, and other machines as well, and the role of zonal flows. In addition, the GTC-Neo code will be applied for calculation of neoclassical fluxes, electric fields, and rotation velocities in realistic shaped geometry, including non-local finite-orbit-size effects throughout the 2006-2010 period. All of this work addresses question T4 of the FESAC Priorities Panel report ("How does turbulence cause heat, particles, and momentum to escape from plasmas?")

The code to simulate microwave reflectometry signals in the presence of toroidal turbulence will be extended to 3D. If necessary for throughput, it will then be parallelized. A more sophisticated paraxial solver will also be developed if required in order to accurately simulate the propagation of reflected beams with large divergence angles.

Future plans for hybrid simulations of alpha-driven Alfvén modes in ITER and other tokamaks include: begin to apply the M3D code to ITER (05-06); improve the M3D code by adding more physics, such as appropriate damping models for TAEs, and collisional effects

of alpha particles (05-09); investigate nonlinear consequence of alpha-driven Alfvén modes; and explore integrated effects of alpha particles on thermal plasmas. The work will possibly be carried out in collaboration with the IFS group and other groups. Other planned collaborations include: collaborations with the JT-60U group to study TAE stability, RSAE modes, bursting TAEs, fishbone modes and sawtooth stabilization for 500 keV N-NBI and ICRF experiments in JT-60U including plasma flow effects; collaborations with the JET group to study alpha particle physics and n=1 modes; collaborations with other domestic fusion research groups such as DIII-D, IFS, and MIT on wave-particle interaction physics; and collaboration with the C-Mod experiment on active TAE excitation experiments to test our models of the continuum damping and other linear damping mechanisms, such as trapped electron collisional damping. This work addresses question T12 of the FESAC Priorities Panel report ("How do high-energy particles interact with plasma?")

For MHD studies of resistive wall modes in collaboration with GA, in the near term (05-06), we plan to complete the conversion of the VACUUM code to Fortran 95, and to eliminate the up-down symmetry limitation of the code. In the near-medium term (06-07), we plan to interface the VACUUM code with nonlinear codes, *i.e.,* with M3D and NIMROD. In the medium term (07-08), we will continue with more simulations of the feedback in DIII-D which is being reconfigured with balanced beam injection to enable low rotation discharges. This will help to eliminate the uncertainties associated with the rotation/dissipation effects and enable a better comparison with a pure MHD feedback model. In the long term (08-10), the plan is to develop a 3D version of the VACUUM code. We will have to decide whether to use Fourier analysis in the toroidal angle or use a grid. If we decide to use a Fourier representation, then we will be developing the necessary capability to calculate the high-n Green's functions needed for the magnetic scalar potential. This is also needed in the studies for high-n peeling/ballooning modes.

The kinetic W approach will be used to study internal kinks in FY06-07, and will be used to compare with the balanced injection DIII-D data, when it becomes available in FY07-08.

Additional collaboration plans over the next five years include: calibration of tokamaks for equilibrium reconstruction; implementation of a rigorous approach for equilibrium reconstruction in the eddy current environment on NSTX, DIII-D, MAST, and ASDEX using a technology of calibrating tokamaks recently developed for CDX-U; for equilibrium reconstruction on JET, implementation of ESC as a standard equilibrium reconstruction code. For real time forecasting (RTF) for the tokamak discharges of the ITER machine, the development of RTF is envisioned as a high priority. Essentially, among numerous existing approaches, based either on fast (like real time EFIT) but truncated physics models, or on transport simulations, the ASTRA-ESC-DCON-BALLOON code system is not only an approach to RTF, but is already a prototype for it.

A.3 Deliverable Goals

- Improve and apply GTC and GTC-Neo for non-circular cross-section tokamaks under collaboration programs (2005/2010)

- Perform more general and realistic calculations for Alfvén eigenmodes for collaborating tokamaks (2005/2009)

- Further develop resistive wall mode capabilities and application (2005/2010)

- Extend accuracy and usability of equilibrium reconstruction for collaborating tokamaks. (2005/2010)

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B. NSTX Project-Related Tasks

B.1 Challenges

The theory and modeling plan for NSTX is based on; meeting the near-term research goals of the NSTX program; advancing the understanding of the physics of spherical torii; and addressing the longer term IPPA goal to determine the attractiveness of an ST as a reactor. Recent results from the experimental program are promising in the context of addressing the short term IPPA goals, and more importantly have been instrumental in identifying exciting new opportunities for advancing fusion science. Understanding these phenomena and developing physics based models to compare with experiment will be critical to provide the basis for extrapolation from the present device to reactor scale. In addition to this, since NSTX operates at extremes of parameter space relative to conventional tokamaks, there is the opportunity to test existing scaling laws at their limits of validity. Finally, modeling of NSTX also offers opportunities to address some aspects of reactor relevant physics in present day devices, notably in the areas of fast particle confinement and plasma boundary interactions.

Theoretical challenges of spherical torii, such as NSTX, are related to: the geometry, reduced aspect-ratio and increased elongation; and the relatively weaker toroidal field, which affects the trapped particle fraction, increases the orbit size and lowers the Alfvén speed. The reduced aspect-ratio leads to enhanced poloidal mode coupling, at the same time the shear is increased. These challenges are reflected in all areas of plasma science.

These ST features present challenges to the present treatment of both neoclassical and turbulent-induced transport. For instance, the high local values of b_t, reaching above 70% as determined from experimental measurements, implies that a full electromagnetic treatment of turbulence is necessary. Even the thermal ion gyro-radius may be comparable to typical plasma scale lengths (e.g., L_p, L_n, L_T) near the plasma edge, bringing into question the validity of the spatial scale length ordering in gyro-kinetic treatments. High rotational shears, with shear rates of up to 1 MHz, can have a profound effect on micro-instability thresholds and turbulence characteristics, and will impact the relative roles of ion and electron transport. Experimental observations show that ion transport is at neo-classical levels within a factor of two, [Fig. B.1], and the dominant thermal transport channel is due to electrons. This is consistent with theoretical modeling, linear calculations indicate suppression of ITG modes and the dominance of ETG modes, but non-linear calculations are needed in order to assess the expected levels of transport from these modes. This requires proper treatment of the geometry, aspect-ratio and non-circular cross-section, as well as electromagnetic effects. The effects of geometry have been introduced into the turbulence code, GTC, and the neo-classical code, GTC-Neo. Introduction of full electron dynamics at high-b is now in progress and will be the focus of applications, starting in FY06. NSTX provides the best platform to test for the existence or absence of ETG modes, as there is weak evidence for ETG modes in tokamaks.

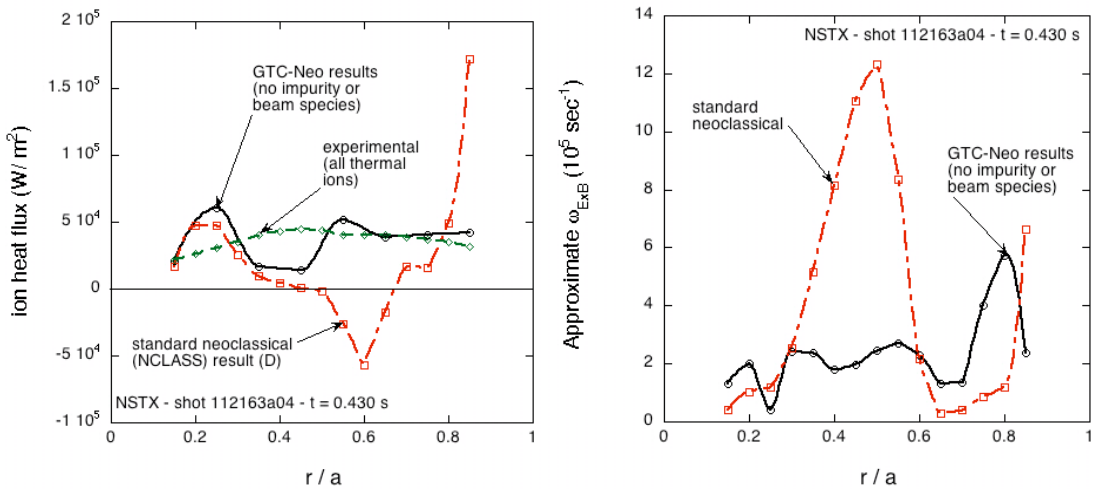

Figure B.1 Comparison of predicted ion heat flux using GTC-Neo, on the left, with experiment and the standard NCLASS result. The predicted shear flow from GTC-Neo differs significantly from the NCLASS result, on right. Improved physics in the codes and accurate experimental data are expected to resolve the differences.

The MHD behavior of NSTX is dominated by the relatively low toroidal field and strong poloidal mode coupling due to toroidal effects, The low aspect-ratio also leads naturally to high elongation as well as high magnetic shear near the edge. There are large Shafranov shifts, even at low b and the sound speed is comparable to the Alfvén velocity. In the presence of NBI the plasma flow velocity is a finite fraction of the sound speed and has a Mach number ~ 0.4 with high velocity shear. Consequently an important thrust for theory and modeling in the macroscopic stability topical area is to include rotation at all levels of equilibrium modeling and stability analysis. The high rotation may be responsible for the observed stabilization of RWMs and the m/n=1/1 mode. Theoretical modeling of the 1/1 with experimental flow rates, shows that the mode's growth-rate is reduced and saturation is possible, [Fig. B.2].

Resistive wall mode theory is routinely used for determining wall-boundary and rotation thresholds, however the dissipation mechanism responsible for slowing the rotation needs to be understood. This might also play a role in suppressing reconnection in tearing mode growth. The physics of dissipation also requires a kinetic description. The assessment of NTM stability requires calculation of Δ', the ideal Mercier-criterion index. The strong poloidal mode coupling in NSTX makes this a greater challenge.

The requirement to generate and sustain toroidal current non-inductively is a major challenge for the success of STs as a fusion device, because of the limited inductive flux that can be provided by the inherently slim center stack. The NSTX program includes co-axial helicity injection as a method for achieving this goal. For plasma startup and sustainment using this scenario, current penetration to the interior is eventually needed for usefully coupling CHI to other current drive methods and to provide CHI produced sustained current during the long pulse non-inductive phase. Assessment of flux closure in

driven systems needs both experimental and theoretical tools. Theoretical tools include equilibrium reconstruction and discharge simulation codes to understand experimental data and MHD codes to understand the physics of closed flux generation. The TSC and ESC codes have been applied to model the experiment and to assess the formation of closed flux surfaces.

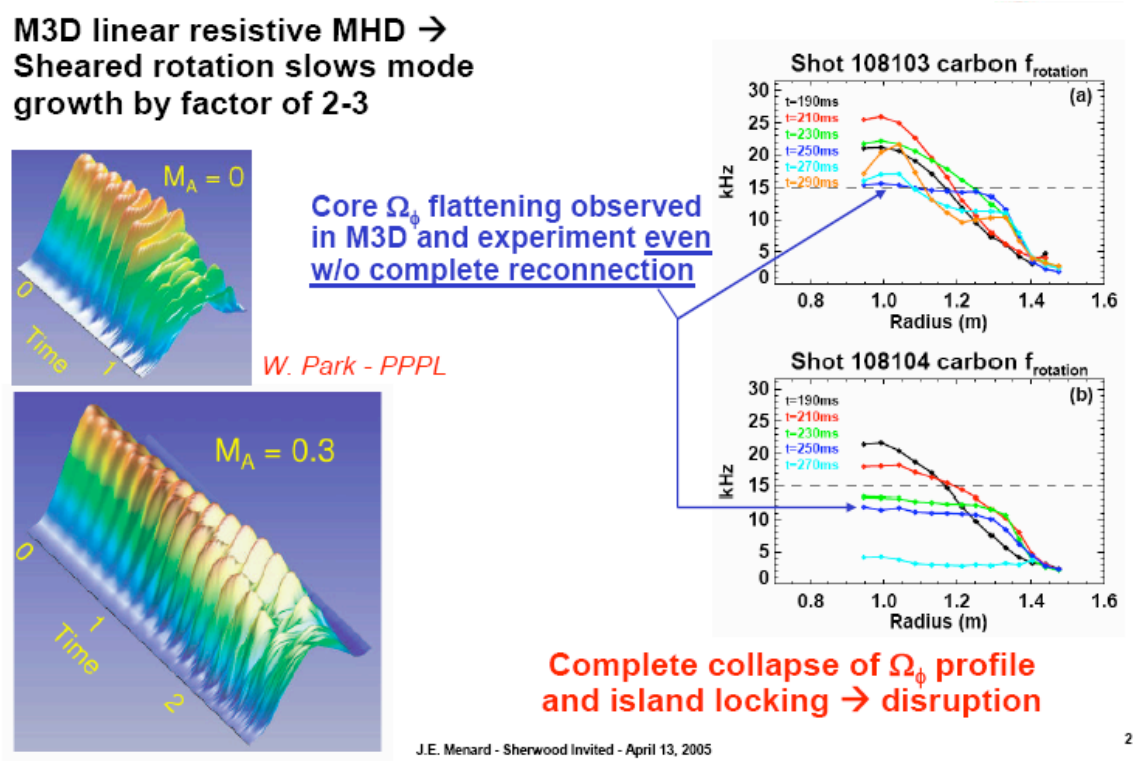

Figure B.2 Theoretical modeling, using the M3D code, shows that high rotation velocity can significantly reduce the growth-rate of the m/n=1/1 mode and even avoid reconnection, as observed in experiment.

In STs the low field and high density imply that the Alfvén speed is low, and fast particles due to NBI are generally super-Alfvénic with velocities of 2 to 4 times the Alfvén speed. This allows for resonance between fast ions and the various Alfvén eigenmodes, while the pressure gradient in real and velocity space provides a source for driving various Alfvénic waves, including TAEs, toroidal Alfvén eigenmodes, EPMs, energetic particle modes and fishbones, as well as CAEs, compressional Alfvén eigenmodes [Fig.B.3].

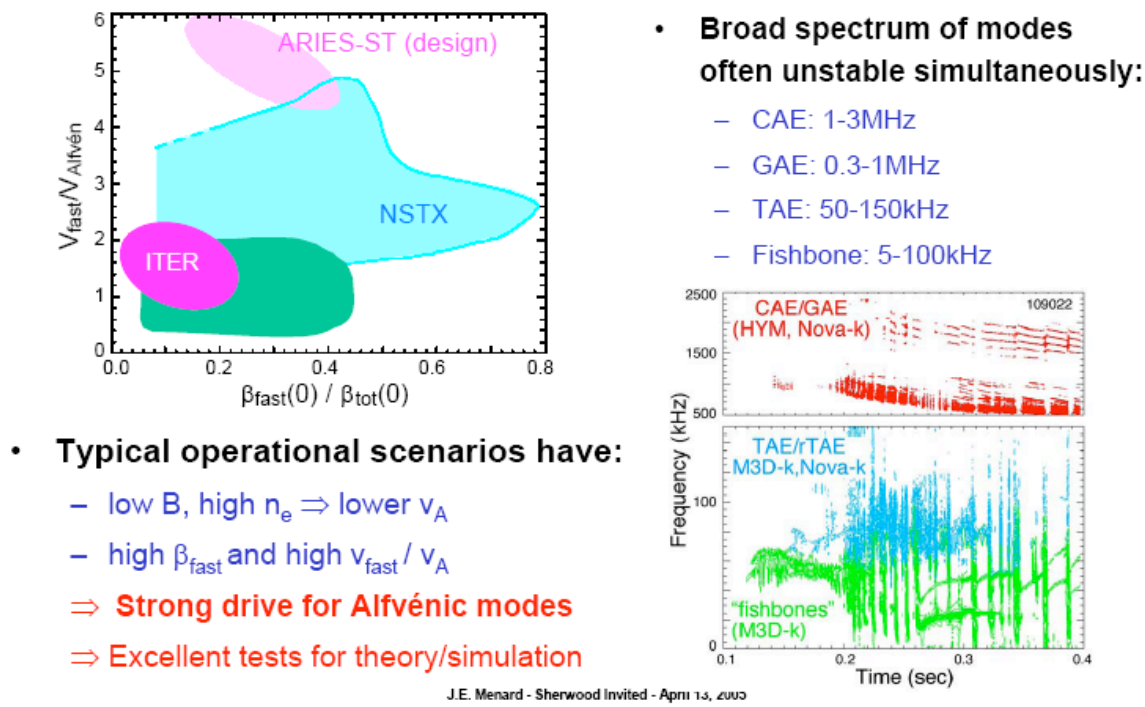

Figure B.3 Operationally NSTX accesses a wide range in parameter space in terms of $v_{fast}/v_{Alfvén}$ and b_{fast}/b_{total}, and overlaps regimes of interest to DIII-D, ITER and ARIES. NSTX also exhibits a full spectrum of energetic particle induced MHD, ranging from low-frequency fishbones to high frequecy compressional and global Alfvén eigenmodes. Different codes are used to model the different frequencies of the spectrum.

Modeling of energetic particle interactions in STs poses new challenges to the traditional methods employed in tokamaks. Some of the additional issues that need to addressed are: the need to keep compressional modes with $\square_c$ corrections in both MHD and kinetic codes; large Larmor radii; high-q and strong poloidal mode coupling; inadequacy of ballooning approximations requiring full geometry representation, strong anisotropy of plasma pressure and anisotropy of beam ion distribution function in velocity space. For example the CAEs are predicted to be strongly poloidally localized, while adding more poloidal harmonics into the calculations introduces an interaction with the shear Alfvén continuum in MHD codes. Resolution of such continuum damping needs kinetic effects and a fine mesh near the resonance surface in numerical codes. The ultimate challenge is to have the capability to model the non-linear consequence of these interactions self-consistently.

In addition to collective effects the confinement of fast beam ions is characterized by their large Larmor radius and large drift orbit radial width. New effects emerge from this, such as non-conservation of the adiabatic invariant m, which has jumps in magnitude when the ion passes the equatorial plane on the low field side of the plasma. If enhanced by the bounce resonances this effect results in stochastic fast ion diffusion. This depends on the ratio of the Larmor radius to the magnetic field scale length and on the collisional scattering frequency.

The large Larmor radius in NSTX makes it necessary to use numerical tools for adequate modeling of prompt ion losses. Strong electric field due to co-injection of beams needs to be properly included to interpret the measurements of particle losses at the edge.

STs are often designed as high power density devices, and heating of targets can limit pulse lengths in some scenarios. For example, the peak heat flux in a diverted H-mode discharge in NSTX with 4.5 MW NBI power was measured to be ~ 10 MW/m^2 Similar to the heat loads expected in ITER. Accurate interpretation of such data and extrapolation with standard analysis codes is critical to assessment of the ST concept and preparation for ITER. Plasma boundary interactions play a critical role in H-mode transitions. Determining a model for the H-mode power threshold is a pre-requisite for assessing the ST concept. H-mode power threshold theories generally do not include trapped-particle effects properly. Typically the equations are linearized and expanded in inverse aspect ratio, epsilon, which runs counter to the ST regime. Work to generalize those models will be needed.

Interpretation of edge measurements is typically done with a 2D fluid model, such as UEDGE, and/or a neutral transport code, e.g. DEGAS-2. The unique magnetic topology in STs, however, may necessitate kinetic theory corrections to standard fluid models. First, STs can have a high mirror ratio approaching 4 in the scrape-off layer (SOL), particularly in high triangularity discharges. This mirror ratio leads to a high-trapped particle fraction (~ 90%) and a change in the velocity-space loss cone. Trapped ions can experience an effective connection length much longer than the physical (rather short) connection length, allowing those ions more time to lose energy before striking and heating the target plate. A second challenge to interpretation and extrapolation of measurements is to have an accurate reconstruction of the separatrix because its radial location largely determines the power flux into the SOL. As in the MHD area, however, the high edge flow speed measured in some NSTX discharges leads to uncertainty about the equilibrium reconstruction technique, which ignores flow speed. Practically, the existing edge data will be modeled with fluid plasma and neutral transport codes, and the large number of free parameters, in these codes, almost assure a reasonable match between data and model. The challenge is to independently use kinetic models of the SOL to estimate the magnitude of kinetic effects, and then devise diagnostic techniques to measure those effects. If these effects are confirmed to be important, then kinetic theory 'patches' may be applied to the fluid models, for example, with the use of free-streaming limit multipliers on parallel transport. The issue of separatrix location is complicated by the relatively large ion poloidal gyro-radius ~ 0.5cm in many NSTX H-mode discharges, which could lead to an ambiguous distinction between the closed and open field lines.

A list of papers relating to NSTX co-authored by Theory department members is given at the end of this section.

B.2 Proposed research activities and Expected Deliverables

Proposed research activities in MHD

Equilibrium and linear stability: The main focus here is to account for plasma flow and to extend stability analysis to different parameter regimes. Equilibrium analysis will continue using FLOW, an ideal MHD equilibrium code developed by U. of Rochester in

collaboration with PPPL, which has the capability of including, sheared toroidal and poloidal flow as well as anisotropic pressure profiles. (2005-).

As NSTX extends its pulse length, it will be important to analyze for NTMs. This requires computation of Δ' in high-b NSTX equilibria, allowing for multi-mode coupling, this is being done with PEST-III. We can then assess the role of rotation as it affects the polarization term in the modified Rutherford equation. (2005-2007)

Nonlinear and kinetic MHD: The main code for this topic is the M3D code with its various extensions. It will be used to explore the underlying physics of various MHD phenomena. These include: Assessment of rotation on linear stability of internal modes. This includes sawteeth as well as high-b internal mode stability. (2006-2010). Develop an understanding of the coupling of error fields to plasmas. The PIES code will be used for stationary plasmas, and M3D for the case with flow, (2005-2008).

Performance improvements: In addition to these physics applications, we will assist in various performance enhancing computations. These include; assist in feedback stabilization of RWMs (2006-2010), profile optimization analysis in high-beta regimes (2006-2010), determine parametric stability boundaries. (2006-2010).

Proposed research activities in Transport and turbulence

Linear analysis: Applications relate to analysis of experimental profiles to help interpret experimental observations. The main codes for this are FULL, GS2, GTC, GTC-NEO and TRANSP. TRANSP will be used to provide equilibrium and plasma profile information for analysis with the stability codes. FULL has been used extensively to benchmark GS2 and GTC. It also has the unique capability to distinguish all the possible unstable modes, unlike the other codes, which follow the growth of the fastest growing mode. It will continue to serve in a support role. (2006-2010) GS2 has been used to examine selected radial positions to determine the fastest growing mode and identify its properties. It will be used extensively both to interpret experiments as well as to guide future experiments, by identifying regions of parameter space where different aspects of transport physics might play a significant role. This includes determination of frequency, growth rate, wave length and mode identification, i.e. ITG, ETG, TEM etc. (2006-2008) with identification of regions in k-space most likely to be affected by flow shear, and portions of the k-spectra most responsible for transport. (2007)

GTC-NEO will be used to address neoclassical physics in NSTX. It includes general geometry, self-consistent electric fields, rotation, and multiple species. It will be applied to NSTX plasmas to examine radial electric structure, heat fluxes, poloidal rotation and angular momentum transport, bootstrap current and possible pinch effects in the large r/L_n and B_{pol}/B_{tor} regime. The goal is to focus on understanding ST plasma transport determined by collisions (2006-2007).

GTC-NEO will address non-linearities in neoclassical physics (2006). Studies will include GK calculations of transport over a wide range of collisionalities, using NSTX profiles (FY

06-08) and of variations of T_e/T_i, n_e and n_i to establish what can be distinguished in an experiment. (FY 06)

Similar studies with GTC will determine whether turbulence-driven and collisionally dominated plasmas have different dependencies (FY 07-FY10).

Non-linear analysis: The GTC code will be used to study the fluctuation spectrum and turbulence-induced transport in NSTX to identify the most favorable plasma conditions for measurements of short wavelength fluctuations which could be related to ETG turbulence and to predict the density fluctuation amplitude and (k, □)-spectra from nonlinear gyrokinetic simulations. (FY 06-07) We plan to initiate modeling efforts using GF and GK codes to develop the physics picture of plasma dynamics observed with $t >> t_E$. We will include kinetic effects and rotation profiles in gyro-kinetic calculations. (FY 05-08) We plan to use or begin to develop tools appropriate for study of transport dynamics (time-evolving kinetic profiles, to develop a predictive capability). (FY 06-08) The goal is to self-consistently predict NSTX pressure profile dynamics, using dynamic transport model, calculations of bootstrap current, local stability analysis, and comparison with experiments, in conjunction with TRANSP. (FY 06-08) Transport control tool development: Using measured profiles, if fluctuation-induced transport dominates. We will estimate requirements for developing flow shear externally (e.g. with RF) to reduce or suppress turbulence. (FY 06-08)

Proposed research activities in CHI

The needs in this area are for a) modeling the experiment, b) optimizing the experiment and c) understanding the underlying physics. Modeling the experiment needs equilibrium codes, which can permit current on open field lines, in addition to the more common situation where the current is only on closed flux surfaces. The TSC and ESC codes can be used for this task. (2006). The TSC code will be used to model the evolution of the discharge and to optimize it (2006-2010). An important issue is to examine the needs of feedback control in the presence of large asymmetric currents, also to be done with TSC, (2006-2010).

Proposed research activities in Fast Particle Effects

There are several codes, which are available to assess the interactions of fast particles with MHD modes. They vary in complexity of the plasma model as well as in their treatment of kinetic effects. In increasing order of complexity, they are as follows. The ORBIT code, which studies the evolution of distribution function, based on single particle orbits in MHD equilibrium. The code allows for inclusion of static MHD perturbations, e.g. m/n=1/1 mode. HINST is a full kinetic code, which uses the local ballooning approximation to look at high-n modes in full geometry. NOVA-K is a non-variational code, which can include a kinetic population in a delta-W approach in a perturbative manner, whereas NOVA-KN is a nonperturbative extension to NOVA-K. The HYM code is hybrid two-fluid plasma and gyro-kinetic fast ion dF code. Finally there is M3D, which has kinetic as well as fluid formulations. These codes have been used successfully in a variety of applications. Future research requires extensions, cross-benchmarks and or more extensive applications. Some specific tasks are indicated below.

For the low frequency codes. Application of HINST for analysis of KBM and R-TAE with full kinetic and non-perturbative treatment. (2006-2008). Application of nonlinear HYM, a hybrid two-fluid plasma and gyro-kinetic fast ion □F code. (2006-2010). Application of nonlinear M3D as a two-fluid dF code. (2006-2010). Application of the Monte-Carlo code ORBIT with several fishbone dispersion relations to look at bounce-frequency fishbones(2006).

Using the high frequency codes. Include $\tilde{w}_c$ corrections in the global linear code, NOVA. (2007-2008). Develop the capability of treating arbitrary beam-ion distributions in HYM and in NOVA-KN(2006-2007). Develop the capability to treat fast particle resonances non-perturbatively(2006-2008). Development and application of non-linear version of HYM to self-consistently model CAEs and GAEs(2006-2008).

For the single particle confinement codes, change EIGOL code to model local fast ion losses into the loss ion detector (2005-2006). Develop a model scattering frequency due to □-non-conservation based on numerical and analytical studies (2006-2007).

Proposed research activities in Plasma-Boundary Interaction

Neutral transport modeling of NSTX gas puff turbulence imaging experiments with the DEGAS 2 code will continue. The previously used simulation techniques may need to be modified to account for modifications in the experimental procedure, such as the use of two atomic emission lines or of supersonic nozzles to inject the gas (2006).

Long pulse (>1 second flat-top) operation of NSTX may require methods of actively controlling the core density. However, developing an approach to controlling the density, such as adding a cryopump, would be premature in the absence of an understanding of the location and relative strength of particle recycling sources and the corresponding contributions to core fueling. Simple particle balance modeling has provided initial insight into this issue, but detailed modeling with DEGAS 2 would yield the required additional detail (2005-2007).

The NSTX supersonic gas injector was installed during 2004. Initial tests were "piggy-backed" onto the end of discharges set up for other purposes. During the injection period, the plasma was shrinking away from the injector, effectively generating a much larger than normal scrape-off layer. The camera images of the SGI operation depicted dramatic gas plumes that would serve as attractive targets for modeling with DEGAS 2. The subsequent, dedicated 2005 SGI experiments provide data on standard SGI operation that are likewise good candidates for simulation with DEGAS 2 (2006-2007).

Future plans for lithium-based particle control techniques in NSTX motivate the addition to DEGAS 2 of the infrastructure and data needed to treat lithium surfaces (2006-2007).

Additional physics topics need to be addressed, but are not within our present scope due to manpower limitations. These include the use of GYRO and other codes to examine core-

edge transport and H-mode pedestal widths and heights. This work is essential for assessing the viability of future ST devices. In particular, knowledge of the scaling of the pedestal height with core parameters is required to connect boundary plasma limits to the density and temperature at the magnetic axis. The ability to perform these studies is also dependent on the availability of diagnostics expected in the 2005-2008 timeframe. Finally, kinetic effects on scrape-off layer transport must be explored. The large mirror ratio and short connection length at low aspect-ratio suggest important effects on electron heat transport and impurity behavior. For this topic both manpower and codes are needed.

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C. Stellarator Theory Program

From the FESAC Priorities Panel Report (April, 2005):

…experiments with differing magnetic configurations, taken together, can reveal the effects of magnetic field properties on plasma behavior…The theory program therefore provides the necessary glue to tie together the research programs of differing configurations and sizes.

Ten-Year Goals:
Understand the coupled dependencies of plasma shape, edge topology, and size on confinement in a range of plasma confinement configurations.
Identify the mechanisms whereby internal magnetic structure controls plasma confinement
Identify the effects and consequences on confinement of large self generated plasma current.
Learn how to control the long scale-length instabilities that limit plasma pressure.
Understand and control intermediate to short wavelength modes responsible for limiting the plasma pressure, particularly at the edge, and extrapolate their effects to the burning plasma regime.
Understand the equilibrium pressure limits in a range of magnetic configurations, including the effects of islands, stochastic magnetic fields, and helical states.
Understand and demonstrate the use of self-generated currents and mass flows to achieve steady-state high pressure confined plasmas and improve fusion energy performance.
Understand how external control can lead to improved stability and confinement in sustained plasmas in a range of magnetic configurations

C.1 Background

C.1.1 Introduction

The PPPL stellarator theory program addresses equilibrium, stability and transport physics issues in the context of three-dimensional magnetic field geometry. For those physics issues that arise also in an axisymmetric context, such as kink stability, the three-dimensional geometry complicates the analysis, and also provides opportunities for control and experimental study that are not available in two dimensions. (e.g. the opportunity to vary the current profile independently of the q profile.) Other physics issues being studied, such as neoclassical ripple transport losses and loss of flux surfaces are intrinsically three-dimensional. These issues are intrinsic to stellarators, but they also are introduced in nominally axisymmetric devices by ripple, by field errors, and by non-axisymmetric instabilities.

The PPPL stellarator theory effort has been pursued in the context of several design studies. The theory group played a key role in the design of the National Compact Stellarator Experiment (NCSX), solving critical problems and introducing important features in the

configuration. At the same time, the theory group also contributed to the design of other domestic stellarator experiments.

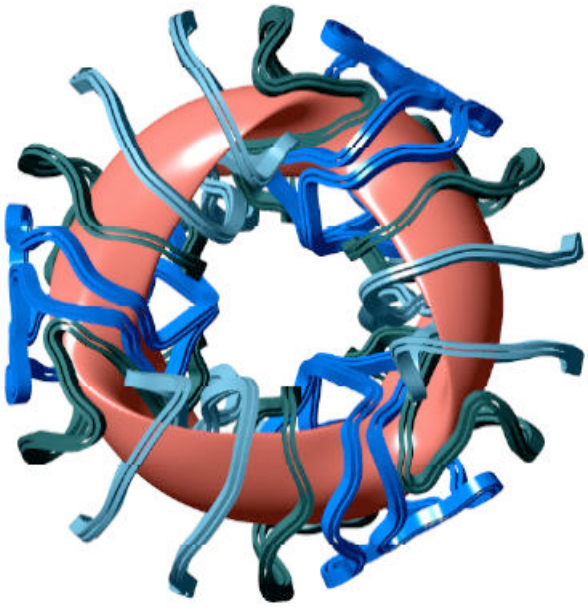

Fig. C.1. NCSX plasma and modular coils.

After the successful completion of the NCSX conceptual design review (CDR) in May of FY02, and the freezing of the NCSX coil design in December of FY03, the PPPL stellarator theory effort turned its focus to fundamental stellarator physics issues, to code development, and to collaboration with existing experiments, with some continued support of the NCSX project on coil issues, edge modeling and diagnostic design.

Construction of NCSX is projected to be completed in the summer of 2009. The quasi-axisymmetric NCSX configuration represents a hybrid between an advanced tokamak and a drift-optimized stellarator. Its design has benefited from theory and codes developed in the context of the tokamak program. When operating, the NCSX will provide a new perspective on some key tokamak physics issues. The improved theoretical understanding that emerges from the experiment, and the codes developed in that context, will not only be critical for optimizing a possible next generation of stellarator configurations, but will also benefit the advanced tokamak program.

C.1.2 Participation in Design of NCSX and other Stellarator Experiments

From FY97 through FY02, the PPPL theory stellarator effort was carried out primarily in the context of the National Compact Stellarator Experiment (NCSX) design study.[2] At the peak of the physics design effort, ten members of the theory group were involved. The NCSX physics design effort was headed by a member of the theory group for a three-year period during which the key features of the configuration were set.

The theory group played a major role in guiding the design of NCSX and in addressing critical physics issues for it. Calculated ballooning β limits of previous quasi-helical and quasi-axisymmetric designs had been less than 2%. The problem of ballooning mode stabilization was solved by an innovative design with strong axisymmetric shaping (a

unique feature of NCSX relative to other stellarators). This solution was closely related to the development of a design strategy which morphed an advanced tokamak design to a quasi-axisymmetric stellarator, introducing externally generated rotational transform while preserving the quasi-axisymmetry and ballooning stability. (rotational transform $\equiv \iota \equiv 1/q$) The goal was to combine the desirable features of advanced tokamaks with those of drift-optimized stellarators.

The desire to stabilize external kink modes even in the absence of a conducting wall led to systematic studies of stabilization via externally generated shear, and to the introduction of a stabilizing nonaxisymmetric corrugation of the plasma boundary when shear stabilization alone proved to be inadequate. The NCSX design uses approximate quasi-axisymmetry to obtain desirable drift trajectories, and the GC3, GTC and ORBIT codes developed at PPPL (as well as ORNL codes) were used to monitor the adequacy of the resulting neoclassical thermal and energetic particle confinement. Theoretical flexibility studies in FY01 and FY02 demonstrated an unanticipated level of flexibility of proposed coil sets to produce a range of configurations with good stability and transport properties.

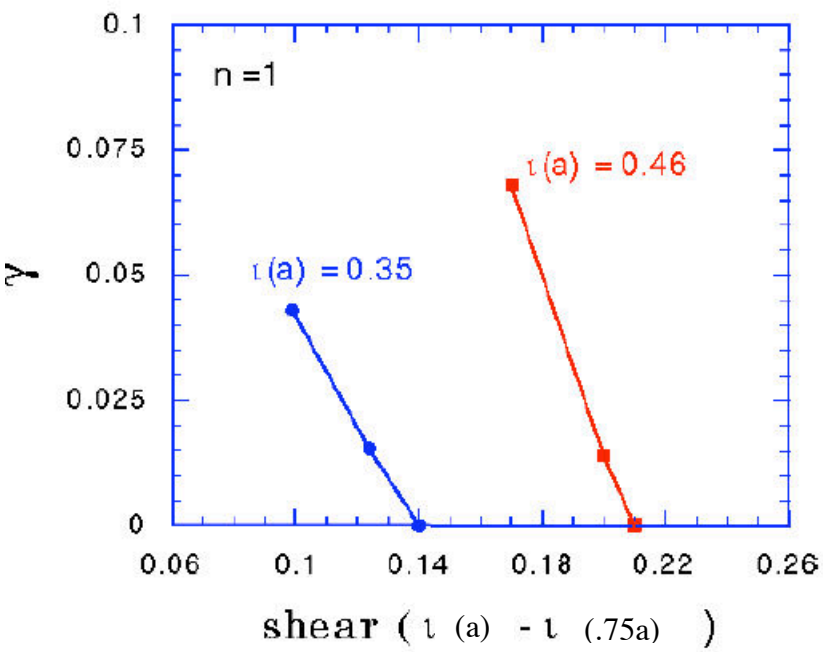

Fig. C.2. Growth rate of the external kink mode (normalized to the Alfven time) vs. externally generated shear calculated using the Terpsichore code for two different configurations. The configurations each have four periods, an aspect ratio of 3, and a β of 6.8%.

Calculations with the PIES code evaluated the flux surface integrity of proposed NCSX designs. These studies led to the identification of classes of configurations with intrinsically favorable fixed boundary flux surfaces. An optimizer built around the PIES code was used to modify the coil design to minimize resonant field components that produce magnetic islands while preserving desired physics and engineering properties. Having eliminated resonant Fourier components for the NCSX reference equilibrium, it was verified that the improvement of the flux surfaces carried over to a range of configurations with varying pressure and current, including a sequence of equilibria corresponding to a startup scenario[3]. The efficacy of proposed trim coils for providing additional control over the flux surfaces was also confirmed.

PIES field error studies for NCSX continued through FY03, supporting the field error tolerances that had been adopted by the engineers. Currently, calculations of the effect of resonant magnetic perturbations are being carried out for simpler model configurations for comparison with semi-analytic models and with the NIMROD and M3D codes. It is expected that these calculations will lead to improved physics understanding that will carry over to future NCSX calculations.

Improvements to the PIES code in FY03 and FY04, implemented in collaboration with M. Drevlak of Greifswald, Germany, facilitated its use for edge modeling studies. The modified code was applied to such studies for NCSX (in collaboration with T. Kaiser at LLNL) as well as to W7X.

Over the past year, a method has been developed for optimizing the placement of magnetic diagnostics in stellarators, and this is being applied to the design of the magnetic diagnostics for NCSX. This will be discussed in greater detail in Section C.1.4.

The PPPL theory group has also contributed to the design of domestic stellarator experiments other than NCSX. Two members of the theory group shared in the ORNL Scientific Research by a Team Award for their contributions to the design of the QPS experiment. MHD stability calculations were done in support of the QPS design, and the PIES code was used to evaluate flux surface integrity for it. Stability calculations were also done to support the design effort for the CTH device at Auburn. There were also contributions to the optimization of the coil design for the Columbia Non-Neutral Torus (CNT) device at Columbia University. [4]

In addressing the key stellarator physics issues in the context of the NCSX design, the theory group exercised its locally developed stellarator codes, and also imported major stellarator codes from Europe and Japan. The experience gained in the course of the design work helped to sharpen the recognition of critical needs for further computational tool development and for improvements in the understanding of fundamental physics issues.

C.1.3 Development and Application of Major Codes

During the course of the NCSX design studies, several major tokamak codes that had been developed at Princeton were modified to allow their application to stellarators. The PIES code had been developed at Princeton for stellarator applications in the mid 1980's, and it too saw major improvements to facilitate its application to NCSX. Numerical tools for characterizing the ballooning stability properties of stellarator configurations, focusing particularly on second stability, have been developed more recently in collaboration with the University of Wisconsin.

The major tokamak codes that have been applied to stellarators are discussed elsewhere in this document, and their background will not be discussed in this section. The nonlinear extended MHD code M3D is discussed in Section II.A. The global gyrokinetic GTC code is

discussed in Section II.B. The ORBIT code, which was used in the NCSX design study for calculations of energetic particles, is discussed in Section II.C.

The HINST code was constructed to calculate high mode number energetic-particle driven instabilities in tokamaks, and it has been modified to read the output of the VMEC 3D equilibrium code. The modified code has been benchmarked against a NIFS (Japan) ballooning code for the ideal ballooning mode analysis of tokamak and LHD equilibria. Work is continuing on converting this code for stellarator applications. The HINST code is described in Sections II.A and II.C.

The new ballooning code, developed in collaboration with C. Hegna of the University of Wisconsin, allows the calculation of marginal stability s-α diagrams for stellarators (see Fig. C.3), a generalization of the Greene-Chance approach that has been widely applied to tokamak ballooning stability properties, particularly second stability [5,6]. This approach has been further extended using an additional perturbation analysis to speed the calculation. The code has been applied to provide the first analysis of second stability properties for a range of stellarator configurations. The stability diagrams have been used to interpret experimental results on W7-AS[1], and have been used in a recent collaboration with Nakajima (NIFS, Japan) suggesting an explanation for the observed stability of LHD[7].

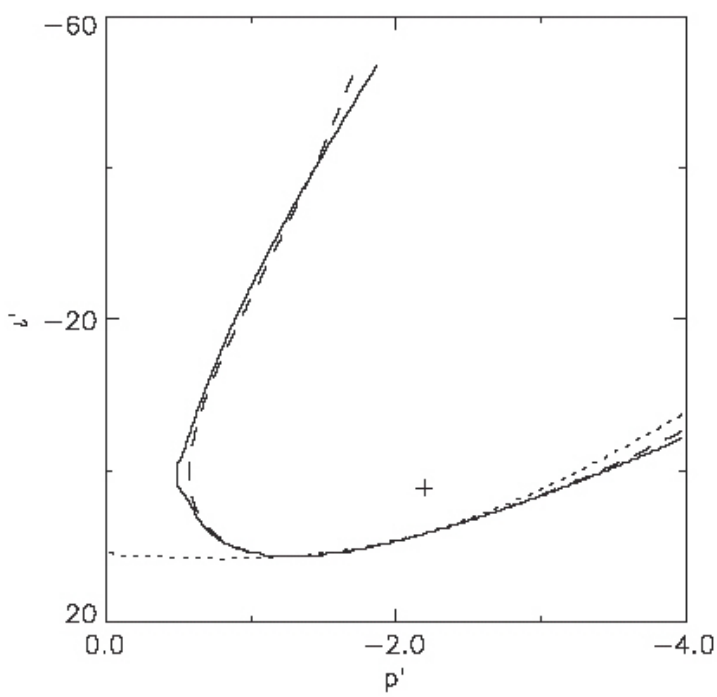

Fig. C.3. Comparison of stability boundary calculated by the method of Greene & Chance (as applied to stellarators; solid line) with second order expansion (dotted) and fourth order expansion (dashed) line for an NCSX equilibrium.

The PIES code is a three-dimensional MHD equilibrium code. Equilibrium calculations are used for the interpretation of experimental data and for theoretical configuration studies, and they are a necessary first step before doing further evaluations such as stability and transport calculations. Conventional three-dimensional equilibrium codes use a flux surface representation for the magnetic field that assumes that the field defines a set of nested flux surfaces. This assumption is never exactly satisfied, but it is believed that it is often a reasonable approximation. The PIES three-dimensional equilibrium code uses a general

representation for the magnetic field, and is therefore capable of handling islands and stochastic regions. (The HINT code, developed in Japan, is also capable of solving three-dimensional MHD equilibria with islands.)

The PIES code was developed at Princeton in the mid 1980's, and has undergone continued modification and improvement since that time. PIES was developed at a time when there was a need for such a code by the W7X design group in Germany, and there has been a long term, strong collaboration with the W7X stellarator group on the development and application of the code. (W7X is a $1 billion class stellarator now under construction in Greifswald, Germany.) There is an extensive set of publications on the algorithm, implementation, verification, validation, convergence properties and applications of the PIES code [1,8,9,10,11,12,13]. As described in Section C.1.2, the PIES code was used extensively in the design of the National Compact Stellarator Experiment (NCSX).

The PIES code has been extensively verified and validated. Each component of the code was independently tested as it was built. Over the years, alternative algorithms have been developed for many pieces of the code, and they have been benchmarked against the original. There are internal checks in the code to verify convergence. The code solves the MHD equilibrium equations in the form $\nabla \times \mathbf{B} = \mathbf{j}(\mathbf{B})$, $\nabla \cdot \mathbf{B} = 0$, where $\mathbf{j}(\mathbf{B})$ is determined by $\mathbf{j}_\perp = \mathbf{B} \times \nabla p / B^2$, $\mathbf{B} \cdot \nabla \left(j_{\ddot{y}} / B \right) = -\nabla \cdot \mathbf{j}_\perp$. The quantity $\mathbf{B} - (\nabla \times)^{-1} \mathbf{j}(\mathbf{B})$ is monitored to verify that it is getting small as the code iterates. The code also monitors the quantity $(\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p$. Since this is not the form in which the equilibrium equations are solved in the code, this quantity will only go to zero to within the discretization error. Convergence studies verified that this quantity does go to zero as the resolution is increased.[9]

The code has been benchmarked against several analytic test cases, and the results of the comparisons have been either published or presented at meetings. Comparisons with Soloveev equilibria and with the large aspect ratio stellarator expansion are discussed in Ref. [9]. Comparisons with helical force-free Bessel function equilibria with islands are described in [10]. Comparisons with the narrow-island, saturated tearing mode solutions of White et al and Zakharov were discussed in [11].

PIES has been benchmarked against several other codes. It has been benchmarked against axisymmetric j-solver equilibria for TFTR and DIII-D. It has been benchmarked against Biot-Savart vacuum field solvers for vacuum fields with magnetic islands. It has been benchmarked against a linearized resistive time-dependent code developed by M. Hughes (then at Grumman) for predictions of marginal stability for tearing modes on TFTR. The PIES code has been benchmarked against the VMEC code for ATF and TJ-II stellarator equilibria with good flux surfaces, and careful convergence studies were done to verify that for these equilibria the two codes converge to the same solution as the resolution is increased.[12] At present, the PIES code is typically run in a mode where it is initialized using a VMEC solution. This provides routine comparisons between VMEC and PIES solutions. Occasionally, when there appears to be a disagreement between the two solutions, a convergence study is done to verify that the disagreement is due to discretization error and goes to zero as the resolution is increased if the flux surfaces are

good. Finally, there has been an initial benchmark against the HINT code for a W7-AS equilibrium, and further comparisons are planned.

Recently, the PIES code has been modified to allow the imposition of an experimentally determined pressure profile. When run in this mode, the code does not flatten the pressure profile in islands or stochastic regions, unless this is indicated by the diagnostic measurements. (In a region of high collisionality, for example, it is reasonable to have a finite pressure gradient even if the field is stochastic.) The modified code has been applied to the analysis of data from the W7-AS stellarator experiment, which indicates that the experiment may have encountered an equilibrium β limit.[1] For these calculations, the pressure profile has been determined by the data from the Thomson scattering system and from the set of magnetic diagnostics. Fig. C.4,[1] which was reproduced in the recent FESAC Priorities Panel Report (Fig. 3.5, p. 30), displays the results of two sets of PIES calculations with an imposed pressure profile and varying β. The calculations predict the formation of a region of stochastic field lines at the plasma edge above a threshold value of β, and that the width of the stochastic region progressively increases as β is further increased. The calculated threshold value for the appearance of the stochastic region and the width of the stochastic region depend on the magnitude of the current in the divertor control coils, I_{cc}. The maximum achievable β in the experiment also depends on the value of I_{cc}, and the achievable β correlates with the width of the stochastic region calculated by PIES. Fig. C.4 shows the fraction of good flux surfaces versus β as predicted by PIES for two different values of the divertor control coil current. The circles indicate the PIES calculations done for the experimentally achieved value of β. The experimentally achieved value of β in each case corresponds approximately to that value where PIES predicts that the outer 35% of the minor radius is filled with chaotic field line trajectories. The results suggest that the loss of flux surfaces degrade the confinement and limit the achievable β value. The value of I_{cc} has little effect on the shift of the magnetic axis, suggesting that the equilibrium β limit is not adequately characterized by the often invoked rule of thumb that assumes that the equilibrium β limit corresponds to a magnetic axis shift of approximately ½ the minor radius. This work is continuing, and will be discussed further in Section C.2.2

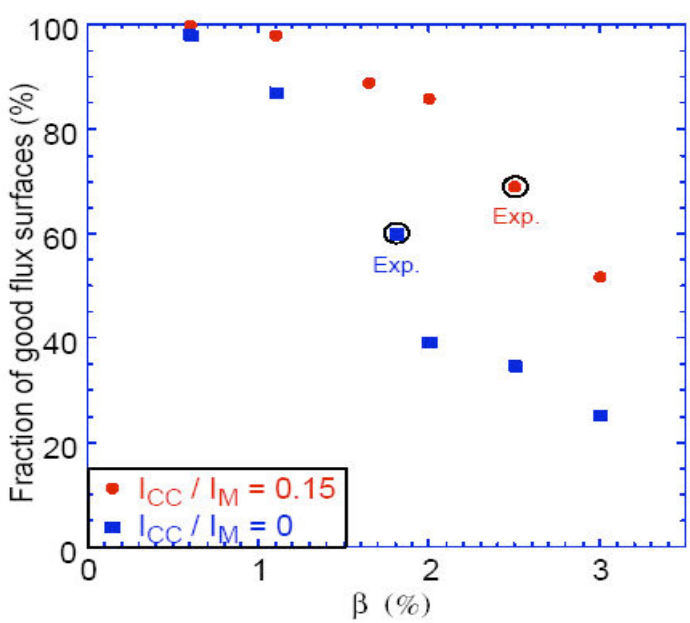

Fig. C.4. Fraction of good flux surfaces versus β as predicted by PIES for two different values of the control coil current for the W7AS stellarator. The circles indicate the PIES calculations done for the experimentally achieved value of β.

C.1.4 Recent Theoretical Progress in Other Areas

In addition to the code applications described in the previous section, the past year has also seen significant theoretical progress in several other areas: an investigation of the interaction between turbulent transport and stellarator neoclassical transport[14], development of an algorithm for optimal design of magnetic diagnostics for stellarators[15], completion of a project investigating the effect of ambipolar flow on the penetration of resonant perturbations in quasi-axisymmetric stellarators [16], and an evaluation of microinstability properties for a range of stellarator magnetic geometries[17].

The transport study was done in collaboration with A. Boozer at Columbia University.[14] A Monte Carlo transport code has been modified to include a spectrum of electrostatic perturbations modeling the effects of turbulence. Calculations show that, while the addition of a fluctuating spectrum to the background fields always enhances transport over neoclassical levels in tokamaks, the fluctuations can sometimes reduce transport losses in stellarators. (Fig. C.5.) The conventional assumption has been to treat neoclassical and turbulent losses as additive.

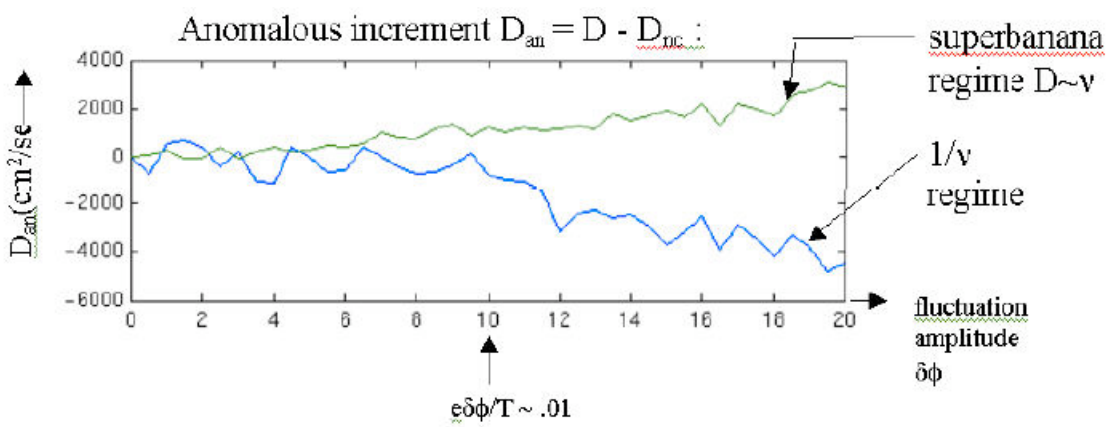

Fig C.5. Plot of anomalous increment $D_{an} = D - D_{nc}$ to neoclassical diffusion coefficient D_{nc} versus amplitude of fluctuations applied, in a conventional stellarator, showing that in some regimes of collisionality ν, the fluctuations can decrease the total radial transport, opposite tokamak-based intuitions.

Over the past year, a method has been developed for optimizing the placement of magnetic diagnostics in stellarators, and it is being applied to the design of the magnetic diagnostics for NCSX [15]. A multivariate statistic "variable selection" algorithm has been developed for this purpose using singular value decomposition methods. The algorithm provides an analysis of how much information on plasma equilibria is accessible, in principle, to a "perfect" magnetic diagnostic set, and provides a scheme for determining a realistic magnetic diagnostic set that recovers the maximum amount of available information. Extensive production runs applying the algorithm to the placement of saddle loops on the NCSX vacuum vessel have been done.

The requirements of the NCSX construction project imposed a deadline on the magnetics design, and this has led to the postponement of work on a 3D equilibrium reconstruction

project using emissivity data. An earlier formal result, generalizing a 2D method of Christiansen & Taylor to 3D systems [18], is now being implemented in a code to test whether the method can be used as a novel diagnostic for stellarators, allowing practical reconstruction of 3D stellarator equilibria from emissivity data. This work is complementary to the V3FIT effort, another stellarator equilibrium reconstruction effort being undertaken in the US.

The theory of the shielding of resonant magnetic perturbations by plasma flow has been extended to include the effects of nonambipolar transport in quasi-axisymmetric stellarators.[16] A particularly interesting regime of intermediate ripple amplitude has been identified, where the deviation from quasi-axisymmetry is sufficiently small to allow the plasma to flow in the toroidal direction with little viscous damping, yet the deviation is sufficiently large that nonambipolarity significantly affects the physics of the shielding. A reference NCSX equilibrium is predicted to be in this regime. The shielding can be enhanced by this mechanism, with implications for the flexibility of NCSX and for possible startup scenarios.

For the microstability study, the microinstability properties of seven distinct magnetic geometries corresponding to different operating and planned stellarators with differing symmetry properties were compared. Specifically, the kinetic stability properties (linear growth rates and real frequencies) of toroidal microinstabilities (driven by ion temperature gradients and trapped-electron dynamics) were compared, as parameters were varied. The ballooning representation was used to enable efficient treatment of the spatial variations along the equilibrium magnetic field lines. The studies provide insights for understanding the differences in the relative strengths of the instabilities caused by the differing localizations of good and bad magnetic curvature and of the presence of trapped particles. The associated differences in growth rates due to magnetic geometry are large for small values of the temperature gradient parameter d ln T/d ln n, whereas for large values of the parameter the mode is strongly unstable for all of the different magnetic geometries.

C.1.5 Collaborations

The main themes of the stellarator theory work at Princeton in recent years have been discussed above. Throughout the course of this work, the stellarator theory group has collaborated extensively with both domestic and foreign stellarator groups. The collaborative activities are briefly summarized in this section.

National Stellarator Theory Teleconference: Initiated about 2½ years ago, the teleconference is held approximately monthly, except when it conflicts with a major scientific meeting. Organized by A. Reiman, the purpose of the teleconference is to help keep stellarator theorists informed of what other people in the community are working on, and to engender discussions of related technical issues.

US/Japan Workshops: D. Monticello has acted as the US organizer for a workshop held at Princeton in FY02, and one held in Japan in FY05.

W7-AS Stellarator group (Germany) [1,19]: PIES calculations of equilibrium flux surfaces for differing control coil current are consistent with the observed dependence of the highest achievable β. Ballooning calculations for a modified mirror ratio are consistent with the observed bifurcated behavior. Terpsichore linear MHD stability calculations predict the appearance of m/n = 2/1 instabilities at intermediate values of β, in agreement with observations.

W7X Stellarator Group (Germany): A long-term collaboration on the development and applications of the PIES code. Most recently, we collaborated with M. Drevlak on the implementation of a method for calculating the magnetic field in the vacuum region outside the PIES grid, and on an application to W7X [13]. The calculations have been benchmarked against predictions of the MFBE code. The enhanced free-boundary capability developed in this collaboration is important for edge modeling studies, and has been applied to NCSX in collaboration with the Livermore group (see below).

TJ-II Stellarator Group (Spain): We have collaborated since the mid 80's on the development and application of the PIES code. Most recently, we have collaborated on a PIES study of TJ-II stellarator configurations with net toroidal current.[20]

LHD and Heliotron-J Stellarator groups (Japan): Full code microinstability studies.[21] PIES calculations for LHD and Heliotron-J, including benchmarking against HINT.[22] Ballooning calculations for LHD.[6,7] Collaboration with Nakajima on modification of the HINST code for calculating kinetic effects on high *n* instabilities in stellarators, including the drive term due to energetic-particles.

Australia National University (ANU), Australia: Collaboration with Dewar's group on a new 3D equilibrium code they are developing.

Oak Ridge National Laboratory (ORNL): ORNL theorists collaborated extensively with Princeton theorists on NCSX design studies. Extensive collaborations on flux surface and stability issues related to the QPS experiment [23]. Two members of the Princeton theory group shared in the ORNL Scientific Research by a Team Award in recognition of these contributions.

Columbia University: Contributions to the optimization of the coil design for the Columbia Non-Neutral Torus (CNT) device [4]. This is a new experiment to confine non-neutral and positron-electron plasmas in a stellarator field. Long-term collaboration with A. Boozer, most recently on the interaction between turbulent transport and stellarator neoclassical transport[14], and on transport in the CNT[24].

NYU and MIT: Collaboration with H. Strauss at NYU and L. Sugiyama at MIT on M3D code development and applications for stellarators.

University of Wisconsin: Collaboration with the group of C. Hegna on stellarator ballooning stability studies.[5, 6] A joint study has recently been initiated to benchmark PIES

calculations against quasi-analytic island solutions for simple model cases, and also against the NIMROD code.

Livermore MFE Group: Collaboration on edge modeling studies for NCSX using the PIES code.

Livermore, Center for Applied Scientific Computing (CASC): Collaboration with Chandrika Kamath, who is developing an AI method for the automated classification of magnetic field lines of 3D toroidal systems.

C.2 Five Year Plan

C.2.1 Plans for the Development and Application of Major Codes

We discuss here the stellarator related plans for M3D, GTC, HINST and PIES. Detailed discussions of the plans for M3D, GTC and HINST development and applications are contained in Sections II.A, II.B and II.C of this document. Here we summarize only briefly the stellarator related plans for GTC, M3D and HINST, and we focus primarily on the plans for the PIES code.

GTC: The GTC code has been applied to calculate neoclassical transport in stellarators, and it was used extensively for this purpose in the NCSX design study. An improved neoclassical version is planned for FY07, with field line following coordinates implemented, and an improved calculation of the ambipolar potential. In FY08, GTC will be modified to enable it to address turbulent transport in stellarators. The three-dimensionality of the magnetic field in stellarators provides a flexibility to vary transport related magnetic field properties not present in axisymmetric configurations. Trapped particle, magnetic shear and curvature properties can differ from those in axisymmetric configurations. Stellarator configurations can have a strong ambipolar electric field and strong flow damping. Comparison of stellarator experiments with transport codes will provide improved understanding of the physics of turbulent transport, and can potentially provide opportunities for control over these transport related properties not available in axisymmetric configurations. No stellarator has been designed to minimize turbulent transport, but this could become feasible. See Section C.2.2 for further discussion of plans to address the interaction between turbulence and neoclassical transport in stellarators. See Section II.B for more extensive discussion of the plans for the GTC code.

M3D: The M3D stellarator work is being pursued primarily by H. Strauss at NYU and L. Sugiyama at MIT, with Princeton playing a supporting role. (Although this is not true of the M3D work on nonlinear energetic particle driven modes, which is being pursued primarily at Princeton.) The code will be used to calculate the nonlinear evolution of instabilities in NCSX and other stellarators, including two-fluid and energetic particle effects. Coupling of the code to PIES equilibria has already been initiated, and this will provide a method for calculating the stability of equilibria with islands and stochastic regions. See Section II.A for more extensive discussion of the plans for the M3D code.

HINST: The HINST code will be modified to allow it to calculate kinetic effects on ballooning modes in stellarators (FY06 – FY08). The fast ion drive will also be added to the 3D capability (FY07 – FY08). See Section II.C for more extensive discussion of the plans for the HINST code.

PIES Code Applications and Development:

In the near term, PIES studies of the magnetic field structure in W7AS, and of the associated β limit, will continue. (FY06 - FY07) A new study is also being initiated to compare analytical calculations for magnetic islands in model configurations with PIES calculations. (FY05 - FY06) Over the next few years, it is planned to incorporate neoclassical effects on magnetic islands (FY06 – FY07) and flow shielding of resonant magnetic perturbations (FY08 – FY09) in the code. The code is being continuously modified as the experience developed with new applications suggests algorithm improvements, but over the next few years there will also be a focused effort to improve the speed and robustness of the code in preparation for the routine analysis of NCSX data, including parallelization of the code. (FY06-FY09) In this context, it may prove desirable to develop a "PIES Lite" version of the code which sacrifices some accuracy to maximize the speed. (FY08 – FY09) The accelerated code will be used to develop databases of free-boundary PIES equilibria for both NCSX and W7X. (FY08 – FY09) In the long term, it is planned to begin the development of a non-axisymmetric time-dependent transport code built around the PIES code, which will be able to handle islands and stochastic regions. (FY09 – FY10)

In collaboration with M. Zarnstorff and the W7-AS team, we will continue the comparison of β limit observations on W7-AS with PIES calculations (Section C.1.3), performing the calculations for a more extensive set of shots, and including a finite driven current profile (with zero net current). For this purpose, the PIES code is being further modified to allow the imposition of an experimentally determined current profile. (FY05)

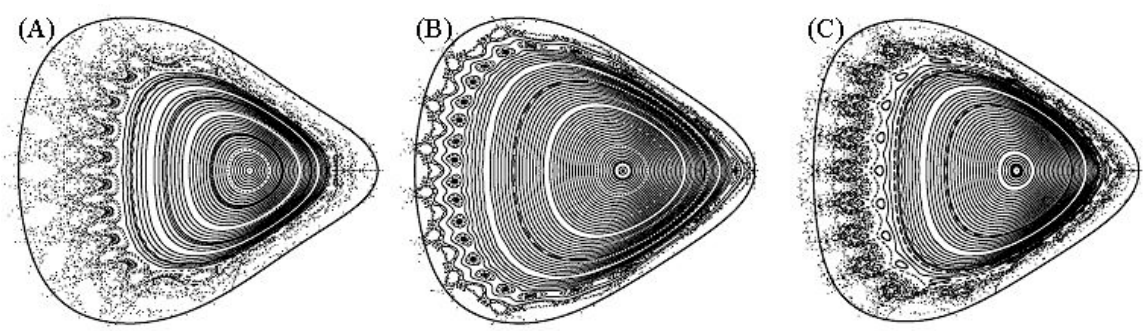

Fig. C.6. PIES calculated Poincare plots for W7-AS for differing values of β and control coil current, I_{CC}: (A) I_{CC}=0 and $\langle\beta\rangle$ = 1.8%, (B) I_{CC}=-2.5kA and $\langle\beta\rangle$ = 2.0%, (C) I_{CC}=-2.5kA and $\langle\beta\rangle$ = 2.7%. In each case the dark line is the VMEC calculated plasma boundary.

The PIES calculations for W7-AS indicate that to properly model the equilibrium β limit we must incorporate a finite pressure gradient in the edge stochastic region. At this point we are imposing an experimentally measured pressure profile in the calculations. We plan to address the question of how the structure of the magnetic field in the stochastic region affects the transport, and the pressure gradient, in FY06 – FY07. The goal will be to develop a self-consistent picture of the equilibrium beta limit, with the field line stochasticity properties affecting the local pressure gradient, and the local pressure gradient in turn affecting the magnetic field stochasticity through the pressure driven current. The expectation is that the radial transport in the edge stochastic region increases with increasing β, leading to a soft beta limit.

The model transport calculations will be supplemented by Monte Carlo calculations using the ORBIT code. In FY06, an interface will be constructed to allow ORBIT to use the output from a PIES equilibrium calculation. Because the particle trajectory following in GTC has been adapted from that in ORBIT, this will also serve as a first step towards coupling PIES to the GTC code.

Edge modeling calculations for W7AS using the PIES code are also being initiated. The observed variations in the heat deposition footprint will be compared with the predicted footprint.

A new study has recently been initiated to compare the predictions of quasi-analytic calculations for magnetic islands in model configurations with numerical calculations of the PIES code to illuminate the critical physics determining island widths in stellarator configurations of practical interest, and to lead to insights on how to improve the quality of magnetic surfaces in stellarators. One focus will be the role of the resistive interchange driving term in determining island widths. The study will require the extension of existing analytic calculations to stellarators with nonzero net current (FY06). The study is being done in collaboration with the University of Wisconsin, and will also involve benchmarking against the NIMROD code. Convergence studies will be done to verify agreement in the limit as the resolution is increased. (FY06) The improved understanding emerging from these studies will also be applied to the analysis of NCSX field errors.

Neoclassical effects will be incorporated in the PIES code (FY06). Comparison with the predictions of quasi-analytic models will be extended to include those effects (FY07). Improvements are currently being made to the PIES code preparatory to the inclusion of neoclassical effects. These include a nonuniform radial grid, with grid surfaces located near island separatrices to allow an accurate determination of currents in that region, and an improved algorithm for mapping between coordinate systems. The modeling of neoclassical effects will be further improved by coupling the PIES code to a 1D flux-surface averaged transport code for determining the profiles on the good flux surfaces (FY07). This work will take advantage of the models for the profiles in the stochastic regions developed in the context of the W7-AS study. Neoclassical effects will be important in the analysis of NCSX experiments.

A subgrid model for the shielding of resonant perturbations by plasma flow will be implemented in FY08 – FY09. For this purpose, a localized current will be incorporated at the rational surface, with existing analytical calculations of the layer physics used to calculate the magnitude of the localized current.

In preparation for the routine analysis of NCSX data, the PIES algorithm will be improved to increase its speed and robustness. (FY07-FY08) The code will be parallelized. The implementation of a Jacobian Free Newton Krylov (JFNK) scheme [25] will be investigated as a possible approach to accelerating the convergence of the code. There have already been discussions concerning a possible JFNK implementation with potential collaborators: applied mathematicians David Keyes and Mark Adams from Columbia University, as well as Ravi Samtaney from the Computational Plasma Physics Group (CPPG) at the Princeton Plasma Physics Lab.

There is interest in generating databases of free-boundary PIES equilibria for both NCSX and W7X. (FY08 – FY09) Similar to the database of VMEC equilibria already constructed for the diagnostics design work, each equilibrium will be characterized by parameters such as I_p and b, and profile shapes for the pressure and current density or iota. It is also important to characterize PIES equilibria by parameters that define magnetic field topology – location and type of islands, size of core confinement region, size of stochastic regions, if any, etc. Subroutines for this purpose already exist in the PIES code, and a collaboration with Chandrika Kamath (Center for Applied Scientific Computing at LLNL) is also investigating AI methods for this purpose. (See Section C.2.2) We anticipate that, eventually, all PIES runs will be catalogued according to the classifier output. This will allow data mining and the facilitation of the design of operating scenarios for NCSX, as well as providing a method for rapid preliminary assessment of experimental results.

For optimization calculations and for rapid analysis of experimental data, it may prove desirable to develop a "PIES-lite", a stripped down version of the PIES code, that sacrifices some accuracy to maximize the speed. This work would take advantage of the planned studies of the physics effects of resonant Pfirsch-Schlueter currents which will provide some insight on how accurately these currents need to be calculated, and it will take advantage of the development of a capability to use a nonuniform grid for calculating currents. The desirability of developing such a version of the code will be investigated in FY08.

It is anticipated that work will begin in FY08 on a time-dependent transport code built around the PIES code, which will be able to handle islands and stochastic regions. This will build on the earlier work coupling PIES to a 1D flux-surface averaged transport code. This project will be discussed further in Section C.2.3.

High-Level Milestones:

- Improve speed and robustness of PIES code ***(2006-2010).***
- Develop self-consistent calculation of equilibrium β limit due to formation of stochastic region at plasma edge, and apply to interpretation of experimental data ***(2006-2007).***
- Incorporate additional physics into PIES code, including neoclassical effects ***(2006 – 2007)*** and shielding of rational surfaces by plasma flow ***(2008 – 2009).***

C.2.2 Plans for Other Stellarator Theory Projects

Design and Interpretation of magnetic diagnostics: In collaboration with E. Lazarus, obtain a final design of saddle loops to be placed on the NCSX vacuum vessel surface. (FY06) Extend singular value decomposition (SVD) analysis to the number and placement of triple-axis B probes, to saddle loops for the analysis of eddy currents on coil casings, etc. (FY06) Investigate the use of Principal Components Analysis and related methods (Cluster Analysis, etc) to determine what equilibrium information is extractable from the external magnetic diagnostic signals in NCSX (FY07). This work will complement the 3D equilibrium reconstruction work plans of the V3FIT group.

Ballooning Instabilities: The local ballooning analysis will be extended to a global formalism using a novel approach to the ray-tracing problem that takes advantage of an analytic calculation of the eigenvalue derivatives (FY06). Extension of the local ballooning analysis to the calculation of global eigenmodes is an outstanding problem in stellarator theory. In collaboration with N. Nakajima (NIFS, Japan), the possibility that FLR effects may regularize this problem will be investigated (FY06).

Automatic Classification of Puncture Plots: A collaboration has begun with Chandrika Kamath (Center for Applied Scientific Computing at LLNL) to implement algorithms for the automatic classification of puncture plots for stellarator systems using artificial intelligence methods. A first version of this orbit classification code is expected to be available in FY05, and it will be tested on PIES data (FY05 – FY06).

Plasma Profiles from Emissivity Data: It has been shown [18] that the Christiansen and Taylor method for inverting tokamak flux surface geometry to determine the underlying plasma pressure and current profiles can be generalized to stellarators with good flux surfaces. Work has begun on developing a computer code to perform the inversion for model NCSX equilibria provided by VMEC. The coding will be completed and tested on VMEC equilibria with different profile and boundary shapes (FY06). The practicality of the inversion technique will be explored, taking into account the incomplete knowledge of flux surface shape provided by soft X-ray data on a limited number of toroidal planes, as well as likely experimental error in the data (FY07).

Transport: Transport studies will continue to have both analytic and numerical components, with coupling between the two. Until the GTC code is modified to be able to handle turbulent transport in stellarator geometries in FY08, numerical turbulent transport studies will continue to use model fluctuations in a guiding center code. The model fluctuation spectra will be refined from those used thus far based on eigenmode solutions from linear stability codes and on experimental fluctuation measurements (FY06).

A long-term effort will continue to investigate the interaction between stellarator neoclassical transport and turbulent transport. The study of the interaction will be extended to also consider the stellarator neoclassical effects on turbulent transport. The variations in

the interaction with stellarator type and mode of operation (e.g. operation in ion or electron root, or combinations of these) will be examined. The effects of a fluctuating spectrum on operation at the ion and electron roots, and the implications for transport barriers formed by jumping between the two will be studied (FY07). The longer-term goal of this work is to find stellarators optimized not just for neoclassical, but for total transport, as well as to understand the variations in overall confinement of existing experiments (FY09 – FY10). In the near term the effort will focus on the use of flexibility of the NCSX coil set to optimize confinement (FY08 – FY10).

At the same time, collaborative analysis of transport in existing stellarator experiments will also be pursued. In the near term, this will focus on a study of the transport in nonneutral plasmas in the new CNT stellarator (Columbia Non-Neutral Torus) at Columbia University (FY06). This device operates with equilibria quite different from those in conventional stellarators, invalidating the assumptions normally made for conventional transport theory.

High-Level Milestones:

- Develop and apply singular value decomposition methods for the design of NCSX diagnostics and for the interpretation of data from stellarator experiments ***(2006-2007).***
- Develop improved understanding of the interaction between stellarator neoclassical transport and turbulent transport ***(2006-2010))*** and apply to the design of NCSX experiments ***(2008 – 2010)*** and to the optimization of next generation stellarators ***(2009 – 2010).***

C.2.3 NCSX Role for Theory Group

The NCSX construction schedule places an important boundary condition on the planning for stellarator theory. Under the proposed presidential FY'06 budget, construction is projected to be completed in July of 2009.

Having played a key role in the design of NCSX, it is expected that the theory group will also play a key role in the planning of experimental campaigns, and in the analysis of experimental data. The codes and theories that were used to design the NCSX will be tested against experimental results, and this is expected to lead to refinements and improvements in the theoretical models.

The codes that have been used to design NCSX reference equilibria that are predicted to be stable to ballooning modes and kink modes will also be useful for designing experiments that test the consequences of violating the stability conditions. Taking advantage of the flexibility of NCSX, nonlinear codes such as M3D will be used to design experiments to elucidate the physics of the nonlinear saturation of unstable modes. It will be of particular interest to gain an understanding of the conditions for avoiding disruptions.

The degree of quasi-axisymmetry will be controllable, and the predicted consequences for neoclassical transport and flow damping will be tested. Theoretical predictions regarding magnetic island formation will be tested. It will be of particular interest to test the predicted neoclassical effects on island widths, providing a new perspective on the physics that drives

neoclassical tearing modes in tokamaks. The effects of flow in shielding out resonant magnetic perturbations will also be studied.

Because a substantial fraction of the rotational transform in NCSX will be produced by the plasma current, and because the rotational transform will change substantially during startup, NCSX will differ from other stellarators in requiring time-dependent programming of the magnetic field coil currents as the plasma current and pressure are increased. Tokamaks routinely rely on time-dependent programming of the currents in their PF coils during startup, but the situation will be more complicated in NCSX, with its nonaxisymmetry, and with the ability to independently control the currents in the different types of modular coils, and in the trim coils, as well as the current in the auxiliary TF coils and in the PF coils. The large change in the rotational transform profile during startup, with low order rational surfaces entering and leaving the plasma at the axis and at the edge, will require attention to the issue of island formation. Modeling of startup scenarios will be important.

Tokamaks routinely use time-dependent transport codes, often called "1½D codes", to design scenarios and to analyze experimental data. The need for such a code for stellarators has not been compelling thus far because stellarator experiments typically have relatively little current, and flux evolution is not a major issue. It will be desirable to have such a code for NCSX. Strand and Houlberg have constructed a code that follows 3D plasma evolution due to flux evolution under the assumption of nested flux surfaces.[26] For NCSX, it will be desirable to have a time-dependent transport code that can handle magnetic islands. As discussed in Section C.2.1, development of such a code is planned.

C.2.4 Tokamak Applications

The quasi-axisymmetric NCSX configuration has been designed as a hybrid between an advanced tokamak and a drift-optimized stellarator. Its design has benefited from an extensive application of codes originally developed for tokamaks and from theoretical understanding that has emerged from the tokamak program. It is expected that the theoretical insights that emerge from the NCSX experiments and the 3D codes developed in the context of the NCSX program will in turn benefit the tokamak program. NCSX will provide a new perspective on key three-dimensional tokamak physics issues such as field errors, neoclassical tearing modes, and resistive wall modes. The theory program will potentially serve as a bridge to bring the benefits of that perspective to the tokamak community.

Field error tolerance is an important issue for ITER. Experiments on tokamak field error penetration thresholds have led to phenomenological scaling laws, but there is no first principles predictive capability at present. The three-dimensional NCSX configurations will have great flexibility to study the physics of magnetic islands. Theoretical modeling of magnetic island formation in NCSX will potentially make a contribution to developing a predictive capability.

As described in Section C.2.1, one of the main thrusts of the PIES code applications for at least the next year or two will be to model the edge stochastic region in W7-AS. This will be relevant also for the understanding of the effect of three-dimensional magnetic fields at a tokamak divertor separatrix. On DIII-D, there has been a series of experiments studying the application of a nonaxisymmetric perturbing field at the divertor separatrix to provide some control over ELMs. More generally, the field lines near a divertor separatrix are sensitive to the amplitude of the field error, and it is of interest to model the self-consistent 3D equilibrium near the divertor separatrix. It is planned to apply the PIES code to model the 3D field in the DIII-D ELM experiments. The DIII-D work will be closely related to the W7-AS work. In both cases there is a region of stochastic magnetic field lines at the plasma edge, and it is important to understand the effects of the field line stochasticity on the transport. The PIES code will provide a capability to do that in a self-consistent manner. This will require developing a model for the transport in the stochastic region, and coupling that into the determination of the pressure profile in the code. The self-consistent model will be developed first for W7-AS, and will later be applied to DIII-D.

In analyzing tokamak experiments, it is routine to reconstruct the associated axisymmetric equilibrium. Often, however, the equilibrium is actually three-dimensional, due to the presence of magnetic islands, for example. The development of a stellarator reconstruction capability for 3D equilibria with islands will also be potentially useful for tokamaks.

In recent years, there have been calculations that take advantage of stellarator transport theory to evaluate the transport in a tokamak in the presence of a magnetic island. As the understanding of stellarator transport progresses, there will be potentially interesting applications also to tokamaks with magnetic islands or resistive wall modes.

An effort is planned to develop a time-dependent transport code for stellarators that can handle magnetic islands. The code will also have the capability to calculate 3D evolution on a transport time scale in tokamaks for realistic values of the magnetic Reynolds number. There are several important 3D phenomena in tokamaks that evolve on this slow time scale, including nonlinear neoclassical tearing modes and resistive wall modes.

The application to tokamak diagnostic data of singular value decomposition methods that have been developed to deal with complex magnetics diagnostic issues in stellarators is being explored. Matrices of image intensity data from gas puff imaging experiments are being analyzed via proper orthogonal decomposition to explore the use of the method to describe blob dynamics and provide a calculation of underlying flow fields.

The NCSX is itself designed, in part, to answer the question whether some key tokamak problems can be solved by the addition of nonaxisymmetric fields. The mainstream tokamak program is moving towards addressing neoclassical tearing modes (NTMs) and resistive wall modes (RWMs) by feedback stabilization. Electron-cyclotron current drive would be used to stabilize NTMs. Time dependent 3D fields would be used to stabilize RWMs. The NCSX will investigate the alternative of adding nonaxisymmetric fields to the equilibrium to achieve passive stability. One clear advantage is the reduction of the recirculating power associated with feedback stabilization and with the generation of

rotational transform via RF current-drive. Three-dimensional shaping would represent a possible alternative evolutionary path for the tokamak. The tokamak has already evolved from an axisymmetric device with circular cross-section to a device with strong axisymmetric shaping. It is currently moving in the direction of adding time-dependent 3D fields and current drive. The NCSX will provide an assessment of a possible alternative evolutionary path that would incorporate non-axisymmetric shaping. For this purpose, it may not prove to be necessary to incorporate the relatively large fraction of externally generated rotational transform available in NCSX. An understanding of this is expected to emerge from the theoretical analysis of the NCSX experiments.

The stellarator theory program has the potential to serve as a bridge to bring the benefits of stellarator progress to the tokamak community, including an improved predictive capability for 3D physics effects, and new options for 3D tokamak optimization.

C.3 Summary: Addressing the FESAC Priority Panel's 10-Year Goals

The program we have described addresses each of the FESAC ten year goals cited at the beginning of this section (III.C).

Effect of plasma shape on stability: In designing the NCSX, extensive calculations were done of the theoretically predicted effects of 3D shaping on plasma stability. The same computational tools will be used to help design experiments on NCSX to test the theoretical predictions, and to help develop an improved understanding of this subject.

Effects of plasma shape and internal magnetic field structure on confinement: The effect of plasma shape on neoclassical transport has also been calculated in the context of the NCSX design study. As described in Section C.2.3, theoretical studies of the effects on turbulent transport are being initiated. Experiments to test the theoretical models will be designed for NCSX. Similarly, the effects of the internal magnetic field structure on plasma confinement are a subject of theoretical study, and the theoretical predictions will be compared with experimental results on NCSX.

Effect of bootstrap current on confinement: Bootstrap currents can, in general, affect plasma confinement both through the generation of a net plasma current, a potential source of free energy for instabilities, and through neoclassical effects on magnetic islands. The NCSX is designed so that the neoclassical effects are predicted to suppress magnetic islands. As described in Section C.2.2, neoclassical effects will be incorporated in the PIES code to provide a quantitative assessment of their impact on island widths. The predictions will be compared with experimental observations on NCSX. The magnitude of the bootstrap current generated in NCSX, as measured by the magnitude of the rotational transform that it generates, is smaller than the typical currents in tokamak experiments. Tokamak confinement scaling is similar to that in stellarators having zero net current, so that currents of this magnitude are not likely to have a deleterious effect on plasma confinement. This prediction, too, will be tested in the NCSX experiment.

Pressure limit due to long wavelength instabilities: Contemporary stellarator experiments are indicating that the β limits predicted from linear instability thresholds are overly pessimistic. Comparisons of NCSX experiments with linear MHD calculations and with nonlinear extended MHD calculations will help to clarify the situation.

Significance of ballooning modes: As described in Sections C.1.3 and C.2.2, improved numerical tools are being constructed for the study of ballooning stability. These tools will aid in the design and interpretation of experiments for studying this type of instability, helping to determine in particular whether toroidally localized ballooning modes pose a particular threat.

Equilibrium pressure limits: As described in Sections C.1.3 and C.2.1, the equilibrium β limit is currently being studied for W7-AS via comparison with PIES code calculations. Code development is proceeding to aid with these studies. The studies will be extended to NCSX.

Reactor-relevant steady-state configurations: The NCSX reference equilibrium was designed to be self-consistent with the bootstrap current, in the sense that a pressure of the assumed magnitude and profile is calculated to drive a current of the assumed magnitude and profile, and therefore will in principle, extrapolate to steady-state operation in the burning plasma regime. The actual pressure profile encountered in the experiment is likely to be somewhat different from the assumed one, leading to corresponding differences in the self-consistent bootstrap current profile. The bootstrap currents driven in NCSX in various regimes will be compared with the theoretically predicted bootstrap current for this quasi-axisymmetric device, and, if necessary, discrepancies will be resolved by improvements in the model. This model will then be used to assess prospects for extrapolation to steady-state configurations in the burning plasma regime.

Extrapolation of optimized configurations to burning plasma regime: The improved theoretical understanding and tools that emerge from the NCSX experiments will be used to further optimize 3D stellarator configurations and to extrapolate with increased confidence to the burning plasma regime.

The common theme that pervades the stellarator theory work discussed in this section (III.C) goes back to the first quote from the FESAC Priority Panel's report, on the first page of this section. NCSX, with its unique magnetic configuration, will provide new perspectives on critical fusion physics issues, and the theoretical studies proposed here will take advantage of that new perspective to advance our fundamental understanding of the effects of magnetic field properties on plasma behavior, aiding us in the design of improved plasma confinement configurations and improving our ability to extrapolate the behavior of these configurations to the burning plasma regime.

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D. Field Reversed Configuration Theory

In order to resolve outstanding scientific issues and establish a reduced-cost path to more attractive fusion energy systems, PPPL's theory and modeling research on field reversed configurations (FRCs) focuses on addressing the following motivating questions identified in the FESAC Priorities Panel Report, *Scientific Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program* (April, 2005).

TI. How does magnetic field structure impact fusion plasma confinement?

T6. How do magnetic fields in plasmas reconnect and dissipate their energy?

T12. How do high-energy particles interact with plasma?

This section provides a brief summary of accomplishments, plans and milestones in the FRC theory and modeling area.

D.1 Theoretical Studies of Field Reversed Configurations

The field-reversed configuration (FRC) is an innovative confinement approach that offers a unique fusion reactor potential because of its compact and simple geometry, and high plasma beta. These attractive features have motivated extensive experimental and theoretical research on FRCs. The most important issues studied are, FRC stability behavior with respect to low-n (toroidal mode number) magnetohydrodynamic (MHD) modes, and new FRC formation methods. A 3D nonlinear hybrid and MHD simulation code called HYM, developed at the Princeton Plasma Physics Laboratory, has been used to study the relative roles of various competing kinetic effects on linear stability behavior, and has demonstrated that the n=1 tilt instability can saturate nonlinearly in highly kinetic FRCs. Over the next five years, it is planned to carry out a detailed theoretical study of the properties of FRCs using the HYM code. The theoretical research will be performed in close collaboration with active FRC experimental groups at PPPL, Swarthmore College, the University of Washington, and other institutions.

The description of the numerical model and results of the extensive and systematic studies of stability properties for prolate FRC configurations using the HYM code are presented in the recent publications listed at the end of Sec. III.D.1. In the HYM code, three different physical models have been implemented: (a) a 3-D nonlinear resistive magnetohydrodynamic model; (b) a 3-D nonlinear hybrid scheme with all particle ions and fluid electrons; and (c) a 3-D nonlinear hybrid magnetohydrodynamic/particle model, where a fluid description is used to represent the thermal background plasma, and a kinetic (particle) description is used for the low-density energetic beam ions. The modeling capabilities of the HYM code also include the options of a two-fluid (Hall-MHD) description of the thermal plasma, and finite electron pressure. A new, MPI-based, parallelized version of the HYM code has recently been developed to run on distributed-memory parallel computers.

Other highlights of recent technical progress include: (a) demonstration that the observed ion toroidal spin-up is related to the resistive decay of the poloidal flux, and the resulting loss of the weakly confined ions; (b) a study of the effects of the energetic beam ions on FRC stability properties has been performed in developing design concepts for the proposed MRX-FRC experiment (Fig. D.1); and (c) three-dimensional MHD simulations of counter-helicity spheromak merging and FRC formation have been completed, and show very good agreement with results from the SSX-FRC experiment [Fig. D.2; C. D. Cothran, et al., Phys. Plasmas **10**, 1748 (2003)]. Two main issues raised in the SSX-FRC experiments, (i) the incomplete reconnection of the toroidal field, and (ii) the slower-than-MHD growth rate of the tilt mode, have been resolved by the simulations.

The planned FRC research over the next five years will focus on the following task activity areas:

1. Perform numerical simulations to study the effects of resistive relaxation and self-organization in FRCs, and compare with the available experimental data.
2. Investigate in detail the ion toroidal spin-up in FRC configurations, and its dependence on FRC parameters and the applied boundary conditions.
3. Develop an analytical model/closure scheme for the inclusion of trapped electron effects, and incorporate this model into the FRC stability calculations using the HYM code.
4. Improve/modify the time-stepping scheme and particle-to-field grid mapping in the HYM code in order to allow larger time steps and increased spatial resolution in the nonlinear hybrid simulations.
5. Improve/modify boundary conditions and vacuum region modeling in the HYM code for accurate comparison with experimental results.
6. Compare the HYM numerical results with the SSX-FRC experimental results, with the goal of improving the basic understanding of FRC formation techniques by counter-helicity spheromak merging, and large-S^* FRC stability properties.
7. Complete HYM code optimization and applications to rotating magnetic field (RMF) configurations, including both the simplified description (already-penetrated rotating magnetic field), and fully 3D simulations of the field penetration process.
8. Complete the concept development and physics design optimization and parameter study for the MRX-FRC ion-beam-stabilized FRC configuration.

A summary of more detailed milestones for the FRC theory and simulation area is presented in Sec. III.D.2.

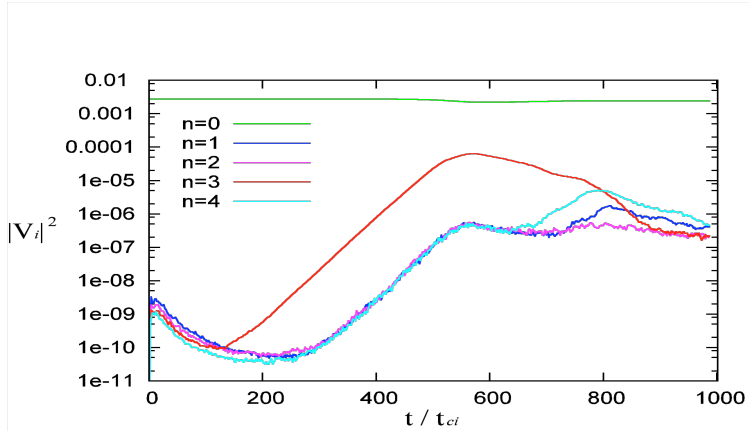

Fig. D.1. Time evolution of the n = 0 - 4 components of the ion kinetic energy from 3D nonlinear hybrid simulations including the effects of a conducting shell and beam stabilization. The n=3 mode is the linearly unstable mode, which saturates nonlinearly at $t \approx 550 t_{ci}$. The resulting configuration remains stable with respect to all global MHD modes as long as the FRC current is sustained. The Alfvén time is $t_A \approx 20 t_{ci}$.

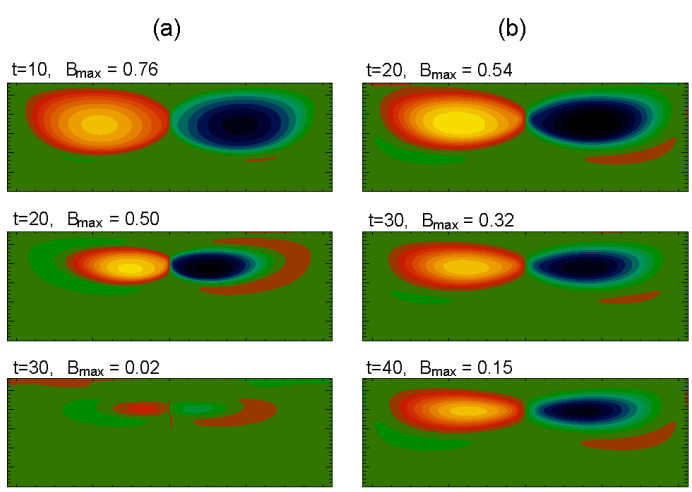

Fig. D.2. Contour plots of the toroidal magnetic field at the poloidal plane obtained from 2D MHD simulations with different values of normalized viscosity (a) μ = 0.001 and (b) μ = 0.004. The maximum toroidal magnetic field value (normalized to the initial edge field) is shown for each plot; time is normalized to Alfvén time.

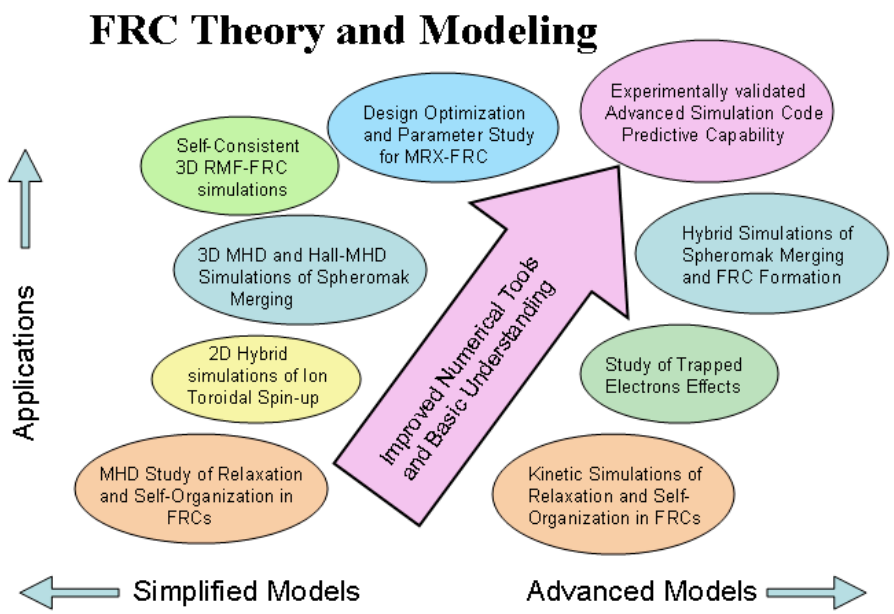

Fig. D.3. High-Level Milestones in FRC Theory and Modeling.

Selected technical milestones for the nearer term (FY 2005 – FY2007) are listed below for the FRC theory and simulation area (see also high-level summary in Fig. D.3):

D.2 FRC Theory and Modeling Milestones

Effects of neutral beam injection:

a. Characterize the stabilization of FRCs by injection of energetic beam ions (January, 2005-completed).
b. Complete physics design optimization and parameter study for the MRX-FRC ion-beam-stabilized FRC experiment (September, 2006).

Linear stability properties:

c. Complete development of an analytical model/closure scheme for the inclusion of trapped electron effects in the FRC stability studies (September, 2005).
d. Incorporate trapped electron physics in the HYM simulation code and investigate the detailed effects on FRC stability properties (September, 2006).

Simulations of the Swarthmore SSX-FRC experiment:

e. Perform three-dimensional simulation studies of the SSX-FRC experiment including kinetic effects, and submit scientific paper describing key technical results to peer-reviewed journal (September, 2005).
f. Complete three-dimensional simulation studies of the SSX-FRC experiment, including Hall-MHD simulations and hybrid simulations (July, 2006).

Resistive relaxation in FRCs:

g. Perform nonlinear hybrid simulations to investigate in detail the ion toroidal spin-up in field-reversed configurations, and its dependence on FRC parameters and applied boundary conditions (December, 2005).
h. Perform MHD and hybrid simulations to study the effects of resistive relaxation, profile consistency, and self-organization in FRCs (April, 2006).

Rotating-magnetic-field FRCs:

i. Assess applicability of the parallelized HYM code for self-consistent 3D rotating magnetic field (RMF) studies (December, 2006).
j. Complete studies of particle confinement for even- (odd-) parity RMFs (May, 2007).
k. Depending on the outcome of the assessment in Task (g), carry out detailed self-consistent 3D RMF studies using the parallelized HYM code (September, 2007).

Recent publications:

E. V. Belova , R. C. Davidson, H. Ji, and M. Yamada, C. D. Cothran, M. R. Brown, M. J. Schaffer, paper IC/P6-34, *Proceedings of 20th IAEA Fusion Energy Conference* (Vilamoura, Portugal, 2004).

E. V. Belova, R. C. Davidson, H. Ji, and M. Yamada, Phys. Plasmas **11**, 2523 (2004).

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E. Non-Magnetic Fusion Applications

Building on the description of topical scientific areas in Sec. II.E, we summarize here the areas of programmatic emphasis in non-magnetic fusion applications over the next five years.

E.1 Ion-Beam-Driven High Energy Density Physics and Fusion

The Princeton Plasma Physics Laboratory has an active theoretical and experimental program in ion-beam-driven high energy density physics and fusion. Research in this area is carried out in close collaboration with LBNL and LLNL under the auspices of the tri-laboratory Heavy Ion Fusion Virtual National Laboratory. As described in the recent National Task Force Report *Frontiers for Discovery in High Energy Density Physics* (July, 2004) and in the Fusion Energy Sciences Advisory Committee Priorities Panel Report *Challenges, Opportunities and Priorities for the U.S. Fusion Energy Sciences Program* (April, 2005), the principal aim of the U.S. heavy ion research effort is to address the compelling scientific question:

T7: How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?

While the long-term objective of the U.S. heavy ion program is to provide a comprehensive scientific knowledge base and the enabling technologies required for inertial fusion energy driven by high-brightness heavy ion beams, the major near-term objective is to explore the limits of compressing ion charge bunches to very short pulses for purposes of investigating ion-driven high energy density physics. A fundamental understanding of nonlinear space-charge effects on the propagation, acceleration and compression of high-brightness (high-current and low-emittance) heavy ion beams is essential to the identification of optimal operating regimes in which emittance growth and beam losses are minimized in periodic focusing accelerators and transport systems for intense heavy ion beam applications to high energy density physics and fusion.

To address the compelling scientific question, the Heavy Ion Fusion Virtual National Laboratory has organized the research campaign on ion-beam-driven high energy density physics into the following five *Research Thrusts*, or task activity areas:

1. ***High-brightness heavy ion beam transport.*** Develop a basic understanding of the limits on beam-channel wall clearance (aperture fill) imposed by gas and electron cloud effects, together with beam matching and magnet nonlinearities.
2. ***Longitudinal compression of intense ion beams.*** Develop a basic understanding of the limits on longitudinal compression within neutralizing background plasma, and the effects of beam-plasma instabilities over distances *greater than one* meter.

3. ***Transverse focusing onto targets.*** Develop a basic understanding of the limits on focal spot size set by chromatic aberrations due to uncompensated velocity spreads from upstream longitudinal compression, and the beam temperature growth from imperfect charge neutralization.
4. ***Advanced beam theory and simulation.*** Develop, optimize, and validate multi-species beam transport codes that can predict self-consistently the beam loss with gas and electron clouds, and develop integrated beam simulation models required to analyze source-to-target beam brightness (temperature) evolution.
5. ***Beam-target interactions.*** Develop a basic understanding of the beam deposition profiles within thin-foil targets and the uniformity of isochoric heating, accounting for target and beam ion charge state conditions, including the development of accurate beam deposition and laser-generated x-ray target diagnostics, and extension of integrated beam simulation models from the source through the target.

A major objective of PPPL's research on ion-beam-driven high energy density physics and fusion over the next five years is to develop advanced analytical and numerical models describing the nonlinear dynamics and collective processes in intense nonneutral beams propagating in periodic focusing accelerators and transport systems, and to identify and mitigate the effects of collective beam-plasma interactions in the target chamber. A second major objective of the planned research, building on PPPL's considerable experimental capability, is to investigate the effects of multielectron loss events, to test the feasibility of heavy ion neutral beams based on negative ions, to develop techniques for preionized plasma formation, and to study collective beam-plasma interactions in the target chamber. A third longer-term objective, building on PPPL's engineering design capabilities, includes investigations of pulse compression, nonlinear beam optics, and the development of engineering design concepts and test facilities for next-generation experimental facilities.

A fundamental understanding of nonlinear space-charge effects on the propagation, acceleration and compression of high-brightness (high-current and low-emittance) heavy ion beams is essential to the identification of optimal operating regimes in which emittance growth and beam losses are minimized in the periodic focusing accelerators and transport systems for ion-beam-driven high energy density physics and fusion. A major objective of the planned research over the next five years is to carry out a vigorous theoretical and computational program that investigates the influence of collective processes and nonlinear space-charge effects on the propagation, acceleration, and compression of heavy ion beams. Building on our extensive record of theoretical accomplishments in this area over the past five years (see, for example, http://nonneutral.pppl.gov), particular emphasis during the next five years will be placed on the following task activity areas relevant to ion-beam-driven high energy density physics and fusion:

Task activity areas for 2005 - 2009:

(a) Develop improved kinetic models based on the nonlinear Vlasov-Maxwell equations to describe the equilibrium and stability properties of intense heavy ion beams propagating in periodic focusing accelerators and transport systems.

(b) Investigate collective instabilities in intense heavy ion beams, including ion-electron two-stream interactions, and identify optimum parameter regimes for stable beam propagation.

(c) Investigate collective beam-plasma interactions in the target chamber. Identify operating regimes that mitigate the effects of two-stream, multispecies Weibel, and resistive hose instabilities.

(d) Develop robust numerical and analytical models of beam compression dynamics and nonlinear beam dynamics in the final focus system, including neutralized drift compression to short pulse lengths in background plasma.

(e) Develop self-consistent theoretical models of charge and current neutralization for intense beam propagation in the target chamber, benchmarked against simulation and experimental results.

(f) Explore mechanisms for halo formation through detailed comparisons between theory, simulation, and experiment. Identify operating regimes that minimize the production of halo particles.

(g) Apply the 2D and 3D nonlinear delta-f simulation schemes to augment and validate the analytical studies in (a)–(f) above, with particular emphasis on collective instabilities, halo formation and control, and emittance growth. Explore the influence of three-dimensional effects on stability behavior, including beam-plasma interactions in the target chamber, and ion-electron two-stream instabilities in the beam transport lines.

A three-dimensional nonlinear perturbative (delta-f) particle simulation scheme has been developed for studying the stability and transport properties of intense charged particle beams for application to ion-beam-driven high energy density physics and fusion. As a numerical method to solve the nonlinear Vlasov-Maxwell equations, the scheme splits the distribution function into equilibrium and perturbed parts. The perturbed distribution function is represented as a weighted summation over discrete particles, where the particle orbits are advanced by equations of motion in the focusing field and self-consistent fields, and the particle weights w_j are advanced by the coupling between the perturbed fields and the zero-order equilibrium distribution function. The nonlinear delta–f scheme exhibits minimal noise and accuracy problems in comparison with standard particle-in-cell simulations. This simulation scheme has been implemented in the Beam Equilibrium Stability and Transport (BEST) code. This code provides a very powerful numerical tool to investigate collective instabilities, periodically-focused beam propagation in alternating-gradient focusing fields, halo formation, and many other important nonlinear processes in intense beam propagation. In the absence of background electrons, the BEST code has been used to demonstrate quiescent (stable) beam propagation over thousands of equivalent lattice periods. In the presence of background electrons, however, a strong two-stream

instability is observed, leading to a dipole (m=1) transverse displacement of the beam ions and background electrons. The

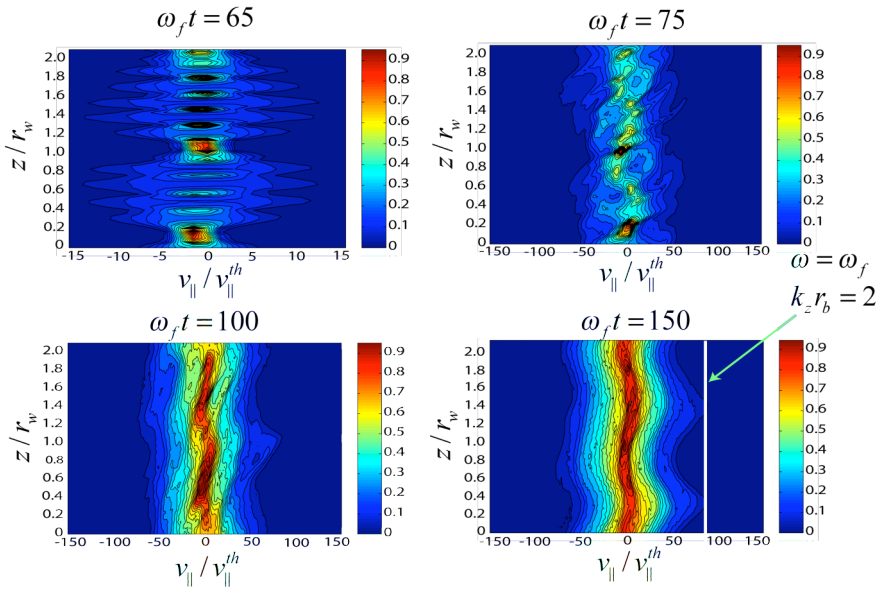

Fig. III.E.1. A one-component intense charged particle beam with large temperature anisotropy is subject to the analog of classical Harris instability. The delta-f particle-in-cell code BEST has been used to study the nonlinear evolution and saturation of the instability. The nonlinear saturation is governed by longitudinal particle trapping by a spectrum of fast-growing waves with a broad band of longitudinal wave numbers and zero oscillation frequency. As shown in the figure, the presence of many waves leads to the nesting and overlapping of particle resonances in longitudinal phase space, and as a consequence, to the fast randomization of the trapped-particle distribution and longitudinal heating of the beam particles.

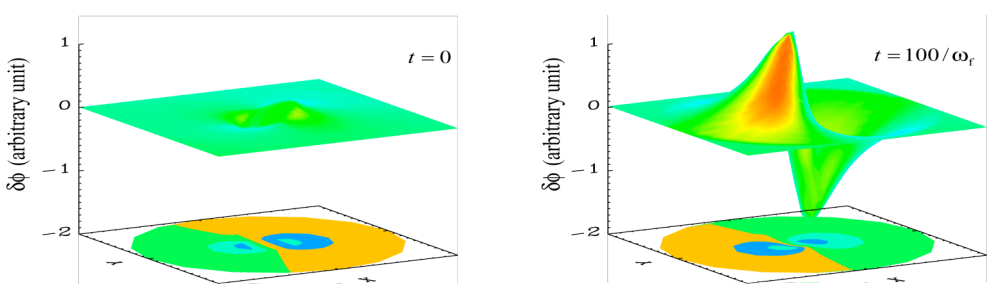

Fig. III.E.2. The presence of an unwanted electron population in high intensity ion accelerators and storage rings can drive the electron-ion two-stream instability. Simulation studies carried out using the BEST code show that the most unstable mode of the instability has a dipole structure. Shown in the figure is the simulation for the electron-proton instability for the Proton Storage Ring at Los Alamos National Laboratory. Simulation results agree with experimental observations in terms of dipole mode structure, eigenfrequency, and growth rate.

BEST code is being used to determine the effects of axial momentum spread, fractional charge neutralization, and beam intensity on detailed stability properties for intense heavy ion beam propagation. The BEST code is also being applied to investigations of 3-D anisotropy-driven instabilities in intense charged particle beams, both for axisymmetric and non-axisymmetric perturbations. The BEST code will continue to be an important simulation tool in the theoretical studies planned over the next five years. It should also be noted that the the nonlinear delta-f simulation scheme has been applied to the case of a periodic-focusing solenoidal field configuration, and quiescent, matched-beam propagation of a thermal equilibrium beam has been demonstrated at high beam intensities over large distances. Illustrative numerical results obtained from the 3-D nonlinear BEST code are illustrated in Fig. III.E.1 for the temperature-anisotropy-driven (Harris-like) instability for a one-component charged particle beam, and in Fig. III.E.2 for the electron-ion dipole-mode two-stream instability for an intense ion beam propagating through a partially-neutralizing background population of electrons.

Particularly important in the theoretical studies during the next five years will be the determination of the class of beam distributions that can propagate quiescently over large distances with a minimum deterioration in beam quality; and the continued development, optimization, and application of nonlinear multispecies 3D perturbative simulation techniques using the Beam Equilibrium, Stability and Transport (BEST) code for investigation of nonlinear collective processes in intense beam propagation.

Shown in Fig. III.E.3 is a schematic that illustrates several of the high-level theoretical milestones over the next five years in the ion beam research area.

Selected theoretical milestones for 2005 – 2007:

Assuming continued funding at the present (FY 2005) level-of effort, the following is a more detailed list of the theoretical milestones in the intense ion beam area planned for the three-year period 2005 – 2006.

1. Optimize analytical and numerical models describing the pulse shaping and neutralized and unneutralized drift compression dynamics for high-intensity heavy ion beams and the Neutralized Transport Experiment (NTX) upgrade options, with emphasis on important second-order effects such as emittance growth and coupling between longitudinal and transverse dynamics (March, 2005).

2. Develop improved analytical and numerical models of 3D bunched beams for electron-ion two-stream interactions. Incorporate secondary electron production models in the 3D BEST code for simulation studies of collective interaction processes (June, 2005).

3. Apply reduced self-consistent analytical and numerical models including ionization and finite electron temperature effects to describe influence of beam charge and current neutralization on focusing of intense ion beams (September, 2005).

4. Complete nonlinear delta–f simulation studies of collective instabilities driven by strong temperature anisotropy for intense coasting heavy ion beams (September, 2005).

5. Complete development of the reduced multispecies electromagnetic Darwin model for simulation of transverse electromagnetic effects in charged particle beams. Implement Darwin model in the 3D BEST simulation code (March, 2006).

6. Complete development of improved analytical and numerical models of 3D bunched beams for detailed investigation of collective effects and instabilities (April, 2006).

7. Complete initial large-scale particle simulation studies of optimized pulse shaping and neutralized drift compression scenarios for heavy ion beam pulses using the LSP and/or WARP-3D simulation codes (June, 2006).

8. Develop and apply optimized analytical models for beam charge and current neutralization in solenoidal and dipole magnetic field configurations with neutralized drift compression (September, 2006).

9. Complete initial large-scale nonlinear perturbative particle simulations of electron-ion two-stream interactions in 3D bunched beams using optimized numerical models, with electron production mechanisms self-consistently included (September, 2006).

10. Complete assessment of the effects of strong temperature anisotropy instability on finite-length bunched beams (November, 2006).

11. Complete the development of optimized models for beam charge and current neutralization in solenoidal magnetic field configurations with neutralized drift compression (March, 2007).

12. Develop analytical and numerical models describing the pulse shaping and neutralized drift compression dynamics for the NDCX experiment, with emphasis on emittance growth, collective interactions, effects of solenoidal magnetic field, and coupling between longitudinal and transverse dynamics (September, 2007).

13. Complete initial assessment of operating regimes that mitigate the deleterious effects of possible instabilities on the integrity of the compressed beam pulse in solenoidal magnetic field configurations with neutralized drift compression (September, 2007).

14. Develop reduced self-consistent analytical and numerical models to include ionization and finite electron temperature effects, and determine their influence on ion pulse charge neutralization and focusing in the NDCX experiment; determine the optimum system parameters for effective transport and focusing of the ion beam pulse (September, 2007).

15. Identify numerically the class of self-consistent periodic kinetic ‘equilibria’ for intense beam propagation in alternating-gradient focusing systems, and extend the nonlinear perturbative particle simulation method to intense beam propagation in periodic focusing

systems with self-consistent, periodic kinetic equilibria: Compare with the results of Hamiltonian averaging techniques for periodic focusing systems (September, 2007).

Over the next five years, we will also carry out a vigorous experimental program that makes use of PPPL's considerable experimental capabilities and off-site research facilities, including the Neutralized Drift Compression Experiment (NDCX) and its upgrades, to investigate several critical problems related to beam propagation and beam-plasma interactions in the drift compression region and the target chamber. These activities include:

(a) Development and application of advanced ferroelectric and rf sources for the formation of preionized plasma in the NDCX experiment and its upgrades at LBNL; experimental investigations of beam-plasma interactions; and development of advanced beam diagnostics.

(b) Detailed calculations of ionization cross-sections for ion beam propagation through background gas, including benchmarking against experimental measurements.

(c) Assess optimum beam ion and energy choices for use in high energy density physics applications.

As noted earlier, this research is carried out through PPPL's integrated participation in the Heavy Ion Fusion Virtual National Laboratory. During 2003 – 2005, PPPL's nonneutral plasma and beam dynamics group has published over fifty-seven research papers in scientific research areas critical for ion-beam-driven high energy density physics and fusion.

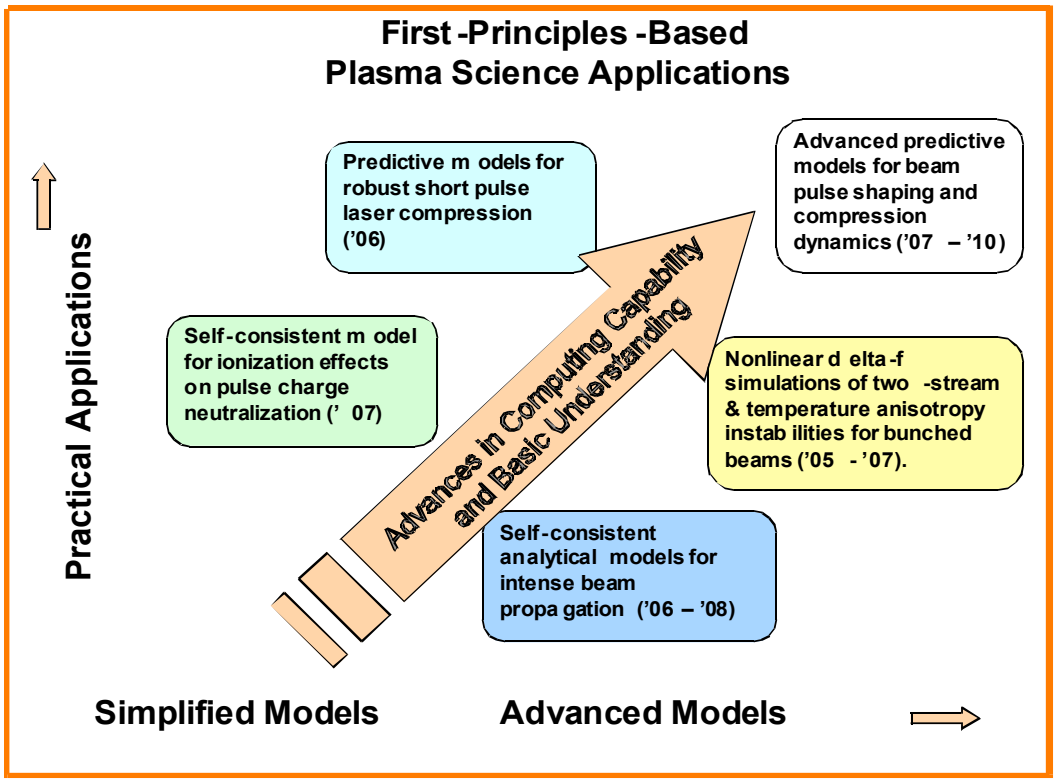

Fig. III. E. 3. High-Level Plasma Science Applications Milestones

Recent related publications:

Scientific publications in the nonlinear beam dynamics area can be found at the website: http://nonneutral.pppl.gov. The reader is also referred to the following recent theoretical publications on intense ion beams:

"Kinetic Description of Neutralized Drift Compression and Transverse Focusing of Intense Ion Charge Bunches", R. C. Davidson and H. Qin, Physical Review Special Topics on Accelerators and Beams **8**, 064201 (2005).

"Survey of Collective Instabilities and Beam-Plasma Interactions for Heavy Ion Beams", R. C. Davidson, I Kaganovich, H. Qin, E. A. Startsev, D. R. Welch, D. V. Rose and H. S. Uhm, Physical Review Special Topics on Accelerators and Beams **7**, 114801 (2004).

"Three-Dimensional Simulation Studies of Temperature Anisotropy Instability in Intense Charged Particle Beams ", E. A. Startsev, R.C. Davidson and H. Qin, Nuclear Instruments and Methods in Physics Research **A544,** 125 (2005).

"Theory of Ion Beam Pulse Neutralization in a Background Plasma in a Solenoidal Magnetic Field", I.D. Kaganovich, E. A. Startsev, R. C. Davidson and D. R. Welch, Nuclear Instruments and Methods in Physics Research **A544,** 383 (2005).

"Self-Consistent Vlasov-Maxwell Description of the Longitudinal Dynamics of Intense Charged Particle Beams", R. C. Davidson and E. A. Startsev, Physical Review Special Topics on Accelerators and Beams **7**, 024401 (2004).

"Drift Compression and Final Focus for Intense Heavy Ion Beams with Non-Periodic Time-Dependent Lattice", H. Qin, R. C Davidson, J. J. Barnard and E. P. Lee, Physical Review Special Topics on Accelerators and Beams **7,** 104201 (2004).

"Scaling Cross Sections for Ion-Atom Impact Ionization", I. D. Kaganovich, E. A. Startsev and R. C. Davidson, Physics of Plasmas **11**, 1229 (2004).

"Nonlinear Plasma Wave Excitation by Intense Ion Beams in Background Plasma", I. D. Kaganovich, E. A. Startsev and R. C. Davidson, Physics of Plasmas **11,** 3546 (2004).

"Korteweg-deVries Equation for Longitudinal Disturbances in Coasting Charged Particle Beams", R. C. Davidson, Physical Review Special Topics Accelerators and Beams **7**, 054402 (2004).

E.2 Laser-Plasma Systems

1. Plasma-Based High-Power Compression of Short Ultra-intense Laser Pulses

Mainly due to the method of chirped pulse amplification, laser intensities have grown remarkably during recent years. However, the attaining of very much higher powers is limited by the material properties of gratings. These limitations might be overcome through the use of plasma, which is an ideal medium for processing very high power and very high total energy. A plasma can be irradiated by a long pump laser pulse, carrying significant energy, which is then quickly depleted in the plasma by a short counter-propagating pulse. This counter-propagating wave effect has already been employed in Raman amplifiers using gases or plasmas at low laser power. Of particular interest here are the new effects, which enter in high power regimes. These new effects can be employed so that one high-energy optical system can be used like a flashlamp in what amounts to pumping the plasma, and a second low-power optical system can be used to extract quickly the energy from the plasma and focus it precisely. The combined system can be very compact. Thus, focused intensities more than 10^{25}W/cm^2 can be contemplated using existing optical elements. These intensities are several orders of magnitude higher than what is currently available through chirped pump amplifiers.

Over the next five years we anticipate emphasis on the following related areas:

(a) Examining in detail how the compression can be made robust to plasma and laser imperfections. This entails a careful description of equilibrium noisy plasma.

(b) Extending our understanding of laser propagation in plasma channels, including parametric instabilities of intense laser pulses in channels, generalizing results for slab channels to channels of arbitrary cross sections, as well as exploring the use of multiple laser beams in a plasma channel.

(c) Developing new concepts and identify and describe new effects in the general area of intense laser propagation in plasmas, including the generation of intense magnetic fields and the direct acceleration of particles to high energy.

(d) Developing suitable analytic and numerical tools for the study of these effects, including acquiring the capability of performing two-dimensional and three-dimensional particle-in-cell simulations.

2. Nonlinear delta-f simulation studies of ion acoustic waves in dense plasmas

In collaboration with researchers at Lawrence Livermore National Laboratory, we have analyzed the properties of ion acoustic waves in multi-species plasma of varying collisionality. We will apply the delta-f particle simulation method, developed in the magnetic fusion community and extended for this purpose, to study the nonlinear behavior

of driven ion acoustic waves. The aim is to be able to predict the level of acoustic wave turbulence as a function of driving amplitude. Understanding the turbulent response to an external drive is central to the development of a predictive capability for the level of scattering of laser light from inertial confinement fusion target plasmas.

E.3 E x B Plasma Flows and Electrical Propulsion

A critical component of satellite technology is the propulsion system that maintains the position of orbiting satellites or transfers the satellite between orbits, including eventually decommissioning defunct satellites. A promising propulsion means is the Hall thruster which employs magnetized electrons in crossed electric and magnetic fields, where the magnetic surfaces are also equipotential surfaces, acting as virtual grids for electrostatic acceleration of unmagnetized ions.

The theoretical effort on Hall thrusters seeks to extend the scientific understanding of Hall thrusters or, more generally, the insulating properties of magnetized plasma. The very important issues of reducing plume divergence and increasing thruster efficiency will rely on advances in the basic understanding of plasma in crossed electric and magnetic fields.

This basic understanding also entails a number of plasma instabilities over a wide range of frequency that accompany Hall-type magnetic insulation.

Theoretical research in this area now concentrates on basic understanding of plasma flow, including the sonic transition in Hall thruster flow and plasma oscillations and instabilities in Hall thruster geometry. The theory effort in this area also benefits from ties to the PPPL Hall Thruster Experiment. This experiment employs novel plasma configurations, including segmented electrodes along the channel, which make the acceleration region as localized as possible. This experiment recently achieved substantial reduction in plume divergence.

Over the next five years, the theoretical effort in this area will benefit from numerical studies of such flows, including particle-in-cells simulations, through in-house development of computational tools and through collaborations.

Finally, shown in Fig. III. E. 3, are selected high-level milestones in the plasma science applications areas summarized in Secs. III. E. 1 – III. E. 3.

E.4 Space Plasma Physics

The primary goal of PPPL's research in space plasma physics is to understand solar activity (such as the solar wind, coronal mass ejection, solar flares, and prominence eruption) and how this solar activity affects plasma dynamics, waves, and instabilities in the magnetosphere and ionosphere. PPPL's research in space plasma physics is funded primarily by the National Aeronautics and Space Administration, and by the National Science Foundation. We have successfully applied the theoretical expertise developed in the fusion theory program to several important areas of space plasma physics. Moreover, the research expertise developed in space plasma physics also has the potential to impact our

study of magnetic fusion plasmas. For example, the kinetic-fluid model that was originally developed for high-beta space plasmas is now being used in modeling energetic particle and wave-particle interaction physics in magnetically confined plasmas.
Furthermore, techniques that are being developed to understand wave structure and dissipation at the magnetopause are relevant to understanding the kinetic dissipation and wave structure of toroidal Alfvén eigenmodes (TAEs) in fusion devices, and the development of self-consistent theoretical models to describe ion cyclotron heating and plasma evolution along auroral field lines involves methods that could be applied to modeling radiofrequency heating in tokamak plasmas.

1. Magnetospheric and Ionospheric Physics

Some of the key questions related to the coupling between the solar wind, magnetosphere, and ionosphere are:

What physical processes are responsible for the transfer of the solar wind plasma, momentum, and energy to the magnetosphere?

How do the magnetosphere and ionosphere couple, leading to ionospheric outflows and the development of accelerating potentials responsible for auroral displays?

What processes are responsible for the onset of the magnetic substorms, and what transport processes are responsible for the dramatic change of magnetospheric configuration?

In order to address these key questions, expertise has been developed in the following areas of research:

(a) A three-dimensional quasi-static equilibrium code, MAG-3D, has been developed to compute the structure of magnetic field, current density, and plasma pressure for a magnetospheric configuration. The present solutions provide a physical understanding of the generation of Region-2 field-aligned current flowing into and out of the ionosphere. The equilibrium code may be used to understand the adiabatic evolution of the magnetosphere under solar wind perturbations and the approach to the configurations favorable to substorm onset. The code is also the starting point for wave stability calculations that may be responsible for magnetospheric transport.

(b) A kinetic-fluid model has been derived that incorporates kinetic effects in a multi-ion plasma with a minimum of modification to the one-fluid MHD equations. Kinetic effects are included in particle pressure tensors that are obtained from the moments of the particle distribution functions. Important global effects such as background density, temperature and magnetic field gradients, magnetic field curvature, large plasma beta, and pressure anisotropy are retained, while kinetic effects such as finite Larmor radius, wave-particle interactions, and bounce resonance are added to the description. We have applied this model to understand the transport properties of low-frequency phenomena such as the dynamical behavior of magnetic substorms, plasma transport processes at the magnetopause, and storm-time plasma transport in the ring current region.

(c) A wave propagation code has been developed that is appropriate for describing electromagnetic ion cyclotron waves in a multi-species, collisional plasma of Earth's magnetosphere. The code is useful for describing how ion cyclotron waves can mode convert so that the waves energy could be transported through heavy ion "stop gaps" to the ground where they are observed. Moreover, the wave solutions also provide information about how much wave energy heats the ions through ion cyclotron heating, and how much wave energy is lost through collisional Joule dissipation in the ionosphere.

(d) Two-dimensional electrostatic and electromagnetic simulation codes have been developed that retain the full dynamics of the ions and electrons. The codes were originally developed in order to study the dynamical development of the magnetopause current layer and the onset of instabilities that broaden the current layer. These codes are ideal for studying plasma transport at the magnetopause in conjunction with the kinetic-fluid model and for studying the time-development of auroral acceleration regions.

Research activity areas and plans:

During the next five years, it is planned to address the following topics:

Magnetopause Transport: Large-amplitude, low-frequency waves are seen in nearly every crossing of the magnetopause boundary between the magnetosheath and the magnetosphere. The waves likely contribute to transport. Recent observations show that the plasma sheet becomes cold and dense during periods of northward interplanetary field. We plan to: (a) investigate coupling of velocity-shear-driven waves with compressional Alfvén waves at the magnetopause using the kinetic fluid model [FY 05 - FY 07]; (b) perform 2D electromagnetic simulations of velocity shear driven instabilities at the magnetopause to investigate plasma transport and broadening of the layer due to Kelvin-Helmholtz instability [FY 06 – FY 08]; and (c) determine the theoretical dependence of various proposed transport mechanisms (reconnection, kinetic Alfvén waves, Kelvin-Helmholtz instability) at the magnetopause on solar wind parameters, and compare with observations [FY 06 - FY09].

Self-Consistent Modeling of Ion Outflows: In the auroral region, spacecraft commonly observe ion outflows in conjunction with electromagnetic ion cyclotron waves. Because the waves propagate into the ionosphere, they can heat the ions. However, heating of the ions leads to changes in the background profiles. Because the wave propagation depends on the background profiles, the slow response of the background profiles alters the wave propagation, and hence the heating rate. It is planned to couple the wave propagation code with a Monte Carlo simulation of ion outflows and to iterate until a steady state or limit cycle is reached [FY 06 – FY 08]. To improve this model further, we will also allow for a parallel potential drop, which would be computed self-consistently with the ion and electron distributions [FY 06 – FY 10]. The wave propagation code will be further improved by including the kinetic response of high-energy ions and electrons by solving an integral equation [FY 07 – FY 10].

Theory and Simulations of Auroral Phenomena: Natural auroras frequently exhibit enhanced intensity within relatively thin (1 km) horizontal layers. The layers have properties remarkably similar to enhanced layers of magnesium and iron; however, it is not known how such layers could provide enhanced emissions. We will carry out analytical calculations and perform particle simulations of instabilities that could occur in such layers to determine whether they could explain the enhanced emissions. The instabilities are expected to be driven by either strong cross-field currents or by electron precipitation. To make the theoretical and simulation studies realistic, we will include ion-neutral and electron-neutral collisions with a Monte Carlo collision operator in the electrostatic simulations of current and beam driven instabilities [FY 06 – FY 08].
Satellite instruments detect strong, localized, quasi-static electric fields associated with energetic particle populations in the auroral region. Wave emissions also appear to coexist with the accelerated distributions and strongly modify the accelerated distributions. Based on global considerations and observations, it is most likely that double layers develop in order to sustain the auroral current system. We plan to perform one- and two-dimensional electrostatic simulations appropriate for the auroral region. We will perform simulations of an initial field free current-carrying plasma to determine how the self-consistent parallel electric field develops [FY 06 – FY 09]. Various instabilities and their relation to double layers will be studied. The extension to two dimensions is a new step, and is important for understanding the thickness of auroral displays and how the double layers organize into the observed 2D structures [FY 08 – FY 10]. We will investigate the so-called Knight relationship between the current and electric field that is employed in macroscale simulations. We will also investigate wave development associated with the formation of the double layers [FY 08 – FY 10].

Substorm Phenomena: Substorms involve a reconfiguration of the magnetosphere. We have developed a scenario to explain the observations of substorm onset and current disruption and the corresponding physical processes. A theory of the kinetic ballooning instability taking into account effects of trapped electron dynamics and finite ion Larmor radius was developed to resolve two key issues: (1) the excitation mechanism and the high plasma beta threshold (> 50) of the observed low-frequency instability that underlies the substorm explosive growth phase; (2) the physical mechanism for the enhanced duskward ion flux that occurs only during the explosive growth phase and leads to excitation of higher frequency instabilities. The kinetic ballooning mode theory is now being applied to study the ballooning mode stability properties in low-aspect-ratio tokamaks such as the National Spherical Torus Experiment.

We plan to perform kinetic-fluid simulations of substorm processes and associated plasma transport, magnetic field dipolarization, energy dissipation and auroral dynamics in the ionosphere [FY 06 – FY 08]. We also will perform a low frequency stability analysis to understand the origin and mechanism of Pc and Pi waves by instabilities such as ballooning-mirror instabilities and associated plasma transport in the plasma sheet, and perform correlation study between theory and satellite observations FY 06 – FY 09].

Recent related publications:

"Dawn-Dusk Asymmetries, Ion Spectra, and Sources in the Northward IMF Plasma Sheet", S. Wing, J. R. Johnson, P. T. Newell, and C.-I. Meng , J. Geophys. Res., in press (2005).
"Physics of Substorm Growth Phase, Onset, and Dipolarization", C. Z. Cheng, Space Science Reviews **113**, 207 (2004).
"MHD Ballooning Instability in the Plasma Sheet", C. Z. Cheng and S. Zaharia, Geophysical Research Letters **31**, L06809 (2004).
"Near-Earth Thin Current Sheets and Birkeland Currents During Substorm Growth Phase", S. Zaharia and C. Z. Cheng, Geophysical Research Letters **30**, 1883 (2003).
"Field Line Resonances in Quiet and Disturbed Time Three-Dimensional Magnetospheres", C. Z. Cheng, and S. Zaharia, Journal of Geophysical Research **108**, 1001 (2003).
"Kinetic Alfvén Waves at the Magnetopause— Mode Conversion, Transport, and Formation of the LLBL", J. R. Johnson and C. Z. Cheng in Earth's Low-Latitude Boundary Layer, Geophys. Monogr. **133**, edited by P. Newell and T. Onsager, 211, American Geophysical Union (2003).
"Stochastic Ion Heating at the Magnetopause due to Kinetic Alfvén Waves", J. R. Johnson and C. Z. Cheng, Geophys. Res. Lett. **28**, 4421 (2001).
"Signatures of Mode Conversion and Kinetic Alfvén Waves at the Magnetopause", J. R. Johnson, C. Z. Cheng, and P. Song, Geophys. Res. Letts. **28**, 227 (2001).
"Particle Transport and Energization Associated with Substorms", S. Zaharia, C. Z. Cheng, and J. R. Johnson, J. Geophys. Res. **105**, 18741 (2000)

2. Solar Physics

The main objectives of solar physics research at PPPL are to understand diverse solar eruptive phenomena such as solar flares, coronal mass ejections and prominence eruptions, which have significant influence to the space environment around the earth. To investigate these phenomena, we have developed various numerical tools and are continuously improving their capabilities to handle disparate physical parameter regimes to address specific phenomena of scientific interest to the solar physics community. In order to identify important problems worth pursuing and to identify ways to solve those problems, up-to-date information on observational data is indispensable. To maintain this observational expertise, we have taken advantage of university collaboration projects and will continue to expand our collaboration network. Although most solar eruptive phenomena are believed to involve magnetic reconnection, the observed fast rate of solar reconnection is not well understood. It is anticipated that the experimental results from the Magnetic Reconnection Experiment (MRX) will be helpful in developing a basic understanding of microscopic processes that may be important in solar magnetic reconnection.

The following are the tools and expertise that have been developed for solar physics investigations:

(a) Two versions of <u>3D magnetohydrostatic equilibrium codes</u> have been developed for arbitrary simply-connected domains. Both versions are based on a magnetofrictional method, but one employs three components of the magnetic field, and the other employs

unmatched Euler potentials. The former is for general configurations with or without magnetic islands. It has been used to generate magnetohydrostatic equilibria of prominence structures. The latter is limited to configurations without magnetic islands, but it can specify field connectivity as precisely as is desired. With this code, it has been shown that force-free fields of multiple flux systems with interwinding flux tubes can have more energy than open fields. This finding is a significant breakthrough in coronal mass ejection studies because closed field lines are observed to open up during eruption.

(b) A 3D global MHD simulation code has been developed in a semi-implicit upwind scheme. This code demands about 1/30 of the computational resources that conventional explicit upwind codes require for the same time span. With this code, we reproduced the observed ascending profile of mass ejection flux ropes in our reconnection model of solar eruption by introducing a spatially confined resistivity pattern. Matching the numerical results and observations, it is found that a quadratic dependence of resistivity on current density can generate many of the observed rising profiles of erupting prominences and coronal mass ejections. The reconnection electric fields in the simulations are also found to be consistent with the values indirectly inferred from observations of moving flare ribbons.

(c) The 3D global MHD code has been expanded to accommodate an arbitrary anisotropic electrical conductivity tensor. To resolve time scales less than MHD scales, a subcycling method is used. This code was employed to simulate the "roll effect" in prominence eruption. When a prominence erupts, the overall structure is observed to roll about the arc-shaped prominence axis. This rolling motion breaks the right-left symmetry adding magnetic helicity in one leg, while reducing helicity in the other leg. The symmetry breaking is attributed to anisotropy of the electrical conductivity in prominence-corona plasma. By numerical simulation, the observed rolling motion has been reproduced.

Research activity areas and plans:

Magnetic Reconnection and Helicity: The redistribution and conversion of magnetic helicity by magnetic reconnection will be studied in relation to solar eruptions. Here we will focus on the generation of a magnetic flux rope by reconnection between small-scale flux tubes or filamentary fields. Not only the integration of helicity in a new flux rope by the merging of individual flux tubes, but also the conversion of mutual helicity between small-scale structures into self-helicity of a large-scale flux rope will be investigated. For this study, we will improve the 3D MHD code to adopt an unstructured grid system [FY 06 – FY 08]. Since PPPL's M3D code employs an unstructured grid system in the poloildal plane, this feature can also be applied to our implementation of similar grid systems in the entire domain in the 3D MHD code developed for space plasma applications. Also, collaboration with the Computational Plasma Physics Group (CPPG) will be pursued to adopt the adaptive mesh refinement (AMR) technique into the 3D MHD code. The study will attempt to answer two questions: how a mass ejection loop is formed and ejected; and how a prominence magnetic structure is formed.

Anisotropic Electrical Conductivity: The breaking of geometrical symmetry in a global system by anisotropy of the electrical conductivity will be further studied. In general, such a

system can hardly settle down to a static equilibrium, but rather tends to undergo a steady motion as seen in the roll effect of erupting prominences. The anisotropy of the electrical conductivity often arises in a multi-component plasma system. To treat such a system, we plan to develop a three fluid (electron, ion, neutrals) code first [FY 07 – FY 08], and subsequently a kinetic MHD code [FY09 – FY 10]. In carrying out this effort, the M3D group will be consulted and use will be made of their technical expertise. In this study, we specifically plan to address the mixing of hot and cold plasmas in the interface of a prominence and the corona.

Coronal Magnetic Fields: The construction of realistic coronal magnetic fields based on photospheric vector magnetograms will be pursued. So far the construction of coronal fields has mostly been performed using pseudo-time-dependent MHD simulations applying an artificial field-aligned electric potential to a potential field. In the first stage of this study, we will also use such a pseudo-dynamic method, but starting from a nonpotential magnetic field whose field connectivity is specified to match the observations as closely as possible [FY 06 – FY 07]. In the initial phase, we will implement flux-crossing boundary conditions in the PIES code, and we will later extend the code for a more general domain geometry. In the second stage of the study, we will develop a nonvariational MHD equilibrium code in an open volume outside the solar surface [FY 08 – FY 10]. Once the code is developed, it will be an indispensable tool for space weather prediction.

Solar Eruption Dynamics: The dynamical evolution of the coronal plasma leading to eruption will be studied by employing the magnetohydrostatic solutions with energy above the open field level as initial conditions. The main question in this study is whether a nonequilibrium or an instability is responsible for the eruption. To answer this question, we will follow the evolution stepwise and try to construct an equilibrium at each step. We will investigate whether an equilibrium is available and whether the sequence is continuous. Since an equilibrium configuration, if one exists, can also serve as the nonlinear end state of the unstable system, we will determine what kind of instability develops. In the first stage of the study [FY 06 – FY 07], diverse idealized initial conditions will be employed, but in the second stage [FY 08 – FY 10] realistic configurations obtained from the study in subsection (c) above will be employed as initial conditions. Both a 3D MHD code and a 3D magnetohydrostatic code are utilized for this study.

Recent related publications:

"Roll Effect in Prominence Eruption Explained by Anisotropic Electrical Conductivity", G. S. Choe and C. Z. Cheng, , to be submitted (2005).

"Flux Rope Acceleration and Enhanced Magnetic Reconnection Rate", C. Z. Cheng, Y. Ren, G. S. Choe, and Y.-J. Moon, Astrophys. J., **596**, 1341 (2003).

"Energy of Force-Free Magnetic Fields in Relation to Coronal Mass Ejections", G.S. Choe and C. Z. Cheng, Astrophys. J. **574**, L179 (2002).

"A Model of Solar Flares Based on Arcade Field Reconnection and Merging of Magnetic Islands", G. S. Choe and C. Z. Cheng, Phys. Plasmas **9**, 2330 (2002).

"Solar Flare Mechanism Based on Magnetic Arcade Reconnection and Island Merging", C. Z. Cheng and G. S. Choe, Earth, Planets and Space **53**, 597 (2001).

"A Model of Solar Flares and Their Homologous Behavior", G. S. Choe and C. Z. Cheng, Astrophys. J., **541**, 449 (2000).

3. Information-Dynamical Studies of Space Plasma Physics

During the time of geomagnetic disturbances such as storms and substorms (collectively known as space weather), high energy electrons can damage or incapacitate meteorological, communications, and defense satellites. Strong currents can also damage power grids, leading to the loss of electrical power for millions of people and for critical services. Such damage is not only expensive, but it could lead to loss of power to hospitals, disrupt business transactions, interrupt military communications, and/or inhibit the use of satellite-based navigational capabilities. Therefore, there is a high demand for models that can predict geomagnetic activity accurately based on solar wind parameters as input, a demand that is likely to increase even more with the Nation's increasing reliance on space-based technologies.

Because the solar atmosphere and the Earth's magnetosphere are complex dynamical systems, it is difficult if not impossible to accurately describe many global coupling phenomena from physical principles. Often the physics is too complex to be described accurately by such models. For example, MHD models provide the only computationally feasible physics-based method to model the magnetosphere-solar wind interaction globally, but important processes that couple the solar wind and the magnetosphere involve kinetic physics in microscale boundary layers cannot be described by MHD models and hamper predictive capabilities.

An alternative approach for understanding the dynamics of many space physics phenomena is to consider statistical models developed from information-theoretical quantities such as entropy, mutual information, and cumulants. This approach can be used to: (a) characterize the underlying dynamics of the solar-wind magnetosphere system; (b) understand the information horizon of the system; and (c) guide in the development of predictive models within the constraints of the information horizon. Because the methods and techniques do not presuppose an underlying dynamics, they are transportable across a wide range of complex nonlinear systems. Consequently, the statistical tools that are being developed could also be useful for characterizing the underlying dynamics of fusion plasmas, developing predictive models for disruptions in fusion devices, and constructing a real-time computational platform for data analysis that could be used to control fusion devices.

The magnetospheric response has historically been classified using magnetic field perturbations detected at the Earth's surface and codified into a geomagnetic planetary index. The nonlinear dependencies inherent to the historical data stream were examined using mutual information and a cumulant-based cost as discriminating statistics, and we were the first to discover the presence of a strong solar cycle nonlinearity in the data stream just prior to solar minimum. We also identified the timescale of the nonlinearity and related it to specific variables in the solar wind responsible for the nonlinear response. We found that the timescale of the nonlinearity was the same as that associated with storms and storm relaxation mechanisms. We also found that the nonlinearity is related to increases in the solar wind velocity, which are commonly associated with increased ULF wave activity

in the magnetosphere---waves that are critical for transport process for the ring current. The relationship between solar wind velocity and increased electron fluxes has previously been considered a mystery, but our analysis provides important clues as to its origin through nonlinearities that operate on specific timescales. We also developed a neural network model to improve the predictive capability of the planetary geomagnetic index beyond that of existing predictive models.

Solar flares provide large releases of energy on the sun. It is commonly believed that flares occur randomly because their waiting time occurrence is well fit by a Poisson distribution. The occurrence of solar flares also provides important clues as to the underlying dynamics responsible for flares---which is a subject of active debate. To understand the flare dynamics, we analyzed the distribution of waiting times between solar flare events to determine whether the flaring distribution results from a nonstationary Poisson process. We examined the mutual information between successive flaring time intervals for historical data and compared with surrogate data consistent with a nonstationary Poisson process having the same distribution as the original data. We determined that the flaring data is inconsistent with the common assumption that flares result from a nonstationary Poisson process, and that there is significant linear and nonlinear relationship between successive flaring events. These results have important implications for understanding whether the flare waiting time distribution results from a storage-release mechanism or is a reflection of self-organized criticality.

Research activity areas and plans:

Over the next five years it is planned to apply the techniques that we have developed to build models that can better characterize the solar-magnetosphere-ionosphere interaction and dynamics which can further advance predictive capabilities.

Magnetospheric Dynamics: It is planned to apply the information-dynamical techniques developed by the space plasma physics group at PPPL to examine more direct measures of the magnetospheric state such as energetic electron flux, tail stretching, and energetic electron precipitation. From this data we will be able to estimate a predictability horizon that will indicate the maximum ``look ahead'' for which the space climate can be predicted. We will also use the information-dynamical measures to identify variables derived from solar wind data that maximize the information content about the magnetospheric response, which would be useful for forecasters. Finally, we will pursue development of predictive models by identifying (a) the most important nonlinearities that should be kept in the model; (b) good candidate data for training parametric models based on information content; (c) multiple dynamical states that can be used to specialize parametric models when the state is identified; and (d) maximizing the information flow in parametric models [FY 06 – FY 10].

Solar Flare Occurrence: To understand better the underlying physics responsible for solar flares, we will build upon our prior work that considered only waiting times between flares. In addition, data is available to consider the strength of flare (class) as well as the longitude and latitude of the flare. Considering a multivariate vector of strength, location, and waiting

time, it will be possible to better identify the dependencies between flaring events. The information gained in such an analysis would be useful for determining how flaring events are related through space and time and to identify additional constraints that can be used to elucidate the underlying dynamics of flares [FY 06 – FY 09].

Recent related publications:

1)"A Solar Cycle Dependence of Nonlinearity in Magnetospheric Activity", J. R. Johnson and S. Wing, J. Geophys. Res. 110, A04211 (2005).

2)"Kp Forecast Models", S. Wing, J. R. Johnson, J. Jen, C.-I. Meng, D. G. Sibeck, K. Bechtold, J. Freeman, K. Costello, M. Balikhin, and K. Takahashi, J. Geophys. Res. 110, A04203 (2005).

F. CPPG Activities

The PPPL Computational Plasma Physics Group (CPPG) develops advanced computational techniques and software systems required for plasma physics research to move forward. The CPPG has considerable interaction with both the theoretical and experimental departments at PPPL, and most of its projects are carried out as part of teams including members from those departments. We list here the major thrust areas.

F.1 Code Parallelization, Optimization and High Performance Computing

The CPPG maintains expertise in large scale parallel programming. There are full time staff assigned to each of the three major SciDAC codes: the 3D gyrokinetics code GTC, the 3D Extended MHD code M3D, and the adaptive mesh refinement MHD code AMRMHD. The CPPG staff work with the research staff in optimizing these codes to new generations of parallel computers and in implementing improved algorithms and more realistic physical models.

In FY04, most of the computational work involving the Gyrokinetic Toroidal Code GTC focused on parallel-vector architectures. The impressive performance achieved by scientific codes on the Japanese Earth Simulator computer in 2002 (26.58 Tflops, 64.9% of peak) revived the interest in vector processors in the US. In 2003, The Oak Ridge National Laboratory acquired a system of similar architecture, a CRAY X1, which is now fully operational although much smaller than the Earth Simulator (512 processors *vs*. 5120).

CPPG participated actively in a performance study of modern parallel-vector architectures in collaboration with an LBNL/NERSC team lead by their Future Technologies Group. As part of this work, the GTC code was ported to both the Earth Simulator and the CRAY X1, and extensive optimizations were carried out. Although similar in their low level inner-workings, the CRAY X1 includes an extra level of parallelism, called multi-streaming, which makes the programming more flexible but requires additional optimizations that are not compatible with the more classic vector programming of the NEC SX6-based Earth Simulator computer.

In order to take advantage of the vector capabilities of these new machines while retaining the ability to scale to a large number of processors, a new MPI-based level of parallelism was added to GTC. Particles inside each geometrical domain are now split between several MPI processors. This allows GTC to reach extremely high statistical resolution by using a very large number of particles. This improved version of GTC achieved an unprecedented 3.7 Teraflops on 2,048 processors of the Earth Simulator supercomputer using 5 billion particles. This new version of GTC that only uses MPI for interprocessor communication also makes possible the use of the PETSc linear equation solver in future versions as additional electron physics is incorporated.

The CPPG M3D effort has focused on porting and optimizing M3D to new computing platforms, including the Cray X1, and on improving the efficiency of the code by

implementing improved linear equation solvers and by implementing the option for using higher-order finite elements.

The coefficient matrices in M3D have been reformulated to have symmetric structure, and this symmetry is utilized in making the linear equation solvers more efficient. There are 13 separate systems of linear equations that are solved in M3D each time step, corresponding to different operators and different boundary conditions, and each one has now been separately optimized using one of several methods, appropriate for that operation. The methods used on the different equations are: conjugate gradient with a Jacobi preconditioner, conjugate gradient with a multi-grid preconditioner, and GMRES with an ILU preconditioner.

Lagrange triangular finite elements, of both second and third order, have now been implemented as an option in M3D. The higher order elements offer dramatic improvement over linear elements in their ability to solve the anisotropic transport heat flux equation, particularly in the limit when the anisotropy ratio becomes very large. We have verified that the use of higher order elements clearly yields more accurate results for the same degree of computational work. We are also exploring the use of a special class of 2nd and 3rd order lumped mass elements that lead to a diagonal mass matrix, which leads to additional efficiency in M3D.

Under the auspices of the DOE SciDAC program, CPPG has also been collaborating with the APDEC scientists in the Applied Numerical Algorithms Group at LBNL to develop a structured hierarchical adaptive mesh refinement (AMR) MHD code. AMR is characterized by the efficient placement of meshes to resolve small spatial length scale phenomenon. The AMRMHD code has been used to study pellet injection in tokamaks, magnetic reconnection and the MHD Richtmyer-Meshkov instability.

At present, the AMRMHD code solves the single-fluid resistive MHD equations expressed in conservation form. The hyperbolic fluxes are calculated by a variant of Colella's unsplit method. The resistive, viscous and heat conduction terms are treated in an implicit manner. The solenoidal property of the magnetic field is preserved using a projection method. The elliptic equations that arise are solved using a multi-grid technique. The code is written in C++ to manage the higher-level data structures and in FORTRAN for the numerical kernels, and utilizes the Chombo library developed at LBNL.

Codes used in experimental data analysis are also being parallelized by the CPPG staff. TRANSP's Monte Carlo fast ion model (NUBEAM) has a fully parallelized orbit slowing down calculation; high performance parallel computation with NUBEAM will be possible when a second section of the code, the neutral beam deposition loop, is fully parallelized as well. Also, TRANSP is being coupled with a parallelized version of the TORIC ICRF full wave solver. These developments in TRANSP will result in experience with a multi-physics calculation consisting of a mix of serial components and independently parallelized modules.

F.2 Code Modernization, Modularization, and Integration

The CPPG promotes standards for the more widely used codes at PPPL. These standards include use of modern programming languages and methods, modular software structure, portable data formats for i/o, and high quality documentation. Such standards improve the maintainability and portability of code, the usability and reuse of software modules, and greater ease of use for the end user. Although the NTCC Modules Library Project (http://w3.pppl.gov/NTCC) is no longer funded, the software standards developed in that project are still adhered to for new code, and accepted as a design goal for modernization efforts applied to legacy code.

CPPG staff maintains and develops the TRANSP code, which is the most widely used tokamak experimental data analysis code in the world. The TRANSP group within CPPG responds to the needs of the experiments as these arise, and participates in the development of new modules and in the interfacing of existing modules. Examples of current requests are for modifications in the equilibrium modules making them more robust and accurate for low-aspect-ratio ST tokamak equilibrium with strong rotation features, and for modifications to the Monte Carlo fast ion model to incorporate RF resonant heating of beam injected or fusion product fast ions. Efforts to address these needs are planned or under way.

The PPPL CPPG maintains a TRANSP production service on the FusionGrid, which was created under the auspices of the SciDAC Fusion Collaboratory Project. The FusionGrid enables authorized users around the world with tokamak experimental data to submit TRANSP runs to PPPL compute servers. Client software are available to remote sites via the NTCC web service, which the PPPL CPPG continues to support. Utilization of the TRANSP run production service has increased steadily since its inception in 2002, with 2600 Fusion Grid TRANSP runs completed in 2004.

Although the NTCC modules library project was discontinued at the end of FY 2004, it was superseded by a new integrated modeling project, PTRANSP, which envisions a predictive upgrade to the TRANSP FusionGrid service. This will include predictive extensions to the traditional "prescribed boundary" TRANSP configuration, followed by "free boundary" upgrades that will be coupled as well to an edge plasma scrape off layer model. This ambitious code integration project is being executed at modest cost using a philosophy of maximum reuse of existing capability. In this context, it has been found that "evolutionary modernization" of legacy systems is feasible, often with the help of careful Python script programming. For example, the entire "fortran-77 COMMON" based internal communications of TRANSP was recently replaced with a dynamically allocated fortran-90 module communications method. This involved a script-based automated conversion of 100,000s of lines of code. The systematic use of "implicit none" (i.e. required explicit declaration of all symbols) and promotion of the arithmetic precision of the entire code from 4-byte to 8-byte floating point, was also done automatically and correctly by similar methods. The CPPG maintains expertise in the use of such tools.

F.3 Data Management and Visualization.

The CPPG is pioneering new plasma physics visualization applications. The use of the powerful software AVS-express is being promoted, and customized visualization packages have been developed for new applications, particularly those involving 3D data. The PPPL Display Wall is a state-of-the-art facility that provides an order of magnitude greater resolution than conventional graphics displays. New applications are being developed that take advantage of the wall. The PPPL Display Wall has also served as a research facility for the testing and evaluation of numerous high performance visualization packages (Ensight-Gold, OpenDX, VTK, SciRUN), as well as a prototype for control room use by operating experiments. Indeed, the NSTX project adopted a Display Wall for their control room in FY 2004.

The application of high end visualization techniques in the context of supercomputing applications, especially those with a high volume of data production, quickly reveals the paramount importance of issues of data management. The PPPL CPPG is pioneering the use of automated data streaming and process workflow, to deliver end-to-end service for users of supercomputer simulations. Data streaming enables the automated transfer of simulation results data from a remote supercomputer to the user's visualization environment as the simulation executes. Workflow enables the automated analysis, monitoring, and display of such data in an environment convenient for the research user. This is an active area of computational science research being pursued by PPPL CPPG, with resulting publications presented at SuperComputing conferences in 2003 and 2004.

IV. Summary

In summary, the PPPL Theory Program is a vital national and international resource for Plasma Sciences. Its expertise is highly pursued for many external collaborations, has played a key role in advancing cost-effective innovation in fusion research, and has enabled optimal leveraging of major national/international investments in experimental facilities. The PPPL Theory program has made significant progress on many of the most important, scientifically challenging problems facing fusion research and has forged strong partnerships with universities, laboratories, and industry. It has also helped lead the Plasma Science community into a strong position for both utilizing and contributing to the exciting advances in information technology and scientific computing. Finally, together with its long-standing commitment to academic and educational excellence, the PPPL Theory Department will continue to play a lead role in attracting, educating, and retaining bright young scientists essential for the future of the Fusion Energy Sciences program.

Appendix A.

Funding Source	FTEs	Topical Area	FTEs
Tokamaks and Alternates	9.75	MFE	
Field Reversed Configurations*	0.52	Macroscopic stability	12
Scientific Computing	6.20	Transport & turbulence	13
SciDAC Initiatives		Wave-particles	3
RF Waves	0.33	Edge physics	2
MHD – CEMM	0.60		
Turbulence – GPS	0.98	IFE	3
FSP -- MHD+RF	1.23	Space-plasmas	2
FSP – Edge+Core	0.75	Teaching	1
		Management	1
Subtotal	**20.36**		
		TOTAL	**37**
Other Project funding			
MFE			
NSTX & NCSX	4.07		
Offsite & University Res.	3.90		
OASCR	2.90		
IFE/HEP	2.10		
Work for others/Space Plasmas	2.50		
Teaching	0.63		
Management	0.80		
Subtotal	**16.9**		
TOTAL	**37.26**		

Table 1. The FTE, Full Time Equivalent, distribution of researchers, including computational scientists; on the left, by the funding source; and on the right by topical area. The numbers on the left are from the Field Work Proposal for FY06. The values on the right are based on the assignments and were subject to rounding, to the nearest integer.

*Funded by the Innovative Confinement Concepts program at OFES.

Appendix B.

Baseline Funding Source	**FY06**	**FY07**	**FY08**	**FY09**	**FY10**
Tokamak Theory	2401	2401	2473	2547	2623
Alternates Theory	1698	1698	1749	1801	1855
Field Reversed Configurations*	208	208	214	220	227
Scientific Computing	2046	2046	2171	2236	2303
SciDAC initiatives					
Wave Plasmas	280	280	288	297	306
CEMM	255	255	263	271	279
Gyrokinetic	320	320	330	340	350
MHD+RF	585	585	585	585	585
Edge+Core	225	225	225	225	225
Total Baseline request	**8018**	**8018**	**8298**	**8522**	**8753**
Incremental Requests					
Computer Hardware	350	360	371	382	394
Collaborations	100	103	106	109	113
Post-docs	199	398	410	422	435
Incremental Request total	**649**	**861**	**887**	**913**	**942**
Total Request	**8667**	**8879**	**9185**	**9435**	**9695**

Table 2. Budget request for the PPPL Theory Department from the OFES Theory Team. Note, that the Baseline requests for FY06 and FY07 are based on the Field Work Proposal, previously submitted to DoE. This is augmented by the budgets for the FSP–SciDAC initiatives for MHD+RF and Edge+Core, which were recently awarded. The figures for the years FY08-FY10 are based on the FY07 numbers with an annual inflation rate of 3%, except for the FSP-SciDACs, which are kept constant. These budgets assume continued support for each of the initiatives, beyond their initial grants.

*Funded by the Innovative Confinement Concepts program at OFES.

Appendix C: Major Codes Supported by PPPL Theory Department:

I. Macrostability (MHD)

(a) Free Boundary Evolving Axisymmetric Equilibrium:
The Tokamak Simulation Code (TSC) developed at PPPL is used extensively at Princeton and throughout the world. It can model the evolution of a free-boundary axisymmetric tokamak plasma on several different time scales. The plasma equilibrium and field evolution equations are solved on a two-dimensional Cartesian grid, while the surface-averaged transport equations for the pressures and densities are solved in magnetic flux coordinates. An arbitrary transport model can be used, including the MMM95 and GLF23. Neoclassical-resistivity, bootstrap-current, auxiliary-heating, current-drive, alpha-heating, radiation, pellet-injection, sawtooth, and ballooning-mode transport models are all included. As an option, circuit equations are solved for all of the poloidal field coil systems, including the effects of induced currents in passive conductors. Realistic feedback systems can be defined to control the time evolution of the plasma current, position, and shape. Required voltages for each coil system can be output as part of a calculation. Vertical stability and control can be studied, and a disrupting plasma can be modeled. TSC can also be run in a "data comparison" mode, in which it reads specially prepared data files for the TFTR or DIII-D experiments. For each of these, there is a special postprocessor to directly compare TSC predictions with both magnetics and kinetics data for particular shots from these experiments. In all modes, TSC calculates the ballooning-mode stability criteria internally, and it also writes files that are read by the PEST code to calculate ideal and resistive stability for low-n modes.

(b) Inverse Equilibrium
The JSOLVER code uses the iterative metric method to simultaneously solve for the plasma equilibrium and the magnetic flux coordinates. During each iteration, it solves an ordinary differential equation for the toroidal field function g so that the surface-averaged parallel current density takes on a prescribed form. It has an automatic-zone-doubling feature to allow efficient generation of high accuracy equilibria.

The ESC Code uses a second-order generalized Newton's method to solve the nonlinear Grad-Shafranov equation. For solving the intermediate linearized Grad-Shafranov equation, it uses either the gridless (sweeping) technique (which guarantees a prescribed accuracy) or the (faster) Runger-Kutta method.

(c) 3D MHD Equilibrium
The PIES code solves for 3D MHD equilibria using a general representation for the magnetic field, and is therefore capable of handling equilibria with islands and stochastic regions, and with a divertor; (The LHD stellarator group in Japan has also developed a 3D MHD equilibrium code that can handle islands, the HINT code.) The PIES code is used internationally by groups associated with major stellarators: W7X (Germany), TJ-II (Spain), Heliotron-J (Japan). The code has also been used extensively in design studies for the NCSX and QPS stellarators. Recent calculations for data from the W7AS stellarator

(Germany) are showing a strong correlation between the predicted loss of flux surfaces and the experimentally achievable value of β. These studies are continuing. In addition to its stellarator applications, the PIES code has also been applied to tokamaks to study error field effects and tearing modes.

(d) 3D Nonlinear Time-Dependent MHD

The code M3D is a nonlinear resistive compressible 3D MHD code. It is a fully toroidal code with no expansion approximation being used. It is an initial value code, and is run analogous to running an actual experiment. As in the experiment, the initial conditions, such as initial density, temperature, and q profiles are first determined. Then, again as in the experiment, the boundary conditions, such as the voltage at the wall, determines the time evolution of the plasma discharge. The code can be run either using a finite-difference structured mesh or a finite element unstructured mesh. The code uses a stream function/potential representation for the magnetic vector potential and velocity that has been designed to minimize spectral pollution. The basic solution algorithm is quasi-implicit in that only certain terms in the fluid portion that are the most time-step limiting are solved for implicitly, with explicit differencing being used for the remaining terms. M3D, the two-fluid version M3D-T, and the particle/MHD hybrid version M3D-K are components of the M3D project.

The AMRMHD code was developed in conjunction with the APDEC center at LBNL, making use of their CHAMBO general adaptive mesh refinement software package. The code solves the MHD equation using a second-order-in-time generalized eight-wave upwind scheme for solving the MHD equations. The code is fully parallel, and has the feature that zones use timesteps proportional to their linear dimension, resulting in a very efficient method for resolving problems with multiple space scales.

(e) Linear Ideal Low-n

PEST-I is a linearized stability analysis code based on a minimization of the Lagrangian. Using a finite-element technique, PEST-I solves for all three vector components of the displacement and returns a physical growth-time. PEST-II is also a linearized stability analysis code. This variational code minimizes a scalar form of the Euler-Lagrange Equations obtained using a model kinetic energy. This allows an analytic minimization of two components of the displacement, so that only a single component needs to be minimized numerically. This leads to a much more efficient (faster) procedure. This procedure gives the correct marginal stability point, but not the numerically correct growth rate or eigenfunction.

(f) Linear Ideal High-n

The BALLOON code integrates the 2nd-order ODE to find ballooning stability limits and the critical-n from a WKB approximation. The Mercier criterion is calculated and a choice of Kinetic Energy Normalization is available. The output includes contours of local magnetic shear, curvature, and delta-W contributions from the various driving terms.

The CAMINO code constructs the s-α stability curves generalized to arbitrary 2-D tokamak equilibria. The curves from all the flux surfaces generate a 3D stability ballooning boundary

in (s, α, ψ). This can be used to tailor the plasma profiles to achieve the second region of stability or optimize the beta for the 1st region.

(g) Linear Non-Ideal Low-n

PEST-III is an outgrowth of the PEST-II code that is used to calculate resistive instabilities. It uses singular finite-element techniques to compute the jump in the logarithmic derivative of global mode eigenfunctions across singular surfaces. This information gives the quantity known as delta-prime, which determines the stability with respect to resistive instabilities. This delta-prime also enters into the theory for the evolution of the neoclassical tearing mode.

(h) Linear Low-n MHD + Particles

The NOVA-K code (and its non-perturbative version NOVA-KN) computes stability of global MHD and non-MHD modes in the presence of energetic particles such as neutral beam and ICRF heated particles and alpha particles for tokamaks with noncircular flux surfaces. The NOVA-K code makes use of a kinetic-MHD formalism that includes kinetic effects through particle pressure in the momentum equation. The plasma pressure is calculated from the particle distribution governed by the gyrokinetic equation including finite orbit width and Larmor radius effects. The NOVA-KN code includes the perturbed particle pressure into the eigenmode equation and solves it iteratively for the mode structure and eigenfrequency.

(i) Linear High-n MHD + Particles

The HINST code computes the spatial structure and stability of high-n modes such as TAE and ballooning modes in the presence of energetic particles such as neutral beam and ICRF heated particles and alpha particles for high-beta tokamaks with noncircular flux surfaces. The HINST code makes use of the Ballooning (poloidal) and Fourier (radial) formalisms to determine the global mode structure and stability. It can be used in two forms to provide the local (1D in the ballooning variable) and the global (2D in the ballooning and radial variables) solutions. It is non-perturbative and includes such effects as particle finite orbit width and Larmor radius.

(j) Vacuum and Active Feedback

In the VACUUM code, the magnetic scalar potential is solved from Laplace's equation using a collocation-Green's function method to calculate the vacuum contribution to delta-W for three topologically distinct wall shapes - toroidal, spherical, and segmented. It calculates the vacuum response in either a Fourier or a Finite representation in the poloidal angle. It also reads the output from stability codes and calculates the eddy current pattern on the shells and also simulates the Mirnov loop readings. A thin resistive shell is now an option and the coding for feedback simulations is being added.

II. Microstabililty (kinetic)

(a) **Linear Local**

The FULL code solves for linear growth rates and real frequencies of ion temperature gradient modes, trapped-electron modes, kinetic ballooning modes, etc, including trapped particles, finite Larmor radius effects, bounce frequency and transit frequency and magnetic drift frequency resonances, and collisions, for all included plasma species. The calculation uses the ballooning representation for high toroidal mode number instabilities, and is thus radially local, solving integro-differential equations along a single chosen unperturbed magnetic field line for the linear eigenfunction. The code exits in both tokamak and stellarator versions. The tokamak versions are either electrostatic or fully electromagnetic, and can use either an s-alpha model equilibrium or a general numerically-calculated MHD equilibrium. The FULL code also evaluates corresponding quasi-linear particle and energy transport expressions for all included species.

(b) Nonlinear Global

The gyrokinetic toroidal code (GTC) has been written in collaboration with the University of California, Irvine. It is a nonlinear (or linear) global particle-in-cell simulation code for tokamak turbulence, with efficient sampling of the 5D phase space. The turbulence level can be regulated by the self-generated zonal flow. It uses a global magnetic-field-aligned mesh for efficiency, thereby reducing the needed number of computations substantially. All toroidal harmonics up to a large number are retained. The code employs the MPI and OpenMP libraries for running on massively parallel processors.

III. Neoclassical

The GTC-Neo code is a global neoclassical code, interfaced with numerical MHD equilibrium codes for noncircular-cross-section tokamak geometry. Using particle-in-cell techniques for finite orbit extent, it calculates neoclassical fluxes of particles, momentum, and energy, the radial electric field, the poloidal velocity, and so on.

IV. Beam

The Beam Equilibrium Stability and Transport (BEST) code is a three dimensional, multi-species, nonlinear delta-f particle simulation code for studying collective effects in high intensity particle beams, with applications to modern high intensity accelerators, heavy ion fusion, and high energy density physics. It is parallelized using the MPI protocol, and scales linearly up to 512 processors. On the IBM SP computer at NERSC, the BEST code advances 4.2×10^{11} particle×time-steps to simulate the e-p two-stream instability in the Proton Storage Ring experiment at Los Alamos National Laboratory.

V. Field Reversed, and other Configurations

The HYM code is a parallel 3-D nonlinear initial-value code. It uses a fourth-order finite-difference scheme with explicit time advance, and includes three different physical models: (a) a resistive MHD or Hall-MHD model; (b) a hybrid scheme with full-orbit particle ions and fluid electrons; and (c) a hybrid MHD/particle model, where a fluid description is used for the thermal background plasma, and a kinetic (delta-f particle) description is used for the low-density energetic beam ions. The code shows good parallel scaling for up to 512 processors on the NERSC IBM SP computer. The code uses generalized orthogonal coordinates, and its geometry can be varied (cylindrical, rectangular or toroidal, for example). So far, the code has been used for FRC and NSTX studies.

VI. Neutral Gas Transport

The DEGAS 2 Monte Carlo neutral transport code simulates the behavior of neutral gas atoms and molecules (e.g., arising from the recycling of plasma fluxes on a divertor target plate) in plasma devices. Models for the interactions of plasma and neutral species with each other and with material surfaces are incorporated into the code. DEGAS 2 has been designed from the outset to be fast and flexible. Fast execution results in part from the fact that the Monte Carlo algorithm parallelizes naturally; run times can be shortened simply by using more processors. Flexibility is ensured through the use of quasi-object oriented programming techniques. The consequence is that new species and interactions can be quickly and easily added to the code. DEGAS 2 has been used at PPPL to simulate experiments on both NSTX and Alcator C-Mod. The code is also in use at other institutions, including LLNL and JAERI.