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 magnetic confinement as an attractive, technically feasible energy option. This involves both development of improved calculational capabilities and also the application of state-of-the-art theoretical and computational tools to the interpretation of experimental results. Predicting the properties of high-temperature plasmas is a grand scientific challenge which depends on the integration of many complex physics phenomena that cannot be reliably deduced from empirical scaling and extrapolation alone. Increasingly powerful computational resources have stimulated progress, and the PPPL theory effort continues to be at the forefront in demonstrating how such capabilities advance scientific knowledge and impact innovation in the field. 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 and to 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. At present, the balance of resources among these four activities within the Theory Department is approximately 40%, 40%, 15%, and 5%. Descriptions of the total resources and associated allocations for the PPPL theory program – both presently provided and those targeted in the future - are provided in the Appendices A and B of this document.

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. With respect to the future, this planning document describes well-motivated goals with deliverables and associated time-lines specified. 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 will strive 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 analysis capabilities 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 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, and other major tokamaks. The continuing improvements in operating regimes in magnetically-confined plasmas and in diagnostic techniques 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 harvesting of key results from experimental facilities and from the identification of attractive new confinement approaches and the associated designs for new 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. In order to ensure proper communication and enhanced productivity, the Theory Department has an active Steering Committee chaired by W. Tang, Chief Scientist of PPPL and Head of the Theory Department, and including R. Davidson, Deputy Head of the Theory Department, for IFE and Non-MFE Plasma Sciences, S. C. Jardin for MHD, T. S. Hahm for Transport, C. Z. Cheng for Waves/Energetic Particle Physics, A. Reiman for Non-Axisymmetric Systems, and E. Valeo for Laser-Plasma Interactions. 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. PPPL expects to maintain strong theoretical programs in each of the following areas:

Fundamental Plasma Theory: Scientists at PPPL have a long productive history of providing Plasma Science with seminal theoretical foundations. 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 will have application to interpretation of key phenomena in both laboratory and natural plasmas.

Collaborations: One of the important goals of the PPPL theory program is to continue the productive collaborations between PPPL Theory 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 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; 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, Columbia University, University of Colorado, 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 Initiative (PSACI). This is an important component of the DOE Office of Science's new advanced computing program called Scientific Discovery through Advanced Computing (SDAC).

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 still holds significant 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 Alfven eigenmodes (TAE), and the practicality of transferring the fusion-product energy directly to the plasma ions or to current drive (alpha channeling). This workscope is particularly important for the Theory Department's productive collaborations on national (DIII-D, C-MOD) and international (JET, JT60U, ASDEX, …) tokamak projects.

Theory of Alternate Confinement Configurations: A significant portion of the theoretical analysis of confinement systems at PPPL is focused on promising confinement configurations other than tokamaks. With the on-site presence of the National Spherical Torus Experiment (NSTX), the spherical torus is a key area of concentration. Many attractive features of the ST have been identified theoretically, including regimes of high performance and regimes where very little external current drive would be required to sustain the configuration. This work will intensify as more experimental results from NSTX as well as the MAST device in Europe become available. 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 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 operaton. This effort has also expanded with increased interactions with two major international stellarator projects -- the LHD experiment in Japan and the upcoming W7-X program in Germany. Studies of innovative confinement concepts such as the Field Reversed Configuration (FRC) and the Reversed Field Pinch (RFP) are also being pursued.

Advanced Scientific Computing: This is an integral part of the research program in the Theory Department. In this area, 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 the problems of extraordinary complexity encountered in the Plasma Sciences. This involves the application of modern computational techniques and high-performance computers to address outstanding issues facing fusion energy research. PPPL's activities in this area also 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 for the Plasmas Science Advanced Scientific Computing Initiative (PSACI). Technical progress, which has entailed close collaboration between the Theory Department and the Computational Physics Group (CPPG) staff, includes the introduction of new physics capabilities and the conversion and optimization of several major PPPL codes to effectively utilize massively parallel computers. The associated activities have involved the introduction of new algorithms and computational techniques, and also the application of state-of-the-art visualization tools.

Non-MFE Plasma Theory: Recognizing that achieving the goal of producing an efficient energy-producing fusion plasma system is still decades away, the PPPL theory research efforts contribute to near-term beneficial applications of plasma science as well. These non-MFE applications have continued to grow -- especially in the accelerator physics, heavy ion fusion, 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 FES 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.

Finally, motivated by the urgent need to help attract, train and assimilate the best and brightest young talent into the field, the Theory Department actively participates in the Princeton University 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.

II. SCIENTIFIC AREAS

A. Macroscopic Stability

FESAC Goal: Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation
5 Year Macroscopic stability goal: *Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects.*

A.1 Ideal MHD

Ideal MHD theory and computations are now quite mature. The PEST I/II codes have been the community standard for evaluating ideal MHD stability in axisymmetric devices for some years. We continue to support these codes, to improve them, to support the use of these codes to benchmark and validate newer codes, and to apply them to new applications. Current improvements that are planned include incorporating an adaptive radial mesh to make the calculation of the stability of high-q equilibrium more efficient, and the development of an improved user interface to allow more seamless computation of the stability of experimental data. Benchmark and validation exercises include benchmarking with GATO, DCON, and SESC using extreme profiles to help understand the strengths and limitations of the different codes. Applications include continuing efforts to understand the current and beta limits of toroidal devices, and their sensitivity to plasma shaping and profiles. An active emphasis area for tokamaks is to better understand the role of ideal MHD in ELMs, and 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.

Three-dimensional magnetic field configurations provide opportunities for the control of MHD instabilities not available in axisymmetric configurations. The

ι (=1/q) profile can be controlled through the use of externally generated transform, and, in particular, stabilizing externally generated shear can be produced. Three-dimensional linear MHD stability calculations at PPPL have been performed with the Terpsichore code developed primarily at Lausanne, Switzerland. Modifications to the code have been made at Princeton to improve its robustness for configurations of interest to us and to add diagnostics to aid in understanding the results we have been obtaining. We expect to continue using this code for our linear stability studies. We will continue to explore the stabilization of kink modes and vertical modes via 3D shaping and the general effect of 3D shaping on MHD stability (ballooning modes, etc.). The stability codes presently start from a VMEC equilibrium which assumes the existence of good magnetic surfaces. A longer term goal is to couple these codes to a code such as PIES that does not assume good flux surfaces.

A.2. Resistive MHD including Neoclassical Tearing Mode and Sawtooth Oscillations

The neoclassical tearing mode (NTM) is caused when a magnetic island develops in a tokamak causing the pressure to flatten, which subsequently causes the neoclassical "bootstrap current" to decrease, in turn causing the island to grow more. Experimentally, this is observed to set the pressure limits in many long pulse tokamak discharges. One of the major thrusts of the M3D effort is to simulate the nonlinear development of the NTM and to differentiate between the competing mechanisms for stabilization. For these studies, an anisotropic thermal conduction model and a neoclassical closure for the ion and electron viscous stress tensors are essential. 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. 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. The M3D code is well suited to investigate these mechanisms as is NIMROD, a similar code developed outside of PPPL. 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 heat 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 and to perform comparison studies between M3D and NIMROD.

Another issue is to better explain the cause and effects of magnetic island rotation. Experimentally, magnetic islands almost always rotate. This rotation is observed in the M3D code when "2-fluid" effects are included, but we do not presently have confidence that we are predicting the correct rotation velocities. A greater emphasis will be placed on extending the realism of the closure model in the 2-fluid equations and on comparing with relevant experimental results. It may turn out that only a full "particle closure" of the equations is sufficient to reliably predict this phenomena.

The PIES code provides a complementary approach to NTMs. Because the NTM grows on a resistive time scale, radial force balance is maintained, and the dynamical nonlinear evolution is described by Faraday's law. In principle, a three-dimensional equilibrium code coupled together with a time-advancement equation for the magnetic field can be used to calculate the evolution of the configuration. At present, PIES maintains a flat current profile in the islands, appropriate to saturated modes. A future upgrade of the code will use the output of a full three-dimensional bootstrap treatment obtained from NIFS in Japan and will introduce gridding in the island interiors, allowing the code to follow the island evolution.

The M3D and PIES efforts are complemented by several other activities in this area. One is to evaluate the semi-analytic formulas of Hegna, et al, using the PEST-III code to calculate delta-prime. There are also plans to extend the SESC to resistive instabilities, which may have some advantages over PEST-III.

The sawtooth instability occurs when the current peaks in a tokamak, creating a region in the center where the safety factor is less than unity, $q<1$. While this instability is normally benign in low pressure, low current plasmas, under certain conditions it can set off a sequence of events that leads to global instability. The challenge is to develop a better predictive model of the sawtooth for all plasma conditions. Excellent agreement has been obtained between a theoretically motivated criterion based on the 2-fluid MHD equations and TFTR data for the occurrence of sawtoothing. This same 2-fluid physics model, supplemented by full ion kinetic effects, is being incorporated

into the 3D extended-MHD code M3D to develop a fully predictive model for when sawteeth occur and what their period is. Extensive benchmarking of this code with experimental data is required. There is also interest in using the 2D linear stability codes to more effectively predict the nonlinear consequences of a linearly unstable configuration with $q_0<1$. Presently, these codes cannot differentiate between a benign repetitive sawtooth oscillation and a discharge-ending global mode. The present plan is to perform comparative studies with the 2D and 3D-nonlinear codes to develop a better 2D semi-analytic model of nonlinear sawtooth activity.

A.3 Prediction of Disruptions and Analysis of Disruption Data

For tokamaks, the highest performance discharges 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. In reactor scale devices, the first wall and structural damage caused by disruptions is also of a major concern. MHD simulations have been used to identify the mechanism of a common type of such disruptions in the Tokamak Fusion Test Reactor (TFTR) as a localized moderate-n ballooning mode nonlinearly destabilized by an internal kink. Further studies with more resolution and improved physics models will be done to produce accurate criterion for such instabilities, which may shed light on ways to control them. This work will be combined with that described in Section 2.3 to understand the difference in disruption mechanisms between tokamaks, current-carrying stellarators, and spherical tori. Of particular interest is to understand how externally generated transform provides some level of disruption protection. Disruption prevention techniques such as massive impurity injection will also be evaluated, extending previous pellet injection simulations.

Several years ago, we began an analysis of disruption data on DIII-D. We found that high disruption rates are found at a wide range of values of beta, density, and edge-q. There is disagreement in the community as to whether this is an intrinsic property of tokamaks or reflects the way that experimental research programs are operated. This work needs to be better fleshed out by an examination of selected sets of disruptions for disruption precursors, evidence of enhanced radiation loss, etc. This should also be extended to analysis of disruption data on CMOD, JET, JT-60, and possibly other tokamaks. There is a need for improved automated analysis of disruption precursors. The goal should be to provide an understanding of all disruptions that occur

experimentally, and ultimately to provide insights leading to disruption-free regimes in tokamaks.

A.4 Three-Dimensional MHD Equilibria

A key issue for stellarator configurations is the existence of good flux surfaces. In three-dimensional equilibria, the fields produced by the pressure driven currents have Fourier components that resonate with rational surfaces, potentially producing magnetic islands and regions of chaotic field line trajectories. The increase in magnitude of these currents with increasing pressure is expected to give an equilibrium beta limit. Although this issue does not arise in axisymmetric equilibria, some aspects of the physics are closely related to that of finite beta tearing modes. The effect of the Pfirsch-Schluter currents is predicted to be determined in part by the resistive interchange criterion. Perturbed bootstrap currents are predicted to play a major role. Depending on the direction of the shear relative to that of the bootstrap current, this effect can either suppress magnetic islands or cause them to grow. The physics of this is the same as that of neoclassical tearing modes in tokamaks.

The PIES code developed at Princeton has been used to calculate three-dimensional equilibrium flux surfaces (without assuming their existance as VMEC does). The PIES code now has a free-boundary capability, and it is used internationally by the stellarator community, in Germany, and Spain, as well as in Japan. Modifications are being made to the code to speed it up, and improved bootstrap current physics is being added to the code. Resistive time-dependent codes provide a complementary way of studying equilibrium island formation in stellarators.

The Princeton M3D code can be initialized with a 3D VMEC equilibrium solution (as can PIES). The predictions of M3D are being benchmarked against those of PIES for stellarator equilibria. The major international experiments will provide an opportunity for benchmarking the codes against experimental observations of magnetic island formation. There is also a need for a careful comparison of both numerical and experimental results with model analytical calculations to get a better understanding of the physics.

A.5 Axisymmetric Evolution

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. We plan to keep developing TSC as the benchmark code of its type, 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 and ST startup by bootstrap overdrive, and a study of methods to prevent the production of runaway electrons in disrupting tokamaks. Initial applications of this code to NSTX have been very successful, demonstrating that the plasma current can be predicted as a function of time for essentially the entire discharge, provided that no 3D MHD activity develops. TSC has a balloon stability diagnostic, and is now fully coupled with the PEST and DCON stability codes. It can thus predict when discharges in NSTX and other devices should develop MHD instabilities, and this capability is being calibrated against experimental data as it becomes available. Future development will concentrate on incorporating better current-drive modules, a better neutral beam package, and incorporation of a more modern graphics package.

A.6 Energetic Particle Modes and Gyrokinetic Particle Closures

The 3D MHD code M3D has available closure schemes using particles. This makes this code a unique tool for calculating the nonlinear consequences of energetic particle modes. We plan to exercise this option much more as increased computer power makes it more feasible. We plan to further investigate the nonlinear consequences of resonant destabilization of discrete and continuum Alfven modes by energetic particles such as fusion alphas or beam-injected ions. This effort includes toroidal Alfven eigenmodes (TAE), "fishbones", and energetic particle modes. Previous studies have been performed in relatively simple geometry using Gyrokinetic-Energetic-Particle/MHD hybrid models. We will extend these energetic particle studies in several ways. The first thrust is to explore the extent that low aspect ratio, non-circular geometry and the interaction of multiple modes bring in significant new effects. . This will be of importance to interpret Spherical Torus (ST) results. The second thrust is to perform more detailed modeling of

the TAE “pitchfork” splitting effects observed during mode saturation on the Joint European Torus (JET) tokamak.

A.7 Theoretical Support for Resistive Wall Mode Active Feedback Experiments

We are performing both linear and non-linear analysis of the resistive wall mode and its active feedback stabilization. This work is contributing directly to experiments underway on DIII-D, and is expected to stimulate new experiments. For the linear analysis, we are modifying the VACUUM code to contain a resistive shell, feedback coils, and (in a later phase) 3D structure. This is being interfaced both to the PEST stability code [PPPL] and to the GATO code [GA] 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. The active feedback analysis is guided by the recently developed circuit equations formulation for kink-mode feedback by Okabayashi and Pomphrey. This effort complements that of the VALEN code [Columbia] in that it has a more self-consistent model of the unstable plasma, but has a less complete model of the surrounding structure (at least for now). These codes are being benchmarked in their regimes of overlapping validity.

For the nonlinear analysis, we will use the nonlinear resistive MHD code M3D and the 3D iterative equilibrium code PIES to investigate nonlinear physics associated with resistive walls and free surface motion of the plasma/vacuum interface. Nonlinear simulations including models for the resistive wall and for plasma flow will provide essential information on resistive wall modes and mode locking. This information will be compared with experimental, linear numerical and analytic results to learn when to expect detrimental MHD activity and how to avoid it. Effects of a resistive wall and flow in RFP simulations will also be investigated to determine the possibility of maintaining discharges longer than shell times. Magnetic feedback will be modeled with time dependent magnetic fields applied from realistic coils. Nonlinear simulations will provide information on the effectiveness of feedback schemes for activity coupling to resistive walls.

The application of the M3D code to this problem requires the development of non-ideal boundary conditions, which may be broken into two pieces: (1)

resistive wall and external vacuum region, and (2) internal vacuum region between the magnetic separatrix and the wall. The resistive wall and external vacuum will be 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. A convenient technique for simulating the internal vacuum region is to insert a large resistivity thereby suppressing current within this region. This requires a 3D interface-tracking algorithm. We will implement a passive scalar field that evolves due to advection with plasma motion to perform this tracking function.

We are also evaluating the suitability of extending the PIES code to be able to address this problem. Because the resistive wall mode evolves on the L/R time scale of the wall, radial force balance is maintained, and the dynamical nonlinear evolution is described by Faraday's law. In principle, we need only to evolve the magnetic field and compute a sequence of 3D equilibrium subject to the correct flux constraints to calculate the evolution. We are presently evaluating the feasibility of implementing this. A free-boundary capability has already been incorporated in the code in collaboration with the stellarator theory group in Germany. A Green's function solution is used for the region outside the wall, and there is a vacuum region between the wall and the plasma. An evolution equation for the wall current will be added to describe the evolution of the mode.

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 scale 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. We are performing high-resolution numerical simulations of the 2-D Hall-MHD equations and

comparing these to MRX data. We are also incorporating two fluid effects in our simulations of reconnection in tokamaks to quantify their effects there. We will begin exploring full 3D reconnection with the goal of identifying 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 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 reversed field pinch or a spherical torus undergoing CHI relaxation exhibit some degree of self-organization. However a detailed understanding of the relaxation physics in the RFP and spherical torus CHI experiments is still lacking.

Such an understanding could result in theoretically derived scaling laws for RFPs, and could also point the direction to improving this concept. For example, could low aspect ratio RFPs induce single-helicity states with improved confinement? A better understanding of this phenomena will also help in designing and interpreting the CHI experiments on NSTX. We plan to examine the importance of two-fluid effects in RFP and spheromak simulations and in the CHI experiments, and to understand the implications for scaling with Lundquist and magnetic-Prandtl numbers.

A summary of MHD task areas and high-level milestones is presented in Table II. A. 2. and Fig. II. A. 1, respectively.

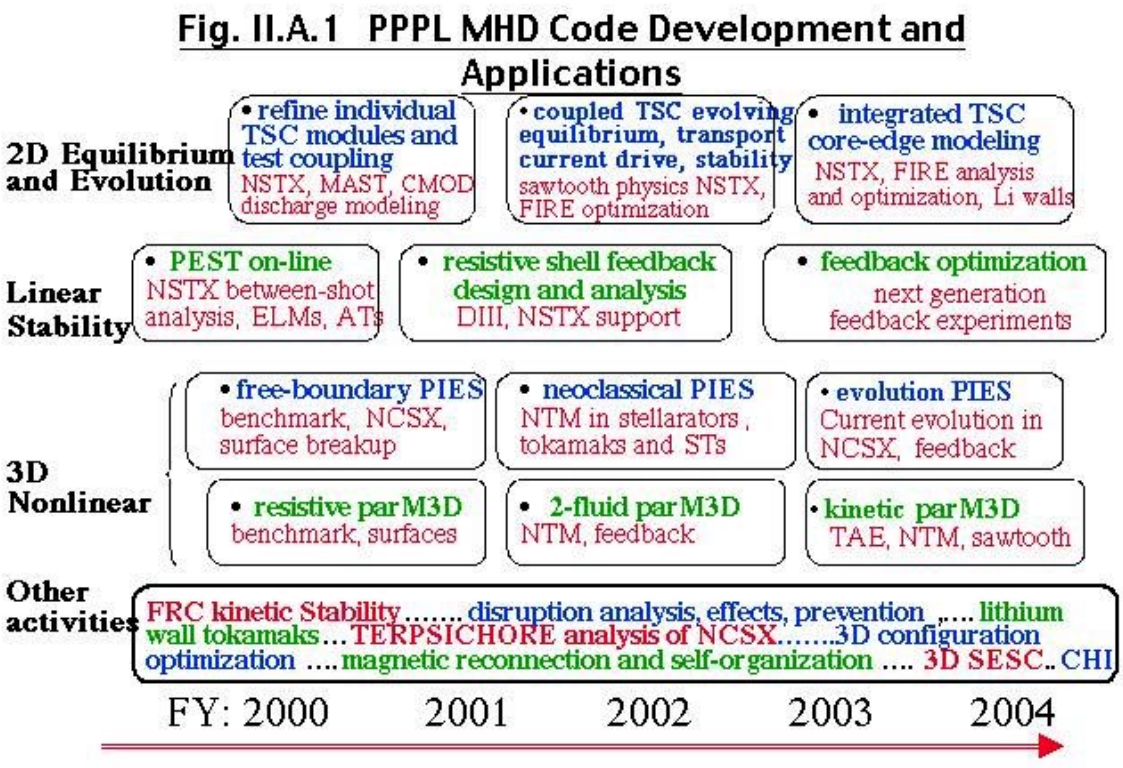


Fig. II. A. 1. High-Level MHD Milestones

B. Turbulence and Transport

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 linear kinetic calculations, analytical theories, and comparisons to experiments. It must be appreciated that the time scale for advances in basic physics is difficult to predict. Nevertheless, over a period of five years, one can expect significantly improved understanding of a variety of fundamental nonlinear processes of relevance to toroidal confinement devices in particular. It will eventually lead, as part of an overall national effort, to the FESAC 5 year objective*; Advance understanding of turbulent transport to the level where theoretical predictions are viewed as more reliable than*

H. Code development	ESC to codes library and TRANSP [LZ, AP]	1. user friendly PEST[JM] 2. addaptive mesh in PEST for high-q[JM] 3. modify GATO for large nq[MC}	(i) develop non-perturbative high-n TAE stability code [NG] (ii) add resistive shell & feedback to VACUUM code [MC]	1. Develop and benchmark parM3D [XT, WP,SJ] 2. Port FRC code to T3E/ improve performance at high S [EB]	1. PIES speedup [DM,AR] 2. Neoclassical in PIES[AR, DM] 3. 3D ESC[LZ] 4. M3D as 3D equil. Code [SH,WP]	TSC improvement / use of standard modules / couple with TRANSP [SJ]	(i) improve DEGAS2 - UEDGE [DS]	
G. Spherical Torus/NSTX		Current and beta limits, analysis of NSTX[JM}	1. Energetic particle studies [NG] 2. resistive modes[JM] 3. 2-fluid ball[LZ]	1. CHI startup [WP] 2. non-linear resistive modes [WP]		Non-inductive current rampup [SJ]		
F. Stellarators		Terpsicore analysis of kink mode stabilization [GF]		(1) Stability of high-bootstrap stellarators and disruptions in stellarators[WP]	NCSX plasma and coil design and optimization [NP]			
E. Adv.Tok. with Feedback Control		RS optimization on JT-60U [JM]	Support DIII RWM, tearing, and feedback expts. [MC,JM]	(i) vacuum + feedback in M3D [MC,AP<WP] (ii) spindown [WP]	(i) vacuum + feedback in PIES [DM]			Circuit equation model of active feedback [NP]
D. Ignited Tokamaks			(i) TAE studies[NG] (2) Stability and other theory of liquid met wall tokamak[LZ]	(i) non-linear TAE, m=1,fishbone studies [WP,NG,GF]				
C. Tokamaks/ Disruptions		ELM studies on JT-60U [JM]	TAE studies on JT-60U[FC,NG]	(i) Disruption effects halo currents, runawys[WP] (ii) island rotation studies and	Neoclassical tearing modes with PIES[AR]	TSC analysis [SJ]	Analyze CMOD with DEGAS2-UEDGE [DS]	
B. FRC/MRX	Equilibrium with large flow [EB]		(i) include plasma flow in NOVA [FC]	Map out and understand large orbit effects on FRC stability, including E, rotation, profile [EB]		2-fluid magnetic reconnection [SJ]		
A.Advanced Computing Initiative				Develop scalable 3D code with multilevel physics and geometry[WP,XT,SJ]				
	1. 2D Equilibrium	2. Linear Self-adjoint stability	3. Linear non-self-adjoint stability	4. 3D nonlinear	5. 3D equilibrium	6.2D MHD and Evolving equilibrium with transport	7. Boundary and Edge	8. Plasma Control

Table II. A. 1. MHD Task Areas

empirical scaling in the best understood systems. Our future effort can be classified into the following four areas.

B.1 Ion Temperature Gradient Turbulence with Zonal Flows and Streamers

Nonlinear simulations of toroidal ion temperature gradient (ITG) driven turbulence have in the past demonstrated the promising aspects and relative merits of gyrokinetic particle-in-cell simulations and gyrofluid simulations. Those methods have significantly contributed to our understanding of the characteristics of the turbulence responsible for anomalous heat transport in tokamaks and progress toward quantitative prediction of transport. An essential role played by turbulence-driven zonal flows in determining transport levels at nonlinear saturation as observed in the previous gyrofluid simulations in flux-tube domains and more recent gyrokinetic simulations motivates us to focus our research on the role of self-organized meso-scale structures such as zonal flows and streamers in determining transport scalings. The global gyrokinetic particle-in-cell simulation is the most natural tool to study these issues since it uses fundamental and primitive equations, and in principle, captures subtle nonlinear kinetic effects such as the inelastic Compton scattering (nonlinear Landau damping), which are not yet accurately described by the gyrofluid closure employed in simulations. Our GTC code successfully reproduces the analytical predictions of the zonal flow damping behavior, and has been benchmarked for the neoclassical (collisional) transport. Global gyrokinetic simulations are also free from subtleties of local turbulence assumptions employed in flux-tube codes and can straightforwardly address the possible importance of long range transport avalanches due to streamers and possible deviation from gyro-Bohm scaling. The gyrofluid approach is still valuable, however, since long-time nonlinear simulations which produce statistically more meaningful turbulence spectra are affordable. It is also easier to compare with nonlinear analytical theory. Some work on modified gyrofluid closures to improve the treatment of certain neoclassical effects was done. Considerable progress was made that improved the agreement with the flow damping of kinetic theory and the nonlinear gyrokinetic particle-in-cell simulations. But some differences remain.

Expected Deliverables

We will develop a more user friendly version of the widely requested global GK code (GTC) to facilitate further dissemination (already done to ORNL, NYU, and UCLA as part of Plasma Science Advanced Computing Initiative (PSACI) activity) [FY00].

Electrostatic gyrokinetic simulations with ion-ion collisions will address the role of zonal flows, streamers, and avalanches in transport scaling with respect to ν_* and ρ^*. The validity regime of mixing length estimates will be critically examined [FY01].

Massive parallelization of the GTC code has been made possible via employment of a scalable Poisson solver. Multidimensional domain decomposition will be implemented to improve the efficiency of parallelization for magnetic coordinates with a globally field-aligned mesh. [FY01].

With completion of the gyrofluid code parallelization in collaboration with the University of Maryland and dissemination to IFS and GA, improvement of gyrofluid closures will continue to achieve better accuracy in the ion thermal transport prediction. Ion-ion collisions will be included [FY01].

Comprehensive diagnostics and visualization for turbulence characteristics and spectral transfer will be developed for advances toward detailed and fundamental understanding of nonlinear saturation mechanisms of turbulence and zonal flows, and for more detailed comparisons with experiments. These include developing simulation diagnostic packages which model experimental measurements (as part of PSACI) [FY01].

On the analytic side, the effective **E**x**B** shearing rate will be generalized to include short radial wavelength components of zonal flows. The role of specific correlation functions and conservation laws in the zonal flow-drift wave system will be elucidated. This will deepen our understanding of the nonlinear mode coupling process associated with the duality of random shearing and zonal flow generation [FY02].

Generation and damping of zonal flows in stellarators will be studied both analytically and computationally using the GTC code. The effects due to the lack of a symmetry direction will be elucidated [FY03].

A continued attempt at clarifying the role of self-organized criticality in turbulent tokamak transport, and its possible connections to intermittency and

submarginal turbulence, will be made by embedding its analysis within the general statistical theory of turbulence and by comparisons to gyrokinetic and gyrofluid results, and considering its relations to other specialties such as front propagation. These insights are relevant to the interpretation of nonlocal transport events and measurable power-law fluctuation spectra [FY03].

A quantitative, entirely self-consistent analytical statistical theory of self-generated shear-flow suppression of turbulence should be within reach [FY04].

B.2 Electron Dynamics and Electromagnetic Fluctuations

The magnetic fusion community has much less understanding of electron dynamics, transport and electomagnetic turbulence compared to its understanding of ion thermal transport and electrostatic turbulence. While the gyrofluid approach has made substantial advances in including tokamak realism such as bounce-averaged trapped electron dynamics and electromagnetic fluctuations, a more accurate full kinetic description of electron dynamics is desirable in the future.

Expected Deliverables

More accurate electron dynamics will be included in the GTC code using the split-weight scheme, in which only the non-adiabatic electron distribution function is advanced, and using the analytically reduced electron fluid model this split-weight scheme has shown promising features in a simple geometry. Electrostatic nonlinear simulations in a torus addressing electron thermal and particle transport will be initiated (as part of PSACI)[FY01].

The role of trapped electron dynamics in affecting the direction of spectral cascade, zonal flow generation, and turbulent transport will be studied via GF simulations with improved closures [FY01].

Nonlinear electromagnetic gyrokinetic simulations in a torus addressing transport scaling with respect to β will be initiated [FY02].

The electromagnetic GF capability will be expanded to larger system size, finer resolution simulations. The zonal flow damping will be benchmarked in the electrostatic limit and the zonal flow dynamics and possible role of

Maxwell stress will be studied in the presence of magnetic fluctuations. This will serve as a bridge between MHD and fully kinetic simulations [FY02].

Often the electron thermal transport remains highly anomalous, although comprehensive kinetic calculations from both the FULL developed at PPPL and the GS2 code developed at the University of Texas predict that there are no linearly unstable modes with toroidal mode numbers in the rough range of 10 ~ 100. Stability of low-mode-number modes will be studied by the global comprehensive kinetic code benchmarked against the PEST and NOVA-K codes. The possible relevance of collisionless skin-depth scale short wavelength turbulence will be studied via the gyrokinetic continuum code in collaboration with IPP-Garching and the University of Maryland. The possible relevance of submarginal turbulence including self-organized-criticality will be studied [FY02].

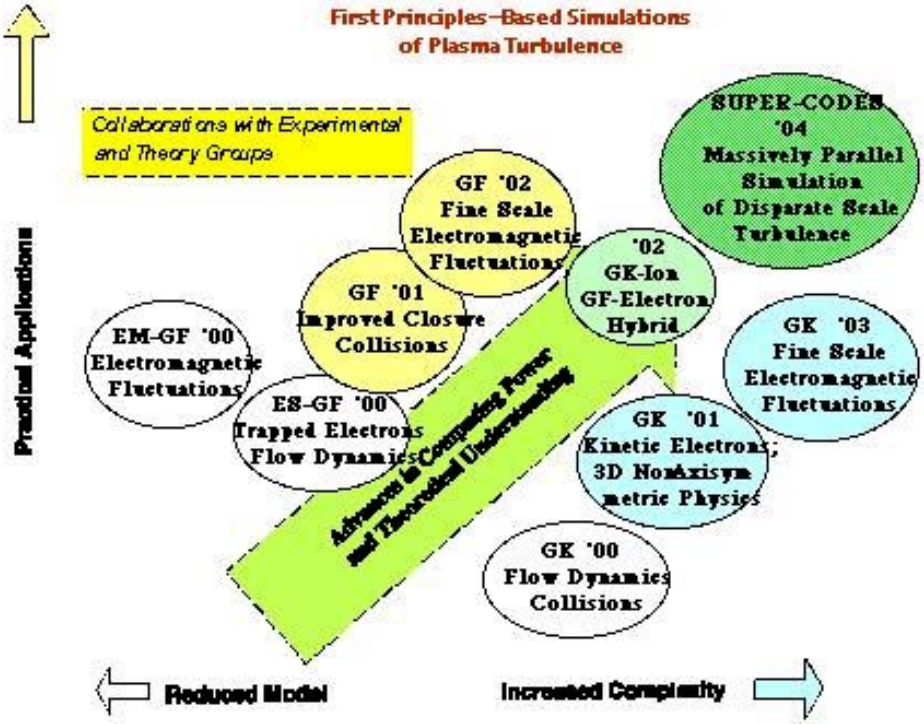


Fig. II. B. 1. High-Level Turbulence Milestones

If we face unexpected difficulties in advancing the electron dynamics capability in the gyrokinetic particle-in-cell code and in improving the gyrofluid closure for zonal flow damping accuracy and nonlinear kinetic

effects, we will explore the gyrokinetic ion, gyrofluid electron hybrid approach at the beginning of FY02 and this will become a leading candidate for the super-code. Otherwise, the super-code(s) which will be developed in 5 years will include the most promising elements of various approaches. Shown in Fig. II.B.1. is a roadmap of high-level milestones in the turbulence simulation area.

B.3 Pathways to Enhanced Confinement by Controlling Turbulence

Ex**B** shear suppression of turbulence is the leading paradigm for confinement enhancement. The well-known heuristic comparison based on the estimated **E**x**B** shearing rate and the linear growth rate of the most unstable mode, calculated from the comprehensive linear kinetic code or the gyrofluid code using the experimentally measured profiles, has shown robust semi-quantitative agreement with the confinement enhancement observed in various experimental devices. The explicit inclusion of the **E**x**B** shear effects in the linear analyses via the comprehensive kinetic code and the gyrofluid code has exhibited a similar degree of success to date.

Neoclassical losses are generally more important in stellarators and spherical tori than in conventional and advanced tokamaks. Depending on machine parameters and collisionality, neoclassical losses can sometimes dominate anomalous losses. Also depending on which species' neoclassical particle loss is larger, the radial electric field in stellarator plasmas can have either sign. Since various forms of enhanced confinement regimes have also been observed in stellarators with a lot of similarities to those in tokamaks, we can get valuable insight in controlling **E**x**B** shear and turbulence by studying transport in stellarators.

Expected Deliverables

Macroscopic **E**x**B** flows will be included in both gyrokinetic and gyrofluid nonlinear simulations to study the transition to enhanced confinement regimes, and the simulation results will be compared to the experimental results [FY00]. (See section III on Programmatic Areas for details.)

Neoclassical physics (especially realistic assessment of ion thermal transport and bootstrap current) in spherical tori and stellarators will be studied via the GTC code [FY00]. These include separately calculating the nonaxisymmetric

part of the particle fluxes for more efficient and precise calculations of E_r in collaboration with Columbia [FY01].

Turbulent transport in stellarators and spherical tori will be studied via linear stability analyses by the FULL code which has been extended to alternate concept geometry [FY00], and the nonlinear gyrokinetic [FY01] and gyrofluid [FY02] simulations.

Collaborations with the macroscopic simulation community have been extremely productive as examplified in the gyrokinetic energetic particle-background MHD hybrid nonlinear simulations and the early work on stability and transport in reversed shear plasmas. One outstanding issue is enhancing performance of tokamak ERS plasmas which are often limited by MHD activity. Quasi-axisymmetry allows sustainment of toroidal rotation in stellarators in which MHD kink modes are expected to have favorable stability properties. Therefore, we can learn valuable lessons in pursuit of simultaneously achieving confinement enhancement and MHD stability from long term collaboration on quasi-axisymmetric stellarator research. This includes the generalization of the calculations on the **E**x**B** shear suppression of turbulence to 3-d geometry [FY02] as well as the various aforementioned nonlinear simulations and linear stability calculations discussed in Sec. III. C on the Stellarator Theory program.

The expected high β and ρ^* values in spherical tori make the coupling between the drift wave type fluctuations (the sound wave branch in a simple context) and the Alfvenic fluctuations stronger, and the distinction between them less obvious. The effects of various Alfven-eigenmodes in spherical tori on transport and Maxwell stress related to zonal flow generation will be studied in collaboration with experts on wave-particle interaction [FY 03].

The physics associated with high frequency waves has been further elucidated by the recent development of high-frequency gyrokinetics via Lie-perturbation theory. Extension of this work to the nonlinear regime and application to IBW-driven flows in reactor-like plasmas will be pursued [FY03].

Following the example of turbulent boundary layers in fluid flows, the mathematical analysis of submarginal turbulence, particularly in the presence of magnetic shear, will be well advanced [FY03]

B.4 Collaboration with Other Theory Groups

We will continue collaborations with other institutions on the following subjects which have in the past had significant impact in the MFE community.

Our gyrofluid simulations and FULL code calculations have in the past provided the nonlinear and linear physics basis respectively for transport models developed in collaboration with the University of Texas (IFS-PPPL model) and with GA (GLF-23 model) and with Lehigh University (Multi-mode-model) and these activities will continue.

The NYU team will extend our GTC code to diverted tokamak geometry to study L-H transition physics. Our global gyrokinetic simulation results from the GTC code will be analyzed by the LLNL team using a comprehensive diagnostic package as a part of the PSACI activity. Gyrokinetic simulation results from LLNL flux-tube codes will be compared to these results to critically examine the effects from profile variation and radially periodic boundary conditions.

Collaborations with IPP-Garching (Germany) and the University of Maryland on the study of electron collisionless skin-depth scale short wavelength fluctuations using a gyrokinetic continuum code will continue.

Collaboration with UCSD has led to the first application of the SOC paradigm to tokamak transport and research in this area will continue in collaboration with UCSD, ORNL, UAF and CEA Cadarache (France).

The theory of zonal flow generation in toroidal geometry is being investigated in collaboration with UCI and ENEA Frascati (Italy).

Our previous collaborations on gyrokinetic simulations have led to a strong gyrokinetic simulation program at JAERI and Yamaguchi University, Japan.

C. Wave-Particle Interaction/Energetic Particle Physics

FESAC Goal: Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.
5 Year Goal of Wave-Particle Interaction Physics: *Develop predictive capability for plasma heating, flow and current drive, as well as energetic particle driven instabilities, in power-plant relevant regimes.*

Our theoretical effort in the area of wave-particle interaction has been mainly in energetic particle physics, which has been developed at PPPL to understand the stability and confinement of fast particles in toroidal magnetic confinement devices. The main goal of energetic particle physics is to insure that super thermal ions (such as 3.5 MeV alpha particles created by Deuterium-Tritium fusion reactions, MeV ion cyclotron wave heated ions, and few hundred keV neutral beam injected ions) are confined well enough to transfer their energy to the thermal plasma, and do not create new plasma instabilities. Energetic particle physics issues need to be understood to insure the successful operation of a fusion reactor. The theory of energetic particle instabilities was initiated at PPPL in the 1980s and has been established as a new discipline of plasma physics, in addition to the traditional disciplines of fluid global MHD and the kinetic theory of microinstabilities, turbulence and transport. At PPPL we have established a basic modeling framework of energetic particle physics based on kinetic-fluid models with minimal modifications to the fluid (MHD) equations. PPPL's energetic particle physics group is now recognized as a world leader, and this expertise in energetic particle physics is being used in many collaborative activities within the fusion community. It is our intention to extend the energetic particle physics research to include ICRF physics which will address issues of RF wave propagation, power deposition and plasma heating, current drive, as well as the interaction of fast ions with RF wave field. The ultimate goal of wave-particle interaction research is to provide a theoretical foundation for understanding burning plasma behavior in magnetic fusion reactors involving physical processes of plasma heating, current drive, confinement and global stability. A roadmap of milestones in the wave-particle interaction/energetic particle physics area is shown in Fig. II. C.1.

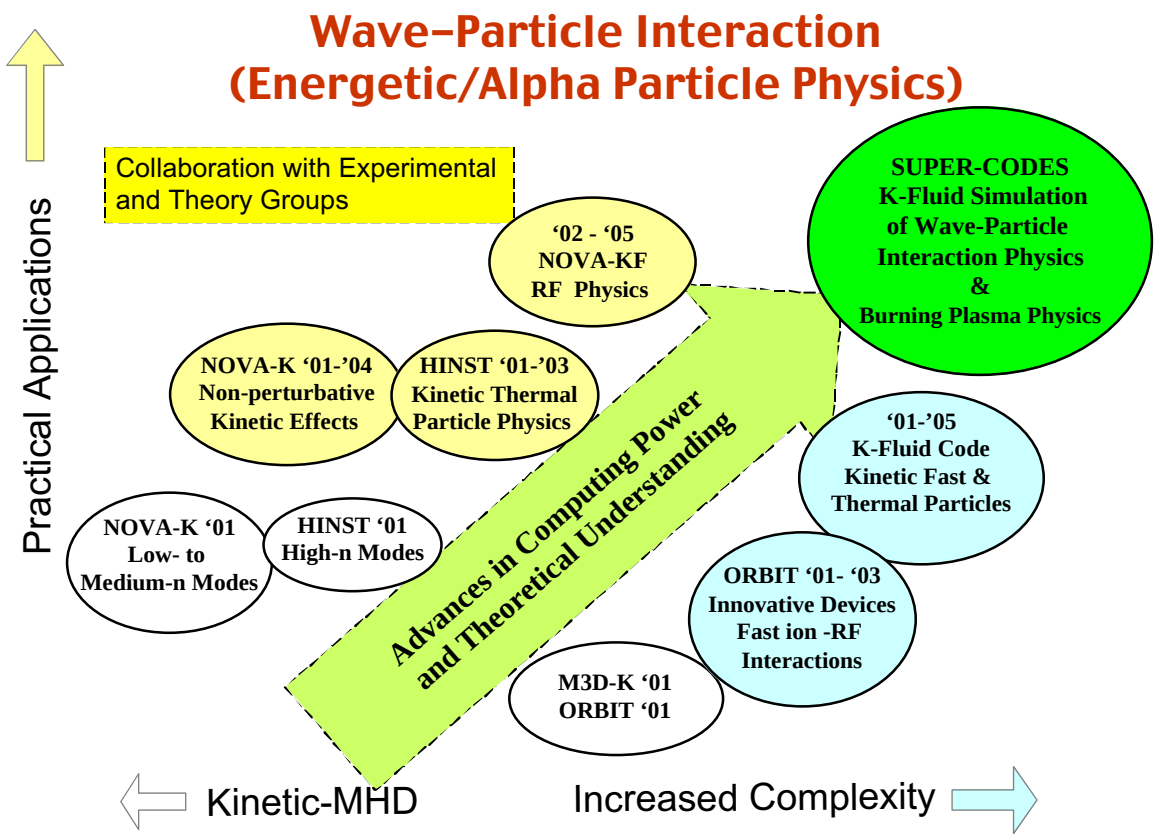


Fig. II.C.1 High Level Wave-Particle Interaction/Energetic Particle Milestones

To ensure proper understanding of energetic particle physics issues we have actively participated in collaborative joint experimental-theoretical programs on applications of fast particle physics in tokamaks, stellarators and other innovative magnetic confinement devices. The collaboration activity will be continued and strengthened in the future. Our past and ongoing joint experimental-theoretical activities include: study of TAE instabilities driven by ICRF minority ions, NBI ions and alphas in TFTR DT operation; collaborations 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; collaborations with the European Fusion Program, particularly for the DT operation in the Joint European Tokamak (JET); collaboration with experimentalists on applications in stellarators and innovative confinement devices such as NSTX, FRC, etc.; and collaboration with outside fusion research groups and universities - DIII-D, ASDEX, IFS, MIT, NYU, LHD, LAPD/UCLA, etc.

C.1 Key Research Areas

(a) Single particle orbits in toroidal confinement devices including systems with strong magnetic shear and spatial gradients (with ion gyroradii on the order of magnetic field shear and gradient scale size). The goal is to understand particle transport due to TF ripple and collision including vacuum field and separatrix, and MHD modes such as tearing modes, internal and external kinks, etc. We need to be able to control particle transport in advanced tokamak operation, ST's, stellarators as well as in other fusion devices.

(b) Collective fast ion/alpha driven instabilities (TAEs, fishbones, kinetic ballooning modes, sawtooth stabilization and fishbones, bursting modes in stellarators, Alfvén ion cyclotron instability, etc.) and their nonlinear behavior. The goals are to understand interaction of fast ions with n=1 internal kink mode in conventional tokamak operations with regard to sawtooth stabilization and fishbone excitation, fast ion/alpha driven TAE type modes (TAE, RTAE, KTAE, EAE, NAE, HAE, etc.), bursting modes resulting from fast ion/alpha interaction with interchange modes which have been observed in stellarators, and control of fast ion/alpha driven instabilities by varying q(r), n(r), and T(r) profiles.

(c) Fast ion/alpha transport induced by collective instabilities. This includes nonlinear saturation, bursting and frequency chirping behavior of collective instabilities; the role of resonance overlap in mode saturation and particle loss in present day and fusion scale devices; accurate prediction of the upper limit of fast ion loss expected in fusion scale devices.

(d) Particle interaction with RF wave fields. One goal is to understand fast ion/alpha loss due to RF waves and effects on plasma heating and current drive efficiency, Helium ash removal based on the idea of bucket transport by frequency chirping RF waves, as well as alpha channeling. We will also study ICRF wave propagation, power deposition and current drive, RF driven thermal plasma flow, and profile pinch effects.

(e) Integration of energetic/alpha particle physics with global plasma stability and confinement, auxiliary heating and current drive in burning plasmas. Interaction between alpha-particles and thermal plasma is a strongly nonlinear process and must be well understood. This processes involve heating and

current drive, alpha channeling, burn control, He ash removal, thermal instabilities, etc.

C.2 Highlights of Accomplishment

In order to properly address the key research areas outlined above, our efforts of analytical theories, numerical simulation and code development have been based on improved theoretical models. At present our simulation codes are mostly based on the kinetic-MHD model which includes fast ion kinetic effects self-consistently, but does not include thermal plasma kinetic effects self-consistently. To improve this model we have recently developed a new kinetic-fluid model by employing one-fluid equations (the mass continuity equation, momentum equation, generalized Ohm's law) with the plasma diagonal pressures and ion gyroviscosity tensor obtained from particle distribution functions. Different levels of kinetic descriptions can be adopted in modeling the electron and ion dynamics. In general, electron dynamics can be properly governed by the guiding center equation of motion. The ion dynamics can be governed by the gyrokinetic equation. However, for systems with ion Larmor radii on the order of magnetic field scale length it is necessary to employ the Vlasov equation. This kinetic-fluid model will be the foundation for our future code improvement efforts.

Several modeling codes have been developed: (a) equilibrium codes including ripple and vacuum field for tokamaks, stellarators, and innovative confinement devices; (b) the ORBIT code (a particle orbit following code) that can efficiently follow energetic particle orbit in the presence of complex magnetic perturbations and the extension of ORBIT code to include a delta-f scheme to study quasi-linear energetic particle interaction with MHD waves in tokamaks; (c) a family of NOVA codes (non-variational global Kinetic-MHD stability codes), which consist of a MHD equilibrium code, a resistive MHD stability code (NOVA-R), a perturbative NOVA-K code for TAE stability that treats energetic particle dynamics perturbativiely (which is correct only when the energetic particle density is much smaller than the bulk plasma density), and a non-perturbative NOVA-K code for studying non-resonant type TAE modes, sawtooth stabilization, fishbones, and kinetic ballooning modes in tokamaks; (d) the HINST code, a high toroidal mode number kinetic-MHD stability code for studying energetic particle related physics such as TAE instabilities and kinetic ballooning modes in tokamaks; (e) the M3D-K code, a nonlinear global kinetic-MHD Simulation code, based on the kinetic-MHD model that

includes low order thermal ion finite Larmor radius effects, as well as energetic ion gyrokinetic effects.

Based on theoretical models and simulation codes we have accomplished several critical areas of wave-particle interaction physics research (a) explanation of the observed "fishbone" instability and sawtooth stabilization by trapped ions in tokamaks; (b) theoretical discovery of the toroidicity-induced Alfvén eigenmode (TAE) for all toroidal magnetic confinement devices as well as theoretical prediction and experimental confirmation of TAEs in fast ion (and alpha) experiments in TFTR, JT-60U, DIII-D, and JET; (c) development of a theory of coupling among TAE mode, resonant-TAE (RTAE) mode and kinetic ballooning mode in the presence of energetic particles; (d) development of a theory of alpha channeling, which can potentially transfer alpha particle energy directly into thermal ions or current drive, instead of collisionally heating electrons; (e) development of a frequency chirping model for inducing non-stochastic, energy-selective transport of energetic ions; (f) development of 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 TAEs and kinks; (g) development of a nonlinear saturation theory of high-n TAE modes via ion Compton scattering process; (h) simulation of low-n TAE saturation via nonlinear wave-particle trapping.

C.3 Critical High Impact Research Areas and Plans

In order to further our theoretical understanding and modeling capability the following critical areas of research must be addressed. These research areas are most long term projects. The progress will depend on the level of manpower commitment. The milestones for these projects are based on the assumption of an increase in manpower over the present level.

(a) Single Particle Orbit Studies

We will perform (a) improvement of the ORBIT code for tokamaks with TF ripples including vacuum region with separatrix and fast ion interaction with RF wave field[FY01-03]; (b) development of a rapid test particle orbit code for stellarator optimization [FY01-03]; and (c) study of the effects of small non-axisymmetric magnetic perturbations on the confinement of alpha particles in JET DT operation, and comparison of these measurements with the ORBIT code [FY01-05].

(b) Fast Particle Driven Instabilities

We will perform (a) development of equilibrium codes including plasma flow, pressure anisotropy, ripple and vacuum field for tokamaks [FY01-03], stellarators [FY01-05], and other innovative magnetic confinement devices; (b) improvement of the NOVA-K codes (both perturbative and non-perturbative versions) based on the kinetic-fluid model to include more thermal and fast particle kinetic physics for tokamaks [FY01-03]; (c) extension of NOVA-K codes for non-axisymmetric toroidal devices [FY03-05]; (d) improvement of the NOVA-K code to include the effects of plasma flow and pressure anisotropy for both tokamaks [FY01-03] and stellarators [FY05 and beyond]; (e) improvement of the high-n TAE stability code, HINST, to couple with numerical equilibrium and to include thermal particle kinetic effects [FY01-03]; and (f) analysis of TAE modes and Alfvén ion cyclotron instability in NSTX including kinetic effects of both thermal plasma and energetic particles [FY01-05].

(c) Development of a General Nonlinear Kinetic-Fluid Model

We will develop an improved kinetic-fluid model for high β plasmas including plasma flow and large ion gyro-orbit physics for general 3D magnetic confinement systems [FY01-03] – foundation for improving NOVA-K and a 3D kinetic-fluid simulation code.

(d) Nonlinear Kinetic-Fluid Simulation Code Development

It is important to develop an improved nonlinear kinetic-fluid simulation code that incorporates the kinetic effects of both fast ions and thermal plasmas for axisymmetric toroidal devices [FY01-03]. Such a code is required to realistically study the nonlinear saturation fast particle driven instabilities and associated transport. Moreover, we will develop a kinetic-fluid simulation code for systems with large particle gyro-orbit such as NSTX or FRC devices [FY03-05]. Extension of the global kinetic-fluid simulation code for stellarators will also be pursued [FY05 and beyond]. The code optimization for MPP computers is also critical.

(e) Simulations of Fast Ion Physics

We will perform study of nonlinear interaction of energetic particles with MHD modes such as TAEs, fishbone modes, other bursting modes, and the associated energetic particle transport using the quasi-linear ORBIT code as well as the kinetic-fluid simulation code [FY01-05].

(f) RF Physics
We will extend the NOVA-K code to a global RF wave propagation and power deposition code for axisymmetric toroidal devices including ICRF Antenna or waveguide [FY02-04]. The code will be based on the kinetic-fluid model which includes full ion dynamics, multiple ion cyclotron resonance, wave-particle resonances, etc. We will also develop a 3D electromagnetic particle simulation code by treating electrons as guiding center particles and following full ion dynamics [FY02-05]. These codes will be used to study RF wave propagation, plasma heating and current drive as well as RF induced plasma flow and profile pinch.

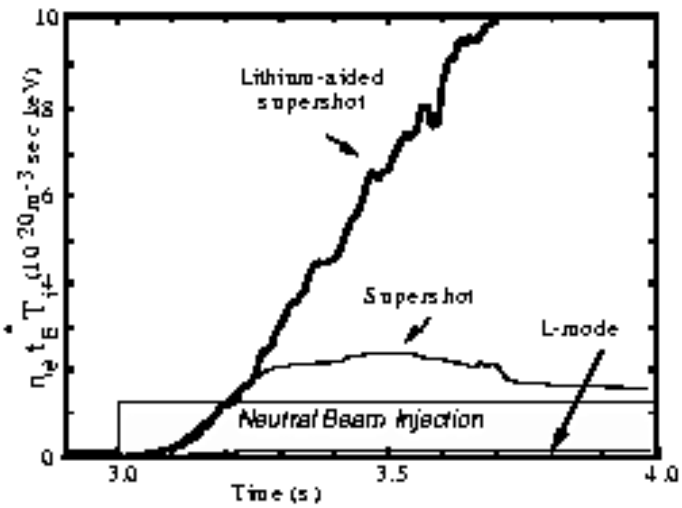
(g) Integration of Alpha and Thermal Plasma Physics in Burning Plasmas
We will study alpha driven instabilities and alpha transport in reactor plasmas by considering alpha heating of plasma and profile control, Helium ash removal, RF wave-alpha particle interaction aimed at understanding the "alpha channeling" and "bucket transport" techniques, and nonlinear interaction of alpha particles with thermal plasmas that can affect global MHD stability and confinement, plasma heating, and bootstrap current. Eventually physics modules will be developed to couple with predictive codes such as TRANSP [FY05 and beyond].

(h) Joint Theory-Experimental Programs
We shall participate in joint theory-experiment research programs {FY01-05] such as NSTX research programs of fast particle physics and RF physics; collaborations with JT-60U group to study TAE stability, fishbone modes and sawtooth stabilization for 500 keV N-NBI and ICRF experiments in JT-60U including plasma flow effects; collaborations with JET group to study alpha-particle physics; collaborations with ASDEX group to study fishbone modes and sawtooth stabilization in ASDEX; collaborations with LHD group and other stellarator groups to study fast particle physics and RF physics; and collaborations with other domestic fusion research groups such as D-III-D, IFS, and MIT

D. Multi-Phase Interfaces

FESAC Goal: Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.

5 Year Multi-phase interfaces goal: *Advance the capability to predict detailed multi-phase plasma-wall interfaces at very high power – and particle – fluxes.*



•*Fig. II. D. 1. – The Kinetic-MHD Increased Complexity depended strongly on the material boundary conditions.*

The topic of "multi-phase interfaces" encompasses not only the regions of plasma - material interactions, but also the consequences of those interactions with the adjacent confined plasma. Figure II.D.1 compares the fusion triple product observed during three distinct modes of TFTR operation. In the L-mode regime, the graphite limiter and other surfaces are well saturated with deuterium. As these surfaces were heated during neutral beam injection, they outgassed and provided a steady edge source of neutral atoms and molecules. The "supershot" mode of operation came to prominence when it was discovered that desaturating, or conditioning, the limiter surface prior to the discharge led to vastly improved plasma performance. An even higher level of performance was achieved by injecting lithium pellets, coating the limiter surface with lithium. This coating served to even further reduce the deuterium and carbon influx into the plasma, resulting in greatly enhanced performance. One of the main challenges for multi-phase interface science is to understand this strong connection between the state of the material surface and plasma performance. The FESAC goals include predictive models of the plasma behavior. The results shown in Fig. II.D.1 imply that a truly predictive model will need to incorporate the surrounding materials as well as the plasma.

The changes in plasma performance exhibited in Fig. II.D.1 and observed in other high confinement regimes, such as H-mode, are driven by the physics of the outer 10% or so of the confined plasma, a region in which the impact of the nearby material surfaces can be directly felt. Studies of the plasma turbulence in these regions are still very immature. New experiments will help to rapidly

advance the theoretical models and drive interest in these topics. For example, Fig. II.D.2 shows turbulent filaments observed at the edge of NSTX. The structure and motion of these filaments will provide important constraints for theoretical models of plasma turbulence.

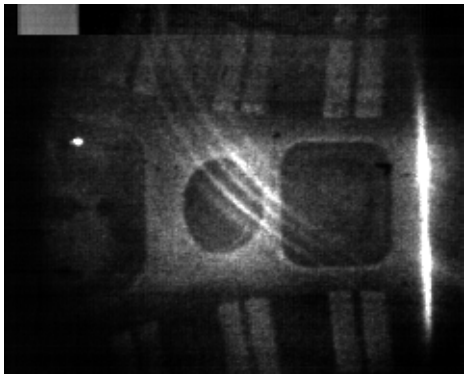


Fig. II. D. 2. - Turbulent edge plasma filaments observed in NSTX with the LANL fast visible camera (courtesy of R. Maqueda and S. Zweben).

The bulk of the boundary physics model development effort at PPPL has and continues to revolve around the DEGAS 2 Monte Carlo neutral transport code. During 1999, coupling between DEGAS 2 and UEDGE was effected and documented [Stotler et al., 1999 PET]. The coupled codes were subsequently used to model JT-60U and DIII-D (albeit in a non-iterative mode) by Takenaga [Takenaga et al., Nuclear Fusion]. Improving these simulation models will require the incorporation of sputtered impurity sources into DEGAS 2; this work will take place during FY-2000 and 2001. Additional data on the sputtering yields and on the hydrocarbon dissociation rates will be accumulated and put into a form appropriate for use in DEGAS 2.

The incorporation of a few minor improvements will permit DEGAS 2 to be coupled to the B2.5 plasma transport code (IPP-Garching) during the FY-2000 and 2001 time frame. In addition to expanding the DEGAS 2 user base, this step will permit comparisons, both in terms of physics and computational performance, between the coupled UEDGE-DEGAS 2 and B2.5-DEGAS 2.

New PPPL experiments with lithium surfaces will soon be undertaken in the CDX-U device. Modeling of these experiments with DEGAS 2 will help elucidate the physics behind the behavior demonstrated in Fig. II.D.1 The relevant data on lithium will be incorporated into DEGAS 2 during FY-2000 and 2001. Generation and collection of such data is currently being undertaken by participants in the ALPS program, such as the PMI group at the University of Illinois Urbana-Champaign. Because CDX-U is the only magnetic fusion

device in the US to work with macroscopic amounts of lithium, these experiments represent a unique opportunity to make DEGAS 2 the first neutral transport code to provide a predictive capability for future lithium experiments. This modeling effort will extend into FY-2002.

The impact of boundary conditions on tokamak performance, exemplified by Fig. II.D.1, is sufficiently strong that predictive models of those conditions need to be developed. However, the ability to diagnose those conditions in present devices is meager. New plasma-facing component diagnostics have been proposed for use on NSTX that will provide rapid, even real time data on the wall conditions. Once available, these data will be used to develop new models for the behavior of plasma-facing materials that would be coupled into DEGAS 2. In addition to providing information on wall conditions, these models would predict erosion and redeposition, essential for monitoring tritium accumulation in fusion reactors. The time frame for this work is FY-2003 and 2004, and will be strongly affected by the availability of relevant data.

The turbulence imaging experiments underway on NSTX and Alcator C-Mod will provide data that will be used to compare with the LLNL BOUT code (Xu). DEGAS 2 modeling of these experiments will also be performed to provide an understanding of the gross character of the emitting regions. The bulk of this work should take place during the FY 2000 and 2001 NSTX experimental campaigns. The result should be an evaluation of the accuracy of BOUT and an identification of possible improvements to it. Eventually, such a turbulence model would be incorporated into the edge plasma transport code UEDGE by LLNL. Likewise, the coupling of an edge plasma code to a core plasma code will be investigated by LLNL and others. The incorporation of DEGAS 2 into this model (FY-2003 and 2004) would result in a nearly comprehensive code for plasma transport simulation.

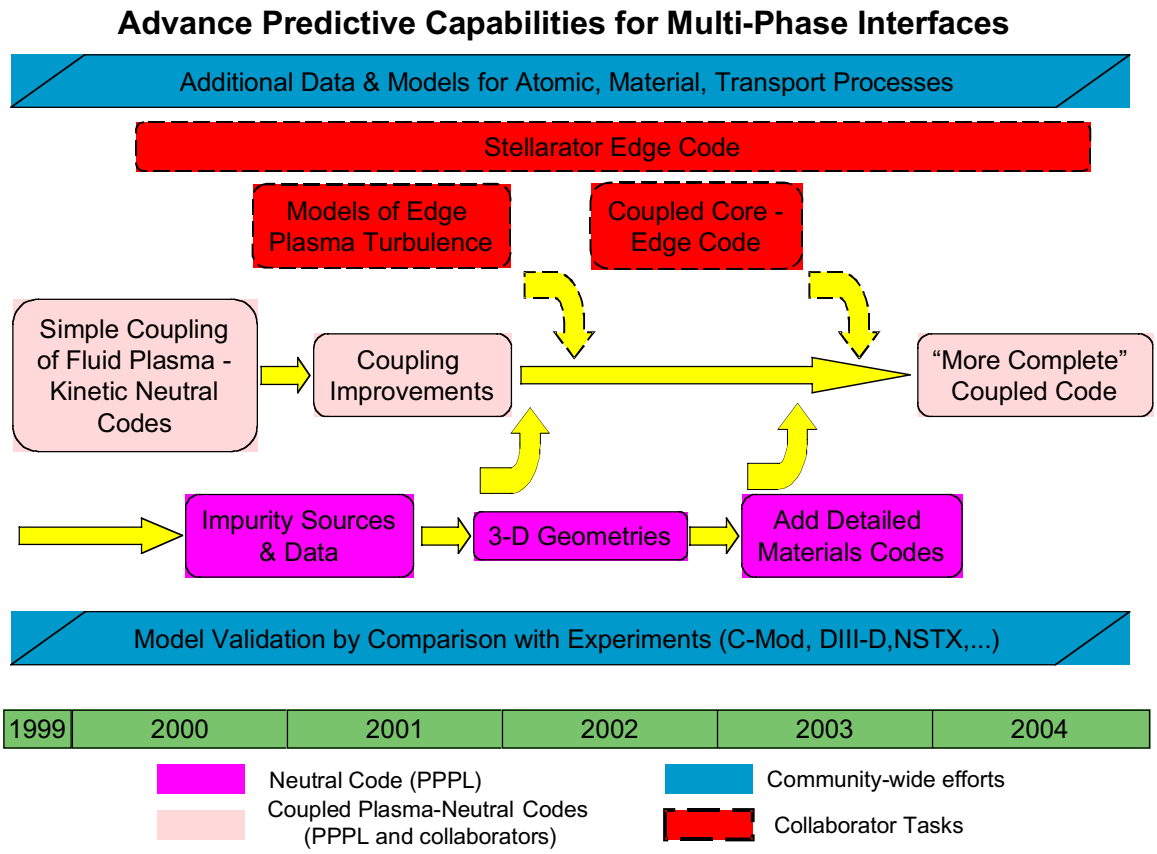


Fig. II. D. 3. Roadmap and High-level Milestones for Multi-Phase Interfaces

Simulating edge plasma and neutral transport in stellarators involves more than generalizing existing codes from 2-D to 3-D since the simplifying flux surfaces are replaced in some regions by 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. The PPPL Boundary Physics Science Focus Group will stay abreast of this development effort and will be prepared to begin using this code once it becomes a practical research tool. During this development period, the capability for simulating three-dimensional geometries in DEGAS 2 needs to be explored. Simple modifications to axisymmetric or translationally symmetric geometries will be examined first starting in FY-2001 and 2002. Techniques for succinctly and accurately describing fully three dimensional geometries will be developed for use in specifying input to DEGAS 2 in

conjunction with the NCSX and W7-X groups as well as with PPPL visualization experts (FY-2004).
The roadmap and high-level milestones for multi-phase interfaces is shown in Fig. II. D. 3.

E. Plasma Science Applications

FESAC Goal: Advance fundamental understanding of plasma, the fourth state of matter, and enhance predictive capabilities, through comparison of well-diagnosed experiments, theory and simulation.

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.*

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 heavy ion fusion, tritium production, spallation neutron sources, and high energy and nuclear physics applications; and the measurement of background neutral pressure and electron collision cross sections with neutral atoms and molecules.

Research on nonneutral plasmas and high-intensity accelerators at the Princeton Plasma Physics Laboratory (PPPL) focuses on two areas: (1) fundamental studies of nonneutral electron plasmas confined in a Malmberg-Penning trap, including the effects of electron-neutral interactions on plasma confinement and stability properties; and (2) analytical and numerical studies of the nonlinear dynamics and collective processes in intense nonneutral ion beams propagating in periodic focusing accelerators and transport systems. Particular emphasis is placed in determination of the class of beam distributions that can propagate quiescently over large distances; and 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.

E.2 Numerical Modeling of Low-Temperature Weakly Ionized Plasma

Applications of low-temperature weakly ionized plasma can be found in many branches of physics and engineering. Plasma etching devices in semiconductor industry, laser printers in electrophotography, and plasma display panels in flat screens are examples. As the devices become more and more sophisticated in these applications, fabrication costs for test facilities become prohibitively high. One possible approach to reduce such costs may be to develop a “virtual laboratory” that makes extensive use of numerical simulation models.

In all the examples given above, weakly ionized plasmas arising from breakdown in a high density neutral gas play an essential role in the process. In the case of electrophotography, for example, ions arising from the corona discharge at atmospheric air pressure are utilized to charge up the photoreceptor to form an image. The ion density and energy must be sensitively controlled in the device to optimize performance. For the case of plasma display panels, neutral atoms excited by electron bombardment emit UV radiation which excites phosphors for visual displays. Predicting plasma behavior in these applications is essential for the performance of the device. It is thus critical to develop numerical simulation models to predict gas discharge and gas breakdown in these devices before investing in expensive new facilities and equipment.

Macroscopic or continuum models and kinetic or particle models are used in many applications. Both types of models have advantages and disadvantages. It is proposed to develop a hybrid code in which particle electrons are followed in time while ions and neutral atoms and molecules are treated as continuum. The code is intended to simulate realistic devices in real-time operation. Various atomic processes leading to neutral gas breakdown, including excitation, ionization and dissociation are highly dependent on the electron energy bombarding the neutral particles. In the presence of a driving electric field for gas breakdown, it is well-known that the electron energy distribution deviates from a Maxwellian, forming a high energy tail. In addition, a large number of atomic and chemical reactions associated with the electrons, such as excitation, ionization, and dissociation, deplete the electron energy, creating holes in energy space. It is therefore important to follow the electron dynamics kinetically, e.g., as particles, rather than in fluid terms. Ions and neutrals, on the other hand, can be well described by a macroscopic continuum model because their energy distributions stay close to Maxwellian. It is therefore natural to consider such a hybrid model with particle electrons and continuum ions and neutral gas components.

E.3 Laser-Plasma Interaction Physics

ICF-Scale plasmas

The primary goal of this research is to develop techniques and codes for hybrid simulation which accurately describe the physics of the generation and transport of nonthermal particle distributions in high energy density plasmas driven by high intensity lasers and particle beams. The representation of such nonthermal distributions by a few velocity space moments is inadequate for many purposes, including determining the nonlinear saturation of laser-driven instabilities and preheat by energetic particles.

The approach used in this research is to apply and extend the nonlinear delta-f *(δf)* method to study the physics of inertial confinement fusion plasmas. The technique exploits the observation that, in many cases, the deviation of the distribution from a known, calculable, f_0 (for instance, a local, shifted, Maxwellian) although essential and nonlinearly dependent on the drive (laser and / or turbulent plasma electric fields) is small. The solution for the deviation $\delta f = f - f_0$ is accomplished by following the evolution of “marker particles” which

preferentially sample the essential "active" region of phase space. The advantages are that: (a) the bulk of the distribution is either prescribed through initial conditions or its evolution is specified in terms of a few moments, greatly reducing the number of computationally expensive marker particles which must be followed by the factor $|\delta f / f_0|^2$ (appropriately normalized); and (b) the inherent statistical rms noise for a given number of markers is reduced by $|\delta f / f_0|$ relative to a full particle-in-cell simulation.

A key research area continues to be the development of robust algorithms which account for the collisional coupling of δf back onto f_0 in order to close the hydrodynamic equations. This feedback appears in the form of additional source terms of energy and momentum in the moment equations.

Parallel efforts are maintained on the application and extension of delta-f techniques to simulation of laser-driven instabilities and micro-scale turbulence and to the transport of nonthermal distributions on macroscopic time and length scales.

LASER-DRIVEN INSTABILITIES

The goal of this research is to achieve a large reduction (~ factor of 100 vs. full particle-in-cell simulations) in the number of particles required to accurately represent the phase space dynamics. The saving in storage and CPU time could make the incorporation of these algorithms into three-dimensional macroscopic simulation codes such as F3D, developed at Livermore, feasible.

For simulations which follow the variation of field quantities on the laser wavelength scale, the storage limitations would then be determined by the fluid and wave variables. Thus, when the wave equations are solved directly, the maximum system size, for a $(1000 \text{ cell})^3$ system, should approach $100\ \lambda_{\text{laser}}^3$. The CPU expense of pushing the delta-f particles would not be expected to dominate the cost of advancing wave and fluid equations since the number of marker particles per cell is modest.

ENERGY TRANSPORT IN PLASMA WITH FINITE COLLISIONAL MEAN FREE PATH

Given a volumetric source of nonthermal particles in an evolving plasma, with finite collisional mean free path determining their transport under the influence of coulomb collisions with the background is a critical issue. If the fractional

density of such particles is small, the delta-f technique should provide an efficient technique to study their evolution.

Laser-plasma Interactions at Ultra-high Intensities and Plasma-based Particle Acceleration

Recent advances in laser technology have made lasers ever more intense, spawning the essentially new area of plasma physics of ultra-intense laser-matter interactions. This regime is characterized by relativistic energies of the plasma electrons. There are a number of practical applications envisioned for such high intensity lasers, including plasma-based particle accelerators and plasma-based radiation sources. Advances in inertial confinement fusion concepts, such as the fast ignitor, may be possible. Also, physical processes, common under astrophysical conditions, can now be explored in the laboratory. These include electron-position pair production, generation of gamma-rays, laser-induced nuclear reactions, and ion acceleration.

The foci of PPPL research in this area are on developing new paradigms for plasma-based particle acceleration as well as on the underlying physical processes of laser-driven plasma accelerators. These processes include: laser propagation in plasmas and plasma channels at high intensities; parametric instabilities; novel schemes for particle acceleration and injection using lasers and plasmas; novel methods for electron beam manipulation in plasmas, and laser-driven sources of coherent radiation. This research has important intellectual ties to ongoing activities on main campus, including experimental work in the Department of Mechanical and Aerospace Engineering on subpicosecond laser pulse propagation in plasma capillaries, and theoretical work in the Department of Astrophysical Sciences on the fast-ignitor concept and laser pulse compression.

E.4 Space Plasma Physics

The purpose of PPPL's space plasma physics program 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. Our 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 the MHD 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 last five years we have participated in the research in space plasma physics of magnetosphere, ionosphere and solar atmosphere. The highlights of our accomplishments and future plans are described in Section III.F.4. We plan to continue actively pursuing these areas of research.

III. PROGRAMMATIC AREAS

A. Tokamak Collaborations and Project Areas

A.1. Progress and Highlights

The PPPL theory group has a long history of advancing the understanding of the physics of tokamaks. In the absence of a large tokamak at Princeton, the group has transferred that expertise through collaborations with other institutions within the USA and abroad. The scope of collaborations includes; understanding the enhanced confinement regimes associated with internal transport barriers, the MHD phenomena related to these confinement regimes, feedback stabilization of external kink instabilities and fast particle effects.

There have been key contributions to development and application of the paradigm which explains the enhanced confinement observed in optimized shear discharges, i.e., suppression of turbulence is attributed to ExB shear. These include the analytical derivation of the ExB shearing rate in general toroidal geometry in collaboration with DIII-D, as well as the calculations of linear growth rates of microinstabilities in TFTR, DIII-D, JT60-U, JET and other tokamaks via the FULL code and gyrofluid code. Experiments in these regimes are known to be susceptible to violent beta limiting phenomena. Our analysis has contributed to the understanding of the pressure driven moderate–n instability, which is considered to play an important role, the infernal mode. Theoretical analysis has shown that the full benefit of these improved confinement regimes can be realized only if the external kink instability can be controlled. This instability manifests itself as the resistive wall mode in experiments and is also observed in other confinement regimes. The physics of the resistive wall mode, RWM, and methods of controlling it through feedback are a major area of collaborative research, in association with Columbia University and General Atomics. The theory group has a key role in

this area of research. The Princeton theory group has followed up its success in describing the fast particle effects in TFTR, by applying the same techniques to other devices. In particular the theory group has played a key role in studying TAE stability in JT-60U

A.2. Challenges and deliverables.

DIII-D and C-MOD
As indicated earlier, the major challenges are, understanding the turbulent behavior due to micro-instabilities and feedback stabilization of the resistive wall mode.
In FY ’00, we will continue efforts to compare the turbulent spectra obtained from gyrofluid nonlinear simulations with the BES measurements on DIII-D. A similar effort, in collaboration with the University of Texas, will be pursued on C-MOD. The RWM feedback program requires the development of many numerical tools. One of these is to incorporate a resistive shell and feedback in PPPL’s VACUUM code. In addition we will develop test cases to enable benchmarking of the feedback codes, VACUUM with Columbia University’s VALEN.
In FY ’01, we will search for the signature of zonal flows observed in gyro-kinetic simulations in the BES data. We will also try to undertake an experiment on DIII-D to make a dimensionless scan to understand the scaling with respect to ν^*. As the hardware for the feedback systems matures on DIII-D we will provide them with theoretical and modeling support for their experiments on the RWM as well as the neo-classical tearing mode. Another major deliverable in this year is a user-friendly GUI for PEST. This will be interfaced to the MDS-plus data tree. This will enable faster analysis of discharges on CMOD as well as DIII-D.

A.3 International Collaborations

The major challenges are related to advancing the understanding of turbulent transport, MHD behavior and fast particle effects in these devices.

On JT60-U, we will provide calculation of fluctuation spectra for comparison with JT60-U core reflectometry measurements. This will be based on equilibria consistent with the measured kinetic profiles. In the MHD area the main emphasis is on understanding the role of the external kink in preparation for

RWM studies. In the energetic particle area we will continue our support for their TAE mode analysis, FY ’00.
These measurements indicate a significant reduction of the radial correlation length of turbulence during formation of the ITB, total stabilization of ITG/TEM mode is not observed. This is in qualitative agreement with calculations by the FULL code and with nonlinear “decorrelation by ExB shear” theories. We propose to advance our understanding of the ExB shear effects, i.e., a distinction between stabilization and decorrelation. In addition to continuing analysis via FULL code, analytical calculations of radial correlation length will also be undertaken. Gyrofluid code calculations and comparisons to experimental measurements (of k-spectra and fluctuation levels) are also planned. In the MHD area, we will use the VACUUM code, with resistive walls, as a design and study tool for feedback stabilization. We will also participate in the design and analysis of their optimized shear experimental program, we hope to extend the fast particle studies to include, fishbone modes and sawtooth stabilization for 500 keV N-NBI and ICRF experiments in JT-60U including plasma flow effects in FY’01.
On JET we propose to continue to help with micro-instability analysis, linear and non-linear, the gyro-fluid code will be applied to a study of the ELMy H-mode. In addition we will complete our study of sawtooth stabilization by energetic particles, FY ’00. We propose a study that will focus on the role of impurities on the linear micro-instability spectrum; another study is intended to measure parametric dependencies of fluxes using the gyro-kinetic and gyro-fluid codes, including electron thermal transport. The selective inclusion of electro-magnetic effects will be used to test various theories. MHD stability analysis will include a study of the role of edge current density in triggering ELMs and feature an application of the hybrid MHD-kinetic code to the analysis of sawteeth, FY’01. A similar collaboration on sawtooth stabilization is proposed for ASDEX.

We propose to introduce turbulence diagnostics and visualization in the gyro-kinetic code. This will be used to model experimental data from the 2-d reflectometry measurements in TEXTOR, FY’01.

As the programs for the different devices evolve in future years, we expect that the PPPL participation will evolve in matching fashion. The main areas are expected to continue to be, improved confinement studies, and modeling of MHD phenomena and suppression of instabilities.

A.4. Next Step Options: Advanced Tokamaks and Burning Plasmas

One of the FESAC goals is to "advance understanding and innovation in high-performance plasmas, optimizing for projected power-plant requirements; and participate in a burning plasma experiment" with the corresponding 5 Year goal to " Assess profile control methods for efficient current sustainment and confinement enhancement in the Advanced Tokamak. Develop and assess high beta instability feedback control methods and disruption control/amelioration in the Advanced Tokamaks."

The most desirable advanced tokamak configurations rely on stabilization of the resistive wall mode. The work described in Section II.A.7 is directly relevant to this topic. However, steady state discharges that have other current distributions are also of interest. What causes the different type of observed ELM behavior? What is the role of line-tying on edge stability? We need to better clarify the MHD phenomena that limit the performance in the ITB and edge barrier. Models and theories need to continue to be benchmarked on DIIID, JET, and JT60U. We will continue to explore reactor implications of advanced tokamaks and other configurations.

Burning plasma experiments will by necessity have a large component of energetic particles produced by the fusion process itself. We are continuing to understand and assess the effects of energetic particle physics with regard to single particle orbit loss and plasma stability in burning plasmas. The background theoretical tools for this work are described in detail in Section II.C.

Disruptions arguably represent the greatest obstacle to the achievement of an attractive magnetic fusion reactor. There are two main challenges to the fusion research program: either to eliminate disruptions or when that is not possible to reduce/mitigate the effects of disruptions. The most desirable approach to the disruption problem is to eliminate disruptions entirely. A promising technique is to use the M3D code to predict what type of profiles are likely to lead to disruption if the ideal or resistive stability boundary is slightly exceeded, and to identify the relation of these studies with the experimental disruption data base.

Profile optimization via active regulation of the profiles should permit higher performance levels to be obtained while maintaining passive stability. Theoretical effort is required to calculate the optimized profiles. The major experimental and modeling issues involve the development of actuators for profile control (e.g. ECCD), and of real-time profile measurement. Real-time stability boundary identification is needed to trigger a secondary disruption avoidance feedback loop or to initiate a pre-emptive termination sequence. Again, the M3D code could potentially be a big asset in developing techniques in this area.

Even with successful implementation of an active feedback system, any device must be able to survive the worst-case disruption resulting from a failure of the feedback system. To achieve this, one must be able to predict the disruption forces and heat loads in future devices. We have been pursuing 2D disruption models based on TSC for years, and the TSC model was in fact the baseline disruption model for ITER. It is now becoming feasible to extend this model to 3D, based on the M3D code. As the capabilities of that code increase, we will increasingly use it to perform detailed modeling of disrupting plasmas and their interaction with surrounding walls and divertor structures. The 3D modeling will address such issues as non-axisymmetric halo currents and heat flux distribution, and 3D effects on runaway generation It will also provide a test bed for discovering disruption precursors and associated mitigation techniques.

We continue to develop innovative techniques for plasma fueling and ash removal, including inside pellet launch, Morozov's ring, and frequency sweeping, or bucket transport. We have begun modeling outside and inside pellet injection with our 2D and 3D MHD codes and comparing our predictions with experiment. The Morozov transporter ring is a current carrying metal ring that is magnetically insulated from the plasma electrons and electrostatically insulated from the ions. These can be used as a transporter of fuel into the plasma. Preliminary theory of this looks very promising. The bucket transport method also deserves more theoretical attention. It would benefit from a 3D modeling in the M3D code.

The PPPL Theory Division is in a good position to link all these considerations together to provide true integrated modeling of a Next-Step-Device. The basis for this integrated modeling now is the 2D Tokamak Simulation Code [TSC], linked together with the linear stability codes. In the future, this modeling will

be further integrated with edge modeling, energetic stability, and 3D nonlinear stability codes for an evermore comprehensive model.

B. NSTX Project-Related Tasks

B.1 Challenges

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 and increases the orbit size. 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. In particular there is a greater burden on the numerical techniques used to assess micro- and macro-stability as codes have to be modified and tested. Of particular importance in STs is the modification of the generalized (high aspect ratio) neoclassical effects both due to the large orbit excursions in STs and the higher fraction of trapped particles. Levels of neoclassical ion confinement, which may limit plasma confinement in enhanced regimes or at high densities, need to be assessed more accurately. Further the geometrical effects leading to enhanced stabilization of microturbulence, and the role of potentially high rotational shear, needs to be assessed further for a range of planned operating conditions, as well as comparing the expected theoretical results to data as these experiments are carried out. Also because of the increased trapped particle fraction and difference in velocity space distributions between low and higher aspect ratios, it will be important to incorporate kinetic effects into edge turbulence codes to assess more accurately the spectrum of edge modes and the effect of scrape-off layers.

Observations from both ohmic and auxiliary heated experiments indicate that plasma stability must be studied within the framework of both ideal and non-ideal MHD in order to explain the variety of MHD activity observed. This activity ranges from oscillatory and locking MHD to kinking modes to Internal Reconnection Events. Of importance in these calculations is assessing the effect that the close-fitting conducting shell (in NSTX) would have on plasma stability, and what the optimal electrical configuration would be for low-n mode stabilization and plasma control. One of the issues

important for STs is determining the strength of the Pfirsch-Schluter stabilizing term in assessing the virulence of Neoclassical Tearing Modes.

A more difficult issue relates to the formation of the discharge and the physics of controlled helicity injection, one of the major techniques used in NSTX. In order to make progress advances in understanding the fundamentals of reconnection physics is essential. TAE modes can potentially impact the confinement of beam ions, whose velocities are several times the Alfven velocity, and both the strength of the mode and the possible effect on fast ion confinement need to be assessed.

B.2 Expected Deliverables

FY '00
NSTX
1. Determination of neoclassical fluxes at representative 25% beta equilibrium. NSTX 25% beta (with assumed pressure, density, and temperature profiles) over a range of rotation speeds (Vphi = 0 Mach 1/3, Mach 2/3, Mach 1) to assess neoclassical ion and electron heat and particle transport coefficients and bootstrap current, and the effect of E_r on collisional cross-field and parallel ST transport.
2. Begin scoping to guide determination of fluctuation diagnostics on NSTX. Gyrokinetic calculation of fluctuation spectrum and turbulence-induced transport for NSTX, with and without "DC" electric field shear, for same 25% beta case (Mach 0 , Mach 1), when electromagnetic effects are able to be included. Identification of regions in k space most likely to be affected by flow shear, and portions of k spectra most responsible for transport.
3. In addition to planned applications of GTC, Gyrofluid, and FULL codes, there will be theoretical support for Probe-measurements (of Reynolds stress, Maxwell stress, and \alpha effects) proposal and [FY 01].
4. Ensure capability of stability analysis codes to analyze NSTX geometry. Improve user friendliness of MHD codes, implement limited between shot analysis.
5. Support MHD analysis of NSTX discharges.
6. Explore stability limits determined by current and pressure profiles through analysis of model profiles as well as the experimental data.
7. Study the effect of current ramp-up on stability.
8. Start modeling studies of CHI.
9. Initiate TAE scoping studies.
10. Start study of sawtooth and fishbone stability as NBI comes online.

FY ’01
NSTX
1. Continue (FY’00, #2).
2. Include kinetic effects and rotation profiles in gyro-kinetic calculations.
3. NSTX transport mechanism identification preparation. Study whether turbulence-driven and collisionally dominated plasmas have different dependencies on T_e, T_i, n_e that can be distinguished in an experiment?
a. Gyrofluid or Gyrokinetic scoping of dependence of fluxes on variations in background profiles by artificially altering input gradients to infer dependence of fluxes on T_e, T_i, n_e).
b. Similar variations to determine dependence of neoclassical fluxes on background profile changes.
c. Turn on and off electromagnetic effects and see if temperature dependencies of fluxes change
d. H-mode pedestal widths. Are observed widths consistent with any particular H-mode pedestal predictions?
4. With the availability of NBI, high-beta stability analysis will become more important.
5. Use non-linear MHD codes to study internal reconnection events.
6. Study the resistive wall mode in high-beta regimes, and determine need for feedback.
7. Extend understanding of CHI.
8. Start non-linear resistive MHD analysis of experiments.
9. Continue study of sawtooth and fishbone stability at high beta.
10. Study TAE modes if observed in the experiment.

FY ‘02
1. Compare measured parametric dependencies of fluxes with GK and/or GF codes.
a. Include electron thermal transport.
2. Implement “virtual fluctuation diagnostics” in GF, GK codes.
3. GF, GK support of aspect ratio scaling studies between NSTX and DIII-D (analysis of fluxes, fluctuation spectra for plasmas with similar cross sectional shape, different aspect ratio).
a. Predictive work to help design experiment.
b. Analysis with experimental profiles to help interpret observed trends.
Support of collisionality scan experiments : GF and/or GK calculations of transport over a wide range of collisionalities, using NSTX profiles obtained in beta scan.

4. Support profile optimization analysis in high-beta regimes, determine parametric stability boundaries.
5. Assist in stabilization of the resistive wall mode.
6. Comparison of resistive MHD with experiment.
7. Study role of energetic particles on MHD.

FY ‘03
1. Fluctuation diagnostic simulation: Compare measured fluctuation spectra in NSTX core with predictions from GF, GK codes, using “virtual diagnostics” implemented in FY ‘02.
2. Initiate modeling effort using GF, GK codes to develop the physics picture of plasma dynamics observed with t >> tau-E. Use or begin to develop tools appropriate for study of transport dynamics (time-evolving kinetic profiles, including bifurcations).
3. Transport control tool development: Using measured profiles, if fluctuation-induced transport dominates, estimate requirements for developing flow shear externally (e.g. with RF) to reduce or suppress turbulence.
4. Support MHD stability analysis for high beta operation.
5. Examine real time stability analysis using stability database and/or fast analysis techniques.
6. Non-linear resistive MHD disruption simulation.

FY ‘04
1. 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.
2. Assist in steady-state high-beta operation. Assist in implementing feedback stabilization for the RWM.

C. Stellarator Theory Program

“A proposal for a CS [compact stellarator] program has been positively peer reviewed as a new PoP component of the U.S. program and is currently in the conceptual design phase. … The CS offers a potentially attractive fusion system by promising stable, disruption-free operation at very high power density but with very low recirculating power.” – FESAC “Summary of Opportunities in the Fusion Energy Sciences Program”, Nov. 1999.

FESAC 5 Year Goal: *Determine the performance of a large Stellarator in the areas of confinement, stability, sustainment and divertor physics through international collaboration.*

FESAC 10 Year Goal: *Determine attractiveness of a Compact Stellarator by assessing resistance to disruption at high beta without instability feedback control or significant current drive, assessing confinement at high temperature, and investigating 3-D divertor operation.*

C.1 Introduction

As described in the discussions of the MHD and transport physics focus areas in Sections IIA and IIB, the theory stellarator program addresses equilibrium, stability and transport physics issues in the context of a 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. Other physics issues being studied, such as neoclassical ripple losses and loss of equilibrium flux surfaces, arise only in nonaxisymmetric configurations.

Theorists are also working closely with engineers on coil design. As in coil design for tokamaks, physics issues arise in terms of plasma free-boundary equilibrium and control. In addition, sophisticated new mathematical algorithms are being developed to handle the complexities that arise in three-dimensional coil design, and theorists are at the forefront in developing these algorithms.

The developing physics understanding of three-dimensional configurations is integrated and applied in configuration optimization studies. The high dimensionality of the parameter design space makes this a qualitatively different activity from the design of axisymmetric configurations, relying heavily on the automated exploration of the available parameter space using numerical optimization methods. Because of the integrative nature of this process, it places a premium on having a team of physics experts who can work closely with each other and with an engineering design team.

The PPPL stellarator theory effort is being pursued in the context of several design studies. Over the past few years the focus has been primarily on the physics design of the National Compact Stellarator Experiment (NCSX).

Secondarily, the theory group is providing support for concept exploration level design studies in the US stellarator community. There is also an international collaboration component of the theory stellarator work that predates the NCSX project, and that can be expected to take on increasing importance as LHD begins to produce significant physics results. PPPL theorists will also be providing input to reactor systems studies for assessing the attractiveness of proposed stellarator reactor concepts. Over the long term, the stellarator configuration optimization effort will continue to fold in new computational techniques and new physics results, culminating in the design of next generation experiments beyond NCSX.

C.2 Applications to NCSX

Over the past few years, the PPPL theory stellarator effort has been carried out primarily in the context of the National Compact Stellarator Experiment (NCSX) design study. Building on earlier work by Nuehrenberg's group in Germany and by Garabedian at NYU, the design of an attractive plasma configuration for NCSX has required key innovations and tool development by the PPPL theory group. Methods have been developed for stabilizing ballooning, vertical and kink modes in quasi-axisymmetric configurations. Good ballooning stability properties have been produced by strong axisymmetric components of shaping, a unique feature of NCSX relative to other stellarators. A combination of externally generated shear and a nonaxisymmetric corrugation of the plasma boundary is used to provide stability to external kink modes even in the absence of a conducting wall. The NCSX design uses approximate quasi-axisymmetry to obtain desirable drift trajectories, and the GTC and ORBIT codes have been used to monitor the adequacy of the resulting neoclassical thermal and energetic particle confinement. The theory group has contributed significantly to the design of the NCSX coils, by developing an improved coil design algorithm that employs singular value decomposition methods and by developing an improved coil cutting method. The PIES code is being applied to evaluate the flux surface integrity of proposed designs, and is being benchmarked against flux surface calculations with the M3D code [FY00].

The NCSX Physics Validation Review [FY01] will require improvements in coils, and in our ability to calculate flux surfaces. New techniques are being developed to aid in the design of simpler coil sets which are sufficiently flexible to produce a range of interesting stellarator configurations. To address the surface issue, bootstrap effects are being incorporated in PIES, and the

algorithm for calculating free-boundary equilibria is being improved. The free-boundary PIES code will be used to help guide the design of a coil set that can produce the reference design with good flux surfaces. It may prove desirable to also have a set of trim coils to control the flux surface integrity in a range of configurations, and PIES would be used in the design of these.

Improvements will continue to be made to the speed and user friendliness of the PIES code [FY01], to allow it to be used routinely by the engineering group to assess the impact of design choices on the flux surfaces. The design of the NCSX divertor will use PIES to calculate the structure of the magnetic field outside the last closed flux surface.

As the configuration design is finalized and the machine enters the construction phase, the theory stellarator effort will increasingly shift its focus to improving its computational tools for addressing the key stellarator physics issues. The tools will also be applied to help design experimental tests of fundamental physics issues to be addressed on the new device [FY02]. Key physics issues to be studied are: 1) Disruption avoidance. What MHD stability boundaries will the machine be capable of exploring? 2) Neoclassical suppression of magnetic islands. 3) Transport. What experiments should be done to demonstrate improved neoclassical transport? To obtain transport barriers?

When NCSX comes on line, the theory group will help to guide the experimental program, and to analyze the experimental observations.

C.3 Other Applications

The PPPL theory stellarator capabilities will also be applied to other domestic and international stellarator experiments, to non-stellarator experiments, to reactor systems studies, and to the design of post-NCSX experiments.

International collaborations are focusing particularly on LHD, and there are also active collaborations with the W7X group and with several existing smaller stellarator experiments. There are collaborations with LHD on applications of the FULL code to the calculation of linear kinetic stability and on applications of the PIES code to the calculation of magnetic islands and loss of flux surfaces. There has also been collaborative work on kink modes in LHD, and a new collaboration is planned on MHD beta limits in LHD. The FULL calculations are examining toroidal drift waves (trapped-electron modes

and ion temperature gradient modes), employing experimental density and temperature profiles and experimentally-reconstructed MHD equilibria. For the PIES LHD collaboration, a Japanese bootstrap code has been coupled into PIES to assess the effects of bootstrap currents on magnetic islands in LHD, and the Japanese HINT code is being benchmarked against PIES.

The PIES code is the centerpiece of an international collaboration in which German, Japanese, Spanish, and Australian collaborators are contributing to code development and applying the code to their experiments. Of particular interest to the W7X group is the application of PIES to analyze their divertor design, and this is motivating continued improvement in the free-boundary capability of PIES, in collaboration with the Germans [FY01]. In addition to the LHD and W7X groups, the groups associated with the TJ-II (Madrid), H-1 (ANU), and Heliotron J (Kyoto) experiments are also involved in the PIES collaboration.

The GTC code will be fully converted to stellarator geometry in FY01, and will provide a unique capability not presently available in the world stellarator program to help provide an understanding of turbulent transport in the large international stellarator experiments.

There are plans in the US national stellarator community to propose concept exploration scale devices in addition to the proof of principle scale NCSX device. There is a quasi-omnigenous stellarator design study that is centered at Oak Ridge, with participation by others in the stellarator community, including Princeton. There is a study centered at Auburn University aimed at designing the CTH device. The Princeton theory group will continue to provide key expertise and codes to aid in the design of these concept exploration experiments. We will aid in addressing issues of stability, magnetic island formation, and transport. The theory group will also participate in analyzing and interpreting the data from small domestic stellarator experiments.

There is also increasing interest in incorporating three-dimensional features to improve nominally axisymmetric alternate concepts. For example, there is interest in the RFP community in spontaneously generated "quasi single helicity" RFP plasmas. Also, externally generated transform generated near the edge of an RFP could be used to maintain field reversal and remove the reliance on the turbulent dynamo for this purpose. The use of nonaxisymmetric fields has been proposed in spherical toruses to provide volt-seconds during startup, and to provide stabilization of external kink modes.

The stellarator theorists at Princeton will serve as a source of new ideas for the fusion program, and will also lend their expertise in evaluating proposed applications of three-dimensional fields.

After the NCSX design is frozen, optimization will focus on developing an attractive QA reactor scenario. There has been discussion of a possible ARIES compact-stellarator reactor study, with some preparatory work in FY 2001, and a full-scale study in FY 2002.

The theory group will continue its development and application of optimization tools that have placed it at the forefront of the international optimization effort. The evolution of stellarator designs in the international program will be influenced by our improvements in theory-based modeling, and by our advances in understanding of transport and MHD issues obtained from analysis of experimental results from NCSX and other stellarator experiments. Assuming positive experimental results from NCSX, this will culminate in the design of a successor experiment to NCSX in the US stellarator program, and will influence the design of the next generation of advanced stellarator experiments in the world program.

D. Innovative Confinement Concepts

FESAC Goal: Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations:
5 Year goals: *Make preliminary determination of the attractiveness of the Spherical Torus, Reversed-Field Pinch, Stellarator. Resolve key issues for a broad spectrum of configurations*.

D.1 Theoretical Study of the Field Reversed Configuration

The Field Reversed Configuration (FRC) has attractive properties because of its simplicity and high beta, but it is well known to be unstable in the MHD limit. However, there is evidence that if operated in a regime where the ion-orbits are comparable to the size of the device, it is relatively stable. We have developed a unique nonlinear computational tool for studying this by modifying our 3D nonlinear MHD code M3D so that it represents the ions as

particles and the electrons as a fluid. It is very computationally intensive as it basically involves resolving the entire six-dimensional phase space for the ions. The initial results of this code are encouraging. For large enough ion-orbits, the linear growth rate is greatly reduced. We have recently found that there can also be substantial nonlinear saturation, and that under certain circumstances, a very long lived configuration can persist. We plan to further study and better understand this nonlinear stabilization and to make contact with relevant experimental results. As part of this investigation, we will study the dependence of this nonlinear saturation on elongation, conducting shell, rotation, energetic particles, profiles, and separatrix beta. We will also clarify the dependence of the nonlinear stabilization on the Lundquist number, S. In an extension to the present study, we will consider the effects of adding nonaxisymmetric equilibrium fields to the FRC in order to investigate the viability of creating a magnetic well configuration. In addition, we need to improve this hybrid code by porting it to a more powerful parallel computer, the T3E or SP-2.

D.2 Reversed Field Pinch Theory

The 3D nonlinear MHD code M3D will be applied to the reversed field pinch configuration to attempt to understand better the dynamics and scaling properties of this device. Among questions that we seek to answer are: What are the conditions for forming and maintaining a single-helicity state with improved confinement? What is the role of two-fluid effects? Can we reproduce experimental results for energy confinement by including pressure evolution including anisotropic heat transport. If so, this will allow a prediction of thermal confinement in simulations with current control via non-inductive current drive.

D.3 Theory of Tokamaks with Lithium Walls

The concept of a tokamak reactor with liquid lithium walls has many attractive features compared to a conventional tokamak. We will continue to develop this concept and to address critical issues in physics and technology. Among these are MHD stability and propulsion issues associated with the lithium itself, the stabilizing effect of the lithium on resistive wall modes, and the stability of the expected plasma configurations. Also of interest is the motion of the liquid lithium during plasma startup, and during off-normal events such as plasma disruptions. This activity will be closely coupled with present and future Lithium wall experiments on CDX-U and other devices.

E. Non-Magnetic Fusion Applications

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

E.1 Heavy Ion Fusion

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 heavy ion fusion. A major objective of the planned research 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 in transport systems. Another major objective is to identify and mitigate the effects of collective beam-plasma interactions in the target chamber, and the effects of electron-ion two-stream interactions in the acceleration and transport region when an (unwanted) component of electrons is present. A second major objective of the planned research, building on PPPL's considerable experimental capability, is to investigate the effects of multielectron loss events, develop techniques for preioinized plasma formation, and study collective beam-plasma interactions in the target chamber.

Under the auspices of the planned research, we will carry out a vigorous theoretical and computational program to investigate the influence of collective processes and nonlinear space-charge effects on the propagation, acceleration, and compression of heavy ion beams. Particular emphasis will be placed on the following task areas relevant to heavy ion fusion:

(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 [FY01].

(b) Investigate collective instabilities in intense heavy ion beams. Identify optimum beam distributions and parameter regimes for stable beam propagation [FY02].

(c) Investigate collective beam-plasma interactions in the target chamber. Identify operating regimes that mitigate the effects of instabilities [FY03].

(d) Explore mechanisms for halo formation through detailed comparisons between theory, simulation, and experiment. Identify regimes for halo-free operation [FY01].

(e) Apply the newly-developed 2D and 3D nonlinear delta-f-simulation schemes to augment and validate the analytical studies in (a)-(d) 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 [FY03].

At moderate beam intensities, the electron-ion two-stream instabilities in (c) and (e) above are also relevant to collective two-stream interaction in the high-intensity proton beams envisioned for the Spallation Neutron Source.

Under the auspices of the planned research, we will also carry out a vigorous experimental program, initiated in FY 2000, that makes use of PPPL's considerable experimental capabilities and off-site research facilities to investigate several critical problems related to beam propagation and beam-plasma interactions in the target chamber. These activities include:

(f) Development and application of rf techniques for formation of preioinized plasma in the target chamber. Experimental investigations of beam-plasma interactions.

(g) Measurement of multielectron loss events for intense ion beam propagation through background gas.

(h) Feasibility study of developing a heavy ion neutral beam driver based on the acceleration of negative ions.

This work will be closely coupled to the analytical and numerical activities described earlier in this section, particularly the beam-plasma interaction studies in (c) and (e).

E.2 Laser-Plasma Systems

1. ICF-Scale Plasma Simulations

LASER DRIVEN INSTABILITIES.

The aim of this research is to develop computational methods, which when implemented on MPP computers, will enable the investigation of macrosopic (NIF - scale) plasma including at the same time the interrelated and competing effects of (finite mean-free-path) transport and laser driven microinstabilities. In order to accomplish this, methods already developed by us for evolving the zeroth order distribution f_0 under the influence of macroscropic gradients and external forces will be extended to include the secular effects (heating and momentum deposition) due to the nonlinear evolution of microscopic turbulence associated with laser driven instabilities (including Brillouin, Raman, and self-focusing instabilities).

The first step will be to develop in two spatial dimensions a delta-f model, implemented for parallel architecture, which evolves f_0 under the influence of collisonal heating and transport. δf will initially account for all other (i.e., microturbulence) effects.

In the second phase, secularities associated with microturbulence will be removed from δf and injected as additional sources for the evolution of f_0. For ICF plasmas, the collision frequency sets a natural time scale for δf to f_0 coupling.

The initial simulations will be done on our local parallel computing PC cluster (PUFFIN). These resources are sufficient to investigate the physics of a single hot-spot (diffraction limited focal volume) in 2D. Larger scale 2D simulations, ultimately approaching the size of a whole laser beam should be achievable on ASCI size machines.

Extension and application of these techniques in 3 spatial dimensions will then be undertaken.

TRANSPORT OF NONTHERMAL PARTICLES.

Adding small spatial variation: The next step will be to apply the hybrid fluid-kinetic approach developed in a homogeneous plasma to a transport problem involving spatial gradients. In the initial studies, a high-*Z* plasma will be assumed, and the spatial variations will be reduced to one dimension in configuration space. Three new issues are envisioned with respect to our previous work: (1) grouping particles for carrying out collisions into space cells, small compared to the characteristic length of the system; (2) computing the self-consistant electric fields that will arise for maintaining return currents, ensuring quasineutrality; and (3) further improving for these more complex systems the most practical separation between the perturbed distribution and the background.

Weak spatial gradients: The spatially 1-D simulations will be carried out for weak of temperature and density variations. In this case, the background can be kept fixed, and the effort focused on the problem of collisions and self-consistent fields. This will permit a benchmark of results against previous numerical solutions of the linearized electron transport equations obtained for all regimes of collisionality.

Strong spatial gradients: In this stage, the code will be extended to include fully nonlinear spatial and temporal gradients of the background plasma. This model, which includes no details of the microturbulence, would be applicable to transport of nonthermal distributions over scales comparable to the plasma size. The corresponding results can be compared with previous, finite-difference solutions of the transport equation in one dimension.

2. Plasma-Based Particle Accelerators

Developing new paradigms of plasma-based particle acceleration is crucial for achieving the goals of high-energy physics: studying fundamental particle interactions at ultra-high energies. Achieving the energies beyond 1 Tev using the presently available accelerating techniques based on radio-frequency waves is expensive because of the limited acceleration gradients. The existing plasma accelerators, however, also fall short of providing high-energy small-emittance beams both because they require ultra-high intensity laser pulses which are subject to various laser-plasma instabilities, and because the propagation and acceleration distance is limited by laser diffraction.

Over the next five years, particular emphasis will be placed on the following research activities:

(a) Developing an analytical and computational description of the colliding-beam accelerator geometry (which employs two counter-propagating laser beams), addressing the issues of laser beam propagation, energy exchange between different laser beams, and longitudinal and transverse particle dynamics in the field of the resulting plasma wave.

(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.

E.3 Industrial Applications

Several projects are underway to help improve industrial processes and products.

1. CRADA with AMTEX Partnership

Supported by the Department of Energy's CRADA program, research is in progress at PPPL to develop a non-contact on-line optical and spectroscopic laser diagnostic instruments to probe synthetic fiber diameter, index of refraction and birefringence. The purpose of such *in-situ* diagnostics is to determine if the fiber diameter and birefringence are within the predetermined design values so that the production line can be stopped or adjusted immediately if the desired values are not obtained, rather than operating the production machinery for extended periods before finding the undesired products.

A laser scattering system has been set up at PPPL to study backscatter signals by a sample fiber provided by the industrial partners. In particular, intensity and the phase angles of the parallel and perpendicular components of the scattered lights are measured using four different wavelength He/Ne lasers. A large database containing scattering intensity and phase angle as functions of fiber parameters has been generated from numerical solutions of the electromagnetic wave equations. The measured values of the intensity and the phase angles are compared with these theoretical predictions to determine the fiber diameter, index of refraction and birefringence. A large number of samples, including DuPont fibers and optical fibers, have been tested and it has been found that the method gives satisfactory results.

So far only circular cross section fibers have been tested for which analytic expressions are available for the scattered laser light. The next step is to extend the method to a non-circular cross section fiber, and in particular to trilobal cross section fibers, widely used by the industry. The scattering laser system and the computer system, both hardware and software, will be tested on a factory floor during the summer of 2000 to demonstrate its feasibility.

2. Experiment and Modeling of Microplasmas.

Supported by the LPDA program, experimental research and modeling is being carried out on the basic physics and applications of microplasmas. These studies feature the integration of three key elements: (1) the development of innovative diagnostic techniques applicable to microplasmas; (2) the complementary development of actual device-scale numerical models that fully utilize modern massively-parallel processing supercomputing resources; and (3) the development of direct applications capable of demonstrating the positive impact of plasma science in areas of great interest to industry. Indeed, it is widely accepted that improved understanding of low-temperature plasma physics can significantly contribute to accelerated development of flat-panel display technology.

In general, experiments in the physics of highly-transient, collision-dominated microplasmas with pulse lengths less than ~1 μsec and dimensions less than a few hundred microns are particularly challenging. Measurement of plasma parameters such as ion and electron densities and temperatures requires development of new diagnostic techniques that can be applied to such microplasmas.

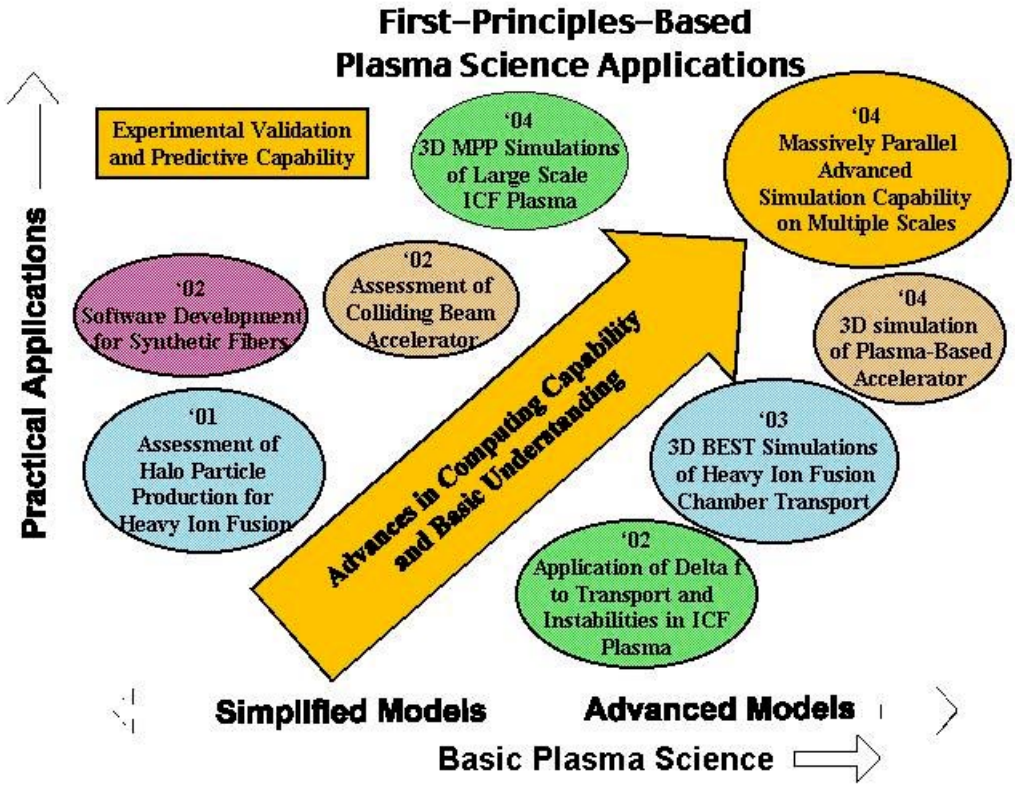
A CW Cavity Ring Down (CRD) interferometry system has been proposed to measure temporally- and spatially-resolved plasma density in microplasmas. This technique is derived from CRD spectroscopy, where the beam path length is significantly extended using a resonant cavity. New modeling techniques are required to simulate the microplasma discharges in real time. A new numerical technique called "particle clumping" is introduced which helps maintain the simulation particles nearly constant in the presence of rapid ionization.

The combination of laboratory studies and new numerical modeling techniques in this project is expected to significantly improve existing plasma display technology so that it can become a mainstream product in the High Definition Television (HDTV) market in a timely manner. Application to plasma lenses, spark-plug plasmas, and plasma switches are possible technological spin-offs.

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.



F*ig. III. E. 1. High-Level Plasma Science Applications Milestones*

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

E.4 Space Plasma Physics

Our 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 in the magnetosphere and the ionosphere. We have successfully applied our expertise in the magnetic fusion theory research to perform research in serveral critical areas of space plasma physics. The research experience in space plasma physics has also benefited our study of magnetic fusion plasmas. For example, the kinetic-fluid model which was originally developed for high β space plasmas is now being used in modeling energetic particle and wave-particle interaction physics in magnetic fusion plasmas.

1. Magnetospheric and Ionospheric Physics

The key research areas are to understand (a) quasi-steady structure of magnetic field, current density, plasma pressure, and plasma convection in the magnetosphere and the ionosphere under various solar wind conditions; (b) substorm dynamics: plasma sheet thinning during growth phase, substorm onset mechanism, substorm expansion and current disruption, plasma turbulence and transport, and eventual diplorization of the magnetic field; (c) energetic particle injection processes during substorms and storms; (d) kinetic effects on low frequency wave and instability phenomena and plasma transport in near Earth plasma sheet; (e) magnetosphere-ionosphere coupling processes: auroral arc formation and dynamics, particle heating and acceleration, the role of Alfvén waves and ion cyclotron waves and their sources and propagation; and (f) MHD wave activity, magnetic reconnection processes and plasma transport in the magnetosheath-magnetopause region under various solar wind conditions. Shown in Fig. III. E. 2. is a roadmap of milestones in the magnetospheric/ionospheric physics area.

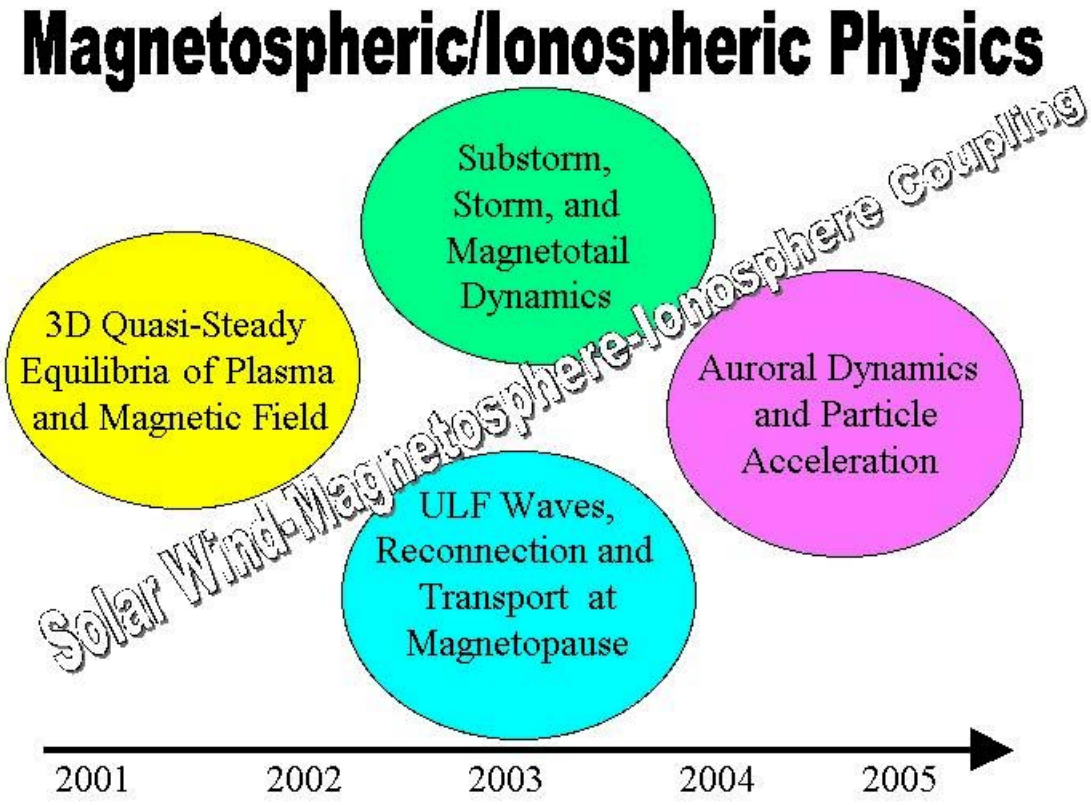


Fig. III. E. 2. High-Level Milestones in Space Plasmas

a. Highlights of Accomplishments

The following are highlights of recent accomplishments in the magnetospheric and ionospheric areas.

(a) Developed a three-dimensional quasi-static equilibrium code, MAG-3D, to compute the structure of magnetic field, current density, and plasma pressure. The present solutions provide a physical understanding of the generation of Region-2 field-aligned current flowing into and out of the ionosphere to cause diffuse aurora. The computed solutions can greatly improve the understanding of the satellite measurements of the magnetic field, particle flux, and plasma current.

(b) Developed a new scenario to explain the AMPTE/CCE spacecraft

observations of substorm onset and current disruption and the corresponding physical processes. By examining the AMPTE/CCE magnetic field and plasma data we found that toward the end of the late growth phase, the plasma beta increases to over 50 and a low frequency instability with a wave period of 50-75 seconds is excited and grows exponentially to a large amplitude at the onset of current disruption (previously called explosive growth phase). A new theory of kinetic ballooning instability taking into account effects of trapped electron dynamics and full ion Larmor radis 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 of 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 in low aspect ratio tokamaks such as NSTX.

(c) Developed a theory of MHD wave propagation, field line resonance and mode conversion to kinetic Alfvén waves to understand the satellite observation of low frequency wave activity in the magnetopause. The model explains the dependence of wave activity on interplanetary magnetic field (IMF) conditions (IMF angle and intensity with respect to the Earth magnetic field). The theory also explains the dependence of plasma transport across the magnetopause on IMF conditions.

(d) Proposed a particle transport and energization model to understand satellite observation of energetic electron and ion flux enhancement events at geosynchronous orbit (6.6 R_E) in the magnetosphere which have been observed in connection with substorms and storm sudden commencements. The particles are transported toward the Earth by an Eastward propagating electromagnetic pulse and are energized via Fermi acceleration mechanism because of the adiabatic invariance of particle magnetic moment. Our modeling results are consistent with geosynchronous satellite observation. The results suggest that the bulk of injected energetic particles arrive from distances less than 9 R_E which are more closer to the Earth than the values (larger than 15 R_E) obtained by previous models. Our results also suggest that the magnetic field dipolarization location during the substorm expansion phase might be at a distance as close as 10 R_E from Earth in the midnight sector.

(e) Developed a theory of electromagnetic ion cyclotron (EMIC) wave propagation from the magnetosphere to the ionosphere along auroral field lines. The theory resolves a decade-long controversy between the ray tracing theory and observations over the issue of how Pc 1 waves with frequency ≈ 1 Hz could be generated in the equatorial magnetosphere and be observed on the ground so reliably. The theory involves mode conversion of EMIC waves in a multi-ion species plasmas and the results demonstrate that EMIC waves are responsible for observed ion heating in the ionosphere.

b. Critical High Impact Research Areas and Plans

We will concentrate on the following critical research areas: (a) develop an improved 3D quasi-steady equilibrium code for magnetosphere-ionosphere for studying a global 3D magnetosphere-ionosphere structure of magnetic fied, current density, plasma pressure and flow under various solar wind conditions [FY01-02]; (b) perform a complete stability analysis of kinetic ballooning instability to understand substorm onset mechanism using realistic plasma sheet [FY01-02]; (c) collaborate with other space physics group with a 3D resistive MHD simulation code for simulating dynamics of solar wind-magnetosphere-ionosphere coupling processes [FY02-05]; (d) develop a 3D global kinetic-fluid simulation code for the magnetosphere-ionosphere [FY03-05]; (e) perform kinetic-fluid simulation of substorm processes and associated plasma transport, magnetic field diplorization, and energy dissipation and auroral dynamics in the ionosphere [FY05 and beyond]; (f) understand the origin and mechanism of Pc and Pi waves by examining low frequency instabilities such as ballooning-mirror instabilities and associated plasma transport in the plasma sheet, and perform correlation study between theory and satellite observations [FY02-05]; (g) study MHD waves, magnetic reconnection and plasma transport at the magnetopause based on realistic magnetopause geometry under various solar wind conditions [FY01-05]; (h) study ion cyclotron wave activity in the magnetosphere and ionosphere by investigating excitation mechanism, wave propagation and mode conversion processes [FY01-05]; and (i) study auroral physics involving field-aligned electric field and current, plasma convection, electron beams, ion cyclotron wave and Alfvén wave activity [FY03-05].

2. Solar Physics

The key research areas are to (a) study quasi-steady structure of magnetic field, current density, plasma pressure in the solar atmosphere under various photospheric boundary conditions; (b) understand prominence formation processes and the dynamics of prominence eruption; (c) understand corona heating mechanisms; (d) understand solar flare mechanisms and the properties of flares such as their homologous behavior; and (e) understand the physical mechanisms of solar coronal mass ejection and their relation with solar flares and prominences. Shown in Fig. III. E. 3. is a roadmap of milestones in the solar physics area.

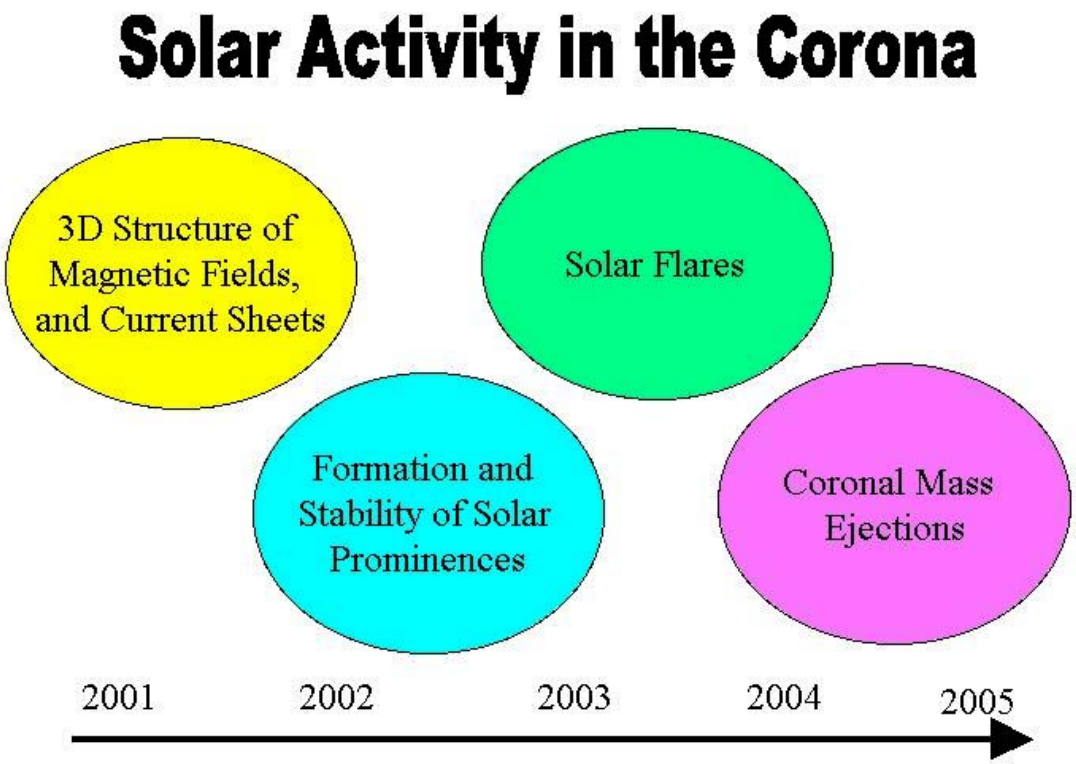


Fig. III. E. 3. High-Level Solar Physics Milestones

a. Highlights of Accomplishments

The following are highlights of recent accomplishments in the solar physics area.

(a) Studied current sheet and prominence formation mechanisms in quadrupolar field geometries. In particular, we have obtained a new current sheet configuration with a sharp downward-pointing tip hanging at a distance above the bottom boundary in the region between two bipolar arcades. Resistive magnetic reconnection in this type of current sheet results in a new field configuration with a magnetic island wrapped in dipped field lines similar to that proposed by Malville. An inverse polarity prominence can stably reside within the magnetic island.

(b) Developed a model describing physical processes of solar flares and their homologous behavior based on resistive MHD simulations of magnetic arcade evolution subject to continuos shear-increasing footpoint motions. In our model, we propose that the individual flaring process consists of magnetic reconnection of arcade fields, generation of magnetic islands in a magnetic arcade and coalescence of magnetic islands. The calculated reconnection electric field is large enough to accelerate electrons to a level higher than 10 keV necessary for hard X-ray emission. The model explains all three phases of flares: the preflare phase, the flash (impulsive) phase and the main phase. The model also properly explains the Yohkoh satellite observation of the two phases of soft X-ray plasma ejecta rising motion.

b. Critical High Impact Research Areas and Plans

We will concentrate on the following critical research areas: (a) develop a 3D quasi-steady solar equilibrium code which contains effects of plasma pressure and plasma flow and resolves chromospheric structure as well as solar wind [FY01-05]; (b) develop a 3D solar resistive MHD code that can realistically model long-term evolution of solar atmosphere including eruptive phenomena [FY01-03]; (c) study current sheet and prominence formation and eruption including magnetic reconnection and thermodynamic processes such as radiative cooling and heat conduction [FY01-05]; (d) study mechanism of solar flare, associated magnetic reconnection processes and magnetic field structure and heating mechanisms involving particle acceleration processes [FY00-05]; (e) study coronal mass ejection mechanisms by considering how to overcome the enclosure of arcade field and gravity [FY03 and beyond]; and (f) study coronal heating mechanisms by considering particle interaction with low frequency waves [FY02 and beyond].

F. CPPG Activities

The PPPL Computational Plasma Physics Group (CPPG) provides a home to develop advanced computational techniques 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 Dissemination, Modernization, and Integration

The CPPG promotes standards for the more widely used codes at PPPL, including those associated with code portability between platforms, good documentation, and standards of portable formats for associated data. Closely associated with this is our role in the National Transport Code Collaboration (NTCC) and its associated modules library. The CPPG maintains the modules library, which is an effective vehicle for "publication" and dissemination of standards, conforming codes, and code components such as modules and subroutine libraries. Codes submitted to this library undergo external review via the national NTCC Modules Library Committee. Another facet of this activity is to develop methodology for flexible interconnection of physics modules, e.g. MHD equilibrium, transport solver, and heating codes. This methodology and these standards provide a structure for collaboration at the codes level between disparate research groups at labs and universities. This is done now primarily for sequential codes, but we plan to extend it in the future to methods for coupling modules which employ parallelized algorithms.

F.2 Code Parallelization

The CPPG maintains most of the expertise at PPPL on parallel programming. It has taken on the responsibility of rewriting several of the major "Grand Challenge" scale vector codes to make them parallel and efficient. The major 3D MHD code, M3D, has been completely rewritten by the CPPG to be optimized to fully distributed memory MPPs. The new code, parM3D, makes use of the PETSc parallel scientific programming package, developed at Argonne as part of DOE2000. This portable parallel library offers a wide range of preconditioners and Krylov subspace methods, and allows the deployment of different schemes at runtime by a flag. The present parM3D

code has been shown to scale well with processor number, up to several hundred processors for sufficiently large problem size. However, to progress, we need to show that these codes continue to scale well to thousands of processors as the newest generation of massively parallel computers becomes available to us.

The major particle-in-cell code, GTC, is also being rewritten. Presently this code has a one-dimensional parallelization, in the toroidal angle. We are in the process in adding a second level of parallelization to allow the code to scale well to thousands of processors. Particle load-balancing techniques and the optimization of parallel communication that is used to perform gather/scatter operations are issues.

Several other major theory codes are in line to undergo major parallel upgrades, including the PIES 3D equilibrium code and the M3D-B hybrid code used for large FLR configurations such as the FRC. The ORBIT code which is a Monte Carlo code following particle orbits in complicated 3D magnetic fields, the DEGAS-2 code, the Breslau reconnection code, and several others have already been made parallel and are now in routine use as productions codes.

In conjunction with the software parallelization effort, the CPPG has constructed an Intel Beowulf cluster with 16 processors called Puffin. Most of our parallel applications that use MPI for communication run on Puffin, and we find it a useful development and production platform, particularly for the smaller applications like ORBIT. We are currently developing an Alpha Beowulf cluster, and may expand this substantially in the future.

F.3 Experimental Data Analysis

The CPPG maintains the TRANSP code, which is the most widely used tokamak data analysis code in the world. The TRANSP subgroup 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 for low-aspect-ratio equilibrium, and for modifications to the Monte Carlo fast ion model to include large Larmor radii, which are important in the high-beta configurations being pursued by NSTX. TRANSP currently operates on the 3 U.S. large toroidal experiments as well as at several foreign sites including JET (U.K), and JT-60 (Japan). For many of these sites

(including PPPL), virtually every experimental research paper makes use of analysis provided by TRANSP. Although primarily maintained at PPPL, the CVS code maintenance package allows joint code development with our remote partners.

F.4 Data Management

The software MDS+, developed within the MFE community, has been demonstrated as being an outstanding tool to unify data access. Presently, the experimental devices at General Atomics, MIT, and PPPL have adopted this software for their experimental data. The data analysis code TRANSP utilizes MDS+ to both obtain raw data from the experiments and to store its output for subsequent analysis.

We are now investigating the use of MDS+ to standardize both the input and output of the MHD modeling code parM3D (and we are coordinating with a similar effort on NIMROD, the other major 3D modeling code in our community). This standardization will greatly facilitate the comparison of modeling data with experimental data. Additionally, both experimental and theoretical researchers across the United States will be able to access this data to aid their research. The existing hardware solutions at the experimental facilities will be used to implement this data storage paradigm eliminating the need to purchase any hardware. Microsoft SQL Server 7 is being used in the experimental community to catalogue large experimental code runs. This system will be extended to allow tracking of runs by the two MHD codes that will be coupled to MDS+. Such a catalogue system will allow a rapid query capability of all runs made by the modeling codes resulting in rapid access to runs of critical interest.

We need to determine how the solutions we are proposing will scale to Theraflu computing. For data management and visualization this translates to the ability to deal with Terabytes of data. From a data management standpoint we propose to place MDS+ on the existing NERSC HPSS mass storage system to test performance. Data retrieval speed both within HPSS and across the ESNET will be quantified. We will also evaluate the remote visualization technologies being pioneered by DOE's Corridor One project. This study will insure that the MDS+/HPSS solution will scale to Terabyte datasets in the outlying years. Results of this study will help us to understand whether more efficient data storage, in the form of summary data and restart files, will be required. Alternatively, we may find that there exists an alternative storage

solution that will meet our performance requirements. For scientific visualization, we will test the new graphics tools against very large datasets to understand the limitations of our hardware/software solution.

F.5 Visualization

The CPPG is pioneering new plasma physics visualization applications. The use of the powerful software AVS is being promoted, and customized visualization packages are being 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 make use of the wall. Currently, parallelized rendering software is being developed to increase the speed of the display. The 9 computers that drive the 9 display wall projectors are being connected via Myrinet to provide a relatively high bandwidth Beowulf cluster that will be used to form the basis for real-time visualization of parallel applications.

In addition to these high-end tools, we are also developing tools in VTK and OpenDX for the routine analysis of multidimensional datasets from the 3D simulation codes. These open source products allow us to use non-commercial hardware (such as the high resolution display wall). These tools probe both field quantities (e.g., plasma pressure and magnetic potentials), phase-space quantities (e.g., phase-space scatter plots for particle component) and hybrid quantities (i.e., moments of the particle distribution). For high-end visualization of the largest data sets, we will begin to explore new techniques in distributed visualization and data manipulation, using client/server architecture.

F.6. Predictive TRANSP

As discussed above, the TRANSP code is one of the most widely used codes in the fusion program. However, TRANSP lacks certain predictive functions that would enhance its usefulness. A project began several years ago to make TRANSP into a predictive code, called P-TRANSP. P-TRANSP was never fully completed and implemented due to budget shortfalls and a staff downsizing concurrent with the completion of TFTR. We plan to reconstitute this activity by subcontracting with Lehigh to develop a modernized version of the P-TRANSP software. The Lehigh group is ideally suited for this activity

since key members of their present staff were involved in developing the original version of P-TRANSP in the mid 1990. This P-TRANSP software would become a NTCC module that would be reviewed by PPPL and installed in TRANSP.

F.7. Opportunities for Collaboration

One of the primary benefits of many of the CPPG activities is that they encourage collaboration in the fusion community. Through projects such as the NTCC, P-TRANSP, and the joint parM3D/NIMROD activity, the CPPG is promoting standards for code integration and maintenance of large working systems, and providing user support and documentation. This standardization makes it feasible for smaller groups, such as at Universities, to focus on smaller well-defined components such as specific physics modules to calculate neutral gas penetration, RF heating, or impurity radiation. These components can much more easily become part of larger packages such as TRANSP or P-TRANSP and be made available to the entire community.

IV. CONCLUSIONS

In carrying out its important role in the U. S. Fusion Energy Sciences theory program, the PPPL theory program has a well-defined objective and approach. The reliable prediction of the properties of fusion plasmas is a major scientific challenge. This is a task which demands both the *understanding* of complex physics phenomena impacting plasma performance and the *integration* of such knowledge into predictive models that prove superior to empirical scaling. The approach involves:

• Shorter-term objectives including the planning and interpretation of experiments on existing facilities, the design of new facilities, and pursuing scientific cross-cuts into other areas of research.

• Medium-term objectives including the development of innovative new tools for analyzing a wider range of phenomena with increased accuracy.

• Longer-term objectives including the generation of seminal concepts advancing basic plasma physics as well as fusion science.

These objectives support the major goals identified by the Fusion Energy Sciences Advisory Committee. Specifically,

• Advance *fundamental understanding* of plasmas through analytical and numerical studies.

• Help develop/optimize *innovative confinement configurations* and interpret experimental results with advanced theory/computational tools.

• Collaborate on analysis and planning of experiments for *high-performance plasmas.*

• Support the development of *enabling technologies.*

• Provide new theory/computational tools to aid development of efficient ion beam (*Inertial Fusion Energy*) systems.

In the pursuit of its objectives, the PPPL theory efforts emphasize accountability and partnerships in advancing plasma science. With respect to accountability, this program has a reliable track record over the years for producing seminal theories and reliable codes. As illustrated in this planning document, the goals are well-motivated with specified deliverables and associated time-lines. With respect to partnerships, the PPPL program will continue to place emphasis on sustaining productive research collaborations as well as developing new collaborative interactions with the theory community and with experimental programs.

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: Costing Plan and Budget Components

PPPL Theory Department
Five Year Costing Plan
(in $M)

	FY2000	FY2001	FY2002	FY2003	FY2004
Tokamak Theory	2.32	2.33	2.57	2.67	2.78
Alternate Theory	1.81	1.78	1.87	1.95	2.03
Advanced Computing Initiative	1.47	2.07	2.07	2.15	2.24
Total	5.60	6.18	6.51	6.77	7.05

Budget Components
(in $M)

	FY2000	FY2001	FY2002	FY2003	FY2004
Research Labor	2.38	2.76	2.88	3.00	3.13
Engineering and Support Labor	.39	.37	.37	.38	.40
Travel	.12	.15	.15	.16	.16
M&S and Other	.71	.75	.34	.35	.36
General & Administrative	2.00	2.15	2.77	2.88	3.00
Total	5.60	6.18	6.51	6.77	7.05

APPENDIX B: Staffing Plan

Theory Department
Five Year Staffing Plan
(in man/years)

	Research Staff				
	FY2000	**FY2001**	**FY2002**	**FY2003**	**FY2004**
Theory/Advanced Computing					
Macroscopic Stability	5.5	5.7	5.7	5.7	5.7
Turbulence and Transport	5.2	5.6	5.6	5.6	5.6
Wave-Particle Interaction/ Energetic Particle Physics	2.0	2.2	2.2	2.2	2.2
Multi-Phase Interfaces	.7	.7	.7	.7	.7
Plasma Science Advanced Computing	3.8	5.0	5.0	5.0	5.0
Management	.3	.3	.3	.3	.3
Total	17.5	19.5	19.5	19.5	19.5