PRINCETON PLASMA PHYSICS LABORATORY THEORY PROGRAM PLANS

DOE OFES REVIEW OF PPPL THEORY PROGRAM

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Princeton, New Jersey

1 June 2000

DISCUSSION TOPICS

- **Perspective & Goals**
- **Scientific Progress**
- **Future Plans**

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PPPL THEORY PROGRAM
Supports Goals Emphasized by FESAC

- **MFE 1: Advance *fundamental understanding of plasmas* through analytical and numerical studies**

- **MFE 2: Help develop/optimize *innovative confinement configurations* and interpret initial experimental results with advanced theory/computational tools**

- **MFE 3: Collaborate on the analysis and planning of experiments for *high-performance plasmas***

- **MFE 4: Support the development of *enabling technologies***

- **IFE: Provide new theory/computational tools to aid development of efficient ion beam (*IFE*) systems**

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PPPL THEORY PROGRAM
Has Well-Defined Target & Approach

- ***TARGET* --- RELIABLE PREDICTIONS OF PROPERTIES OF FUSION PLASMAS**
  - **<u>Scientific Challenge</u>*:* *Understanding* of complex physics phenomena impacting plasma performance & *Integration* of such knowledge into predictive models that prove superior to empirical scaling**

- ***APPROACH*:**
  - **Planning and interpretation of experiments on existing facilities; design of new facilities; cross-cuts to other areas of science *(shorter-term impact)***
  - **Develop innovative new tools for analyzing wider range of phenomena with greater accuracy *(medium-term impact)***
  - **Generate seminal concepts advancing basic physics as well as new ideas for confinement systems improvements *(longer-term impact)***

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PPPL THEORY/ADVANCED SCIENTIFIC COMPUTING PROGRAM
Emphasizes Accountability & Partnerships in Advancing Plasma Science

- ***ACCOUNTABILITY***
  - **Strong track record for producing seminal theories & reliable codes**
  - **Well-motivated goals with deliverables & associated time-lines**
  - **Steering Committee to facilitate productivity & communication**
    - **IFE & Non-MFE Plasma Science (Davidson); MHD (Jardin); Transport (Hahm); Waves/Energetic Particles (Cheng); Non-Axisym. Systems (Reiman); Laser-Plasma Interactions (Valeo)**

- ***PARTNERSHIPS***
  - **With theorists and theory groups, nationally & internationally**
  - **With experimentalists and experimental groups, nationally & internationally**
  - **With advanced scientific computing community**
  - **With technology development**

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PPPL THEORY PROGRAM
Addresses a Wide Range of Scientific Areas

- **Scientific Objectives have been identified together with expected deliverables over next two to five years**
  - **Consistent with Scientific Challenges highlighted in *FESAC Report on Priorities and Balance (8/99)***
- **Advanced Scientific Computing plays key role in all areas of research: (*cross-cuts* + *efficiency*)**
  - **MACROSCOPIC STABILITY**
  - **TURBULENCE & TRANSPORT**
  - **WAVE-PARTICLE INTERACTIONS (Energetic Particles)**
  - **MULTI-PHASE INTERFACES (Boundary Physics)**
  - **NON-MFE PLASMA SCIENCE (IFE, Space Physics, ….)**
- **High-level Roadmaps (examples of targeted deliverables & associated time-lines)**

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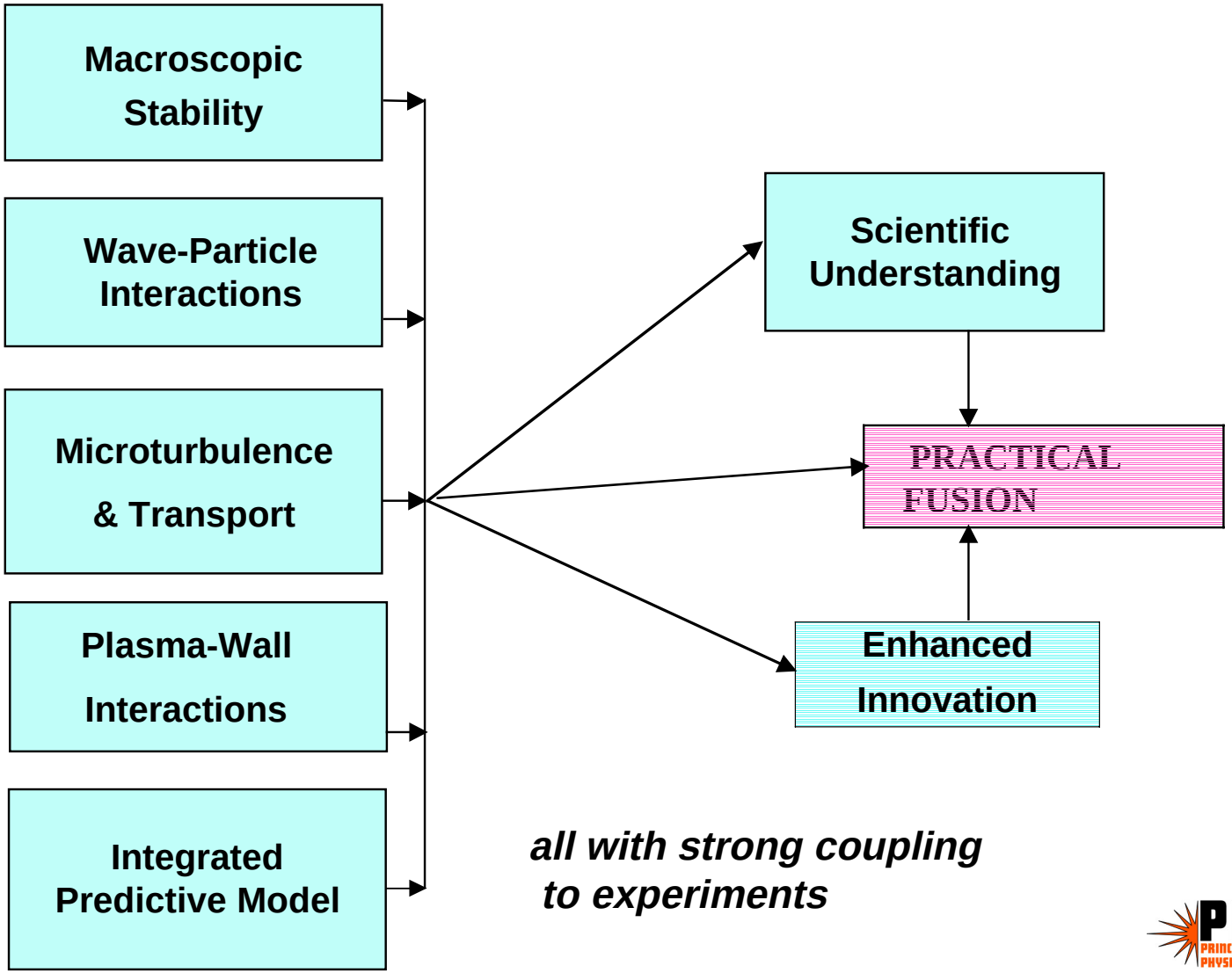
ROLE OF IT/ADVANCED COMPUTING IN MAGNETIC FUSION RESEARCH



all with strong coupling to experiments

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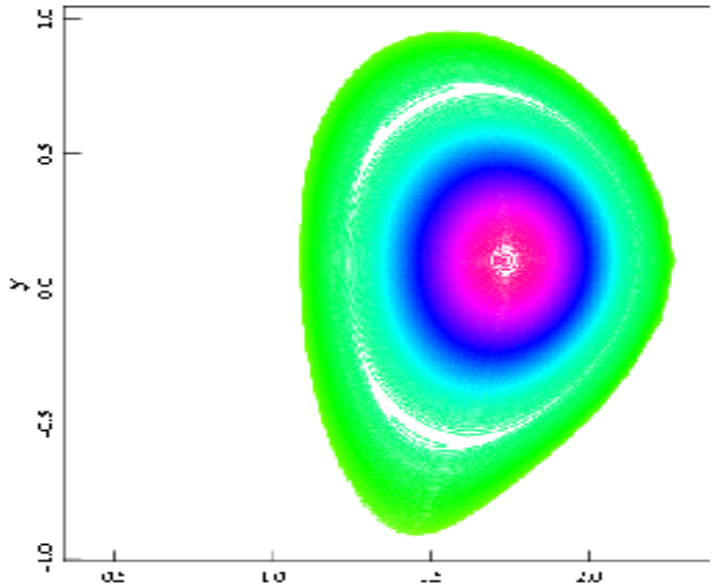
Neoclassical Tearing Mode (NTM) Analysis Capability



- **Self-consistent closure for Neoclassical Fluid Eq.'s being developed & applied to NIMROD and M3D**
- **Results to be cross-benchmarked & validated against experimental results**
- **Enable assessment of NTM impact on beta limit for long-pulse, high-performance tokamaks**

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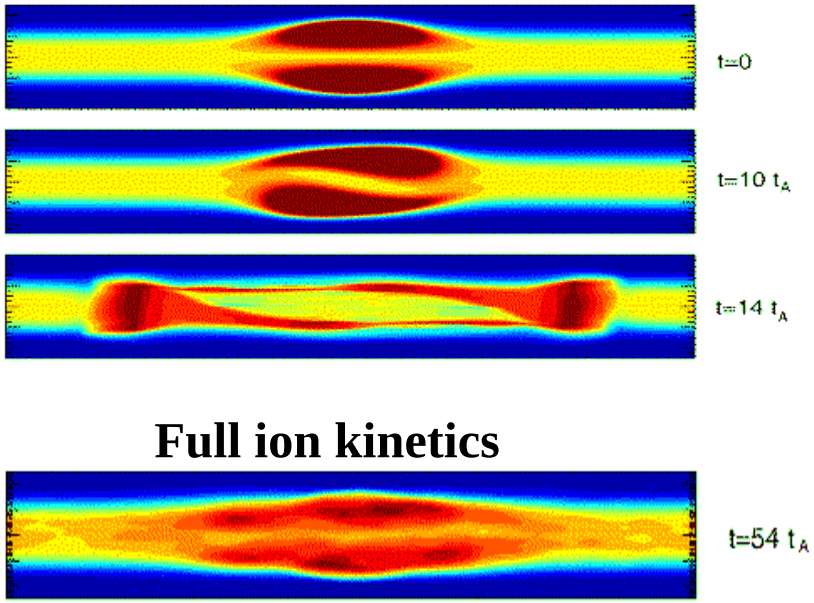
Innovative Confinement Concepts: FRC

MHD



Full ion kinetics

Comprehensive analysis of FRC stability now includes: *full ion kinetic effects* in addition to:

- **plasma rotation**
- **pressure distribution**
- **plasma elongation**
- **finite-size particle orbits**
- **axis-encircling particles**
- **open field lines**
- **nearby conductors**

Hybrid (fluid/kinetic) analysis demonstrating possible nonlinear kinetic stabilization of FRC

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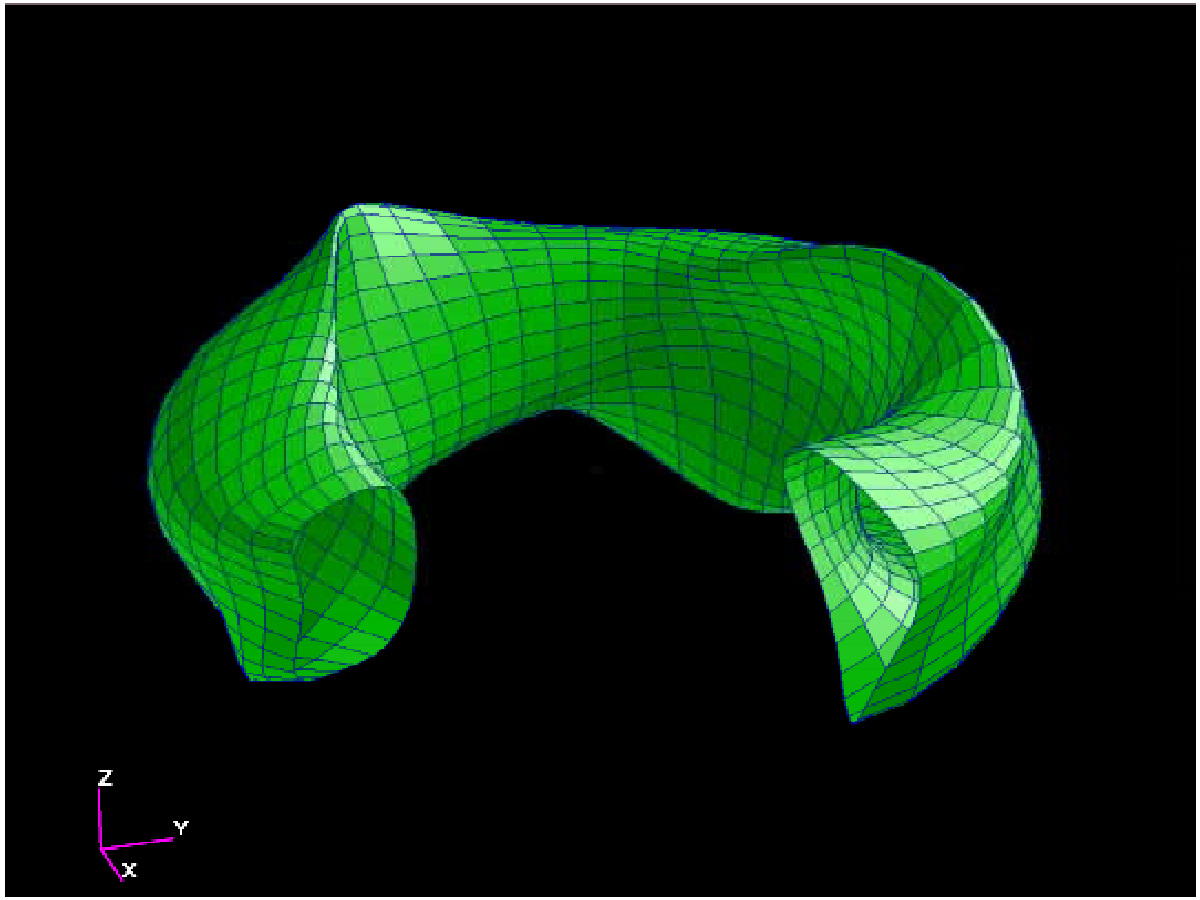
Stellarator Design Studies

Optimization of Stability, Transport, and Constructability



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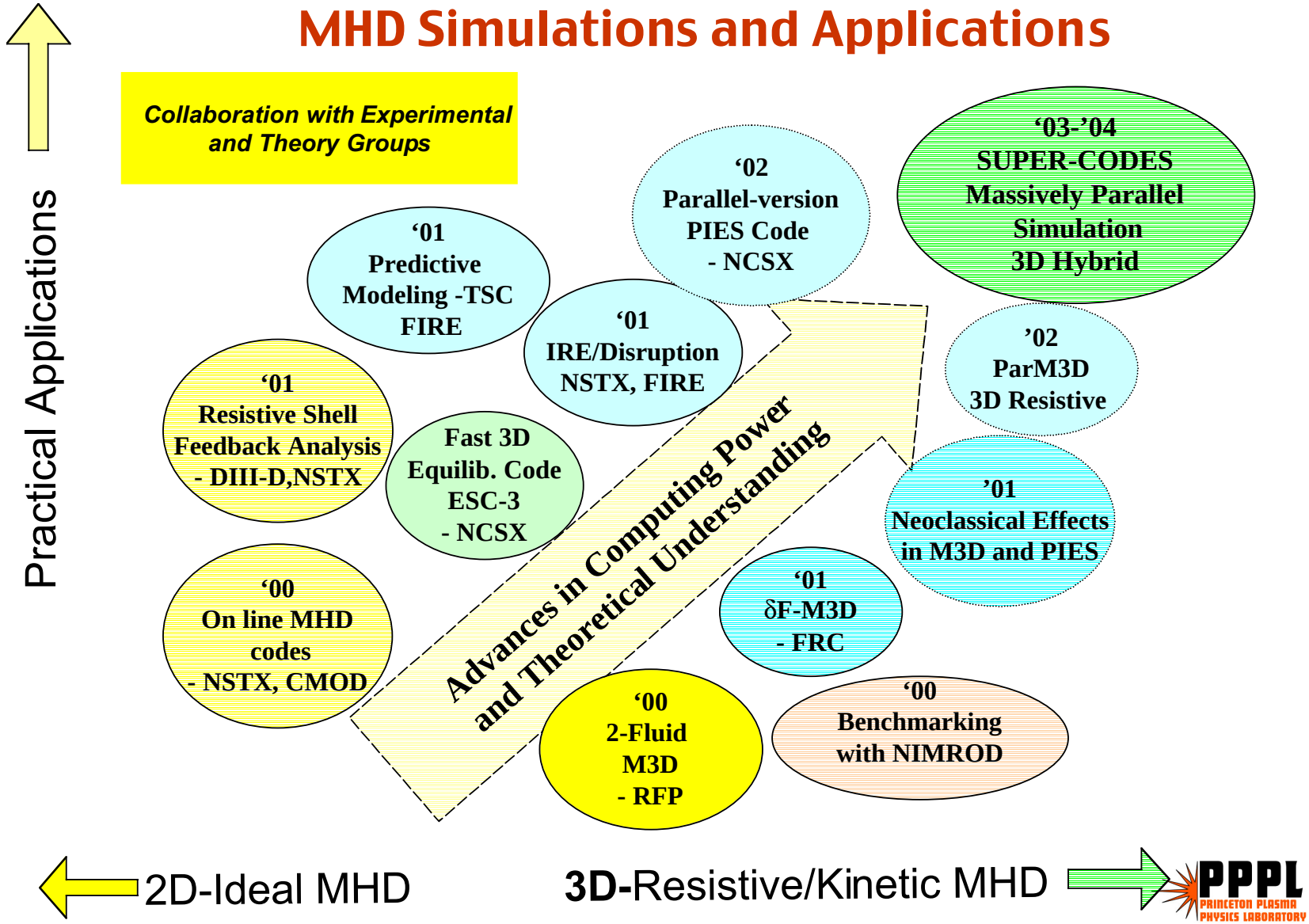
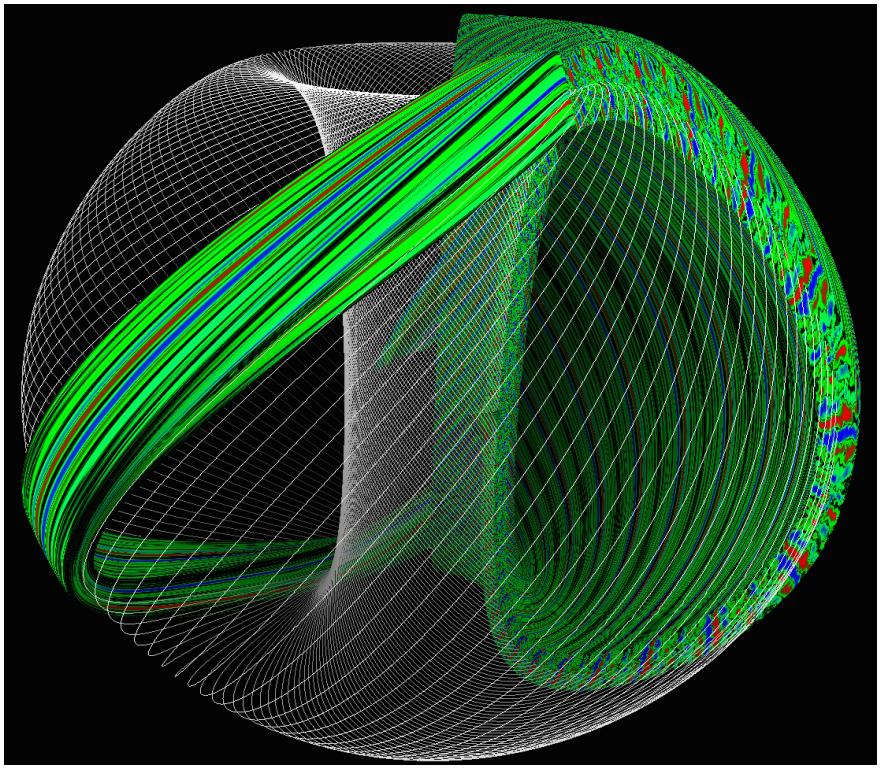
MHD Simulations and Applications



PLASMA TURBULENCE SIMULATIONS

- **Realistic Geometry**
  - **Full Torus (3D)**
  - **Flux Tube Codes**
- **Efficient Algorithms**
  - **Gyrofluid --- *Landau Closures***
  - **Gyrokinetic --- *PIC***
- **Demonstrated scaling to many processors**



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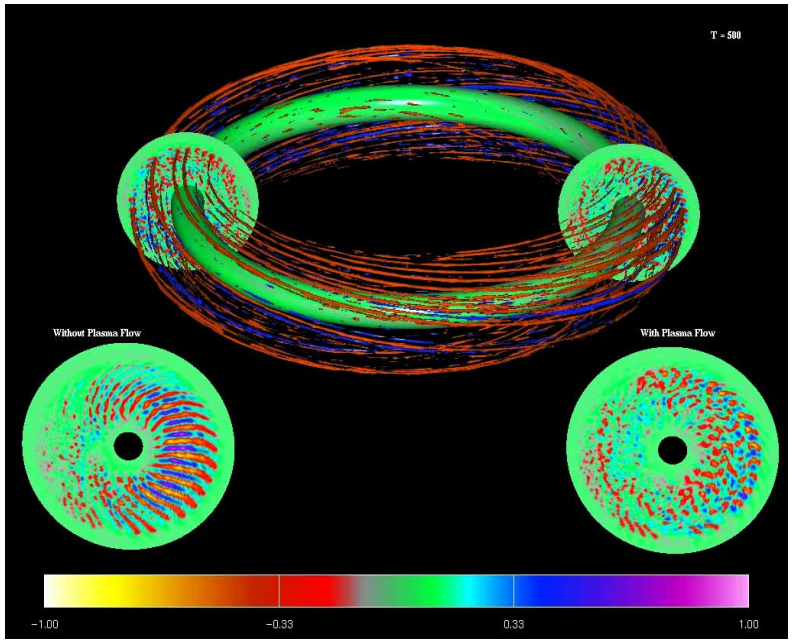
3-D TURBULENCE SIMULATIONS ON POWERFUL NEW MPP COMPUTERS

- **These exciting new simulations not feasible just few years ago**

- **Reduction of turbulence needed to keep fusion plasmas well confined**

- **<u>SCIENCE</u> Vol. 281, 1835 (Sept., 1998); <u>PRL</u> Vol. 83 , 3645 (Nov., 1999)**



- **Highly-dimensional data requires Advanced visualization: PU/PPPL Collaboration**

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3D Particle Simulation of Plasma Turbulence: Massively Parallel Computation

Turbulent Transport Reduction by Zonal Flows

Princeton Plasma Physics Laboratory
Princeton University

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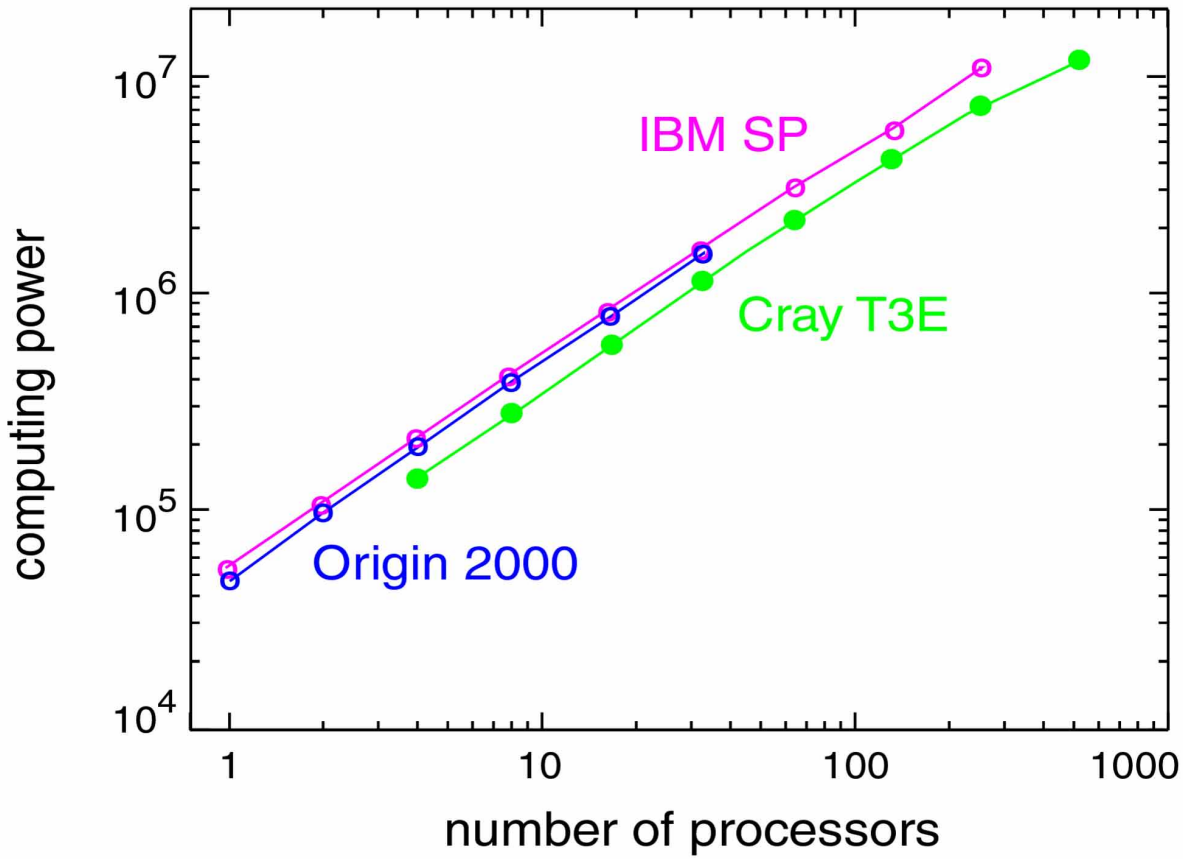
3D Gyrokinetic Turbulence Code (GTC)
Scalable on Massively Parallel Computers



- Y-axis: the number of particles which move 1 step in 1 second

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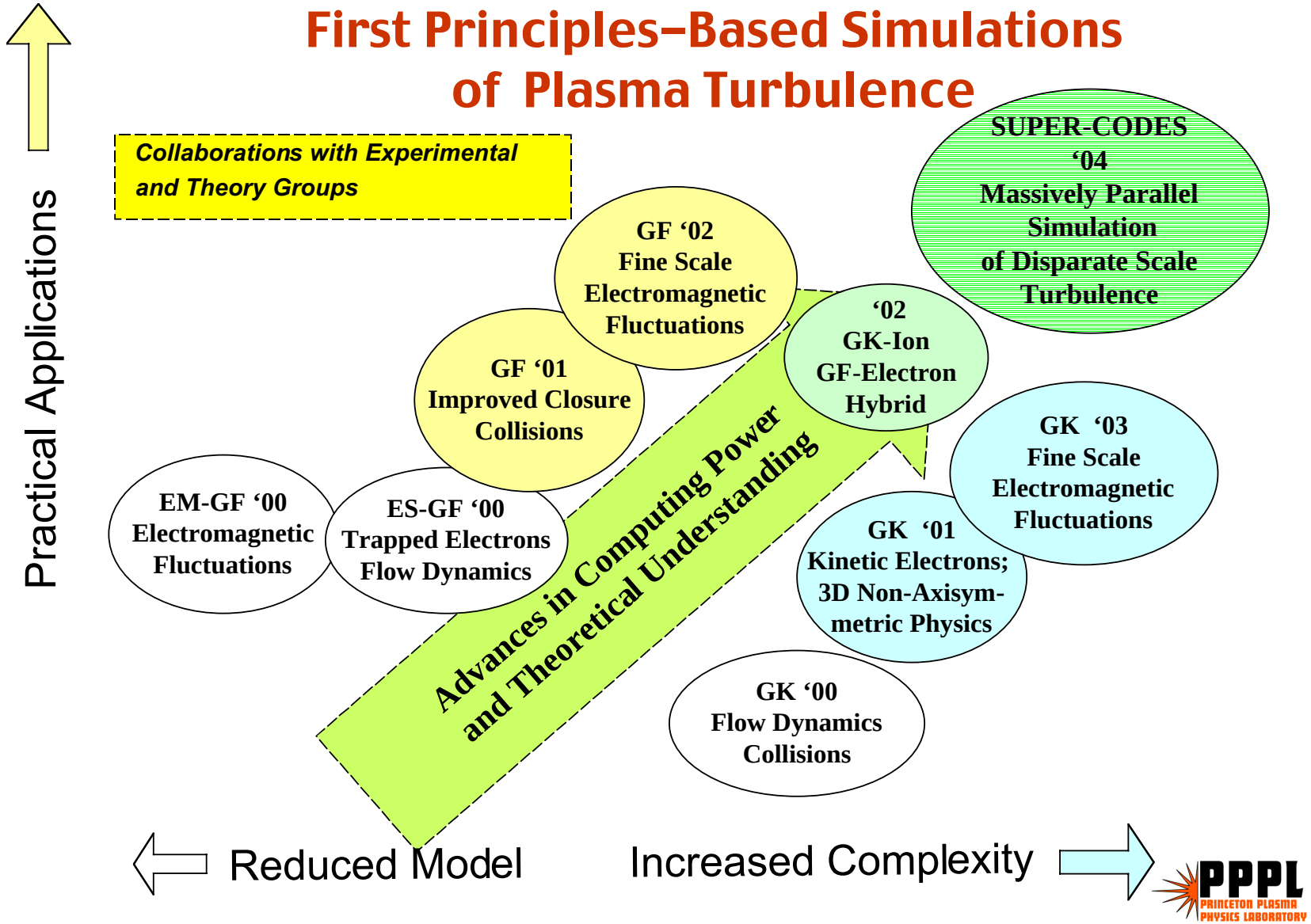
First Principles–Based Simulations of Plasma Turbulence



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OTHER PPPL THEORY RESEARCH AREAS

- Wave-Particle Interactions (Energetic Particles) -- e.g, seminal contributions such as TAE with strong theory/exp. Impact
- Boundary Physics (Neutrals Modeling) -- e.g., DEGAS-2 as powerful new tool for divertor/edge analysis with excellent MPP compatibility
- PPPL Theory plays key role in **Heavy Ion Fusion Virtual National Laboratory** (HIF-VNL) together with LBNL and LLNL.
  - lead positions in the HIF-VNL including Deputy Director (R. Davidson) and Deputy Head of Theory and Modeling (W. Lee)
  - Advanced analytical and numerical modeling of intense beam propagation and beam-plasma interaction
- Laser-Plasma Interactions -- for ICF & Plasma-based Accelerators {***Presidential Early Career Award for Scientists & Engineers*** to **G. Shvets**, April 11, 2000}

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Examples of "Theory/Theory" Collaborations

- High-impact results from sharing of state-of-art global GK code (*GTC*) to zonal flow turbulence suppression studies [Diamond (***UCSD***), Chen (***UCI***)] and also to divertor/separatrix dynamics [Chang (***NYU***)]
- Development & applications of 3D nonlinear resistive MHD code (M3D) [Strauss (***NYU***), Sugiyama (***MIT***); also cross-comparisons with ***NIMROD*** team
- Improvement of advanced stellarator assessment capabilities/tools [Nuhrenberg (***IPP-Germany***); Cooper (***Lausanne***); Nakajima (***NIFS, Japan***); Boozer (***Columbia U.***); Hirshman/Spong (***ORNL***)]
- Further development of Gyrofluid and GK-Continuum approaches to turbulence simulations [Dorland (***U. Md***.); Kotschenreuther (***IFS, U. Texas***); Jenko (***IPP-Germany***)]

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Examples of "Experiment/Theory" Collaborations

- Experiment/Theory investigations of shear-flow suppression of turbulent transport [K. Burrell (***DIII-D***) with T. S. Hahm]
- ICRF-induced rotation and ripple loss in Tore Supra [X. Garbet, et al. (***Cadarache***) with R. White]
- Collaborative development of RWM analysis capability for ***DIII-D*** with ***GA & Columbia U.*** [M. Chance -- @ ***GA*** for one year]
- Highly productive collaborations on international facilities (***JET, JT60U, LHD, ASDEX,*** ..) addressing Turbulent Transport (Rewoldt, Beer); MHD (Manickam, Monticello); Energetic Particles (Cheng, Gorelenkov, White); Boundary Physics (Stotler)

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PPPL THEORY PROGRAM
Has Strong Ties to Non-MFE Plasma Science and to Academic Community

- **NON-MFE RESEARCH** **including:** ***Space and Solar Physics (Johns Hopkins), Laser-Plasma Systems (LLNL), …..***
- **INDUSTRIAL APPLICATIONS** **including:** ***Plasma Display Panels (Sarnoff), Plasma Thrusters (PU), Accelerators (LLNL), Textile Studies (AMTEX) , ….***
- **EDUCATION** **including:** ***major Graduate Program/Postdocs/Visiting Scientists*** **-- impact of distinguished graduates/post-docs on community**

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PPPL has helped establish stature/visibility of Plasma Science in Advanced Scientific Computing community

- In response to OFES, PPPL has played a lead role in successfully establishing the ***Plasma Science Advanced Computing Initiative (PSACI)***
  - **Plasma Science Advanced Computing White Paper very well received by DOE Headquarters**
  - **Pilot Programs in Turbulent Transport and MHD Simulations received excellent peer reviews & were launched in FY'00**
  - **Active Program Advisory Committee (with distinguished members from outside & within FES)**
  - New DOE Office of Science Initiative for ***"Scientific Discovery through Advanced Computing" (SDAC)*** **----** FES has excellent opportunity to be prominent member of this broader scientific portfolio with access to significant new resources in SDAC program

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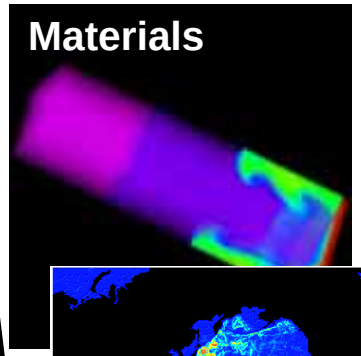
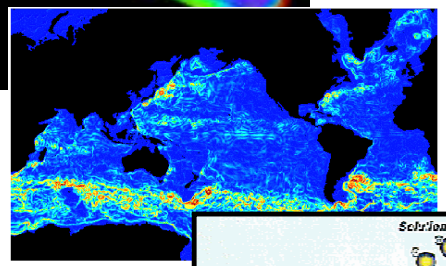
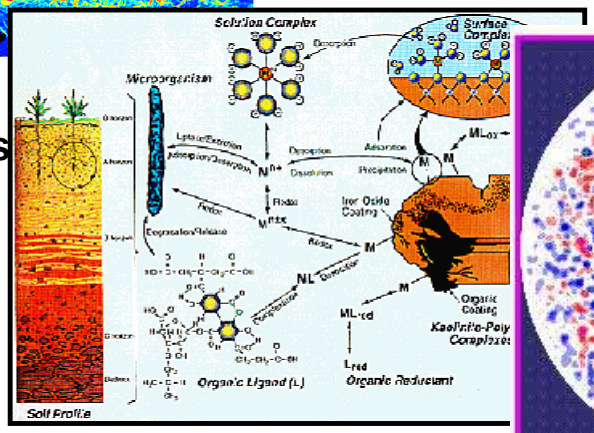
Key Elements of DOE Advanced Computing

DOE Science Programs Need Dramatic Advances in Simulation Capabilities To Meet Their Mission Goals

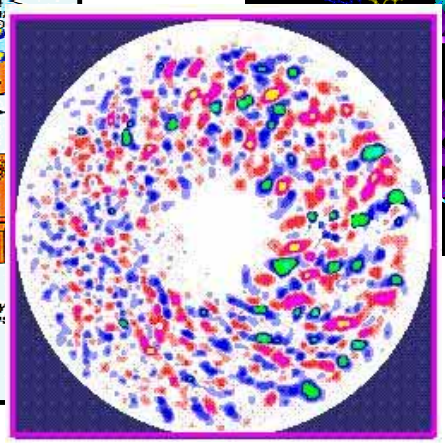




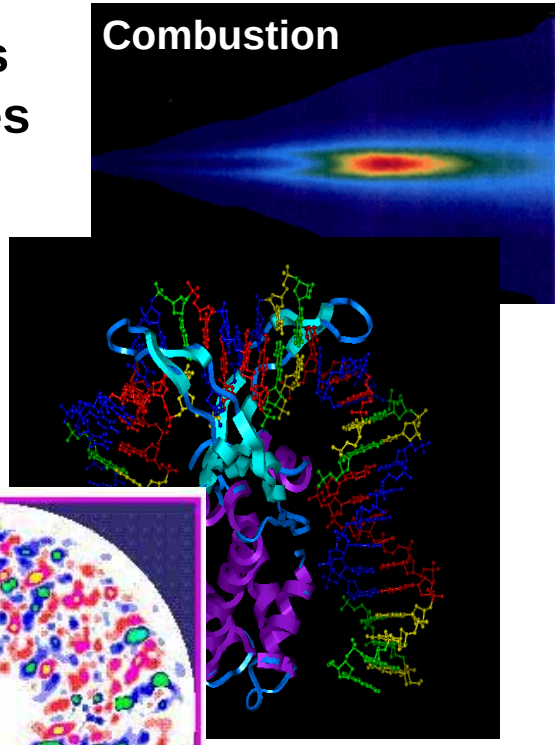
Global Systems



Subsurface Transport



Fusion Energy



Health Effects, Bioremediation

Graduate Program in Plasma Physics

- **Active students in program: 35**
- **Recent history of graduates & employers:**

–	Park, Jaeyoung	EX	1998	LANL
–	Long, Hui	TH	1998	Santa Clara Corp.
–	Wright, John C.	TH	1998	U of Wisconsin
–	Menard, Jon	EX	1998	PPPL
–	Herrmann, M.*	TH	1998	LLNL *APS-DPP Thesis Award, 2000*
–	Chen, Yang	TH	1998	U of CO, Boulder
–	Wang, Zhehui	EX	1998	Los Alamos Nat. Lab
–	Schwartz, Peter	EX	1998	Colorado College
–	Qin, Hong	TH	1998	PPPL
–	Oliver, Hilary	TH	1998	NIWA, New Zealand
–	Uzdensky, D.	TH	1998	U of Chicago
–	Malyshev, M,	EX	1999	Lucent Technologies
–	Heeter, Robert	TH	1999	LLNL
–	Trintchouk, F.	EX	1999	PPPL
–	Chao, Edward	EX	1999	GE Medical Systems
–	Savchenko, V.	TH	1999	Princeton University
–	Boldyrev, S.	TH	1999	Inst. of Theo. Physics
–	Snyder, Philip	TH	1999	General Atomics
–	Fong, Bryan	TH	1999	NCAR/HAO, U. of CO
–	Leng, Lufeng	EX	1999	Lucent Technologies
–	Karasik, Max	EX	2000	NRL
–	Hsu, Scott C.	EX	2000	Caltech

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PPPL LINKAGES TO MAIN CAMPUS

- **Astrophysical Sciences:**
  Graduate Program in Plasma Physics
- **School of Engineering: Program in Plasma Science and Technology; Mechanical & Aerospace Engineering**
- **Computer Science:**
  Graduate Education (PICASso), Visualization (Display Wall), Shared Hardware (Origin 2000)
- **PEI: Center for Energy and Environmental Studies**
- ***With opportunities for further growth***
  - ***PU is well-positioned to take advantage of opportunities in IT/Advanced Computing via inter-departmental collaborations (CS, PPPL, Astro, Geo, MAE, ..,)***

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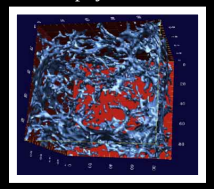
PICASso

Driving Applications

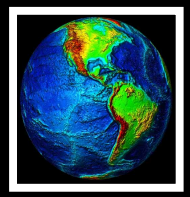
Science/Engineering

Astrophysics

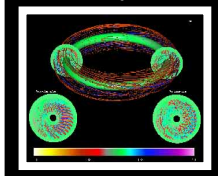


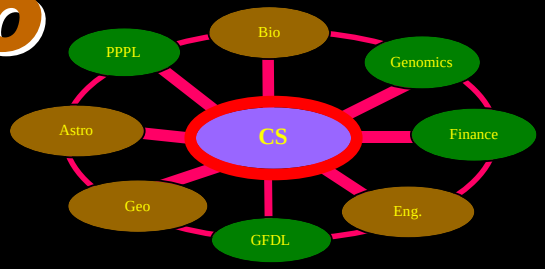
Biology, Genomics

Geosciences



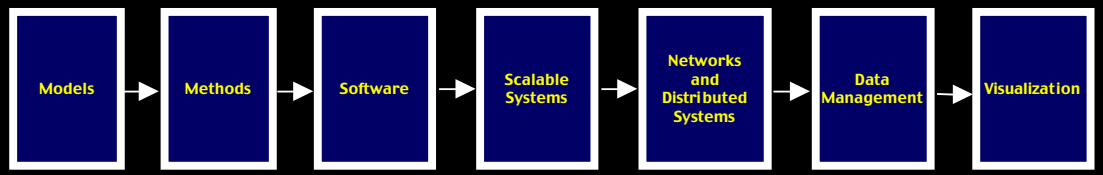
Plasma Physics





Program in Integrative Computer and Application Sciences

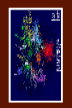
The Computational Pipeline



Integrative Research and Training in Entire Computational Pipeline

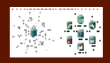
Scalable Services

Internet Services



Mobile Services

Information Archives



KEY NEAR-TERM TARGETS IN MHD

- **Parallelized M3D (parM3D) capable of utilizing large distributed memory MPP's @ NERSC (FY'01-02)**

- **Confirmation of Magnetic Surfaces in 3D Configurations via systematic applications/comparisons of VMEC, M3D, and PIES (FY'01)**

- **Develop non-inductive current build-up strategies for minimizing pulse length requirements (CMOD, NSTX) via Axisymmetric Modeling of Current Drive and Current Profile Control (FY'01)**

- **Feedback Stabilization Scenario-development for RWM (DIII-D) (FY'01)**

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KEY NEAR-TERM TARGETS IN TRANSPORT

- **Neoclassical Ion Transport and Bootstrap Current Properties in ST's and 3D (non-axisymmetric) Systems (FY'01)**

- **User-friendly version of state-of-art codes such as GTC and ORBIT for community collaborations (FY'01)**

- **Applications of linear GK (nonlocal low-n) & of NL GF (magnetic perturbations & equilibrium ExB shear) to interpretation of fluctuation measurements from JT60U, JET, DIII-D, C-MOD, & NSTX (FY'01)**

- **Influence of Trapped-Electron Dynamics in global 3D GK analysis of Tokamak Microturbulence (FY'03)**

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NEAR-TERM TARGETS

- ***WAVES/ENERGETIC PARTICLES***
- **Develop and apply Energetic Particle (e.g., TAE) Analysis for experimental planning and interpretation on NSTX, FIRE (FY'01-02)**
- **Assessment of TAE Stability for N-NBI Experiments with plasma flow on JT60U (FY'01)**
- **Analysis of Fishbone Modes & Sawtooth Stabilization on ASDEX (FY'01)**

- ***BOUNDARY PHYSICS***
- **Simulation of turbulence imaging for SOL studies on NSTX in collaboration with LLNL (FY'01-02)**
- **Application of Coupled DEGAS2-UEDGE to liquid lithium experiments on CDX-U (FY'01)**

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PPPL 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

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CONCLUSIONS

- **PPPL Theory/Advanced Scientific Computing Program is key National/International Resource:**
  - highly desired for many ***external collaborations***
  - critical to ***cost-effective innovation*** in fusion research
  - enables ***optimal leveraging*** of major national/international investments in experimental facilities

- **PPPL Theory/Advanced Scientific Program combines:**
  - long-standing ***commitment to academic and educational*** excellence
  - ***accountable progress*** on many of most important, scientifically challenging problems facing FES research
  - ***strong partnerships*** with universities, laboratories, & industry

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