Overview of MHD Activities in the PPPL Theory Department

PPPL Theory Review

June 1, 2000

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Presenting for

E.Belova, M.Chance, G. Fu, S. Hudson, J.Manickam, D.Monticello, W.Park, N.Pomphrey, A.Reiman, L.Zakharov

5 Year FESAC Goal: *Develop detailed predictive capability for macroscopic stability, including resistive and kinetic effects*

Overview of Major MHD Research Areas

- **2D axisymmetric equilibrium and evolution**
  - efficient and accurate equilibrium solvers **SESC**
  - evolving equilibrium, transport, plasma control **TSC**

- **linear stability analysis**
  - ideal and resistive stability **PEST-I, -II, III**,
  - feedback stabilization of MHD modes **VACUUM**
  - non-variational extensions **NOVA, NOVA-W, NOVA-R**

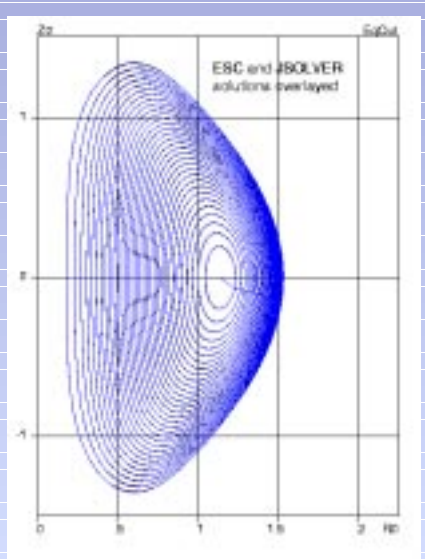
- **3D non-linear equilibrium and stability**
  - equilibrium of 3D magnetic configurations **PIES**
  - time dependent evolution and stability **parM3D**

- Major theory collaborations

- Major application areas

Advances in Calculation of 2D Equilibrium

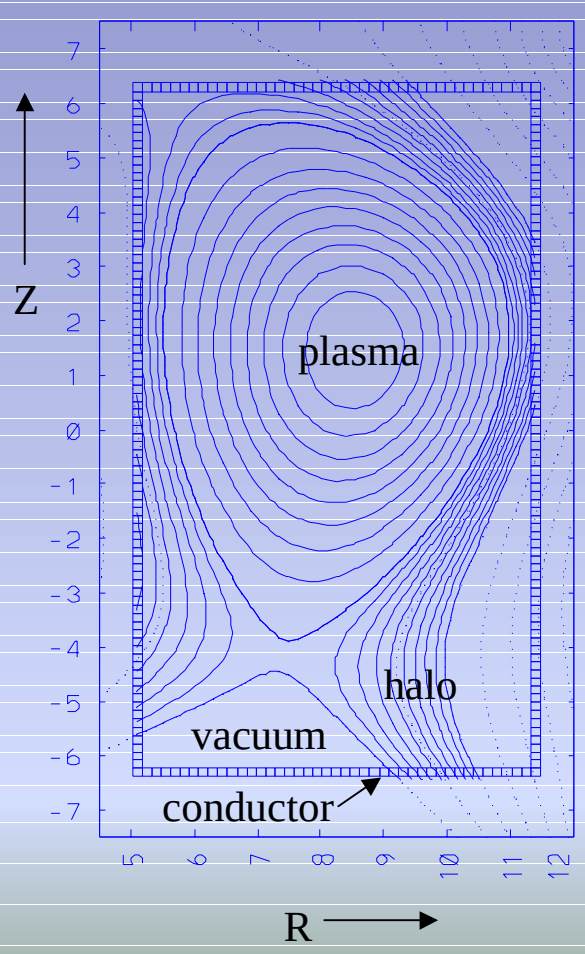
- **SESC** code uses new sweeping technique with Newton acceleration for fast and accurate equilibrium solutions
- Older **JSOLVER** code used to debug and benchmark **SESC**
- **SESC** is now being used in **TRANSP**
  - fast (×10), reliable, includes X-point
  - internal accuracy control
- **Future developments**:
  - Equilibrium reconstruction using **EFIT** boundary and MSE data for NSTX
  - Ideal MHD stability based on δA version of energy principle
  - quasilinear MHD stability for islands
  - 3-D equilibrium and stability



Contours overlaid

Zakharov and Pletzer, PoP, **6** (1999) 4693

Tokamak Simulation Code (TSC) is unique tool for modeling the evolution of a free-boundary axisymmetric plasma on the resistive time scales



- arbitrary transport model
- neoclassical-resistivity
- bootstrap-current,
- auxiliary-heating
- ballooning-mode transport
- current-drive,
- alpha-heating,
- radiation,
- pellet-injection,
- sawtooth model,
- circuit equations for all the poloidal field coils
- induced currents in passive conductors, halo
- feedback systems for I_P, position, and shape.

TSC was chosen by ITER as the standard model for:

- poloidal flux consumption and pulse length
- timescales for current rampup and rampdown
- shape control requirements

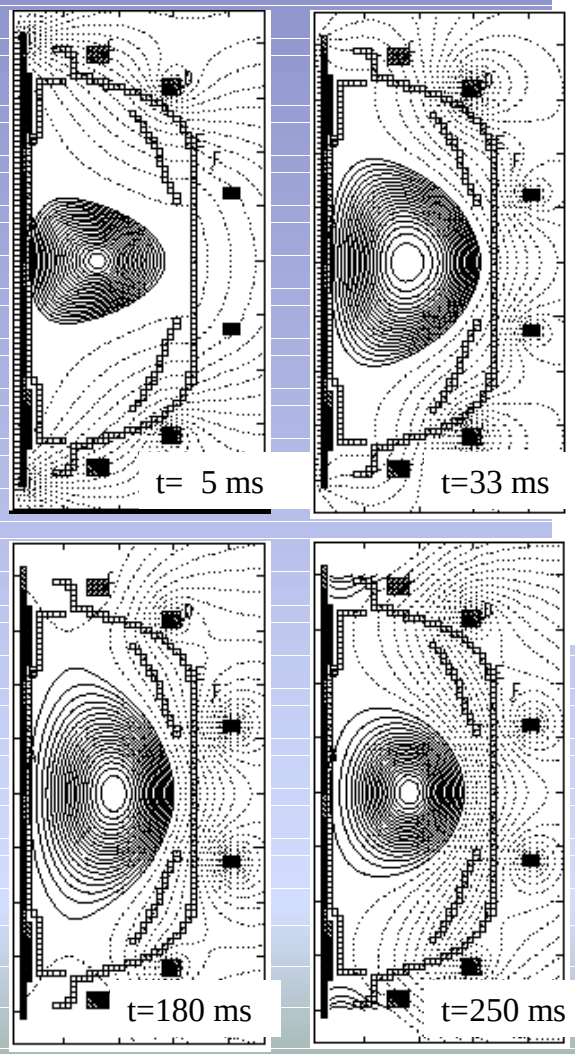
New Directions:

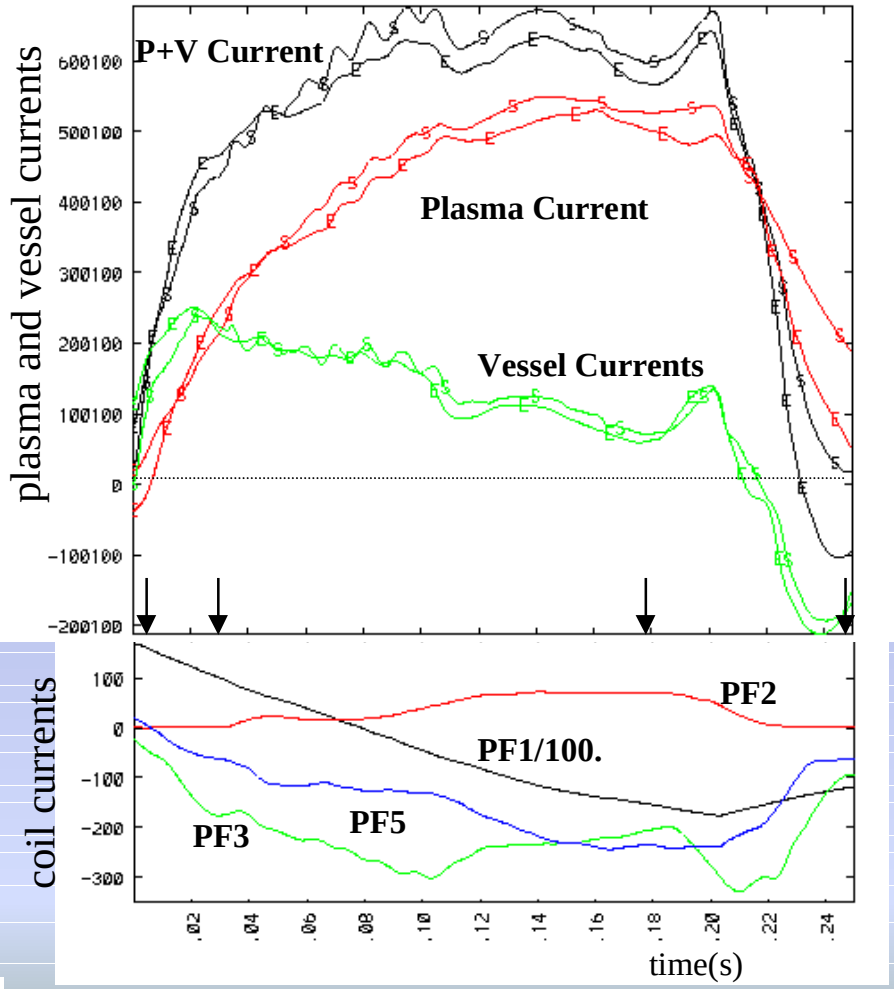
- integrated modeling of core and edge
- improved models of non-linear saturation of high-β m=1 mode, ELMs, balloon-unstable region

Jardin, et al, Nucl. Fus. 39 (2000) 923

TSC simulation of NSTX shot 100920

E .. experimental data S..computed by TSC





Simulation uses experimental coil currents: computes plasma and vessel currents

Linear MHD Stability is centered around the energy principle

$$\delta W(\vec{\xi},\vec{\xi}^*) = \frac{1}{2}\int d\tau \left[\left|\vec{Q}\right|^2 - \vec{\xi}^* \bullet \vec{J} \times \vec{Q} + \gamma P_0 \left|\nabla \bullet \vec{\xi}\right|^2 + (\nabla \bullet \vec{\xi}^*)\vec{\xi} \bullet \nabla P_0 \right] + \delta W_V$$

Full numerical minimization using physical KE :

PEST-I

Minimization over 2 components of ξ semi-analytically, 3rd component numerically using modified KE :

PEST-II

Minimization over 2 components of ξ semi-analytically, 3rd component numerically allowing displacement to diverge at rational surfaces to model effects of finite resistivity:

PEST-III

Extend δW_V to include resistive conductors, sensors, feedback systems:

VACUUM

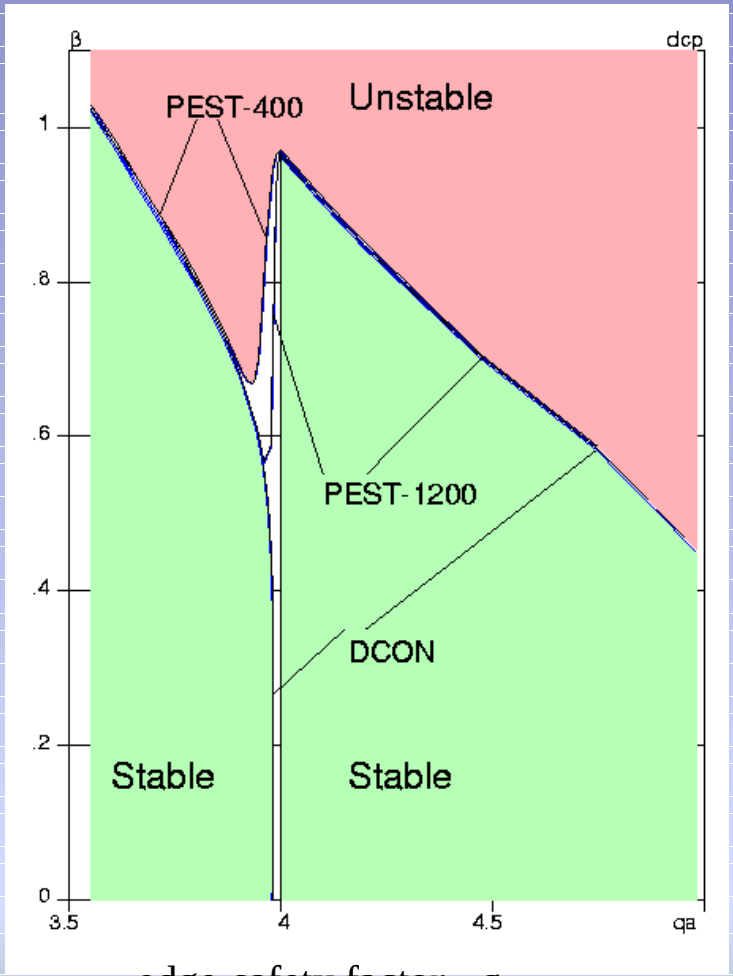
Non-variational extensions to include plasma kinetic effects, energetic particles and plasma resistivity :

NOVA, NOVA-K, NOVA-R

PEST-I/II codes used for benchmarking new codes for ideal MHD Stability

% β

- A large effort has gone into benchmarking **PEST** results with the **DCON** code of Glasser, et. al. for extreme cases near singularities
- For many configurations, **DCON** now gives an accurate result in less time than **PEST**, but for other cases such as low-A, high-q, **PEST** may still have an advantage.
- Similar benchmarking now going on for **VALEN**
- Useful to have different approaches available



edge-safety factor - q_a

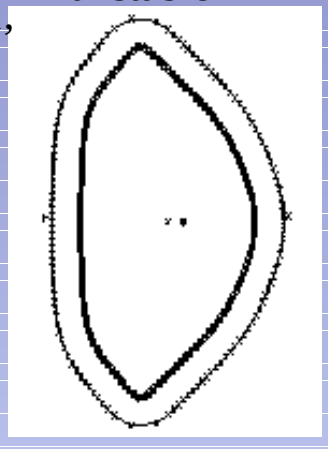
q_0=1.2, A=4, no wall

Zakharov
Manickam

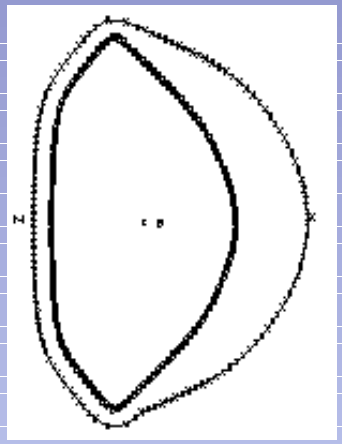
PEST-I/II codes are still yielding new understanding of ideal MHD Stability

β = 28%, R/a = 1.31,
κ=2.0, δ=0.35

unstable



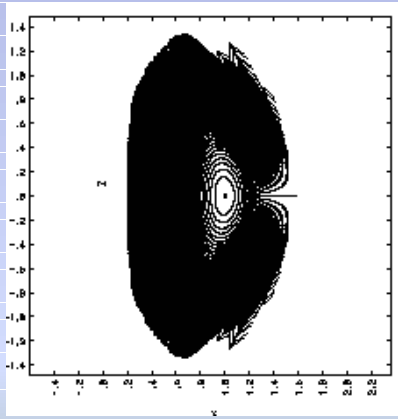
stable



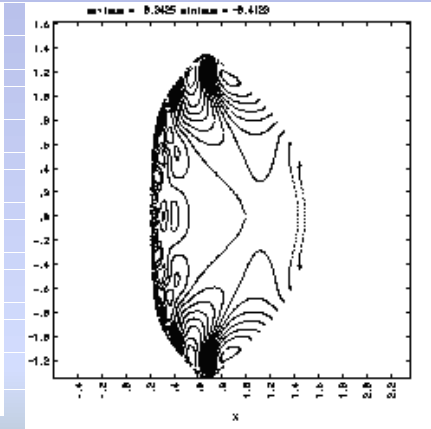
- low-A presents new challenges and new physics results
- high-A relation between displacement and perturbed field changes

New Directions:

- Continue to increase speed and accuracy at high edge-q
- New applications in MHD physics of ELMs and internal transport barriers



displacement

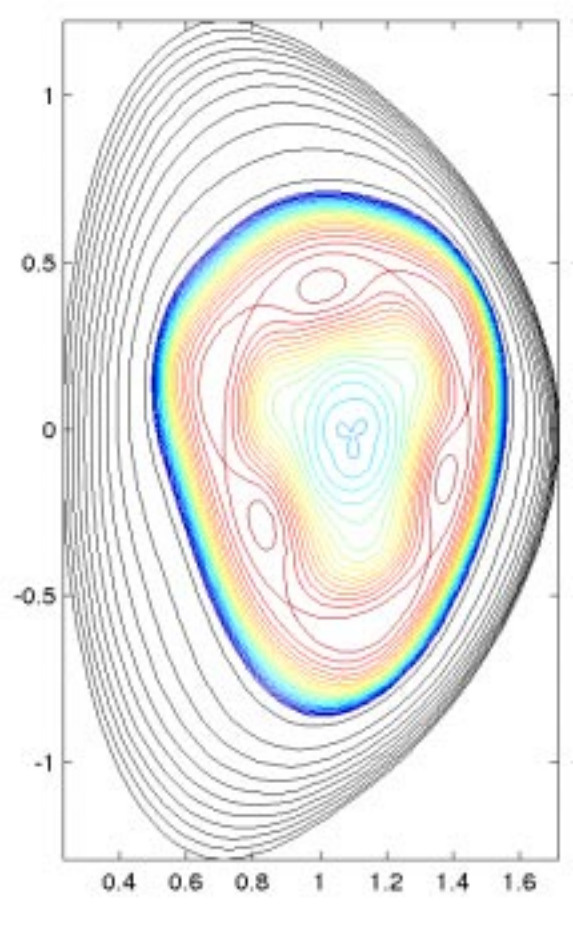


Perturbed field

Manickam, Nucl. Fus. **39** (1999) 1819

PEST-III code is unique capability for implementing asymptotic theory of resistive instabilities

- very efficient and accurate method of computing linear resistive stability by only solving "outer solution" where ideal MHD is valid
- calculates the toroidal Δ' which extends analytic work done for simple 1D geometry
- this Δ' is used by semi-analytic neoclassical tearing mode theories of Hegna and other to calculate saturated island size



Pletzer, PoP **4** 3141 (1997)

TSC simulation and PEST analysis of a 12 T, 7.7 MA Q=10 FIRE Discharge

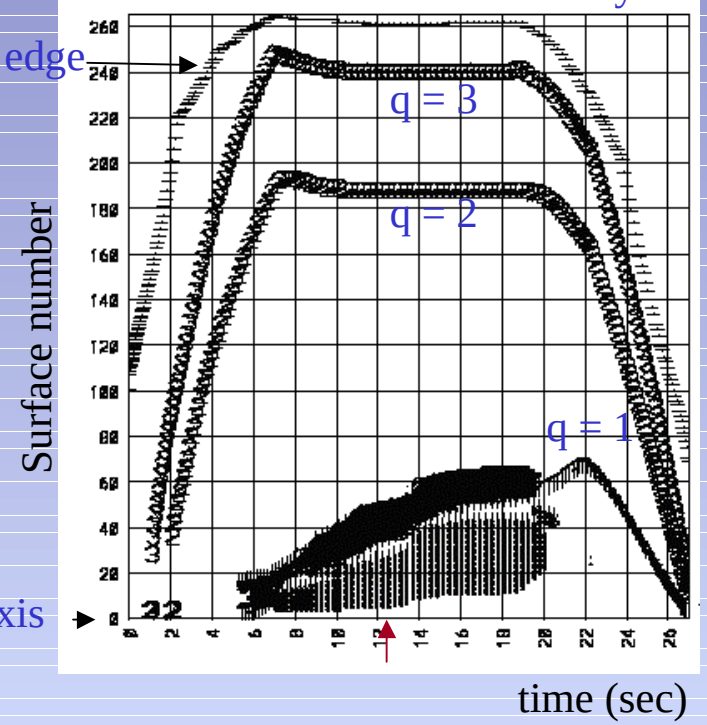
- Linear stability analysis of high-β discharge typically shows unstable MHD mode near q=1 surface

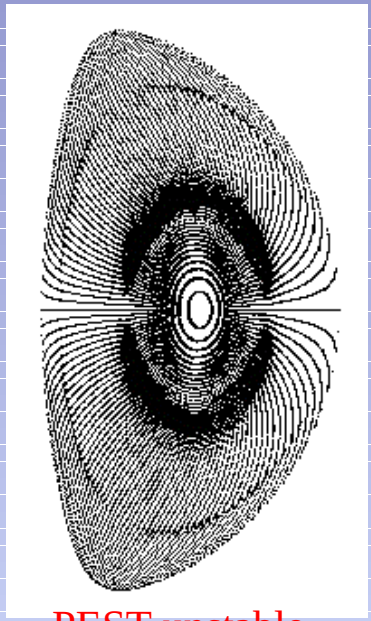
Future Directions:

- need to use 3D nonlinear code and experimental calibration to develop better prediction of nonlinear saturation of linearly unstable m=1 modes.

- also, need to extend simulations to plasma edge region

Balloon and Mercier stability

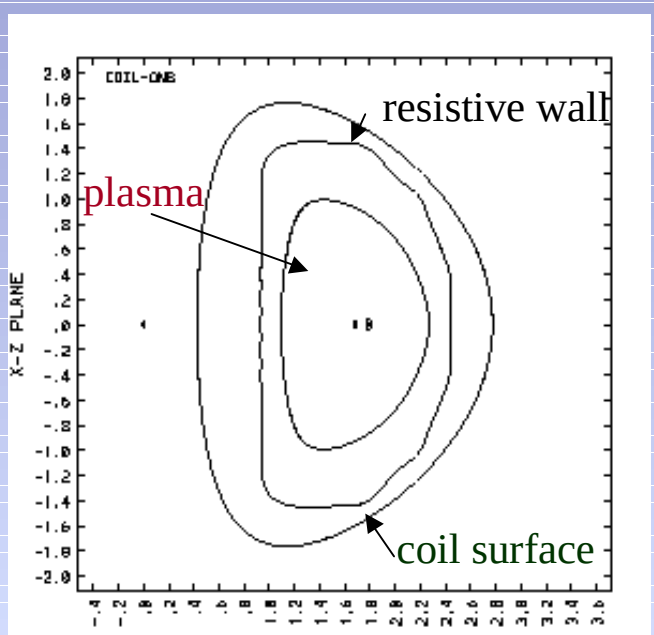


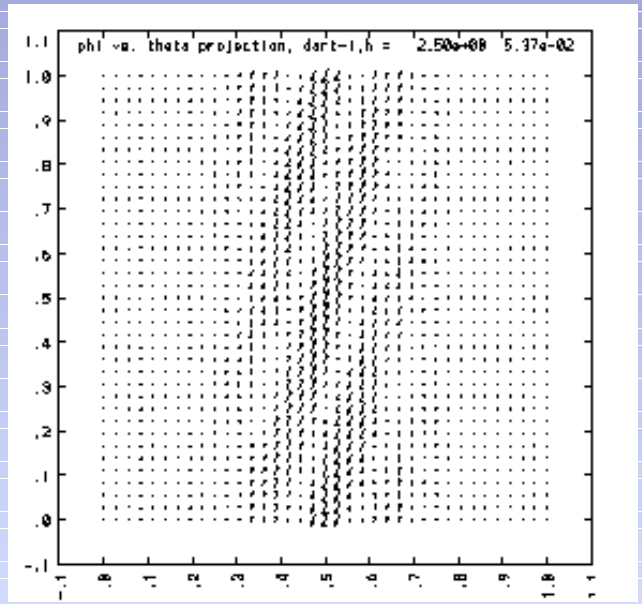


PEST unstable eigenfunction at t=12.5 sec

Resistive Wall Mode and Active Feedback Stabilization

We are developing a major extension of the linear stability codes to include resistive walls, coils, circuit equations, feedback systems, with self-consistent plasma response…interface with both PEST and GATO





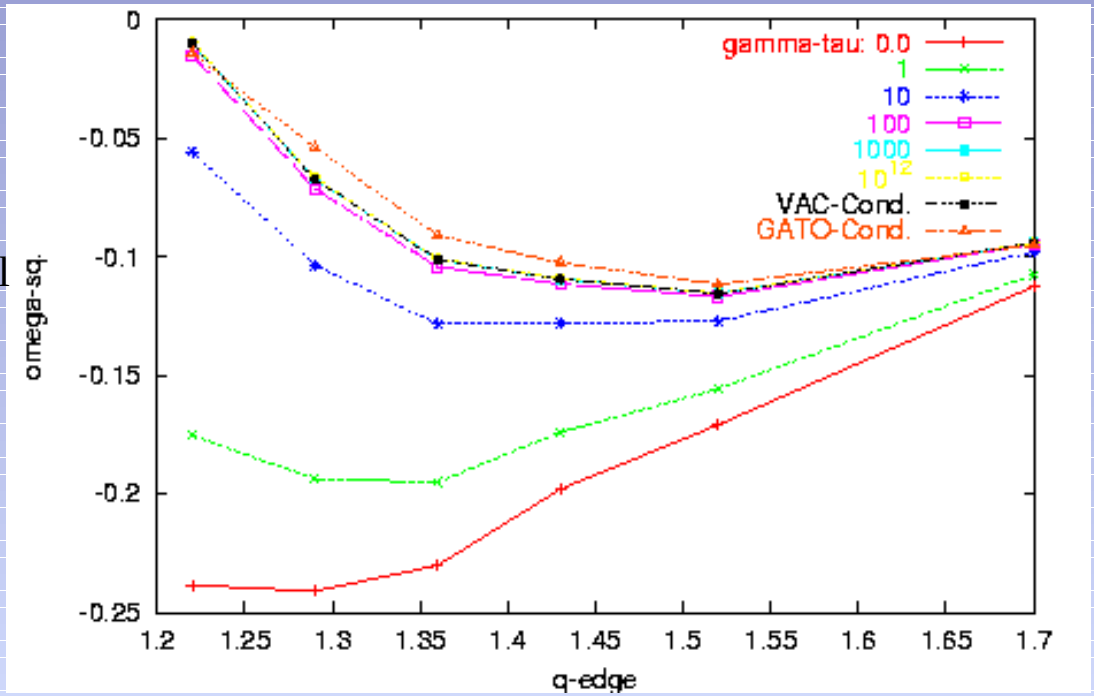
VACUUM model includes plasma, wall, and coil surface

Induced currents in wall in absence of feedback

Chance, et al. IAEA 2000, Phys. Plasmas 4 (1997) 2161

ω^2 vs q_{edge} for various $\gamma\tau_s$ using GATO + VACUUM: for a conformal resistive shell at b = 0.5 a.

- $\gamma\tau_s \rightarrow \infty$ reproduces perfectly conducting shell results
- $\gamma\tau_s \rightarrow 0$ gives no-wall limit
- $\gamma\tau_s$ in between gives intermediate result

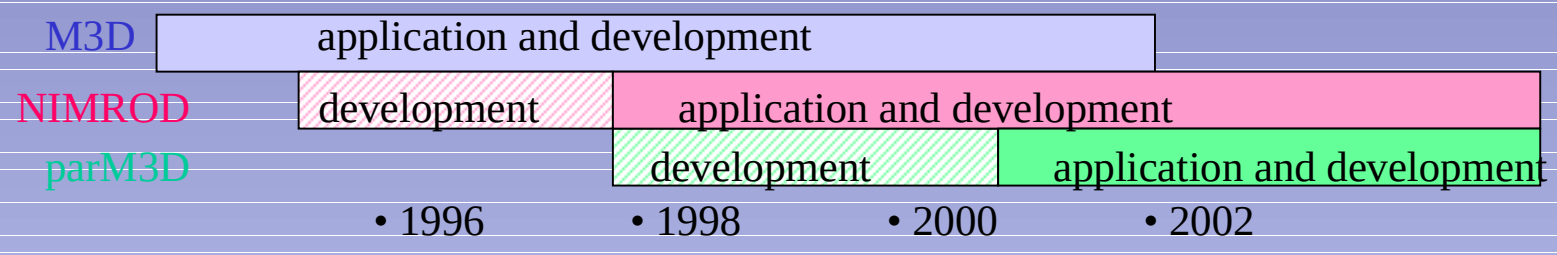


Future Plans:

- include sensor and feedback coils in system while keeping the self-adjoint property

M.Chance, PoP, 4 (1997) 2161

Major non-linear 3D MHD codes in our community



M3D

- quasi-implicit
- stream function/ potential
- 1 poloidal plane / processor
- Finite difference in toroidal direction
- **scales well on 32-64 processors on ORIGIN 2000 with OpenMP**
- multi-level physics description includes particles

NIMROD*

- strongly implicit
- uses B and V
- domain decompositon in poloidal plane using MPI
- pseudo-spectral parallel decomposition in toroidal direction
- **near ideal scaling demonstrated on 256-512 processors on T3E**
- single and two-fluid

* not a PPPL-developed code

parM3D:

- builds on M3D algorithm and physics description
- domain decompositon in poloidal plane
- Finite difference in toroidal
- uses MPI and PETSc
- **good scaling of elliptic solvers demonstrated up to 512 processors on T3E**
- now undergoing benchmark exercises with M3D and NIMROD

M3D (and parM3D) have different levels of physics description

Less complex model, valid for high-collisionality, strong fields, long times

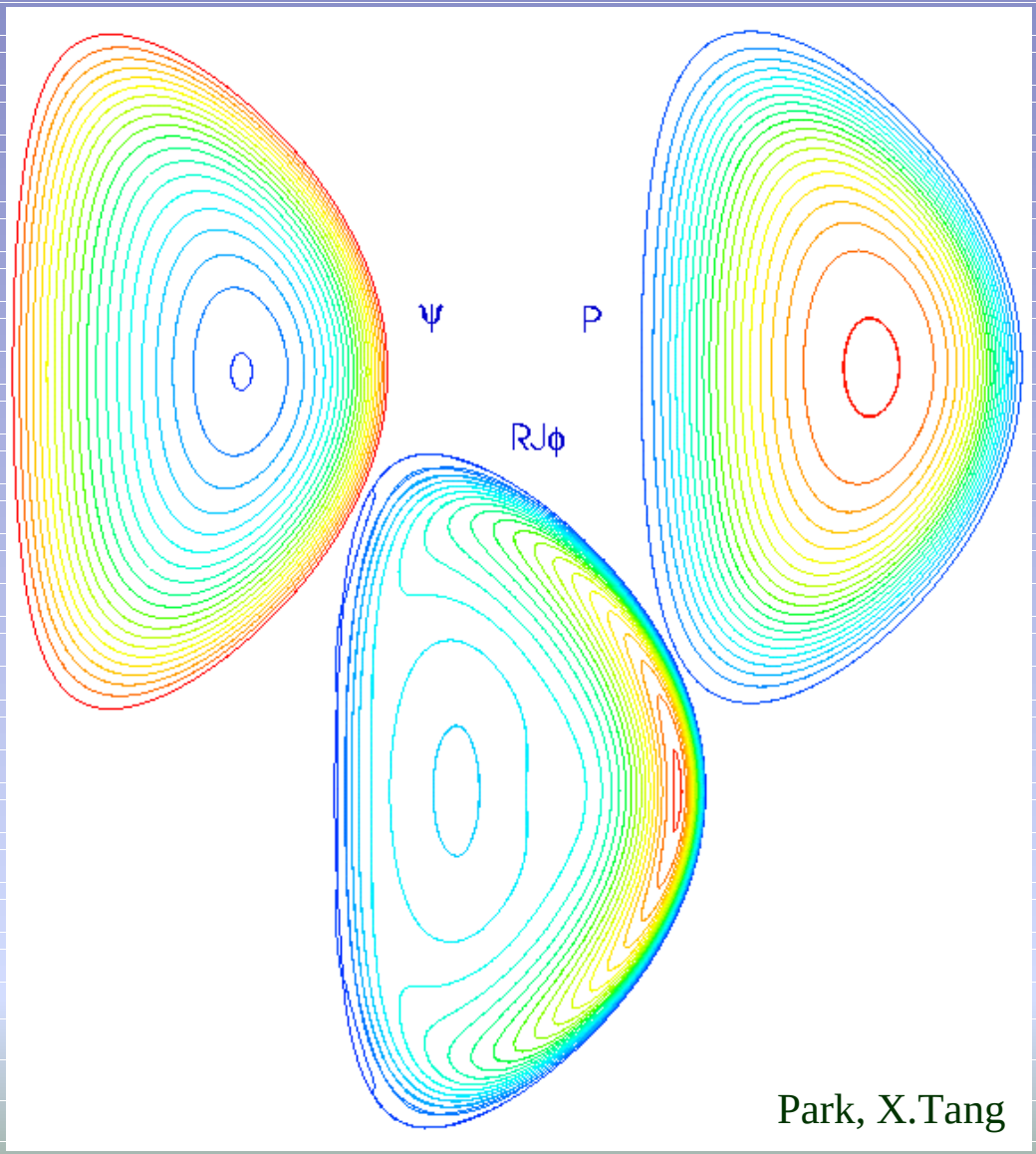
More computationally demanding. Required to describe many important but subtle phenomena.

Single Fluid Resistive MHD	Two Fluid MHD (electrons and ions)	Two Fluid MHD plus energetic gyro-particles	Gyro-particle ions and fluid electrons	Full orbit particle ions and fluid electrons
External kink modes	**Neoclassical tearing mode (including rotation)** **Collisionless reconnection**	**MHD modes destabilized by wave-particle resonance with energetic species**	**Kinetic stabilization of internal MHD modes by ions**	**Tilting and interchange modes in FRC**

Park, Belova, et al, PoP **6** (1999) 1796

Application of parM3D to reproduce high-β tokamak equilibrium from VMEC

- **parM3D** solves for steady state solution for problem with axisymmetric boundarys
- contours from **parM3D** and **VMEC** are overlaid



Park, X.Tang

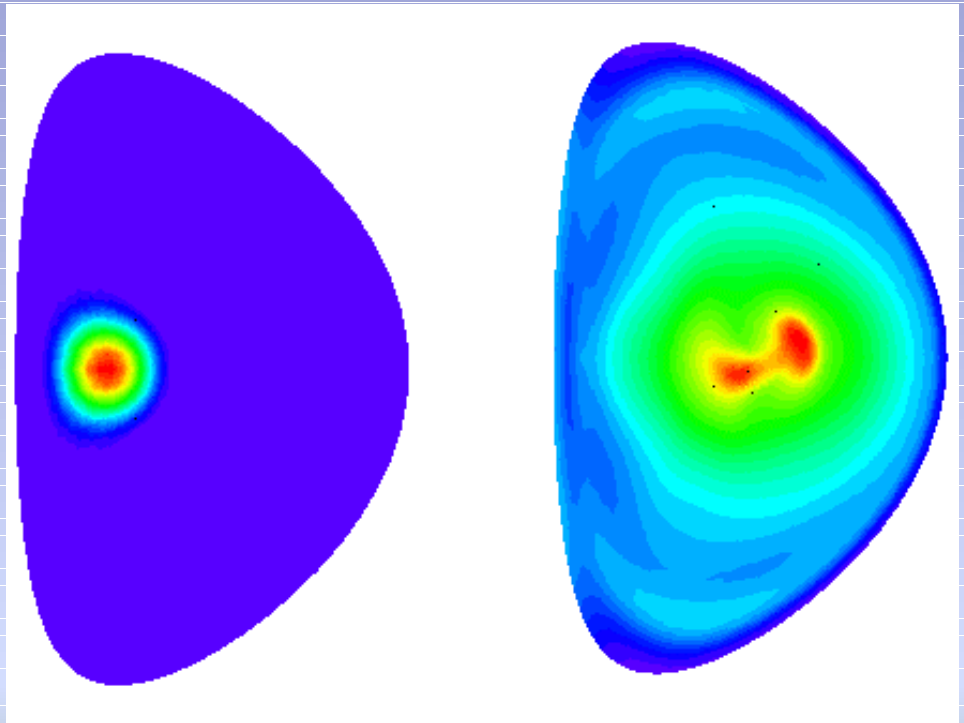
M3D code applied to explain physical mechanism for deep penetration of inside pellet launch

- first 3D simulation of this experimentally discovered phenomena

[Strauss, Park, et al, Phys. Plasmas **7** (2000) 250]

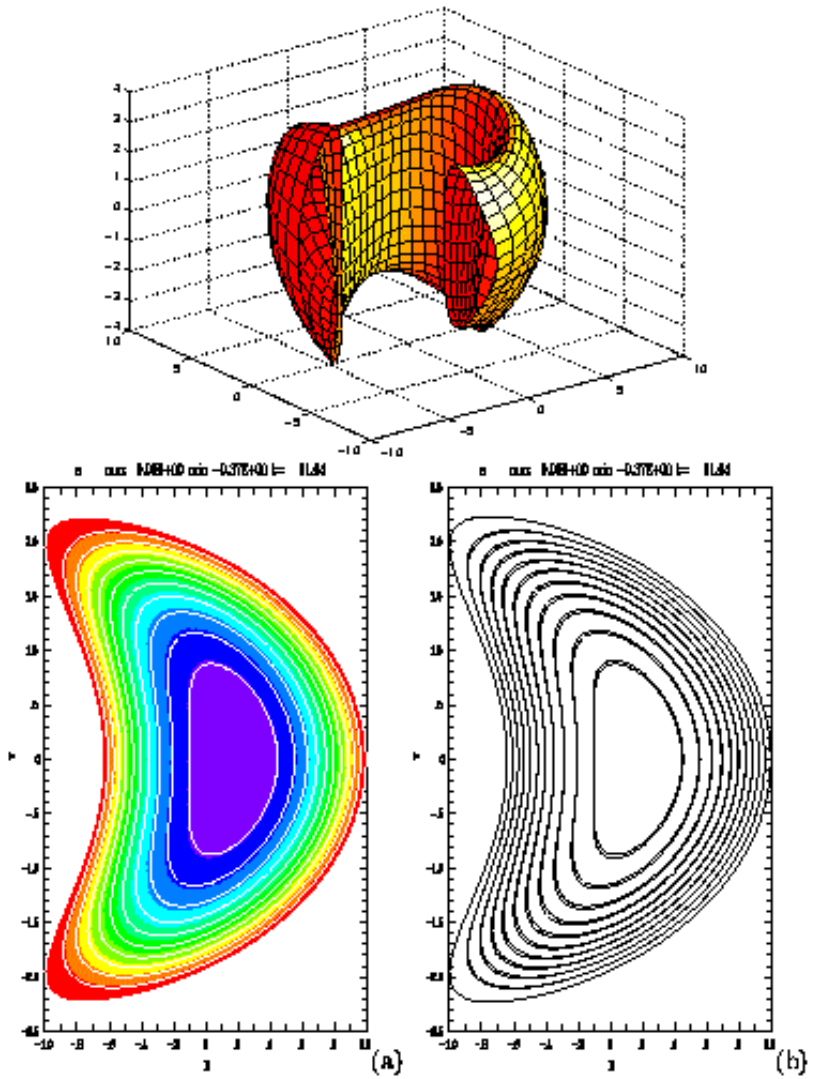
- led to development of 2D model now in **TSC** code

[Jardin, Schmidt, et al, Nucl. Fusion **39** (2000) 923]



parM3D code being applied to stellarators

- Solve time dependent equations to steady state for stable 3D equilibrium configurations
- 3D grid gives advantage over **NIMROD** for this application



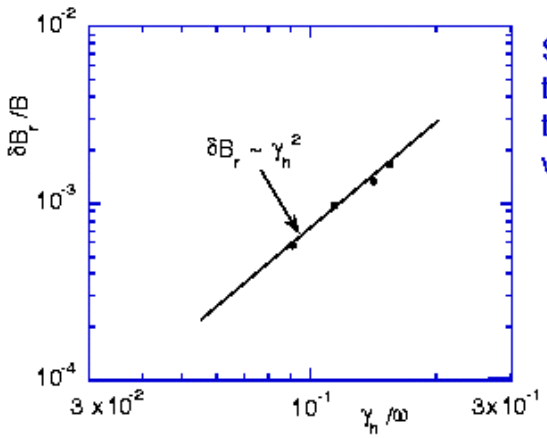
Strauss, Park

Hybrid Gyrokinetic Hot Particle /MHD Simulation

(Fu and Park, Phys.Rev.Lett **74** 1594 (1995))

Stream lines

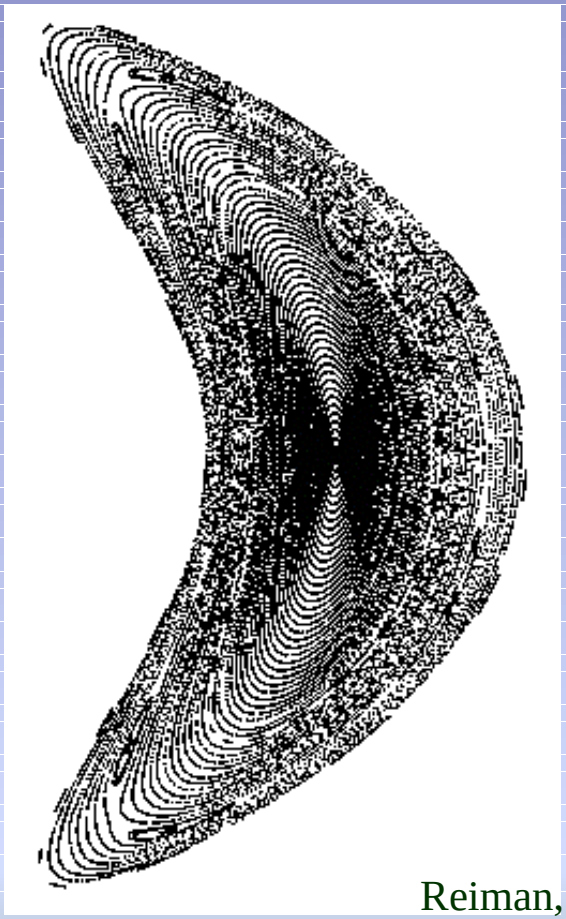
Nonlinear Saturation of Alpha driven TAE Modes.



Saturation is found to be due to wave-particle trapping, and the saturation amplitude agrees with analytic theory.

Princeton Iterative Equilibrium & Stability Code (PIES)

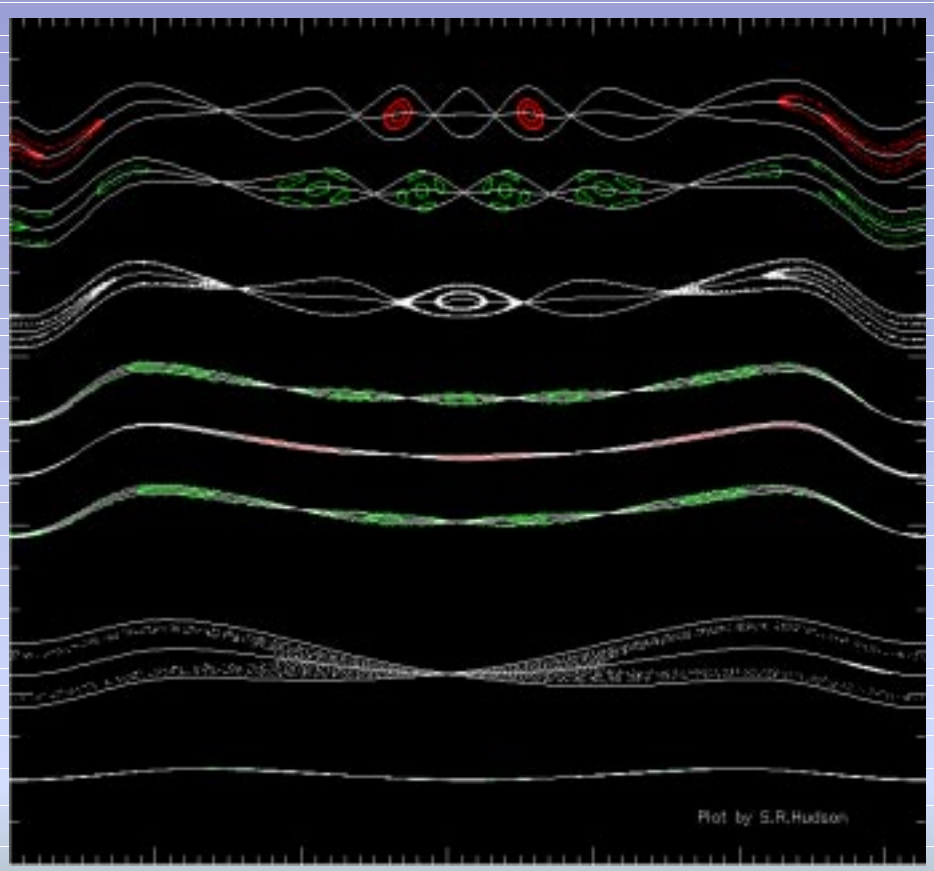
- Unique tool for calculating 3D field structure:
  - does not assume good surfaces,
  - free from the inertial time scales
- Now being used to calculate surface quality and beta limits
- Free-boundary capability developed recently in collaboration with IPP [Arndt, Merkel,Monticello, Phys. Plasmas 6 1246 (1999)]
- Simplified bootstrap model now being implemented
- Recent code improvements have increased efficiency 2-15 times (problem dependent)
- **Future directions:**
  - more complete model planned in collaboration with the Japanese
  - time evolution being looked at



Reiman, Monticello, Pomphrey

PIES and parM3D are being compared for stellarator equilibrium

- magnetic surface quality is a major issue for stellarator designs
- the 2 non-linear codes **PIES** and **parM3D** each calculate 3D equilibrium subject to the same boundary conditions but by totally different methods.
- cross-comparison gives confidence in results
- new algorithm by Hudson automatically locates all islands and quantifies island size for comparison



Hudson, Dewar Phys. Lett. A 226 (1997) 85

Major PPPL MHD Theory Collaborations

TSC Collaborators: NSTX, ORNL, LANL, MIT, IGNITOR, CRPP, INEEL, Hydro-Quebec, IPP-Garching, Juelich, MAST, JAERI, KBSI

PIES Collaborators: W7X (Germany), LHD (Toki, Japan), Heliotron-J (Kyoto, Japan), TJ-II (Spain), H-1 (Australia)

FRC Theory Consortium: GA, U.Washington, Cornell, Dartmouth

Vacuum/RWM: GA, Columbia U.

parM3D/NIMROD: CPPG, NYU, MIT / NIMROD group

PEST: CPPG, LANL, GA, CMOD, JET, JT-60

Also: ARIES, ITER, FIRE, APEX, ALPS,

Application areas to be discussed in subsequent talks:

ICC – kinetic stability of the Field Reversed Configuration (FRC), physics of the liquid lithium walled tokamak, magnetic reconnection of spheromaks, Hall Thrusters

Tokamak Collaborations –MHD of transport barriers, magnetic feedback, codes-on-line (also, disruption prediction and effects, physics of ELMs)

NSTX – double tearing modes, co-axial helicity injection (CHI)

NCSX – ideal linear stability of 3D configurations, 3D configuration optimization, surface integrity

CPPG – modernization of major MHD codes

PPPL MHD Code Development and Applications

2D Equilibrium and Evolution

- **refine individual TSC modules and test coupling**
  NSTX, MAST, CMOD discharge modeling
- **coupled TSC evolving equilibrium, transport current drive, stability**
  sawtooth physics NSTX, FIRE optimization
- **integrated TSC core-edge modeling**
  NSTX, FIRE analysis and optimization, Li walls

Linear Stability

- **PEST on-line**
  NSTX between-shot analysis, ELMs, ATs
- **resistive shell feedback design and analysis**
  DIII, NSTX support
- **feedback optimization**
  next generation feedback experiments

3D Nonlinear

- **free-boundary PIES**
  benchmark, NCSX, surface breakup
- **neoclassical PIES**
  NTM in stellarators, tokamaks and STs
- **evolution PIES**
  Current evolution in NCSX, feedback
- **resistive parM3D**
  benchmark, surfaces
- **2-fluid parM3D**
  NTM, feedback
- **kinetic parM3D**
  TAE, NTM, sawtooth

Other activities

FRC kinetic Stability…….disruption analysis, effects, prevention,….lithium wall tokamaks…TERPSICHORE analysis of NCSX…….3D configuration optimization ….magnetic reconnection and self-organization…3D SESC ...CHI

FY: 2000 2001 2002 2003 2004

Summary – PPPL MHD Theory

- vibrant activity in all major areas of MHD:
  - 2D equilibrium and time-evolution
  - 3D equilibrium, linear stability, nonlinear evolution
  - ideal, resistive, kinetic, active feedback
- strong record of past achievements
- exciting new directions
- many applications to new and proposed experiments
- strong connections to the community outside PPPL through collaborations and benchmark activities