Macroscopic Stability[1] and Integrated Modeling

Presented by:

S. C. Jardin

10 October 2005

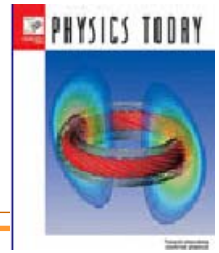
PPPL Theory Department five-year plan review

[1]Stellarators & FRCs covered in other presentations

Outline

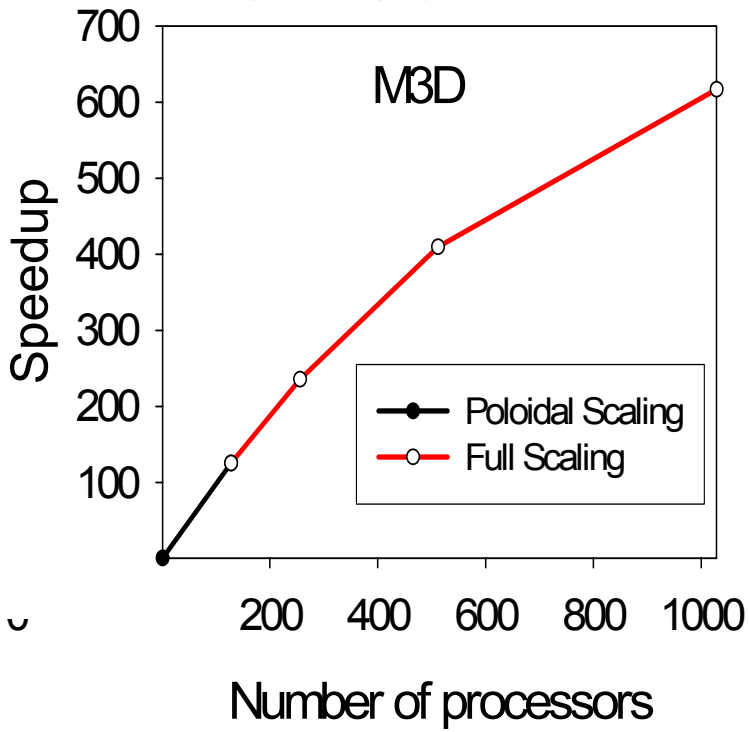
- Progress and plans in 3D MHD Modeling
- Relation to Integrated Modeling
- Progress and plans towards the 1½D Integrated Plasma Simulator
- Other activities
- Summary

3D MHD Modeling: M3D code



- Nonlinear time-dependent Extended MHD
- Valid for stellarators and tokamaks
- multi-level physics
  - resistive MHD
  - two-fluid MHD
  - hybrid particle/MHD
  - fully kinetic particles
- partially implicit time-stepping
- unstructured triangular mesh: linear, 2nd & 3rd order finite elements
- uses PETSc library … however..
- recent work to optimize this for the Cray-X1E vector computer at ORNL

Strong scaling: typical problem size



→ Very good parallel scaling for an implicit, multi-physics code

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  - Sawtooth
  - ELMs
  - NTM
  - Energetic Particle Modes
  - RWM
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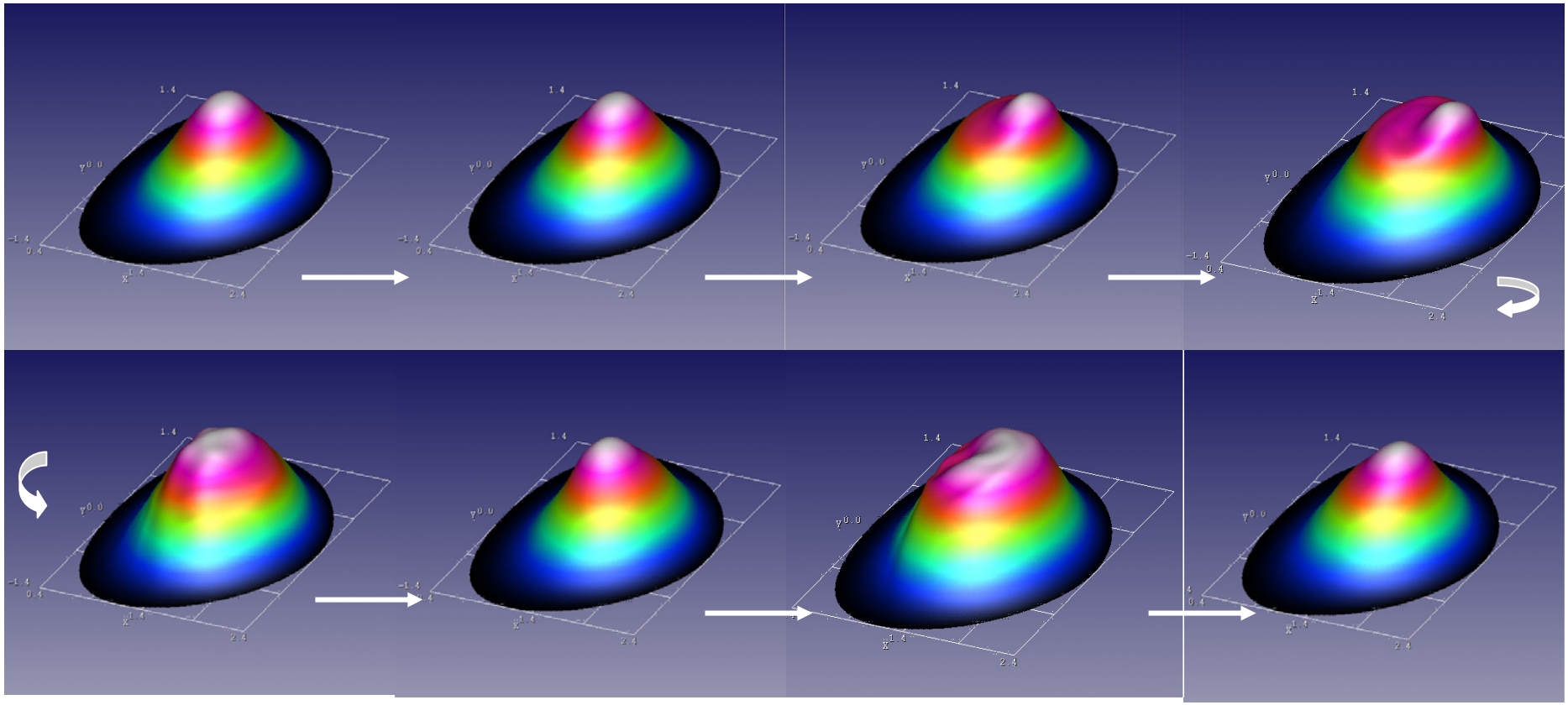
Campaign to model sawtooth in CDX-U using actual parameters of that discharge



After first crash

After second crash

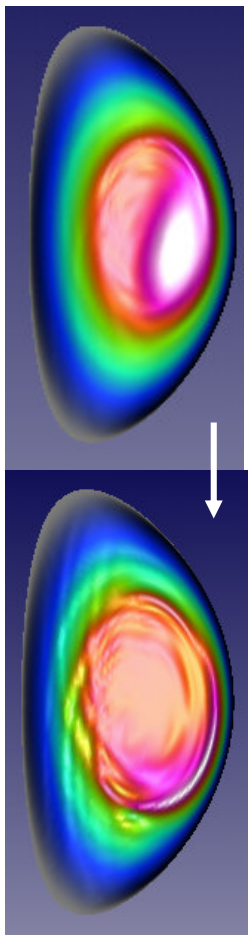
Breslau
M3D

Sawtooth period ≈ 100 μs in good agreement with experimental CDX sawtooth period ≈ 125 μs

NSTX: M3D 2-fluid modeling of q_0<1 discharges with strong toroidal rotation is in qualitative agreement with recent experimental results:

MHD

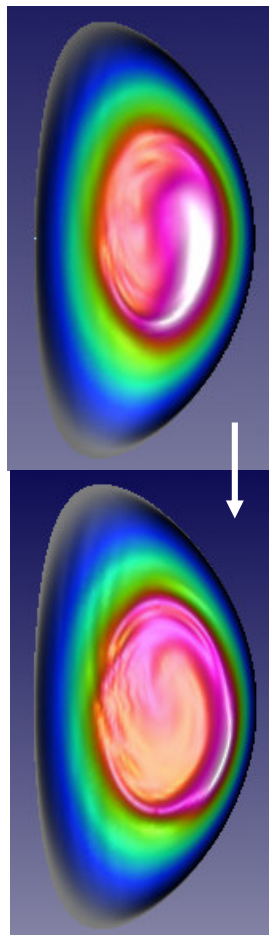
M_A=+-0.3



Crash

Counter 2Fuids

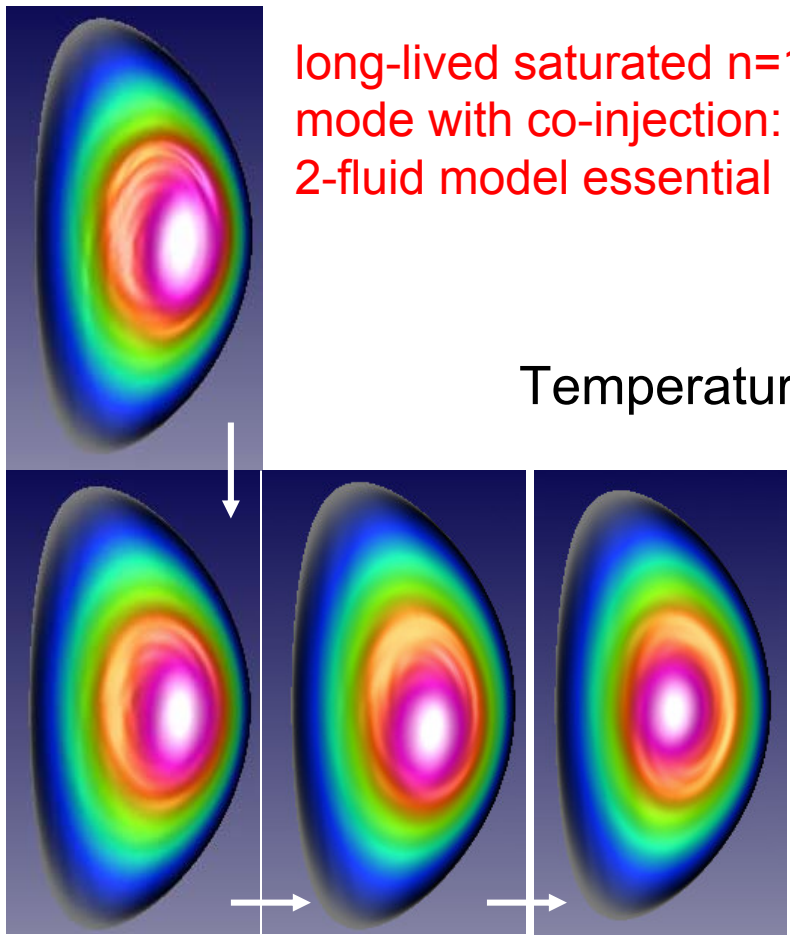
M_A=-0.3



Crash faster than MHD case

Co 2Fuids

M_A=+0.3



Saturation with hot spot pulled away from x-point

long-lived saturated n=1 mode with co-injection: 2-fluid model essential

Temperature

Milestones:

- Complete and publish CDX-U simulation results.***(CEMM 2006)***
- Extend the CDX-U work to larger, higher temperature tokamaks ***(CEMM 2008).***
- Incorporate energetic particle effects into the predictive sawtooth modeling for a burning plasma (***2010).***
  - » PPPL: J. Breslau, J. Chen, G. Fu, W. Park, NYU: Strauss, MIT: Sugiyama
- Produce a publication on the physics of RF inducement of sawteeth ***(SWIM 2008).***
  - » PPPL: S. C. Jardin, J. Breslau, G-Y Fu, D. McCune, W. Park, J. Chen ORNL: D. B. Batchelor, L. A. Berry, S. P. Hirshman, W. A. Houlberg, E. F. Jaeger, D. A. Spong, D. E. Bernholdt, E. D'Azevedo, W. Elwasif, M. R. Fahey, S. Klasky Indiana Univ: R. Bramley Columbia Univ: D. Keyes GA: D. P. Schissel CompX: R. Harvey SAIC: D. Schnack MIT: J. Ramos, L. Sugiyama

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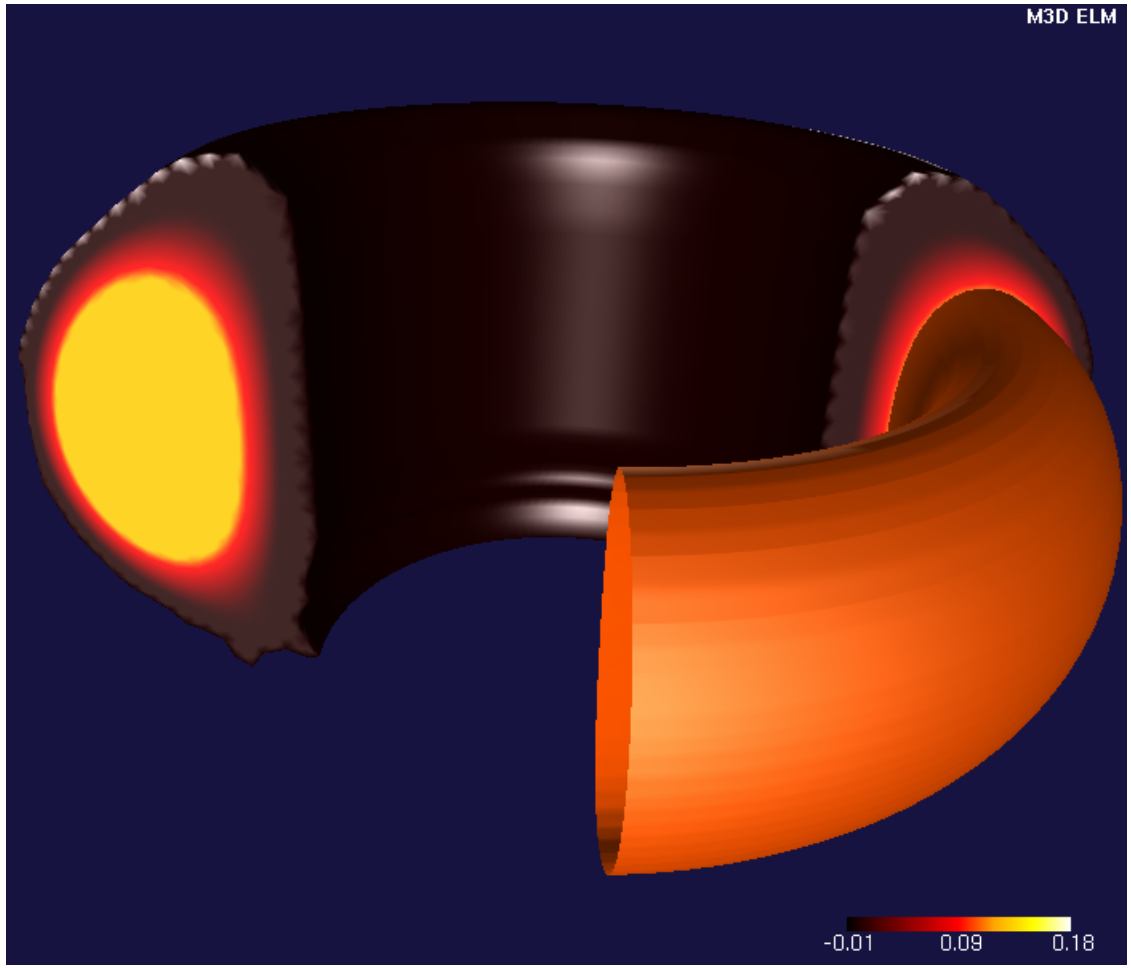
M3D has extended it's computational domain to allow computation of Edge Localized Modes (ELMs) and other free-boundary modes

Nonlinear evolution of an unstable ELM in DIIID shaped tokamak

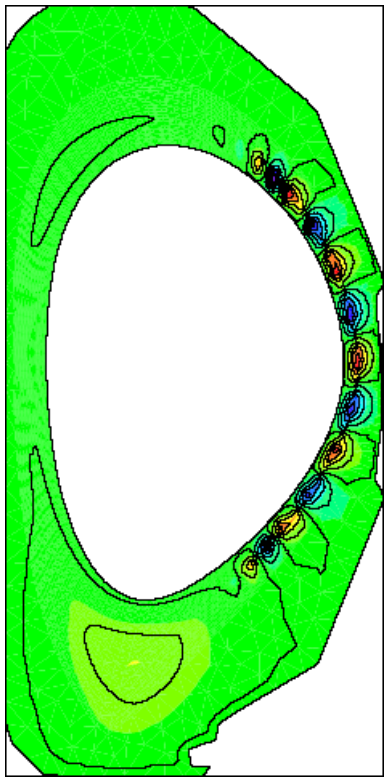
(pressure contours shown)



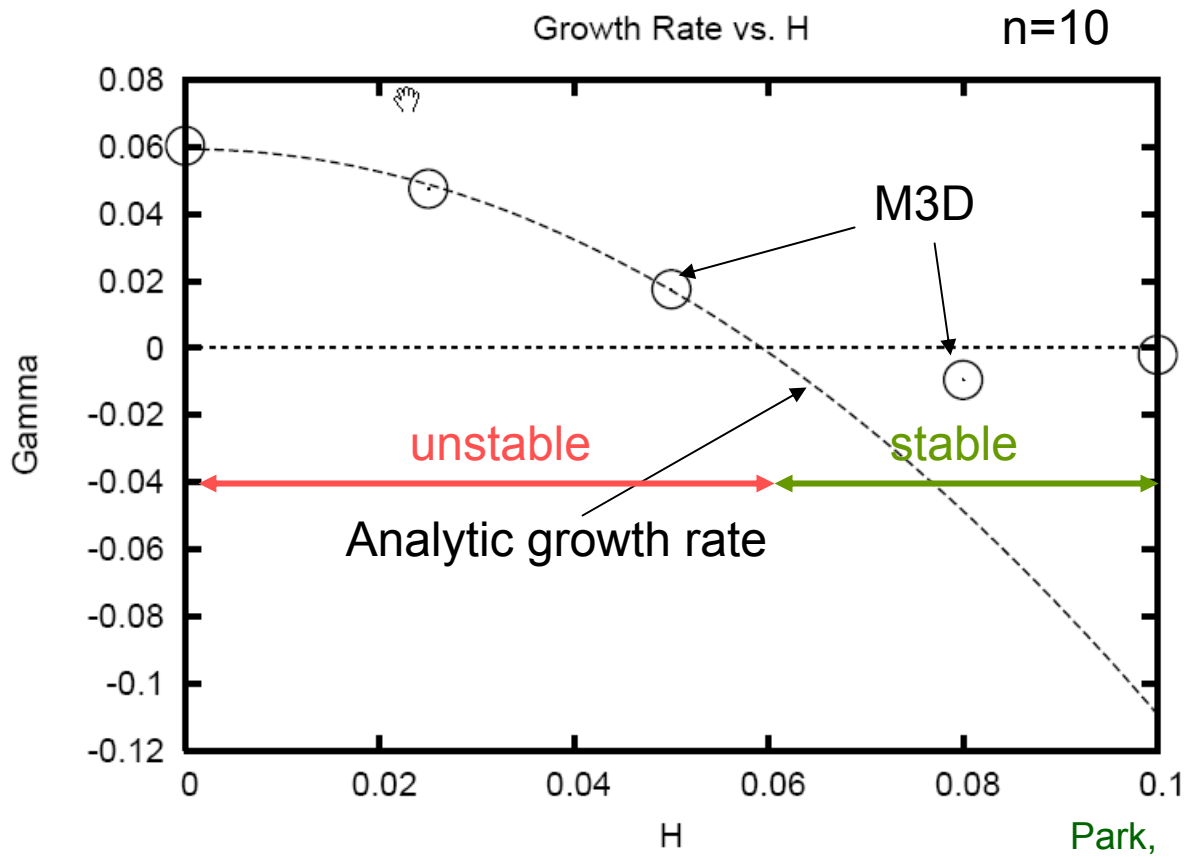
Strauss, Sugiyama, Park, Klasky (M3D)

- Scoping runs were done with 16 planes, limited to $n < 8$. Uses 2nd order lumped mass finite elements.

M3D two-fluid model demonstrates linear gyroviscous ELM Stabilization in agreement with theory



DIII-D n=10 Linear Eigenmode



Park, Strauss

H= $\frac{c}{\omega_{pi} R}$ is two-fluid (hall) parameter

Non-linear calculation is very demanding as fine structure is generated requiring extreme resolution

Milestone:

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

  » PPPL: J. Breslau, M. Chance, J. Chen, G. Fu, W. Park, NYU: Strauss, MIT: Sugiyama

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  - Neoclassical Tearing Mode
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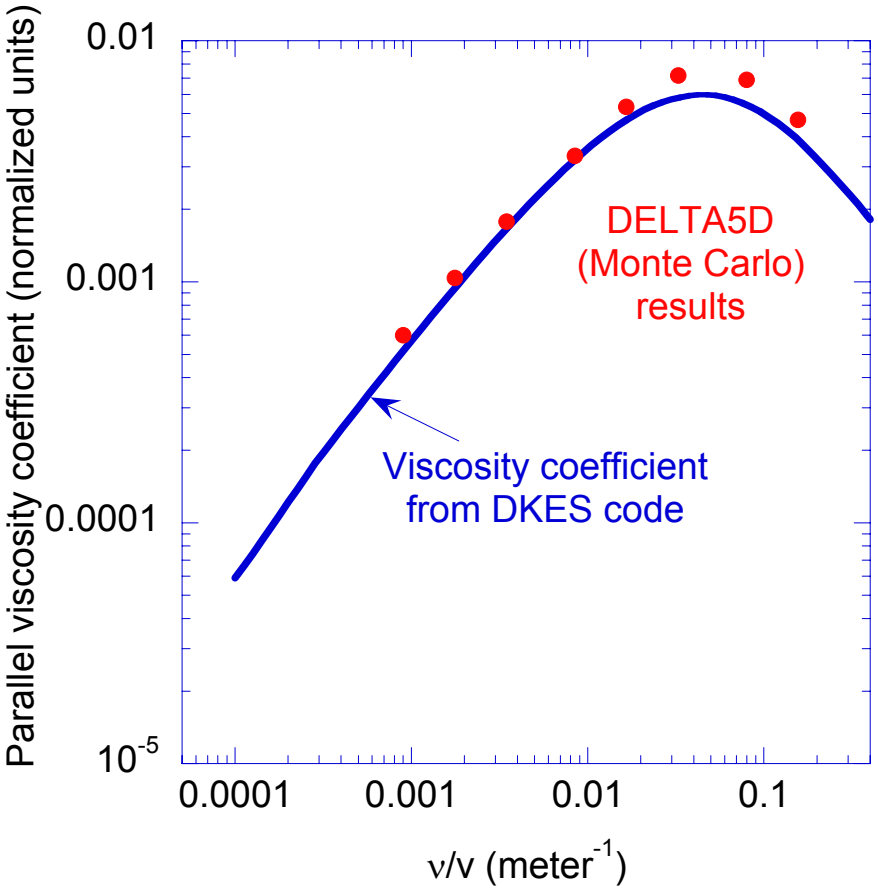
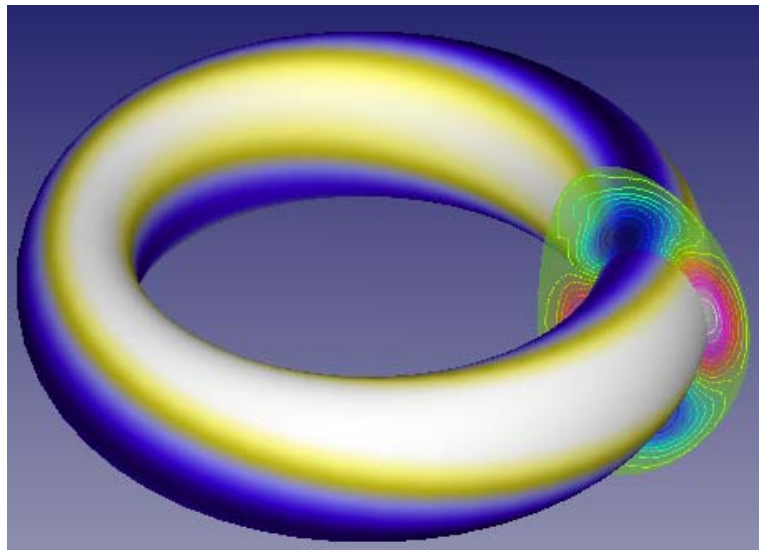
Joint project with ORNL to develop neoclassical closure for M3D for NTM - implement on Cray X1E



Spong



Nonlinear M3D 2/1 tearing mode

Park

$$\begin{bmatrix} \mathbf{B}\cdot(\nabla\cdot\Pi) \\ \mathbf{B}\cdot(\nabla\cdot\Theta) \end{bmatrix} = \begin{bmatrix} M_1 & M_2 \\ M_2 & M_3 \end{bmatrix} \begin{bmatrix} V_{\parallel} \\ Q_{\parallel} \end{bmatrix} + \begin{bmatrix} N_1 & N_2 \\ N_2 & N_3 \end{bmatrix} \begin{bmatrix} \frac{1}{n}\frac{\partial p}{\partial s} - e\frac{\partial \phi}{\partial s} \\ -\frac{\partial T}{\partial s} \end{bmatrix}$$

Into M3D

$$\text{where } M_j, N_j \propto \int_0^\infty dE\, e^{-E/kT} \sqrt{E} \left(E - \frac{5}{2}kT \right)^{j-1} \mu_{\parallel}, N(E)$$

From DKES

•DKES: Drift Kinetic Equation Solver

Hirshman, et al Phys Fluids 29 (1986) 2951

from Sugama & Nishimura, PoP 9 (2002) 4637

Milestones:

- Develop a predictive model of neoclassical tearing modes in tokamaks and STs together with researchers at ORNL ***(2008).***
  - » PPPL: W. Park, G.Y. Fu, J. Breslau, J. Chen, S. Jardin ORNL: D. A. Spong, E. F. D'Azevedo, D. B. Batchelor, D. del-Castillo-Negrete, M. Fahey, S. P. Hirshman, S. Klasky , R. T. Mills
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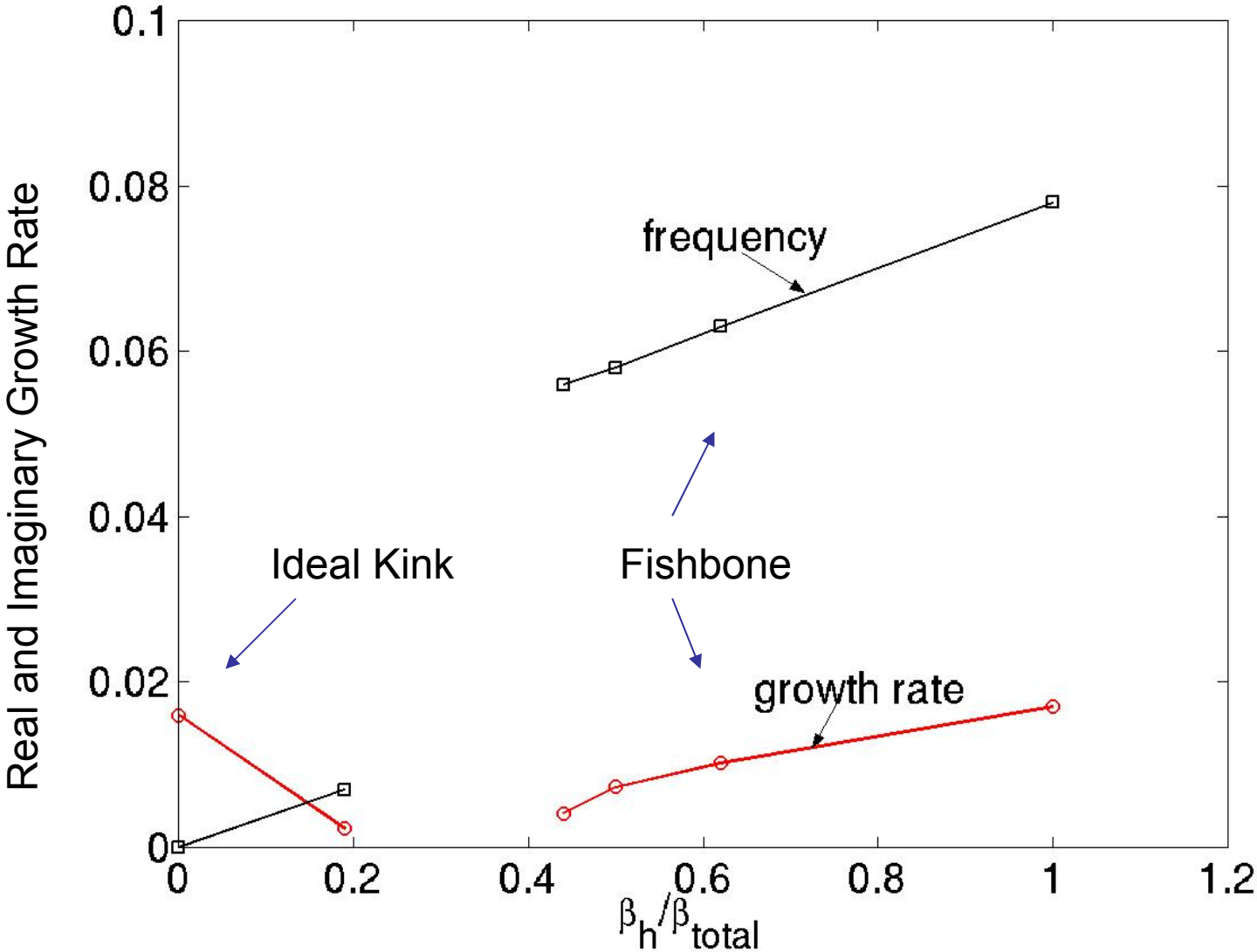
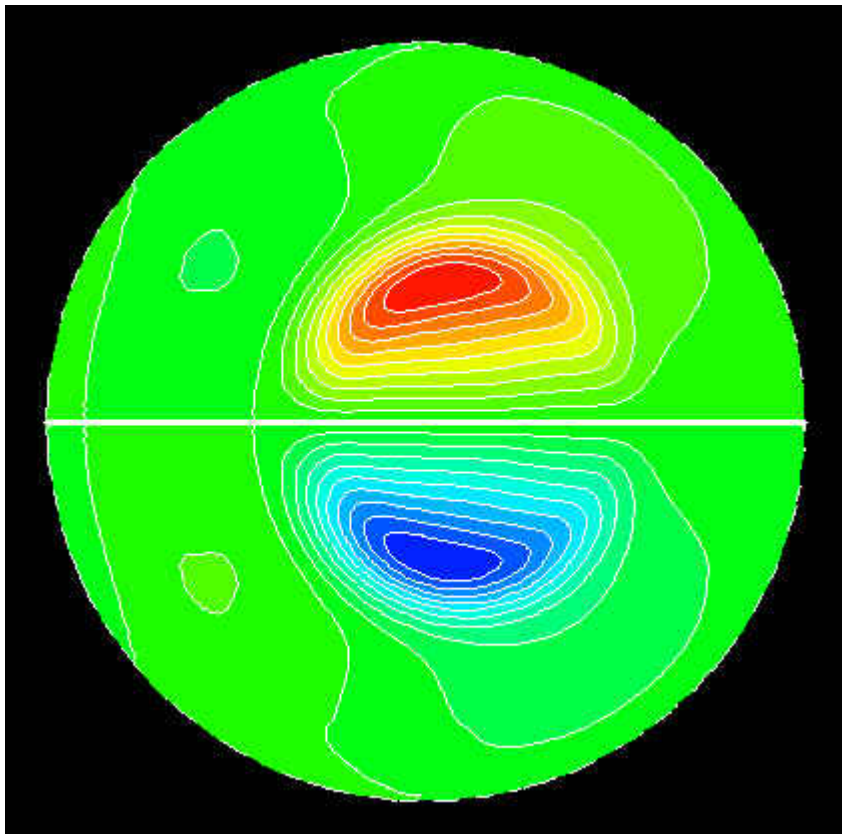
M3D-hybrid (linear) calculation of energetic particle stabilization of Ideal Kink and excitation of Fishbone



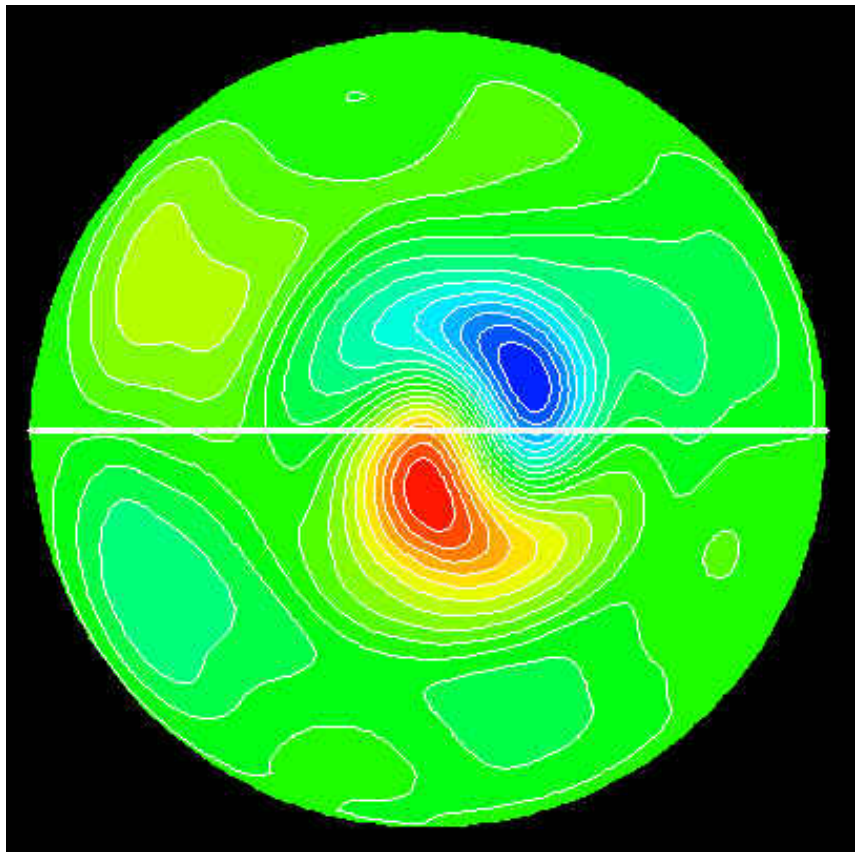
Circular
R/a=2.76
q(0)=0.9,
q(a)=2.5
β(0) = 5.7%

Fu

Mode structure of Fishbone twists and rotates relative to Ideal Kink mode structure



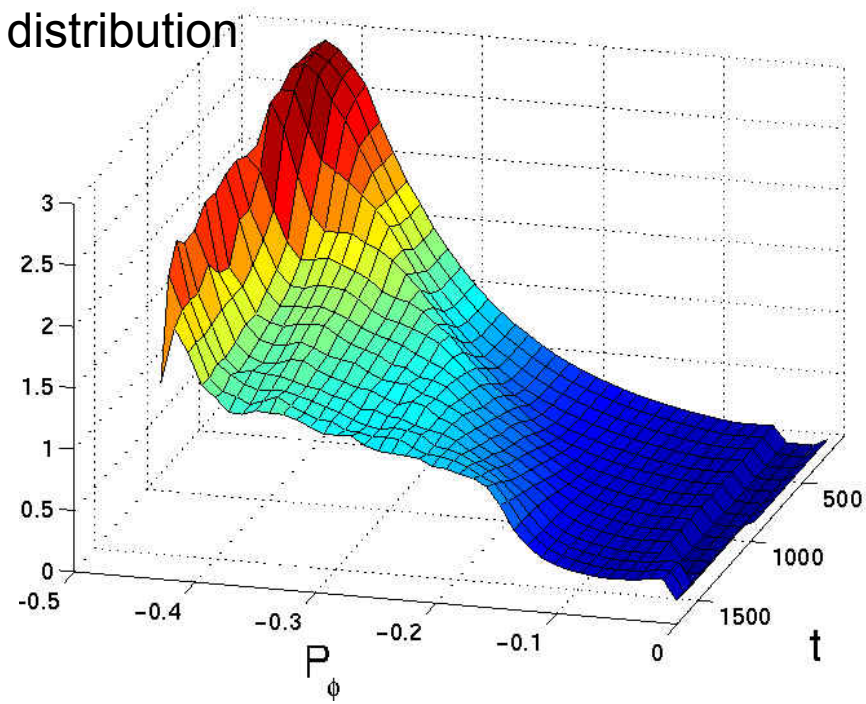
Ideal Kink

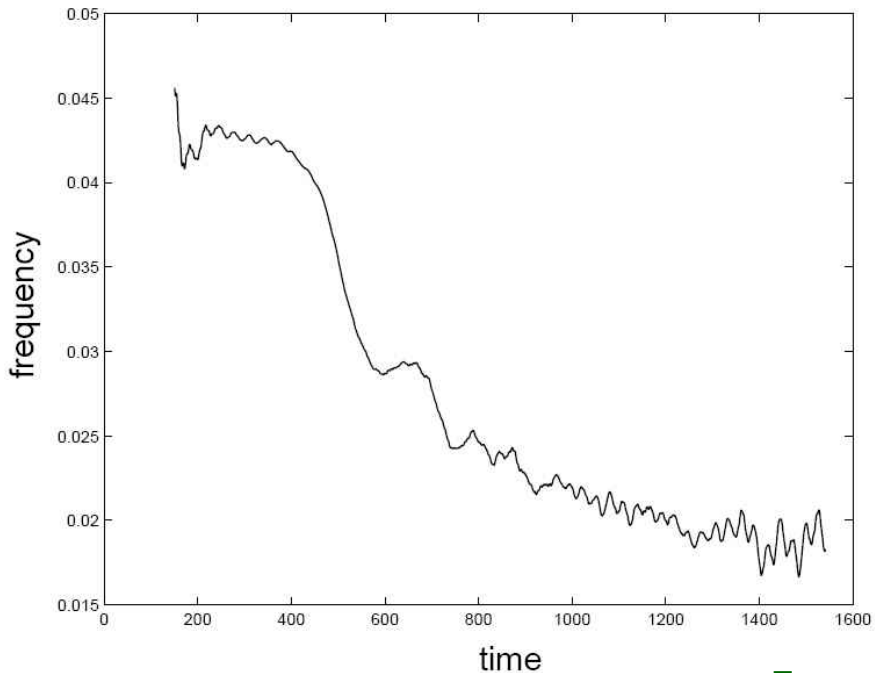


Fishbone

Fu

In nonlinear fishbone calculation, distribution function flattens and broadens and mode frequency chirps down.





Fu

Milestones:

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

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Normal Mode Analysis: The DCON, VACUUM, and a Circuits code have been combined to produce a self-consistent linear RWM code

- represent an arbitrary plasma displacement as a linear combination of a <u>complete set</u> of plasma eigenfunctions (including stable eigenmodes)

$$\delta W_p + \delta W_V = 0 \quad \Rightarrow \quad \vec{\xi} = \sum_{i=1}^{N} a_i(t)\vec{\xi}_i(x)$$

- add the feedback system, inertia, and conductors; specify ω, and calculate the self consistent response

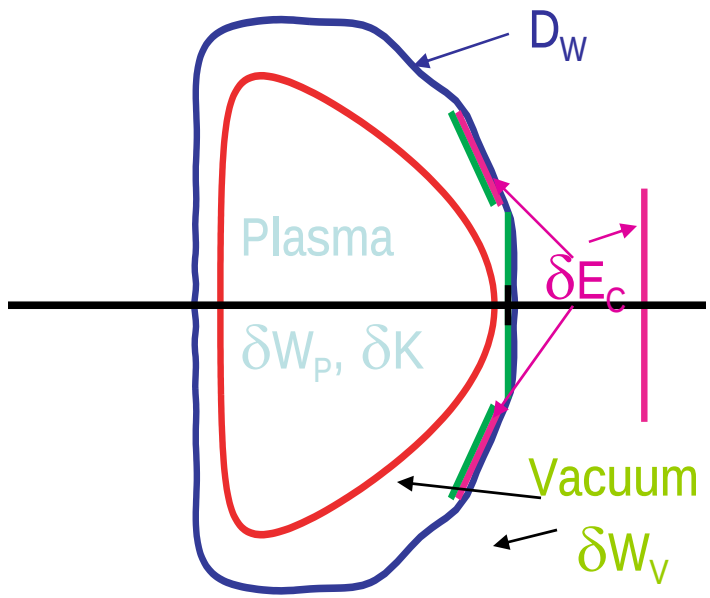
$$\delta W_p + \delta K(\omega) + \delta W_V + D_W(\omega) + \delta E_C(\omega) = 0$$

Kinetic Energy — Wall Dissipation — Coil Excitation Energy

- vary ω and use Nyquist techniques to evaluate stability

- It was found that it is important to keep the feedback system effects in determining the eigenfunction

(important to keep the "stable" modes in the analysis)



Chu, Chance

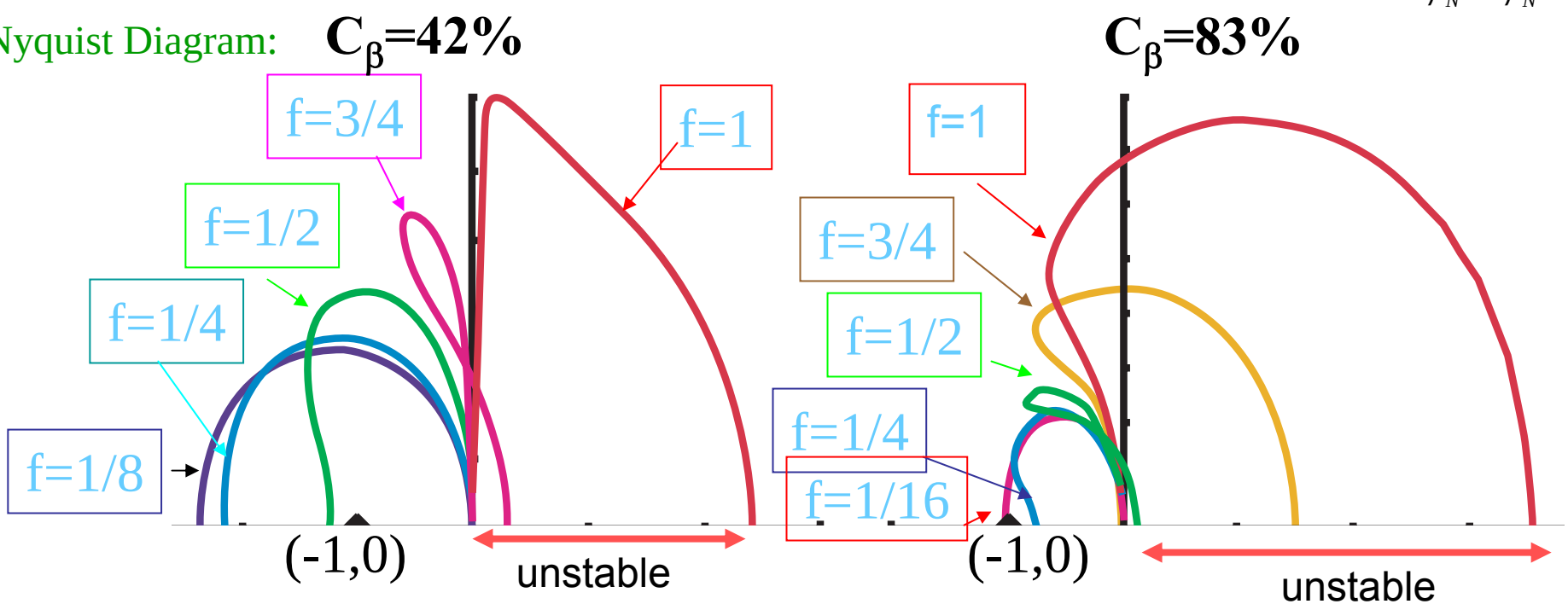
The n=1 RWM feedback system always appears more stable if we use a rigid eigenfunction (ie, remove the "stable" modes)

To illustrate the importance of the stable modes (eigenfunction deformability) we <u>artificially remove them</u> by multiplying them by a constant f→0 and show how the stability diagram changes:

$R_i \longrightarrow f\,R_i$ for all stable modes, let f→ 0

$$C_\beta = \frac{\beta_N - \beta_N^{NW}}{\beta_N^{IW} - \beta_N^{NW}}$$

Nyquist Diagram:

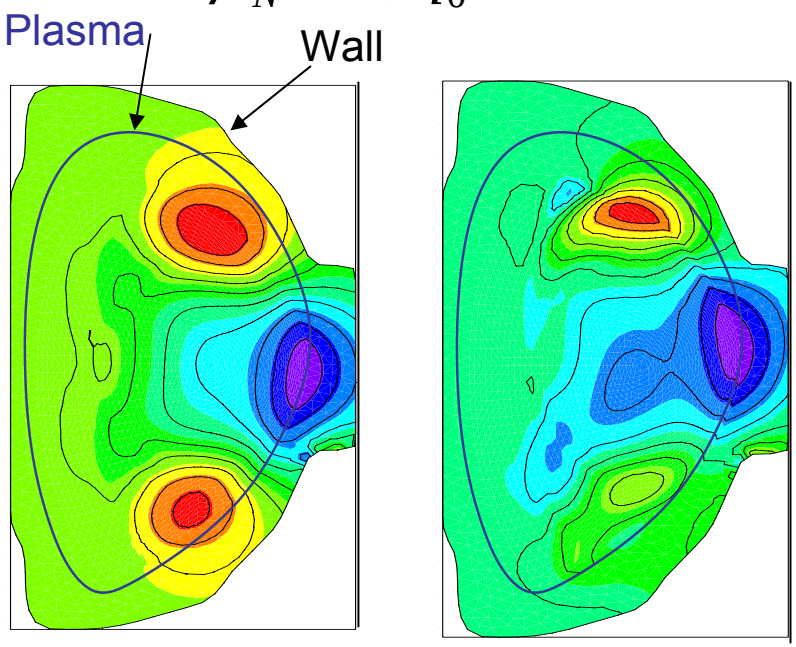


Stable if transfer function P(ω) encircles (-1,0)

Chu, Chance

M3D simulations examining role of plasma η and rotation on the resistive wall, resistive plasma mode

$$\beta_N = 5, q_0 = 1.7$$



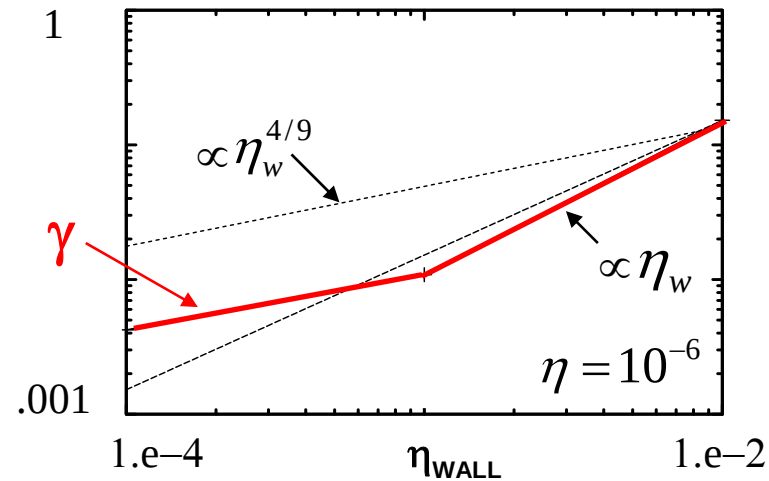
Perturbed Poloidal flux at $\Omega = 0$

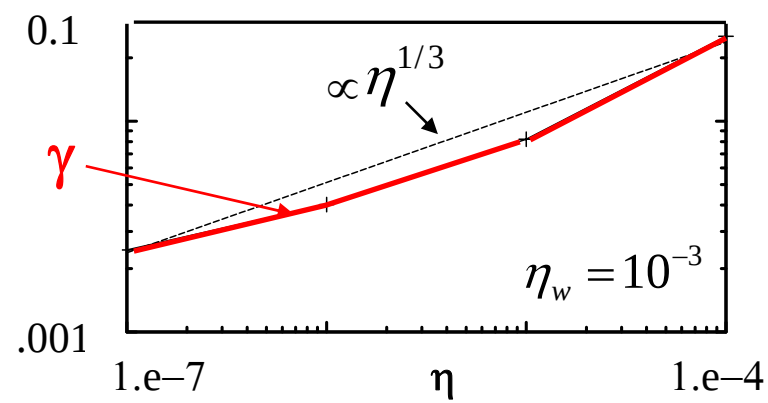
Saturates at $\Omega = 0.05 \frac{v_A}{R}$ w/ collisional viscosity

Better dissipation models (closures) needed

$$\gamma \sim \eta^{1/3} \eta_w^{4/9}$$ similar to analytic scaling

Finn 1995; Betti 1998





RWM interacts w/ tearing / η-ballooning mode

Strauss, Sugiyama, Park

Milestones:

- Extend the VACUUM code to be fully up-down asymmetric capable, and incorporate the same vacuum code in M3D that is used in the linear eigenvalue codes ***(2006).***

- Perform a study on NSTX, similar to what was done on DIII-D, of RWM feedback as a function of the geometry and placement of the coil system. ***(2007)***

- Extend the vacuum treatment to allow for 3D structures ***(2007-2008).***

  » PPPL: M. Chance, W. Park, J. Breslau, GA: Chu, NYU: H. Strauss

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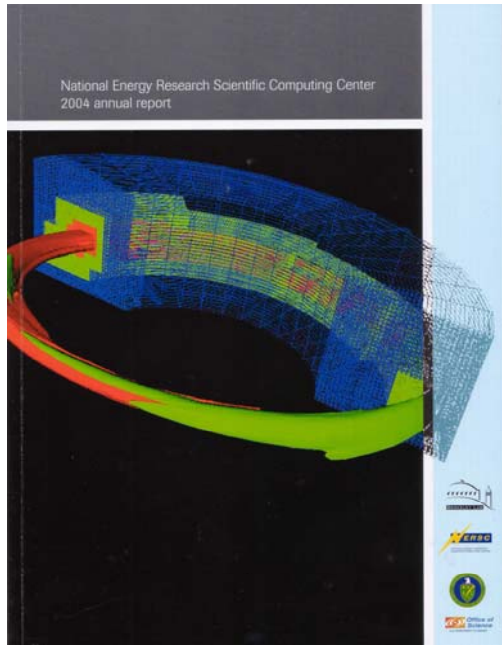
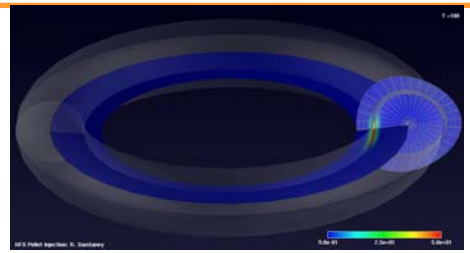
Adaptive Mesh Refinement (AMR) MHD Code is an exploratory project with LBNL

- Initial focus is on the MHD associated with frozen pellet or supersonic gas injection into a tokamak
- We implemented conservative finite volume upwind numerical method for MHD into CHOMBO: now part of release
- Together with LBNL, introduced a non-orthogonal flux coordinate system into the CHOMBO AMR framework
- Electron heat flux model by Ishizaki, Parks
- Full 3D toroidal geometry
- Will be presented in invited talk at 2006 DPP-APS
- Now exploring combining with “implicit” ODE solver (Samtaney, Reynolds, Woodward (LLNL)



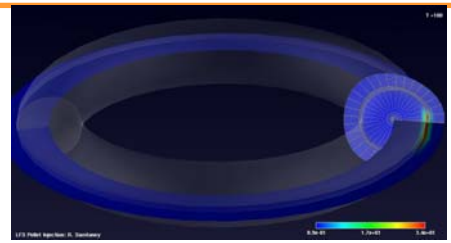
R. Samtaney with APDEC center: P. Colella

AMR-MHD code simulation of pellet injection show qualitative differences between HFS and LFS launch

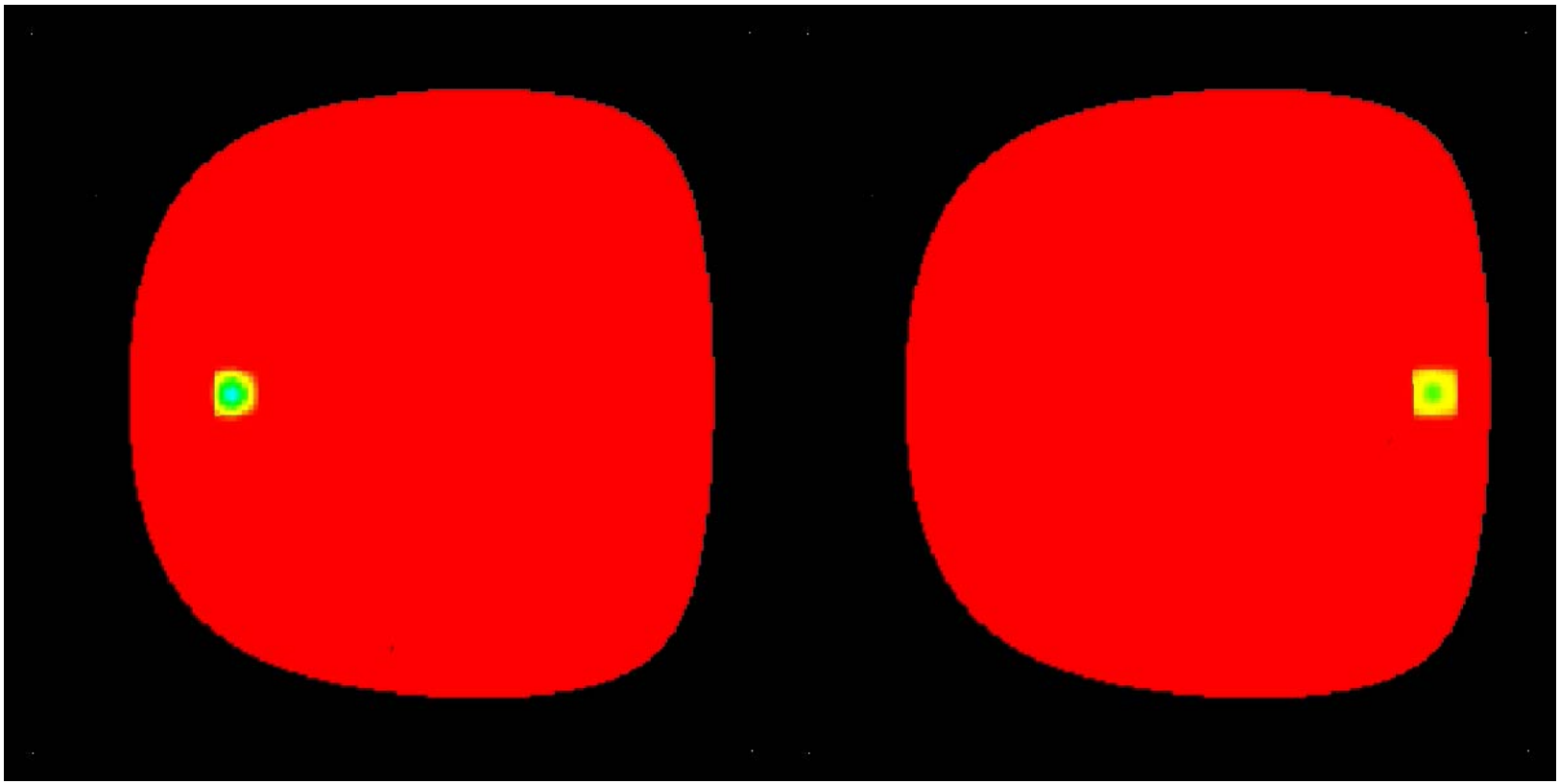


High-Field Side Launch

Density



Low-Field Side Launch



Milestones:

- Develop a realistic 3D model of pellet injection into a tokamak based on the AMR technique, publish this, and present as an APS invited talk ***(CEMM 2006)***

- Improve efficiency, and use to compare inside and outside pellet simulations with JET data ***(CEMM 2008)***

- Further improve efficiency and use to project pellet injection simulations to ITER ***(CEMM 2010)***

  » PPPL: R. Samtaney, S. Jardin LBNL: P. Colella, D. Reynolds, LLNL: D. Reynolds, C. Woodward

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New Directions in Nonlinear Extended 3D MHD

We are looking to improve the M3D spatial representation, time advance, and physics models through a number of exploratory projects that we or our collaborators are involved in:

- 2nd and 3rd order lumped mass finite elements (Strauss, Sugiyama, Chen)
- Spectral Elements with semi-implicit time advance (Strauss, Hientzsc)
- Spectral Elements with Newton/Krylov time advance on structured adaptive mesh (Glasser, Lukin)
- C^1 elements: high-order, high-continuity, implicit time advance on unstructured adaptive mesh: **M3D-C^1** (Jardin, Breslau, Chance, Chen, Ferraro, Miah, Bauer)

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M3D-C[1] code has full Extended MHD (2-fluid) equations with implicit differencing that allows time step to be determined by accuracy only:

$$\vec{V} = \nabla U \times \hat{z} + \nabla_{\perp}\chi + V_z$$
$$\vec{B} = \nabla \psi \times \hat{z} + I\hat{z}$$

$$\begin{bmatrix} S^v_{11} & S^v_{12} & S^v_{13} \\ S^v_{21} & S^v_{22} & S^v_{23} \\ S^v_{31} & S^v_{32} & S^v_{33} \end{bmatrix} \bullet \begin{bmatrix} U \\ V_z \\ \chi \end{bmatrix}^{n+1} = \begin{bmatrix} D^v_{11} & D^v_{12} & D^v_{13} \\ D^v_{21} & D^v_{22} & D^v_{23} \\ D^v_{31} & D^v_{32} & D^v_{33} \end{bmatrix} \bullet \begin{bmatrix} U \\ V_z \\ \chi \end{bmatrix}^{n} + \begin{bmatrix} R^v_{11} & R^v_{12} & R^v_{13} \\ R^v_{21} & R^v_{22} & R^v_{23} \\ R^v_{31} & R^v_{32} & R^v_{33} \end{bmatrix} \bullet \begin{bmatrix} \psi \\ I \\ T_e \end{bmatrix}^{n}$$

Equations expressed in a form that allows non-trivial subsets of lower rank equations:

Alfven Wave physics

$$\begin{bmatrix} S^p_{11} & S^p_{12} & S^p_{13} \\ S^p_{21} & S^p_{22} & S^p_{23} \\ S^p_{31} & S^p_{32} & S^p_{33} \end{bmatrix} \bullet \begin{bmatrix} \psi \\ I \\ T_e \end{bmatrix}^{n+1} = \begin{bmatrix} D^p_{11} & D^p_{12} & D^p_{13} \\ D^p_{21} & D^p_{22} & D^p_{23} \\ D^p_{31} & D^p_{32} & D^p_{33} \end{bmatrix} \bullet \begin{bmatrix} \psi \\ I \\ T_e \end{bmatrix}^{n} + \begin{bmatrix} R^p_{11} & R^p_{12} & R^p_{13} \\ R^p_{21} & R^p_{22} & R^p_{23} \\ R^p_{31} & R^p_{32} & R^p_{33} \end{bmatrix} \bullet \begin{bmatrix} U \\ V_z \\ \chi \end{bmatrix}^{n+1} + \begin{bmatrix} Q^p_{11} & Q^p_{12} & Q^p_{13} \\ Q^p_{21} & Q^p_{22} & Q^p_{23} \\ Q^p_{31} & Q^p_{32} & Q^p_{33} \end{bmatrix} \bullet \begin{bmatrix} U \\ V_z \\ \chi \end{bmatrix}^{n}$$

Whistler, KAW, field diffusion physics

Phase-I: Reduced 2-field MHD:

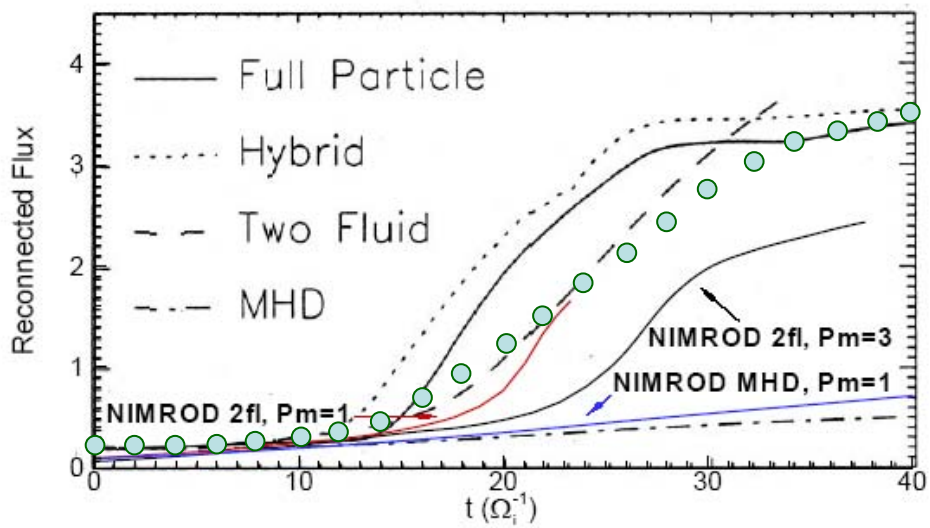
$$\frac{\partial}{\partial t}\nabla^2 U + \left[\nabla^2 U, U\right] - \left[\nabla^2\psi, \psi\right] = \mu\nabla^4 U$$
$$\frac{\partial \psi}{\partial t} + \left[\psi, U\right] = \eta\nabla^2\psi$$

Phase-II: Fitzpatrick-Porcelli 4-field model:

$$\frac{\partial}{\partial t}\nabla^2 U = \left[U, \nabla^2 U\right] + \left[\nabla^2\psi, \psi\right] + \mu\nabla^4 U$$
$$\frac{\partial V_z}{\partial t} = \left[U, V_z\right] + c_\beta\left[I, \psi\right] + \mu\nabla^2 V_z$$
$$\frac{\partial \psi}{\partial t} = \left[U, \psi\right] + d_\beta\left[\psi, I\right] + \eta\nabla^2\psi$$
$$\frac{\partial I}{\partial t} = \left[U, I\right] + d_\beta\left[\nabla^2\psi, \psi\right] + c_\beta\left[V_z, \psi\right] + c_\beta^2\eta\nabla^2 I$$

M3D-*C*[1] has been tested against a number of test problems, including the GEM Challenge Problem (Birn, et al. JGR)

Reconnected magnetic flux in the GEM Challenge problem as a function of time

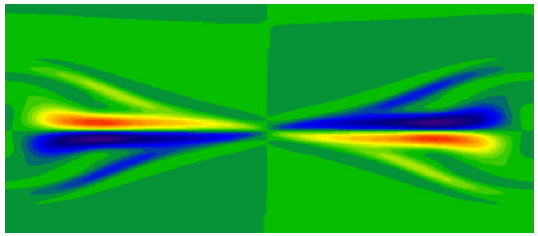


M3D-*C*[1], *zero ion pressure, uniform density, $\eta=\mu=0.001$*

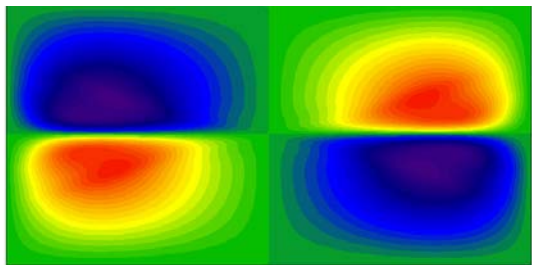
- The calculations presented in this figure all have different physics models and slightly different initial conditions and parameters
- However, all models with two-fluid physics (ie, the Hall Term) show fast reconnection. Single fluid resistive MHD does not
- **M3D-*C*[1]** also shows fast reconnection
- Demanding problem with no guide field, and in which Alfvenic, highly compressible flows develop

M3D-*C*^{1} 61x61 triangles, no symmetry imposed: t=30
GEM Magnetic Reconnection: 6-field 2-fluid model: t=30, $V_{MAX} \sim 0.8\ V_A$

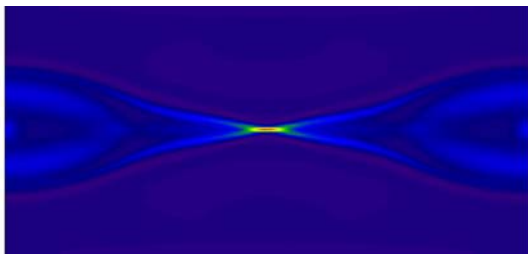
$\nabla^2 U$
Vorticity



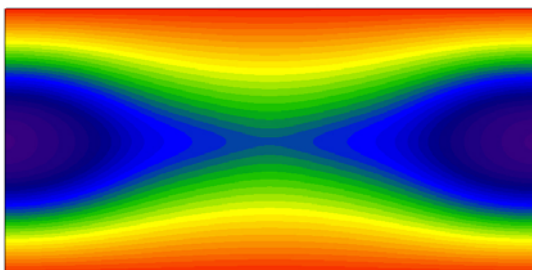
U
Stream Function



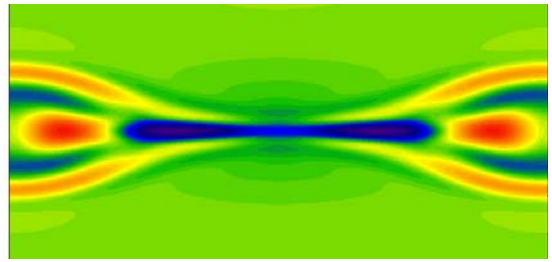
$J = \nabla^2 \Psi$
Toroidal Current



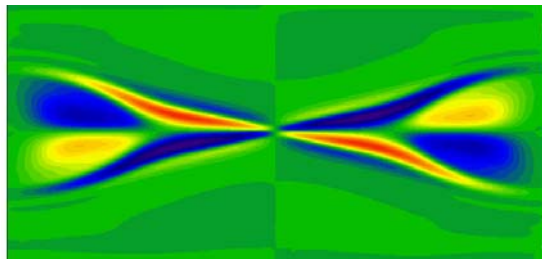
Ψ
Poloidal Flux



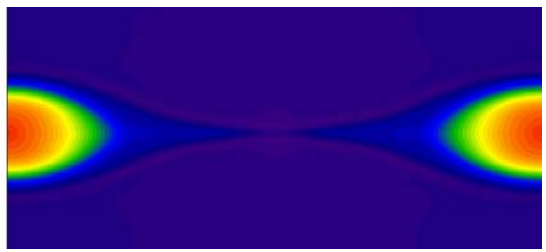
V
Toroidal Velocity



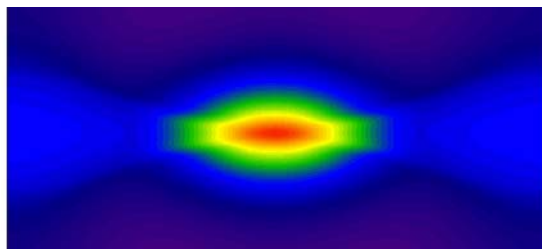
I
Toroidal field



P_e
Electron Pressure



χ
Velocity Potential



Milestones:

- Extend C^1 elements to 2-fluid linear 3D simulation (CEMM 2007)
- Extend C^1 elements to full 2-fluid non-linear 3D simulation (CEMM 2008)

» PPPL: Jardin, Breslau, Chance, Chen, Ferraro, Miah RPI: Bauer

Outline

- Progress and plans in 3D MHD Modeling
- Relation to Integrated Modeling
- Progress and plans towards the 1½D Integrated Plasma Simulator
- Other activities
- Summary

What is Integrated Modeling?

1½D Integrated Plasma Simulator

- Equilibrium Module
- MHD Module
- α-particle and beam Module
- Edge Module
- RF Modules
- Transport Module

Reduced models

"first principles" codes

- 5D Gyrokinetics Code
- 3D Extended MHD Code
- Full Wave RF Code
- …

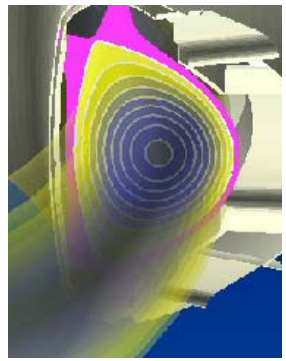
"first principles" coupled codes

- 5D Gyrokinetics Code + 3D Extended MHD Code
- 3D Extended MHD Code + Full Wave RF Code

- develop new understanding
- improve reduced models

In the foreseeable future, *comprehensive integration* will mean using a 1½ D IPS with reduced models, and using the "first principles" code to examine time slices and develop improved reduced models.

Integrated Plasma Simulator:
1½ D Transport timescale code with *reduced models* for 3D phenomena
(with fast timescales averaged over)



0 100 200 300 400

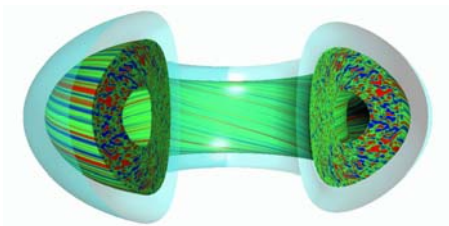
Time (sec)

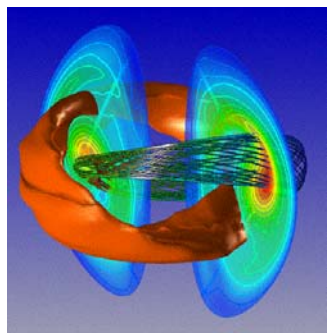
Telescope in on time of interest to examine short timescales in more depth

Turbulence, MHD, or coupled code (s)
(with fast timescales being calculated)

0 100 200

Time (μsec)





Outline

- Progress and plans in 3D MHD Modeling
- Relation to Integrated Modeling
- Progress and plans towards the 1½D Integrated Plasma Simulator
  - TSC →TSC/TRANSP → PTRANSP → FSP
- Other activities
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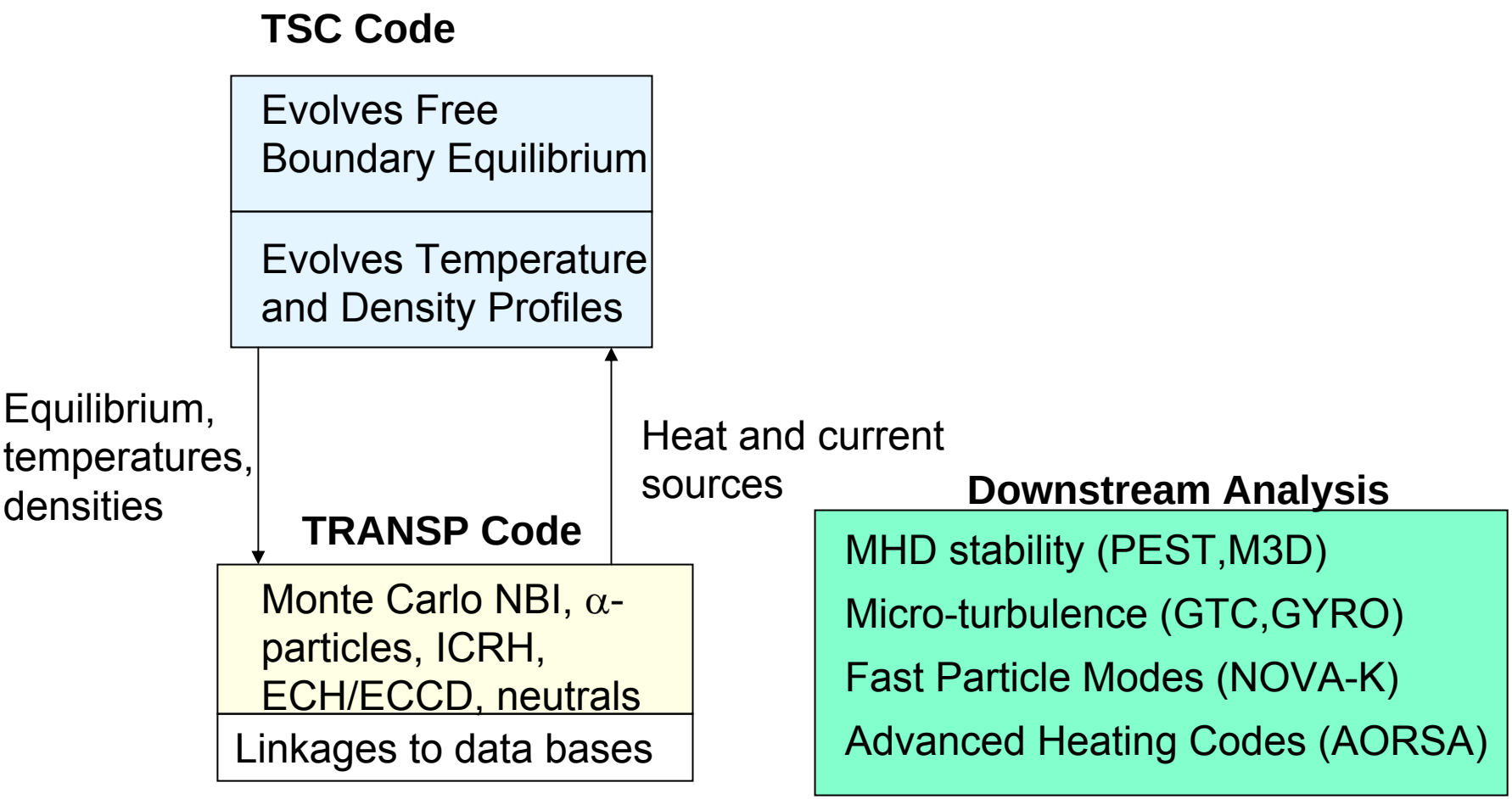
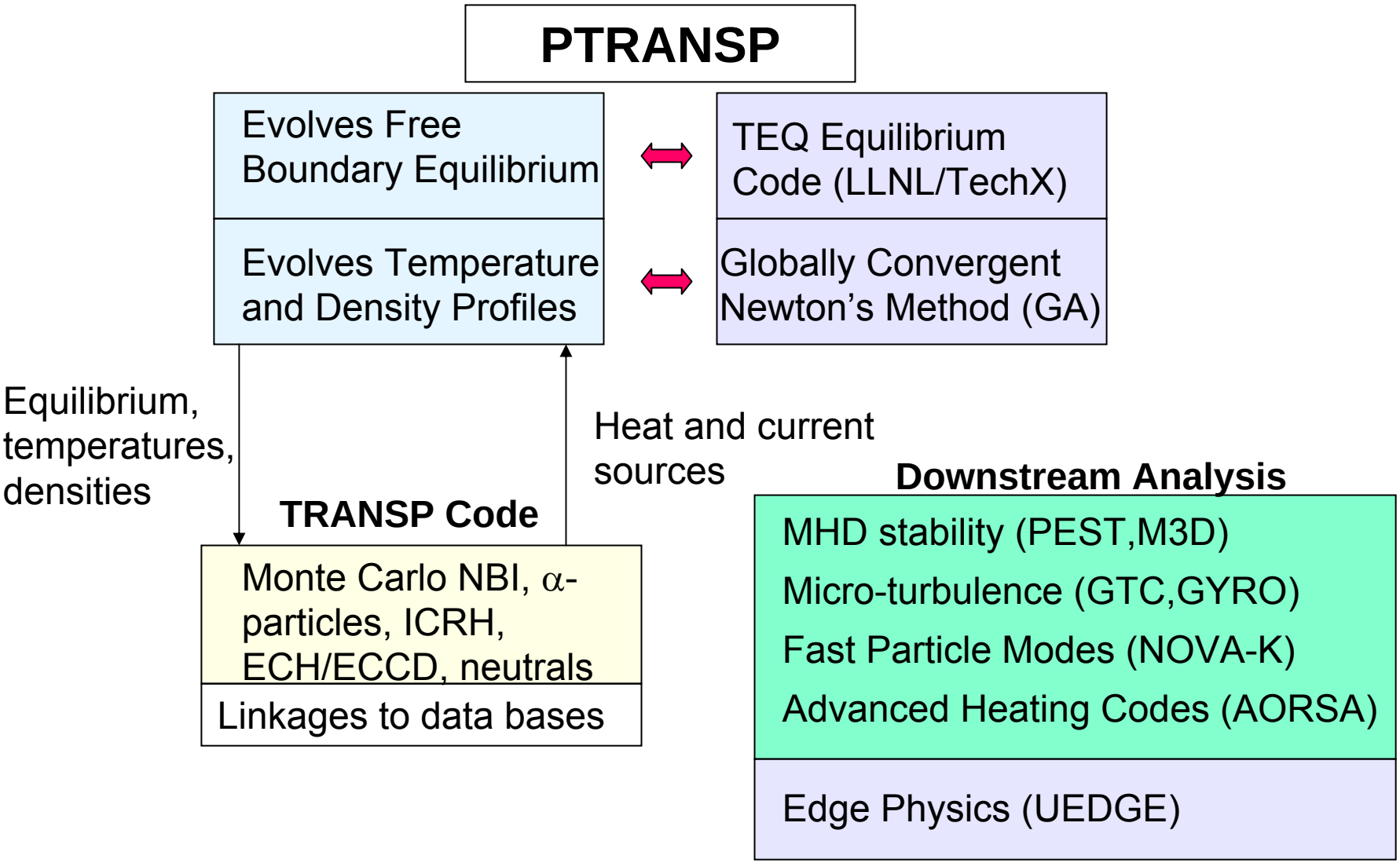
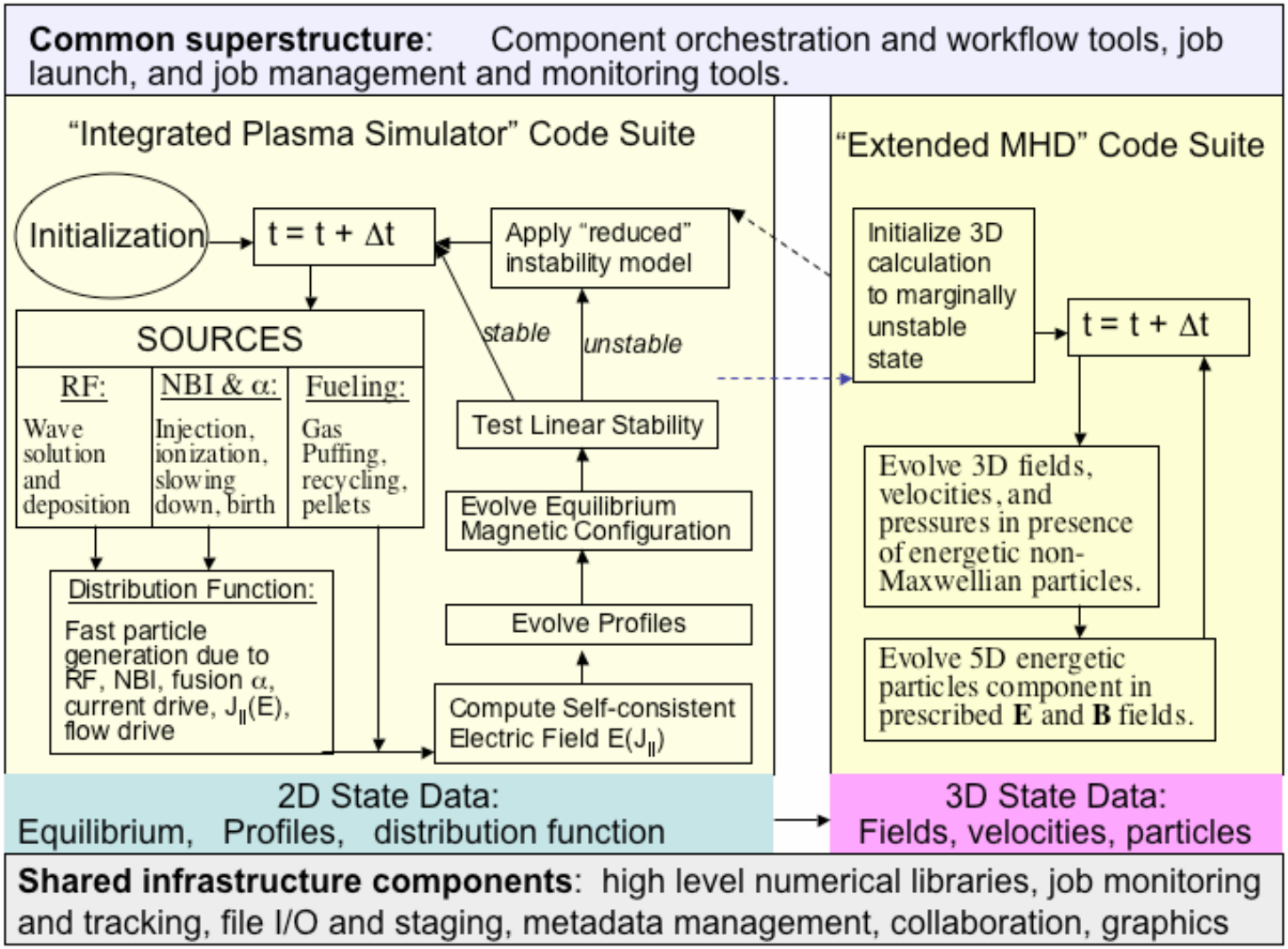
Initial Implementation of the 1½D Integrated Plasma Simulator



Initial Implementation of the 1½D Integrated Plasma Simulator



The Simulation of Wave Interaction with MHD (SWIM) project will extend this to RF/MHD Coupling



"Fast MHD Campaign"From Batchelor, et. al. SWIM proposal.

Milestones:

- Predictive TRANSP code capable of performing ITER-relevant calculations routinely in the fixed and free-boundary modes, capabilities for linkage to existing databases and post-run analysis codes and with coupling to UEDGE. ***(2007 PTRANSP)***

  » PPPL: Jardin, McCune, R. Andre, K. Indireshkumar, Ku, Kessel GA: StJohn LLNL: LoDestro, Ronglien, Cohen LeHigh U.: Bateman, Kritz TechX: Carlson

- Complete SWIM "Fast MHD" campaign including the use of Fokker-Plank codes to calculate RF modified distribution function, and the transfer and analysis of this by the 3D stability codes. ***(2010 SWIM)***

  » PPPL: S. C. Jardin, J. Breslau, G-Y Fu, D. McCune, W. Park, J. Chen ORNL: D. B. Batchelor, L. A. Berry, S. P. Hirshman, W. A. Houlberg, E. F. Jaeger, D. A. Spong, D. E. Bernholdt, E. D'Azevedo, W. Elwasif, M. R. Fahey, S. Klasky Indiana Univ: R. Bramley Columbia Univ: D. Keyes GA: D. P. Schissel CompX: R. Harvey SAIC: D. Schnack MIT: J. Ramos, L. Sugiyama

Outline

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Other Activities

- Equilibrium Reconstruction
  - Developed new code Cbc2e which uses time-history in equilibrium reconstruction to accurately account for eddy currents
- Real-Time Forecasting (RTF) for Tokamak Discharges
  - Prototyped a system for Real Time Forecasting to evolve plasma models to make real-time decisions in operating tokamaks (extension of RT-EFIT)
- The LiWall Concept
  - Extensive analysis of a high-beta Spherical Torus with liquid-lithium walls as a path to Fusion Energy
- CHI Physics
  - Developed special equilibrium reconstruction and evolution codes to support NSTX Coaxial Helicity Injection (CHI) experiments
- MRX Modeling
  - High resolution numerical simulations of the 2D 2-fluid MHD equations and comparing with MRX data (PhD Thesis)

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Summary of Activities and Milestones:

- ITER analysis with free boundary PTRANSP code: coupling to UEDGE and downstream stability codes (PTRANSP)
- Study of Sawtooth (with energetic particle), EPM, RWM, ELM, Pellet Injection & development of C^1 element code (CEMM)
- (De)Stabilizing effects of RF on MHD for Sawtooth and NTM in ITER relevant plasmas (SWIM)
- Predictive model of NTM in tokamaks and STs using new neoclassical closures (on Cray X1E) (with ORNL)
- Self-consistent linear analysis of RWM in NSTX and ITER.
- Interpret beam-driven modes in NSTX.
- Basis studies of reconnection. Kinetic effects on MHD.
- Real time forecasting of tokamak discharges.
- Heterogeneous parallel computational services, advanced visualization and data workflow, improved parallelization efficiency (CPPG)

PPPL personnel involved:
J. Breslau, M. Chance, G. Fu, W. Park, L. Zakharov (Theory)
R. Andre, J. Chen, K. Indireshkumar, D. McCune, R. Samtaney (CPPG)
N. Ferraro, V. Lukin, M. Miah (students)