Field Reversed Configuration Theory and Modeling

presented by Elena Belova

PPPL

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Objectives and Collaborations

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

FESAC Priorities Panel Report:

T5. How are electromagnetic fields and mass flows generated in plasmas?

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

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

Main Objectives:

- Develop and apply state-of-the-art numerical simulations to provide an improved understanding of FRC formation and stability properties.
- Validate the theoretical models, and improve agreement between theory and existing experimental results.
- Provide theoretical support and guidance for FRC experiments.

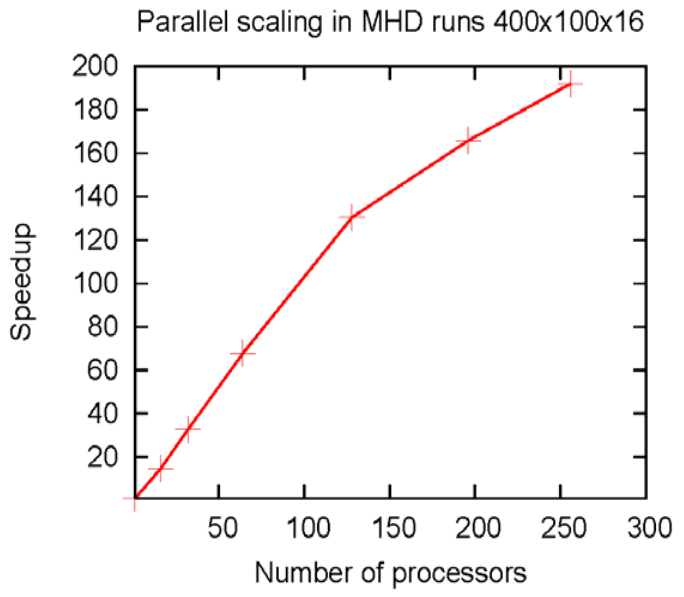
Personnel: E. Belova, R.C. Davidson, H. Ji, M. Yamada

Collaborations: M. Brown and C. Cothran (Swarthmore College), M. Schaffer (GA), R. Milroy and *Plasma Science and Innovation Center* (U. Washington), S. Cohen, MRX team (PPPL)

HYM – Unique Parallel Hybrid/MHD Code

HYM code developed and used to investigate FRC formation and stability properties

- 3-D nonlinear.
- Three different physical models:
  - Resistive MHD & Hall-MHD.
  - Hybrid (fluid electrons, particle ions).
  - MHD/particle (one fluid thermal plasma, + energetic particle ions)
- Full-orbit kinetic ions.
- For particles: delta-f / full-f numerical scheme.
- Parallel (3D domain decomposition, MPI).

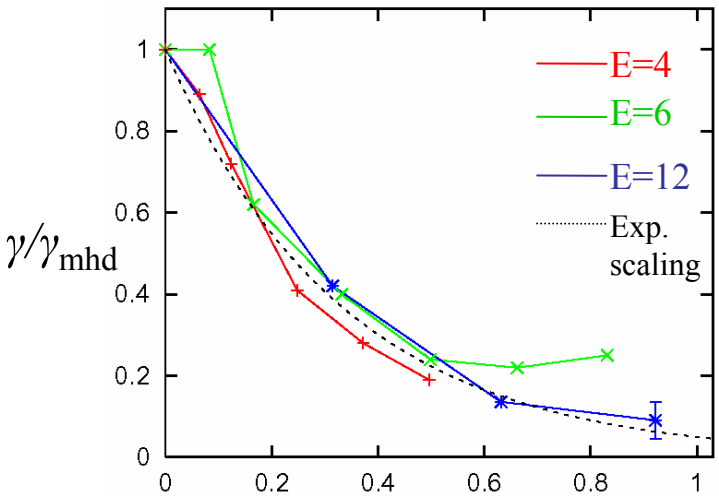


N_{procs}

New MPI version of HYM show very good parallel scaling up to 250 processors for production-size jobs.

HYM Explains S*/E Scaling Observed Experimentally

Hybrid simulations have shown that ion FLR effects determine linear stability properties of the *n*=1 tilt mode in prolate FRCs[1].



Hybrid simulations for equilibria with elliptical separatrix and different elongations: *E*=4, 6, 12. For *E/S**>0.5, resonant ion effects are important.

New empirical scaling:

$$\gamma = \underbrace{\frac{V_A}{R_s E}}_{\text{MHD}} \underbrace{\exp\left(-3E\frac{\rho_i}{R_s}\right)}_{\text{kinetic (FLR)}}$$

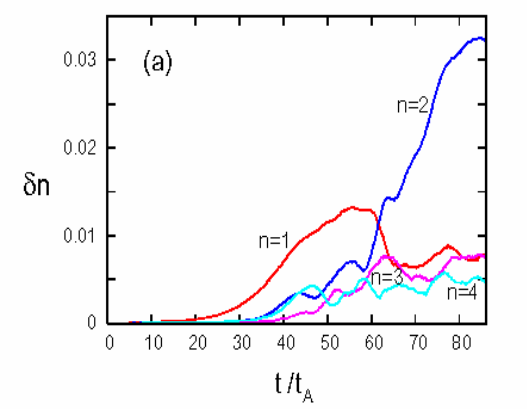
Elliptical equilibria:

- For *S*/E>1-2* growth rate is function of *S*/E.*

Racetrack equilibria - *S*/E*-scaling does not apply.

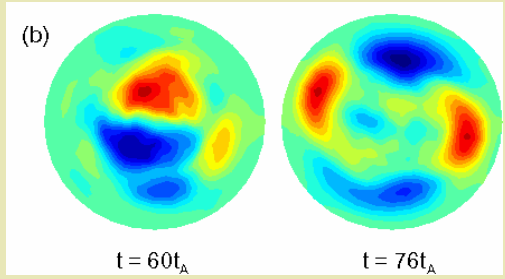
[1]*S*/E* parameter determines the experimental stability boundary [*M. Tuszewski,1998*].

Nonlinear Evolution and Ion Toroidal Spin-up are Now Understood



Time evolution of different Fourier harmonics of density perturbation.

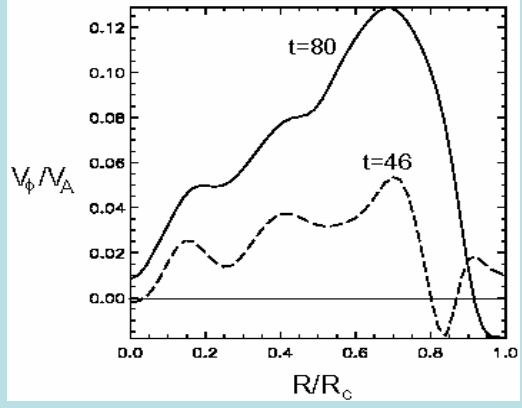
Nonlinear studies of the evolution of MHD modes in FRC configurations demonstrate the importance of ion toroidal spin-up on the nonlinear saturation of the *n*=1 tilt mode, and growth of the *n*=2 rotational instability.



Contour plots of density perturbation from 3D hybrid simulations of a kinetic prolate FRC.

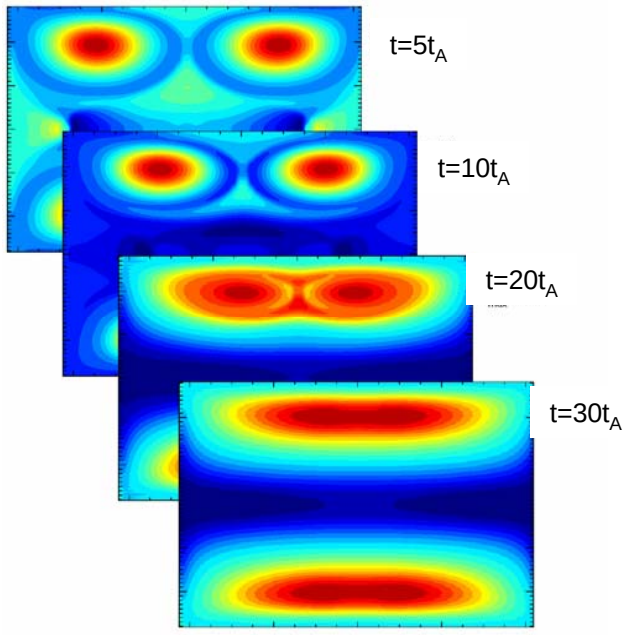
Ion spin-up is related to the resistive decay of magnetic flux and the resulting loss of weakly confined particles from the closed-field-line region.

- Spin-up up to 0.1- 0.3V_A in the direction of the current observed at t>40 t_A.
- Similar ion rotation is seen in the experiments.



Radial profile of ion flow velocity.

Simulation Study of Counter-Helicity Spheromak Merging and FRC Formation



2D counter-helicity spheromak merging simulations in support of SSX-FRC experiment. Pressure evolution.

New FRC formation method by counter-helicity spheromak merging has been developed in U. Tokyo, MRX and SSX-FRC experiments.

- Three-dimensional MHD simulations of counter-helicity spheromak merging using HYM code provides an explanation for the observed plasma behavior in the SSX-FRC experiment:

  Persistence of the toroidal fields and slower-than-MHD growth of the tilt instability are shown to be related to field line-tying effects and large viscosity in SSX plasmas.

- New signatures of Hall-reconnection have been observed in two-fluid simulations of MRX experiment with different magnetic field polarities.

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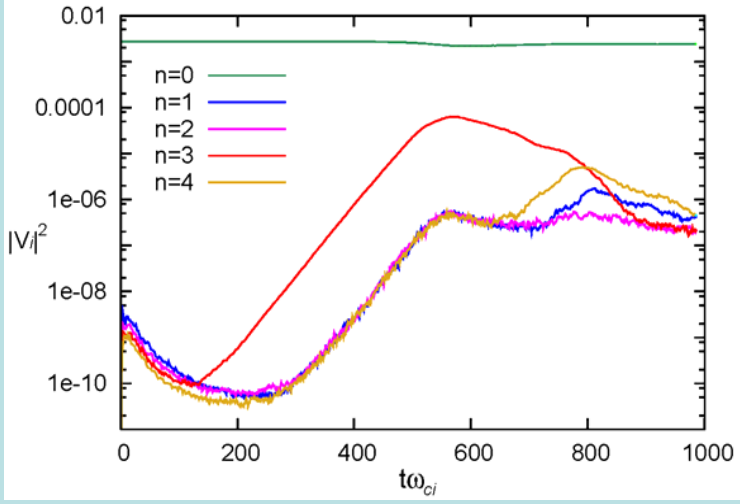
NBI Stabilization of MHD Modes in Oblate FRCs

- For oblate and E~1 FRCs the most dangerous MHD modes are: the *n*=1 tilt mode and *n*≥2 co-interchange (kink) modes.
- The tilt mode can be stabilized by a close-fitting conducting shell, but the *n*≥2 modes remain unstable; growing modes are localized near magnetic null.
- Energetic NBI ions with V ~ $6V_A$ and n_b~3% can stabilize the *n*=2 mode, and reduce the linear growth rate of the *n*=3 mode.
- Residual instabilities saturate nonlinearly at small amplitudes.
- The resulting configuration remains stable with respect to ***all global MHD modes*** as long as the FRC current is sustained.

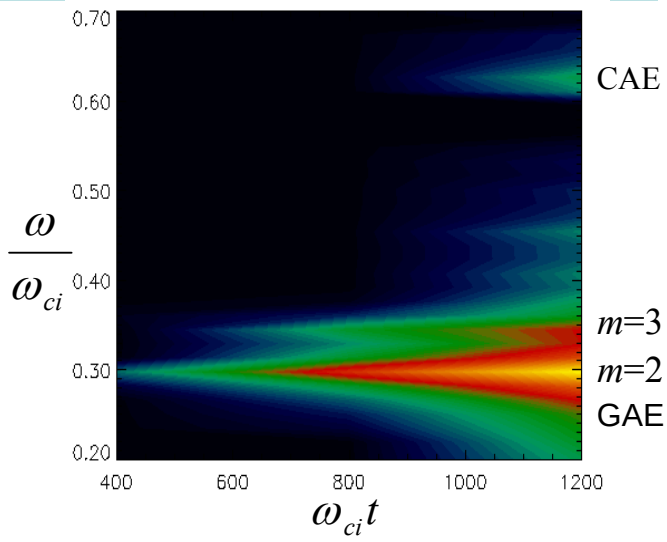


Time evolution of the n = 0 - 4 components of the ion kinetic energy obtained in 3D nonlinear hybrid simulations including the effects of a conducting shell and beam stabilization.

Other Program Accomplishments and Applications:

- Study of stochasticity of ion orbits in FRC plasmas, and its effect on FRC stability properties (2003-2004).
- Numerical study of velocity shear stabilization of MHD modes in FRCs (2000-2002).
- Investigation of effects of pressure profile and separatrix shape on stability of interchange and co-interchange modes in oblate and prolate FRCs (2001-2004).

- Numerical study of beam-driven instabilities of sub-cyclotron-frequency modes in NSTX using HYM code: simulations of Compressional Alfven Eigenmodes (CAEs); predicted instability of Global Alfven Eigenmodes (GAEs) (2003-2005).
- Future potential applications: studies of CT injection in NSTX (fueling).
- Initial simulation studies of Hall reconnection in MRX (2005).

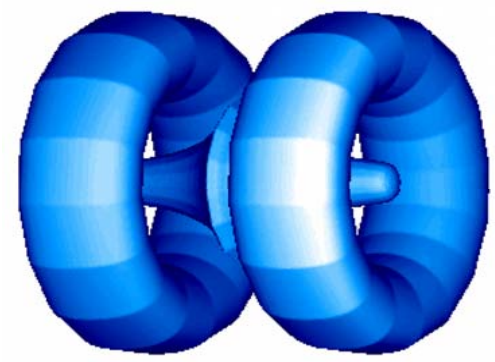


Spectrum of unstable modes from NSTX simulations for $n = 4$.

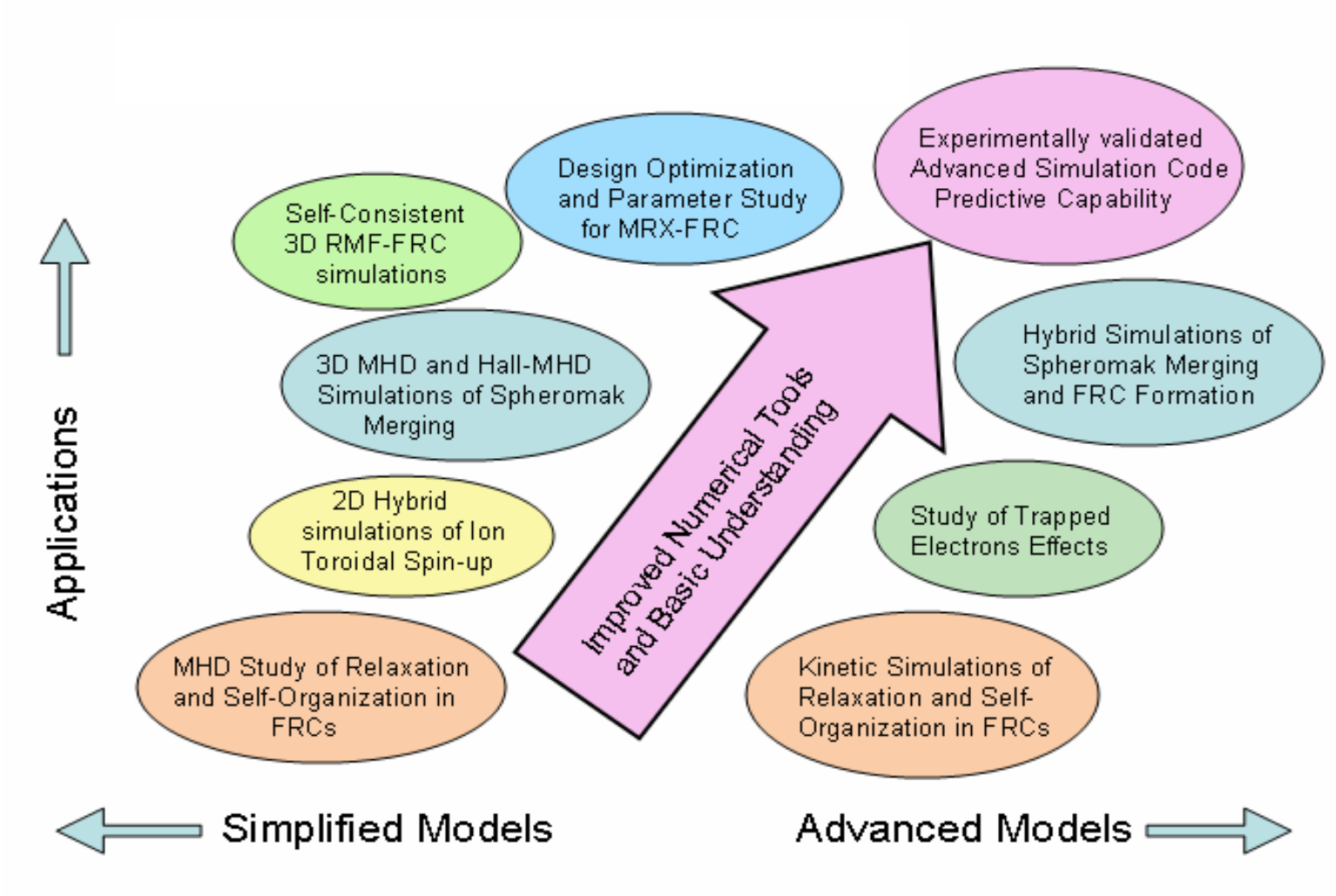
5-Year Task Activity Areas

- Study resistive relaxation and self-organization in FRCs.
- Include trapped electron effects in the FRC stability calculations.
- Improve/optimize the HYM code for large-scale high-resolution nonlinear simulations.
- Improve the basic understanding of FRC formation techniques by counter-helicity spheromak merging.
- Compare HYM numerical results with SSX-FRC and MRX experimental results.
- Apply the HYM code to rotating magnetic field (RMF) configurations.
- Complete the concept development and physics design optimization and parameter study for the MRX-FRC ion-beam-stabilized FRC configuration.

MHD simulation of counter-helicity spheromak merging.



High-Level Milestones in FRC Theory and Modeling



Conclusions

- FRC theoretical studies at PPPL have contributed significantly to the FESAC goal of resolving outstanding scientific issues for FRC configurations:

  Linear and nonlinear stability properties of prolate kinetic (theta-pinch-formed) FRCs have been explained, including behavior of the tilt and rotational instabilities, and the ion toroidal spin-up.

- New FRC formation method by counter-helicity spheromak merging has been investigated in support of several current FRC experiments. A new stability regime has been discovered for oblate FRCs with a close-fitting conducting shell and energetic beam ion stabilization.

- Close collaboration with FRC experimental groups has provided improved scientific understanding and guidance for FRC experiments, and a critical benchmark of the theoretical models.

- Advances in plasma science:

  Magnetic reconnection, relaxation, high-beta stability, and large-ion-orbit effects on stability of MHD modes.

Back-up Slides

Five-Year Plan

- Perform numerical simulations to study the effects of resistive relaxation and self-organization in FRCs, and compare with the available experimental data.
- Develop an analytical model/closure scheme for the inclusion of trapped electron effects, and incorporate this model into the FRC stability calculations using the HYM code.
- Improve/modify the time-stepping scheme, boundary conditions, and improve parallel performance of the HYM code in order to allow large-scale two-fluid and hybrid nonlinear simulations with increased spatial resolution for accurate comparison with experimental results.
- Compare the HYM numerical results with the SSX-FRC and MRX experimental results, with the goal of improving the basic understanding of FRC formation techniques by counter-helicity spheromak merging, and large-S^* FRC stability properties.
- Complete HYM code optimization and applications to rotating magnetic field (RMF) configurations, including both the simplified description (already-penetrated rotating magnetic field), and fully 3D simulations of the field penetration process.
- Complete the concept development and physics design optimization and parameter study for the MRX-FRC ion-beam-stabilized FRC configuration.

Milestones for FY2006- FY2007

- ***Simulations of the Swarthmore SSX-FRC and MRX-FRC experiments:***
  - Perform three-dimensional simulation studies of the SSX-FRC experiment including two-fluid and kinetic effects (2006-2007).
  - Perform three-dimensional simulation studies of the MRX-FRC experiment, including Hall-MHD simulations and hybrid simulations (2006-2007).
- ***Linear stability properties:***
  - Complete development of an analytical model/closure scheme for the inclusion of trapped electron effects in the FRC stability studies; incorporate these effects in the HYM simulation code and investigate the detailed effects on FRC stability properties (2006).
- ***Effects of neutral beam injection:***
  - Complete physics design optimization and parameter study for the MRX-FRC ion-beam-stabilized FRC experiment (2006).

Milestones for FY2006- FY2007

- ***Resistive relaxation in FRCs:***
  - Perform nonlinear hybrid simulations to investigate in detail the ion toroidal spin-up in field-reversed configurations, and its dependence on FRC parameters and applied boundary conditions (2005).
  - Perform MHD and hybrid simulations to study the effects of resistive relaxation, profile consistency, and self-organization in FRCs (2006).
- ***Rotating-magnetic-field FRCs:***
  - Assess applicability of the parallelized HYM code for self-consistent 3D rotating magnetic field (RMF) studies (2006).
  - Complete studies of particle confinement for even- (odd-) parity RMFs (2007).
  - Depending on the outcome of the assessment, carry out detailed self-consistent 3D RMF studies using the parallelized HYM code (2007).

Selected Publications

- ***2003-2005 Peer-Reviewed Publications***
  - E.V. Belova, et al., Phys. Plasmas **13,** manuscript in preparation (2005).
  - E. V. Belova, R. C. Davidson, H. Ji, M. Yamada, C. D. Cothran, M. R. Brown, M. J. Schafer, submitted to Nuclear Fusion (2005).
  - E. V. Belova , R. C. Davidson, H. Ji, and M. Yamada, C. D. Cothran, M. R. Brown, M. J. Schaffer, paper IC/P6-34, Proceedings of 20th IAEA Fusion Energy Conference (Vilamoura, Portugal, 2004).
  - E. V. Belova, R. C. Davidson, H. Ji, and M. Yamada, Phys. Plasmas **11**, 2523 (2004).
  - E. V. Belova, R. C. Davidson, H. Ji, and M. Yamada, Phys. Plasmas **10**, 2361 (2003).
  - E. V. Belova, N. N. Gorelenkov, and C. Z. Cheng, Phys. Plasmas **10**, 3240 (2003).
  - N. N. Gorelenkov, E. Belova, H. L. Berk, C. Z. Cheng, E. Fredrickson, W. W. Heidbrink, S. Kaye, and G. J. Kramer, Phys. Plasmas **11**, 2586 (2004).
- ***2003-2005 Invited talks***
  - 47th DPP APS Meeting, Denver CO, October 2005
  - 45th DPP APS Meeting, Albuquerque, NM, October 2003.
  - International Sherwood Fusion Theory Conference, Corpus Christi TX, April 2003.