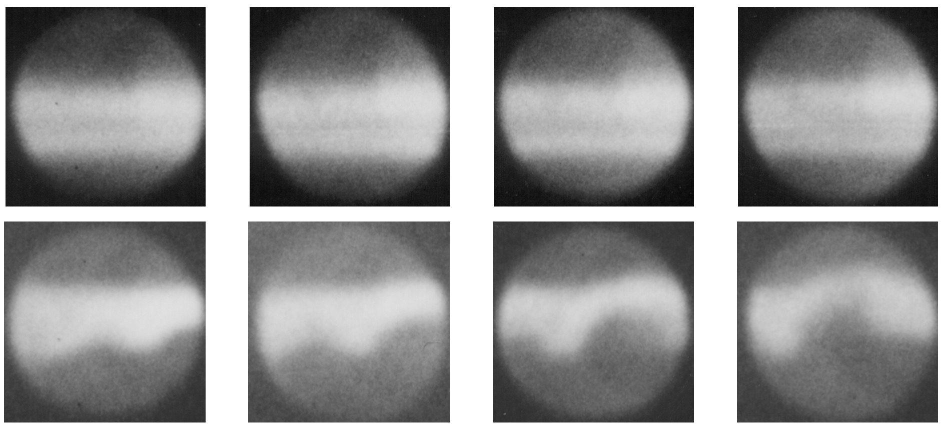
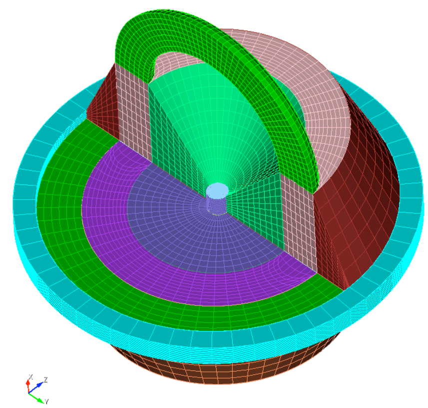
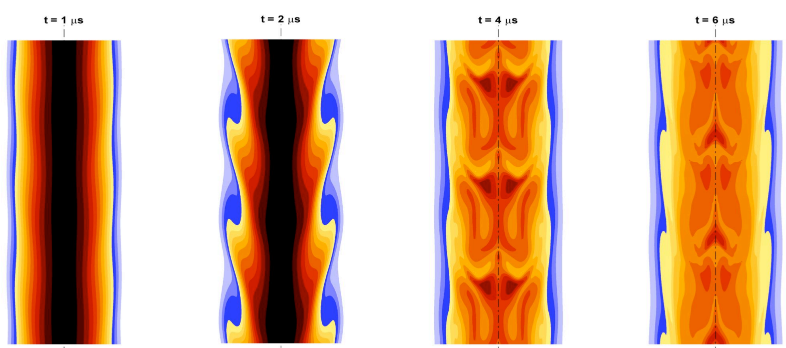
Astrophysical Connections from Magnetic Confinement Fusion Research: Interface & Shear Flow Instabilities

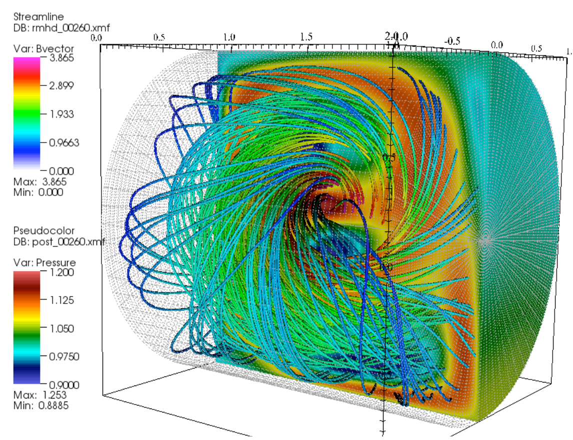
Uri Shumlak, University of Washington

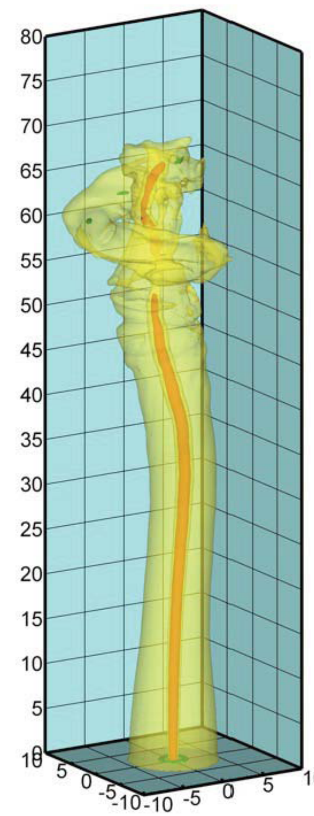
Carolyn Kuranz, Ian Mann, Aaron Miles, Marc Pound, Dmitri Ryutov









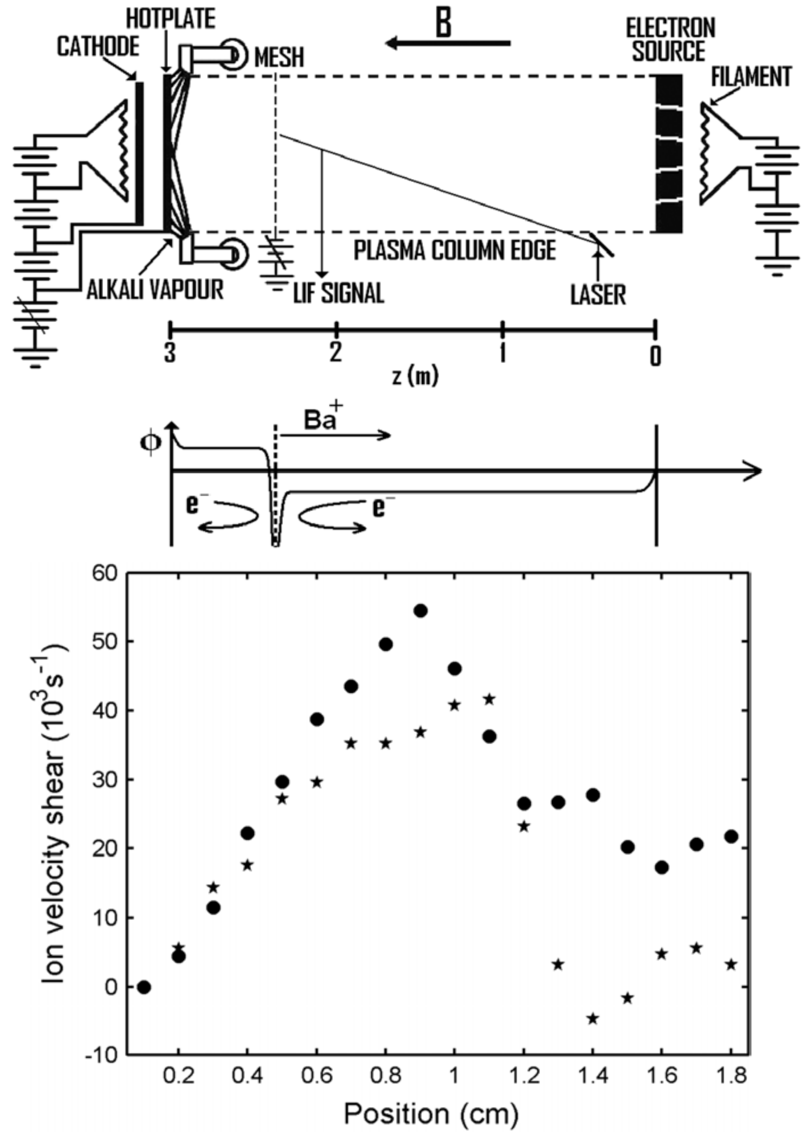


Potentially Applicable Research in MFE

- Shear flow effects on plasmas
  - WVU: shear-flows to drive fluctuations relevant to space physics [Koepke, Reynolds]
  - DIII-D: shear-flow stabilization of ballooning modes in a tokamak, transport barriers, LH transition [Burrell, Waltz]
  - MST: shear-flow reduction of fluctuations in the RFP [Chapman]
  - GDT, MCX: rotational stabilization of flute instabilities in a mirror [Beklemishev, Ellis, Hassam]
  - ZaP: shear-flow stabilization of gross modes in Z-pinch [Shumlak, Golingo]
- Plasma interactions with / entrainment of background gases
  - CalTech, ZaP, static filled plasma foci [Bellan, You]
- Computational tools and applications to astro & space physics
  - WARPX, NIMROD, HiFi (high-order accurate, resolve high speed flows & anisotropic properties) [Glasser, Hakim, Loverich, Lukin, Shumlak, Sovinec]

Flows are driven in Q-machines to drive fluctuations.

- Sheared flows have been driven and measured in Q-machines to drive drift instabilities. Electrostatic axial acceleration and annular electrodes produces sheared flows parallel (stars) and perpendicular (circles) to B.
- The experiment produces ion cyclotron and lower hybrid waves associated with flow-shear-driven plasma fluctuations.
- Simultaneous parallel and perpendicular sheared flows are relevant to geospace plasmas.



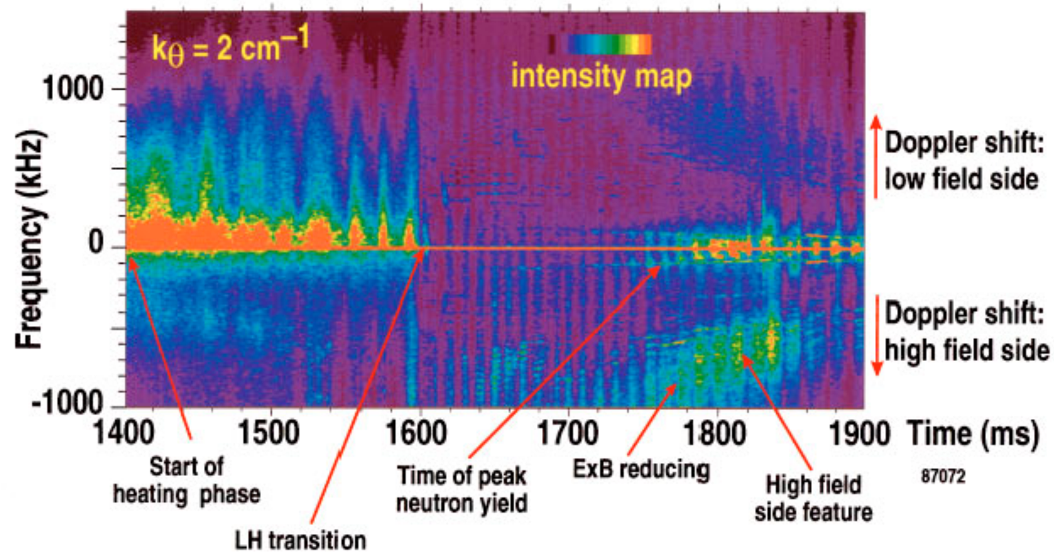
Koepke & Reynolds, Plasma Phys Control Fusion (2007)

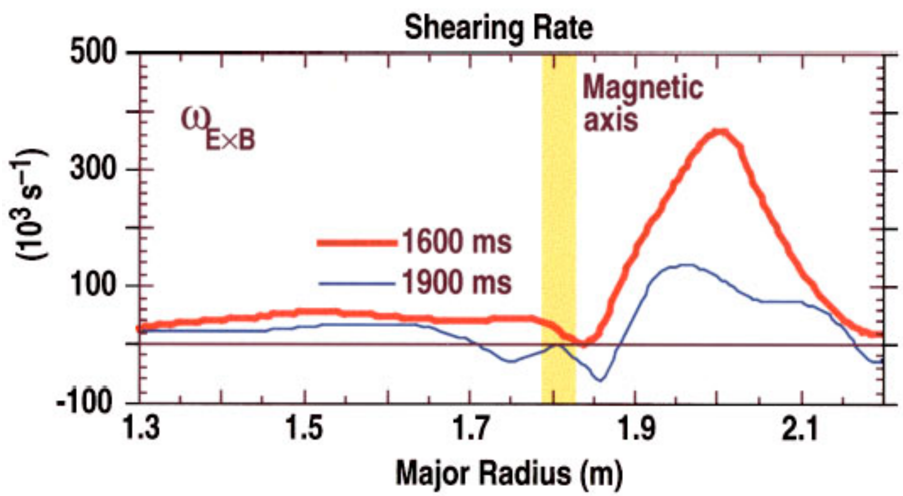
Shear flow can stabilize tokamak plasmas.

Shear flows driven by ExB have been observed to stabilize interchange (ballooning) modes, create internal transport barriers, and are associated with LH transition.

Transport reduction occurs through velocity shear decorrelation of turbulence.

This general result has been observed on several tokamaks: DIII-D, JT-60U, JET, TFTR,… and stellarators (W7-AS).



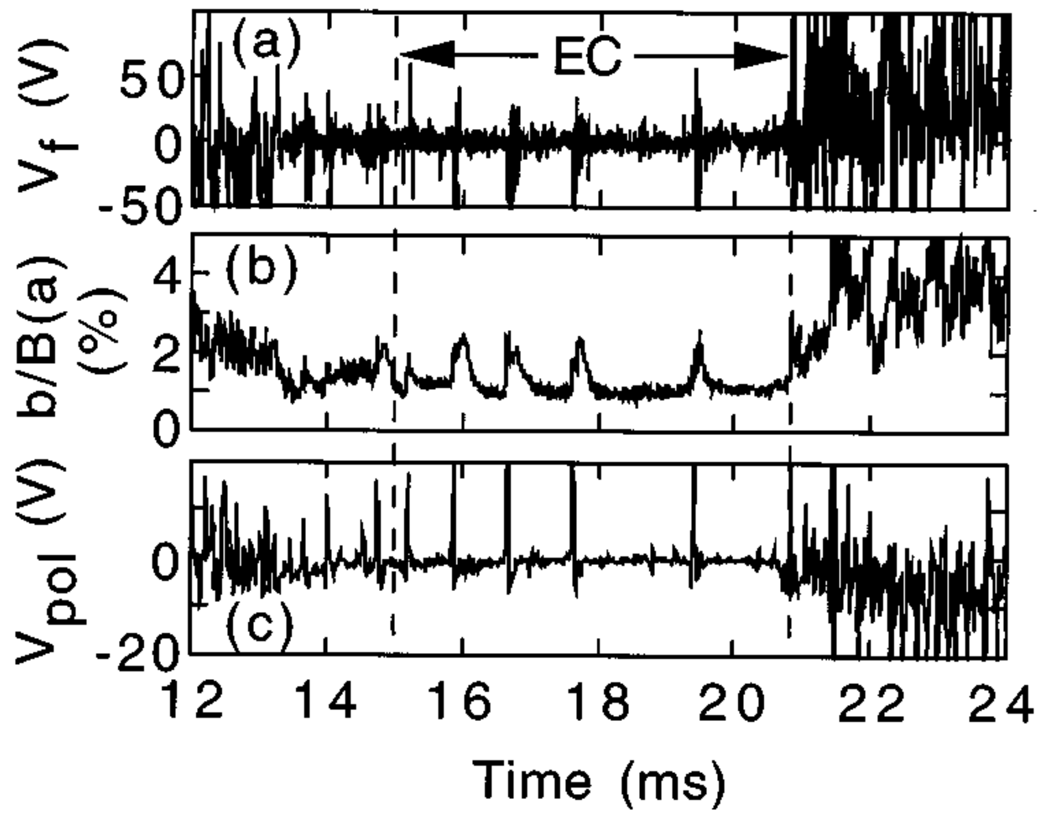


Burrell, Phys Plasmas **4** (1997)

Shear flow may reduce fluctuations in an RFP.

ExB shear flows have been driven in the reversed-field pinch (RFP), for example in enhanced confinement discharges, where reductions of edge electrostatic and global magnetic fluctuations are observed.

Shown are experimental data from MST. Other RFPs have observed similar effects.



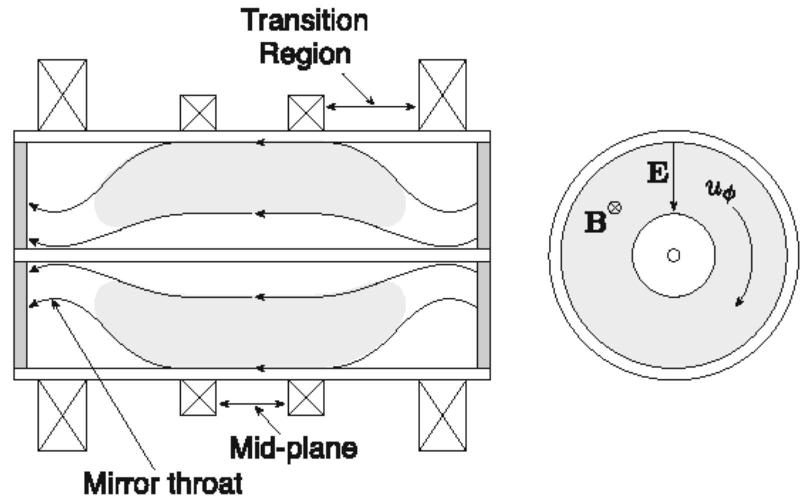
Chapman et al., Phys Plasmas **5** (1998)

Rotational flows can have a stabilizing effect on mirrors.

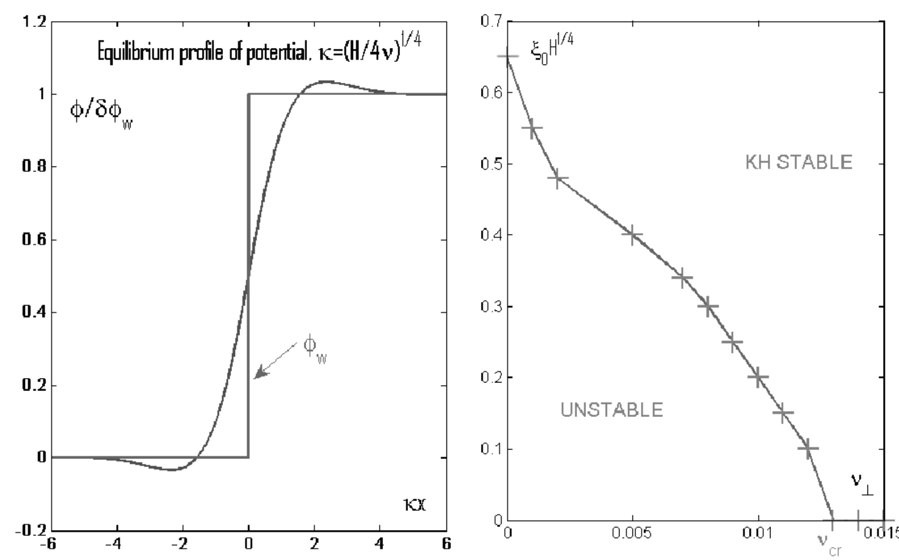
Sheared azimuthal flows are generated in mirrors by electrically biasing the inner/outer walls [MCX] or annular end electrodes/outer wall [GDT] to generate a radial E. The sheared ExB flow stabilizes interchange, fluting modes – RT analog.

KH instability can be controlled by adjusting potential profiles.

Combination of the shear flow and FLR is sufficient for the nonlinear “vortex” confinement in simulations, which are in good agreement with GDT data.



Uzun-Kaymak et al., J Fusion Energ **28** (2009)

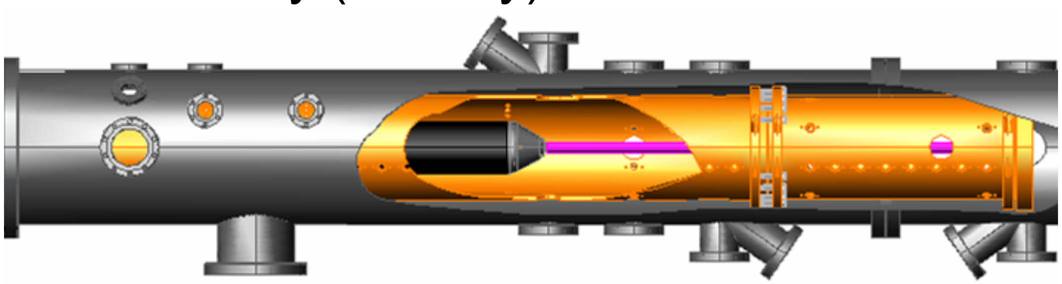


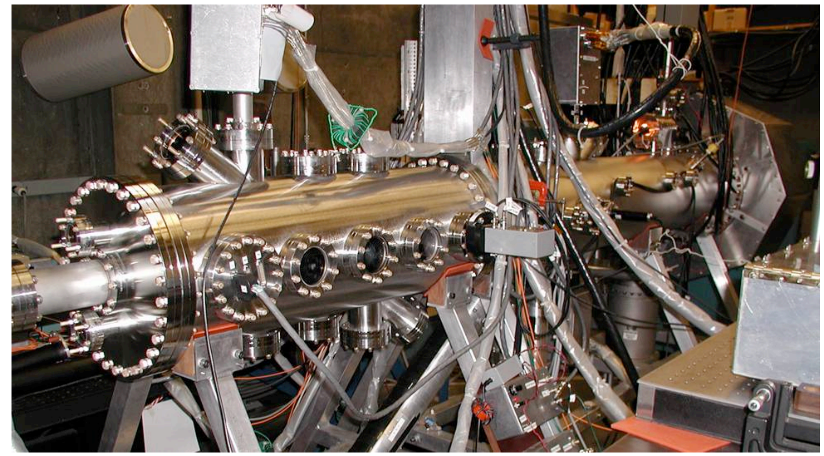
Beklemishev, Theory Fusion Plas (2008)

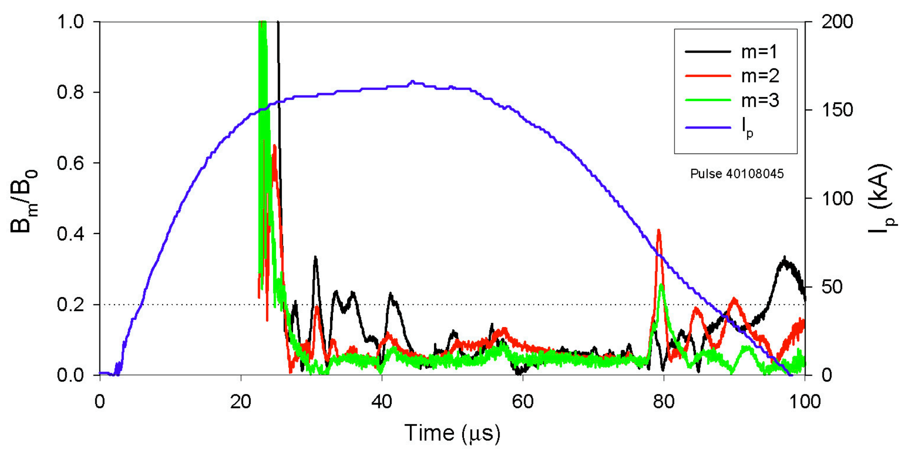
ZaP studies shear flow stabilization in a Z-pinch.

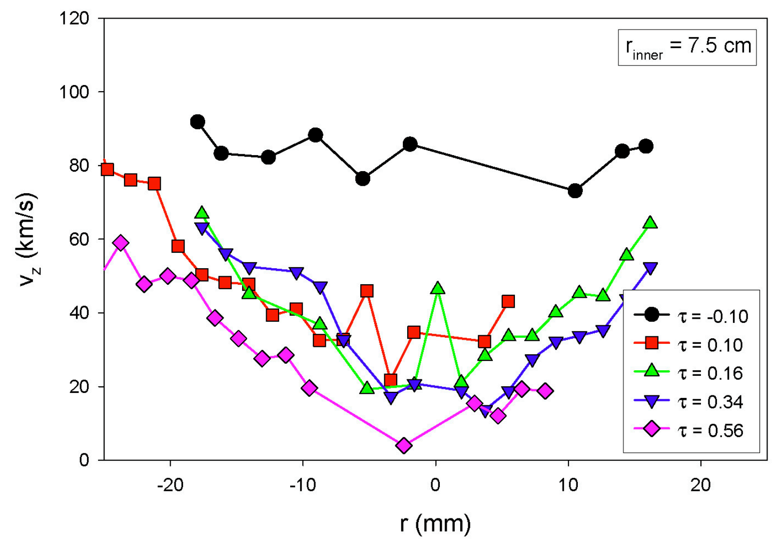
Coaxial accelerator coupled to a pinch assembly region generates a large aspect ratio Z-pinch with an embedded axial flow, similar to astrophysical objects.

Experimental diagnostics measure plasma parameters (equilibrium), plasma flow, and magnetic mode activity (stability).





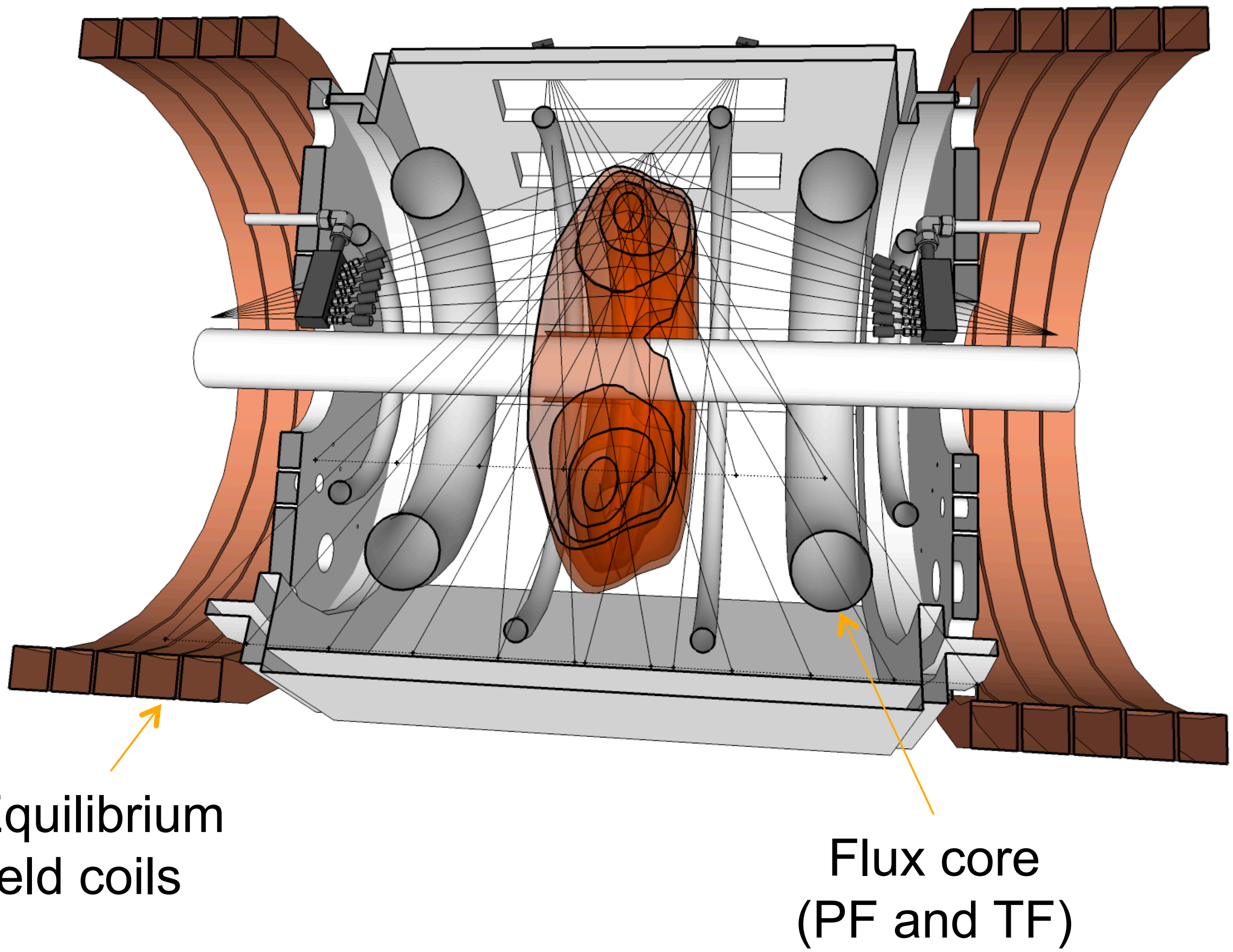




Shumlak et al., Nucl Fusion **49** (2009)

Velocity tomography diagnostic in reconnection experiments

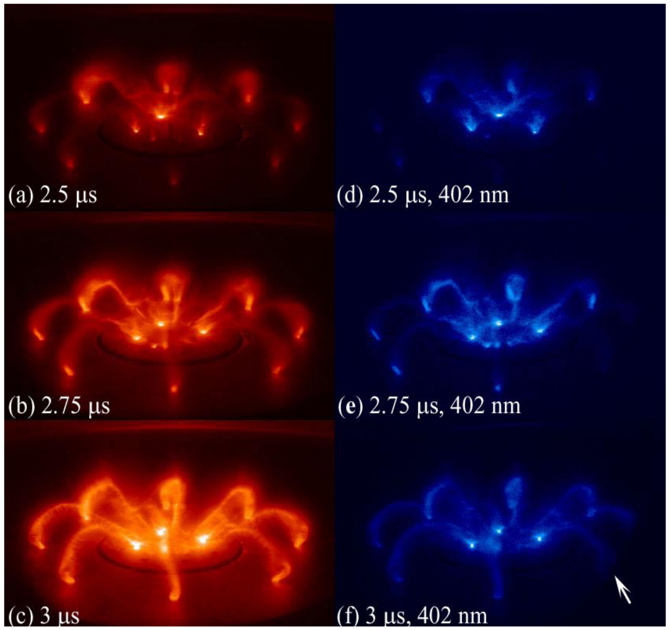
Spherical tokamak experiment (TS-4) has developed a 42-channel diagnostic to measure 3D velocity evolution using tomography. The diagnostic has been used to measure canonical momentum during merging and reconnection of counter-helicity spheromaks.



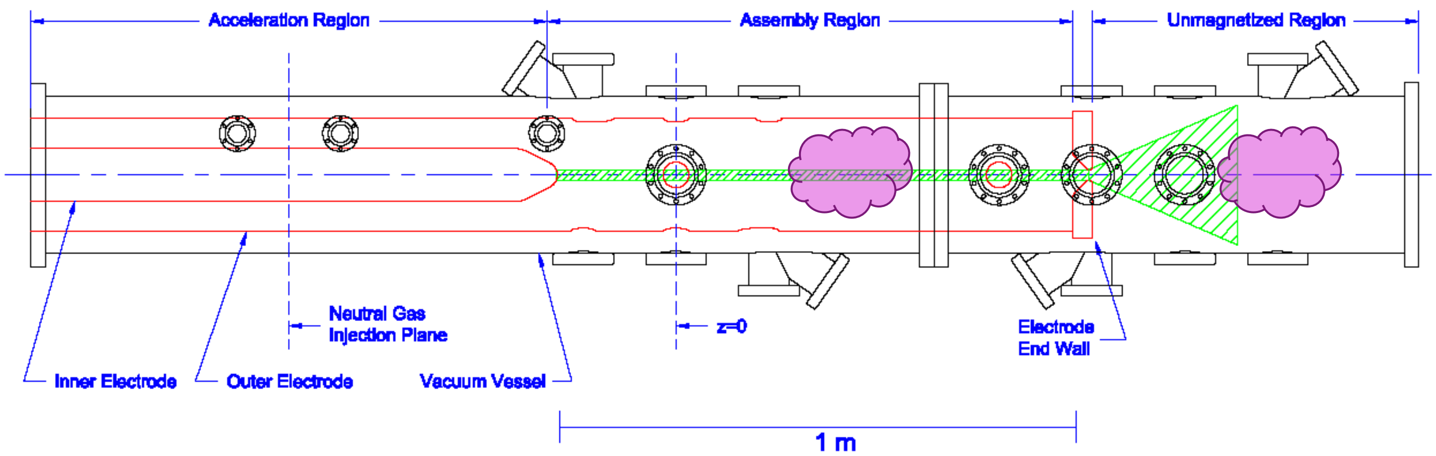
You et al., BAPS **54** (2009)

Plasma interaction with / entrainment of background gas.

- Neutral gas entrainment into plasma-filled magnetic flux tubes has been studied at CalTech by injecting distinct gases from the cathode and anode.
- Plasma interactions with background gases can be studied in similar devices. After formation of a magnetized or unmagnetized plasma structure (e.g. jet), the plasma can impinge upon a different neutral gas to study interactions and entrainment within the existing plasma structure.



You et al., PRL **95** (2005)



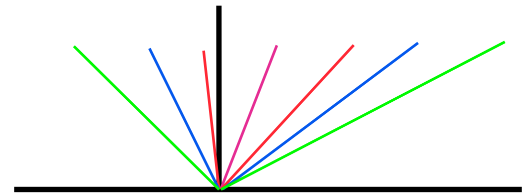
Shumlak et al., Astrophys Space Sci **307** (2007)

Computational tools applied to astro & space physics.

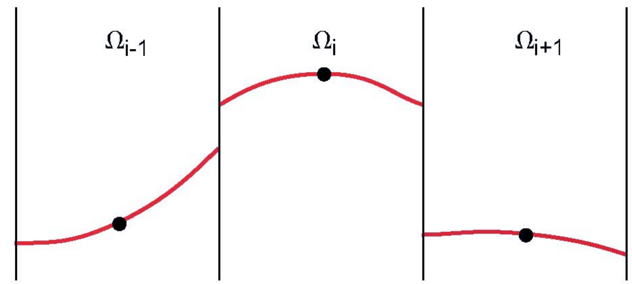
Computational tools have been developed for magnetic confinement research. These tools are applicable to astrophysics & space physics.

WARPX solves the multi-fluid plasma model with complete Euler equations for each fluid (e.g. electrons, ions, neutrals) and Maxwell's equations.

$$\frac{\partial Q}{\partial t} + \nabla \cdot \mathbf{F} = S$$



The code uses a discontinuous Galerkin finite element spatial representation with approximate Riemann numerical fluxes.



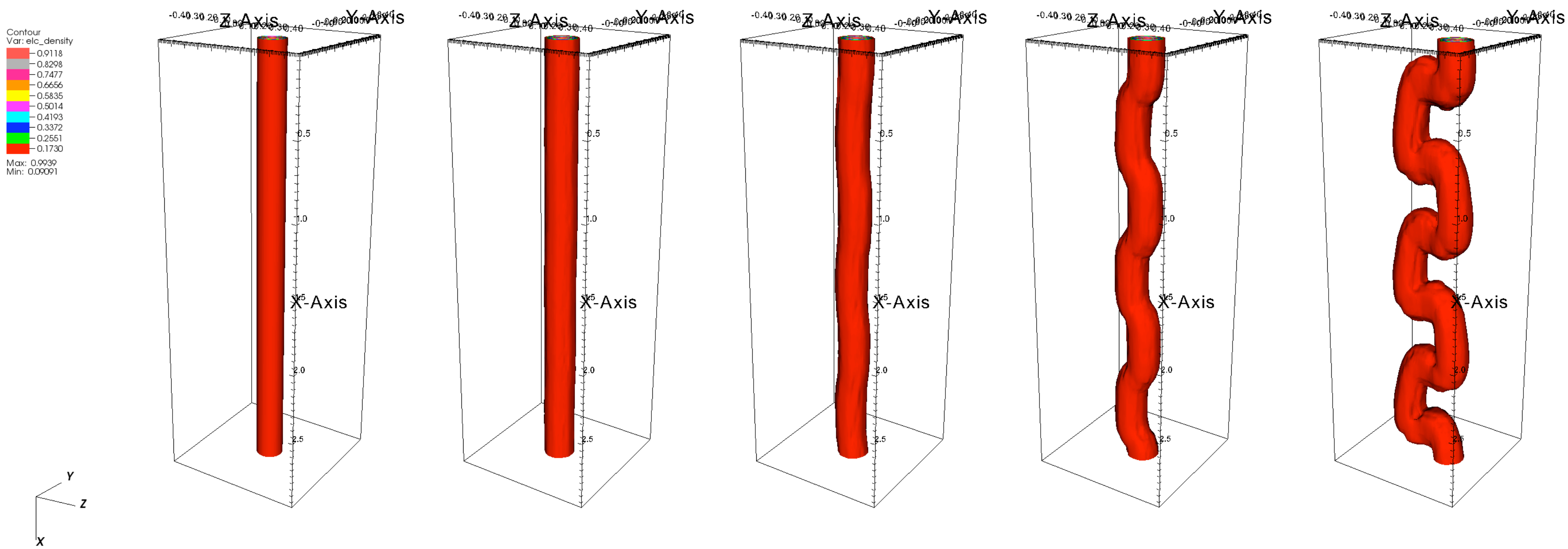
$$\int_{\Omega} v_h \frac{\partial Q}{\partial t} dV + \oint_{\partial\Omega} v_h \mathbf{F} \cdot d\mathbf{A} - \int_{\Omega} \mathbf{F} \cdot \nabla v_h \, dV = \int_{\Omega} v_h S \, dV$$

The code captures high speed flows including those with shocks and other discontinuities. Time is typically advanced with a 3rd order TVD, Runge-Kutta method.

Shumlak & Loverich, JCP **187** (2003); Loverich & Shumlak, CPC **169** (2005)

Computational tools applied to astro & space physics.

WARPX has been used to solve the two-fluid plasma model (electrons & ions) to study instabilities in Z-pinches and other magnetically confined plasmas.

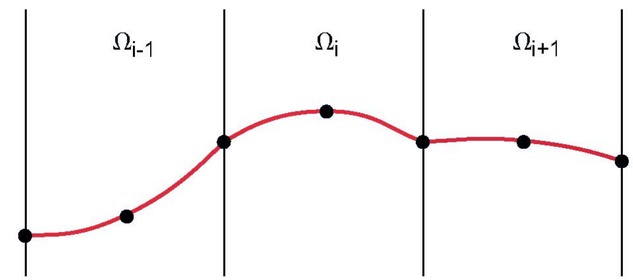


Opportunities exist to apply the code to study other astrophysical objects, particularly objects that have high speed flows & shocks.

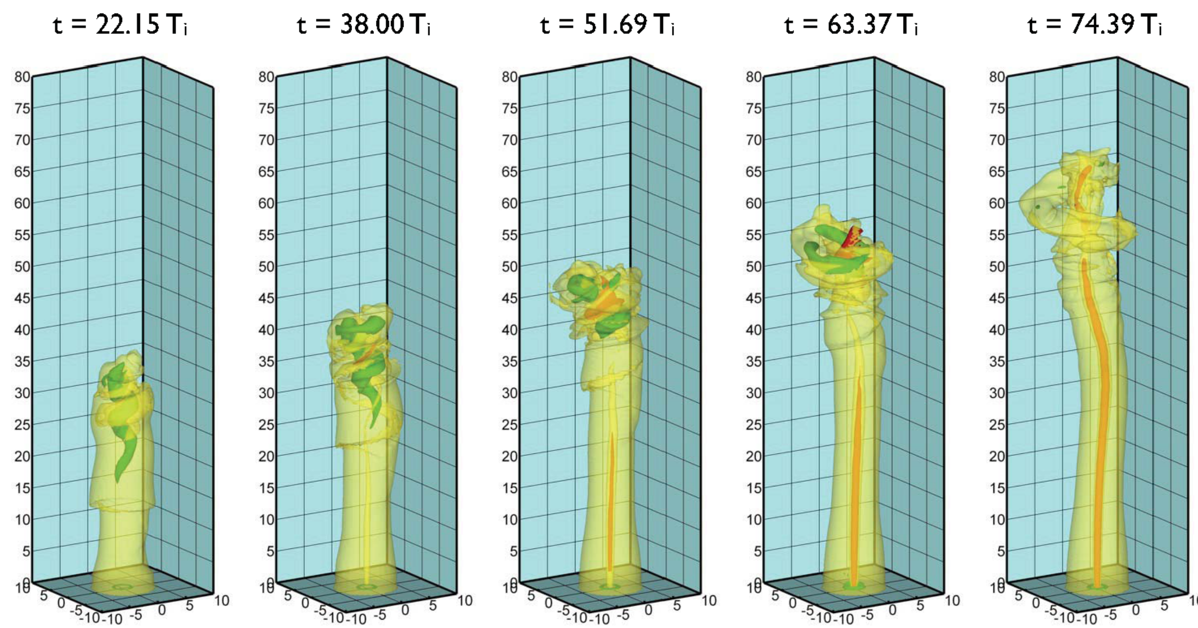
Hakim et al., JCP **219** (2006)**;** Loverich & Shumlak, Phys Plasmas **13** (2006)

NIMROD has been applied extensively in MFE.

NIMROD solves the 3D, visco-resistive MHD plasma model. The code has been developed for several years throughout the MFE community. The code uses a continuous finite element spatial representation. The time advance is accomplished with a semi-implicit method. The code has been applied to wide variety of plasma experiments and to magnetospheric physics, and recently to astrophysics.



Further opportunities exist.

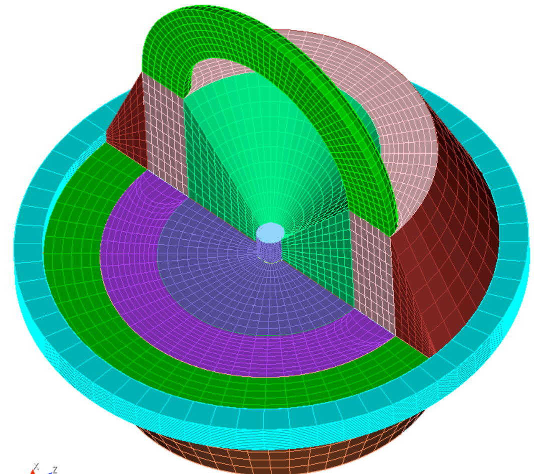


Sovinec et al., JCP **195** (2004), Carey & Sovinec, ApJ **699** (2009)

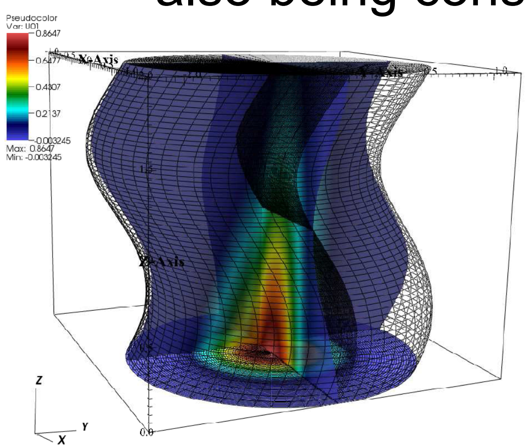
HiFi is a more recent code development from MFE.

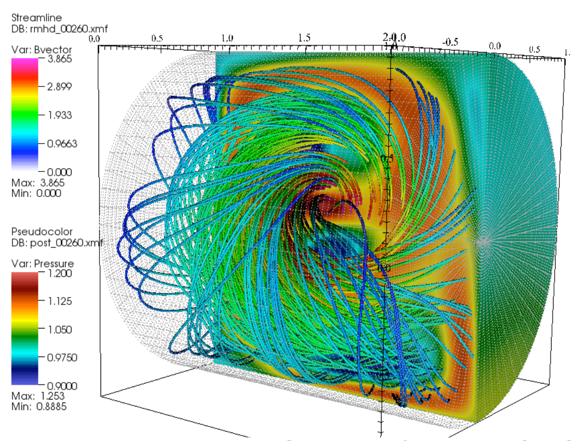
HiFi also uses a continuous finite element spatial representation that simulates plasma in arbitrary geometries using full 3D discretization. The code uses a fully implicit time advance with a general “flux – source” form to solve extended MHD.

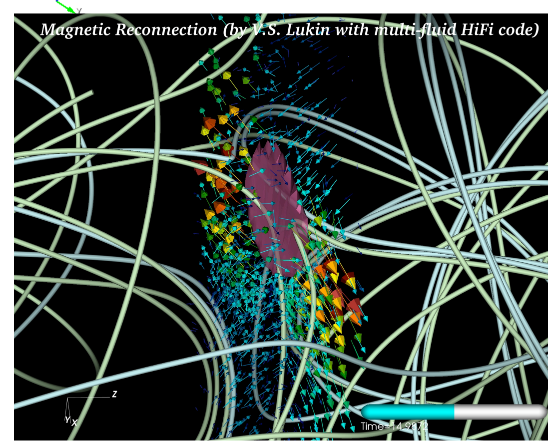
The general form and multi-block grid simplifies extending the physics models and applying to a variety of plasma configurations.



The code is currently being used to study solar physics, e.g. coronal magnetic reconnection and CME initiation. Astrophysical applications are also being considered.







Glasser & Tang, CPC **164** (2004)**;** Lukin et al., JCP (submitted 2009)

Opportune time to apply MFE research to astro & space physics

- Several MFE experiments produce sheared flows. Can these results be compared to astrophysics?
  - Requires detailed measurements of velocity and plasma structures to relate flow shear and stability with the aim of isolating the physics.
  - Must produce supersonic flows, perhaps through radiative cooling of lab plasmas after flow is developed.
- Can the interactions of flowing plasmas with background gases produce relevant shock systems? How is the gas entrained in the plasma flow? Do knots form and do they interact?
  - This could be investigated in field-aligned flows (magnetic flux tubes), cross-field flows (Z-pinches), and unmagnetized flows.
- Applying computational tools to astrophysics & space physics could have a near-term impact.
  - Recent development of high-order accurate codes that can resolve high speed flows, shocks, discontinuities, & anisotropic properties