An Introduction to Magnetohydrodynamics for Magnetic Confinement

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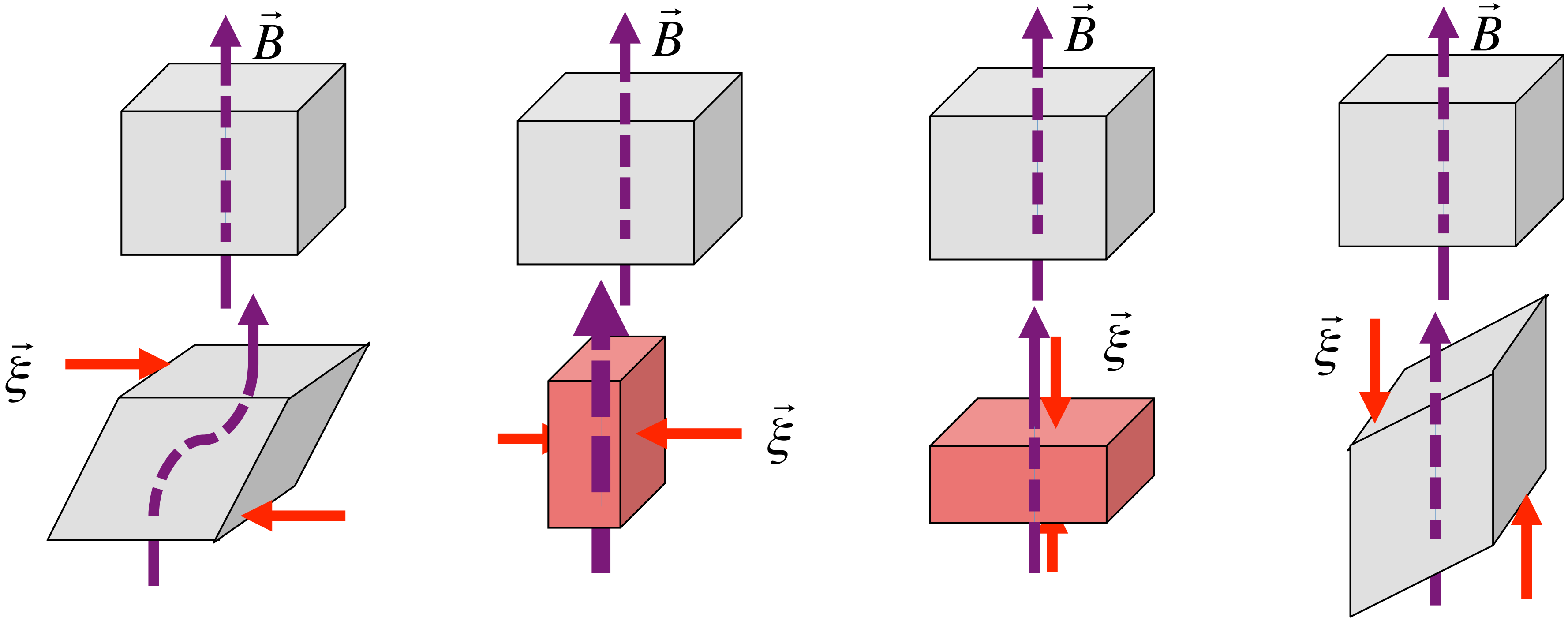
Outline

- Introduction
  - What MHD describes
  - Relation to plasma physics
- Examples of macroscopic dynamics
- MHD models
  - Ideal vs. non-ideal
  - Reduced
  - Application - Aflvén waves
- Paradigm typically used in analysis
  - Equilibrium
  - Stability
  - Nonlinear evolution
  - Violation of conventional paradigm
- Conclusions
- Plasma Physics at UW-Madison

Magnetohydrodynamics describes the interaction of electrically conducting fluid and magnetic field.



Perpendicular shear bends magnetic field.

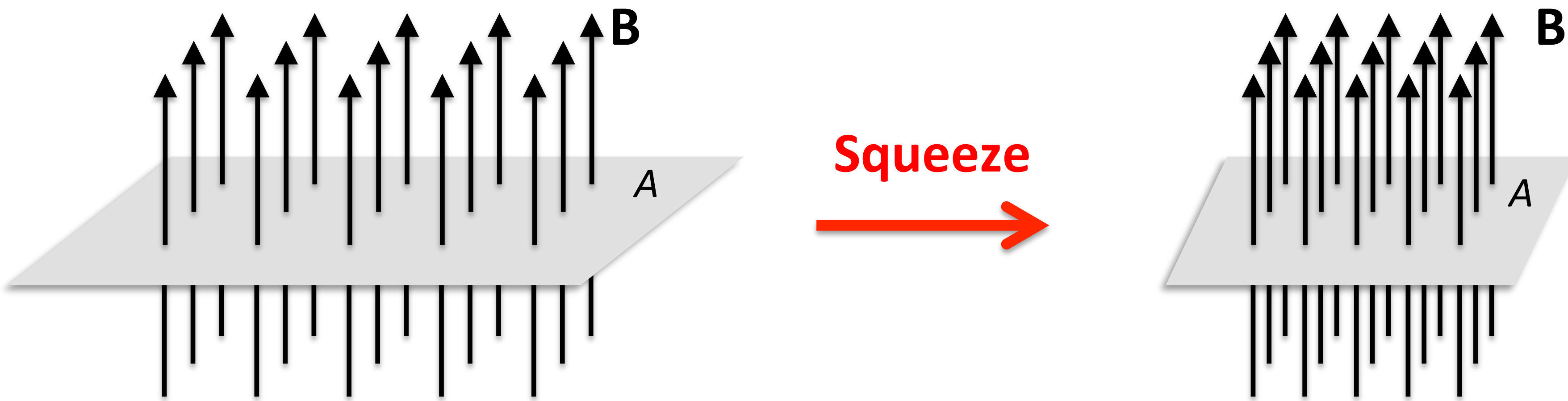
Perpendicular compression increases magnetic field and fluid pressure.

Parallel compression only increases fluid pressure.

Parallel shear does not excite stress in ideal MHD.

“Frozen magnetic flux” is a fundamental concept.

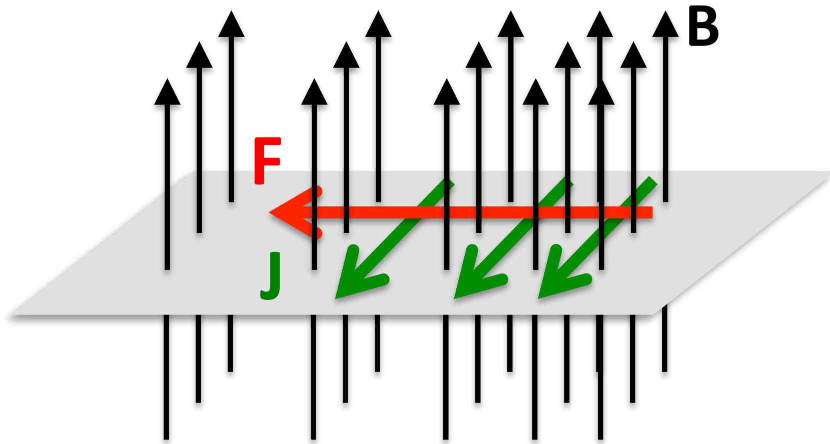
- Magnetic flux is frozen into (or out of) each parcel of an extremely good (“ideal”) conductor.
  - Faraday’s law: $\frac{d}{dt}\Phi_m = -\oint_{\partial A} \mathbf{E}\cdot d\mathbf{l} \qquad \Phi_m = \int_A \mathbf{B}\cdot d\mathbf{S}$
  - Ideal conductor: **E**=0 in fluid-parcel reference frame.

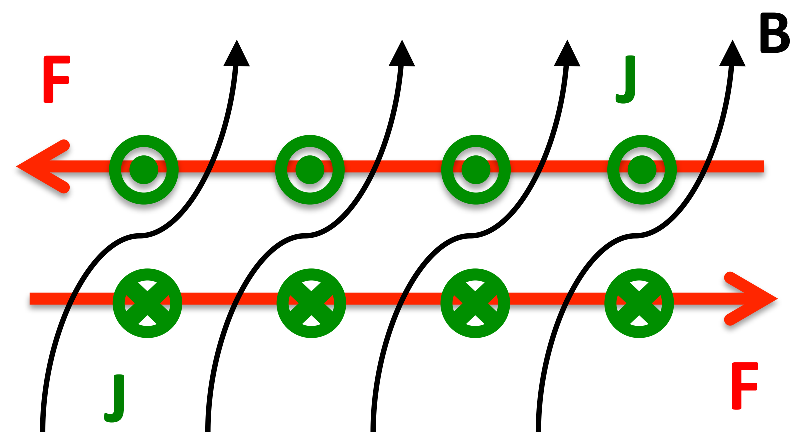


➢ Magnetic field-lines are tied to electrically conducting fluid parcels.

Electrical current density that is perpendicular to **B** leads to force-density.

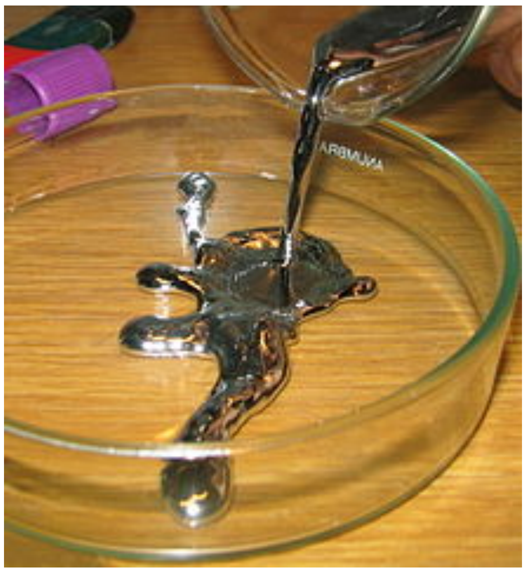
- *Roughly*, bending of **B** or spatial variation of |**B**| leads to electrical current density.
  - Ampere's for magneto-'statics' (or slow wrt *c*): $\mathbf{J} = \frac{1}{\mu_0}\nabla \times \mathbf{B}$
  - Lorentz force density: $\mathbf{F} = \mathbf{J} \times \mathbf{B}$



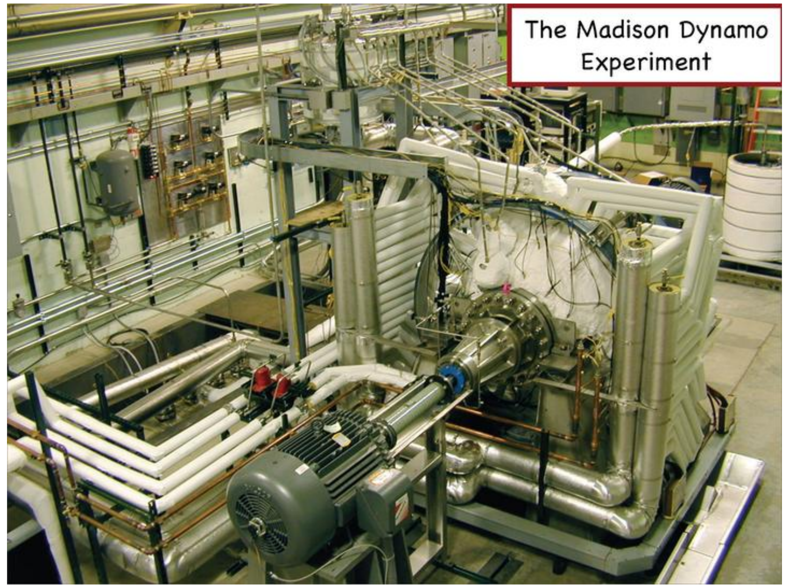


➢ Magnetic field and conducting fluids interact though Lorentz force density and frozen-flux effects.

MHD is an excellent model for liquid metal/ magnetic field interaction.



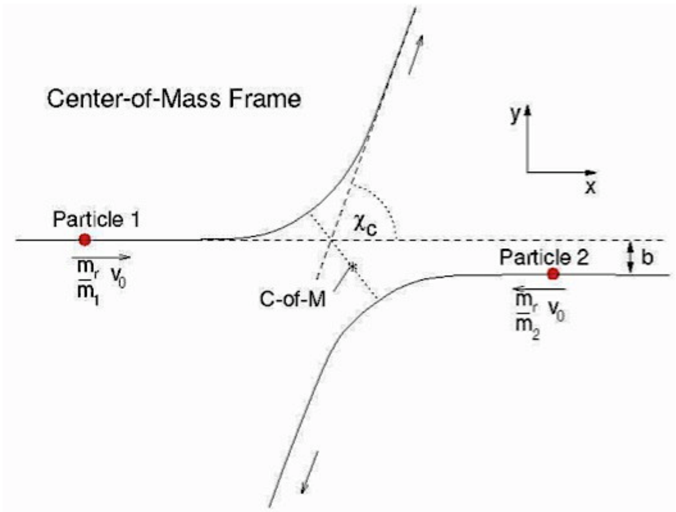
Mercury at room temperature [Wikipedia].



Liquid sodium dynamo experiment at Wisconsin [plasma.physics.wisc.edu/viewpage.php?id=mde].

Applying MHD to magnetically confined plasma invokes many simplifications.

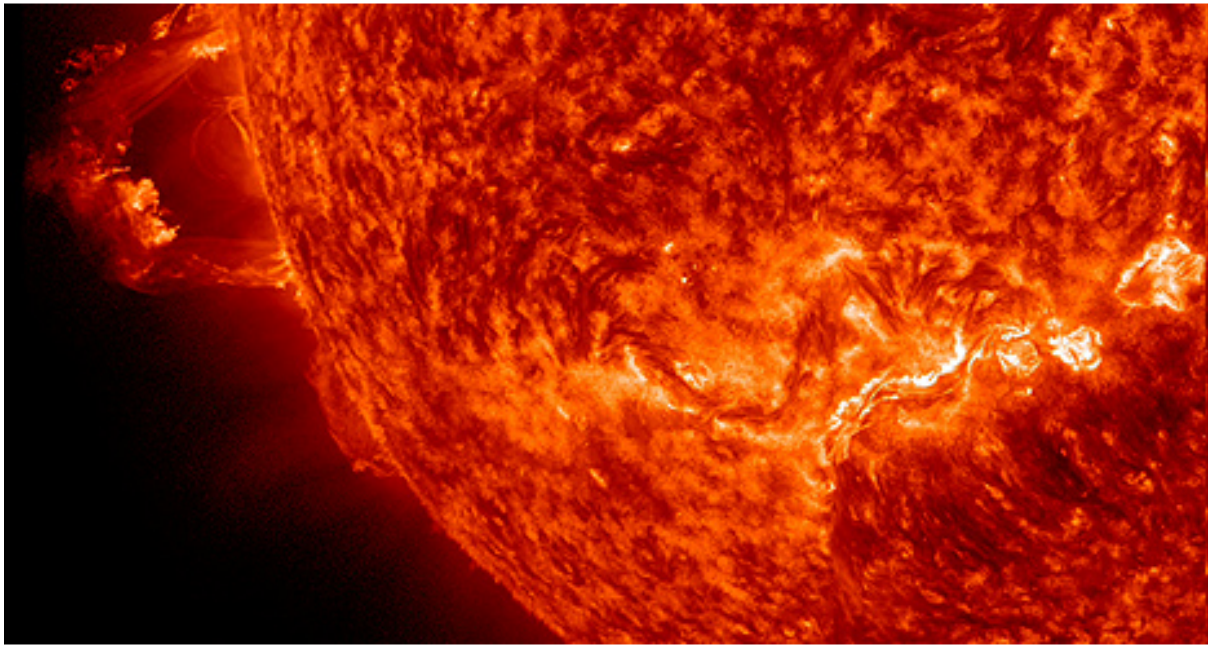
- Fluid models for plasma species are valid when:
  - Particles effectively collide with each other faster than dynamical evolution.
  - Effective particle mean-free path is shorter than scales of dynamics.
  - Particle gyro-orbits are small relative to spatial scales.



Particle collision sketch from MIT Open Course Ware 22.105.

- MHD represents further approximations.
  - Plasma remains approximately charge-neutral.
  - Dynamics are slow relative to gyromotions and light-wave propagation.
- Macroscopic dynamics in magnetic confinement plasma seldom satisfy all of these conditions!
  - For example, T_e=1 keV, n=5×10^{19} m^{-3}, mfp ~ 300 m >> L .

Nonetheless, MHD provides a good starting point for understanding macroscopic plasma dynamics.



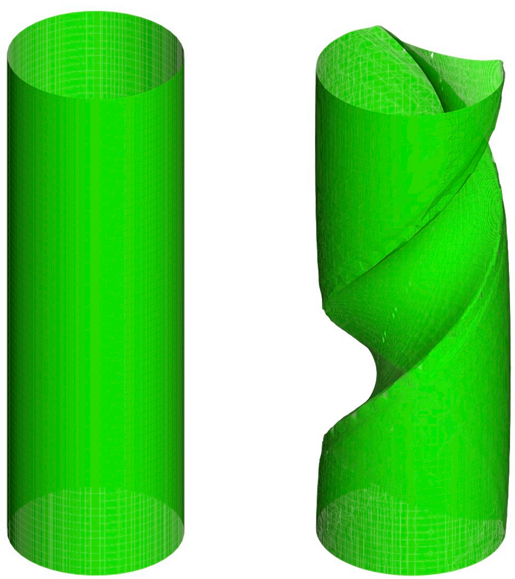
Double solar prominence eruption on Nov. 16, 2012 imaged by NASA's Solar Dynamics Observatory. [See sdo.gsfc.nasa.gov]

You can't understand plasma dynamics by studying MHD alone, but you probably won't understand magnetized plasma dynamics without studying MHD.

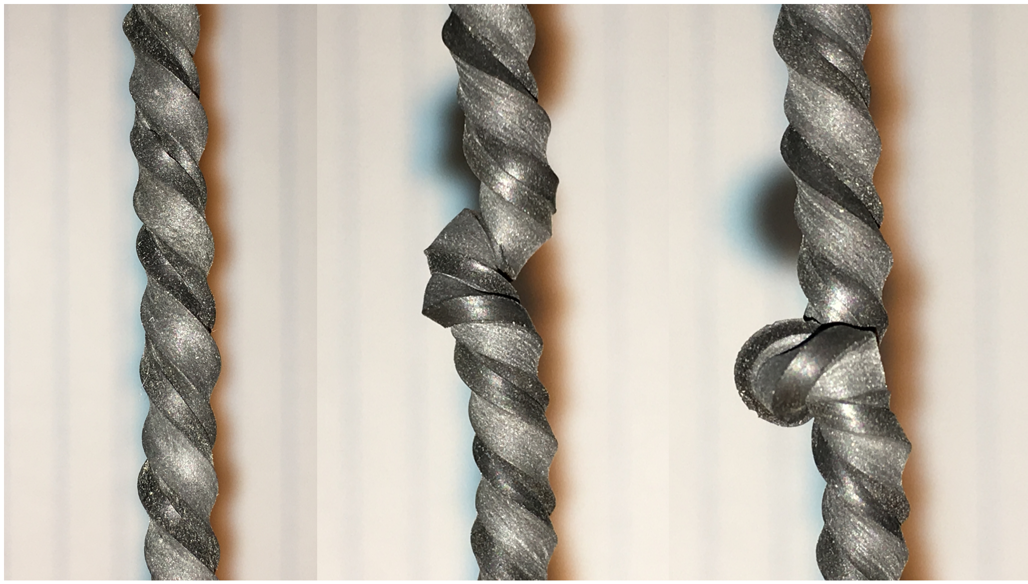
Examples of MHD: 1) External kink deforms the plasma surface or entire plasma shape.

- Kink deformation is analogous to the formation of knots on twisted rubber bands.
- The deformed state has less potential energy than a symmetric state with the same degree of twist / current density.

Initial Shape During Kink



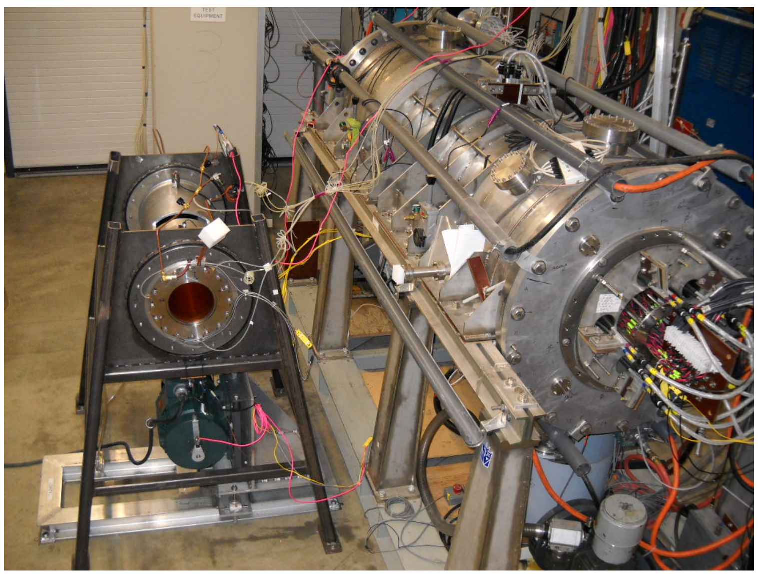
Cylindrical MHD computation of (1,1) external kink.



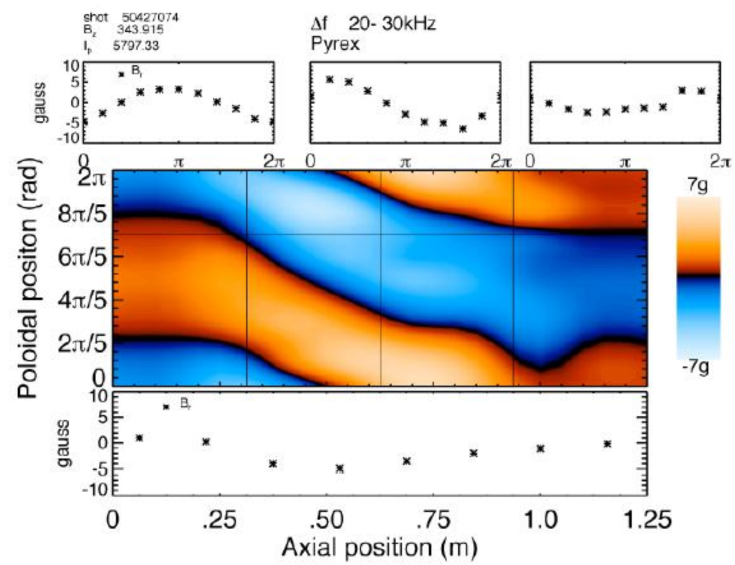
Knot formation with increasing twist of a rubber band.

External kink dynamics need to be controlled in experiments.

- Discharge profile control is the first step.
- Passive conductors and active magnetic feedback can be used.
- Rotating plasma relative to conductors helps maintain stabilizing eddy currents.

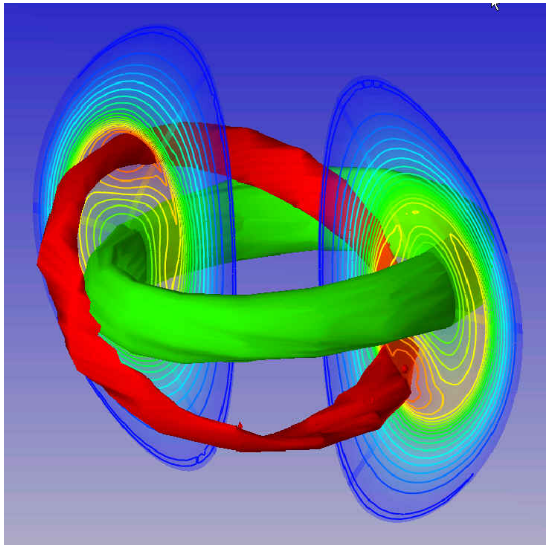


The Rotating Wall Machine investigated relative plasma/conductor motion.

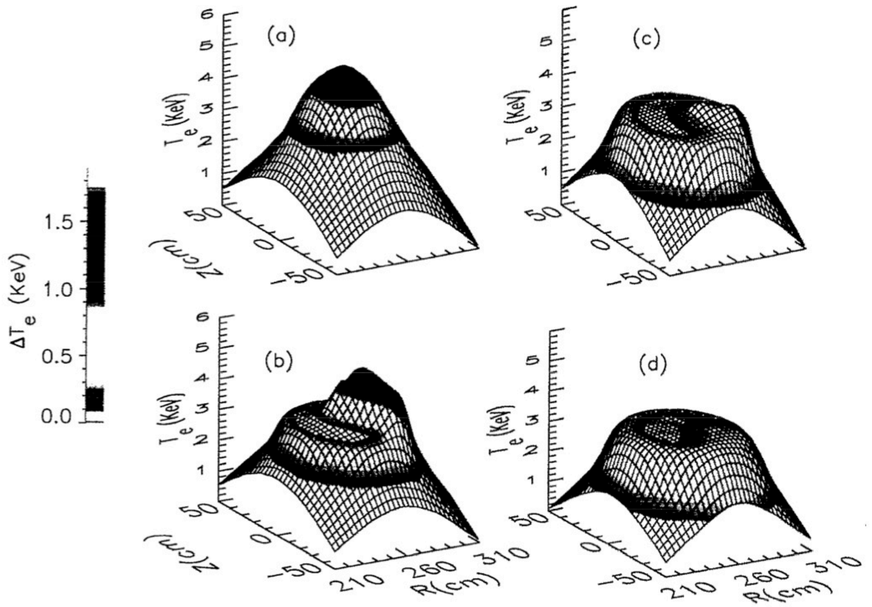


Kink deformation is evident from surface-**B** measurements. [See plasma.physics.wisc.edu/rwm-gallery]

2) Internal kink is related but only affects the core of the plasma.

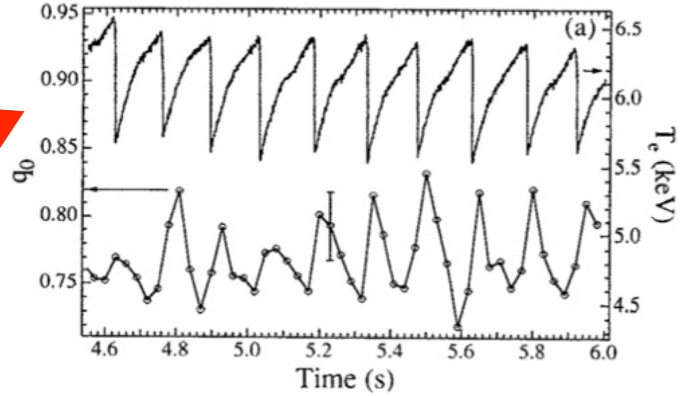


Simulation of internal kink in NSTX by W. Park, PPPL.

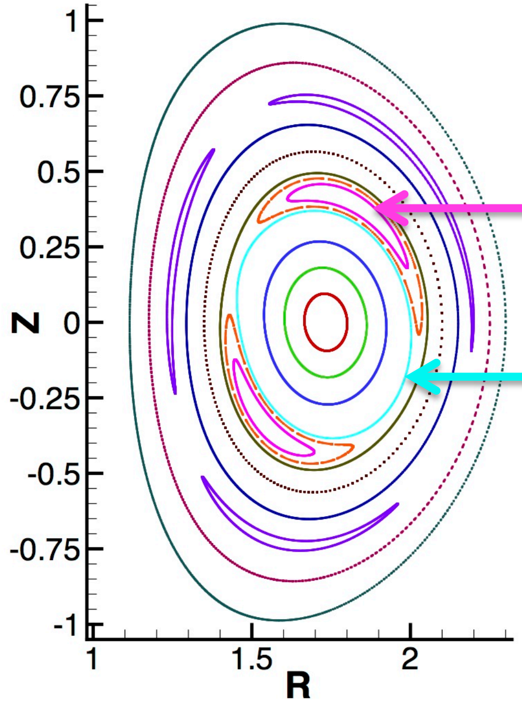


TFTR electron temperature profile is lopped-off by sawtoothing [Yamada, *et al.*, Phys. Plasmas **1**, 3269].

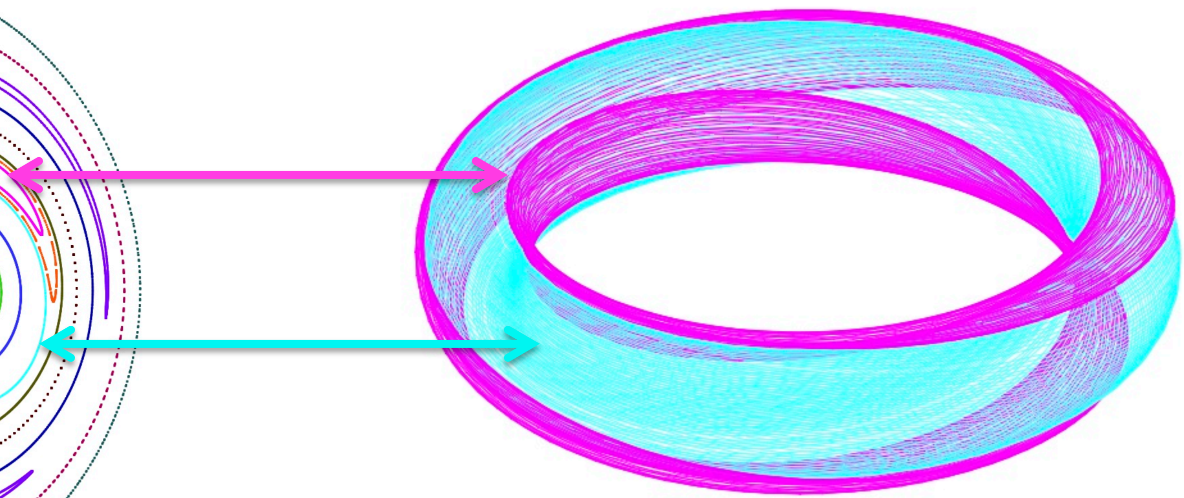
- Internal kink can be relatively benign.
- Repetitive kink behavior is called "sawtoothing" due to its effect on central-T_e. [Yamada, *et al.*]



3) The development of large magnetic islands alters confinement.



Magnetic “reconnection” alters field-line connectivity.

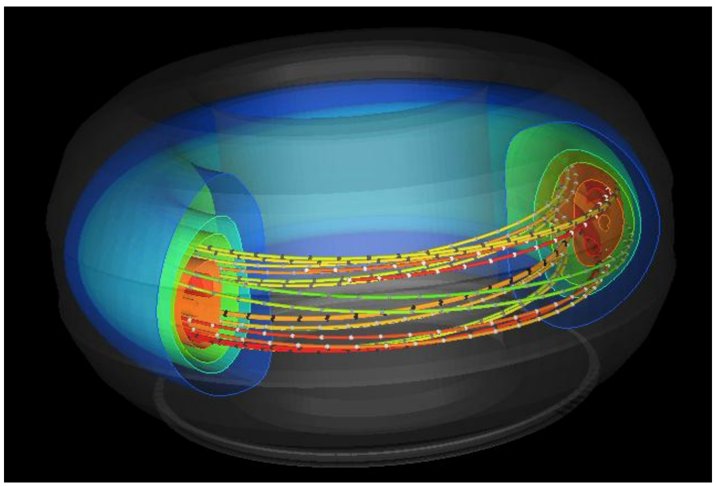


Magnetic islands are topologically isolated helical structures that result from reconnection. [from NIMROD computation]

- Isolated magnetic islands in tokamaks provide limited short-circuits for heat to escape more readily.

The overlap of magnetic islands in tokamaks is more problematic.

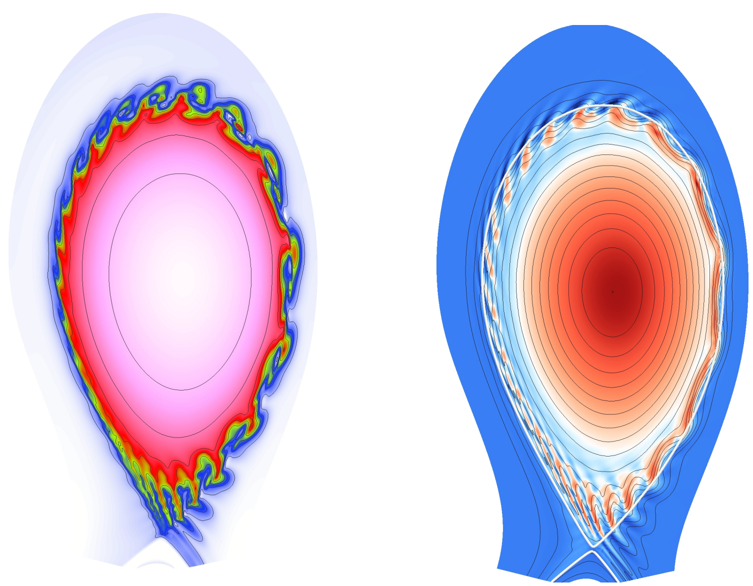
- Magnetic-island overlap allows significant and rapid energy loss and changes in electrical conductivity.
- This process results in a disruptive termination of a discharge.



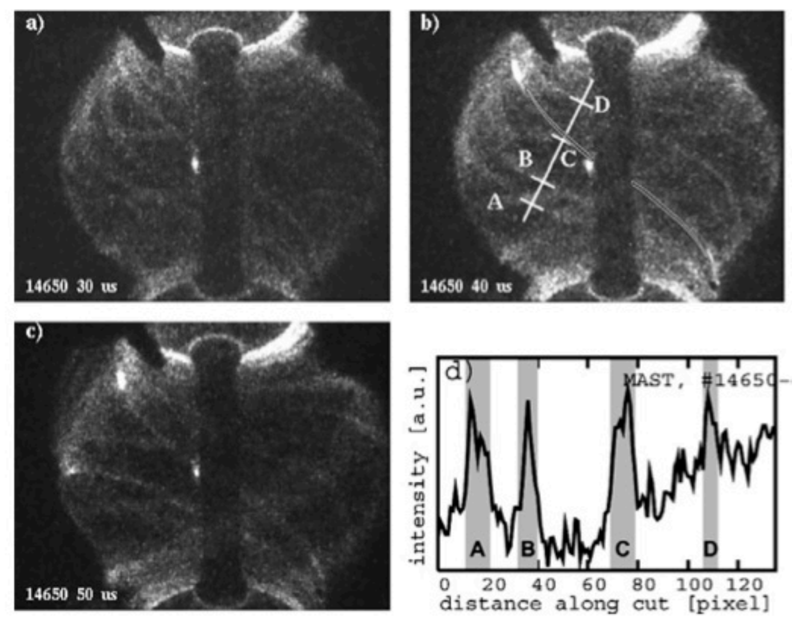
High-pressure disruption simulation by S. Kruger and A. Sanderson [Phys. Plasmas **12**, 56113].

4) Edge-localized modes are a combination of "ballooning" and surface kink.

- Edge-localized modes (ELMs) result from large gradients near the edge of the confinement region.
- ELMs make heat loading intermittent – a concern for ITER.



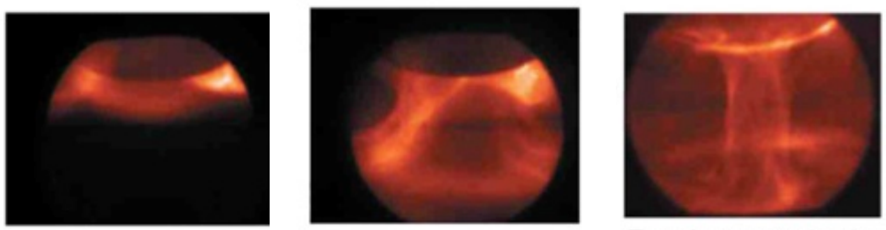
Particle and current density from an ELM simulation by G. Huysmans [PPCF **51**, 124012].



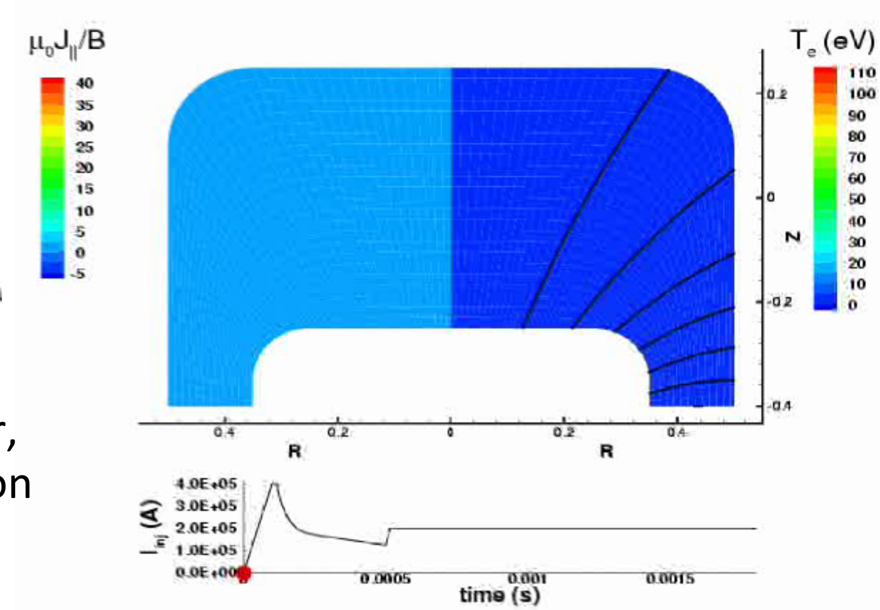
Framing-camera images of ELMs in the MAST experiment [Koch, *et al.*, JNM **363**, 1056].

5) Magnetic relaxation is non-disruptive MHD that alters magnetic configurations.

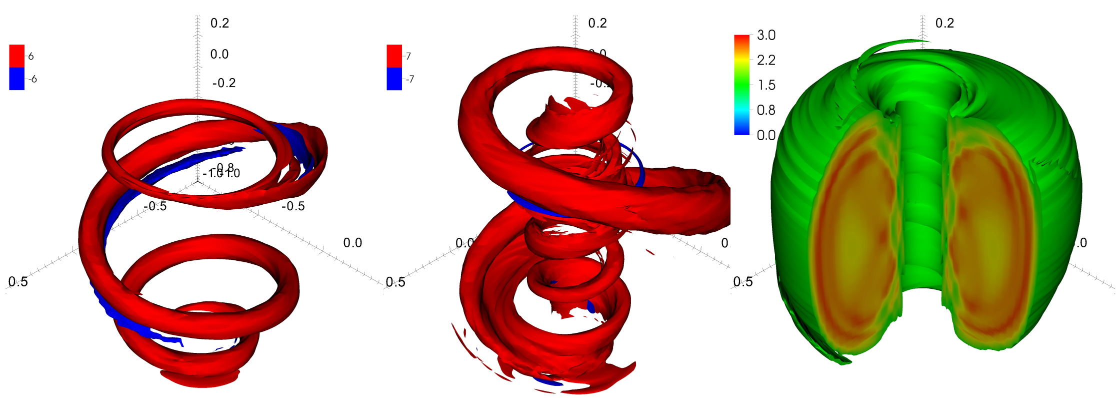
- Relaxation involves nonlinear MHD and magnetic reconnection.



Ballooning out of gun (t ~ 35 μs)   Ballooning reaches bottom of flux conserver (t ~ 40 μs)   Transient central column formation (t ~ 50 μs)



Images from SSPX experiment (above) [Hooper, *et al.*, PPCF **54**, 113001] and NIMROD simulation (right) [Sovinec, *et al.*, PRL **94**, 035003].



Simulation of Pegasus startup by J. O'Bryan [PPCF **56**, 064005].

MHD Models: Dependent variables are densities that are related to conserved quantities.

- The independent variables are position (**x**) and time (*t*).
- The dependent variables are:
  - Mass density $\rho(\mathbf{x},t)$
  - Momentum density ÷ ρ, i.e. center-of-mass flow velocity $\mathbf{V}(\mathbf{x},t)$
  - Internal energy density × $(\gamma - 1)$, i.e. fluid pressure $p(\mathbf{x},t)$
  - Magnetic induction ("field"), $\mathbf{B}(\mathbf{x},t)$

MHD systems of equations represent conservation laws.

- The most basic ideal system excludes dissipative effects.

➢ Mass: $\frac{\partial}{\partial t}\rho + \nabla\cdot(\rho\mathbf{V}) = 0$

➢ Momentum: $\frac{\partial}{\partial t}(\rho\mathbf{V}) + \nabla\cdot\left[\rho\mathbf{VV} + \left(p + \frac{B^2}{2\mu_0}\right)\underline{\underline{\mathbf{I}}} - \frac{1}{\mu_0}\mathbf{BB}\right] = 0$

➢ Energy: $\frac{\partial}{\partial t}\left(\frac{\rho V^2}{2} + \frac{p}{\gamma-1} + \frac{B^2}{2\mu_0}\right) + \nabla\cdot\left[\frac{\rho V^2}{2}\mathbf{V} + \frac{\gamma p}{\gamma-1}\mathbf{V} + \frac{1}{\mu_0}\mathbf{E}\times\mathbf{B}\right] = 0$

➢ Magnetic flux: $\frac{\partial\mathbf{B}}{\partial t} + \nabla\cdot\left[\underline{\underline{\mathbf{I}}}\times\mathbf{E}\right] = 0$

➢ Divergence constraint: $\nabla\cdot\mathbf{B} = 0$

➢ Constitutive relation (ideal-**E**): $\mathbf{E} = -\mathbf{V}\times\mathbf{B}$

Other forms admit alternative interpretation of terms.

- Using vector identities, the same system is equivalent to:

➢ Mass: $$\frac{\partial}{\partial t}\rho + \mathbf{V}\cdot\nabla p = -\rho\nabla\cdot\mathbf{V}$$

➢ Flow evolution: $$\rho\left(\frac{\partial}{\partial t}\mathbf{V} + \mathbf{V}\cdot\nabla\mathbf{V}\right) = \underbrace{\mathbf{J}\times\mathbf{B}}_{\text{Lorentz}} - \underbrace{\nabla p}_{\text{pressure gradient}}$$

➢ Pressure: $$\frac{\partial}{\partial t}p + \mathbf{V}\cdot\nabla p = -\gamma p\nabla\cdot\mathbf{V}$$

➢ Faraday's: $$\frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$$

➢ Divergence constraint: $\nabla\cdot\mathbf{B} = 0$

➢ Constitutive relations: $\mu_0\mathbf{J} = \nabla\times\mathbf{B}$ $\quad\mathbf{E} = -\mathbf{V}\times\mathbf{B}$

Non-ideal MHD systems include dissipative effects.

- Adding electrical resistance, viscous stress, and thermal conduction leads to:

➢ Mass: $$\frac{\partial}{\partial t}\rho + \mathbf{V}\cdot\nabla p = -\rho\nabla\cdot\mathbf{V}$$

➢ Flow evolution: $$\rho\left(\frac{\partial}{\partial t}\mathbf{V} + \mathbf{V}\cdot\nabla\mathbf{V}\right) = \underbrace{\mathbf{J}\times\mathbf{B}}_{\text{Lorentz}} - \underbrace{\nabla p}_{\text{pressure gradient}} - \underbrace{\nabla\cdot\underline{\underline{\Pi}}}_{\text{viscous stress}}$$

➢ Internal energy: $$\frac{\rho k_B}{m(\gamma-1)}\left(\frac{\partial}{\partial t}T + \mathbf{V}\cdot\nabla T\right) = \underbrace{-\frac{\rho k_B}{m}\nabla\cdot\mathbf{V}}_{PdVol\ \text{work}} - \underbrace{\nabla\cdot\mathbf{q}}_{\text{conduction}} + \underbrace{\eta J^2 + \underline{\underline{\Pi}}:\nabla\mathbf{V}}_{\text{heating}}$$

➢ Resistive-MHD Ohm's: $$\mathbf{E} = \underbrace{\eta\mathbf{J}}_{\text{resistive }\mathbf{E}} - \mathbf{V}\times\mathbf{B}$$

➢ Constitutive relations: $\mathbf{q} \propto -\nabla T \quad \underline{\underline{\Pi}} \propto -\left[\nabla\mathbf{V} + \nabla\mathbf{V}^T - \frac{2}{3}\mathbf{I}\nabla\cdot\mathbf{V}\right]$

Reduced systems build-in approximations to isolate dynamics of interest.

- "Reduced MHD" assumes that dynamics avoid perpendicular compression [Strauss, Phys. Fluids **19**, 134].

- In the limit of large aspect ratio ($R/a = 1/\varepsilon >> 1$) and guide field (B_ϕ), and vanishing pressure (after normalizing):

➢ Stream function evolution

$$\frac{\partial}{\partial t}\nabla_\perp^2 U + \mathbf{V}_\perp \cdot \nabla_\perp \nabla_\perp^2 U = \mathbf{B} \cdot \nabla \nabla_\perp^2 A_\phi$$

$$\mathbf{V}_\perp = \nabla \times \left(U\hat{\phi}\right)$$

➢ Parallel vector potential

$$\frac{\partial A_\phi}{\partial t} = \mathbf{B} \cdot \nabla U + \frac{\varepsilon}{\mathrm{S}} \nabla_\perp^2 A_\phi$$

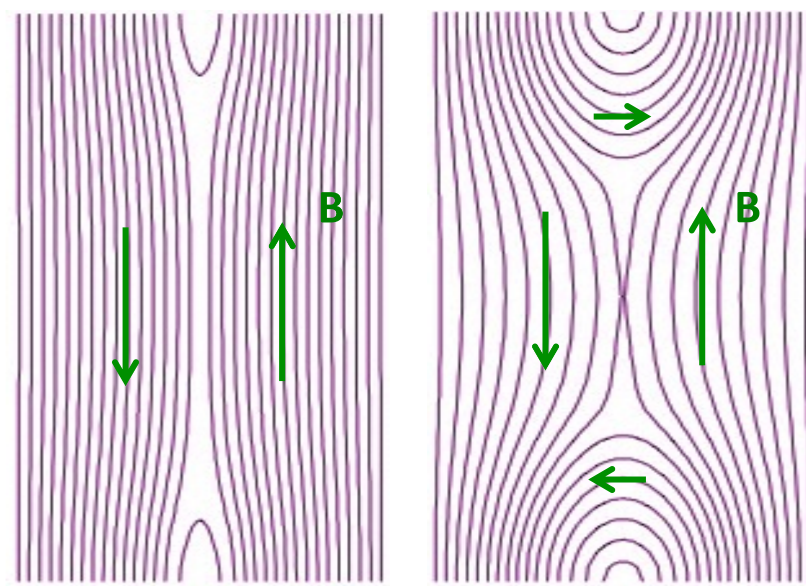
$$\mathbf{B}_\perp = \nabla \times \left(A_\phi \hat{\phi}\right) \qquad \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{A} - \nabla \chi$$

$$\mathrm{S} = \mu_0 v_A a^2 / R\eta_0 \qquad \chi = -B_\phi U$$

- Incompressible Navier-Stokes is a similar reduction for fluid dynamics.

The different MHD systems have different uses.

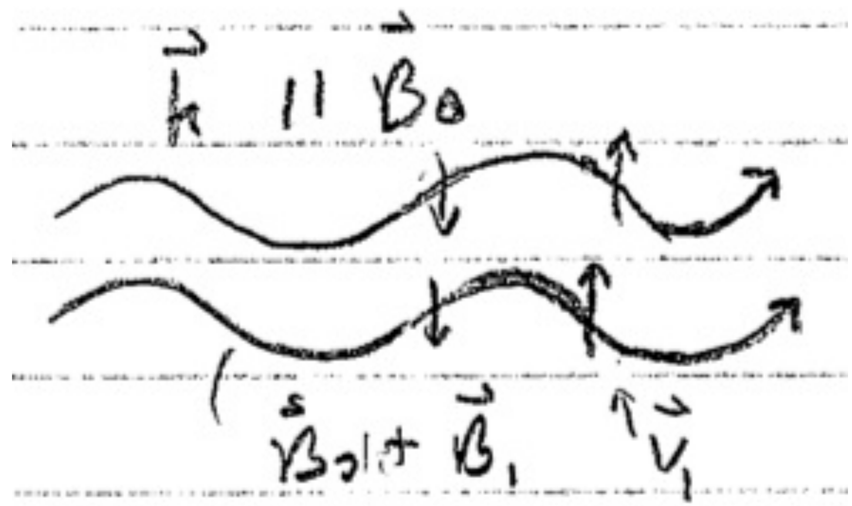
- Ideal MHD describes fast dynamics.
  - MHD waves
  - Fast instabilities
- Resistive MHD describes slippage of **B** and imperfectly conducting fluid.
  - Magnetic reconnection [see Prof. Loureiro's presentation]
  - Slower instabilities
- Reduced MHD is an efficient description of subtle dynamics that remain near force-balance.



Contours of magnetic flux from a simple configuration illustrate magnetic reconnection.

Application of MHD equations - Alfvén waves

- Alfvén waves are fundamental to MHD behavior.
- They are electromagnetic and wiggle magnetic field.
- They can transfer information and energy.



Sketch of Alfvén-wave dynamics.

Sinusoidal perturbations along uniform $\mathbf{B}_0$ allows a quick derivation.

1. Distinguish small perturbations ($_1$) from uniform background ($_0$).

2. Assume oscillatory, sinusoidal flow (justify later).

$$\mathbf{V}_1 = \hat{V}_1 \cos\left(kz - \omega t\right)\hat{\mathbf{y}}$$

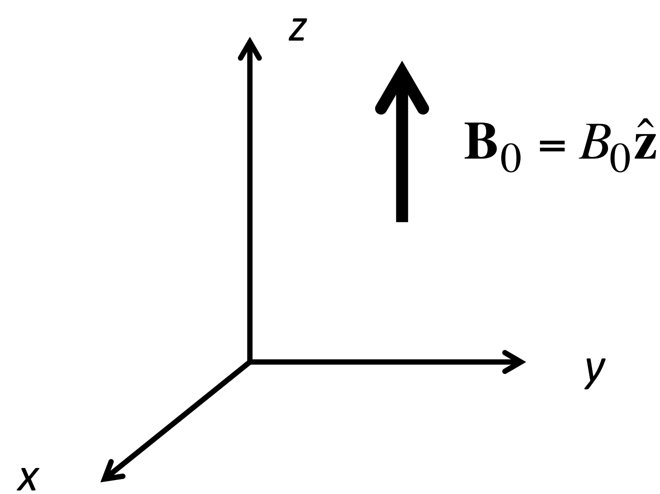
3. Evaluate $\mathbf{E}_1$.

$$\mathbf{E}_1 = -\mathbf{V}_1 \times \mathbf{B}_0 = -\hat{V}_1 B_0 \cos\left(kz - \omega t\right)\hat{\mathbf{x}}$$

4. Find $\mathbf{B}_1$ by integrating Faraday's.

$$\frac{\partial}{\partial t}\mathbf{B}_1 = -\nabla \times \mathbf{E}_1 = -\hat{V}_1 B_0 k \sin\left(kz - \omega t\right)\hat{\mathbf{y}}$$

$$\mathbf{B}_1 = -\frac{\hat{V}_1 B_0 k}{\omega}\cos\left(kz - \omega t\right)\hat{\mathbf{y}} + \cancelto{0}{\mathbf{f}(z)}$$



5. Ampere's provides $\mathbf{J}_1$.

$$\mathbf{J}_1 = \frac{1}{\mu_0}\nabla \times \mathbf{B}_1 = -\frac{\hat{V}_1 B_0 k^2}{\omega \mu_0}\sin\left(kz - \omega t\right)\hat{\mathbf{x}}$$

6. Find Lorentz force density.

$$\mathbf{J}_1 \times \mathbf{B}_0 = \frac{\hat{V}_1 B_0^2 k^2}{\omega \mu_0}\sin\left(kz - \omega t\right)\hat{\mathbf{y}}$$

Relating force density and acceleration leads to a dispersion relation.

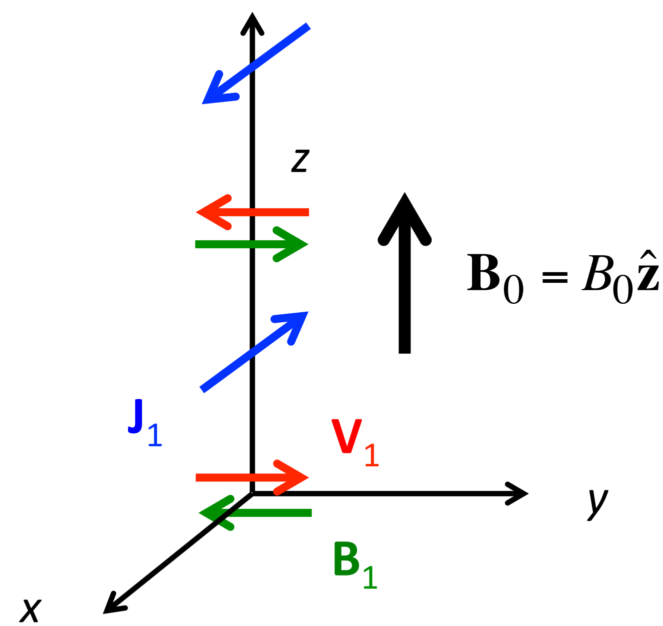
7. Evaluate acceleration.

$$\frac{\partial}{\partial t}\mathbf{V}_1 = \omega\hat{V}_1 \sin(kz-\omega t)\,\hat{\mathbf{y}}$$

8. Assemble in flow-velocity equations for perturbations – supports $\mathbf{V}_1$ oscillation.

$$\rho_0 \frac{\partial}{\partial t}\mathbf{V}_1 = \mathbf{J}_1 \times \mathbf{B}_0$$

$$\omega\rho_0\hat{V}_1 \sin(kz-\omega t)\,\hat{\mathbf{y}} = \frac{\hat{V}_1 B_0^2 k^2}{\omega\mu_0}\sin(kz-\omega t)\,\hat{\mathbf{y}}$$



Relating coefficients, we find the dispersion relation for Alfvén waves:

$$\underline{\omega^2 = \frac{B_0^2}{\rho_0\mu_0}k^2} \quad \text{or} \quad v_{phase}^2 = \frac{\omega^2}{k^2} = v_A^2 = \frac{B_0^2}{\rho_0\mu_0}\;, \quad \text{independent of } k$$

Paradigm: Standard analysis considers equilibrium, linear stability, and nonlinear evolution.

- The approximate toroidal or cylindrical symmetry of many configurations motivates analysis about symmetric states.
- Equilibrium refers to force-balance of symmetric states.
- Linear stability assesses whether equilibrium states that are perturbed infinitesimally tend to return.
- Mechanical analogies are insightful.

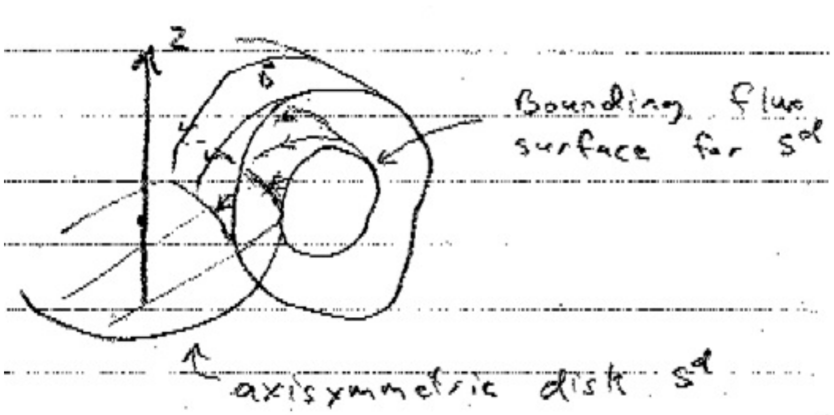
Stable equilibrium example.

Unstable* equilibrium example.

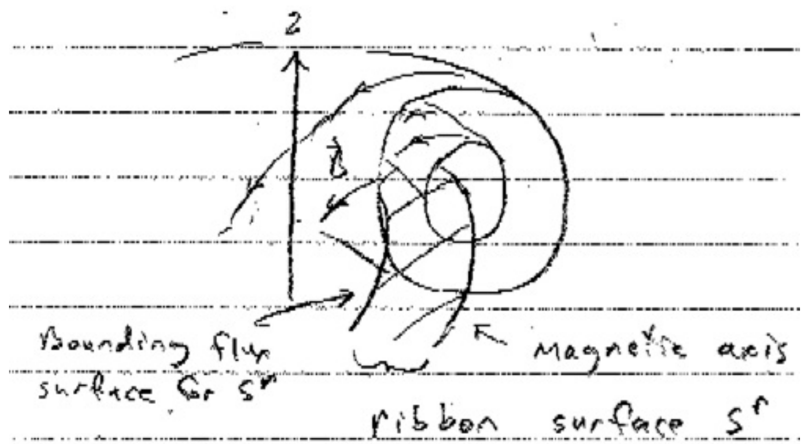
*nonlinearly due to dimples

Static force-balance is a reduction of the flow-velocity equation.

- In the absence of flows, the pressure gradient balances the Lorentz force density: $\mathbf{J}_0 \times \mathbf{B}_0 = \nabla p_0$
- Well-posed boundary value problems are formulated in terms of magnetic flux functions.
  - **B**-field lines trace-out surfaces in symmetric configurations
  - Magnetic flux functions are integrals of **B**·*d***S** between surfaces.



Sketch of poloidal disk-flux computation.



Sketch of poloidal ring-flux computation.

The Grad-Shafranov equation is a solvable restatement of the force-balance condition.

- The dependent variable is related to the ring flux: $\psi = \psi^r / 2\pi$
- Magnetic field is expressed as

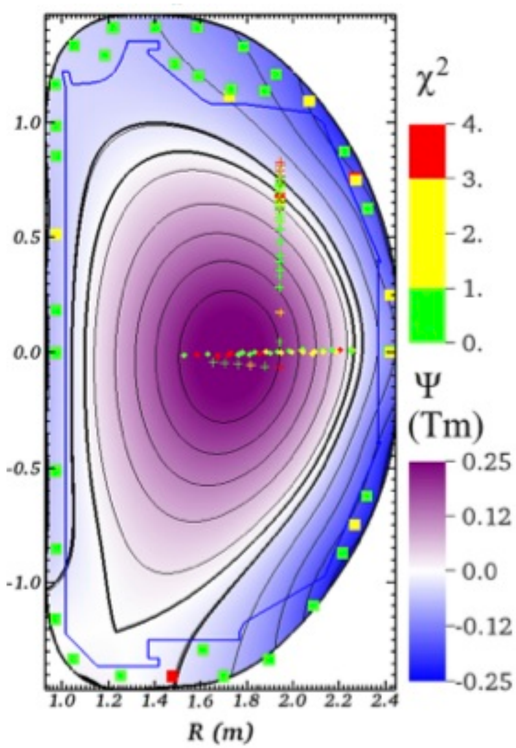
$$\mathbf{B}_0 = \nabla\phi \times \nabla\psi + \left(RB_\phi\right)\nabla\phi$$

- The force-balance relation implies that p_0 and $I = RB_\phi$ are functions of ψ-only.
- Using this information, one can express $\mathbf{J}_0 \times \mathbf{B}_0 = \nabla p_0$ as the Grad-Shafranov equation:

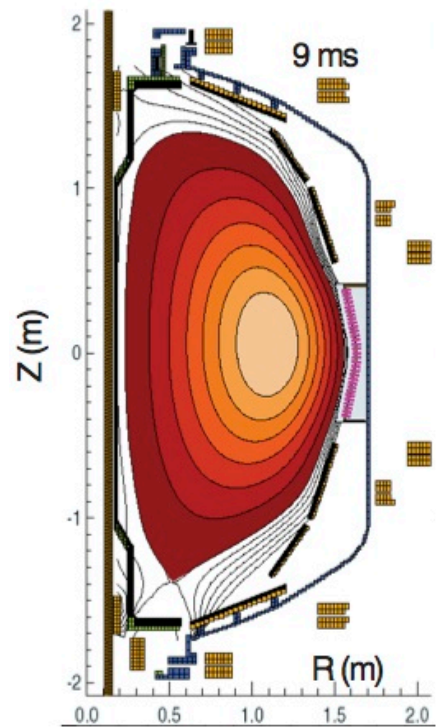
$$R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial}{\partial R}\psi\right) + \frac{\partial^2}{\partial Z^2}\psi = -I\frac{dI}{d\psi} - \mu_0 R^2 \frac{dp_0}{d\psi}$$

- Boundary conditions fix ψ on a surface or represent ψ from external coils.

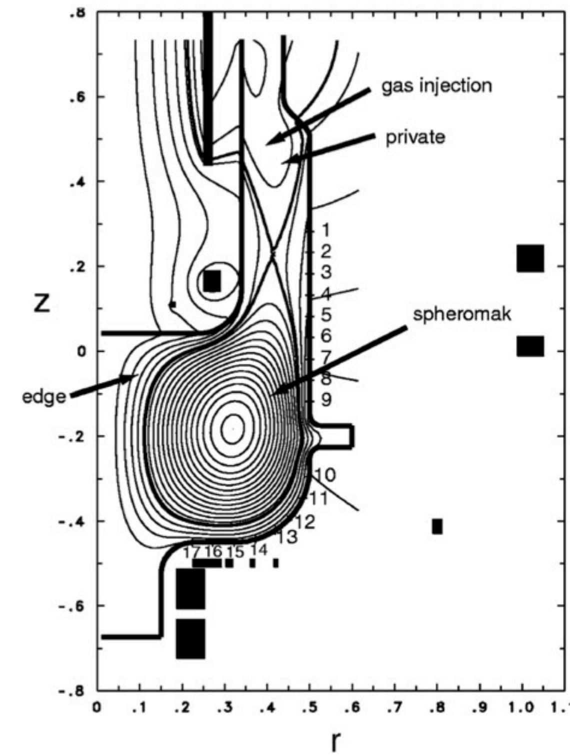
Grad-Shafranov solutions represent a variety of magnetic confinement configurations.



DIII-D tokamak [King, *et al.*, PoP **24**, 012504].



NSTX spherical torus during helicity injection [Raman, *et al.*, PRL **97**, 175002].



Gun-driven SSPX spheromak [Hooper, *et al.*, PPCF **54**, 113001].

- Equilibria are often fit to sets of laboratory measurements.

Two general approaches are used assess linear perturbations.

- Eigenvalue equations consider solutions $\vec{\xi}(\mathbf{x},t)=\vec{\xi}_{\omega}(\mathbf{x})\exp(-i\omega t)$ for the linearized equations.
    - Growth rates (and frequencies) are determined.
    - The Alfvén-wave derivation is a simple example.
- The ideal-MHD energy principle of Bernstein, Frieman, Kruskal, and Kulsrud [Proc. Royal Soc. A **244**, 17 (1958)] focuses on stability.*
    - The analysis is related to variational principles of linearized continuum mechanics.
    - ➢ A system is linearly stable if all physically possible displacements increase potential energy.

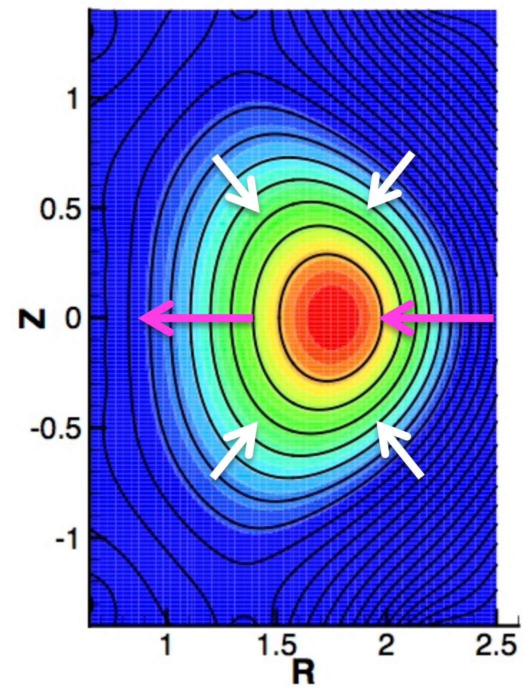
*Also see J. P. Freidberg, Rev. Modern Phys. **54**, 801 (review paper) and *Ideal Magnetohydrodynamics*, Cambridge Univ. Press (1993).

Magnetic confinement has two primary sources of potentially destabilizing energy from MHD.

- In toroidal geometry, $\mathbf{B}_0$ must twist to prevent net outward drifts. [See Dr. Collins' presentation.]
- The resulting $\mathbf{B}_0$ has toroidal *and* poloidal curvature.

✧ #1) The alignment of curvature $\boldsymbol{\kappa} = \hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}}$ with ∇P leads to free energy; the perturbed ideal-MHD energy contribution is

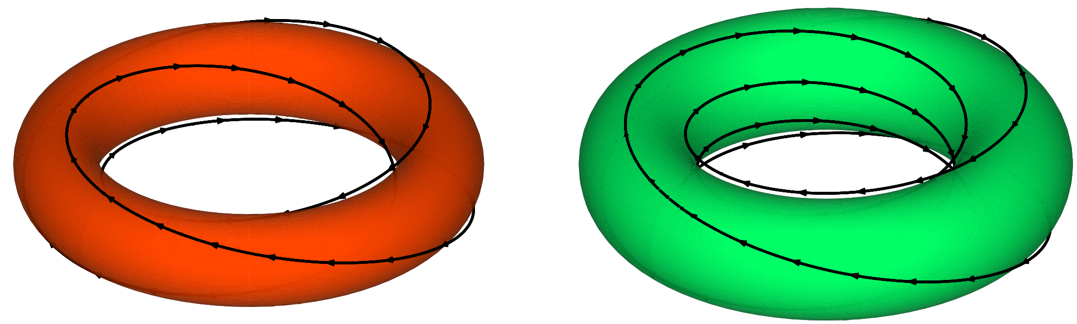
$$-\int_{R_{pl}} \left(\vec{\xi}_\perp \cdot \nabla P_0\right)\left(\vec{\xi}_\perp^* \cdot \boldsymbol{\kappa}_0\right) dVol \sim \mathbf{F} \cdot \Delta \mathbf{s}$$



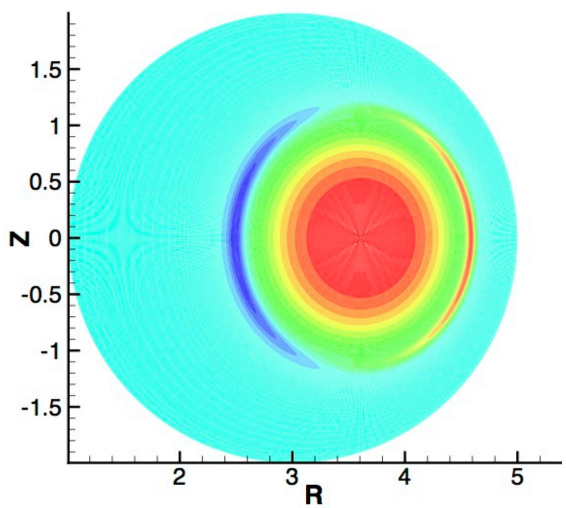
Cross section of plasma pressure contours (color) and magnetic flux (black lines). $\boldsymbol{\kappa}$ from $\mathbf{B}_{pol}$ (white) and from B_ϕ (magenta).

There are two primary sources of free energy (cont).

- In axisymmetric systems, twist is provided by charge current running through the plasma.
- Except in FRCs, current density is largely parallel to **B**.



Two surfaces of a toroidal equilibrium show 3/2 (left) and 5/2 (right) twist, i.e. safety factor (*q*).



Contour plot of λ for the same configuration shows significant spatial variation.

✧ #2) Spatial variation of the "parallel" current density, $\lambda = J_{||}/B$, also contributes free energy:

$$-\int_{R_{pl}} \lambda\left(\vec{\xi}_{\perp}^{*}\times\mathbf{B}\right)\cdot\nabla\times\left(\vec{\xi}_{\perp}\times\mathbf{B}\right)dVol \sim IV\Delta t$$

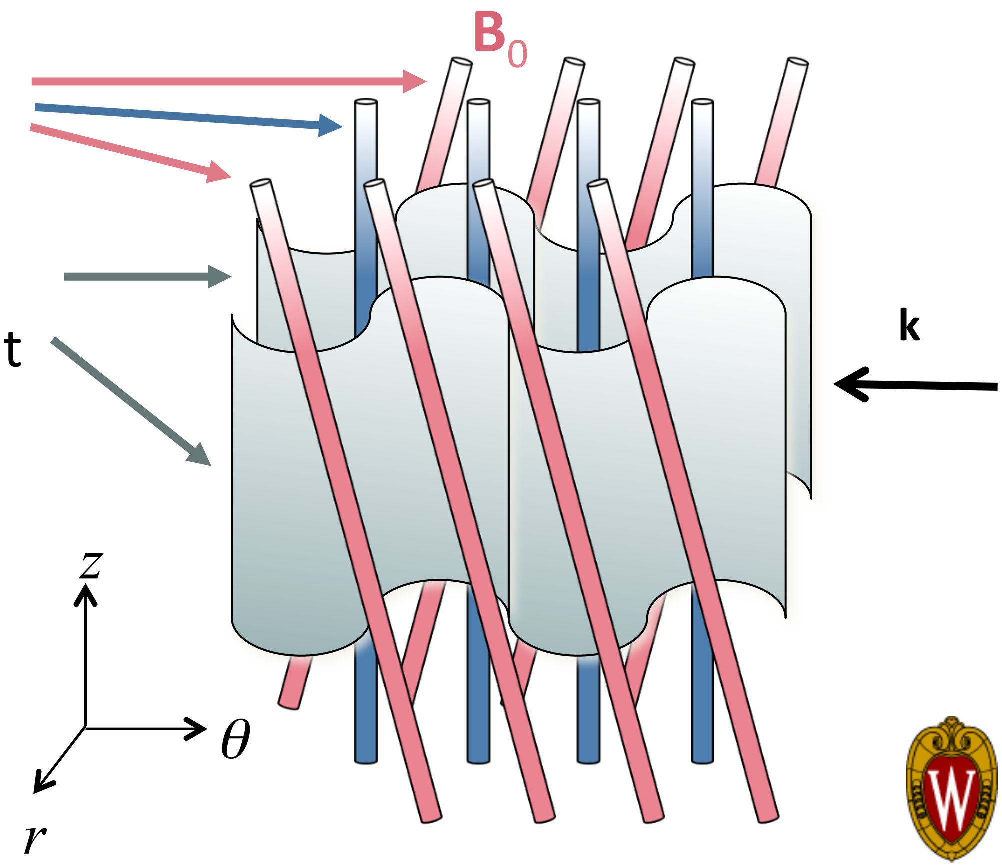
- Stability is a matter of whether the positive-energy contributions exceed these two negative-energy contributions.

Resonances for helical shear-Alfvén waves ($\omega \rightarrow 0$) play an important role.

- Restoring force density from bending is weak where wavefronts align with $\mathbf{B}_0$, hence susceptibility to instability.
- Resonant instability in sheared field leads to spatial localization.

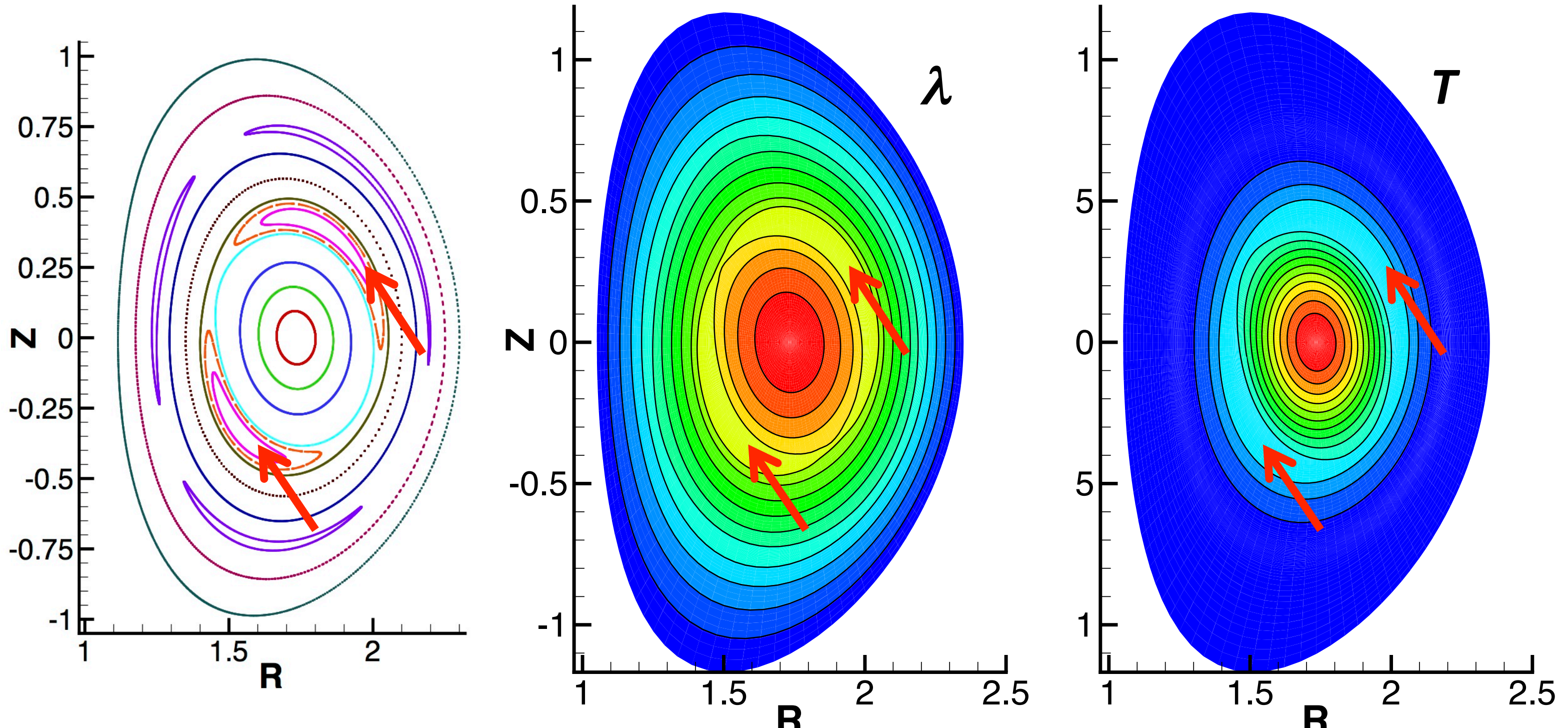
Background magnetic field is sheared.

Rational-winding wavefronts align with $\mathbf{B_0}$ along the resonant surface ($\mathbf{k}\bullet\mathbf{B_0} = 0$).



Nonlinear analysis considers how finite perturbations alter the system.

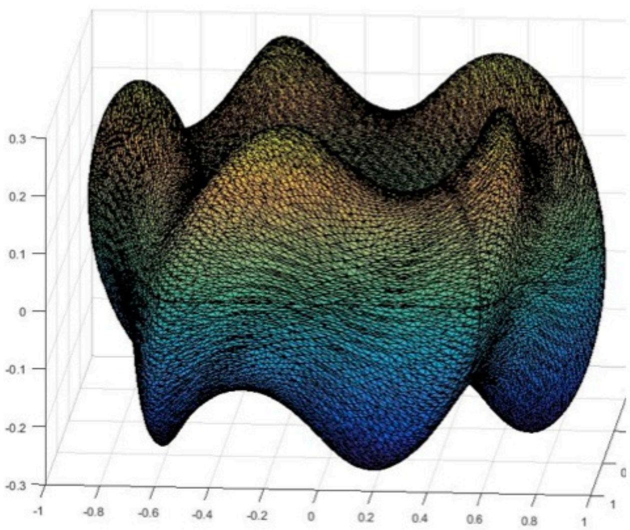
- Nonlinear systems are often solved numerically; the magnetic island shown earlier is one example.
- Island locations are resonances for helical perturbations.



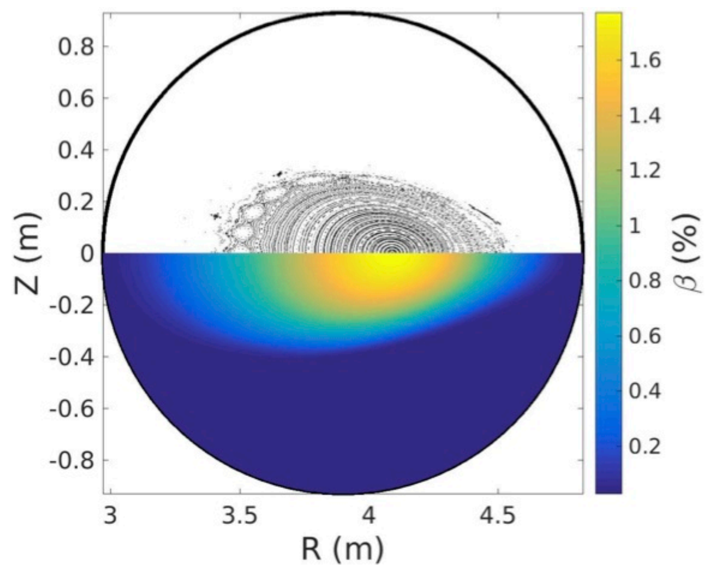
The tearing instability saturates nonlinearly by making λ uniform along **B**, and strong parallel heat flux equilibrates T over the island.

The conventional paradigm does not fit systems that are inherently asymmetric.

- Stellarators use toroidally asymmetric external helical coils to twist **B**.
- Increasing pressure often leads to continuous evolution among 3D states.



Flux-surface shape in a 5-field period stellarator configuration.



Computed evolution of magnetic topology and pressure.*

*T. Bechtel, 4/30/17 NIMROD Team meeting presentation [https://nimrodteam.org/meetings]

Conclusions

- MHD is a useful starting point for understanding macroscopic dynamics in magnetized plasma.
- MHD is a rich topic in itself.
- MHD analysis has analogies with continuum mechanics and fluid dynamics.
- The equilibrium / linear stability / nonlinear evolution paradigm is useful for many, but not all, configurations.

Overview of Plasma Opportunities at U. Wisconsin-Madison

presented by

Prof. Carl Sovinec, Engineering Physics

From March 3, 2017 Recruiting Presentation

photo by Jeff Miller

Theme: Wisconsin's breadth in plasma research offers many opportunities for graduate study.

Here, we discuss

- Plasma research areas
- Experiments
- Research centers
- Collaborations
- Plasma classes

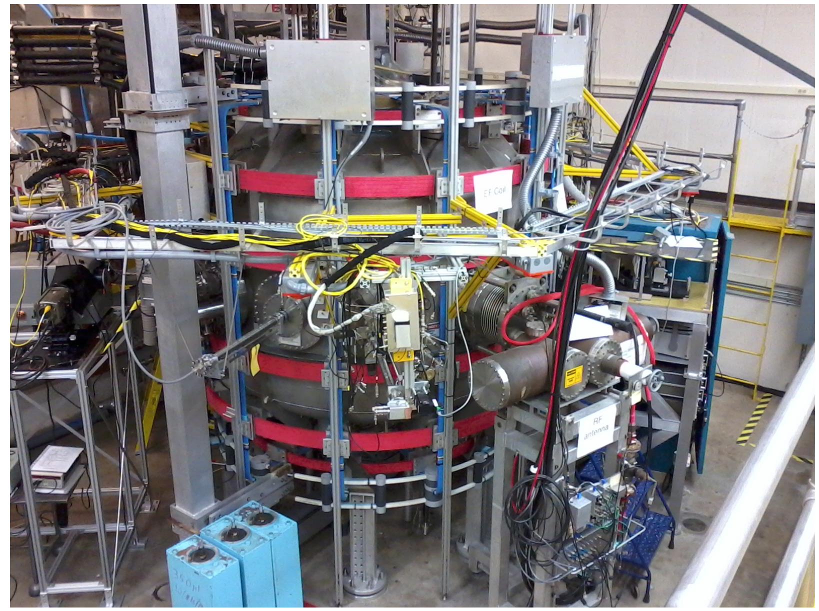
Research areas: Wisconsin activities span many plasma sub-fields.

- Magnetic confinement
  - Conventional
  - Alternates
- Basic plasma physics
  - Magnetic reconnection
  - Plasma-surface interaction
  - Magnetic dynamos
- Theory and computation
  - Magnetohydrodynamics
  - Turbulence
- Naturally occurring plasma
  - Astrophysics
  - Magnetosphere
- Technology
  - Fusion neutronics
  - Technology transfer
- Plasma applications
  - Industrial
  - Space propulsion
  - Oscillators and amplifiers

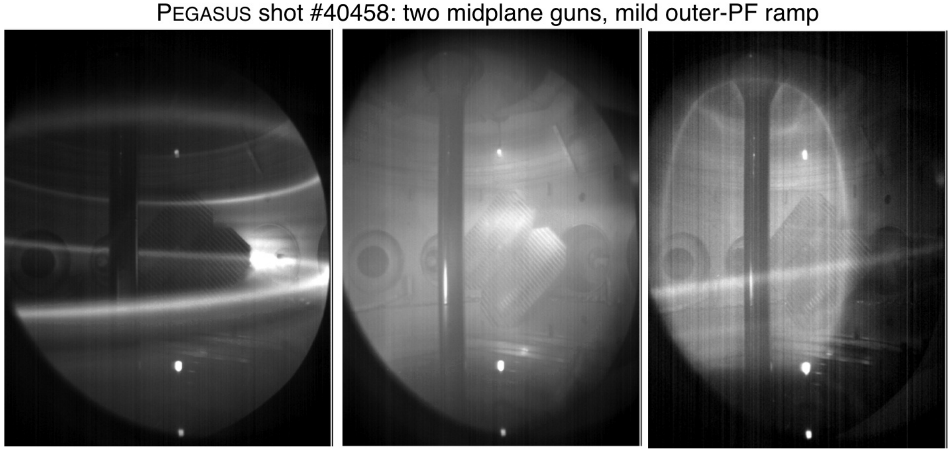
Experiments: Wisconsin is a leader in university-scale plasma experiments.

Pegasus is a spherical tokamak in Engineering Physics.

- Prof. Ray Fonck is the principal investigator.
- 5-10 graduate students, plus undergrads, scientists and engineers



PEGASUS shot #40458: two midplane guns, mild outer-PF ramp



$t=21.1$ ms, $I_p=2$-3 kA Filaments only	$t=28.8$ ms, $I_p=42$ kA Driven diffuse plasma	$t=30.6$ ms, $I_p=37$ kA Guns off, Decaying

Pegasus is used to study:

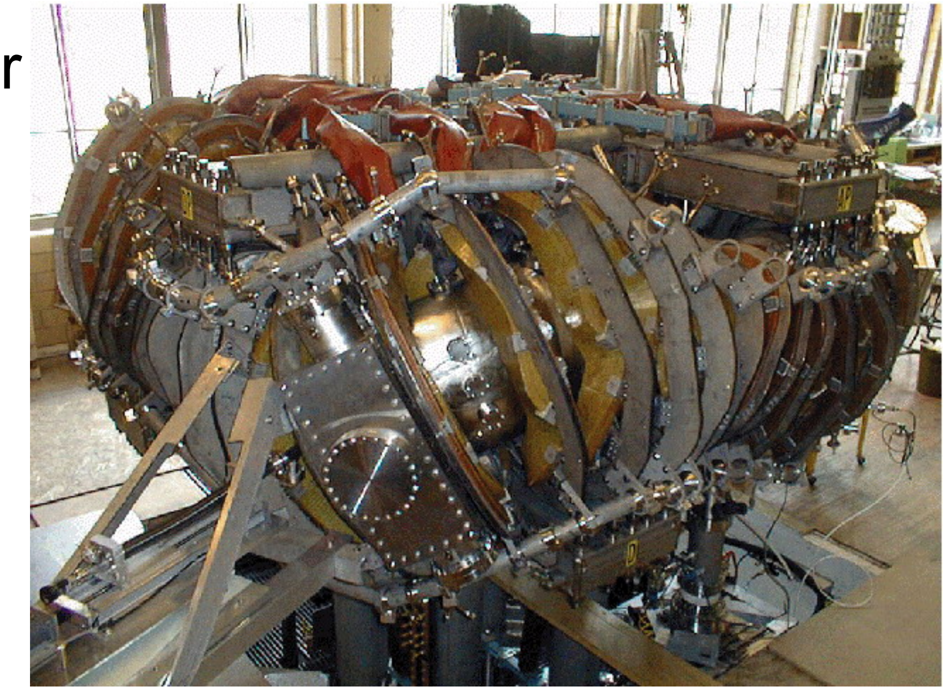
- Low-aspect ratio MHD
- Non-inductive plasma startup

Wisconsin's magnetic confinement experiments investigate innovative paths to fusion development.

HSX in Electrical and Computer Engineering is the world's first quasi-symmetric stellarator.

• Prof. David Anderson is the principal investigator.

• 5-10 graduate students, plus scientists and postdocs



HSX is used to study:

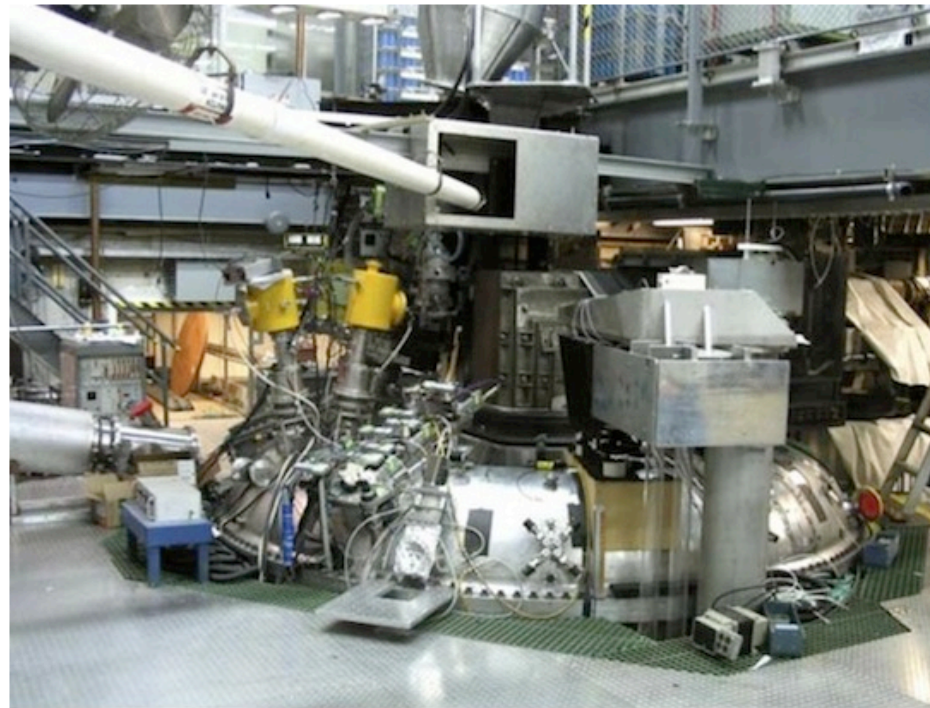
• Neoclassical and anomalous transport in quasi-symmetry

• Plasma confinement without net current

These larger experiments contribute to multiple areas of plasma research.

MST reversed-field pinch in Physics has contributed to plasma and fusion science for more than two decades.

- Prof. John Sarff is the principal investigator.
- 10-20 graduate students, 5+ postdocs, 5-10 scientists, plus engineering staff



MST is used to study:

- Fluctuation-induced transport
- Magnetic relaxation
- High engineering-β
- Pulsed and AC current drive

Wisconsin experiments address basic scientific questions for plasmas in nature.

Profs. Cary Forest and Jan Egedal of Physics run several experiments.

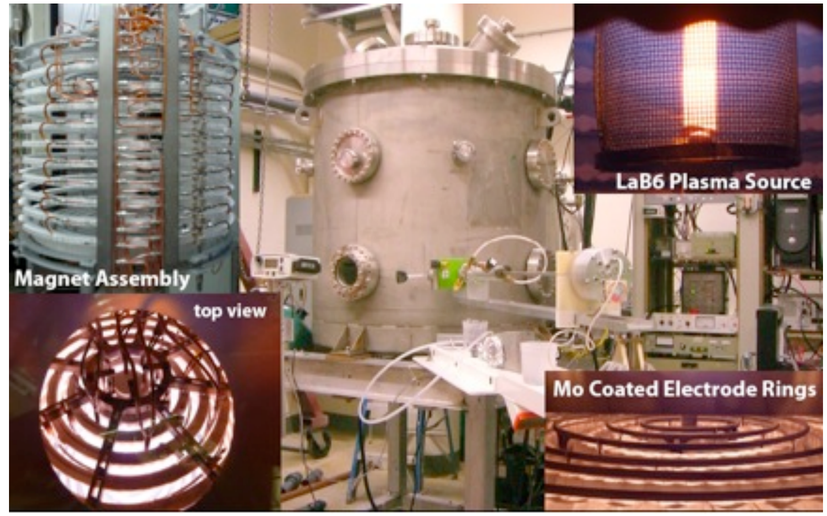
• The Madison Plasma Dynamo Exp. (**MPDX**) and **MDX** (liquid Na) are used to study magnetic field generation.

• The Terrestrial Reconnection Experiment (**TREX**) explores reconnection at low collisionality.

• **PCX** and **MPDX** investigate mageto-rotational instability.

• The Line-Tied Reconnection eXperiment (**LTRX**) is used to study line-tying and resistive-walls.

• Several graduate students per experiment, plus postdocs, scientists and engineers.



Plasma Couette-flow Experiment

MPDX and TREX share this large spherical chamber.

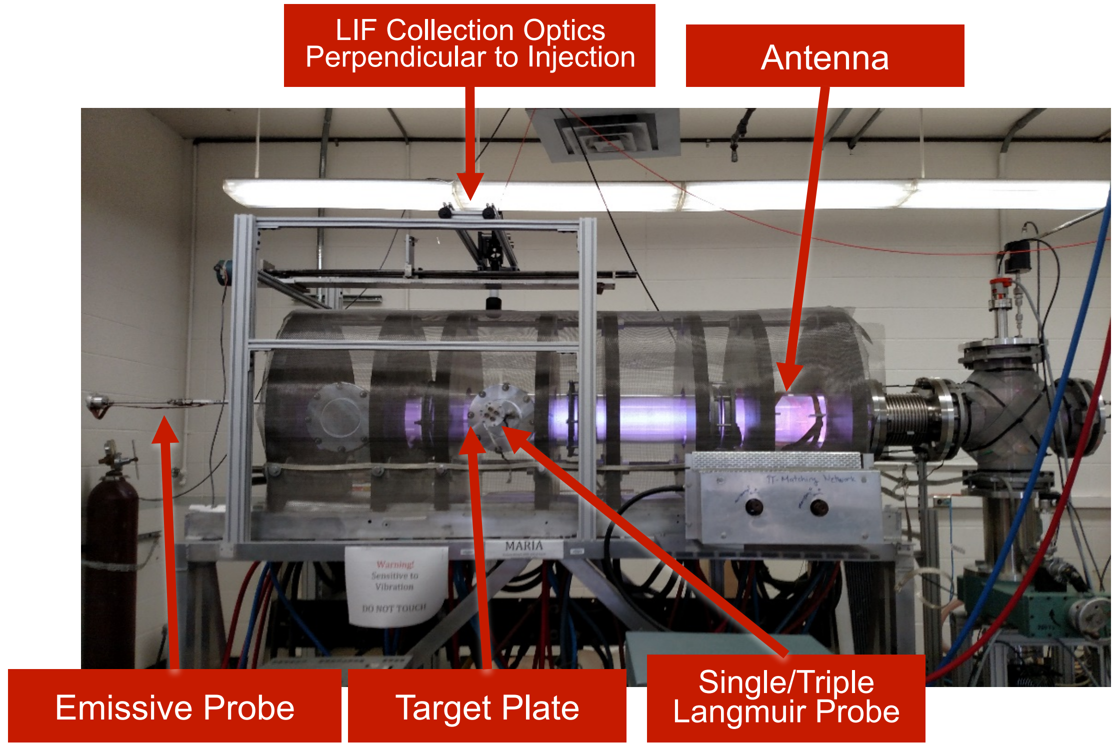
RF-driven experiments provide flexible platforms for science and technology.

Prof. Oliver Schmitz has reconfigured the **MARIA** experiment.

- Basic plasma physics
- Development of material-exposure capability

The group presently has 7 graduate students and 2 undergrads.

MARIA was originally developed by Prof. Emeritus Noah Hershkowitz to study helicon plasma and magnetized sheath physics.



Research centers facilitate cooperative efforts in several areas.

- Center for Plasma Theory and Computations (CPTC)
  - Prof. Chris Hegna, Director
  - Highlighted in following slides
- Fusion Technology Institute (FTI)
  - Prof. Paul Wilson, Director
- Center for Plasma in the Laboratory and Astrophysics (CPLA)
  - Prof. Cary Forest, Director
  - Based in Physics

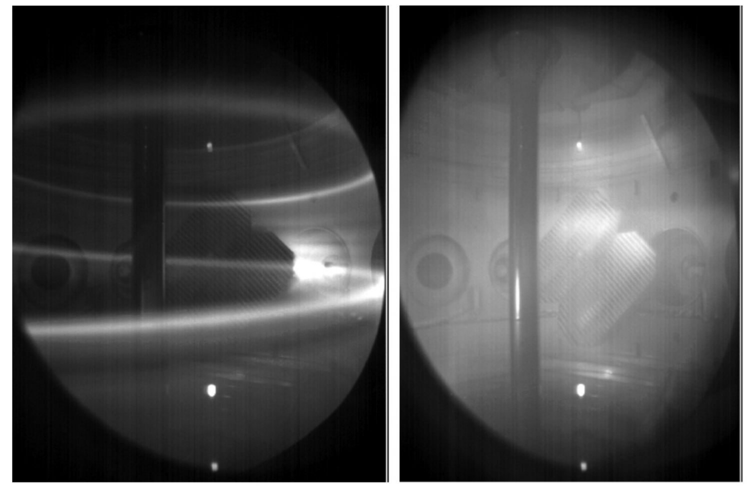
Plasma theory at Wisconsin includes studies of local experiments, national & international experiments, and independent theoretical topics.

Faculty and senior scientists:

- Prof. Stanislav Boldyrev, Physics, *turbulence and astrophysical plasmas*
- Prof. James Callen, EP (emeritus), *kinetics and transport*
- Prof. Chris Hegna, EP (CPTC director), *MHD and kinetics*
- Dr. Vladimir Mirnov, Physics, *MHD and kinetics*
- Prof. Greg Moses, EP (emeritus), *ICF theory and computation*
- Prof. Carl Sovinec, EP, *computational MHD*
- Prof. Paul Terry, Physics, *plasma turbulence and transport*
- Prof. Ellen Zweibel, Physics and Astronomy, *astrophysical plasmas*

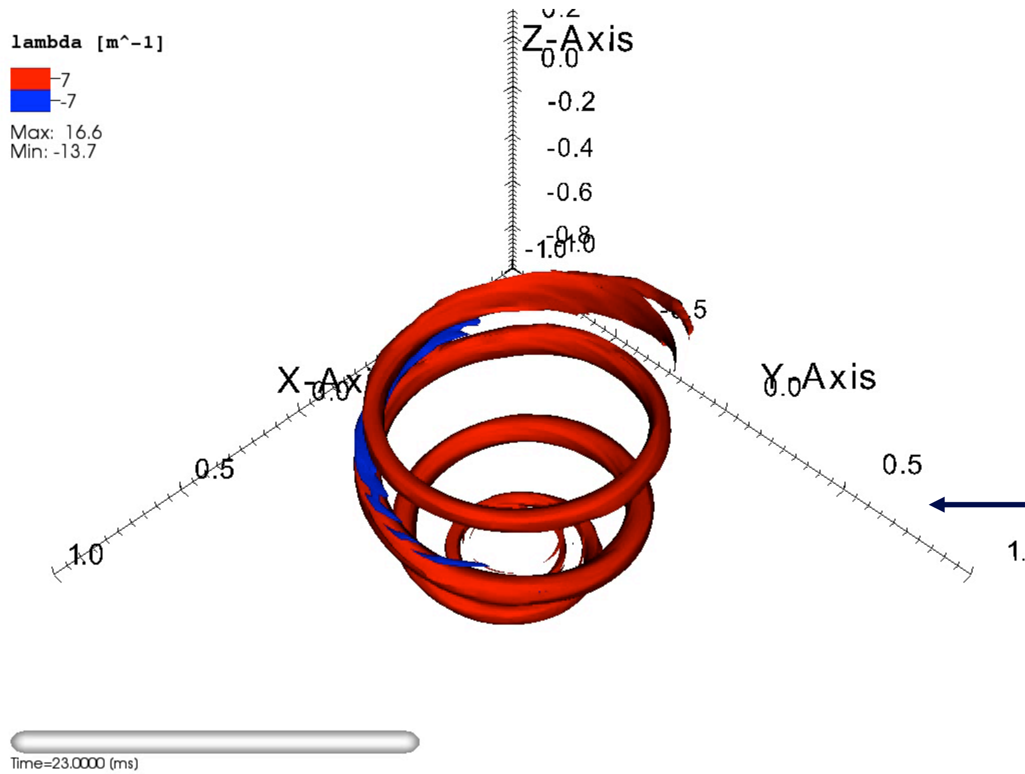
Our study of current-filament relaxation is an example of theory applied to local experiments.

Relaxation theories describe global aspects of Pegasus' non-inductive startup.



t=21.1 ms, I_p=2-3 kA
Filaments only

t=28.8 ms, I_p=42 kA
Driven diffuse plasma

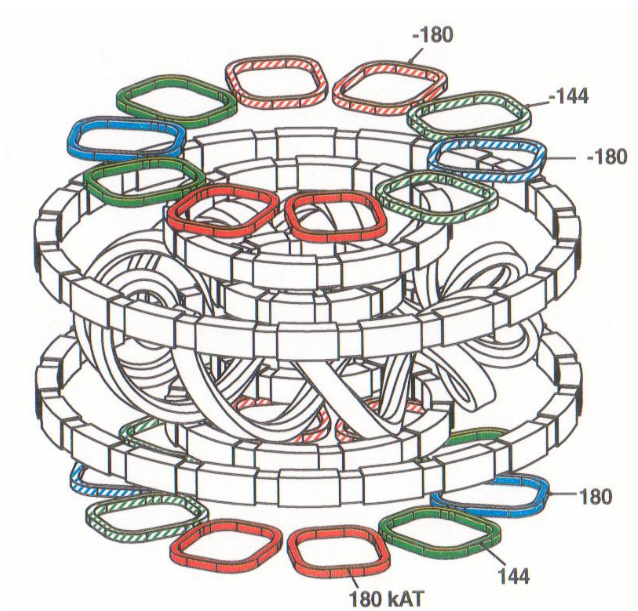


Numerical computation is applied to understand how current mixes into a diffuse discharge.

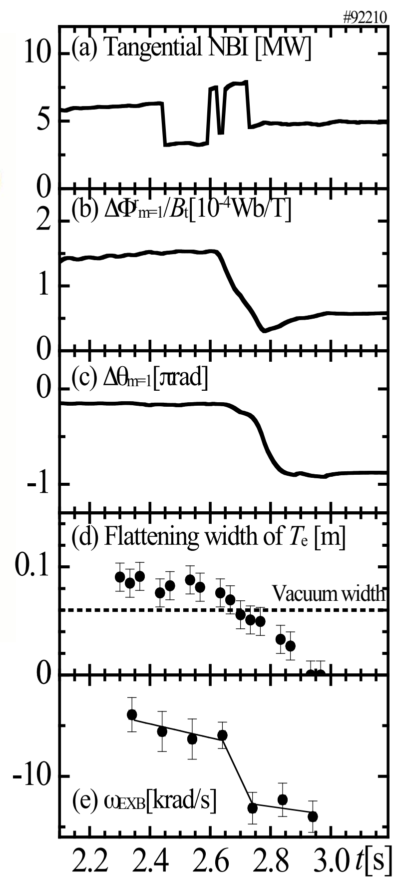
Simulation results from the NIMROD code. (J. O'Bryan)

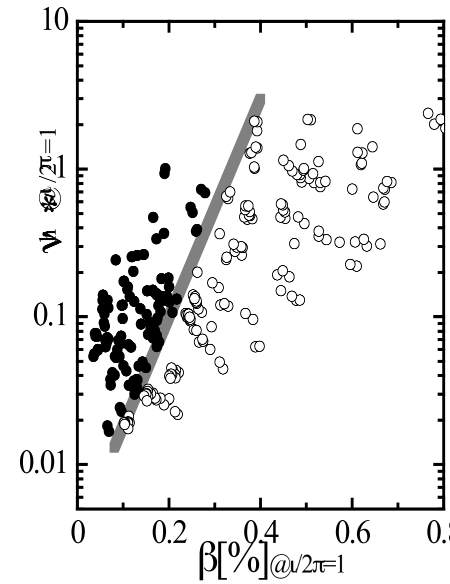
UW theorists have significant connections to the broader national and international programs.

- Example: Configuration studies of LHD (Japan)



Experiments show abrupt transitions of plasma flow and magnetics.





Theory modeling correctly predicts transition onset.
- Hegna et al

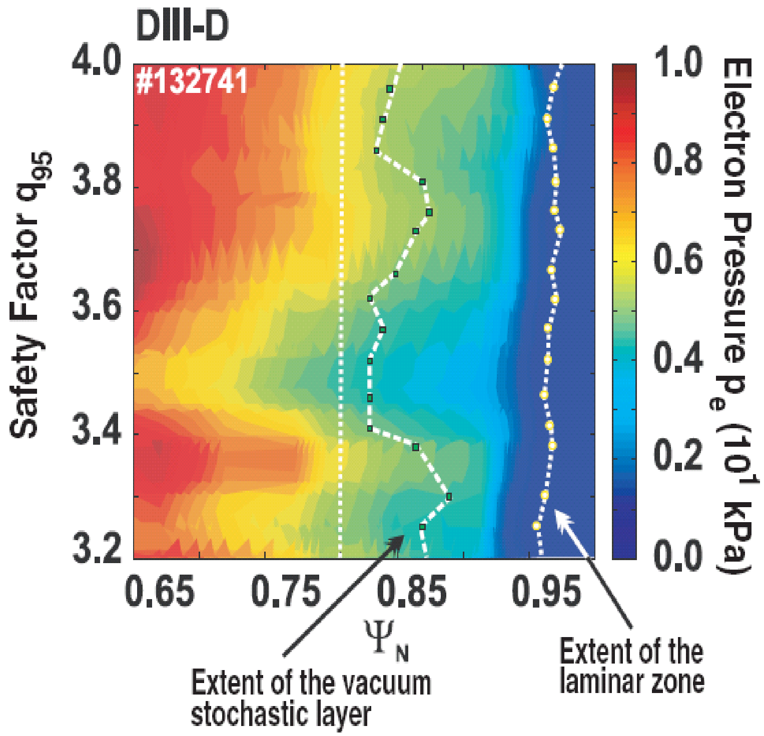
- Hegna is also leading a theory/modeling effort to improve the stellarator concept.

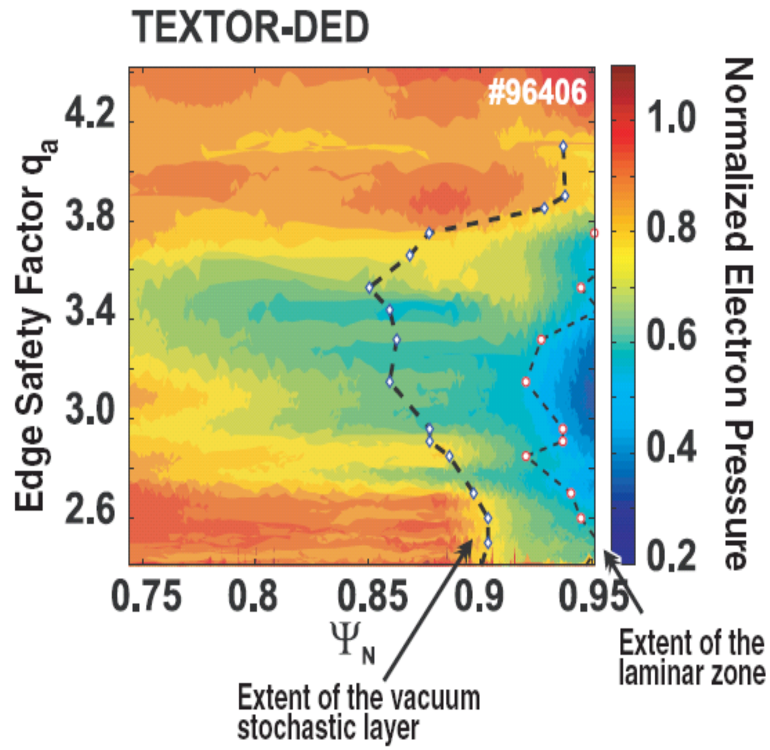
Collaborations: Wisconsin has a strong tradition in plasma-related collaboration.

- On campus:
  - Theory/experiment collaborations across campus
  - Students and scientists working on projects located in departments other than their own
- Nationally:
  - Experimental research on national facilities such as DIII-D and NSTX (Fonck, Schmitz, McKee, Smith and students, for example)
  - Large-experiment theoretical support (Callen, Hegna)
  - Computational collaborations on code development and application (NIMROD Code Team, CEMM)
- Internationally:
  - Tokamak experimental contributions to DIII-D and TEXTOR (Schmitz)
  - Neutronics for ITER (Wilson)
  - Stellarator theory for LHD in Japan (Hegna)
  - Stellarator edge physics in LHD and W7-X (Schmitz)
  - Computational collaboration with Max Planck Institute (Terry, Forest)

Prof. Oliver Schmitz brings strong collaborative ties to DIII-D and European experimental programs.

- Experiment and modeling investigate 3D transport in edge plasma.
- Group contributes to control of ELM activity in tokamaks / ITER.





⇨ **Field line connection length L_c compared to**
(a) Kolmogorov Length L_K and
(b) electron mean free path λ_e

- **Laminar Zone: $L_c < L_K \sim \lambda_e$ (Ψ_N>0.95)**
- **Stochastic Layer: $L_c > L_K \sim \lambda_e$ (Ψ_N>0.8)**

Plasma classes: Classroom instruction provides important background and skills for research.

- ECE/NE/Physics 525 - *Introduction to Plasmas*
- ECE/NE 526 - *Laboratory Course in Plasmas*
- ECE/NE/Physics 527 - *Plasma Confinement and Heating*
- ECE/NE 528 - *Plasma Processing and Technology*
- ECE/NE/Physics 724 - *Wave and Instabilities in Plasmas*
- ECE/NE/Physics 725 - *Plasma Kinetic Theory*
- ECE/NE/Physics 726 - *Plasma Magnetohydrodynamics*
- NE 903 - *Special Topics in Plasma Physics*
- ECE/NE/Phyisics 922 - *Seminar in Plasma Physics*

In summary …

There are a lot of great reasons to learn, research, and apply plasmas at Wisconsin!

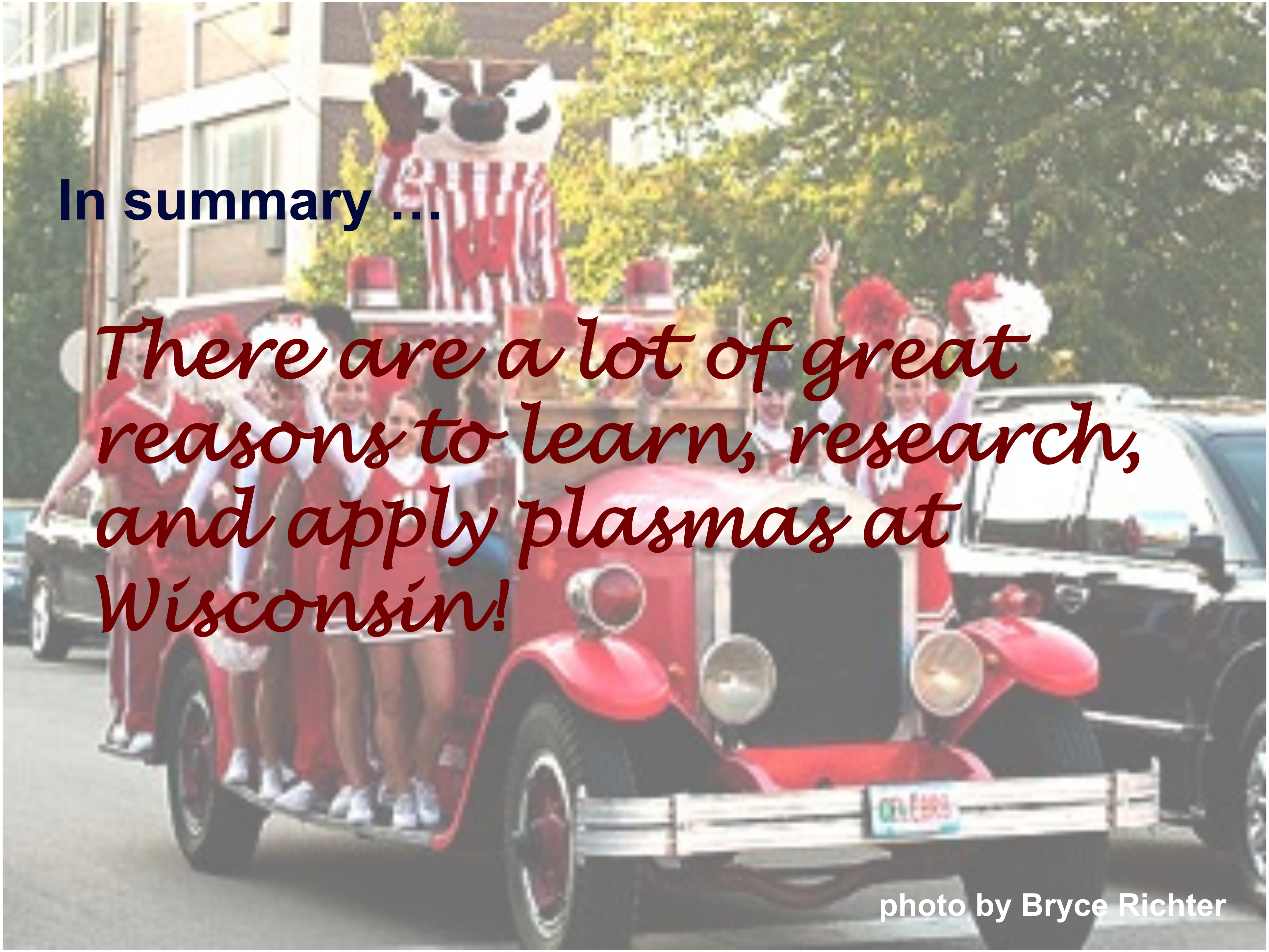


photo by Bryce Richter