BEYOND LIQUID METAL DYNAMO EXPERIMENTS

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THE UNIVERSITY of WISCONSIN MADISON

Magnetic Field Generation in Experiments, Geophysics, and Astrophysics

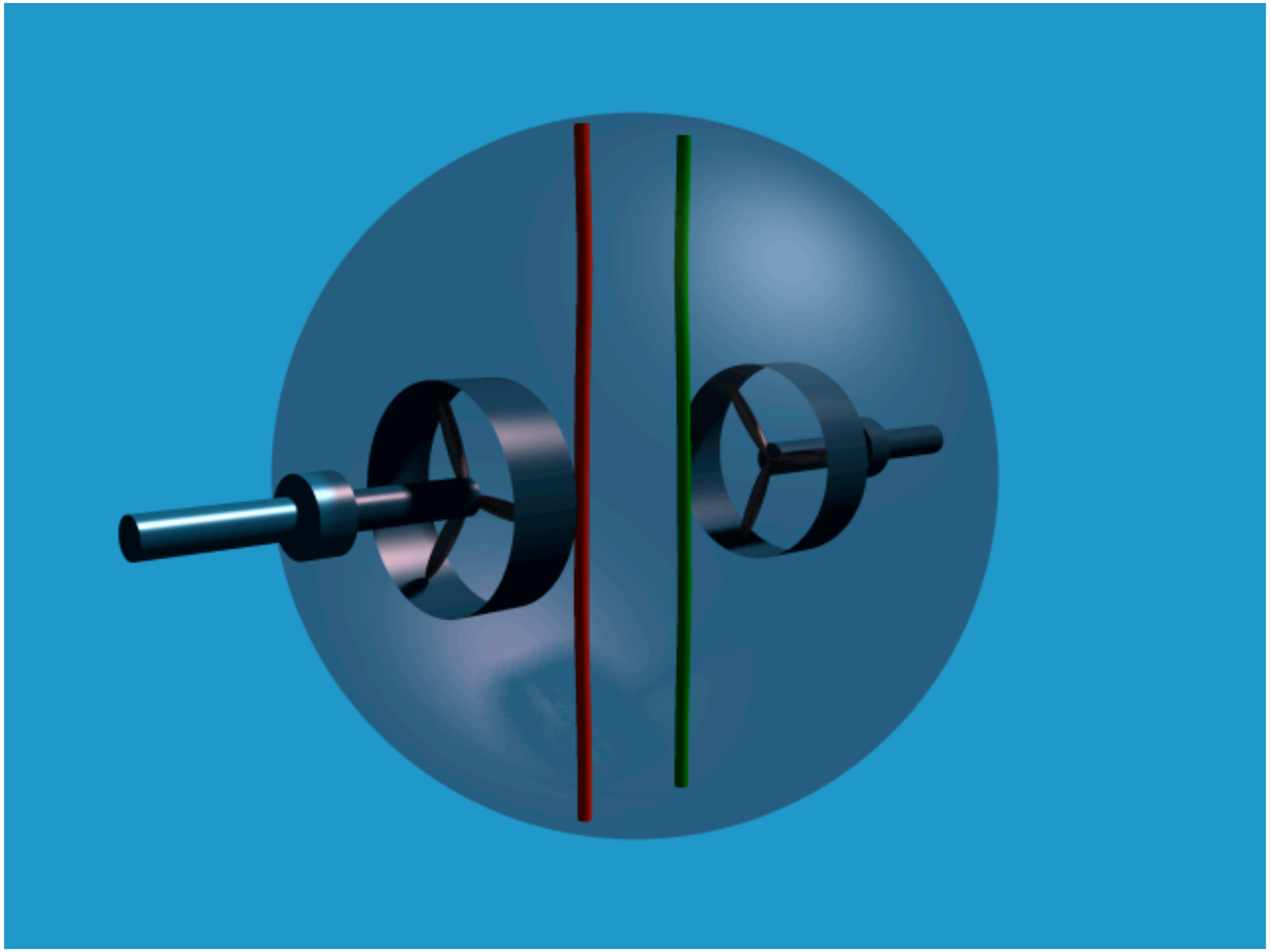
Kavli Institute for Theoretical Physics UCSB

16th JULY 2008

Outline

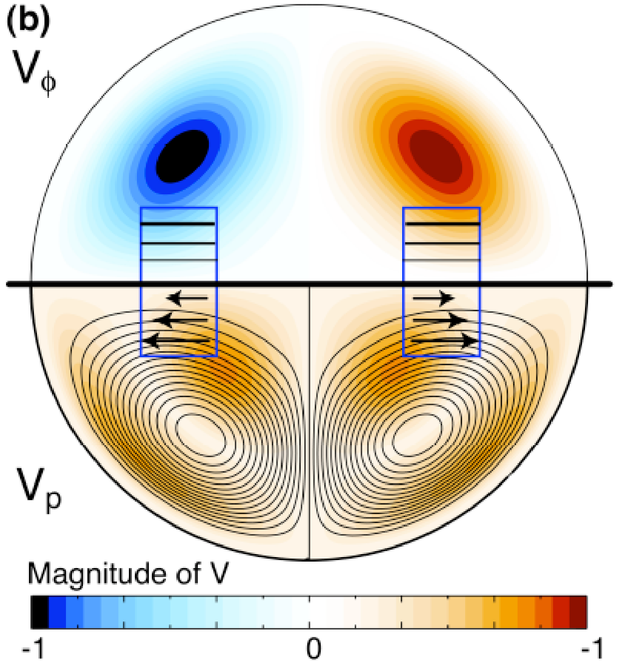
- Quick review of results from Madison (with references)
  - Observation of fluctuation driven currents
- Near term plans on the Madison Dynamo Experiment
  - adjustable vanes for helicty and turbulence control
  - subcritical transitions with externally applied fields
- Future plans
  - turbulence reduction and flow control
  - A Plasma based MRI and Dynamo Experiment

Dynamo is of the stretch-twist-fold type: field line stretching, geometric reinforcement, and reconnection leads to dynamo



For liquid metals, Re>>Rm

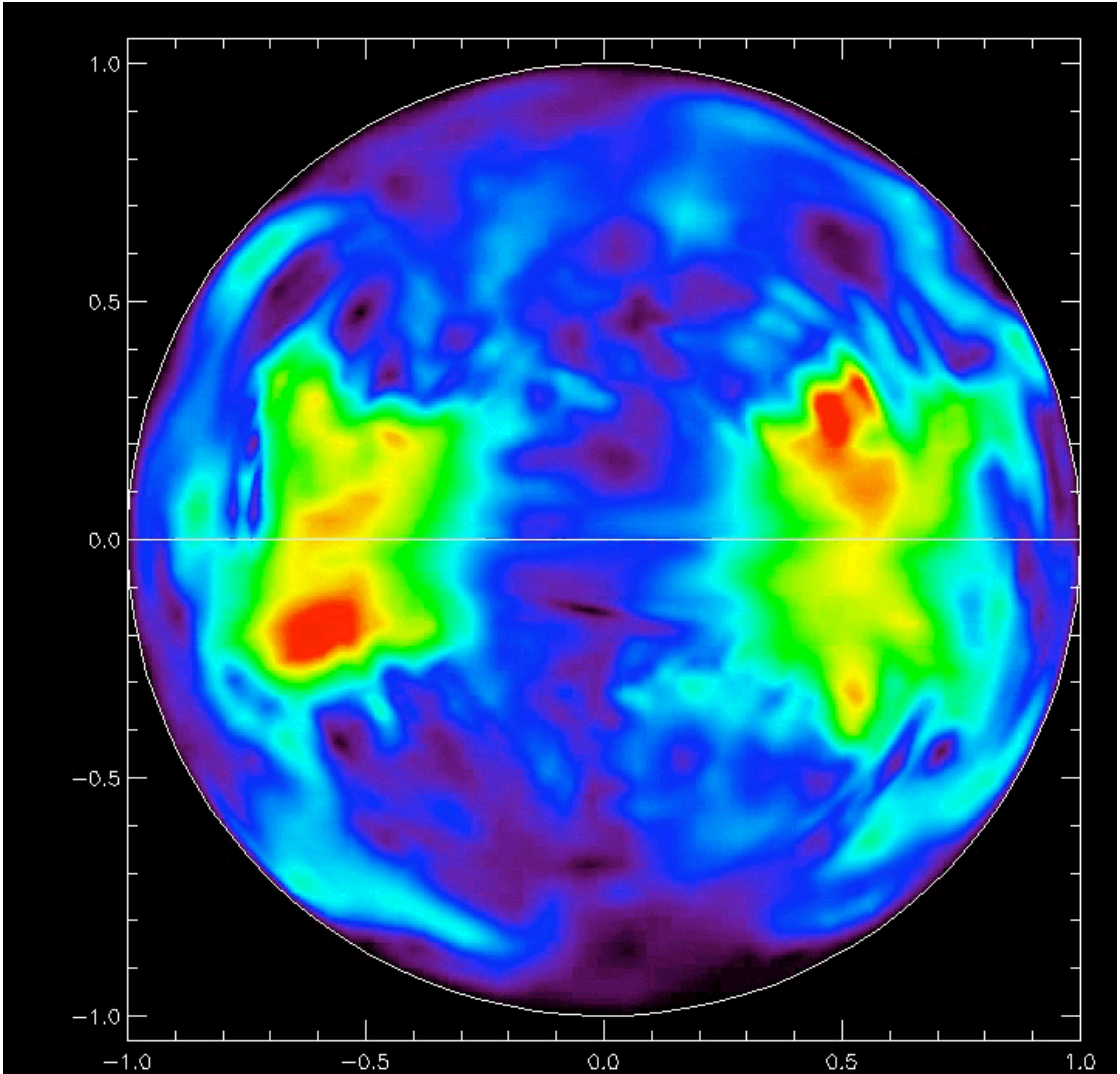
- Direct Numerical Simulations of MHD equations with mechanical forcing
- Re=2200; turbulence for Re>450



$$F_\phi(\rho, z) = \rho^2 \sin(\pi\rho b)$$

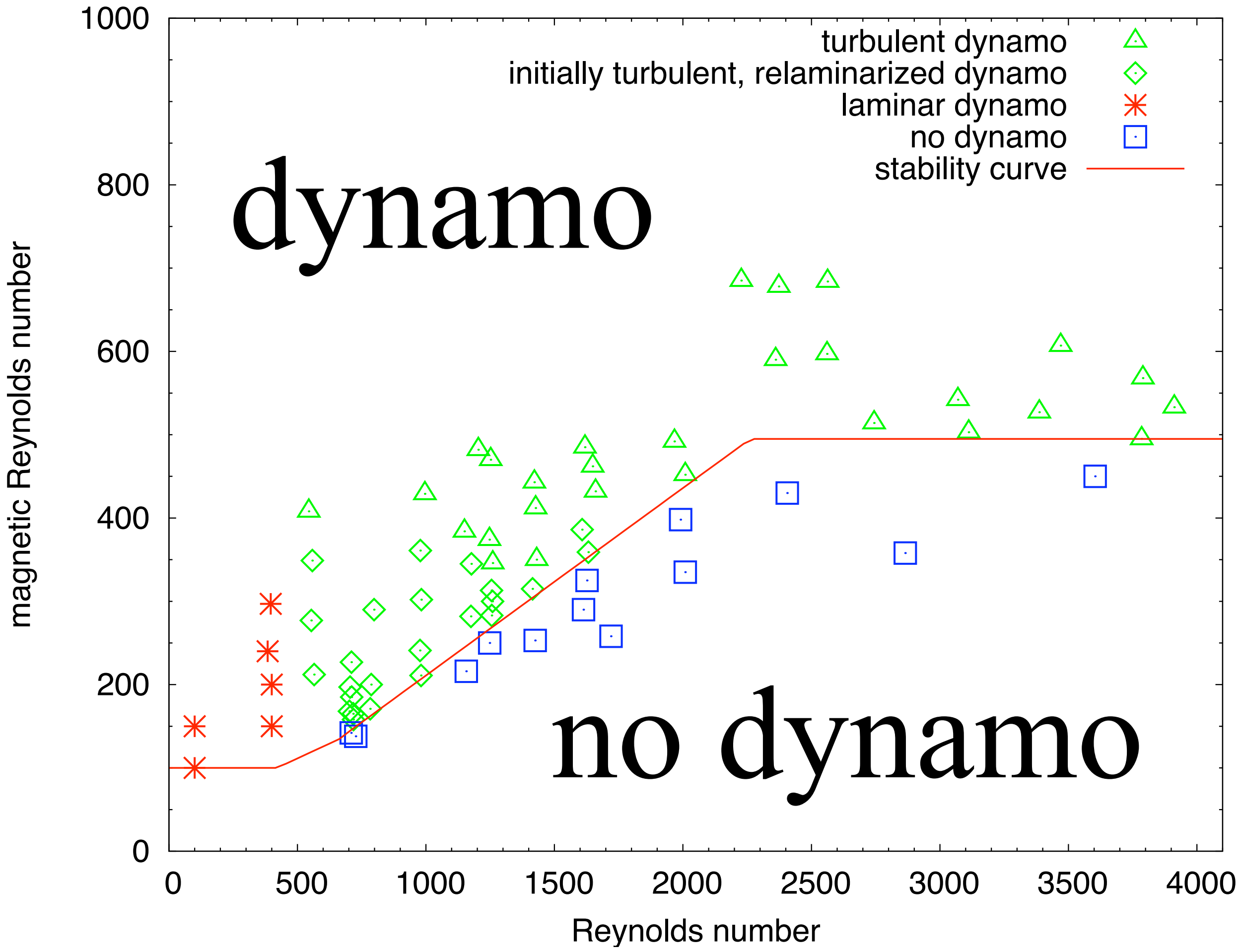
$$F_z(\rho, z) = -\epsilon \sin(\pi\rho c)$$

$$0.25a < |z| < 0.55a,\ \rho < 0.3a$$



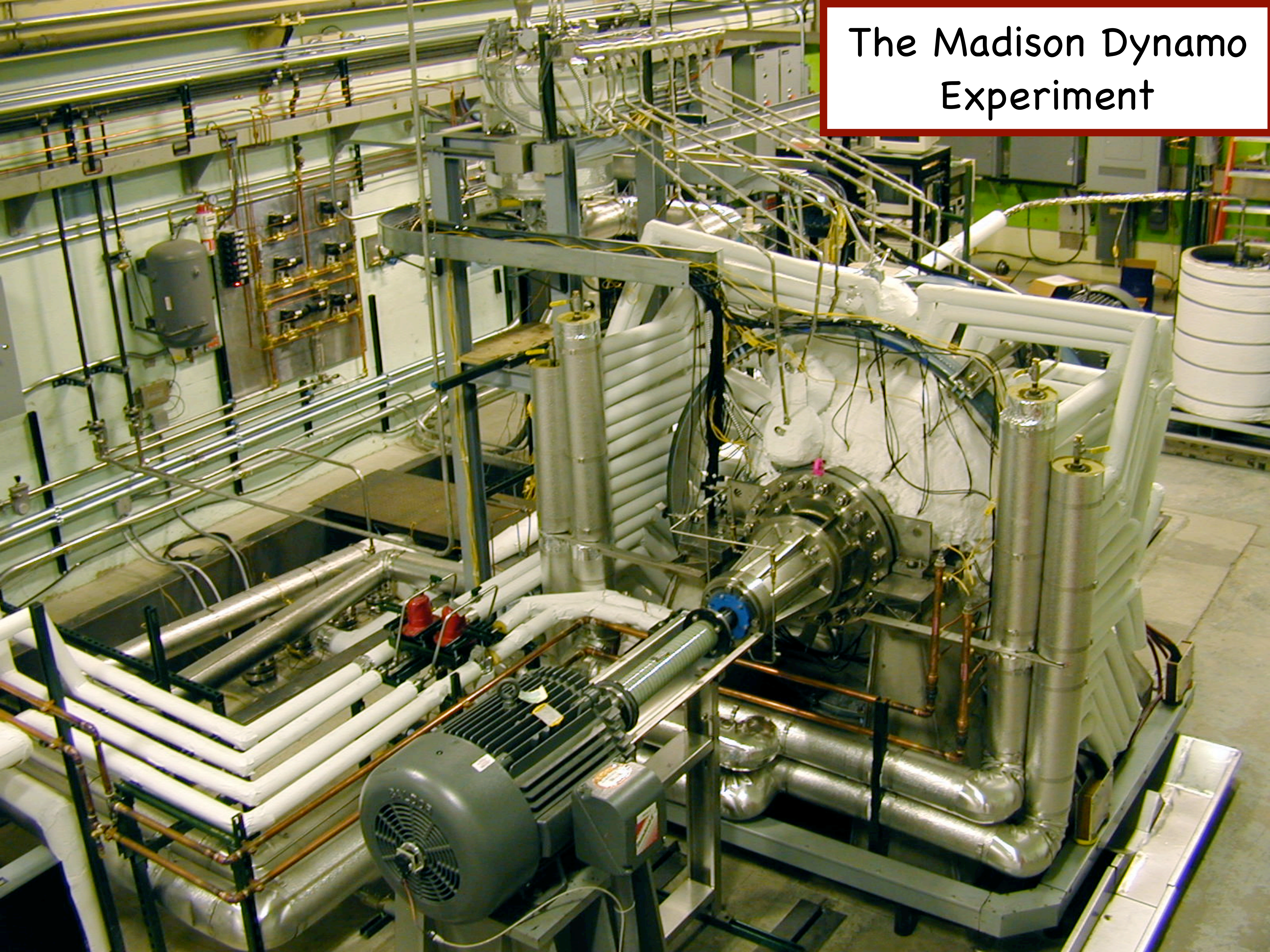
Turbulence, in the two-vortex dynamo, increases Rm_{crit} by factor of 5

Bayliss, Nornberg, Terry and Forest, *Numerical simulations of current generation and dynamo excitation in a mechanically-forced, turbulent flow, Phys. Rev. E,* (2006)



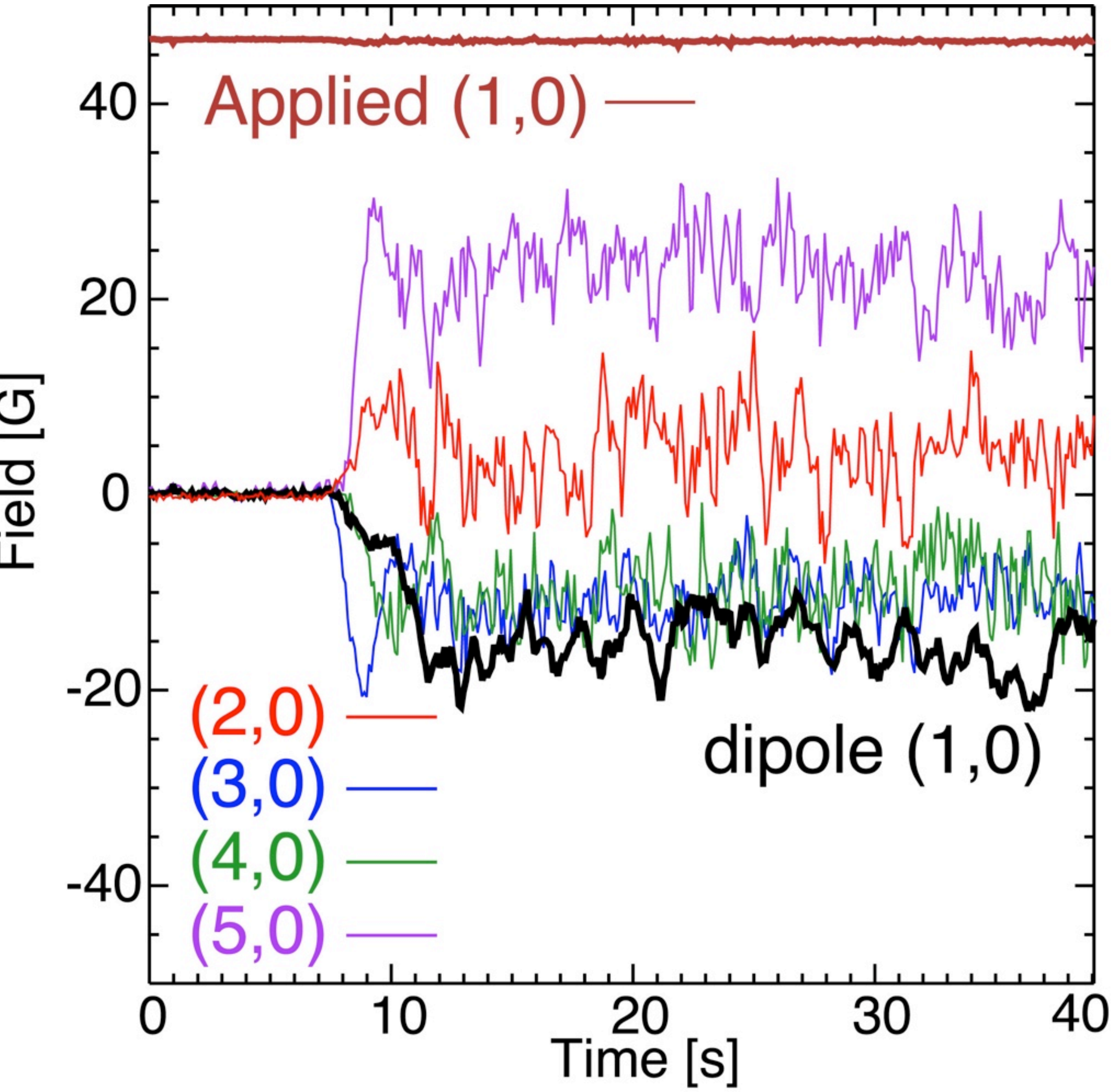
- Recent, fully resolved MHD simulations (no hyperviscosity, no LES) extended to Re~5000
- proper boundary conditions and mechanical forcing term

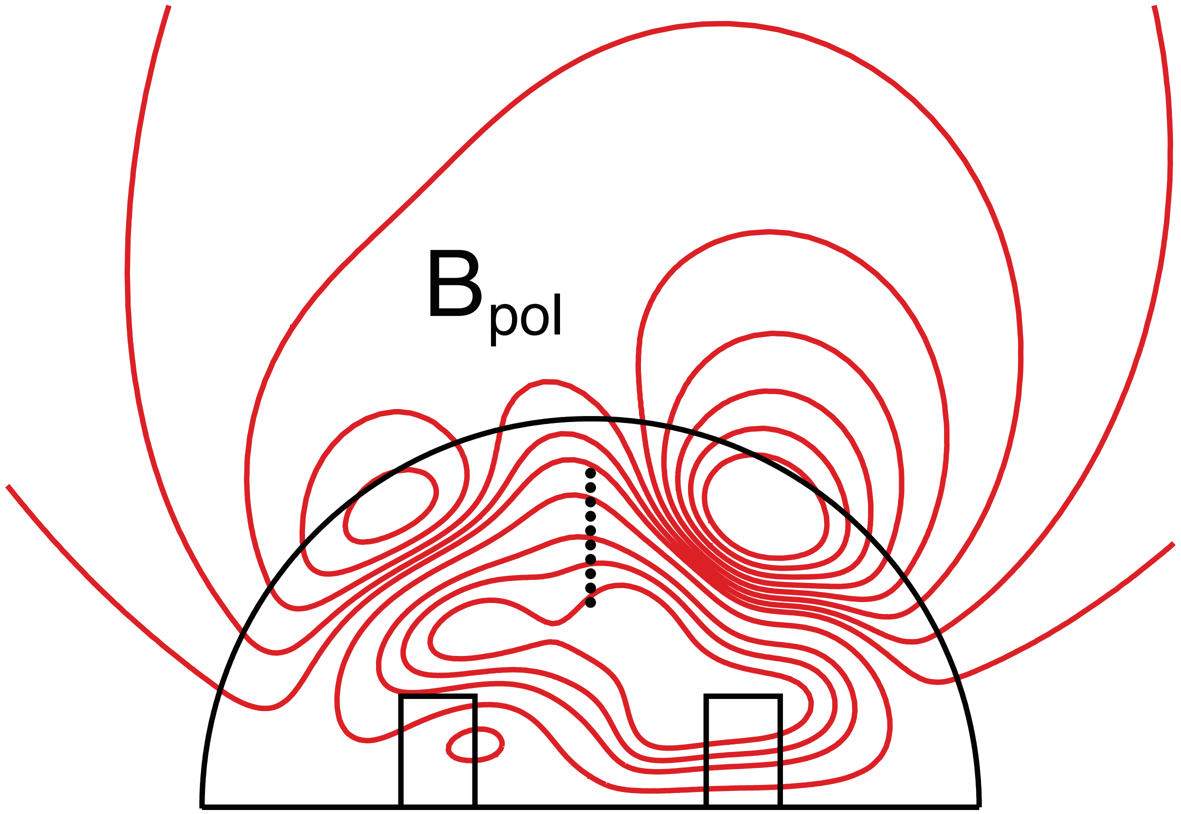
The Madison Dynamo Experiment



Previous Results from the Madison Dynamo Experiment

components of Y_{lm}

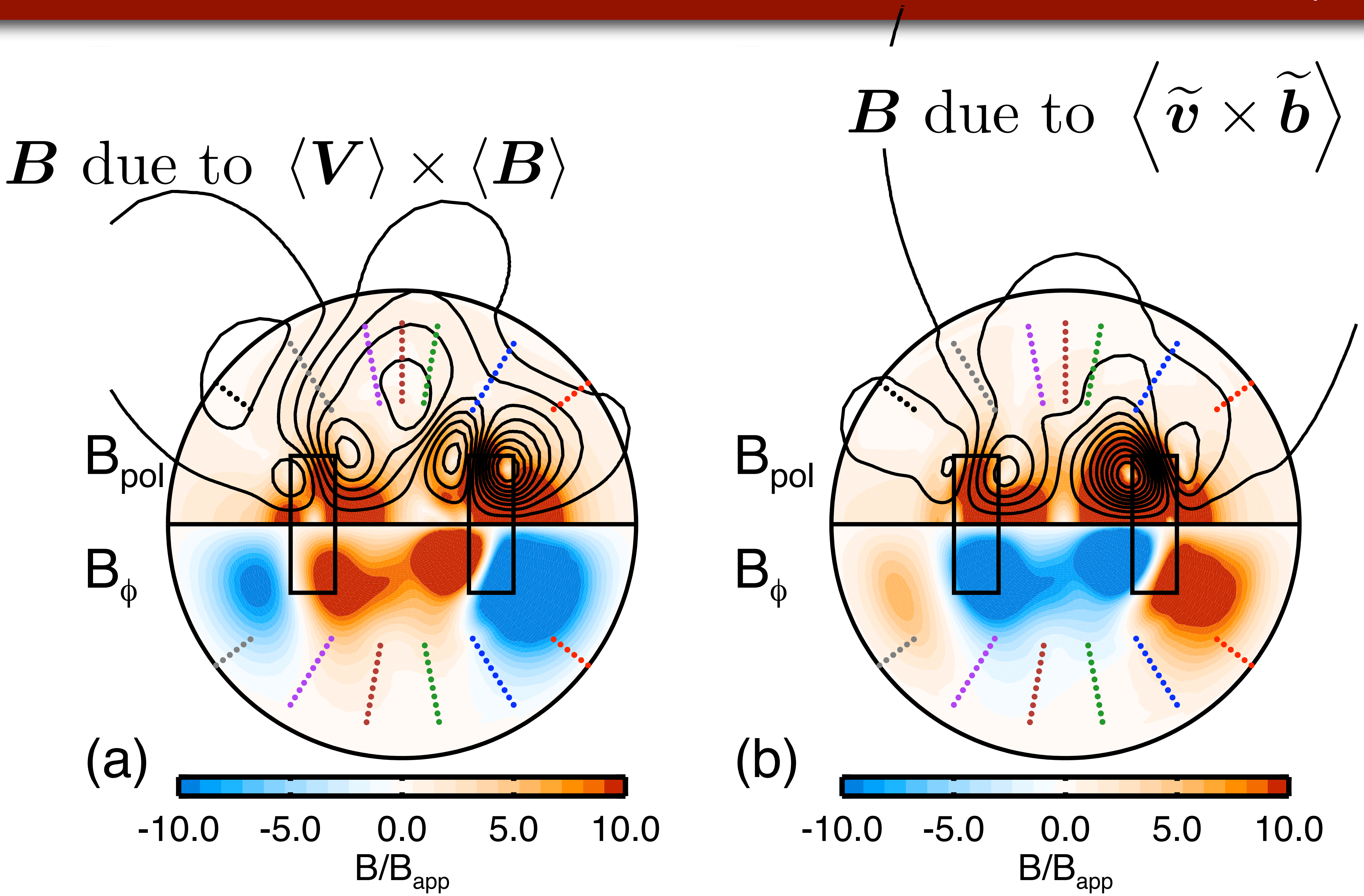




Impossible to reconstruct with axisymmetric flows!

Spence, Nornberg, Jacobson, Kendrick, and Forest, *Observation of a turbulence-induced large-scale magnetic field*, Phys. Rev. Lett. **96** 055002 (2006).

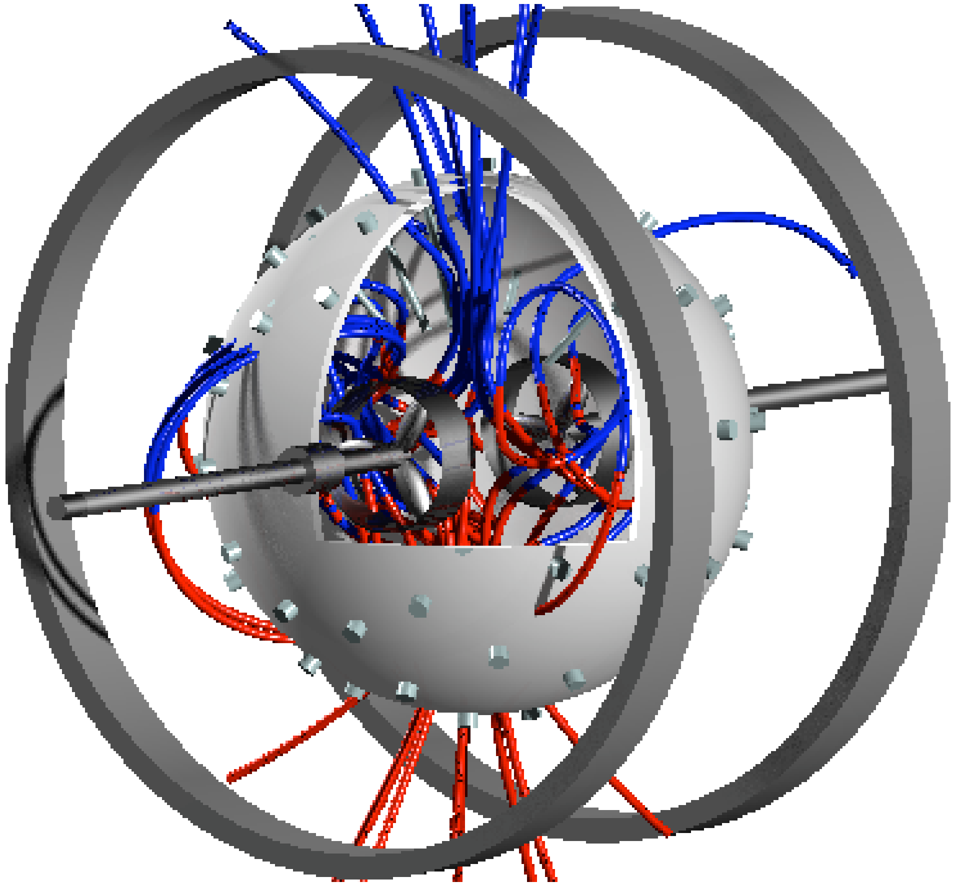
Previous Results from the Madison Dynamo Experiment



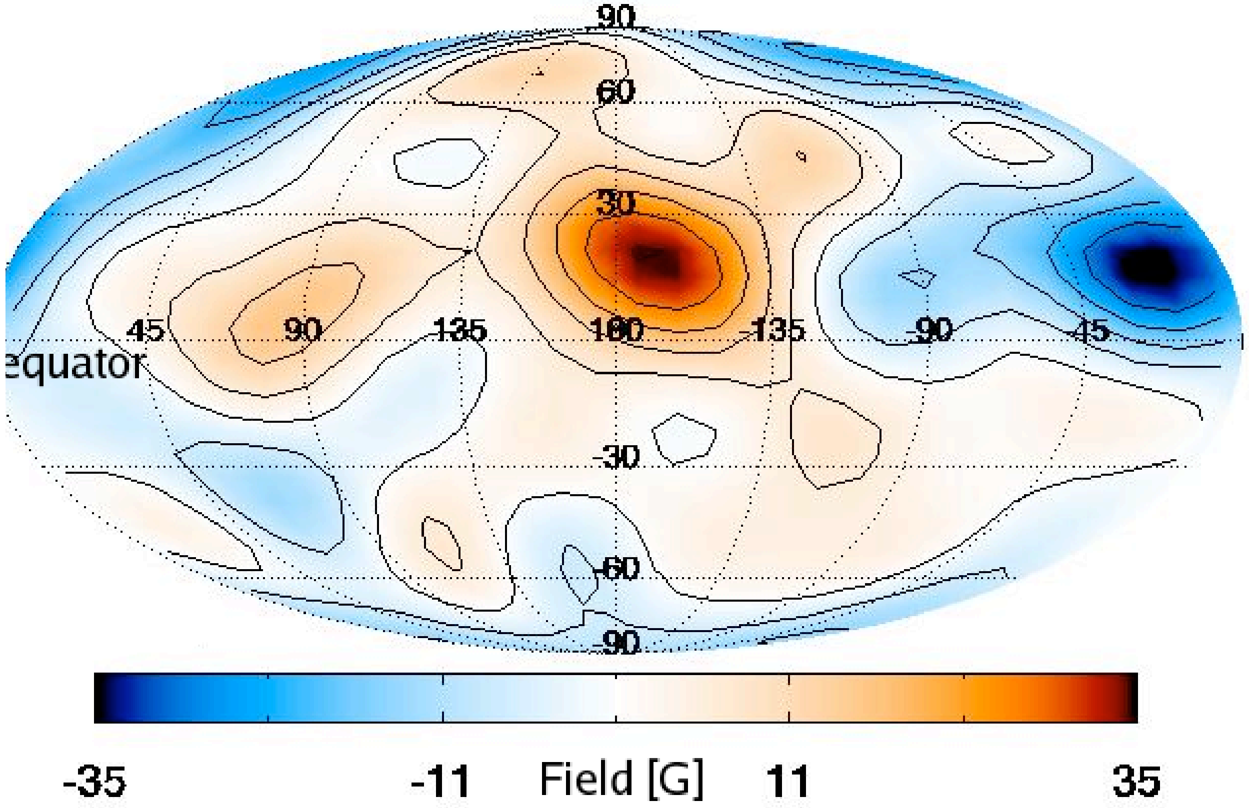
Spence, Nornberg, Jacobson, Parada, Kendrick, and Forest, *Turbulent Diamagnetism in Flowing Liquid Sodium*, Phys. Rev. Lett. **98** 164503 (2007).

Previous Results from the Madison Dynamo Experiment

Predicted



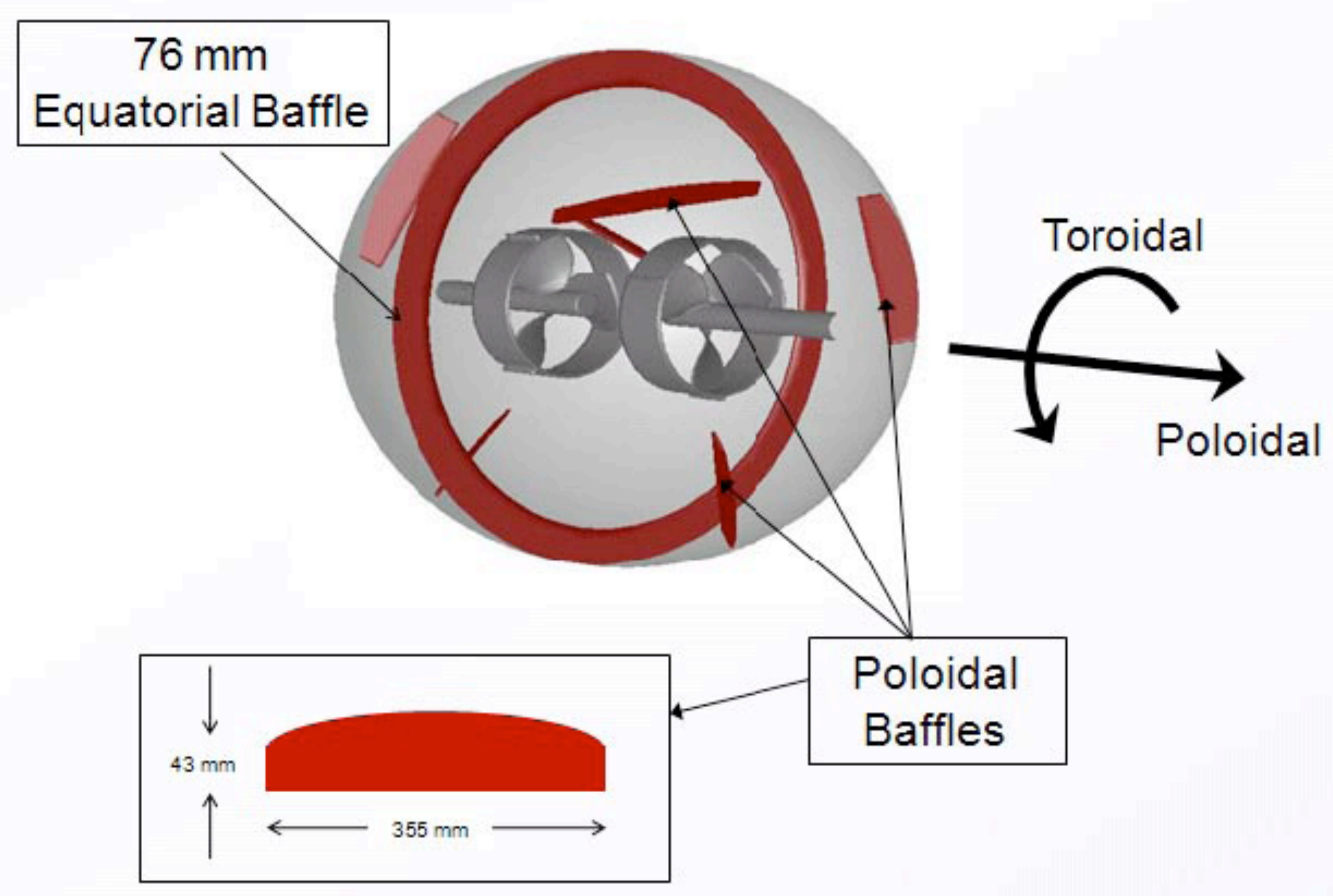
Observed



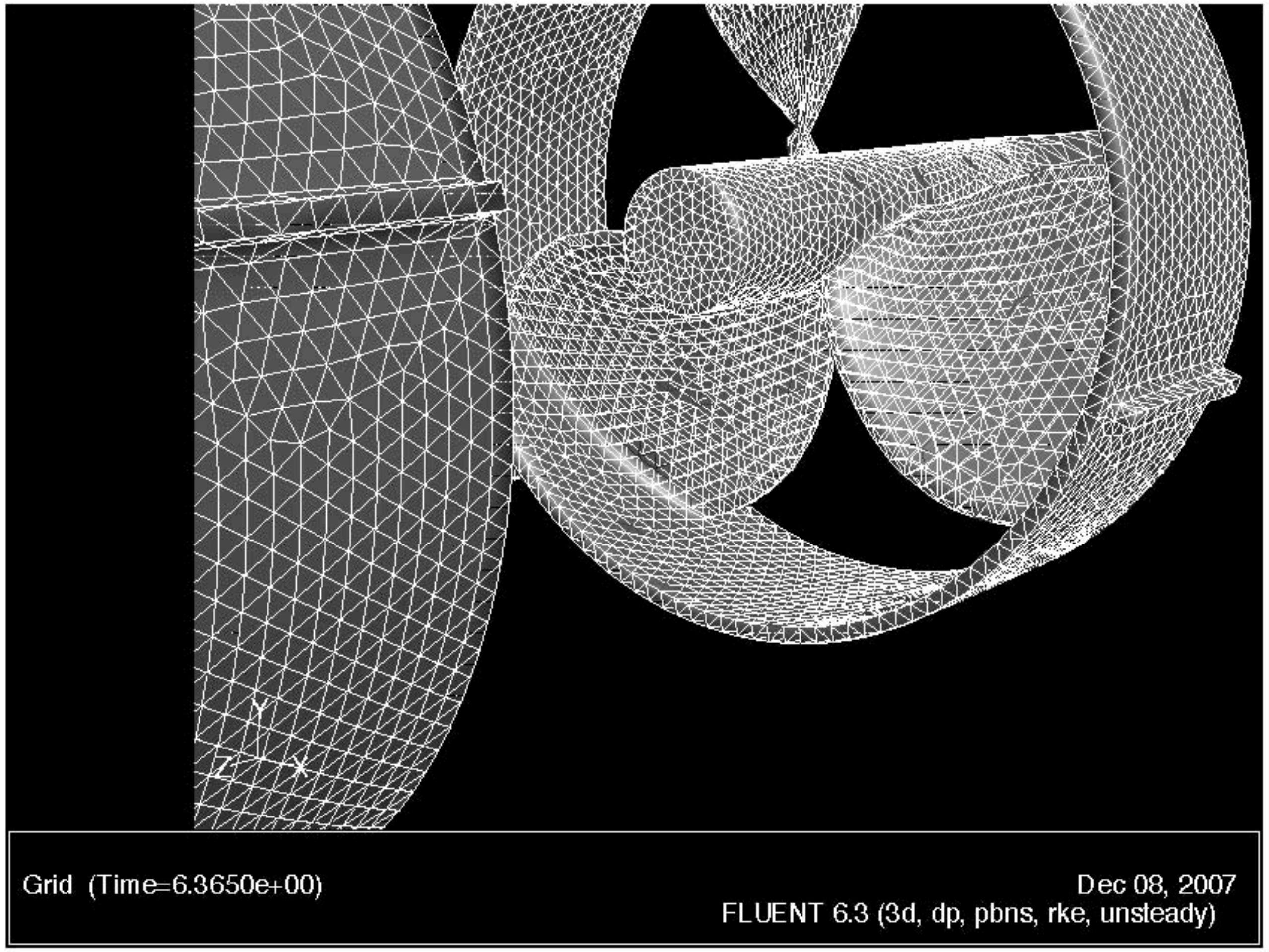
Nornberg, Spence, Jacobson, Kendrick, and Forest, *Intermittent magnetic field excitation by a turbulent flow of liquid sodium,* Phys. Rev. Lett. 97 044503 (2006).

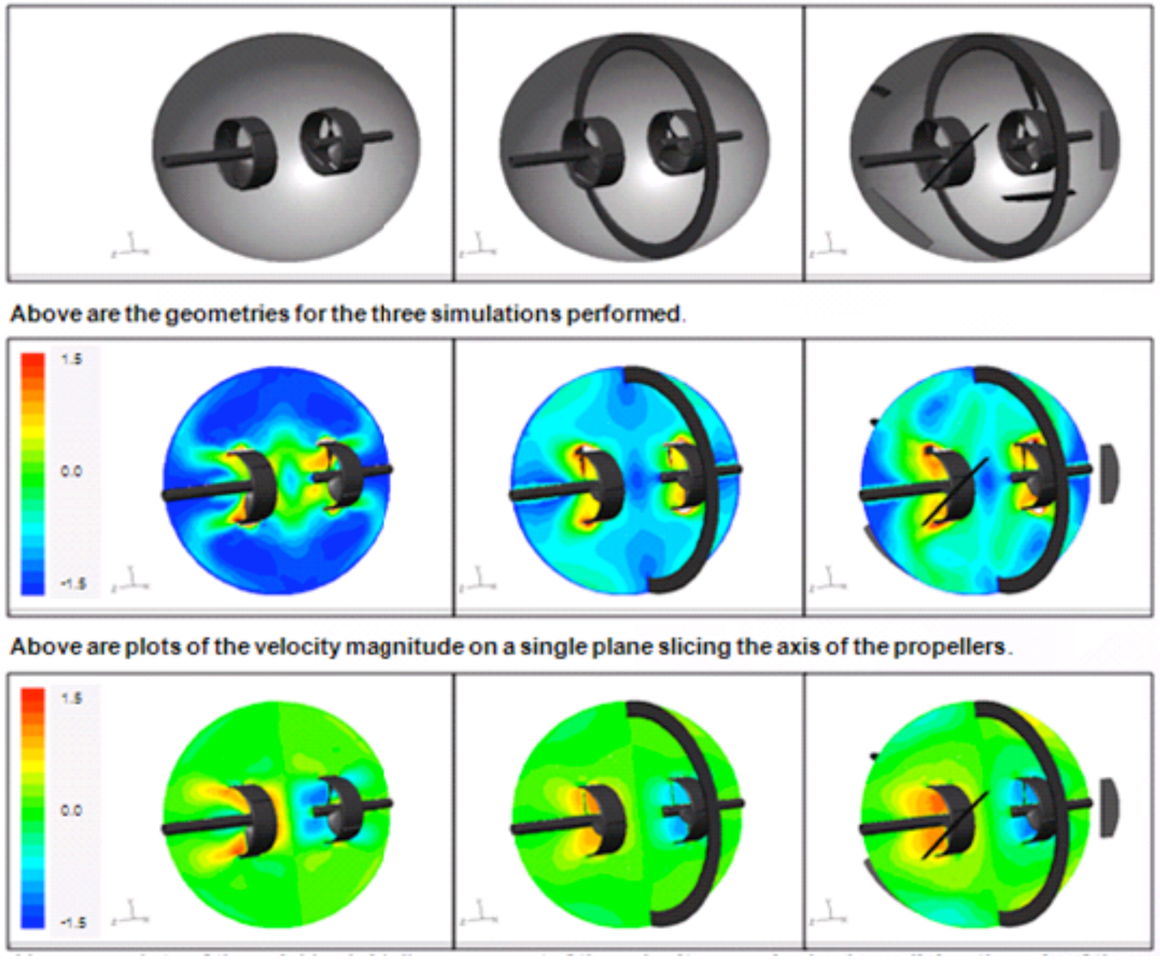
Future Plans for Madison Dynamo Experiment

- Adding internal baffles for flow control and turbulence reduction



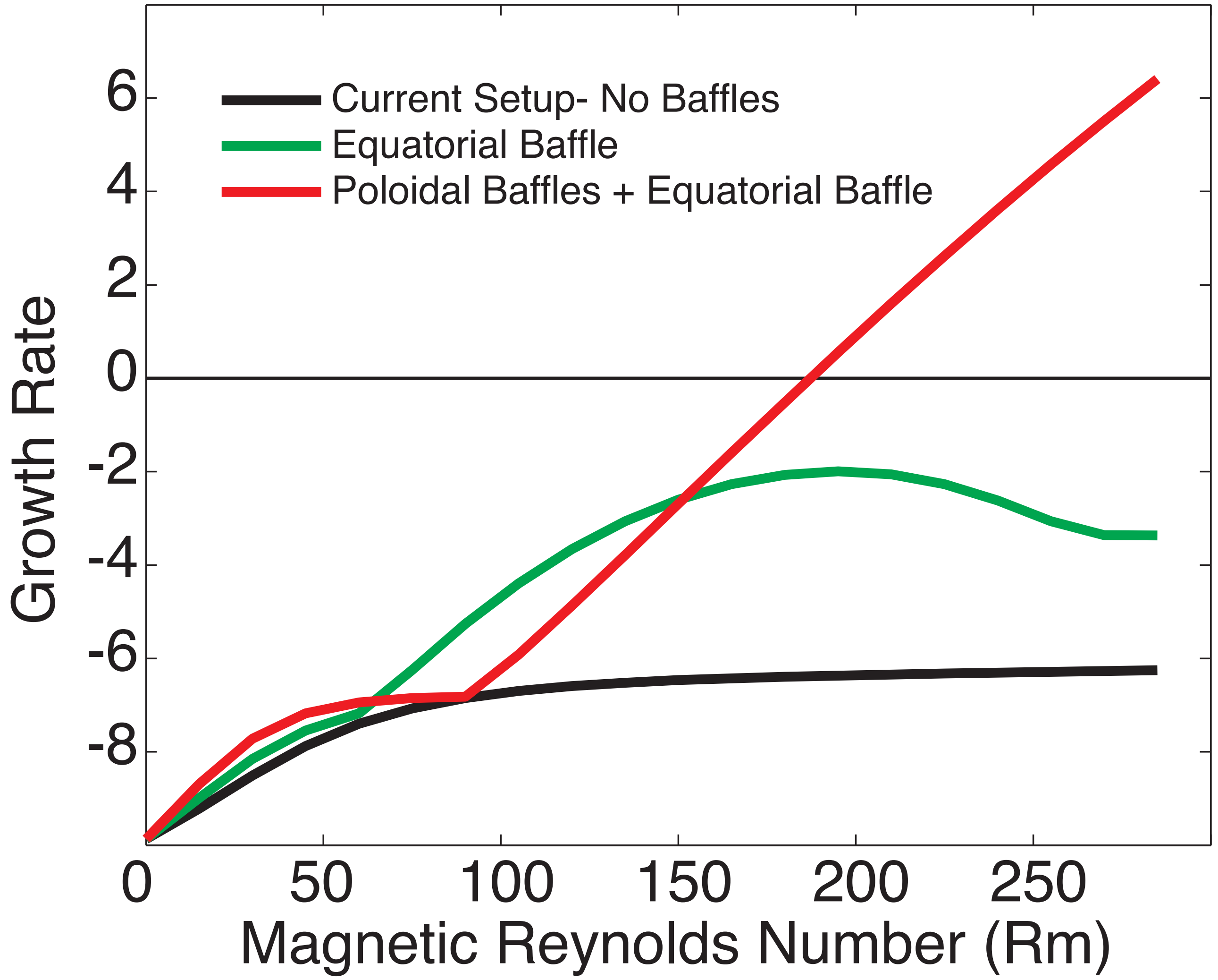
CFD (FLUENT) has been used to study baffles and further optimize flow




Above are the geometries for the three simulations performed.

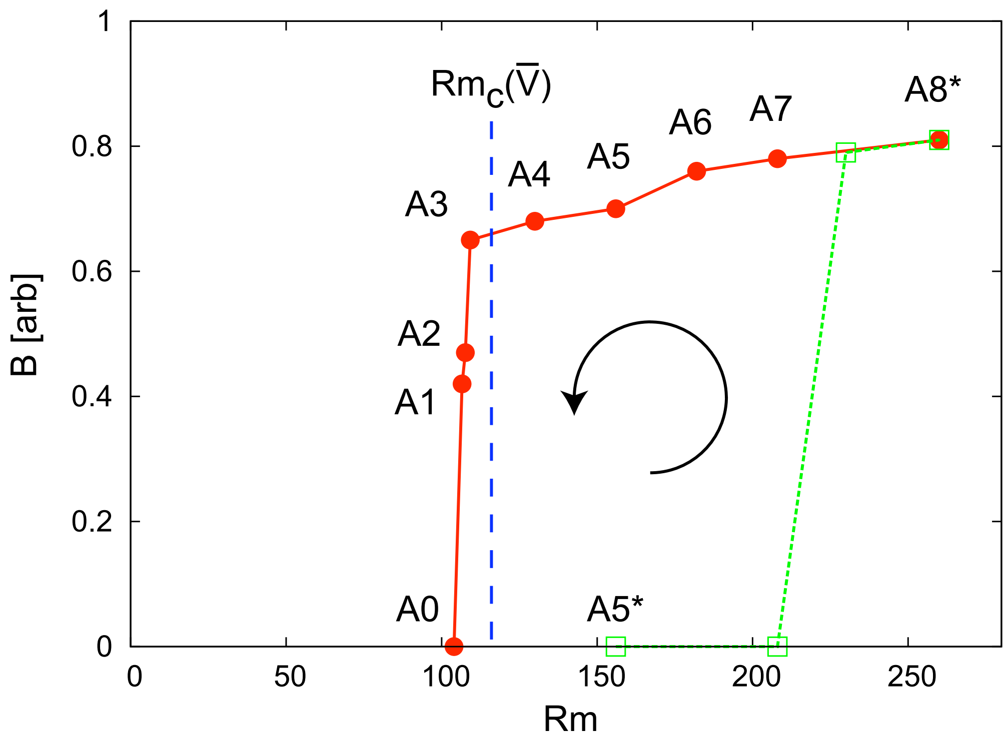
Above are plots of the velocity magnitude on a single plane slicing the axis of the propellers.

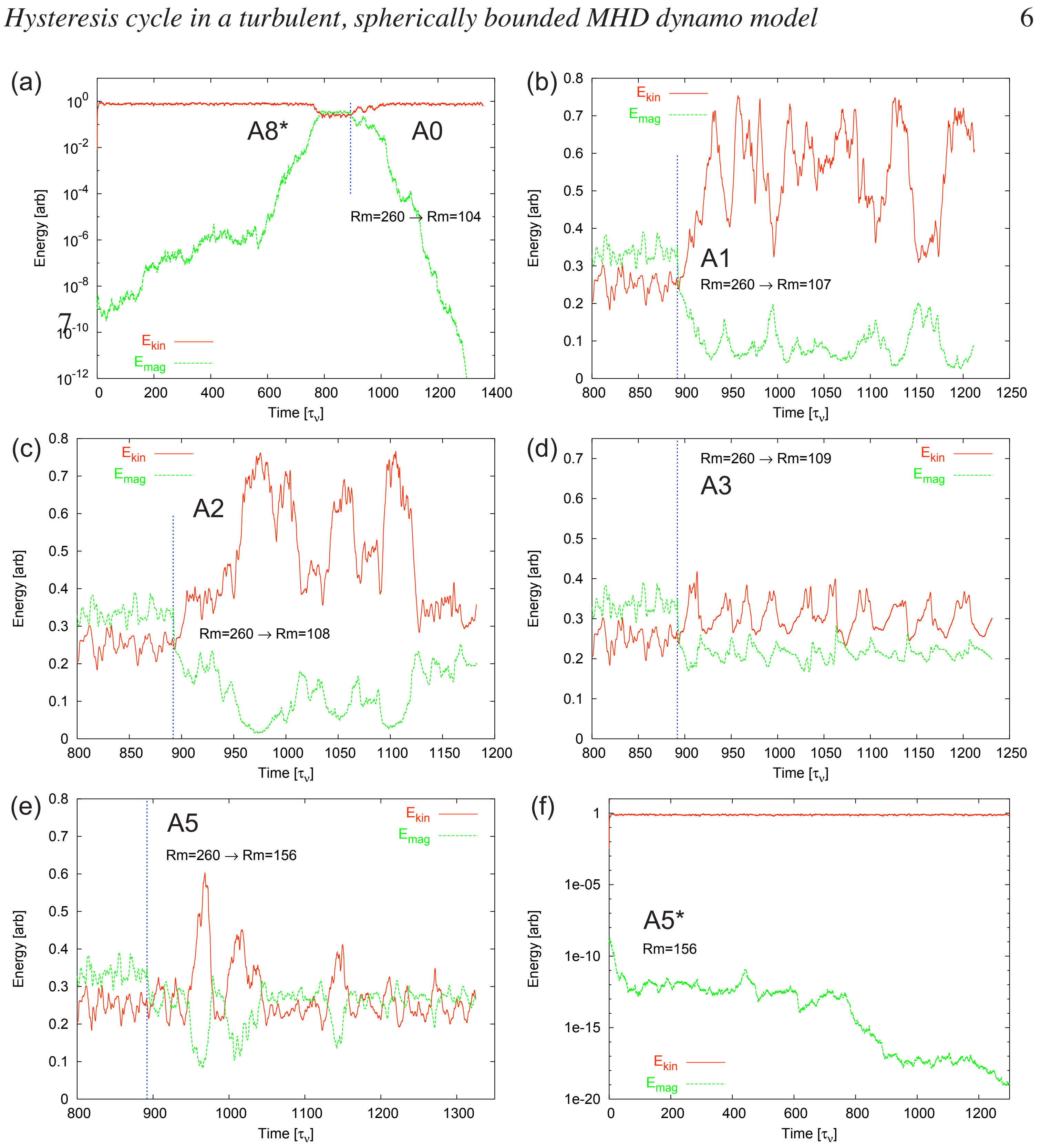
CFD predicts lower fluctuation levels and better optimized pitch of propellors



case	turbulent energy
no baffles	$0.71\ m^2/s^2$
equatorial baffle	$0.42\ m^2/s^2$
poloidal vane	$0.10\ m^2/s^2$

Hysteresis Observed in Simulations





Hysteresis cycle in a turbulent, spherically bounded MHD dynamo model 6

Reuter, Jenko, and Forest, *Hysteresis cycle in a turbulent, spherically bounded MHD dynamo model,* submitted to New Journal of Physics (2008)

Externally applied field can access dynamo at lower Rm

Hysteresis cycle in a turbulent, spherically bounded MHD dynamo model 10

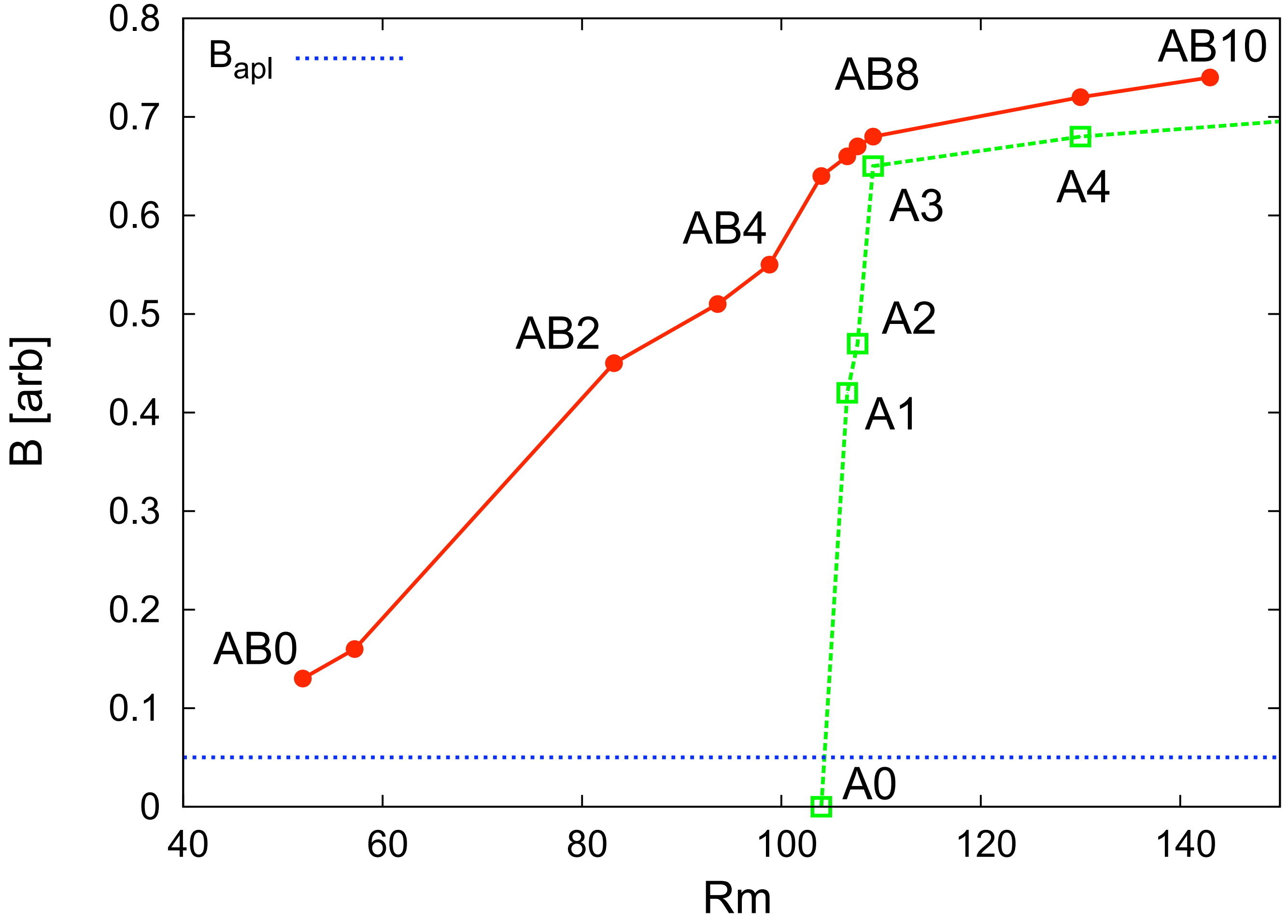
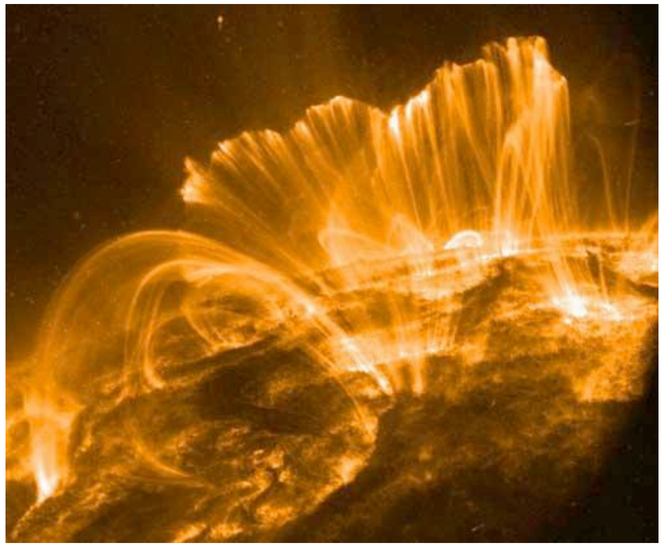


Figure 4. Magnetic field amplitudes during the stationary states of the runs in series AB (red solid dots). For comparison, the magnetic field amplitudes from series A are shown (green open squares). The amplitude of the externally applied field is indicated by the blue dotted line.

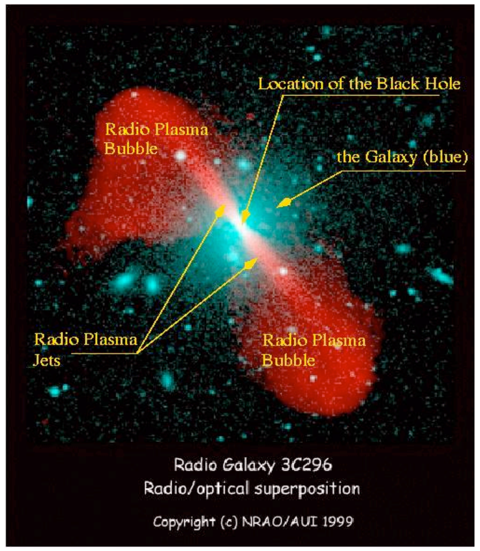
Big Questions in Astophysics have a Common Theme Related to Magnetic Field Generation from Plasma Flow

SOLAR MAGNETIC FIELD



-Dynamic and well measured
-weak large scale strong smale scale
Rm = 10^7
Pm = 10^{-3}

ACCRETION DISKS



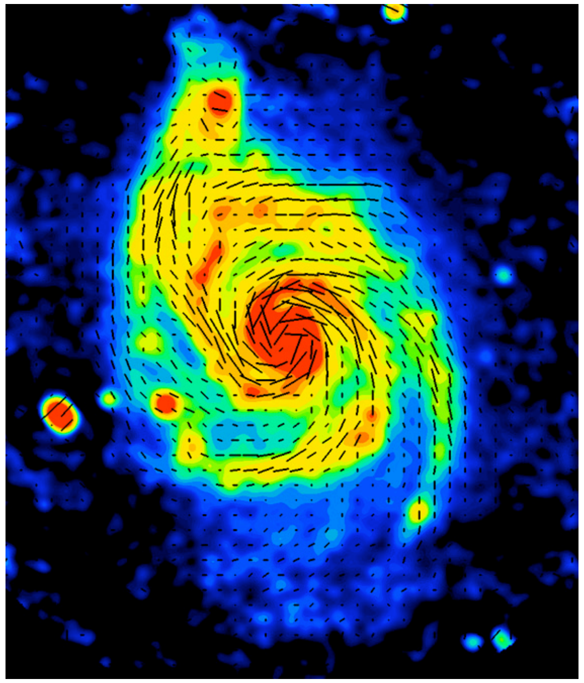
Radio Galaxy 3C296
Radio/optical superposition
Copyright (c) NRAO/AUI 1999

-Collisionless close to hole
-Galaxy is ejecting plasma and magnetic field into the surrounding IGM
-Rm = 10^{19}
-Pm = 10^5

GALACTIC MAGNETIC FIELD

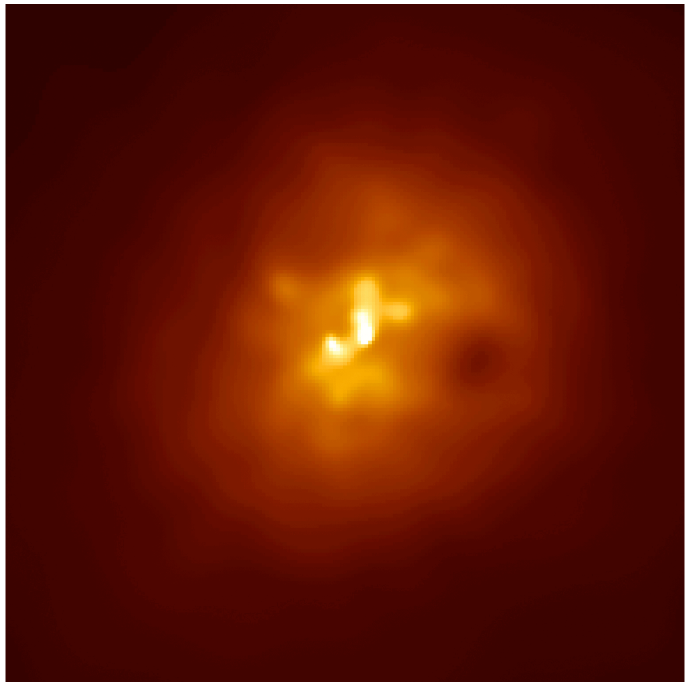
-M51 Spiral Galaxy
-Polarization of 6cm emission Indicates direction of B field in the hot plasma between the stars.
-Rm = 10^{14} (?)
-Pm = 10^5

Large scale coherent field



GALAXY CLUSTERS

Xray image of Abel 2597 from Chandra
-Collisionless plasma (Te=10 keV); mean Free path size of a galaxy.
-Turbulent.
-Magnetized: $\beta \sim 3$
-Rm = 10^{29}
-Pm = 10^4



Poorly Understood, Fundamental Plasma and MHD Processes Can Benefit from Experimental Studies

- **Large Scale Dynamo**: What is the size, structure and dynamics of the mean magnetic field created by high magnetic Reynolds number flows—particularly rotating flows? At low Pm, does turbulence suppress the Large Scale Dynamo? Is helical turbulence necessary for a turbulent LSD?
- **Small Scale Dynamo**: How do random turbulent (high Rm) flows create random and turbulent magnetic fields—what is the structure of these fields?
- **Plasma Turbulence**: What is the nature of plasma turbulence when magnetic fields and velocity fields are in near equipartition? How is energy dissipated? How are heat, momentum and current transported in stochastic magnetic fields that have little large scale structure?
- **Magnetorotational Instability**: How does angular momentum get transported by magnetic instabilities? Can the MRI be a dynamo?
- **Explosive Reconnection Driven by Plasma Flow**: How does plasma flow generate magnetic energy which can accumulate and ultimately be released in explosive instabilities?
- **Plasma Instabilities**: Do plasma instabilities beyond MHD such as the firehose, mirror, or energetic particle driven exist in collisionless, turbulent plasma flows? How do these instabilities saturate? Do they change the macroscopic dynamics?

Important Dimensionless Numbers

Cowling	C	$\frac{\frac{B^2}{2\mu_0}}{\frac{1}{2}\rho U^2}$
Magnetic Reynolds	Rm	$\mu_0\sigma UL$
Reynolds	Re	$\frac{UL}{\nu}$
Magnetic Prandtl	Pm	$\mu_0\sigma\nu$

Minimum requirements for experimentally addressing each Plasma Process

$$\tau_\sigma = \mu_0 \sigma a^2$$

Plasma Process	Rm_{crit}	Re	C	$\frac{\lambda}{L}$	β
large scale dynamo					
laminar	$\gtrsim 100$	< 100	$\ll 1$	-	-
with turbulence	$\gtrsim 500$	> 1000	$\ll 1$	-	-
small scale dynamo	$\gtrsim 500$	$\gtrsim 1000$	$\ll 1$	?	?
MHD turbulence	$\gtrsim Re$	$\gtrsim 1000$	~ 1	-	-
MRI					
with mean field	$\gtrsim 10$	—	$\lesssim 1$	?	?
without mean field	$\gtrsim 15000$	—	$\ll 1$	?	?
B field stretching	$\gtrsim 100$	< 100	~ 1	-	-
Plasma Instabilities	$\gtrsim Re$	$\gtrsim 1000$	$\lesssim 1$	$\gtrsim 1$	$\gg 1$

Large, High Te, fast flowing plasmas

Low B, fast flowing plasmas

Liquid Metal Experiments are limited: the next frontier for experimental dynamo studies should be plasma based

- Liquid metals have advantage that confinement is free and conductivity is independent of confinement, BUT:
  - ➡ Unfortunate Power Scaling Limitation: $P_{mech} \sim Rm^3 / L$
  - ➡ Prandtl Number is always very small: $Rm \ll Re$
- Plasmas have the potential for
  - Variable Pm
  - $Rm \gg 100$
  - intrinsically include "plasma effects" important for astrophysics (compressibility, collisionality)
  - broader class of available diagnostics

Dynamo and MRI Process

1. Begin with small magnetic field ($C \ll 1$)
2. Stir until $Rm > Rm_{crit}$
3. Magnetic field spontaneously created

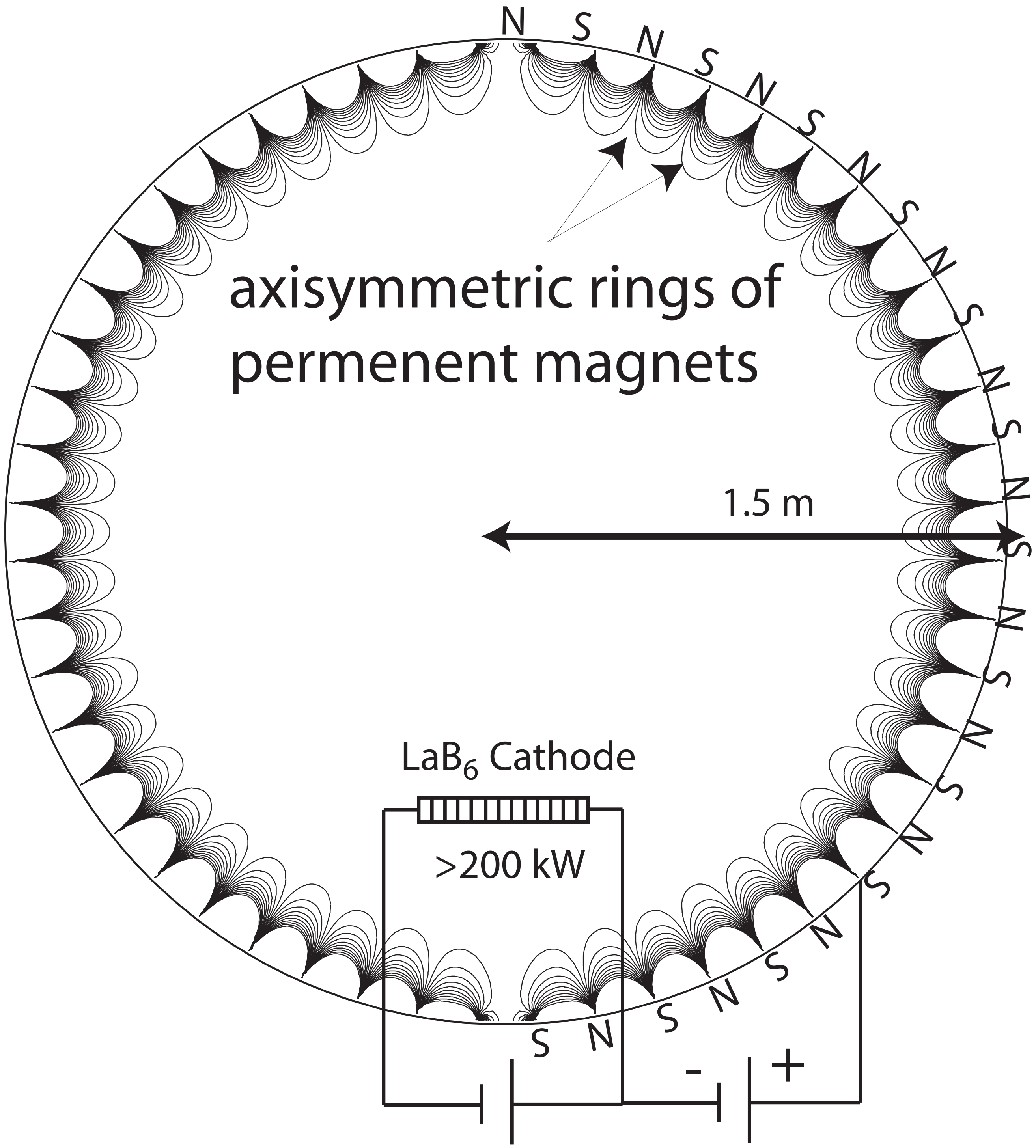
Challenge: to create a large, highly conducting, unmagnetized, fast flowing laboratory plasma for study

-difficult to stir a plasma

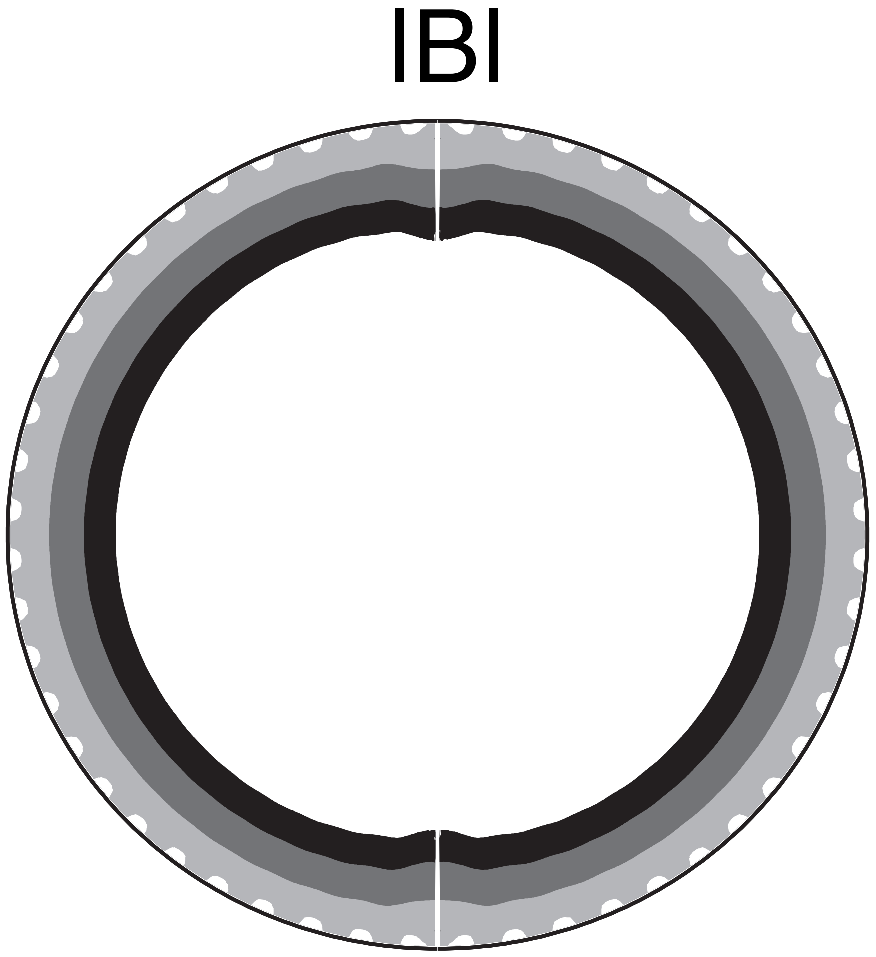
-need some confinement for plasma to be hot

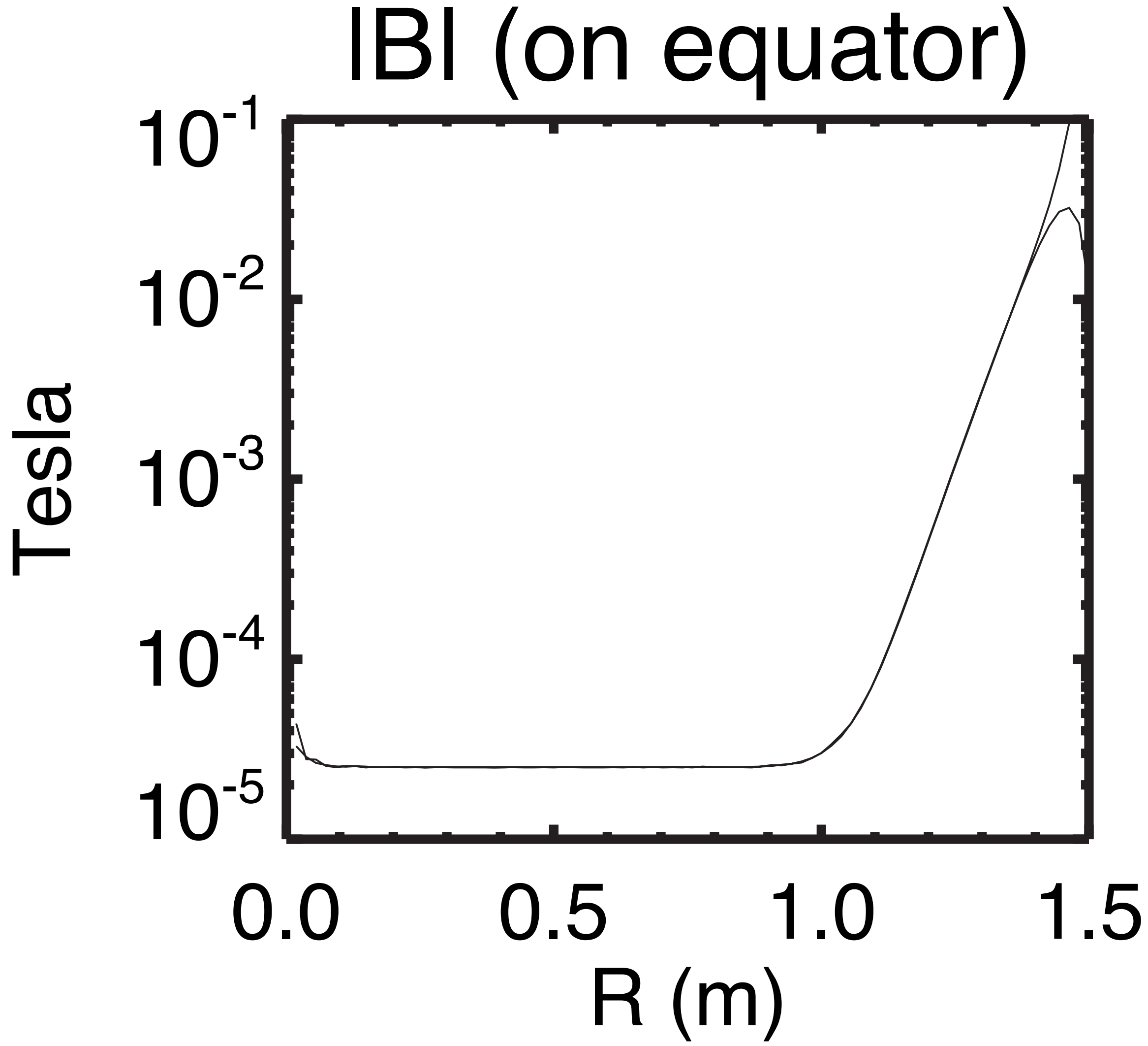
Plasma Dynamo Facility is needed to study high Rm, high C plasmas

- Axisymmetric Ring Cusp
- edge confinement provided by 1.5 T, NdFeB Magnets
- high power plasma source using LaB_6
    - 200 kW, DC power supplies
    - similar to LAPD, CDX technology
- Challenges
    - cooling of magnets
    - insulators


axisymmetric rings of permement magnets

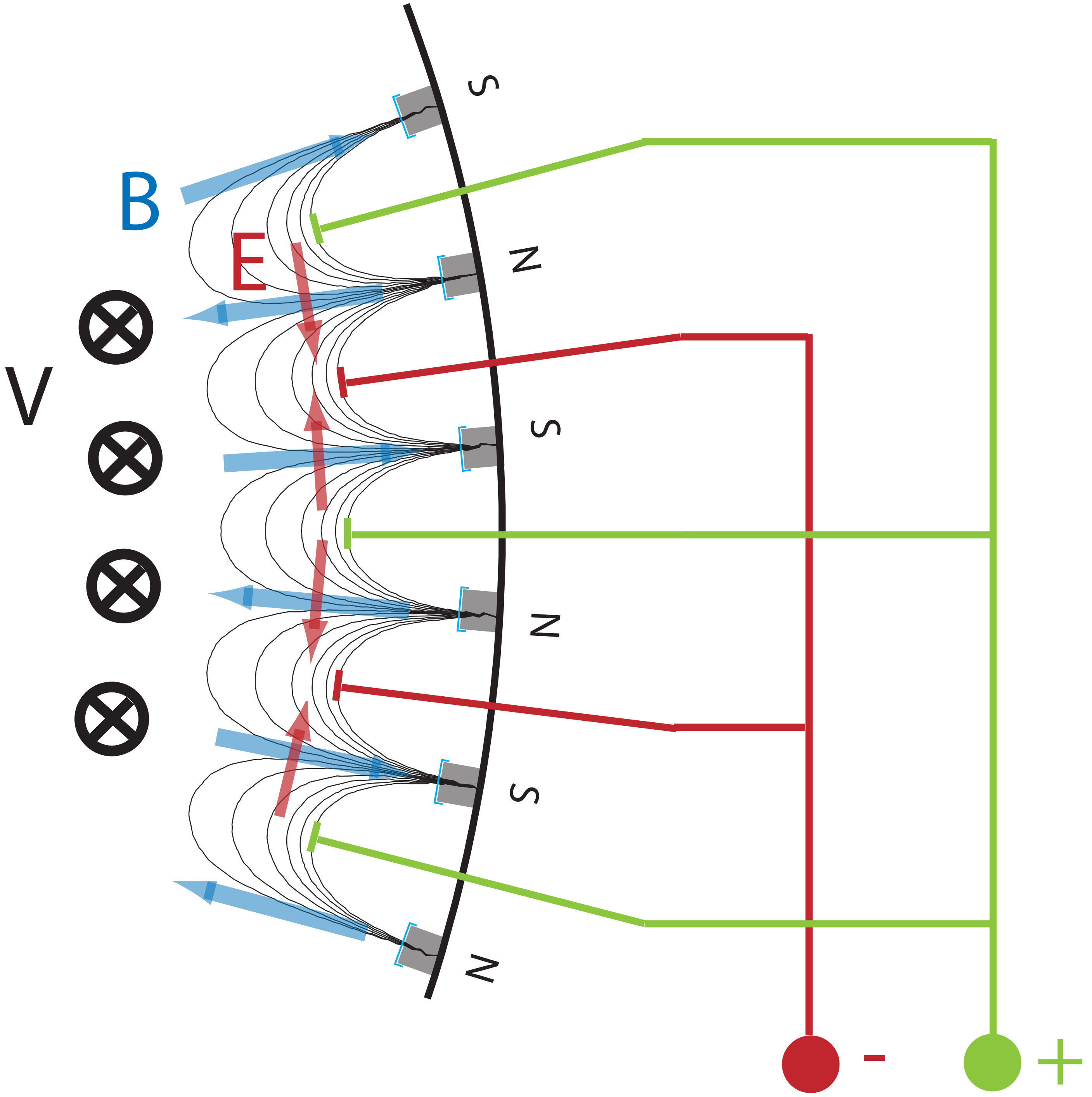
Large, Magnetic Field Free Volume Plasma





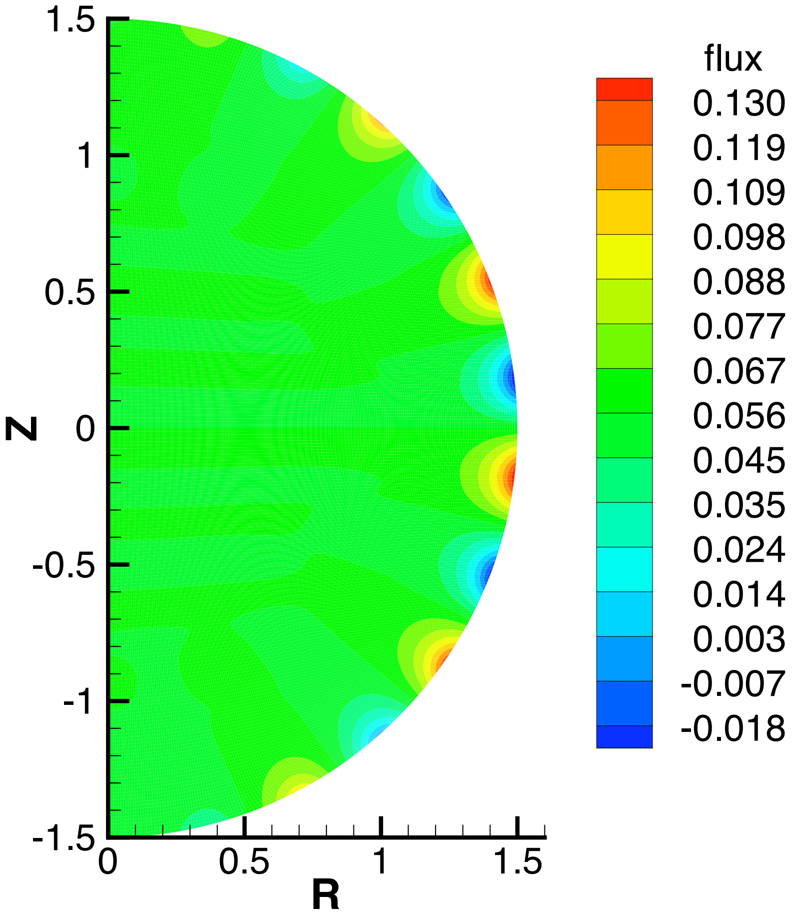
Magnetic field provides confinement similar to wall in fluid experiments

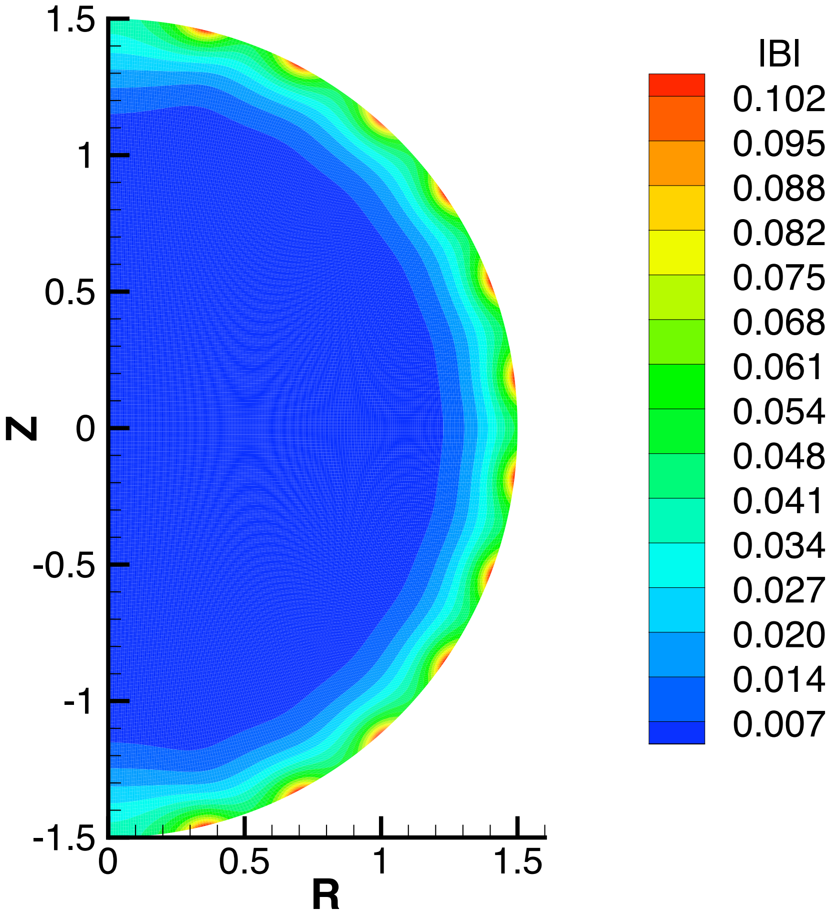
Multipole Magnetic Field can be used to drive flow at edge

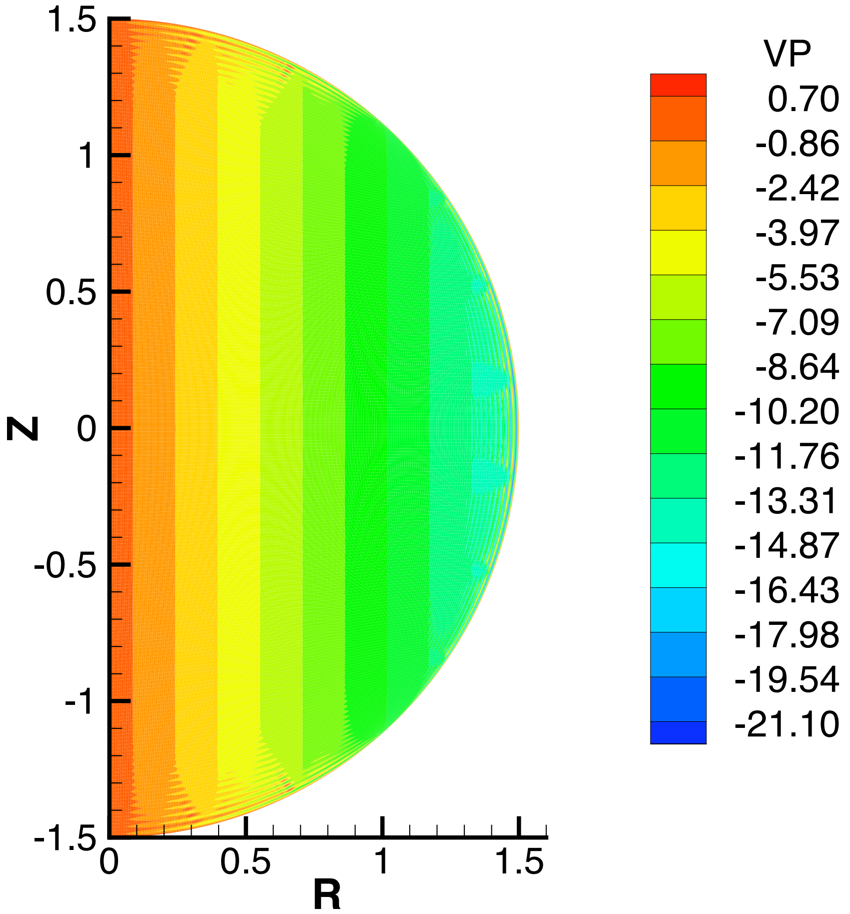


Arbitrary Vφ (r = a, θ)

NIMROD Simulations using $E_{tan}=R\ \Omega\ B_r$ gives rigid rotation with cusp field







Formulary of Key Dimensionless Parameters

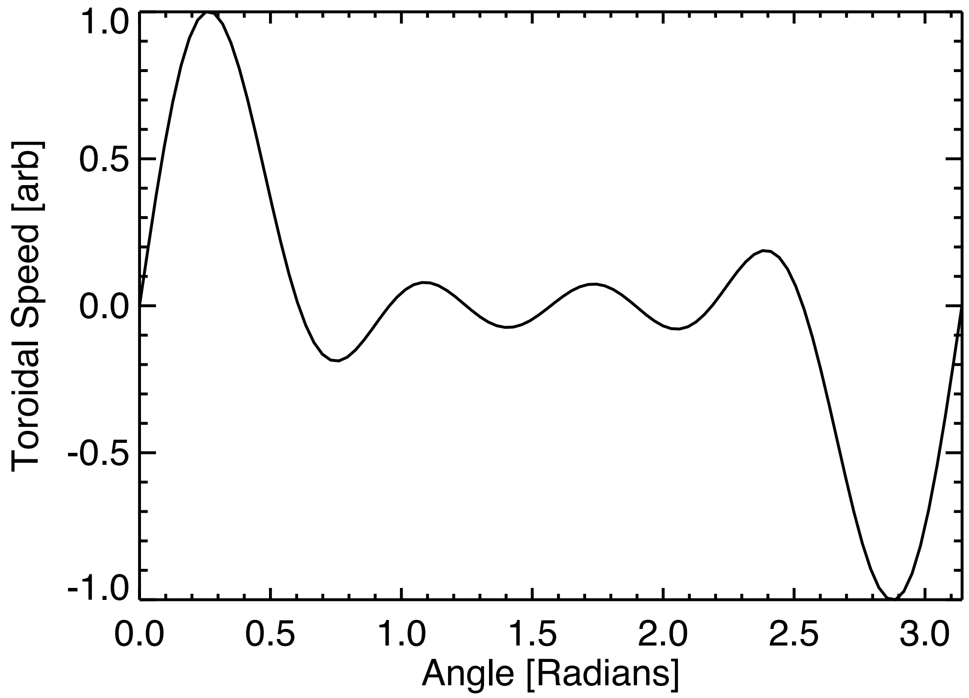
Magnetic Reynolds Number	Rm	$\mu_0 \sigma U L$	1.5	$\frac{T_{\mathrm{e,eV}}^{3/2} U_{\mathrm{km/s}} L_{\mathrm{m}}}{Z}$
Reynolds Number	Re	$\frac{UL}{\nu}$	8	$\frac{a_{\mathrm{m}} U_{km/s} \mu^2 n_{18}}{T_{\mathrm{i,eV}}^{5/2}}$
Magnetic Prandtl Number	Pm	$\mu_0 \sigma \nu$	0.18	$\frac{T_{\mathrm{e,eV}}^{3/2} T_{i,eV}^{5/2}}{\mu^2 n_{18}}$
Cowling Number	C	$\frac{\frac{B^2}{2\mu_0}}{\frac{1}{2}\rho U^2}$	4.75	$\frac{B_{\mathrm{G}}^2}{\mu n_{18} U_{km/s}^2}$
Lundquist Number	Lu	$Rm \times C^{1/2}$	3.26	$\frac{T_{\mathrm{e,eV}}^{3/2} B_{\mathrm{G}} L_{\mathrm{m}}}{Z\sqrt{\mu n_{18}}}$
Magnetization		$\frac{\rho_e}{L}$	0.0238	$\frac{T_{\mathrm{e,eV}}^{1/2}}{B_{\mathrm{G}} L_{\mathrm{m}}}$
Ion Collisionality		$\frac{\lambda_{mfp}}{L}$	0.012	$\frac{T_{\mathrm{i,eV}}^2}{n_{18} L_{\mathrm{m}}}$
Plasma Pressure	β	$\frac{2\mu_0 n T}{B^2}$	40	$\frac{n_{18} T_{\mathrm{e,eV}}}{B_G^2}$

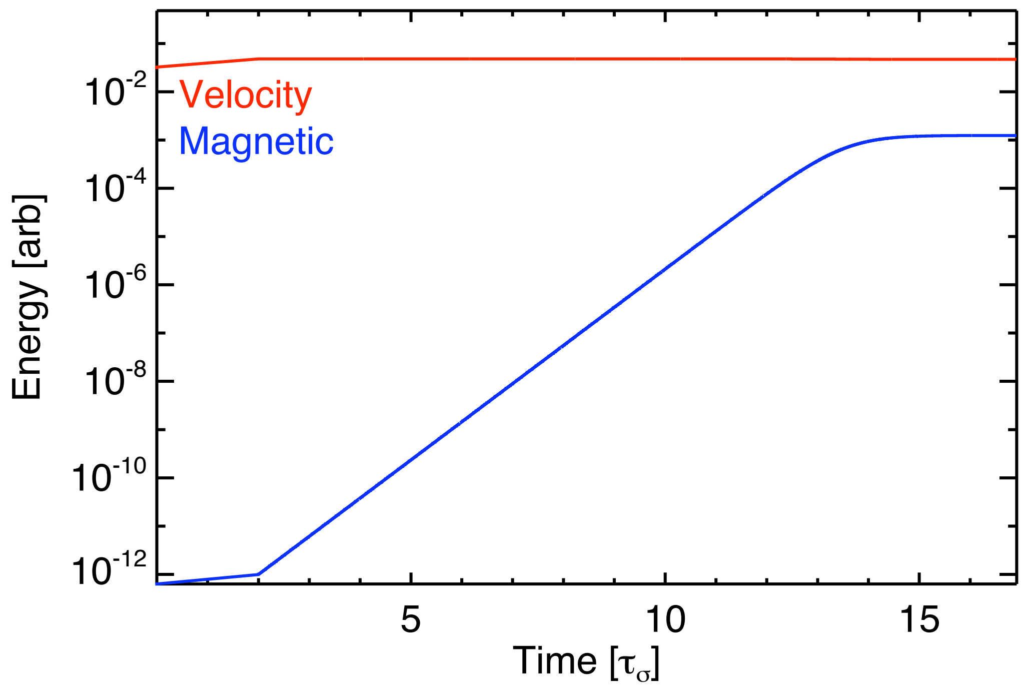
Plasma Parameters

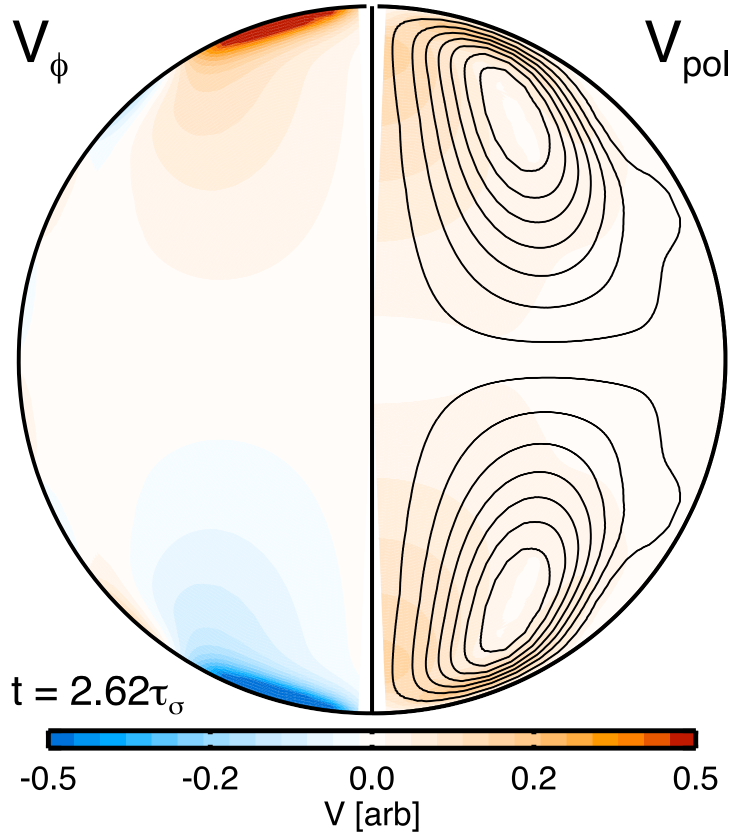
plasma radius	a	1.5	m
density	n	10^{17}—10^{19}	m^{-3}
electron temperature	T_e	2—20	eV
ion temperature	T_i	0.5—2	eV
peak flow speed	U_{max}	0—20	km/s
ion species	H, He, Ne, Ar	1, 4, 20, 40	amu
magnetic field	$r < 1.2$ m	<0.1	gauss
magnetic field	at cusp	$>10^4$	gauss
current diffusion time	$\mu_0 \sigma a^2$	50	msec
pulse length	τ_{pulse}	5	sec
heating power	P	< 0.5	MW

Rm_{max}	> 1000
Re	24—3.8×10^6
Pm	3×10^{-4}—56
C	10^{-4}
β	10^4

Two Vortex Plasma Dynamo Flow can be driven at boundary (spherical Von Karman Flow)



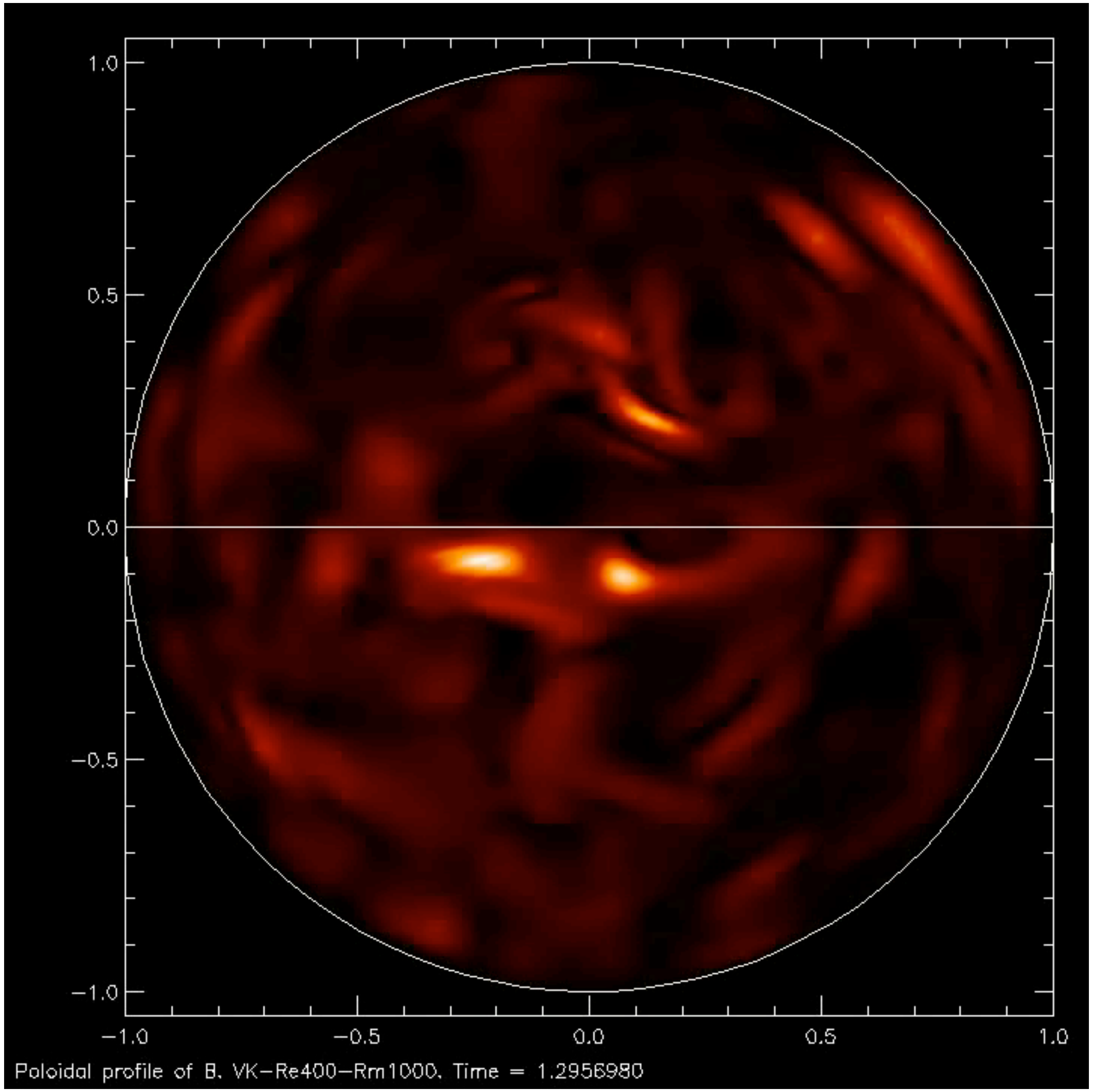




- Plasma Rm=300, Re=100
  - Te=10 eV
  - U=10 km/s,
  - n=10^{18} m^{-3}
  - Hydrogen

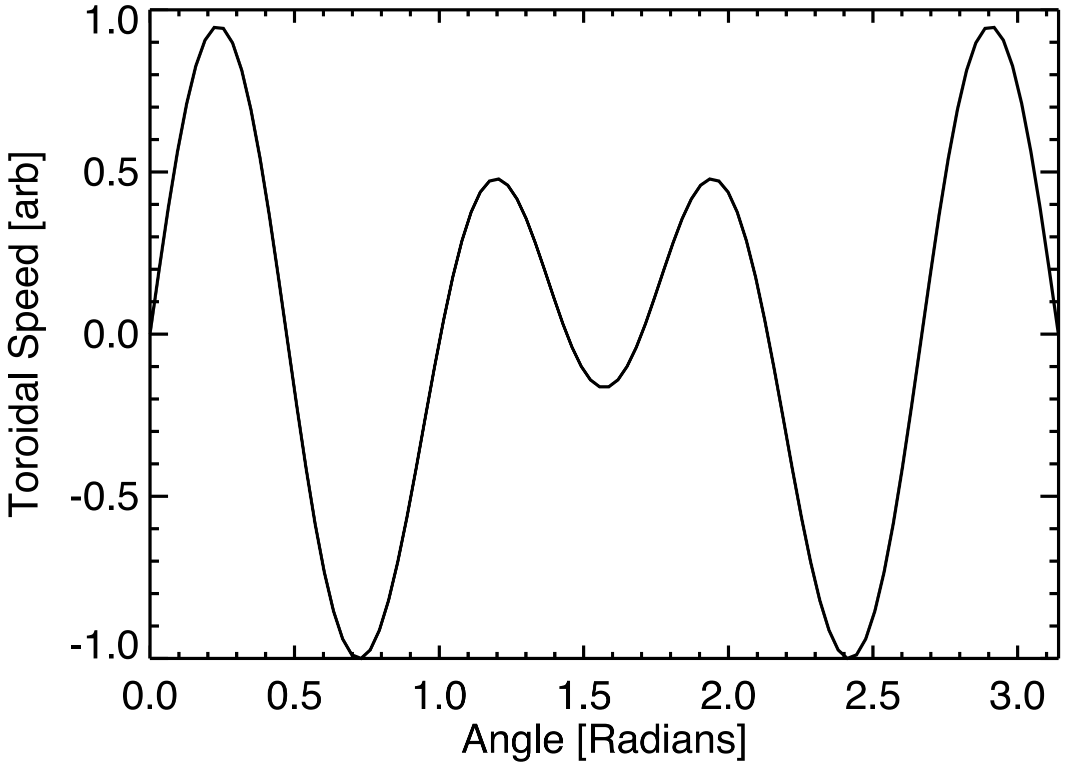
Small Scale Dynamo at Pm>1

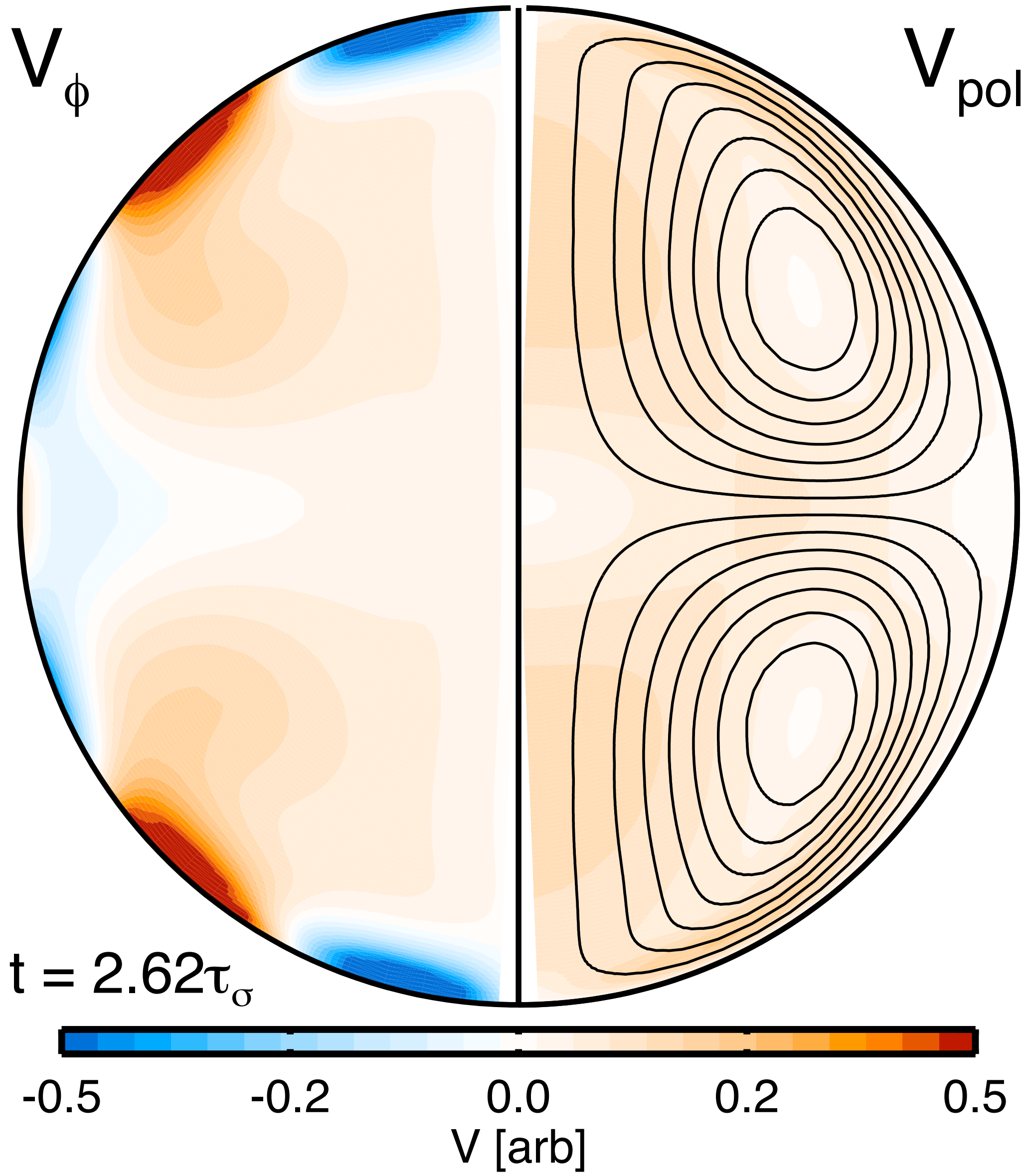
- Rm=1000
- Re=400
- Plasma
  - Te = 13 eV
  - Ti = 1 eV
  - deuterium
  - U = 15 km/s
  - n = 10^{18} m^{-3}



Poloidal profile of B. VK−Re400−Rm1000. Time = 1.2956980

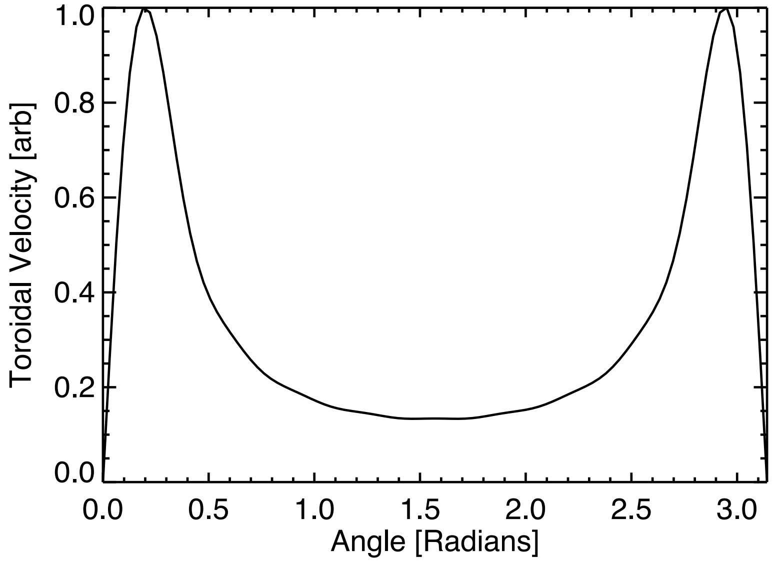
More complicated large scale dynamo flows (even time dependent) are possible (difficult mechanically)

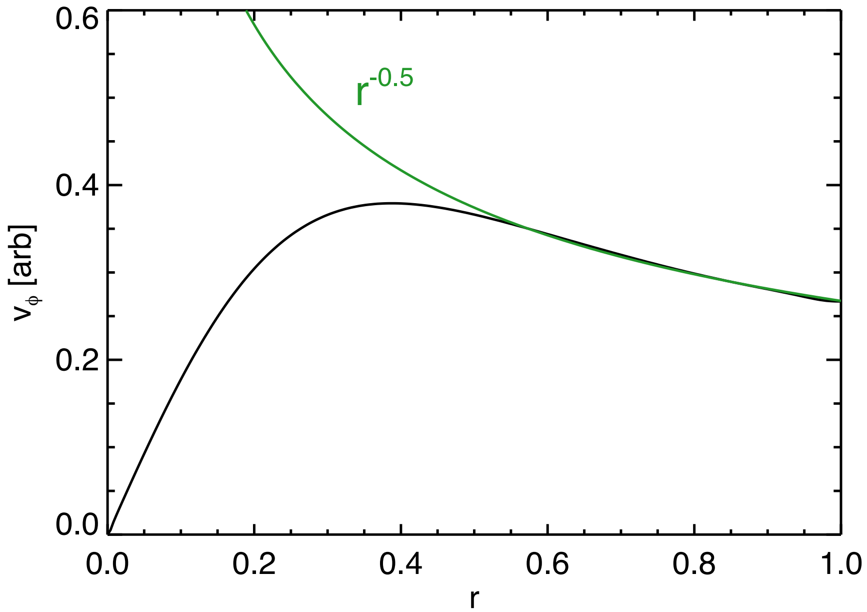


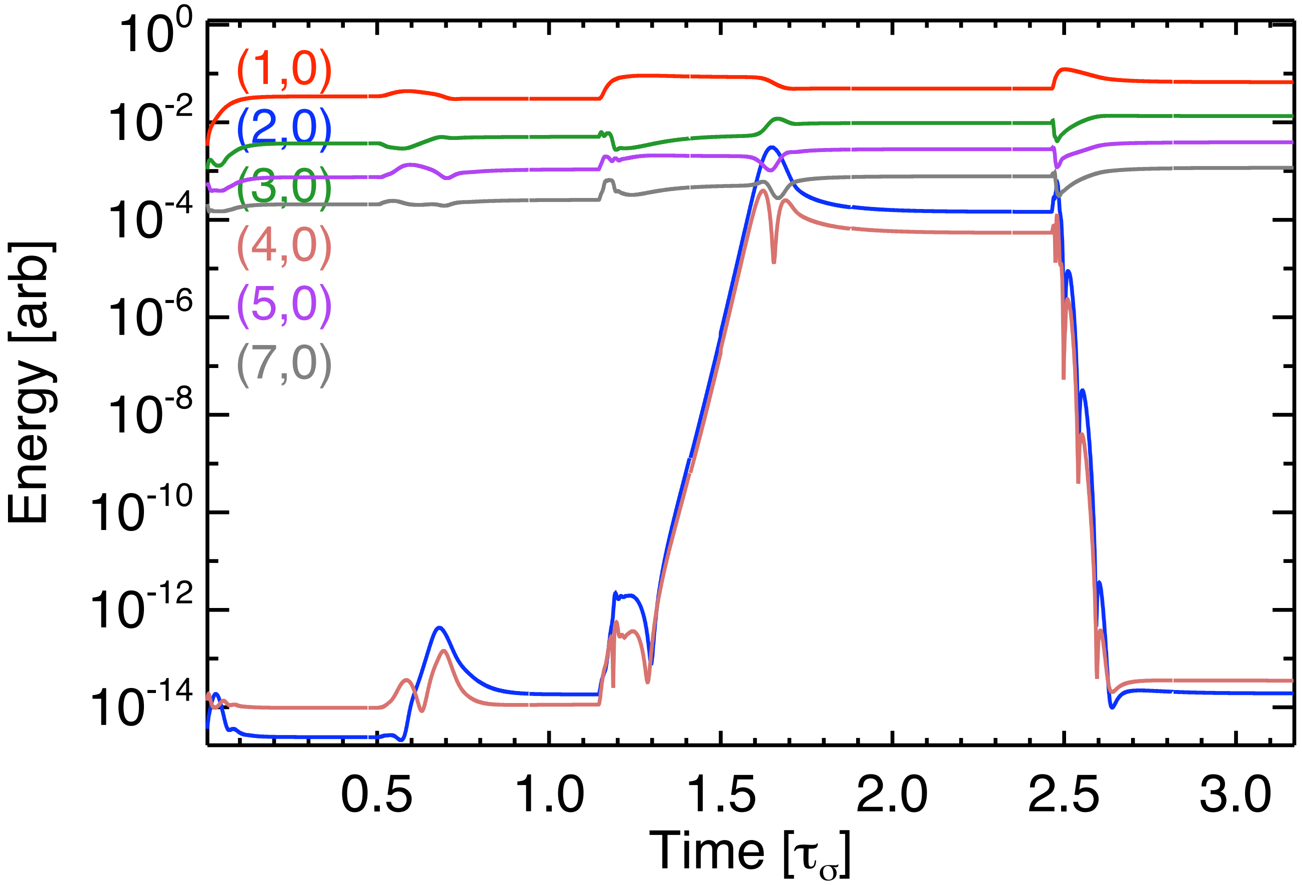


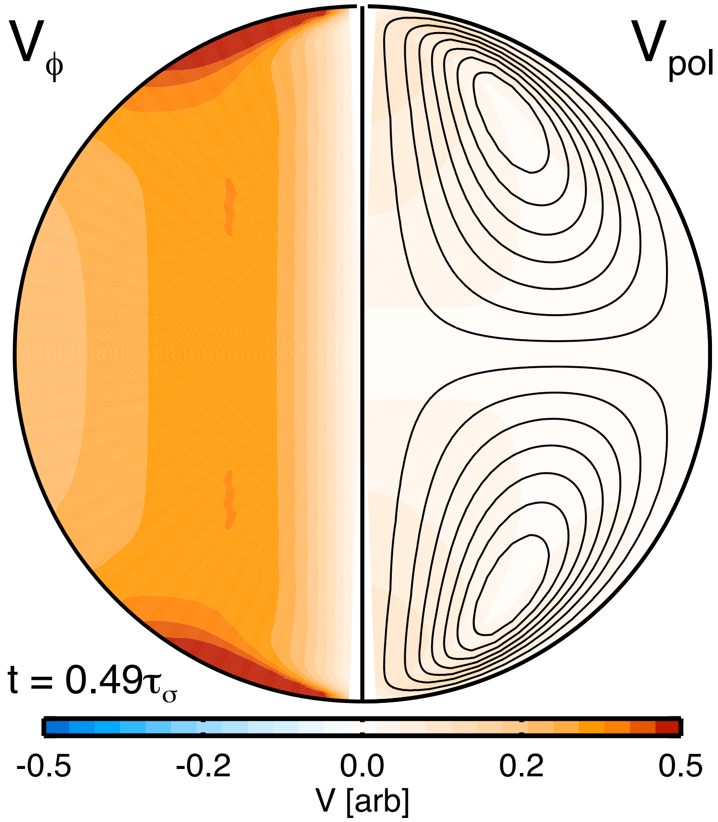
- Rm_{crit} = 250

MRI is also possible due to flexible BCs

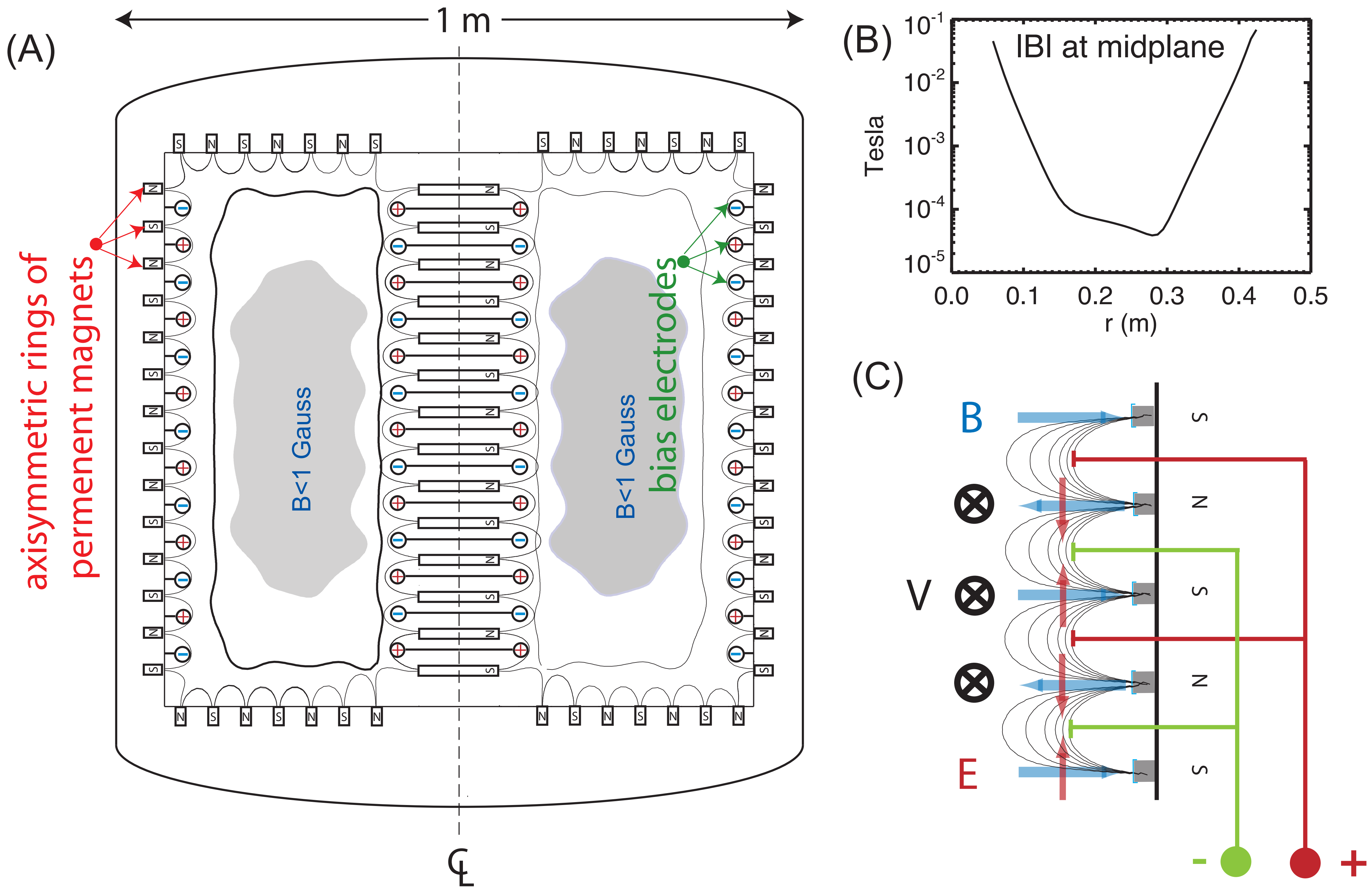


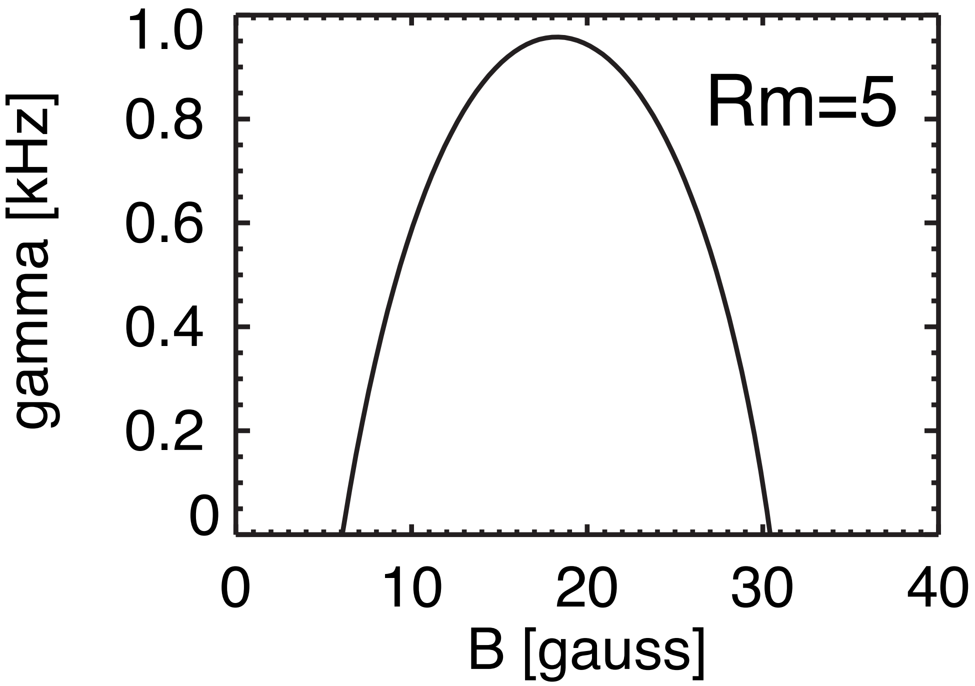


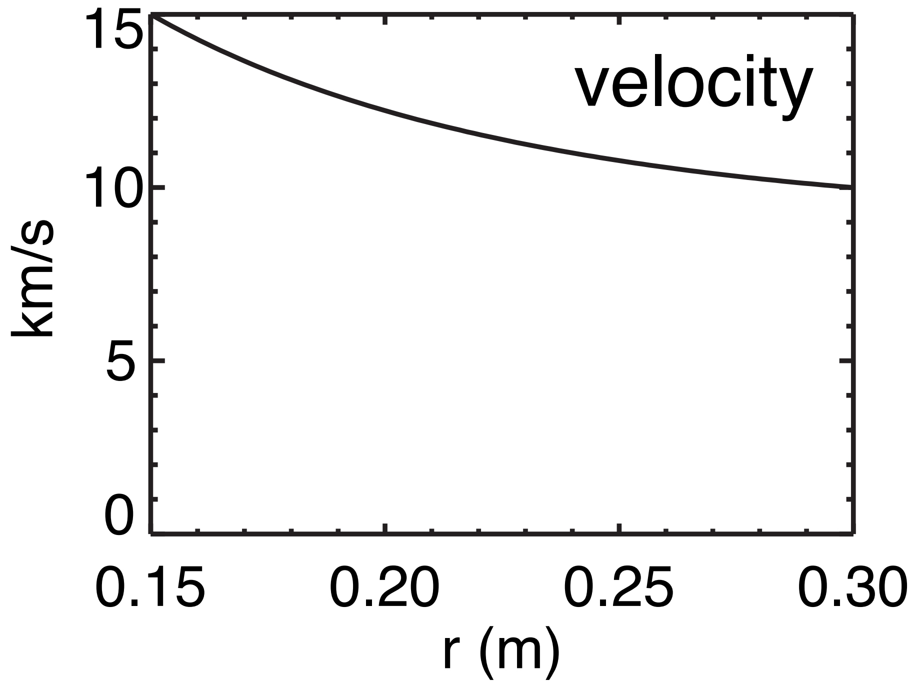


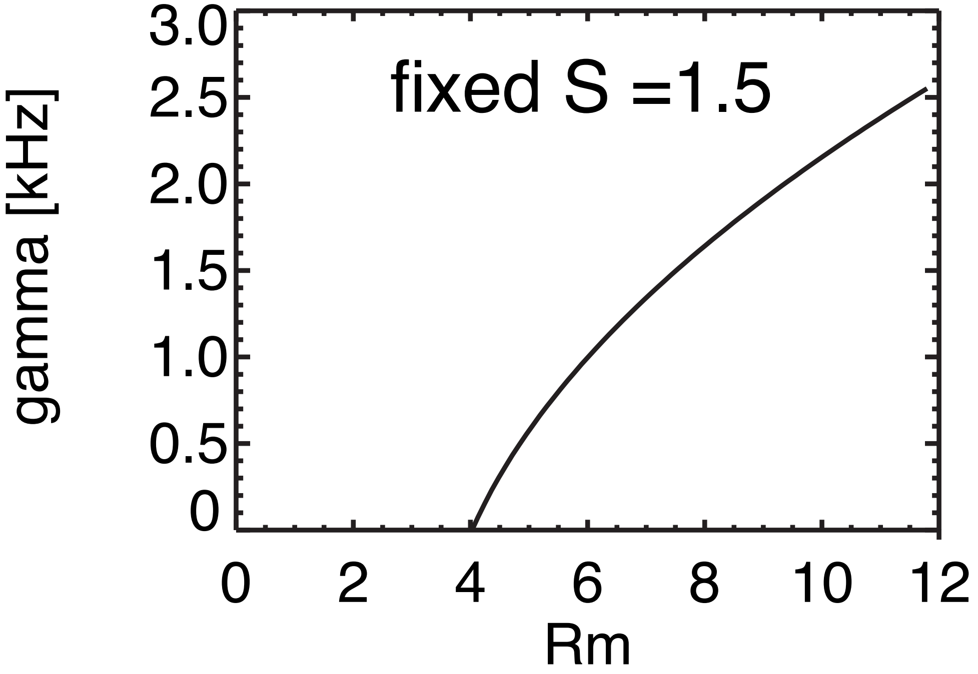


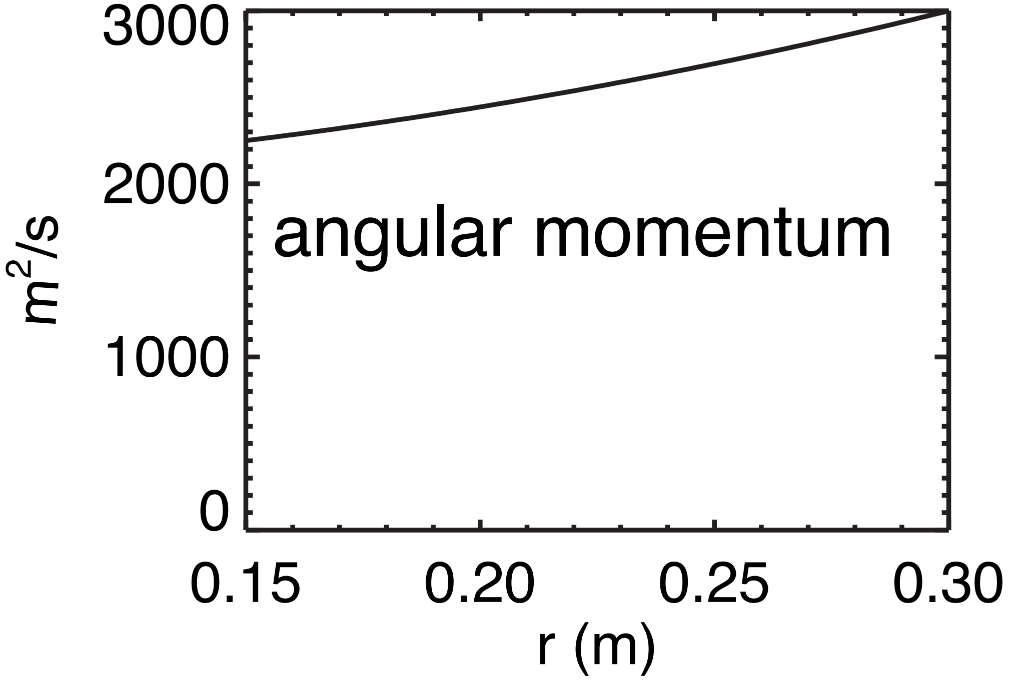
Prototype Experiment is being constructed to study a plasma Couette Flow



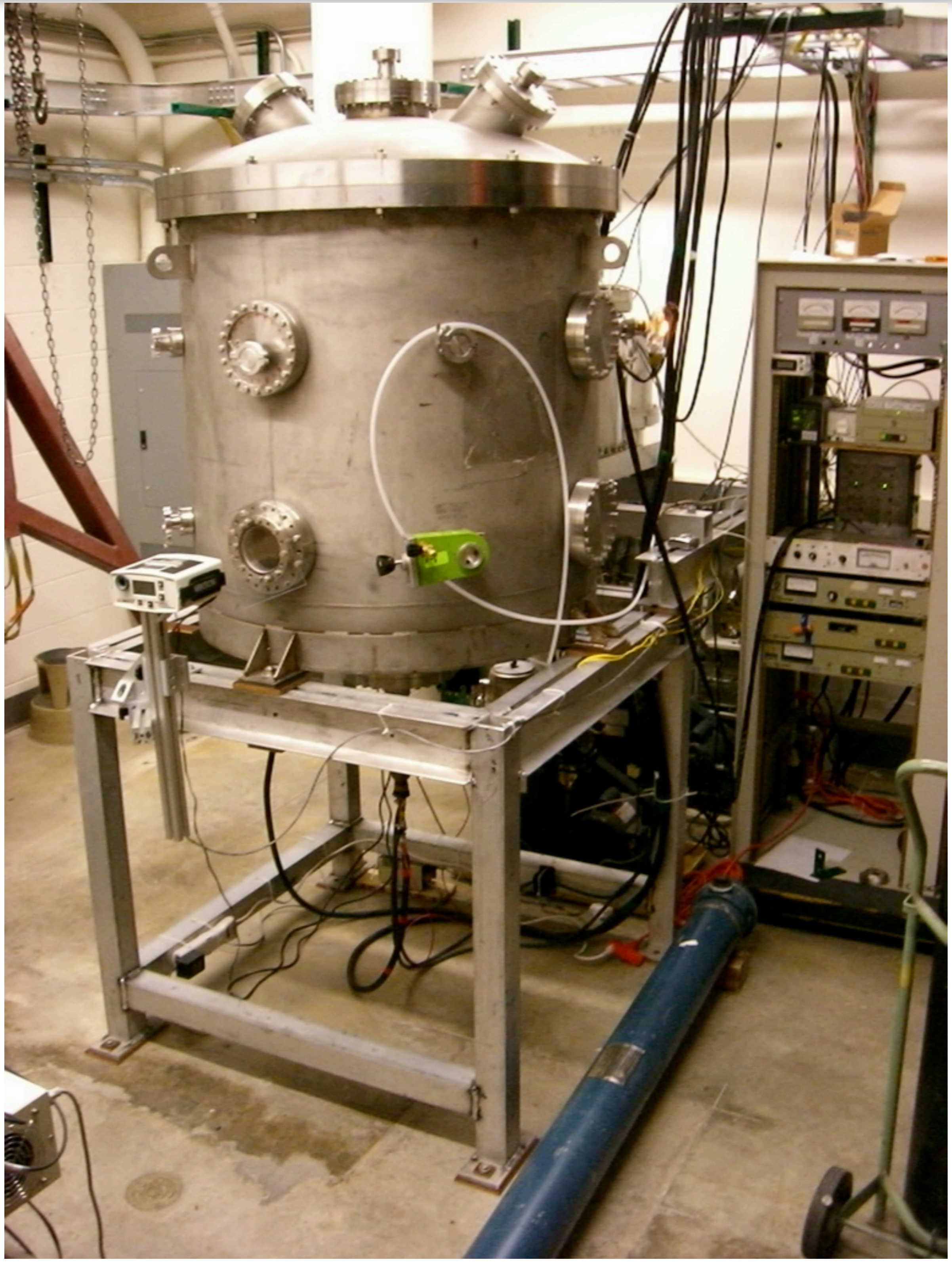

Rm=5
gamma [kHz]
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
B [gauss]

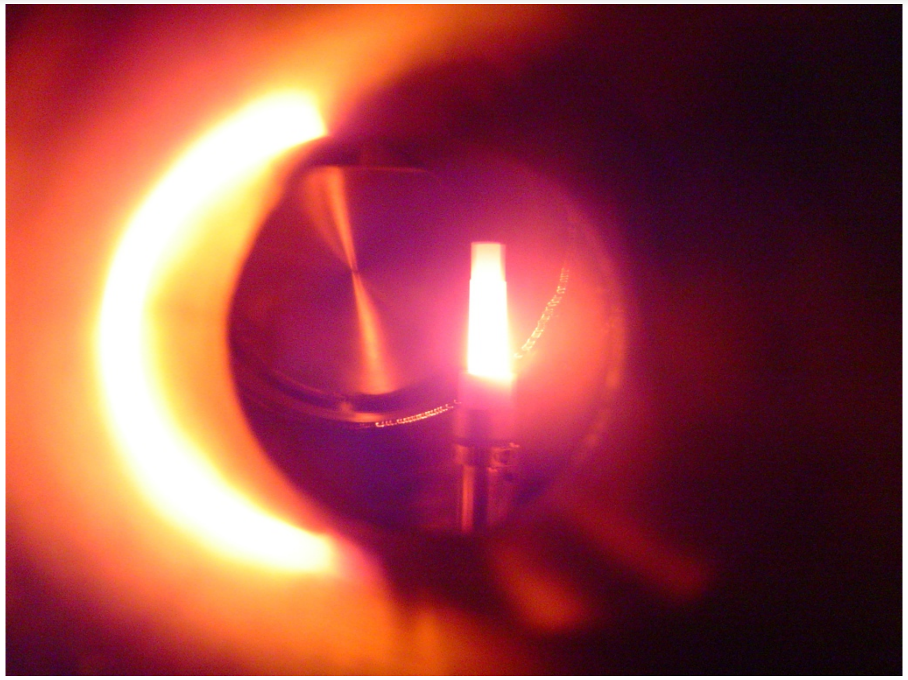

velocity
km/s
15
10
5
0
0.15
0.20
0.25
0.30
r (m)


fixed S =1.5
gamma [kHz]
3.0
2.5
2.0
1.5
1.0
0.5
0
0
2
4
6
8
10
12
Rm


angular momentum
m^2/s
3000
2000
1000
0
0.15
0.20
0.25
0.30
r (m)

Plasma Couette Flow Experiment is a prototype for dynamo experiment





Summary

- Main Results from Madison Experiment
  - Dipole generation by turbulence
  - measurement of the magnetic field generated by fluctuations
  - Intermittent self-excitation
- Overview of Plasma Dynamo Experiment
  - Rm=1000, arbitrary Pm, flexible boundary conditions
  - Plasma Couette flow experiment just beginning