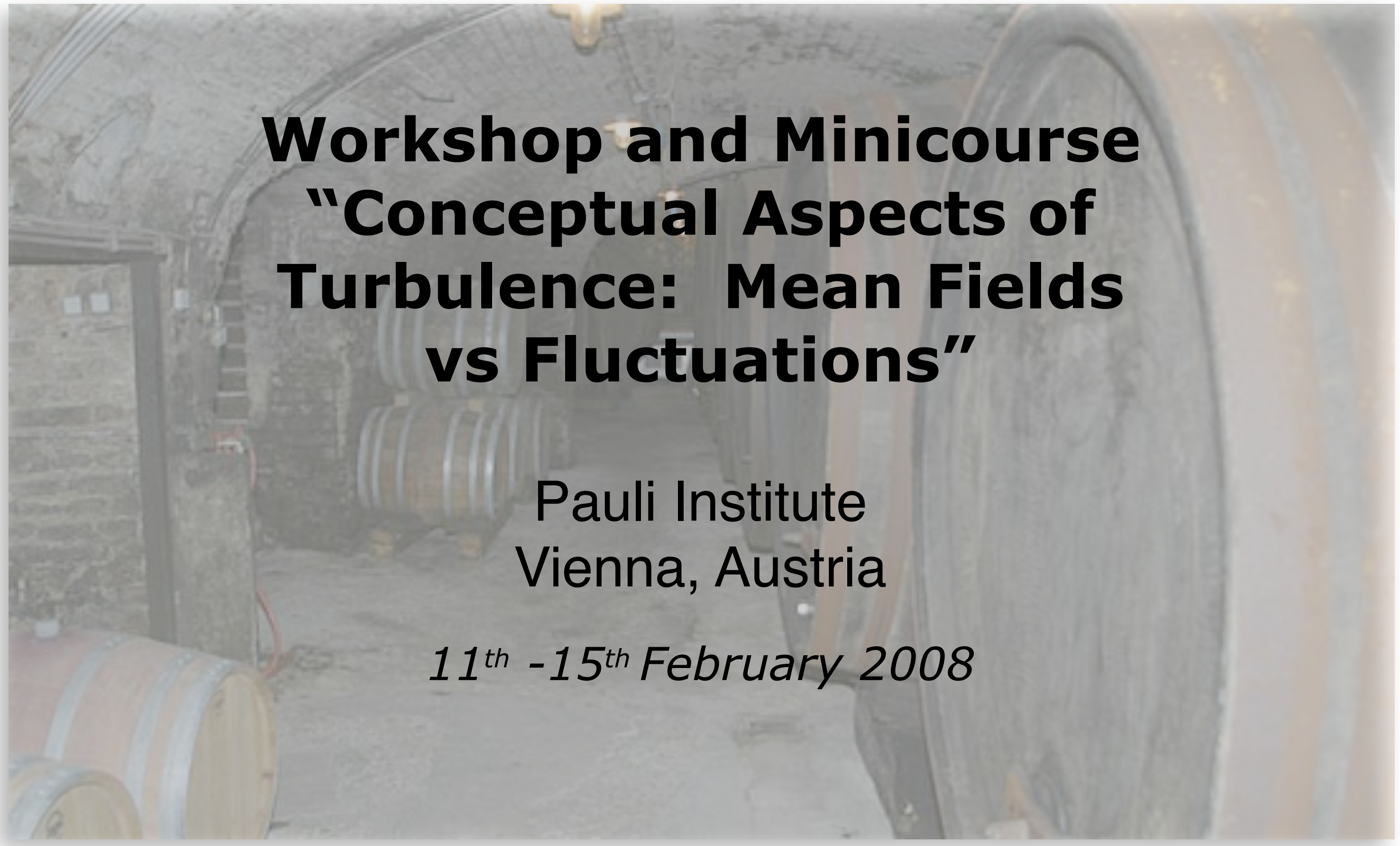
A Plasma Dynamo Experiment

Cary Forest

THE UNIVERSITY *of* WISCONSIN
MADISON



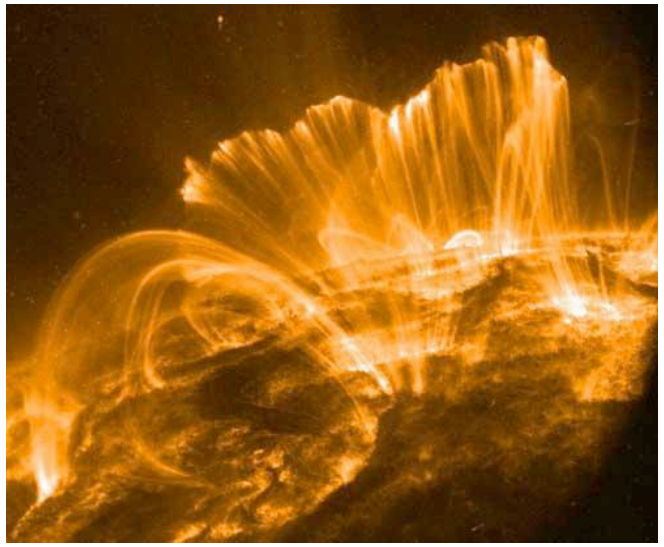
Workshop and Minicourse
"Conceptual Aspects of Turbulence: Mean Fields vs Fluctuations"

Pauli Institute
Vienna, Austria

11th -15th February 2008

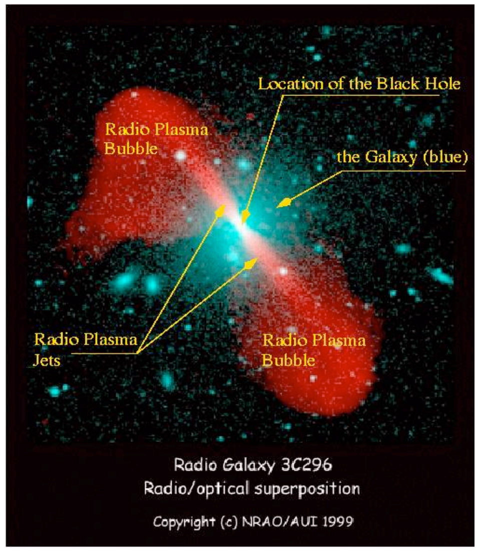
Big Questions in Astophysics have a Common Theme Related to Magnetic Field Generation from Plasma Flow

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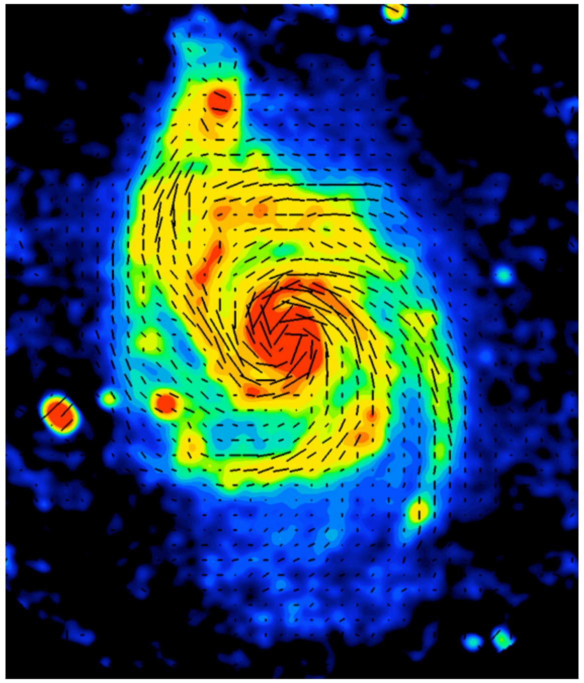
-Collisionless close to hole
-Galaxy is ejecting plasma and magnetic field into the surrounding IGM
-Rm = 10^{19}
-Pm = 10^5

GALACTIC MAGNETIC FIELD

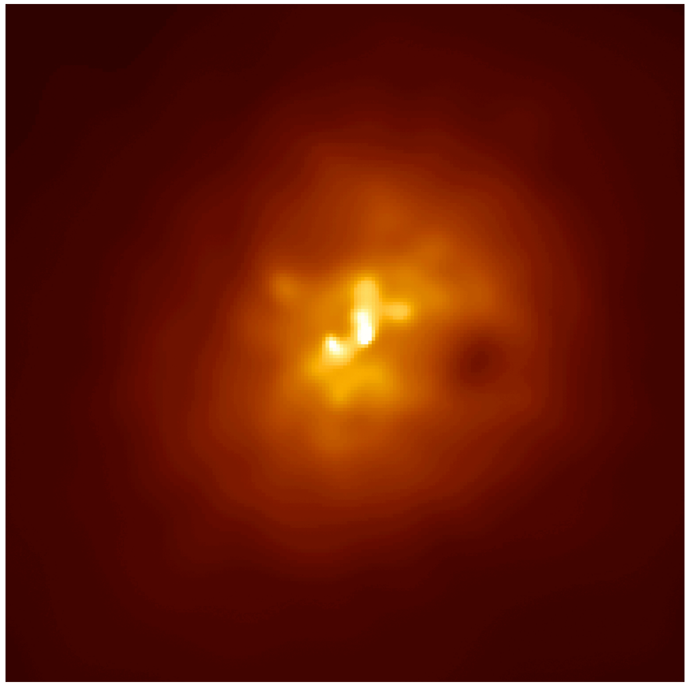
-M51 Spiral Galaxy
-Polarization of 6cm emission Indicates direction of B field in the hot plasma between the stars.
-Rm = 10^{14} (?)
-Pm = 10^5

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	$\mu_0 \sigma U L$
Reynolds	Re	$\frac{UL}{\nu}$
Magnetic Prandtl	Pm	$\mu_0 \sigma \nu$

Minimum requirements for experimentally addressing each Plasma Process

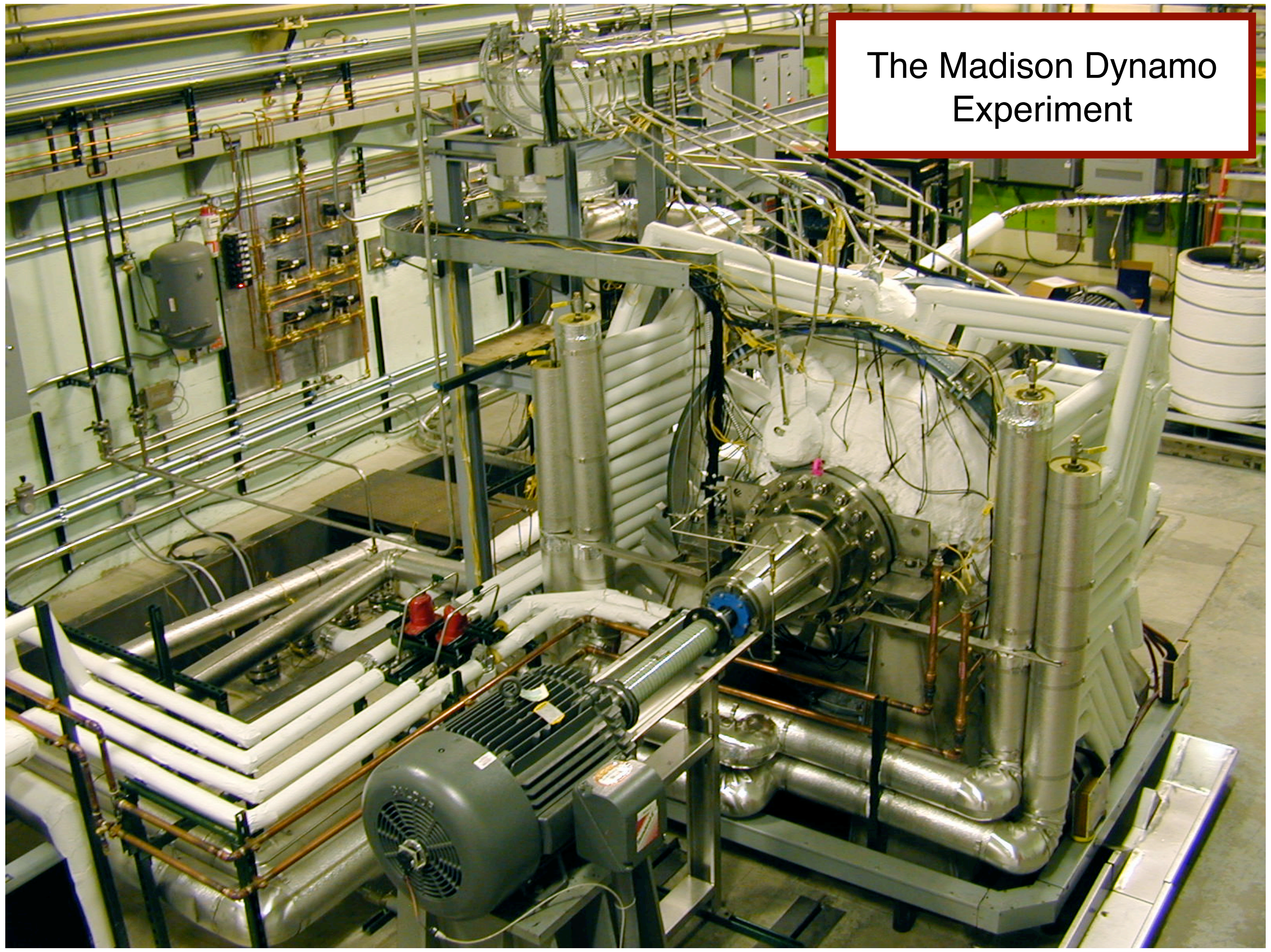
$\tau_\sigma = \mu_0 \sigma a^2$

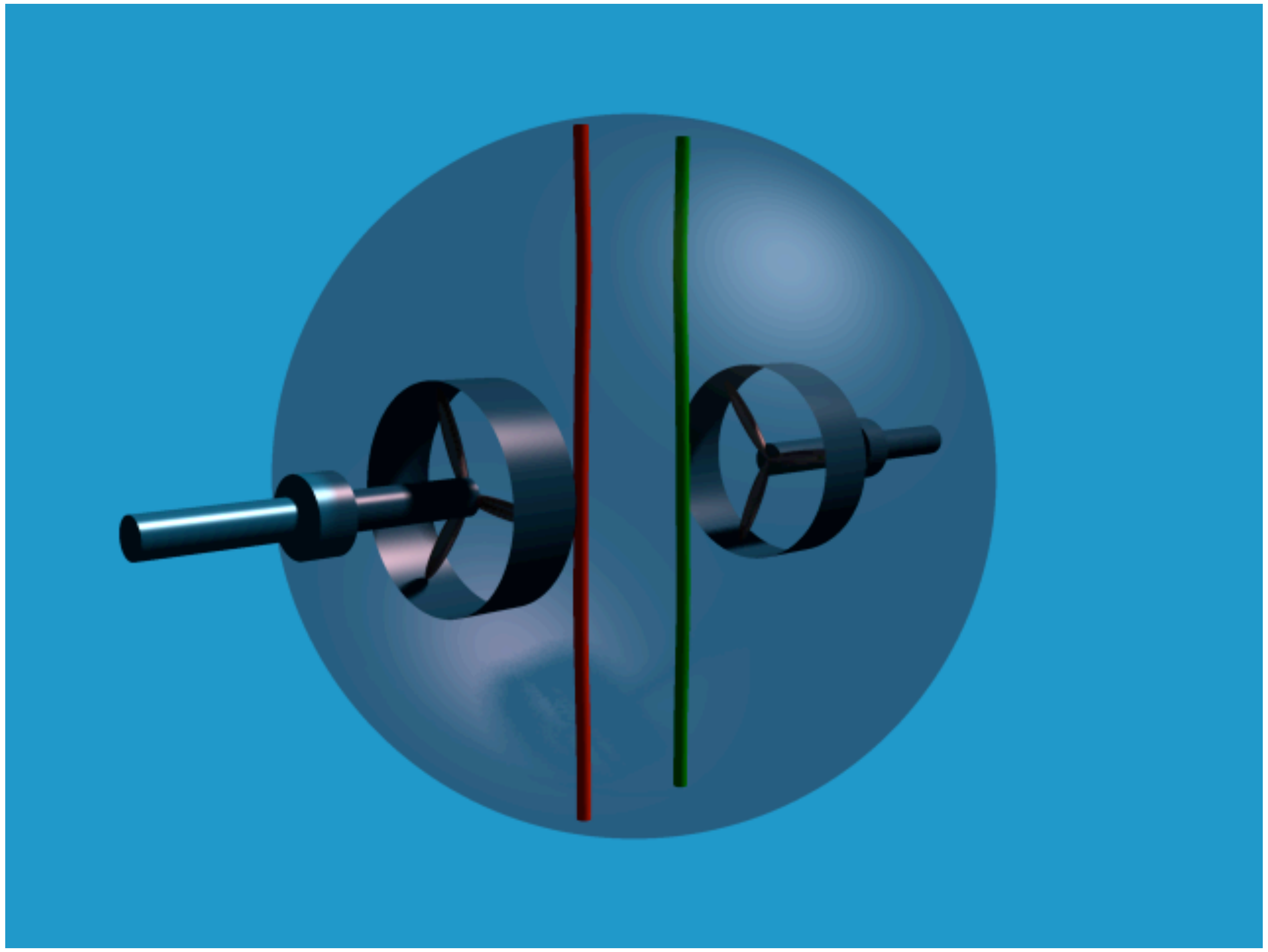
Plasma Process	Rm_{crit}	Re	C	$\frac{\lambda}{L}$	β
large scale dynamo					
laminar	$\gtrsim 100$	< 100	$\ll 1$	-	-
with turbulence	$\gtrsim 500$	> 1000	$\ll 1$	-	-
small scale dynamo	$\gtrsim 500$	$\gtrsim 1000$	$\ll 1$	?	?
MHD turbulence	$\gtrsim Re$	$\gtrsim 1000$	~ 1	-	-
MRI					
with mean field	$\gtrsim 10$	—	$\lesssim 1$	?	?
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 can partially address the Large Scale Dynamo process





- Power scaling is challenging: $P_{mech} \sim Rm^3 / L$ [$Rm=100$, $P_{mech}=100$ kW]
- $Pm=10^{-5}$ (always turbulent)

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<<1)
2. Stir until $Rm > Rm_{crit}$
3. Magnetic field spontaneously created

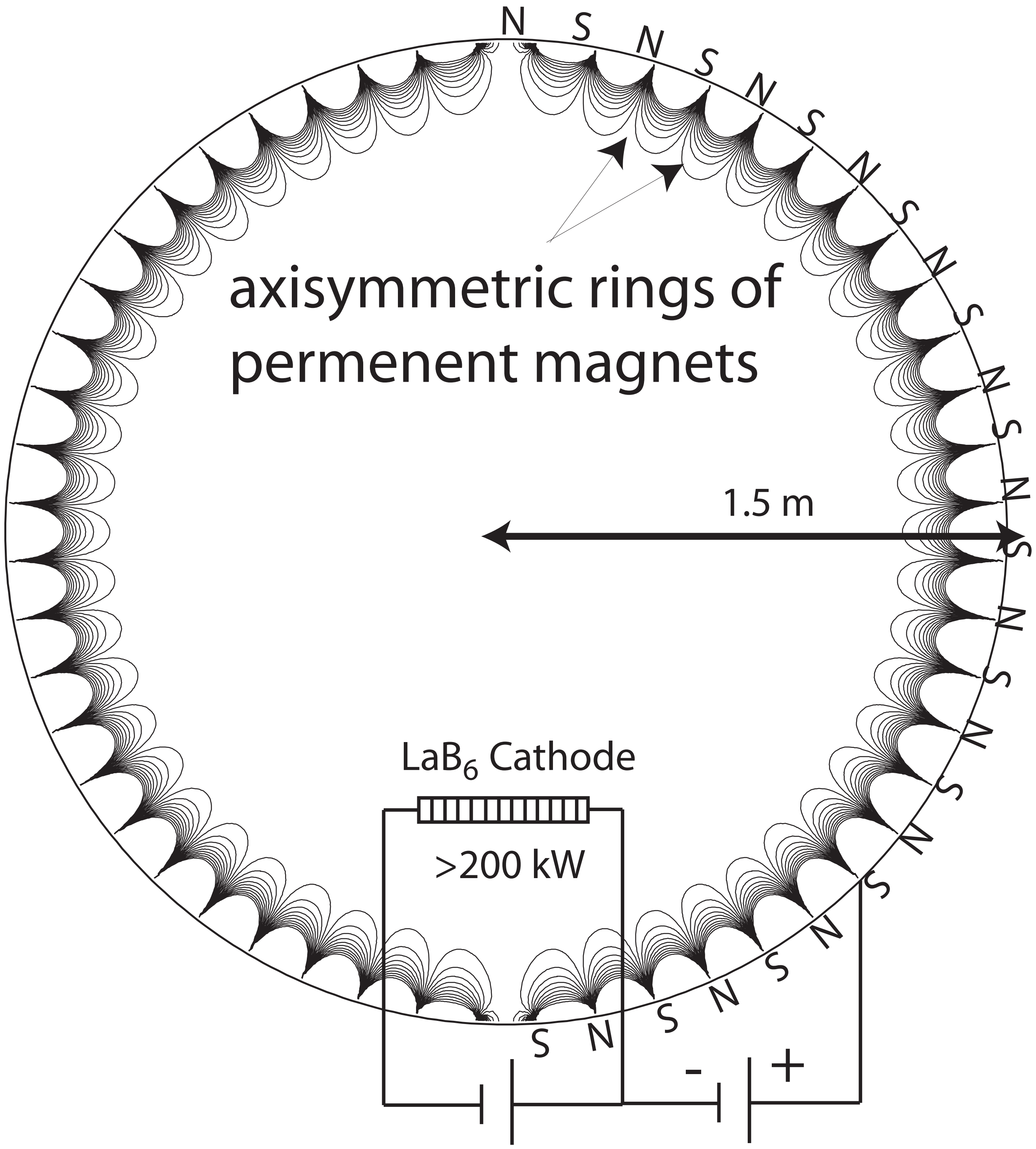
Challenge: to create a large, highly conducting, unmagnetized, fast flowing laboratory plasma for study

-difficult to stir a plasma

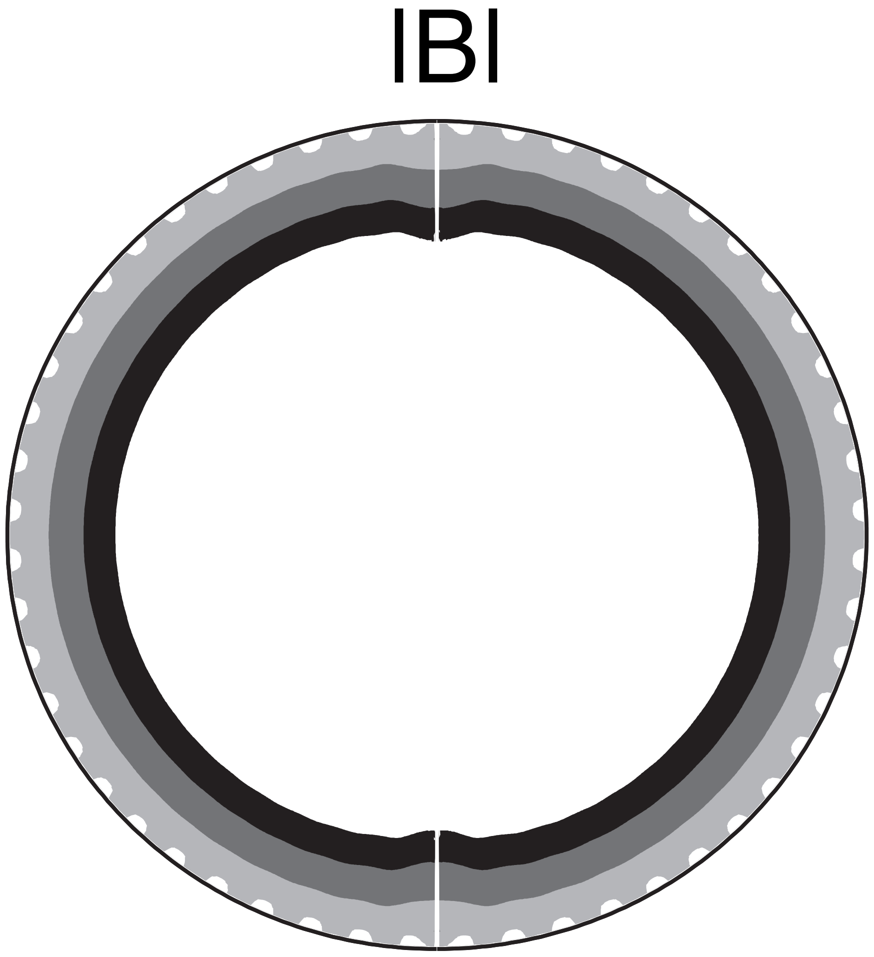
-need some confinement for plasma to be hot

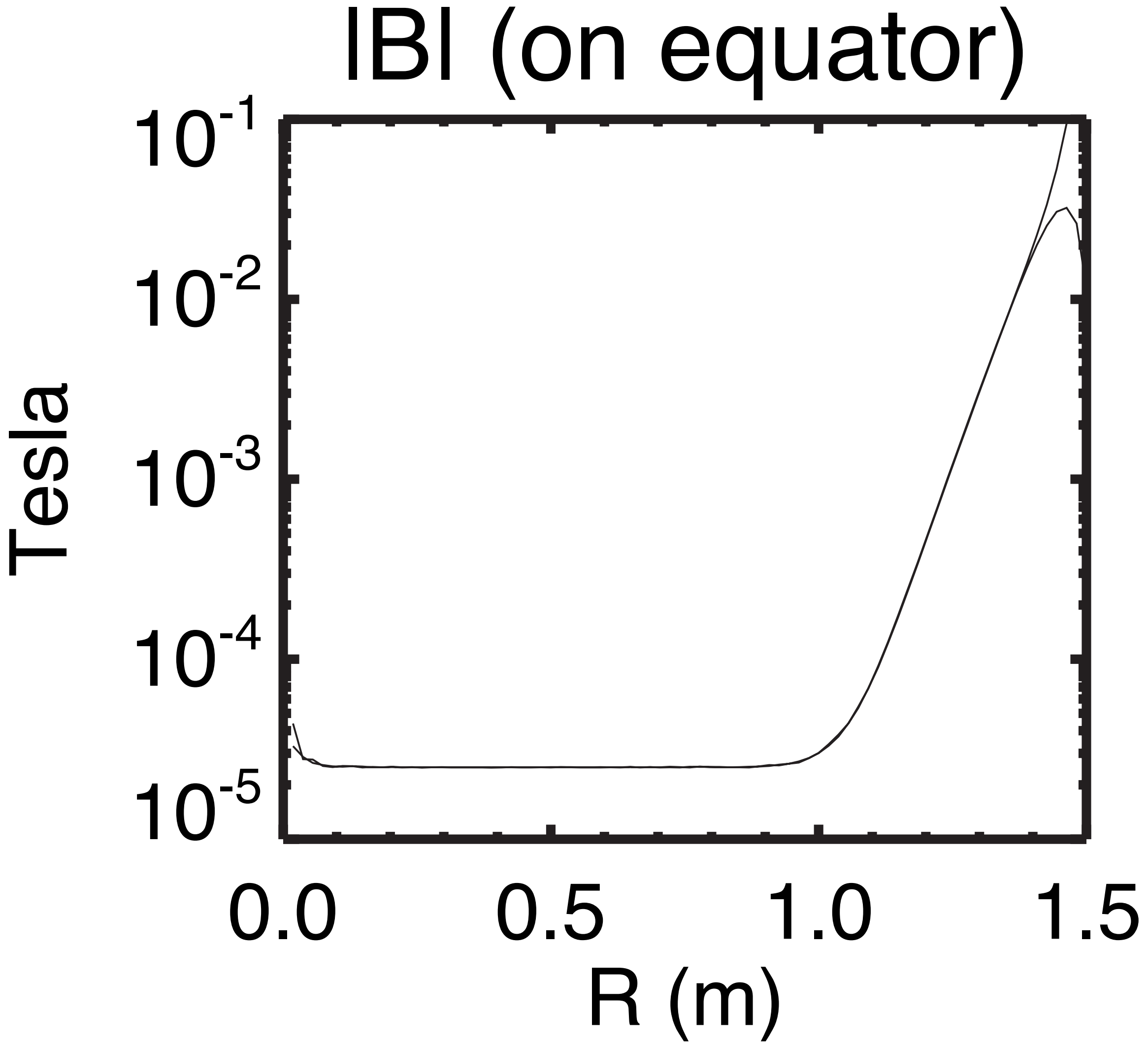
Plasma Dynamo Facility is needed to study high Rm, high C plasmas

- 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



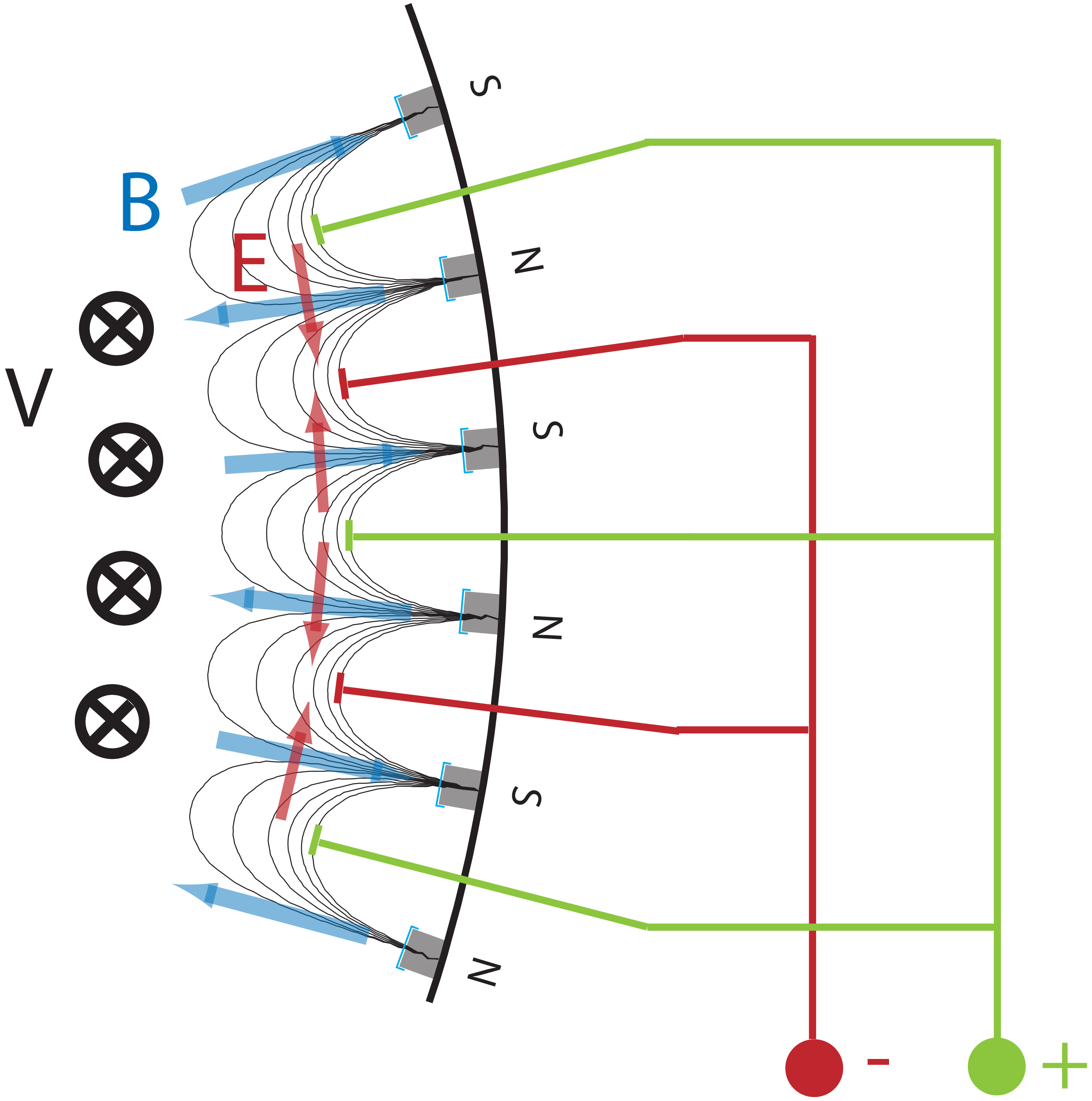
Large, Magnetic Field Free Volume Plasma





Magnetic field provides confinement similar to wall in fluid experiments

Multipole Magnetic Field can be used to drive flow at edge



Arbitrary $V\varphi\ (r = a, \theta)$

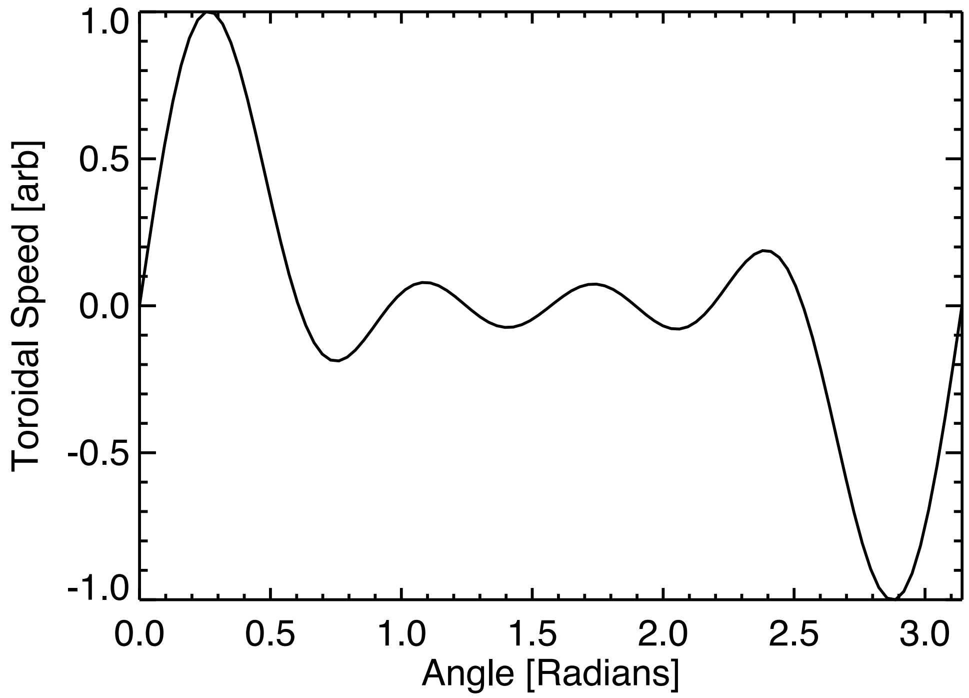
Formulary of Key Dimensionless Parameters

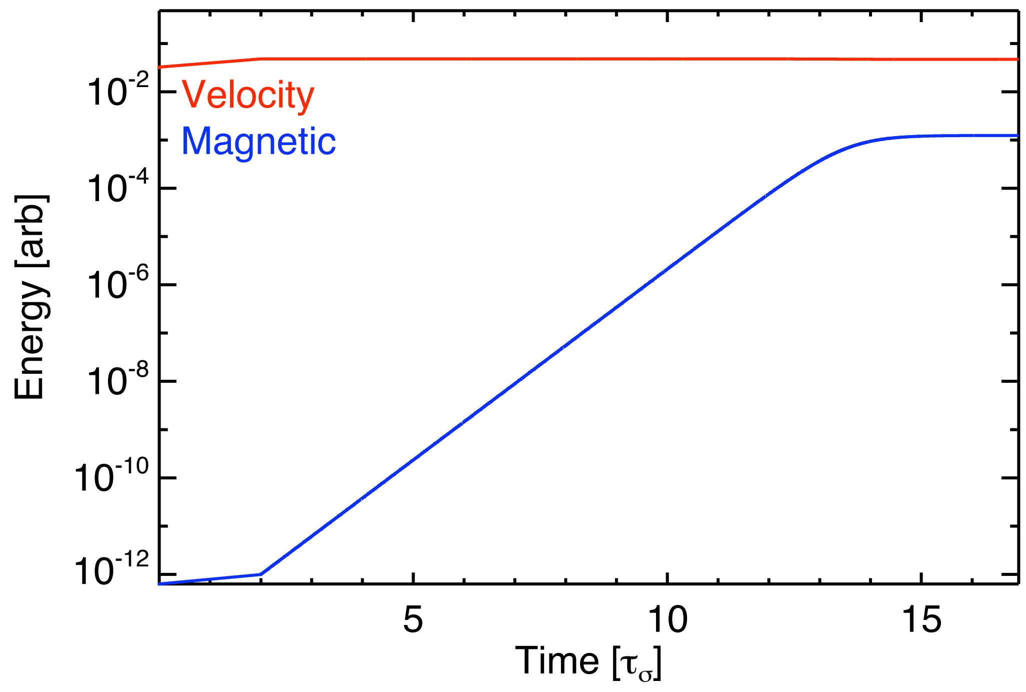
Magnetic Reynolds Number	Rm	$\mu_0 \sigma U L$	1.5	$\frac{T_{\mathrm{e,eV}}^{3/2} U_{\mathrm{km/s}} L_{\mathrm{m}}}{Z}$
Reynolds Number	Re	$\frac{UL}{\nu}$	8	$\frac{a_{\mathrm{m}} U_{km/s} \mu^2 n_{18}}{T_{\mathrm{i,eV}}^{5/2}}$
Magnetic Prandtl Number	Pm	$\mu_0 \sigma \nu$	0.18	$\frac{T_{\mathrm{e,eV}}^{3/2} T_{i,eV}^{5/2}}{\mu^2 n_{18}}$
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	$\frac{n_{18} T_{\mathrm{e,eV}}}{B_G^2}$

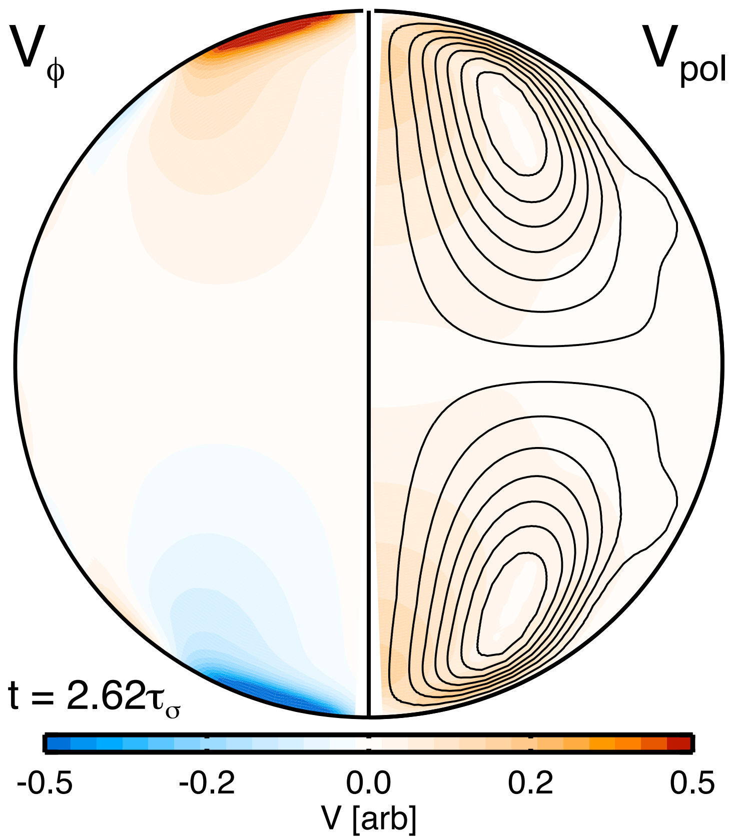
Plasma Parameters

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)



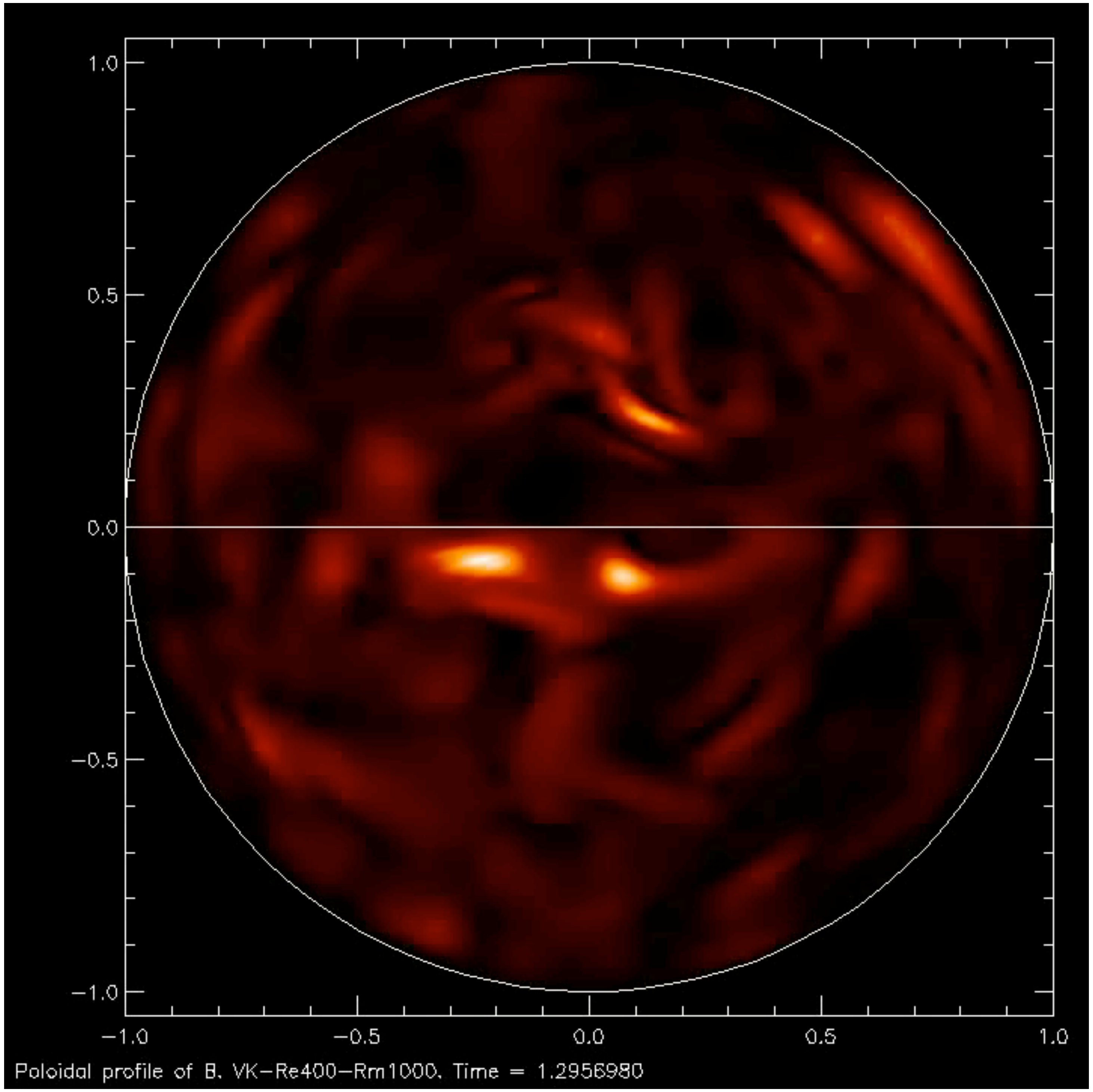




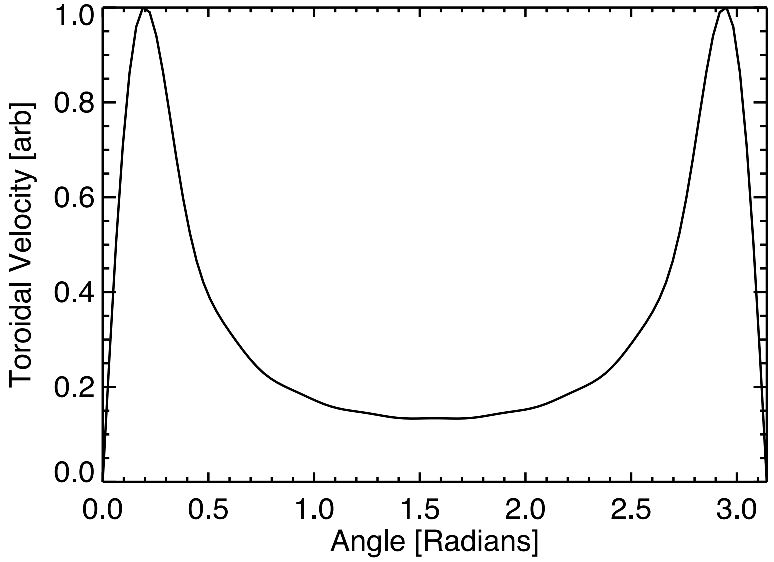
- Plasma Rm=300, Re=100
  - Te=10 eV
  - U=10 km/s,
  - n=10^{18} m^{-3}
  - Hydrogen

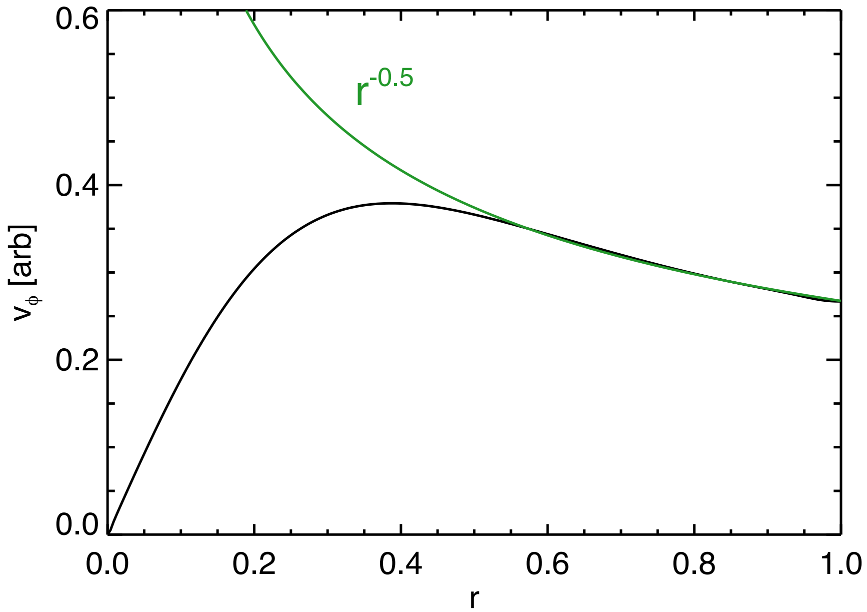
Small Scale Dynamo at Pm>1

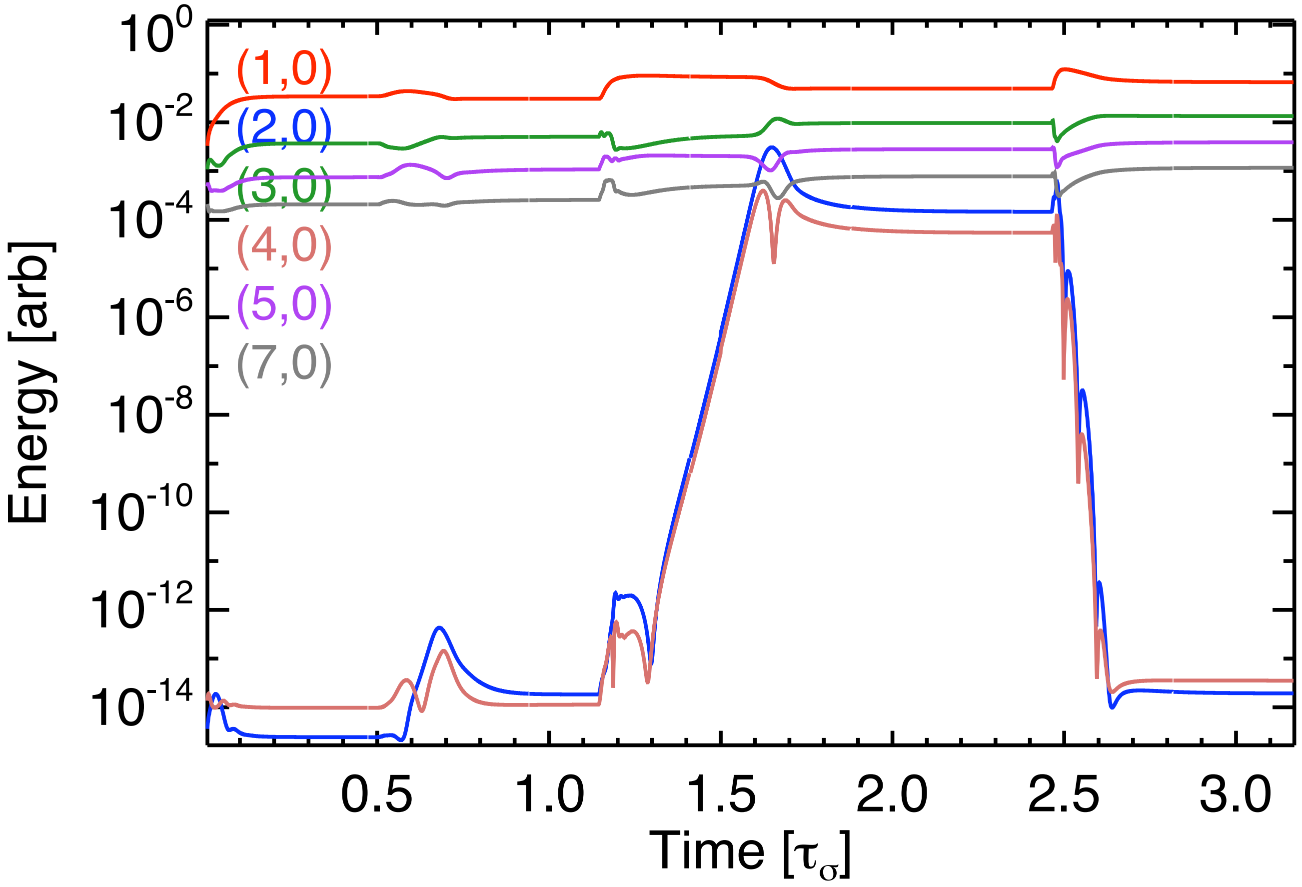
- Rm=1000
- Re=400
- Plasma
  - Te = 13 eV
  - Ti = 1 eV
  - deuterium
  - U = 15 km/s
  - n = 10^{18} m^{-3}

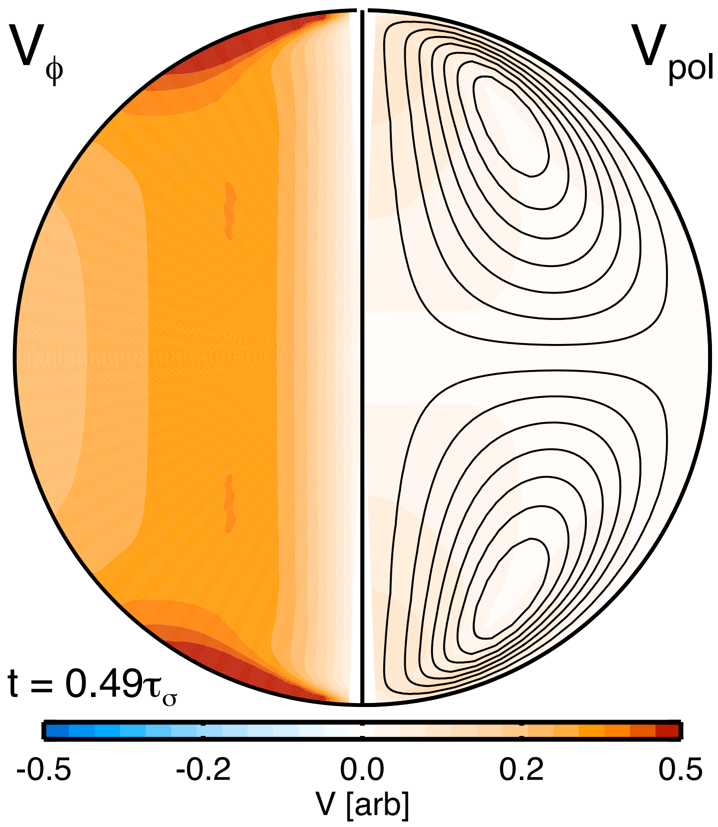


MRI is also possible due to flexible BCs

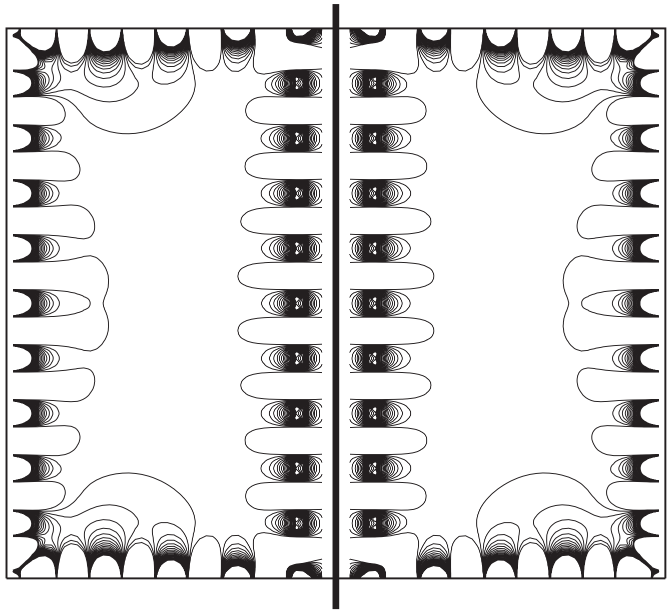


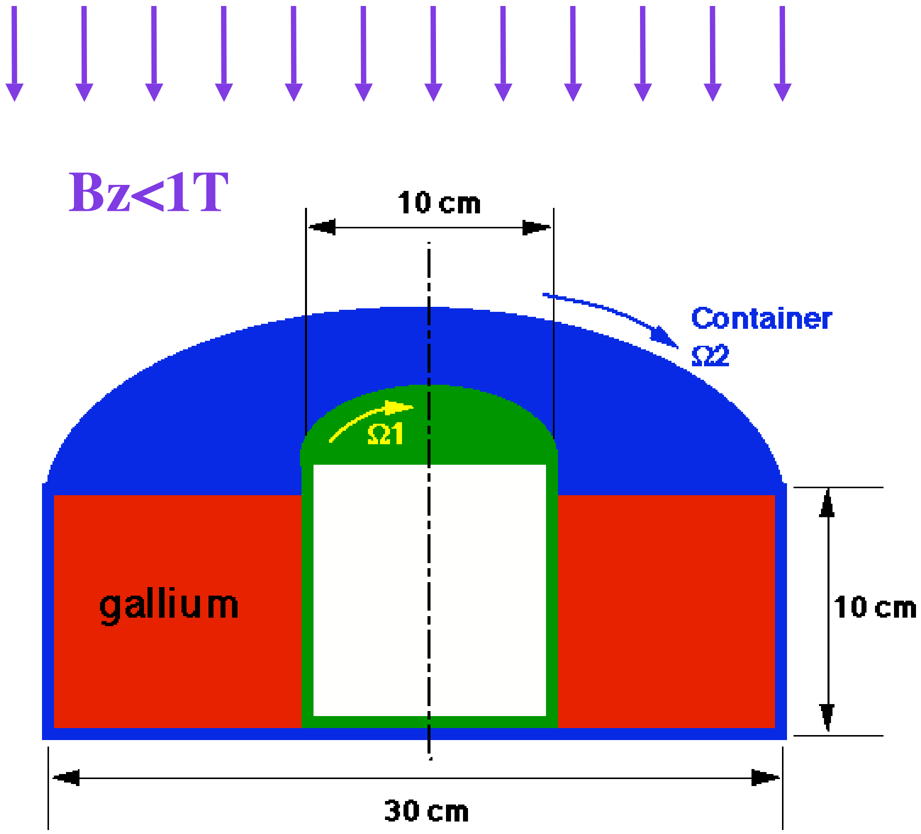


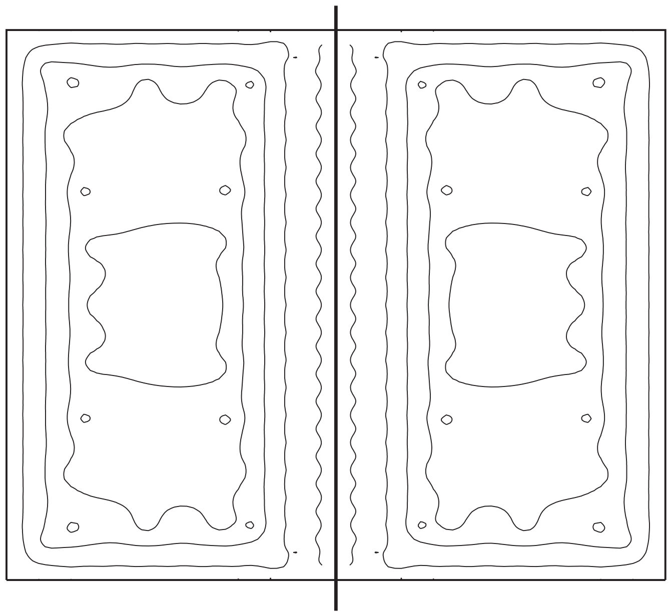




Prototype Experiment is being constructed to study a plasma Couette Flow


Flux

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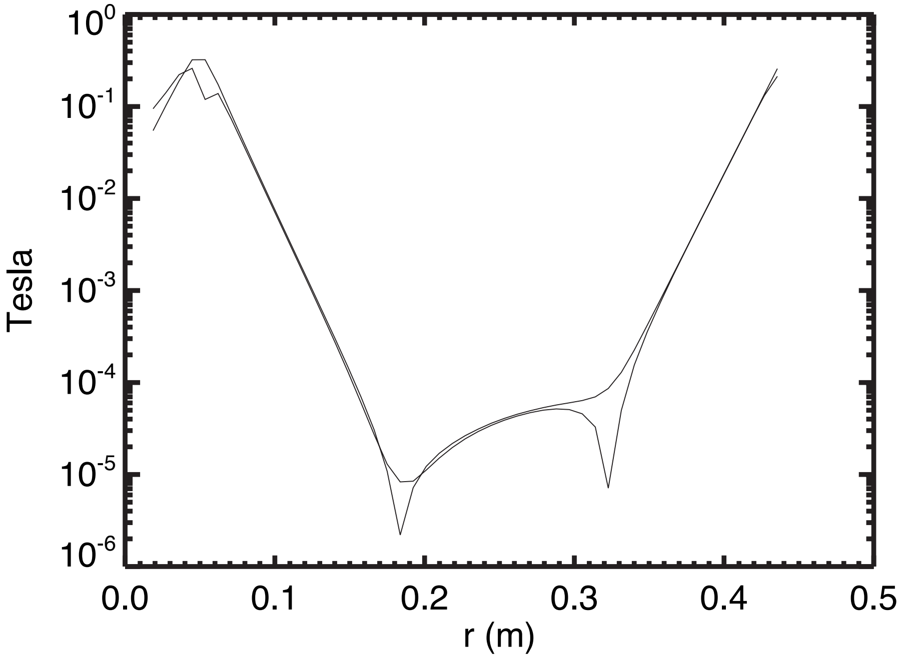
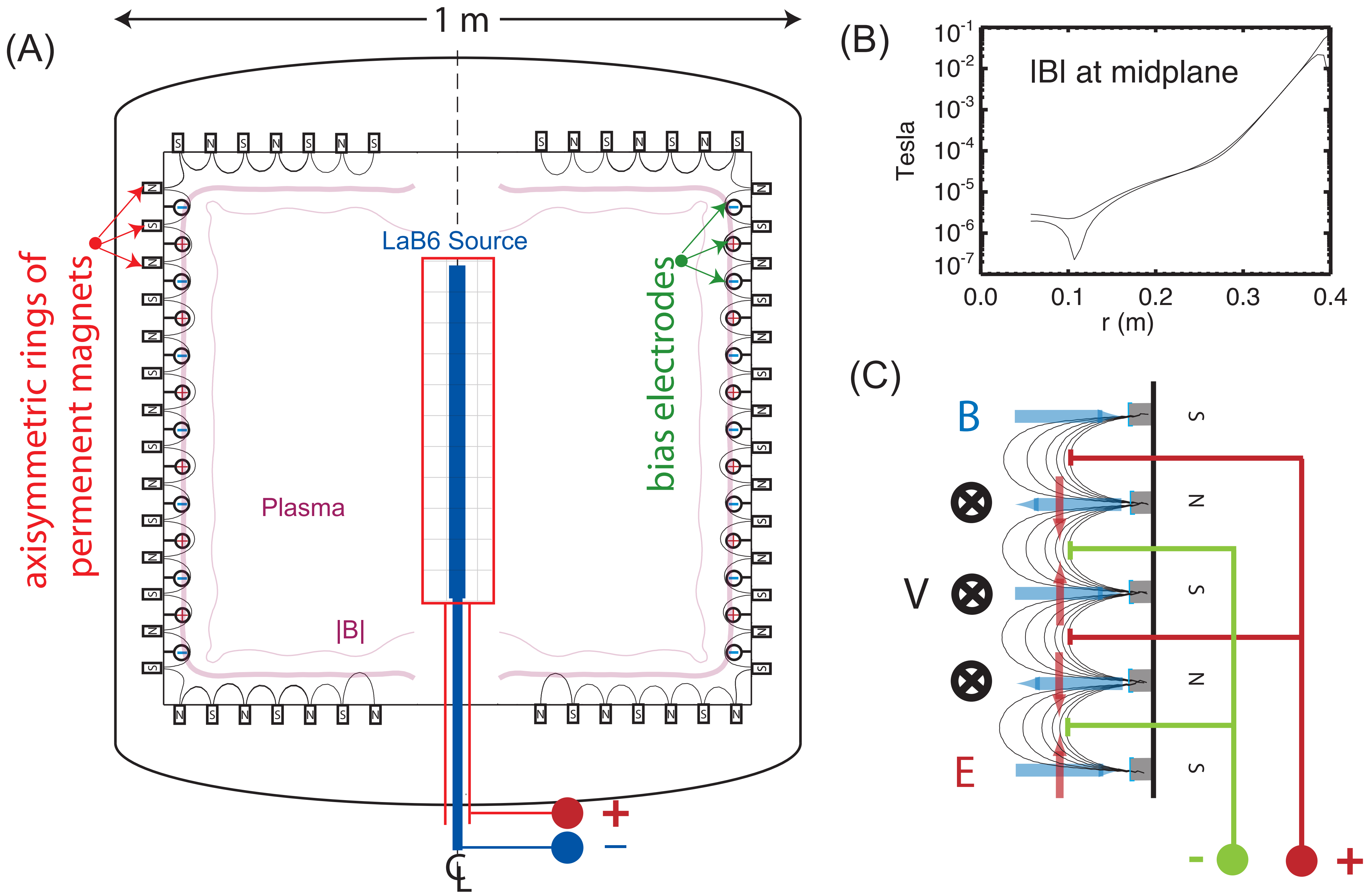
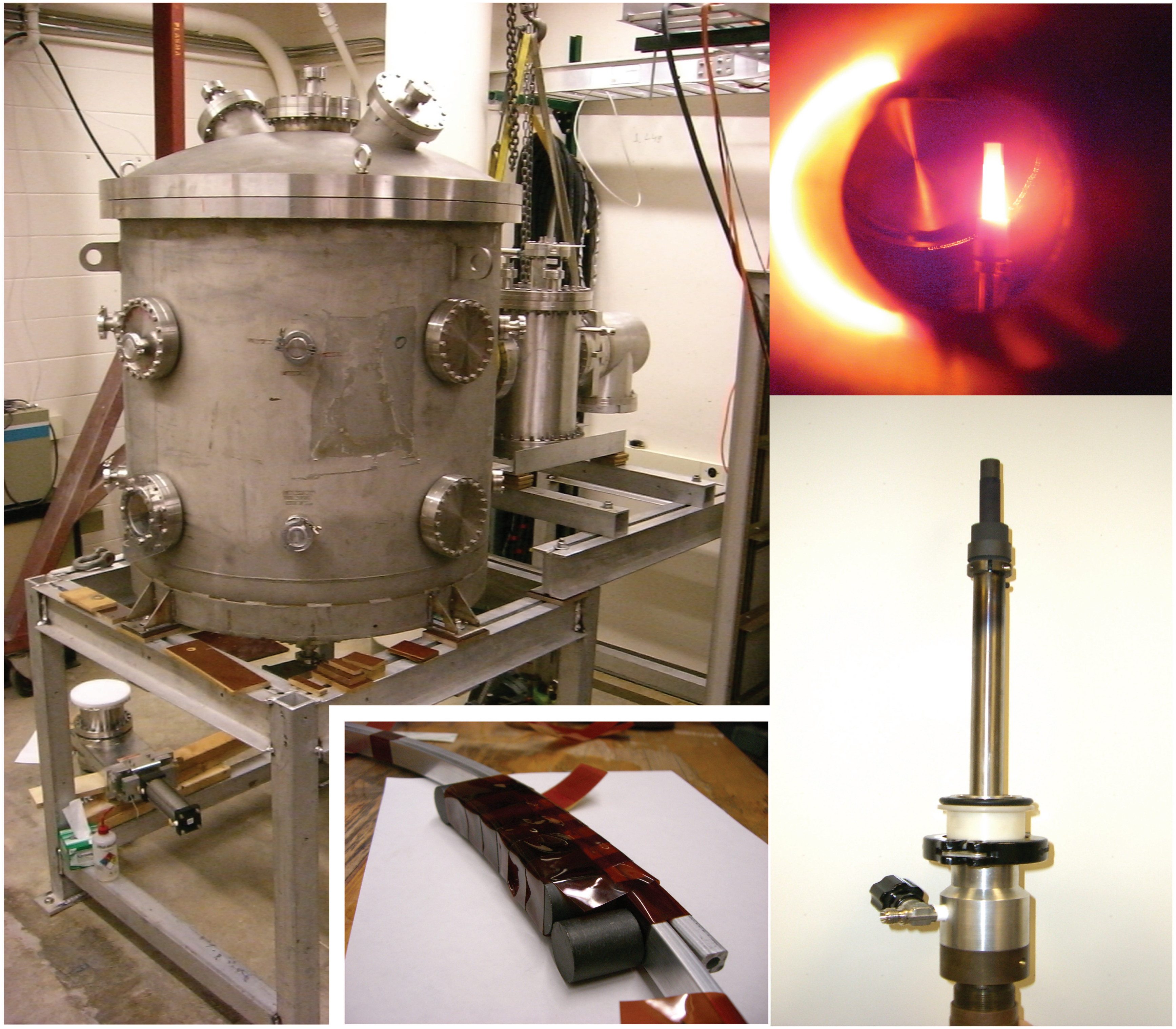

B

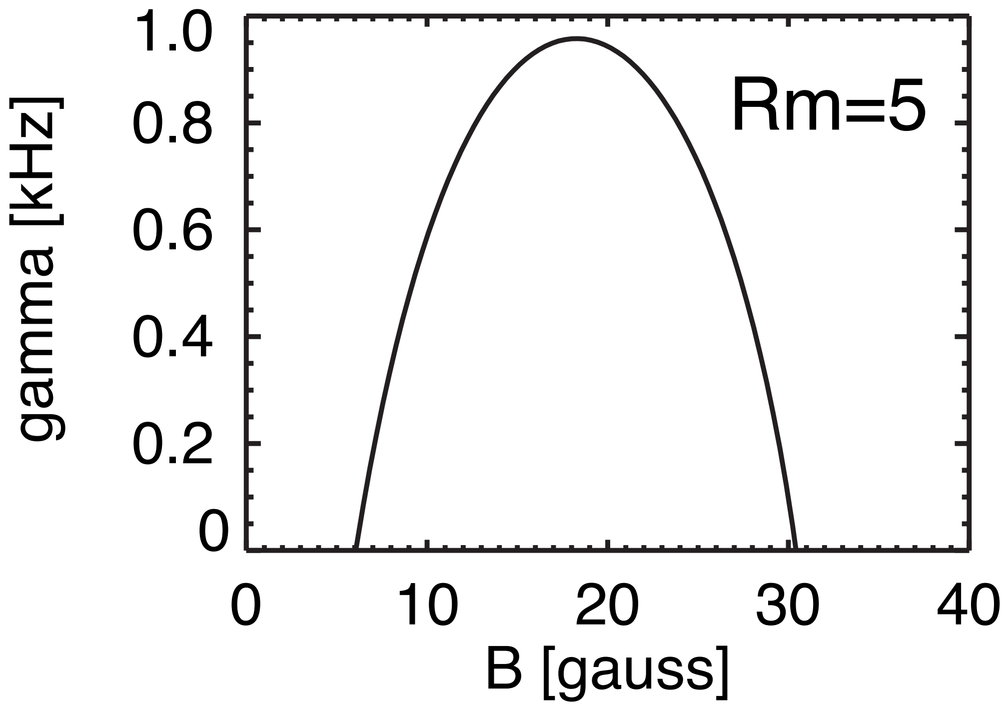
Prototype investigates plasma Magnetorotational Instablity

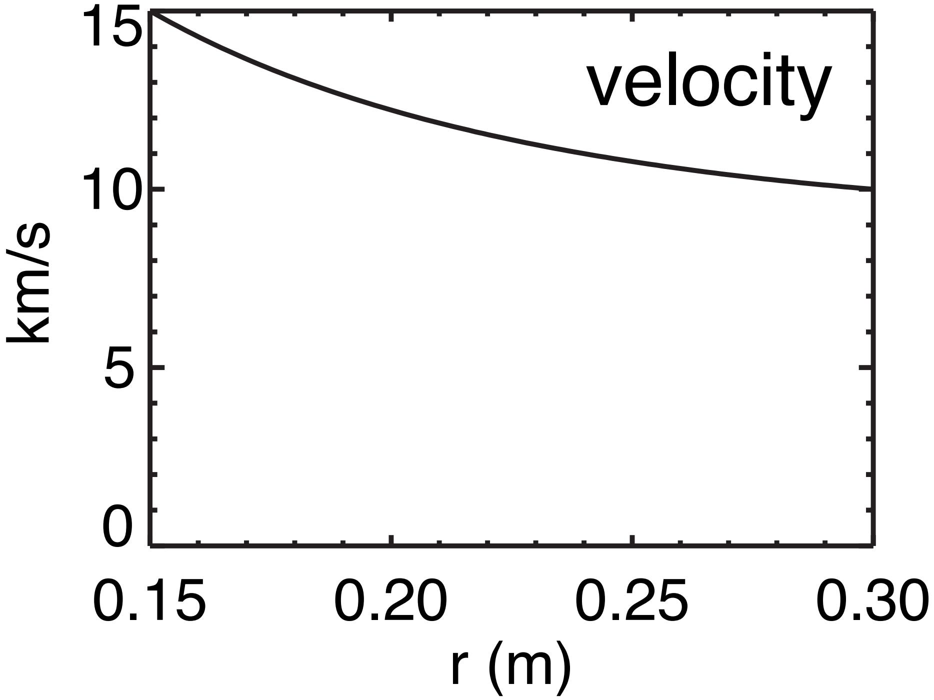


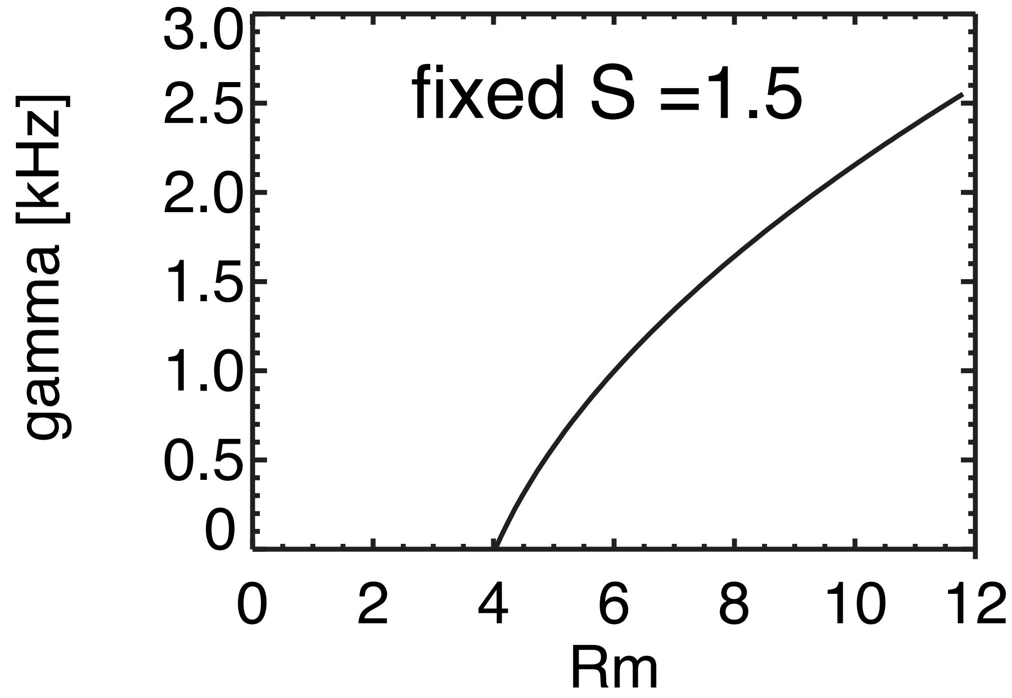
Prototype experiment is underconstruction

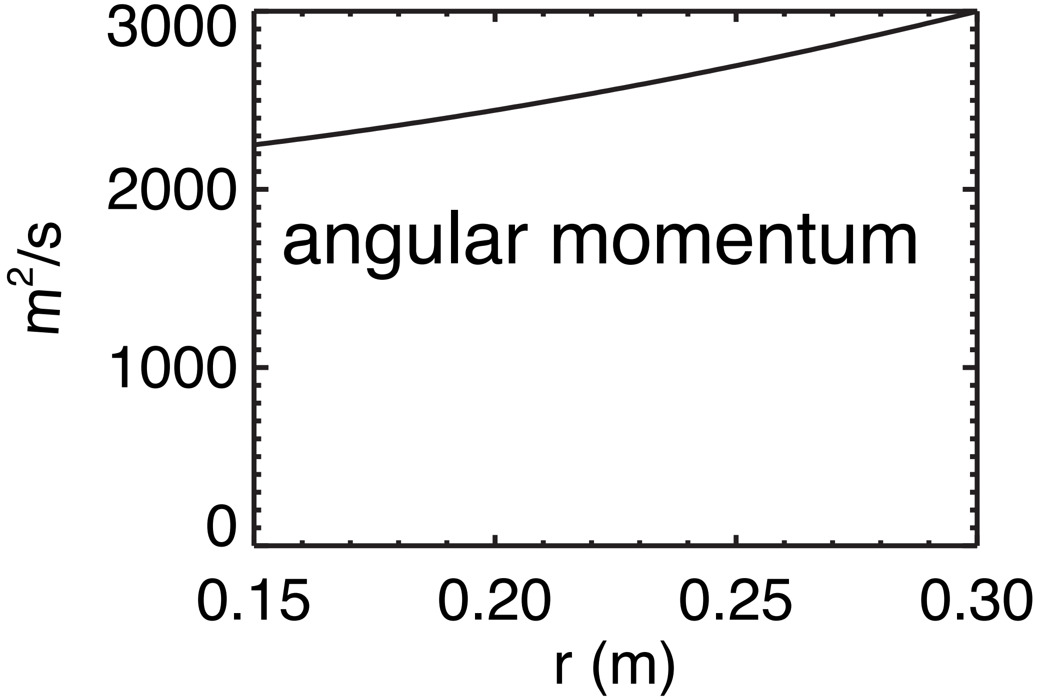


MRI instablity predicted for small $B_{applied}$









Important Differences between Plasmas and Incompressible Liquids

- small magnetic field can introduce anisotropies
  - transport of momentum, current and energy are different along magnetic field and perpendicular to magnetic field
  - kinetic effects inherently important
- Compressibility makes convection possible

Summary

- Liquid metal experiments are beginning to investigate self-exciting dynamos
  - constrained helical flows are dynamos
- Main Results from Madison Experiment
  - Dipole generation by turbulence
  - measurement of the magnetic field generated by fluctuations
  - Intermittent self-excitation