Opportunities for Experimental Studies of Plasma Dynamos

Cary Forest

THE UNIVERSITY of WISCONSIN MADISON

Dynamos: continuous transfer of flow energy (or thermal energy) → magnetic energy

Cowling	C	$\frac{\frac{B^2}{2\mu_0}}{\frac{1}{2}\rho U^2}$	$C \leq 1,\ (\frac{V}{V_A} \gg 1)$
Magnetic Reynolds	Rm	$\mu_0 \sigma U L$	
Reynolds	Re	$\frac{UL}{\nu}$	
Magnetic Prandtl	Pm	$\mu_0 \sigma \nu$	

Quasistationary

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For plasma experiments: steady-state, large, flowing, unmagnetized, hot

Experimental Studies of Fundamental Plasma and MHD Processes will inform observations

- **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?
- **Small Scale Dynamo**: How do turbulent (high Rm) flows create turbulent magnetic fields? What is the nature of **plasma turbulence** when magnetic fields and velocity fields are in near equipartition?
- **Magnetorotational Instability**: How is angular momentum in Disks transported by magnetic instabilities? Can the MRI be a dynamo?
- **Flow Driven Reconnection**: How does plasma flow generate magnetic energy that can accumulate and ultimately be released in explosive instabilities?
- **Plasma Instabilities**: Do plasma instabilities (i.e. pressure anisotropies) beyond MHD play a role in collisionless, turbulent plasma flows?
- **Geometry:** Convection, flow shear, and stratification

Outline

- Liquid Metal Experiments:
  - Simple Two Vortex Flow Geometry as basis for dynamo experiments
- Why plasmas?
  - High Rm, variable Pm, compressible, collisionality, anisotropy
- The Madison Plasma Dynamo Experiment (MPDX)
  - a facility for investigating flow-driven MHD phenomena

Dynamo, MRI, and other Flow Driven MHD Processes

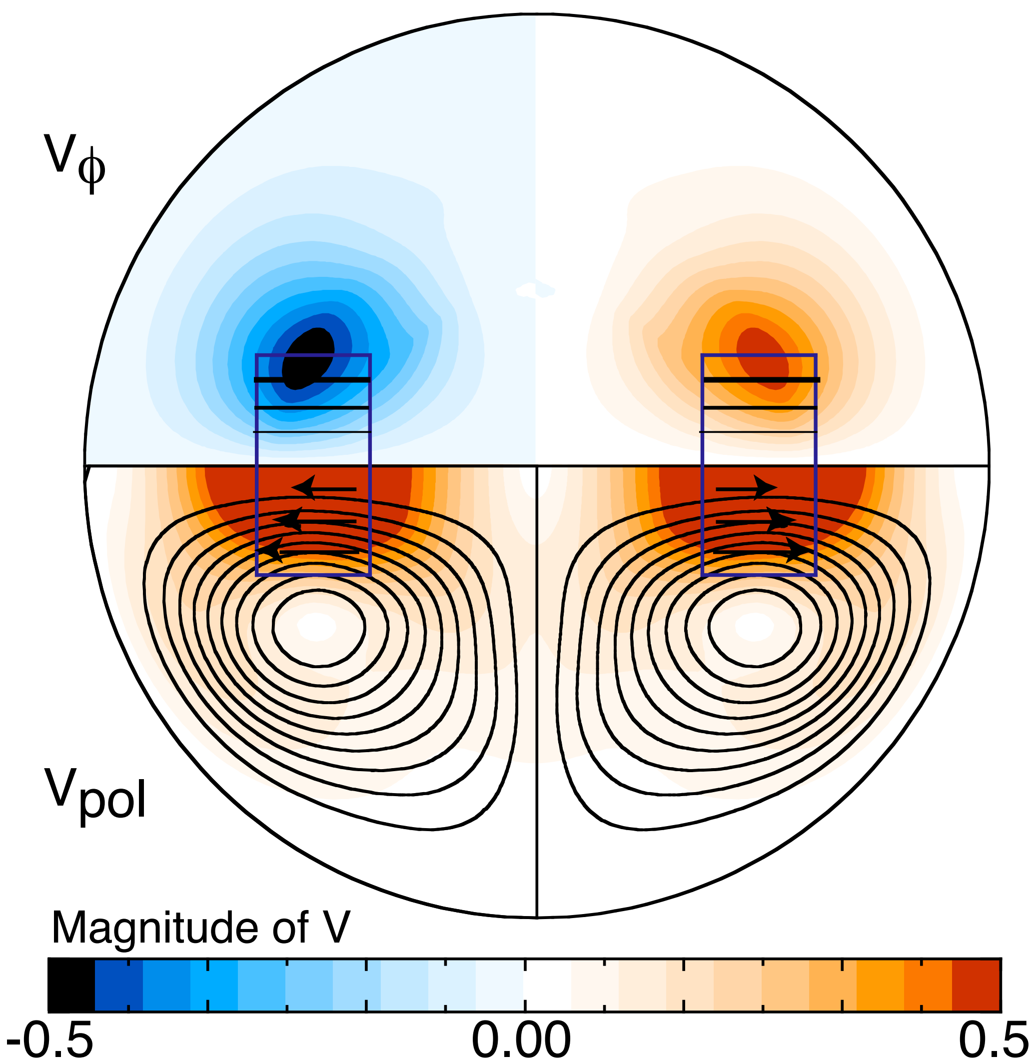
1. Begin with small magnetic field ($V/V_{Alfvén} >> 1$)
2. Stir until $Rm > Rm_{crit}$
3. Magnetic field spontaneously created

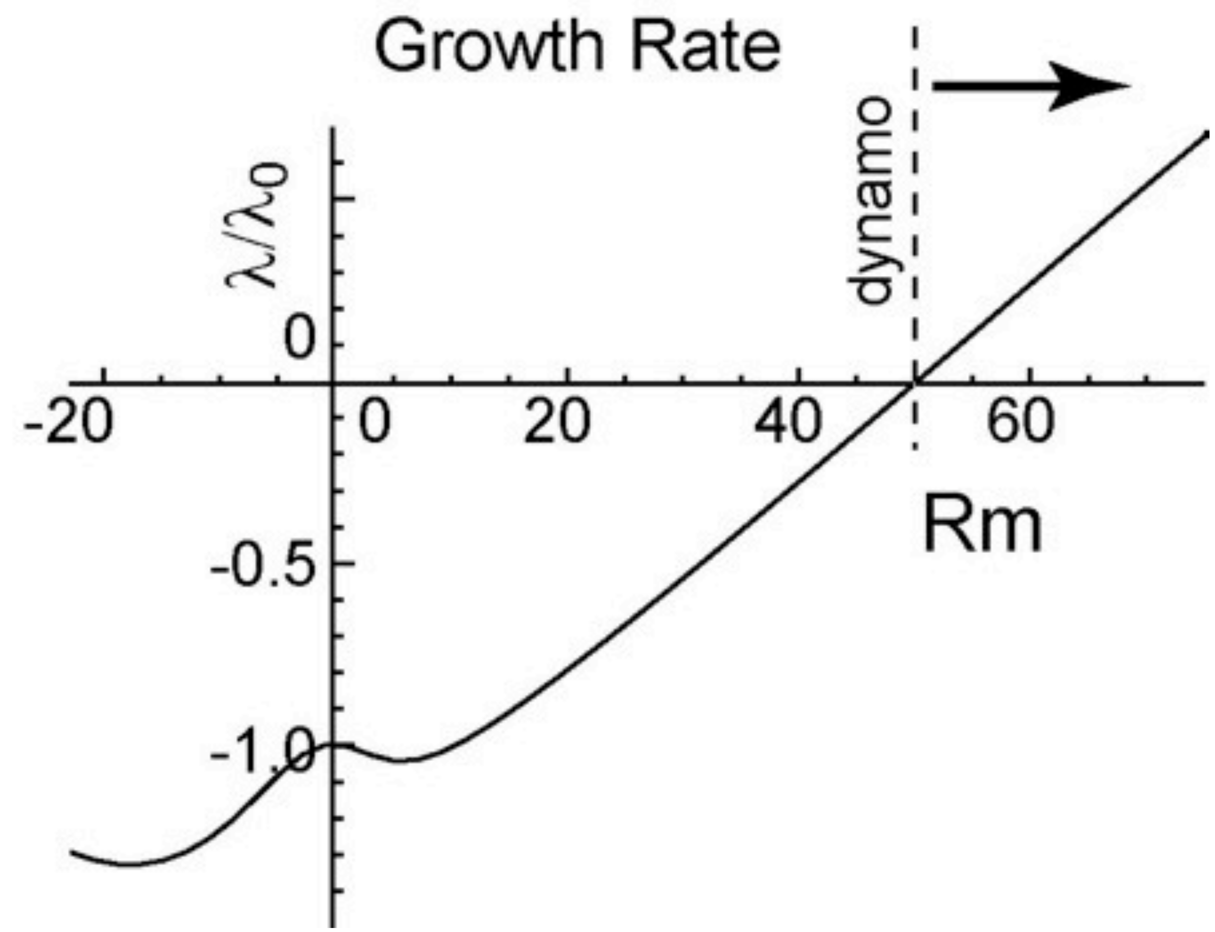
Challenge: to create a large, highly conducting, unmagnetized, fast flowing laboratory plasma for study

-difficult to stir a plasma

-need some confinement for plasma to be hot

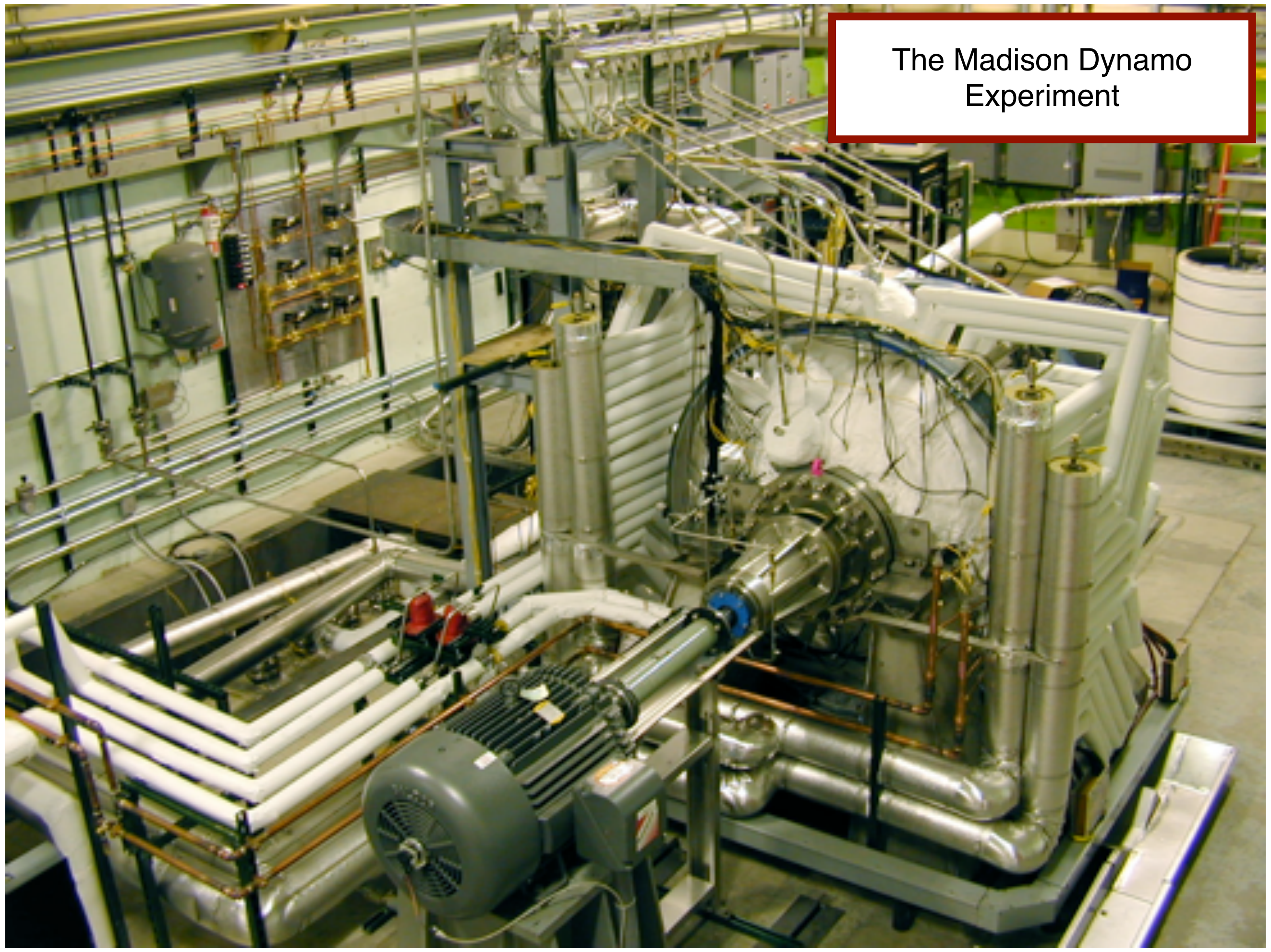
This simplest possible self-exciting flow: a two vortex flow with Rm_{crit}~50

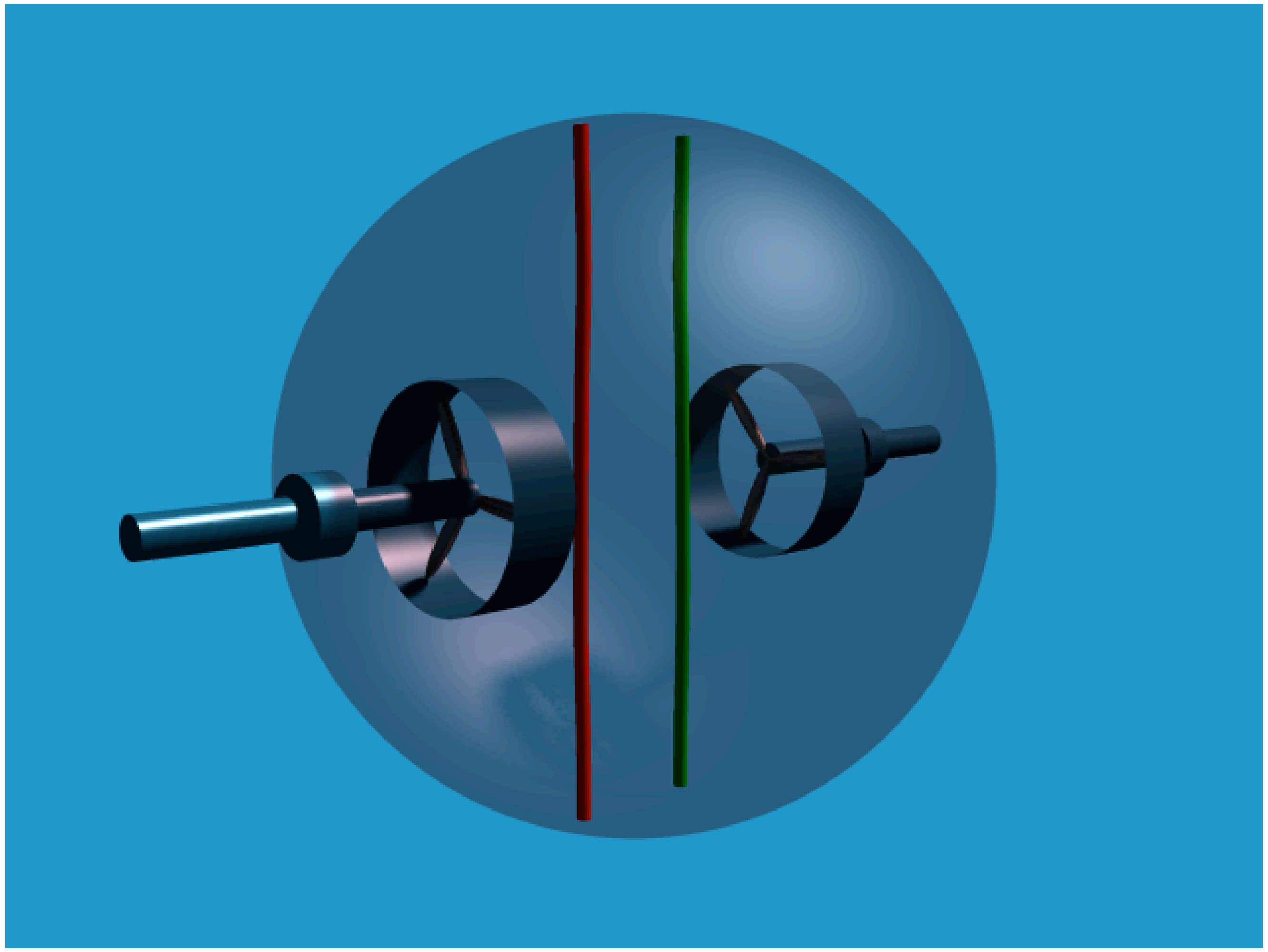




Dudley and James, *Time-dependent kinematic dynamos with stationary flows*, Proc. Roy. Soc. Lond. A. **425** 407 (1989).

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); geometry sets spatial scale of turbulence
- Self-excitation observed in: constrained flows (Riga, Karlsruhe); with Ferromagnetic Boundaries (VKS); and intermittently in unconstrained flows

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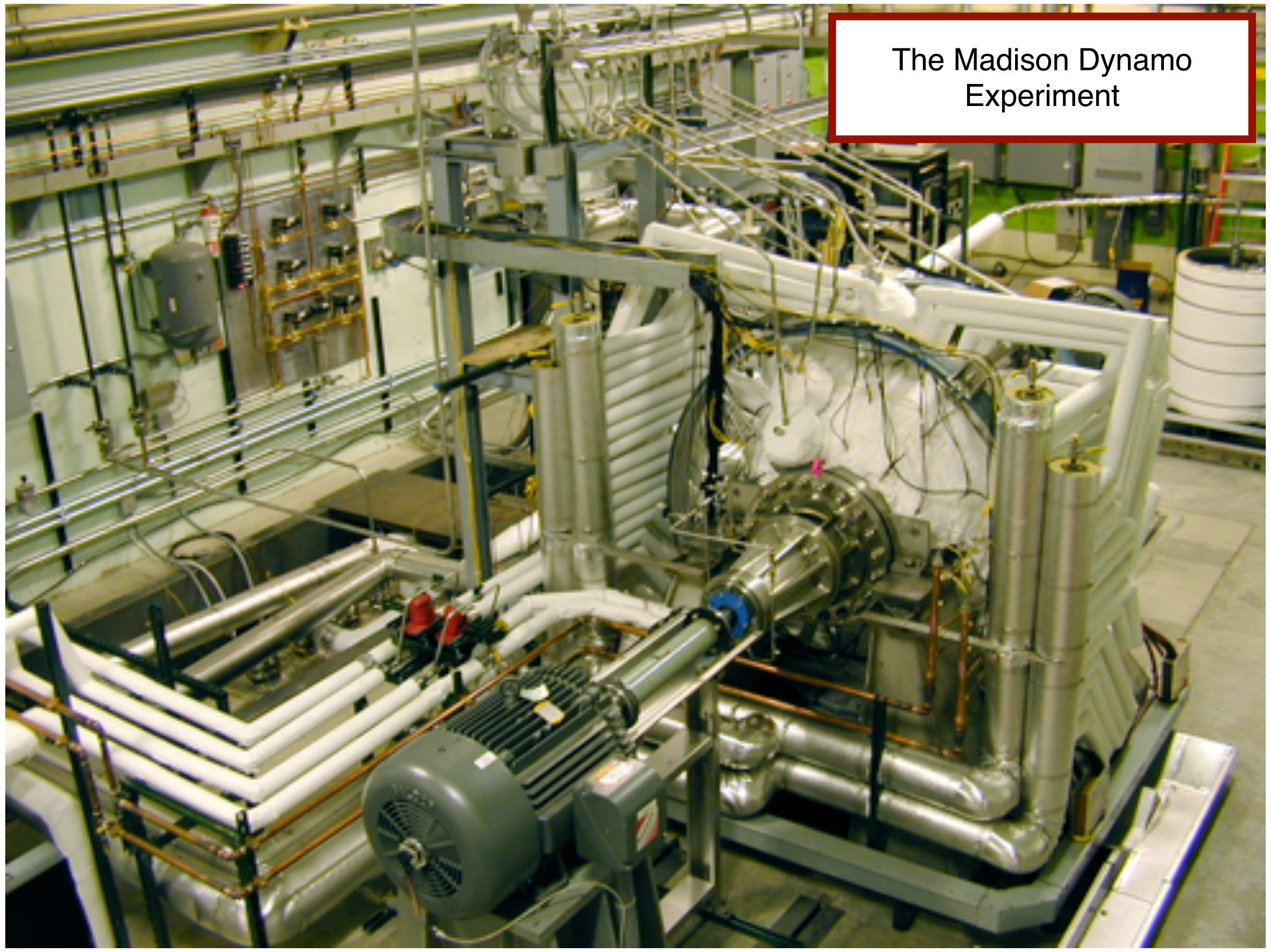

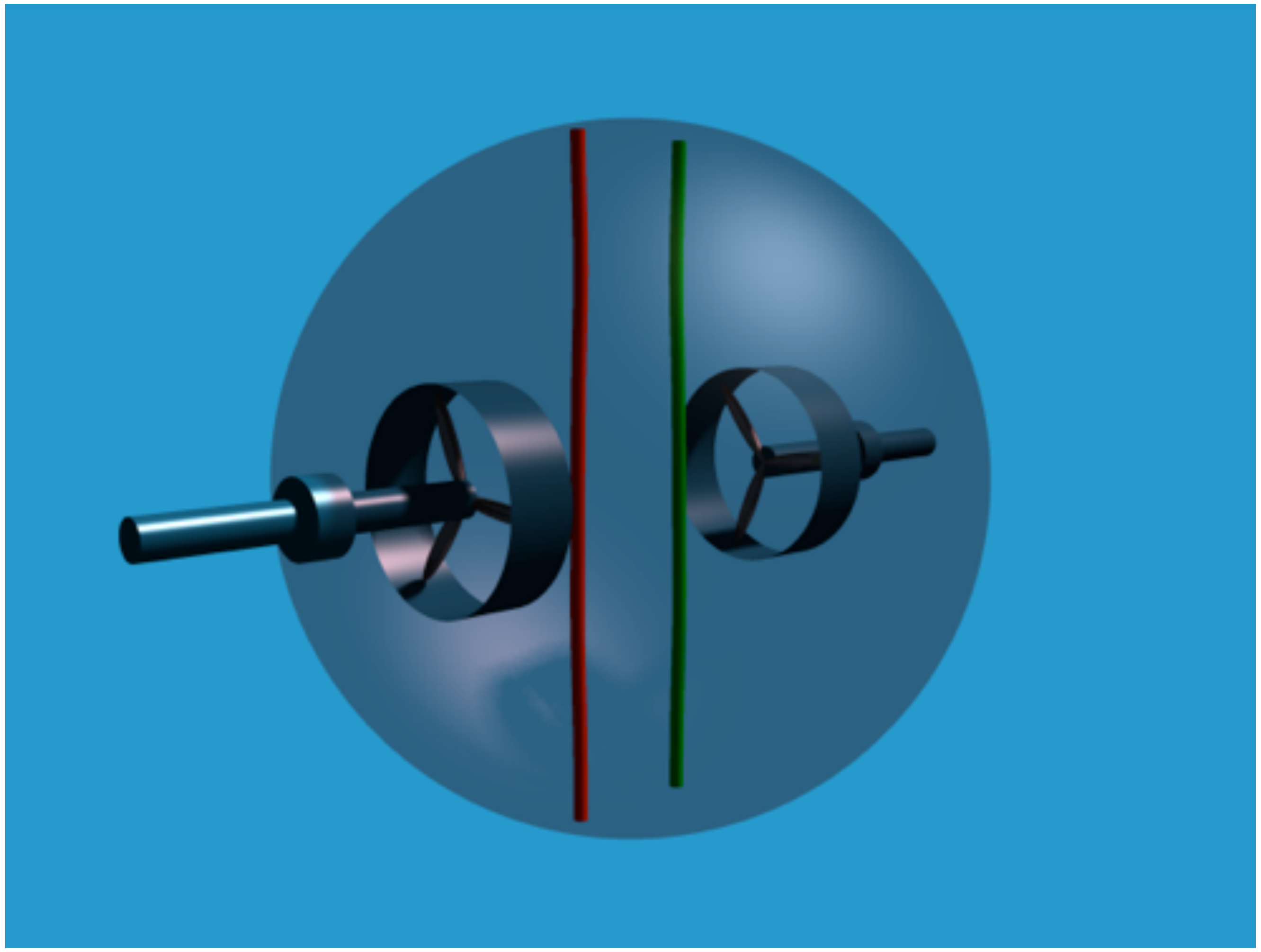

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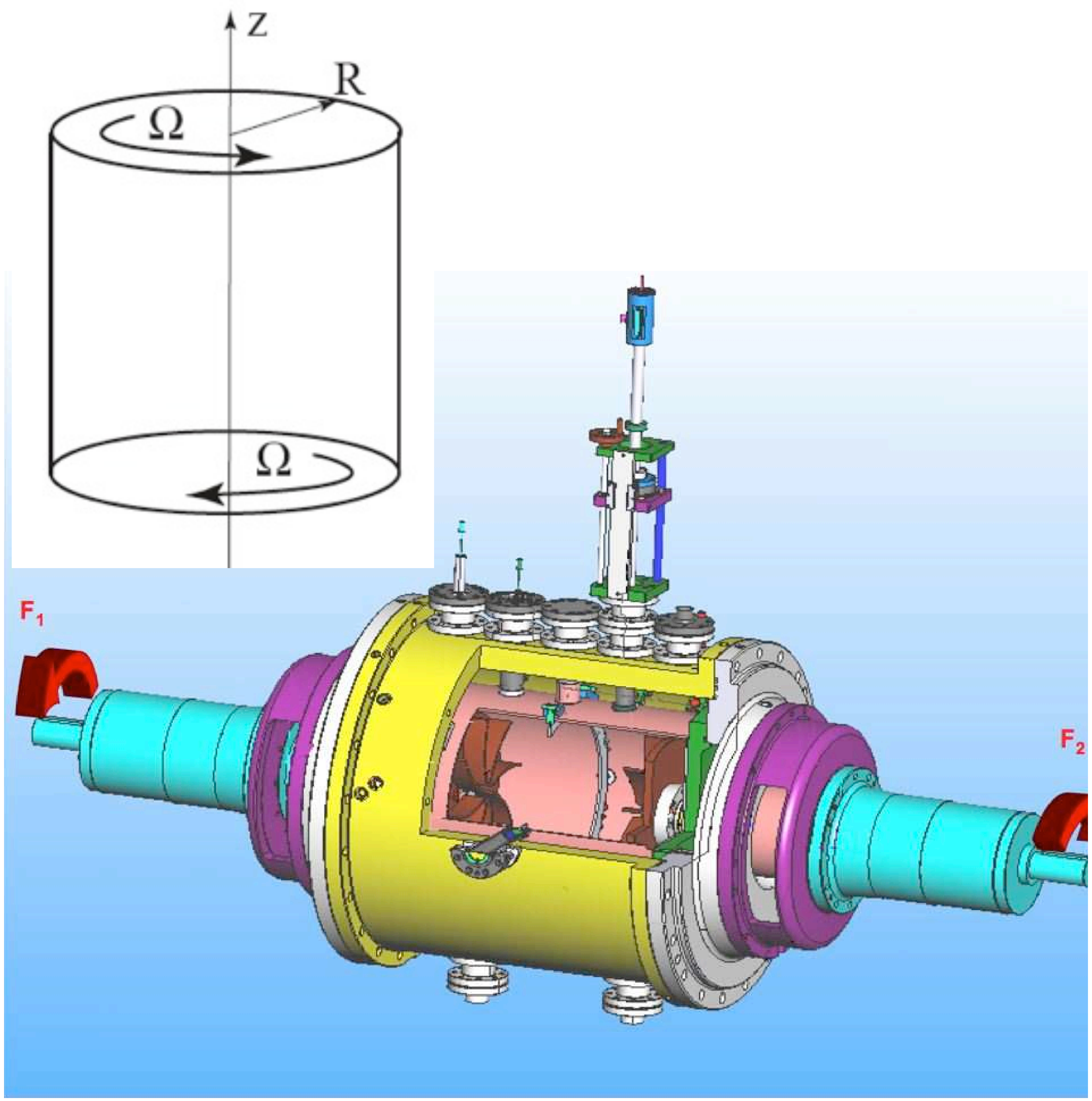
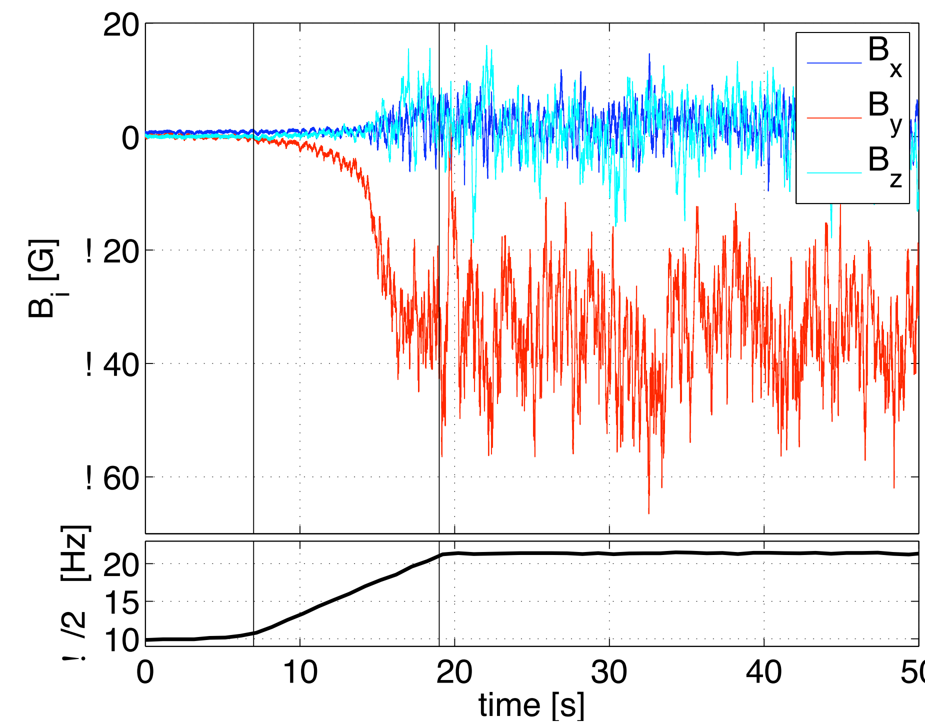
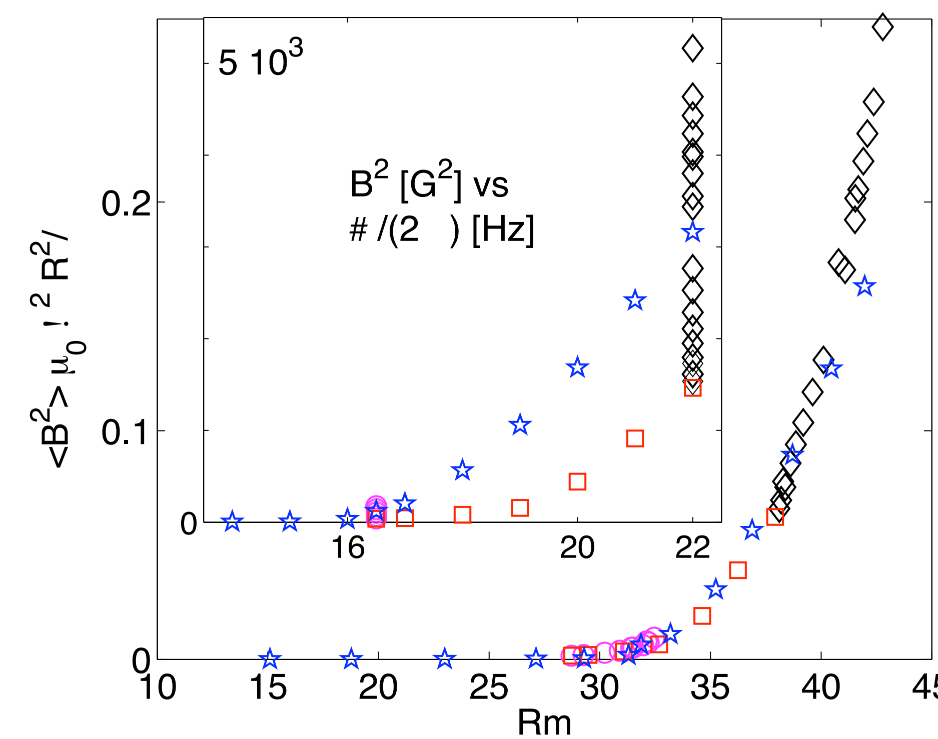
Liquid Metal Dynamo Experiments

- Rm < 150, Pm = 10^{-5}
- Self-excitation observed in constrained flows, or using ferromagnetic boundary conditions (Riga, Karlsruhe, VKS Cadarache)
- turbulent EMFs and transient self-excitation observed in Madison Experiment
- Closely related experiments on Magnetorotational Instabilities (Maryland, Princeton, New Mexico Tech, Potsdam)
- large scale turbulence apparently hinders the dynamo

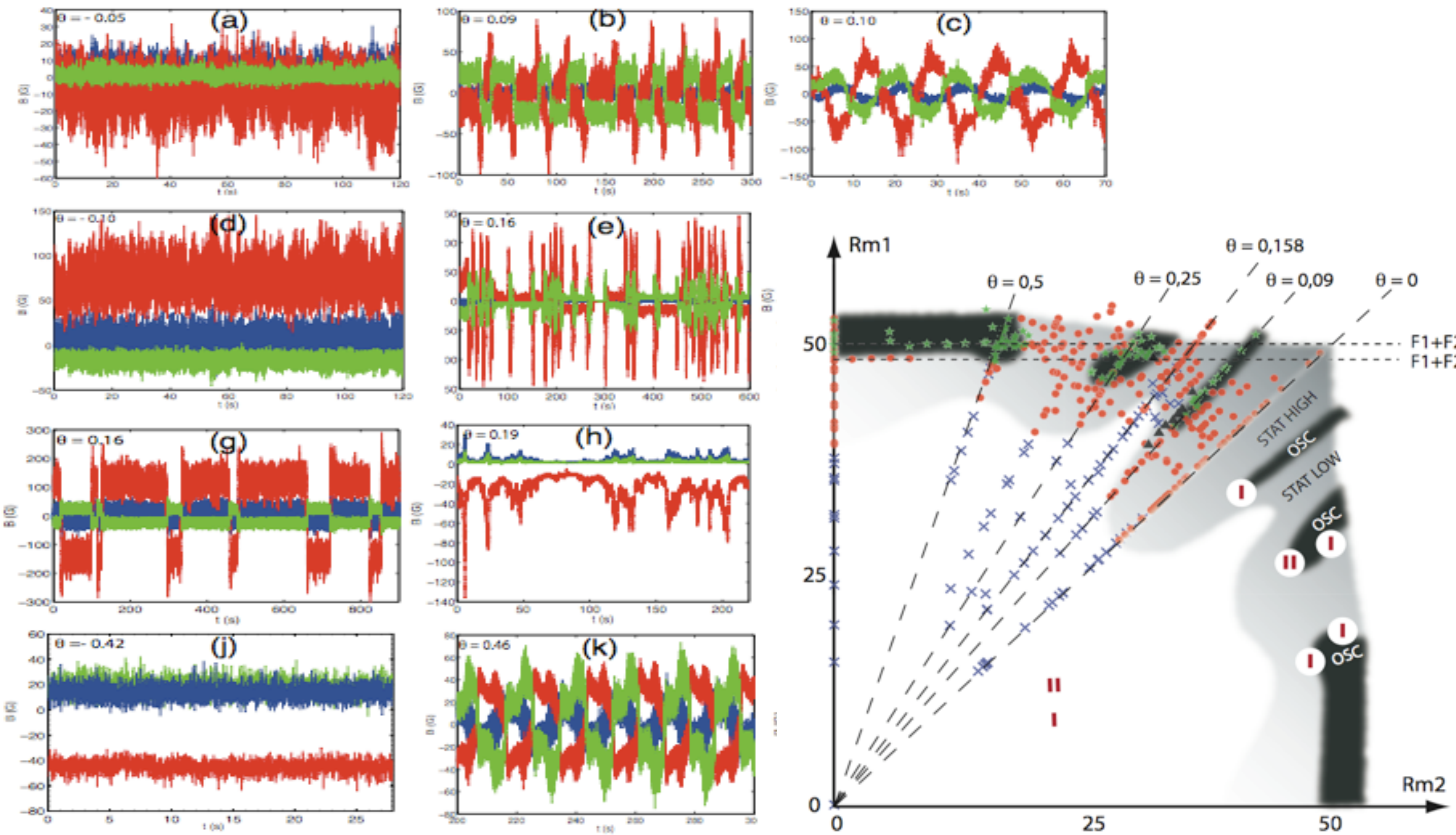
France: The VKS-II Experiment in Cadarache recently self-excited using iron impellers







Self-excited VKS dynamos have diverse dynamical behaviour



Monchaux et al., *The von Kàrmàn Sodium Experiment: turbulent, dynamical dynamos*, Physics of Fluids **21** (2009).

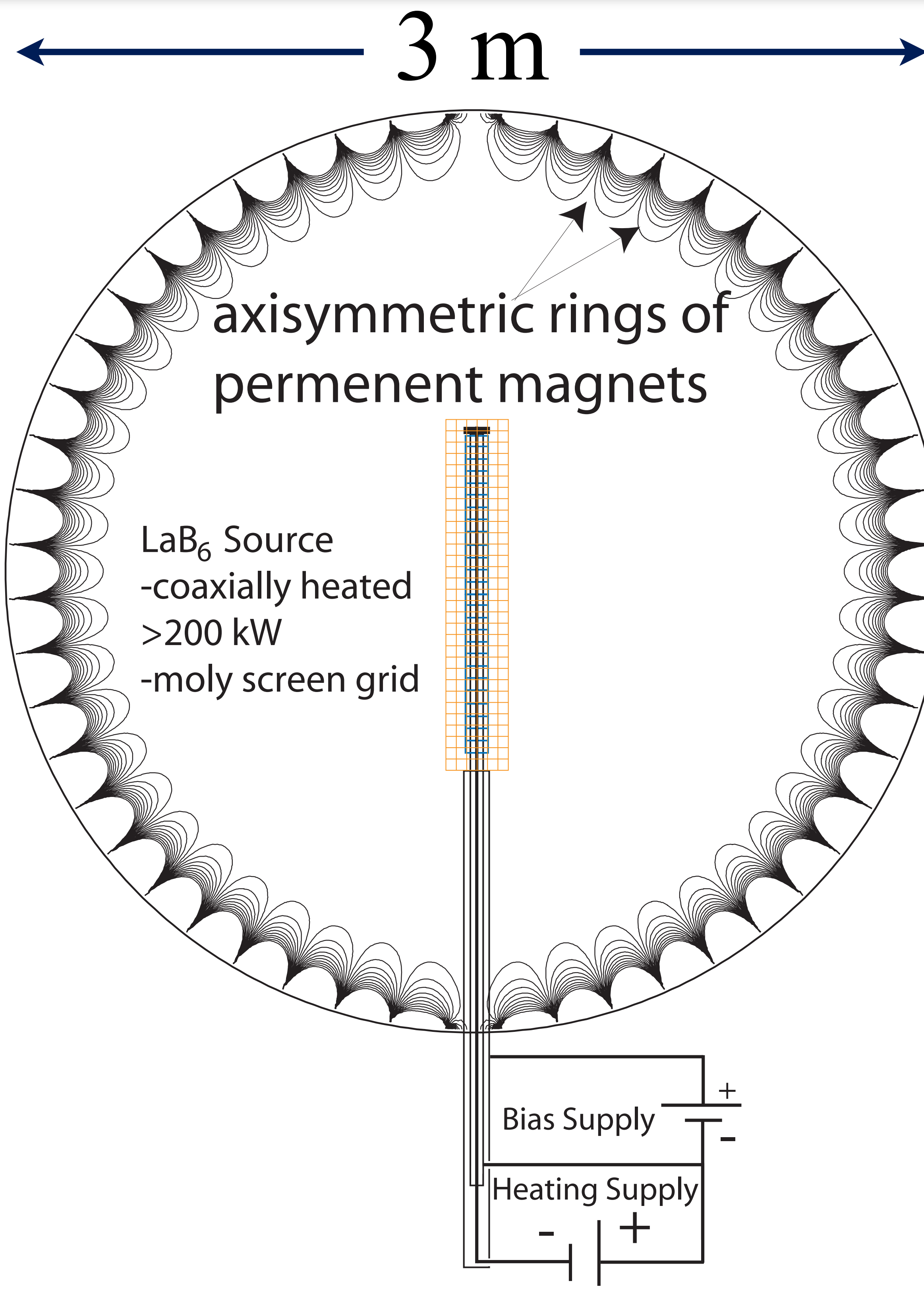
Liquid Metal Experiments are limited: the next frontier for experimental dynamo studies should be plasma based

- 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, stratification)
  - broader class of available diagnostics
  - matching simulations parameters for code verification

The Madison Plasma Dynamo Experiment

A Large, Hot, Unmagnetized, Flowing Plasma

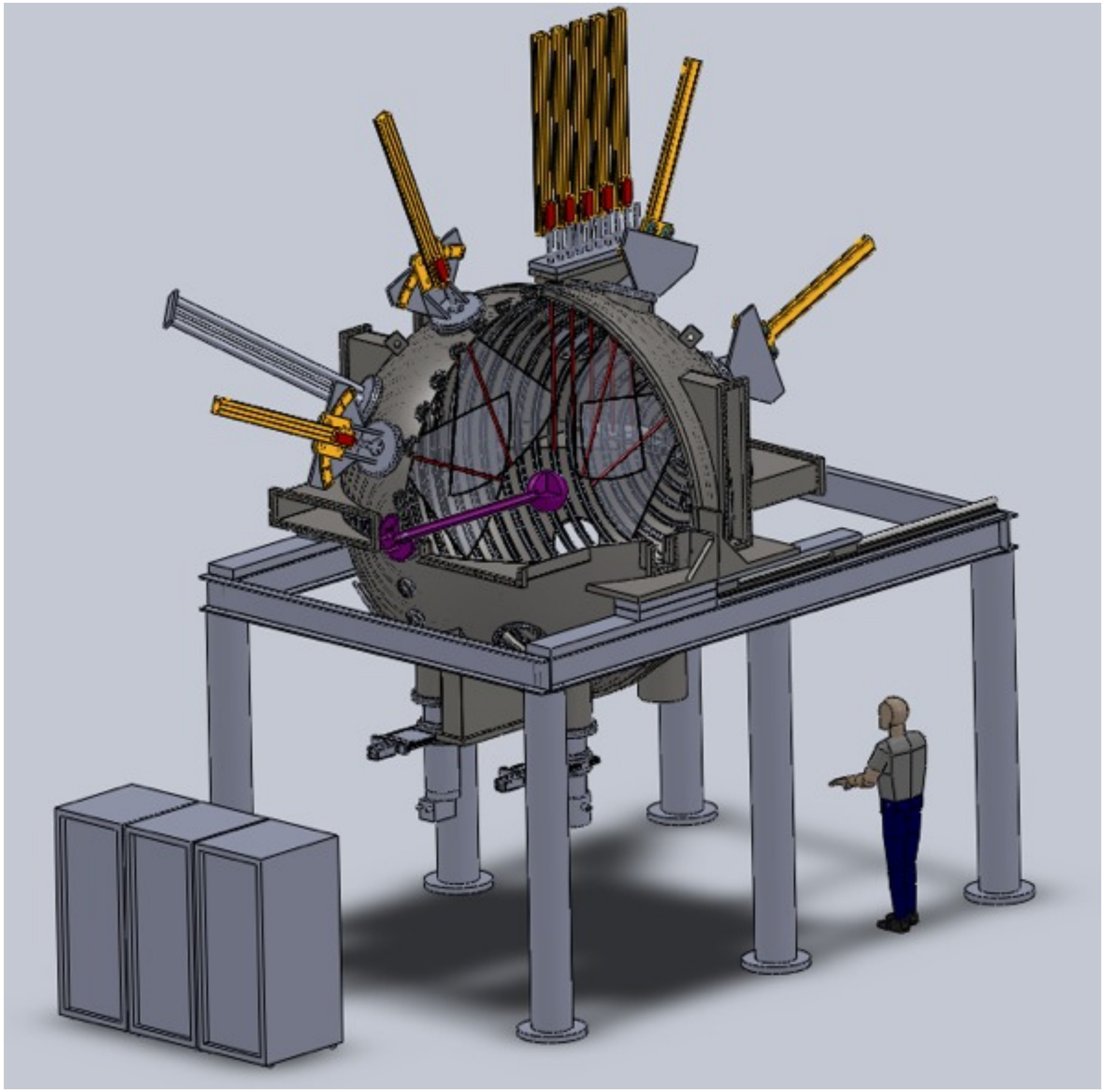
- Axisymmetric Ring Cusp
- edge confinement provided by 1.5 T, NdFeB Magnets
- high power plasma source using 2.45 GHz ECH, LaB_6 cathodes
- Challenges
  - cooling of magnets
  - insulators



MPDX Engineering Design

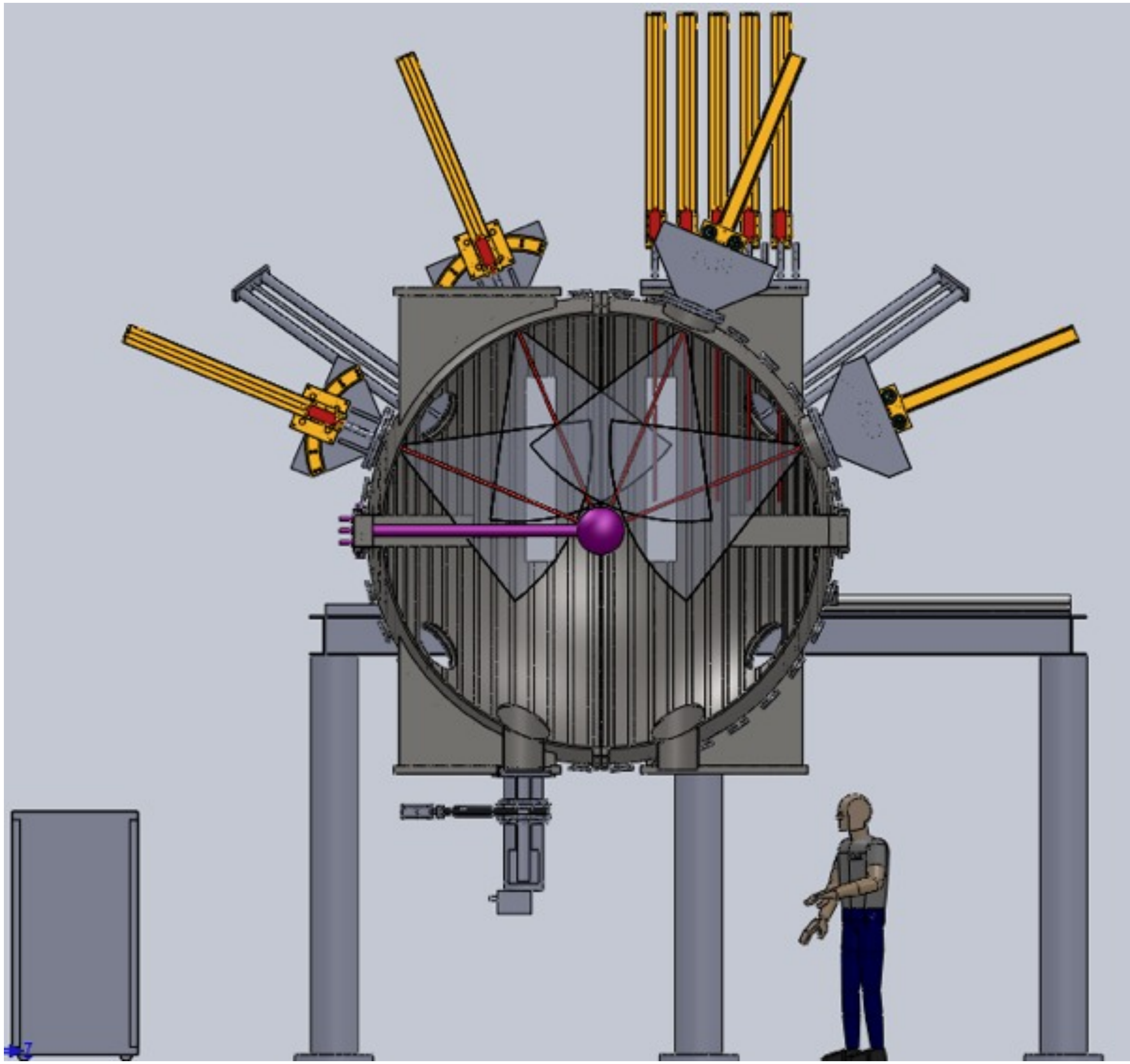
Specifications:

- 3.1m ID
- 2 Hemispheres
- 1 Hemisphere slides open
- ¾" Thick Aluminum Chamber
- 10^{-7} Torr Vacuum
- 36 Rings of NdFeB Magnets attached directly to chamber
- 72 electrically isolated electrodes
- 12 Diagnostic boxports
- 6 Sweeping probe ports
- 18 Magnet Cooling ports
- LaB_6 Source, future ECH
- 2 Large pumping ports
- Ports for vacuum diagnostics and gas introduction
- Water cooling on chamber exterior
- Alumina coated, insulating interior

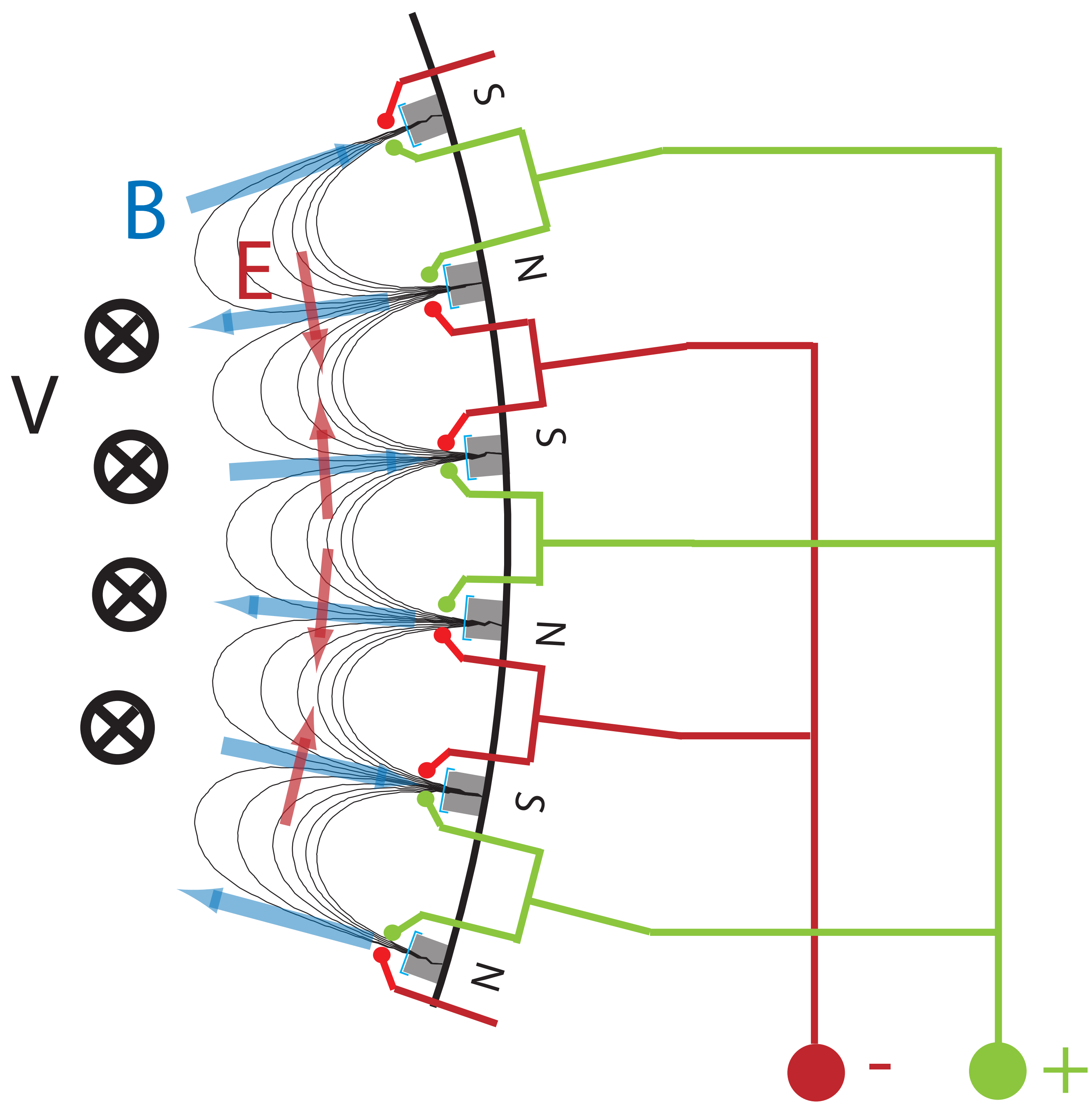


Diagnostics Plan

- •Linear Insertion probe array
- • 6 sweeping probe arrays
- •Straight through boxports for scanning mm wave interferometer and spectrometers
- •Hall probes on chamber interior
- •Fast Framing cameras with Gas Puff Imaging for density fluctuations

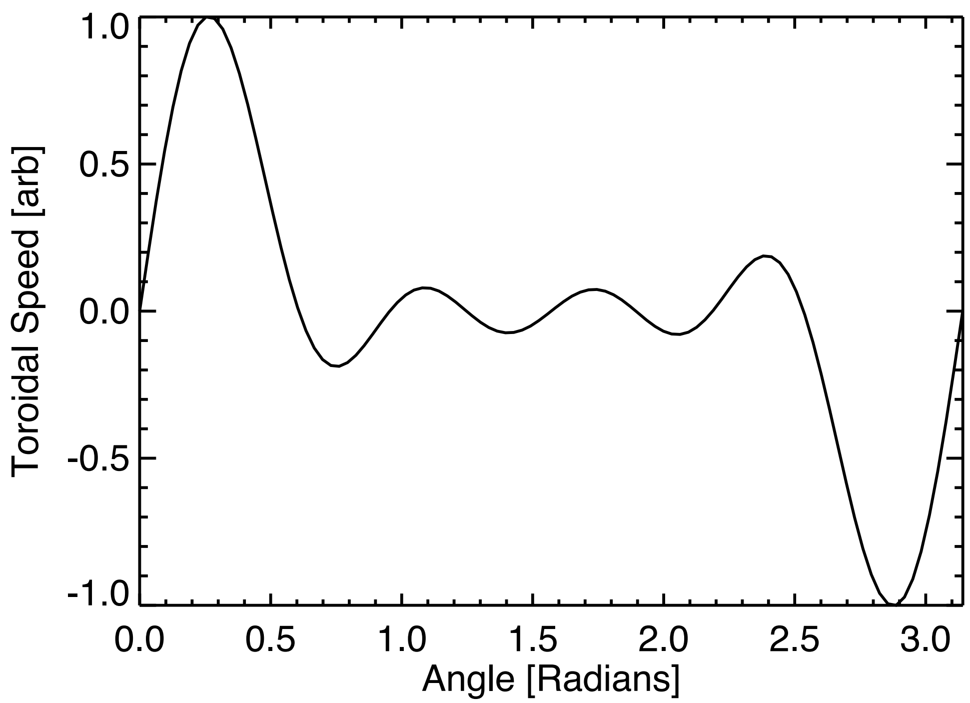


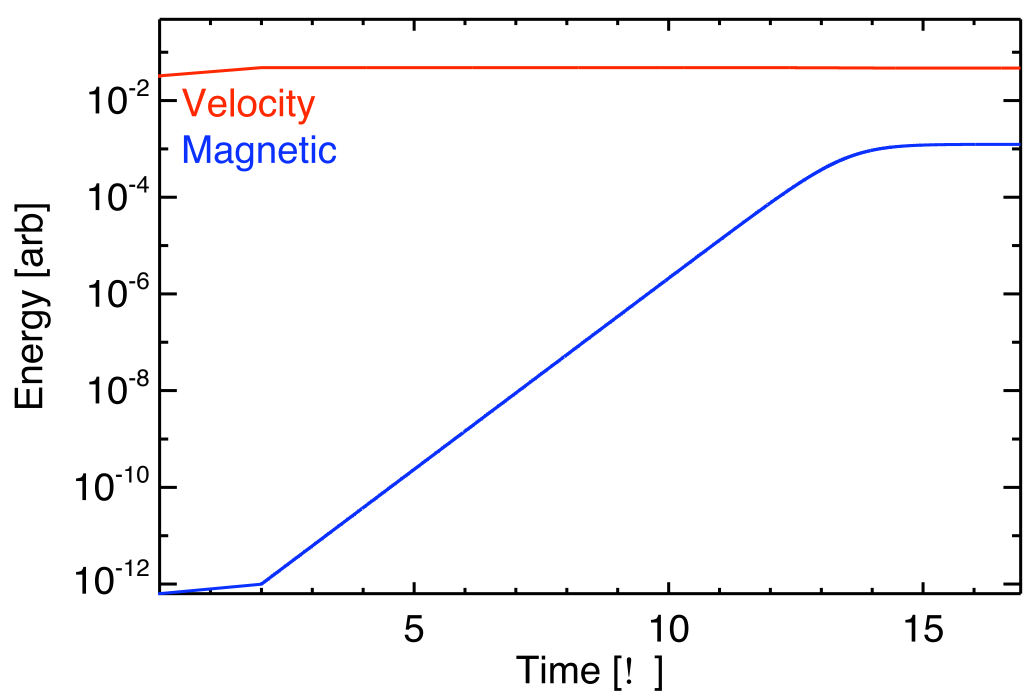
Multipole Magnetic Field can be used to drive flow at edge

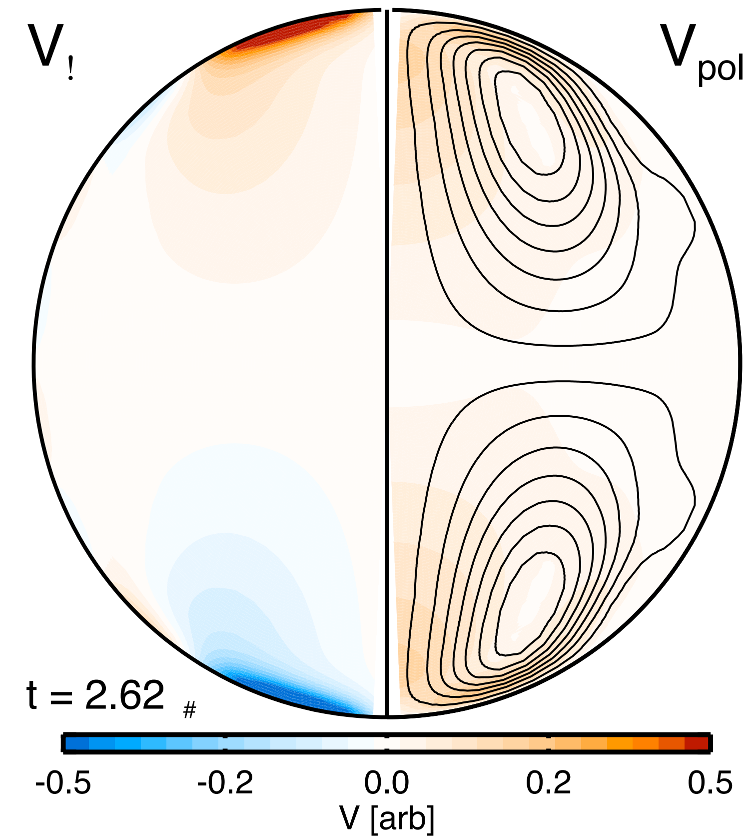


Arbitrary Vφ (r = a, θ)

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

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	

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}

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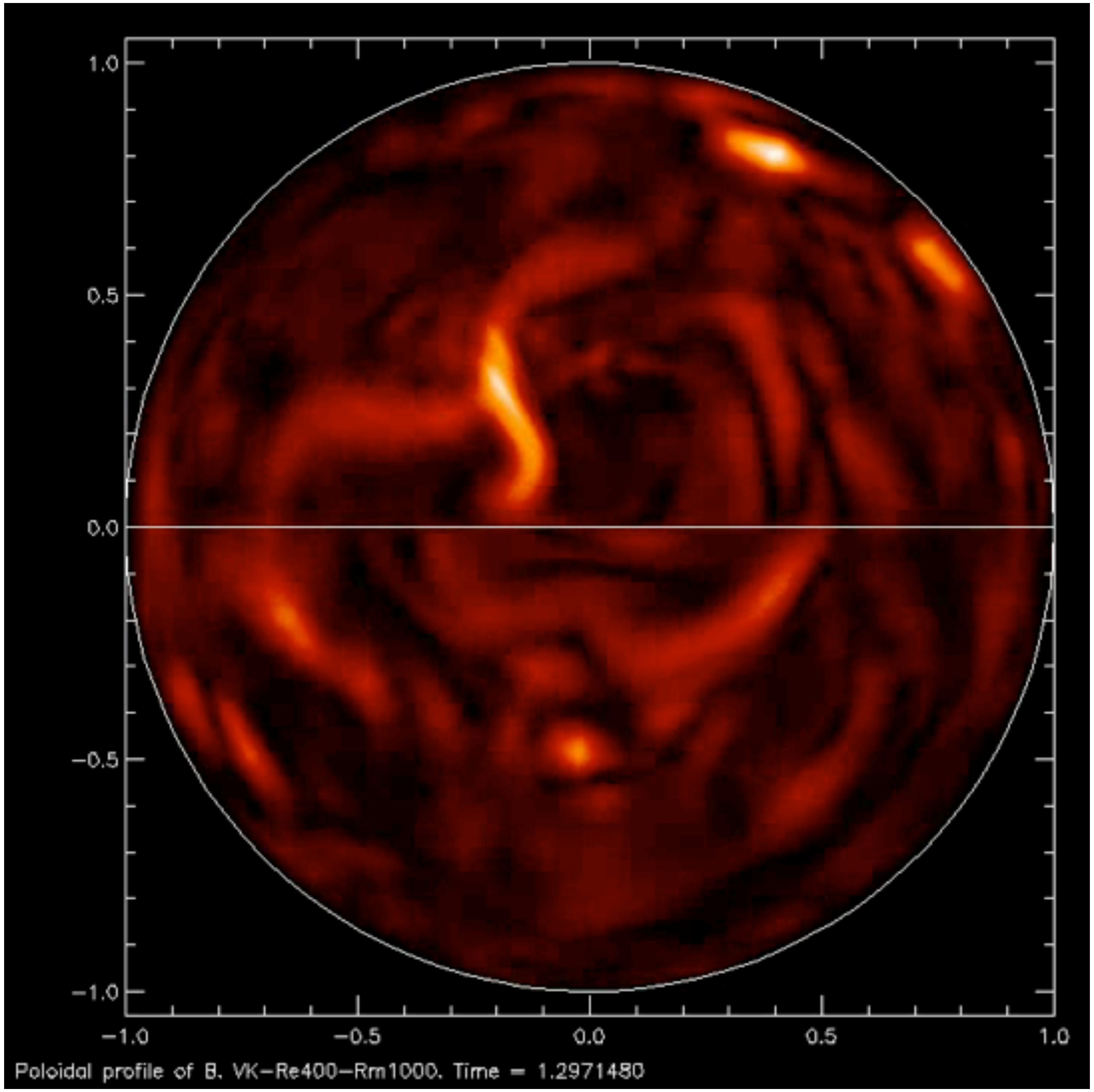
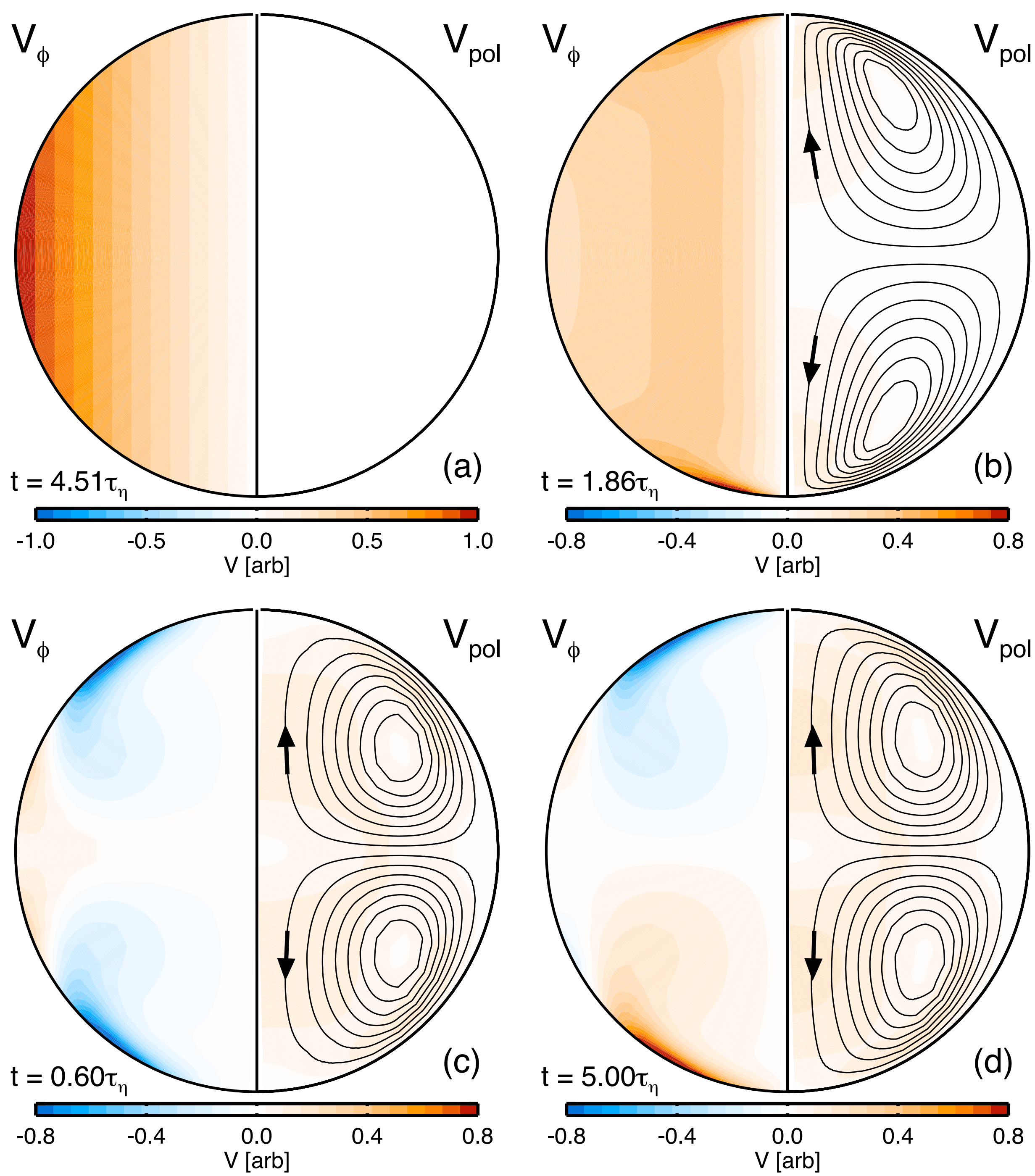
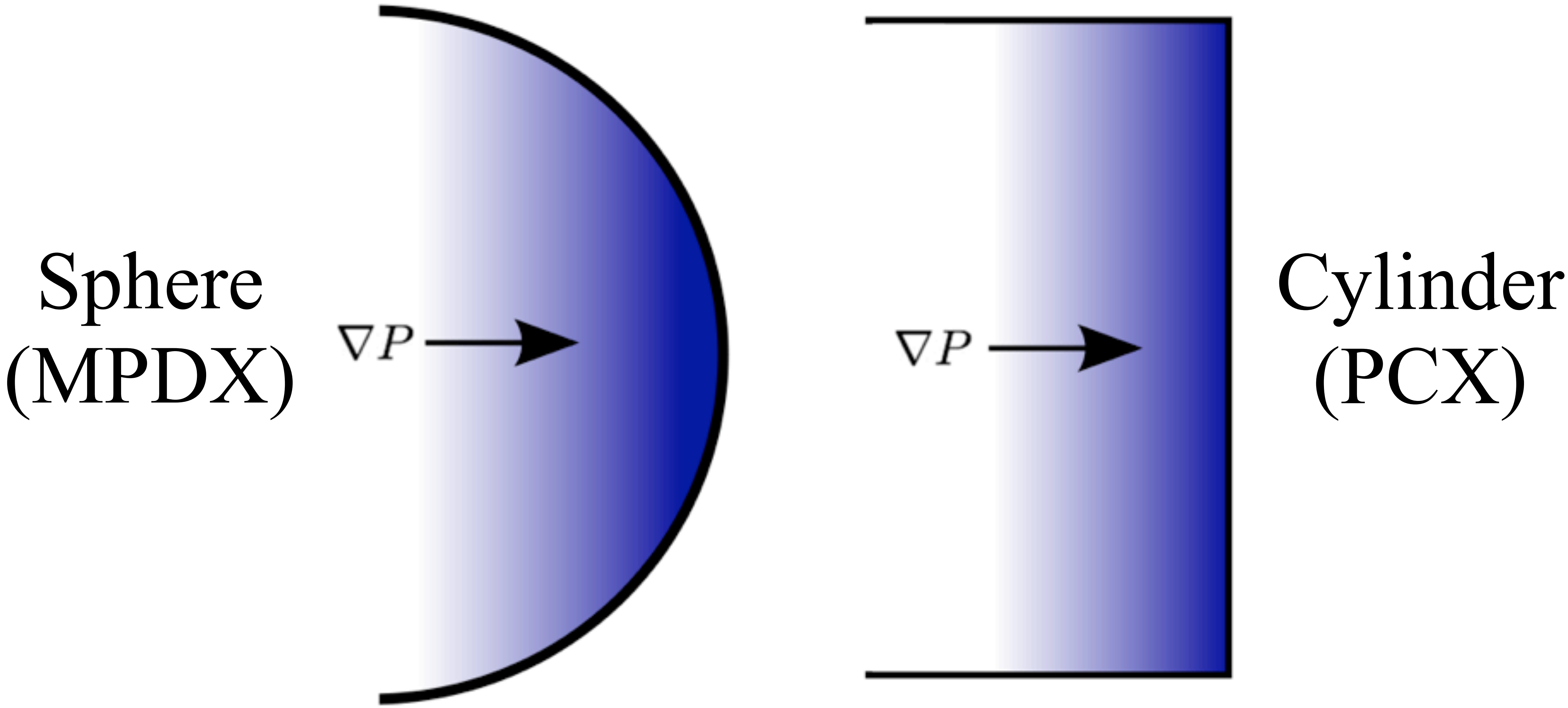


Boundary Stirring gives flexibility (time dependent flows are also possible)



Centrifugal Stratification



Stratified, rotating Plasma

$$g \approx 10^{10} \left(\frac{v_\phi}{10\text{km/s}} \right)^2 \text{ cm/s}^2$$

$$n = n_0 e^{r/H_n} \qquad H_n = \frac{k\, T_{e,\text{eV}}}{2\, A\, m_H} \frac{1}{\Omega^2\, r}$$

$$H_n \approx 50\, \frac{T_{e\,\text{eV}}}{A} \left(\frac{r}{r_o} \right)^{-1} \left(\frac{v_\phi}{10\text{km/s}} \right)^{-2} \text{ cm}$$

$$\text{H at 10 eV} \implies H_n \approx 500\,\text{cm}, \quad N_h \sim 2/3$$

$$\text{He at 10 eV} \implies H_n \approx 125\text{ cm}, \quad N_h \sim 0.2 \qquad v_\phi = 10\text{ km/s}$$

$$\text{Ar at 10 eV} \implies H_n \approx 12.5\text{ cm}, \quad N_h \sim 2.\bar{7}$$

Buoyancy Driven Convection

- Target: stratified (strongly rotating) plasma
- Drive Convection:
  - Thermal (outside ECH)
  - Compositional (light ion puffing into heavy ion plasma)
  - magnetic

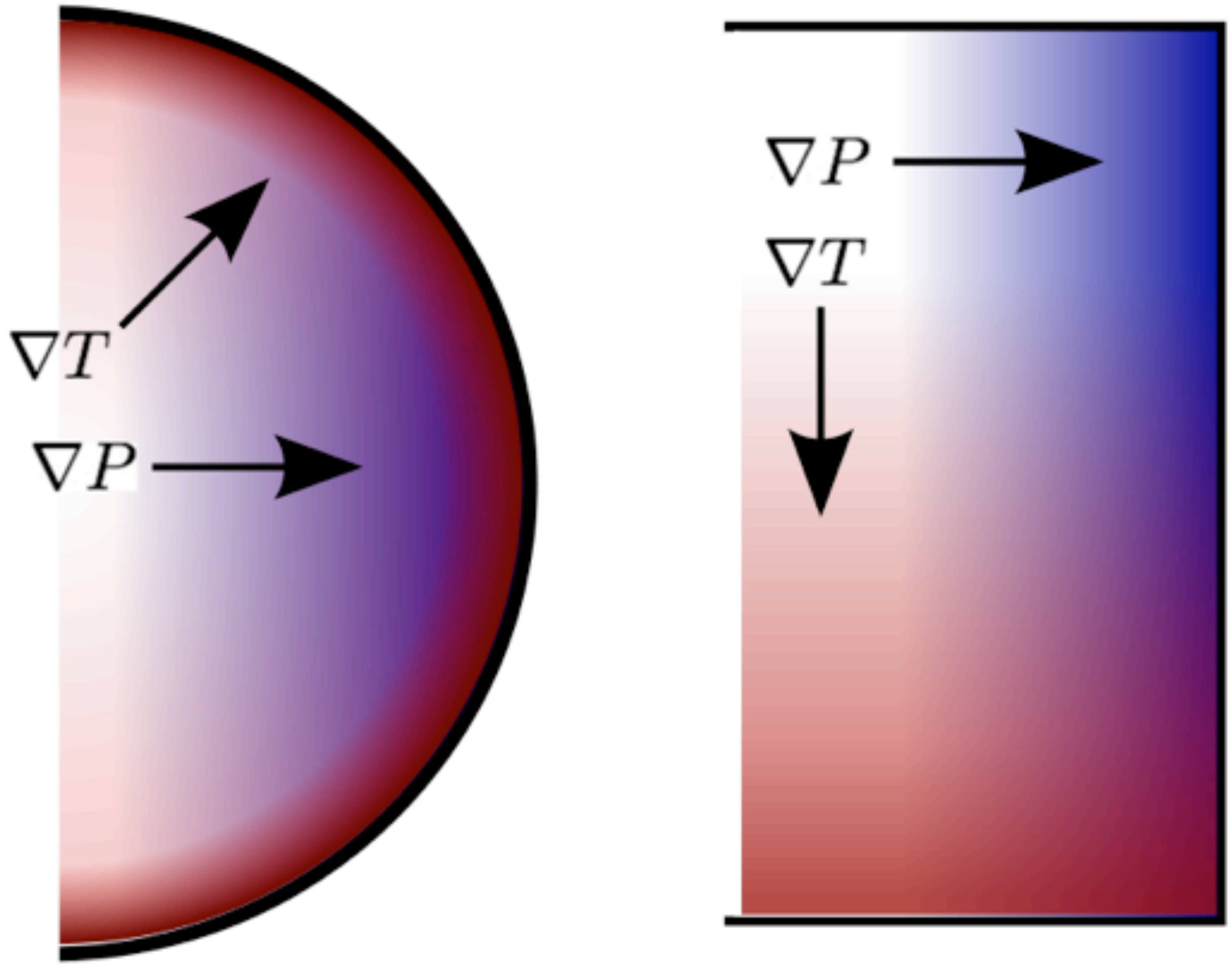
$$\rho V_{\mathrm{conv}}^2 \equiv \int^a \Delta\rho\Omega^2 R dR$$

$$Rm_{\mathrm{conv}} = \mu_0 \sigma \Omega a^2 \sqrt{\frac{\Delta\rho}{\rho}}$$

$$Ra \approx \sqrt{\frac{\Delta\rho}{\rho}} Re^2$$

Driving Baroclinicity

Sphere (PDX)



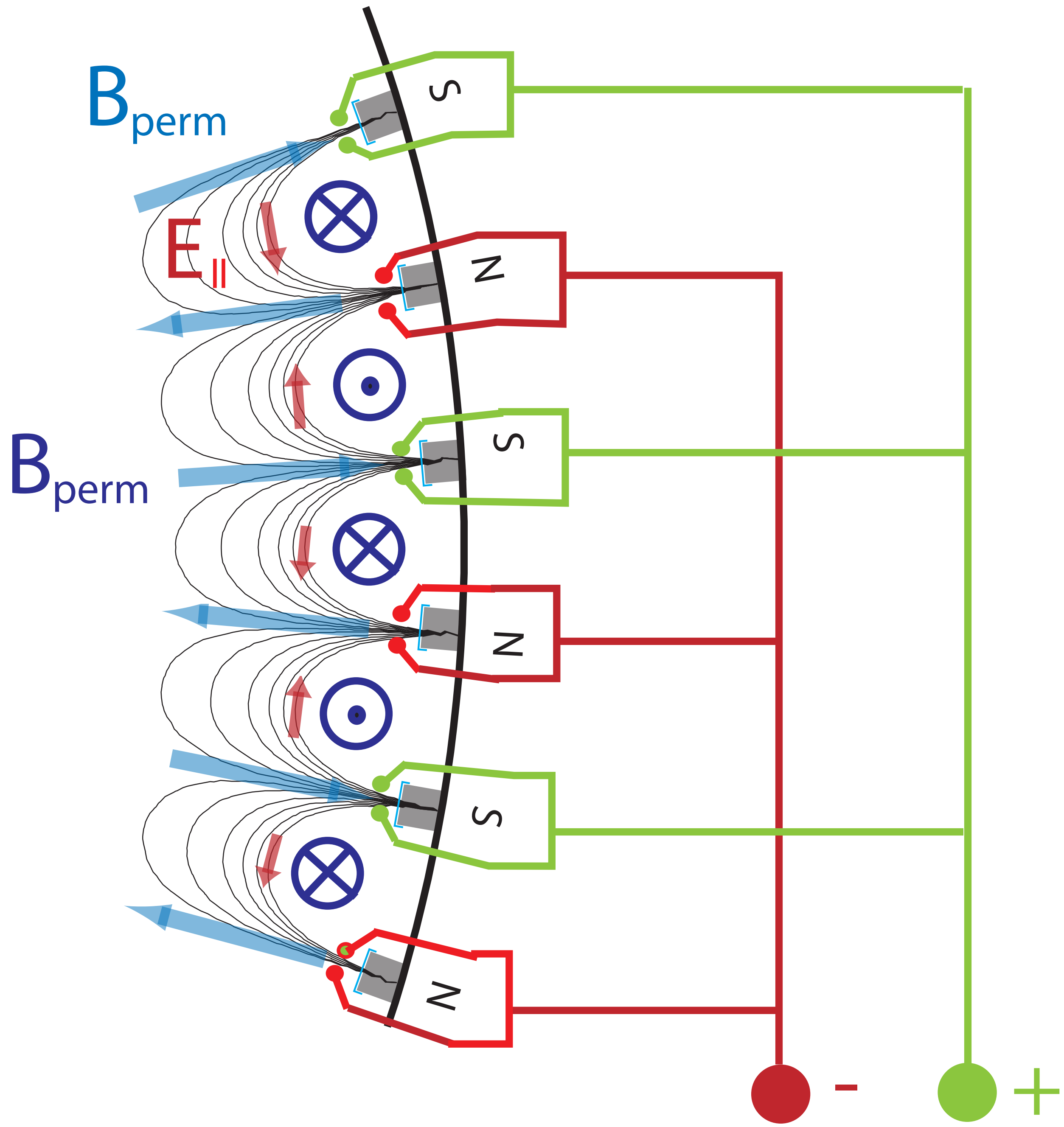
Cylinder (PCX)

ECH at outer boundary

ECH at bottom boundary

$$\frac{\partial \omega}{\partial t} = \frac{1}{\rho^2} \nabla \rho \times \nabla P$$

Inside out tachocline experiment using magnetic buoyancy driven by magnetic helicity injection at boundary



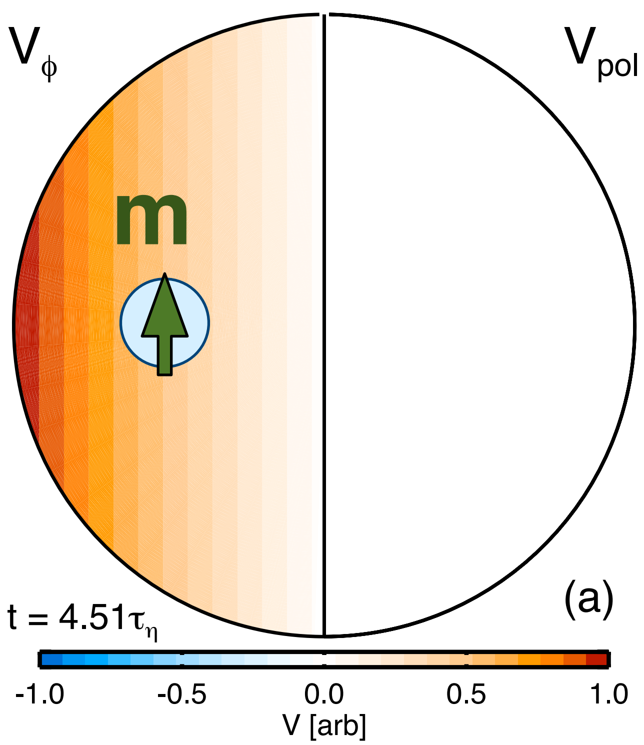
Magnetic Helicity generation via E|| biasing arrangement [also possible to drive flow as before Vφ (r = a, θ)]

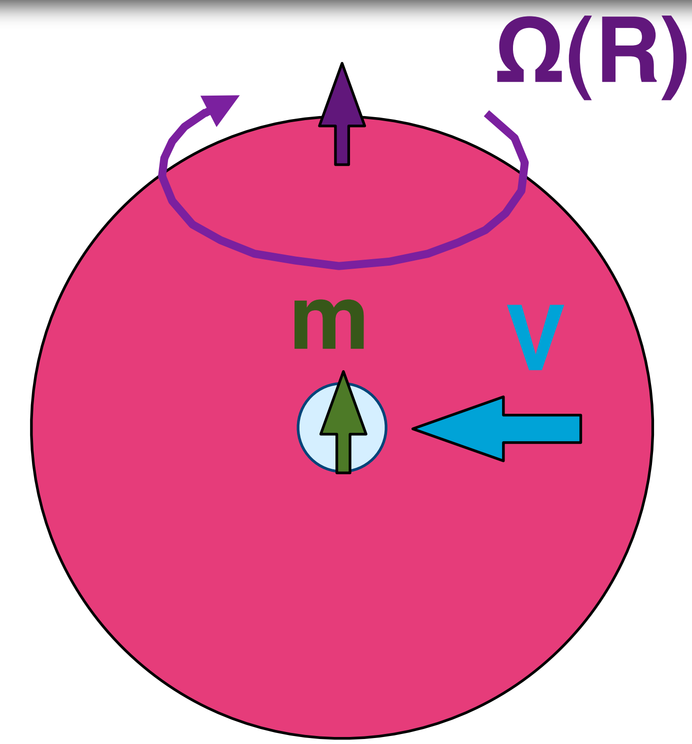
FACILITY CAN ADDRESS BROAD RANGE OF FLOW DRIVEN MHD PROBLEMS OF IMPORTANCE IN ASTROPHYSICS

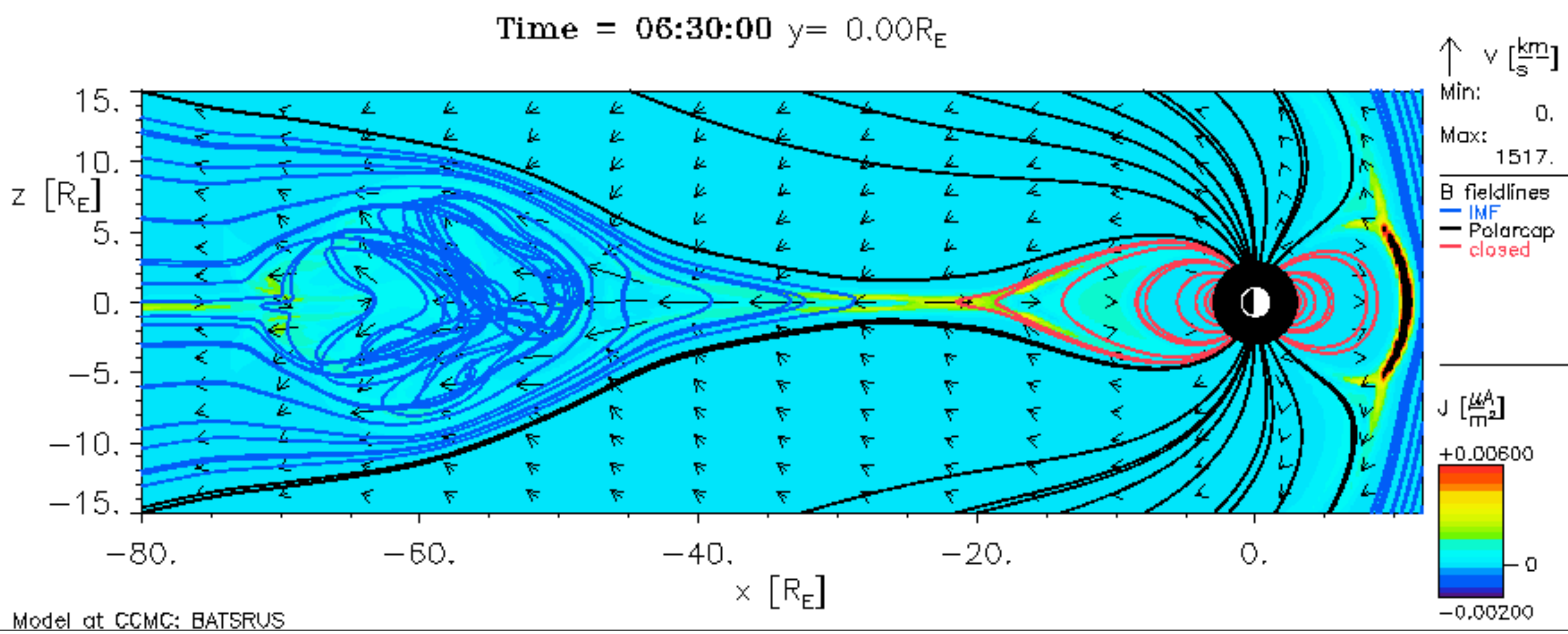
1. Laminar and turbulent two vortex dynamo at high Rm and variable Pm
2. MRI
3. JET Formation by differentially rotating boundary, into background plasma
4. Terella Experiment to study Solar Wind-Magnetosphere Interaction (steady-state, high Rm, large Area)
5. Collisionless high beta turbulence and Dynamos
6. Buoyancy (magnetic and compositional)
7. Baroclinic Instabilities
8. Pulsar Wind and bow shock experiments (spinning dipoles)

CMSO Workshop on Flow Driven MHD Instabilities in Plasmas and Kickoff of the MPDX, Madison, Dec. 2009.

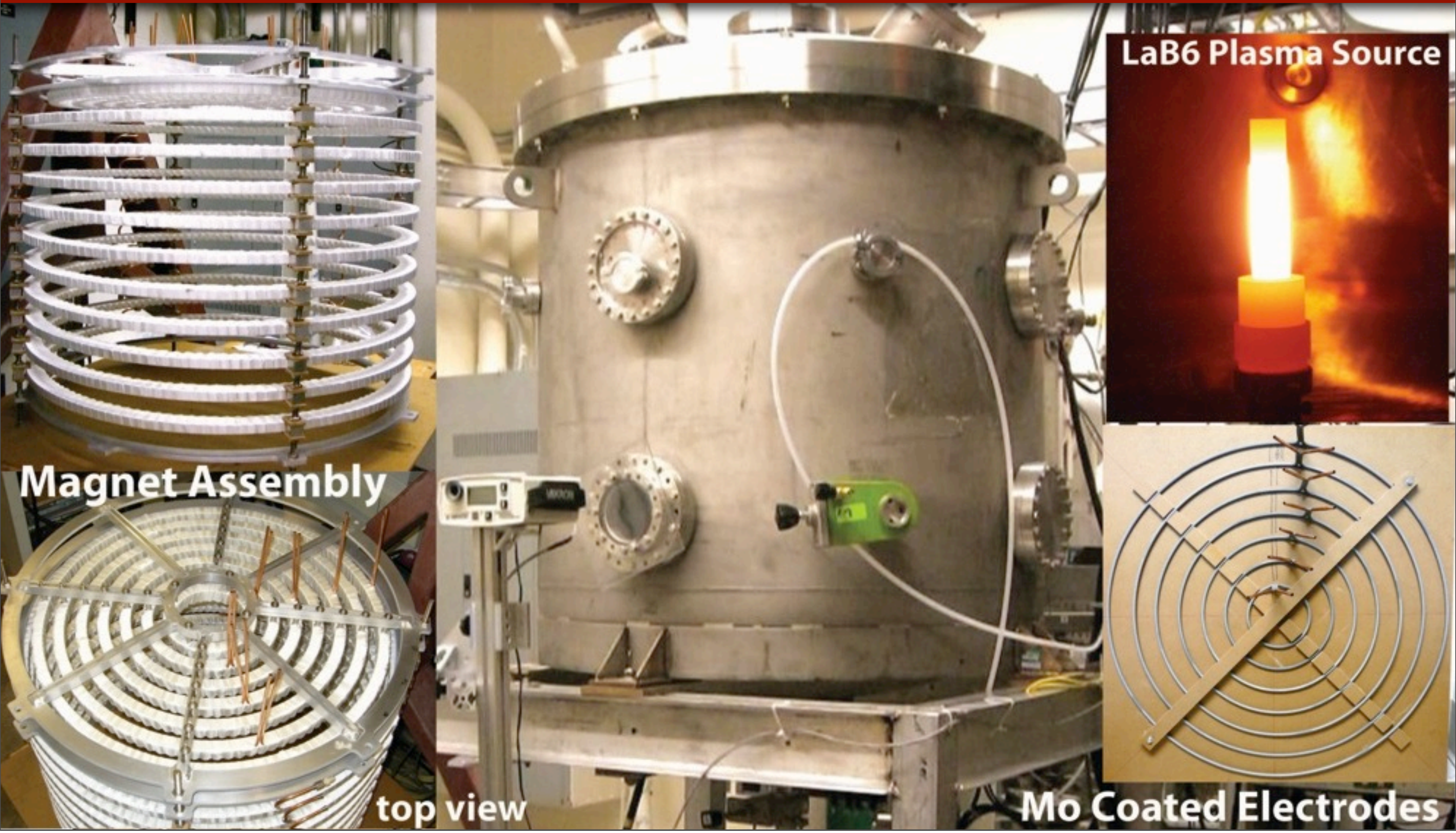
Rotating Plasma Forms Wind Tunnel For Flow Driven Reconnection around Dipole inserted into flow







Plasma Couette Flow Experiment is a prototype for dynamo experiment and will be used to study MRI



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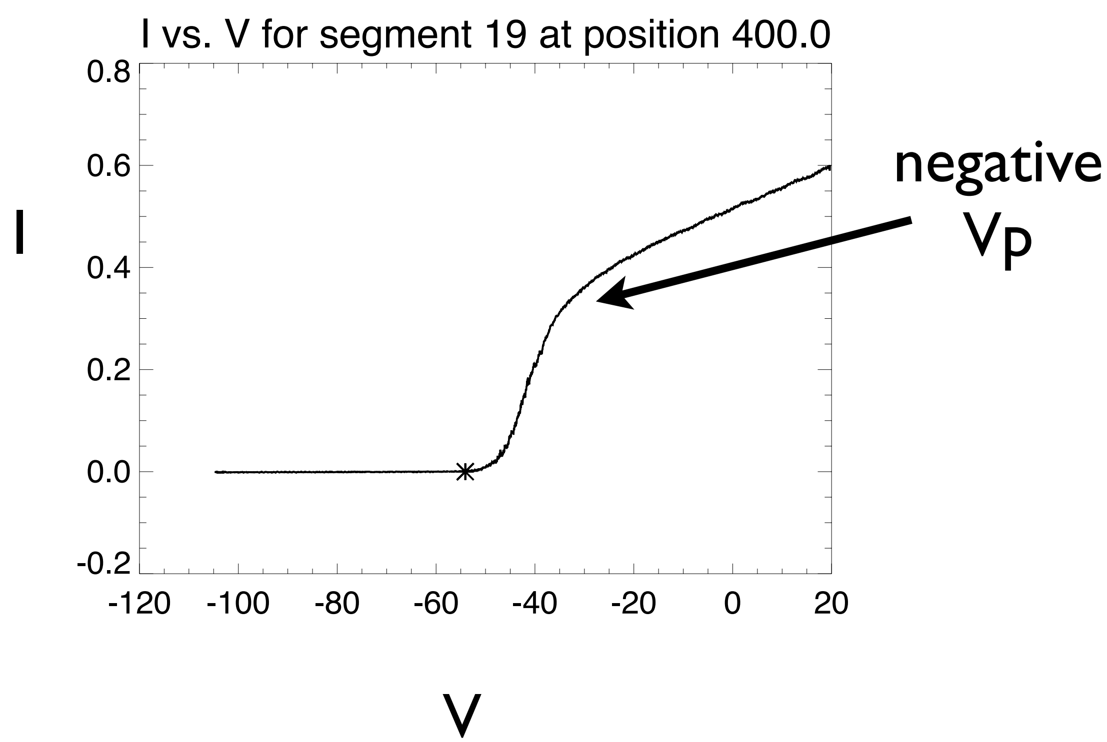
- At only 1400 ºC, 2 mTorr: Te ~ 2.8 eV, density~ 1.5×10^{11} cm^{-3}



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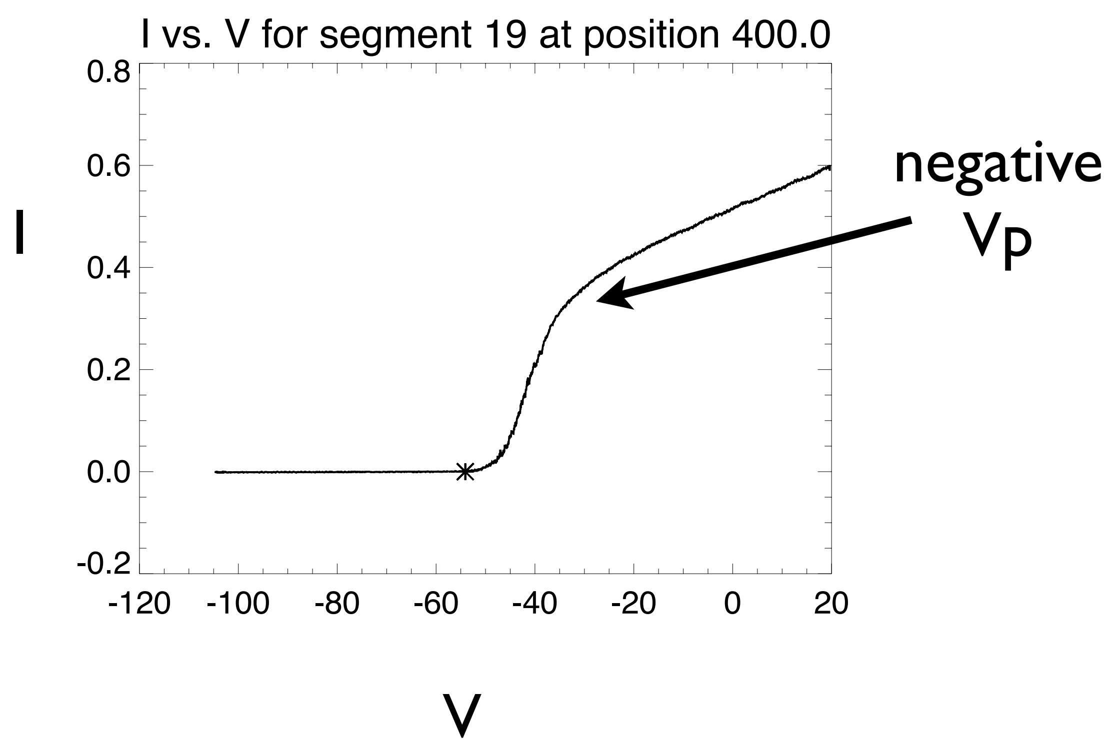

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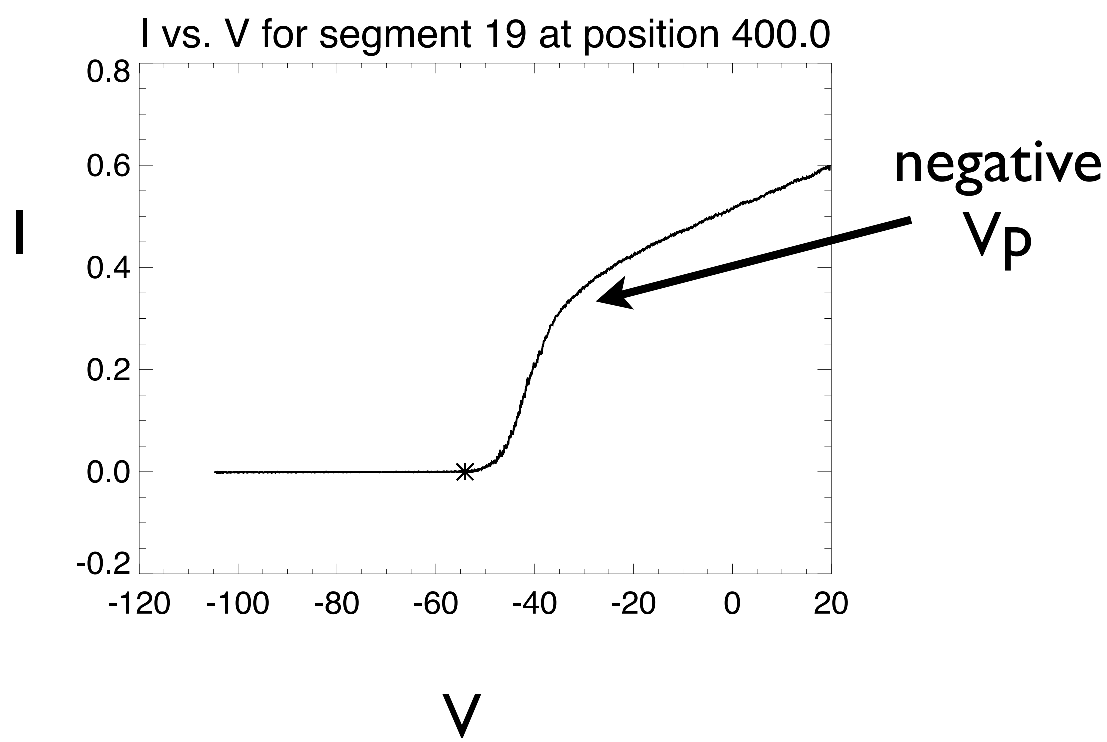

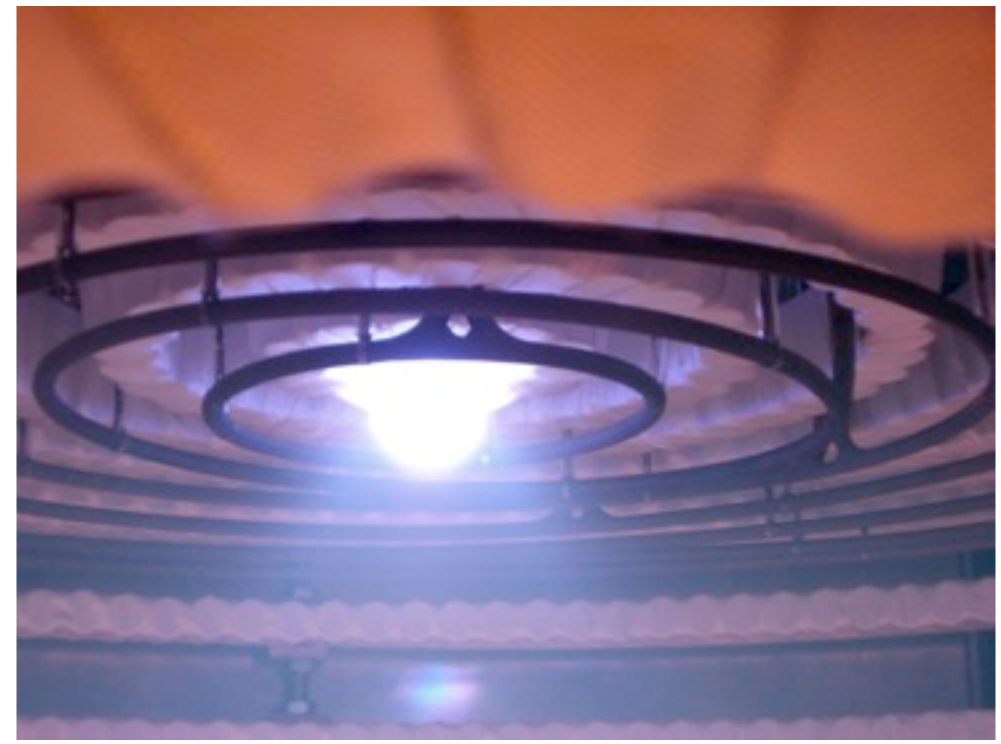

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- 1 mm interferometer/polarimer will measure line integrated density

$$\Delta\phi = \left(\frac{e^2}{2c\omega m_e \epsilon_0}\right)\int n_e d\ell = 2.85 * 10^{-15}\lambda \int n_e d\ell$$

assuming unmagnetized, collisionless plasma with $\omega_{pe} << \omega$

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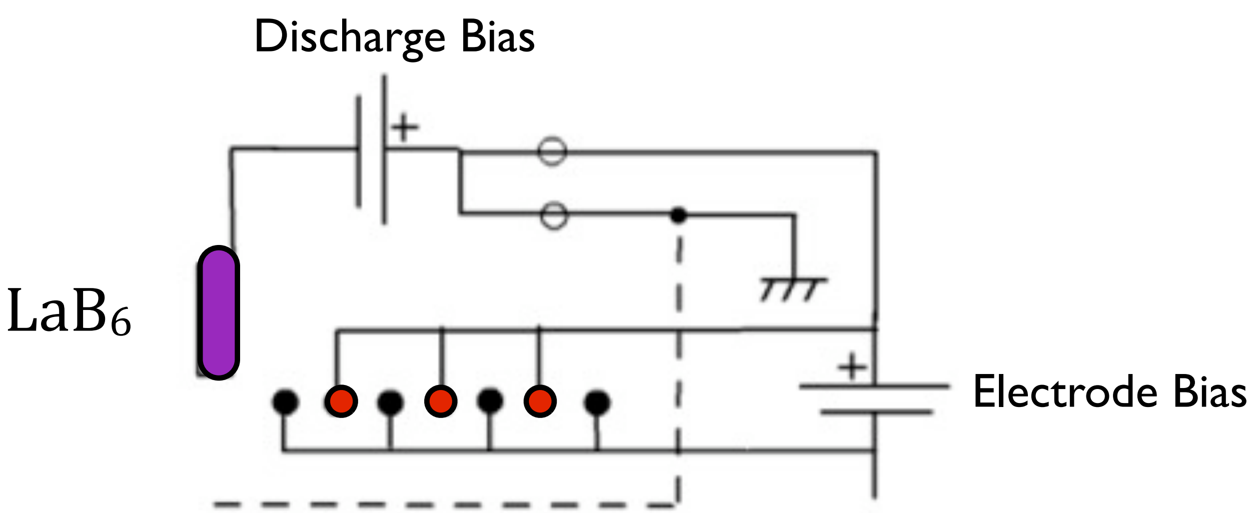

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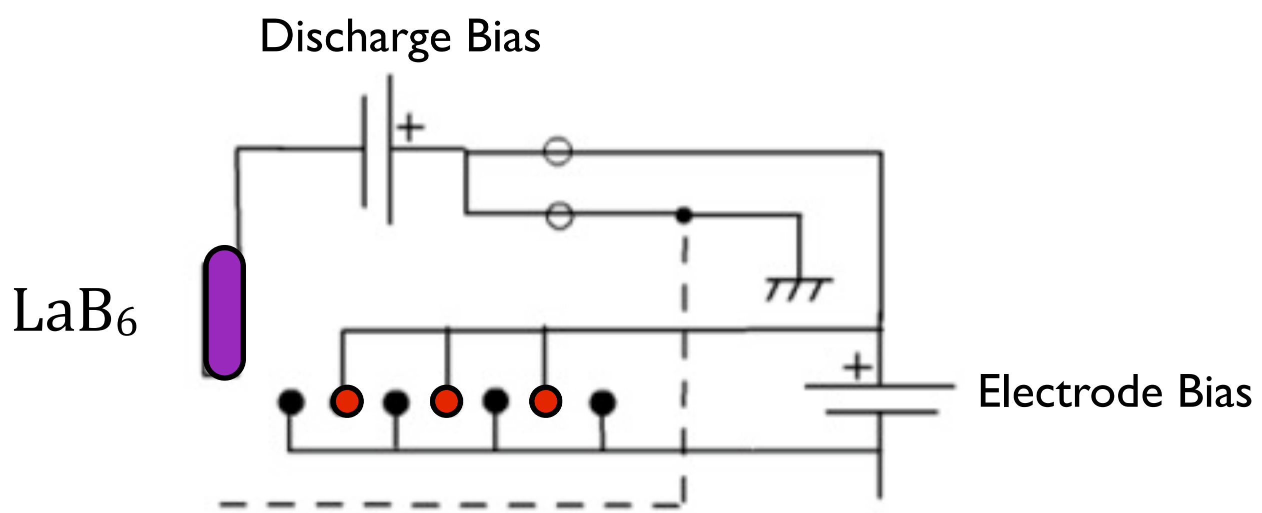

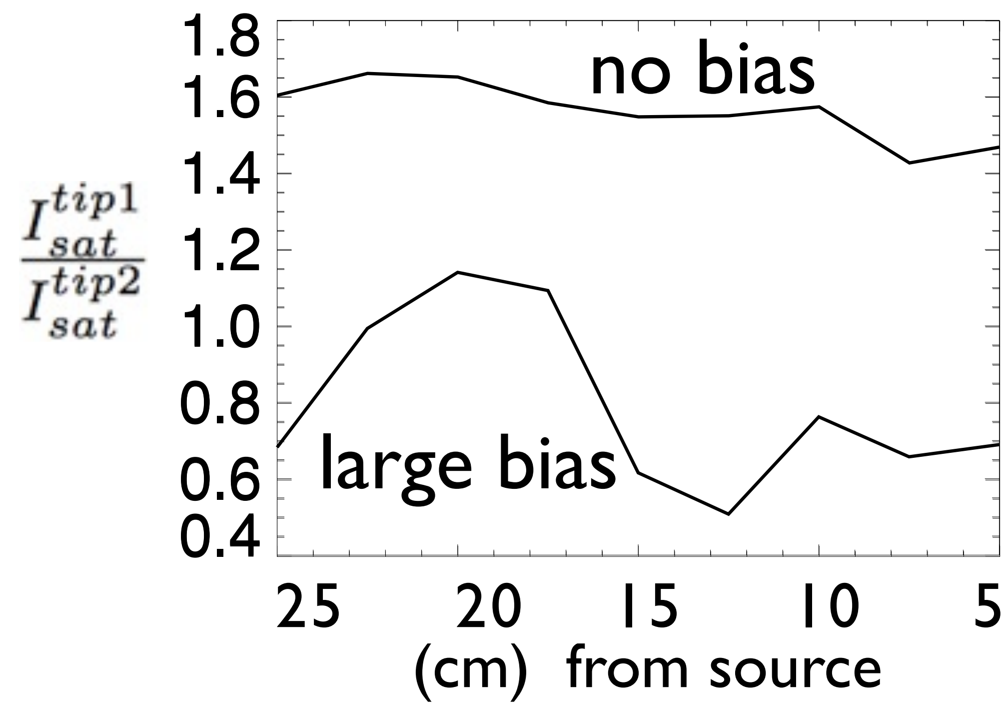

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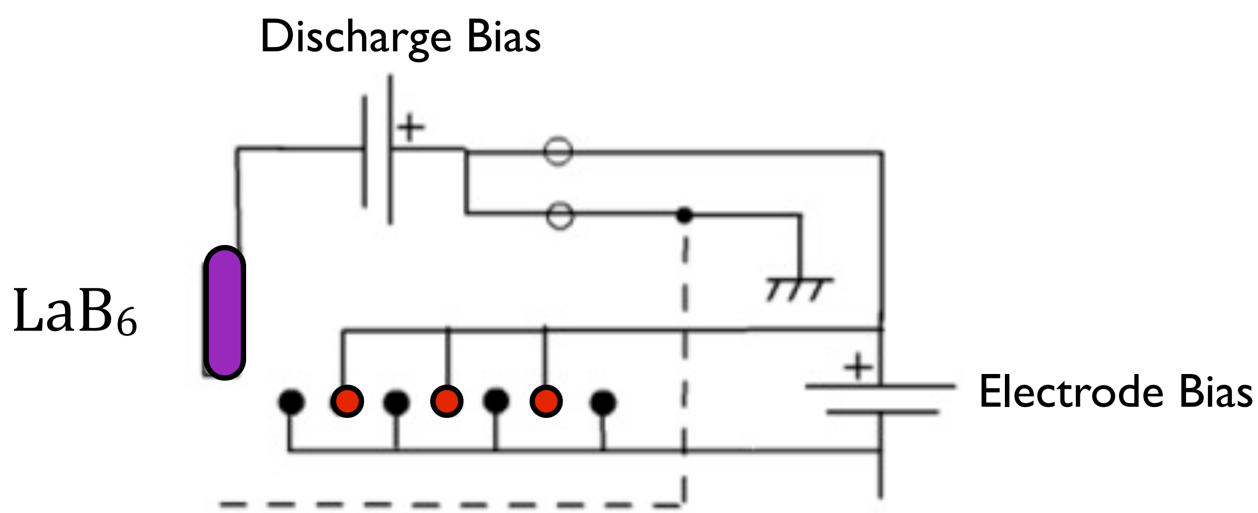

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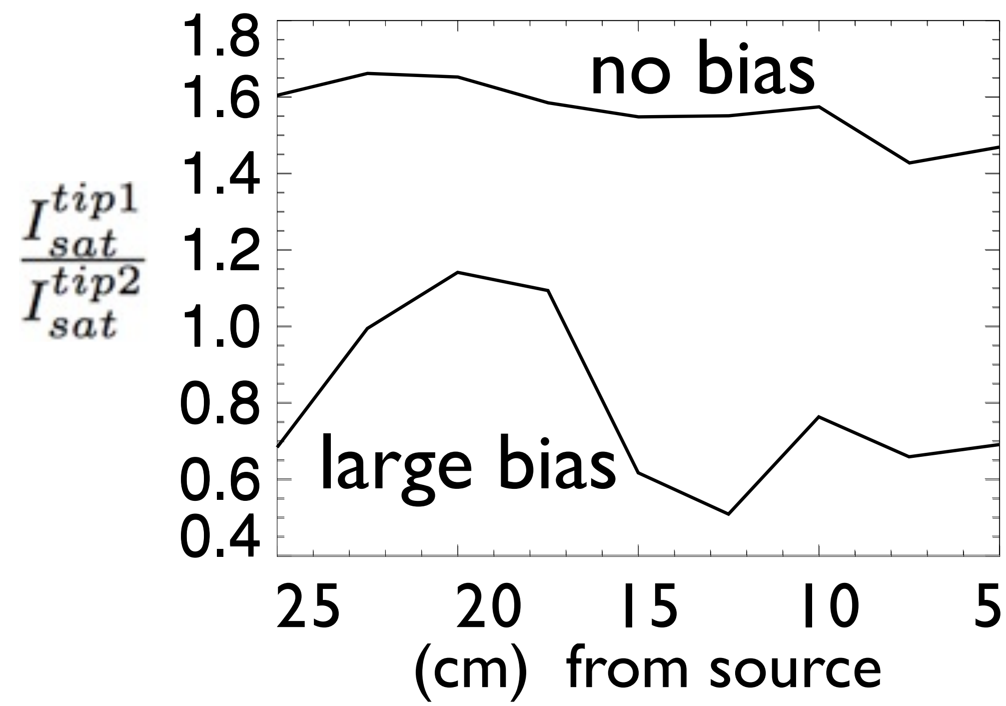
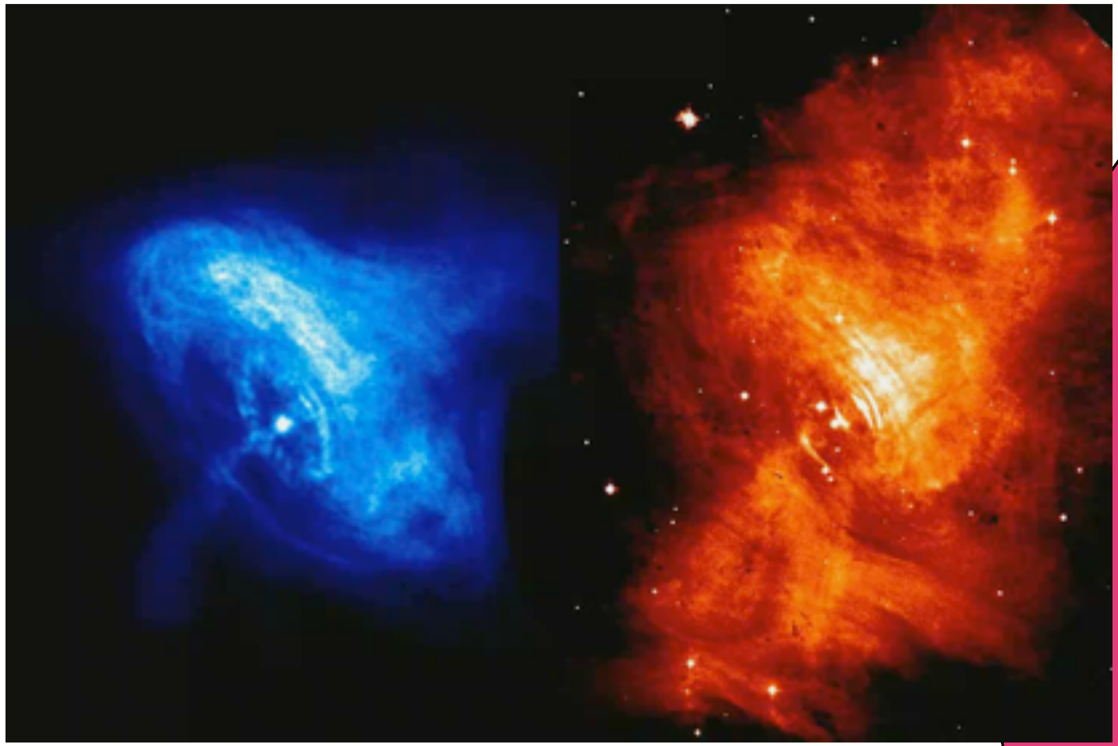
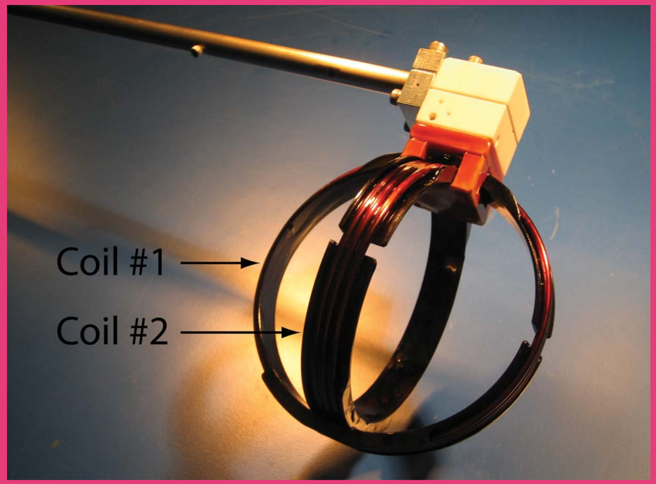


- Plasma potential will be determined using an **emissive probe** and can be related to flow

$$\Phi(R) = \frac{M_i T_e}{2e(T_e + T_i)} \Omega^2 R^2$$

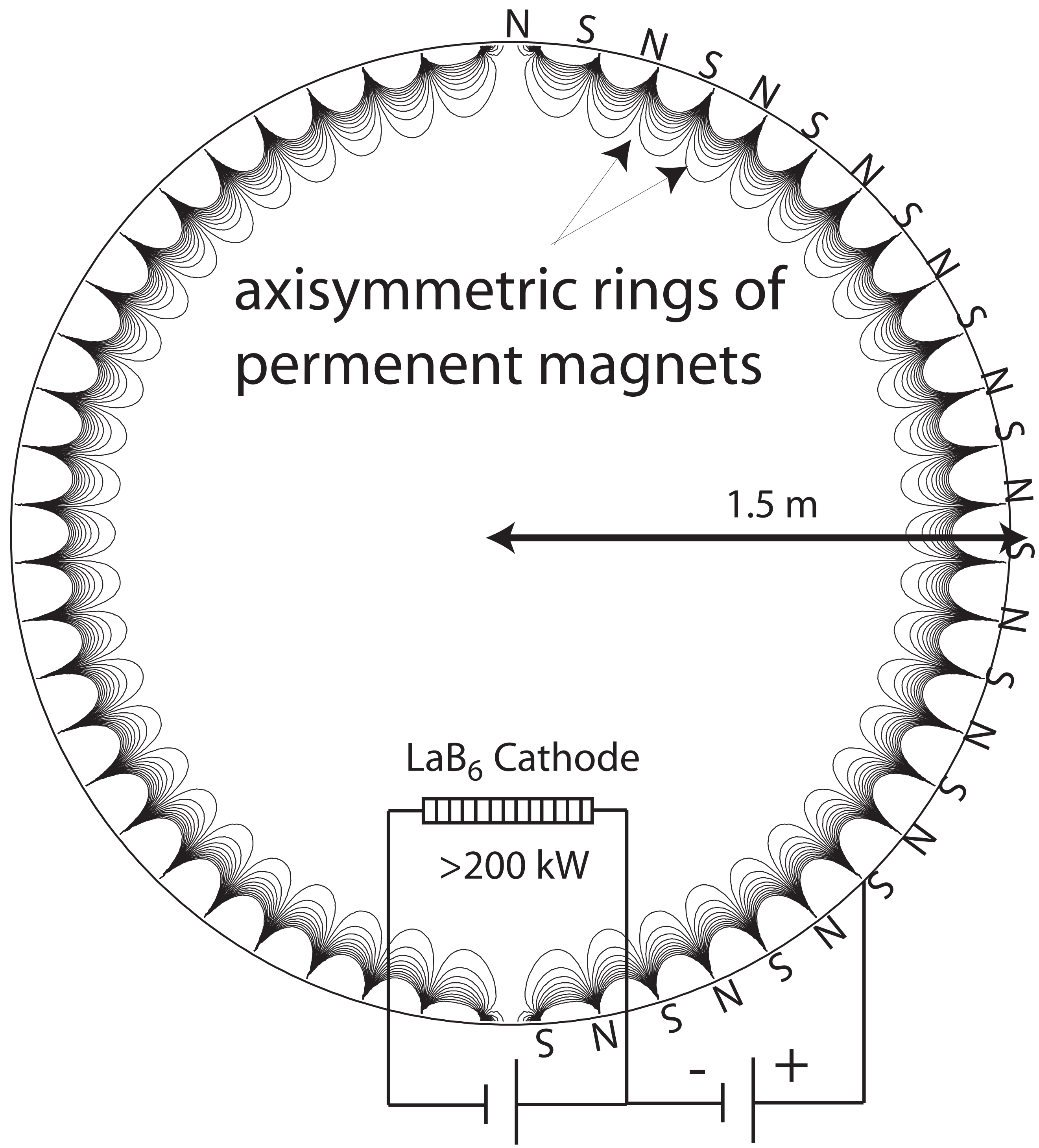
Pulsar Winds from Orthogonal Loop Antenna





Inverse Cascade Experiment via Small Scale Helicity Injection on Plasma Boundary

- Apply alternating potential between magnet faces->helicity at small scale on edge, all of same sign
- Into rotating plasma, this may give magnetic buoyancy on outer edge



Jet Formation Experiment to mimic (Spruit, Blandford and Payne) Equilibrium and Jet Collimation

Program Keplerian Flow in Upper Hemisphere