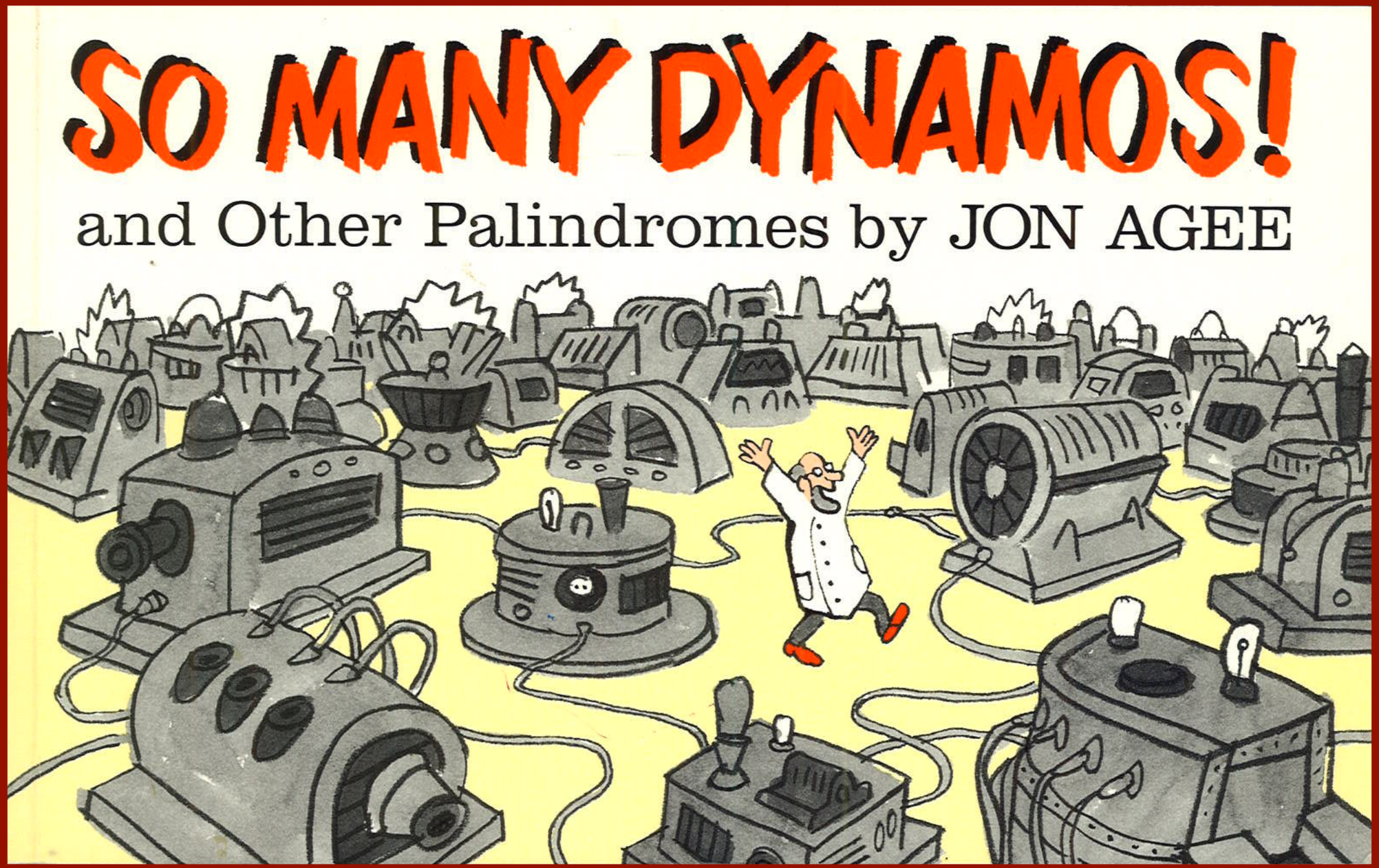
Plasma Dynamo Experiments

Cary Forest

PPPL Colloquium

5th June 2013



So many dynamos (sō men´ē dī´nuh-mōz´), *1. a phrase which reads the same backwards and forwards, i.e. a palindrome. 2. a whole slew of electric generators.*

So Many Dynamos

- Mechanical
- Astrophysical
- Numerical
- Liquid metal
- Plasma

What is a self-exciting dynamo?

Faraday's Law of Induction

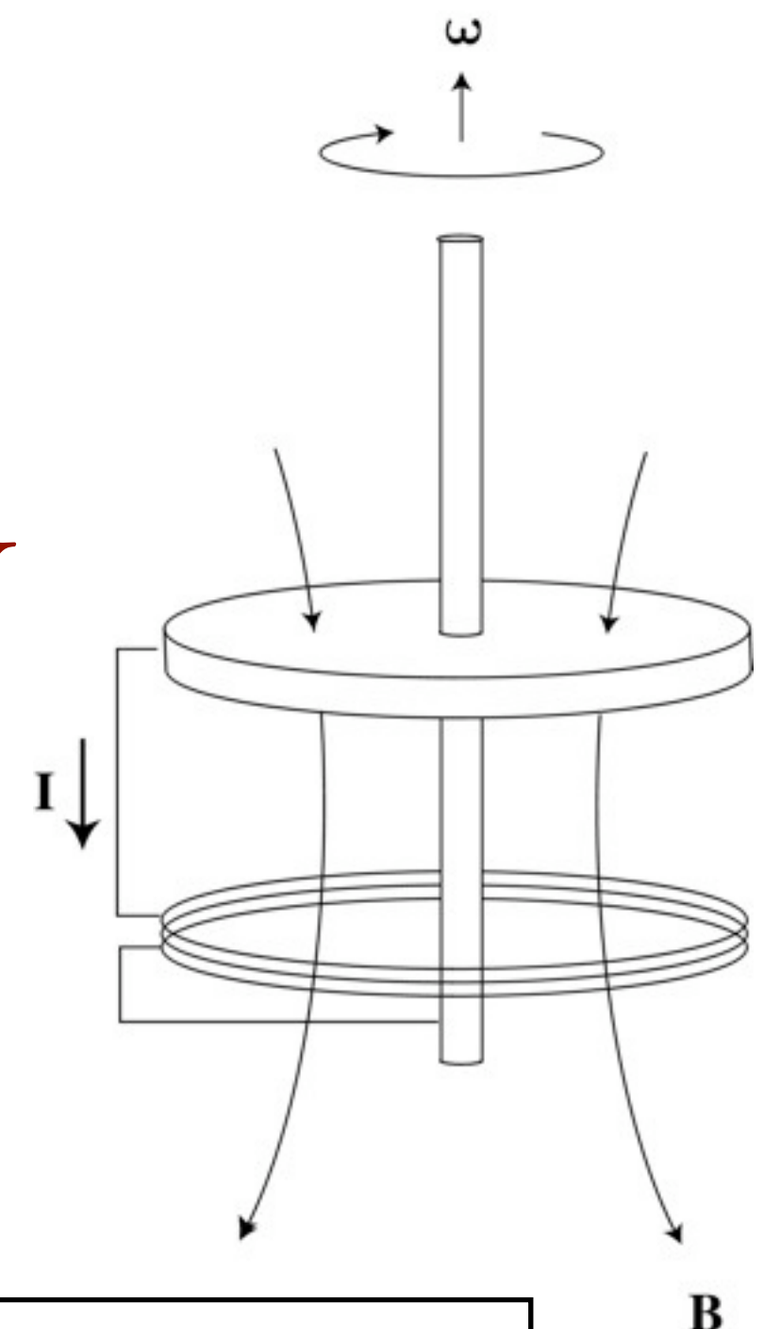
$$\vec{J} = \sigma\left(\vec{E} + \vec{V} \times \vec{B}\right)$$

feedback

Induction Equation

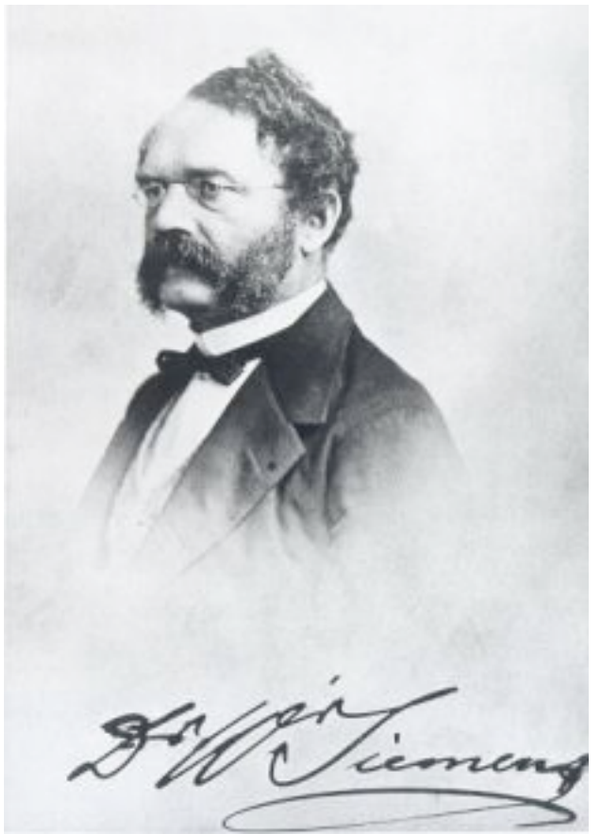
$$\frac{\partial I}{\partial t} = \left(\frac{\omega L}{2\pi N R} - 1\right)\frac{I}{\tau_{L/R}}$$

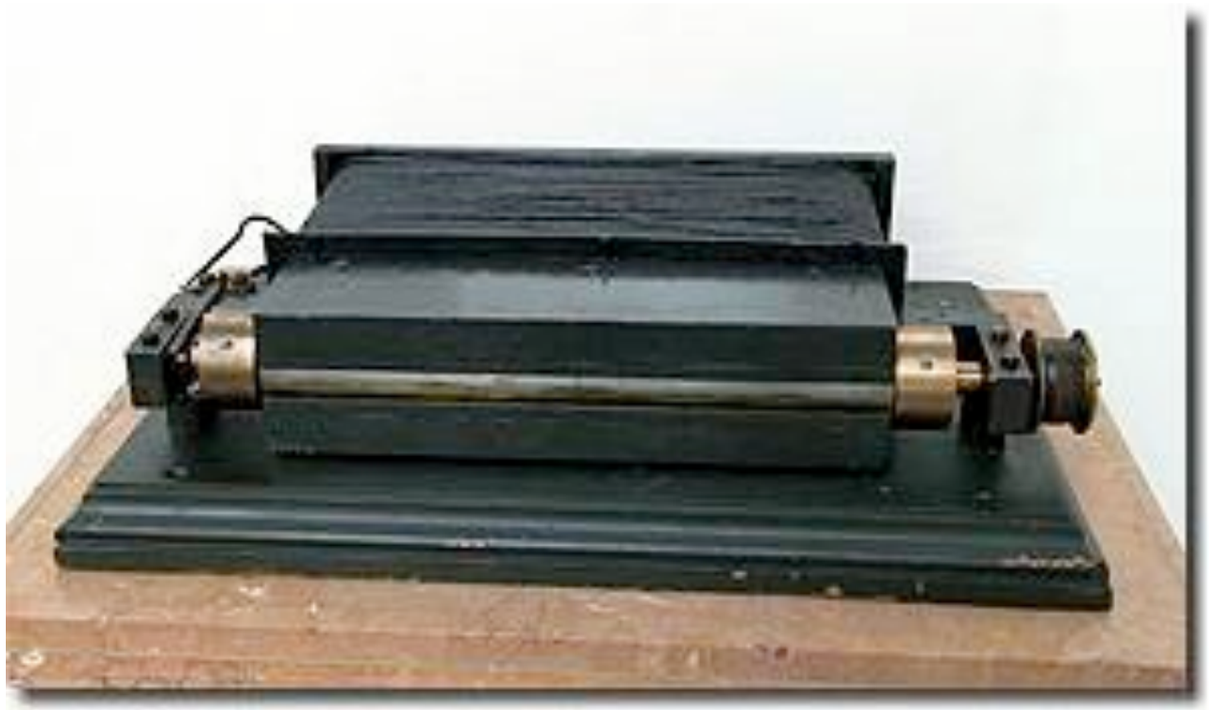
$\mu_0 \sigma L V$



Magnetic energy from Kinetic energy

The self-excited generator of Werner von Siemens (1866)





The “dynamo electric principle”

MHD in the limit of high conductivity and weak magnetic fields

Induction Equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{V} \times \mathbf{B} + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

$$\frac{\nabla \times V \times B}{\frac{1}{\mu_o \sigma} \nabla^2 B} \sim \mu_o \sigma L V_0 \equiv Rm$$

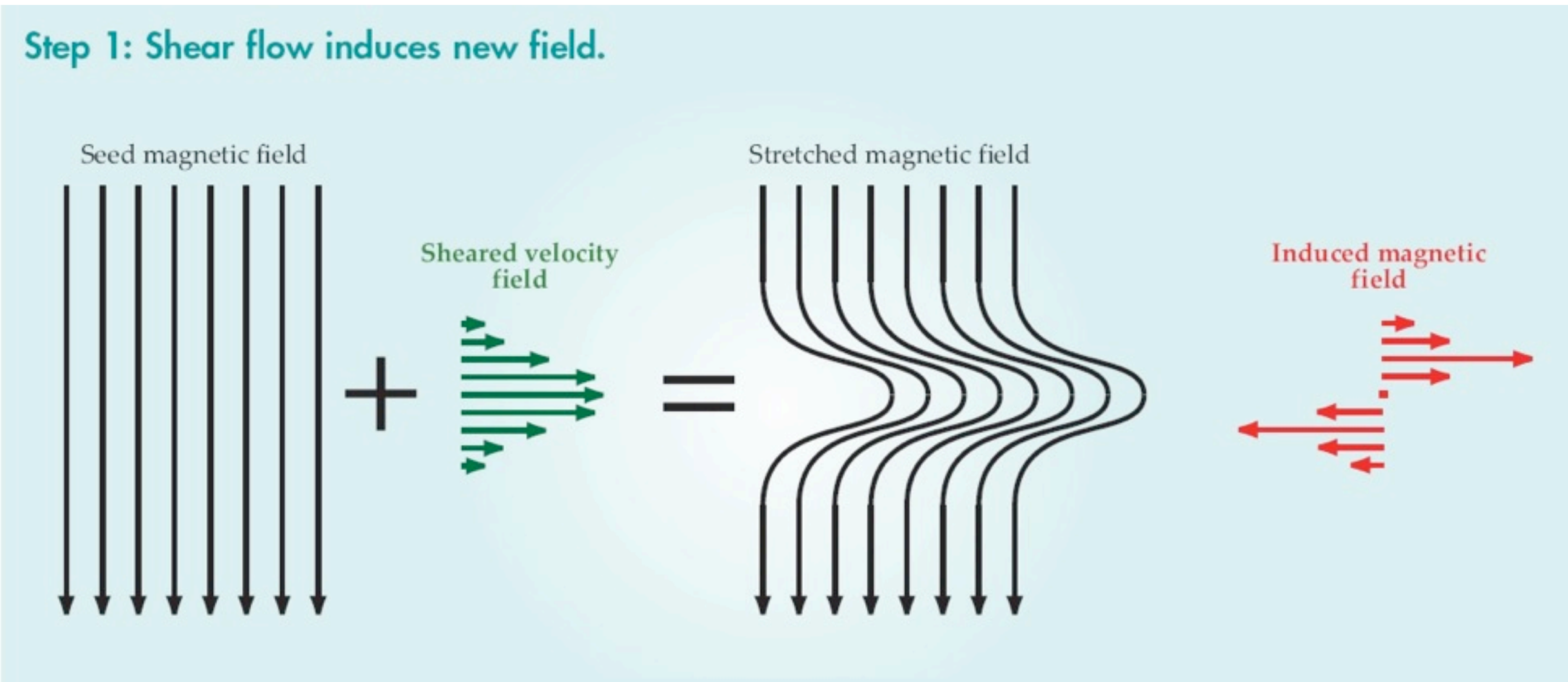
Equation of Motion

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla p + \mathbf{J} \times \mathbf{B} + \mu \nabla^2 \mathbf{V} + F_{prop}$$

$$\frac{J \times B}{\rho V \cdot \nabla V} \ll 1 \text{ implies } \frac{1}{2} \rho V^2 \gg \frac{B^2}{2\mu_0} \text{ or } V/V_A > 1$$

When Rm ≫ 1 and $V/V_A \gg 1$
B is frozen into and stretched by moving fluid

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{V} \times \mathbf{B} + \cancel{\frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}}$$



Astrophysical Dynamos

- Highly conducting and fast flowing

$$Rm = \mu_0 \sigma V L \gg 1$$ Magnetic Reynolds

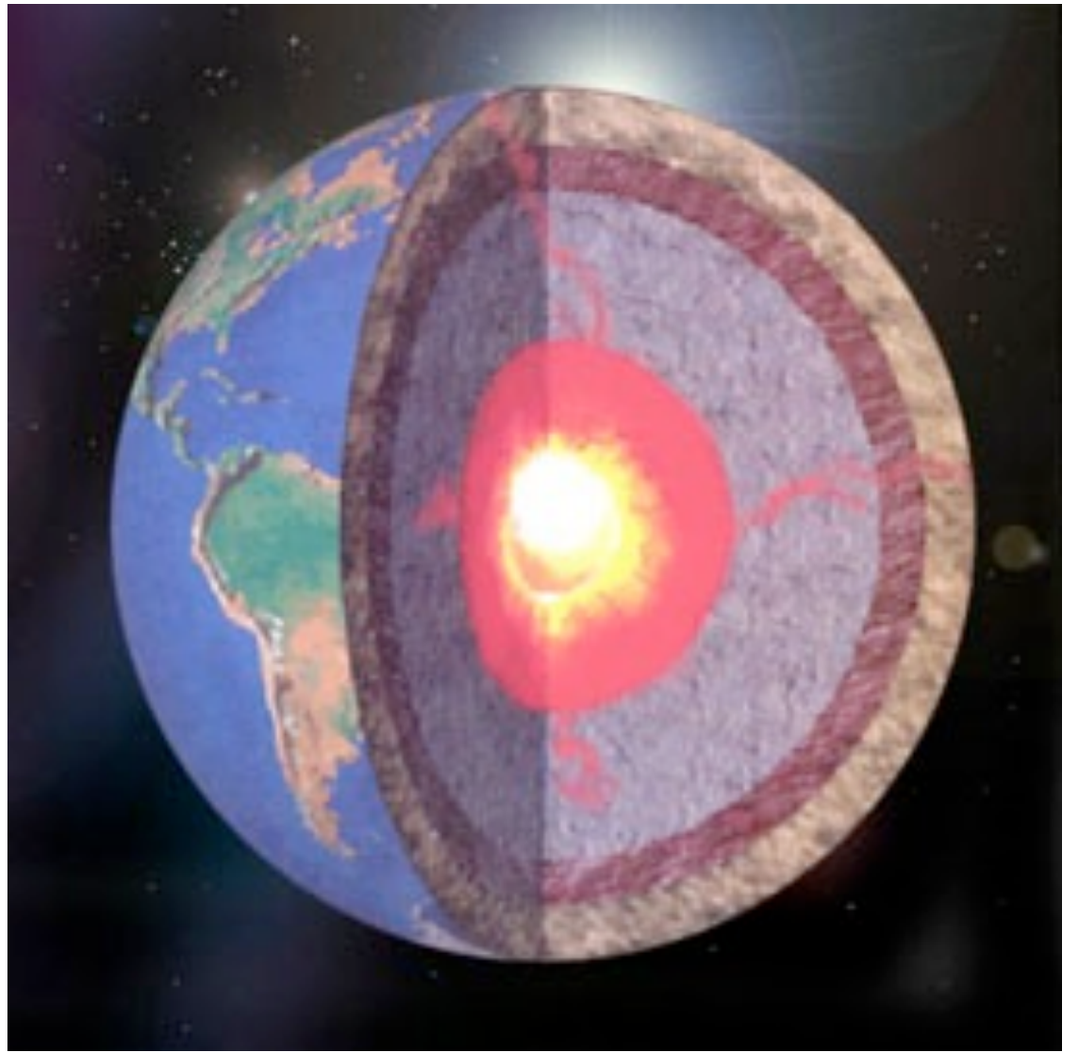
- Turbulent

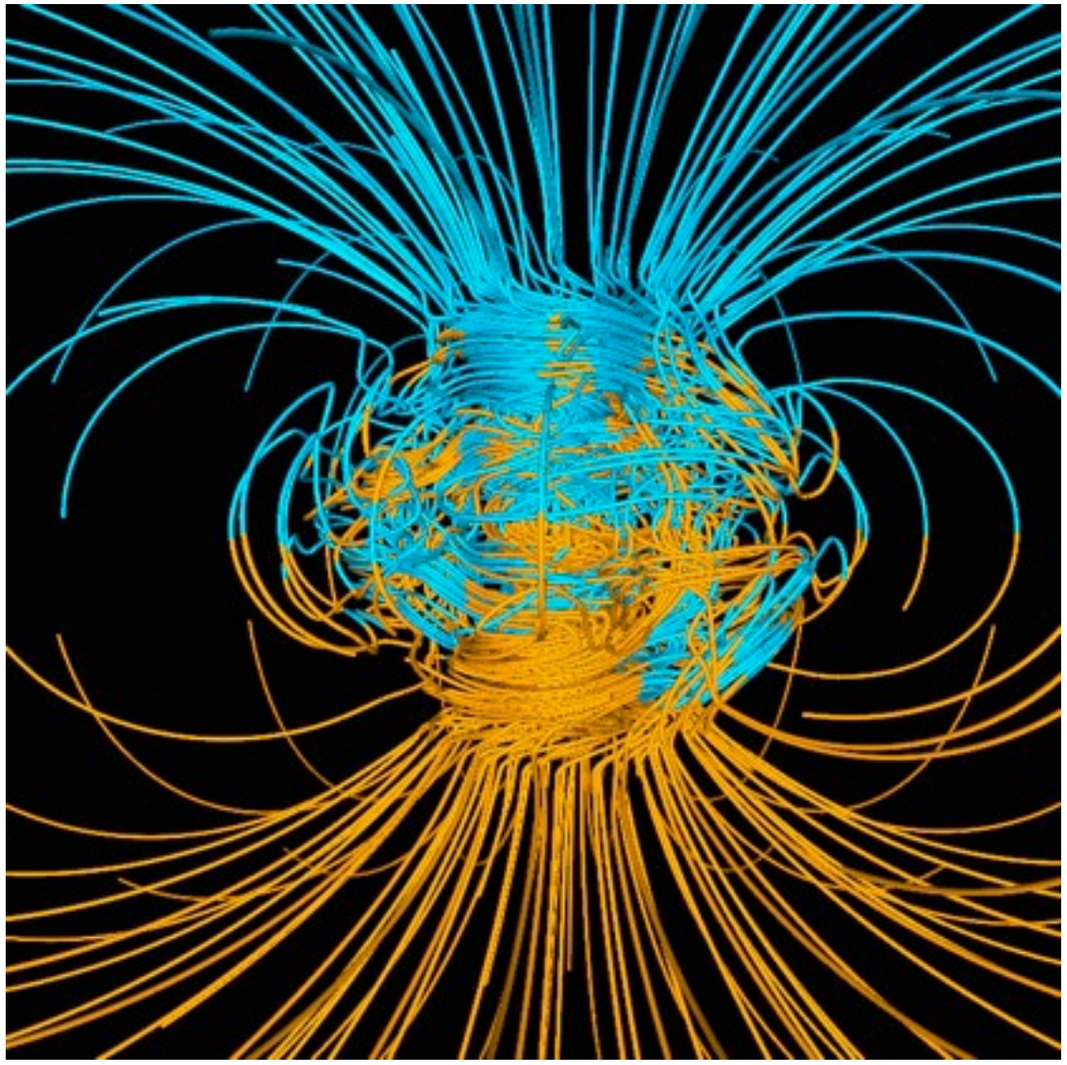
$$Re = \frac{VL}{\nu} \gg 1$$ Kinetic Reynolds

- Kinetic energy dominated

$$\frac{1}{2}\rho V^2 \gg \frac{B^2}{2\mu_0} \text{ or } V/V_A > 1$$ Alfvén Mach

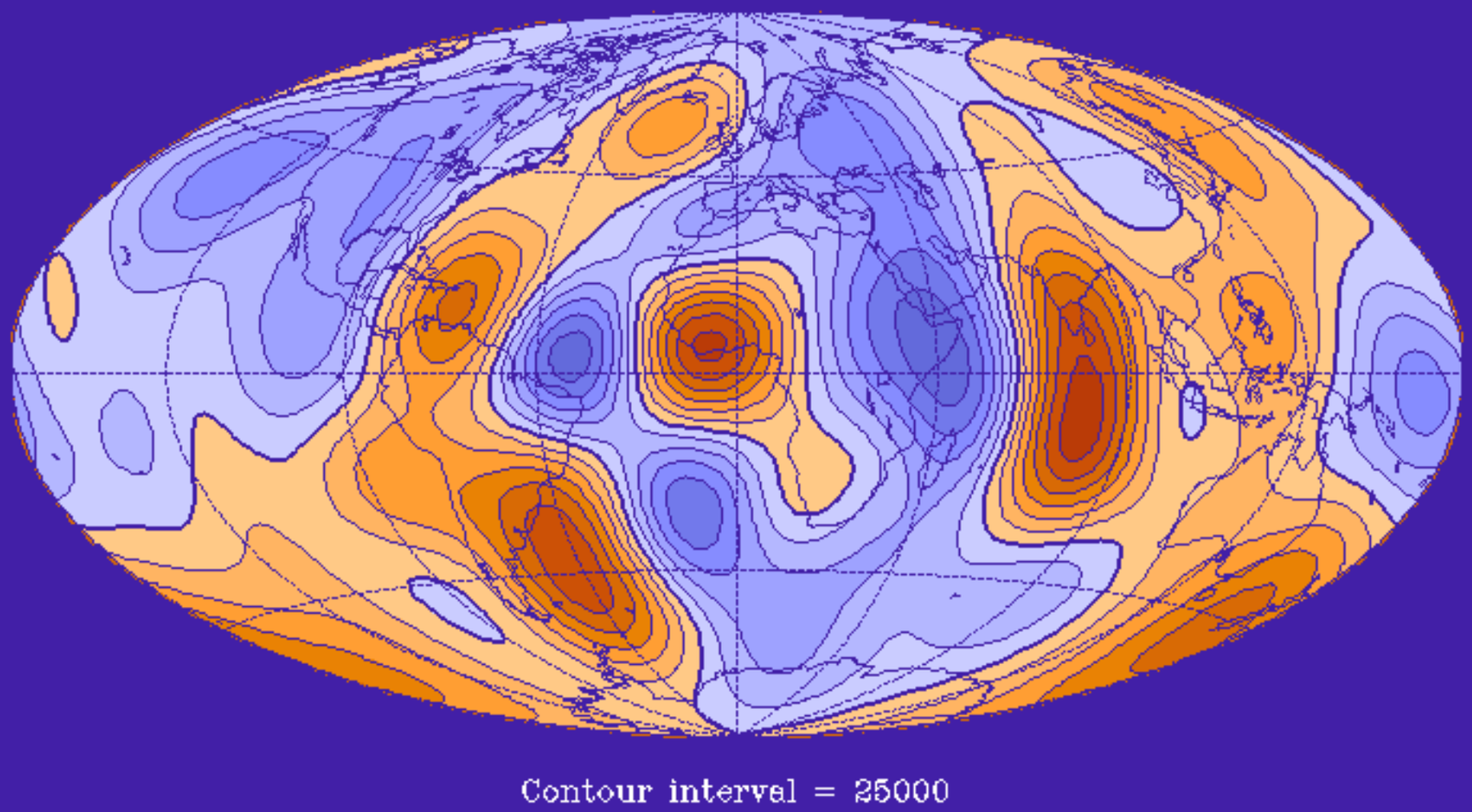
The Earth dynamo

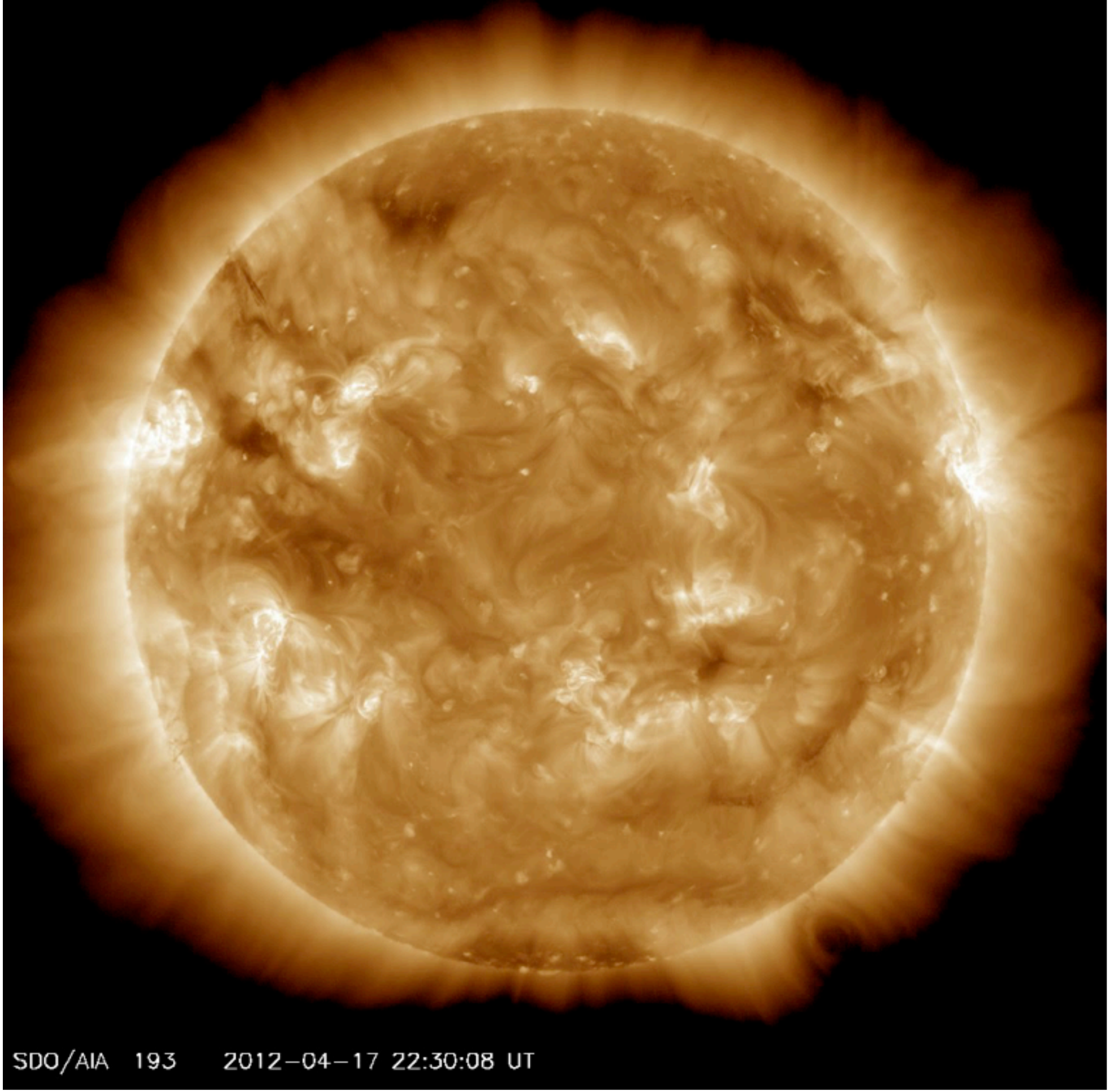




Rm~500-1000, Re=10^9, Liquid Metal

+ smaller scale fluctuations

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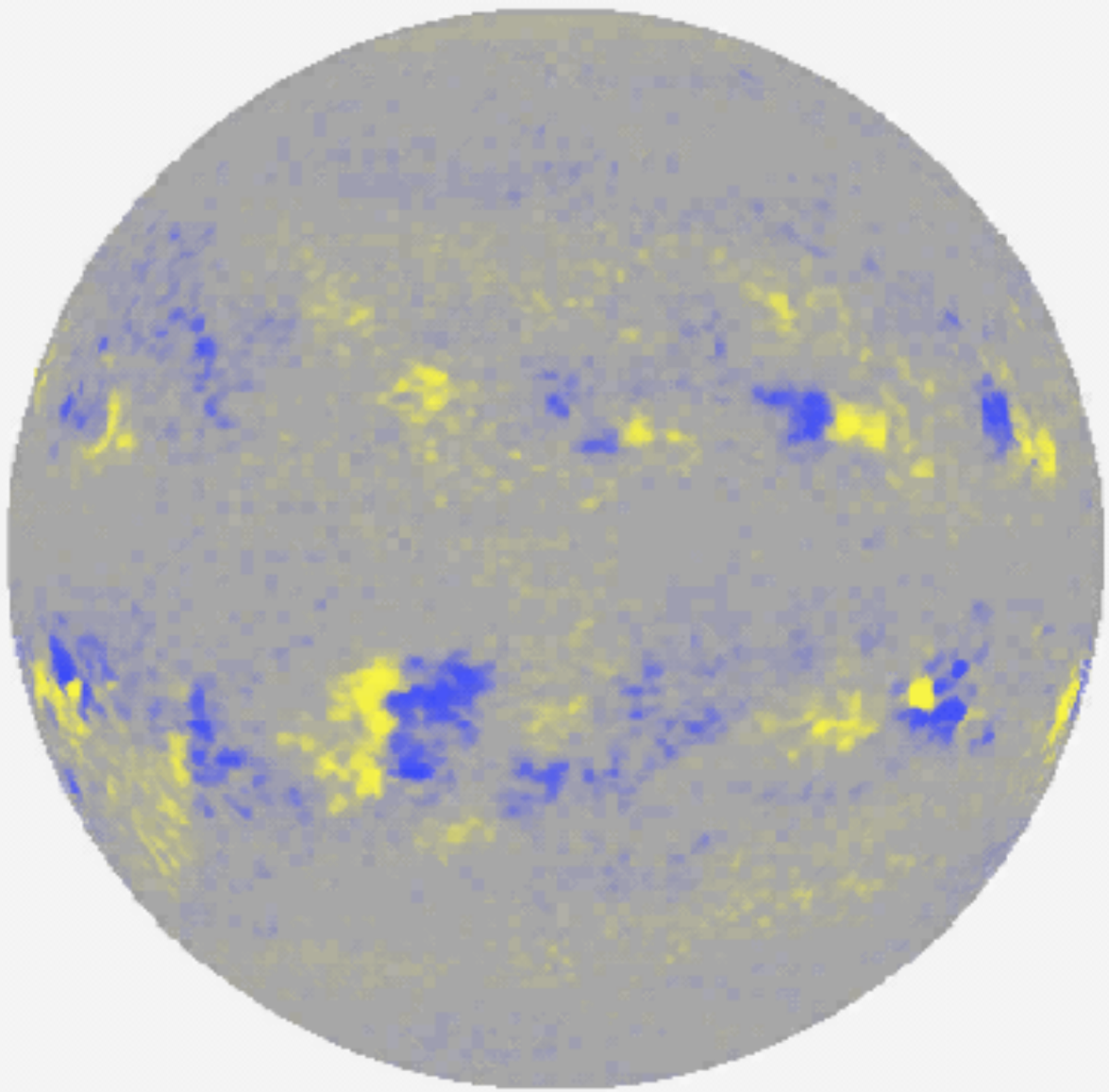
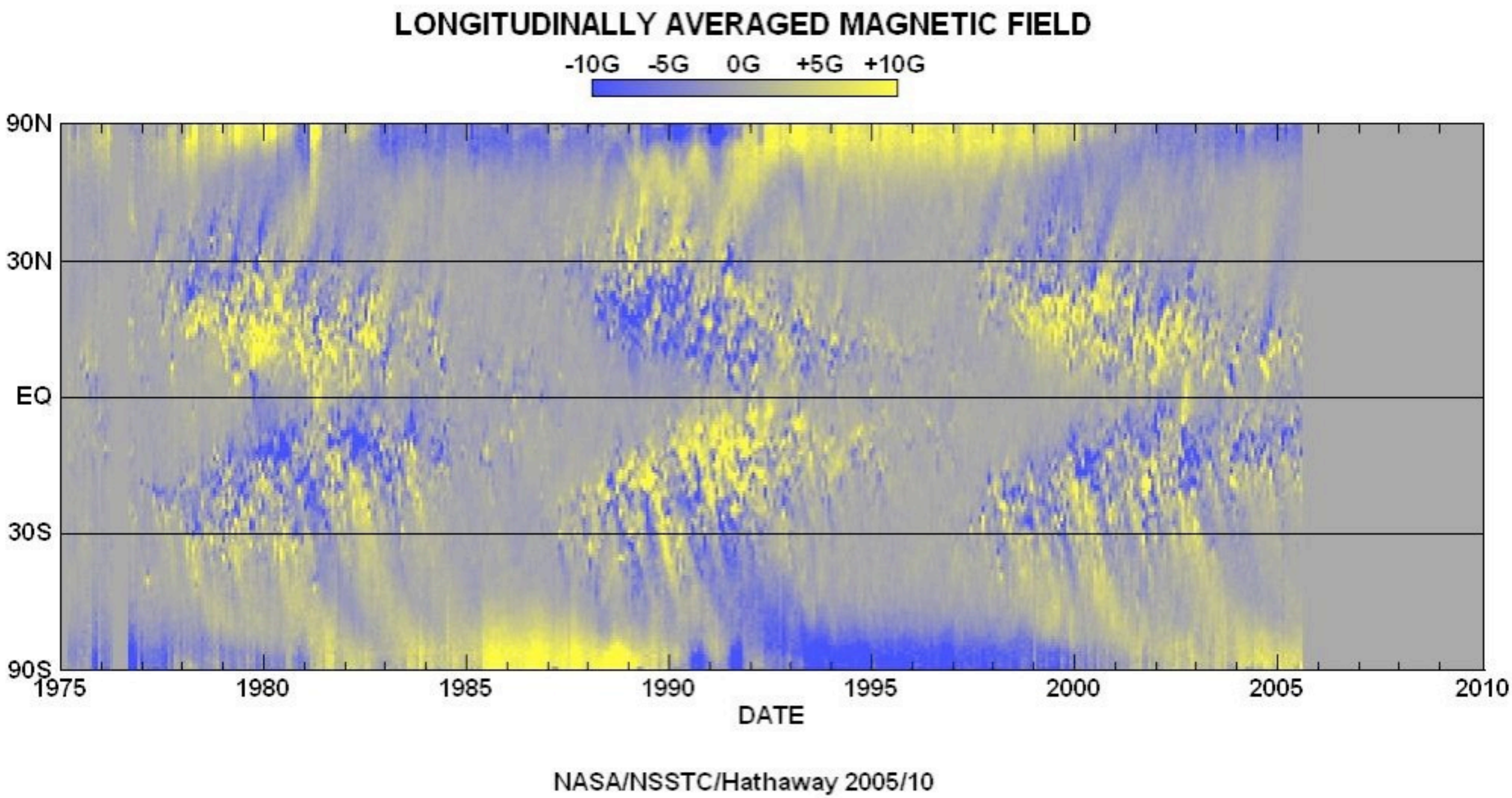
The Sun dynamo

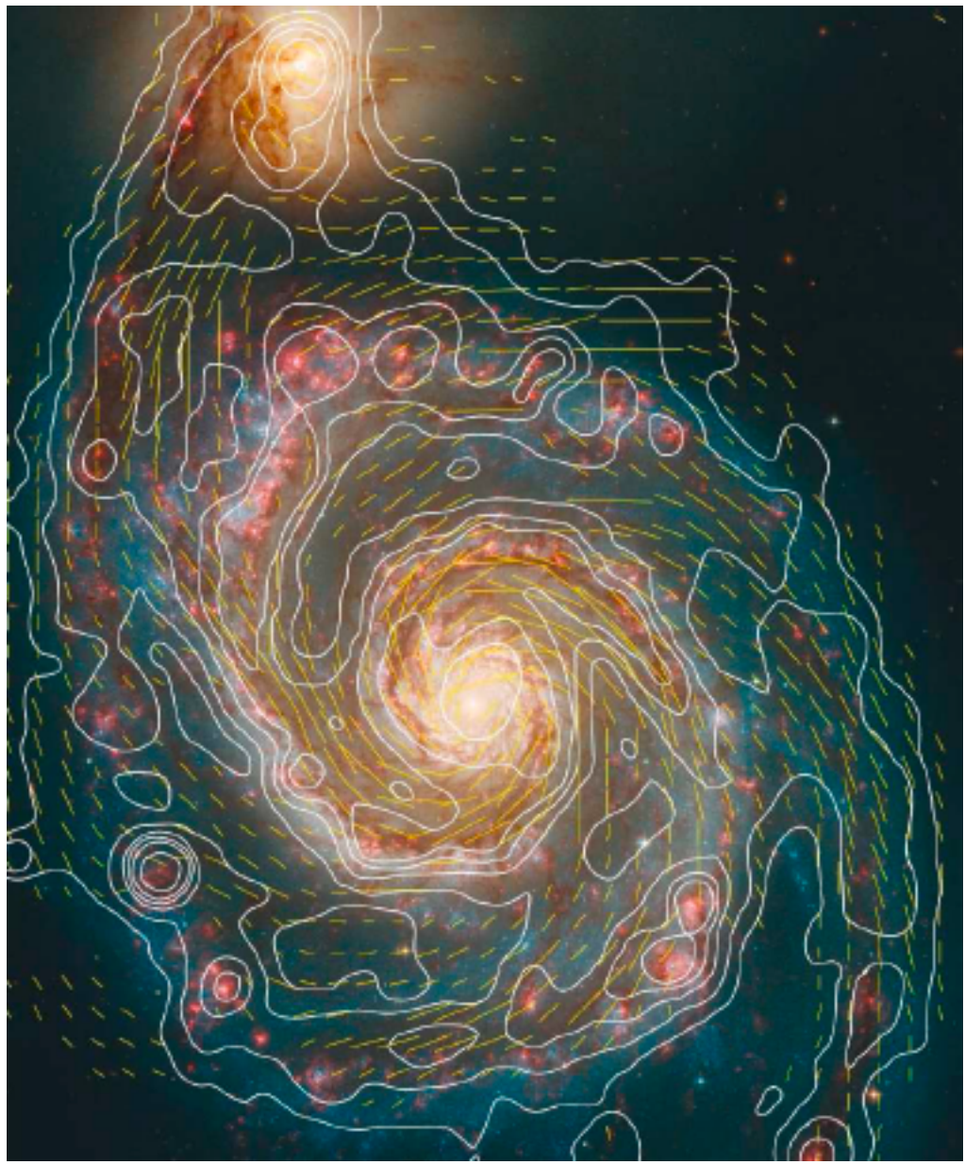


$Rm \sim 10^8$, $Re = 10^{11}$, Plasma

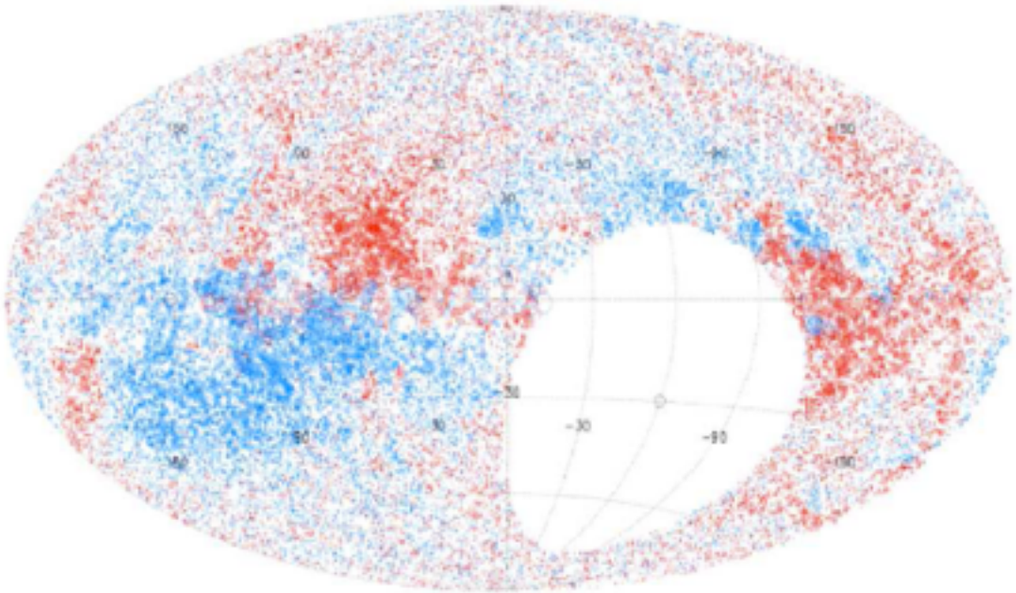
weak large scale field



Galactic Magnetic Fields: weak large-scale field + much stronger small-scale



M51



Faraday rotation along 38000 lines of sight
In the Milky Way (NVSS survey)

$Rm \sim 10^{14}$, $Re = 10^{9}$, Plasma

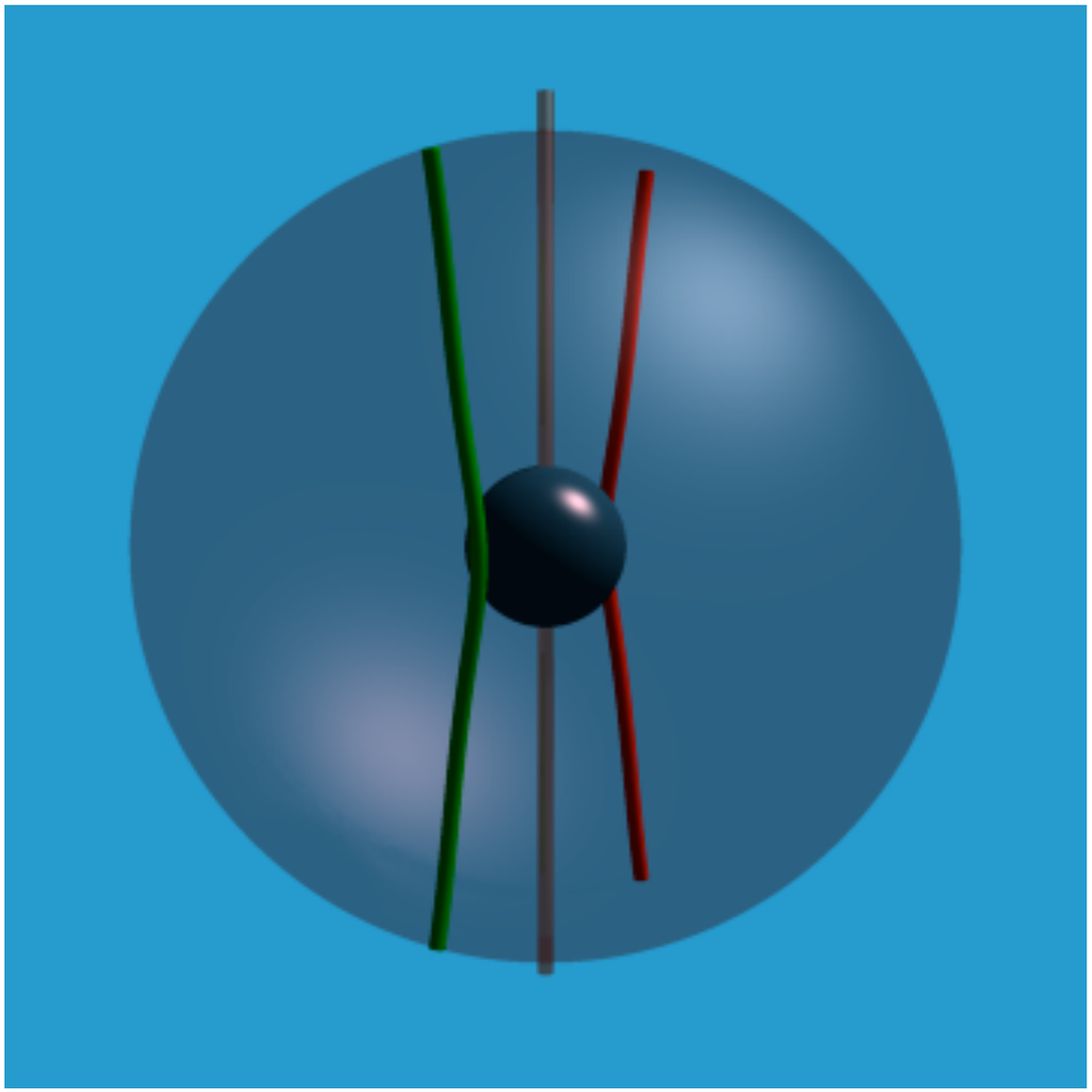
How could a rotating body, such as the Sun become a magnetic?

" . . . possible for the internal motion to act as a self-exciting dynamo, and maintain a magnetic field at the expense of some of the energy of the internal circulation."

J. Larmor Br. Assoc. Adv. Sci. (1919)

Standard Model of an MHD dynamo

Step 1: dipole field can be converted into strong toroidal field



The "Ω effect"

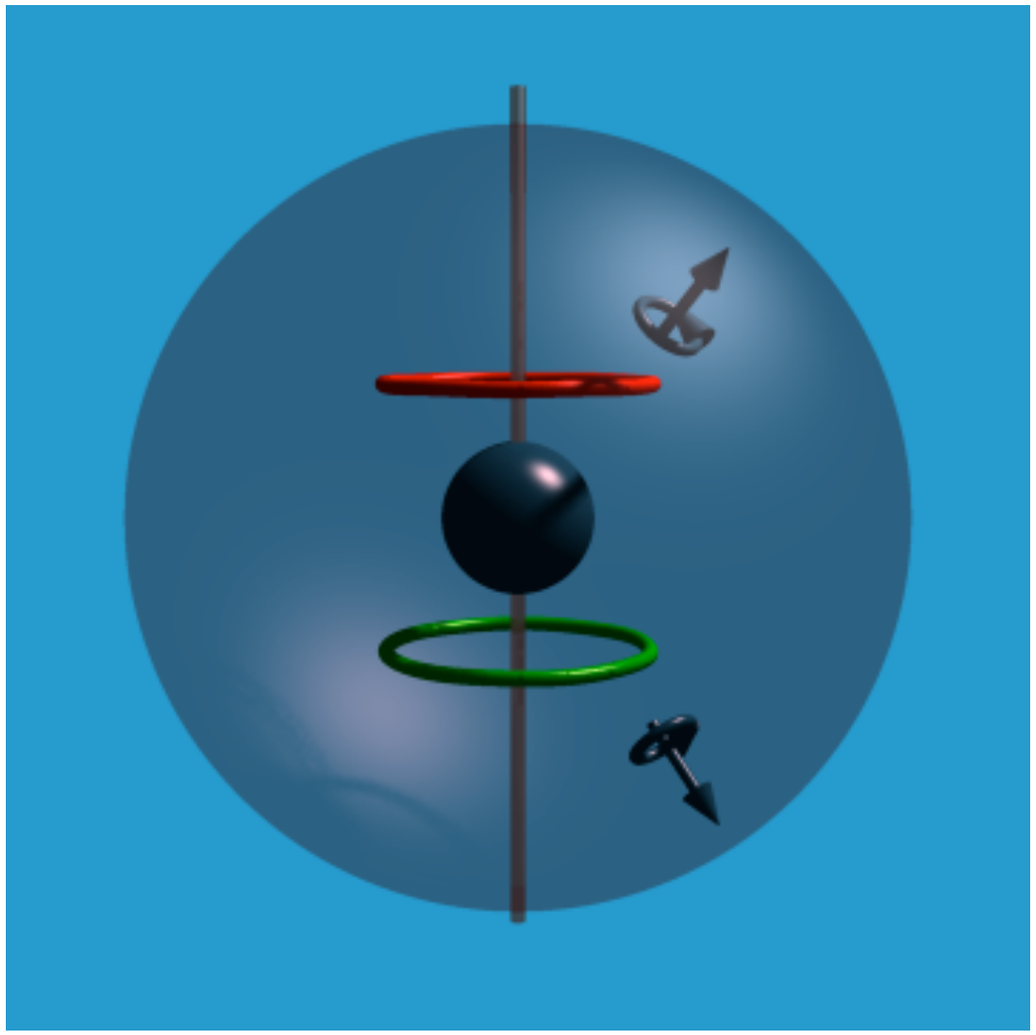
The Dark Ages of Dynamos (1920–1955)

When the magnetic field and the fluid motions are symmetric about an axis...no stationary dynamo can exist.

T.G. Cowling, *The magnetic fields of sunspots*, Monthly Notices Roy. Astron. Soc. **94** 39 (1933).

Standard Model of an MHD dynamo

Step 2: Nonaxisymmetric, helical flows convert toroidal field back into dipole



The "α effect": generates current in direction of B

E.N. Parker, *Hydromagnetic dynamo models*, Astrophys. J. **122** 293 (1955)

Overarching Goal

Create a steady, large, hot, weakly magnetized flowing plasma in which the kinetic energy of the flow drives magnetic instabilities

$Rm = \mu_0 \sigma U L \gg 1$

K.E.≫M.E. (super Alfvénic: $\rho U^2 \gg B^2/\mu_0$)

New regime for plasma experiments–astrophysical applications

Plasmas are Challenging

-difficult to stir

-some confinement required with weak B

(conductivity: plasma must be hot)

Use Liquid Metals

-confinement is free

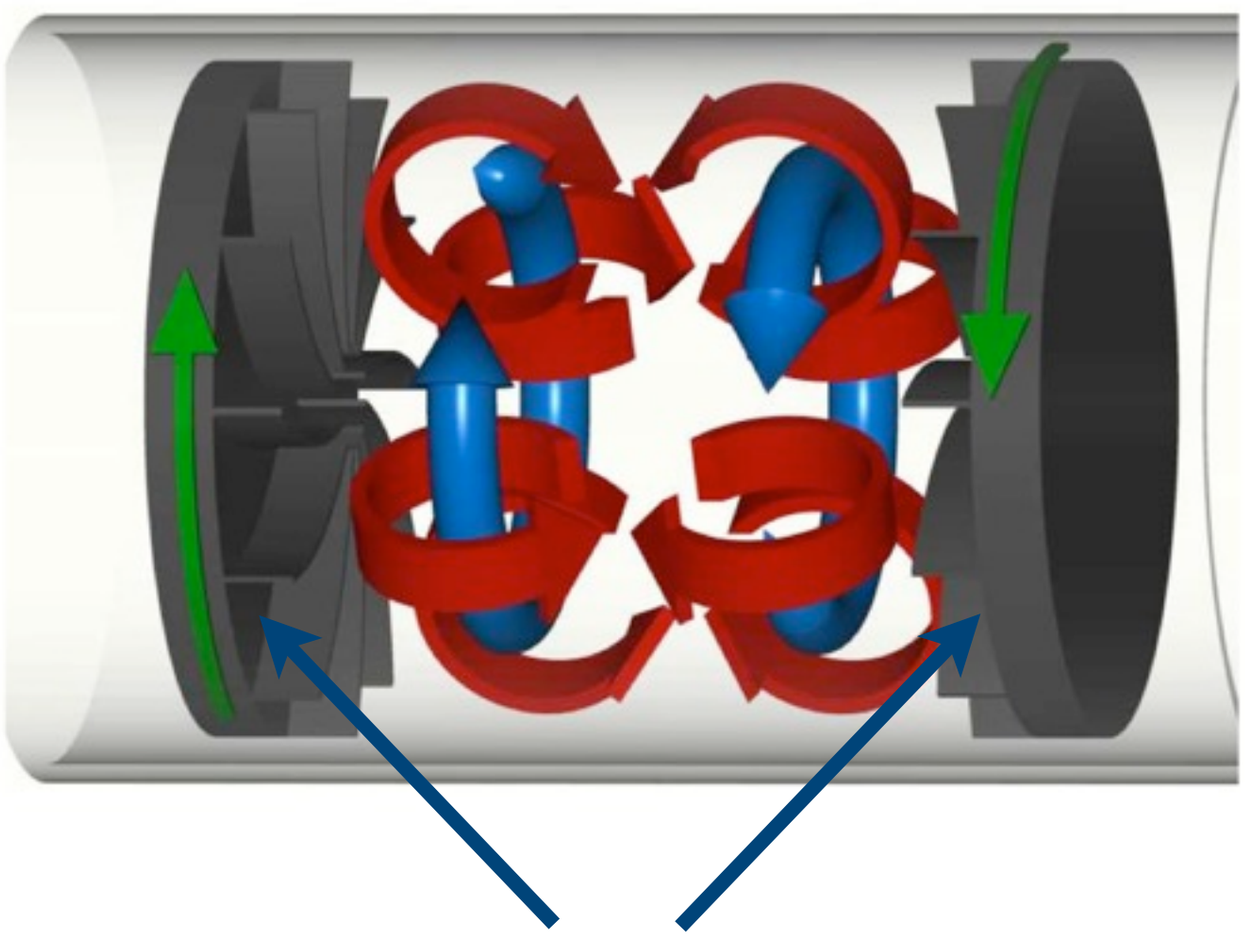
-easy to stir

-BUT power scaling is challenging: $P_{mech} \sim Rm^3 / L$

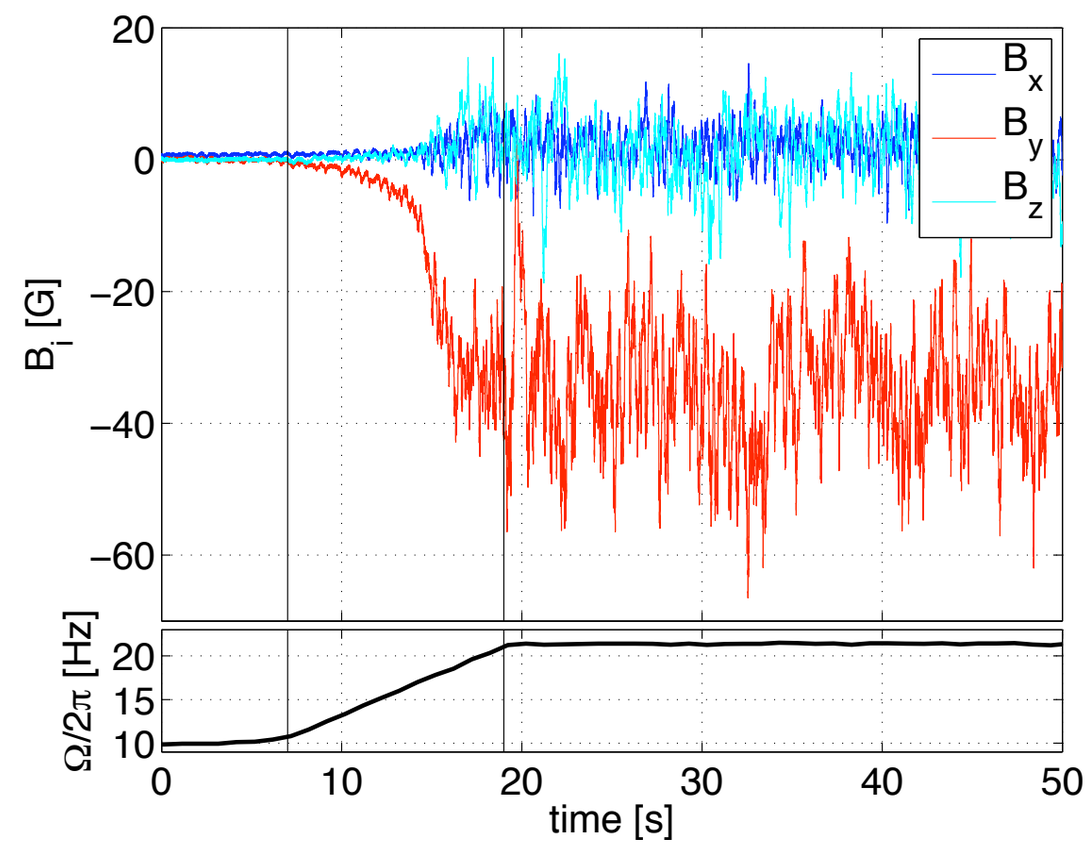
[Rm=100, P_{mech}=100 kW]

-Re = 10^5 Rm (always turbulent)

VKS Liquid Sodium Dynamo at Cadarache



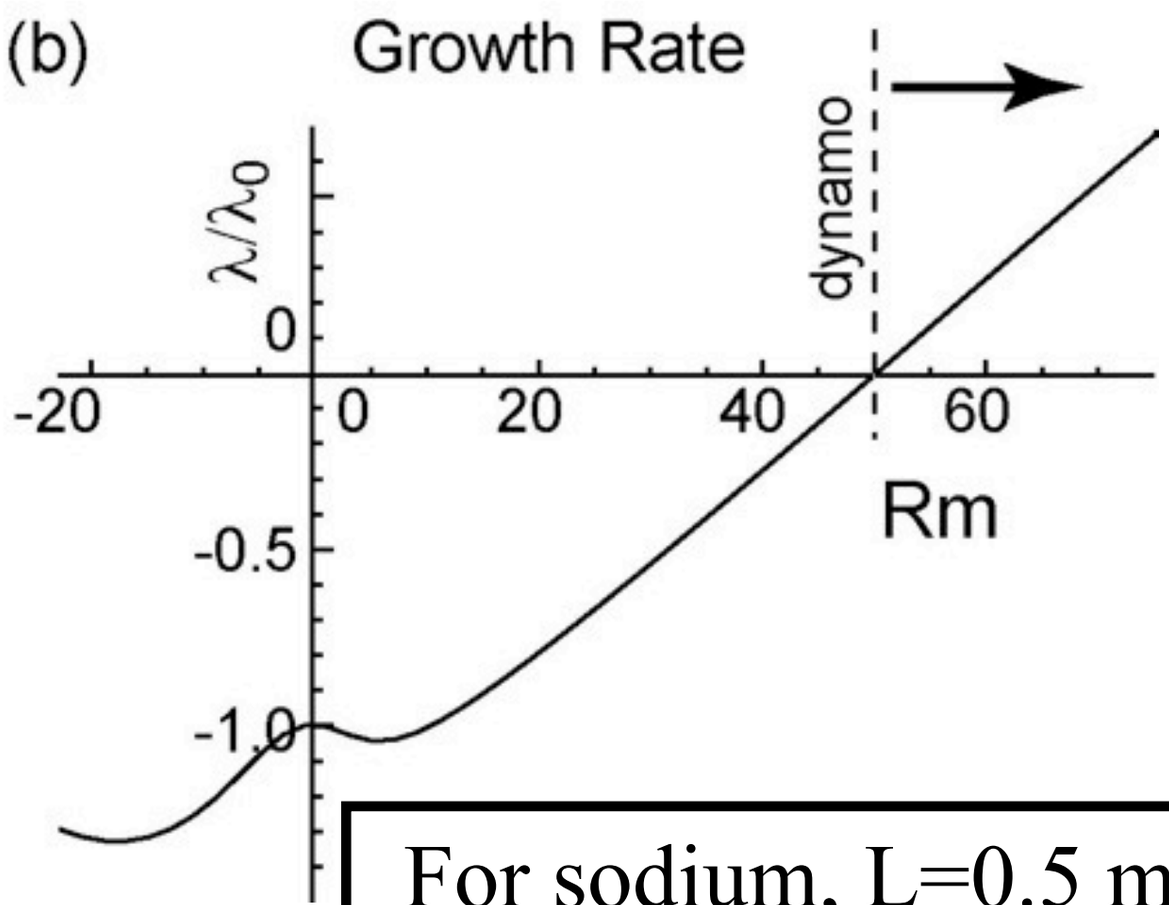
Counter Rotating
Iron Disks and Impellers

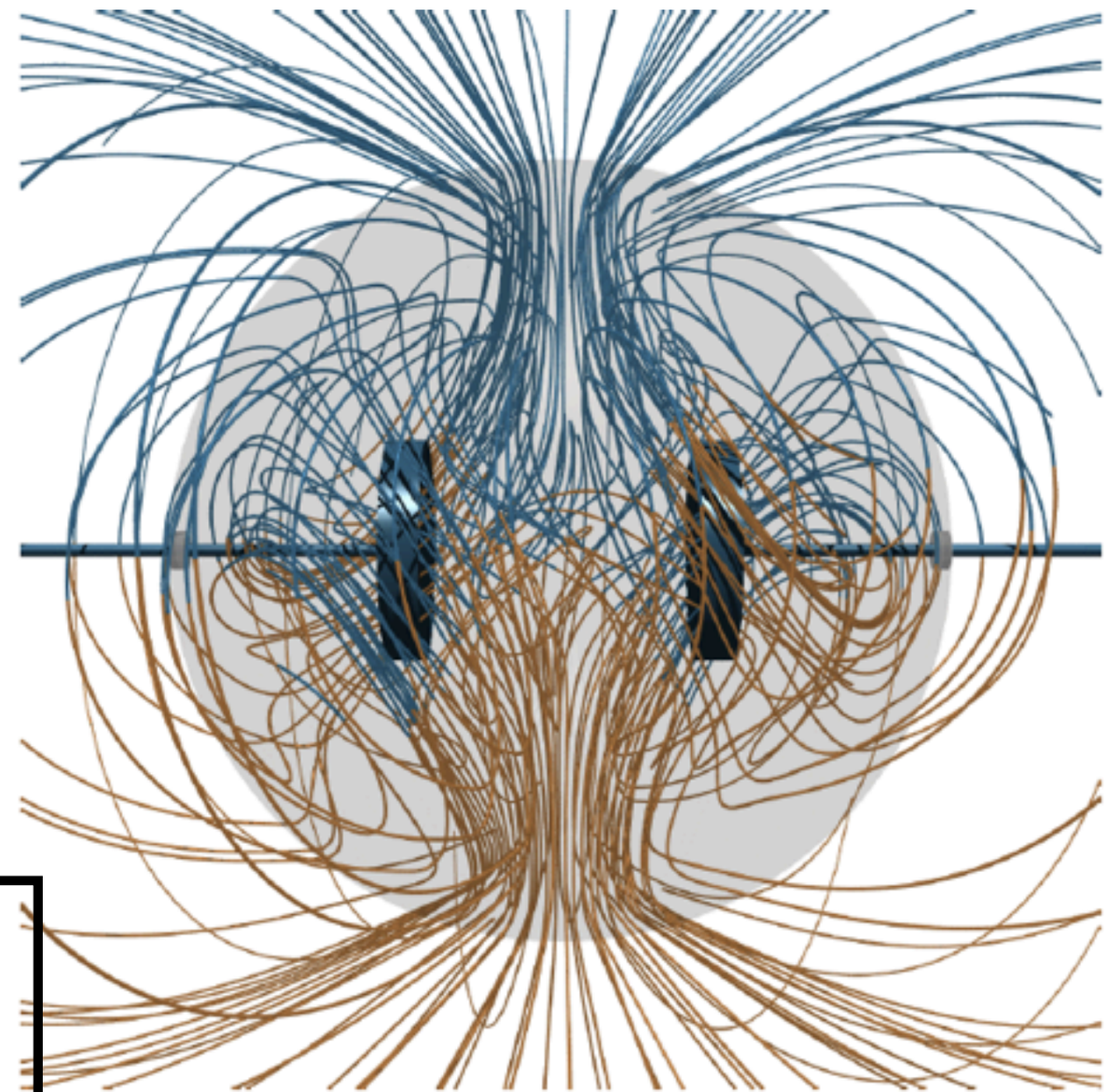


Two vortex flow is simplest flow which generates a stationary dipole (Rm_{crit}~50)

Flow

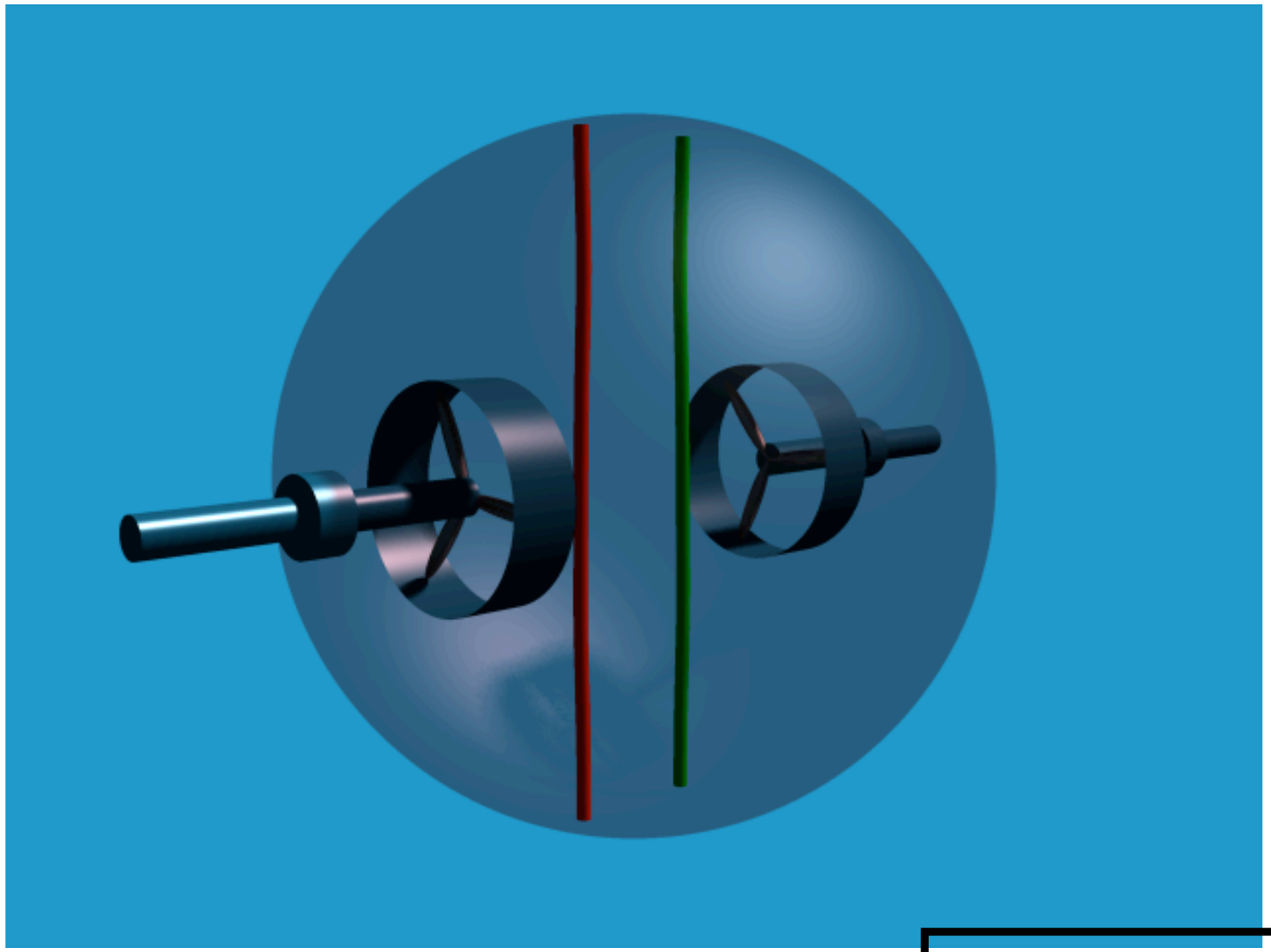
Magnetic Field





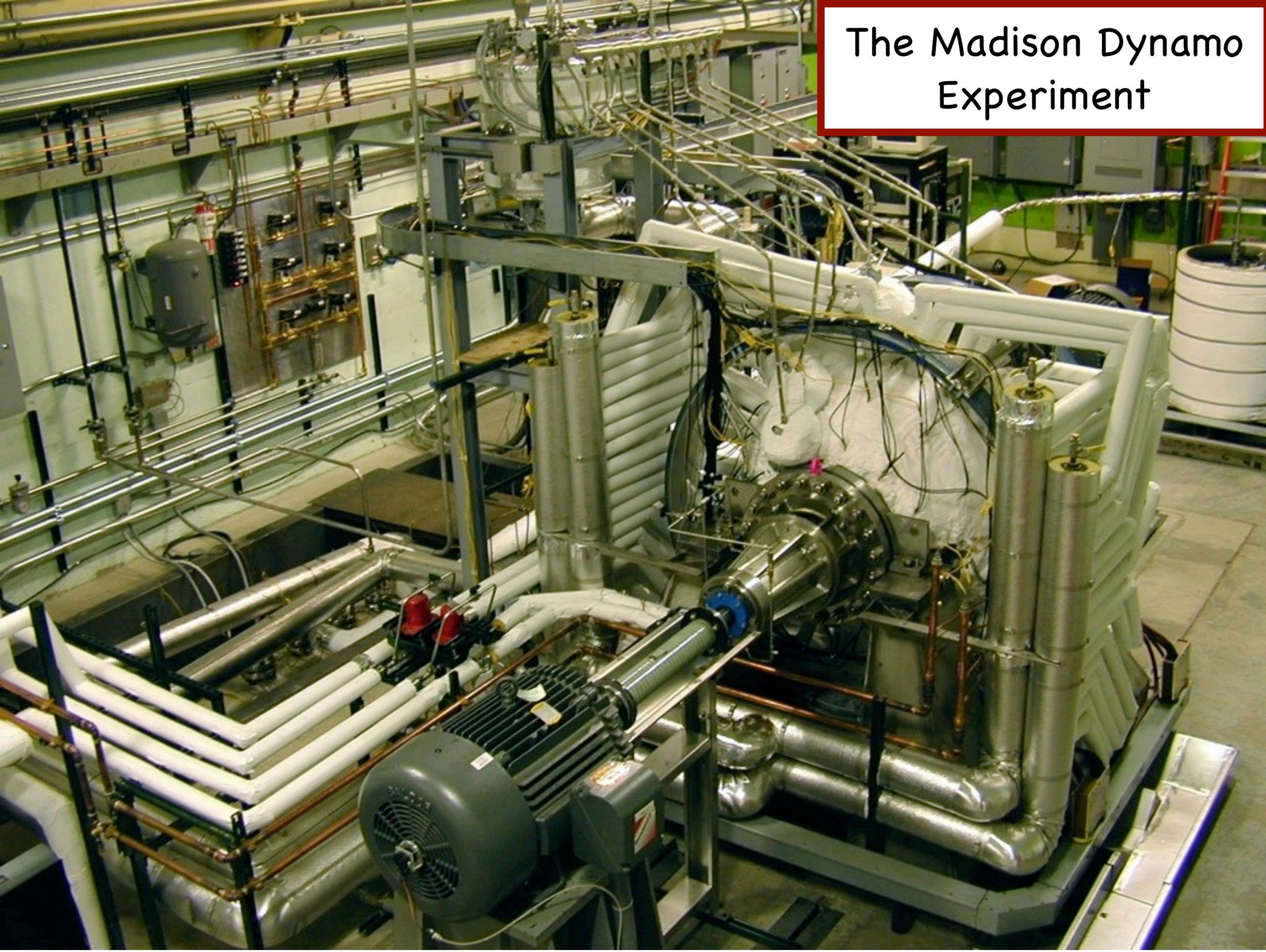
For sodium, L=0.5 m,
Rm = 6 x $V_{[m/s]}$

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



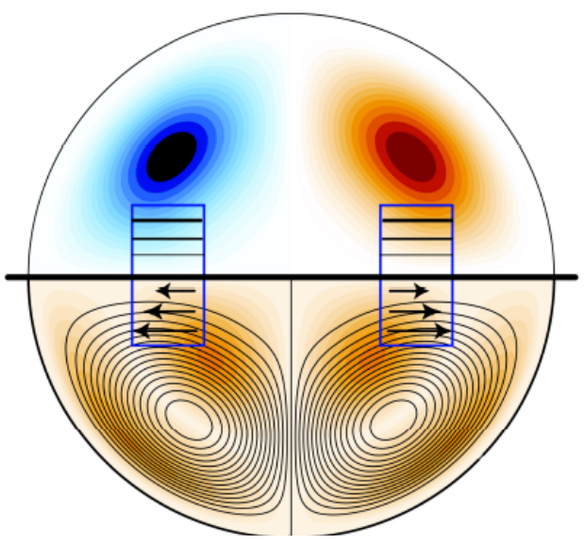
For sodium, L=0.5 m,
$Rm = 6 \times V_{[m/s]}$

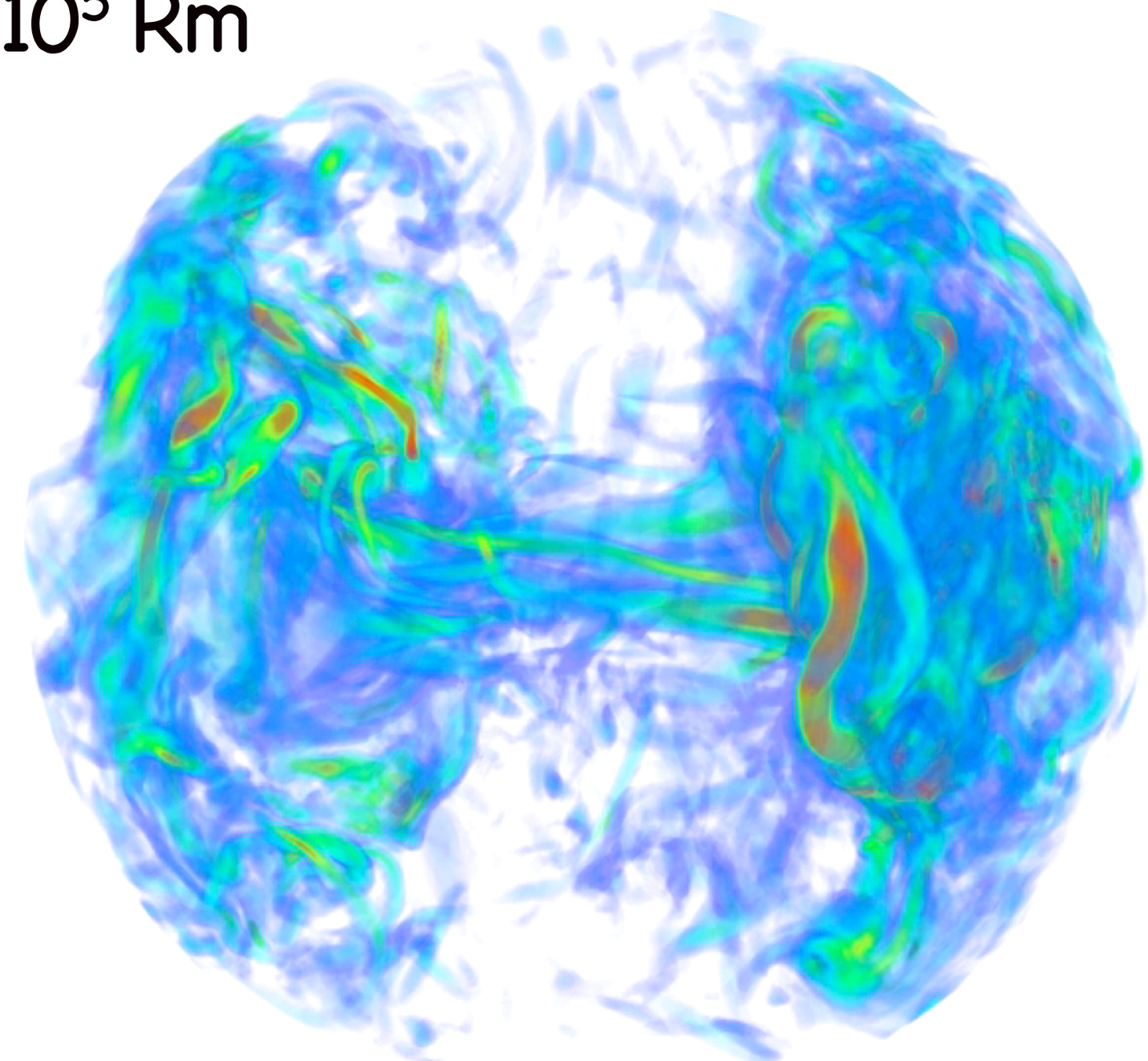
The Madison Dynamo Experiment



Turbulence makes homogeneous dynamos notoriously difficult

For liquid metals Re~10^5 Rm





Re~2000

Long Standing Prediction: Turbulent transport of magnetic field

- Transport of B is controlled by turbulent EMF

$$\mathcal{E} = \left\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{b}} \right\rangle$$

- closure ansatz: $\mathcal{E} = \alpha \mathbf{B} - \beta \nabla \times \mathbf{B}$

$$\alpha \propto \text{ flow helicity}$$

$$\beta = \frac{1}{3}\tilde{v}^2 \tau_{corr} \equiv \frac{\tilde{v}\ell}{3}$$

- Modifies induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{V} \times \mathbf{B} + \nabla \times \alpha \mathbf{B} + \eta_{turb} \nabla^2 \mathbf{B}$$

$$\eta_{turb} = \frac{1}{\mu_0 \sigma} + \frac{\tilde{v}\ell}{3}$$

Turbulence Enhances Effective Resistivity

Definitions

$$Rm = VL/\eta \qquad Rm_T = \tilde{v}\ell/\eta \qquad \eta = \frac{1}{\mu_0 \sigma}$$

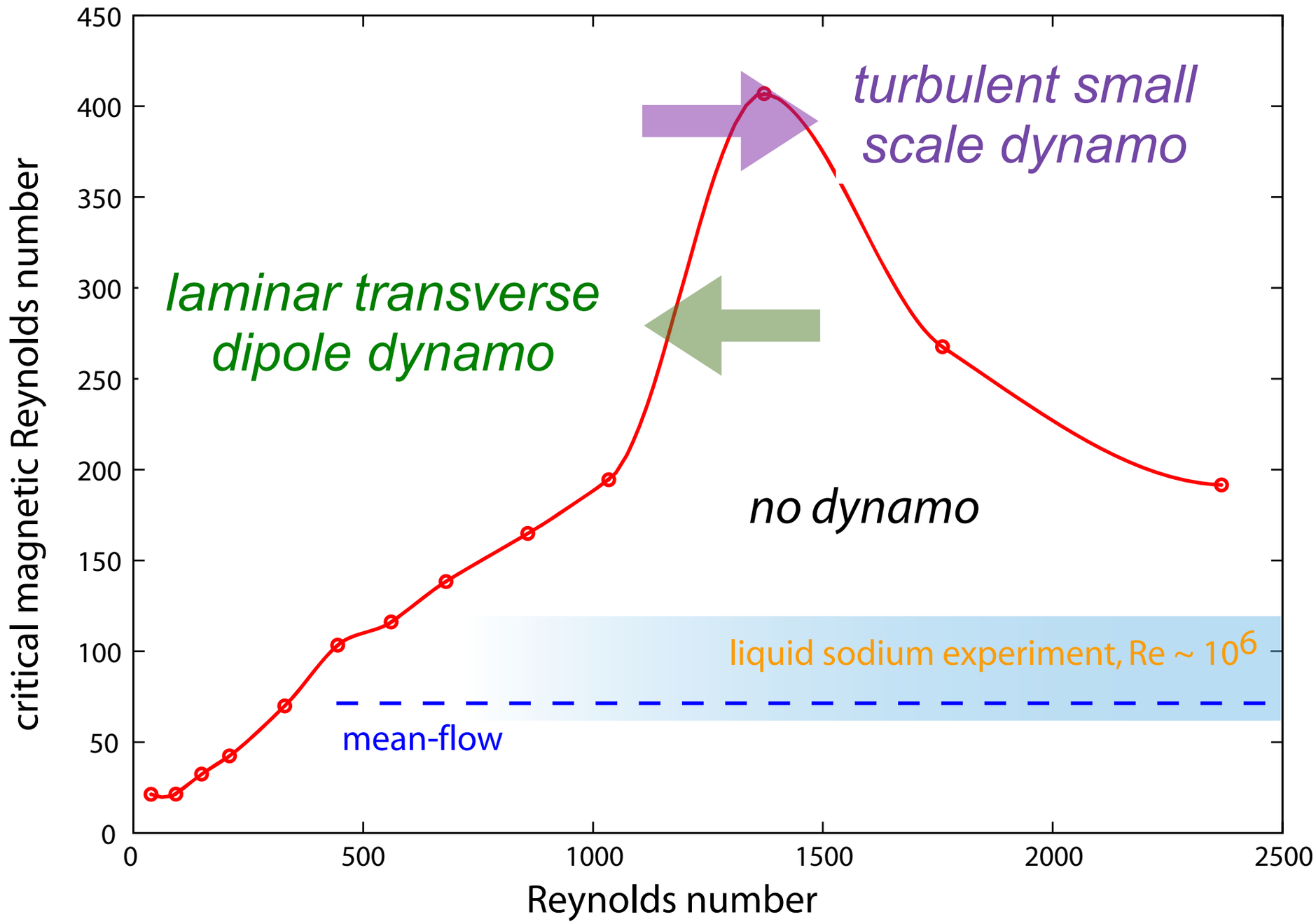
Mean-Field Electrodynamics predicts
(confirmed by measurements)

$$\eta_T = \eta\,(1 + Rm_T/3)$$

Self-Excitation Requirement

$$\boxed{Rm \geq Rm_{crit}(1 + Rm_T/3)}$$

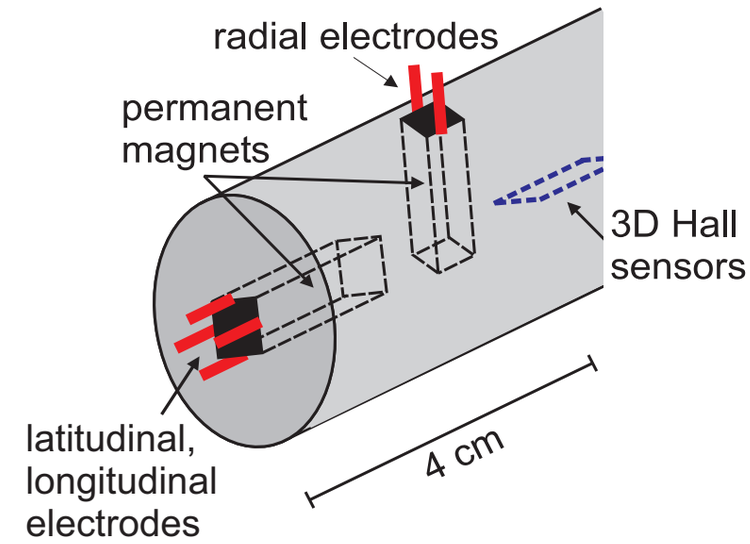
Numerical simulations show turbulence suppresses the dynamo for Unconstrained Flows

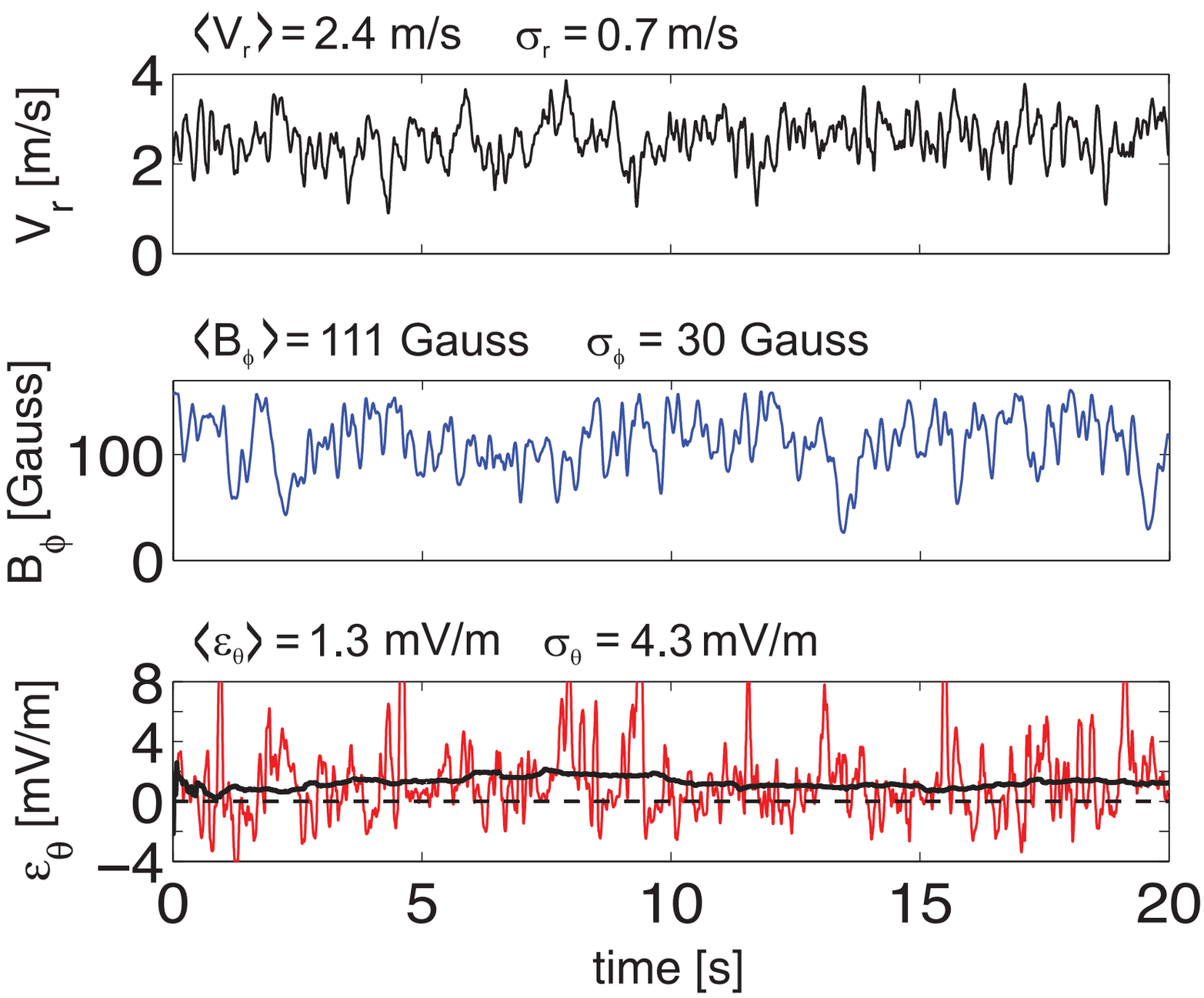


Turbulent MHD dynamo action in a spherically bounded von Kármán flow at small magnetic Reynolds number
Reuter, Jenko, and Forest, New Journal of Physics 13 073019 (2011).

Localized measurement of the turbulent EMF

Three-axis velocity and magnetic field probe

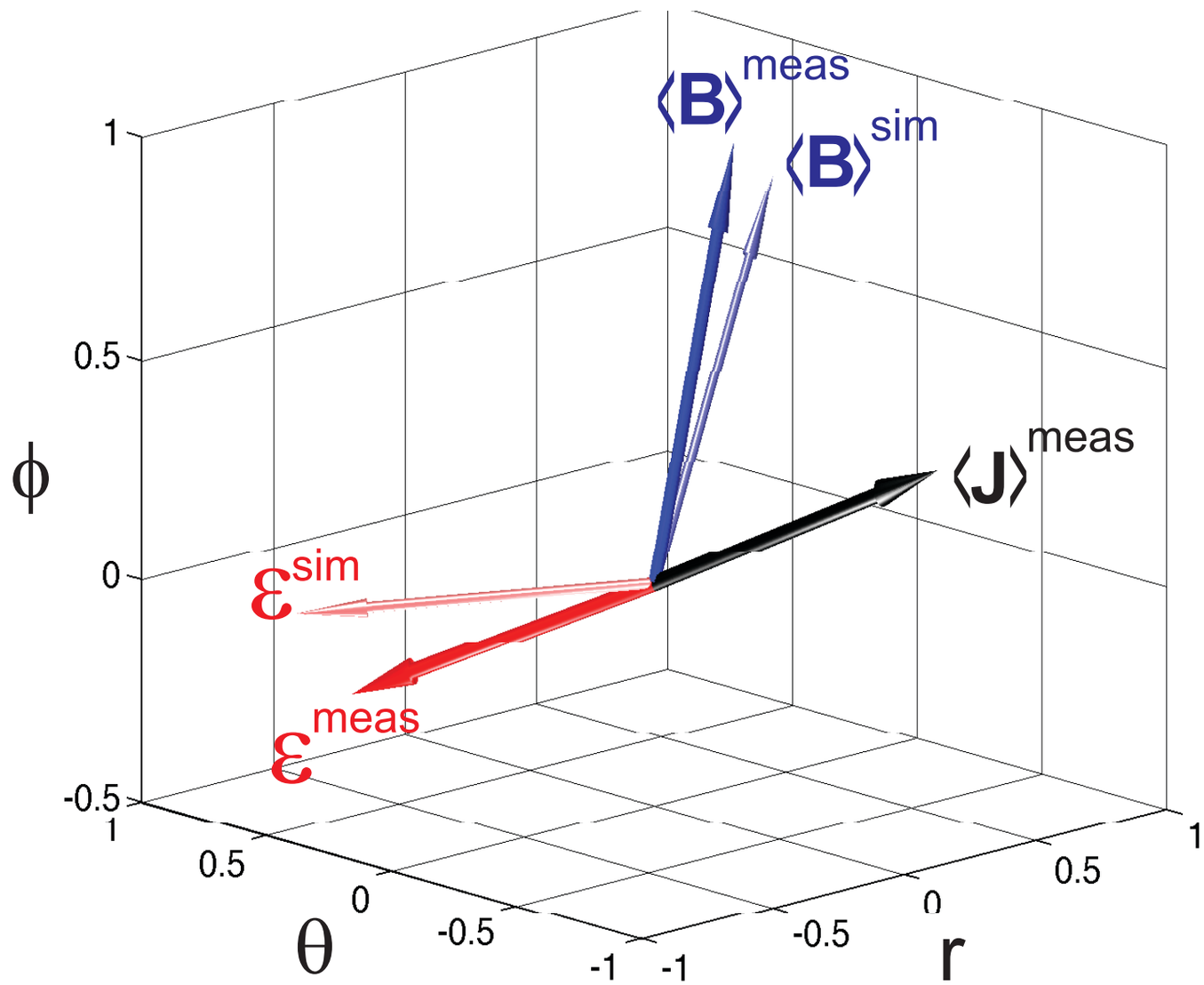




$$\mathbf{V}^{\mathbf{meas}} = \langle \mathbf{V} \rangle + \tilde{\mathrm{v}}$$
$$\mathbf{B}^{\mathbf{meas}} = \langle \mathbf{B} \rangle + \tilde{\mathrm{b}}$$

$$\varepsilon^{turb} = \left\langle \tilde{\mathrm{v}} \times \tilde{\mathrm{b}} \right\rangle$$

The turbulent EMF opposes the local current, equivalent to increase resistivity



$$\eta_{eff} = \eta + \frac{\tilde{v}\ell}{3}$$

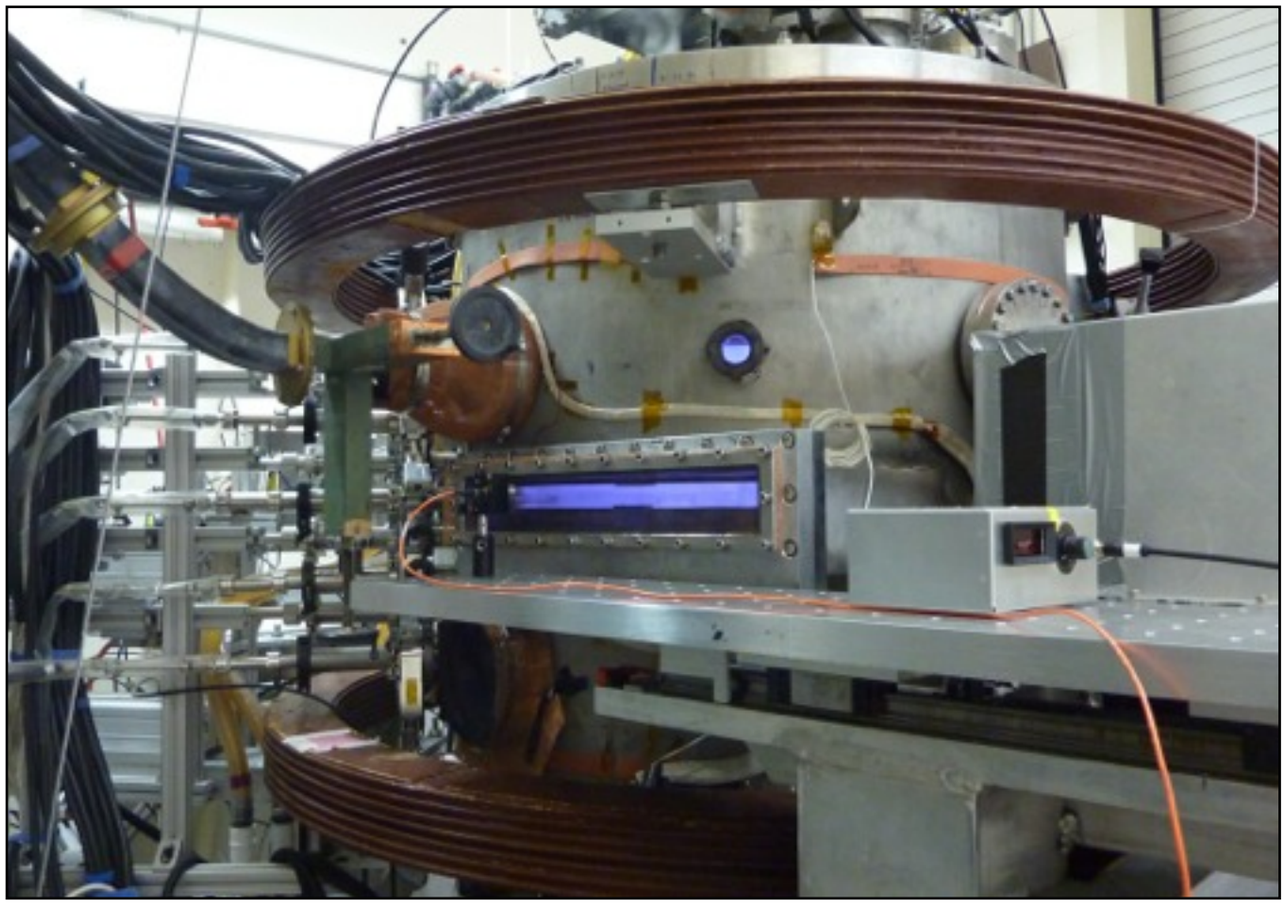
Next Step: Plasma Dynamo Experiments

- Rm > 1000 $\quad Rm = 50\, T_{e,10eV}^{3/2}\, V_{km/s}\, L_m$
- Independent $\quad Re = 8\, \mu^{1/2} n_{10^{18}m^{-3}}\, V_{km/s}\, L_m / T_{i,eV}^{5/2}$
- Rapidly Rotating
- Compressibility, stratification, buoyancy
- Plasma Effects beyond MHD: neutrals, kinetic effects, Hall MHD

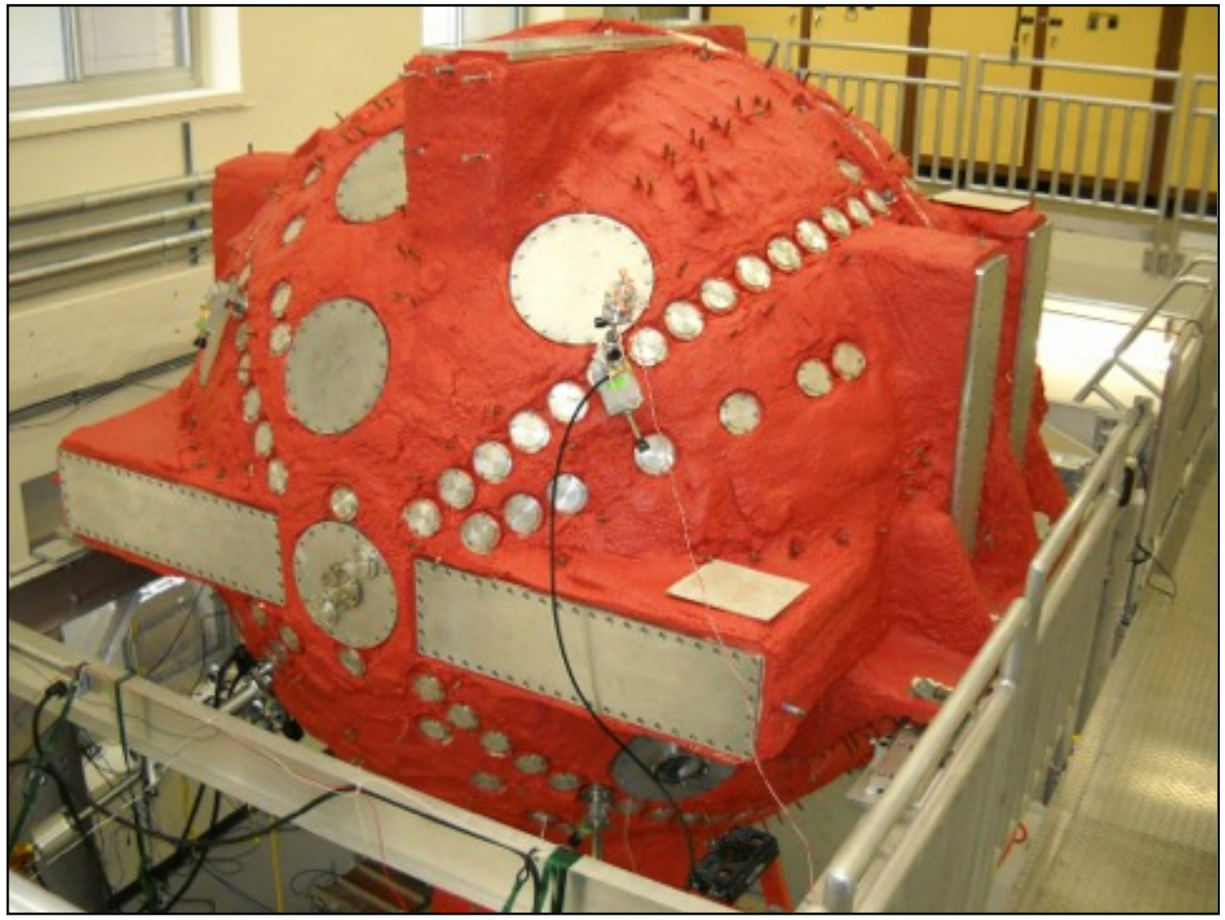
→Study confinement and stirring in an unmagnetized plasma

Flowing, unmagnetized plasmas in the Lab

Plasma Couette Experiment

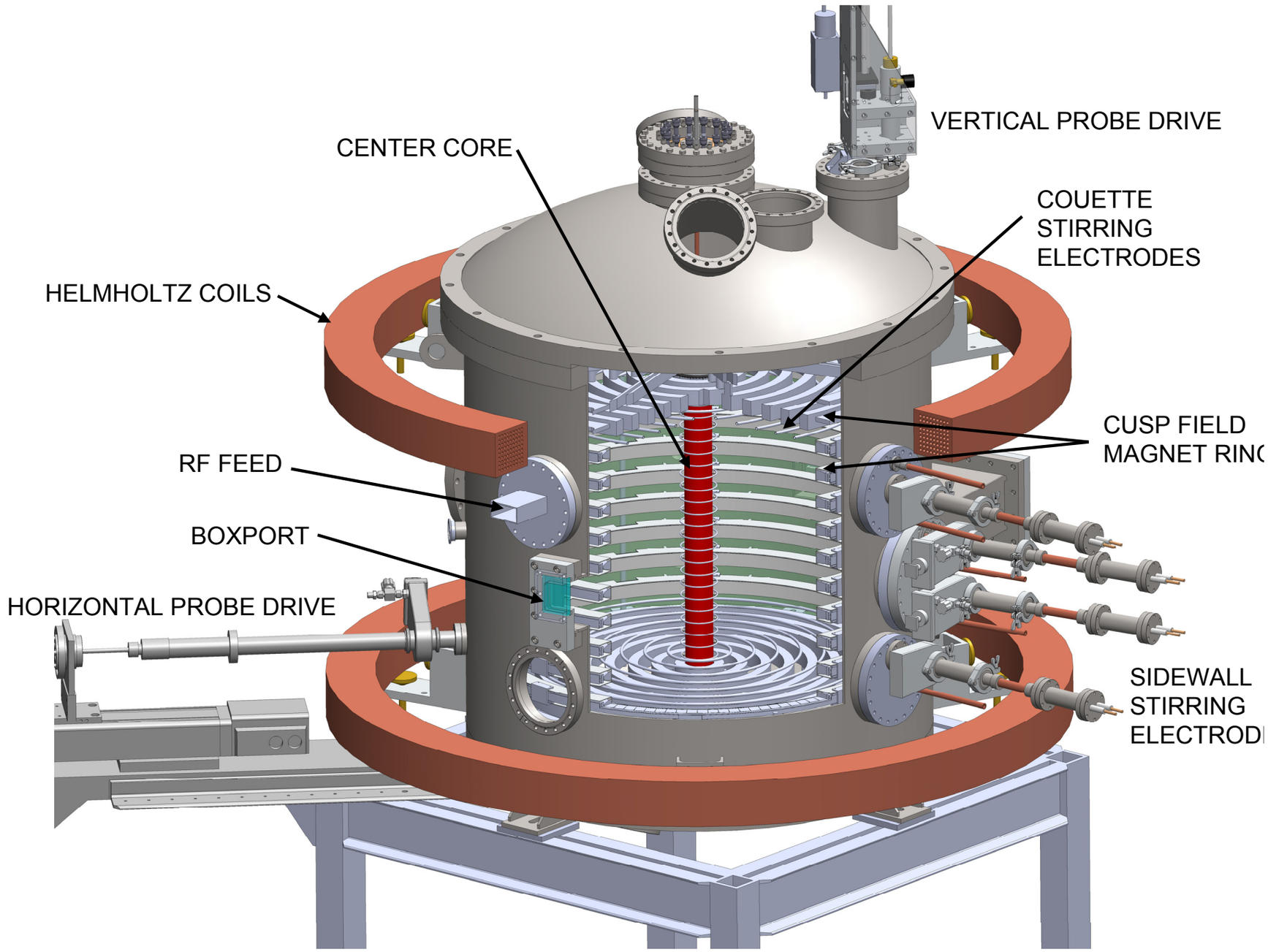


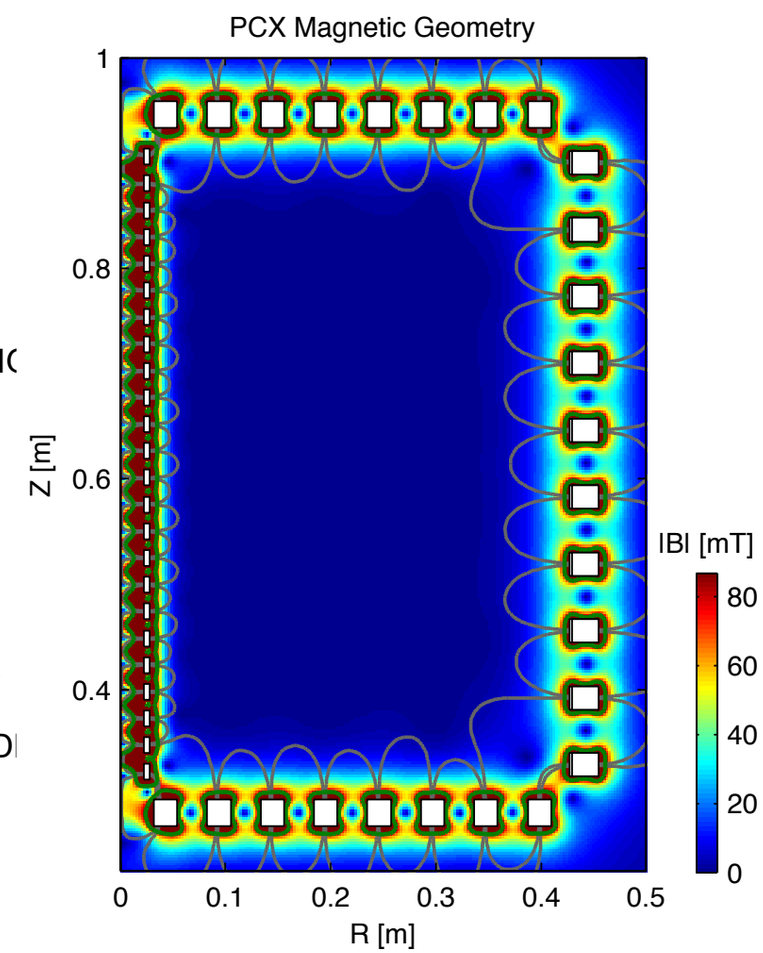
Madison Plasma Dynamo Experiment



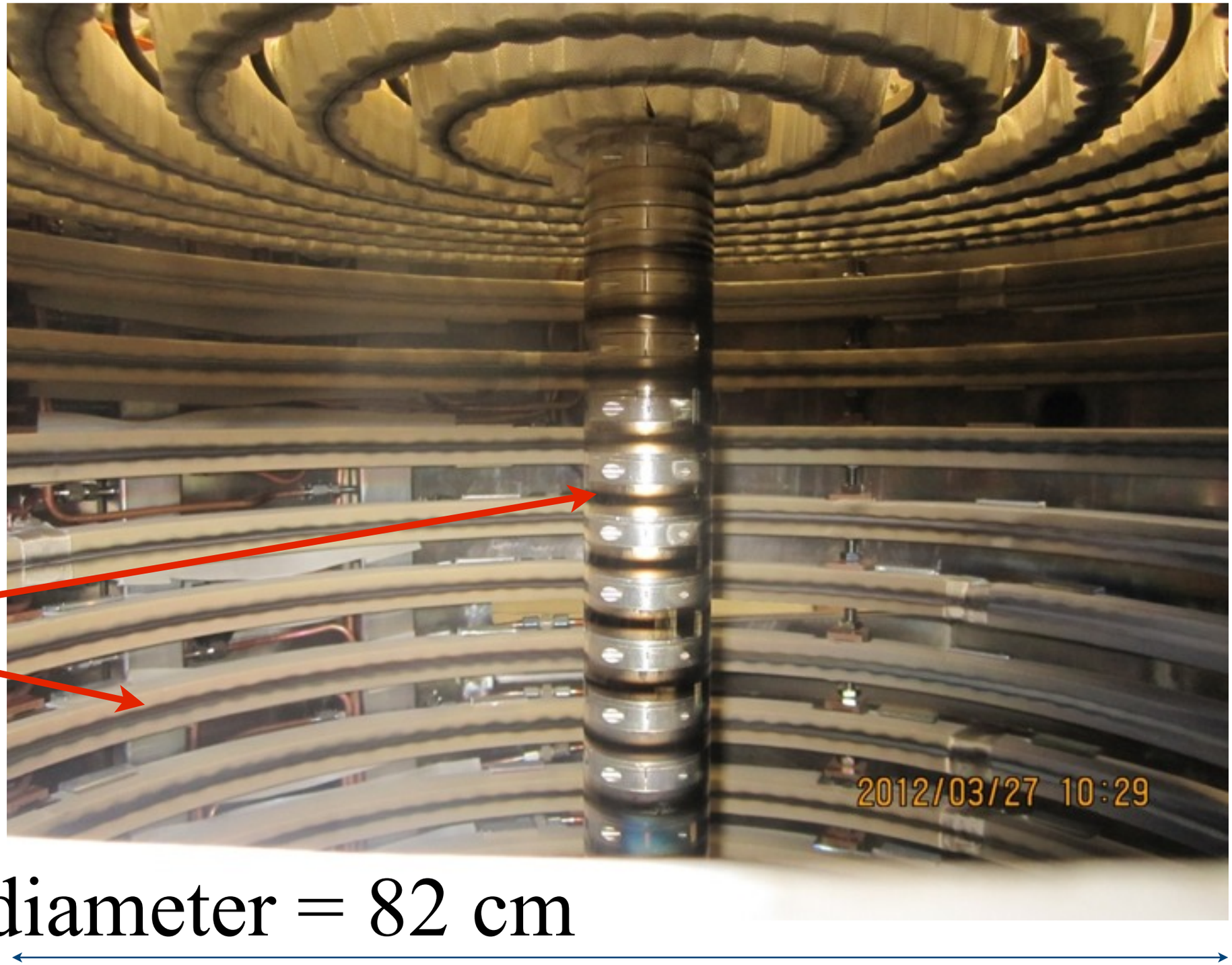
- Challenge:
  - -Need confinement for plasma to be hot (σ) and dense (ρ)
  - -Difficult to drive flow in an unmagnetized plasma

Plasma Couette Experiment is a prototype





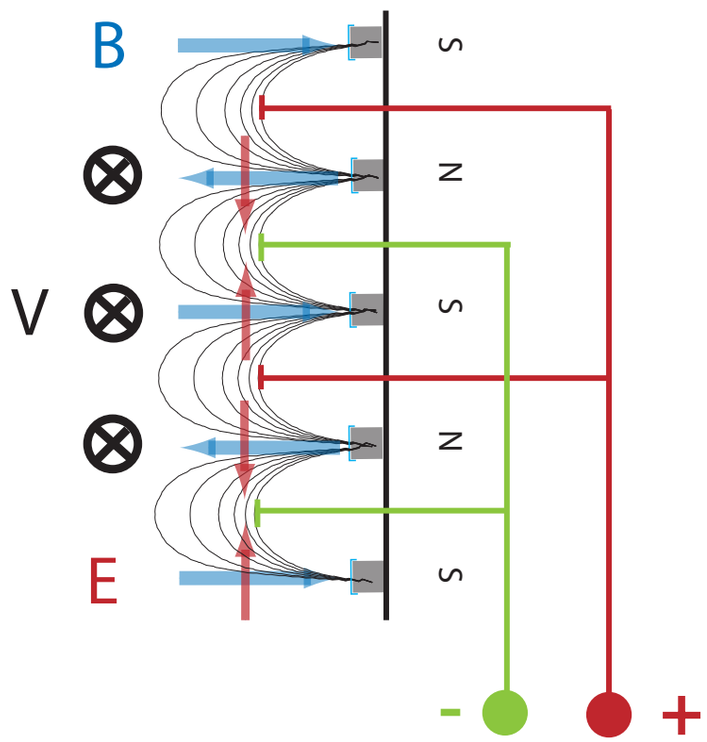
Multicusp confinement reduces loss area



Mirror losses leave deposits

diameter = 82 cm

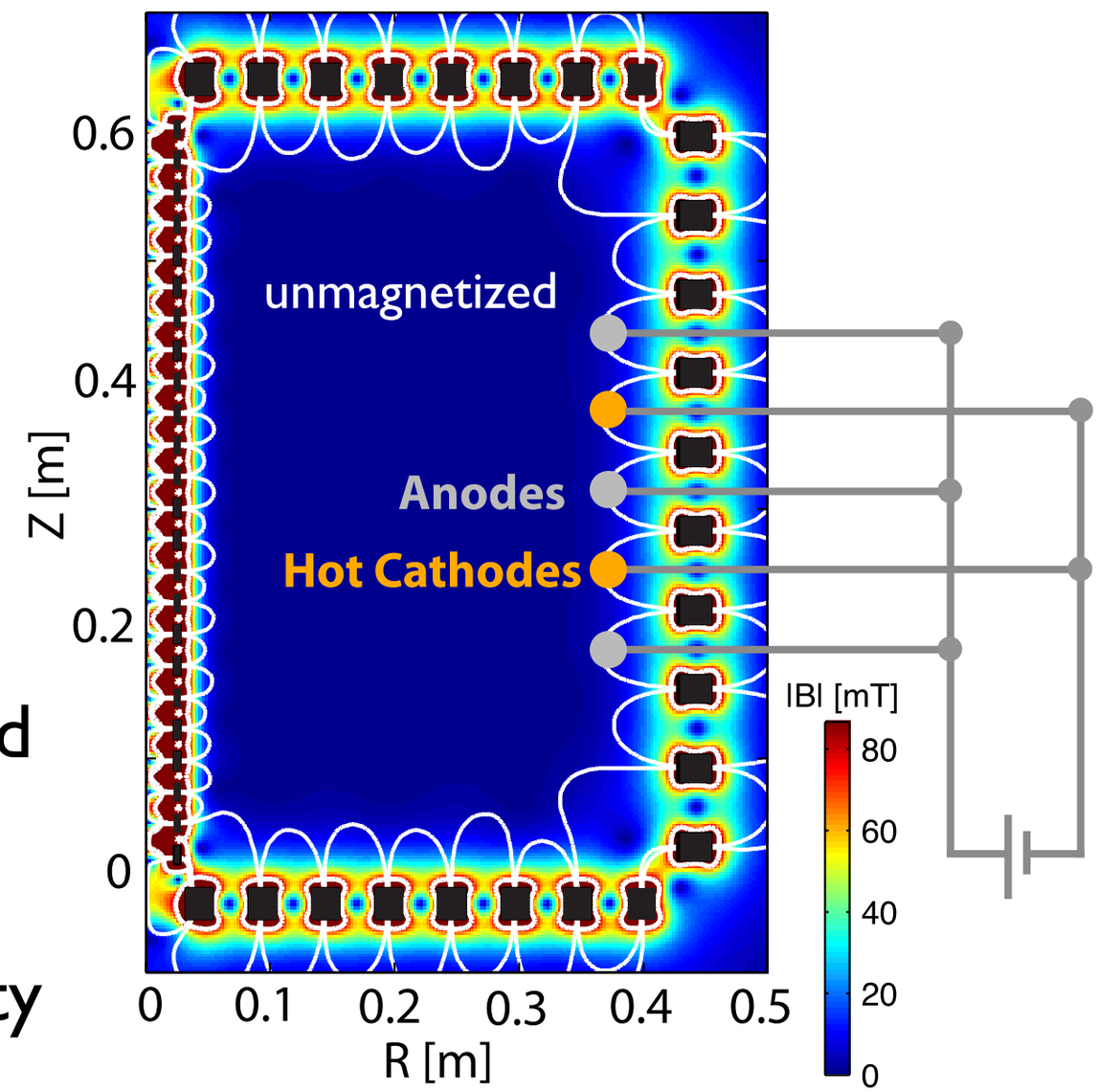
The Concept: Create Plasma Rotation Using Biased Cathodes



Cathode

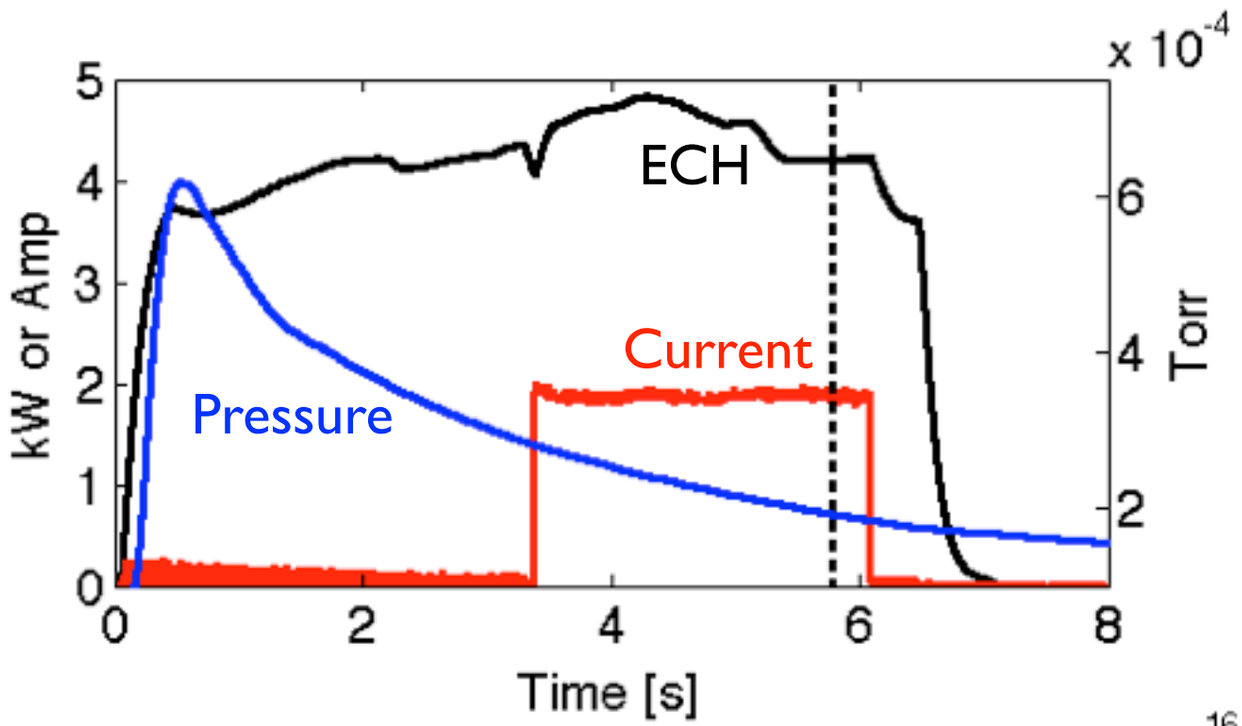
Mach Probe

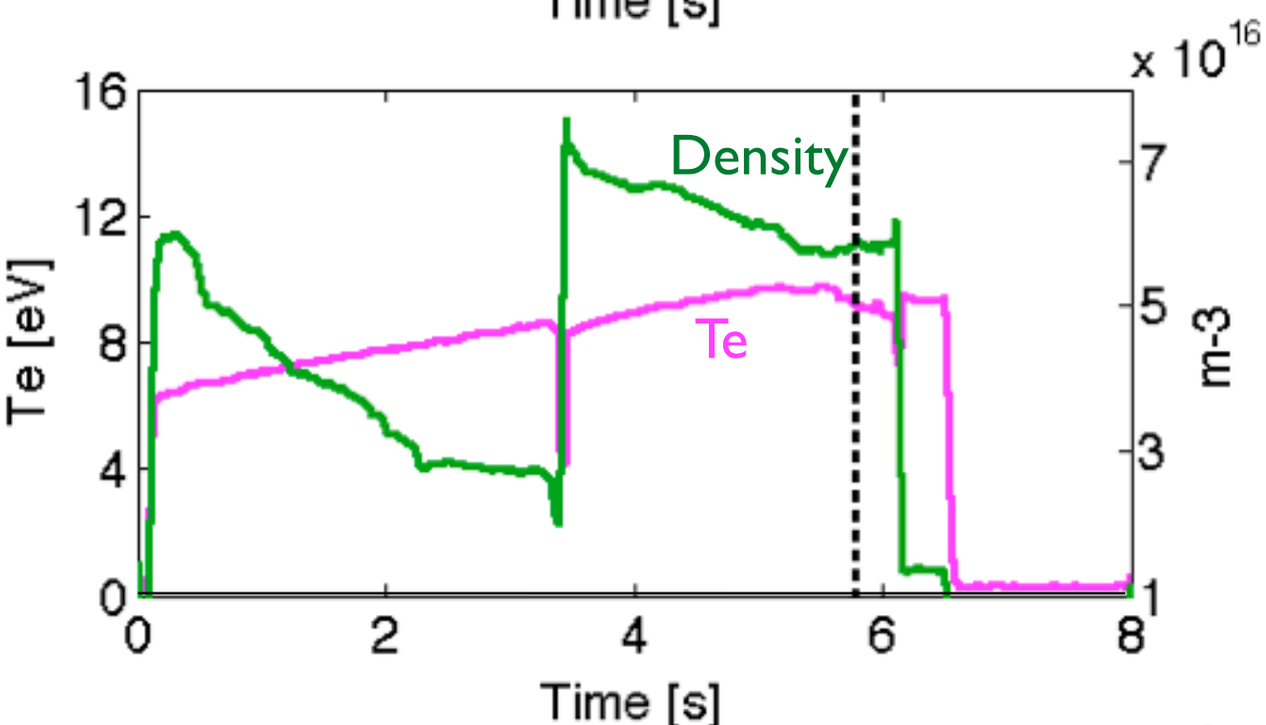
Initial Setup for Spinning from Outer Boundary



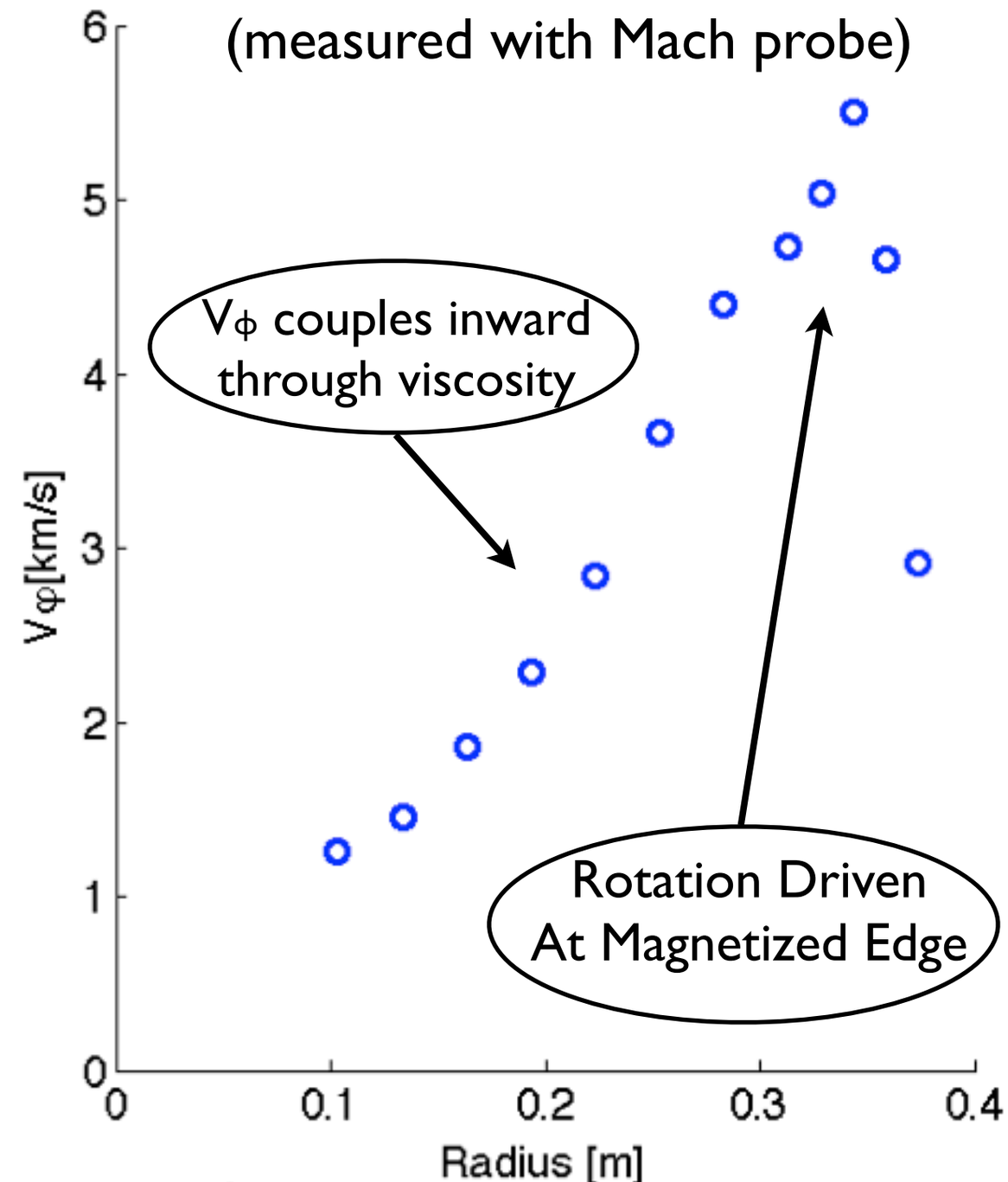
- Toroidally localized electrodes are biased to create JxB torque
- Velocity couples inward through viscosity
- Rotation is axisymmetric

The Rotation Scheme Works!





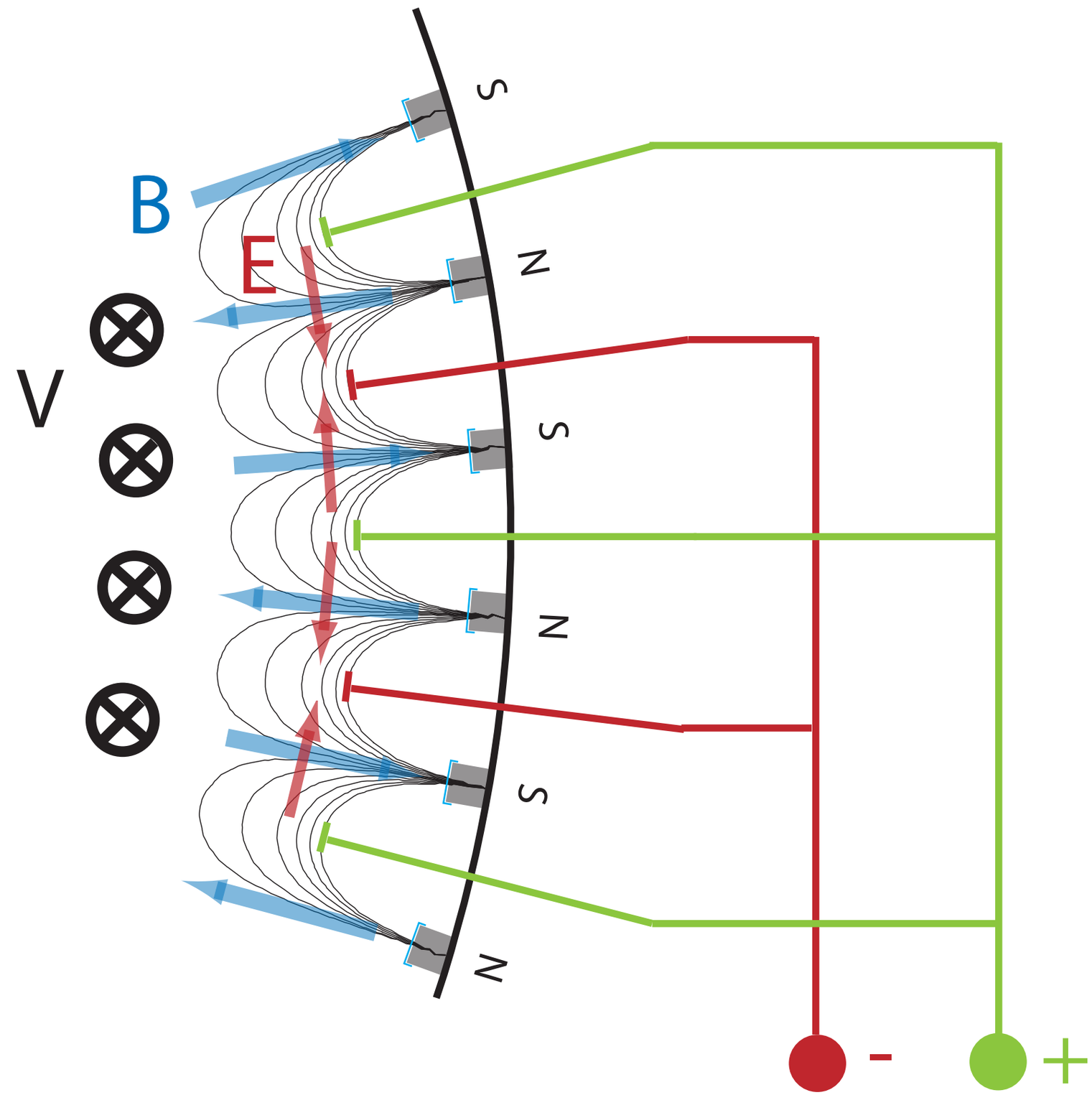
He Velocity Profile
2 Outer Cathodes Biased 550 V
(measured with Mach probe)



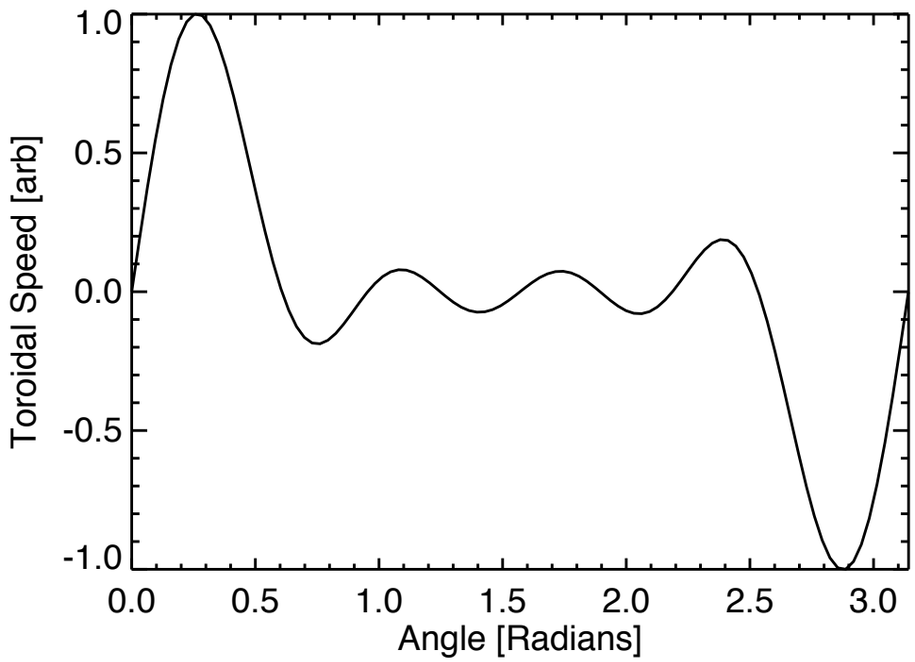
Pm~10 Rm~50

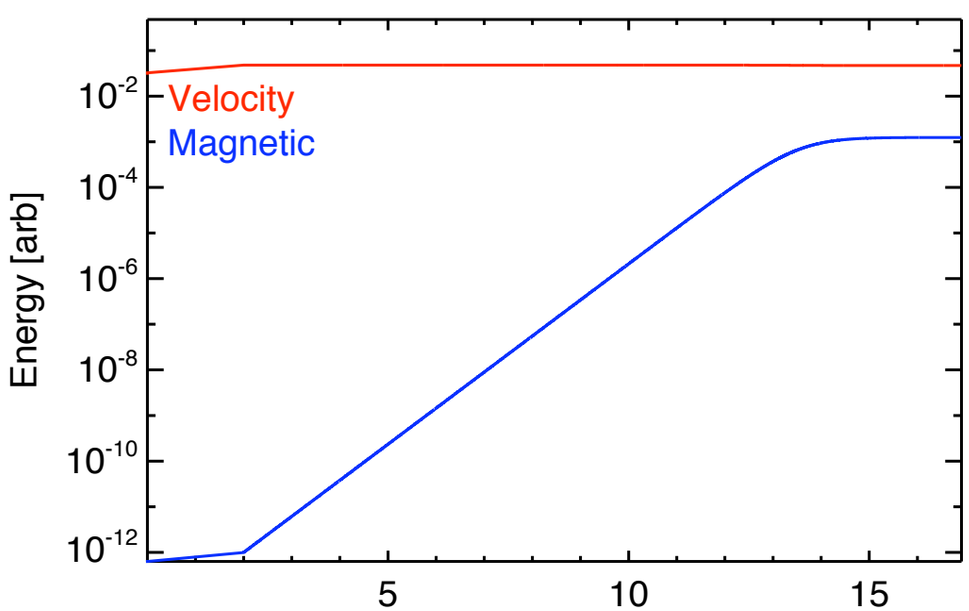
Electrostatic biasing controls edge rotation

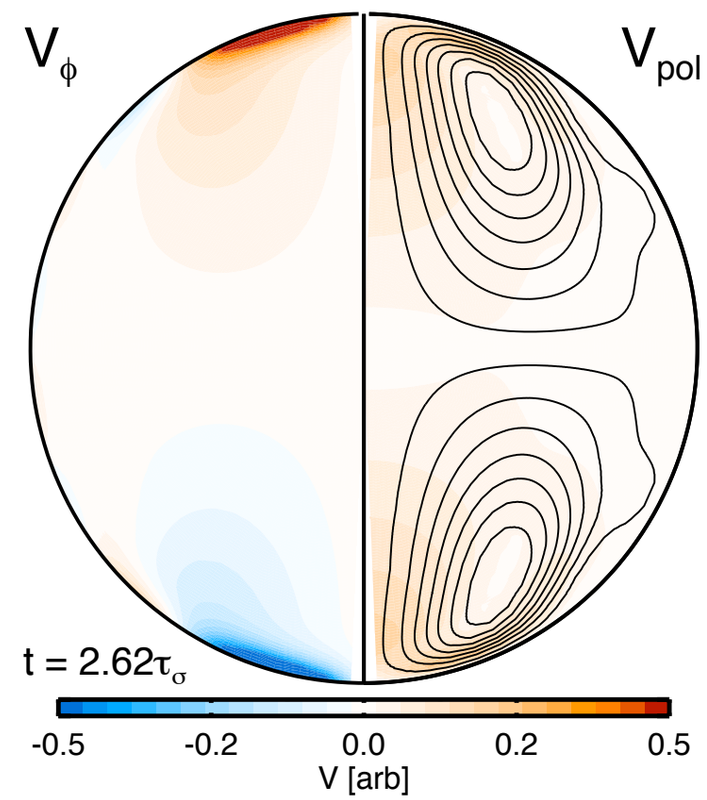
Arbitrary
$V_\varphi\ (r = a, \theta)$



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

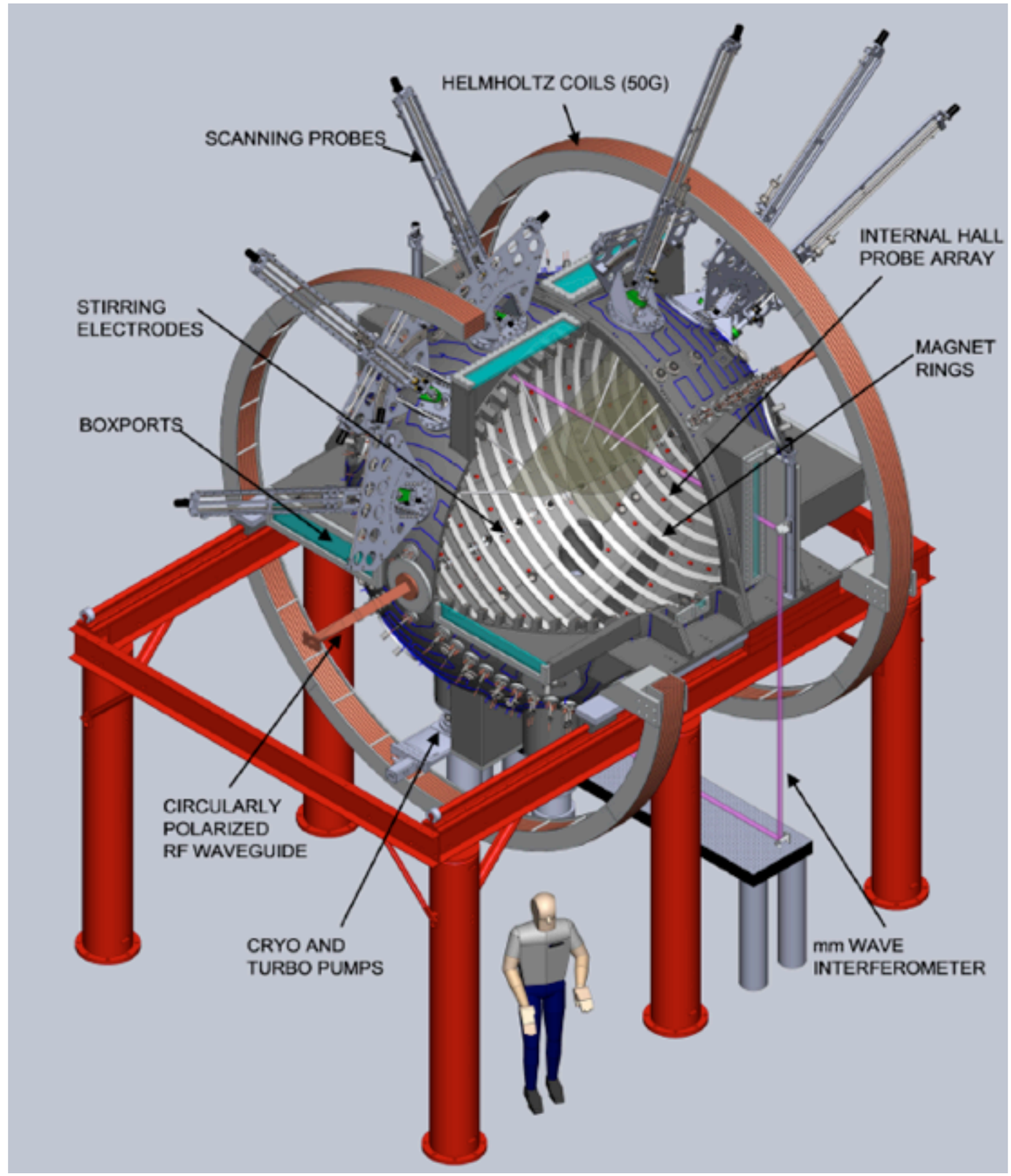
Spence, Reuter, and Forest, *A Spherical Plasma Dynamo Experiment,* The Astrophysical Journal **700** 470 (2009).

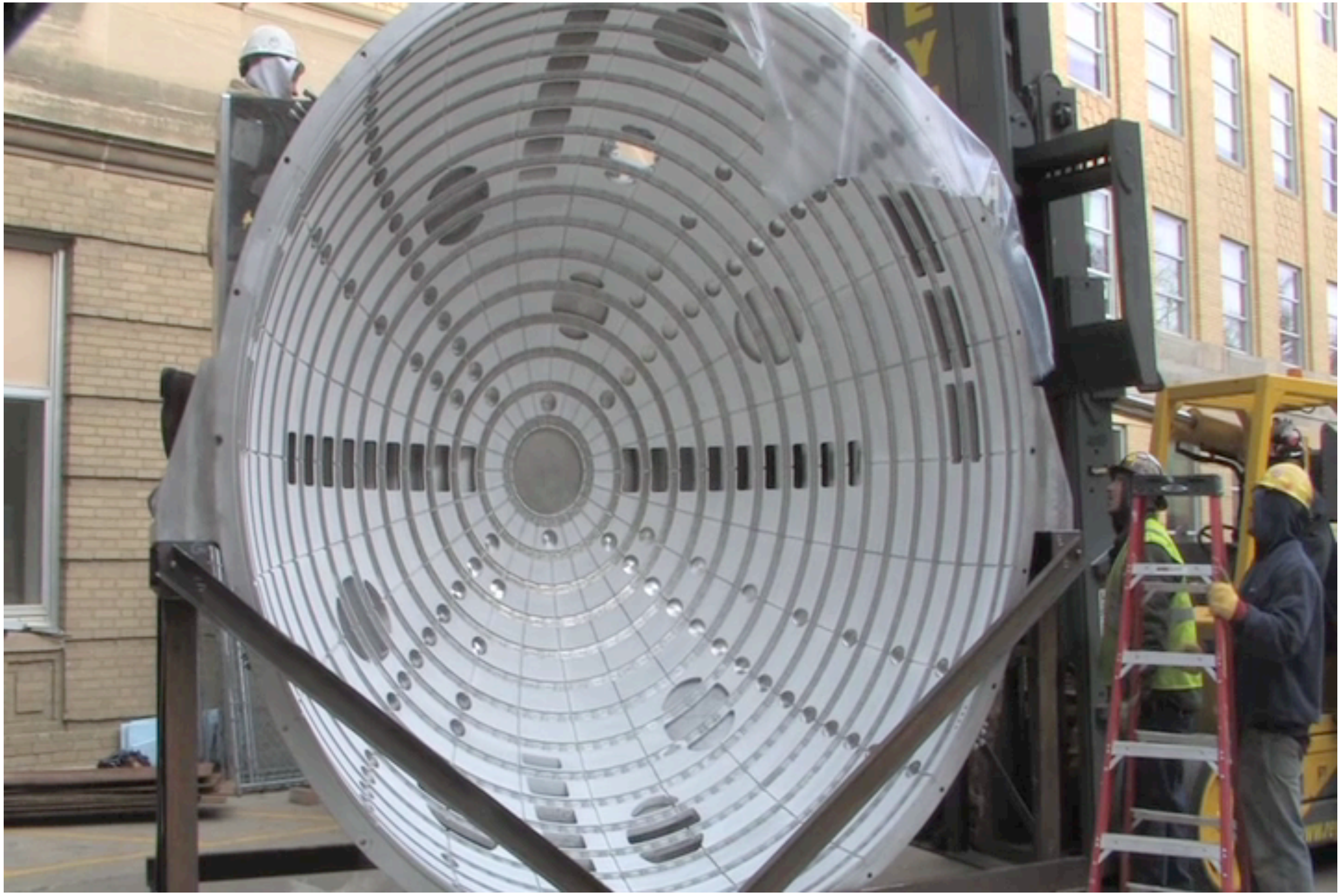
Madison Plasma Dynamo Experiment

$L=1.5$ m
$P_{ECH}=100$ kw@2.45GHz
$P_{cathodes}=250$ kW

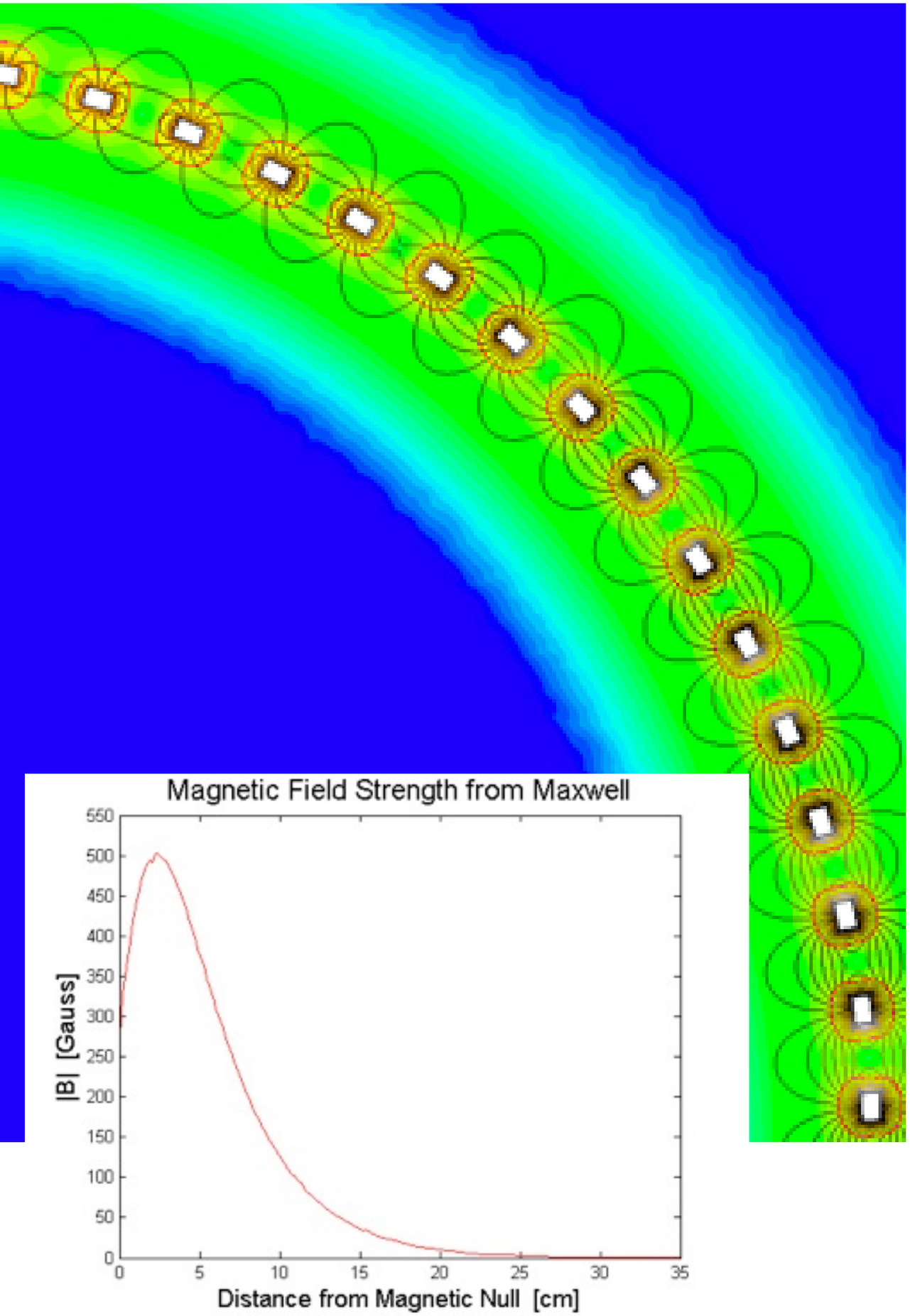
$f_{ionization}\sim 1$
$Te=20$ eV
$n_e=10^{17}\text{-}10^{19}\ m^{-3}$
$V=0\text{-}20$ km/s

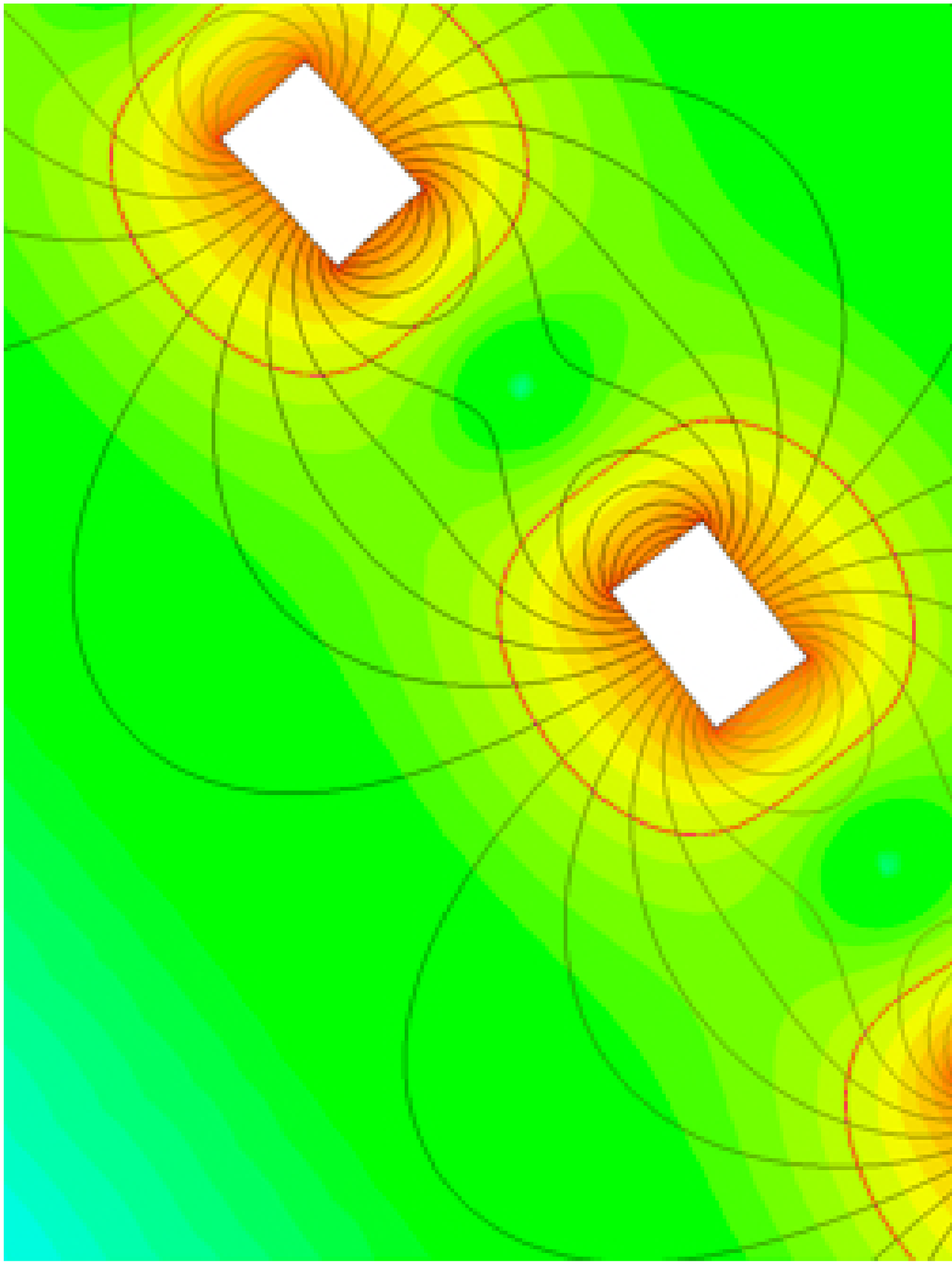
$Rm > 1000$
$Re \sim 1\text{-}10^4$

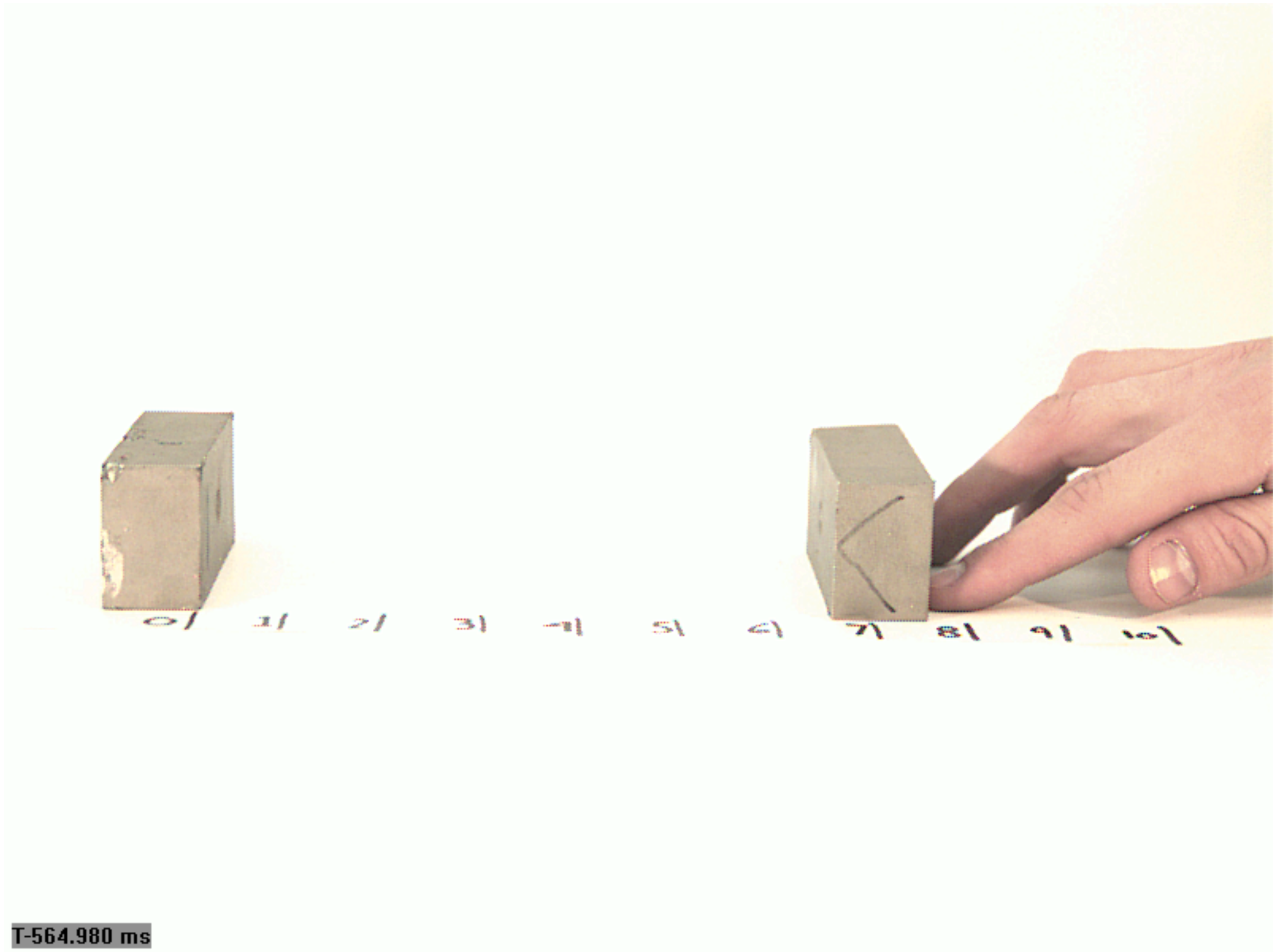




3000 4 kG SmCo magnets installed MPDX


Magnetic Field Strength from Maxwell
|B| [Gauss]
Distance from Magnetic Null [cm]
0
50
100
150
200
250
300
350
400
450
500
550
0
5
10
15
20
25
30
35

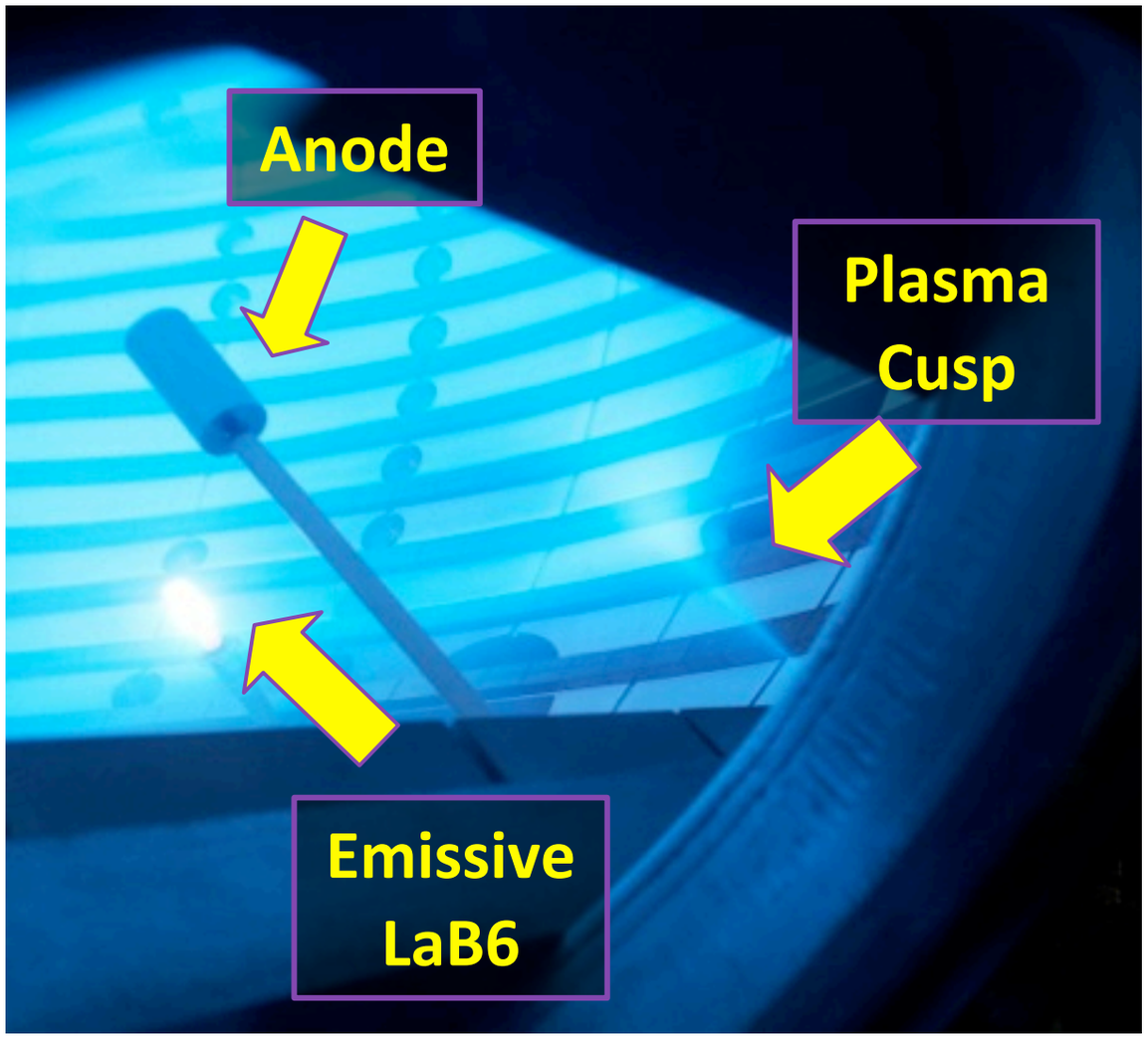


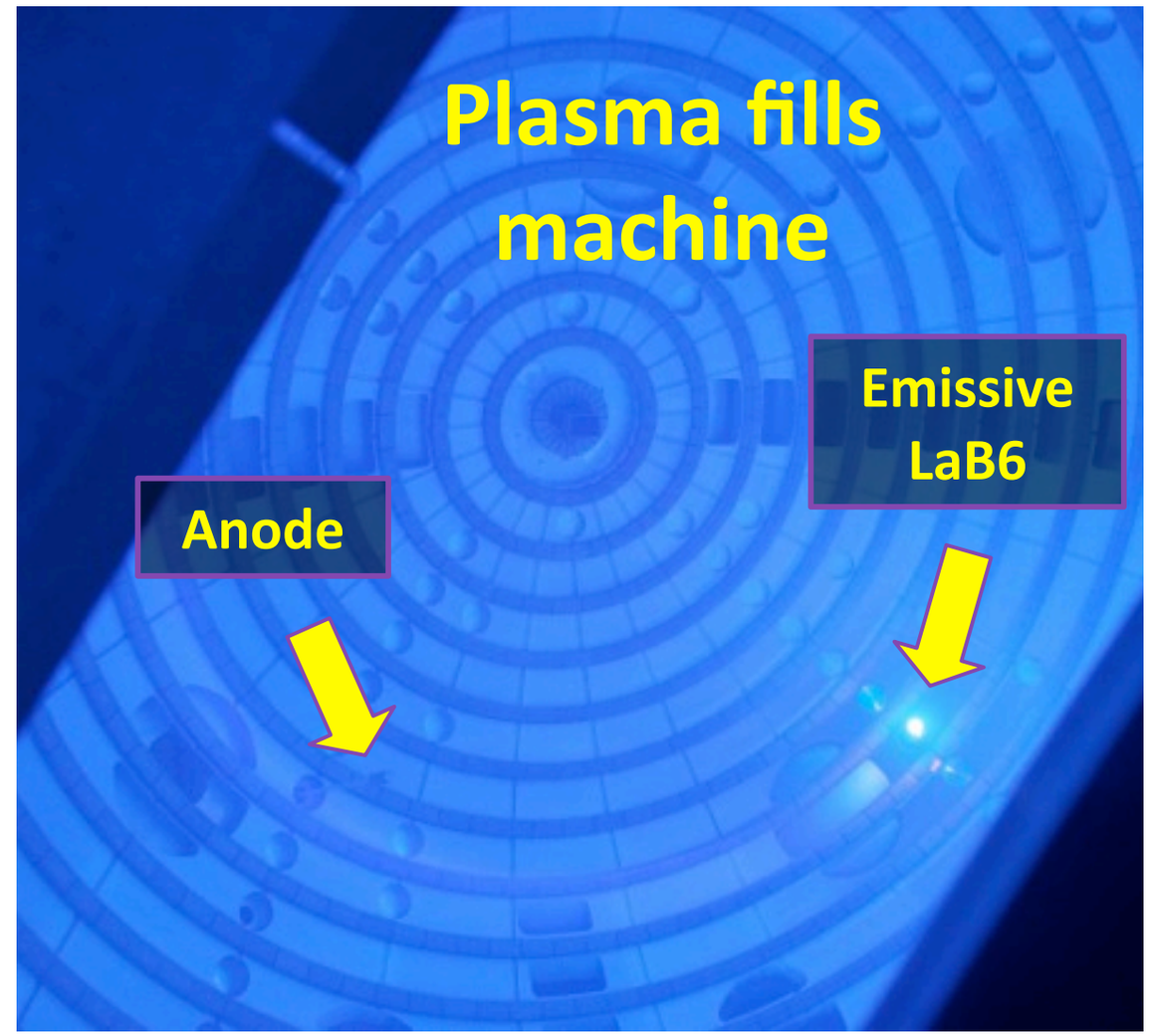

T-564.980 ms

3000 4 kG SmCo magnets installed MPDX

First Plasmas use hot cathodes

LaB_6 **30** cm inside magnets in *un*magnetized region

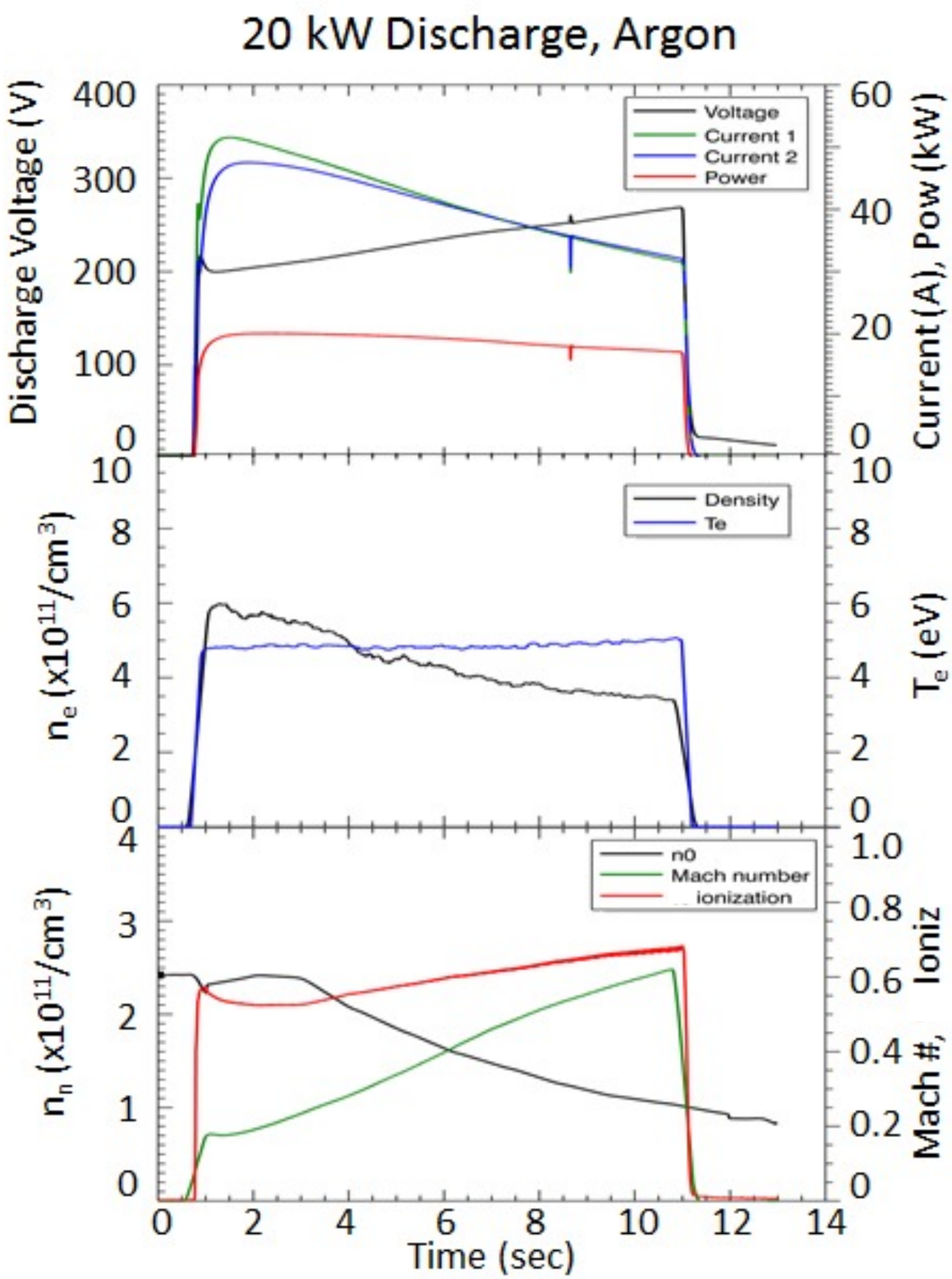




V_{disch} = 350 V, I_{disch} = 30 A, P_{disch} = 10.5 kW

Final Phase: 16 LaB_6 x 10 kW > 150 kW heating

High Ionization fraction and rotation observed

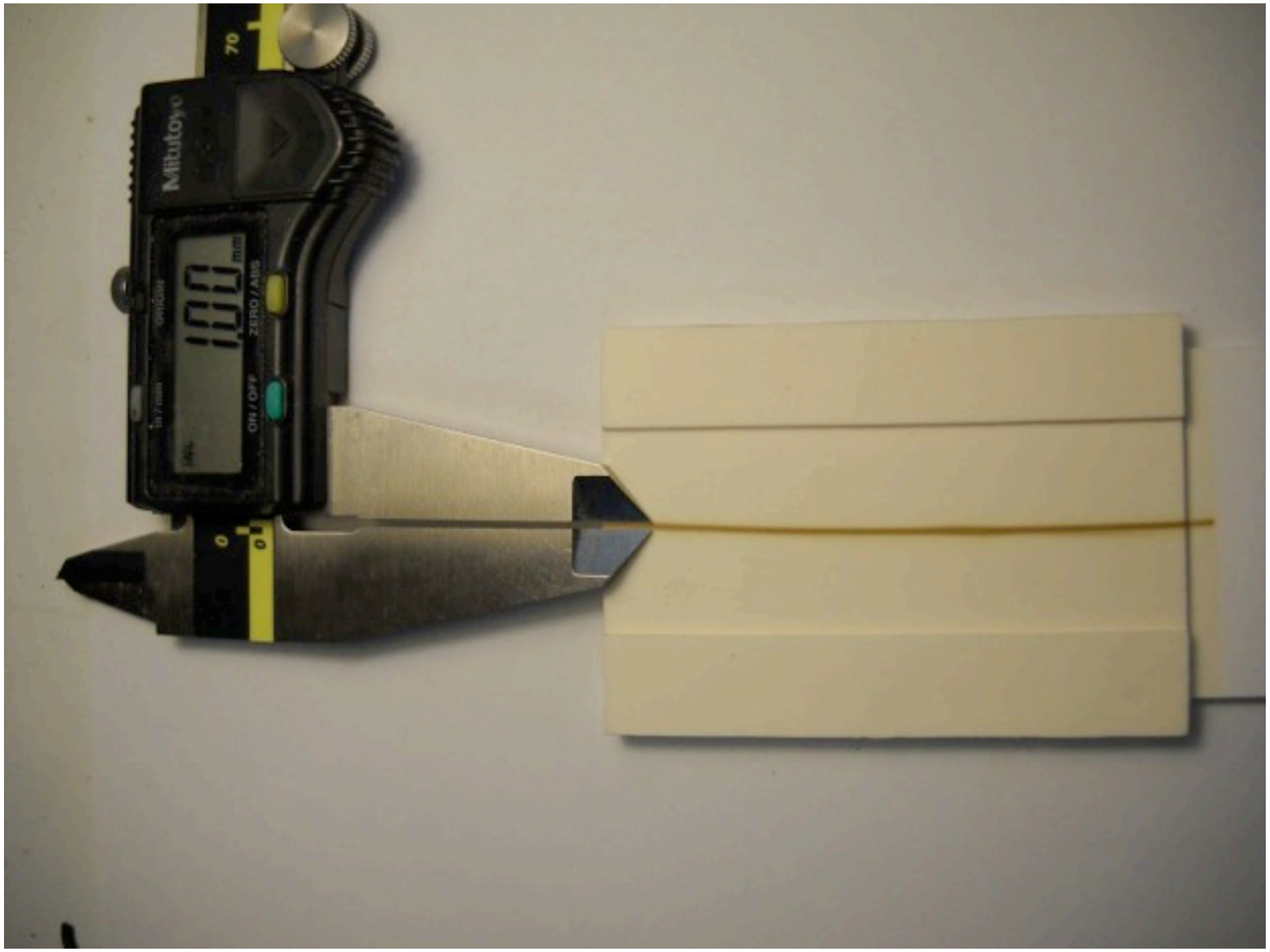


- LaB_6 injects power as electron beam
- T_e rises, n_e drops as n_n drops
- n_n depleted by pumps, Ionization % climbs, drag lessens and v_p rises (~2 km/s)

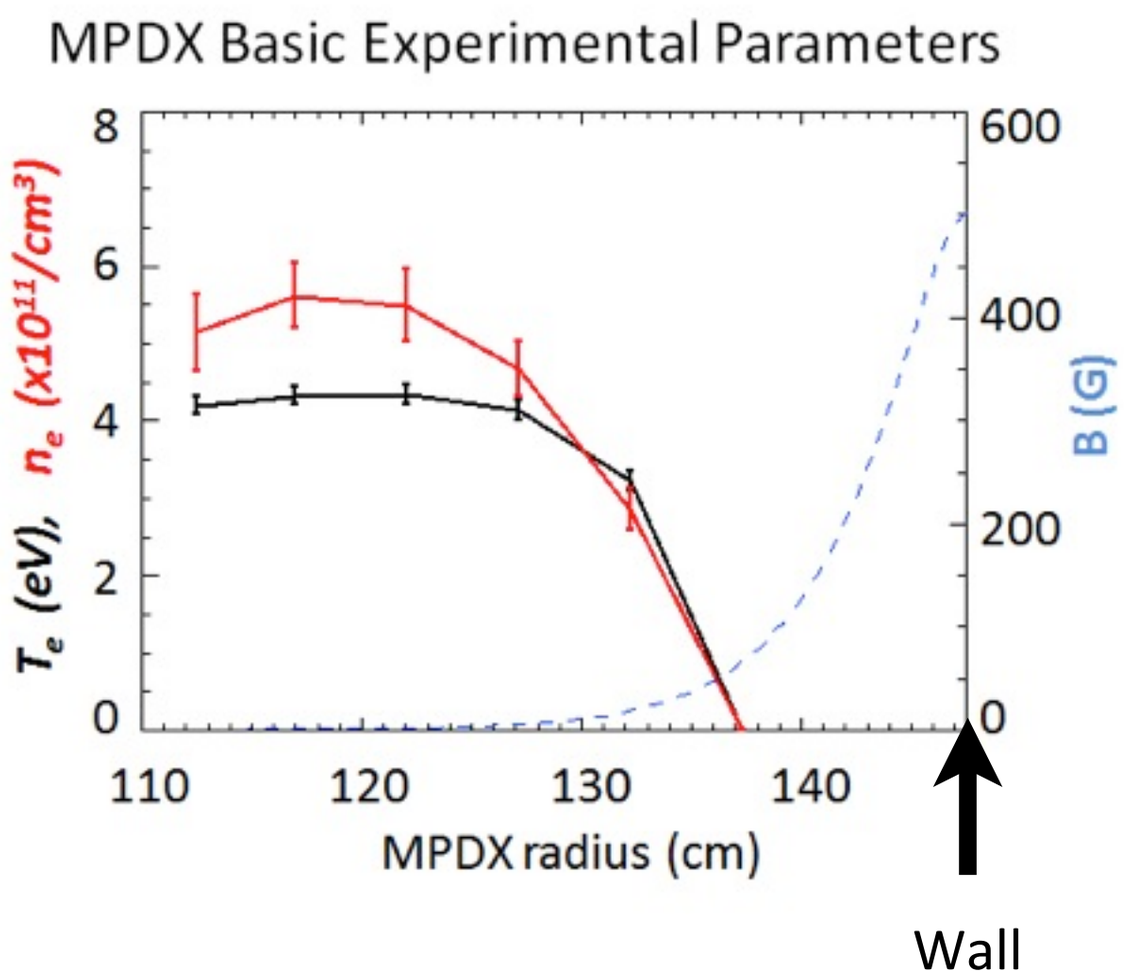
Particle balance

$$\frac{dn}{dt} = \frac{1}{2}\frac{c_s n A_{loss}}{V_{plasma}}$$

$$\begin{aligned} V_{plasma} &= 10\ \mathrm{m}^3 \\ A_{loss} &= W_{cusp} \times L_{cusp} \\ W_{cusp} &= 4\sqrt{\rho_e \rho_i} \sim 1\ \mathrm{mm} \\ L_{cusp} &= 220\ \mathrm{m} \end{aligned}$$

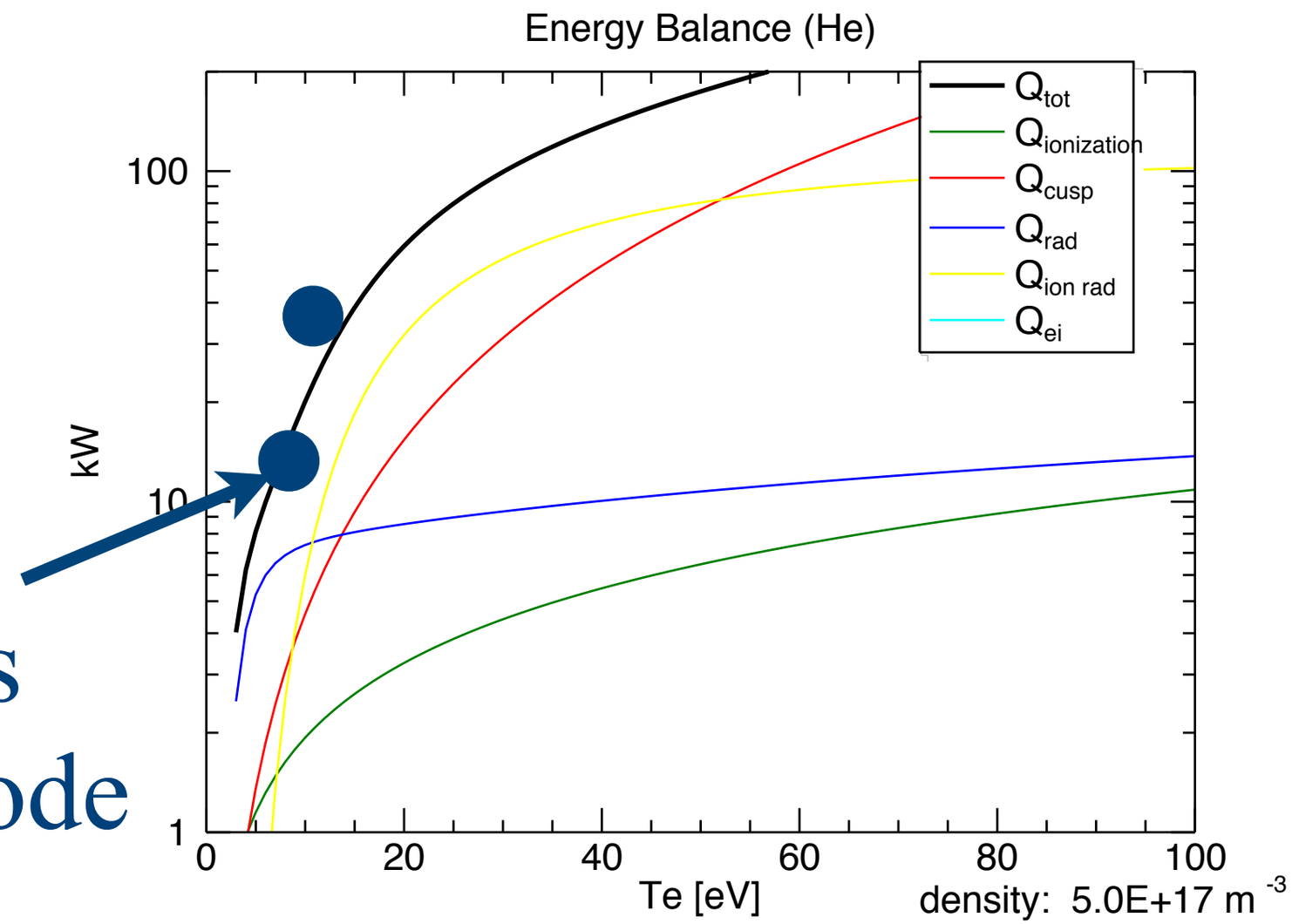


Unmagnetized plasma confined by ring cusp



2 LaB_6 cathodes, 400 V @ 45 A = 18 kW, n_n=5.2x10^{11}/cm^3 Ar, T_i=1 eV

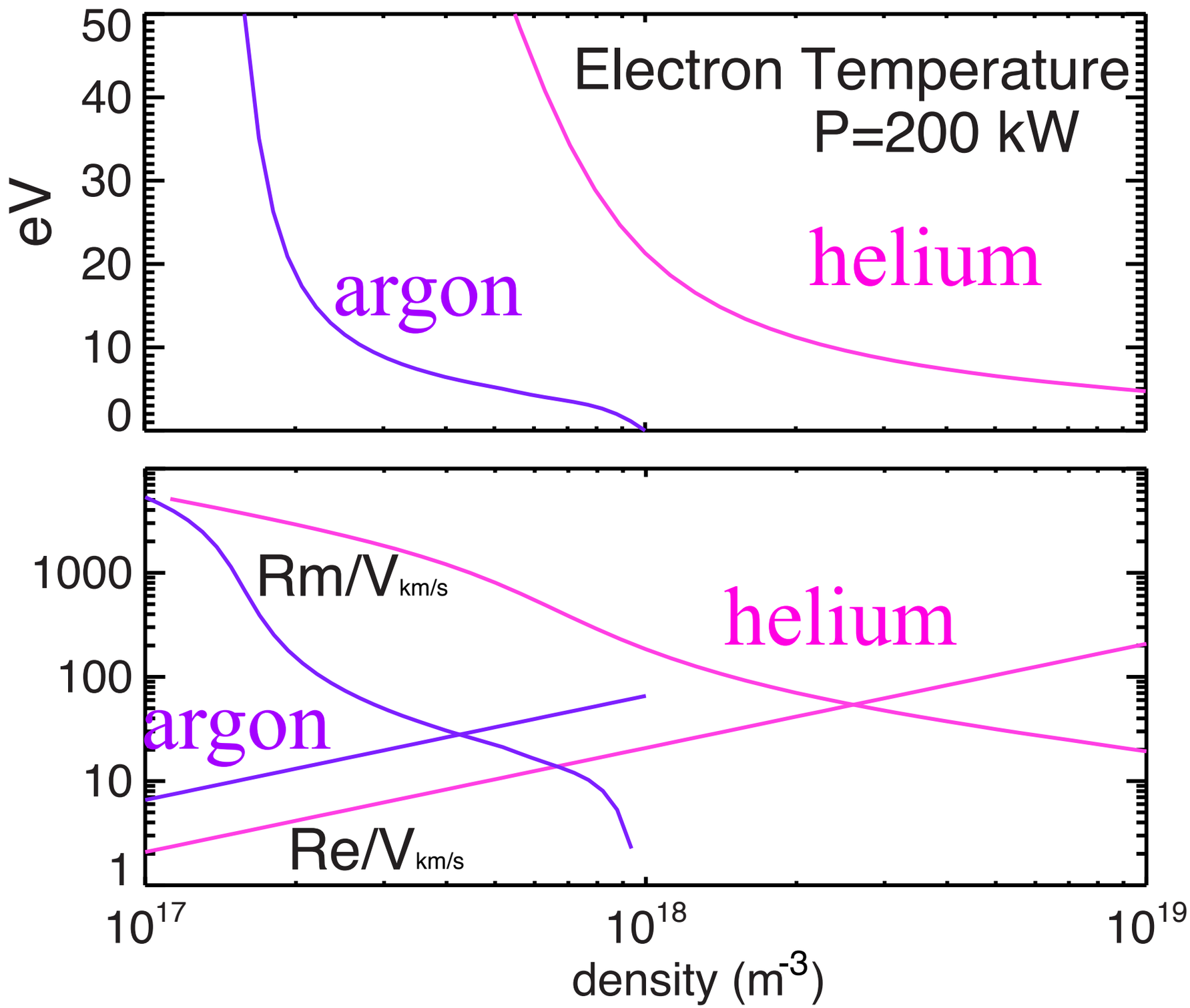
Power balance consistent with first results



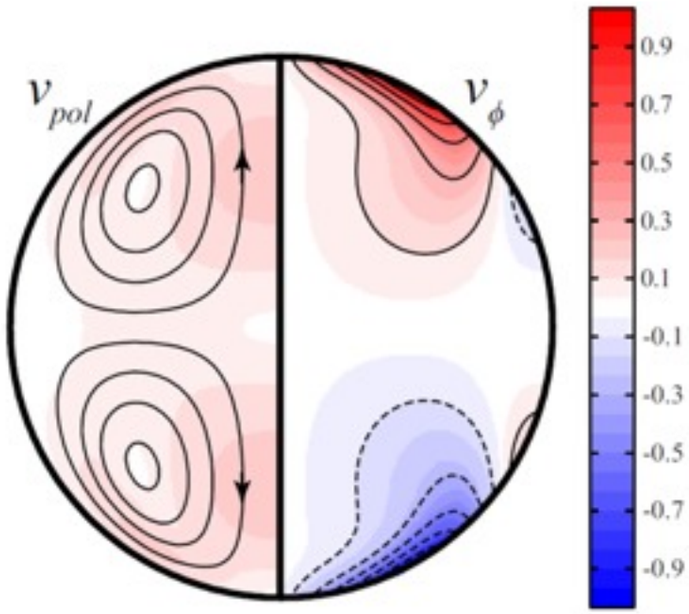
First results with hot cathode

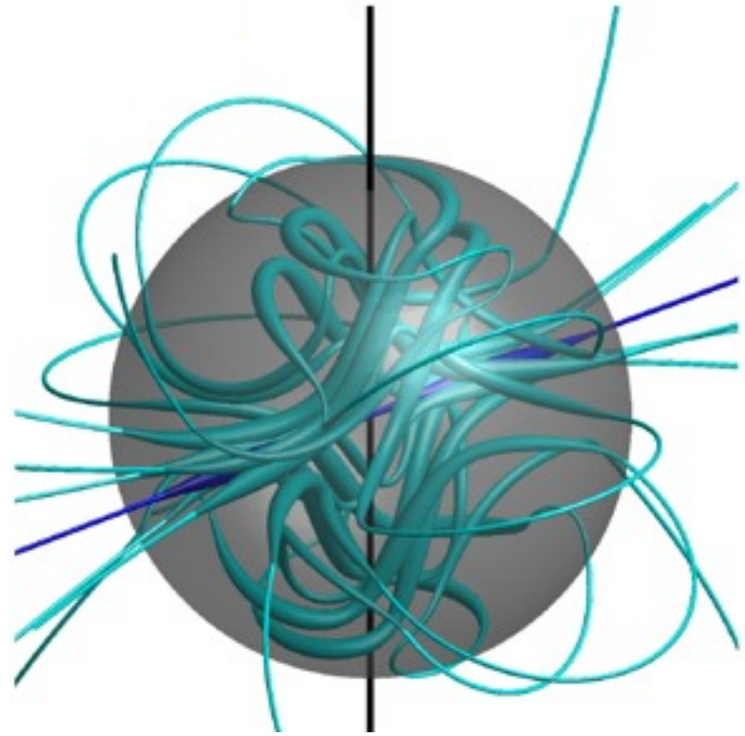
Loss Mechanism	Expression [Energy/Time]
Ion losses at cusps	$\Gamma A_{\text{cusp}}(e\Delta V + \frac{3}{2}T_i)$
Electron losses at cusps	$\Gamma A_{\text{cusp}}(\frac{3}{2}T_e)$
Replacement ionization	$Q_{\text{ioniz}} \equiv \Gamma A_{\text{cusp}} E_{\text{ioniz}}$
Neutral radiation	$M(T_e)Q_{\text{ioniz}}$
Charge-exchange collisions	$\frac{3}{2}nn_0\langle\sigma_{cx}v\rangle e(T_i - T_0)Vol$
Ion radiation	$n^2 R^i(T_e)Vol$

Operational space set by power, density, and ion species

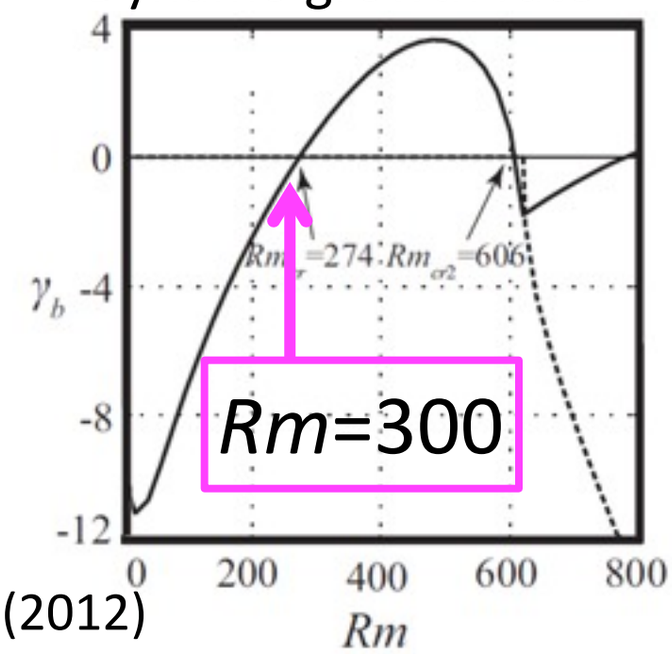


Von Kármán Flow Dynamo Scenario ★

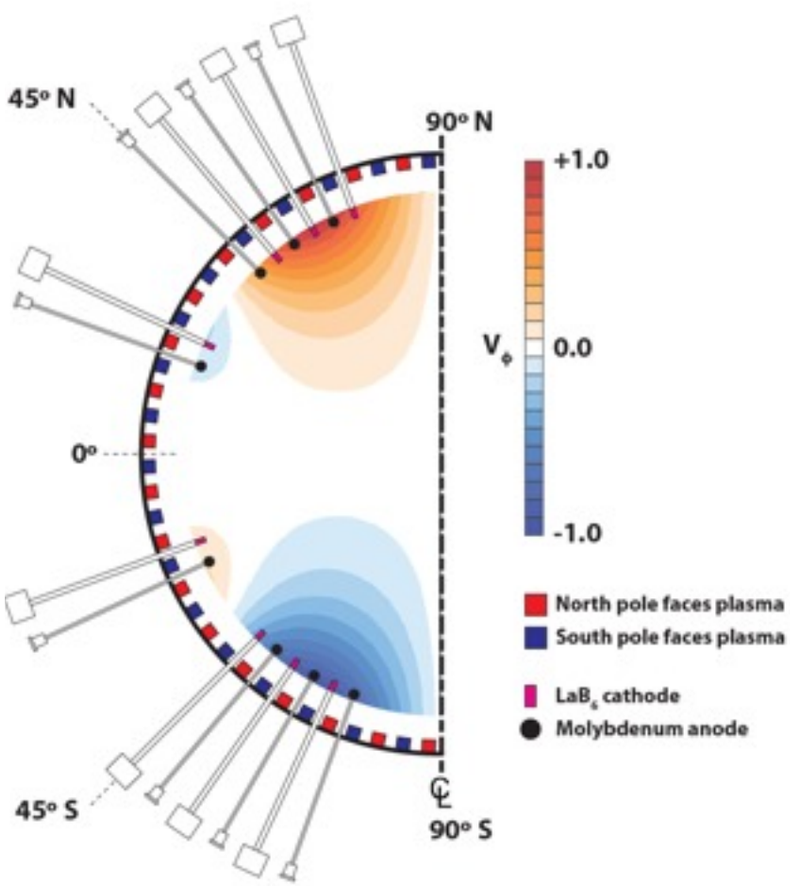




Dynamo growth rate



Khalzov et al, Phys of Plasmas **19** 112106 (2012)

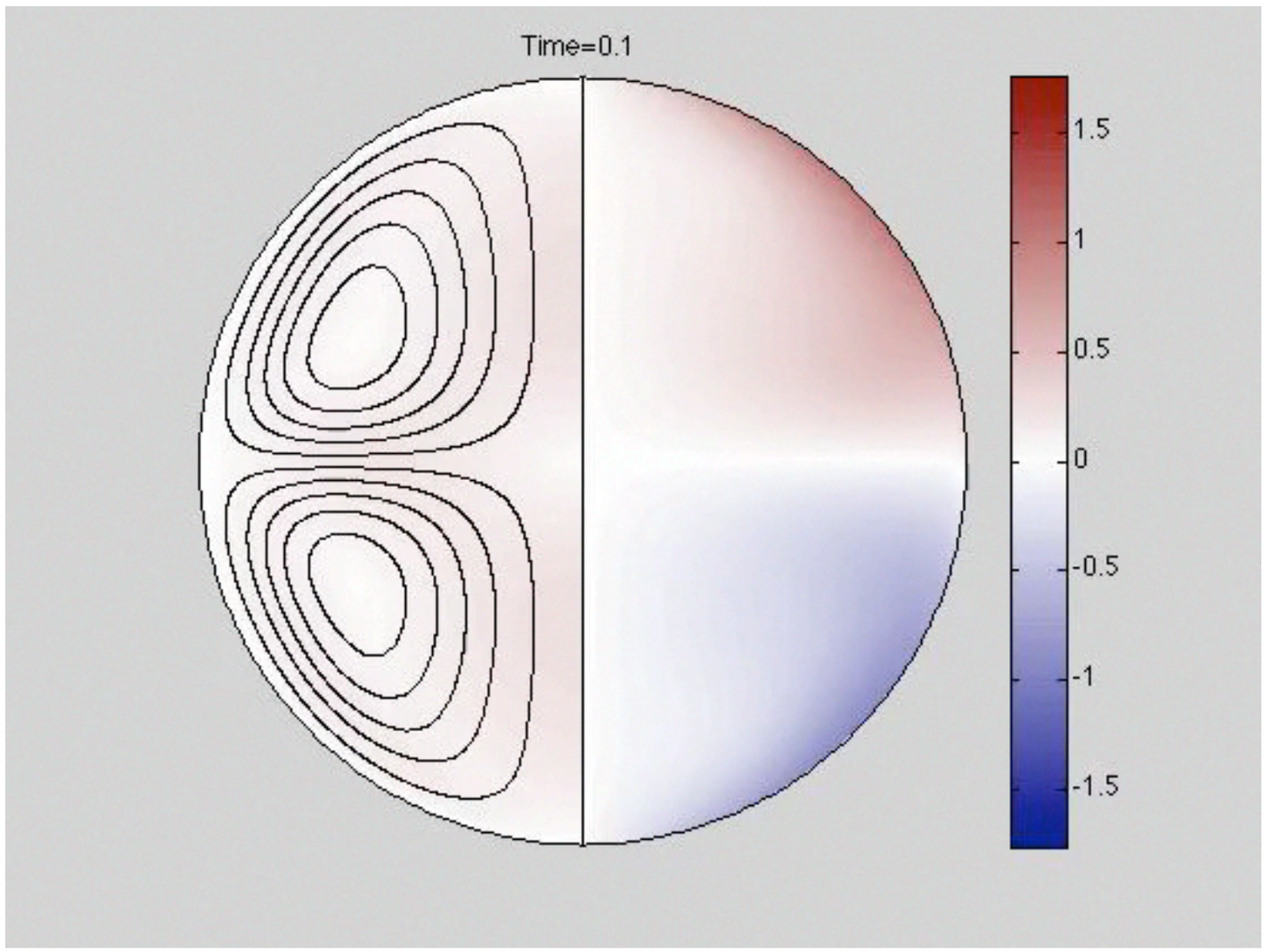


Von Karman type dynamo		
Re=150, Rm=300		
Parameter	Argon	Helium
n_e (1/cm^3)	2X10^{11}	1.2X10^{12}
T_e (eV)	7.5	12
power (kW)	100	140
v_{edge} (km/s)	6	3
B_{eqp} (G)	8	3

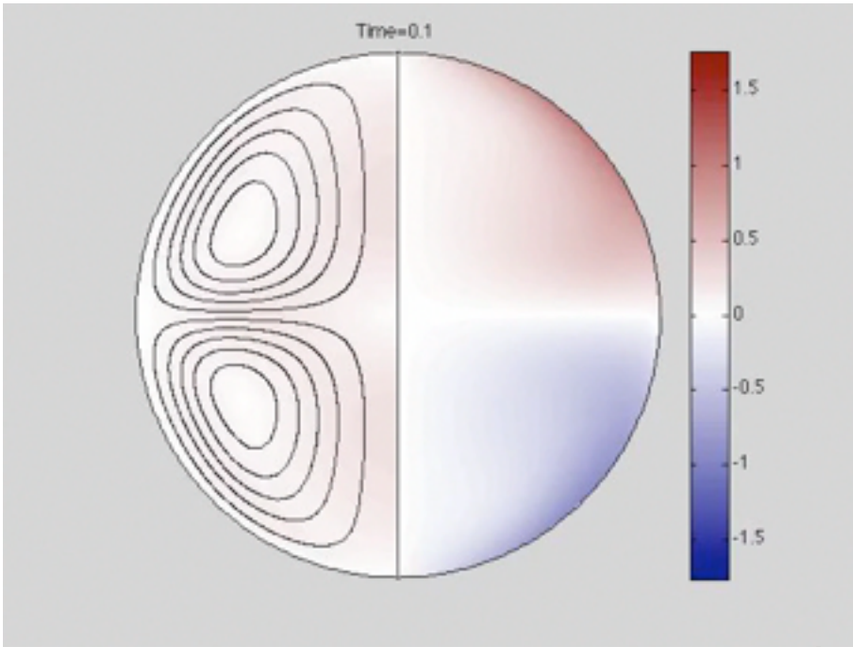
Steady state flows with DC LaB_6 bias set $v_\phi(\theta)$

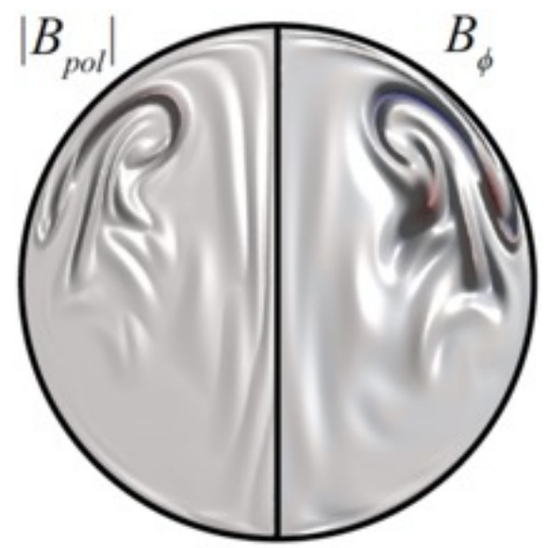
Time dependent flows are also feasible

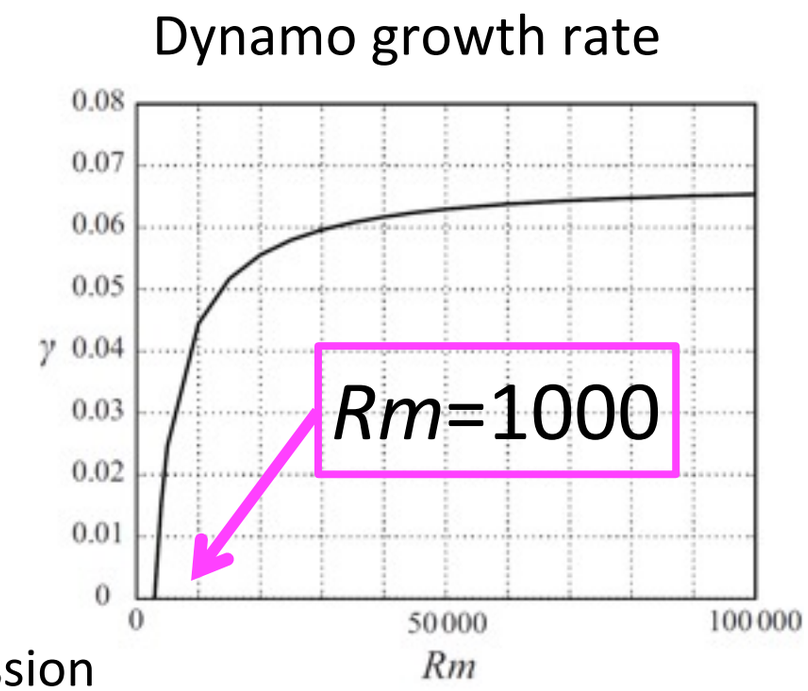
- MPDX Galloway-Proctor Flow gives smooth but chaotic flow



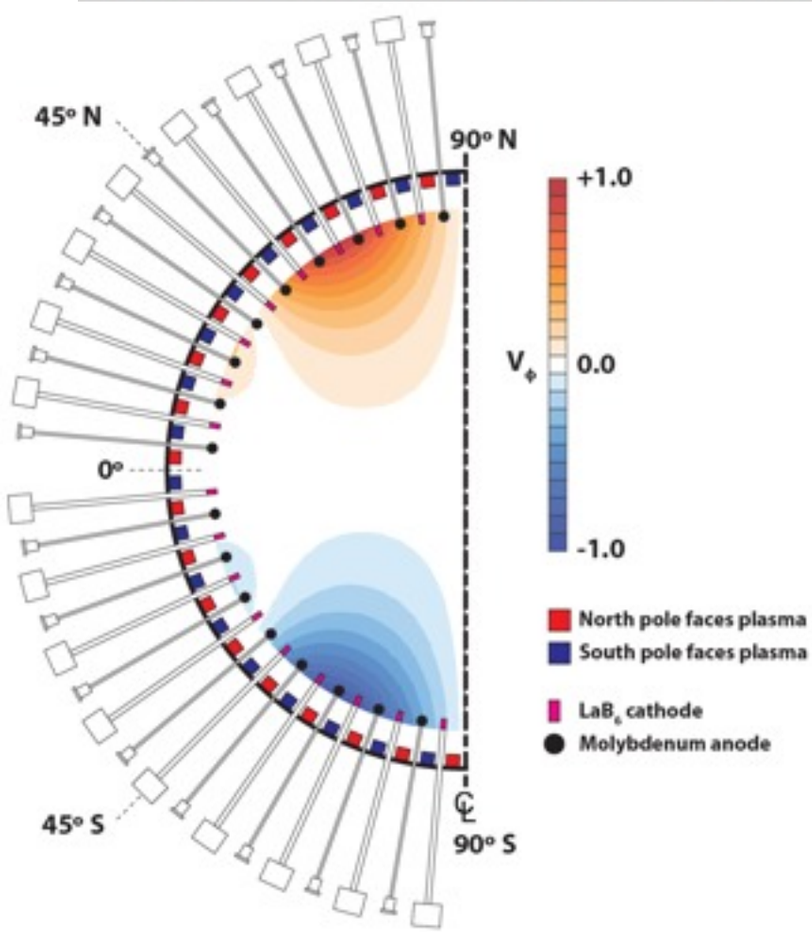
Fast Dynamo Scenario ★







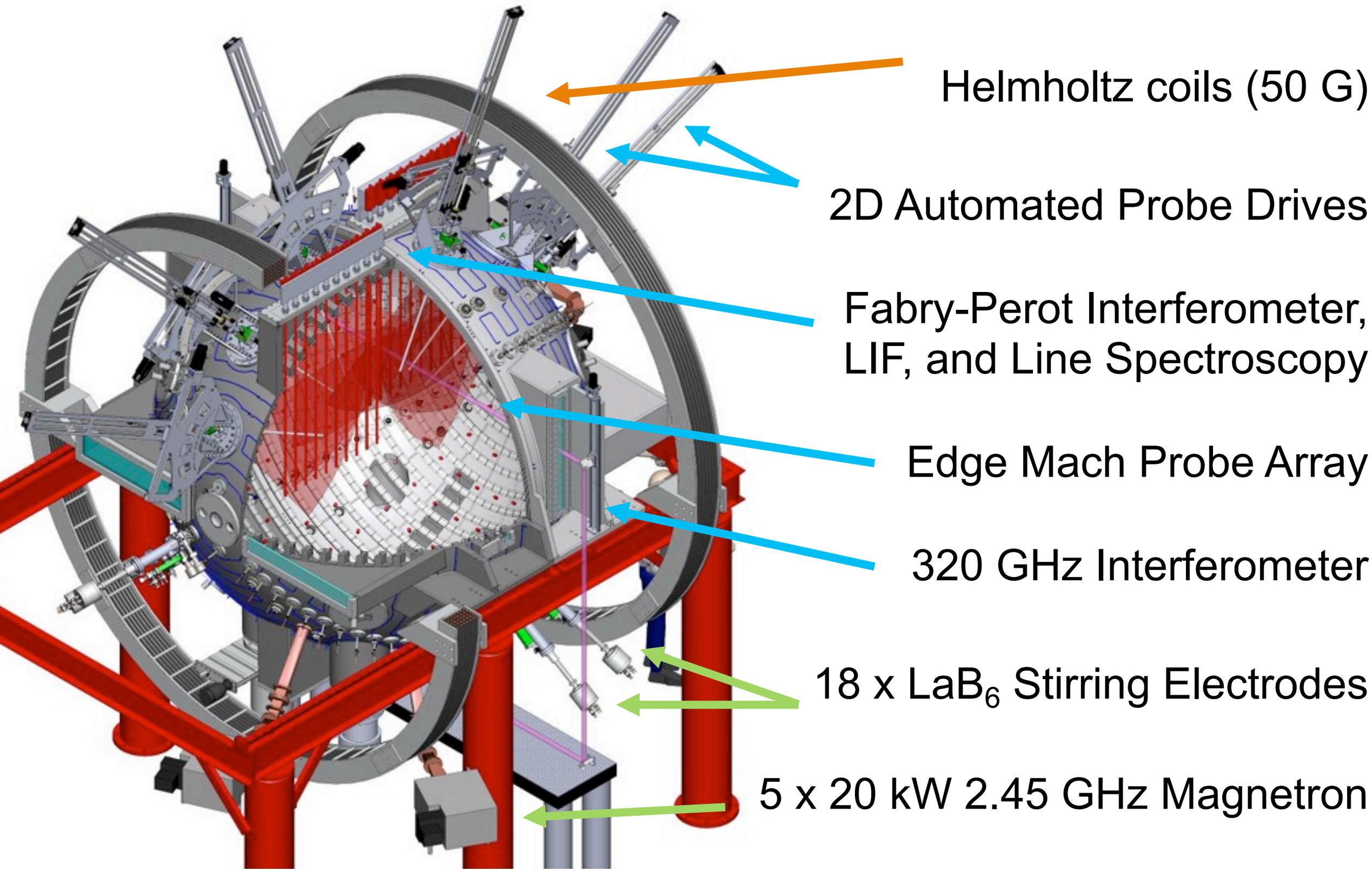
Khalzov et al, PRL in process of submission

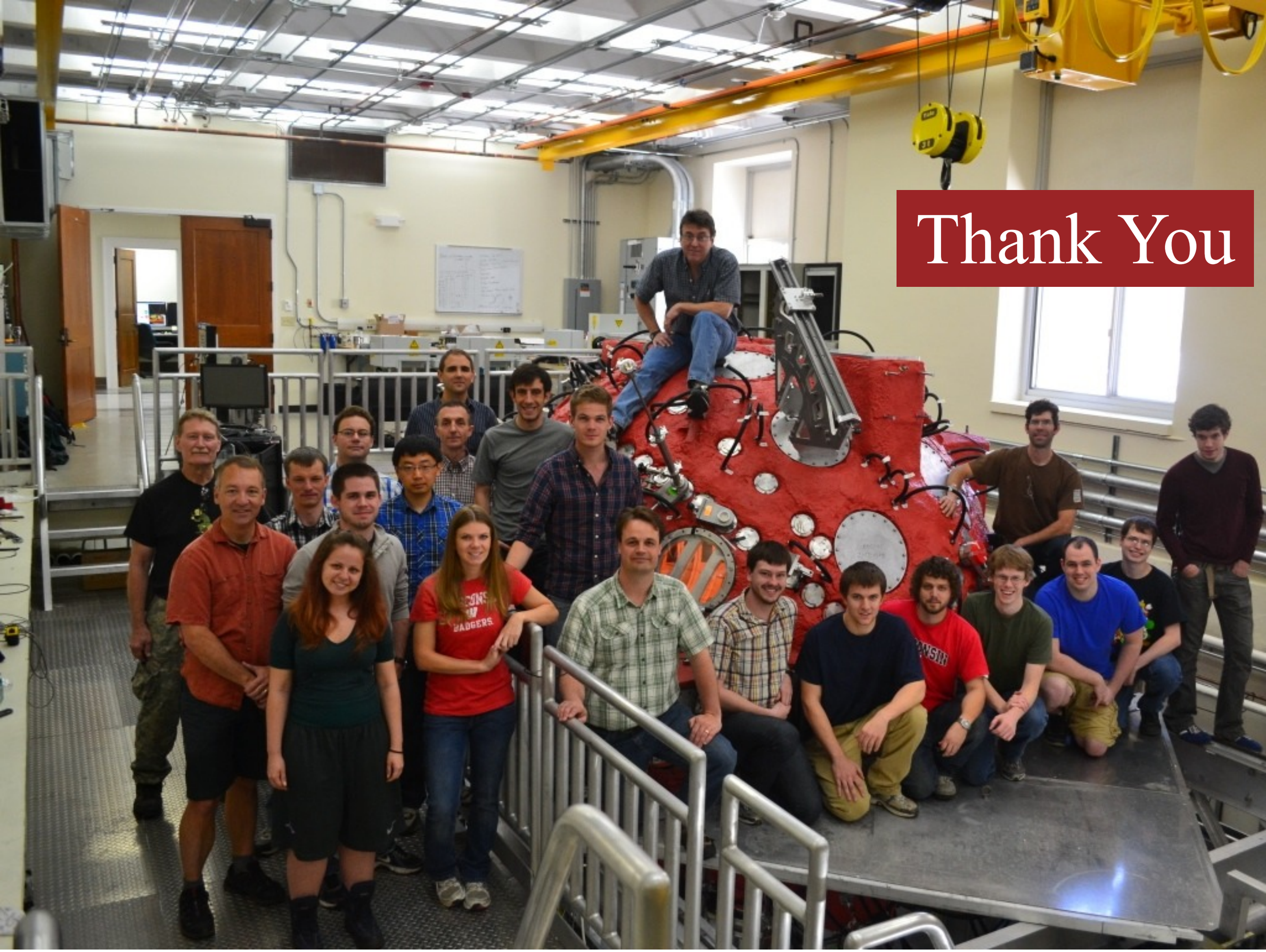


Galloway and Proctor type dynamo		
Re=100, Rm=1000		
Parameter	Argon	Helium
n_e (1/cm^3)	1X10^{11}	8X10^{11}
T_e (eV)	12	27
power (kW)	50	250
v_{edge} (km/s)	10	3
B_{eqp} (G)	9	3
f_{drive} (Hz)	637	191

Time dependent flows and LaB_6 bias set $v_\phi(\theta,t)$

2013: Diagnostics and ECH will be installed

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