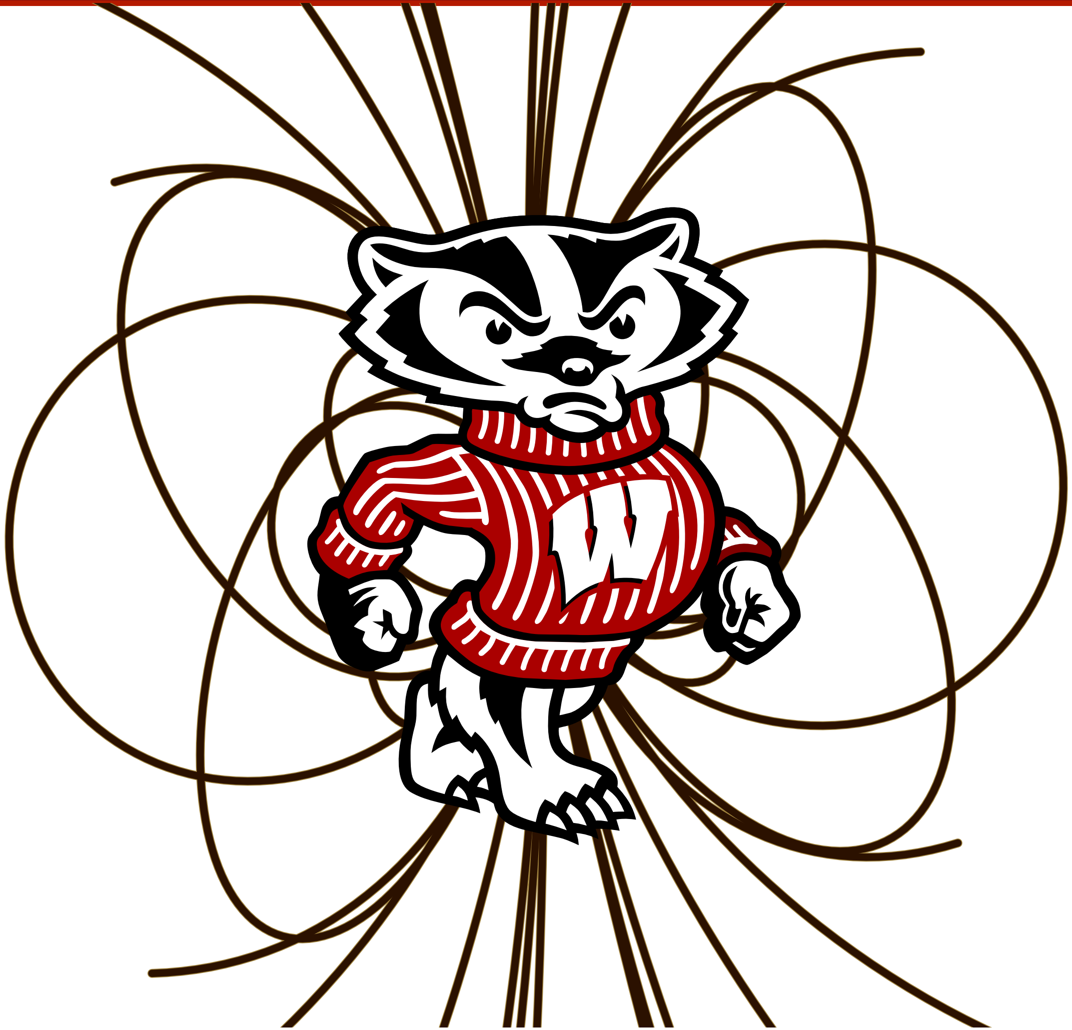
Dynamos Experiments



Cary Forest

École de Physique
des Houches 2017

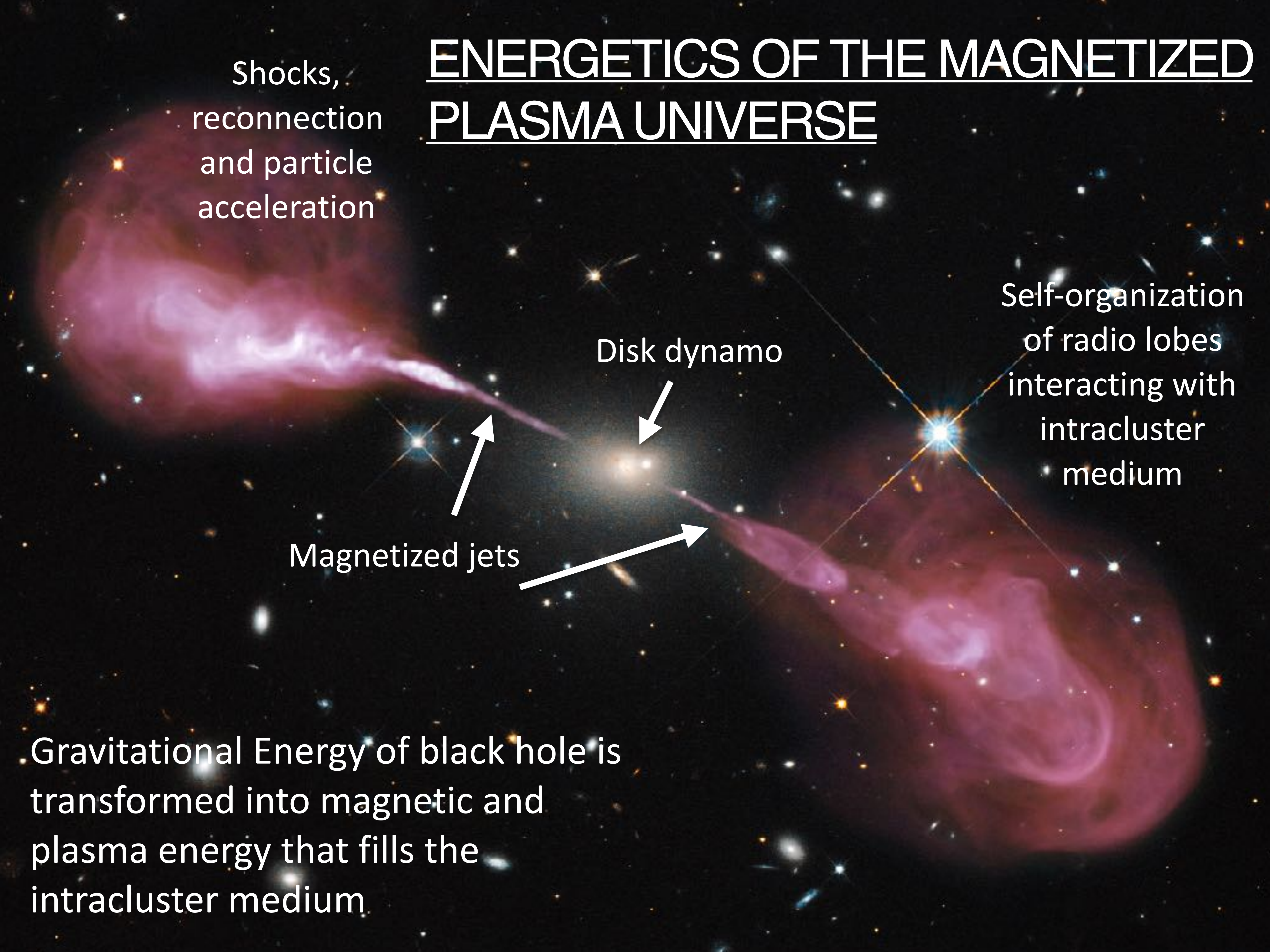
Frontier of non-equilibrium thermodynamics

energy transformation between **forms** in plasma

$$\frac{MG}{r},\ \frac{1}{2}\rho U^2,\ \frac{3}{2}nkT,\ \frac{B^2}{2\mu_0},\ E_{C.R.}$$

- Magnetic Reconnection: $\frac{B^2}{2\mu_0} \rightarrow \frac{1}{2}\rho U^2, \frac{3}{2}nkT$
- Dynamos: $\frac{1}{2}\rho U^2 \rightarrow \frac{B^2}{2\mu_0}$
- Particle Acceleration: $\frac{1}{2}\rho U^2, \frac{B^2}{2\mu_0} \rightarrow E_{C.R.}$
- Accretion and Jets: $\frac{\rho GM}{r} \rightarrow \frac{3}{2}nkT,\ \frac{1}{2}\rho U^2$

ENERGETICS OF THE MAGNETIZED PLASMA UNIVERSE



Shocks,
reconnection
and particle
acceleration

Disk dynamo

Self-organization
of radio lobes
interacting with
intracluster
medium

Magnetized jets

Gravitational Energy of black hole is transformed into magnetic and plasma energy that fills the intracluster medium

Energetics Experiments Require:

Frozen in flux: $Rm = \mu_0 \sigma U L \gg 1$

Flow dominated: $\rho U^2 \gg B^2/\mu_0$

Pressure dominated: $nkT \gg B^2/\mu_0$

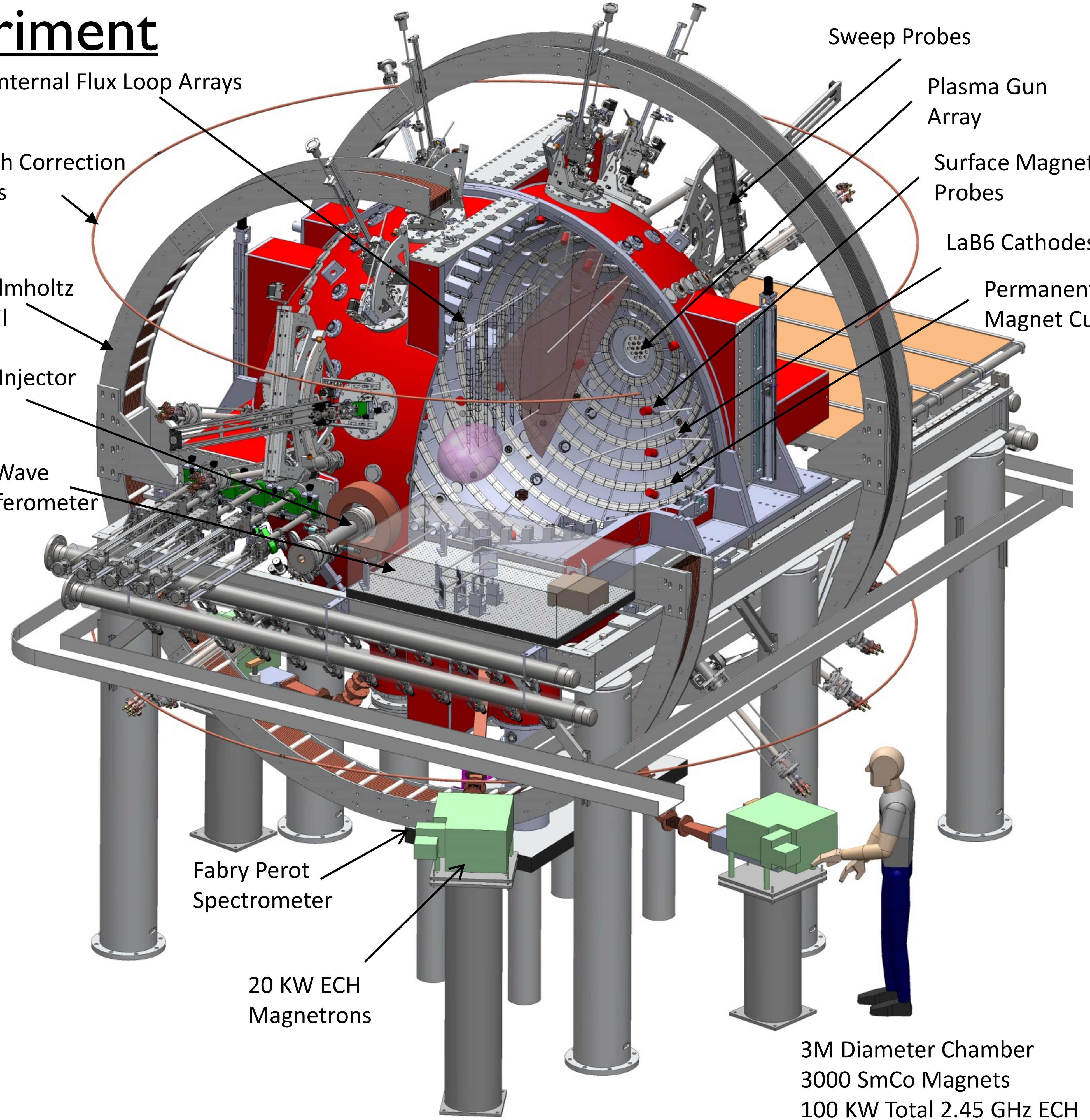
Turbulent: $Re = UL/\mu \gg 1$

Continuous: $T \gg \mu_0 \sigma L^2$

New regime for plasma experiments: require confined (hot and dense) and flowing, unmagnetized plasmas

Energetics Experiment

large, hot, B=0



Internal Flux Loop Arrays

Earth Correction
Coils

Helmholtz
Coil

CT Injector

mm Wave
Interferometer

Fabry Perot
Spectrometer

20 KW ECH
Magnetrons

Sweep Probes

Plasma Gun
Array

Surface Magnet
Probes

LaB6 Cathode

Permanent
Magnet Cu

3M Diameter Chamber
3000 SmCo Magnets
100 KW Total 2.45 GHz ECH

Outline

1. Dynamo Basics (theory)
2. Dynamo Experiments
3. Flow-dominated Experiments
   - Magneto-rotational instabilities
   - Parker Spiral
   - Shocks

Philosophy of this talk:

“What I cannot create, I do not understand”

-Feynman

Astrophysical Dynamos

Systems which Continuously convert kinetic energy of Flowing plasma into magnetic energy

MAGNETOHYDRODYNAMICS 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

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \mathbf{J} \times \mathbf{B} + \rho \mathbf{g} + \mathbf{F}_{visc}$$

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

Dynamo Regime: Flow Dominated Plasma

Frozen in flux: $Rm = \mu_0 \sigma U L \gg 1$

Flow Dominated: $M_A = U/V_A \gg 1$

Continuous: $T \gg \mu_0 \sigma L^2$

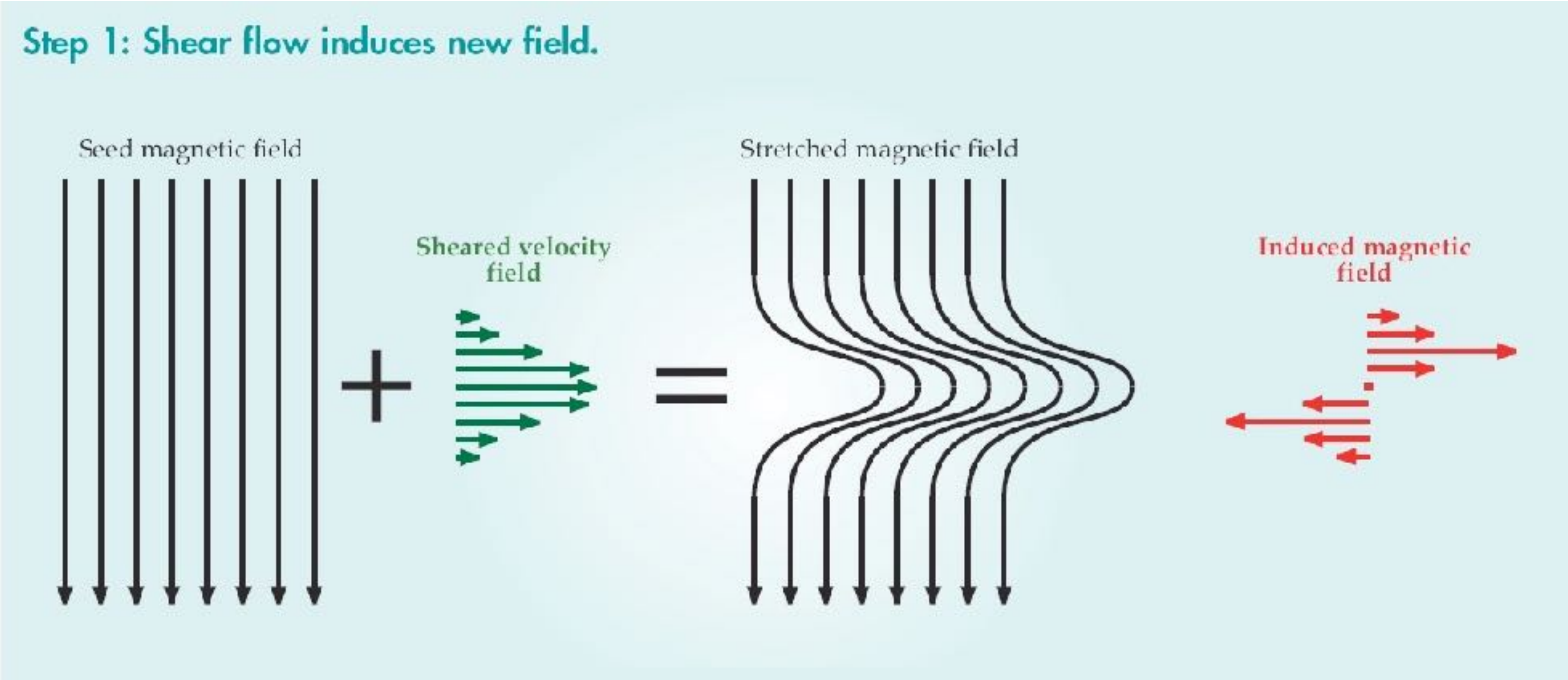
Unexplored by plasma experiments

Behavior Depends upon:

$Pm = Rm/Re, \quad Re = UL/\mu,$

FUNDAMENTAL TENET OF PLASMA ASTROPHYSICS
(WHEN $R_M \gg 1$, $M_A \gg 1$)

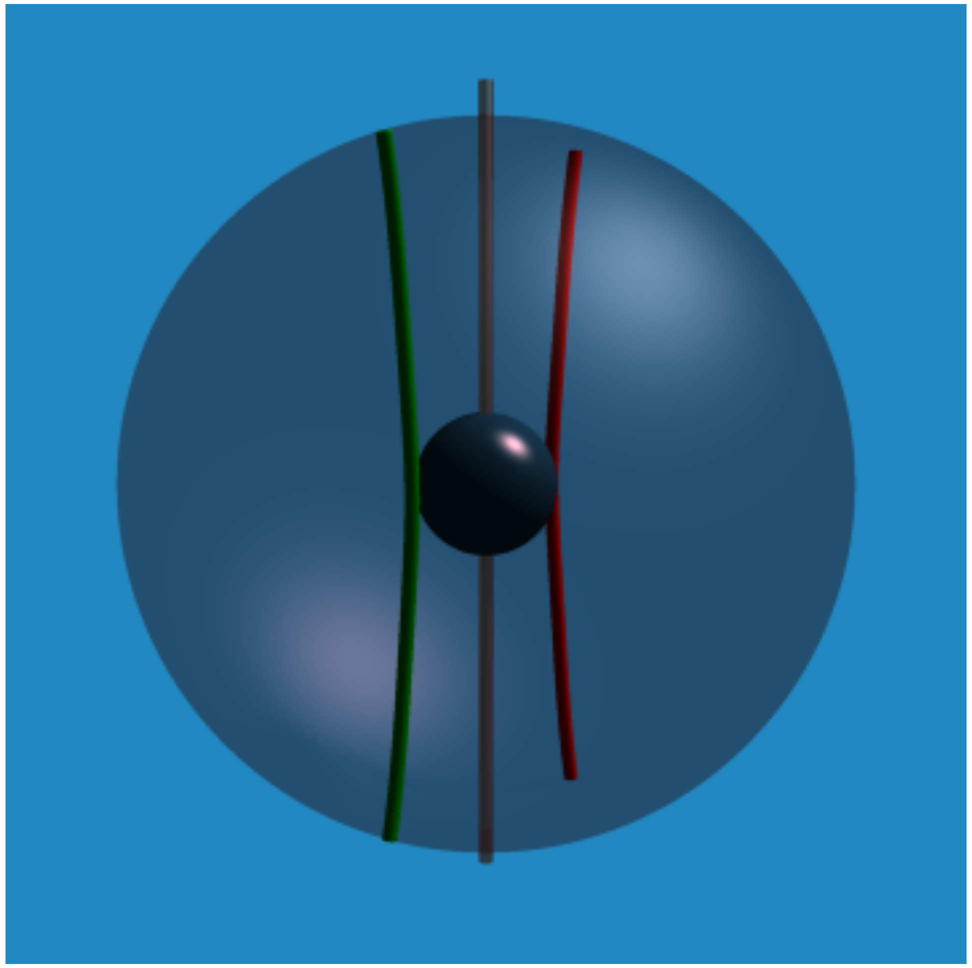
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{V} \times \mathbf{B} + \xcancel{\frac{1}{\mu_0 \sigma}\nabla^2 \mathbf{B}}$$



Step 1: Shear flow induces new field.

STANDARD MODEL STEP 1:

STRONG TOROIDAL FIELD FROM POLOIDAL



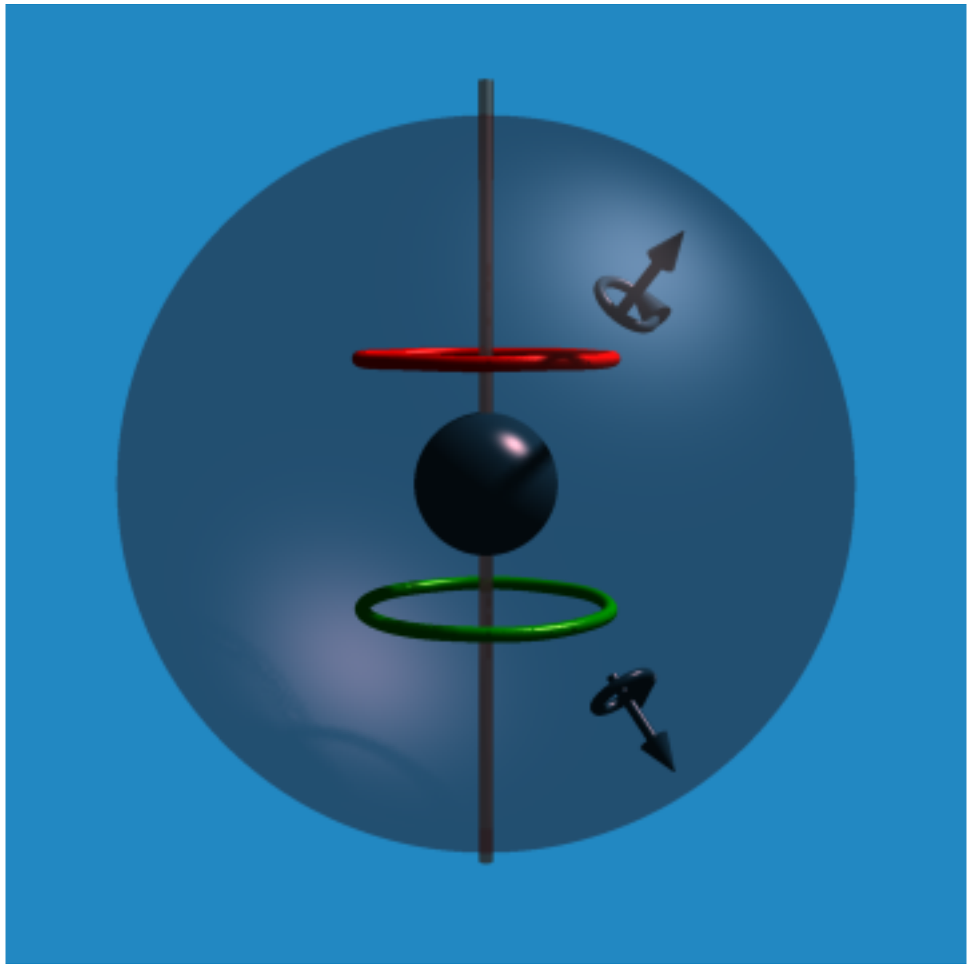
The "Ω effect"

STANDARD MODEL STEP 2: HELICAL TURBULENCE REGENERATES POLOIDAL FIELD

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

T.G. Cowling(1933)

The "α effect"



$$J_\phi = \alpha B_\phi$$

E.N. Parker (1955)

TURBULENCE: FRIEND OR FOE?

- Transport of B is controlled by turbulent EMF

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

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

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

- β - effect is like resistivity (diffuses large scale B)

$$\beta = \frac{1}{3} \tilde{v}^2 \tau_{corr} \equiv \frac{\tilde{v}\ell}{3} \qquad \eta_{turb} = \frac{1}{\mu_0 \sigma} + \frac{\tilde{v}\ell}{3}$$

- α - effect driven by helical flow

$$\alpha = \frac{1}{3} \left\langle \widetilde{\boldsymbol{v}} \cdot \nabla \times \widetilde{\boldsymbol{v}} \right\rangle \tau_{corr}$$

Dynamo Classification

small vs Large Scale

small: magnetic field generated at (or below) scale of flows (relies on chaotic stretching)

Large: relies on lack of reflexional asymmetry

Slow vs Fast Dynamos

slow requires resistive diffusion (moderate Rm)

Fast Dynamos: independent of resistivity (very large Rm)

Astrophysics: Large-Scale, Fast Dynamos (Rm>>1, turbulent generation of net Flux)

EXPERIMENTS?

...in magnetohydrodynamics one should not believe the product of a long and complicated piece of mathematics if it is unsupported by observation.

Enrico Fermi

Dynamo Experiments Require:

Frozen in flux: $Rm = \mu_0 \sigma U L \gg 1$

Flow Dominated: $\rho U^2 \gg B^2/\mu_0$

New regime for plasma experiments-
astrophysical applications

Hydrodynamics:

$Re = UL/\mu, \quad Pm = Rm/Re$

Plasmas are Challenging

-difficult to stir

-some confinement required with weak B

Use Liquid Metals

-confinement is free

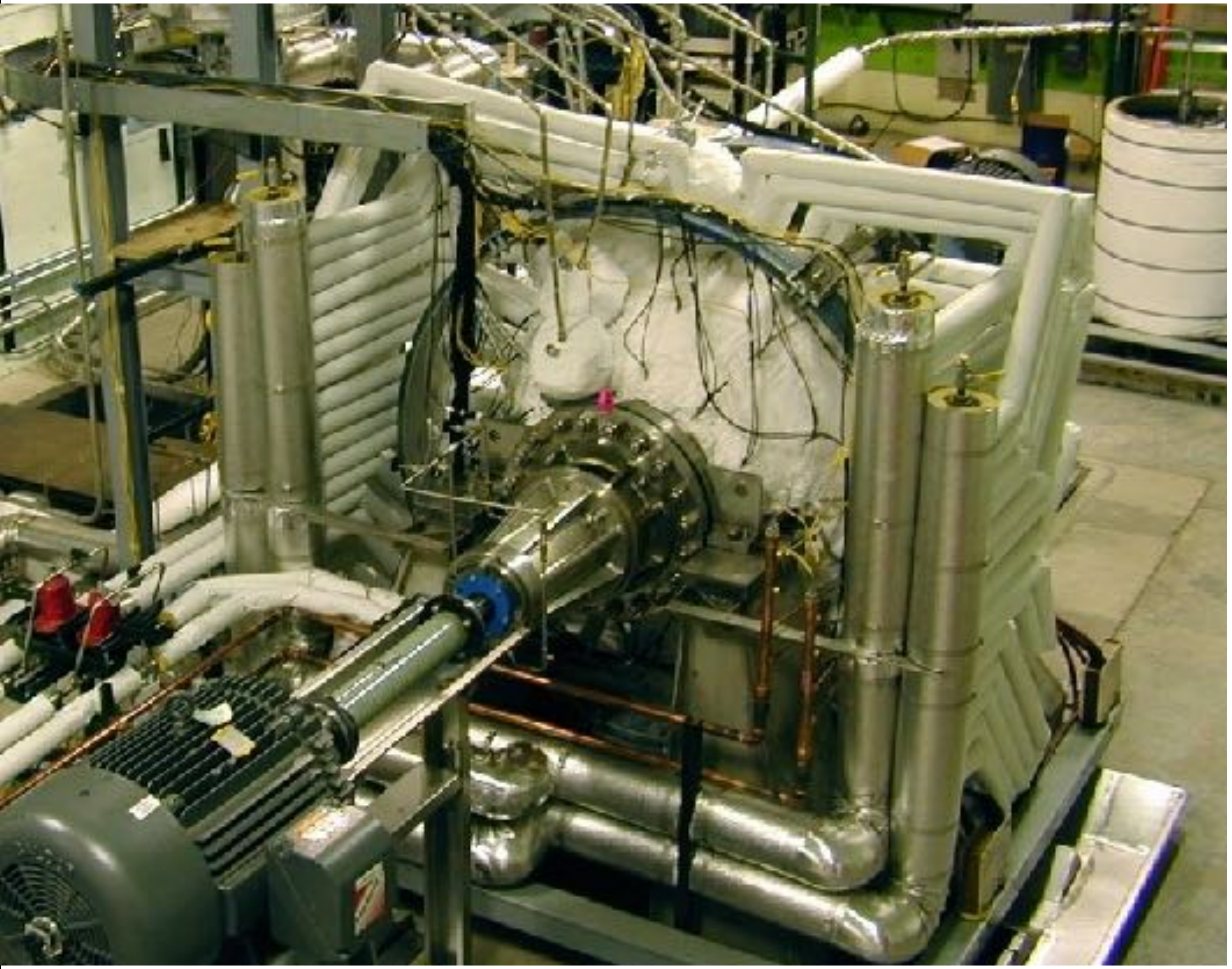
-easy to stir

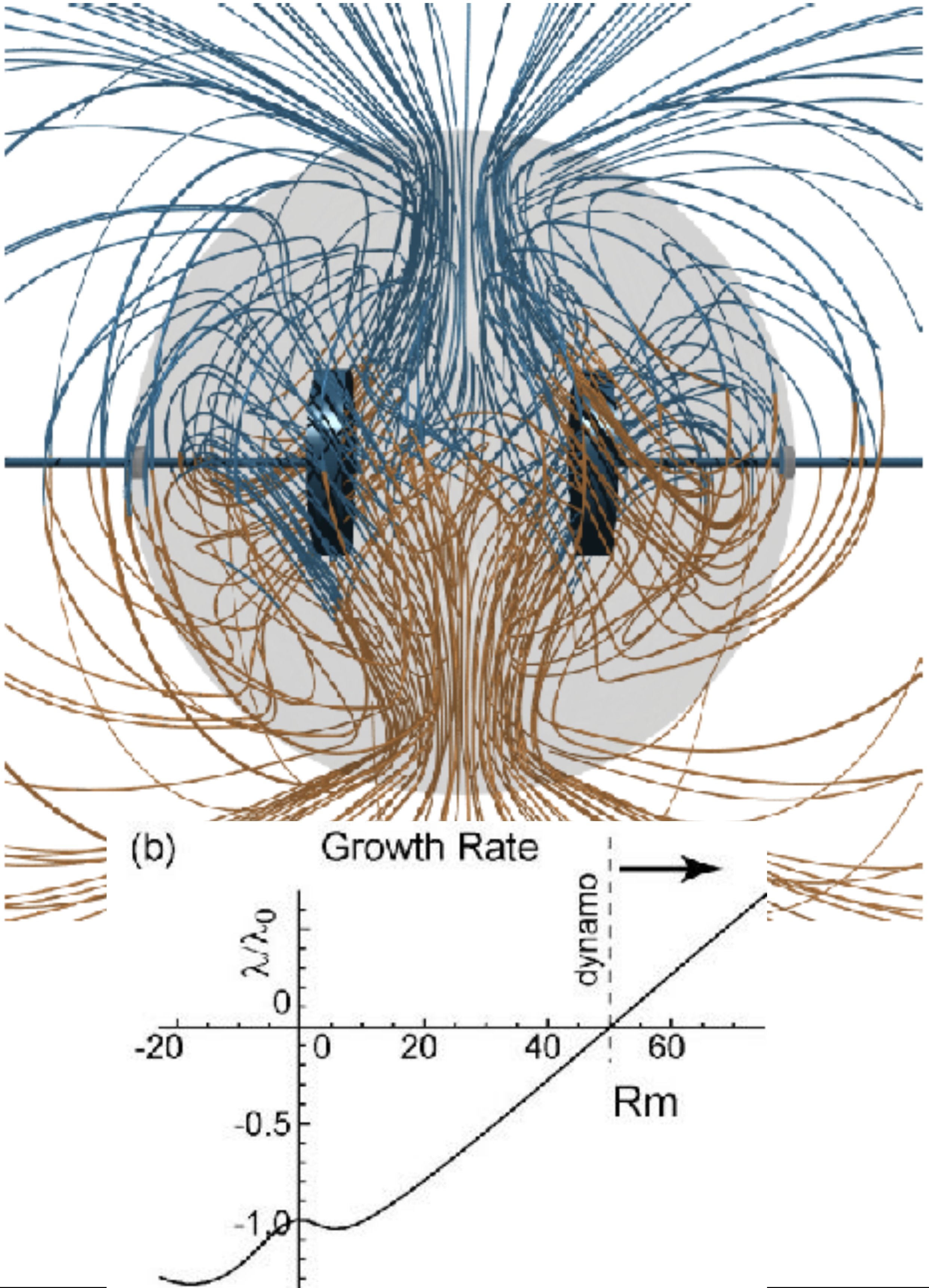
-BUT power scaling is challenging: $P_{mech} \sim Rm^3 / L$

[Rm=100, P_{mech}=100 kW] — just barely at threshold

-Re = 10^7 (Pm=10^{-5}, turbulent)

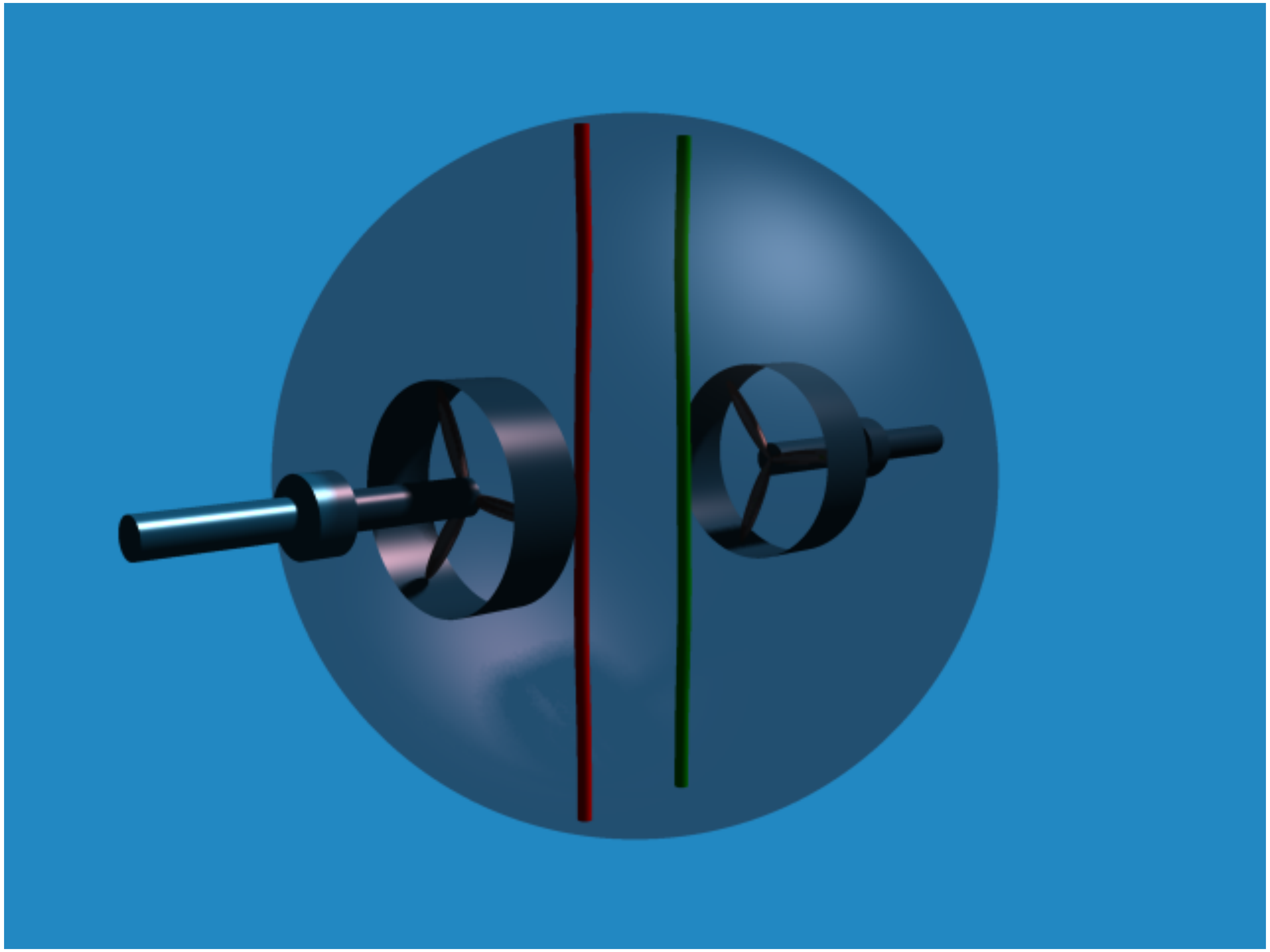
THE MADISON SODIUM DYNAMO EXPERIMENT



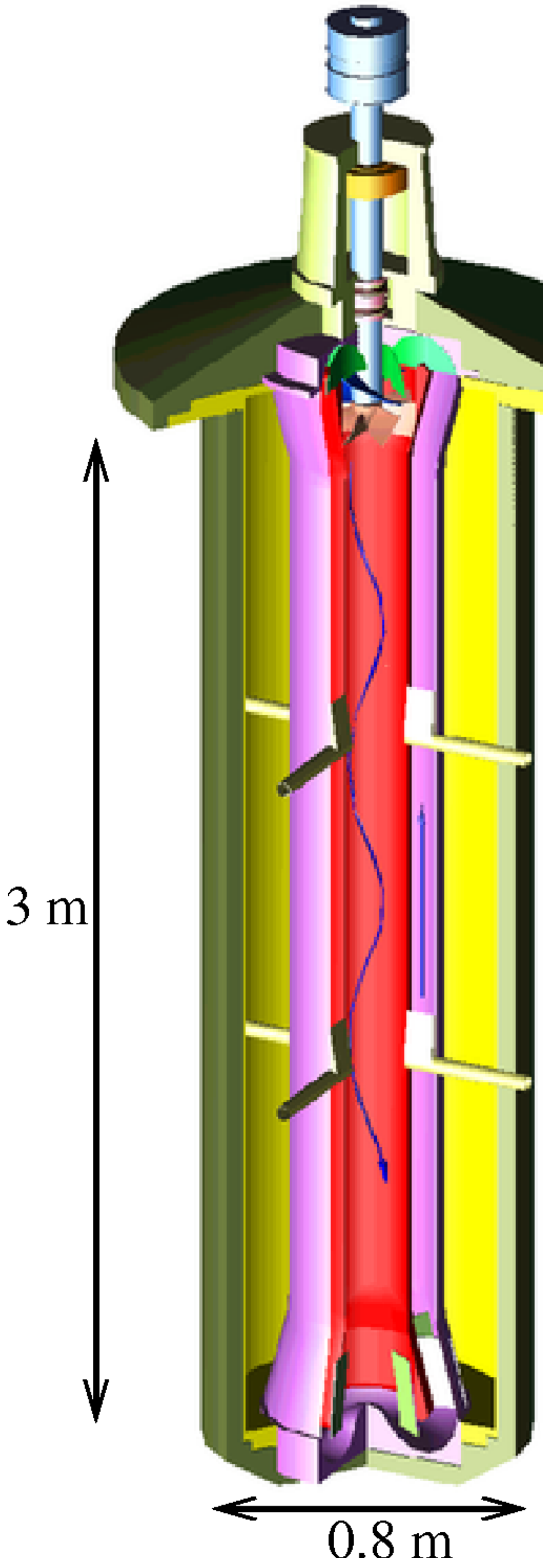


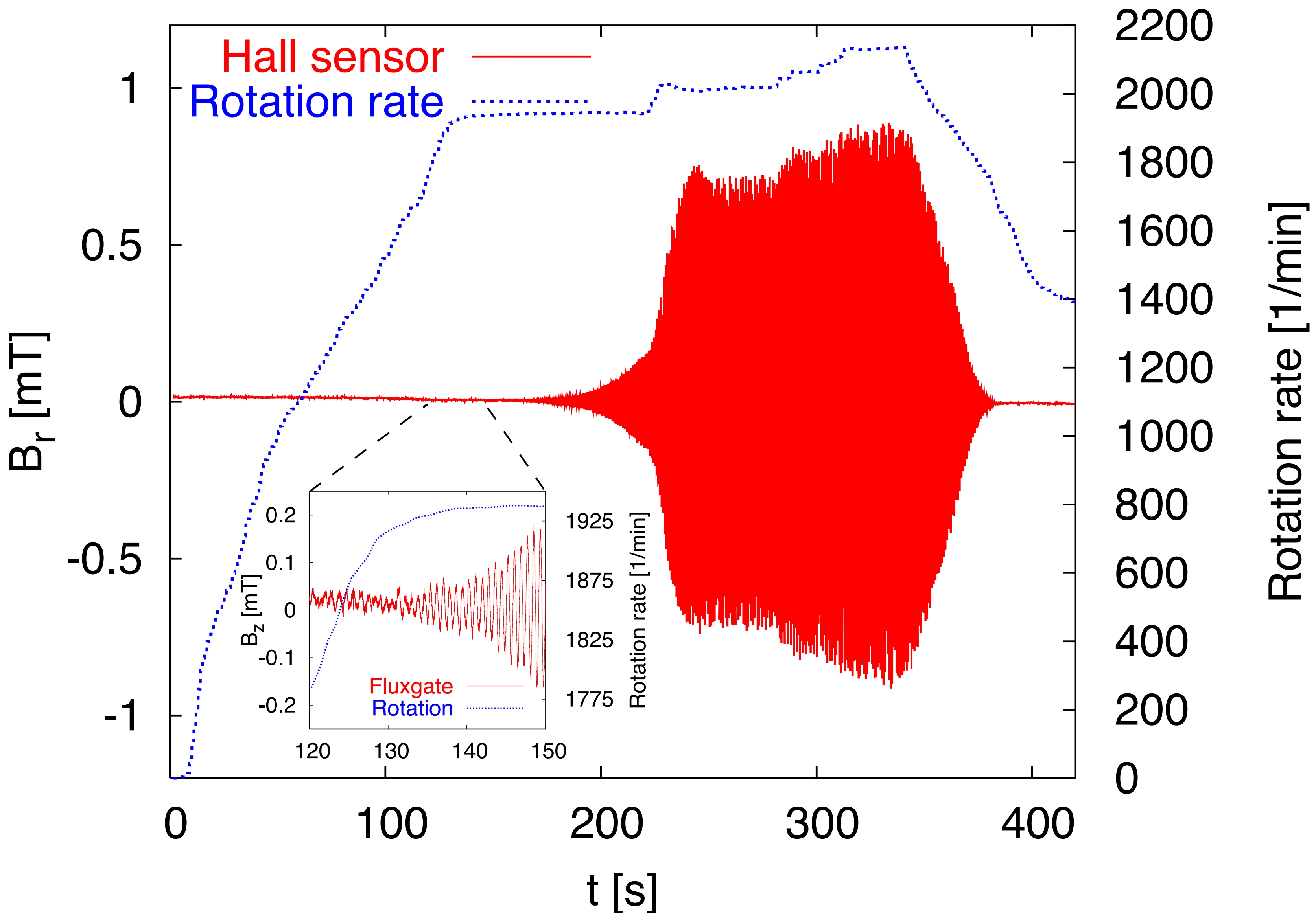
The Madison Dynamo
Experiment
a=0.5m, V=10 m/s
P=150kW, Rm_{max}=100

stretch-twist-fold Dynamo in Sphere



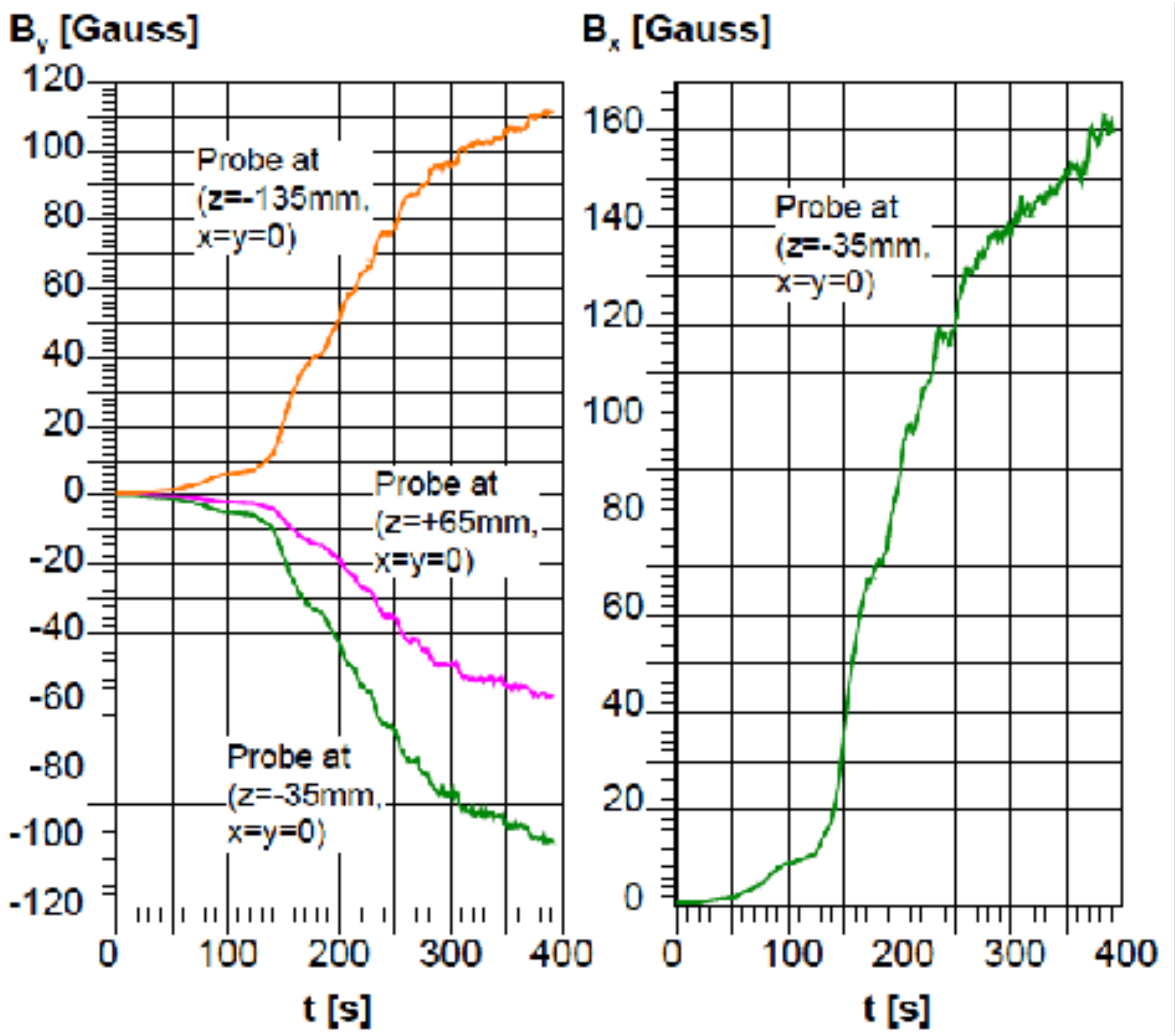
2001: RIGA SINGLE SCALE DYNAMO





- Turbulence played no role in self-excitation
- backreaction changed pitch of flow to saturate

KARLSRUHE MULTI-SCALE DYNAMO

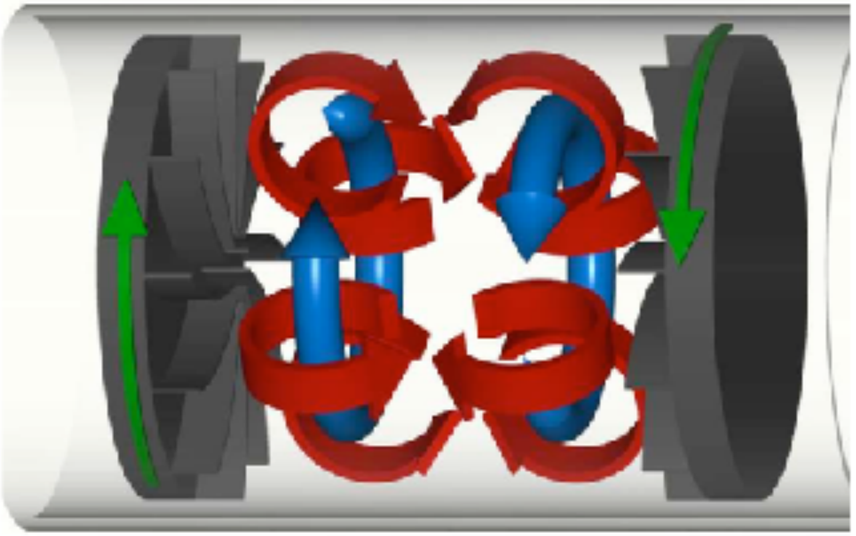


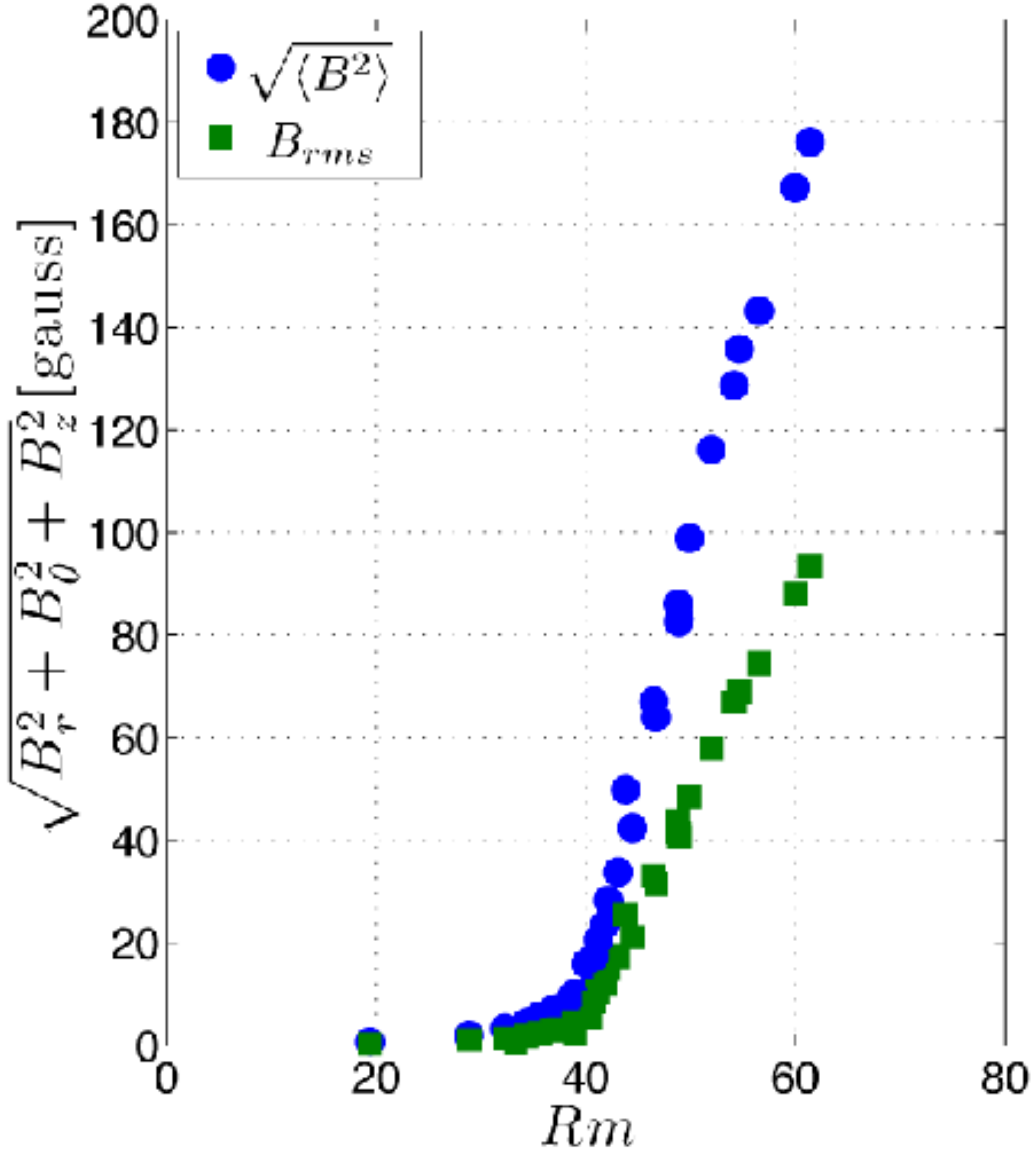
- again, turbulence played no role in self-excitation
- backreaction on flow pitch of flow to saturate

Muller and Stieglitz (2001).

THE VON KÁRMÁN DYNAMO (CADARACHE)

Two Vortex Impeller Driven Flow





Rimpeller = 0.155 m
Rvessel = 0.289 m
160 L liquid sodium
300 kW mechanical power
T° between 120°C and 150°C (with 200kW cooling)
$Rm^{max} = 90$
$Re > 10^6$

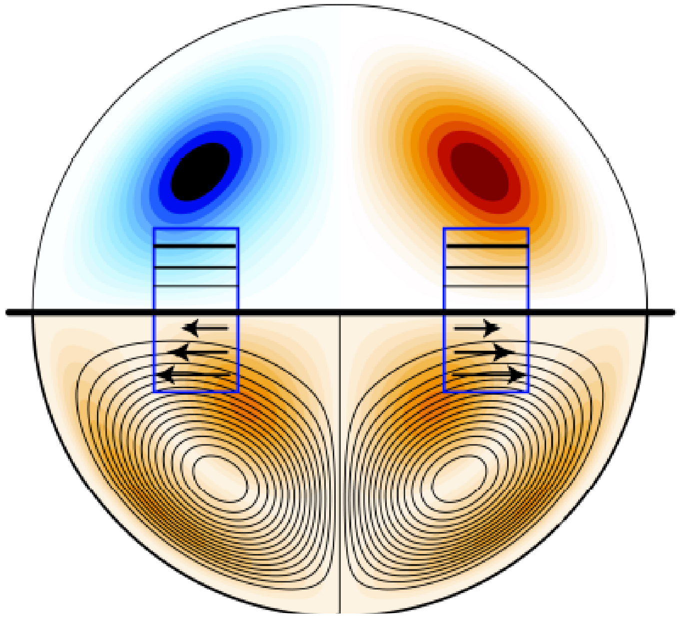
Fe Impellers!!!

A. Monchaux et al (2007)

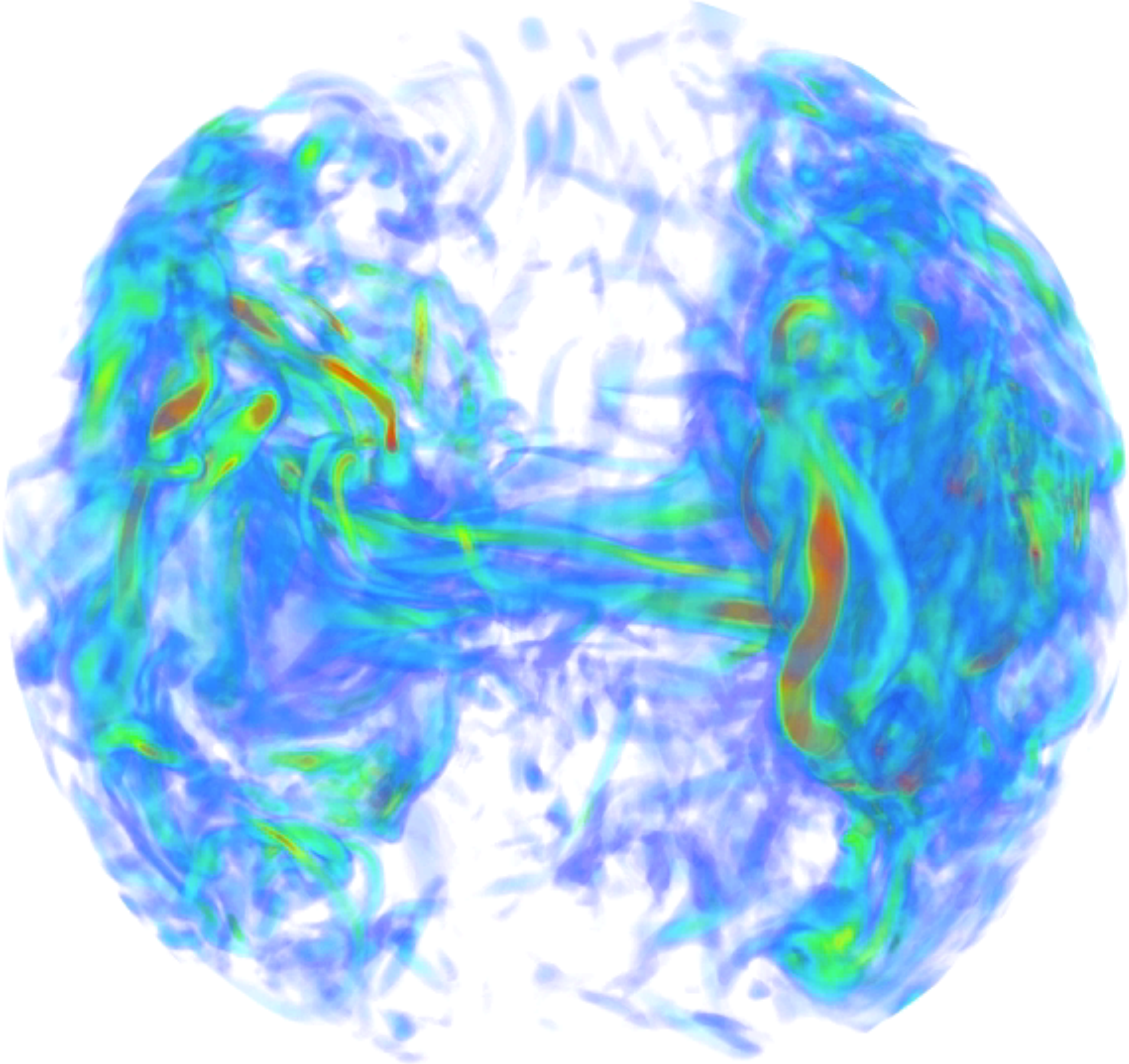
LIQUID METAL DYNAMOS ARE TURBULENT

For liquid metals

$Re \sim 10^5\, Rm$



$Re \sim 2000$



LARGE SCALE DYNAMO SUPPRESSION:
TURBULENT RESISTIVITY GOVERNS ONSET

Definitions

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

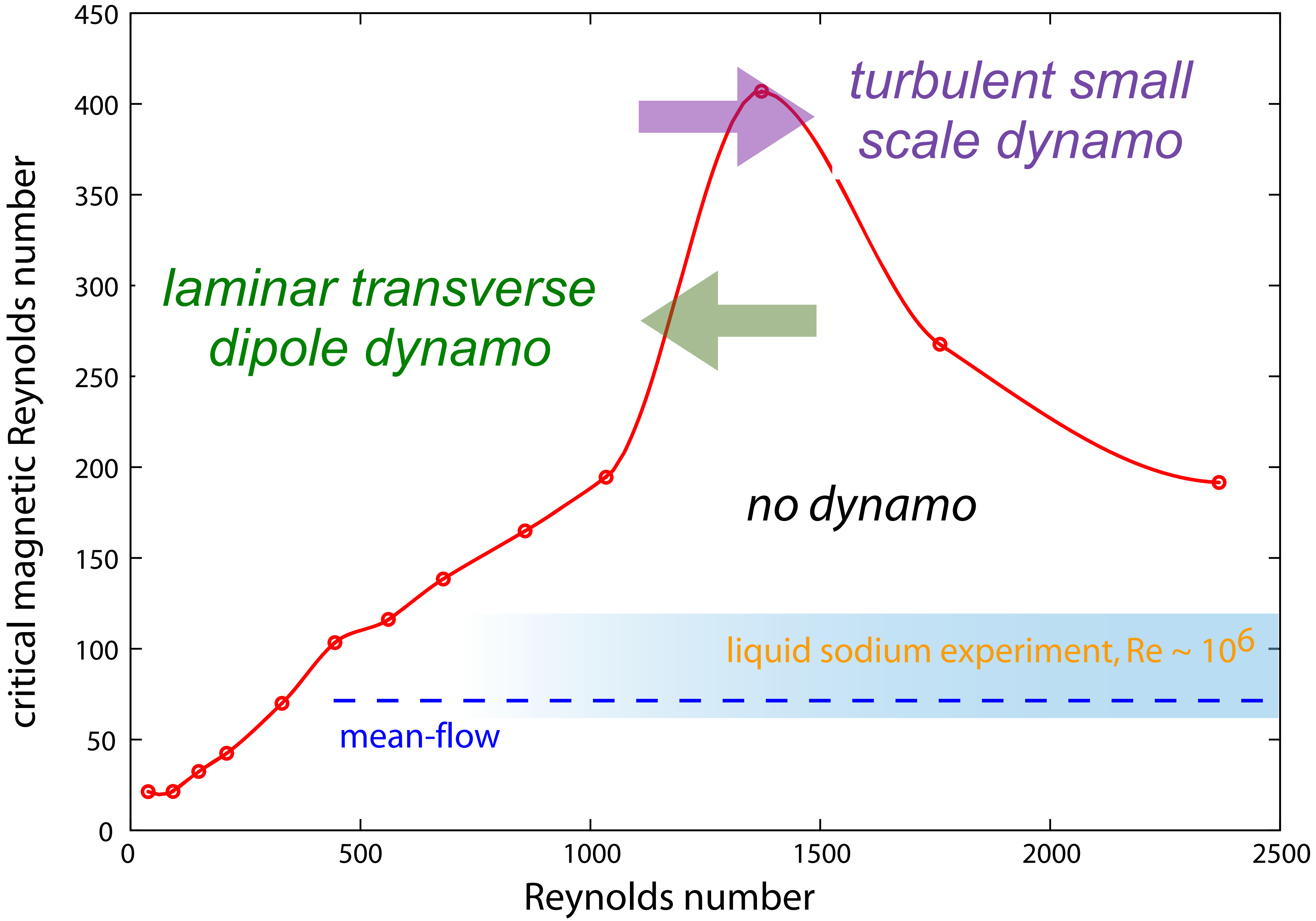
Mean-Field Electrodynamics predicts
(confirmed by measurements)

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

Self-Excitation Requirement

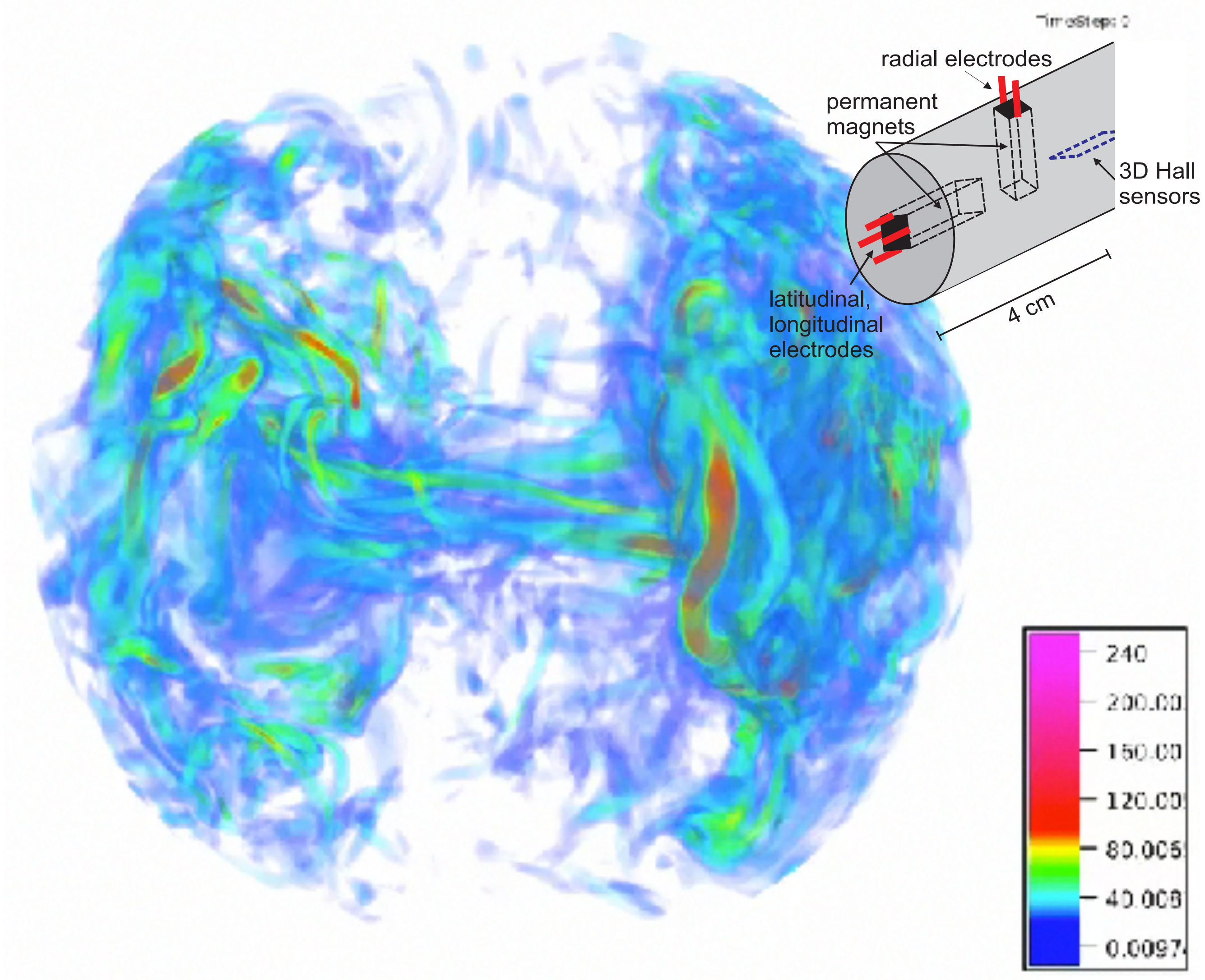
$$\boxed{Rm \geq Rm_{crit}(1 + Rm_T/3)}$$

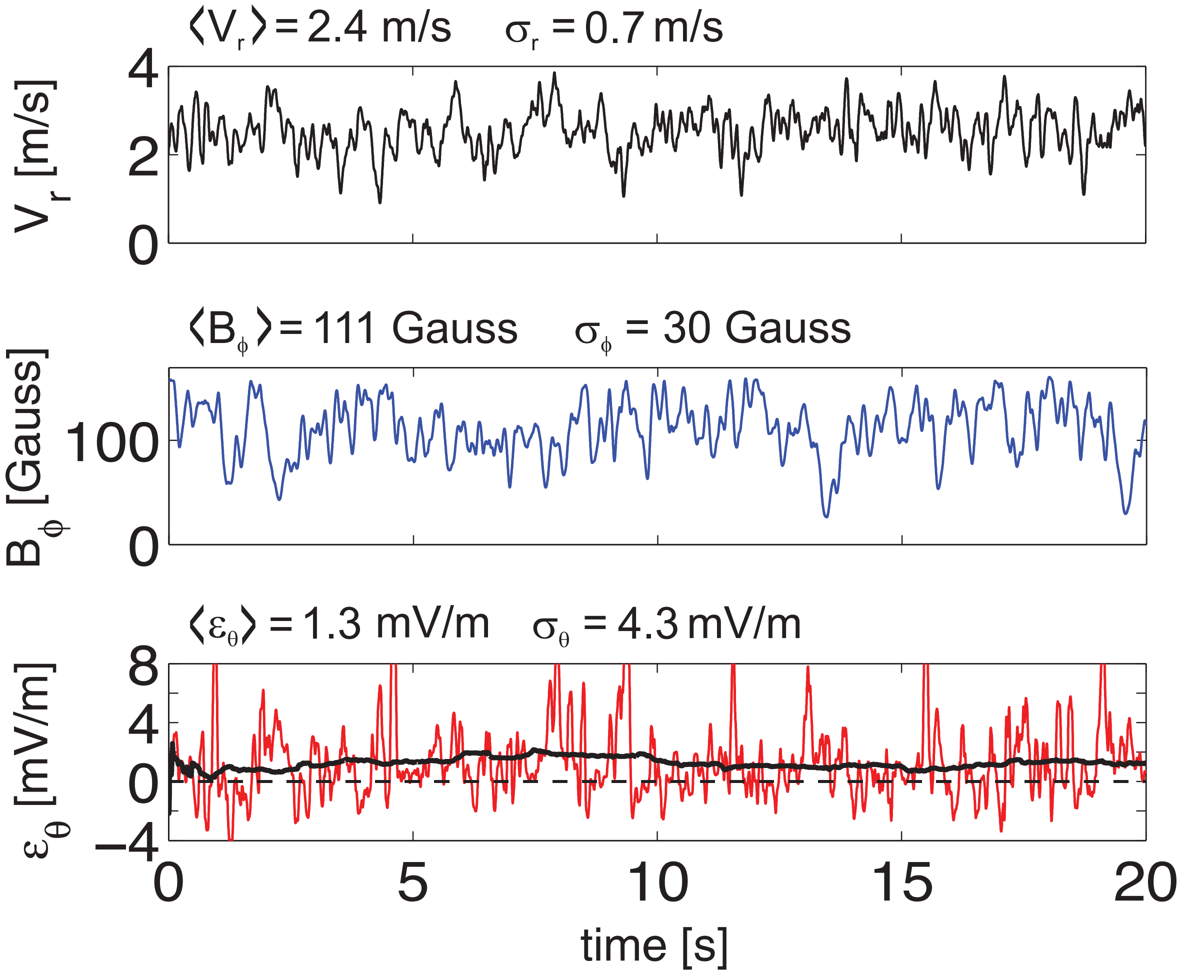
NUMERICAL SIMULATIONS SHOW TURBULENCE SUPPRESSES LARGE SCALE DYNAMO



Reuter, Jenko, and Forest, (2011).

TURBULENT EMF DIRECTLY MEASURED

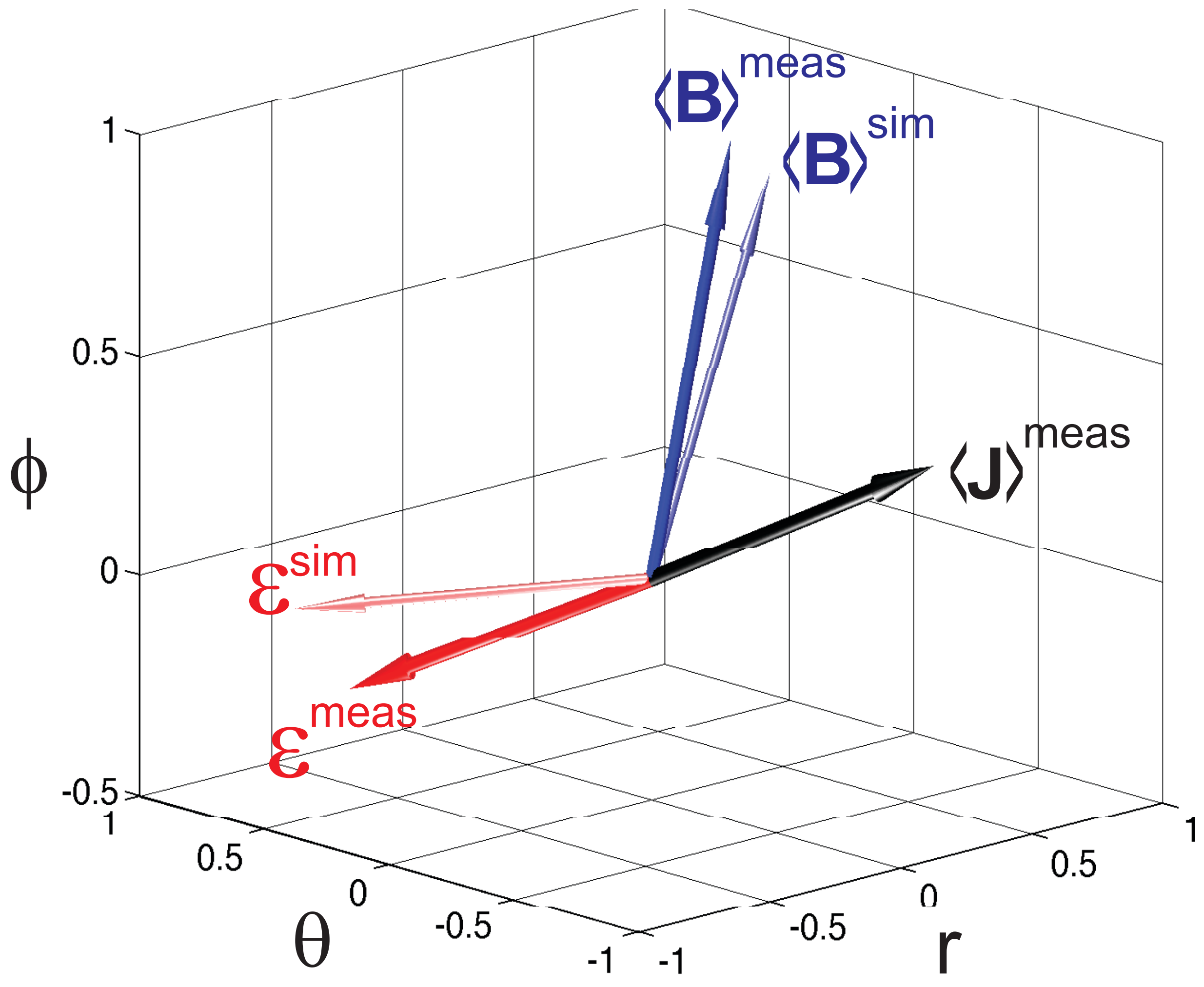


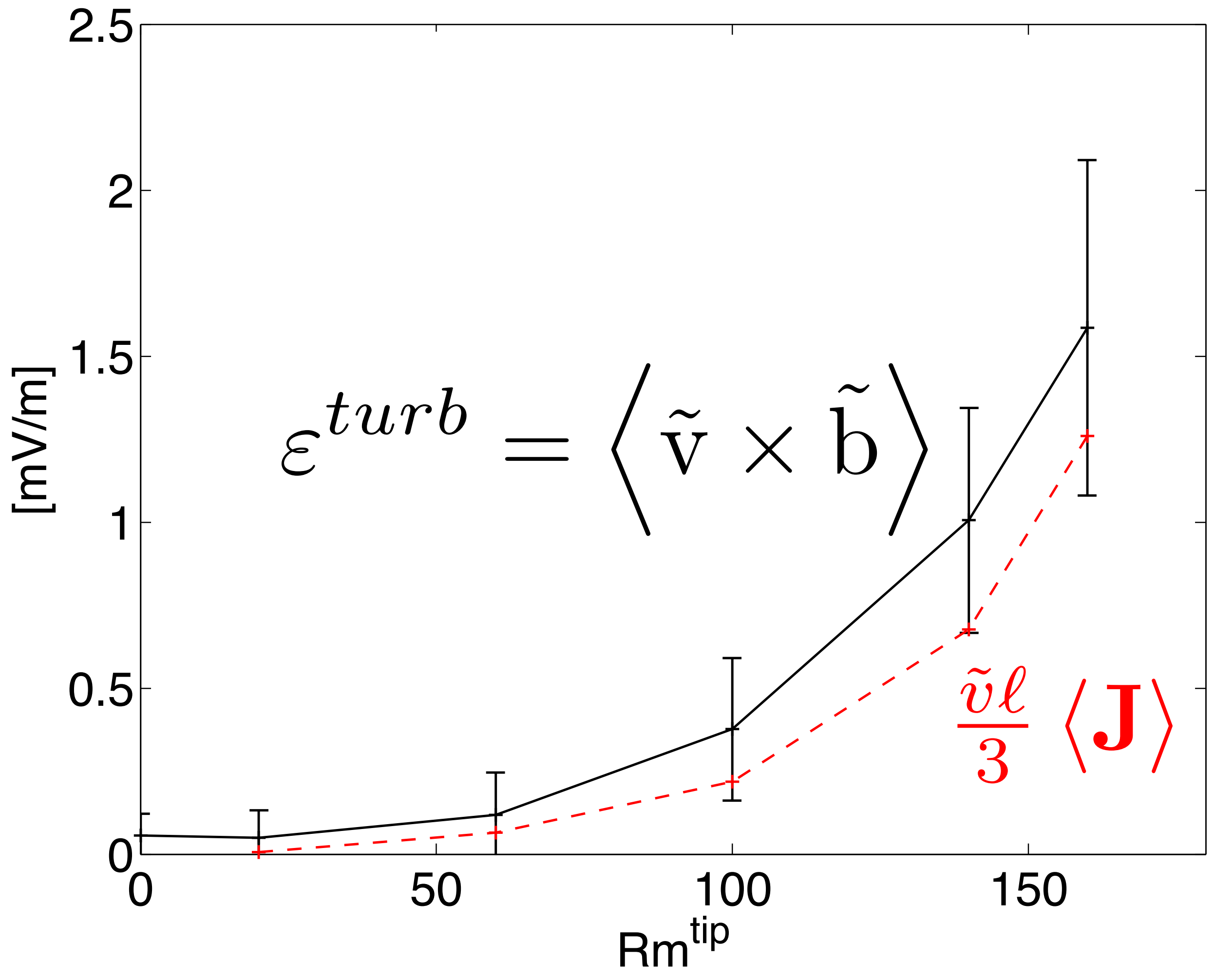


$$\varepsilon^{turb} = \left\langle \tilde{\mathrm{v}} \times \tilde{\mathrm{b}} \right\rangle$$

Rahbarnia 2012.

THE TURBULENT EMF OPPOSES THE LOCAL CURRENT, EQUIVALENT TO INCREASED RESISTIVITY (β EFFECT)





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

NEXT STEP: PLASMA DYNAMO EXPERIMENTS

- Rm > 1000
- Vary Pm: laminar/turbulent, small scale
- Rapidly Rotating
- Compressibility, stratification, buoyancy
- Plasma Effects beyond MHD: neutrals, kinetic effects, Hall MHD

→Study confinement and stirring in an unmagnetized plasma

Plasma parameters determine viscosity and conductivity

Dynamo experiments require:

$\mathrm{Re} = UL/\eta = 7.8\frac{n_{18}\sqrt{\mu}Z^4 U_{km/s} L_m}{T_{i,eV}^{5/2}}$	**>100**	Dense
$\mathrm{Rm} = \mu_0 \sigma U L = 1.6\frac{T_{e,eV}^{3/2} U_{km/s} L_m}{Z}$	**>>1**	Hot
$M_A = \sqrt{\mu_0 \rho} U/B = 0.46\frac{\sqrt{n_{18}\mu} U_{km/s}}{B_G}$	**>1**	Unmagnetized

Plasma Hydrodynamics controlled by Boundary

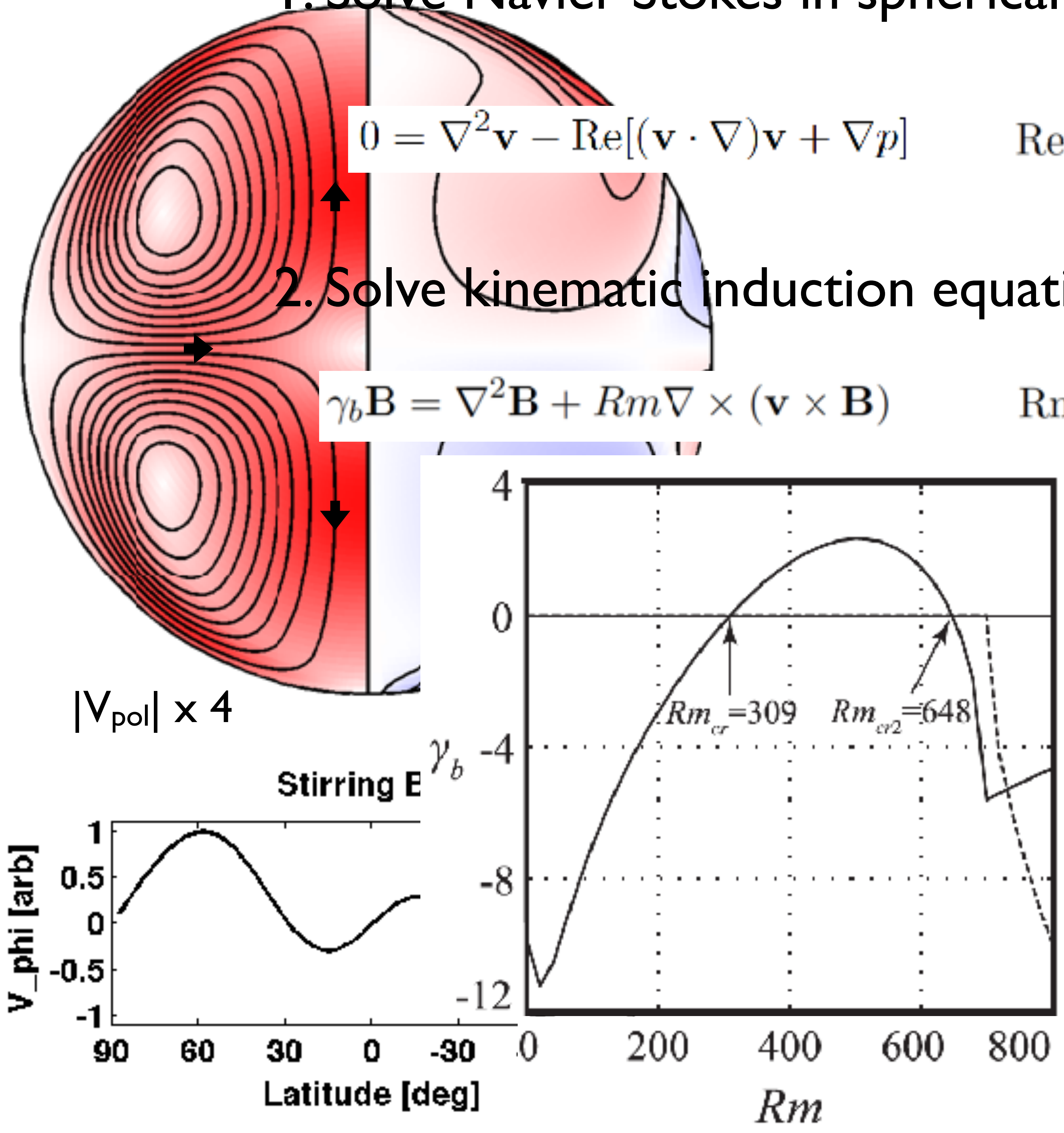
Re=300

1. Solve Navier-Stokes in spherical geometry

$$0 = \nabla^2 \mathbf{v} - \mathrm{Re}[(\mathbf{v}\cdot\nabla)\mathbf{v} + \nabla p] \qquad \mathrm{Re} = \frac{R_0 V_0}{\nu}$$

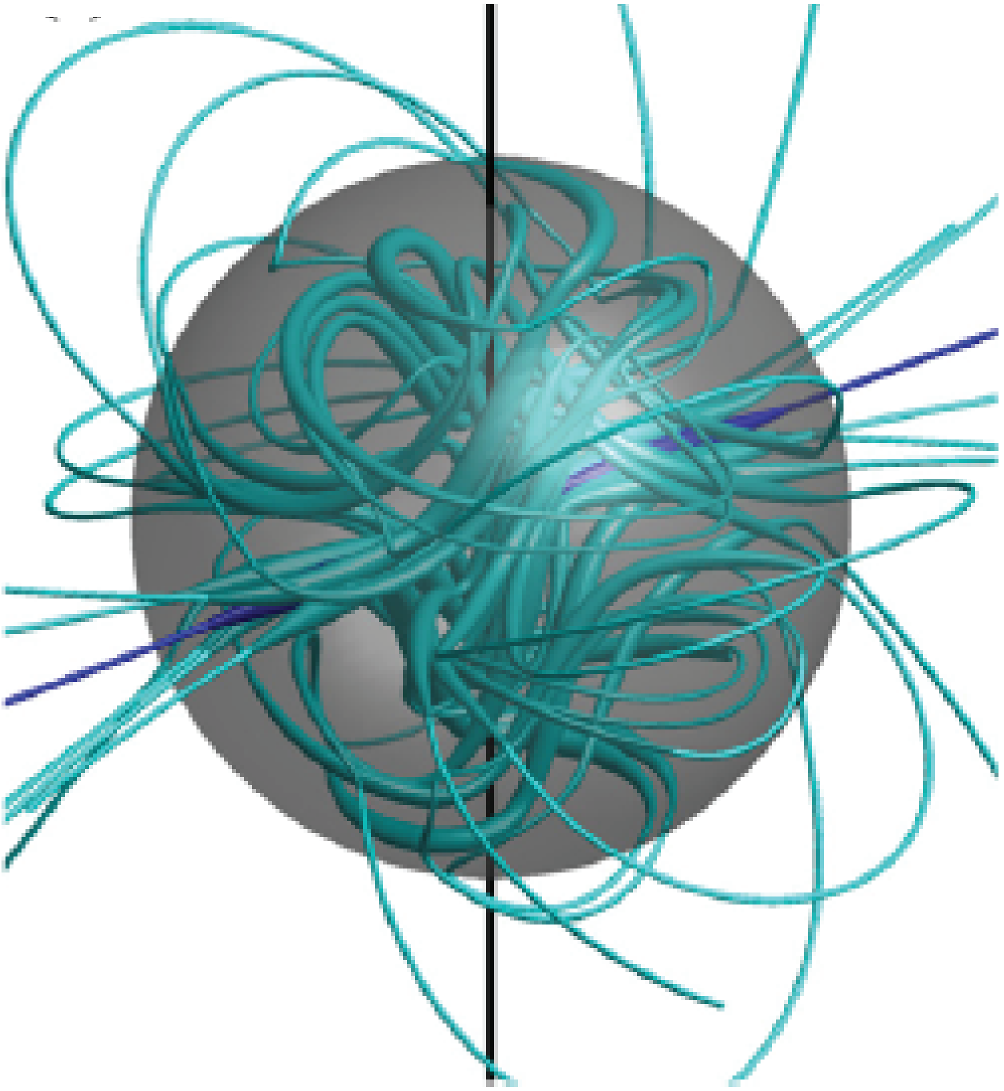
2. Solve kinematic induction equation

$$\gamma_b \mathbf{B} = \nabla^2 \mathbf{B} + Rm\nabla \times (\mathbf{v} \times \mathbf{B}) \qquad \mathrm{Rm} = \frac{R_0 V_0}{\eta}$$



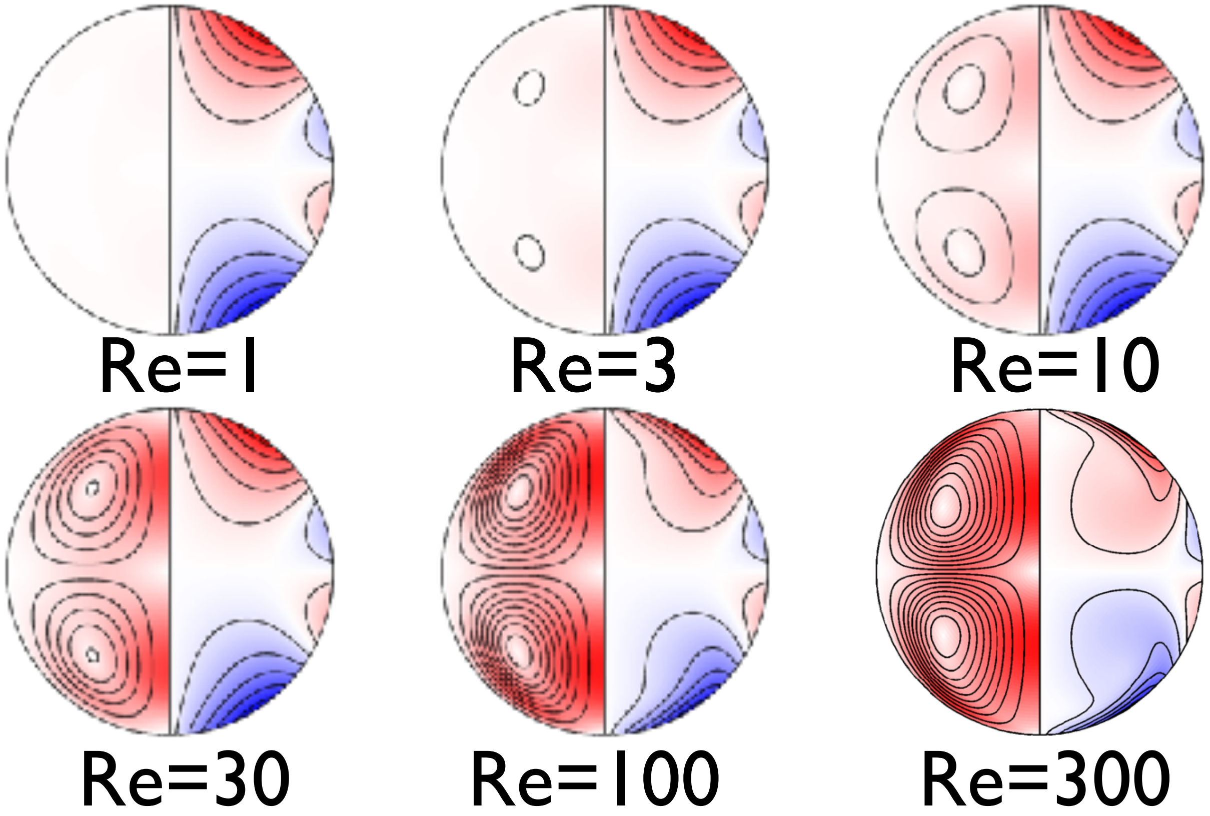
Spence, Reuter, and Forest,(2009).

Slow Large Scale Dynamo

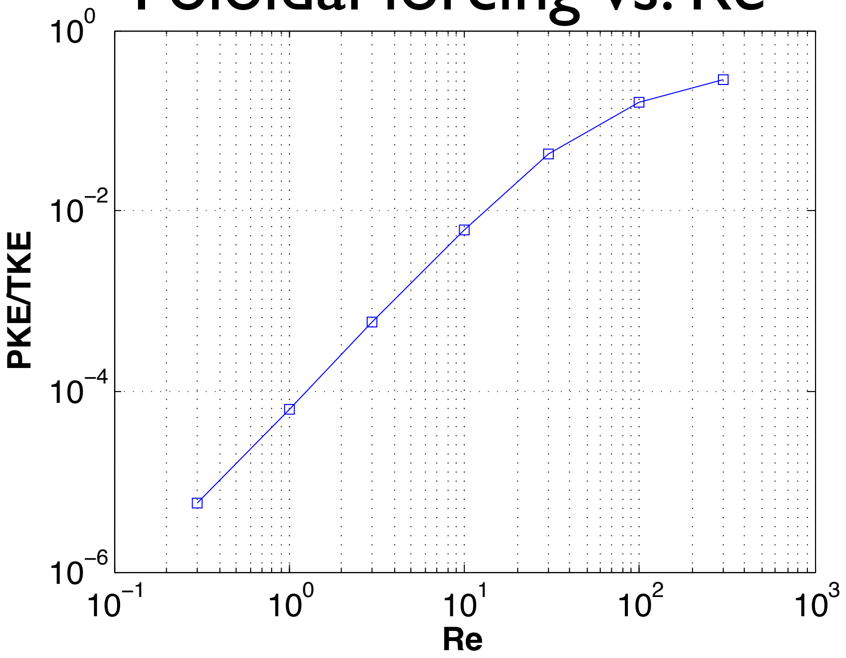


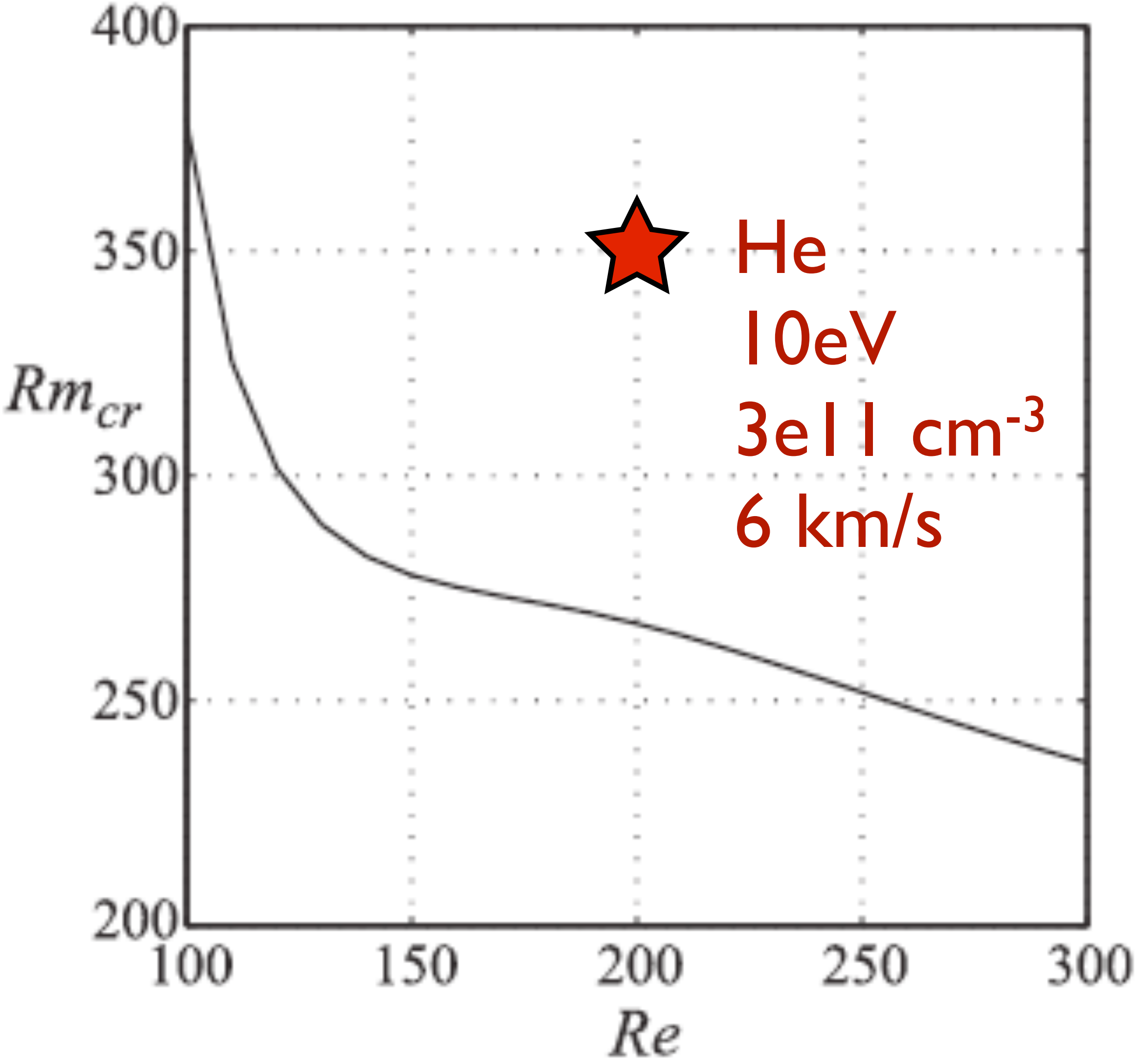
-low Rm_{crit}
-magnetic field grows on resistive time
-No dynamo at high Rm

Velocity field controlled by Re


Re=1 Re=3 Re=10

Re=30 Re=100 Re=300

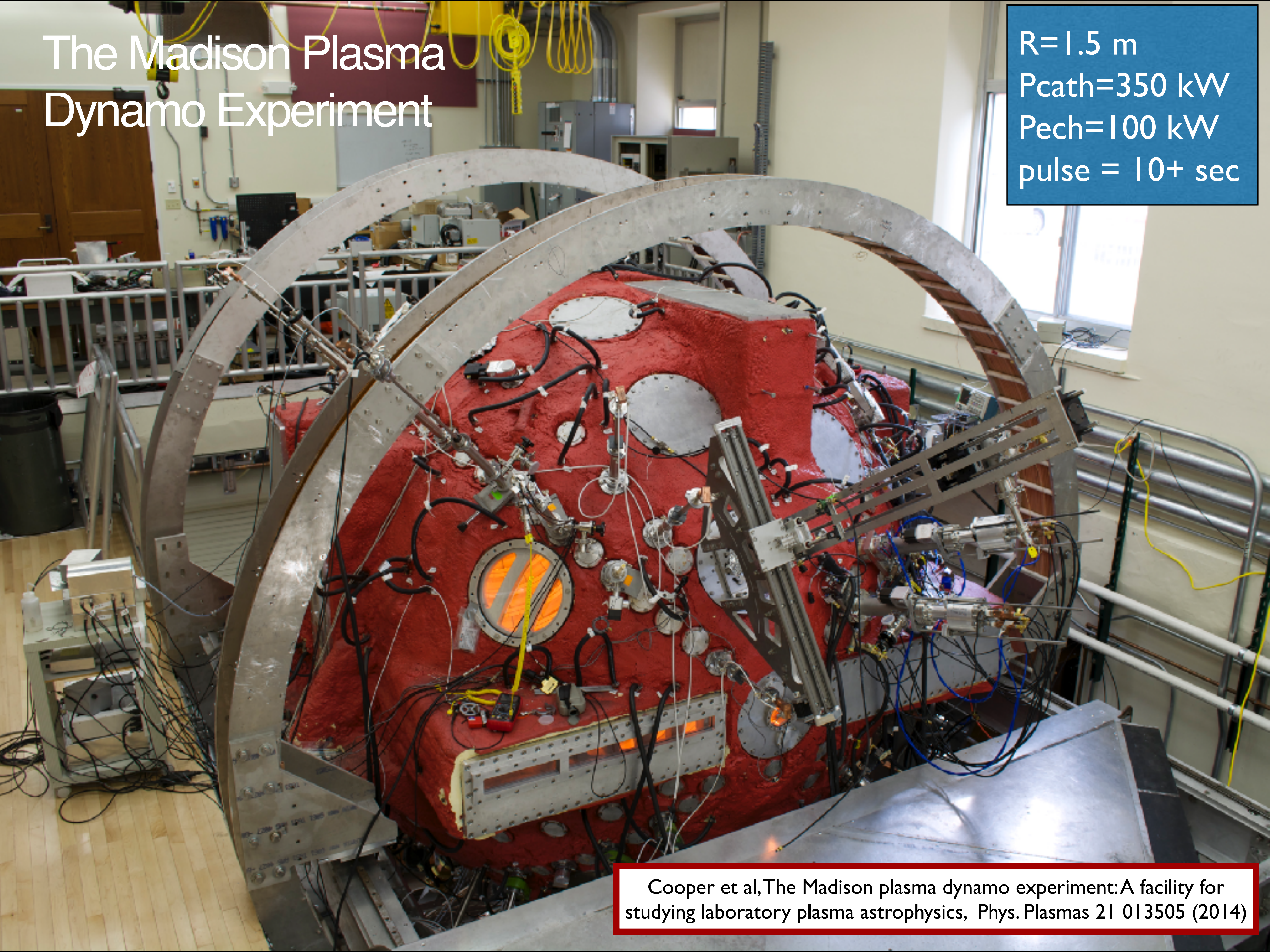

Poloidal forcing vs. Re


Dynamo onset vs. Re

He
10eV
3e11 cm^{-3}
6 km/s

Khalzov, et al, Optimized boundary driven flows for dynamos in a sphere, PHYSICS OF PLASMAS 19, 112106 (2012)

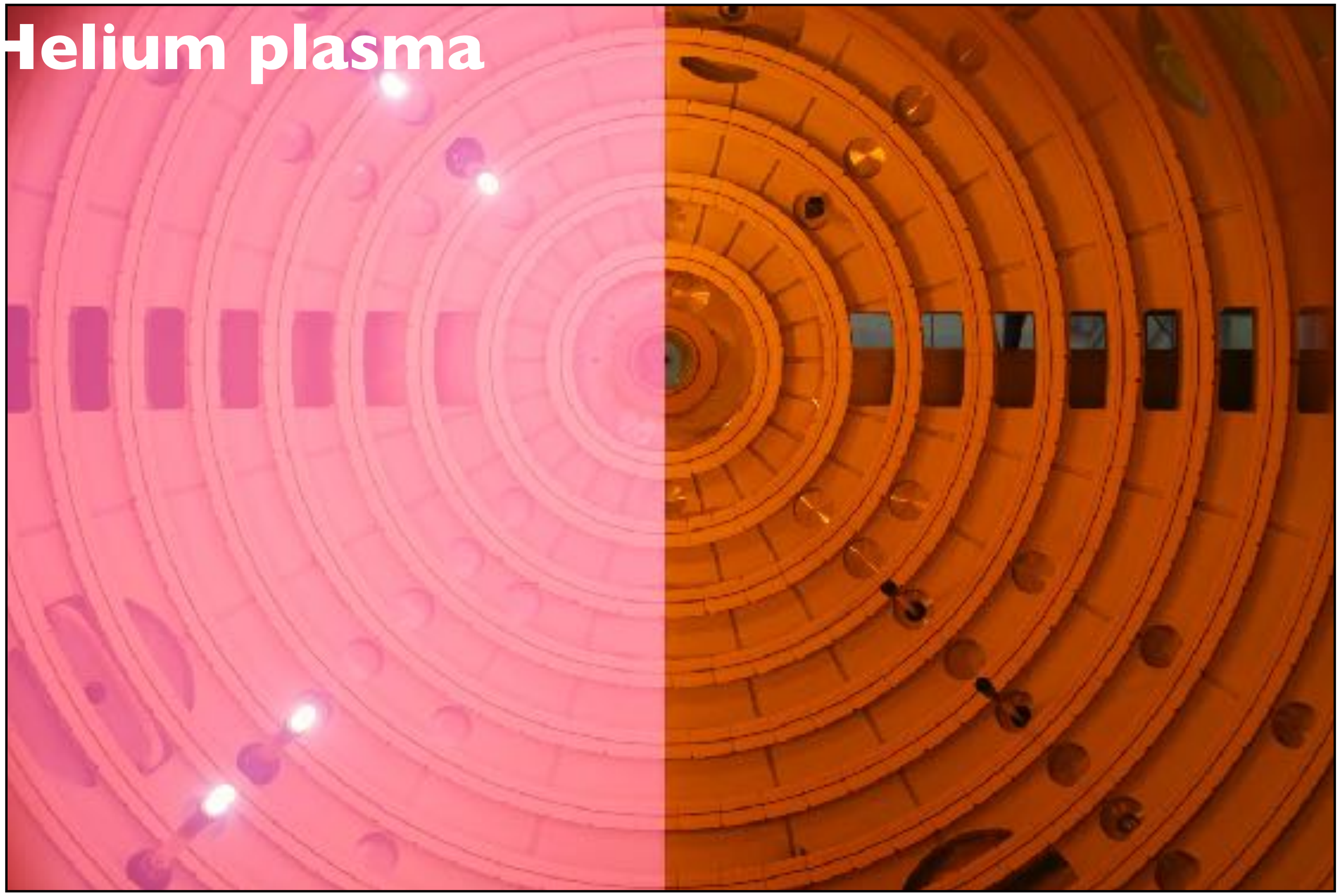
The Madison Plasma Dynamo Experiment

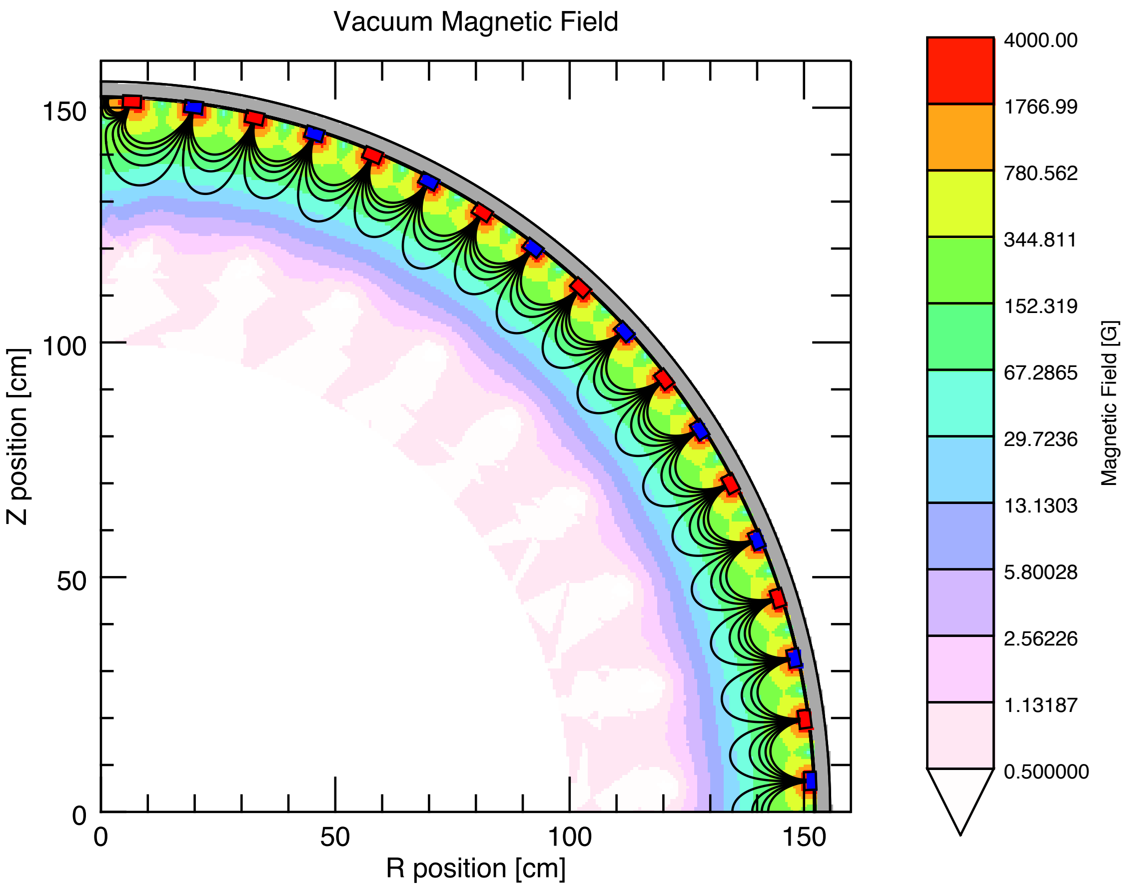


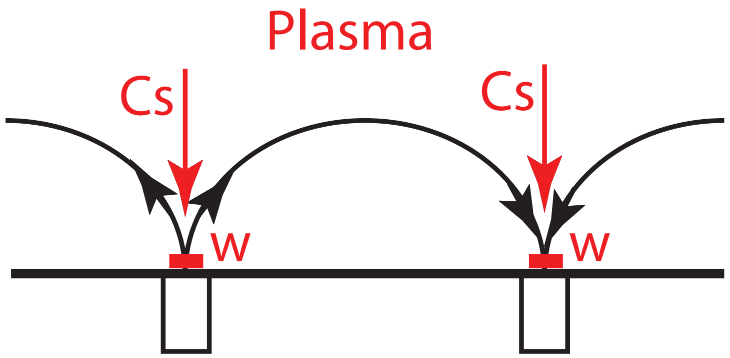
R=1.5 m
Pcath=350 kW
Pech=100 kW
pulse = 10+ sec

Cooper et al, The Madison plasma dynamo experiment: A facility for studying laboratory plasma astrophysics, Phys. Plasmas 21 013505 (2014)

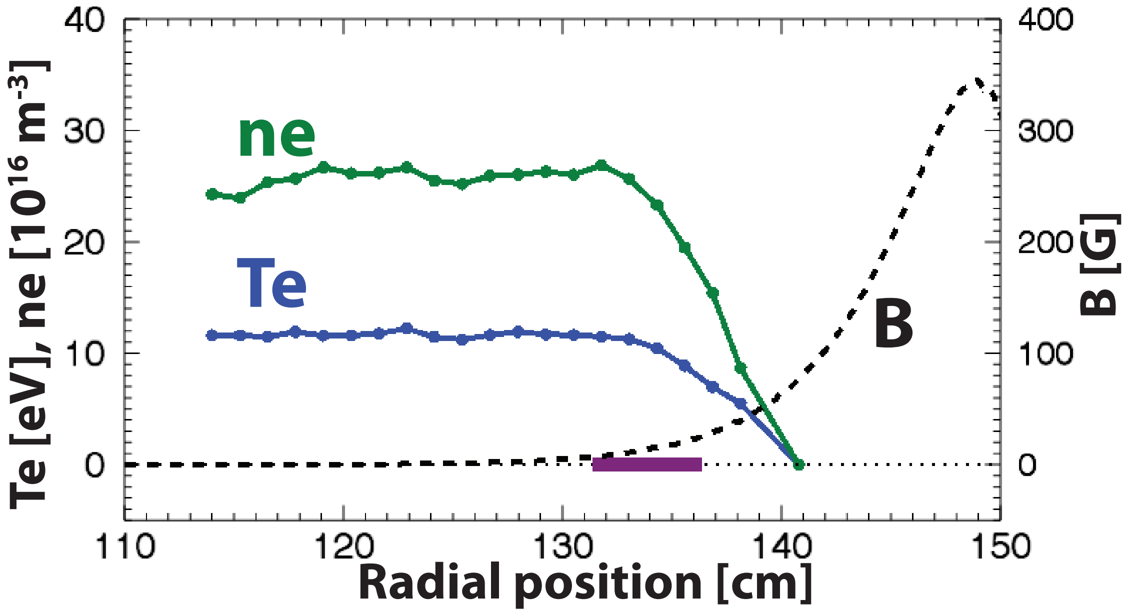
3000 permanent magnets confine unmagnetized plasma



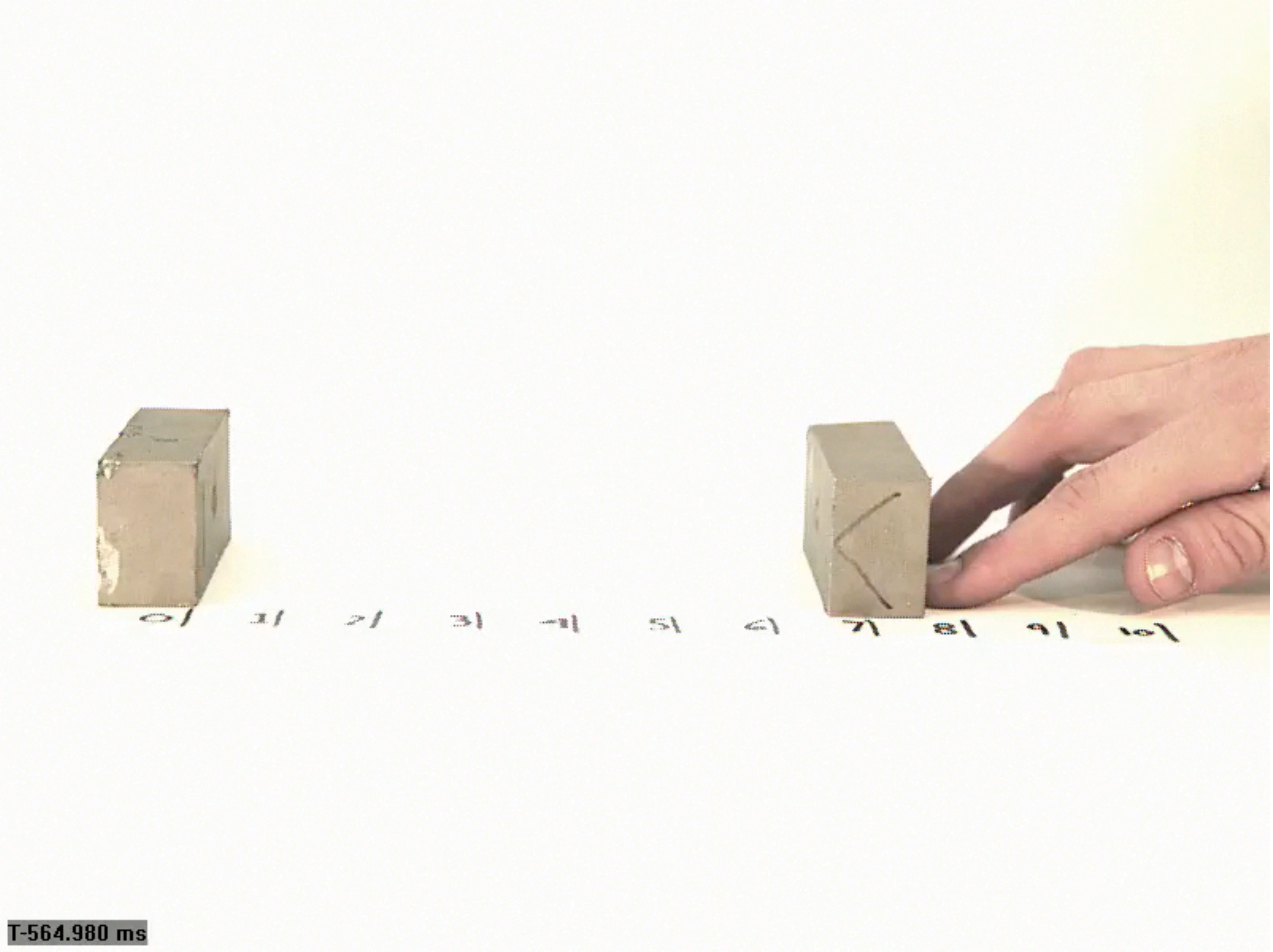




Plasma is only lost through magnetic mirrors at rings



3000 4 kG SmCo magnets


0
1
2
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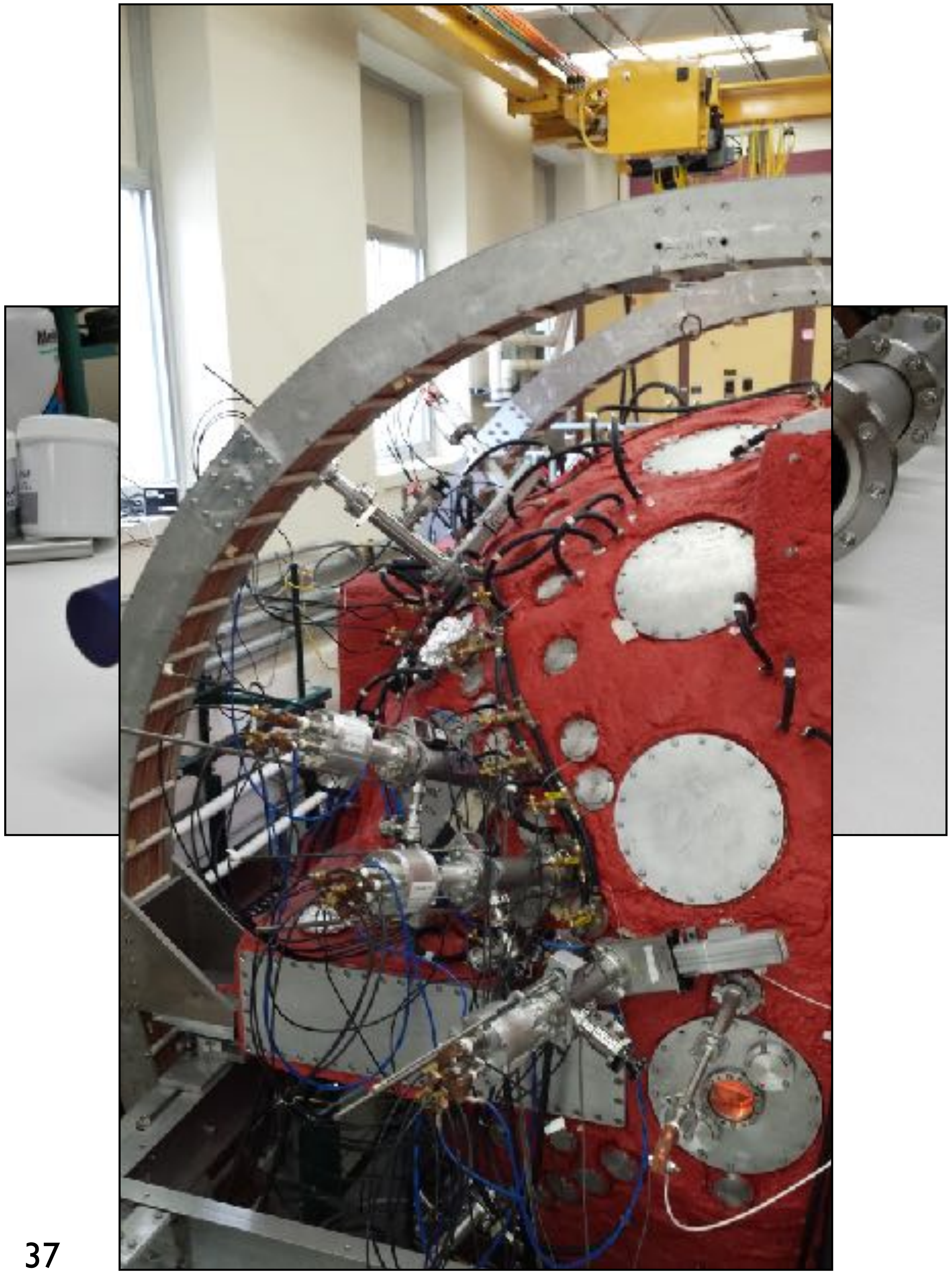
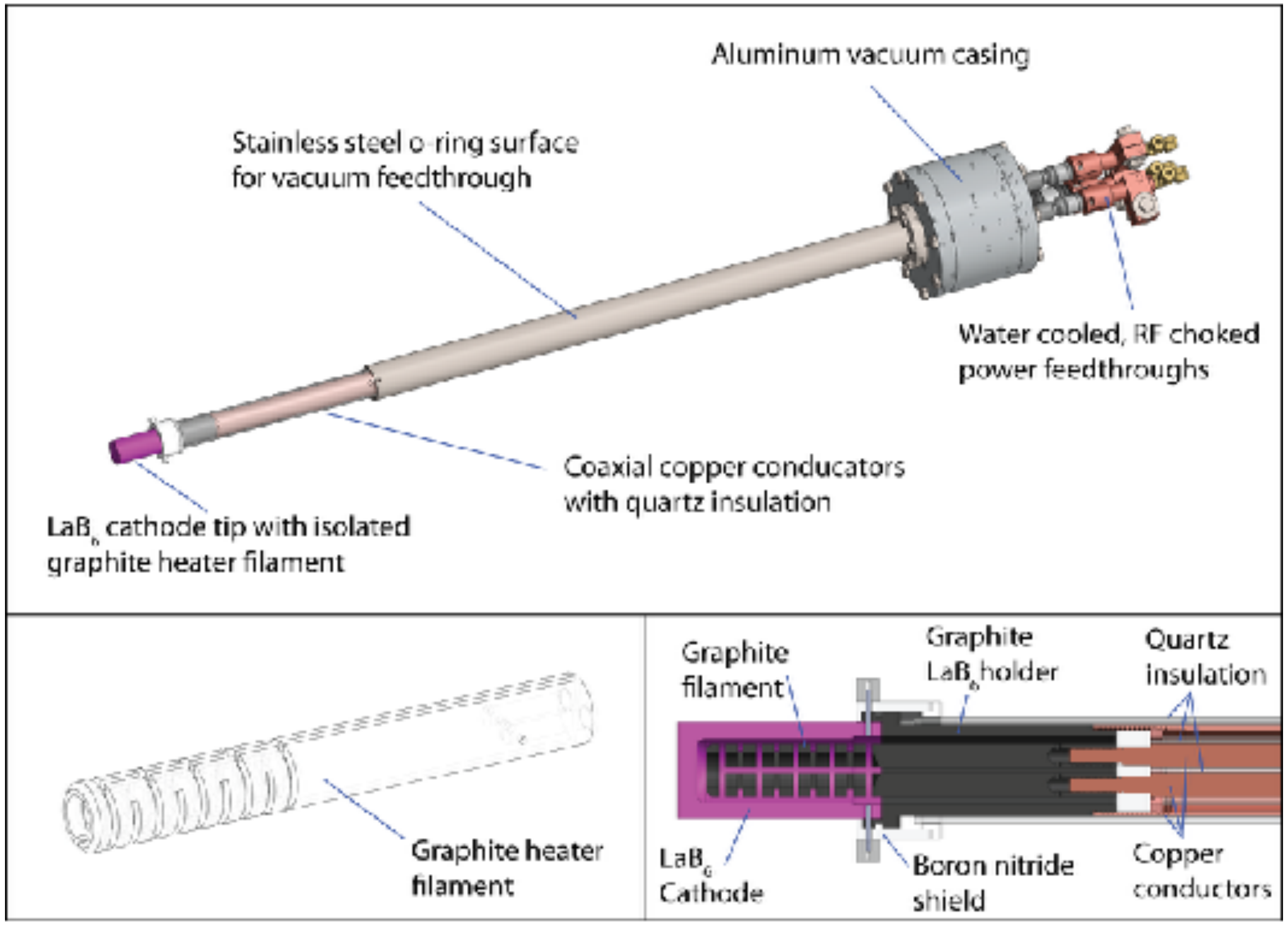
T-564.980 ms

LaB_6 cathodes create high power discharges

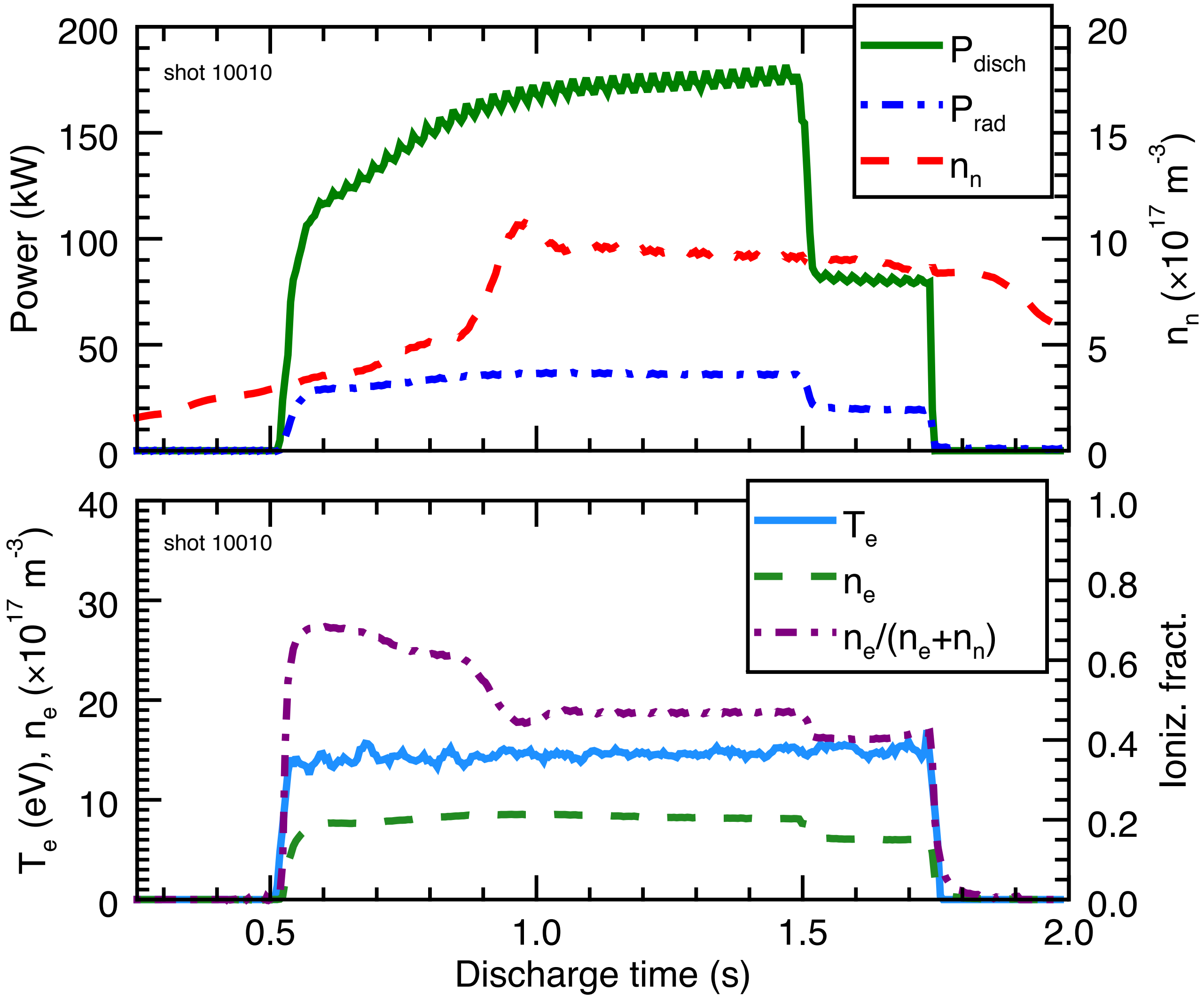




Discharge Voltage	Discharge Current	Discharge Power	Uptime
200-500 V	< 100 A	< 36 kW	> 6 months

Total installed power: 360kW

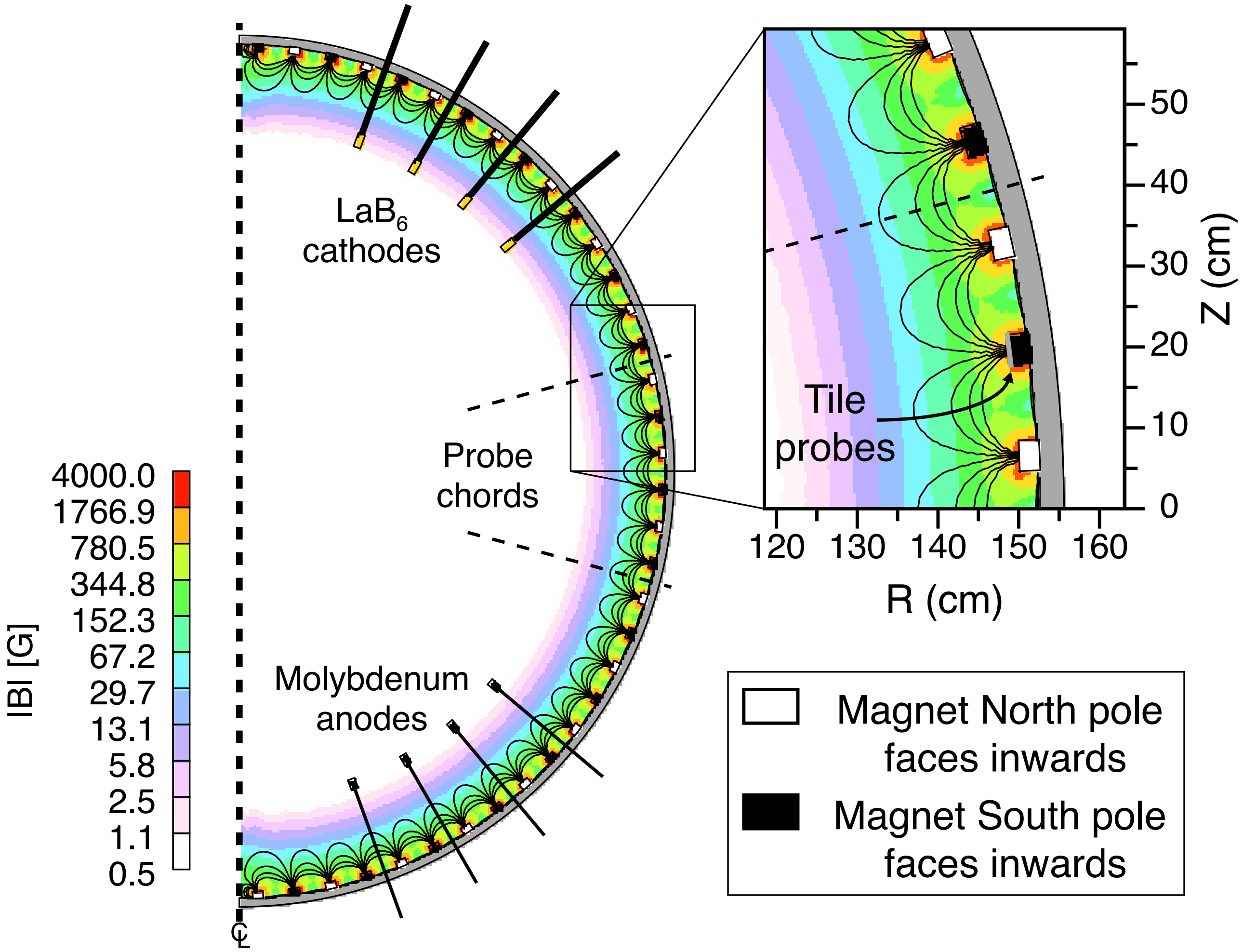
LaB_6 cathodes facilitate high power discharges



Discharge Voltage	Discharge Current	Discharge Power	Uptime
200-500 V	< 100 A	< 36 kW	> 6 months

Total installed power: 360kW

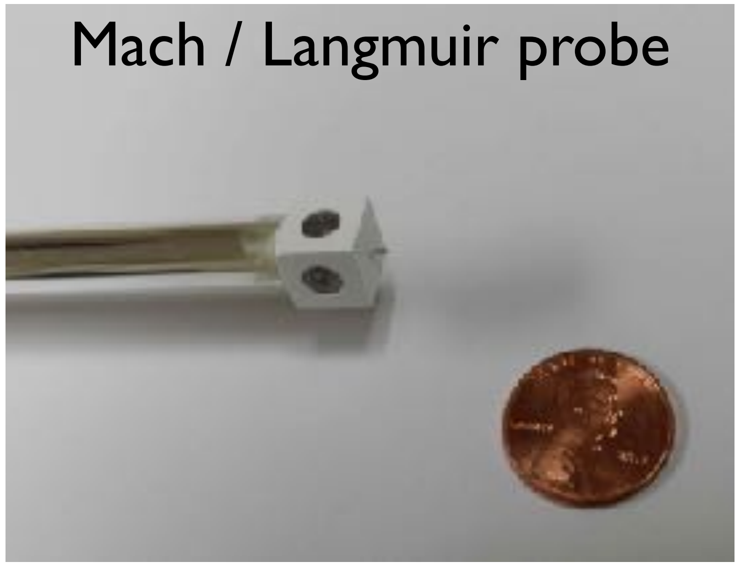
Plasma diagnostics measure parameters in plasma core and edge

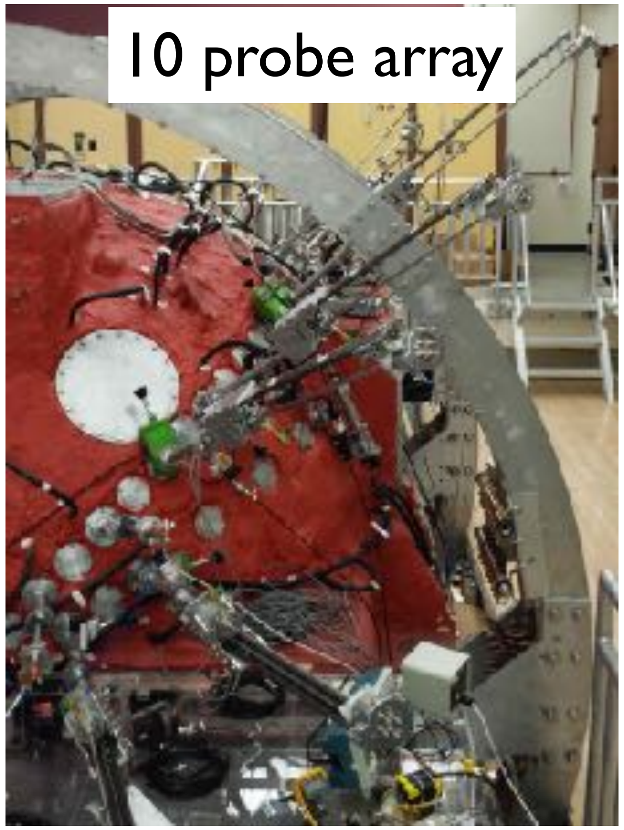


- mm-wave interferometer (n_e)
- Fabry-perot interferometer (T_i)
- Langmuir/Mach 10-probe array (n_e, T_e, phi velocity, theta velocity)
- Pyroelectric bolometer
- Survey spectrometer array

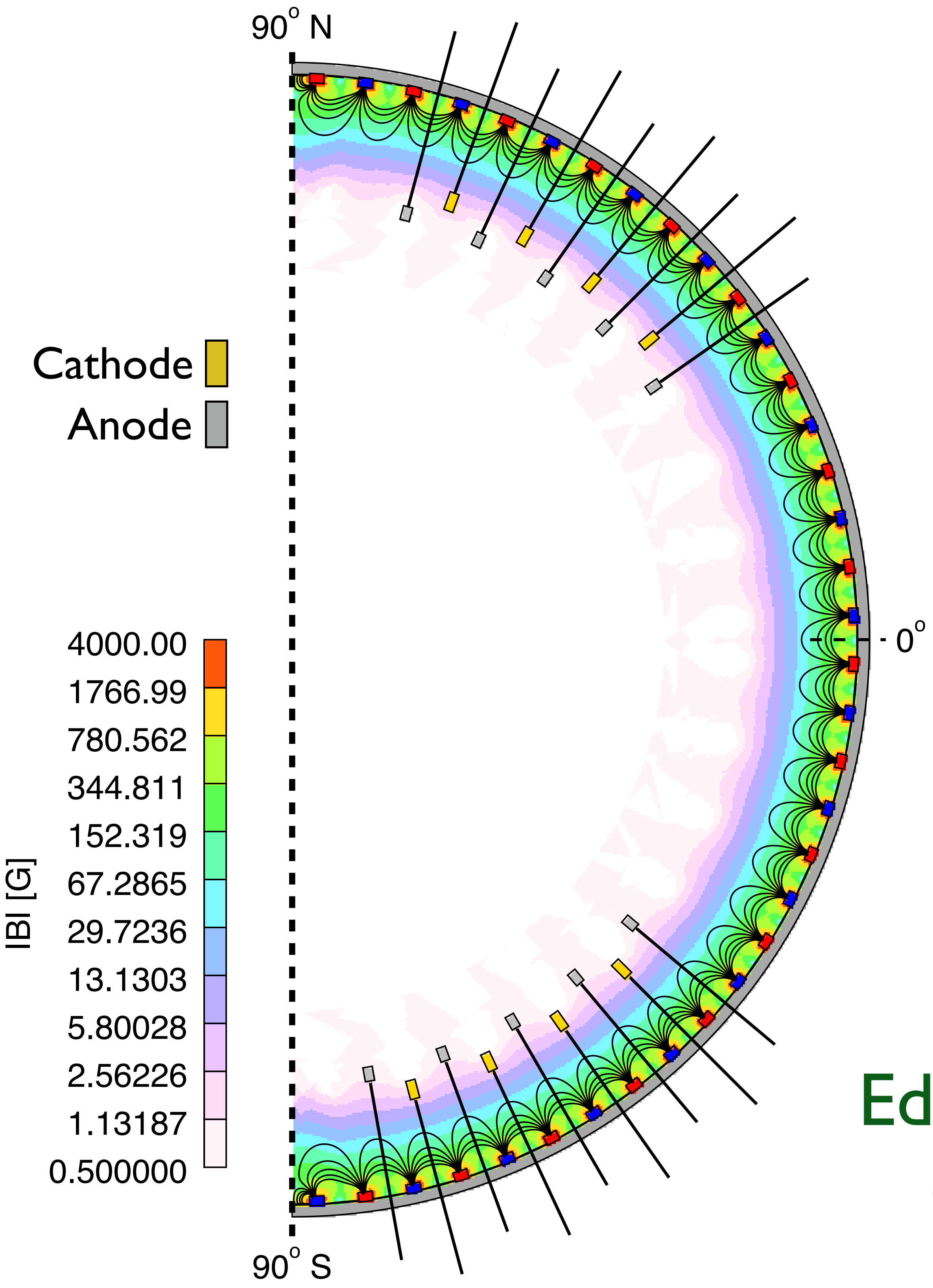
Edge tile Langmuir probes

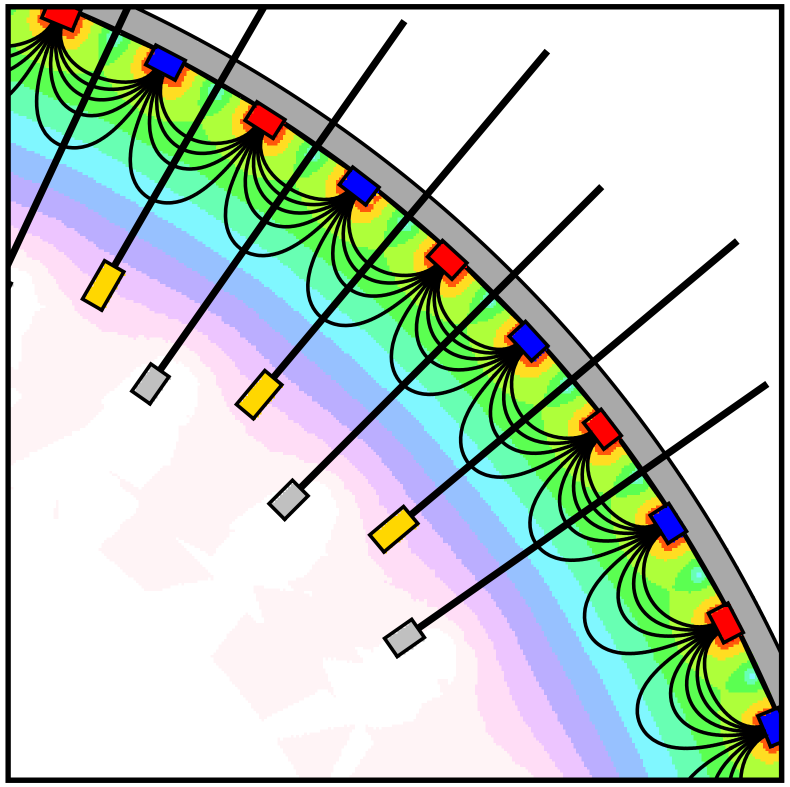
Pyroelectric bolometer

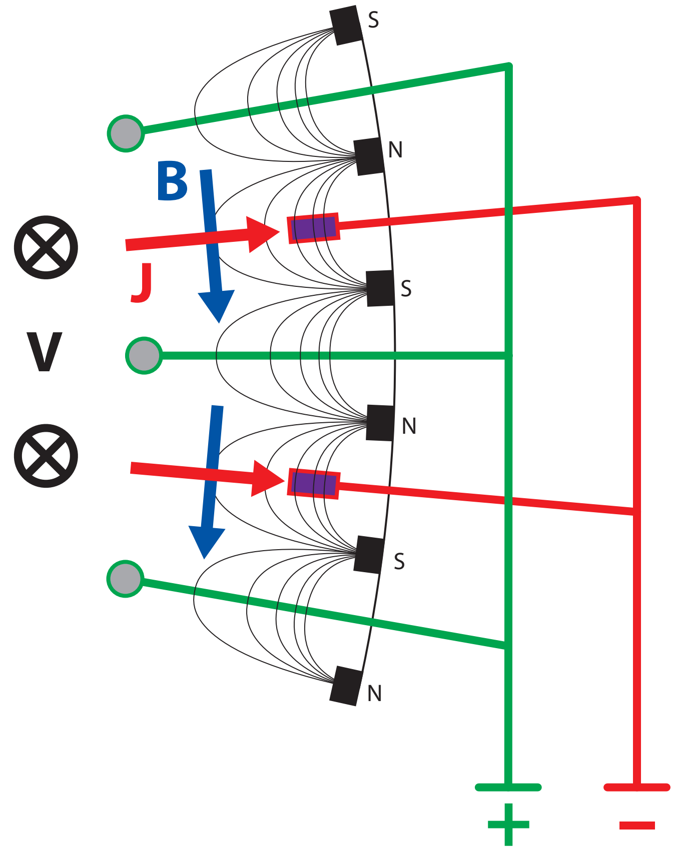

Mach / Langmuir probe


10 probe array

Magnetized cathodes stir from plasma edge

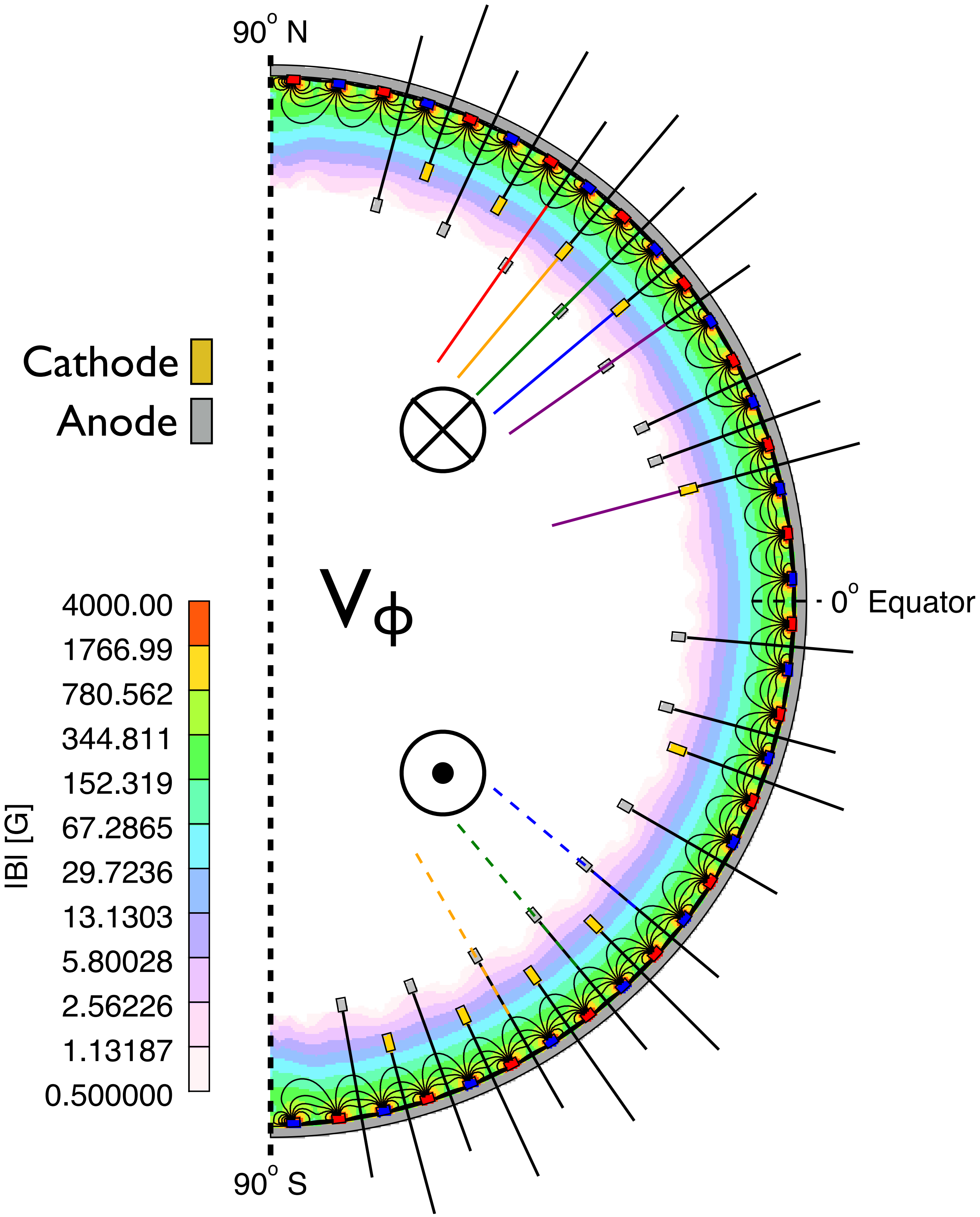


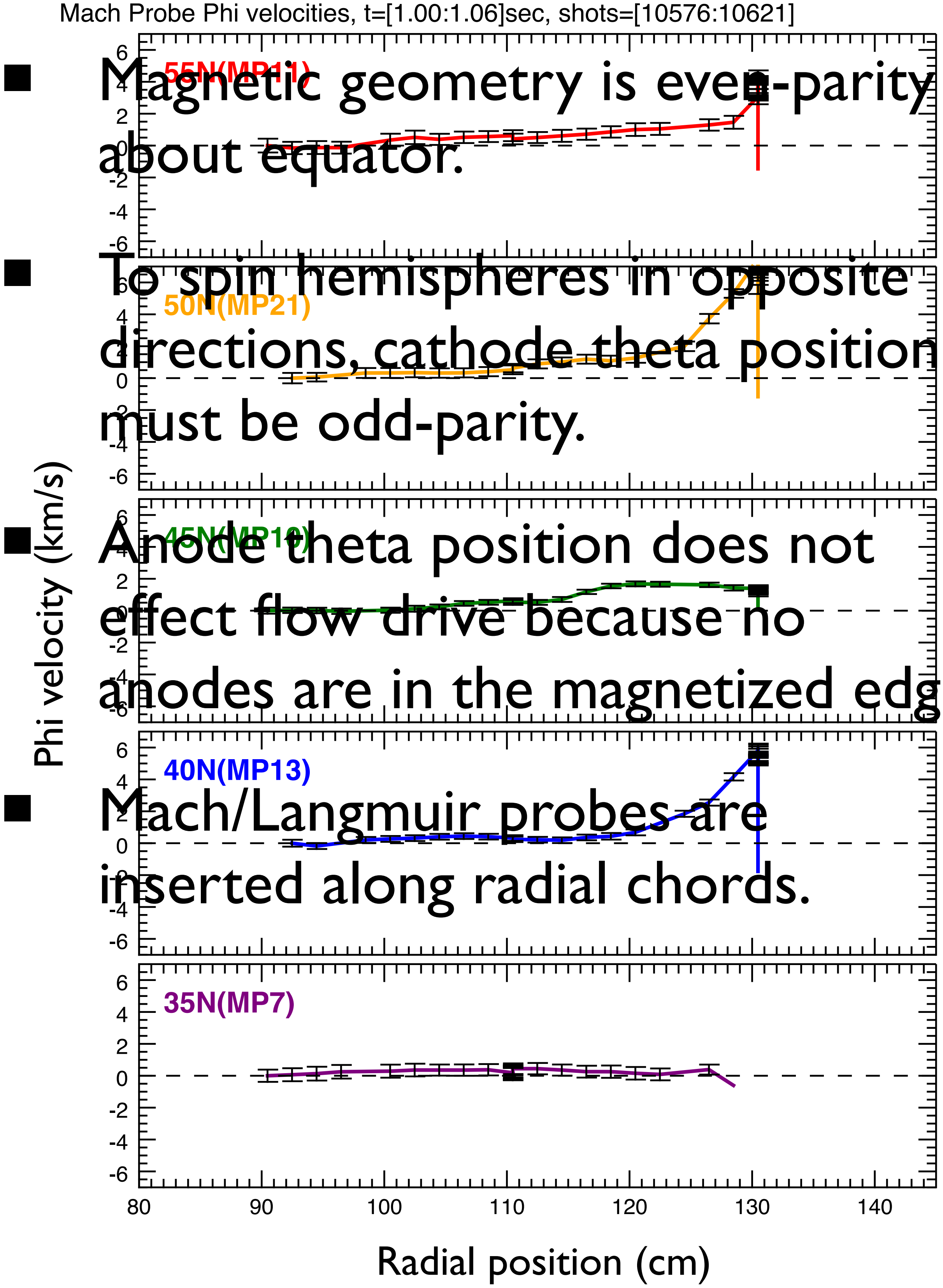




$$\frac{d\mathbf{v}}{dt} = \underbrace{\frac{1}{\rho}(\mathbf{J}\times\mathbf{B})}_{\text{Edge flow drive}} - \underbrace{\frac{\mathbf{v}}{\tau_{in}}}_{\text{Neutral drag slows flow}} + \underbrace{\nu\nabla^2\mathbf{v}}_{\text{Ion viscosity spins up core}}$$

Viscously-coupled flow: counter-rotation

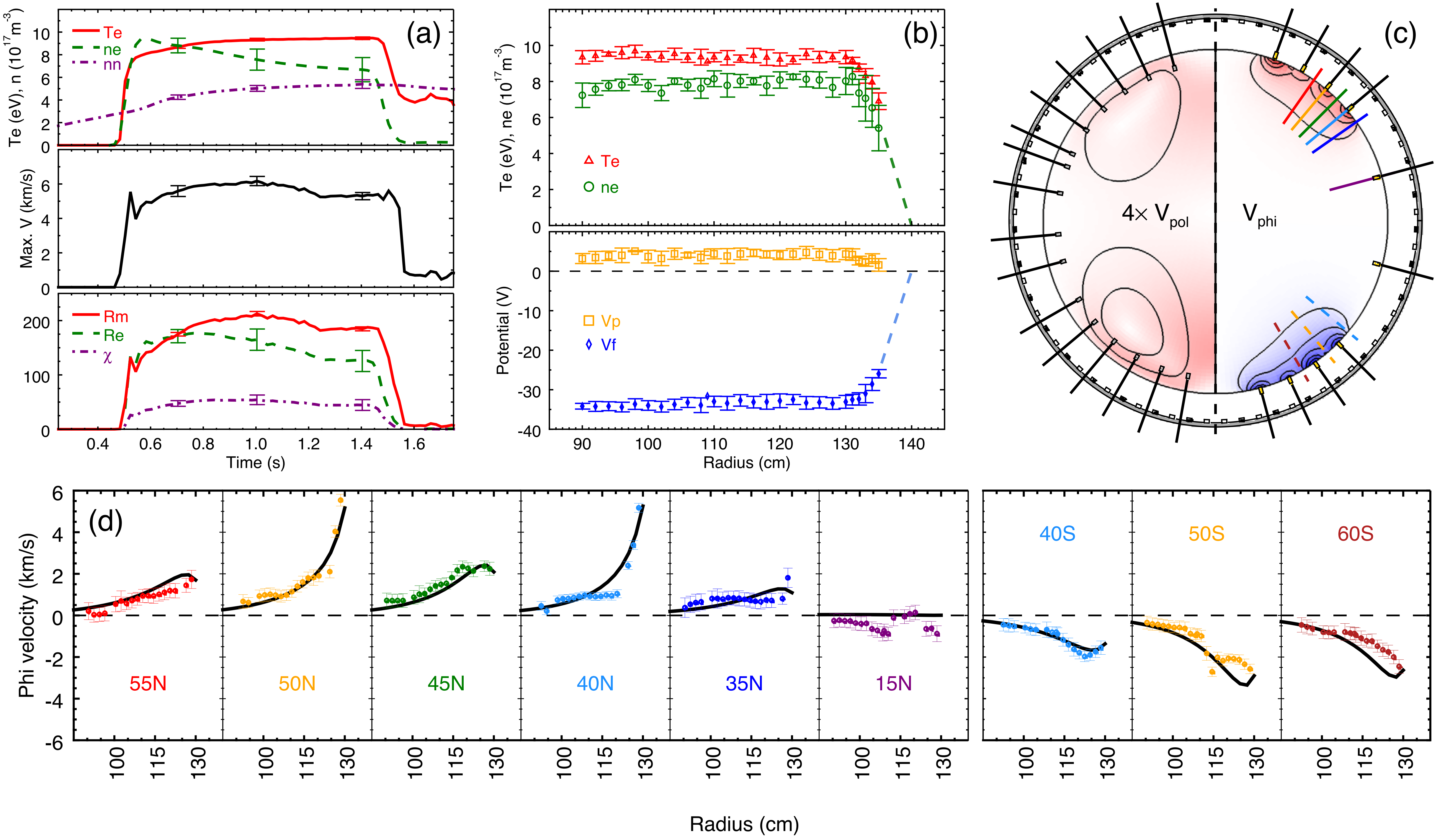




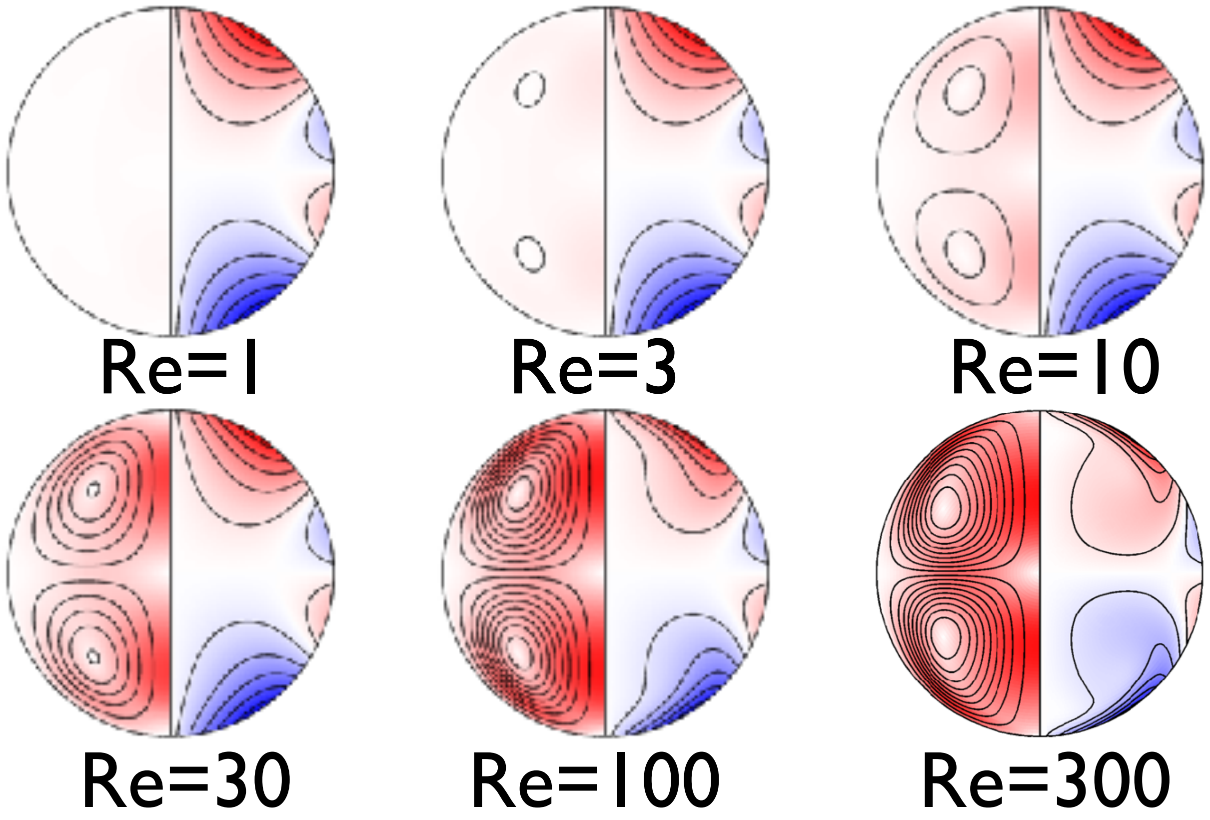
- Magnetic geometry is even-parity about equator.
- To spin hemispheres in opposite directions, cathode theta positions must be odd-parity.
- Anode theta position does not effect flow drive because no anodes are in the magnetized edge.
- Mach/Langmuir probes are inserted along radial chords.

Counter-rotating hemispheres successfully drive differential rotation

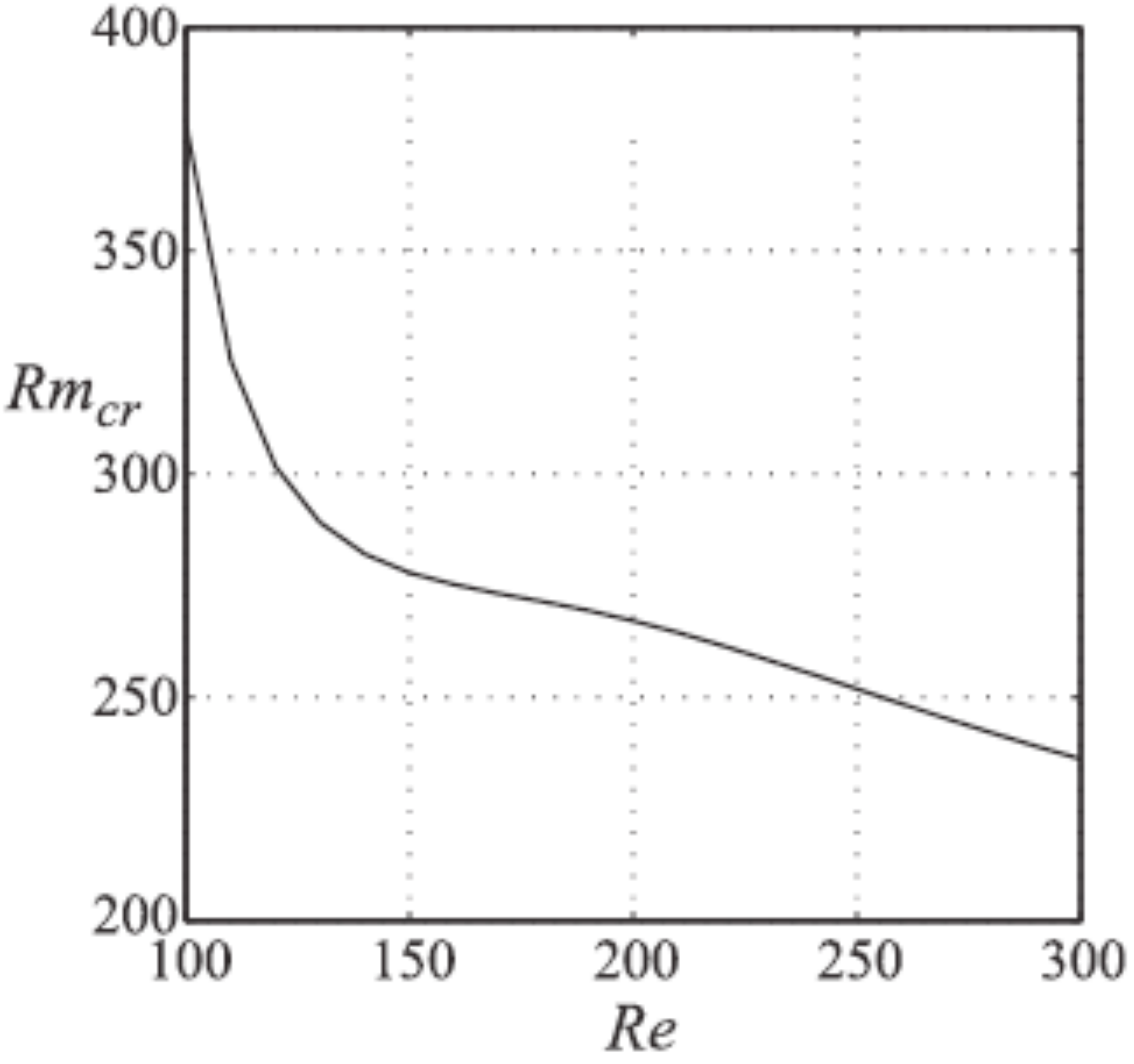
Counter-rotating hemispheres



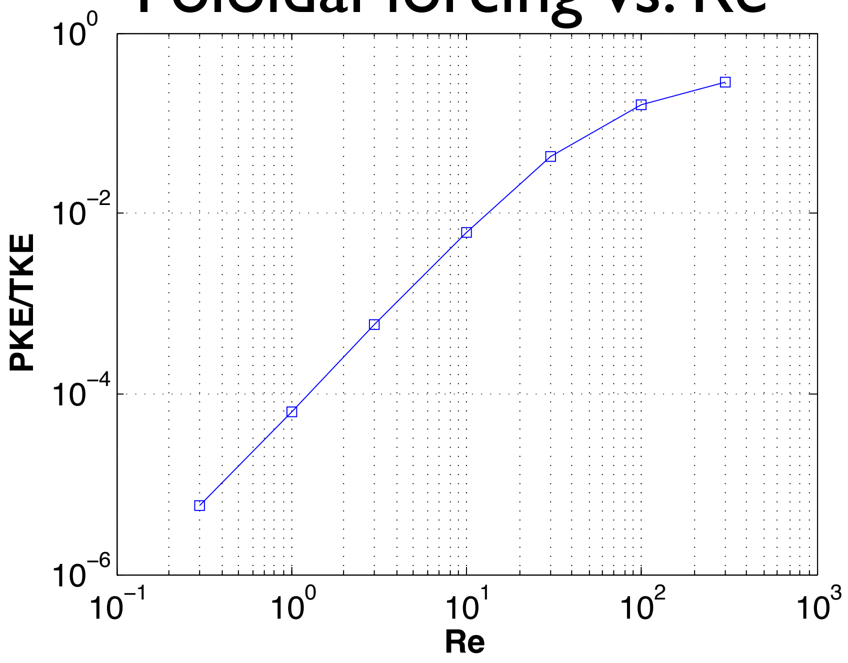
Velocity field controlled by Re



Dynamo onset vs. Re

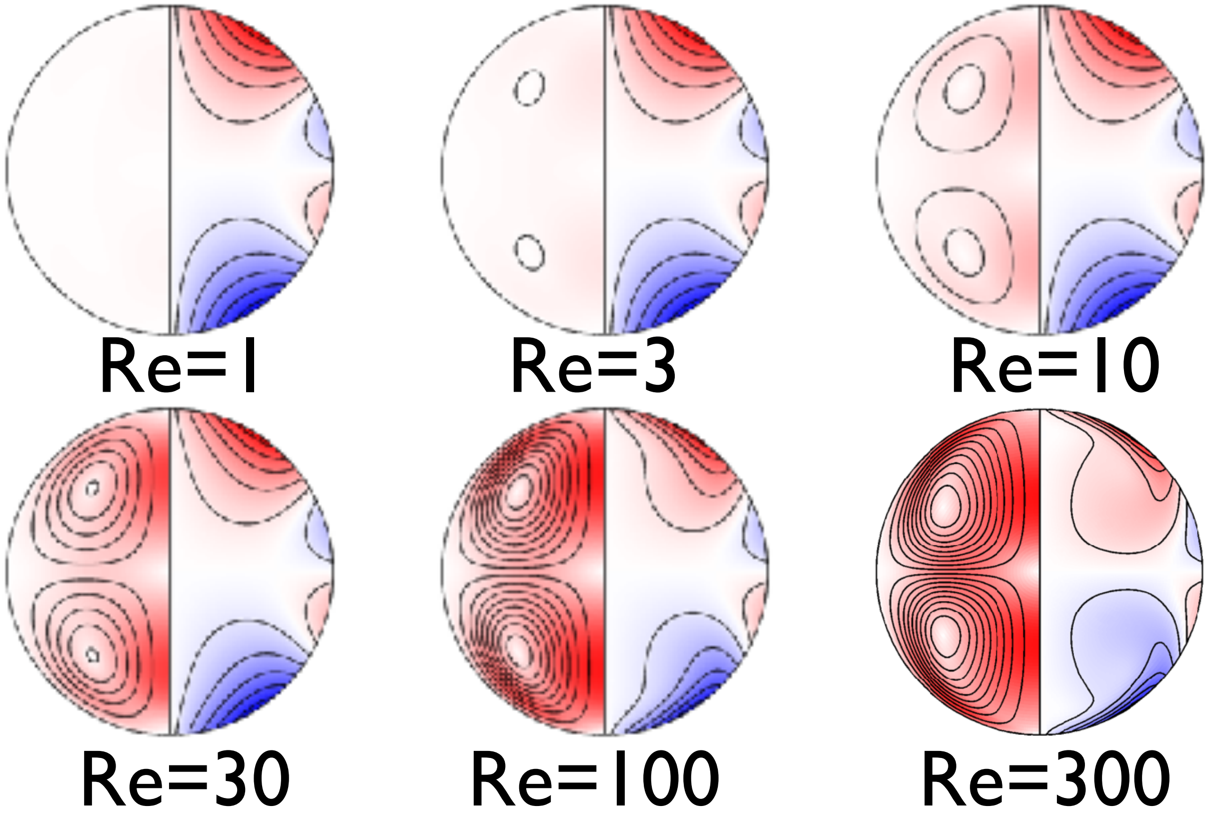


Poloidal forcing vs. Re

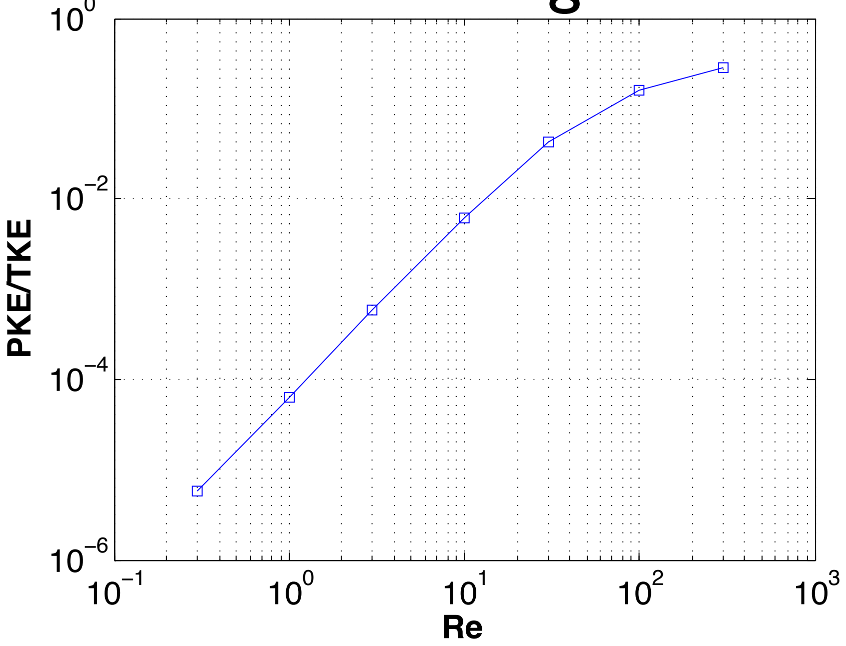


Khalzov, et al, Optimized boundary driven flows for dynamos in a sphere, PHYSICS OF PLASMAS 19, 112106 (2012)

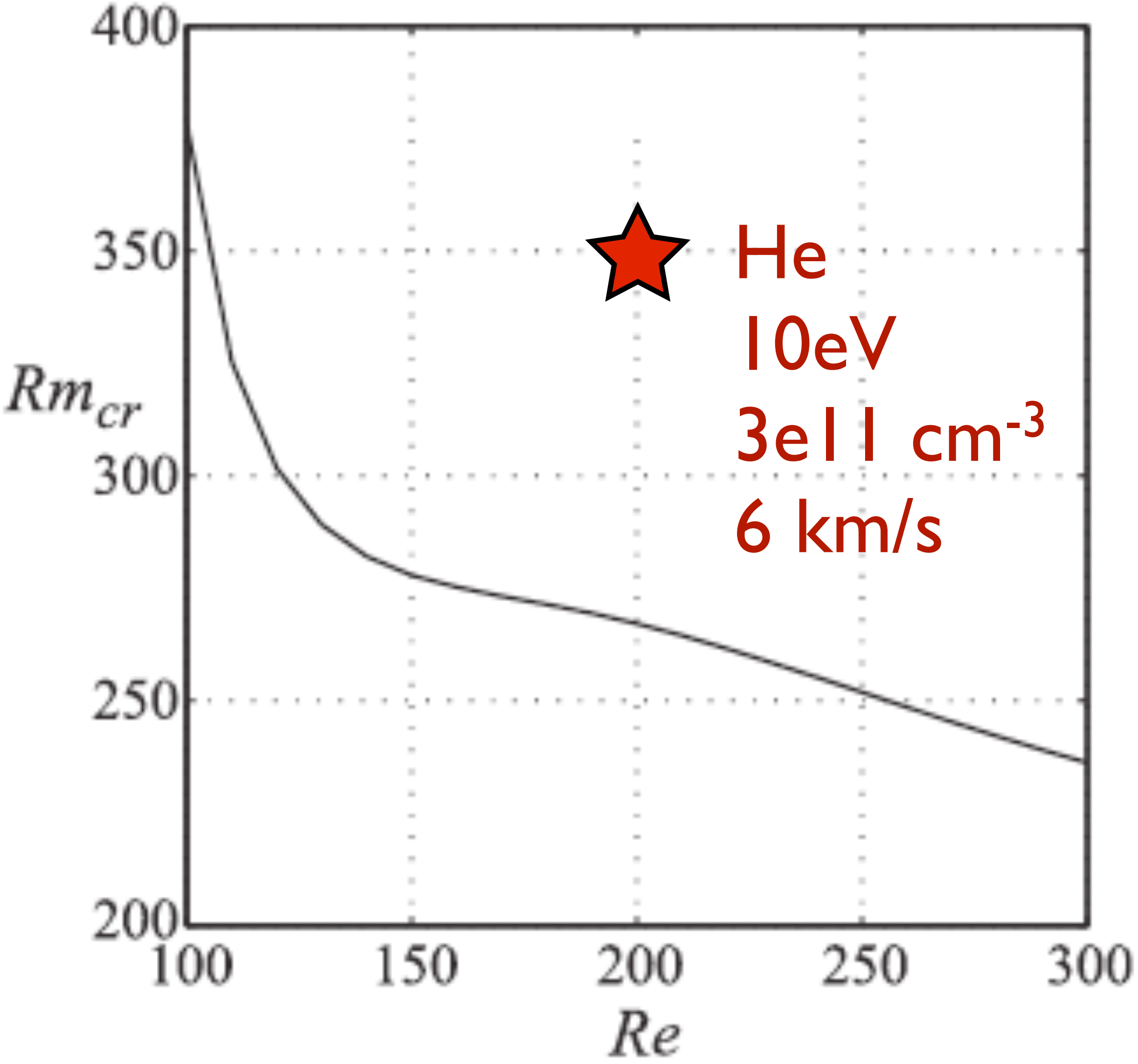
Velocity field controlled by Re



Poloidal forcing vs. Re



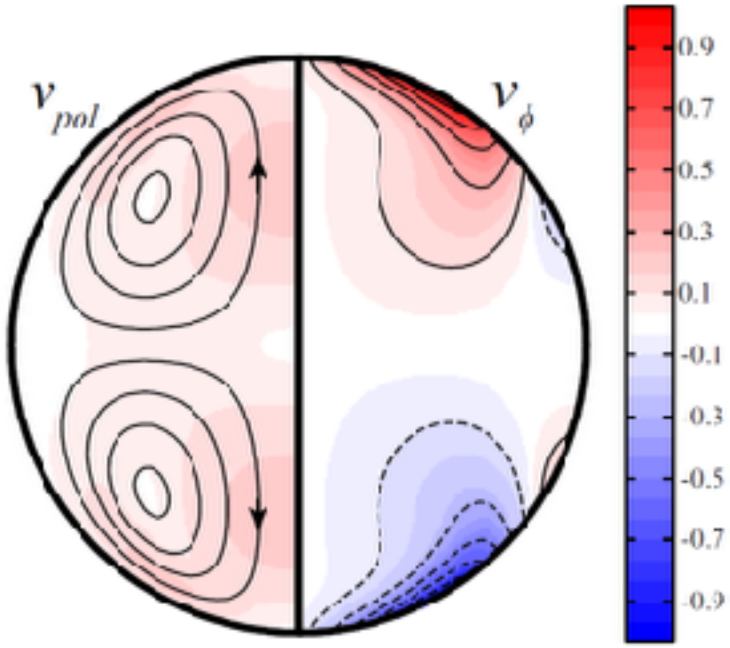
Dynamo onset vs. Re

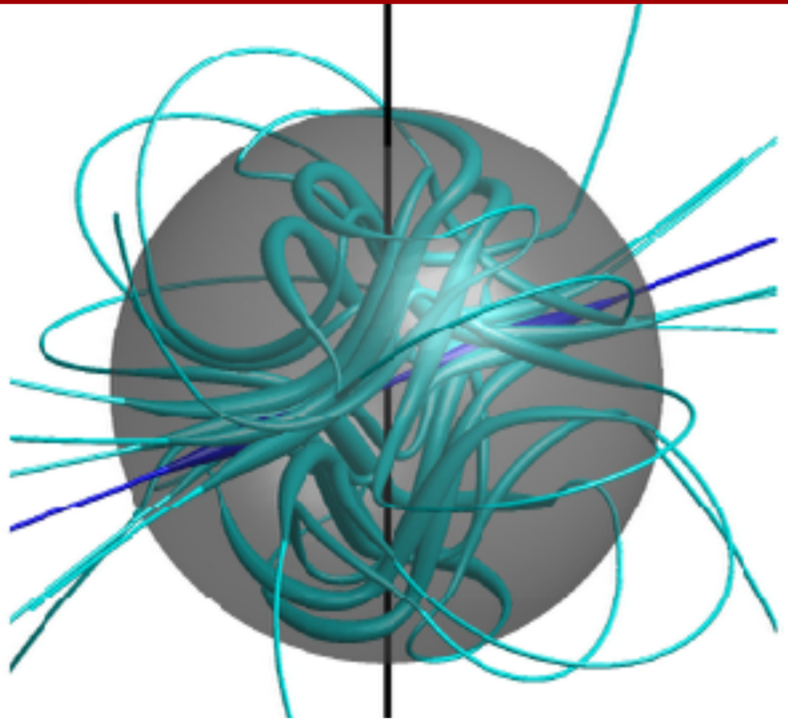


He
10eV
3e11 cm^{-3}
6 km/s

Khalzov, et al, Optimized boundary driven flows for dynamos in a sphere, PHYSICS OF PLASMAS 19, 112106 (2012)

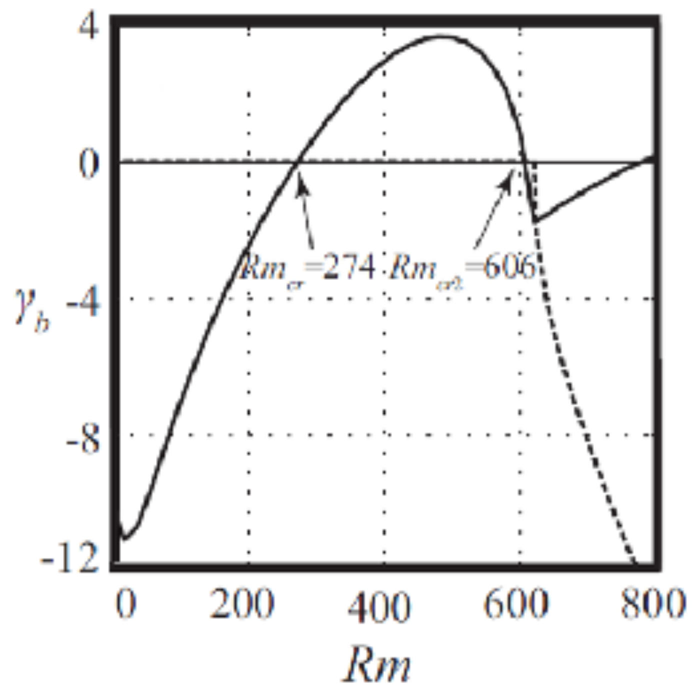
NEXT STEP: 12 CATHODES TO SEARCH FOR A DYNAMO TRANSITION

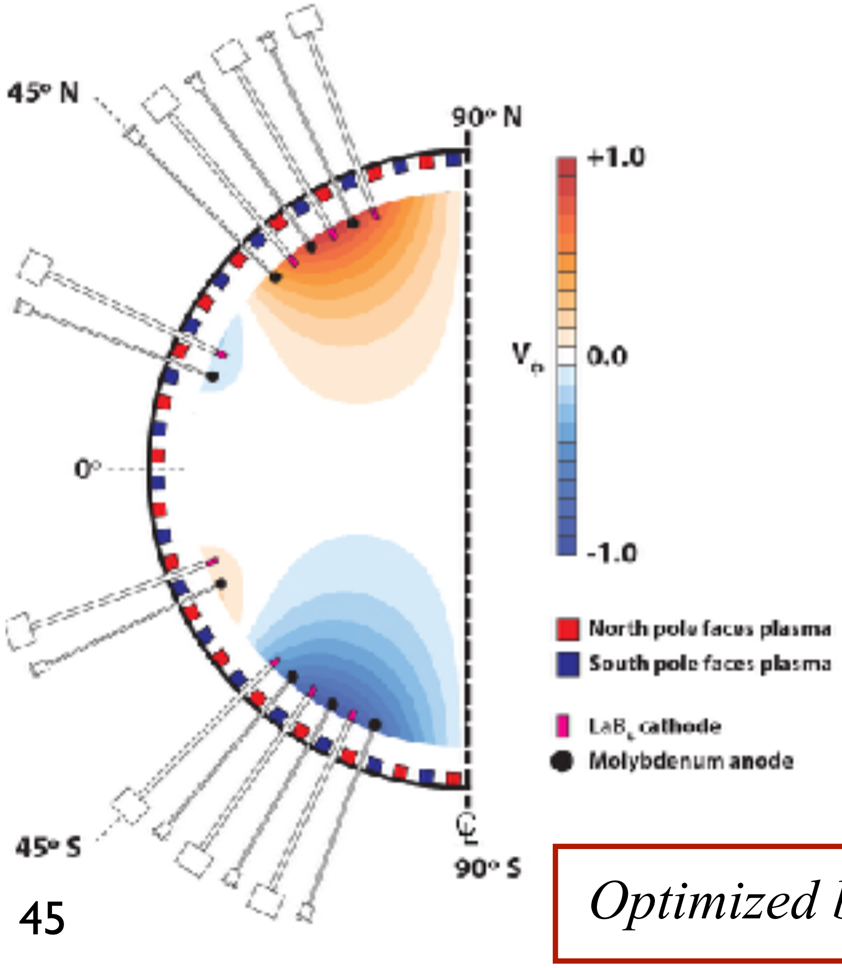




Rm=300

Dynamo growth rate





Von Karman type dynamo		
Re=150, Rm=400		
Parameter	Argon	Helium
n_e (1/cm^3)	3X10^{11}	1X10^{12}
T_e (eV)	10	10
power (kW)	100	140
v_{edge} (km/s)	5	6
B_{eqp} (G)	8	5

Steady state flows with DC LaB6 bias set v_φ (θ)

Optimized boundary driven flows for dynamos in a sphere, Phys. Plasmas **19** 112106 (2012).

Fast Dynamos

small-scale or *turbulent*: magnetic field generated at (or below) scale of flows (relies on chaotic stretching)

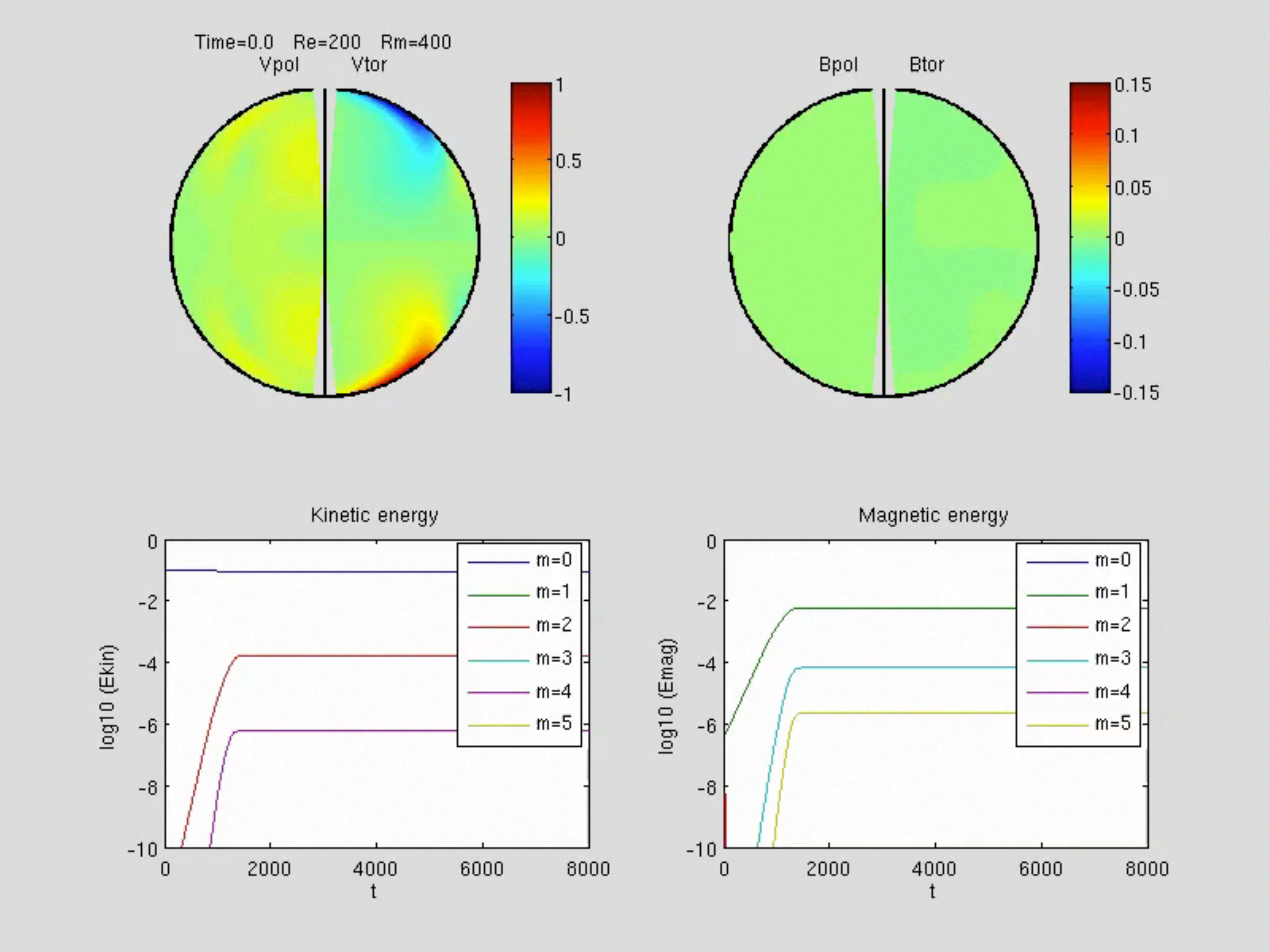
Large: net flux; relies on lack of reflectional asymmetry

S*low:* requires resistive diffusion (moderate Rm)

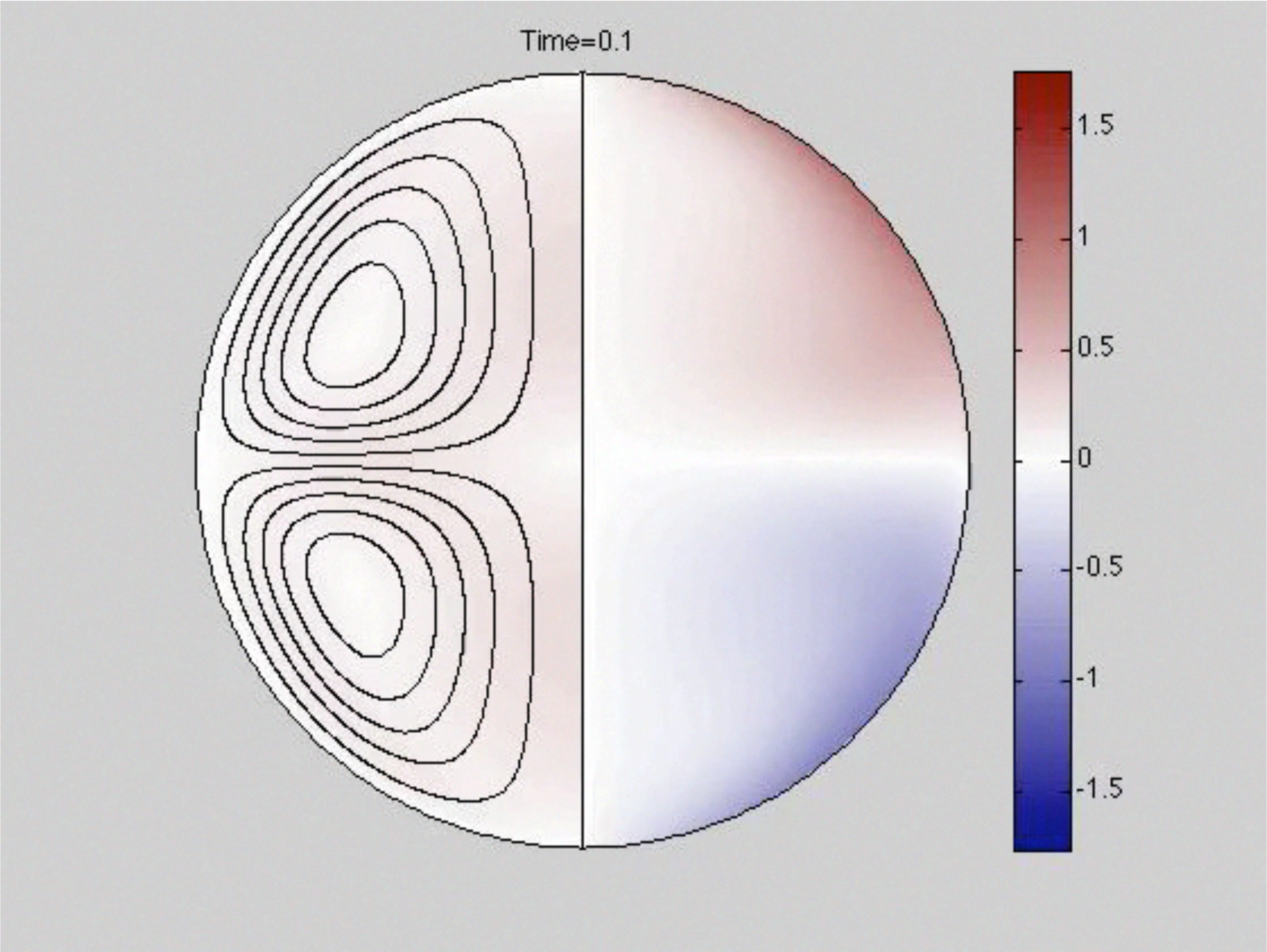
Fast: independent of resistivity (very large Rm)

Astrophysics: Large-Scale, Fast Dynamos (Rm>>1, turbulent generation of net Flux)

SATURATED FIELDS ARE SMALL (FOR V=10 KM/S, HE, 10^{12} CM^{-3}; B = 1 GAUSS)

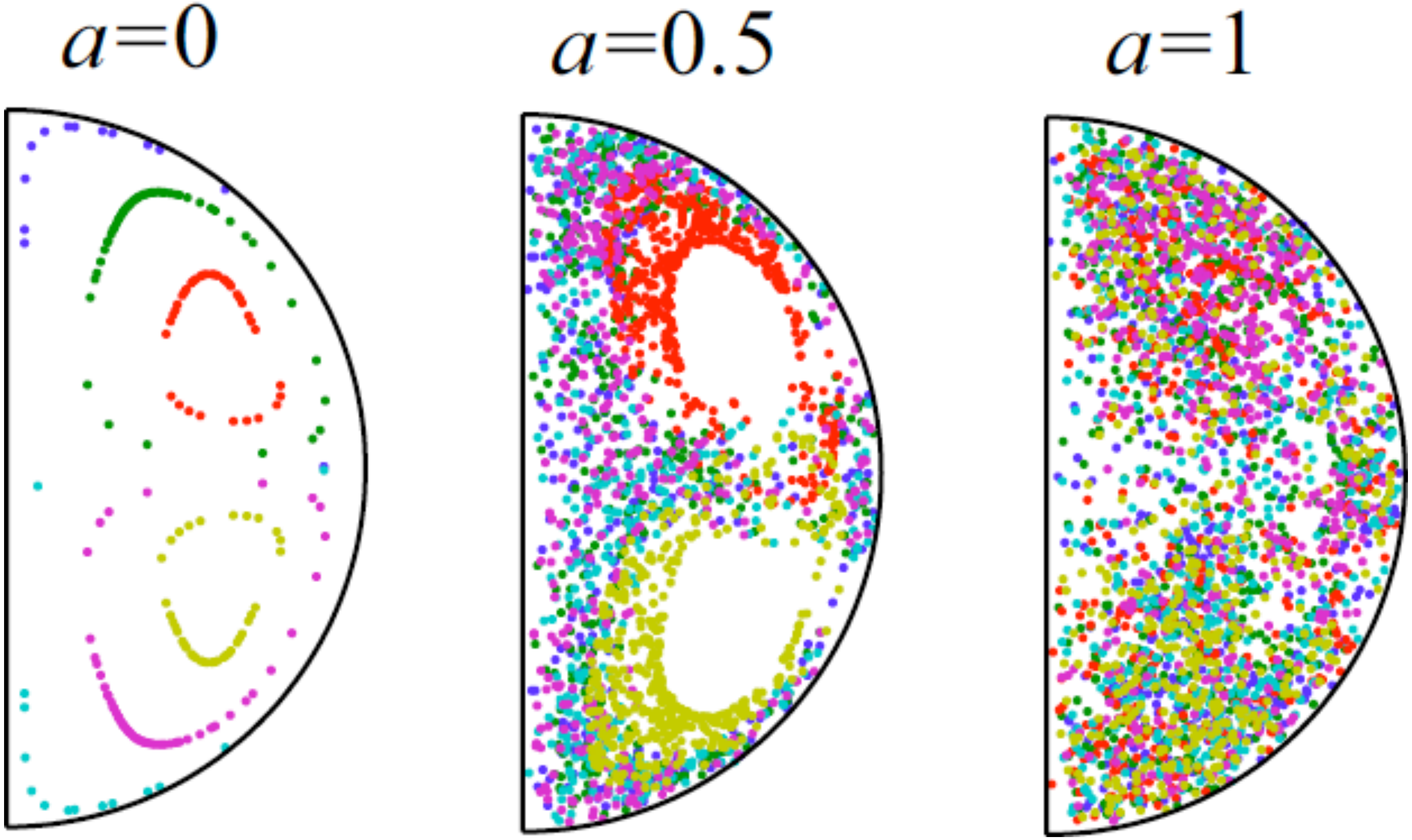


Time dependent flows are also feasible



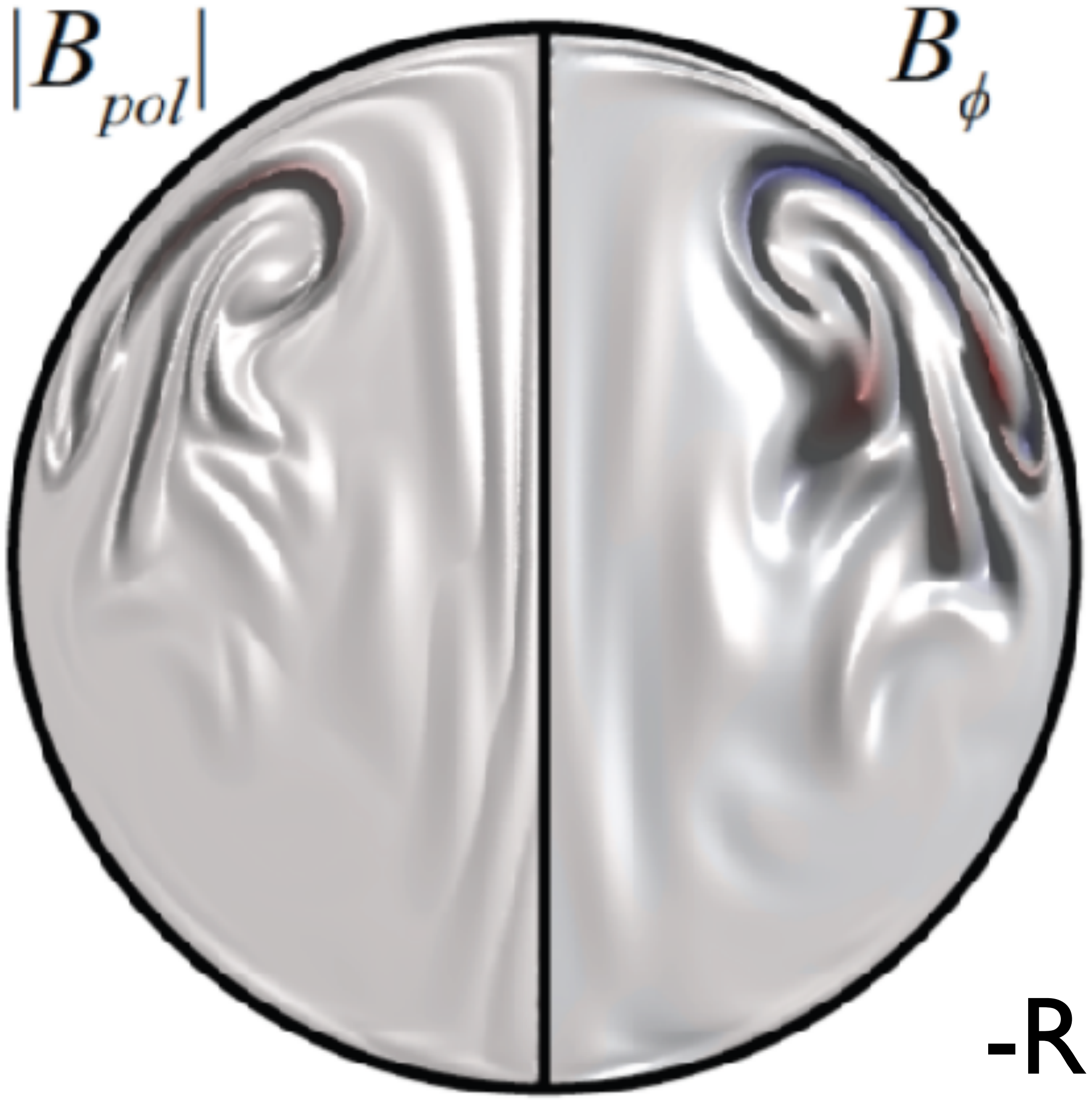
Chaos in time-periodic flow

- Boundary: Re=200, ω=0.6

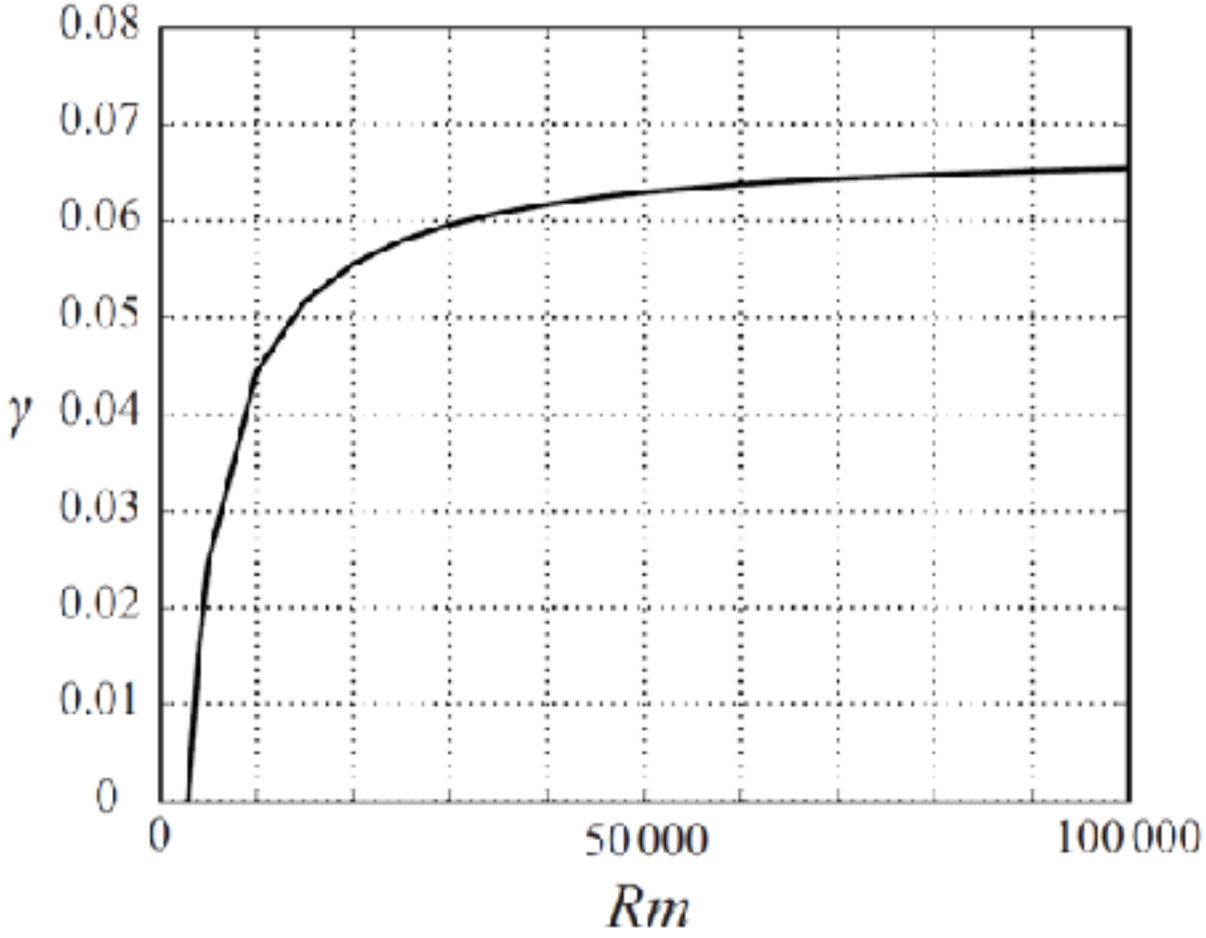


SMALL-SCALE FAST DYNAMOS FEASIBLE WHEN RM IS LARGE

Rm=1000



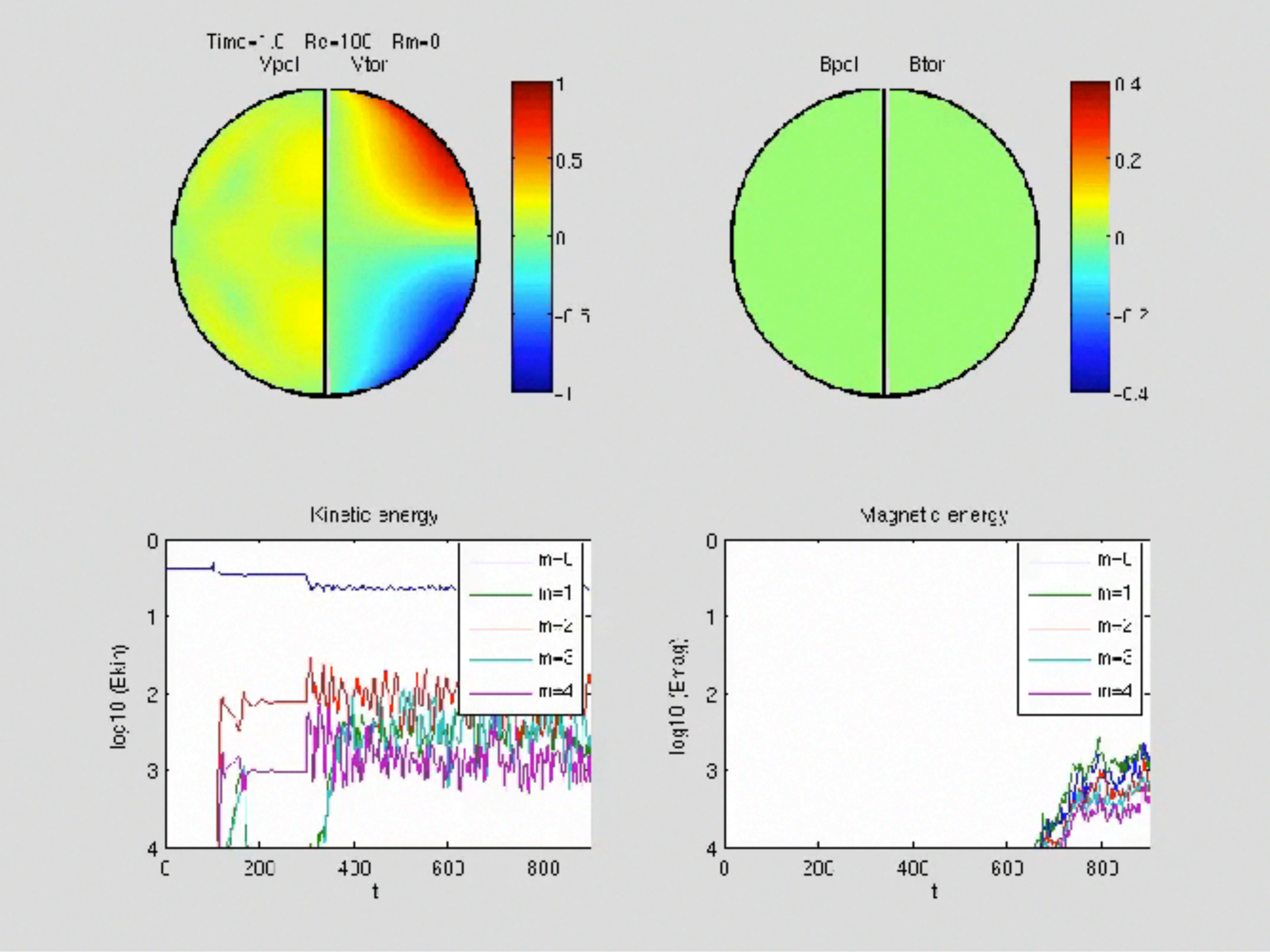
Dynamo growth rate



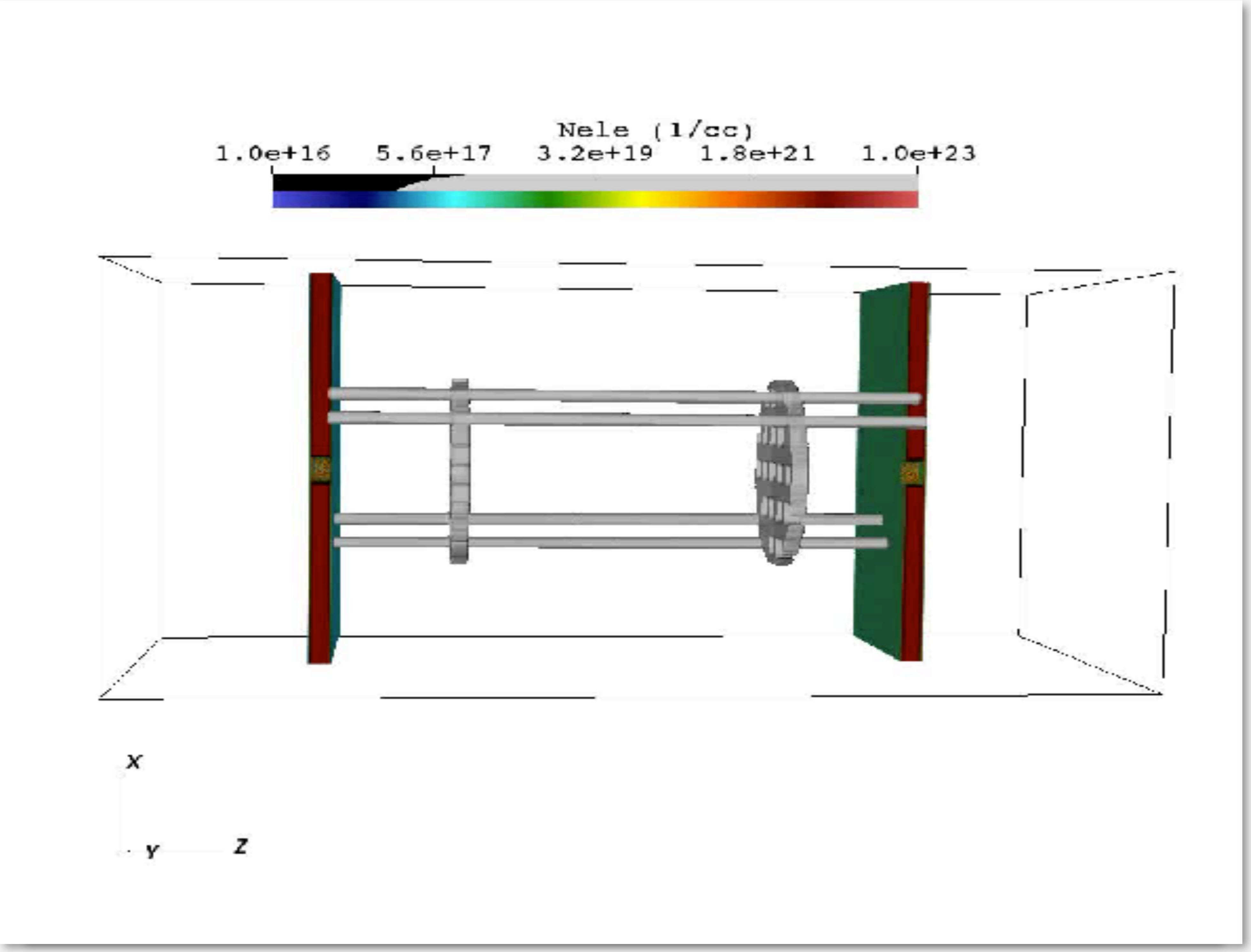
- $Rm_{crit}>1000$
- growth on eddy turn-over time
- easiest when Rm>>Re (Pm>>1)

Small Scale, turbulent, Fast dynamo is possible (at high Pm)

Re	**Rm**	**V** (km/sec)	**T**$_{eV}$	**n** (10^{11} cm^{-3})
100	200	3	10	3
200	800	6	17	3
500	5000	10	40	5

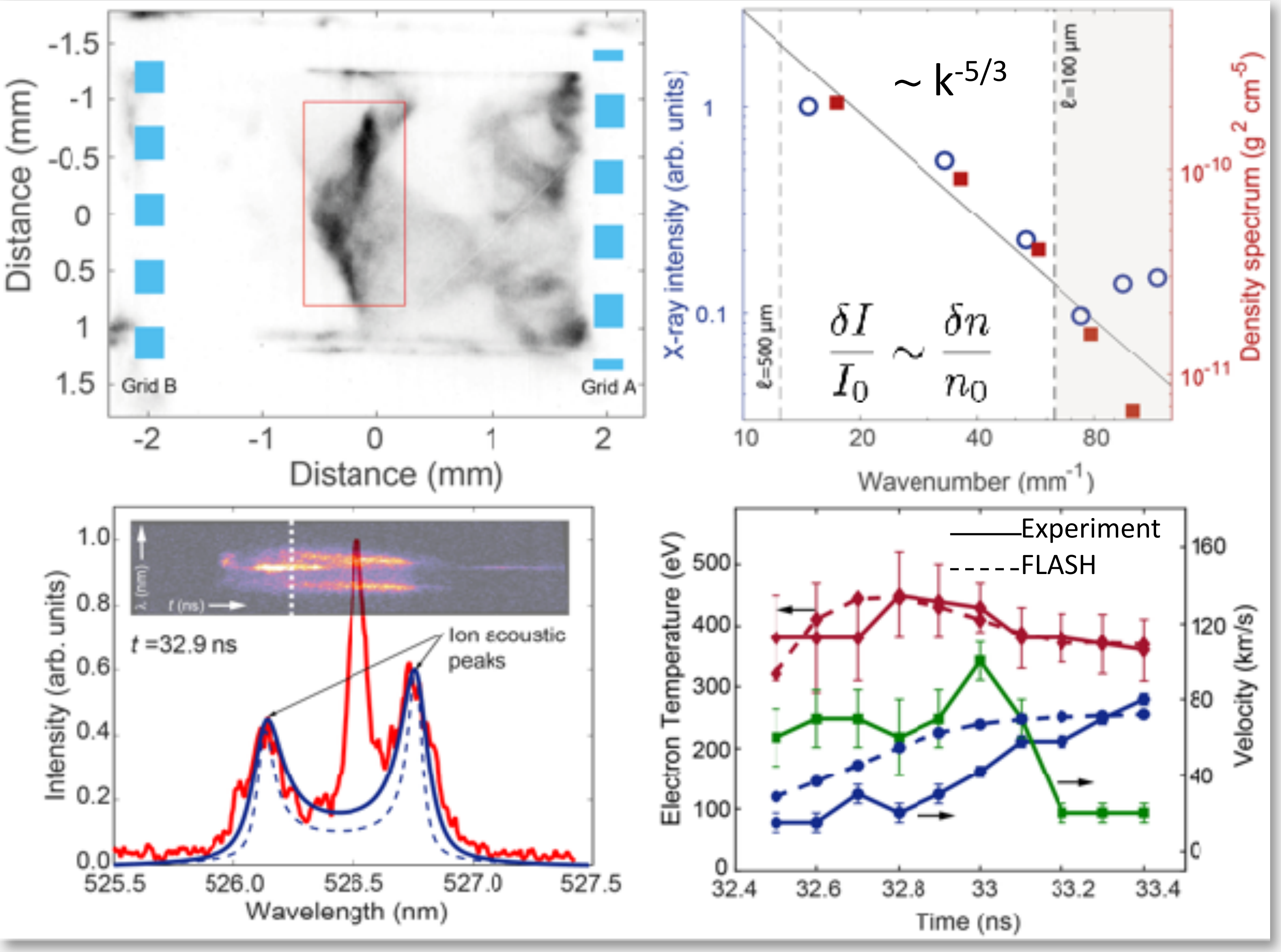


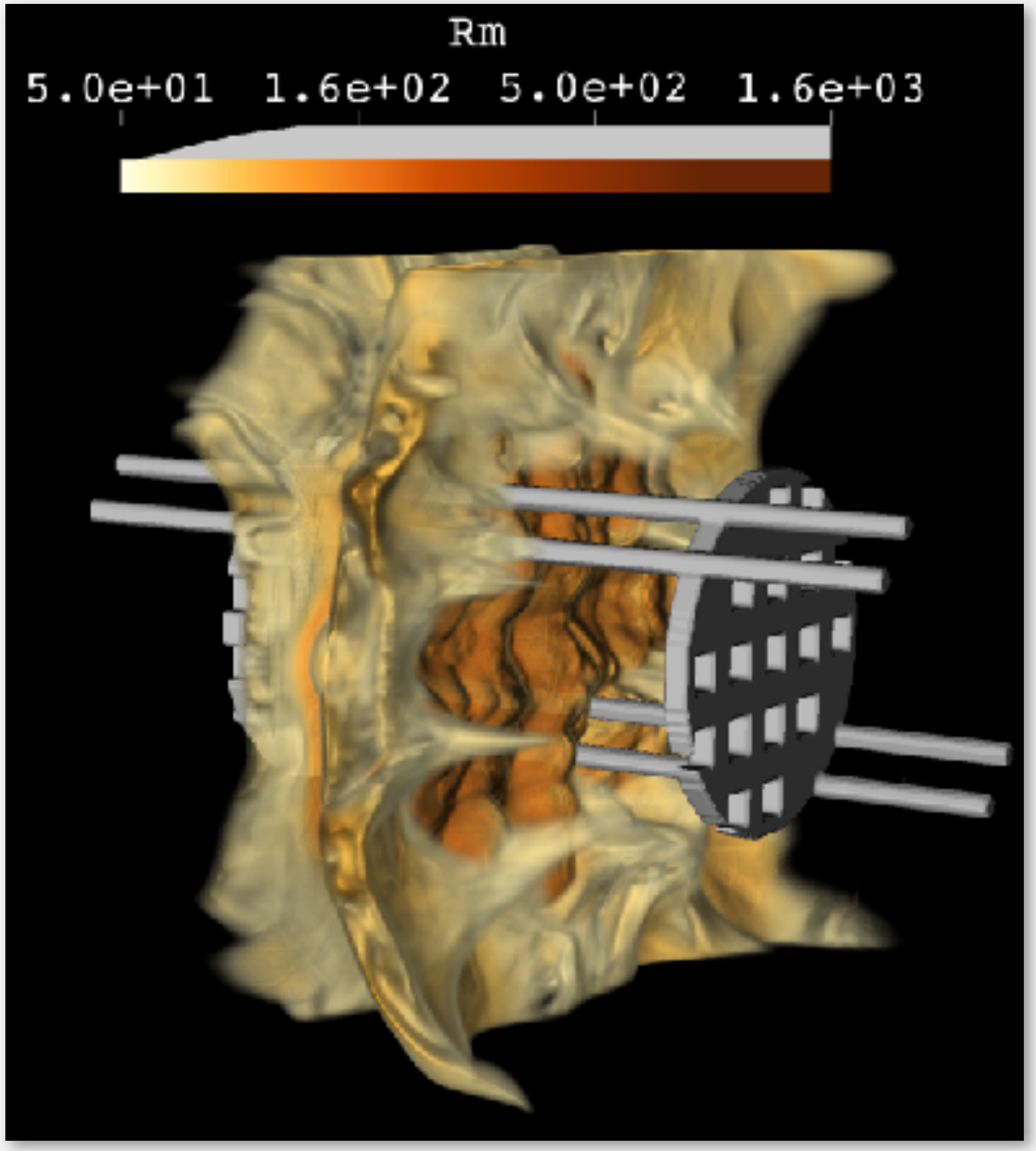
TDYNO Experiment at Omega



- ❑ Experimental platform fielded at Omega, LLE (Tzeferacos et al. 2017a,b). The design was the outcome of radiation-MHD FLASH simulations that combine elements from pathfinder experiments carried out at Vulcan, RAL (Meinecke et al. 2014, 2015).

Developed Turbulence at High Rm



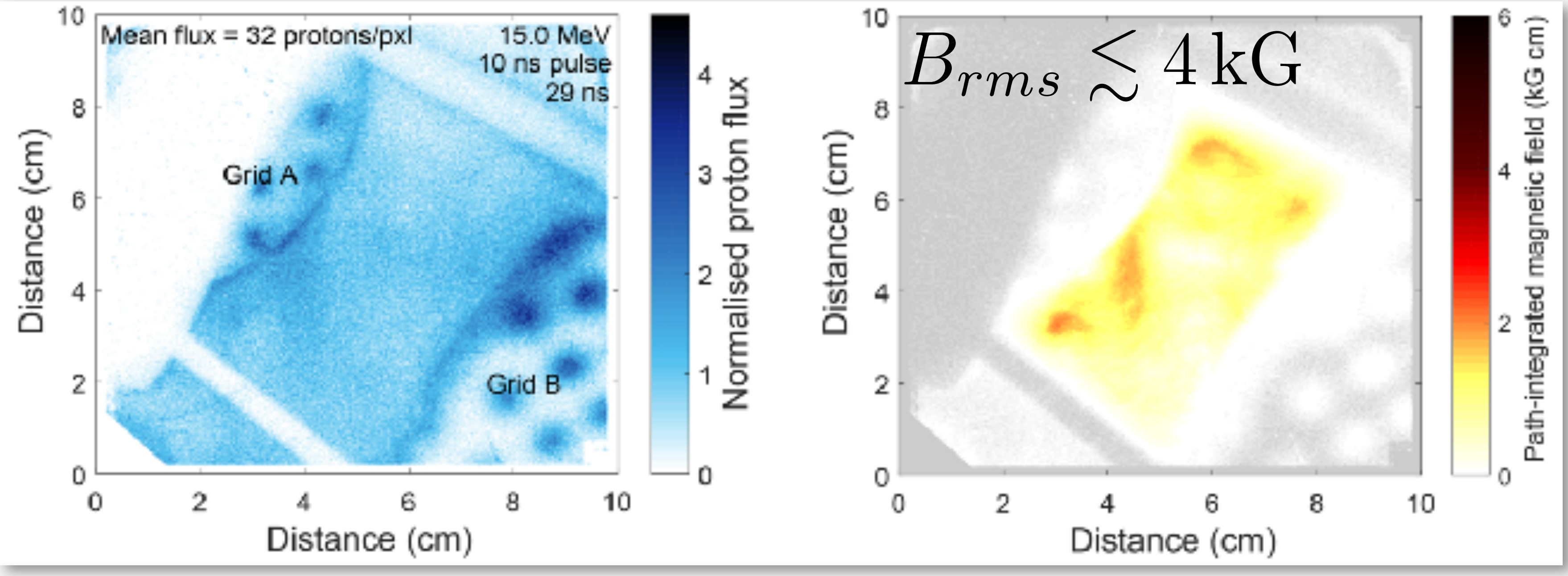


- ❑ The X-ray images of the turbulent region reveal good agreement with FLASH predictions. From the 2D intensity fluctuations we recover the 3D density power spectrum (Churazov et al. 2012), which is consistent with Kolmogorov scaling (analysis by Archie Bott).

- ❑ Thomson scattering data yield temperatures and velocities that correspond to Rm ~ 700, with peaks of ~ 1,400, in the Pm ≤ 1 regime. Such values of Rm are above the threshold value required for dynamo action (Schekochihin et al. 2007).

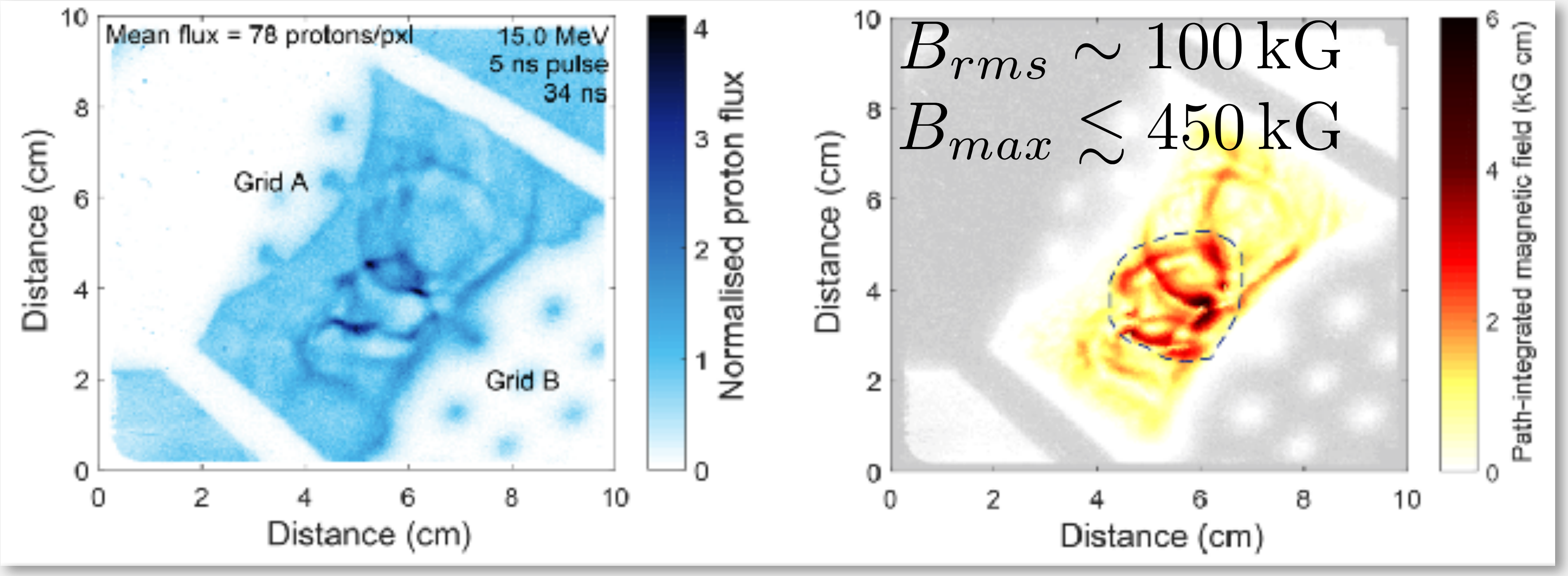
Dynamo Magnetic Field Amplification

- Proton radiography reveals the topology and strength of the magnetic fields (Li et al. 2006).



- At early times, protons undergo small deflections while they traverse weak Biermann battery seed fields.

- At late times, dynamo action amplifies the seed fields. We see pronounced filamentary structures, typical of MHD turbulence.



- Path integrated B-field reconstruction (Graziani et al. 2016, Bott et al. in preparation) yields quantitative estimates of the field strength. Magnetic field values are independently verified by Faraday rotation measurements (Thomson scattering polarimetry).

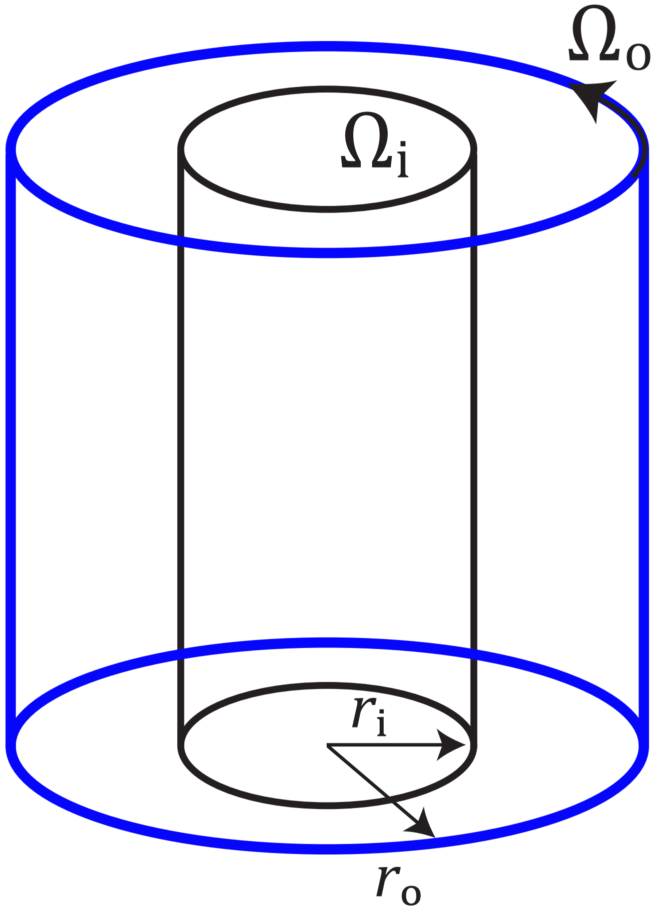
The Magnetorotational Instability

Conversion of gravitational energy into jets, magnetic fields and particles

Two classic geometries for fluid dynamics use boundary driven flows

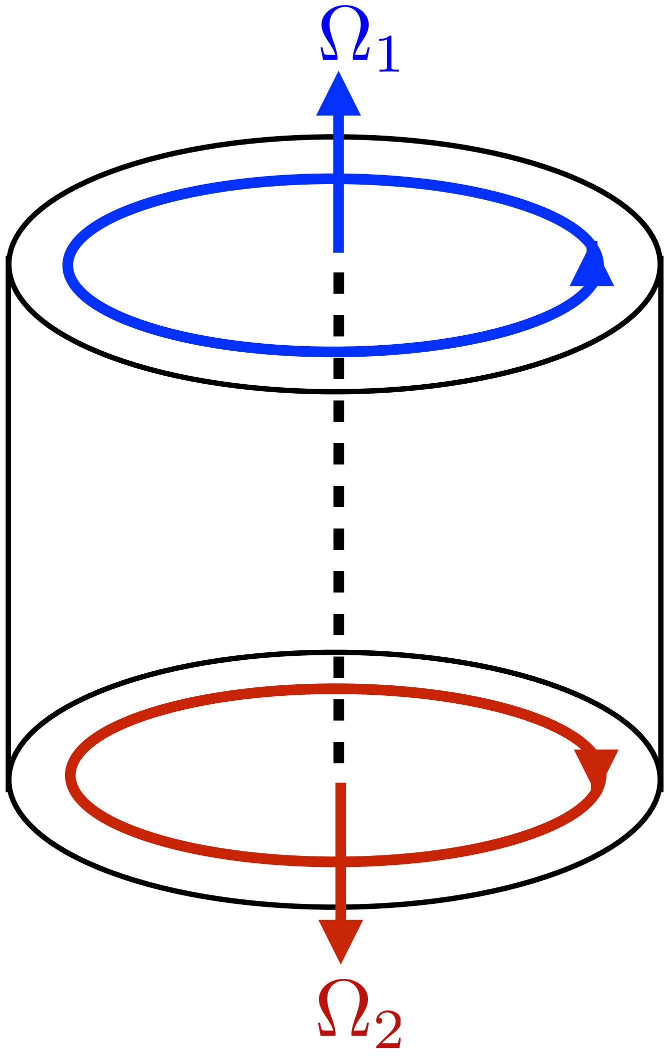
Couette Flow

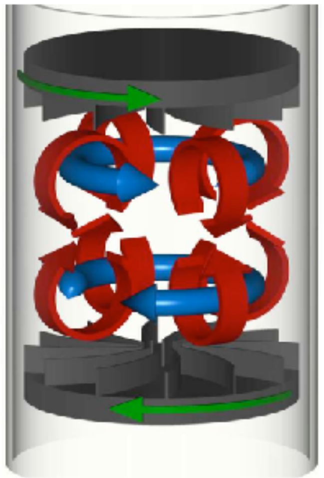
accretion



Von Kármán Flow

dynamos

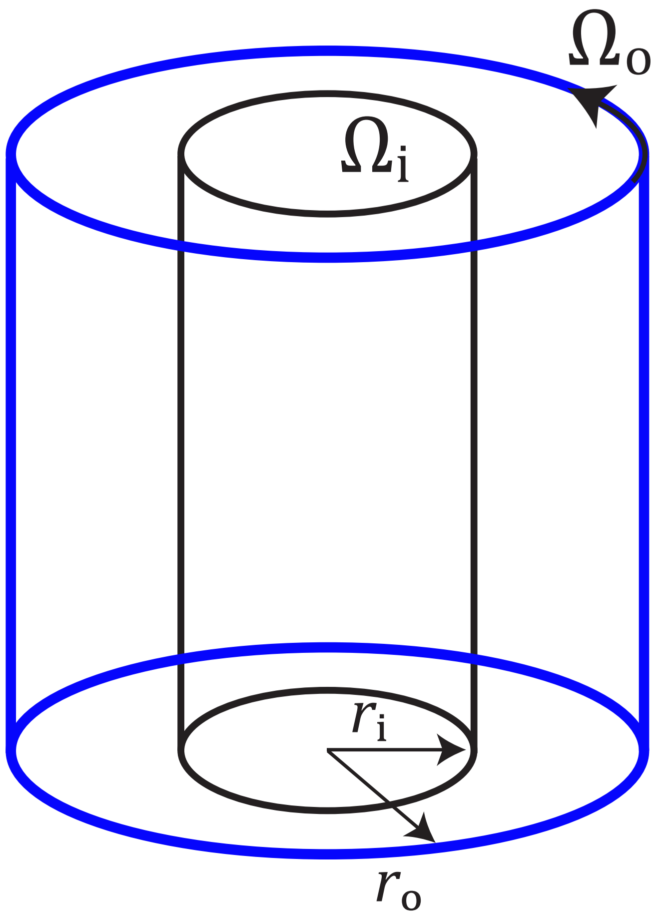


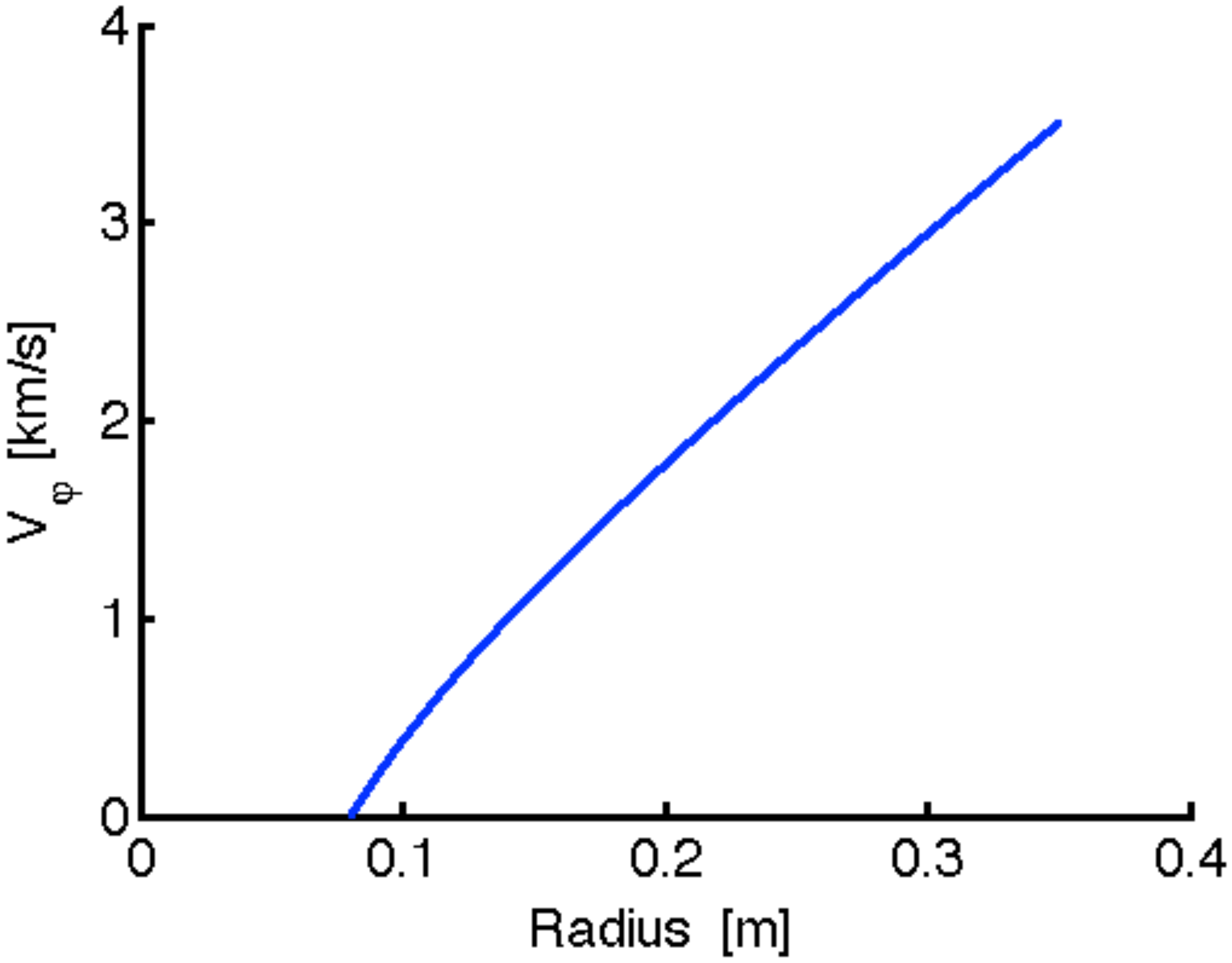


Both rely on viscous coupling to moving boundaries

Couette: Flow Between Concentric Cylinders

Spin from Outside

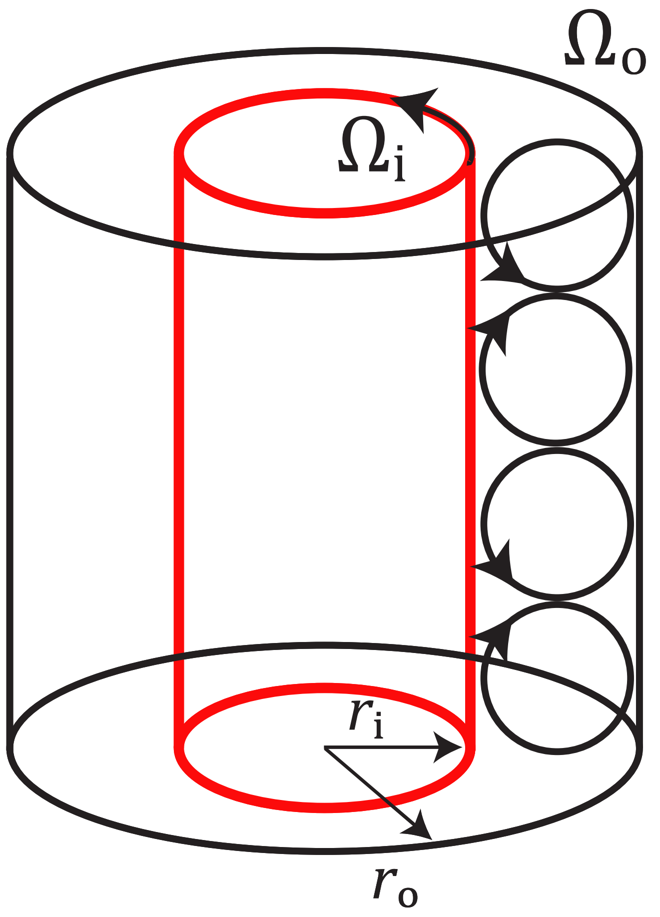


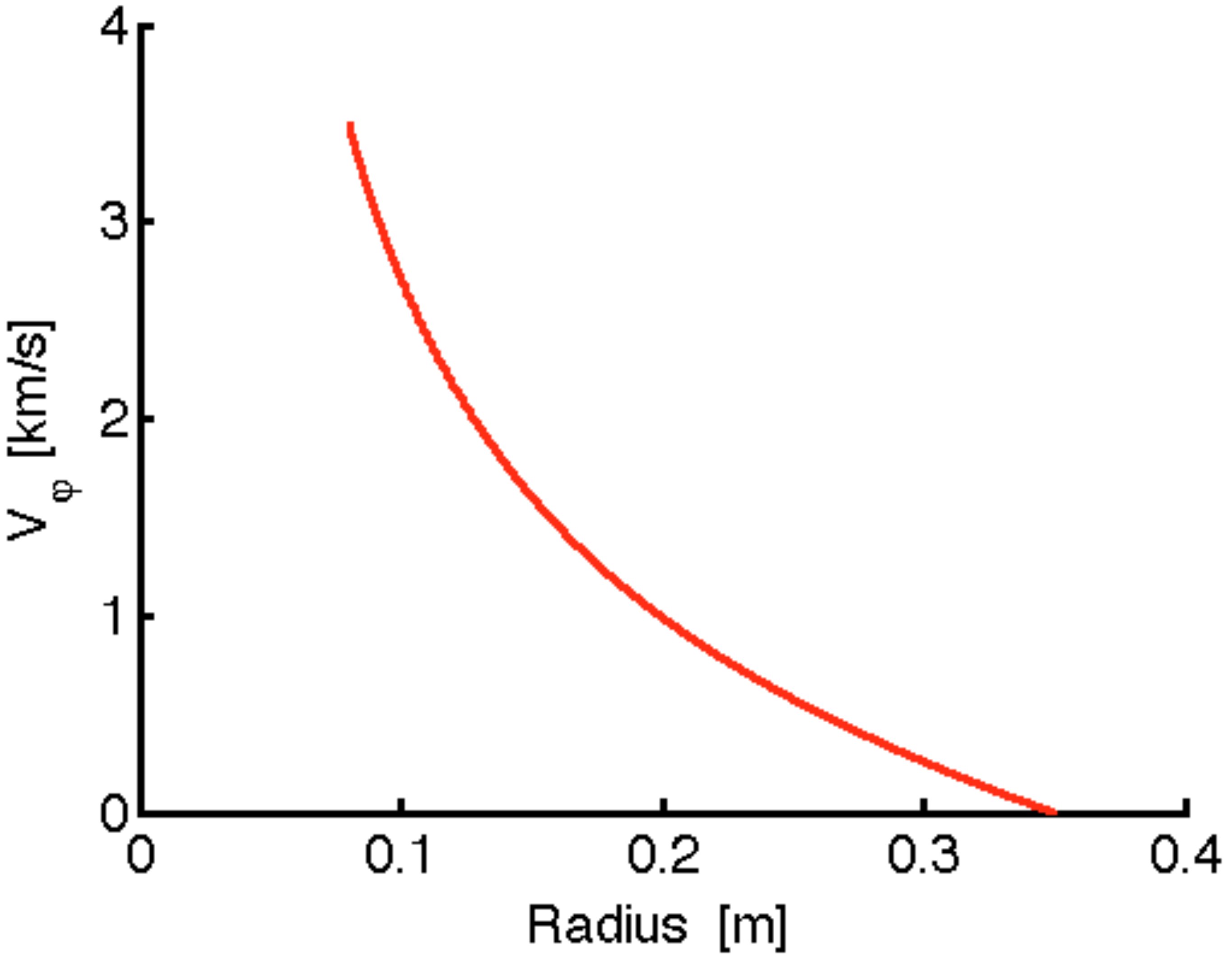


- Outer boundary rotation is hydrodynamically stable
- Couette flow originally used for viscometer, centrifuge

Couette Flow Can Be Hydrodynamically Unstable

Spin from Inside

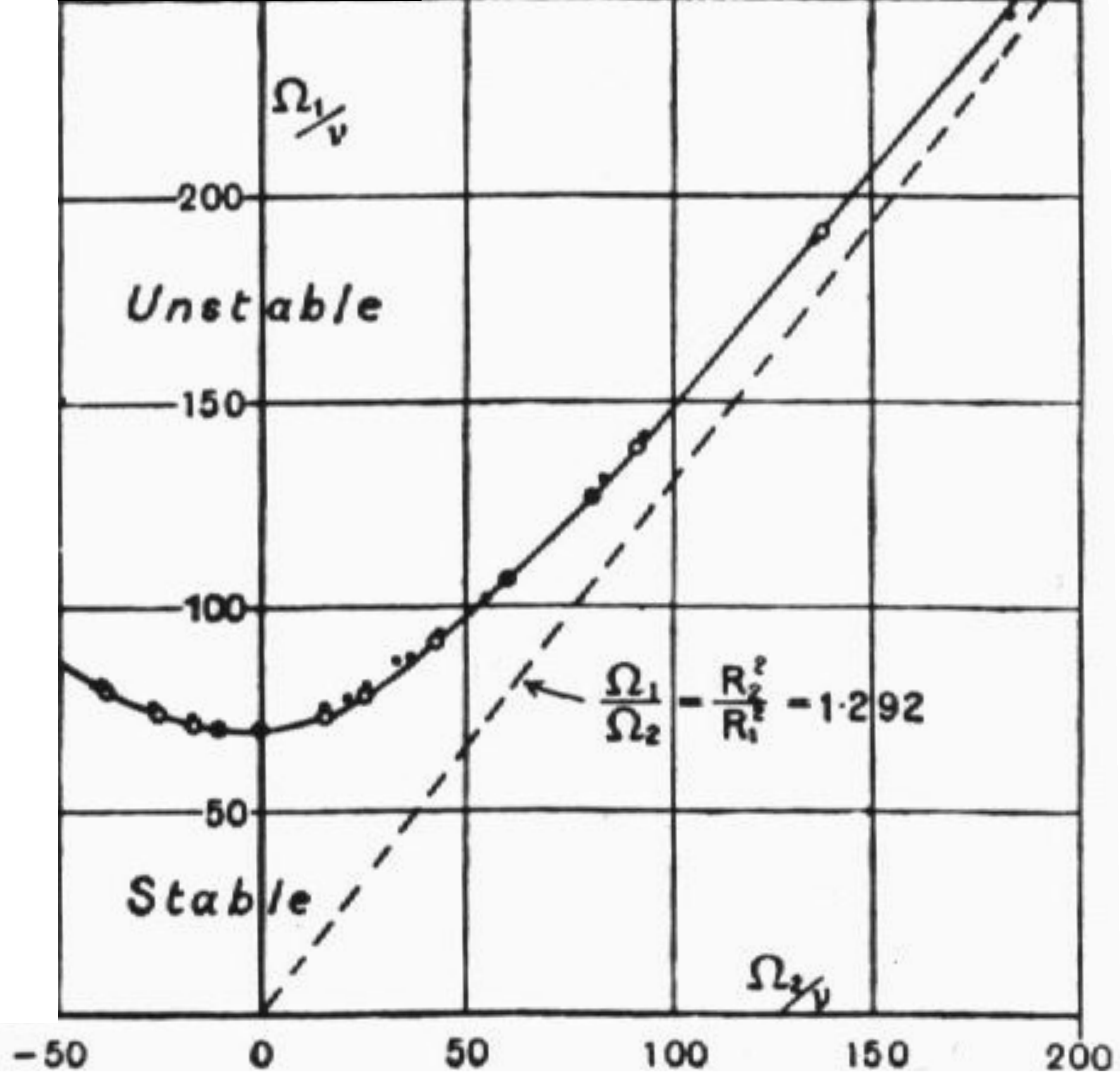


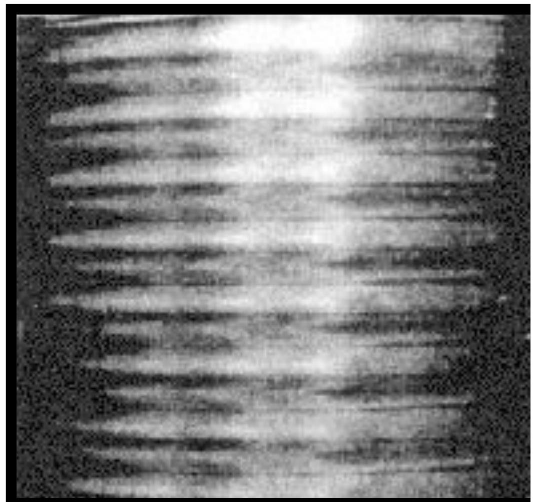


Rayleigh's criterion (1917):
An inviscid, rotating flow is centrifugally unstable for a rotating inner boundary and stationary outer boundary

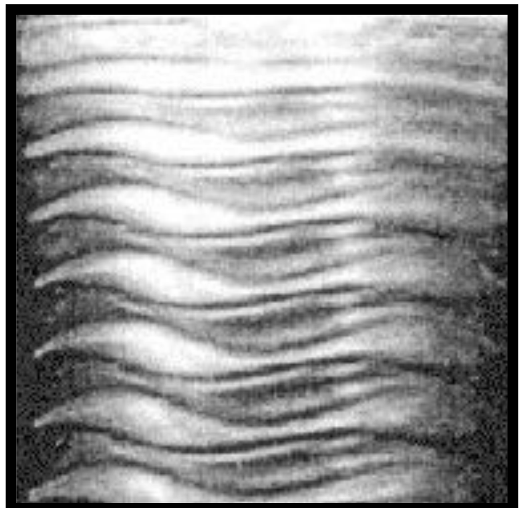
Unstable Taylor - Couette Flow

Taylor (1923)

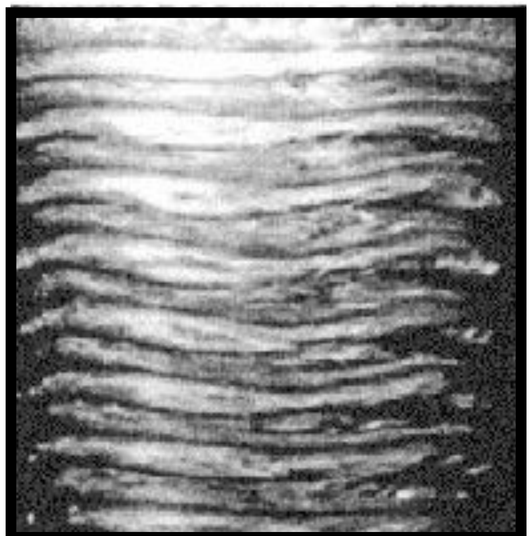




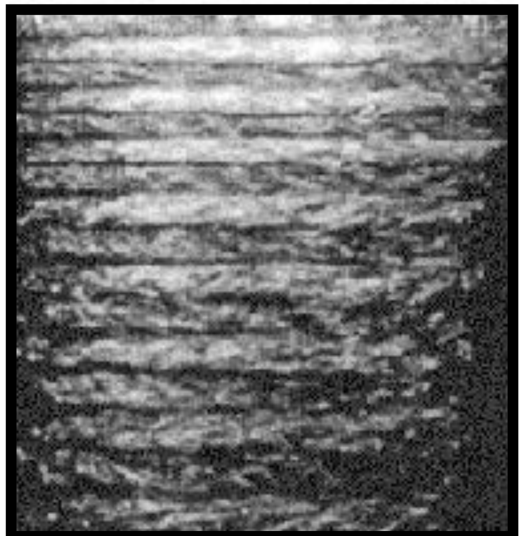
time-independent Taylor vortex flow



time periodic wavy Taylor vortices

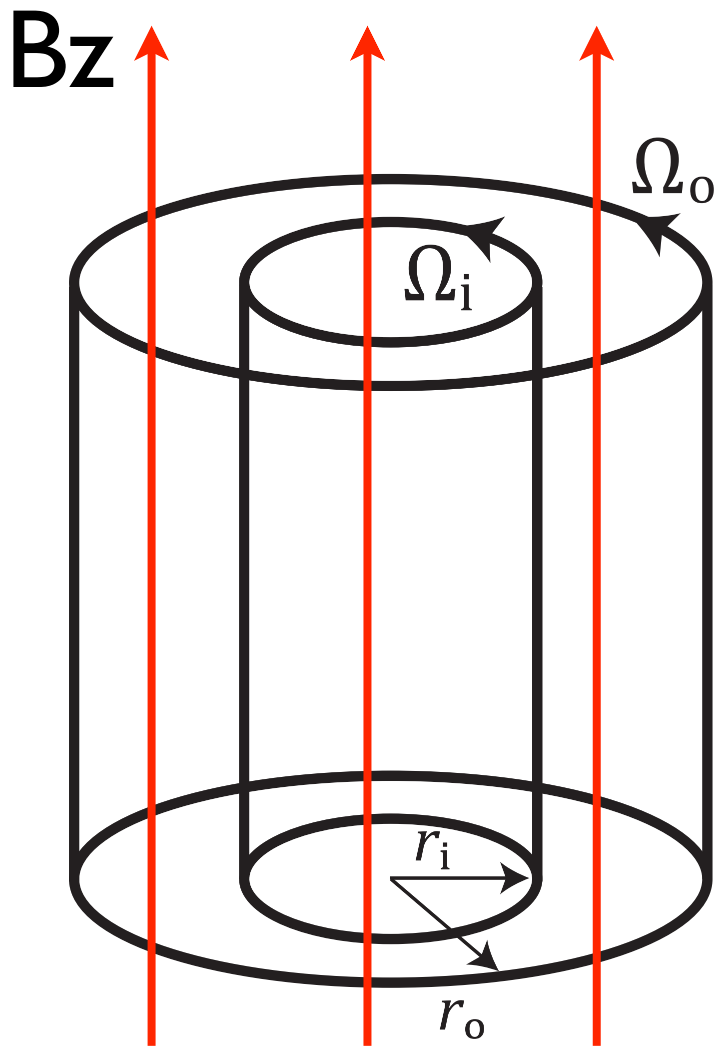


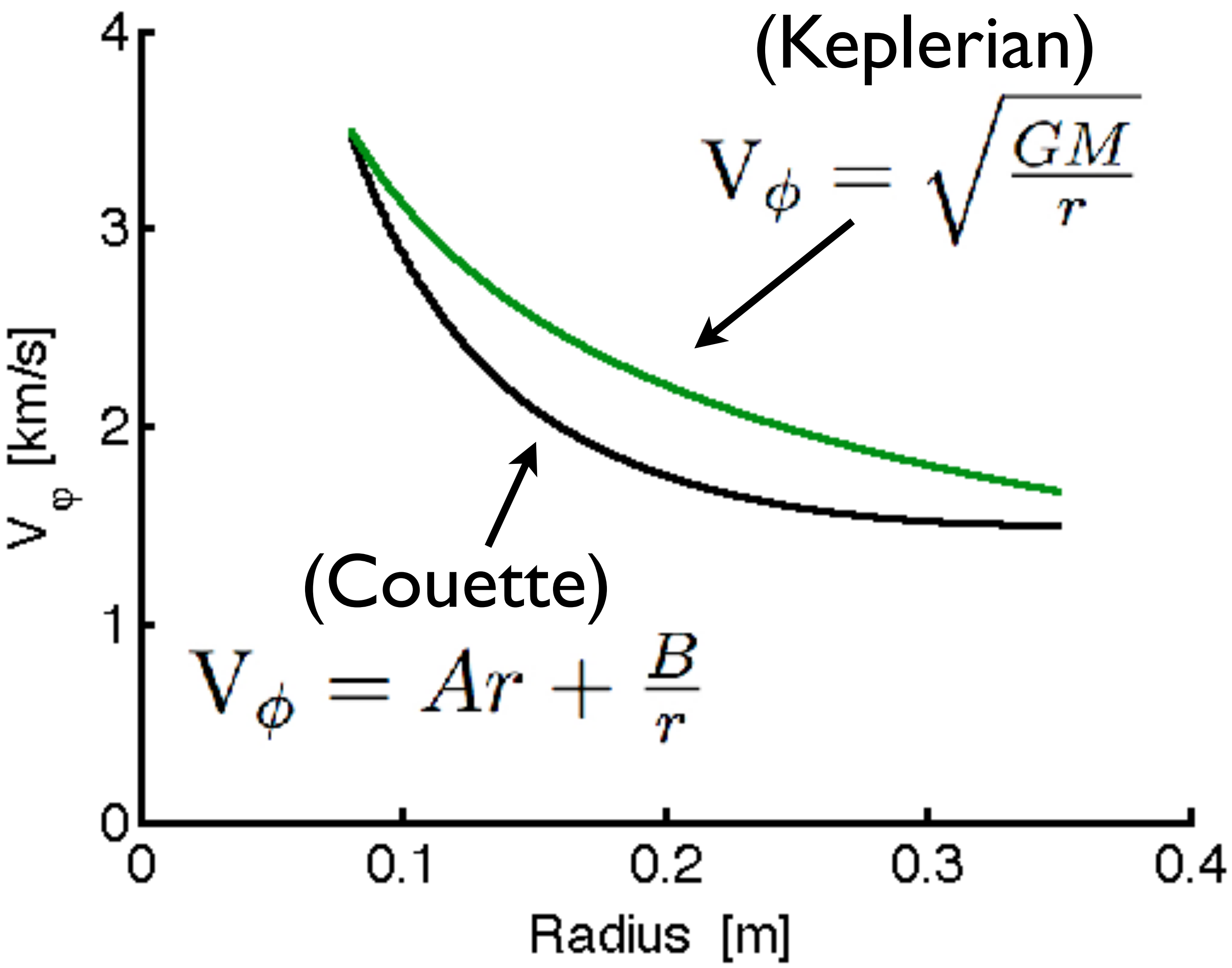
chaotic Taylor vortices



weakly turbulent wavy vortices

This Talk: Couette Flow of Plasma

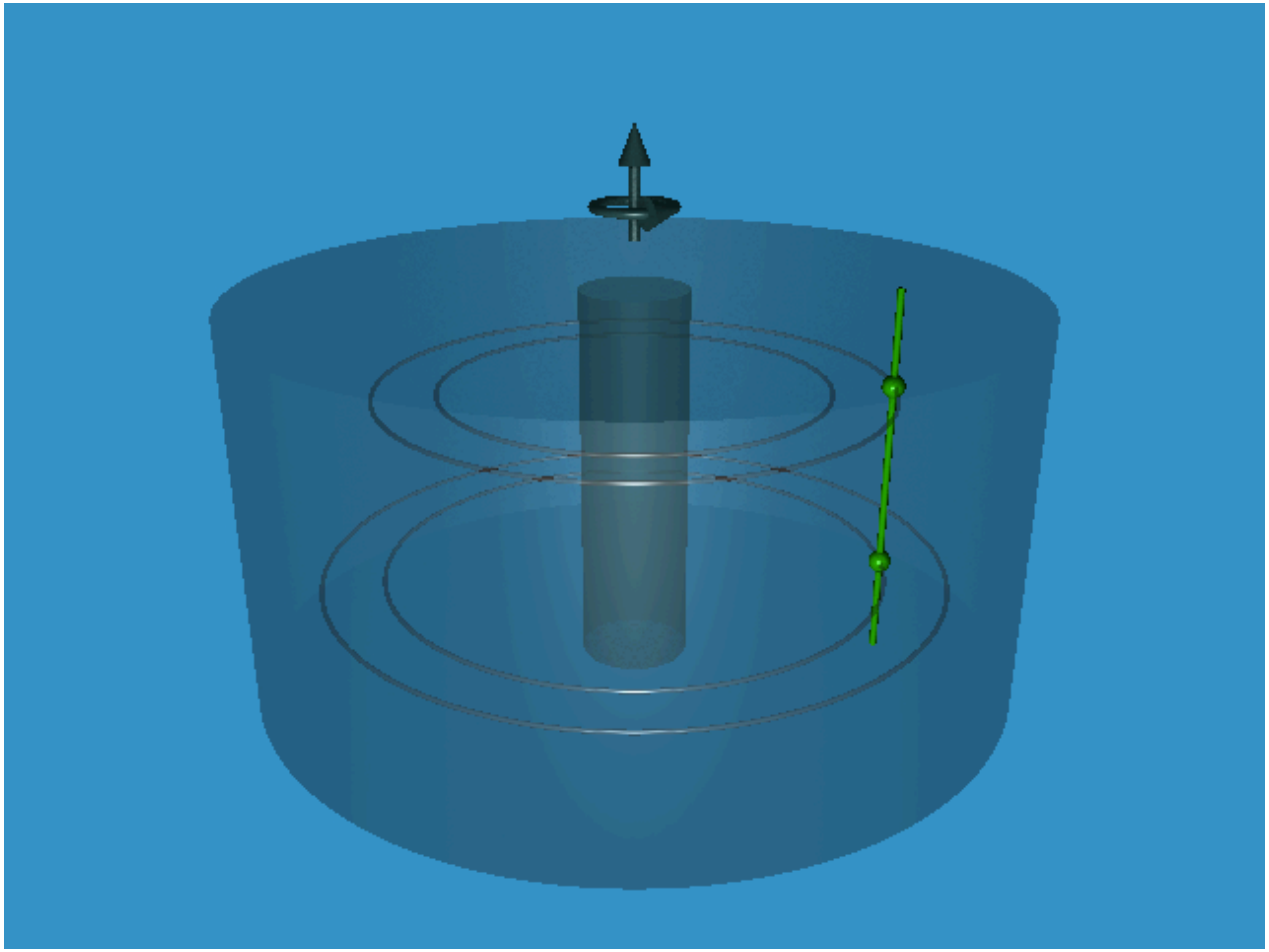




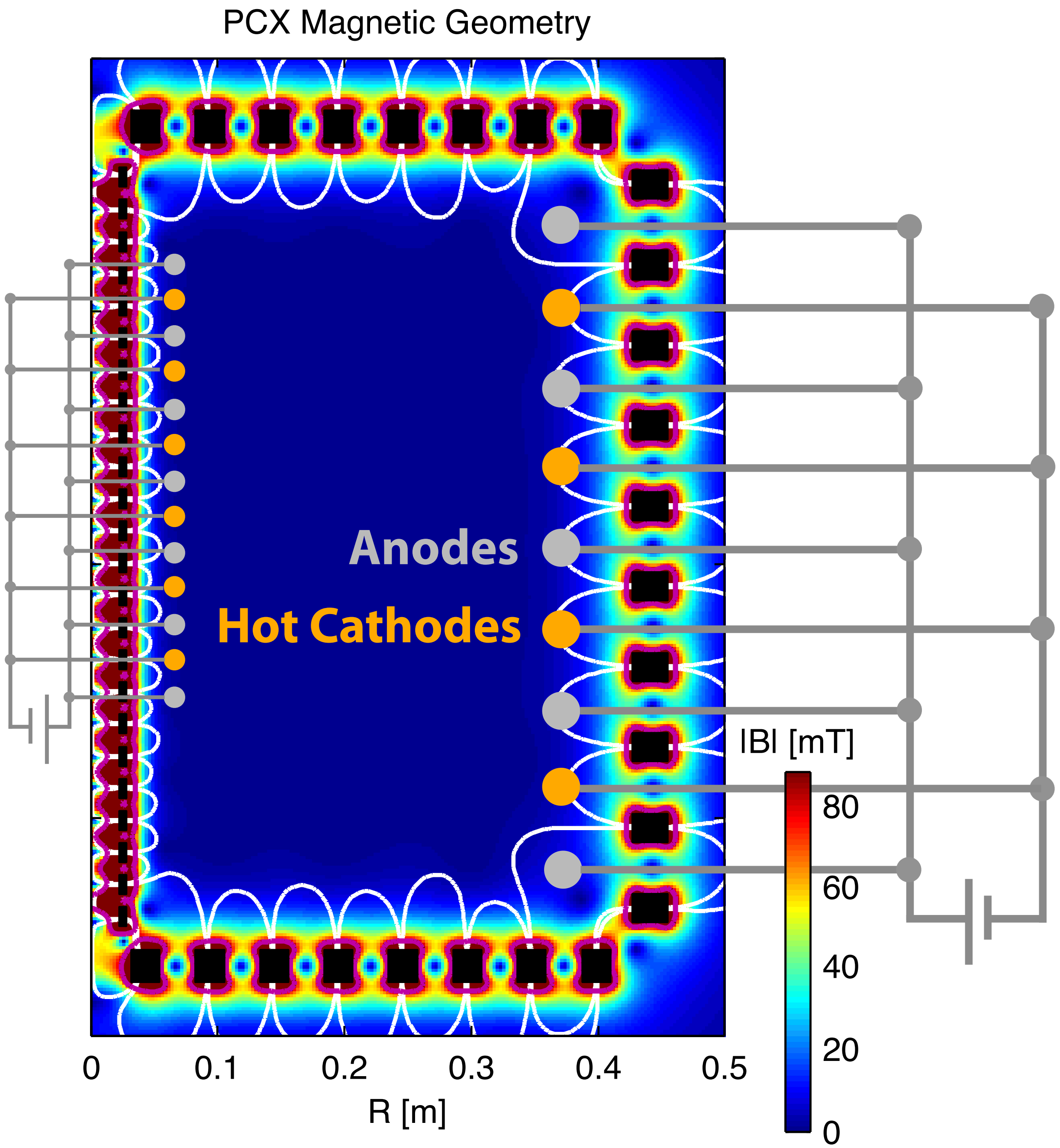
- Keplerian flows of conducting fluids are hydrodynamically stable
- Can be *destabilized* by a magnetic field: the magnetorotational instability (MRI)

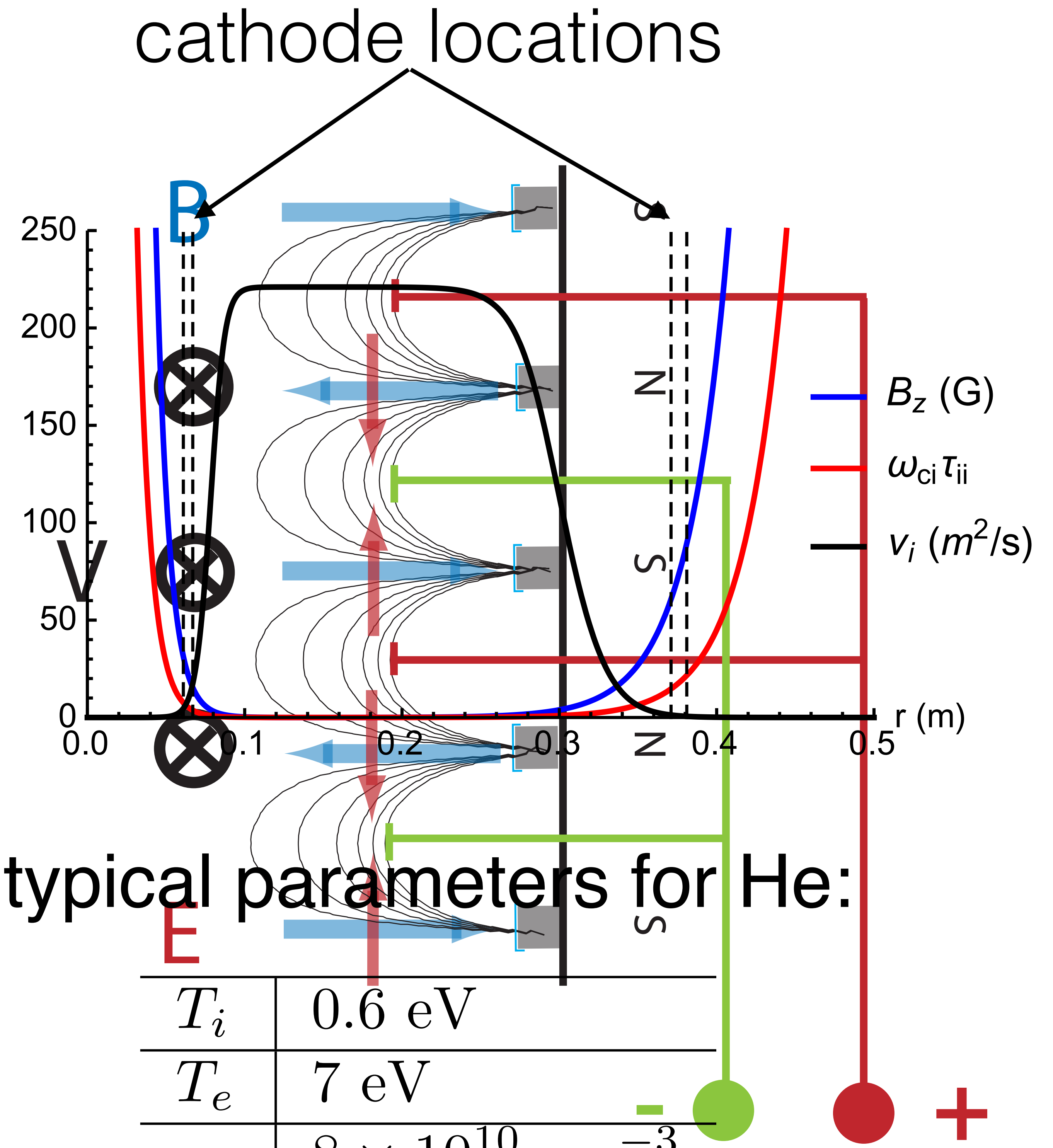
- Conditions for MRI

$$\frac{\partial \Omega}{\partial r} < 0 \qquad \frac{\partial (r^2 \Omega)}{\partial r} > 0$$



Multicusp confinement and stirring



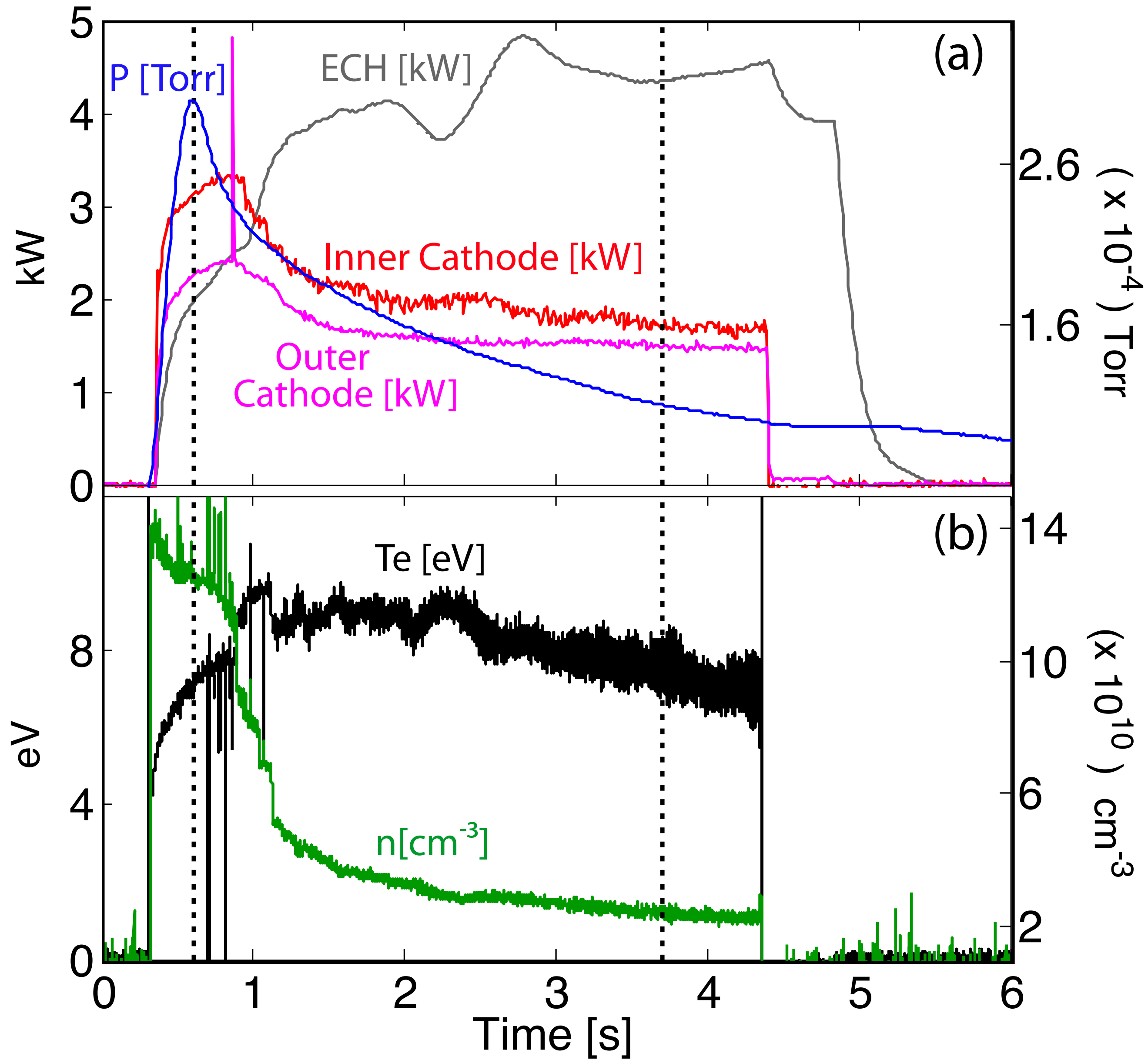


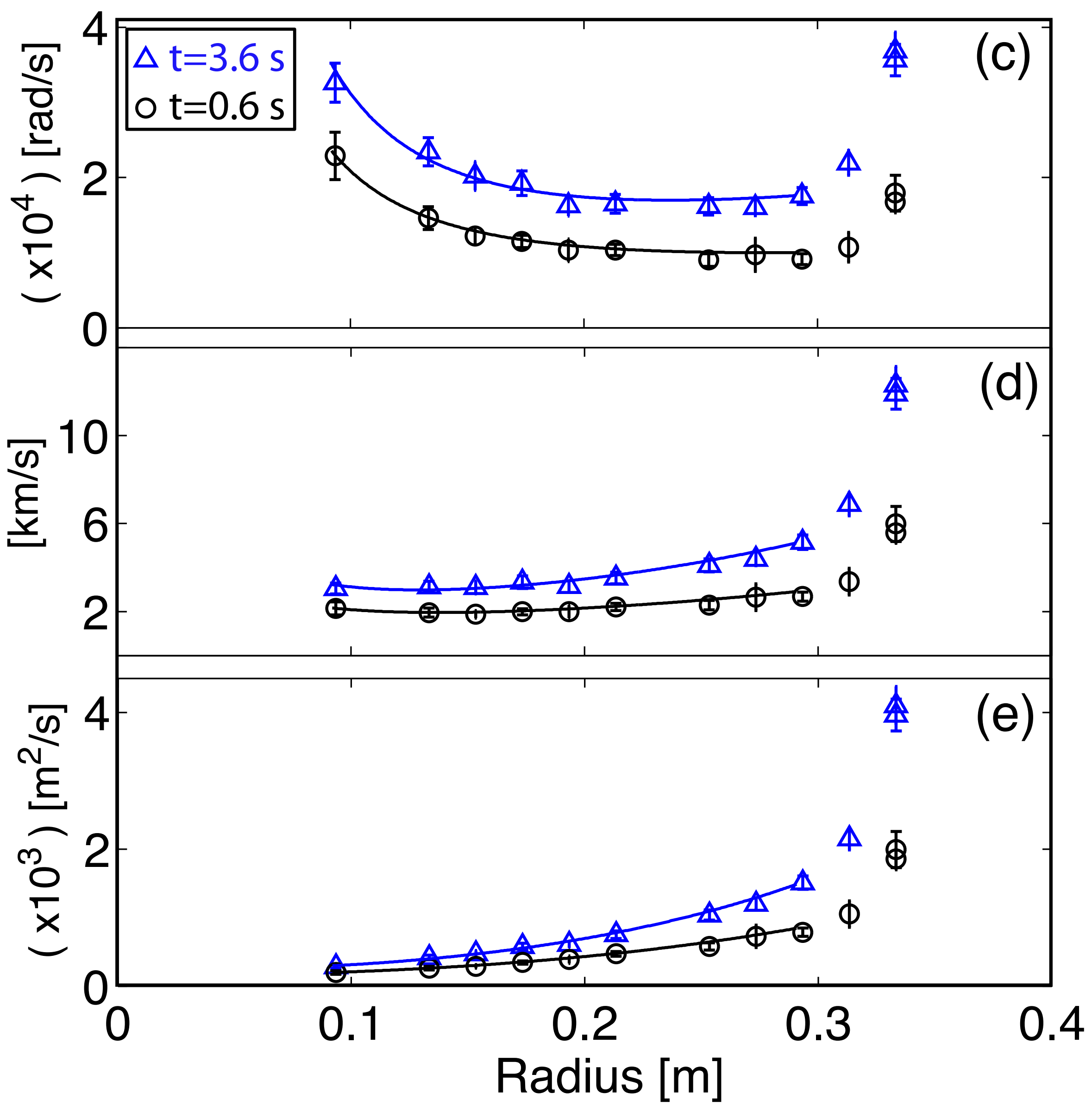
typical parameters for He:

T_i	$0.6\ \mathrm{eV}$
T_e	$7\ \mathrm{eV}$
n_e	$8\times10^{10}\ \mathrm{cm}^{-3}$
P_0	$10^{-4}\ \mathrm{torr}$

$\Rightarrow \quad f_{\%} = 2.4\ \%$

Differential flow!!!

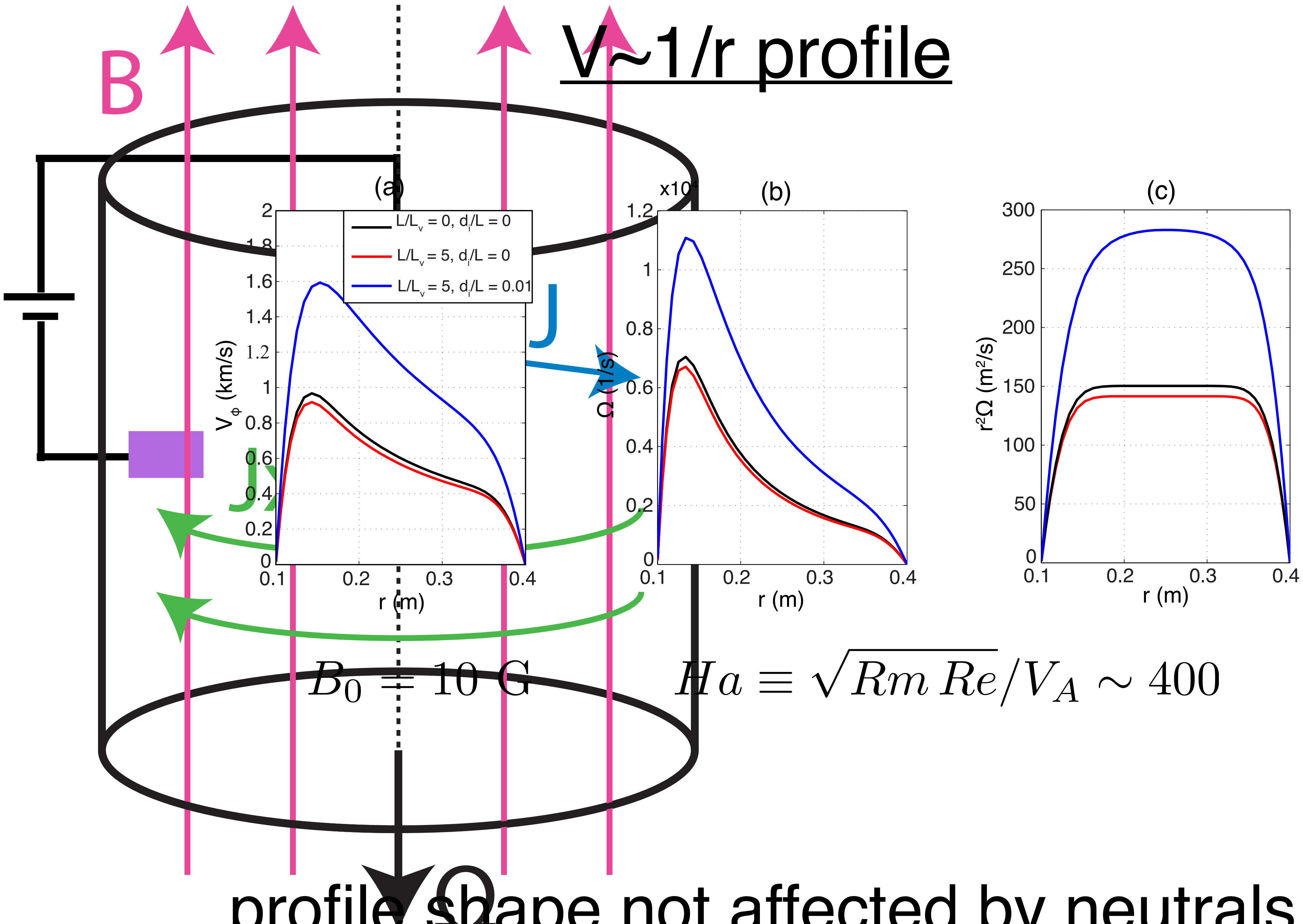




Parameter	$t = 0.6$ s	$t = 3.6$ s
Pm	12	2.5
Rm	30	65
Re	2.5	26

At r~0.1-0.3 m “ideal” MRI conditions are met

Volumetric flow drive (VFD)



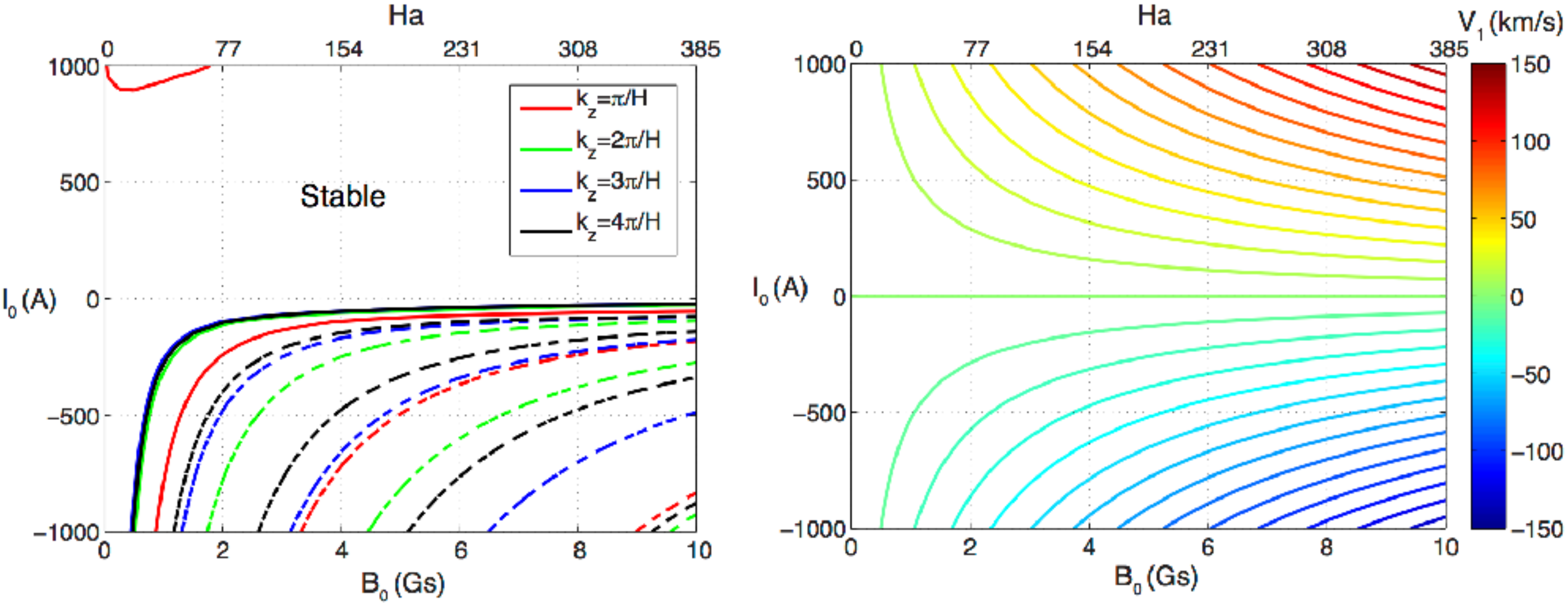
V~1/r profile

$B_0 = 10$ G

$Ha \equiv \sqrt{Rm\,Re}/V_A \sim 400$

profile shape not affected by neutrals

Exciting the MRI with VFD



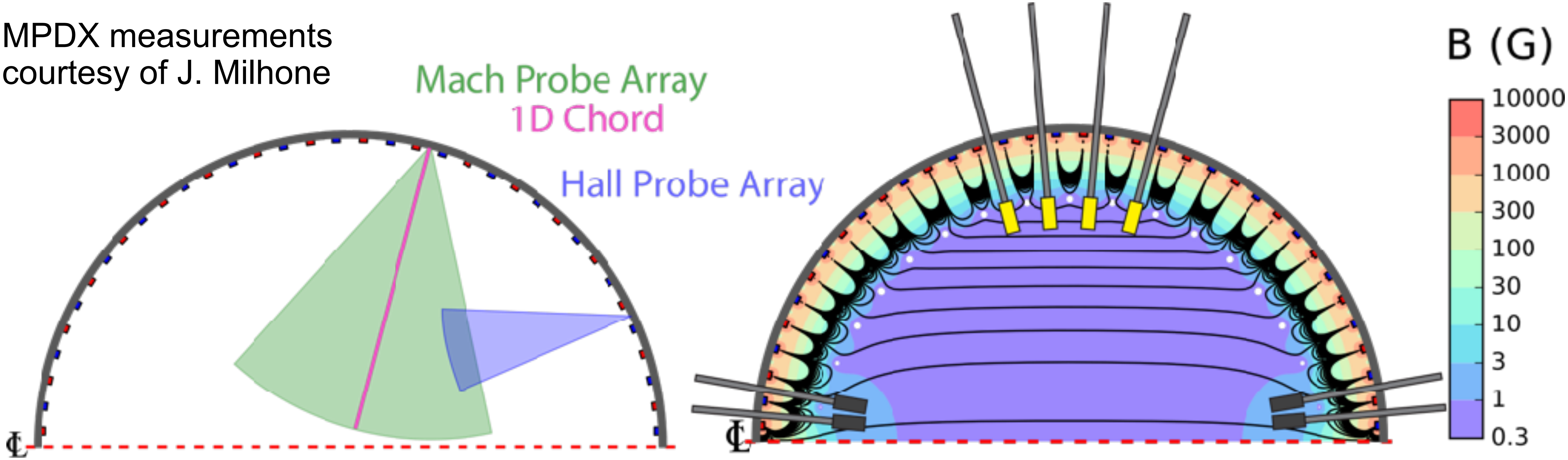
$$Te = 12 \text{ eV}$$

$$n = 10^{12} \text{ cm}^{-3}$$

$$f_{\%} = 75 \ \%$$

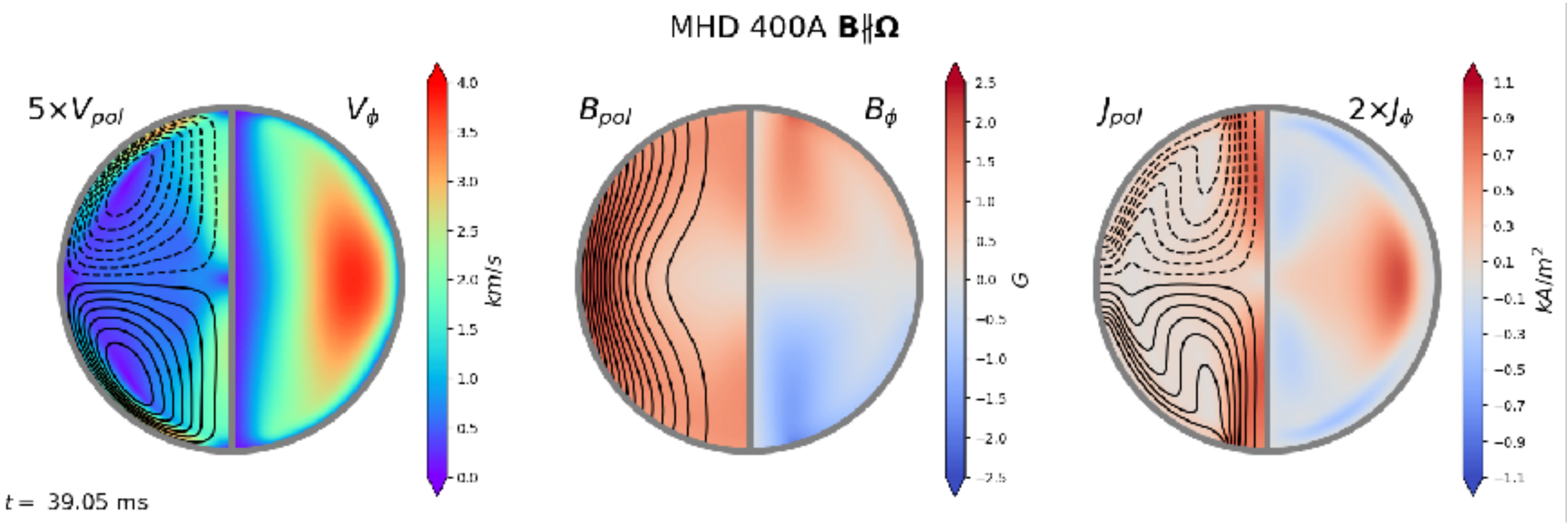
VFD on MPDX

MPDX measurements
courtesy of J. Milhone



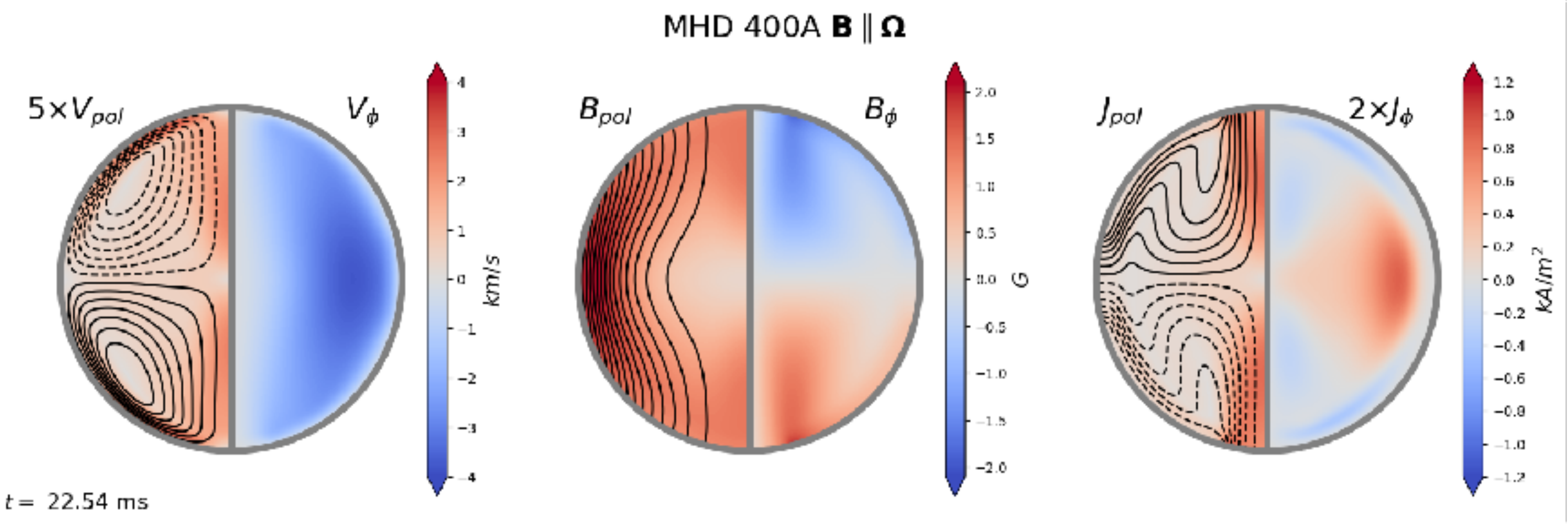
- Weak 0.5G applied magnetic field
- <300A max discharge current
- Mach probe measurements made wrt floating faces due to low plasma potentials caused by discharge
- 3 axis Hall probe array provides B measurements
- 1D flow profiles made along a radial chord (converted to cylindrical R for following plots)

Current injected at poles and removed at equator



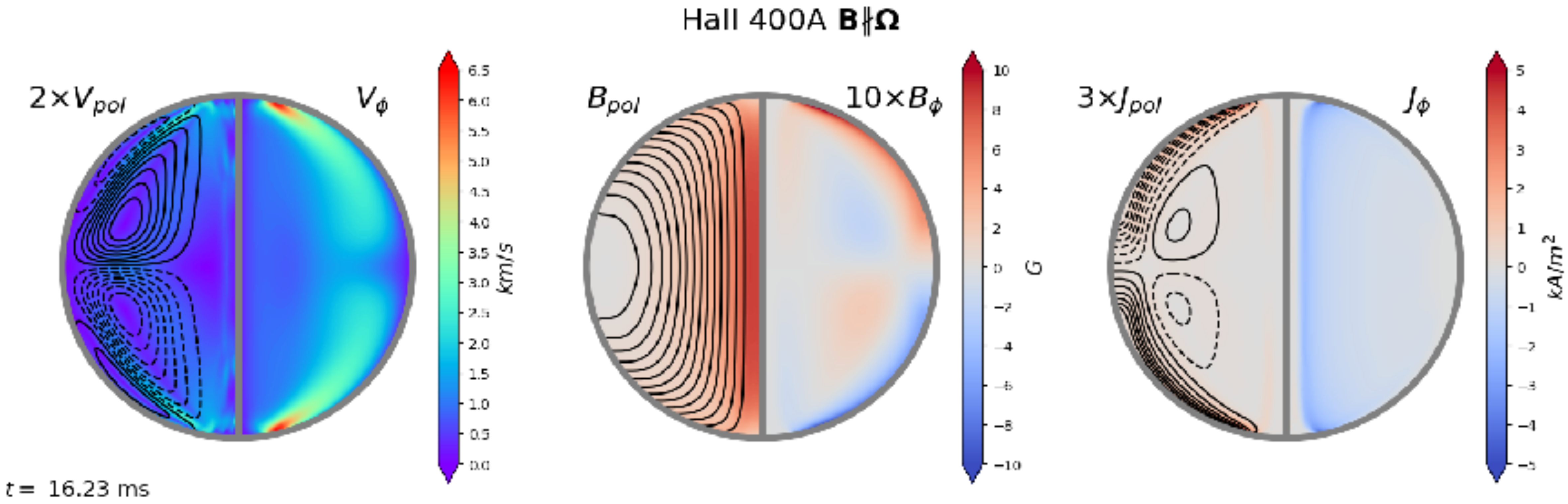
MHD 400A $\mathbf{B} \nparallel \mathbf{\Omega}$

Current injected at equator and removed at poles

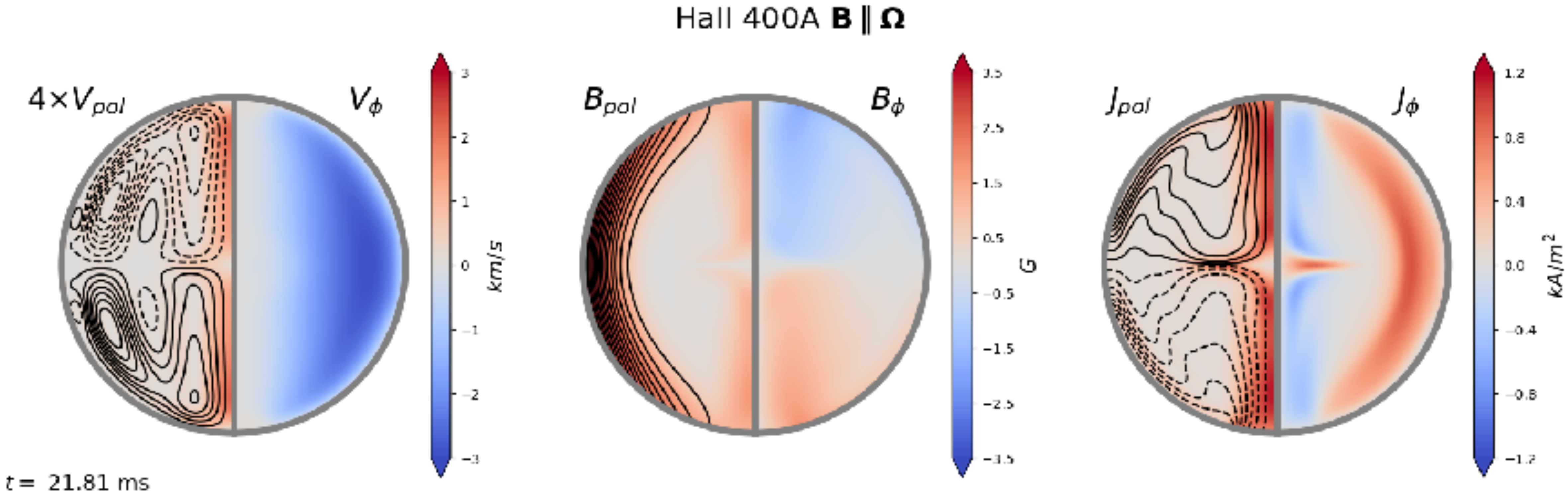


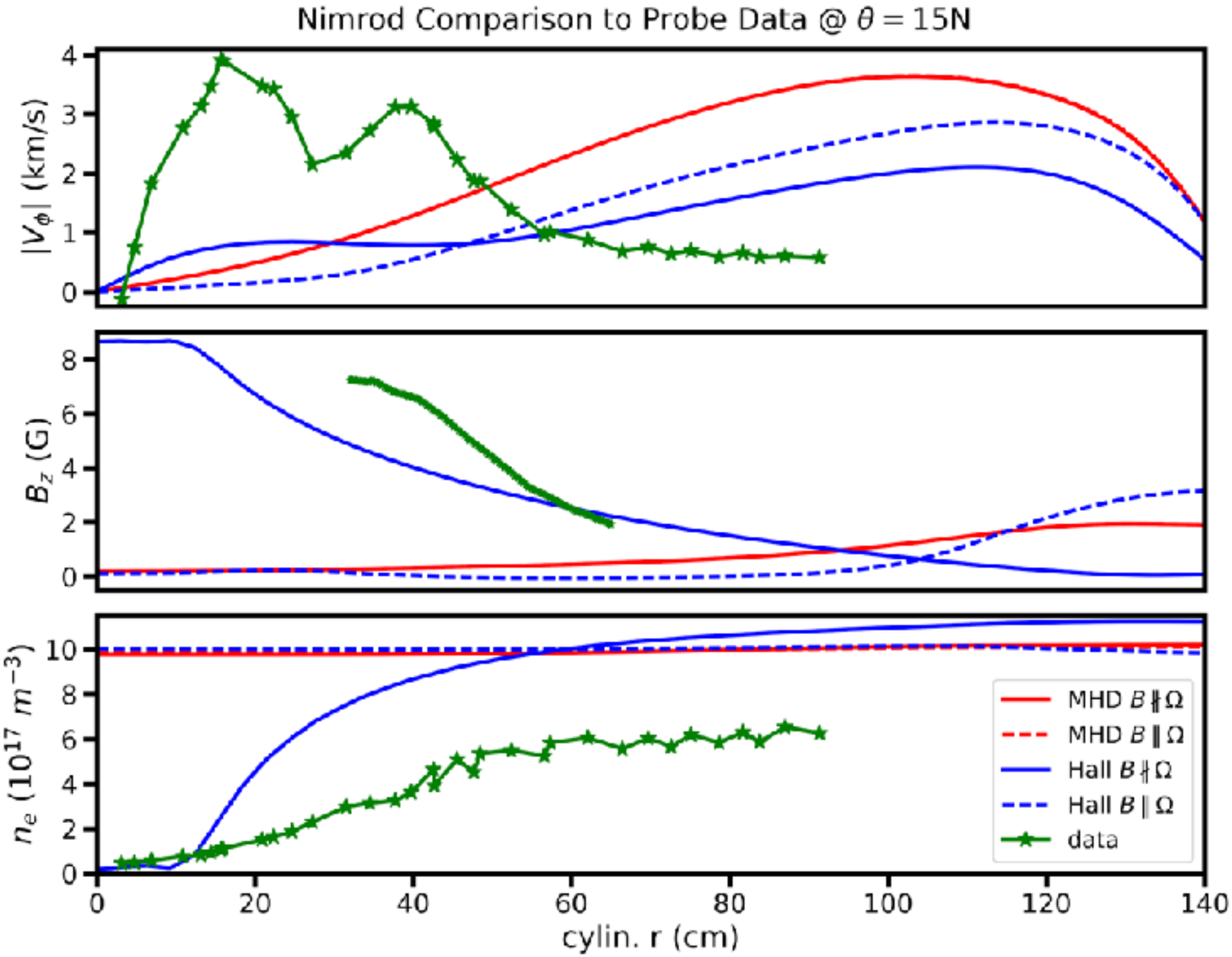
MHD 400A $\mathbf{B} \parallel \mathbf{\Omega}$

Favorable alignment for Hall-MRI



Similar to MHD cases





So far Nimrod runs have not matched experimental data very well.

However, the antiparallel Hall case does have Bz compression and a density depletion in the center like the experiment.

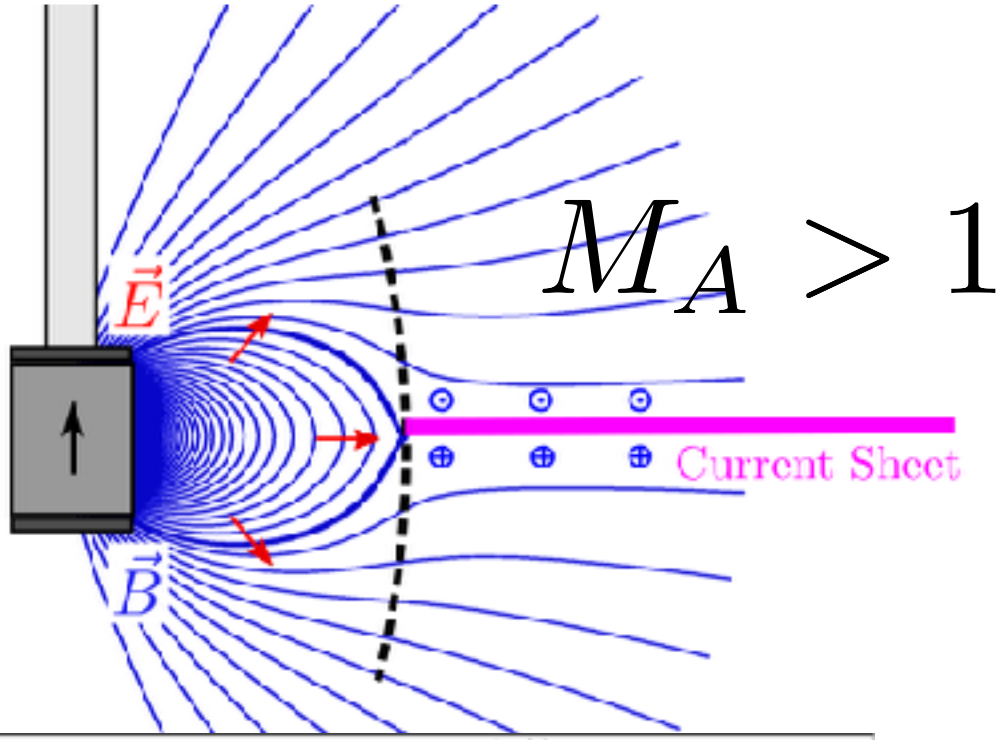
Including a neutral profile (peaked at outside) will

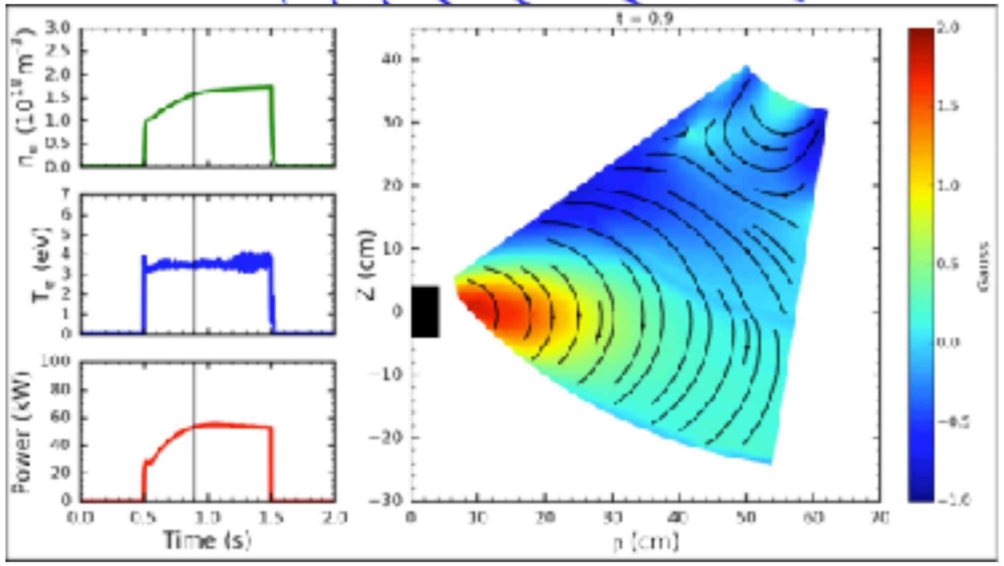
Parker Spiral

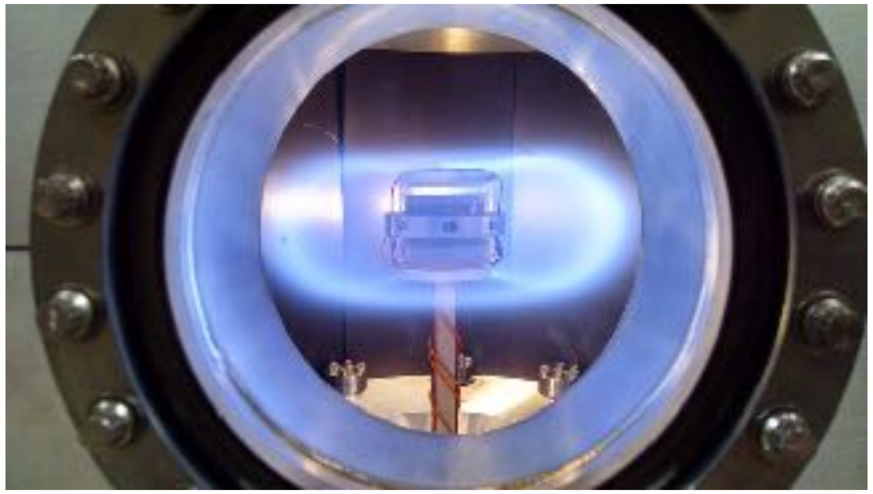
test fundamental tenet…

Inverse Magnetosphere Confinement, Centrifugally Driven Stellar Winds, and Parker Spiral experiments now beginning

Student Doug Endrizzi supported by NSF Graduate Student Fellowship

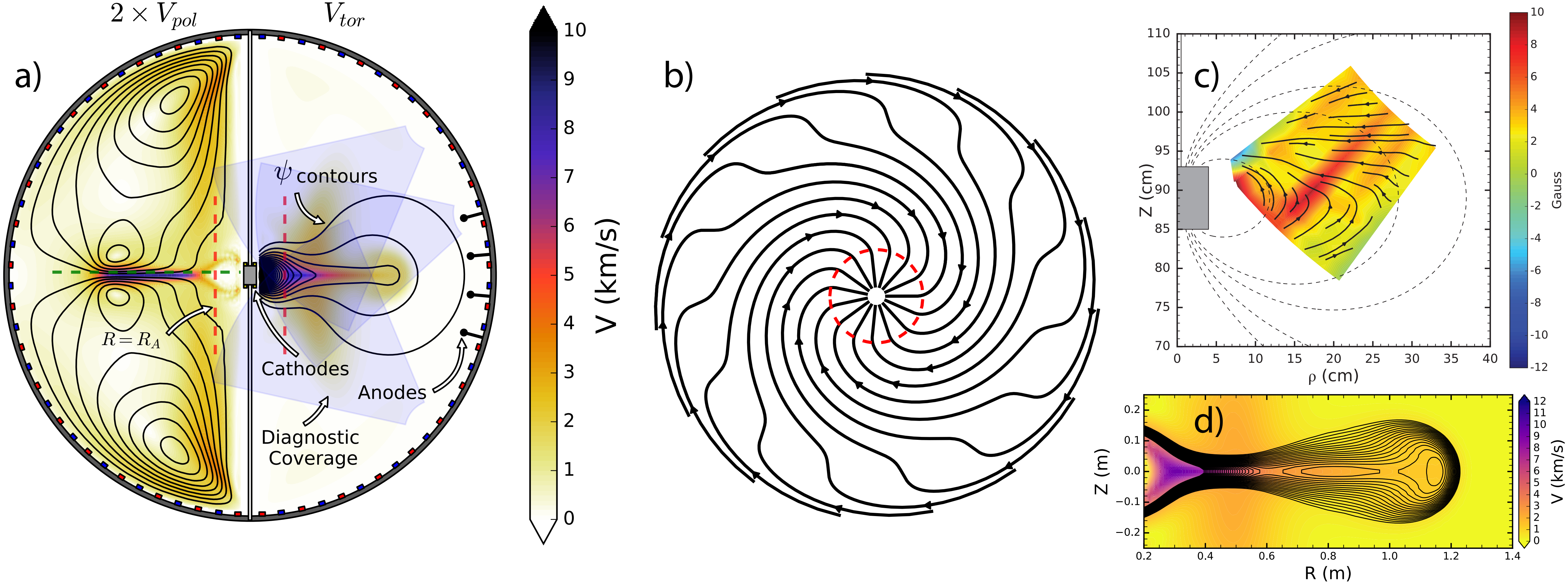




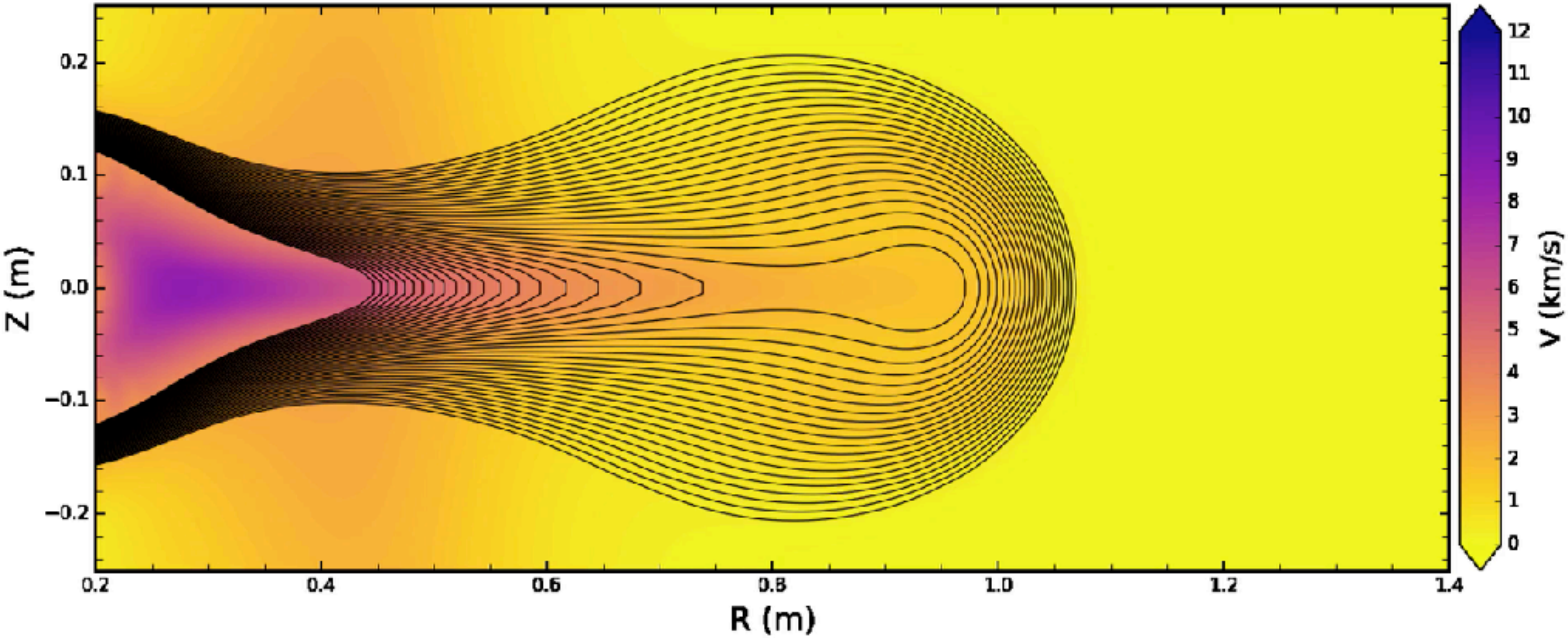


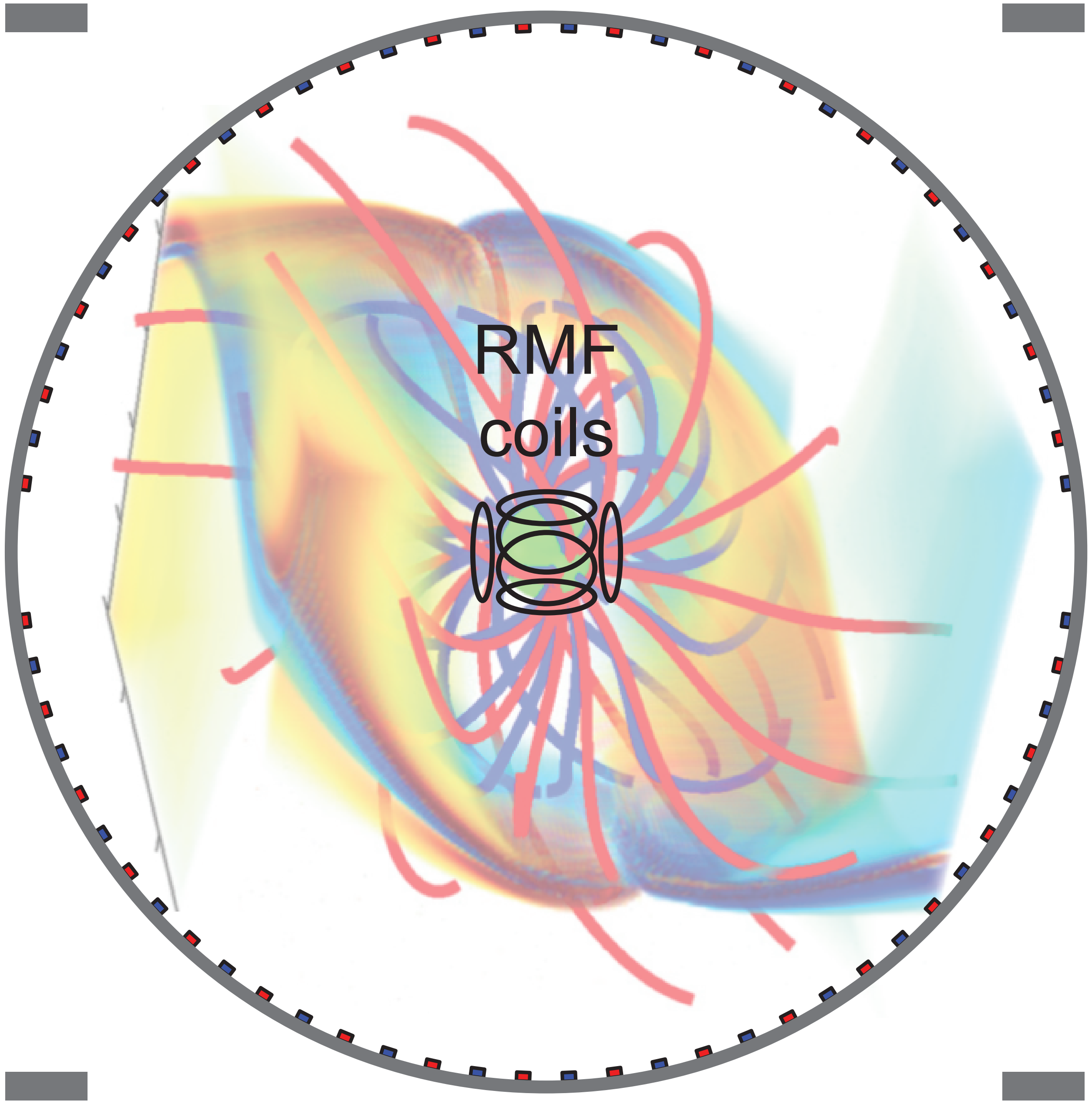
Outreach: Terella in Physics 407
(plasma confinement in magnetosphere)

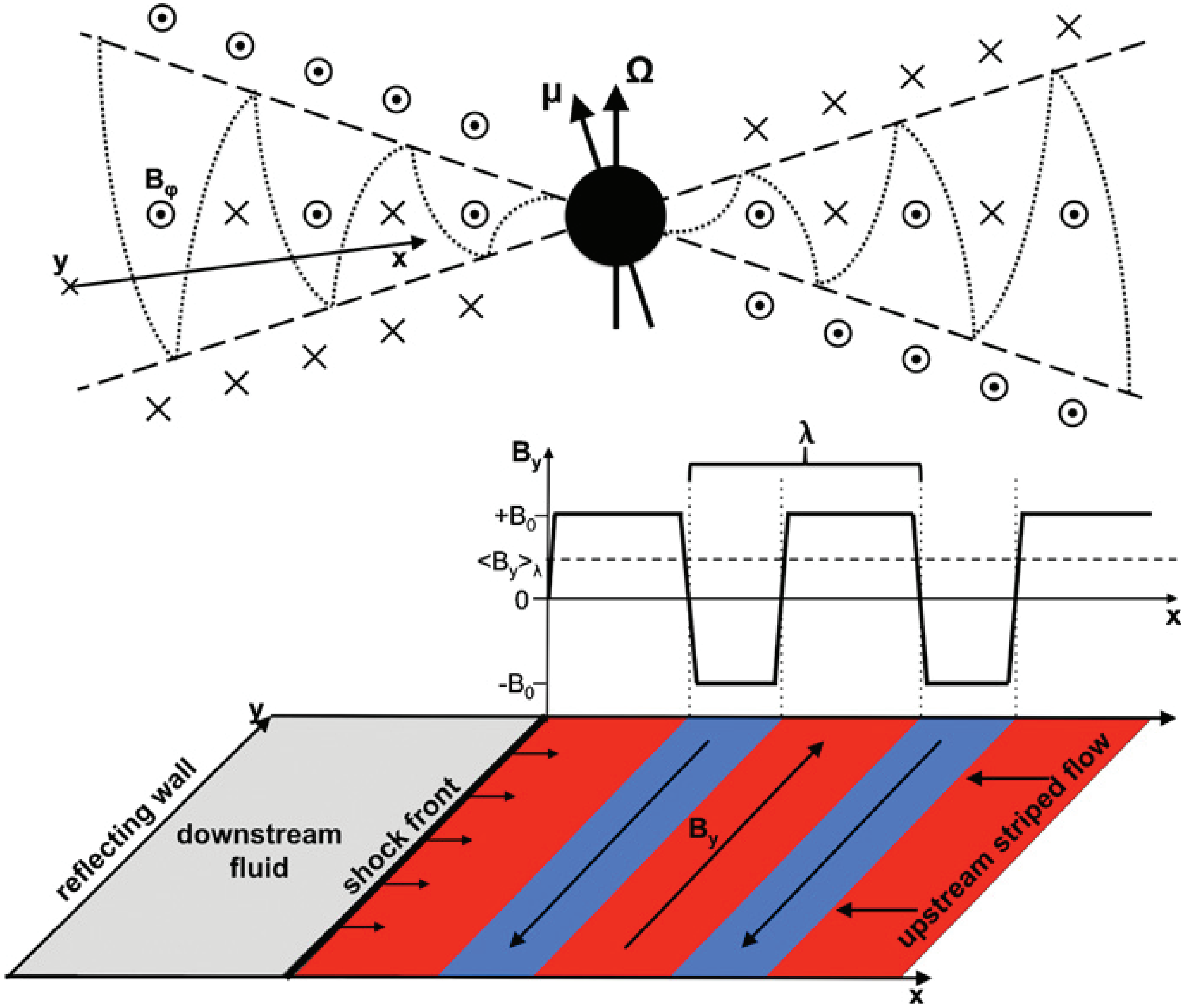
Diamagnetic current profile and flows have been measured



$2 \times V_{pol}$
V_{tor}
a)
ψ contours
$R = R_A$
Cathodes
Anodes
Diagnostic Coverage
10
9
8
7
6
5
4
3
2
1
0
V (km/s)
b)
c)
110
105
100
95
90
85
80
75
70
Z (cm)
0
5
10
15
20
25
30
35
40
ρ (cm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
Gauss
d)
0.2
0.1
0.0
−0.1
−0.2
Z (m)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
R (m)
12
11
10
9
8
7
6
5
4
3
2
1
0
V (km/s)


Z (m)
0.2
0.1
0.0
−0.1
−0.2
R (m)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
V (km/s)
12
11
10
9
8
7
6
5
4
3
2
1
0

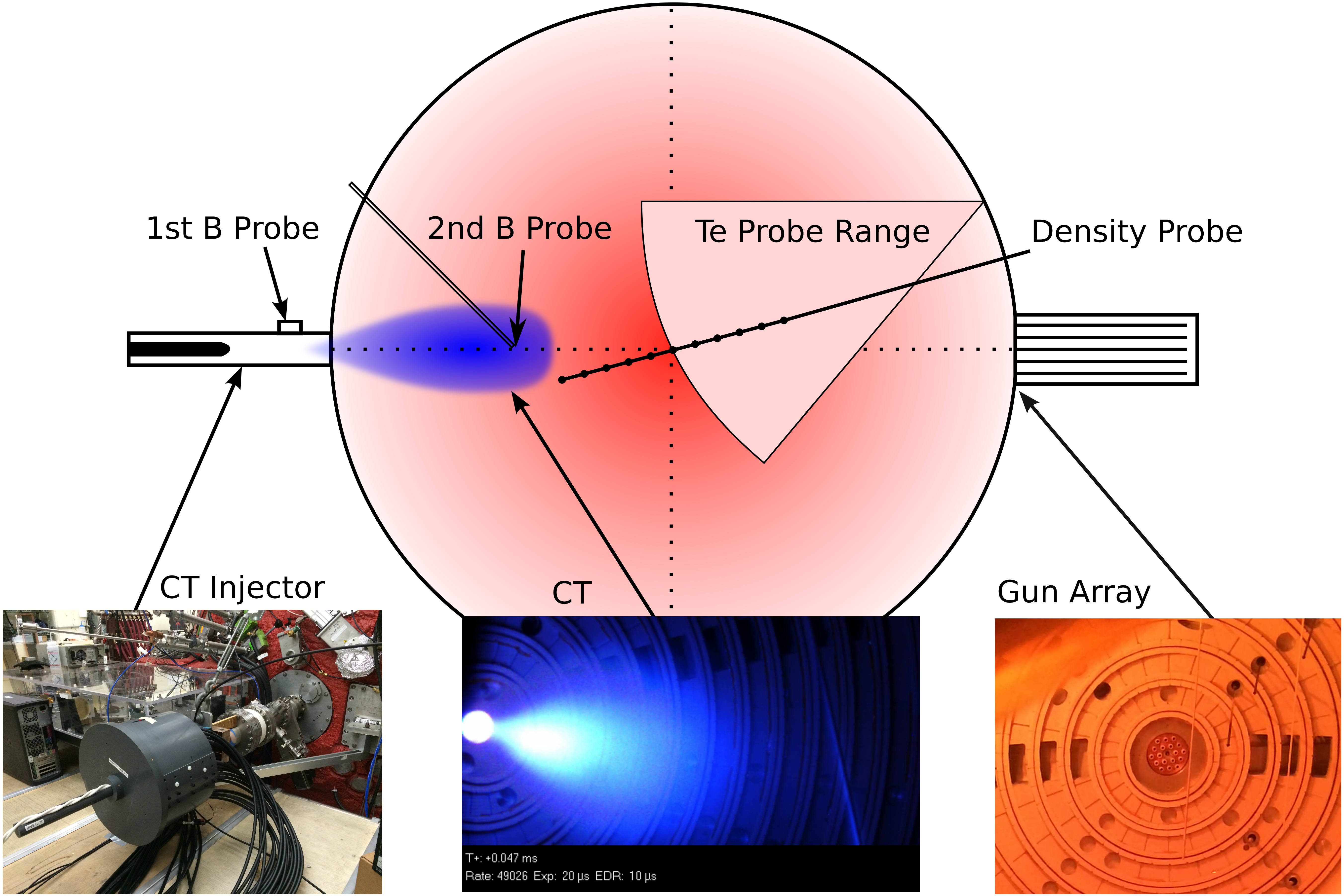

RMF
coils


μ
Ω
B_φ
y
x
λ
B_y
+B_0
<B_y>_λ
0
-B_0
x
y
reflecting wall
downstream
fluid
shock front
B_y
upstream striped flow
x

Shocks

Acceleration of particles by explosive jets of plasma

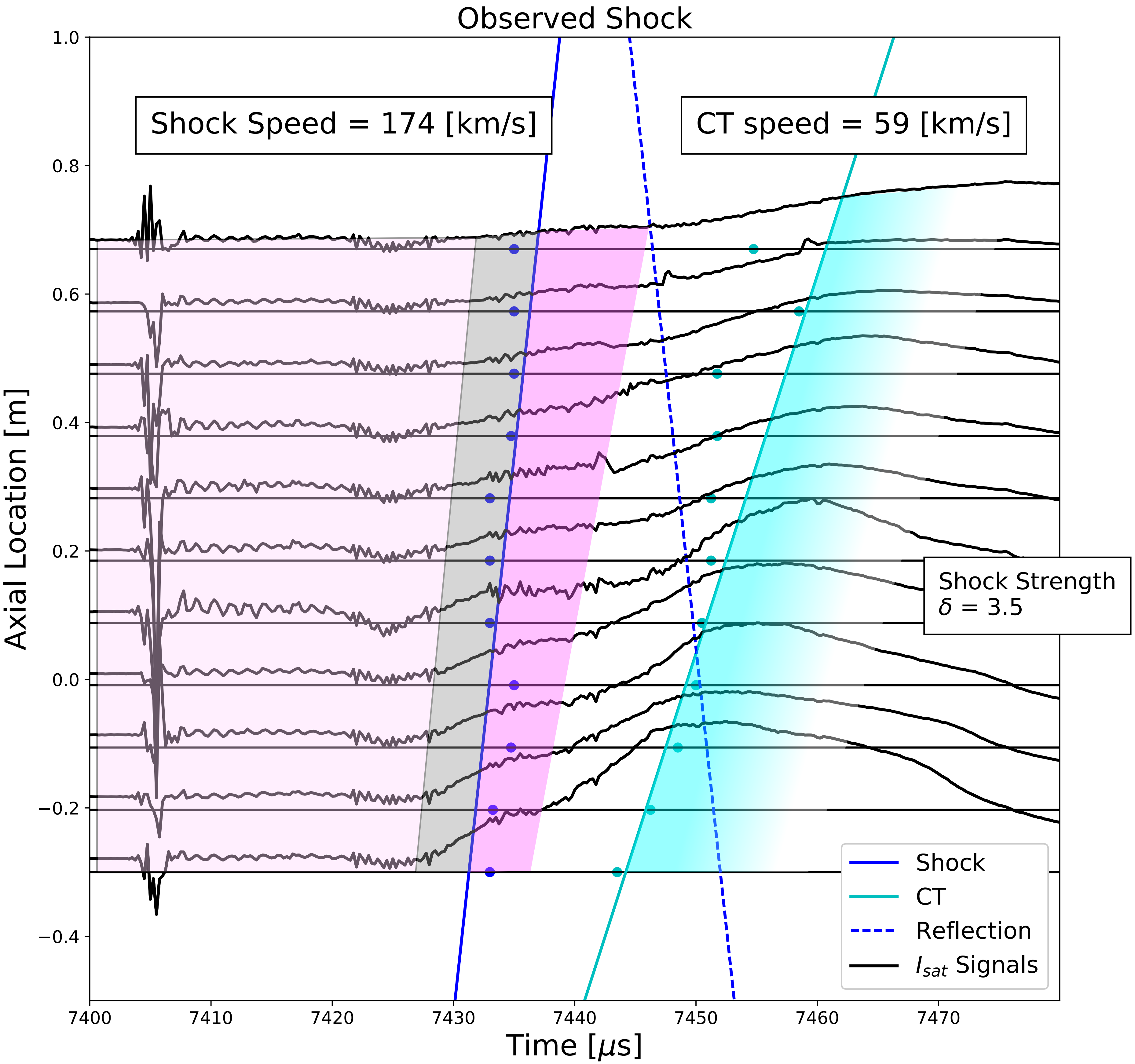
Experiment Layout



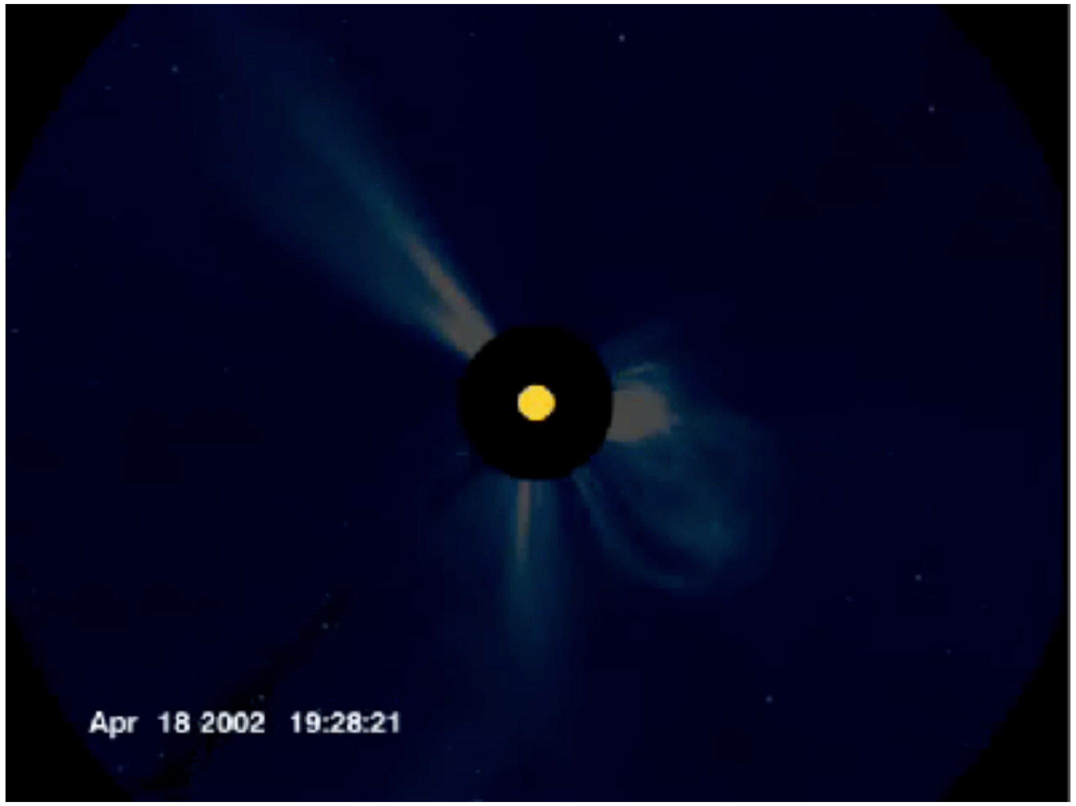
Rail Gun Accelerates Supersonic Plasma to 500,000 mph

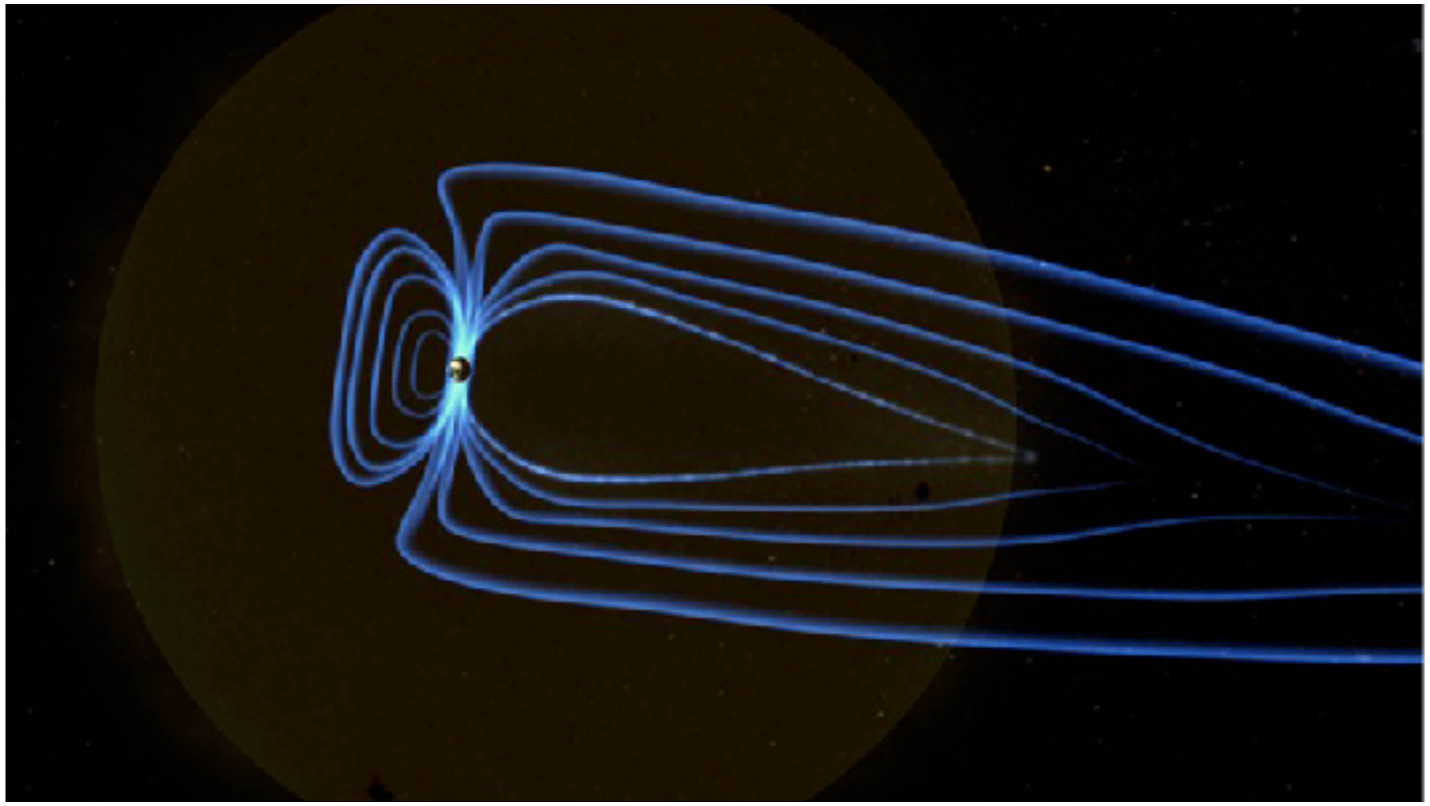
T+: -0.218 ms

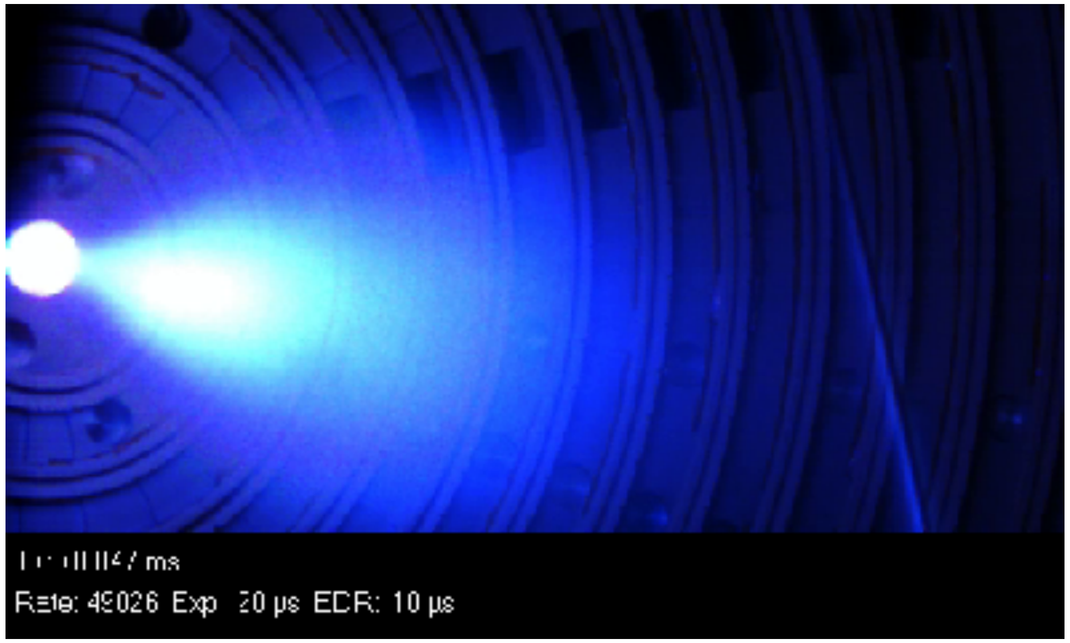
Rate: 49026 Exp: 20 µs EDR: 10 µs

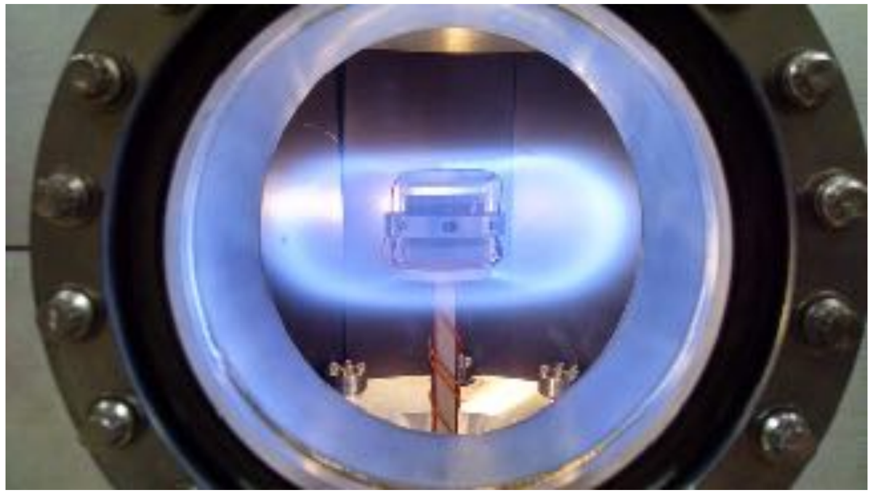

Observed Shock
Shock Speed = 174 [km/s]
CT speed = 59 [km/s]
Shock Strength
δ = 3.5
Shock
CT
Reflection
I_{sat} Signals
Axial Location [m]
Time [μs]
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
7400
7410
7420
7430
7440
7450
7460
7470

Space Weather









Thank You!!!