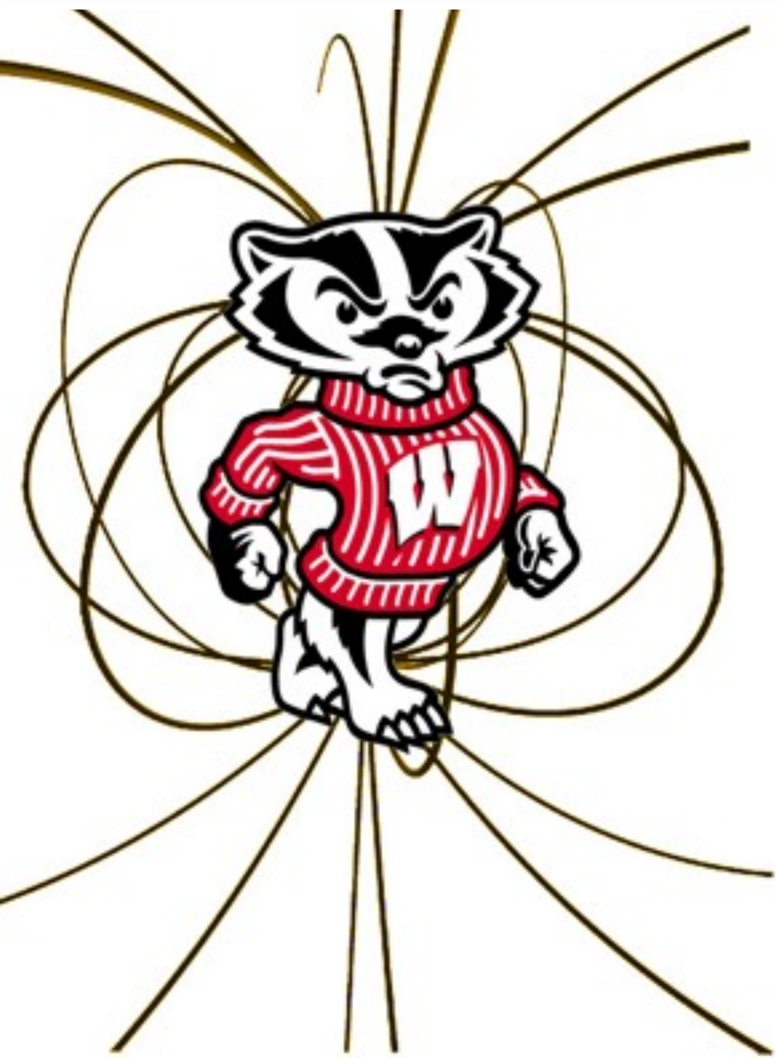
Plasma Dynamo Experiments



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The Dynamo regime requires steady:

- Highly conducting and fast flowing

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

- Turbulent or laminar

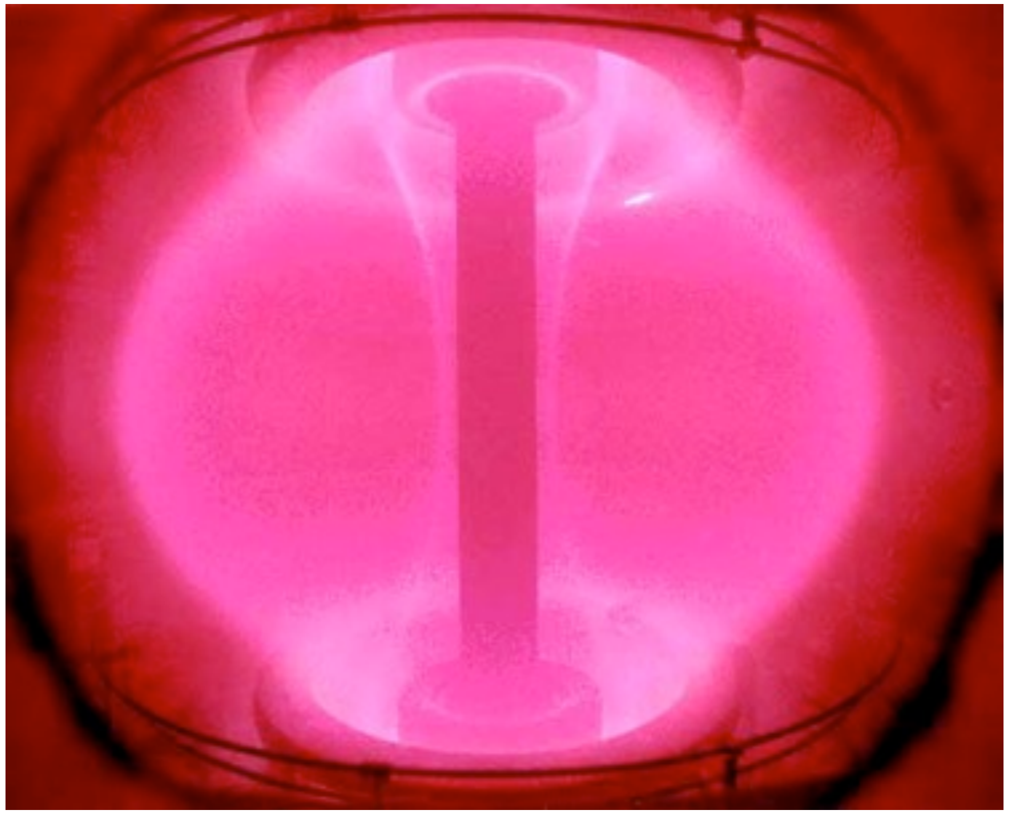
$$Re = \frac{VL}{\nu} \gg 1$$ Kinetic Reynolds

- Kinetic energy dominated

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

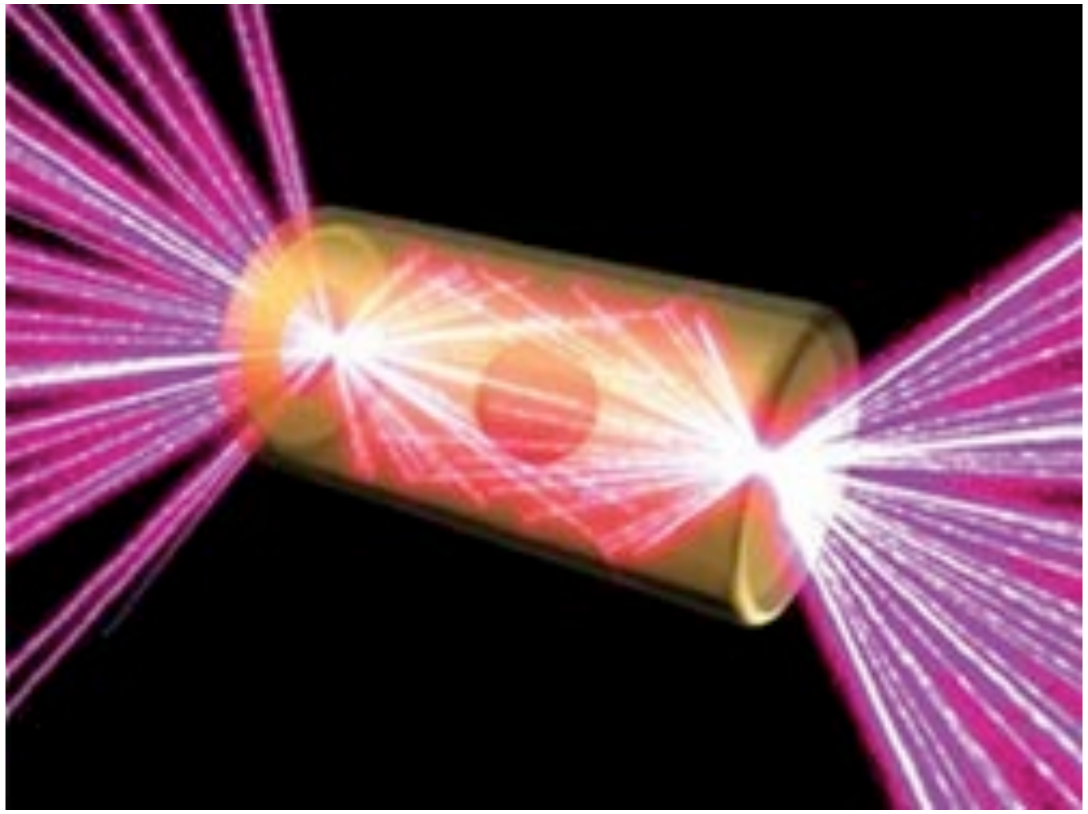
Most plasma experiments are not suitable for dynamo studies

Magnetically Confined Plasmas



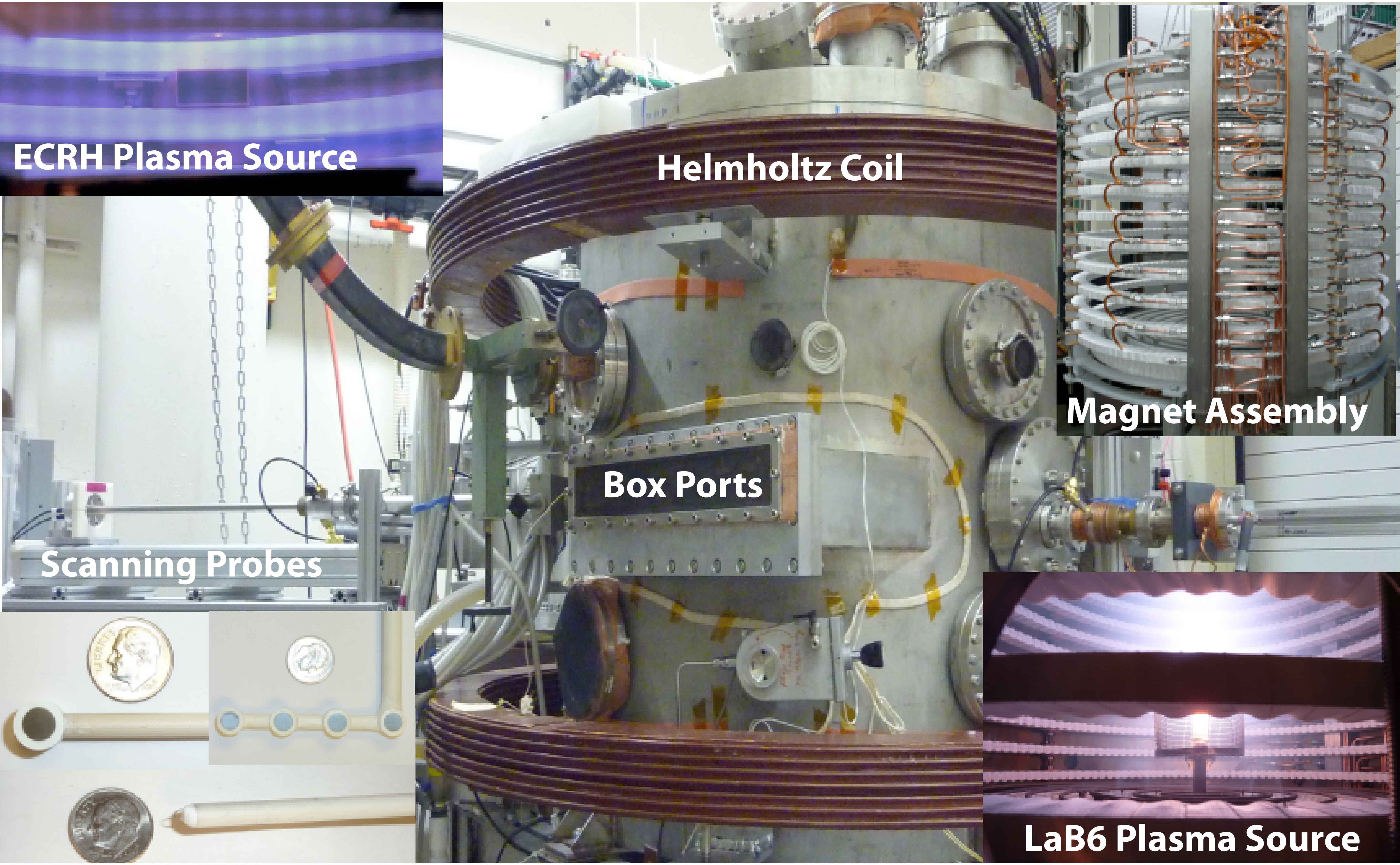
- $V = 100$ km/s, T=1 keV, B=1 T
- high Rm
- strongly magnetized
- pressure and magnetically driven MHD
- $\tau \ll \mu \sigma L^2$

Inertially Confined Plasmas

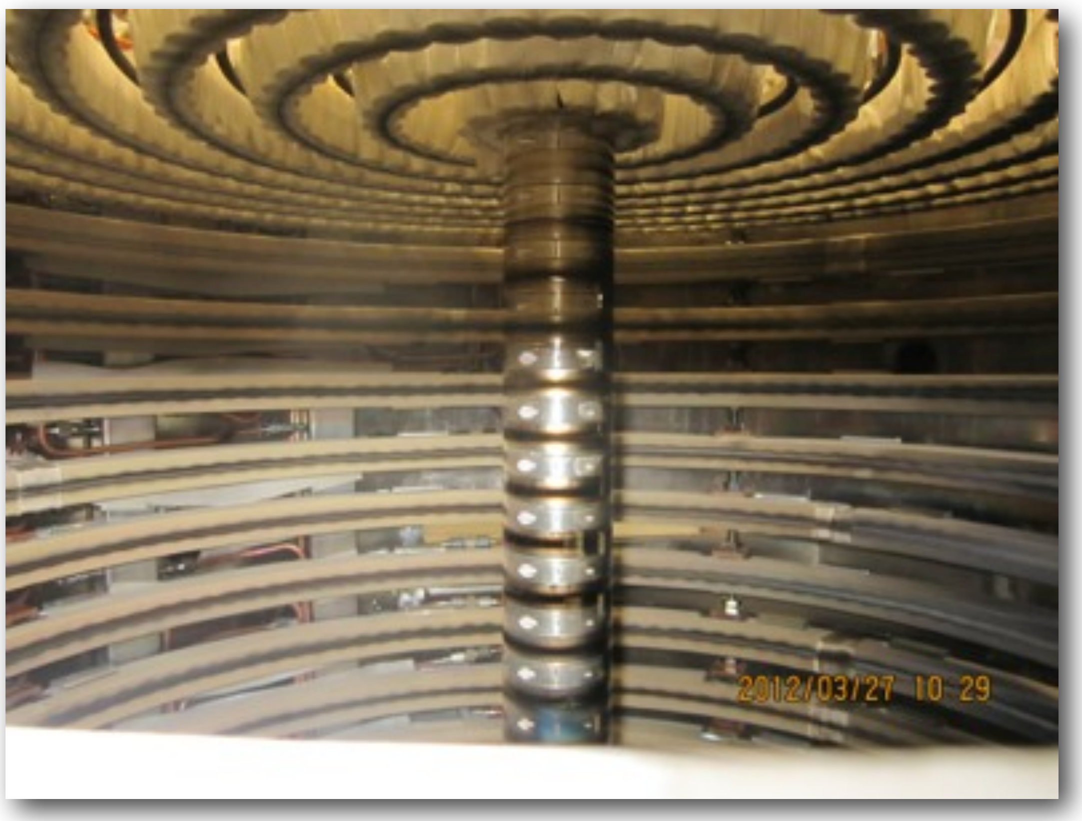


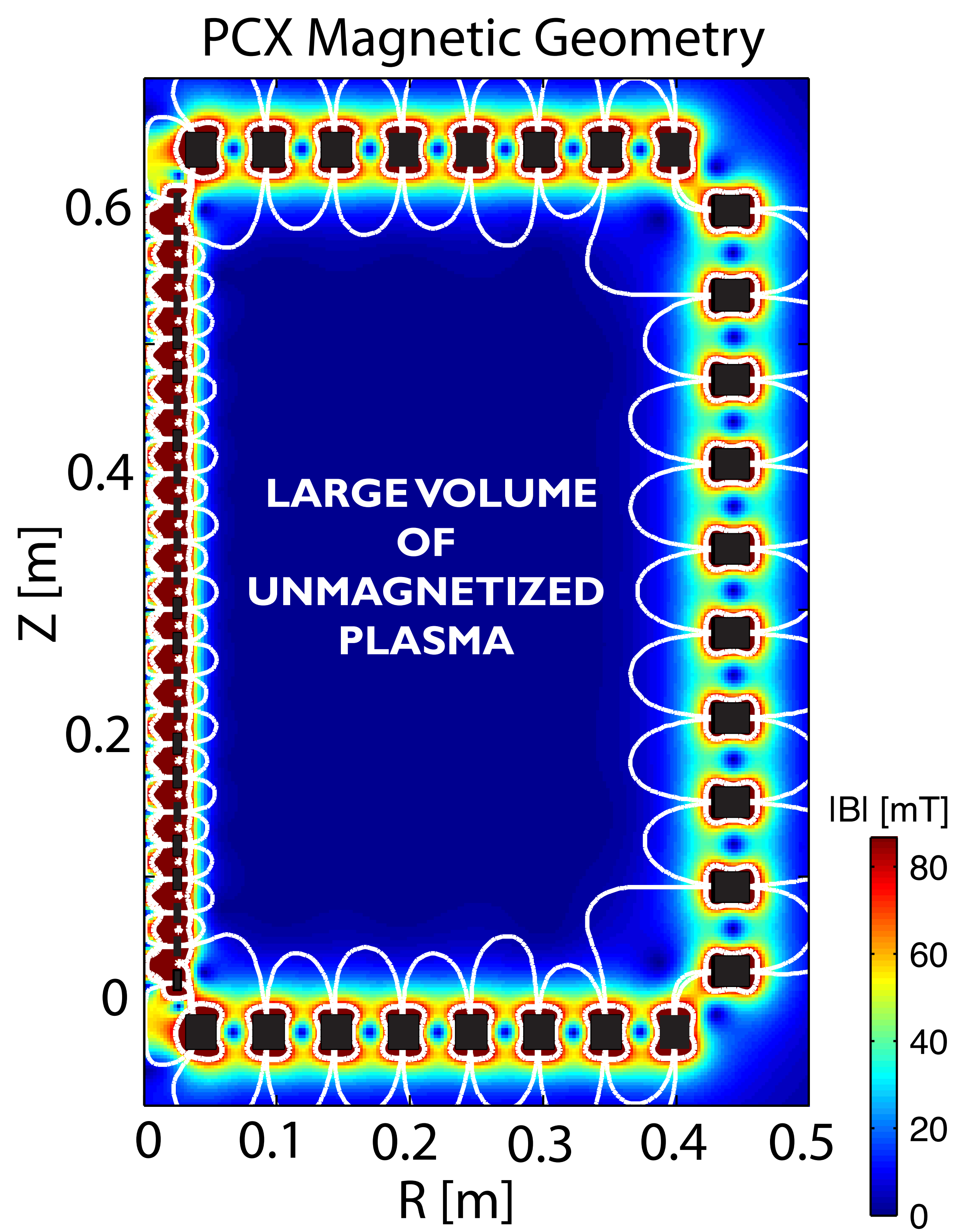
- $V \sim 50$ km/s, $T_e \sim 100$ eV
- modest Rm
- weakly magnetized
- $\tau \sim a/V \ll \mu_0 \sigma L^2$

Review: Stirring Unmagnetized Plasma

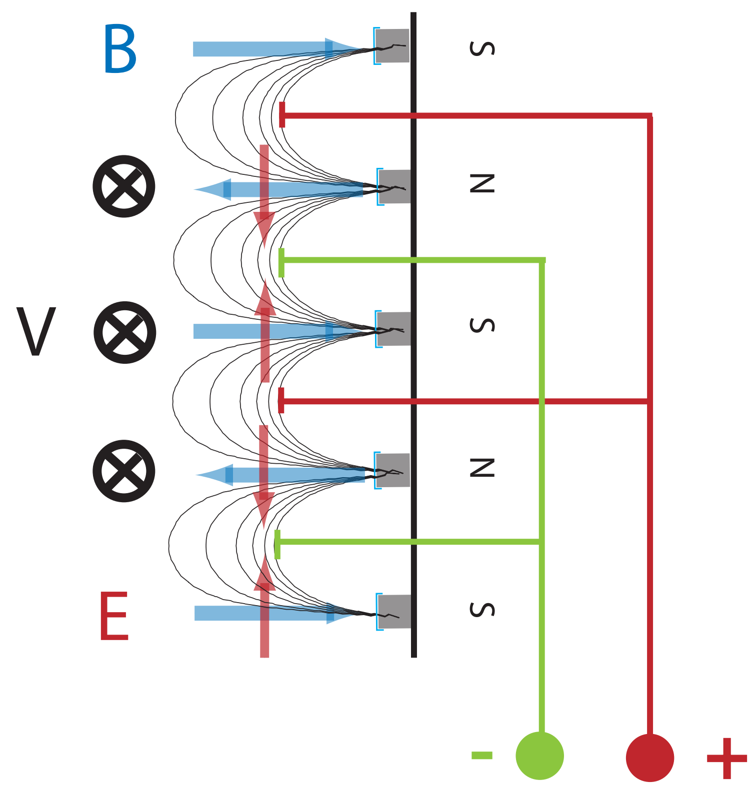


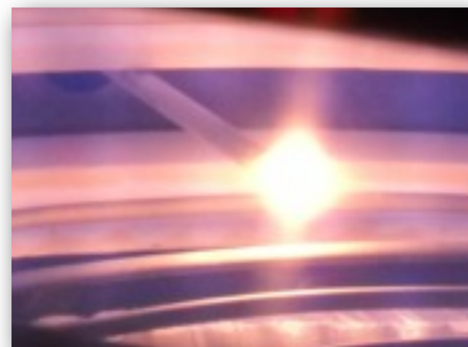
Axisymmetric Plasma Bucket Provides confinement

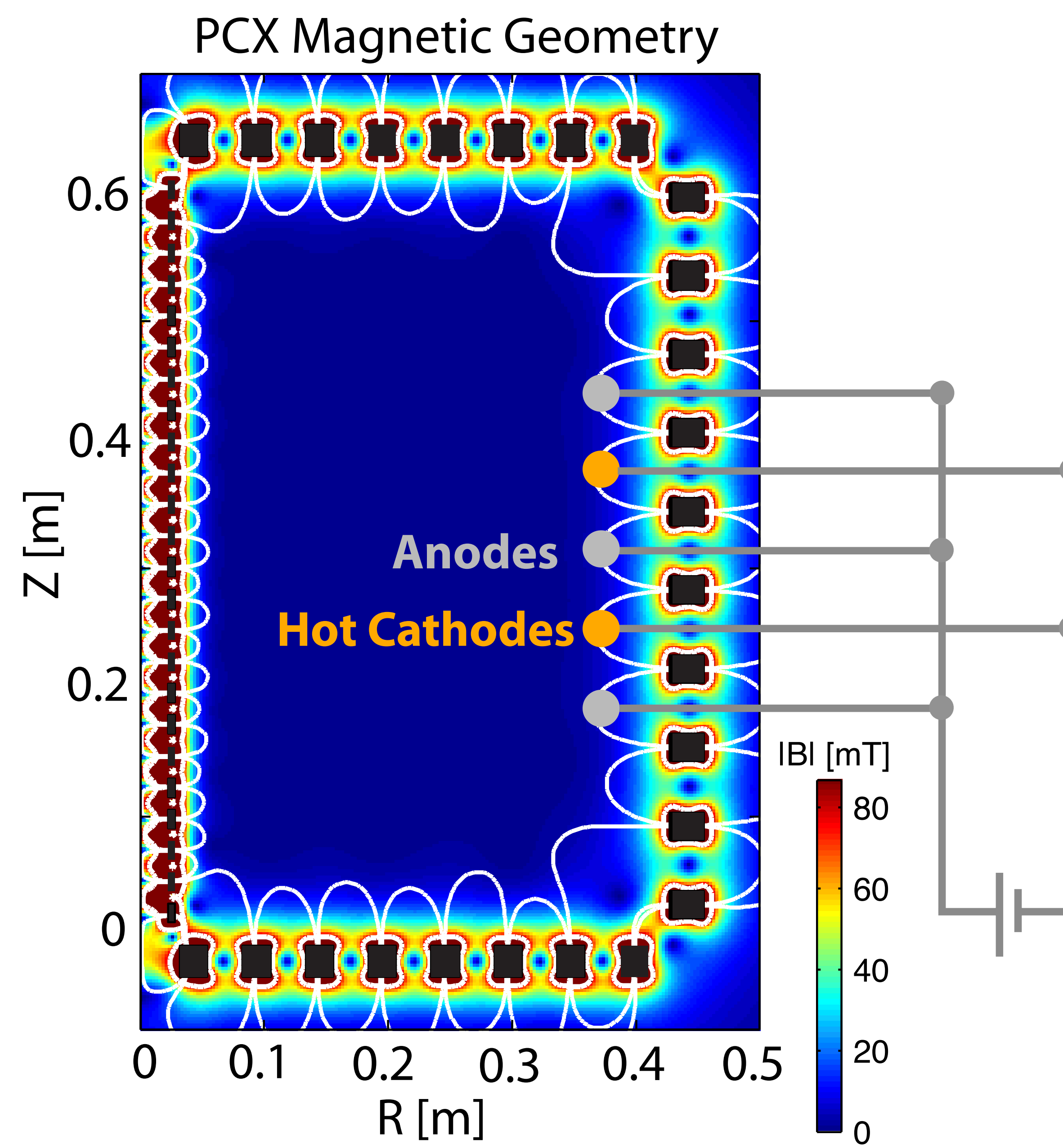




Plasma Stirring from boundary using electrodes

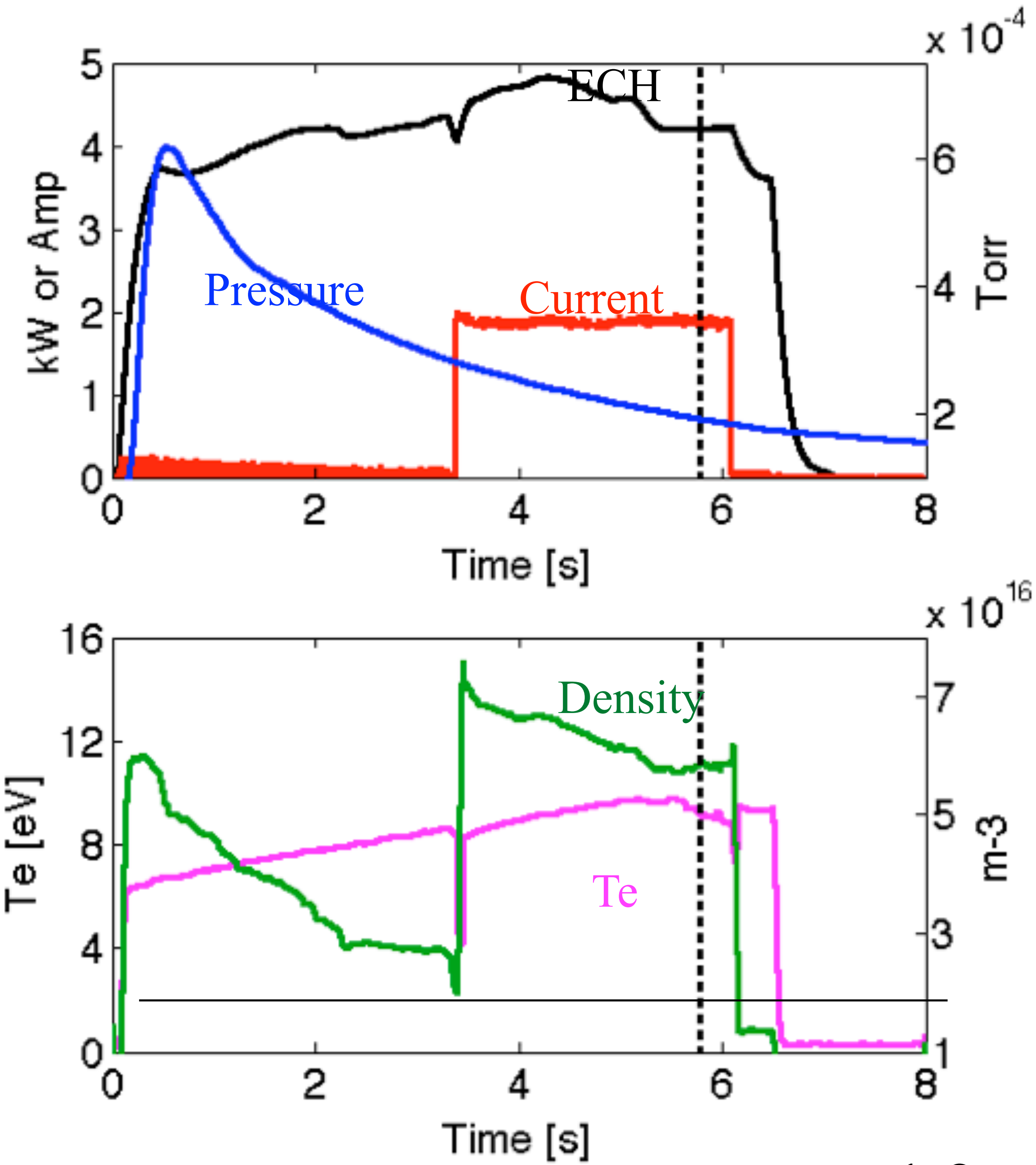


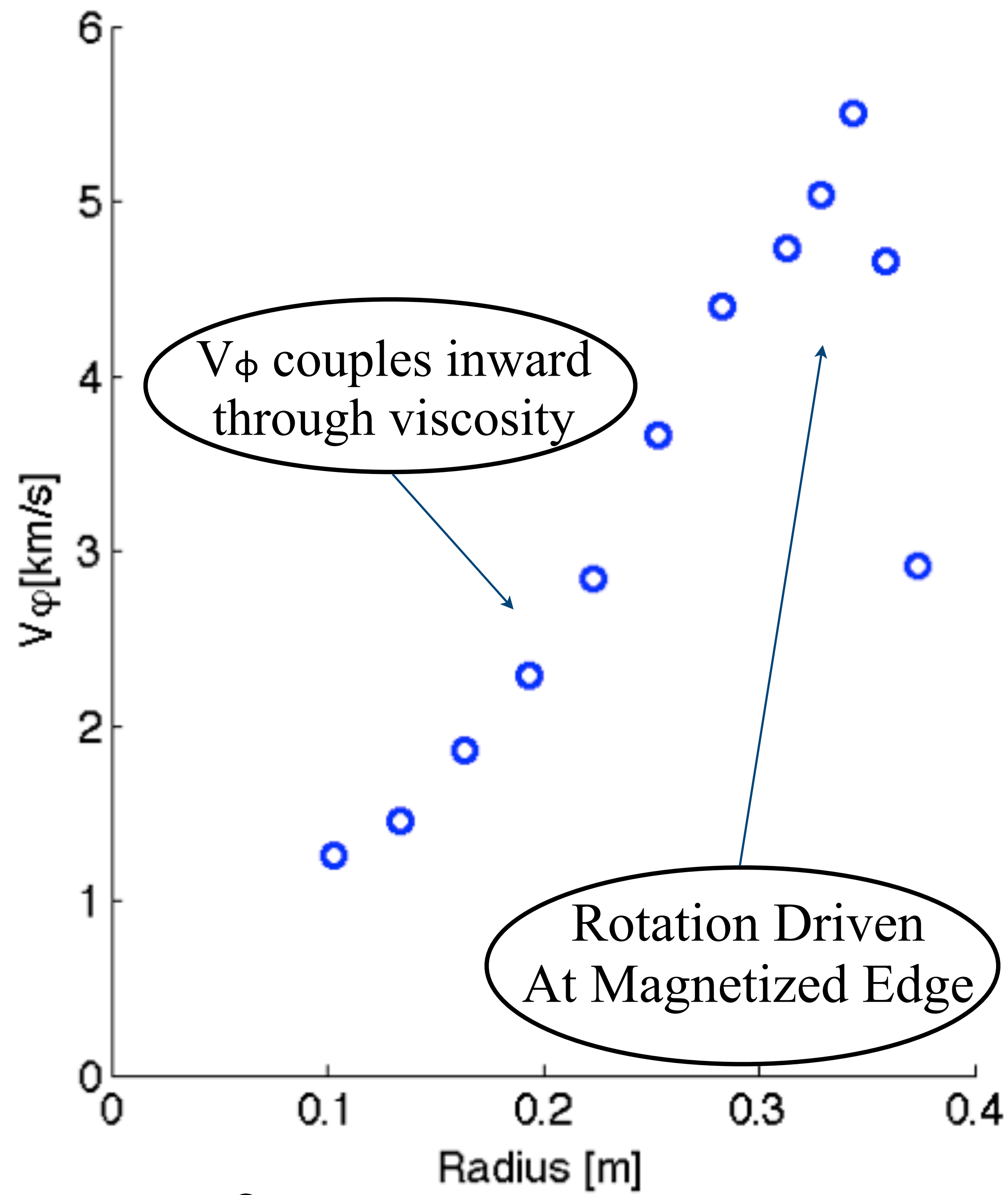




- Toroidally localized cathodes and anodes are differentially biased to create JxB torque
- Velocity couples inward to the unmagnetized region through viscosity
- Rotation (measured with Mach probe) is axisymmetric

High speed flows in unmagnetized core!

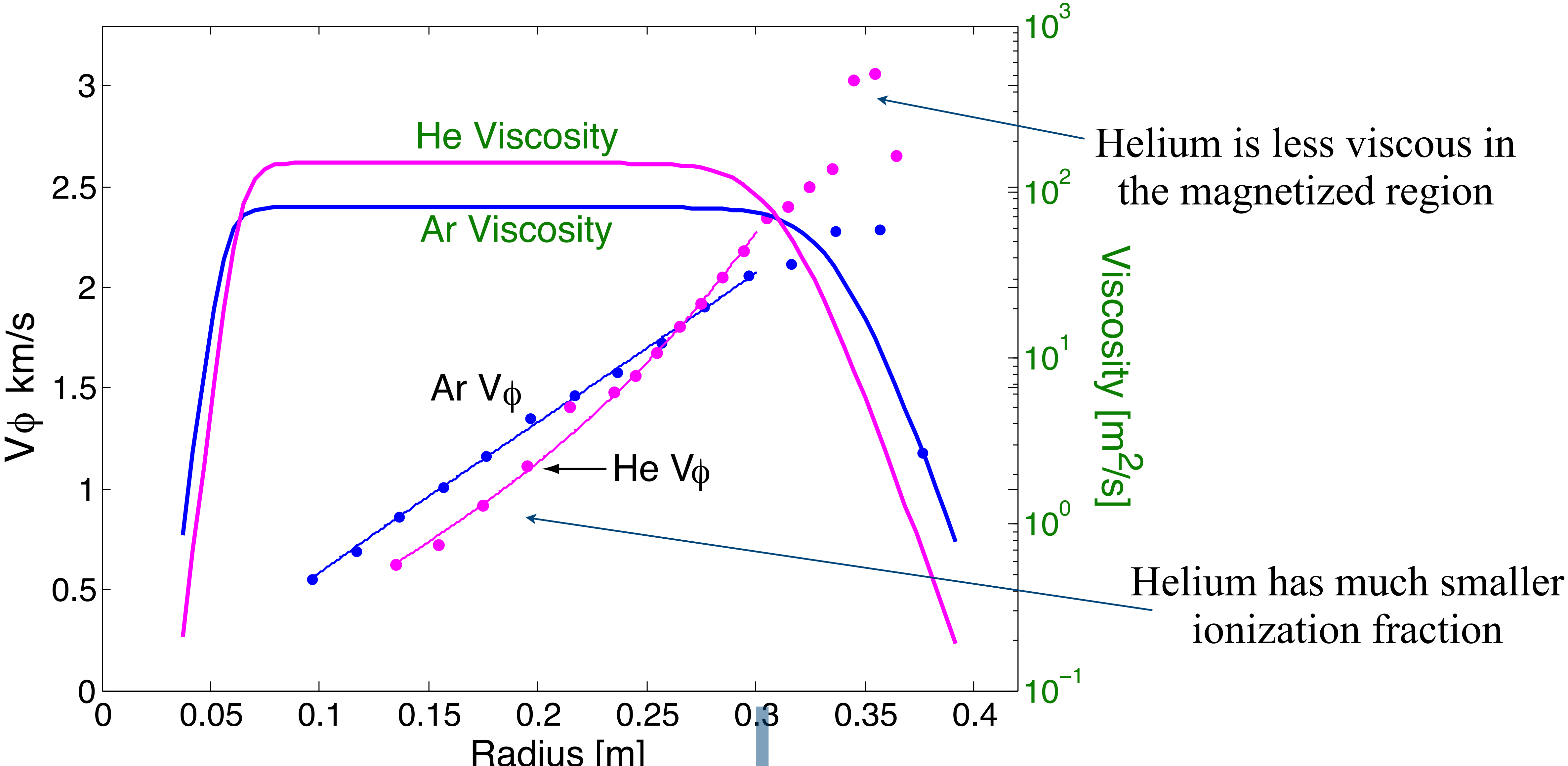




$Pm \sim 10 \quad Rm \sim 50$

Plasma Viscosity Depends on Magnetization

Case	n x 10^{11} (cm^{-3})	f_{ion} %	Te (eV)	Ti_{fit} (eV)	V_{max} (km/s)	Rm	Re	Pm
Ar400VT2	.77	27	7	0.6	2.2	11	8	1.3
He400VT1	.45	0.6	11	0.4	2.4	22	5	4.5



$$\nu \sim \frac{\lambda_{ii}^2}{\tau_i} \propto \frac{T_i^{5/2}}{n\sqrt{\mu}}$$

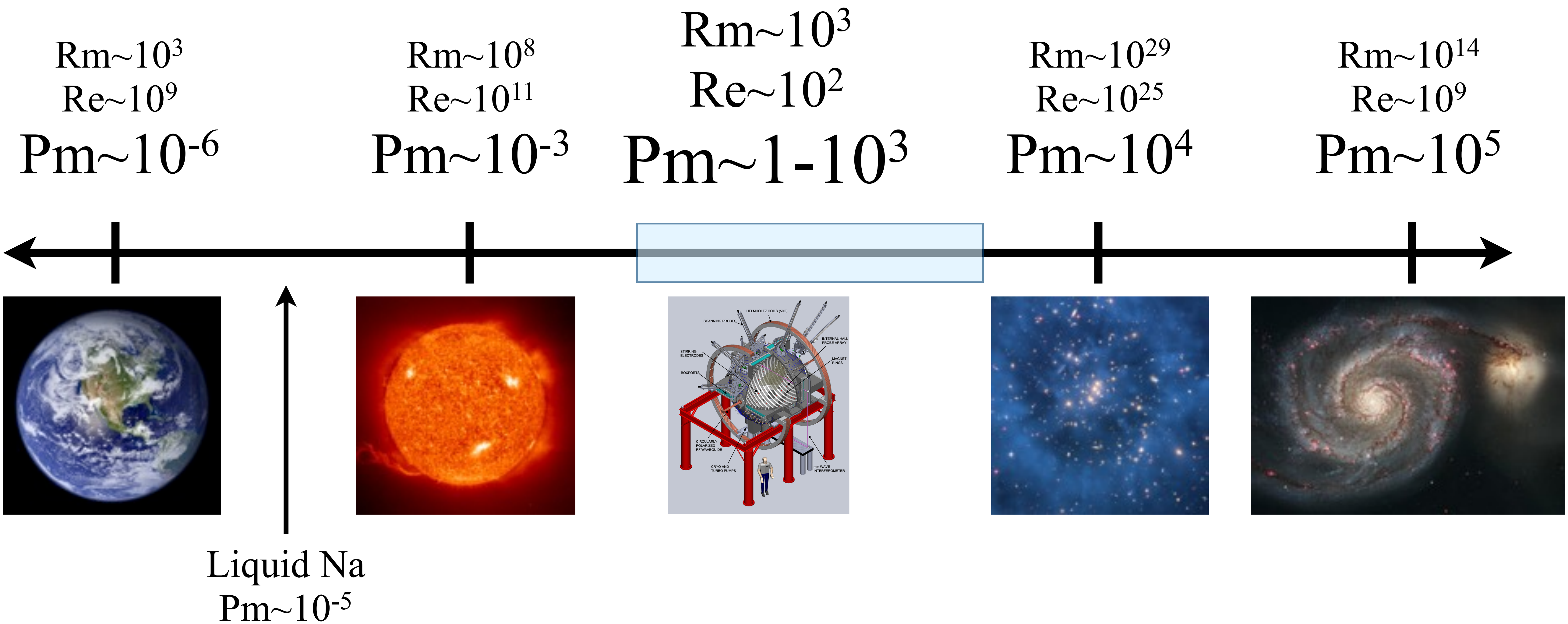
$$\nu \sim \frac{\rho_i^2}{\tau_i} \propto \frac{n\sqrt{\mu}}{B^2\sqrt{T_i}}$$

Next Step: Plasma Dynamo Experiments

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

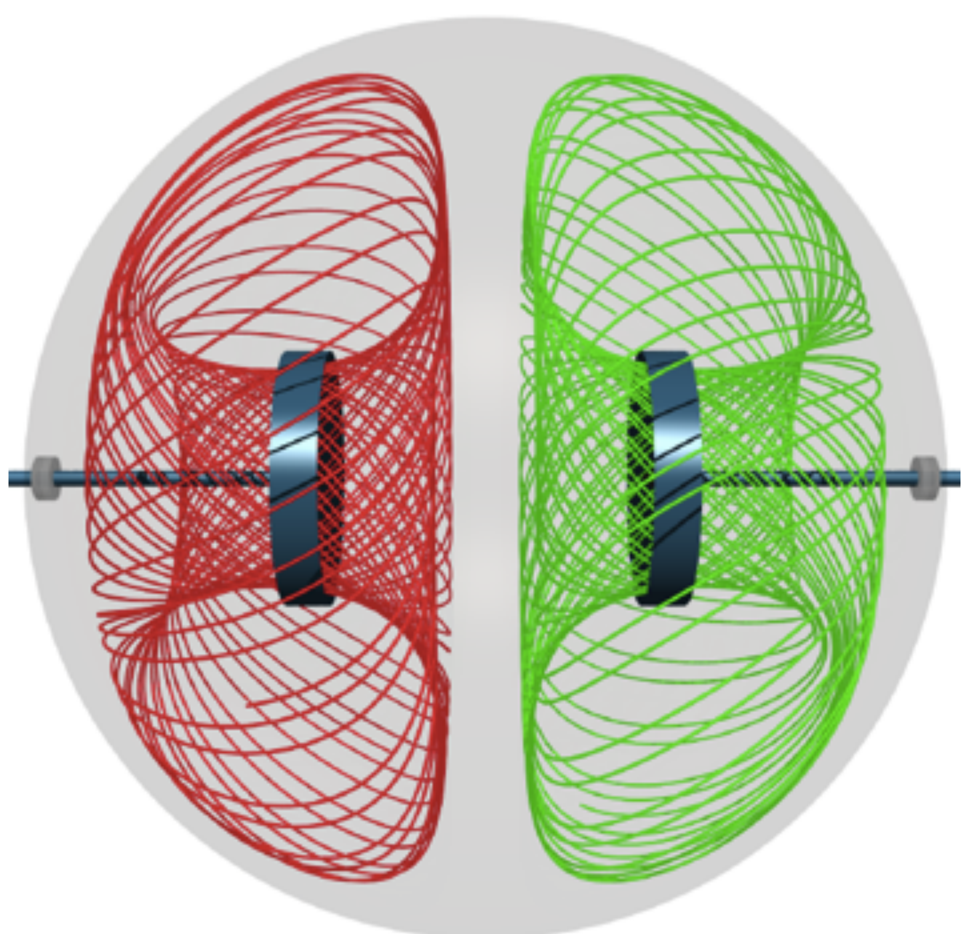
→Study confinement and stirring in an unmagnetized plasma

Why Plasma Dynamos? complements LM experments, computationally accessible

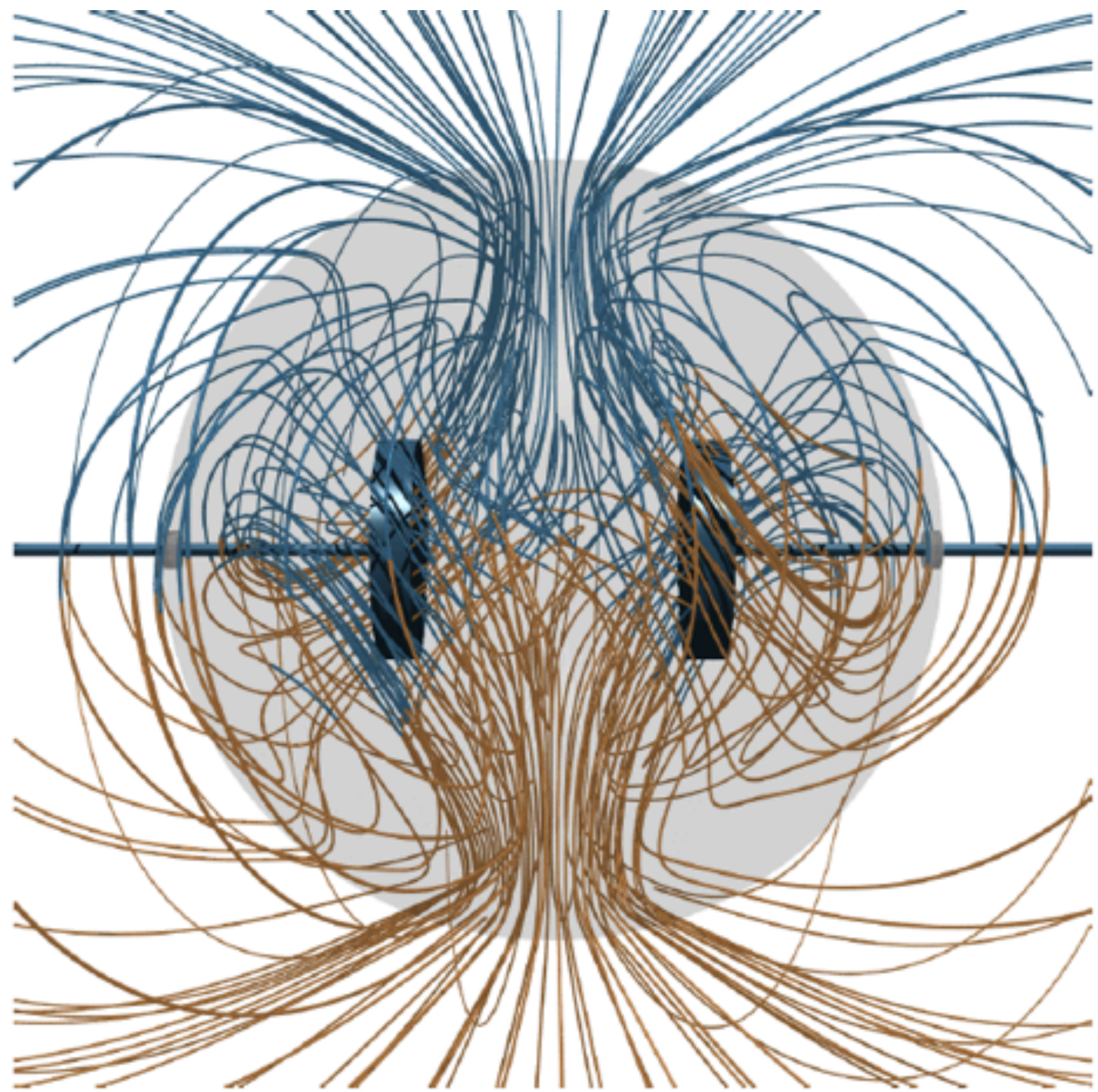


Two vortex dynamo
(minimum speed set by Rm > 50)

Flow

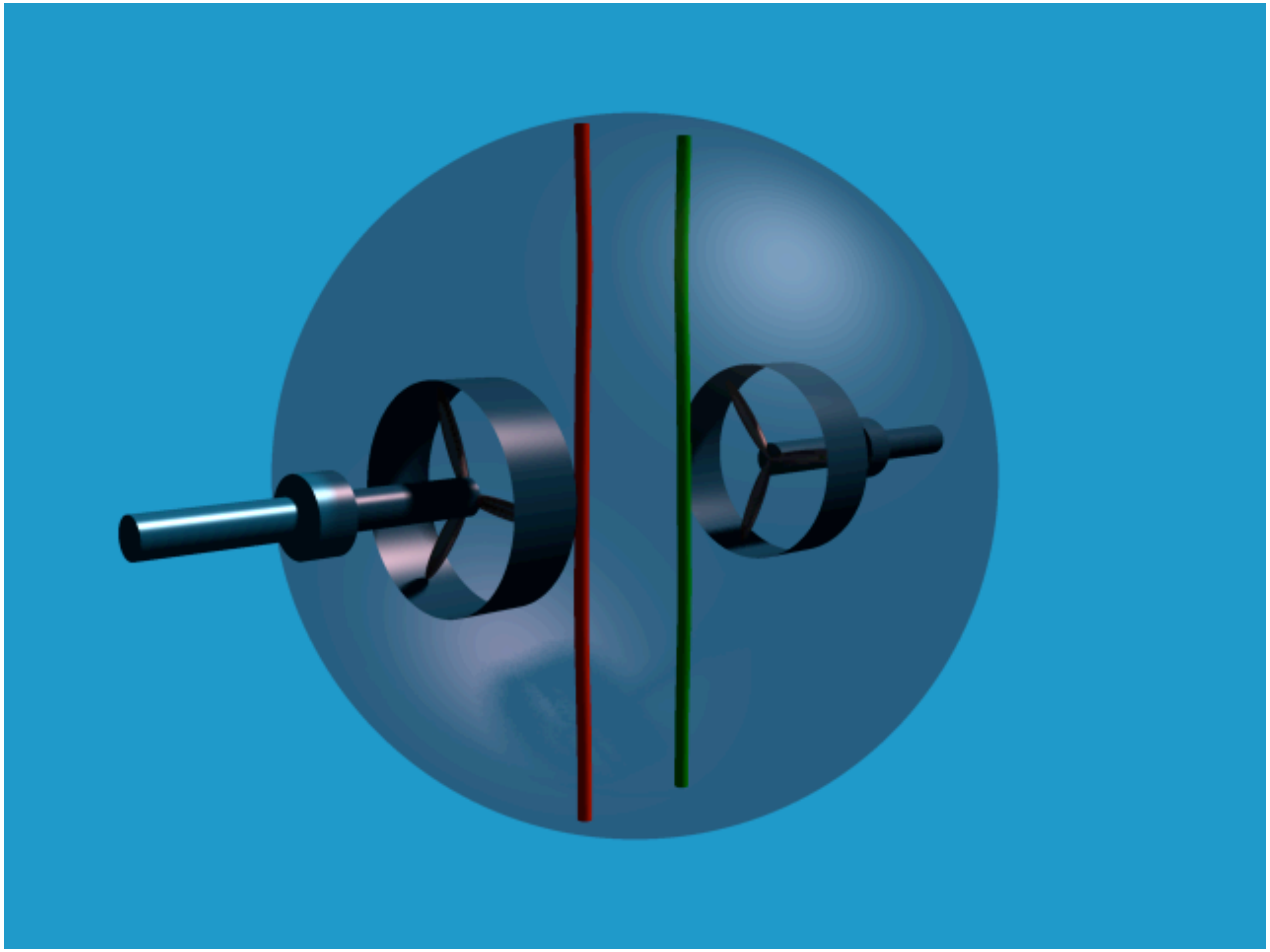


Magnetic Field

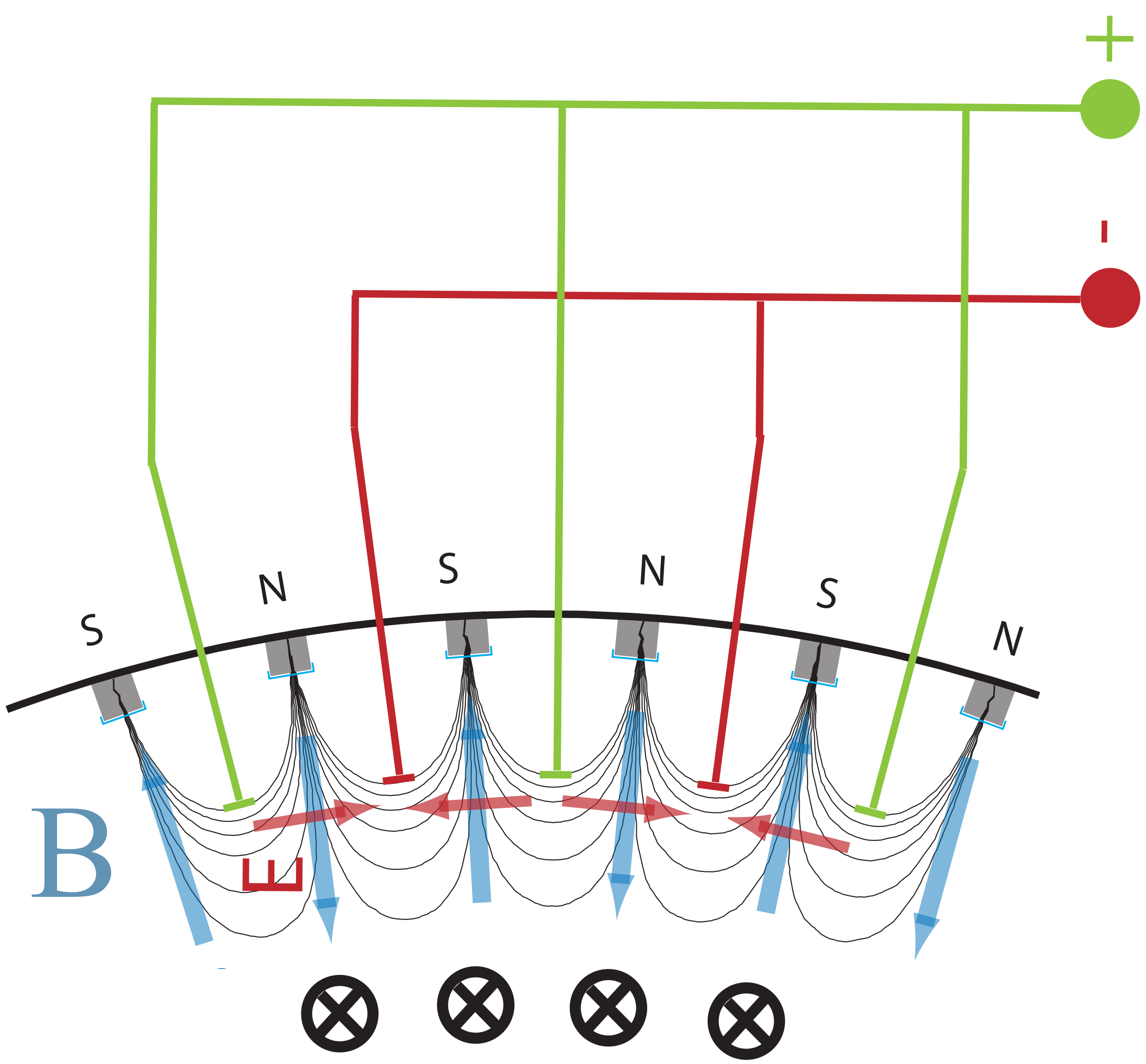


For sodium: $Rm = 12\ a_{[m]}\ V_{[m/s]}$

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

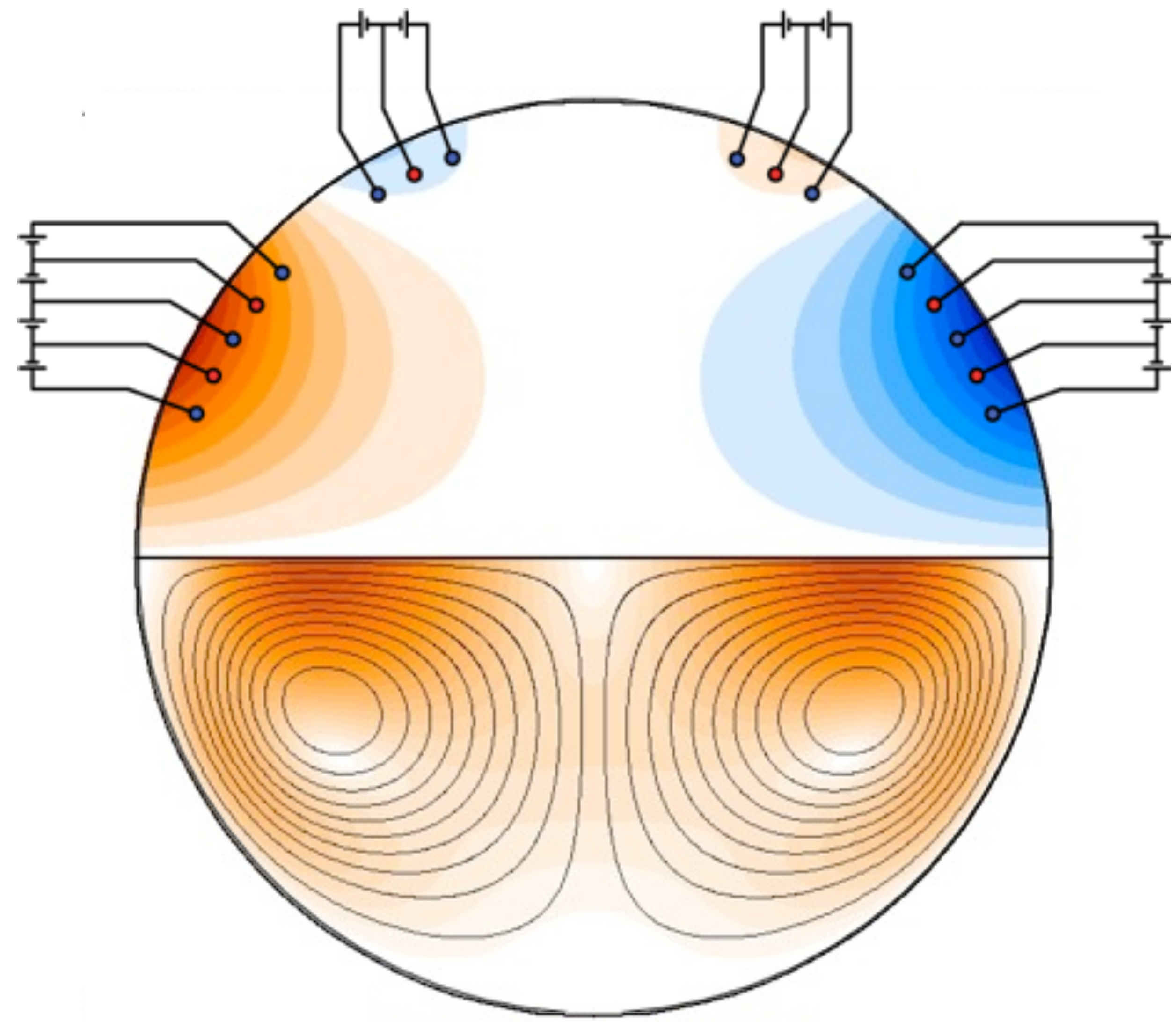


Electrostatic biasing controls edge rotation

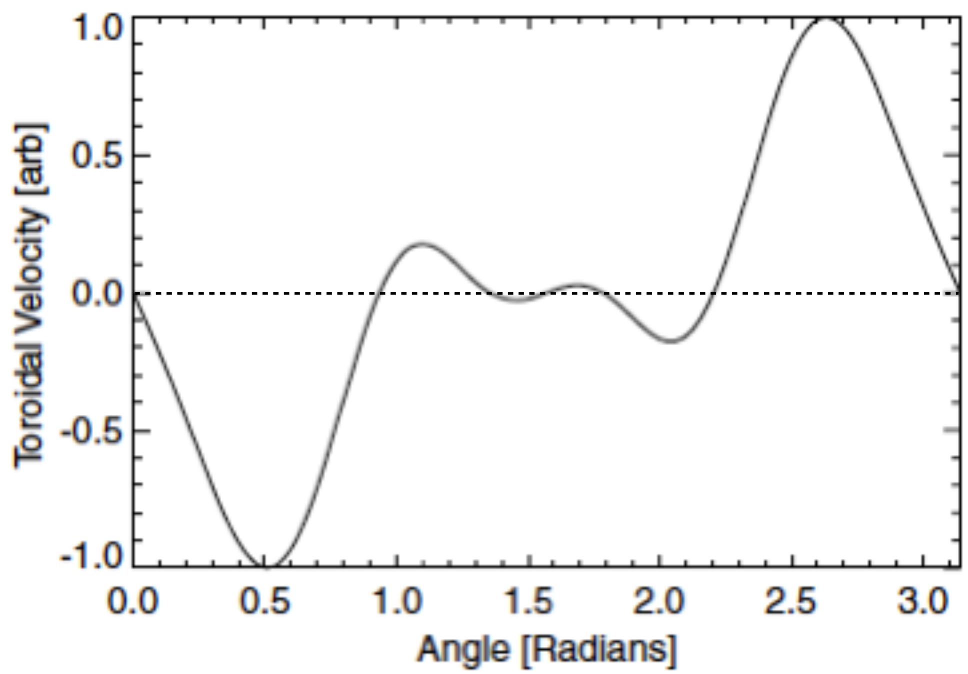


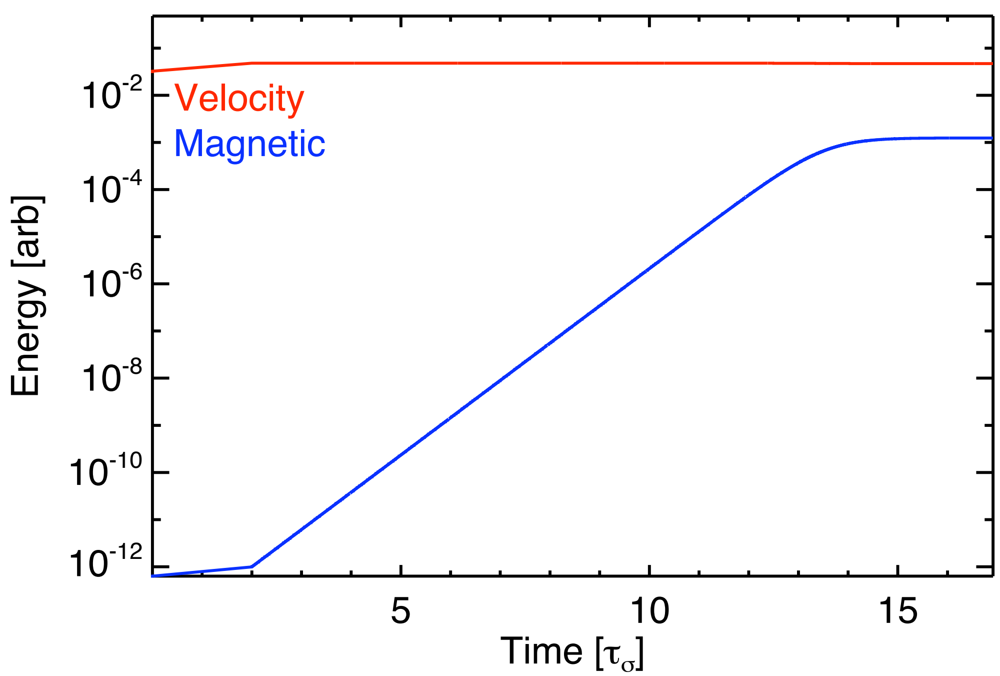
Arbitrary

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

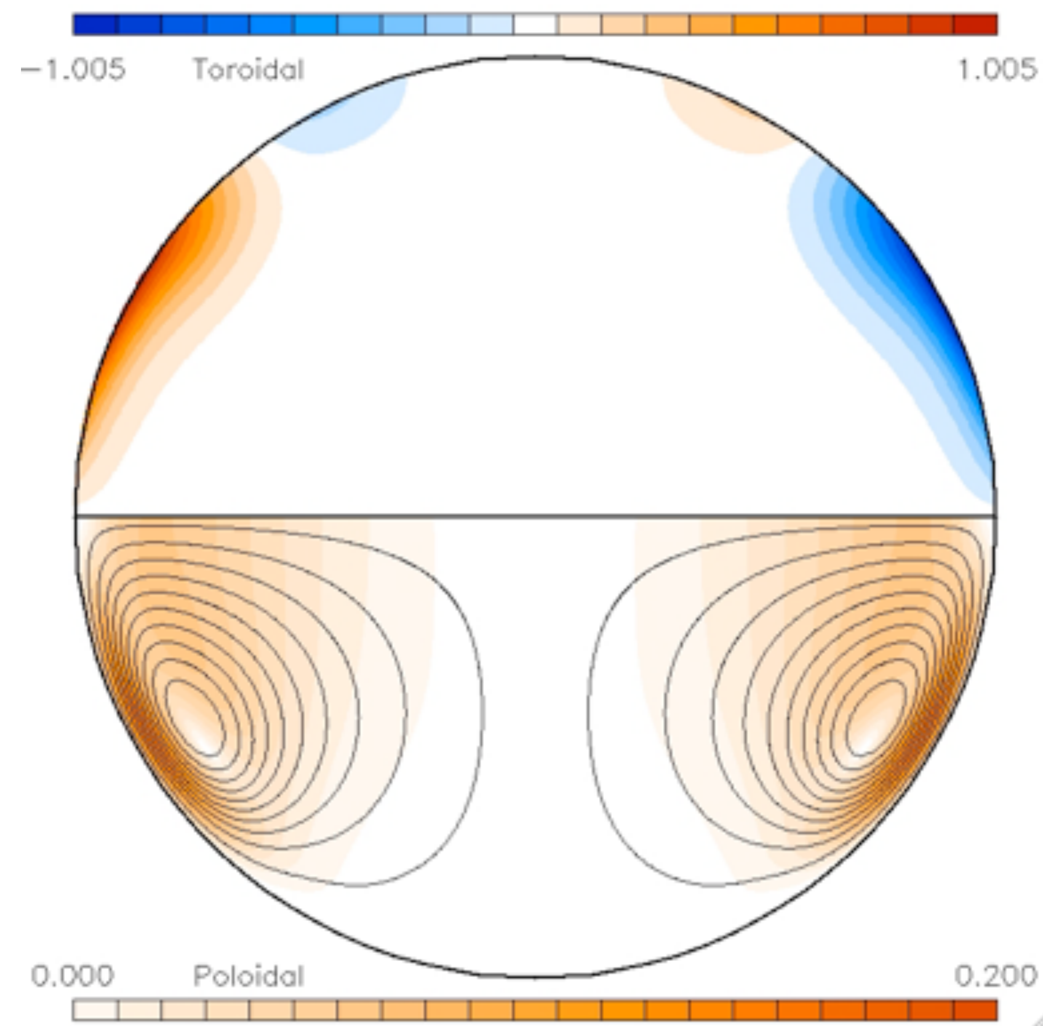


MHD Computation predicts laminar plasma dynamo





Rm=300, Re=100



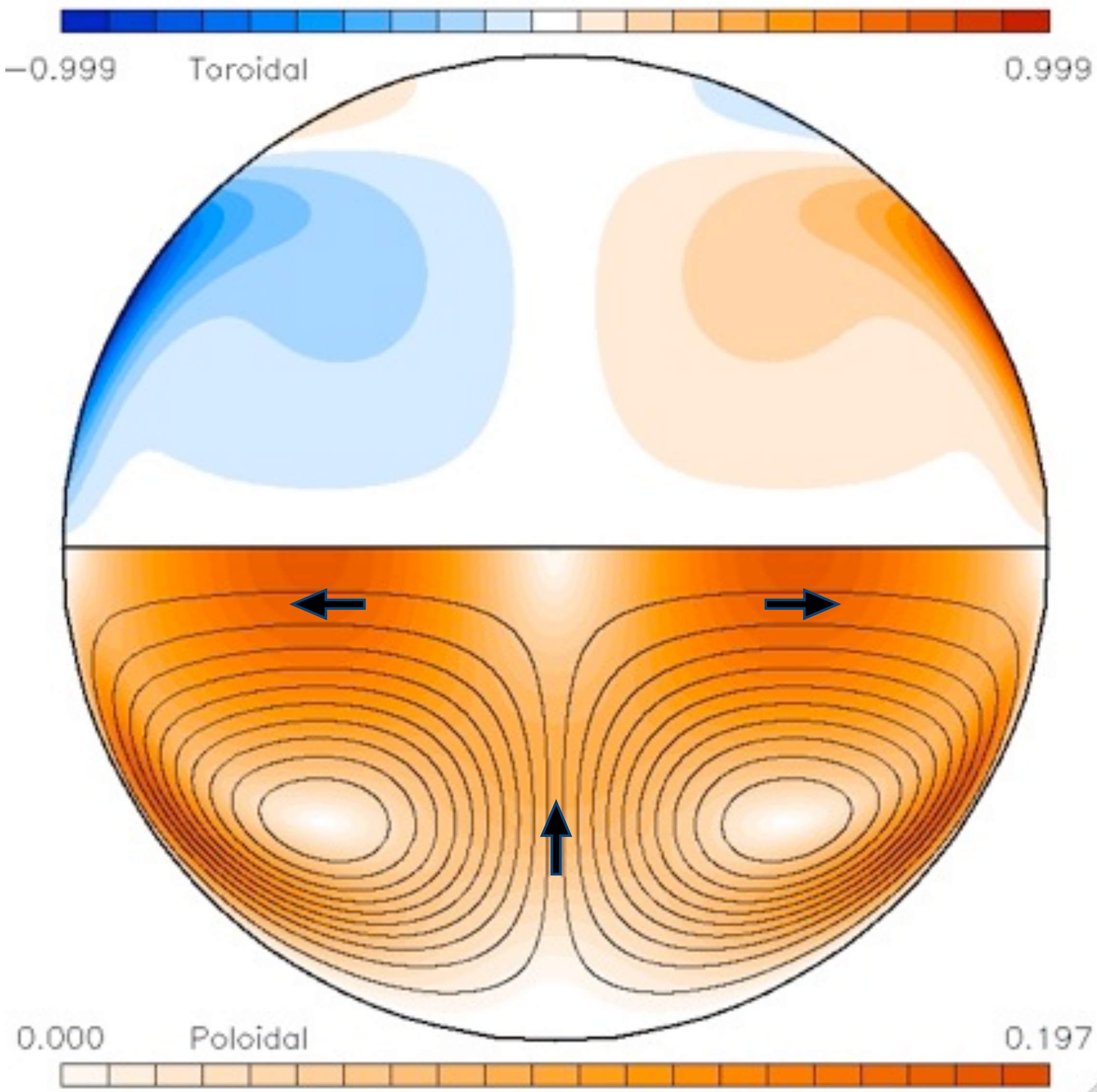
Te = 9 eV, n = 8 x10^{17} m^{-3}

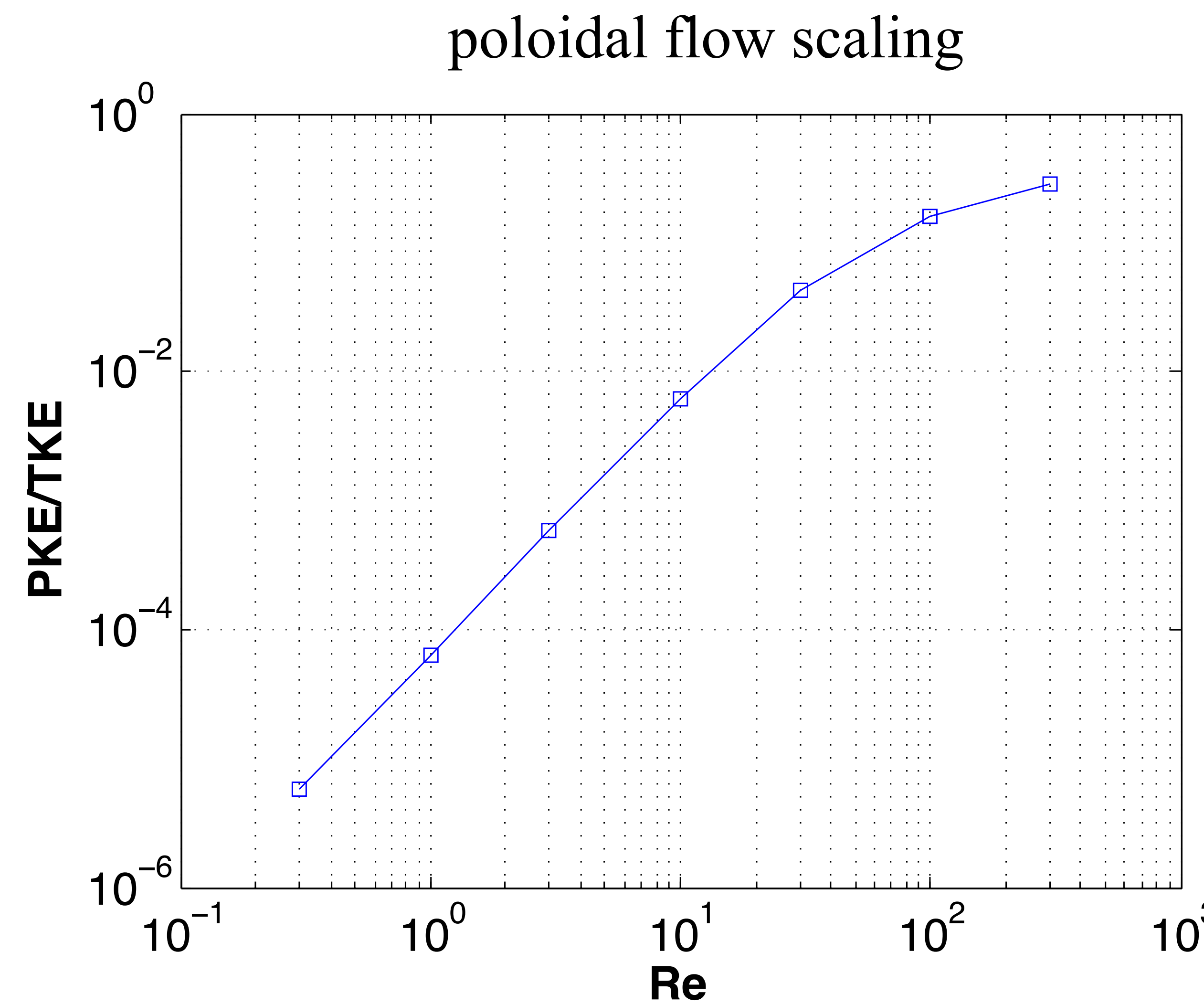
U_{max} = 5 km/s, Helium

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

Hydrodynamics: toroidal forcing drives poloidal flow

Rm=300, Re=300

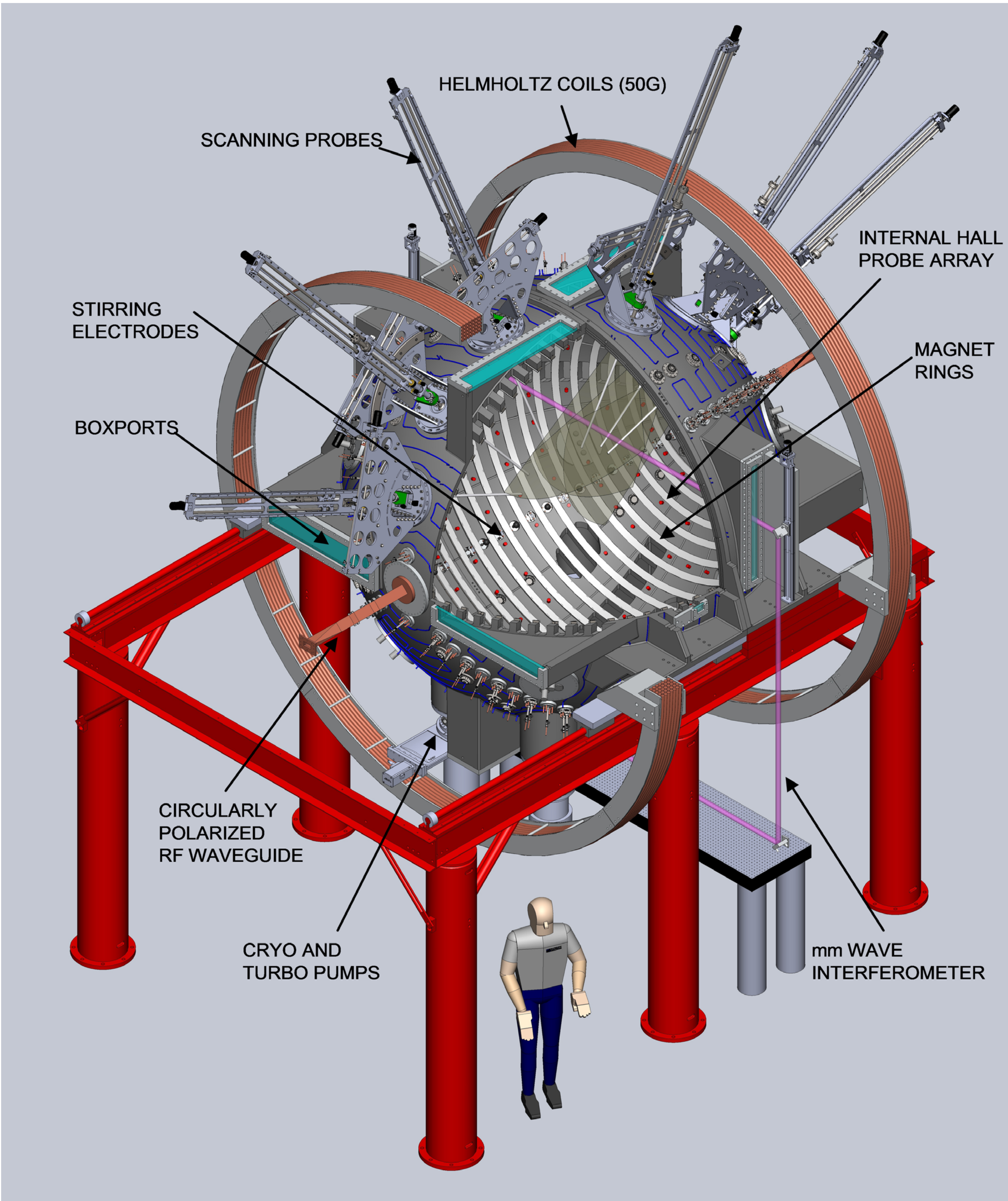


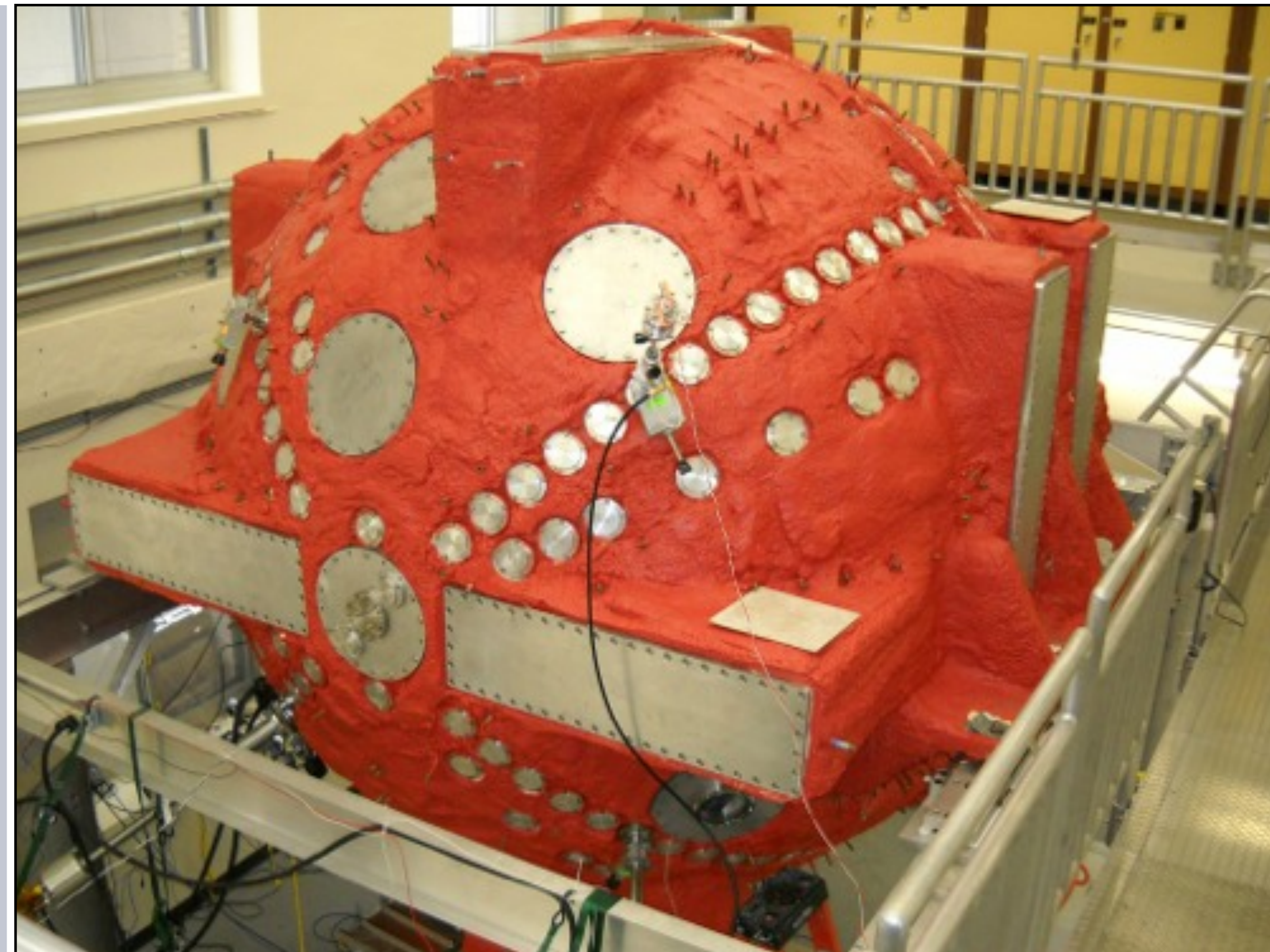


Te = 9 eV, n = 2.5 $\times 10^{18}$ m^{-3}

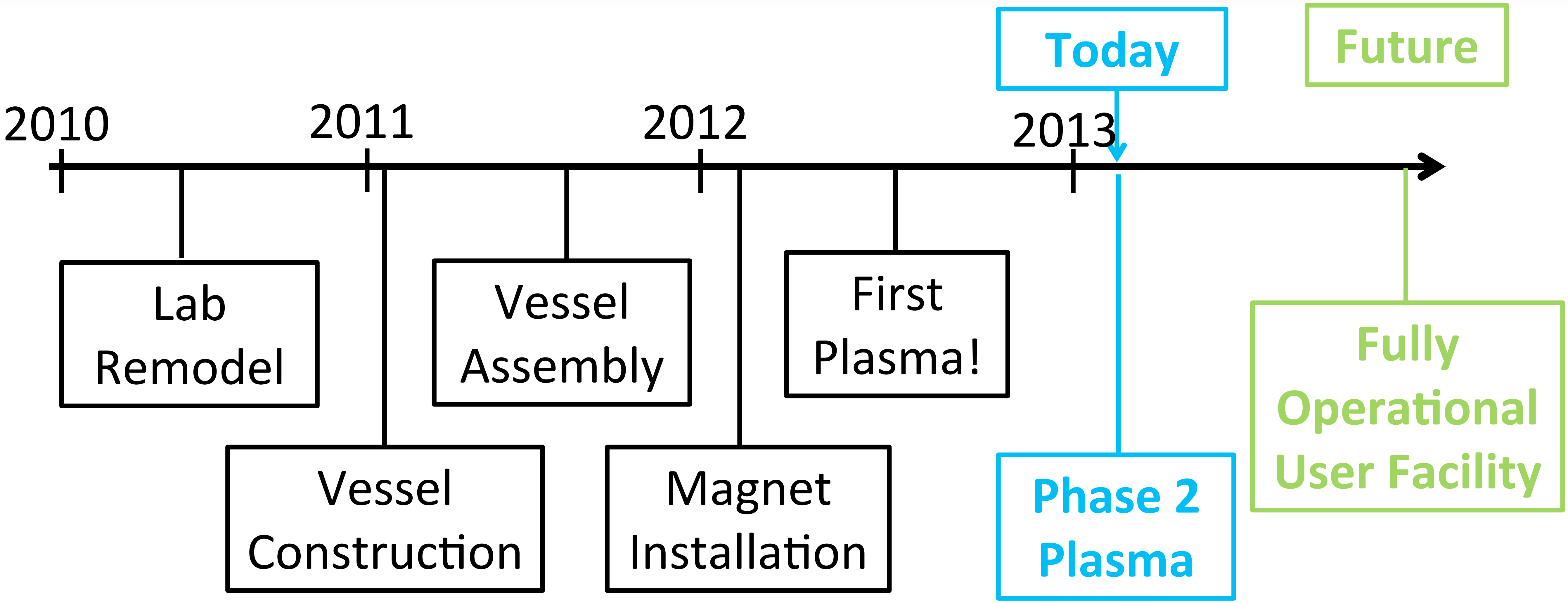
U_{max} = 5 km/s, Helium

The Plasma Dynamo Experiment

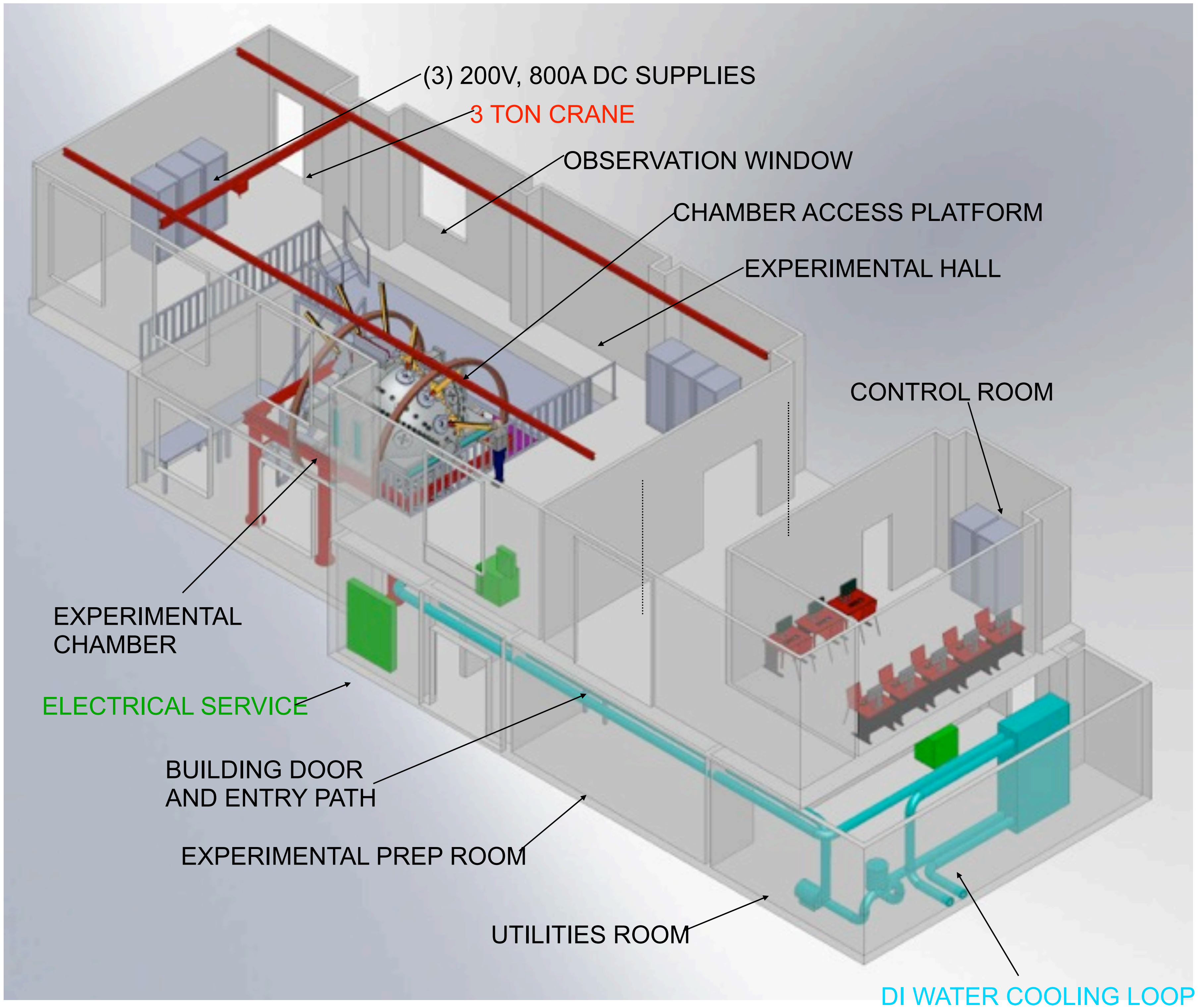




MPDX Timeline



MPDX Facility

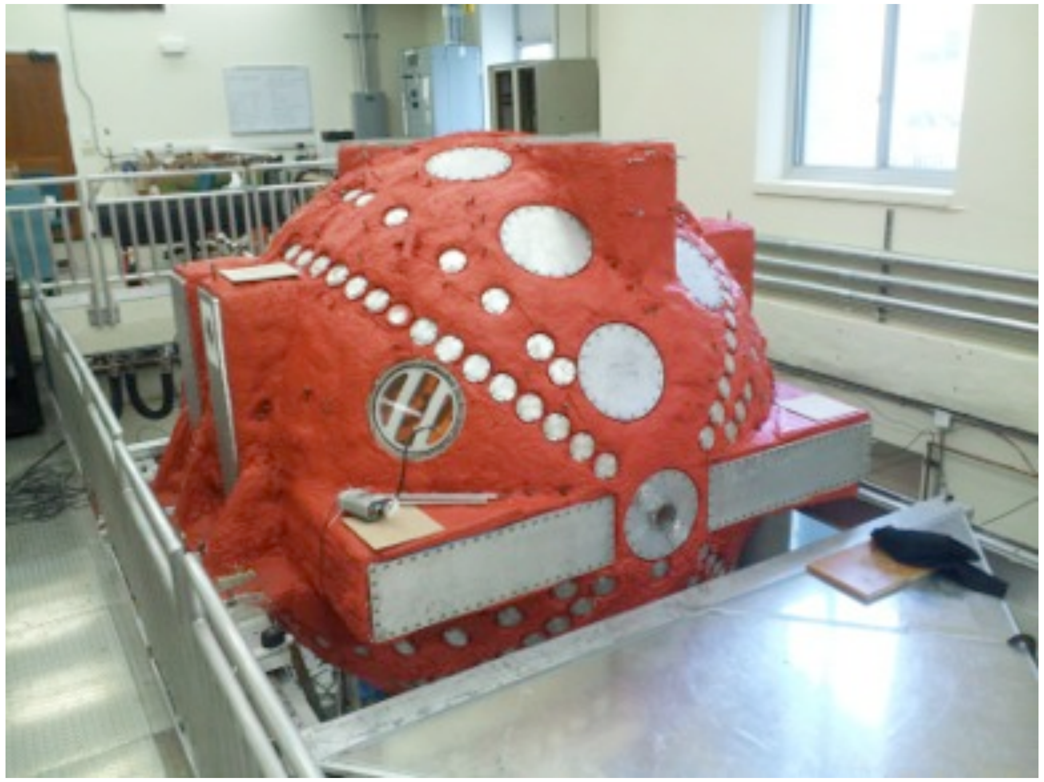


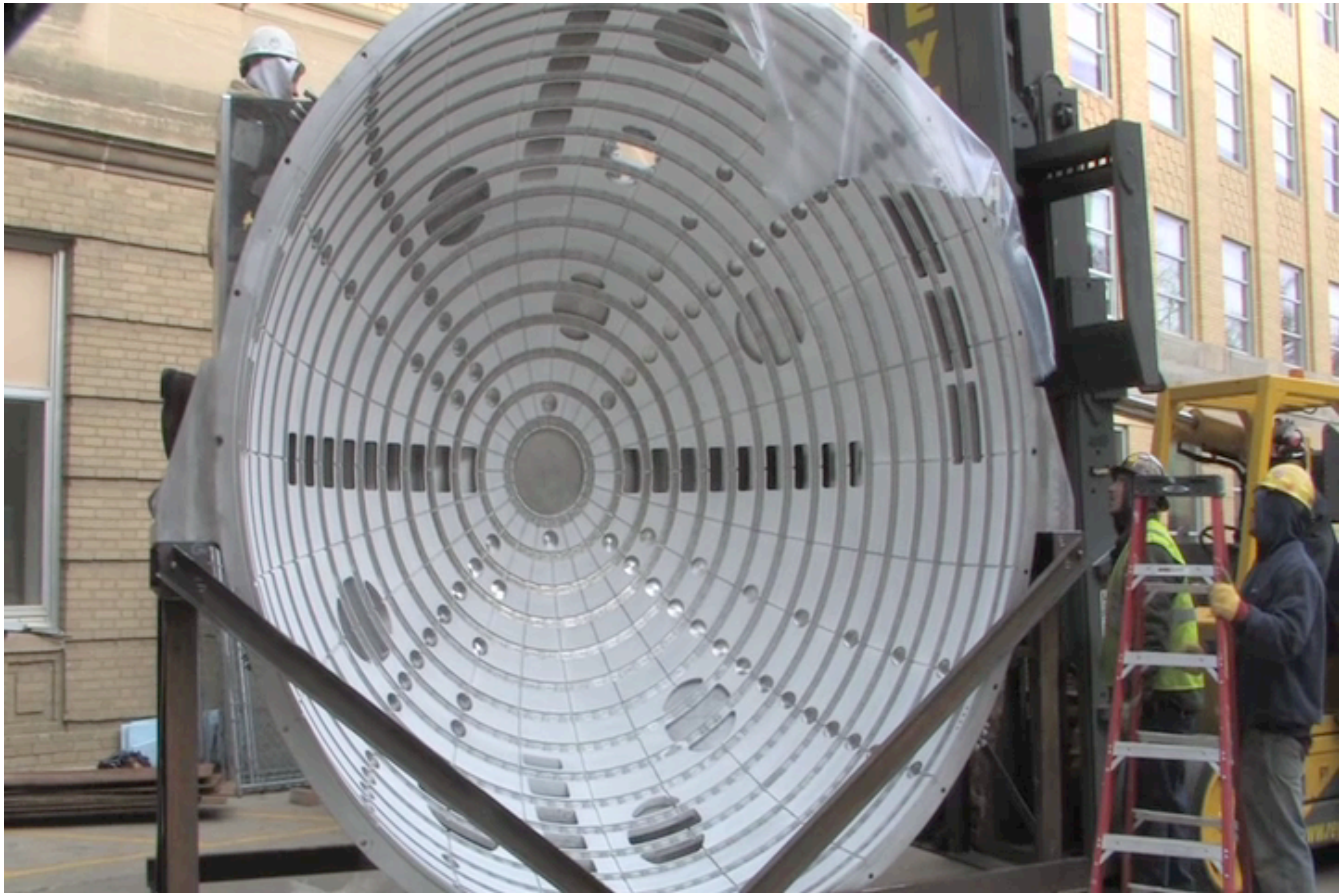
Remote operation from control room

steady-state operation possible with installed cooling

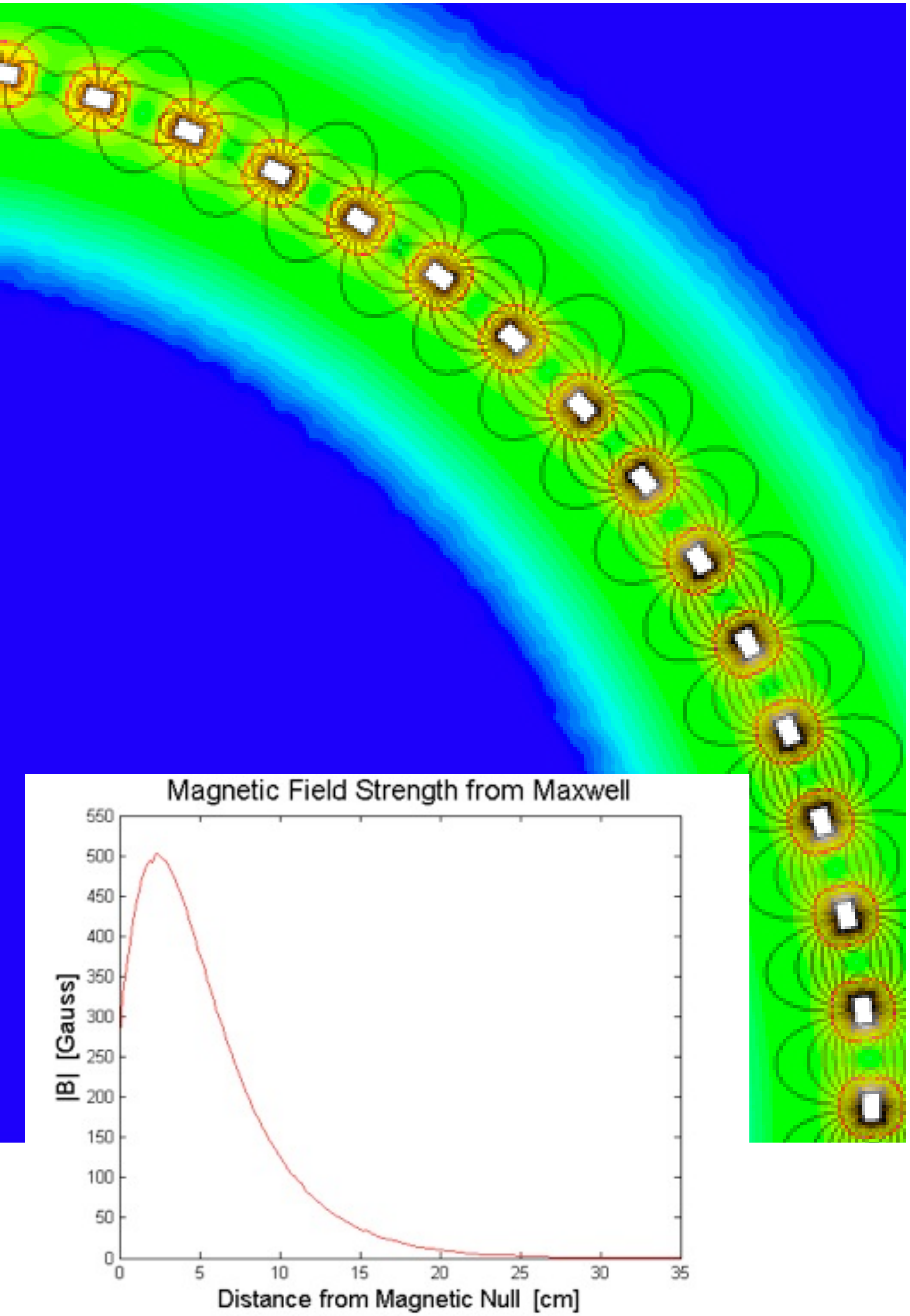
Vessel Construction

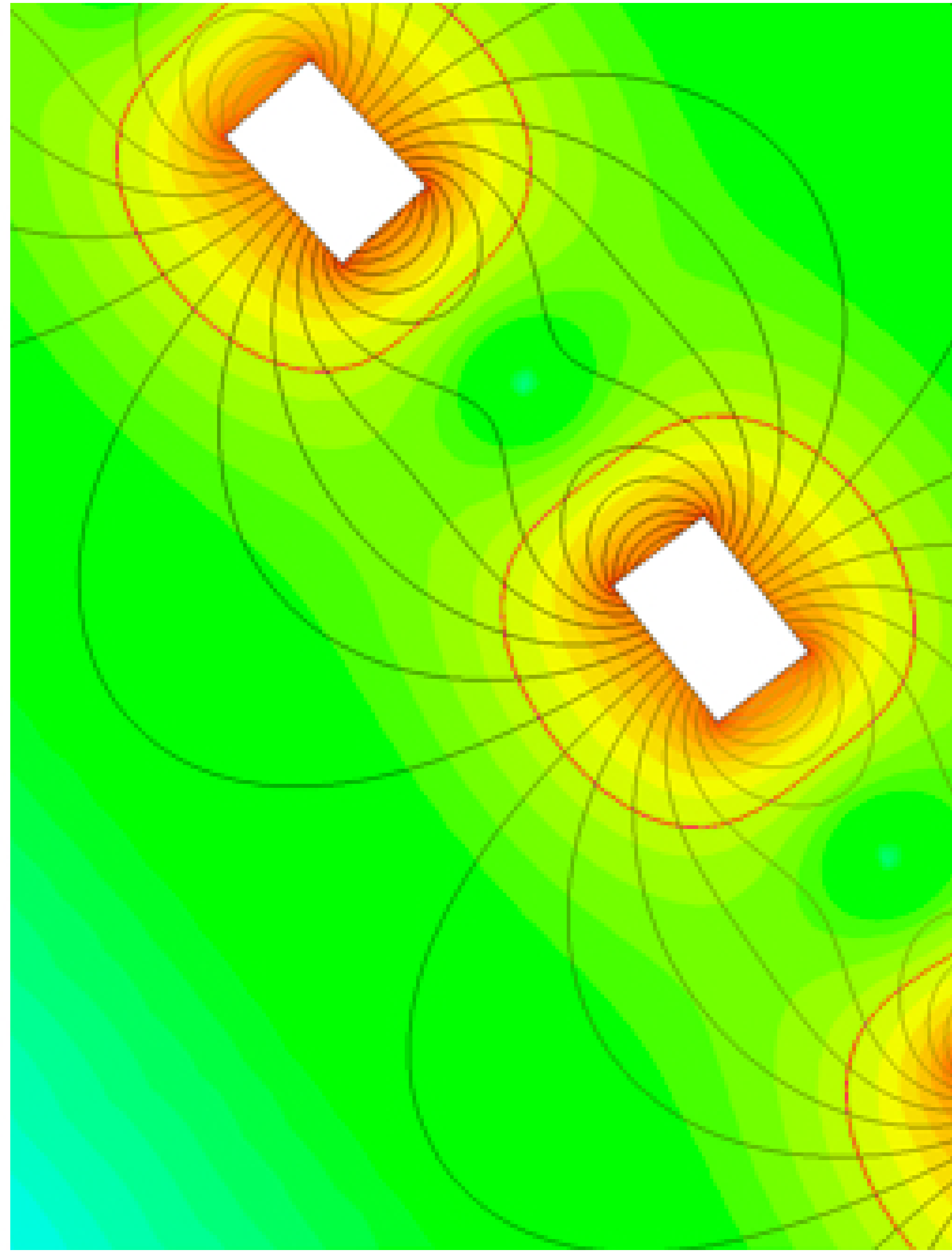


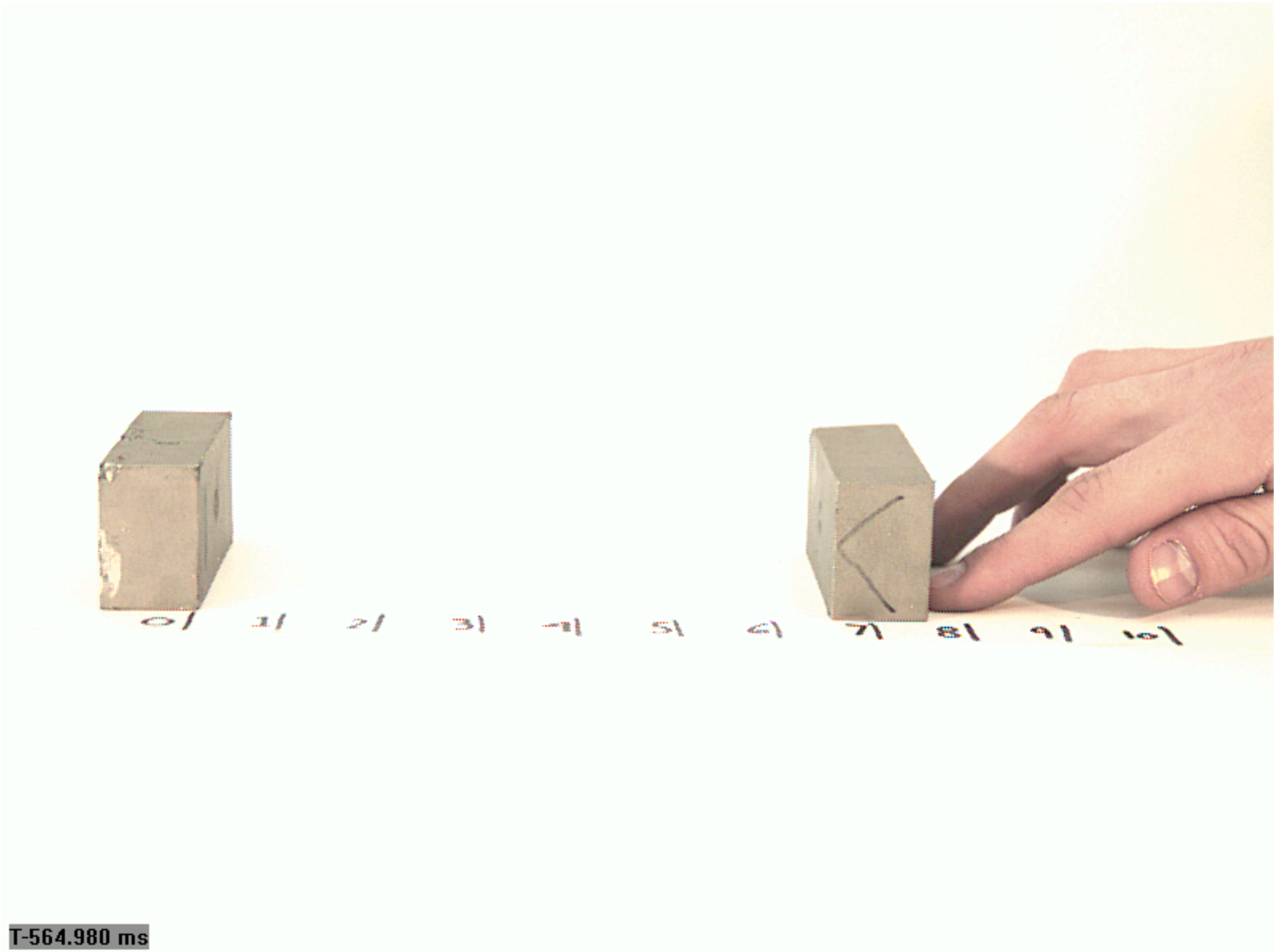





3000 4 kG SmCo magnets installed MPDX


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

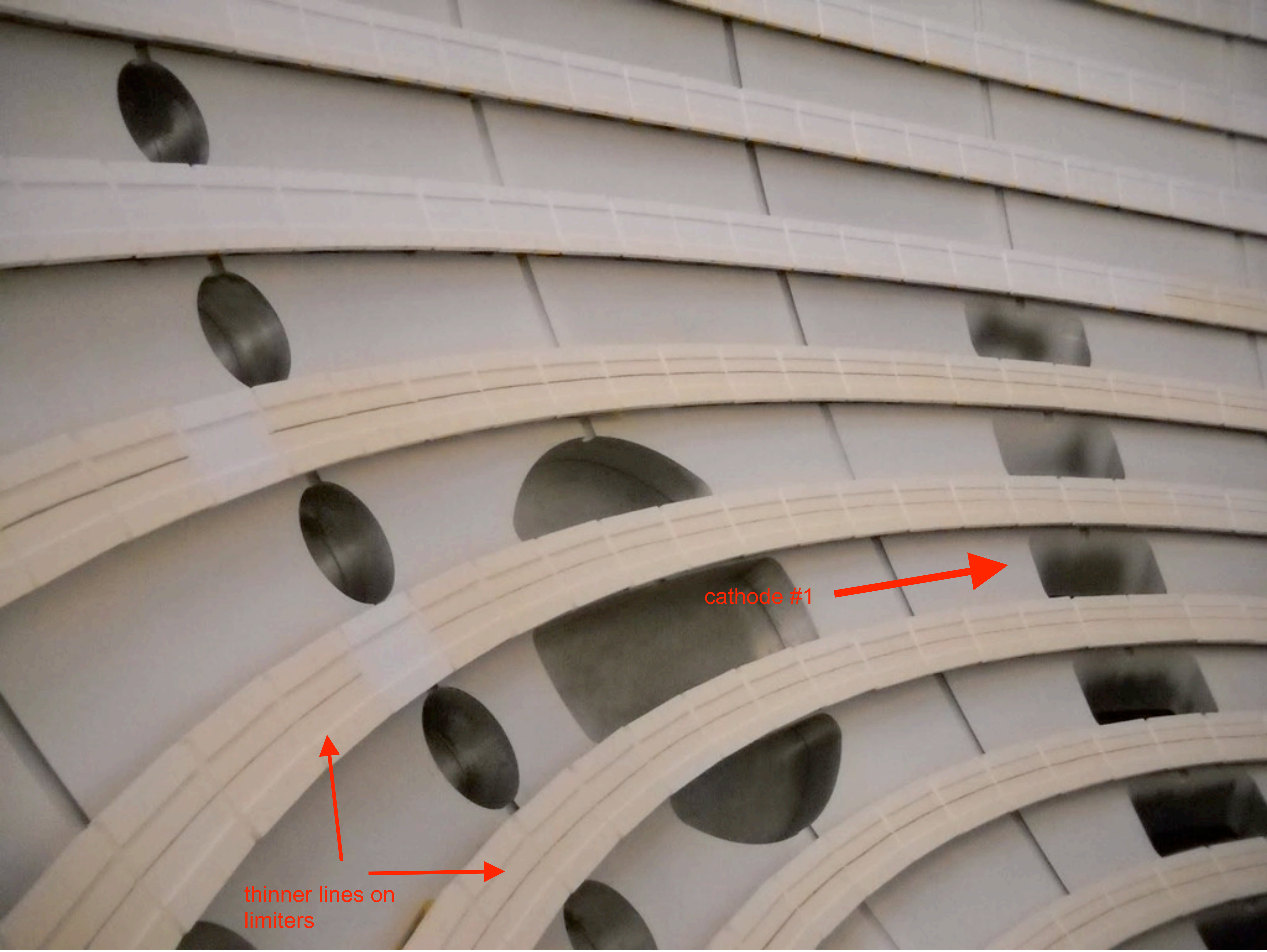




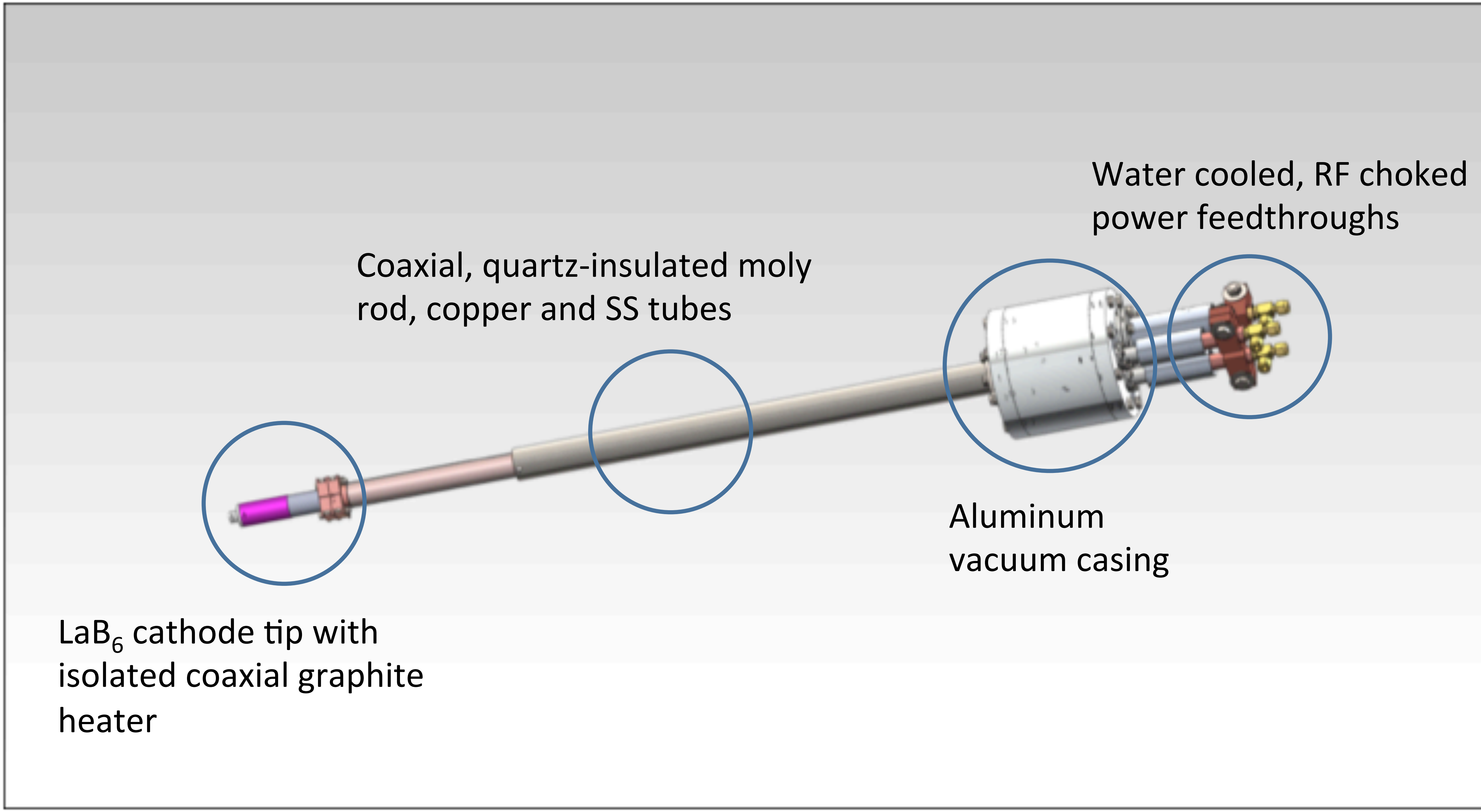
0
1
2
3
4
5
6
7
8
9
10
T-564.980 ms

Magnet Installation in MPDX

Lever designed by John Wallace

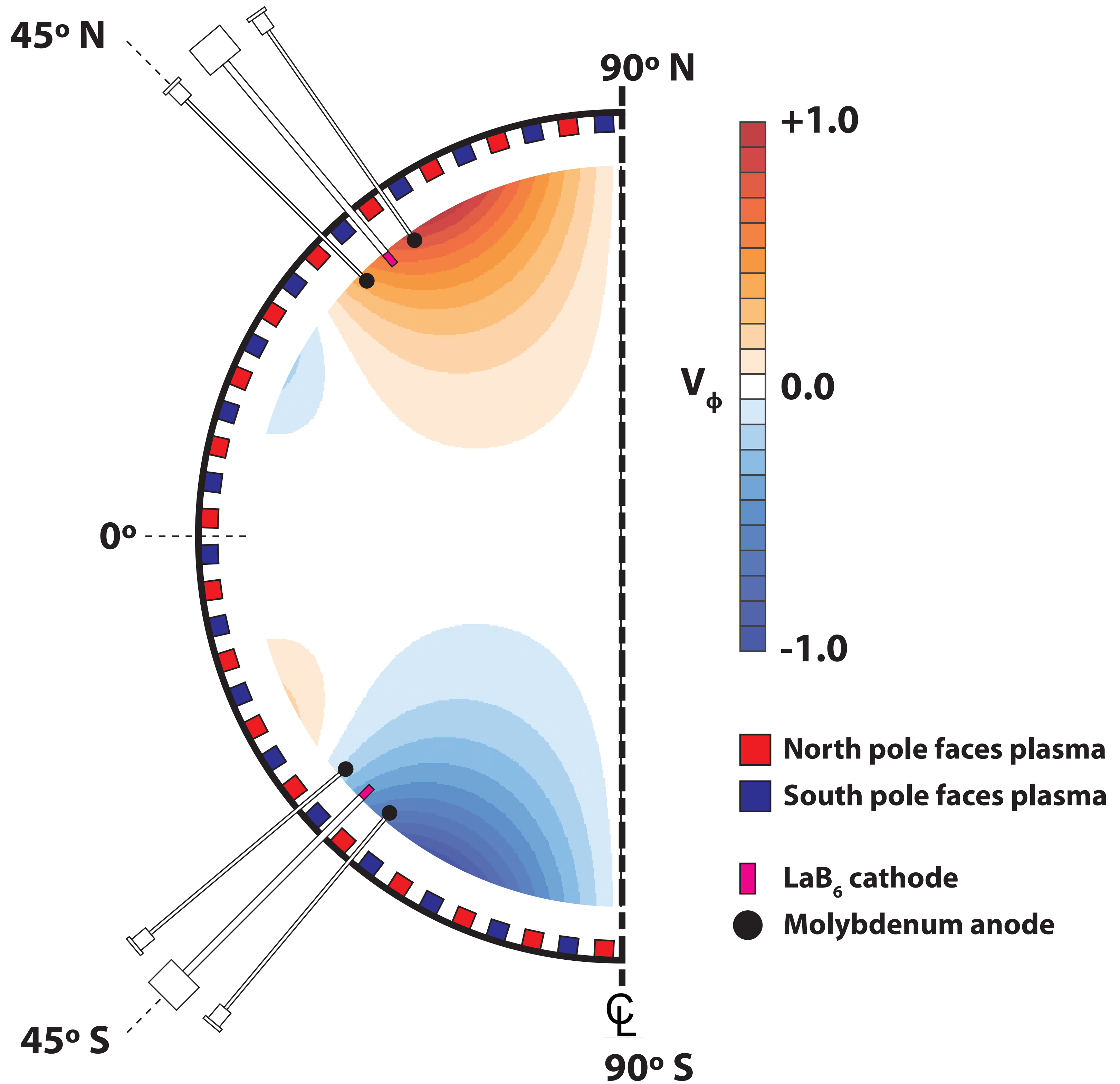

cathode #1
thinner lines on limiters

Hot LaB6 cathodes for heating and stirring plasma

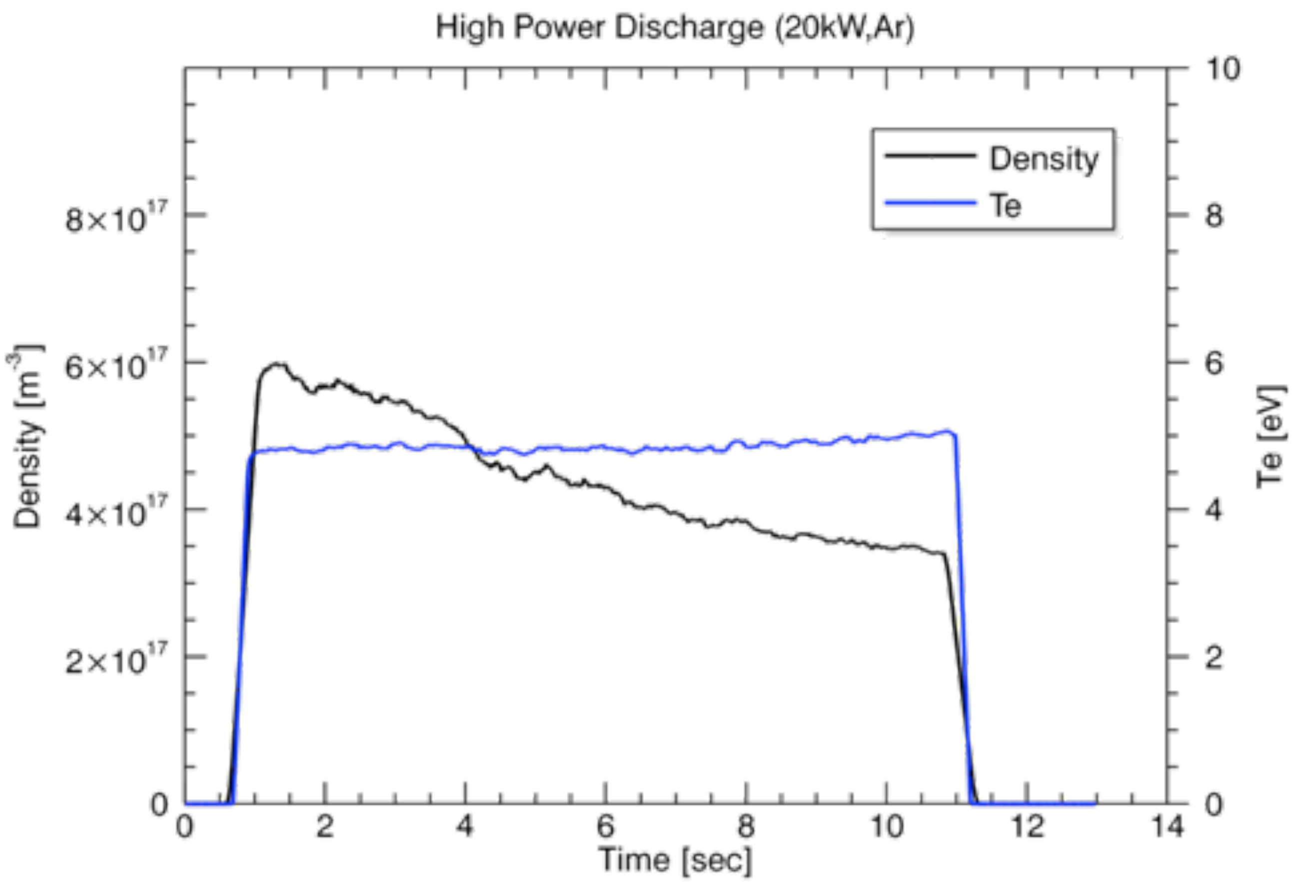


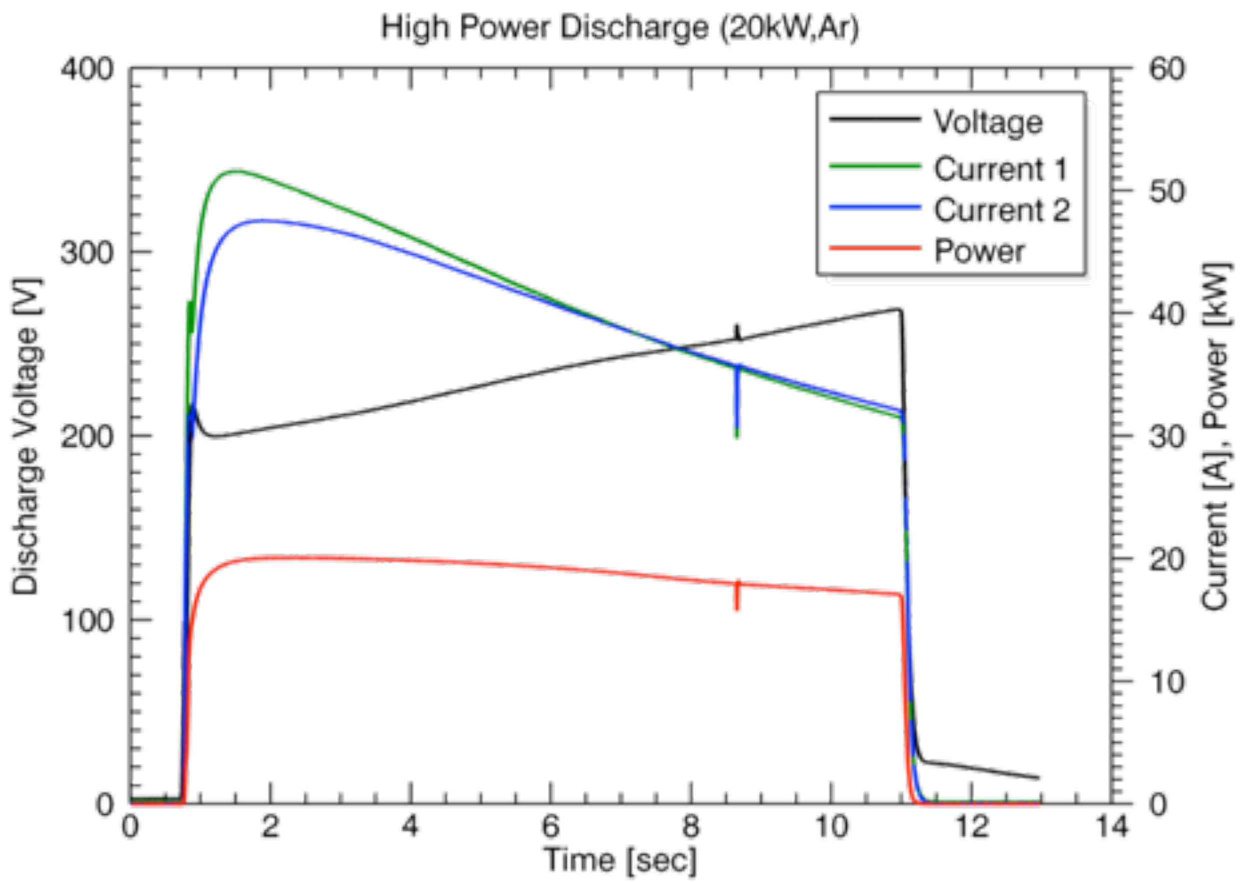
Two cathodes have been constructed

current setup

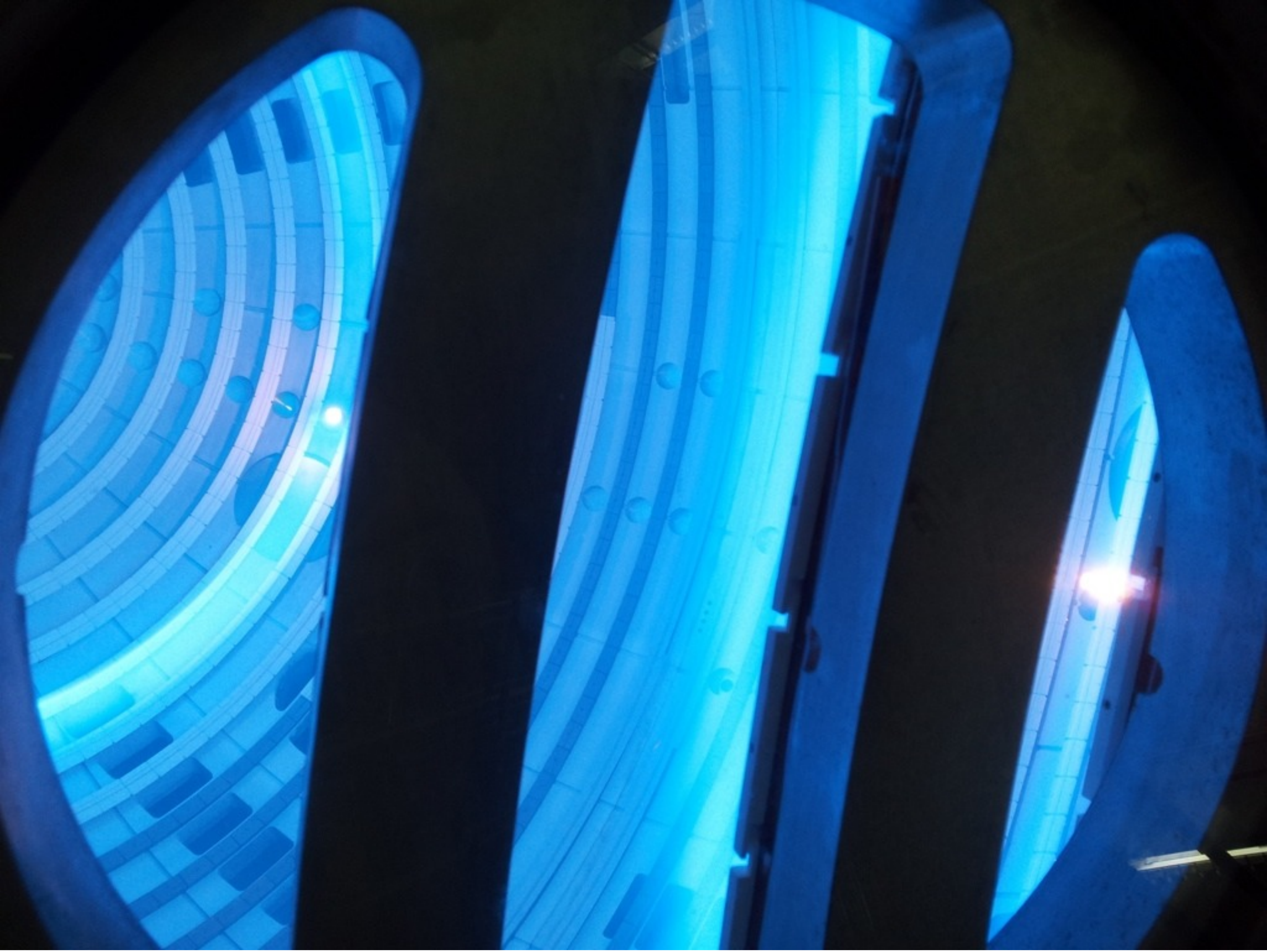


Even without microwave heating, LaB_6 stirring cathodes create hot, dense plasmas

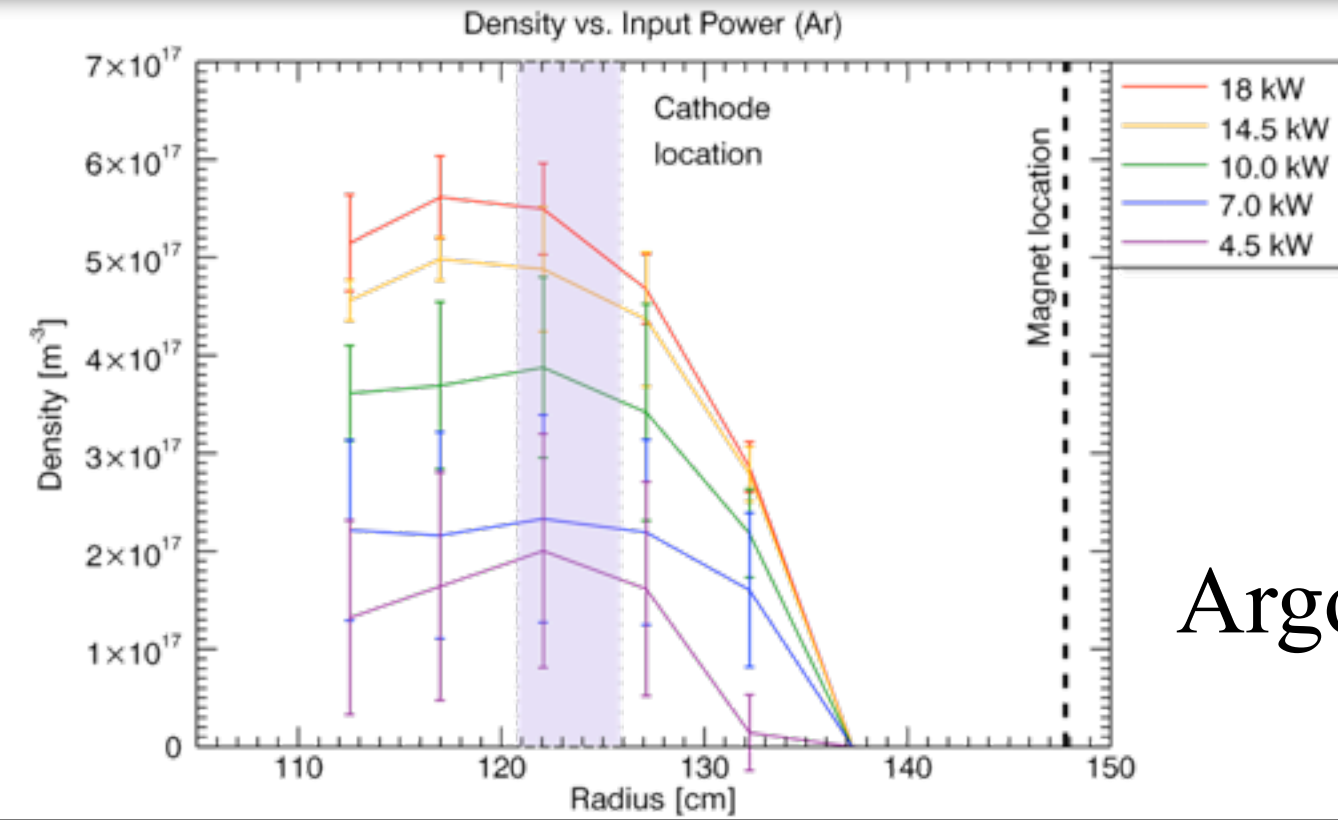


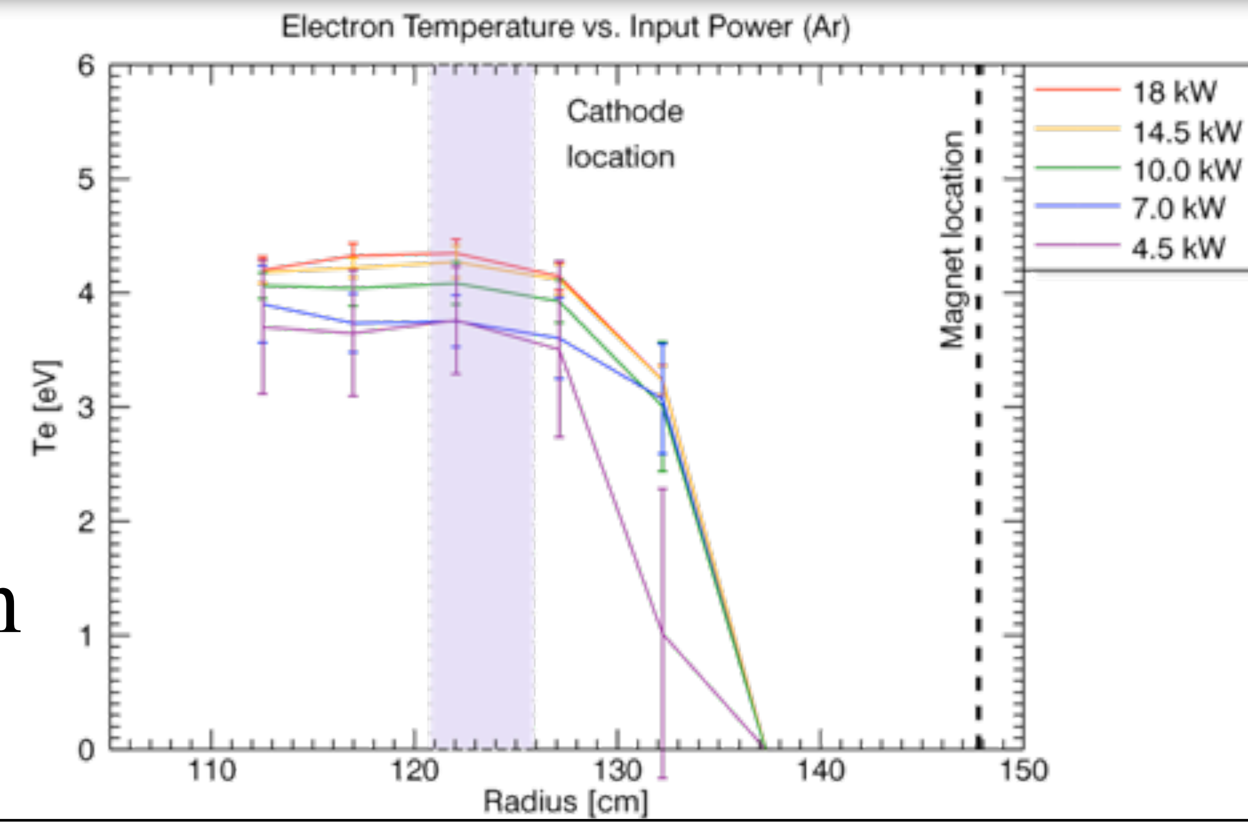


- Discharge powers of up to 20 kW result in $n_e = 5 \times 10^{17}\ m^{-3}$, Te = 5 eV plasmas.
- LaB_6 cathodes draw up to 50A each during each 10 second plasma discharge.

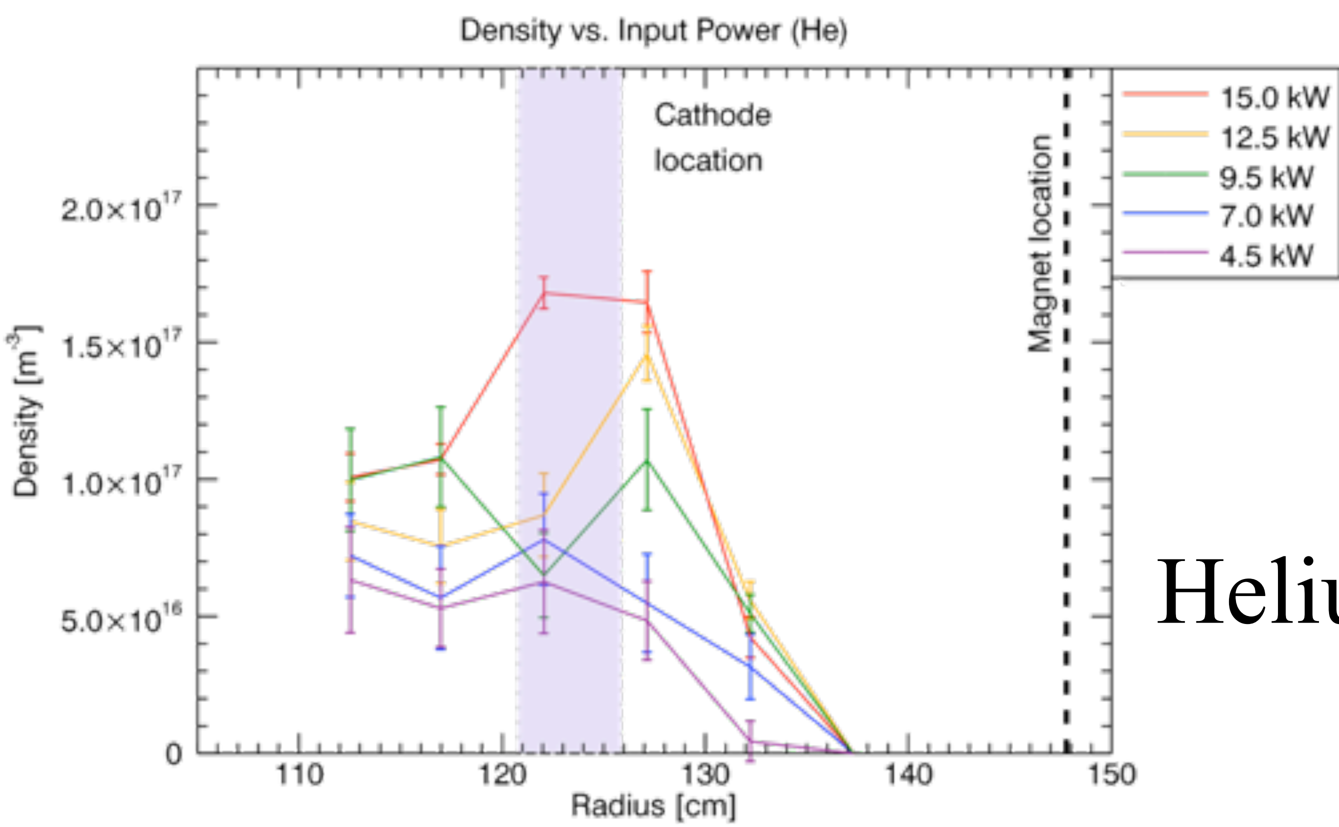


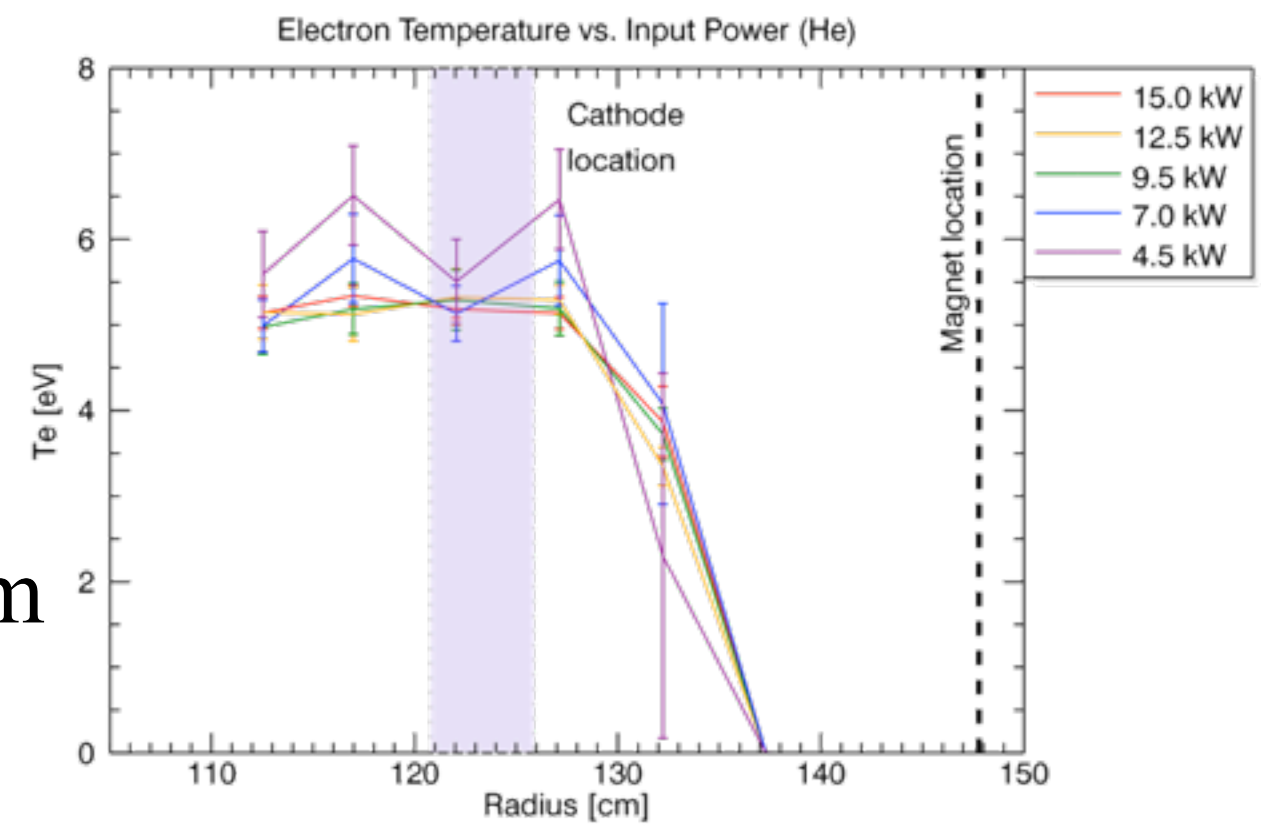
Argon and Helium plasmas are well confined by cusp field





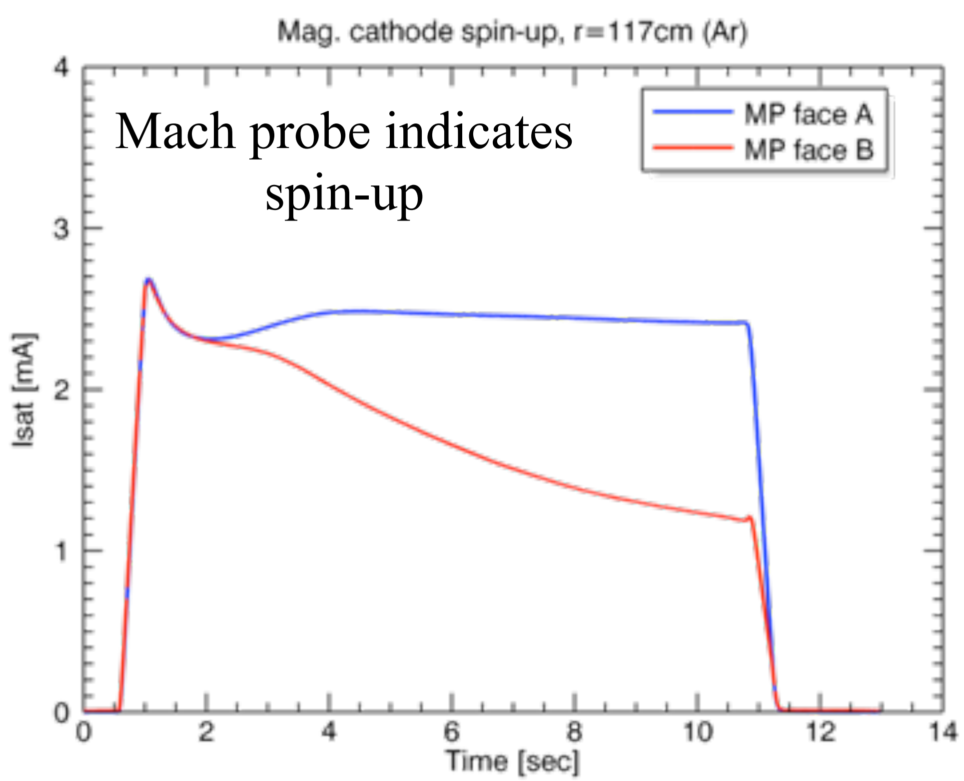
Argon

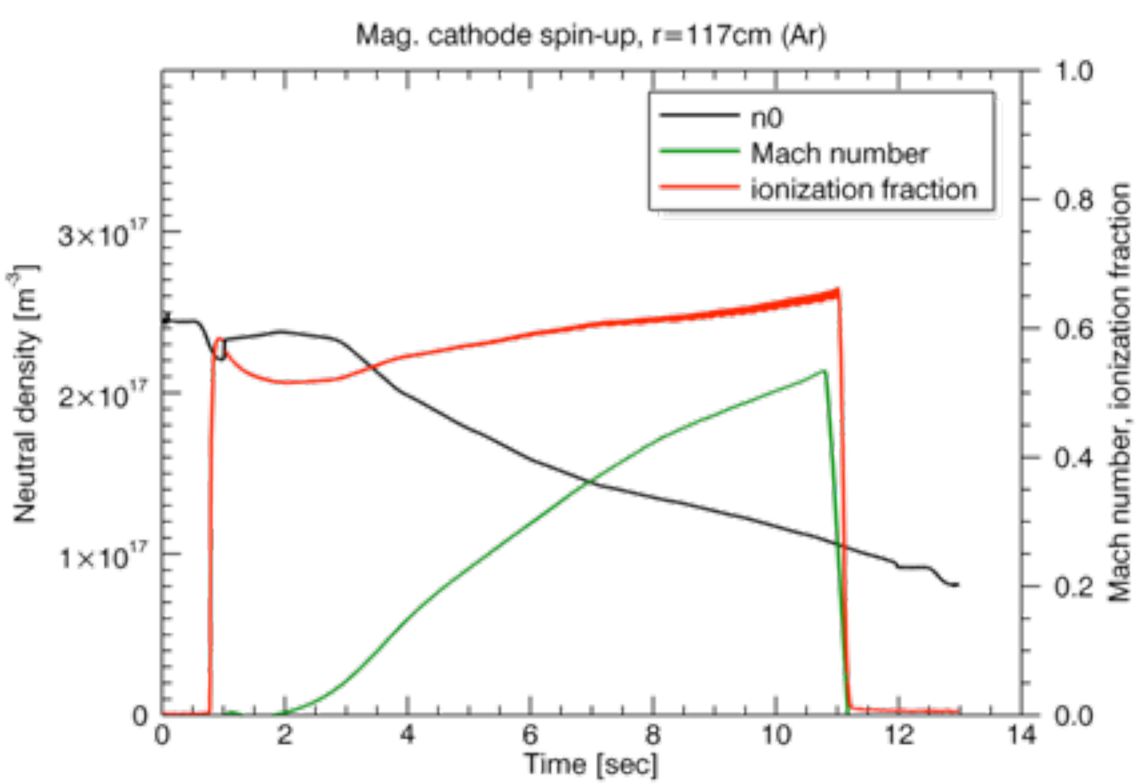


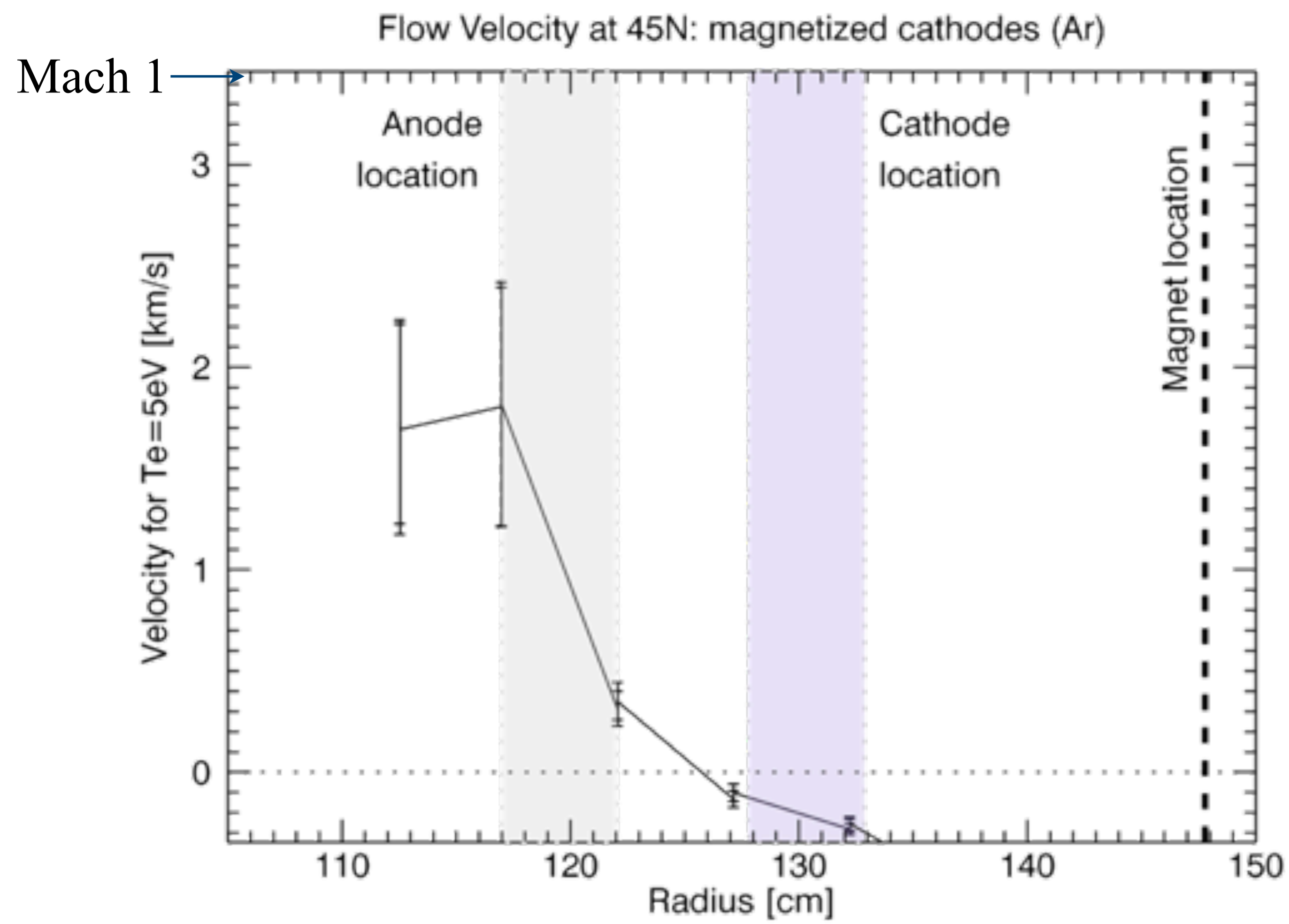


Helium

Flow observed with cathodes withdrawn into magnetized region







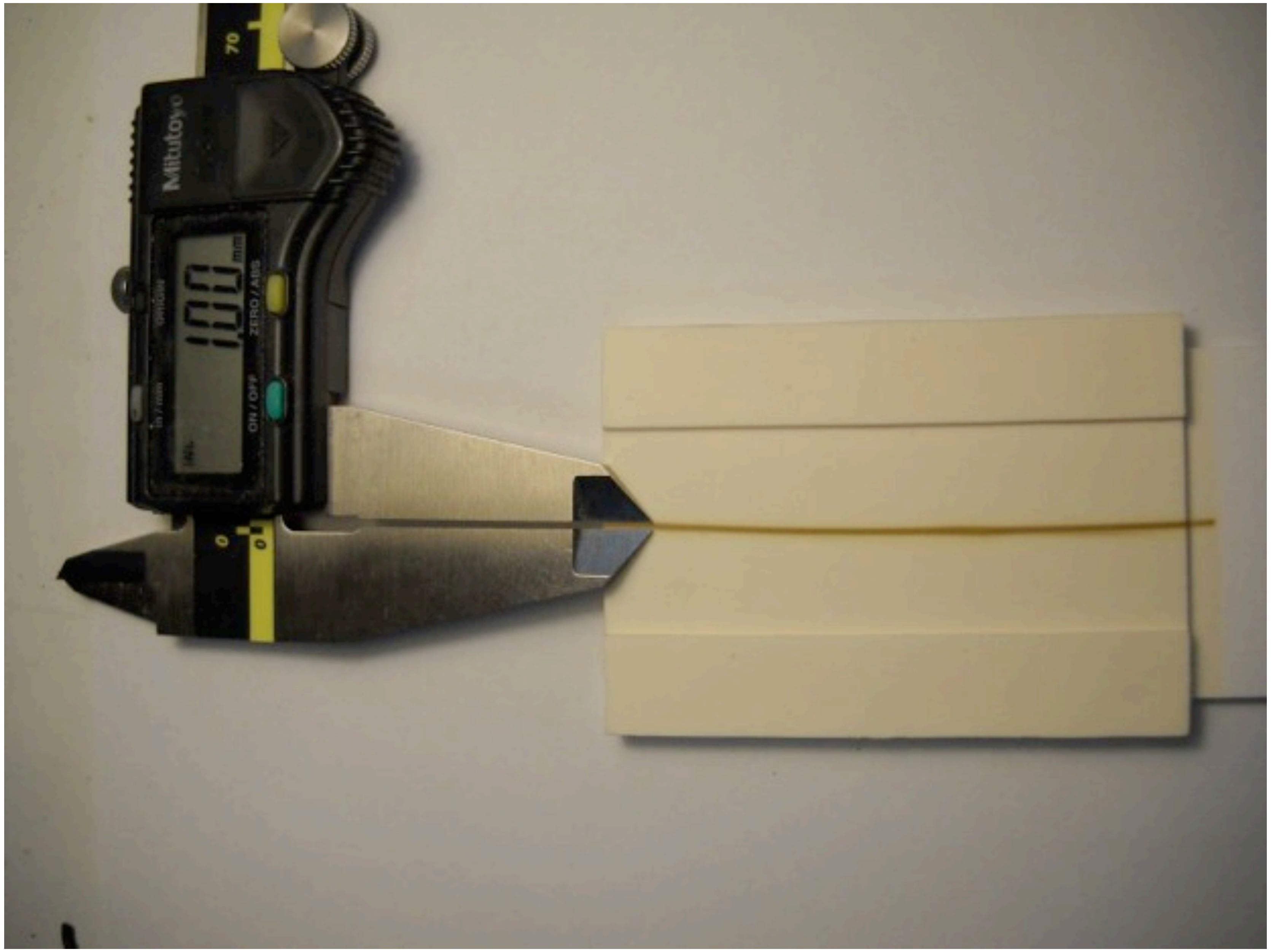
- Max velocity measured near anode location.
- Plasma spins up on neutral pump-out timescale.

$$mn\frac{du_\phi}{dt} = (\mathbf{J}\times\mathbf{B})_\phi - \frac{mnu_\phi}{\tau_{i0}} + mn\nu_{ii}[\nabla^2\mathbf{u}]_\phi$$

Particle balance

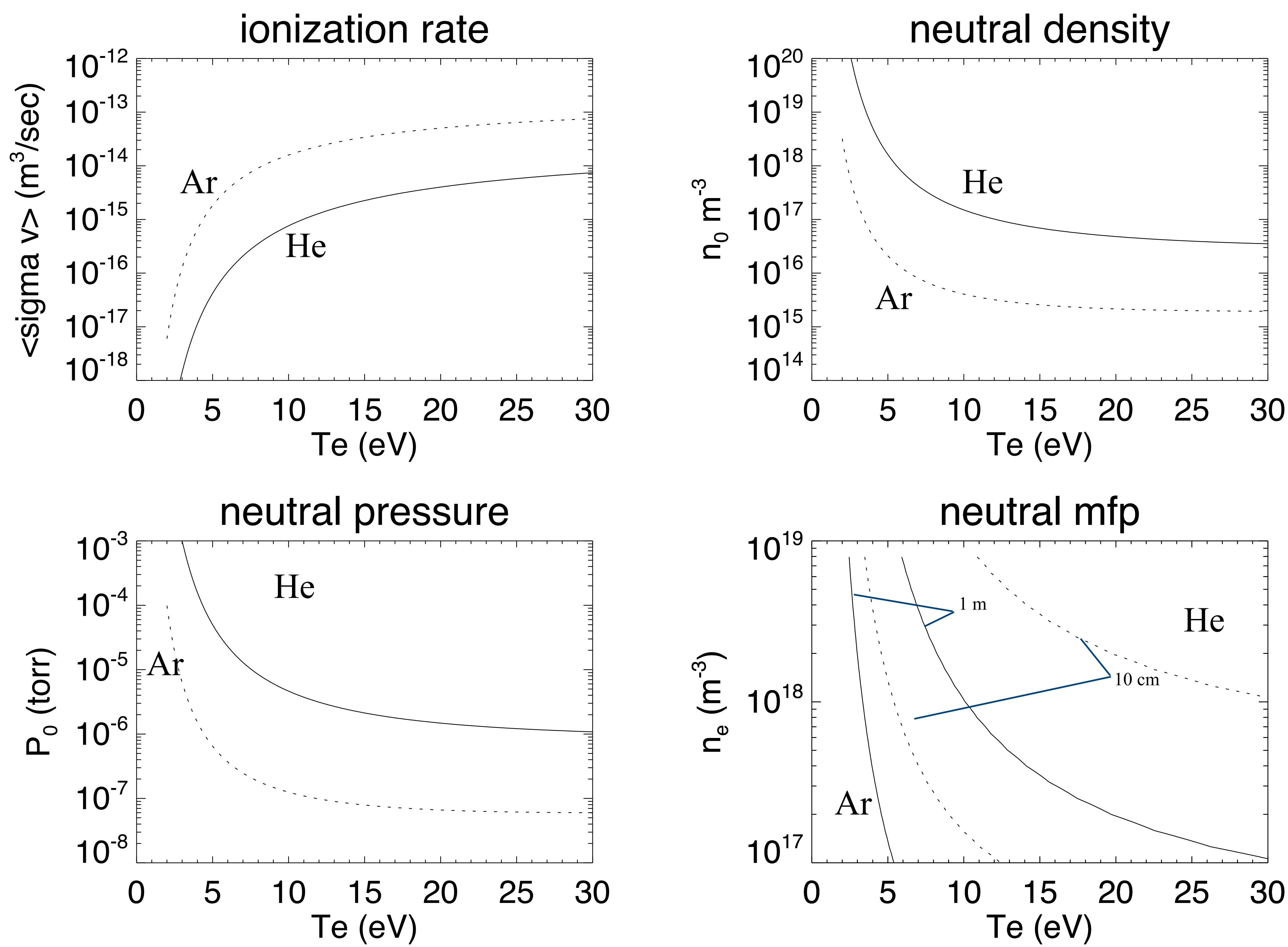
$$\frac{dn}{dt} = \frac{1}{2}\frac{c_s n A_{loss}}{V_{plasma}}$$

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

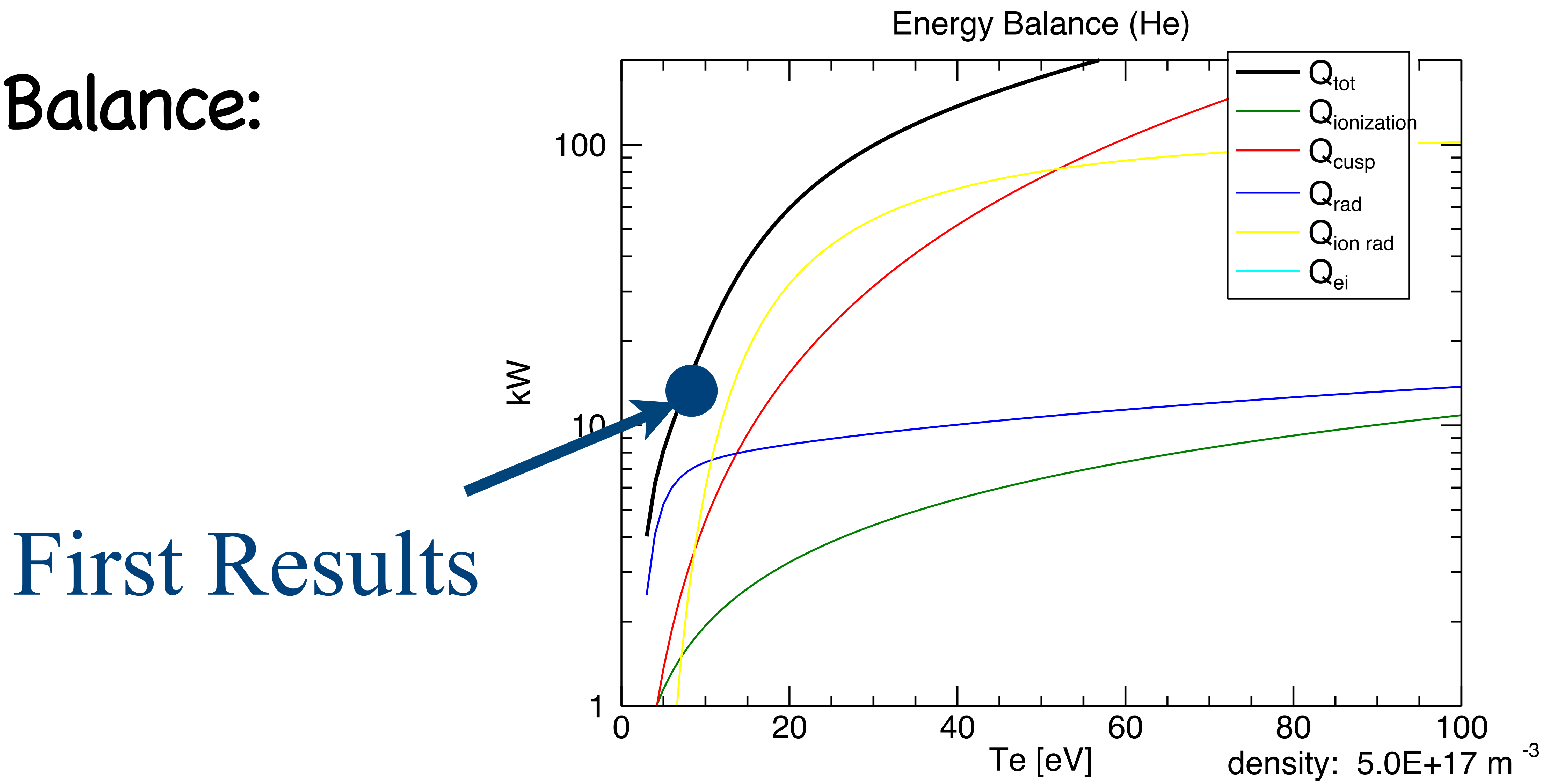


particle balance is $\frac{1}{2} n_e c_s A_{loss} = \langle \sigma_i v \rangle \, n_e n_0 V_{plasma}$

so $n_0 = \frac{1}{2} \frac{c_s}{\langle \sigma_i v \rangle} \frac{A_{loss}}{V_{plasma}}$ is just a function of Te

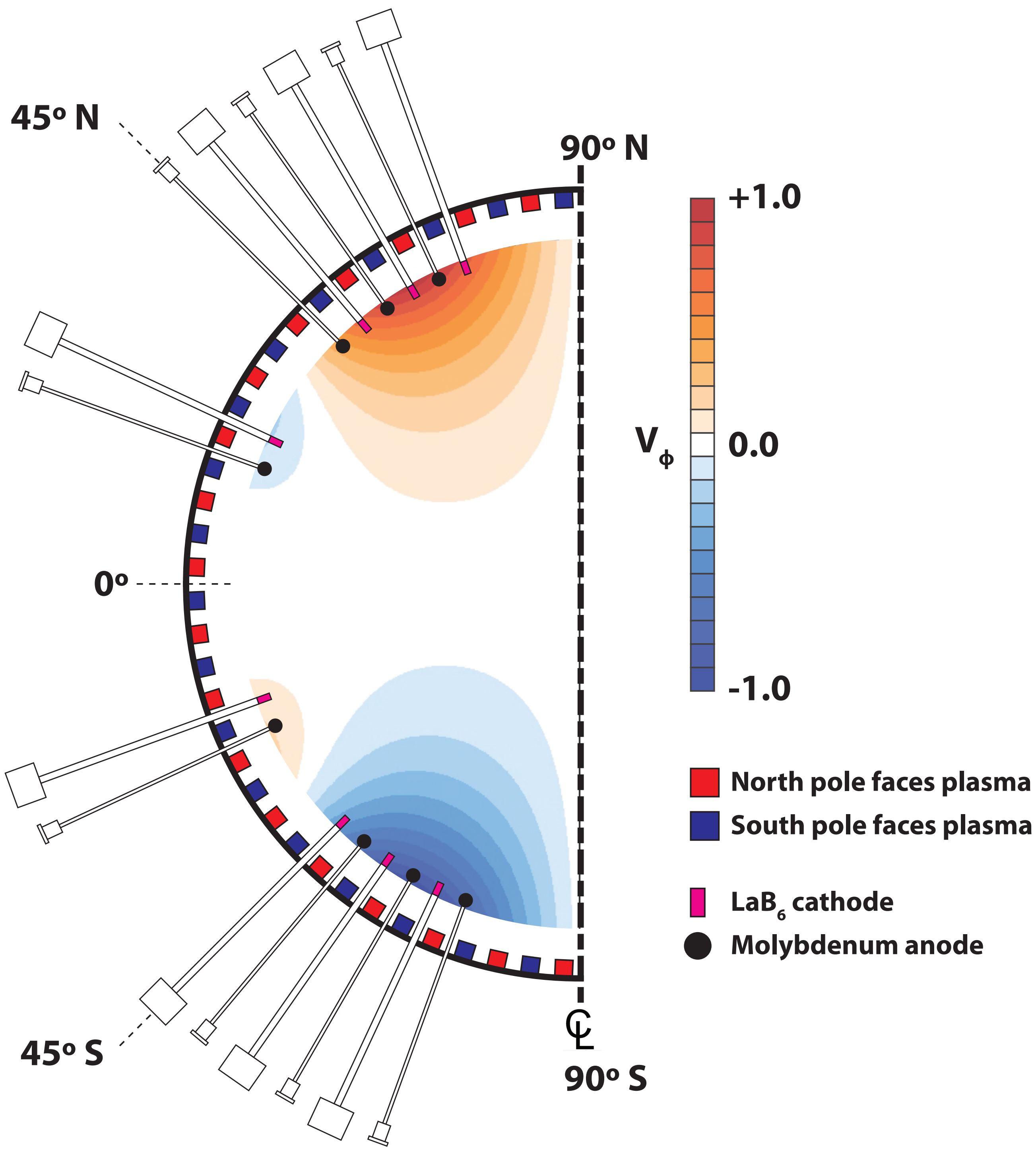


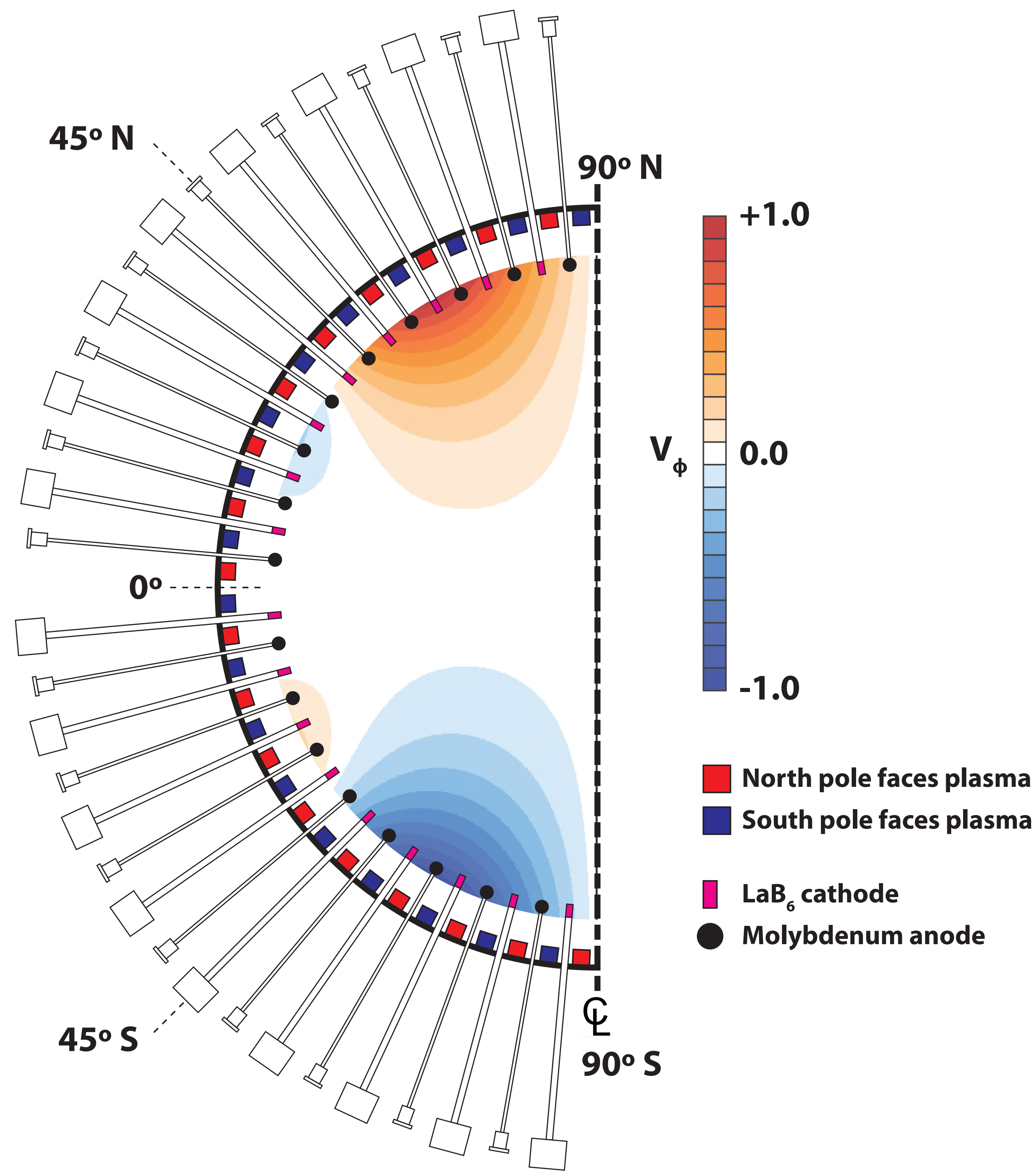
Power Balance:



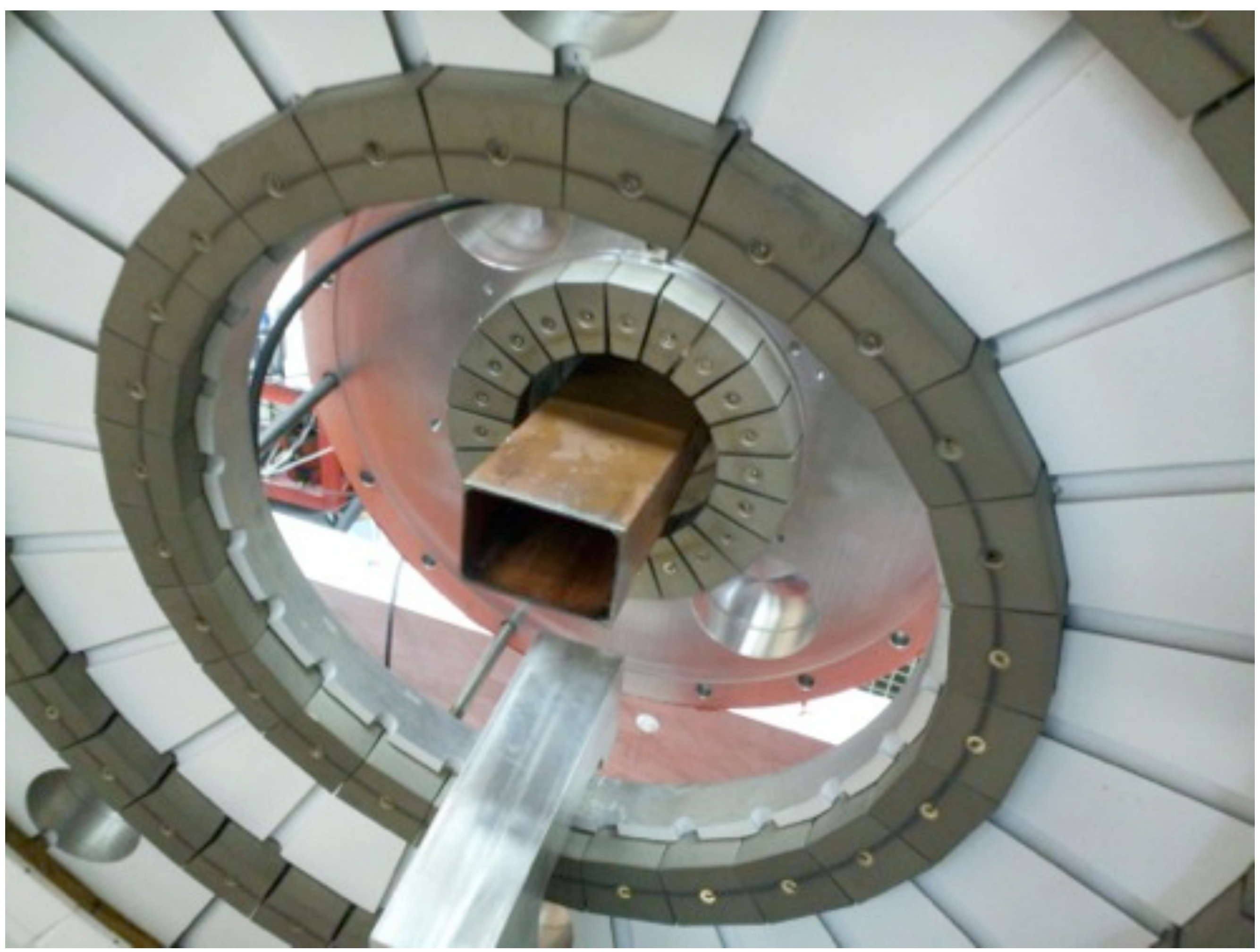
Loss Mechanism	Expression [Energy/Time]
Ion losses at cusps	$\Gamma A_{\mathrm{cusp}}(e\Delta V + \frac{3}{2}T_i)$
Electron losses at cusps	$\Gamma A_{\mathrm{cusp}}(\frac{3}{2}T_e)$
Replacement ionization	$Q_{\mathrm{ioniz}} \equiv \Gamma A_{\mathrm{cusp}} E_{\mathrm{ioniz}}$
Neutral radiation	$M(T_e)Q_{\mathrm{ioniz}}$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

Soon (May, 2013) ... eventually (Fall, 2013)





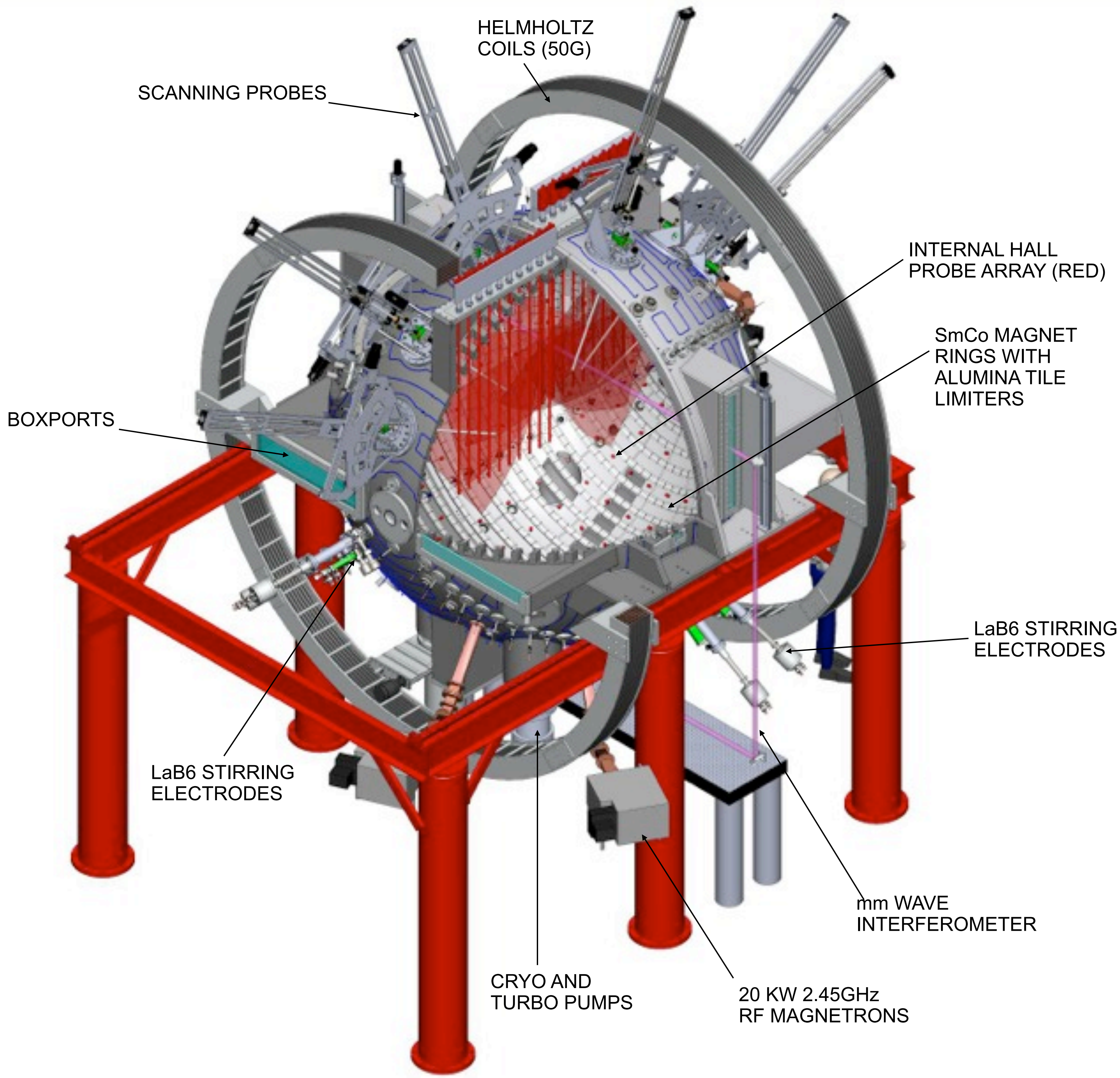
Additional Heating from Microwaves



- Magnetrons produce Microwave radiation at 2.45 GHz (like at home)
- May, 2013
- Total heating power:

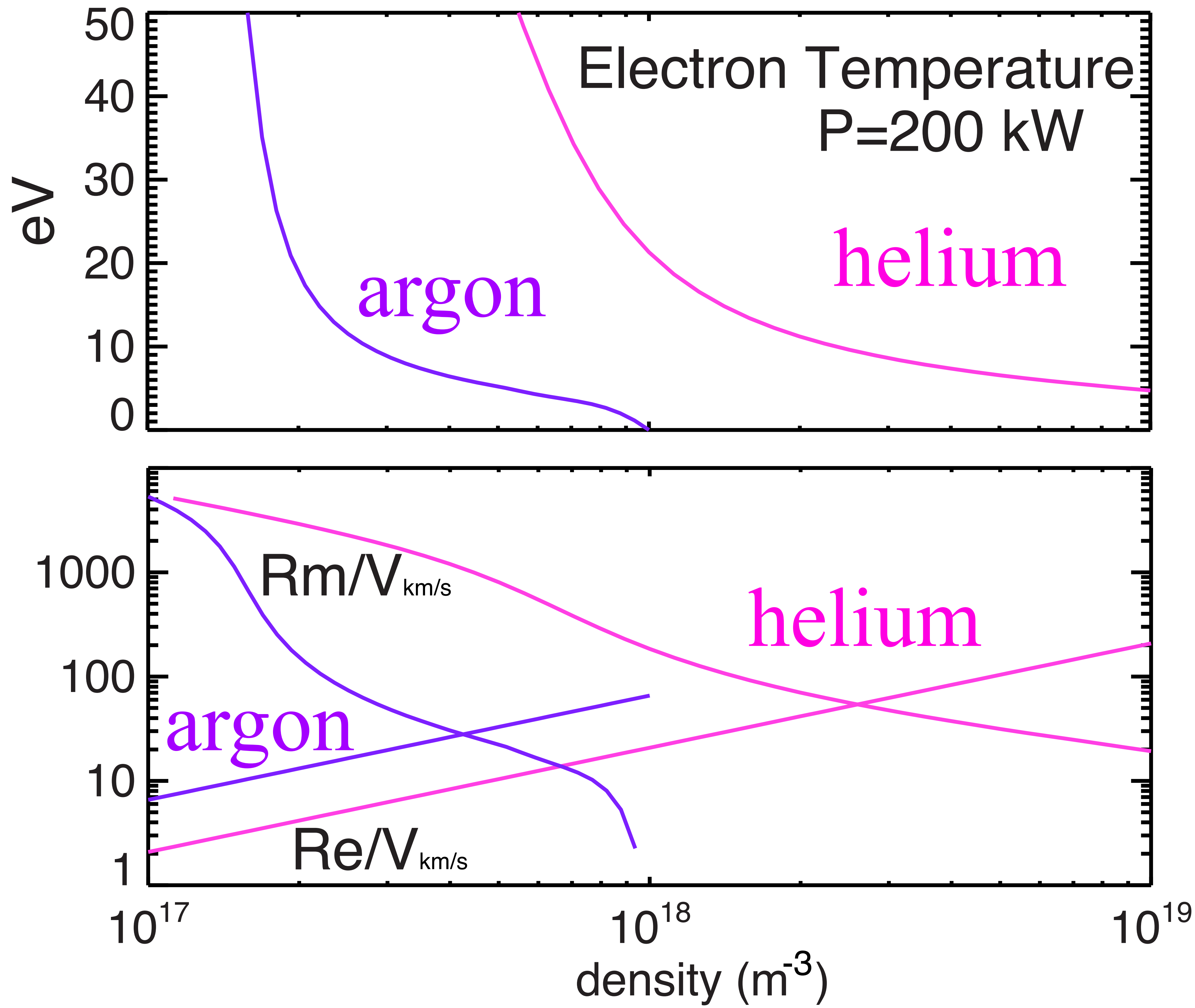
5 x 20 kW = <u>100 kW</u>

Diagnostics

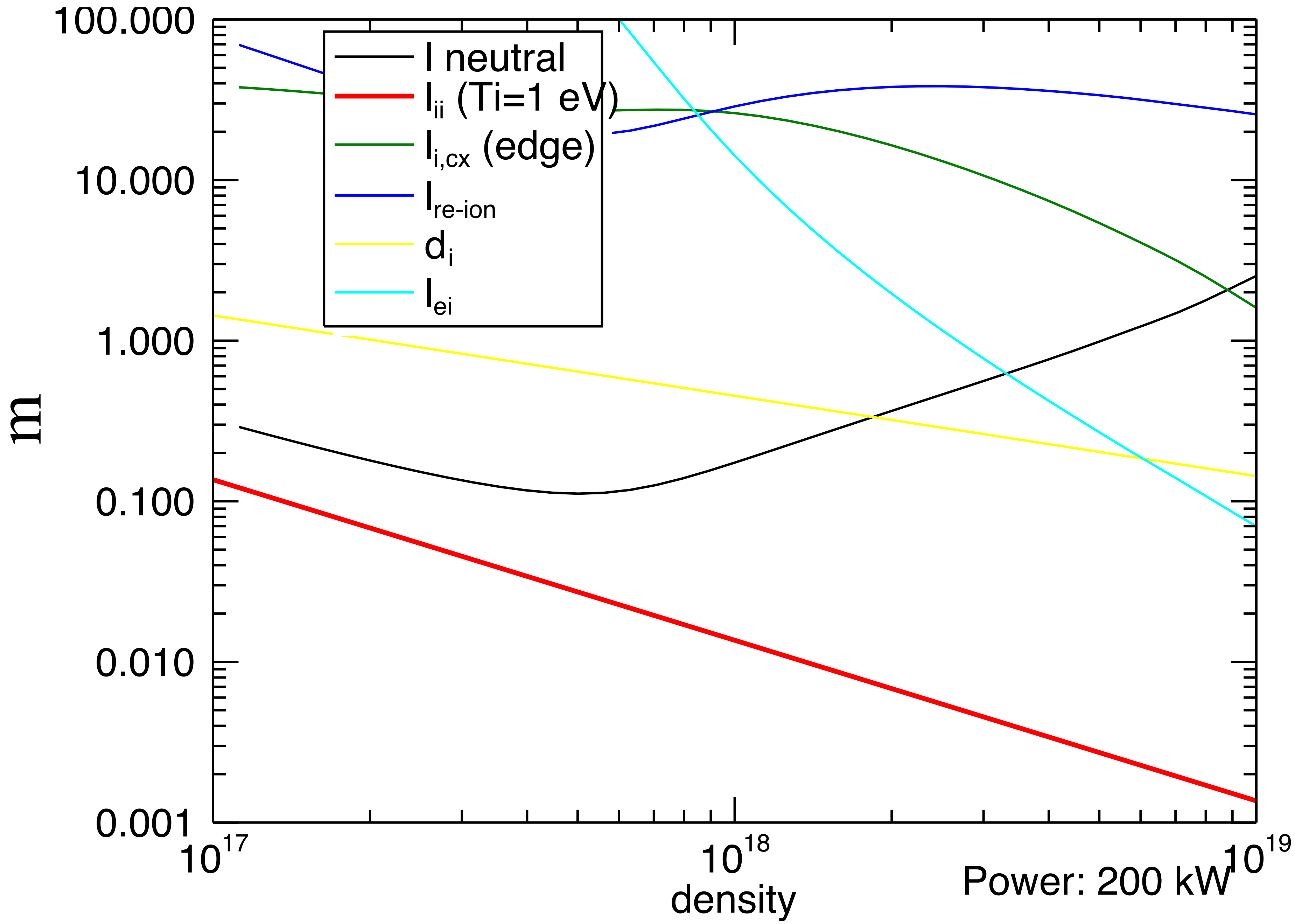


- 3-D Probes (n, **V, B**)
- 1 mm inteferometer/ polarimeter (n, B)
- line-ratio spectroscopy (Te, n)
- Fabry-Perot Ion Doppler Spectroscopy (Ti, V)
- Laser induced Fluorescence (Ti, V)
- Neutral Particle Analyzer
- Fast imaging camera
- edge magnetic array **B**(a,theta)
- edge Mach Probe Array Vphi(a,theta)

Operational space set by power, density, and ion species



At low density, low collisionality plasma effects will play role



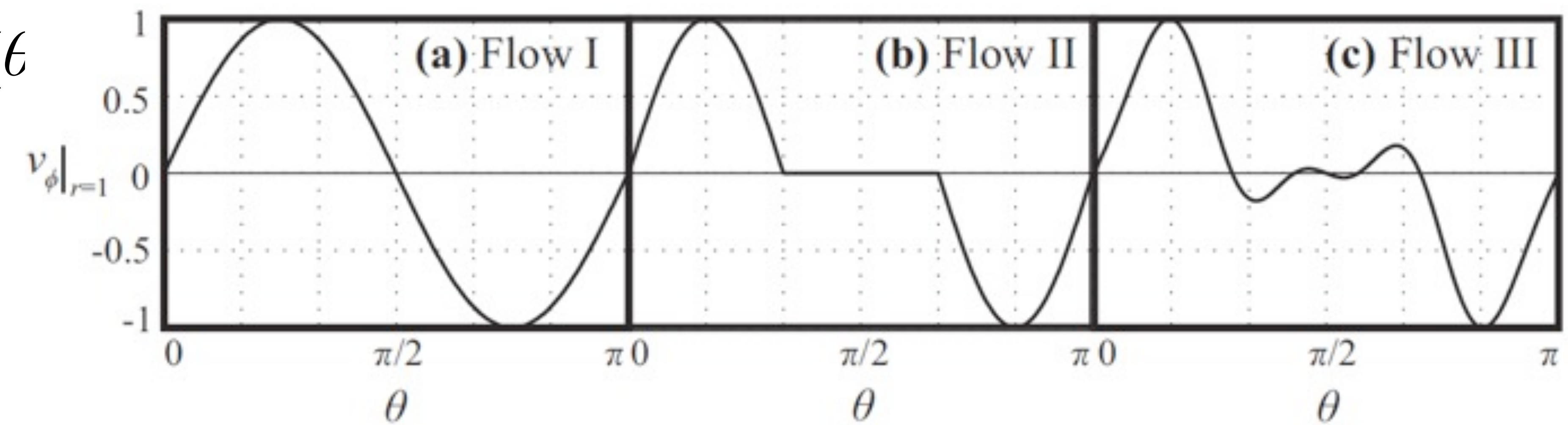
$$\rho_i = 1.02 \frac{\sqrt{\mu T_{\mathrm{i,eV}}}}{B_{\mathrm{g}}} \ \mathrm{m}$$

$$\rho_e = 0.023 \frac{\sqrt{T_{\mathrm{e,eV}}}}{B_{\mathrm{g}}} \ \mathrm{m}$$

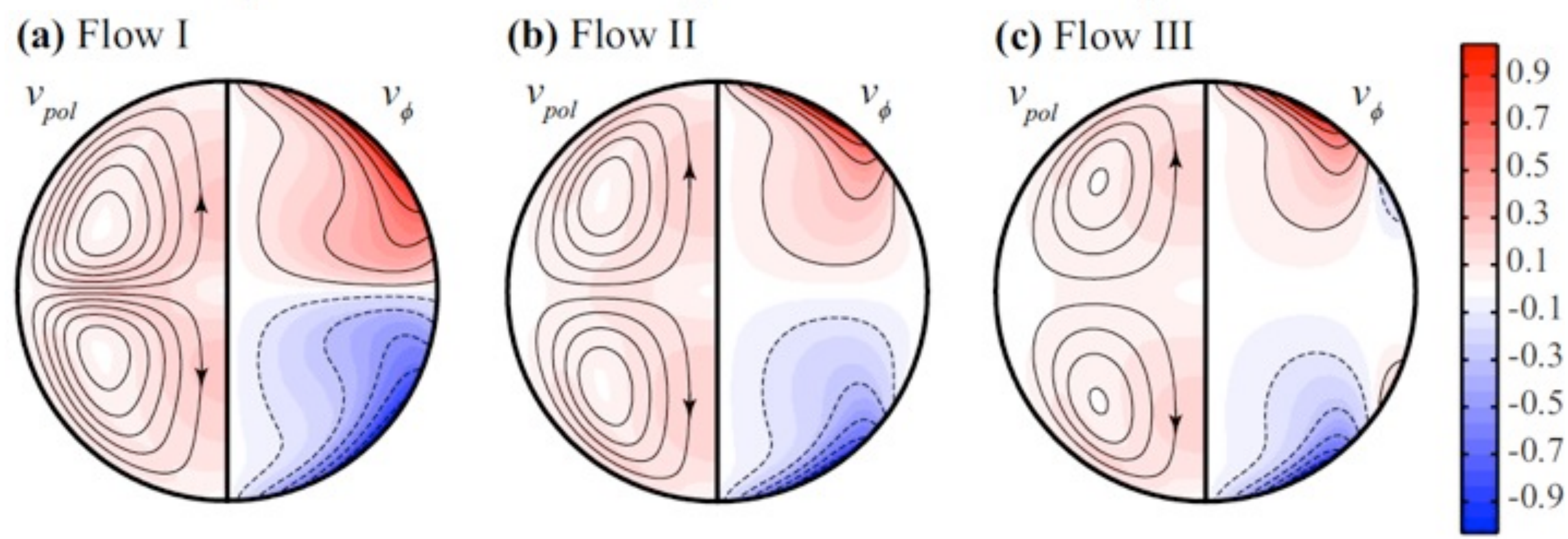
Boundary-driven flows

$$(\mathbf{v}\cdot\nabla)\,\mathbf{v}+\nabla p-\frac{1}{Re}\nabla^2\mathbf{v}=0,\ \ \nabla\cdot\mathbf{v}=0$$

Driving velocity $v_\phi(\theta$
at the boundary



Flow structure (Re=150)



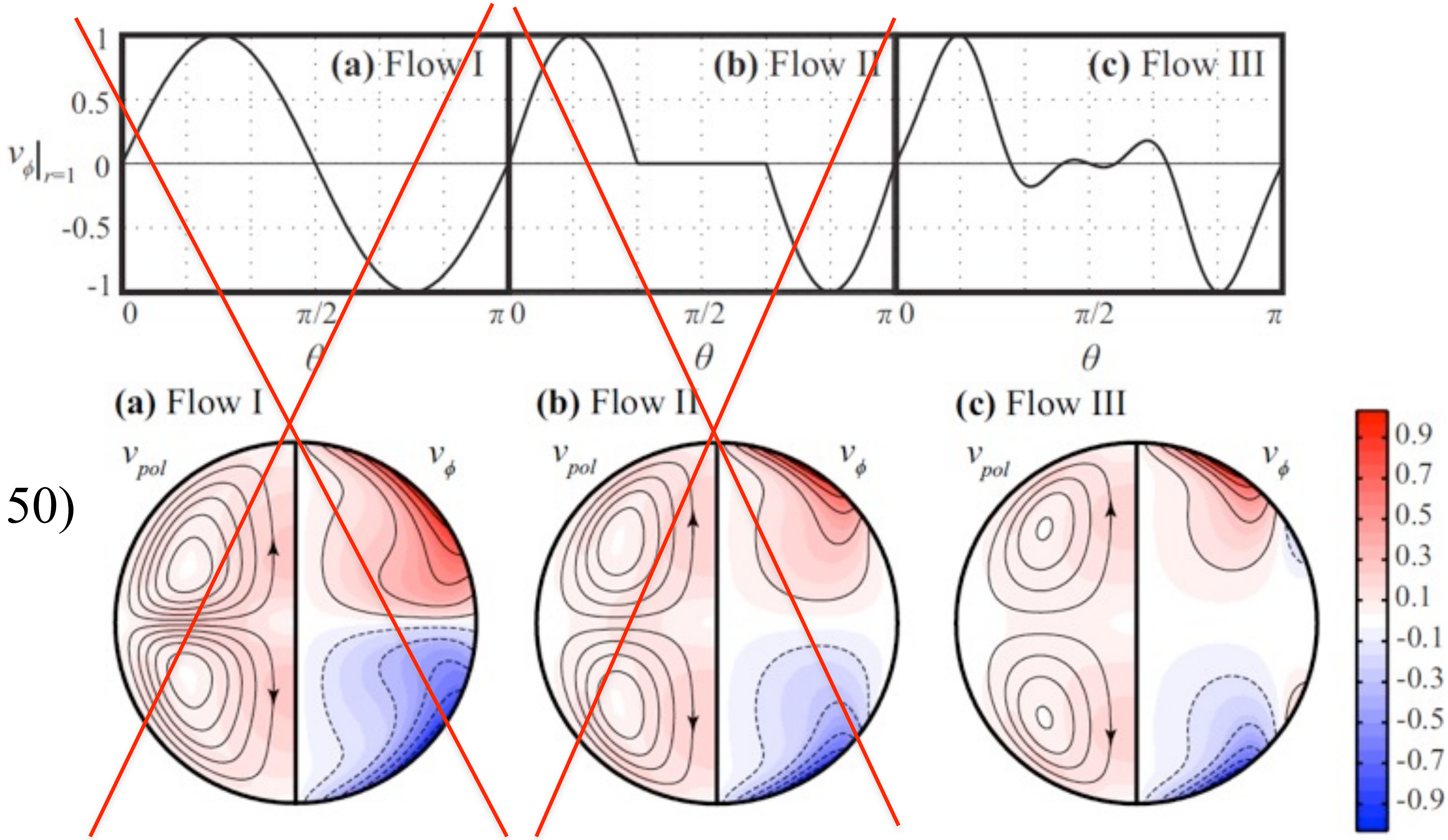
- Which flow can result in dynamo?

Boundary-driven flows

$$(\mathbf{v}\cdot\nabla)\,\mathbf{v}+\nabla p-\frac{1}{Re}\nabla^2\mathbf{v}=0,\quad \nabla\cdot\mathbf{v}=0$$

$v_\phi(\theta)$
at the boundary

Flow structure (*Re*=150)

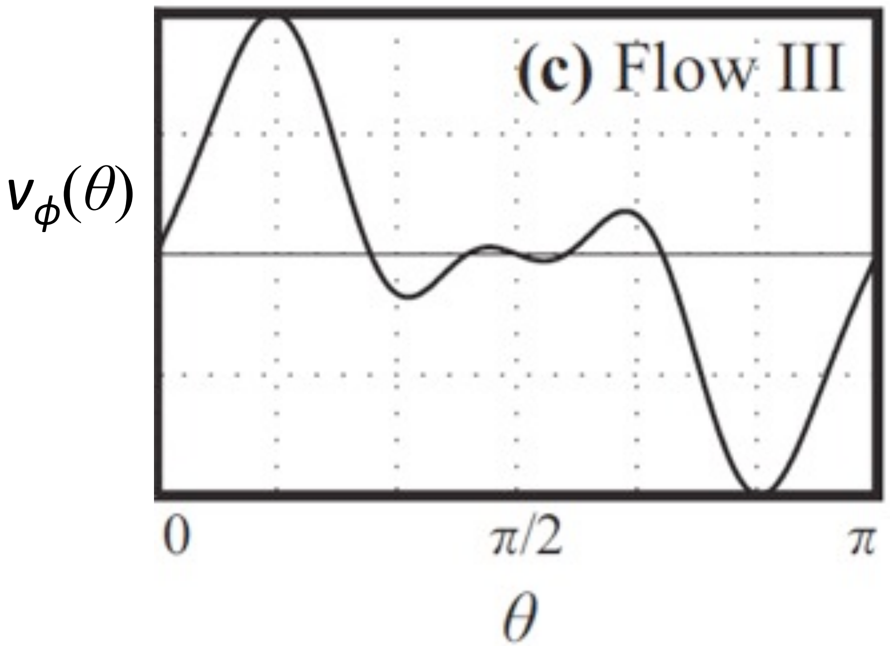


Dynamo!

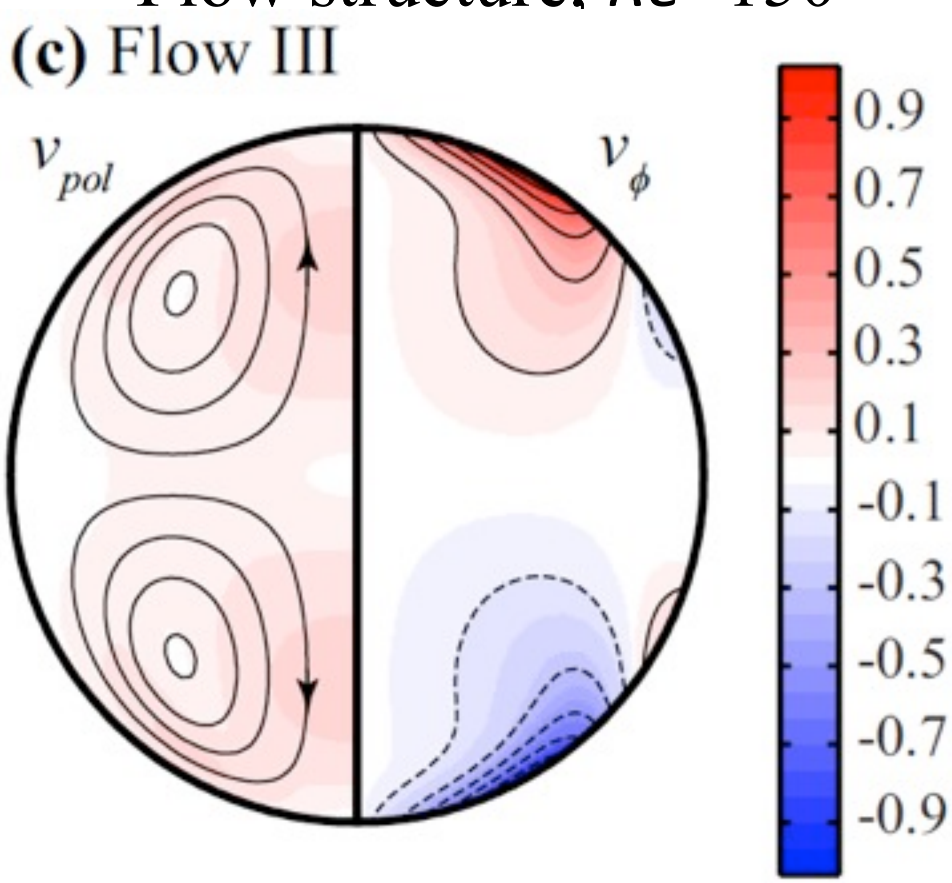
- Which flow can result in dynamo?
- Only flow III [from Spence et al., 2009]!

Dynamo in flow III

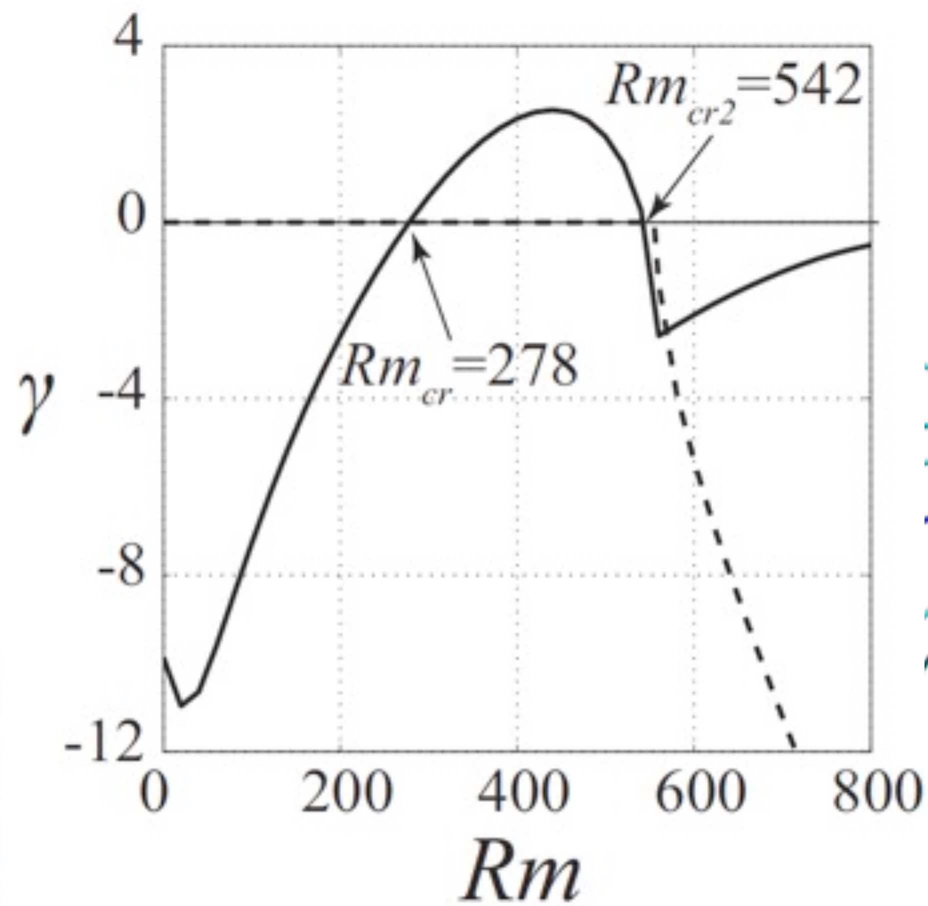
Boundary drive



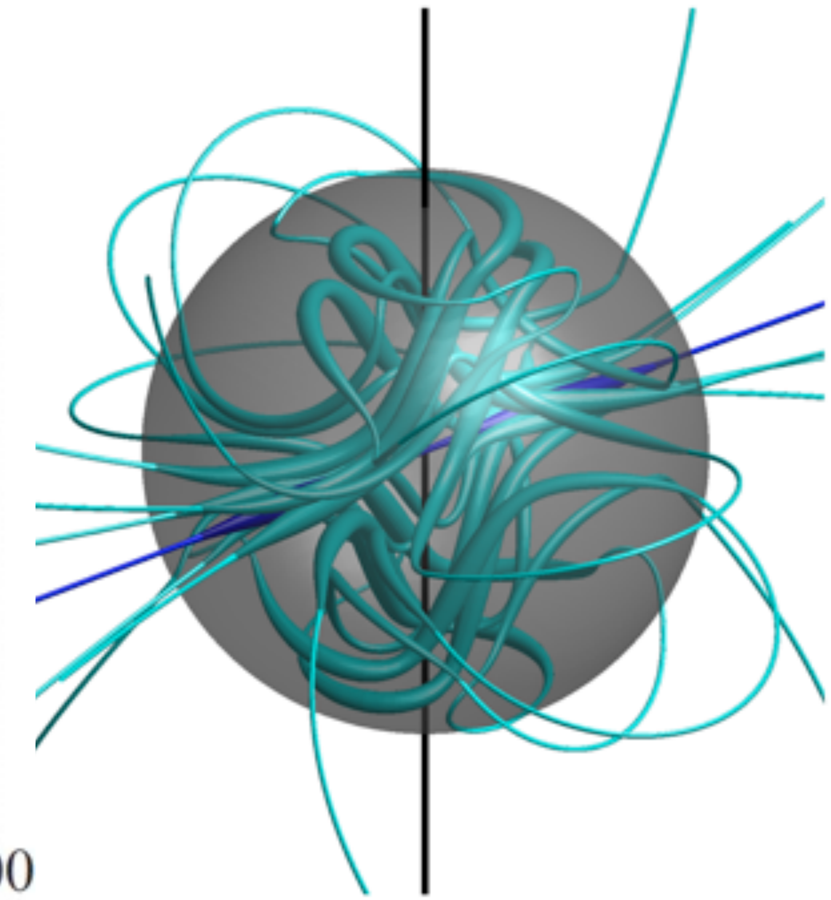
Flow structure, *Re*=150



Growth rate vs. *Rm*
(mode *m*=1)



Dynamo field, *Rm*=400

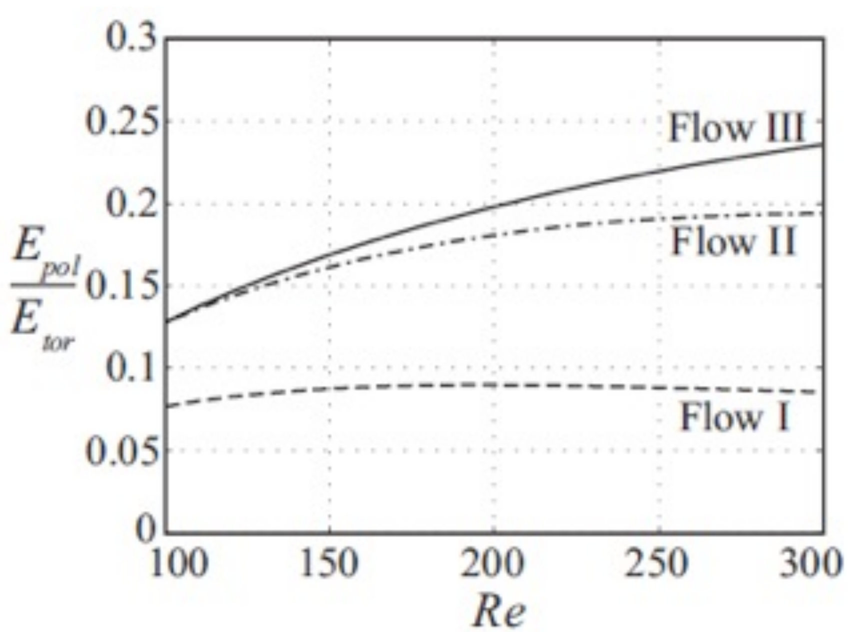


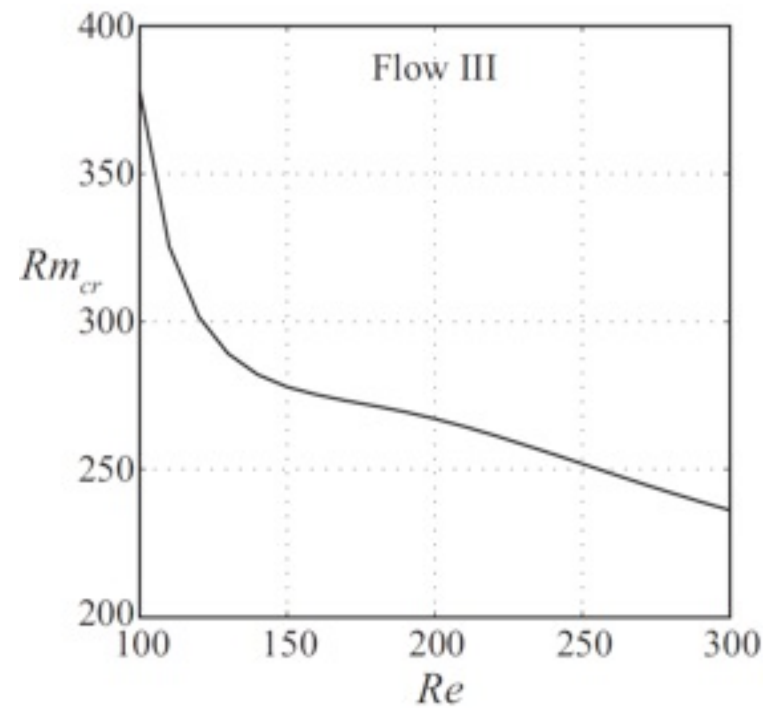
- This is achievable in MPDX with argon plasma, V_0=5 km/s, n_0=10^{18} m^{-3}, T_e=10 eV, T_i=1 eV
- Growth rate γ is normalized by resistive time

$$\tau_\sigma = \frac{R^0}{\eta} \approx 0.13 \text{ sec}$$

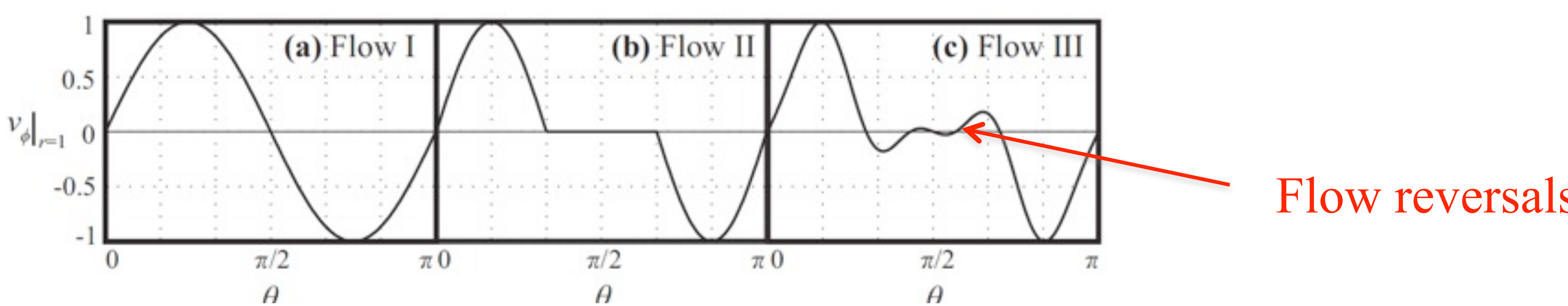
What determines dynamo onset?

- Pure toroidal flow cannot support dynamo [Elsasser, 1946]
- Dynamo onset depends on poloidal flow



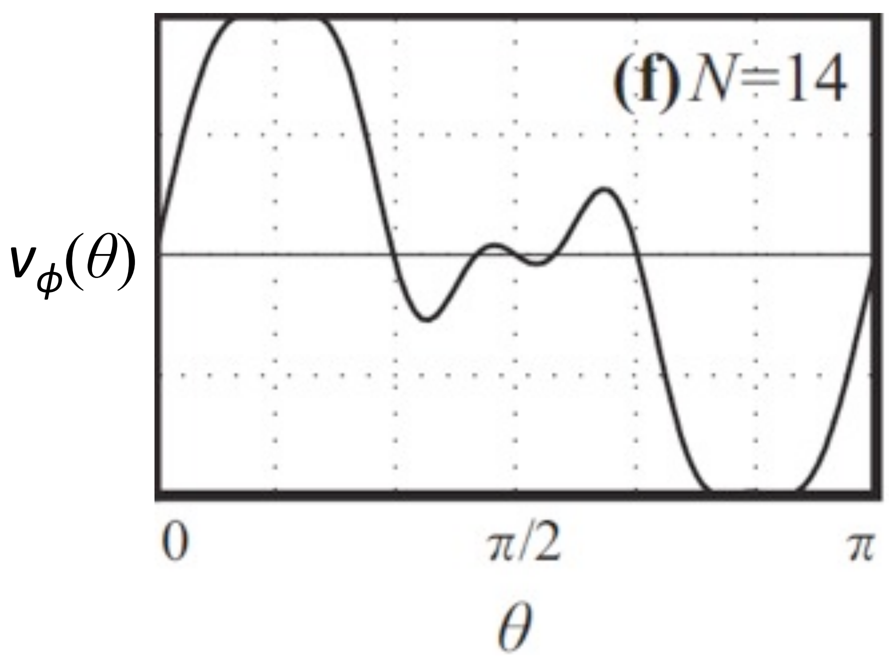


- Poloidal flow is necessary for dynamo, but not sufficient
- Details of flow structure play important role:

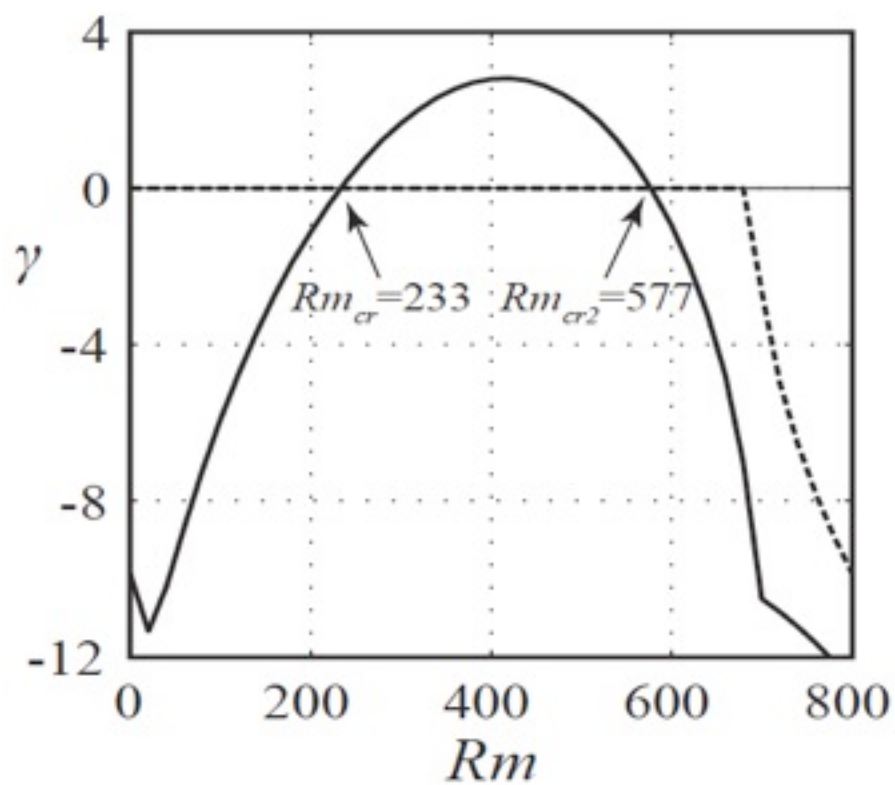


Optimized flow

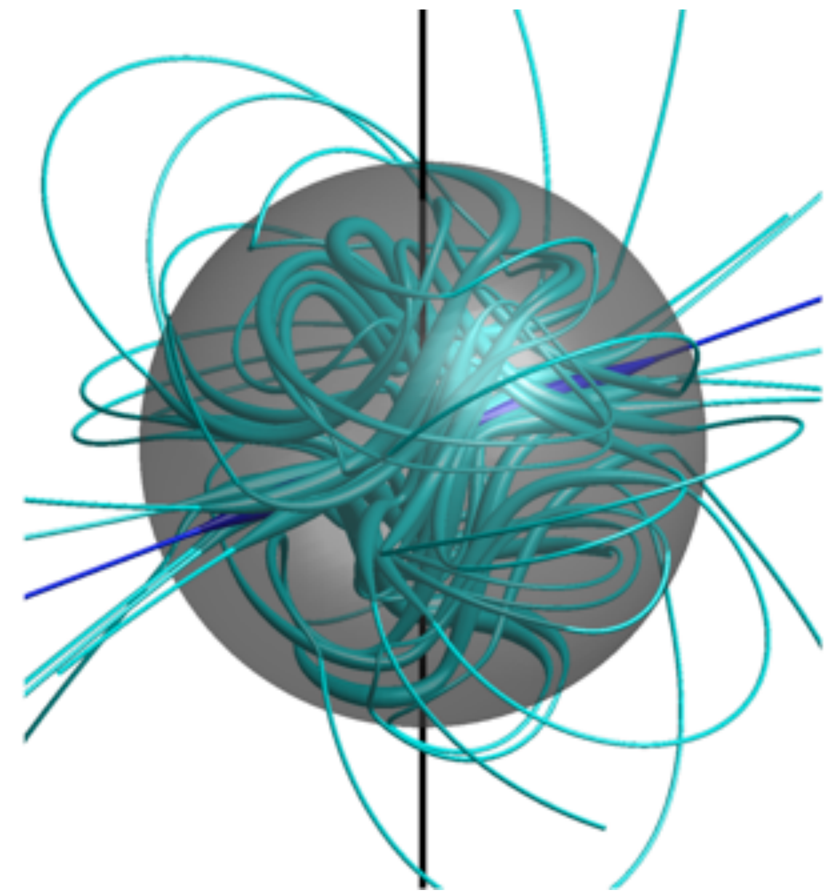
Boundary drive



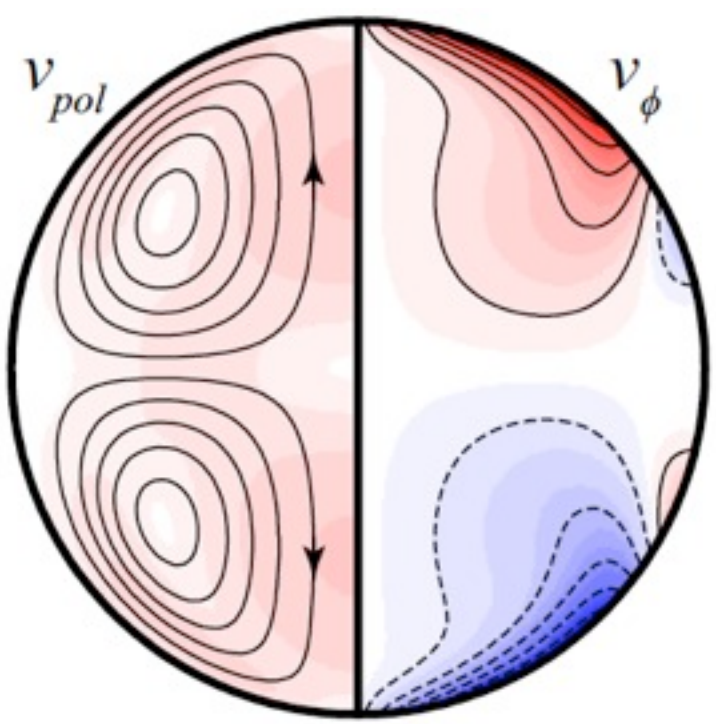
Growth rate vs. *Rm*

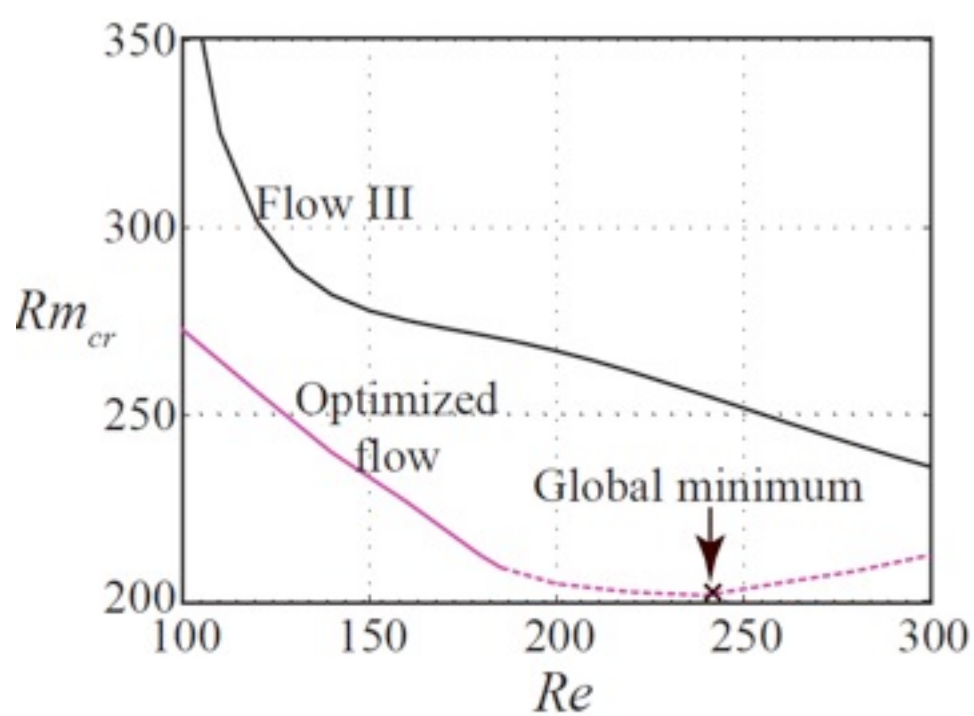


Dynamo field, *Rm*=400



Flow structure, *Re*=150





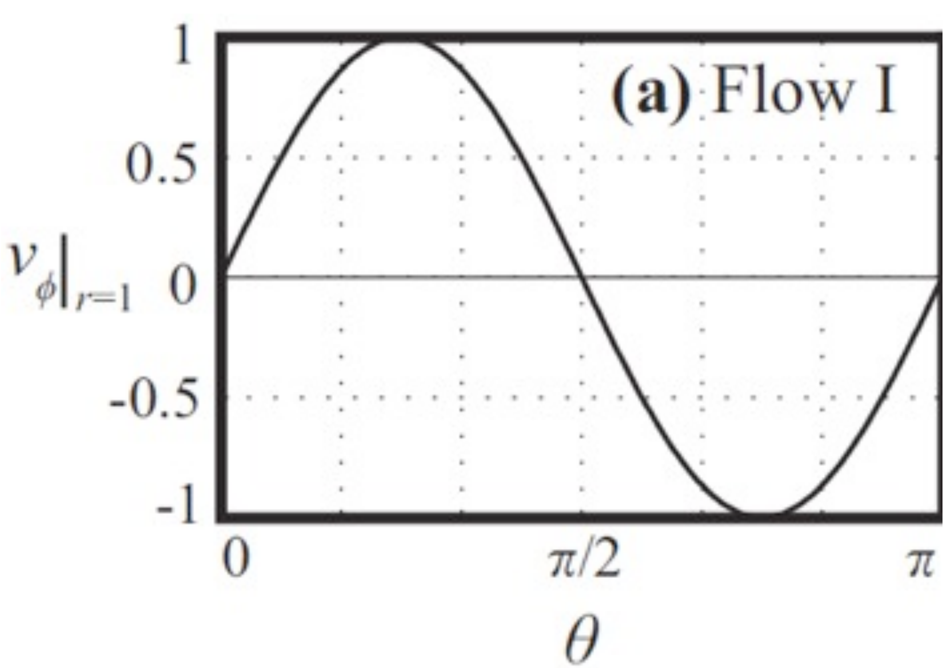
- The lowest Rm_{cr}≈200 achieved at *Re*≈240

Spherical von Karman flow

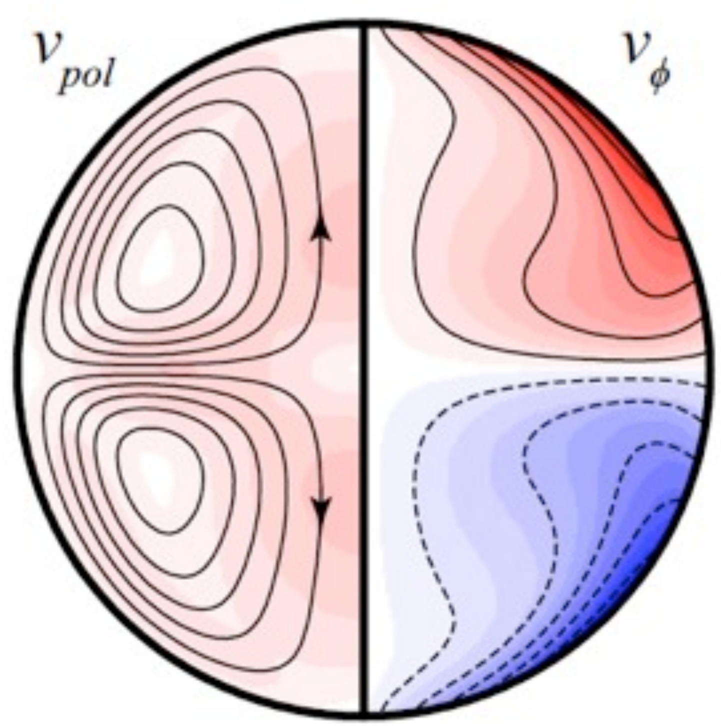
- Idea: create a **hydrodynamically unstable** flow, so non-axisymmetric modes are induced
- Solve full MHD system:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\,\mathbf{v} + \nabla p - \frac{1}{Re}\nabla^2 \mathbf{v} = 0, \;\; \nabla \cdot \mathbf{v} = 0, \;\; Re = \frac{R_0 V_0}{\nu}$$

Boundary drive
$v_\phi(\theta)=\sin(2\theta)$

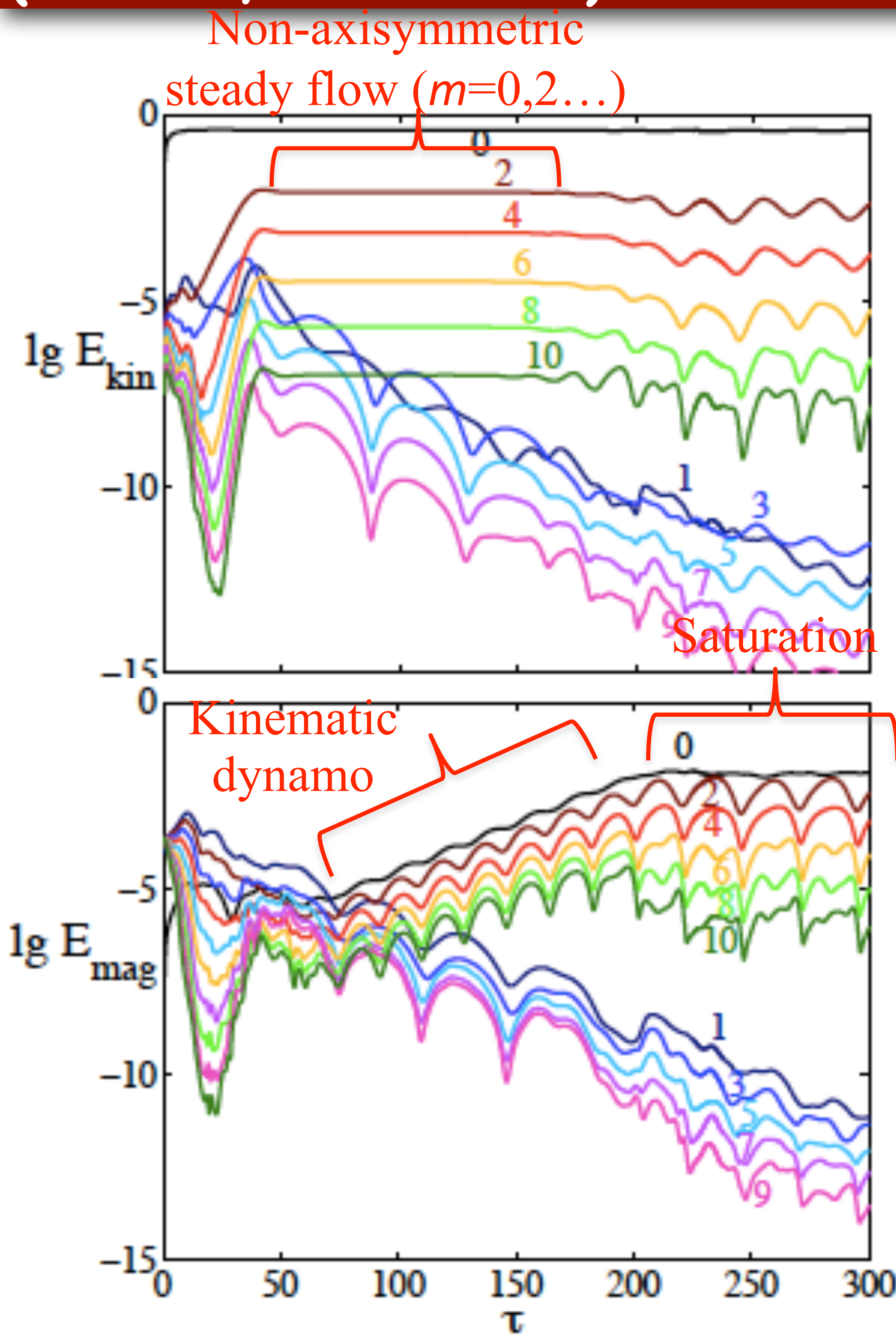


Axisymmetric flow structure,
Re=150

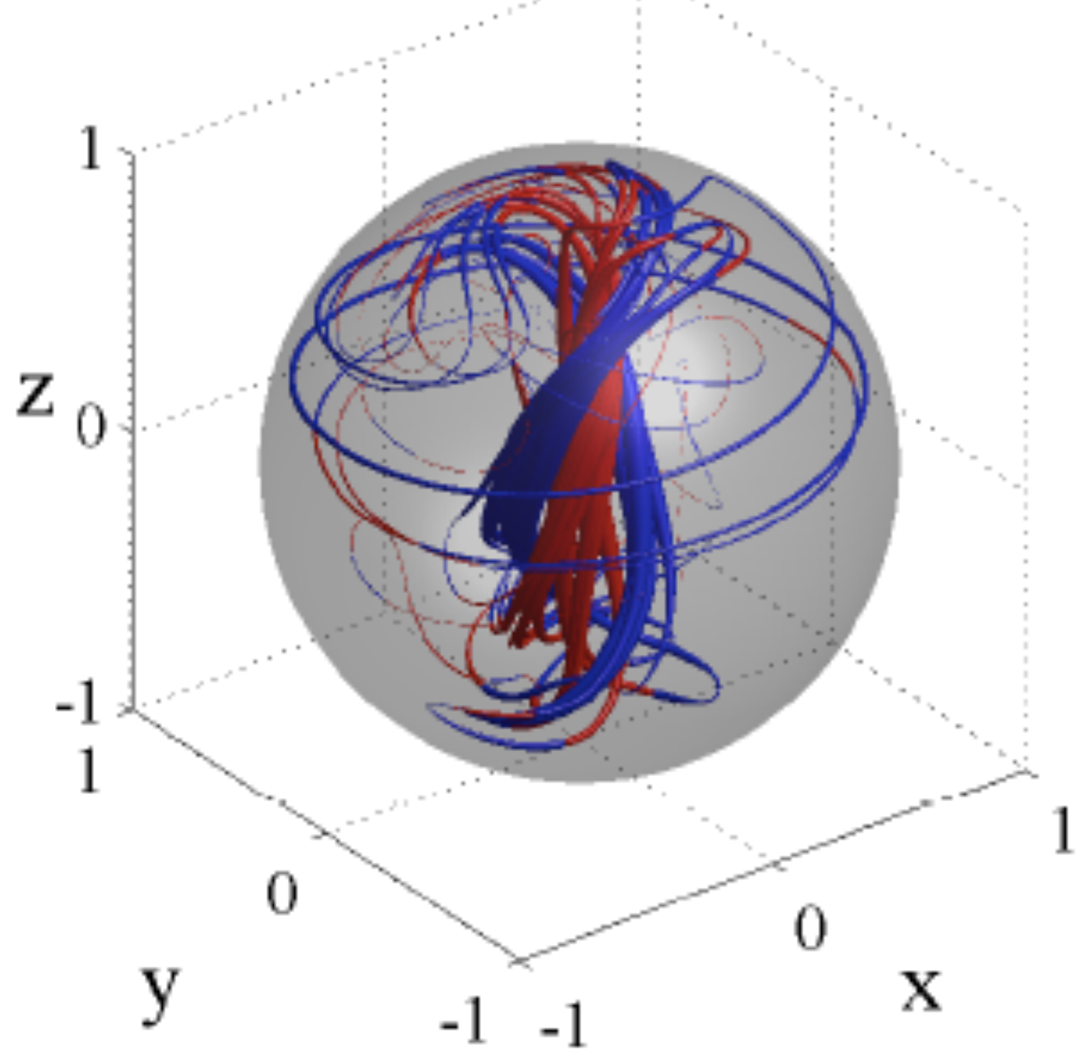


- This flow is unstable hydrodynamically with respect to mode m=2 when Re>115

Dynamo in non-axisymmetric flow
(Re=150, Rm=2000)

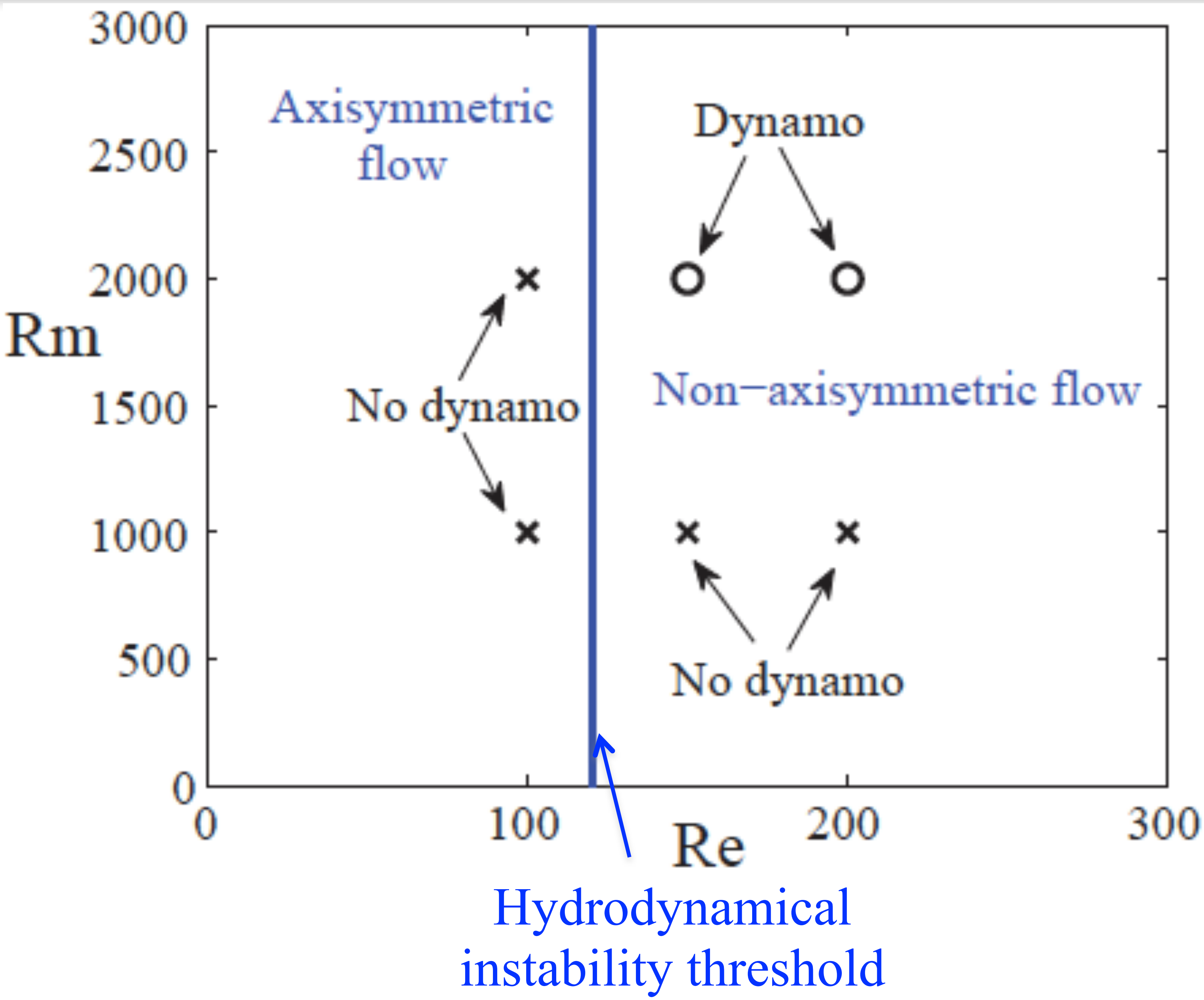


Magnetic field lines at t=237.9



- Saturated state is time-periodic
- Both flow and field have only even harmonics with m=0, 2, 4,...
- Regime corresponds to argon plasma with V_0=10 km/s, $n_0=10^{18}$ m^{-3}, T_e=18 eV, T_i=1.3 eV

High Pm Domain of dynamo parameters
(conducting wall, steady von Karman flows)

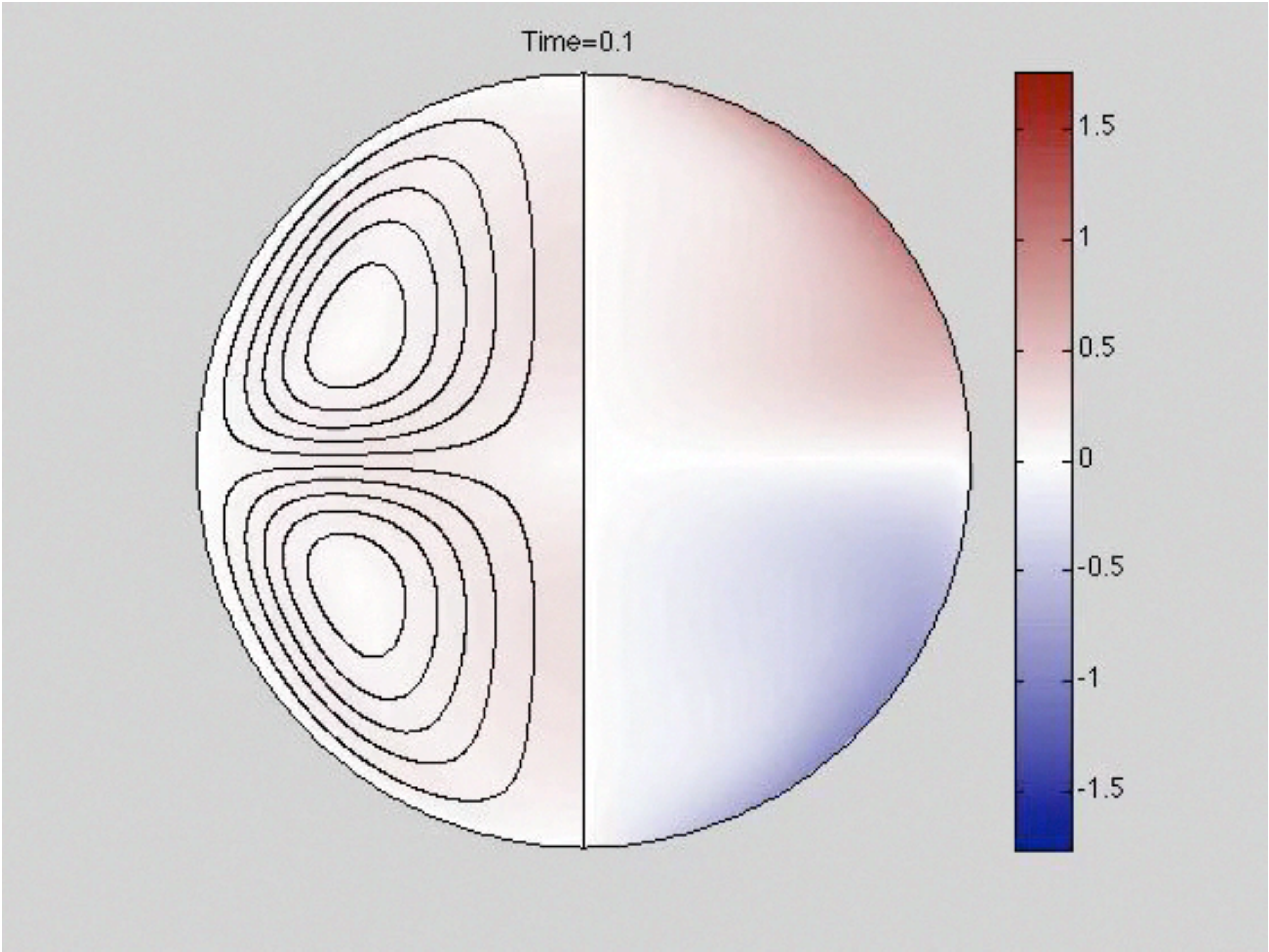


• Dynamo excited in non-axisymmetric von Karman flows (*Re*>115) for sufficiently high *Rm* (*Rm*>1500)

Galloway-Proctor flow in sphere driven by time dependent boundary flow

- Consider driving velocity: $V_\phi(\theta, t) = \sin 2\theta + a \sin\theta \sin\omega t$

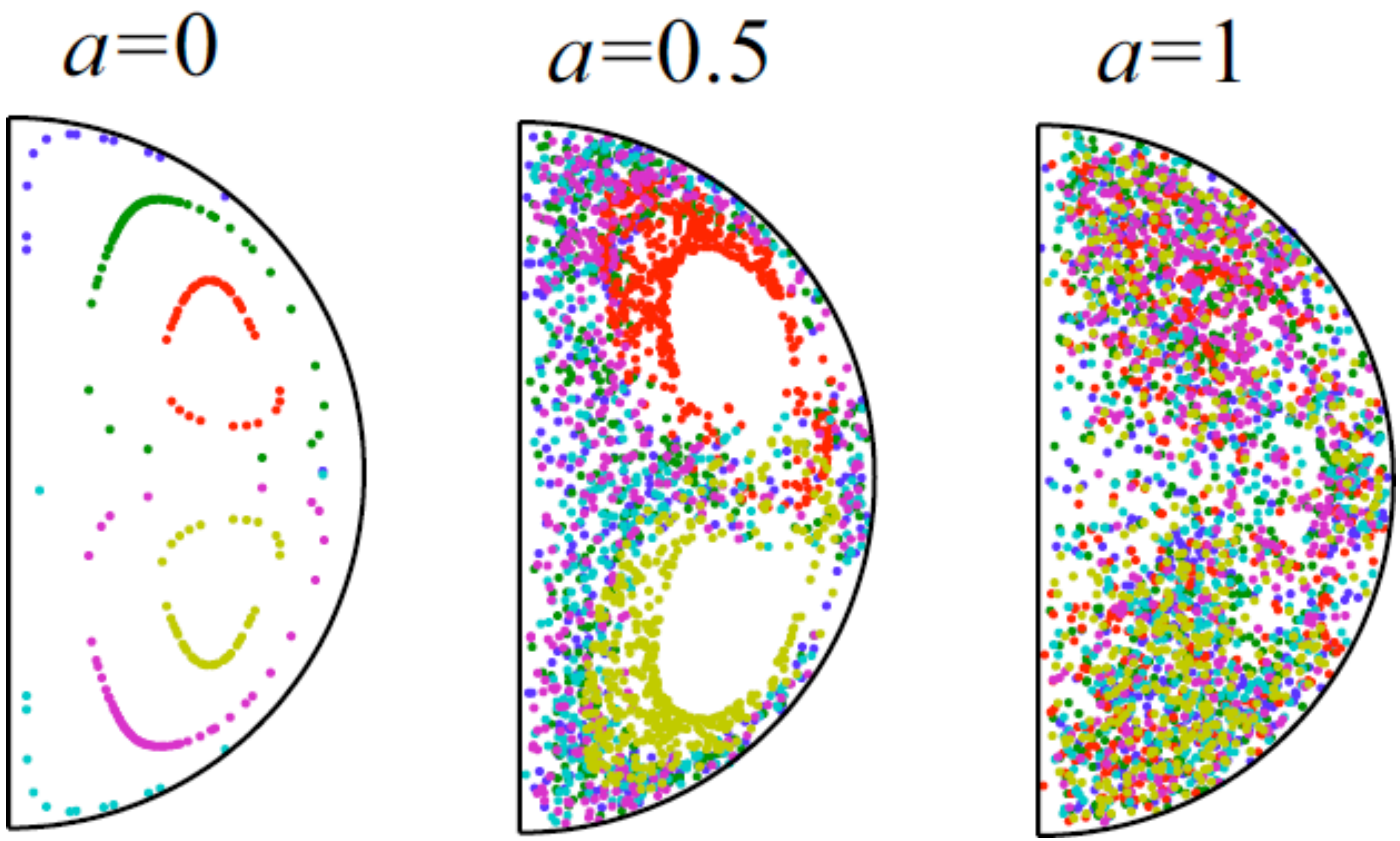
Re=100, a=1, ω=1



solves Navier-Stokes: $$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\,\mathbf{v} + \nabla p = \frac{1}{Re}\nabla^2\mathbf{v}$$

Chaos in time-periodic flow

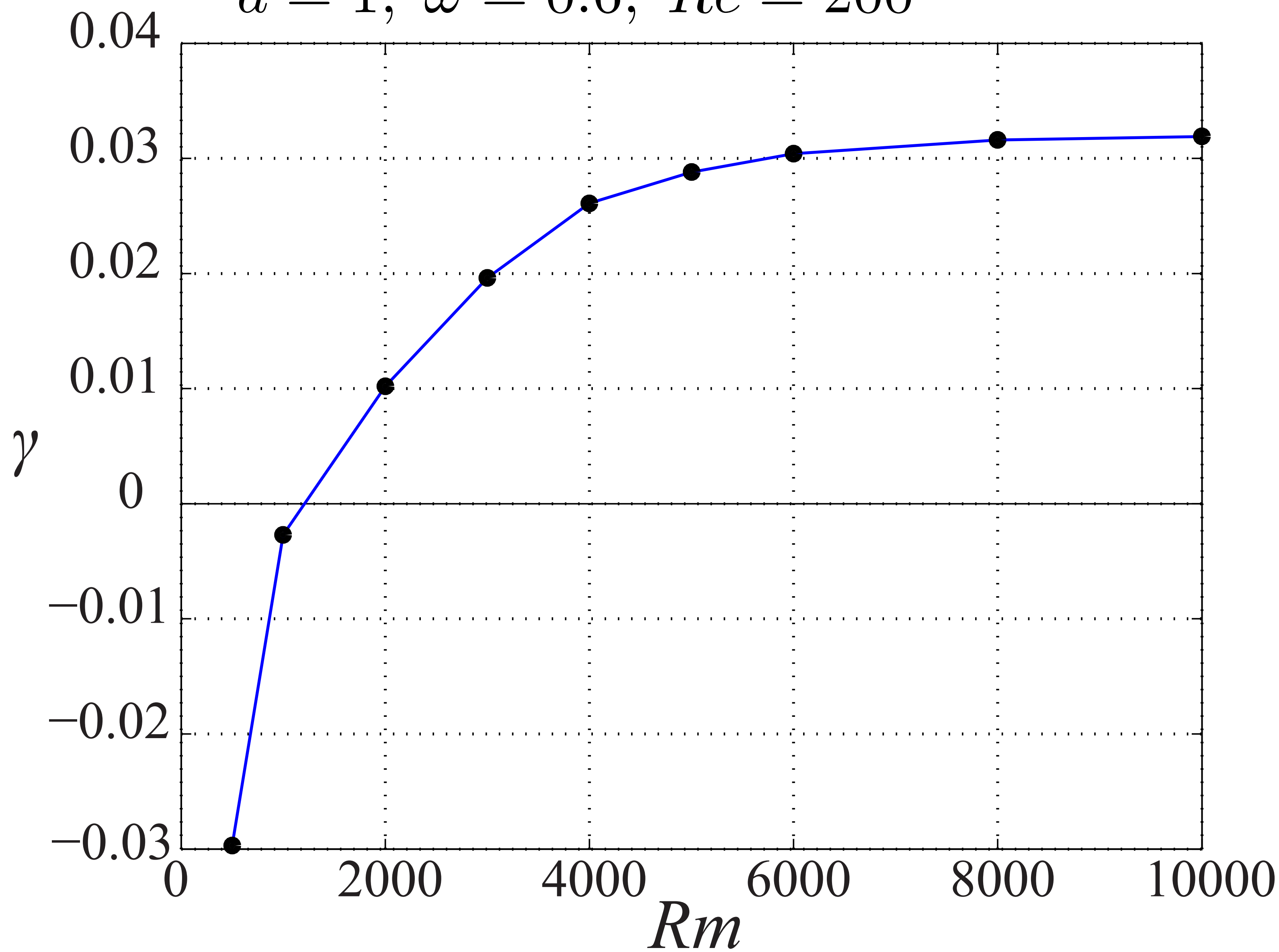
- Boundary: Re=200, ω=0.6 $V_\phi(\theta, t) = \sin 2\theta + a \sin\theta \sin\omega t$



Growth rate vs. Rm shows dynamo is a fast dynamo

Drive: $V_\phi(\theta, t) = \sin 2\theta + a \sin\theta \sin\omega t$ Unit of time: $t_0 = R_0/V_0$

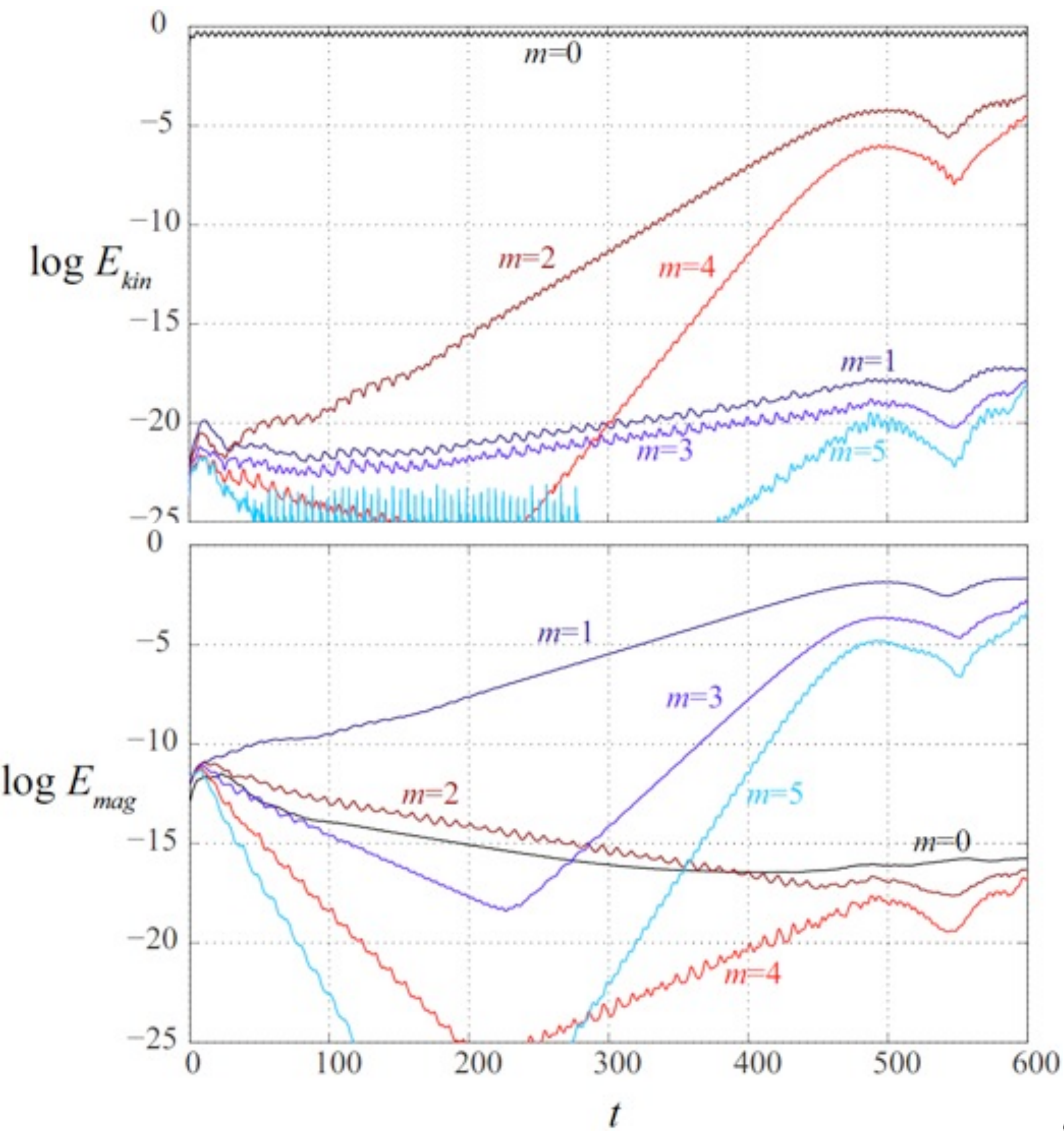
$a = 1,\ \omega = 0.6,\ Re = 200$



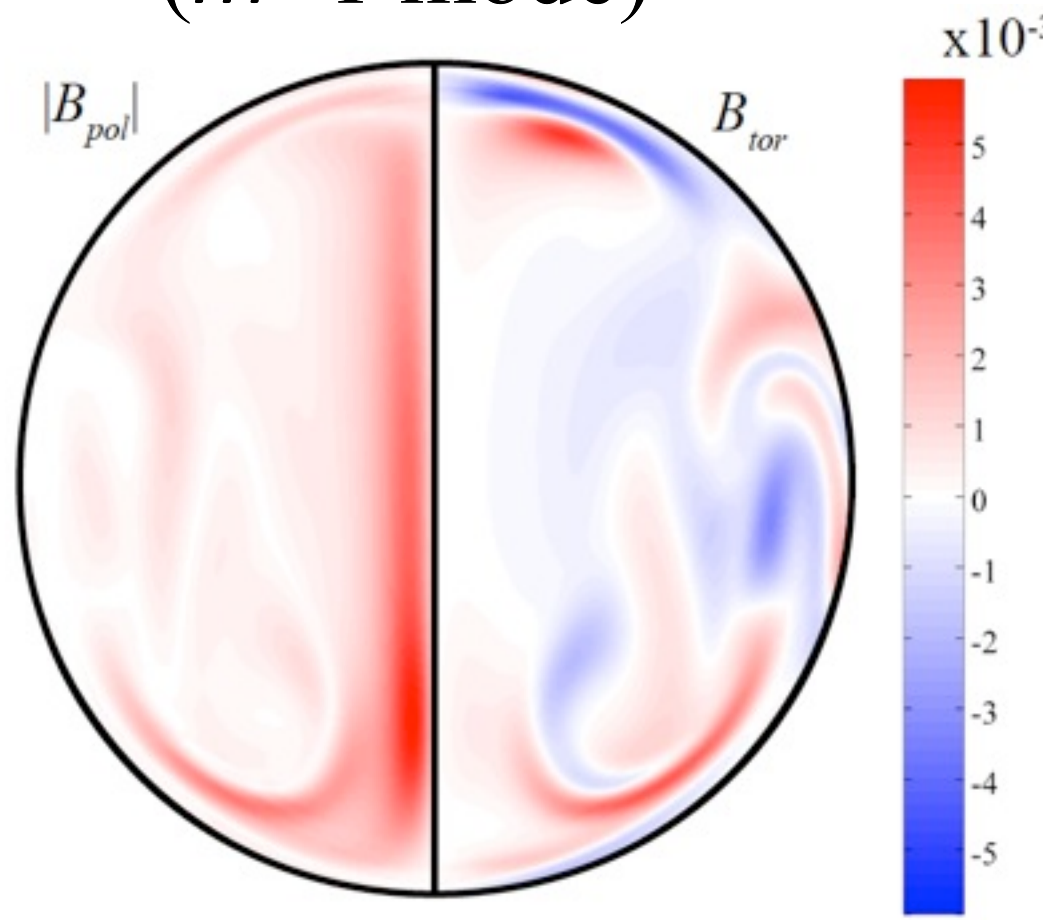
- Floquet Theory Eigenmode code (Khalzov)

Small-scale dynamo

Energies of modes vs. time

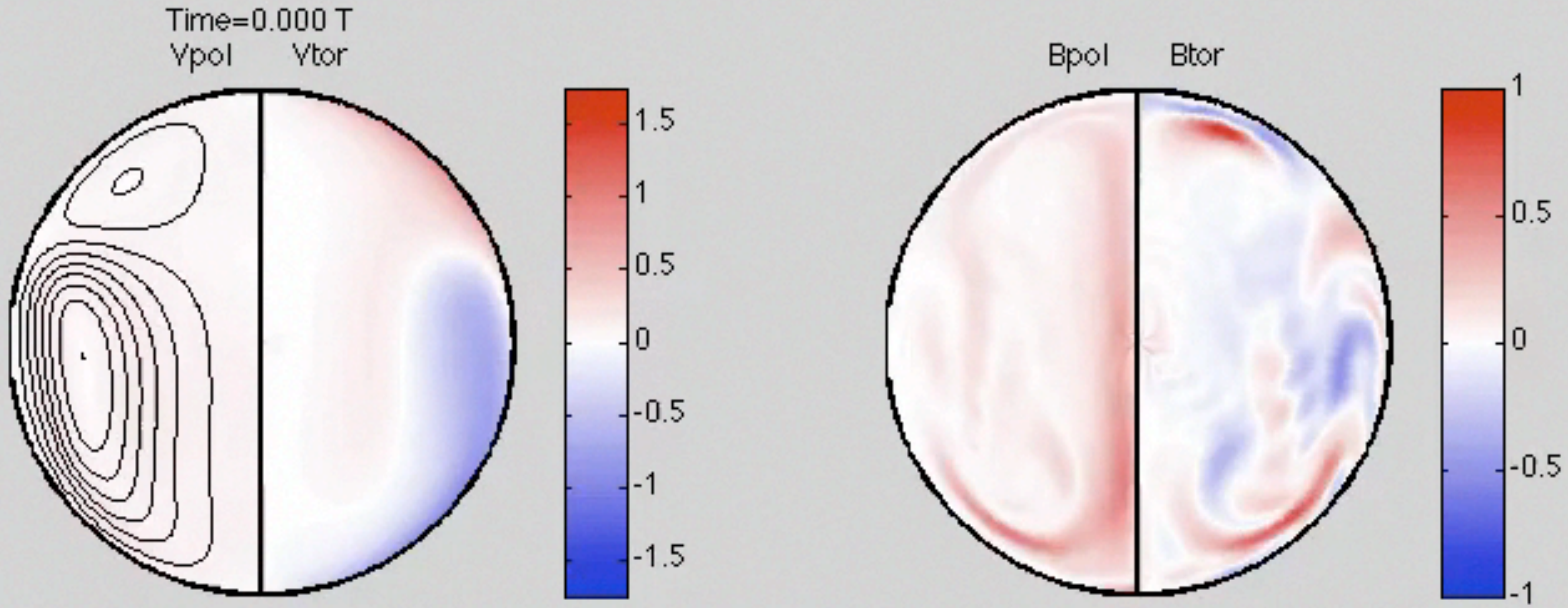


Dynamo field at t=300
(m=1 mode)



$$V_\phi(\theta, t) = \sin 2\theta + a \sin\theta \sin\omega t$$

$$a = 1,\ \omega = 0.6,\ Re = 200,\ Rm = 5000$$



Time=0.000 T
Vpol
Vtor
1.5
1
0.5
0
-0.5
-1
-1.5
Bpol
Btor
1
0.5
0
-0.5
-1

Fast dynamo eigen-mode structure
(*Re*=200, *Rm*=5000, *m*=1)

- Dynamics during one period $T=2\pi/\omega=10.47$ (unit of time: $t_0=R_0/V_0$)