Lab Experiments on Magnetically Driven Jets

Paul Bellan

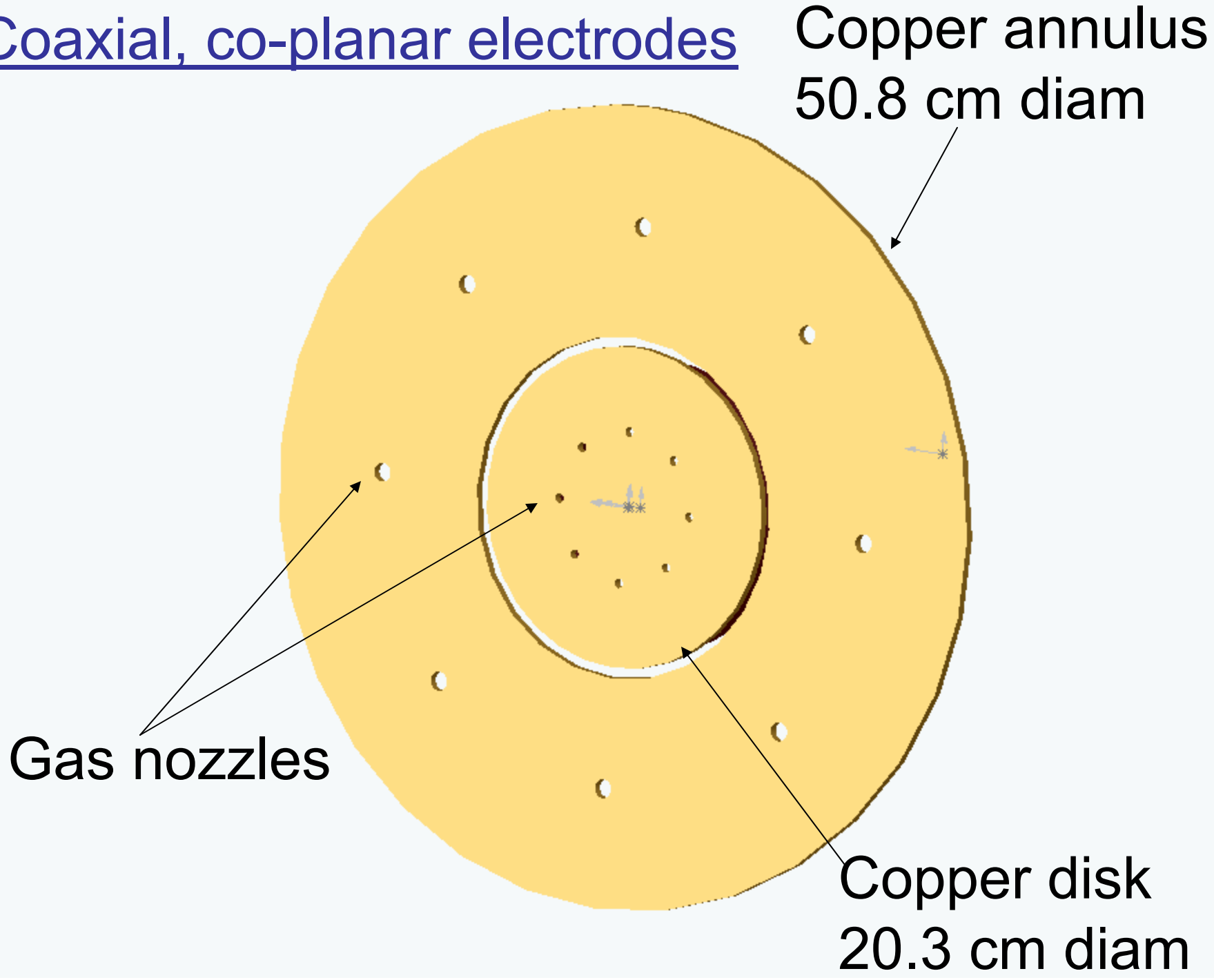
Caltech

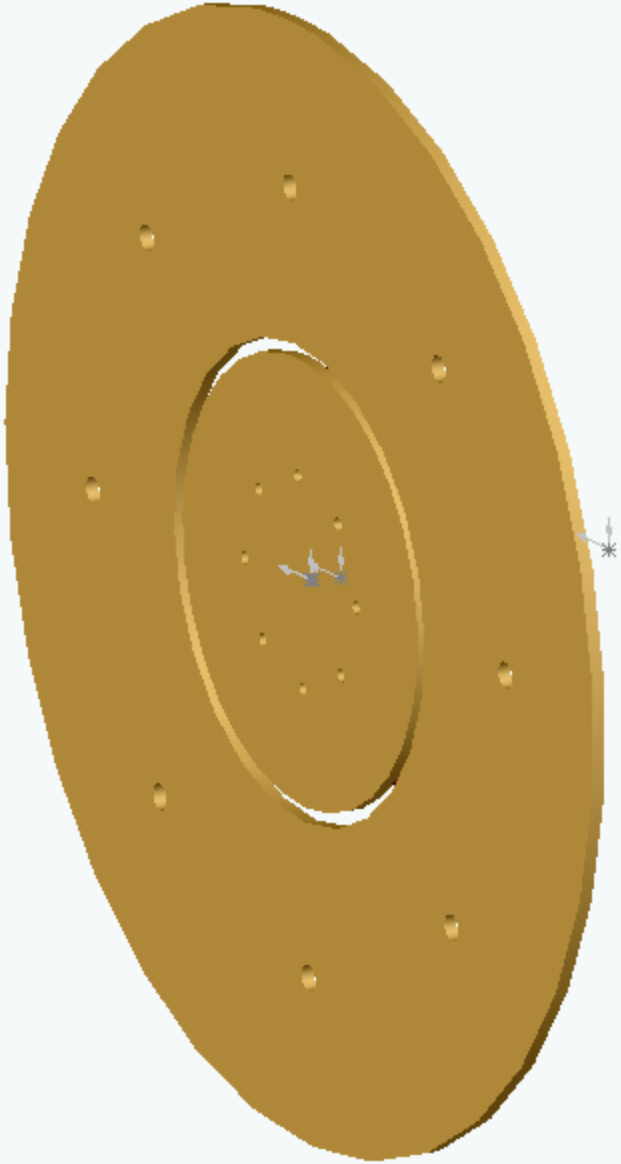
Students, postdocs

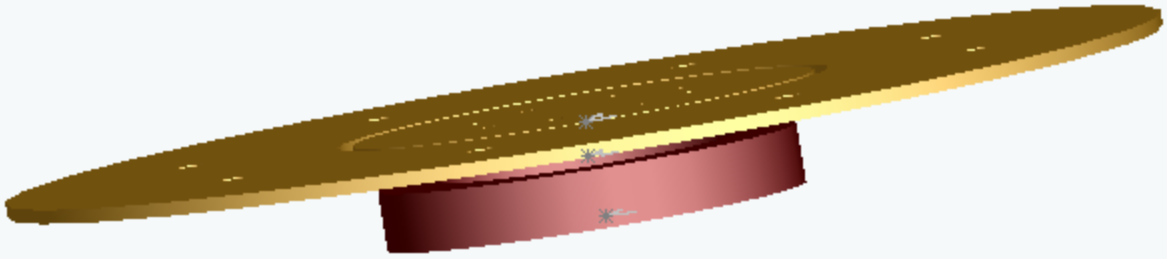
Scott Hsu (now at LANL)
Sett You (now at U. Tokyo)
Shreekrishna Tripathi (now at UCLA)
Gunsu Yun (now at LAM Research)
Auna Moser
Deepak Kumar
Rory Perkins
Eve Stenson

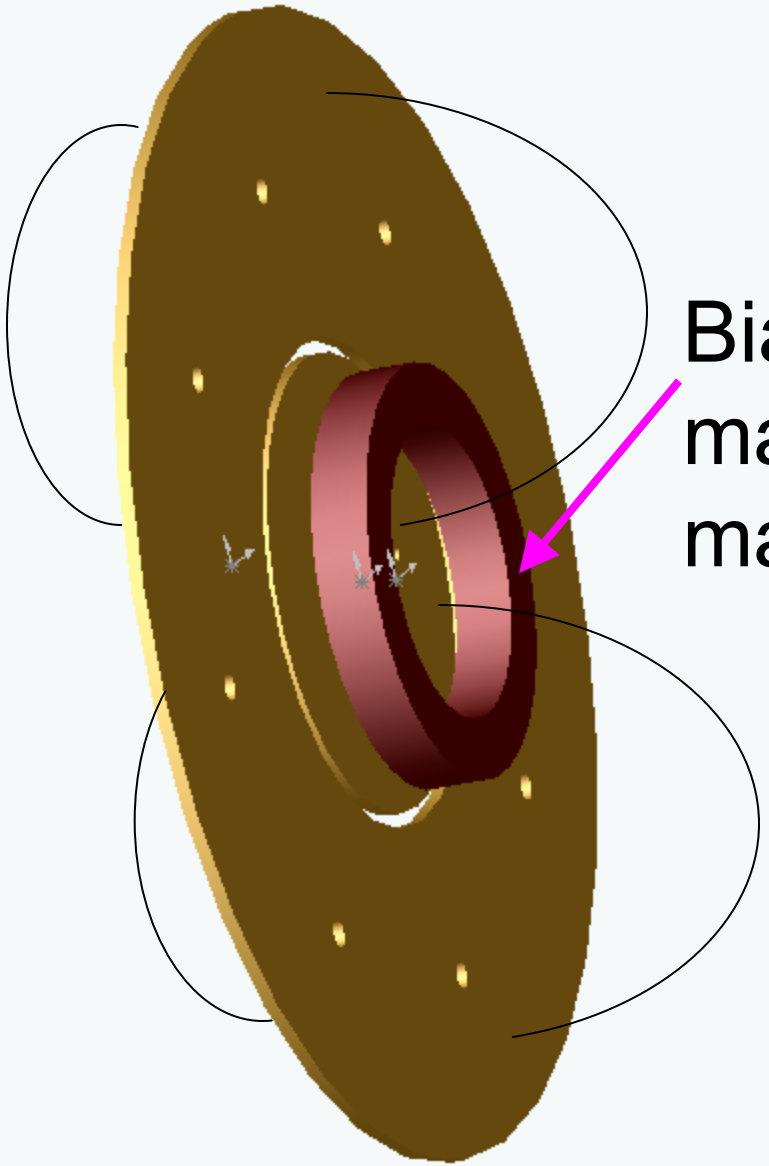
Setup

Coaxial, co-planar electrodes

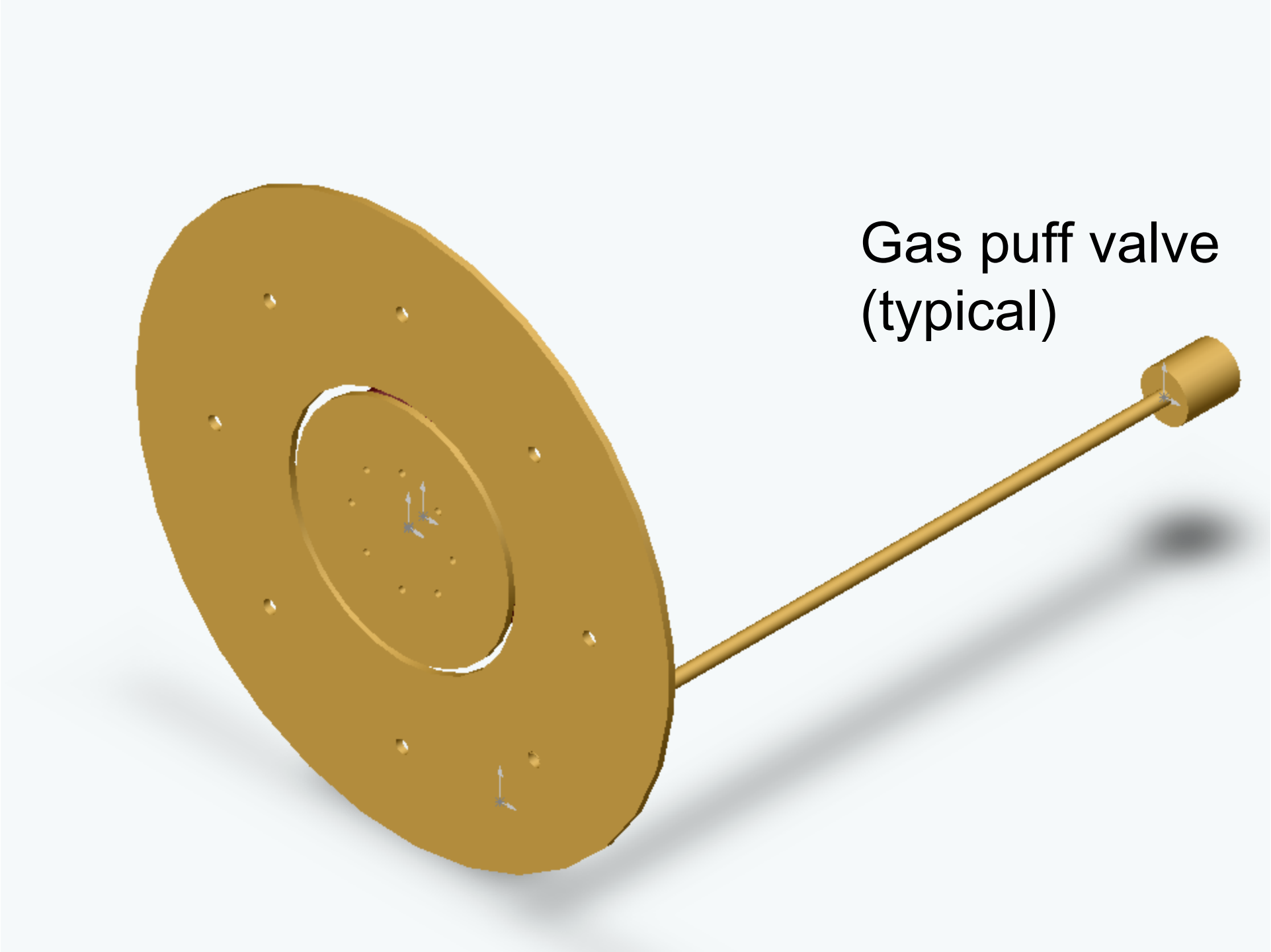


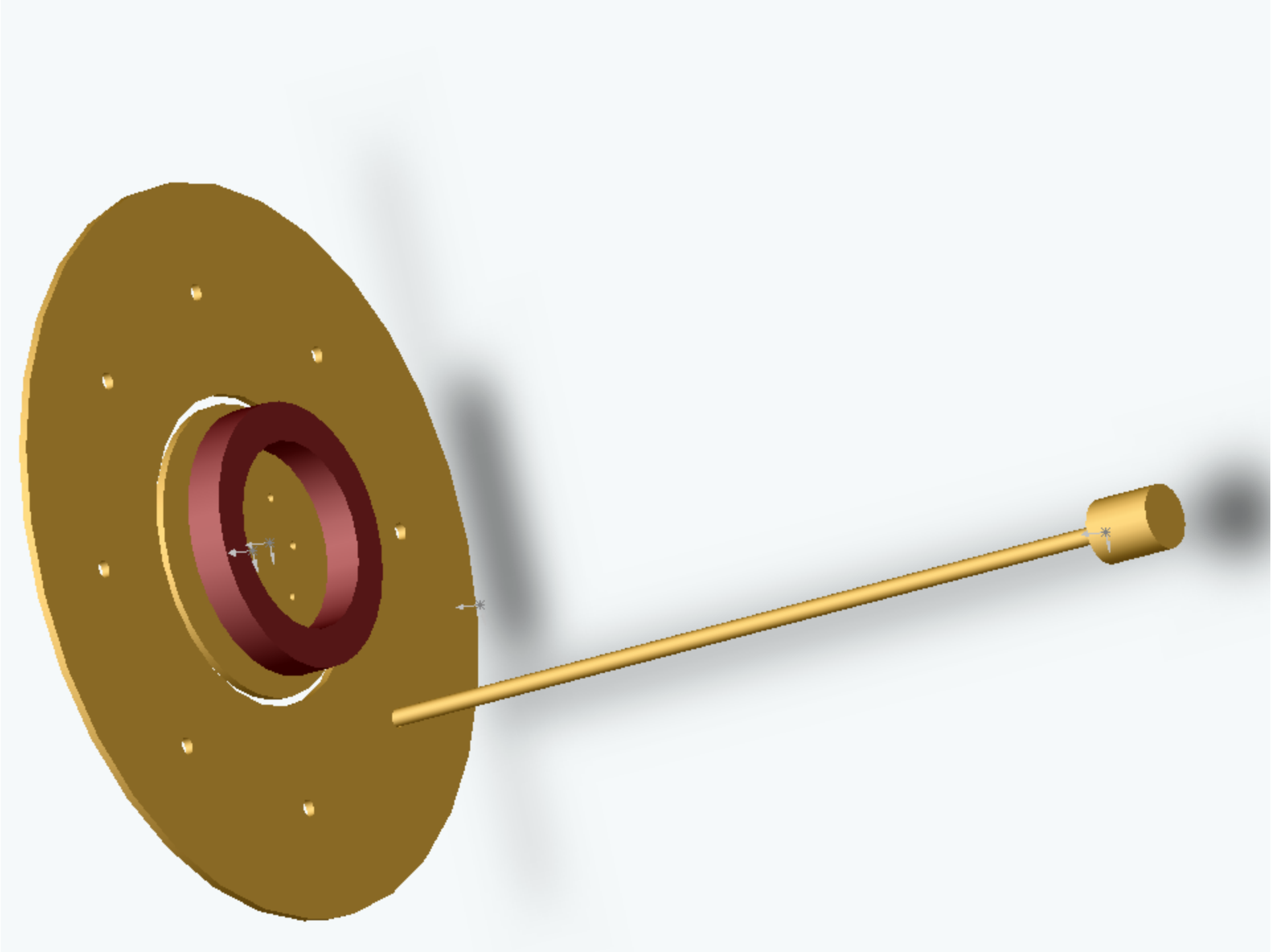


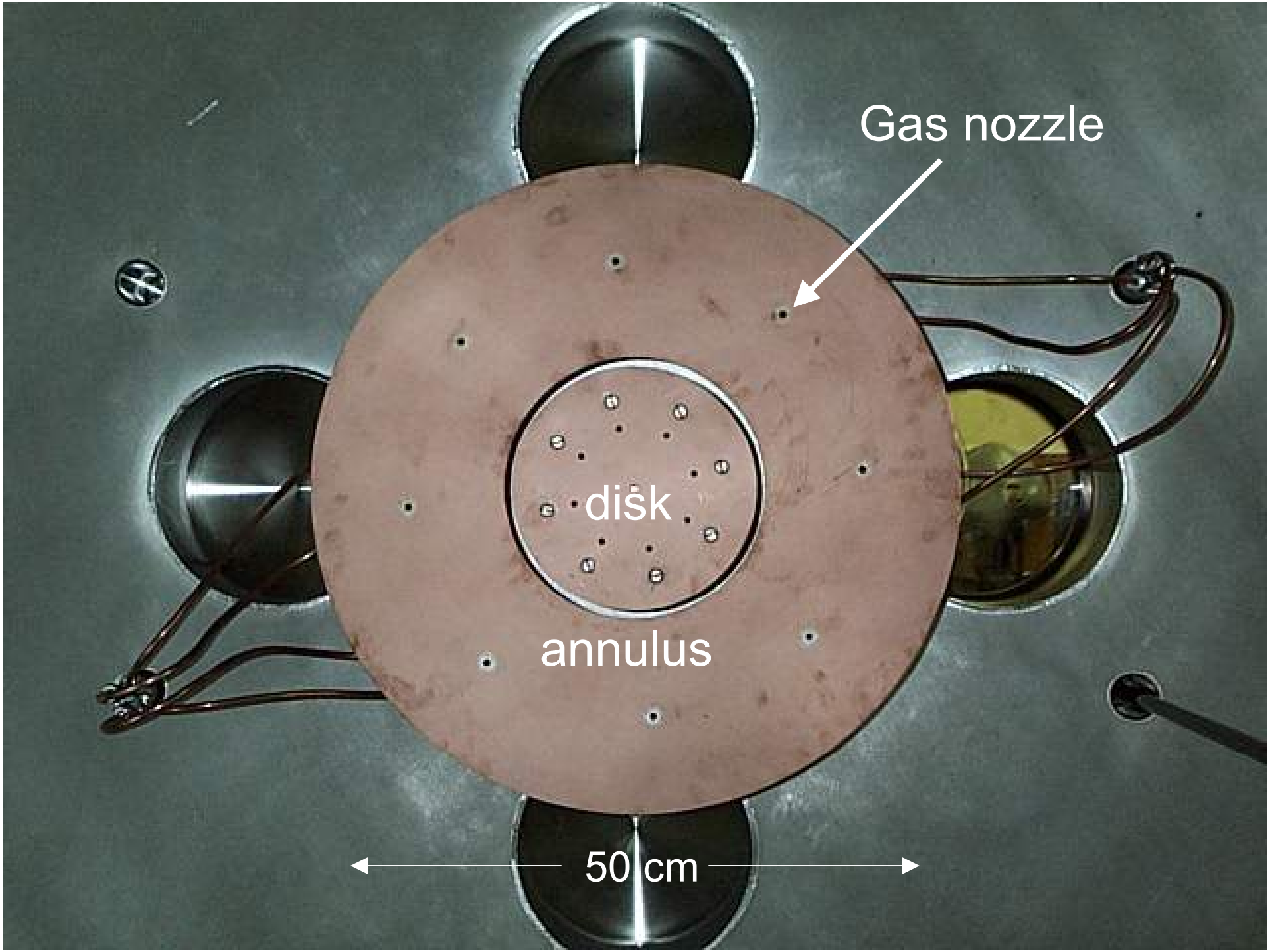


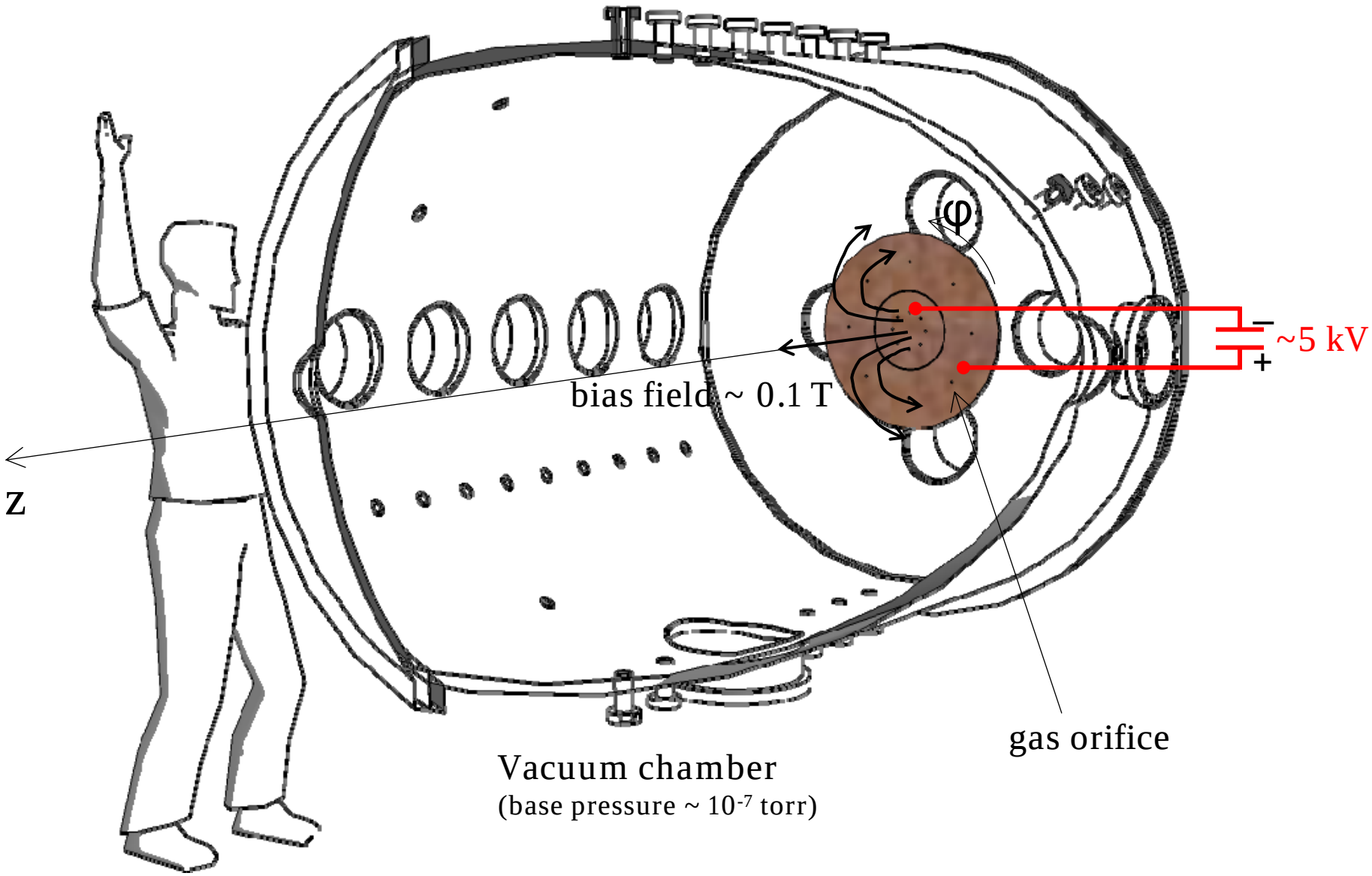


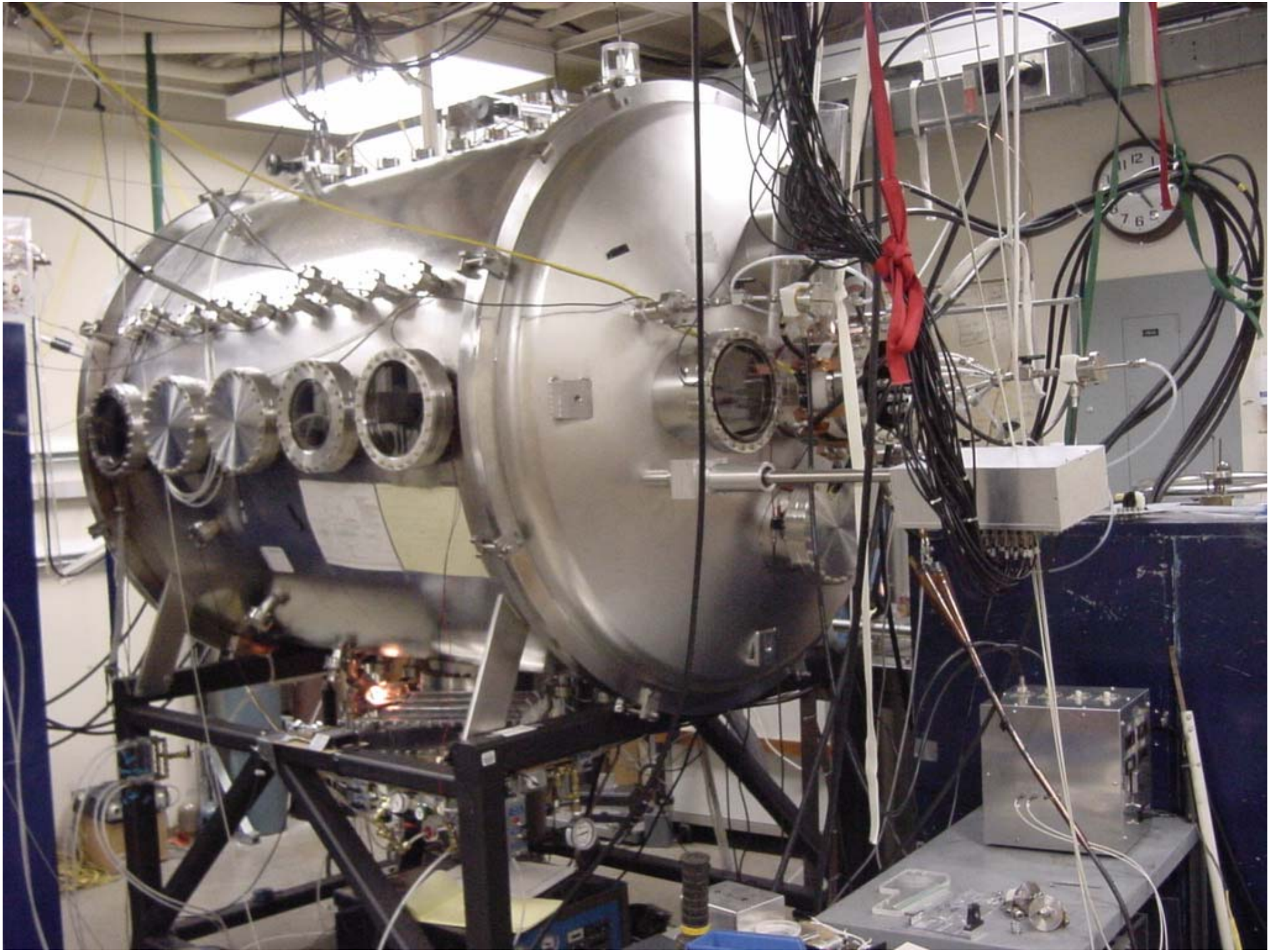
Bias field coil makes linked magnetic flux


Gas puff valve
(typical)




Gas nozzle
disk
annulus
50 cm


φ
~5 kV
−
+
bias field ~ 0.1 T
z
gas orifice
Vacuum chamber
(base pressure ~ 10-7 torr)



Nominal parameters

t	1 to 20 μs
B	0.01 to ~ 0.1 T
I	~150 kA
V	3 to 6kV on cap bank
Gas	H, D, Ne, N, Ar, Xe
n	up to 10^{23} m^{-3}
L	5 to 50 cm
β	<<1 to 1
Lundquist	~10^3

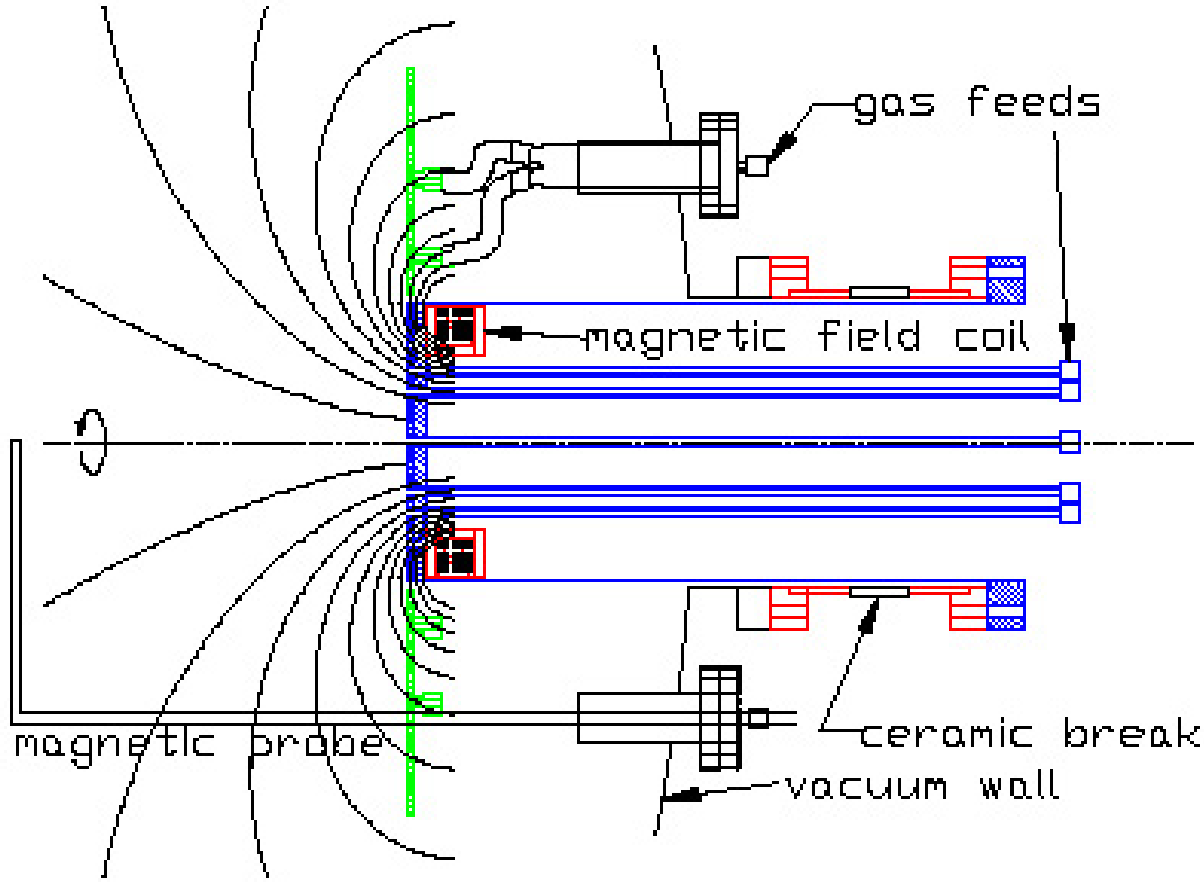
Diagnostics

- High speed photography (10 million frame/sec)
- Magnetic probe array for internal magnetic fields
- Electric current
- Voltage
- Soft x-ray diodes
- Hard x-ray scintillator
- Spectroscopy –Doppler shift velocity
- Spectroscopy –Stark broadening plasma density
- Laser interferometry – plasma density
- Fast ion gauge for neutral density profile

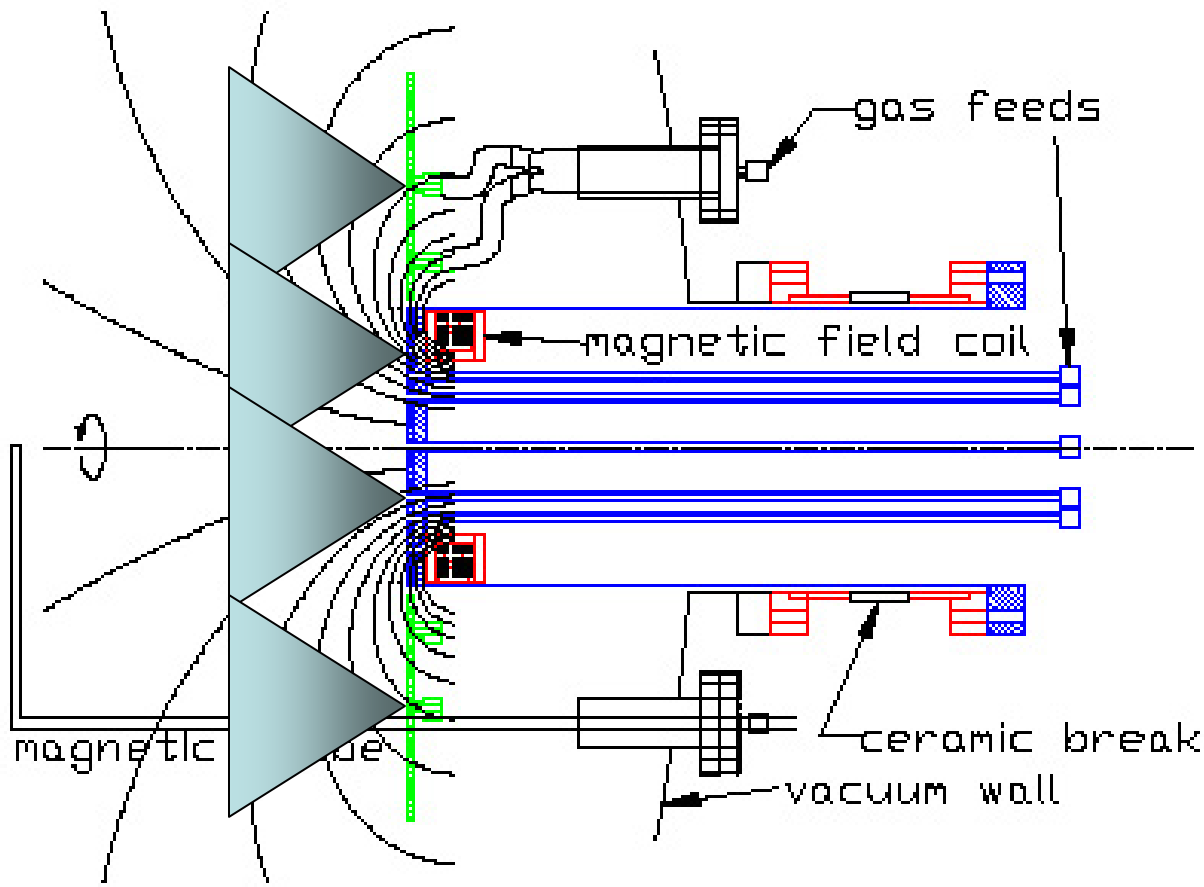
Sequence

Bias field

high vacuum



Puff in neutral gas

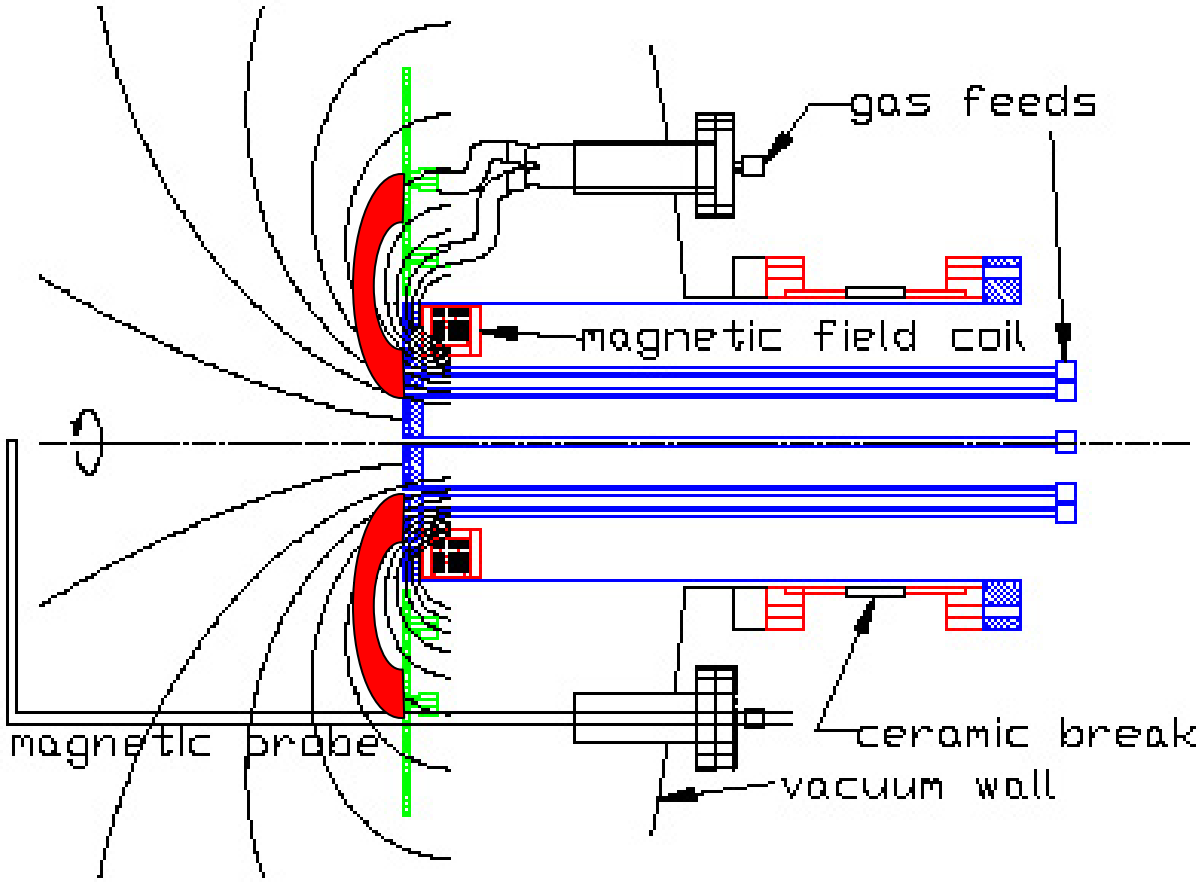


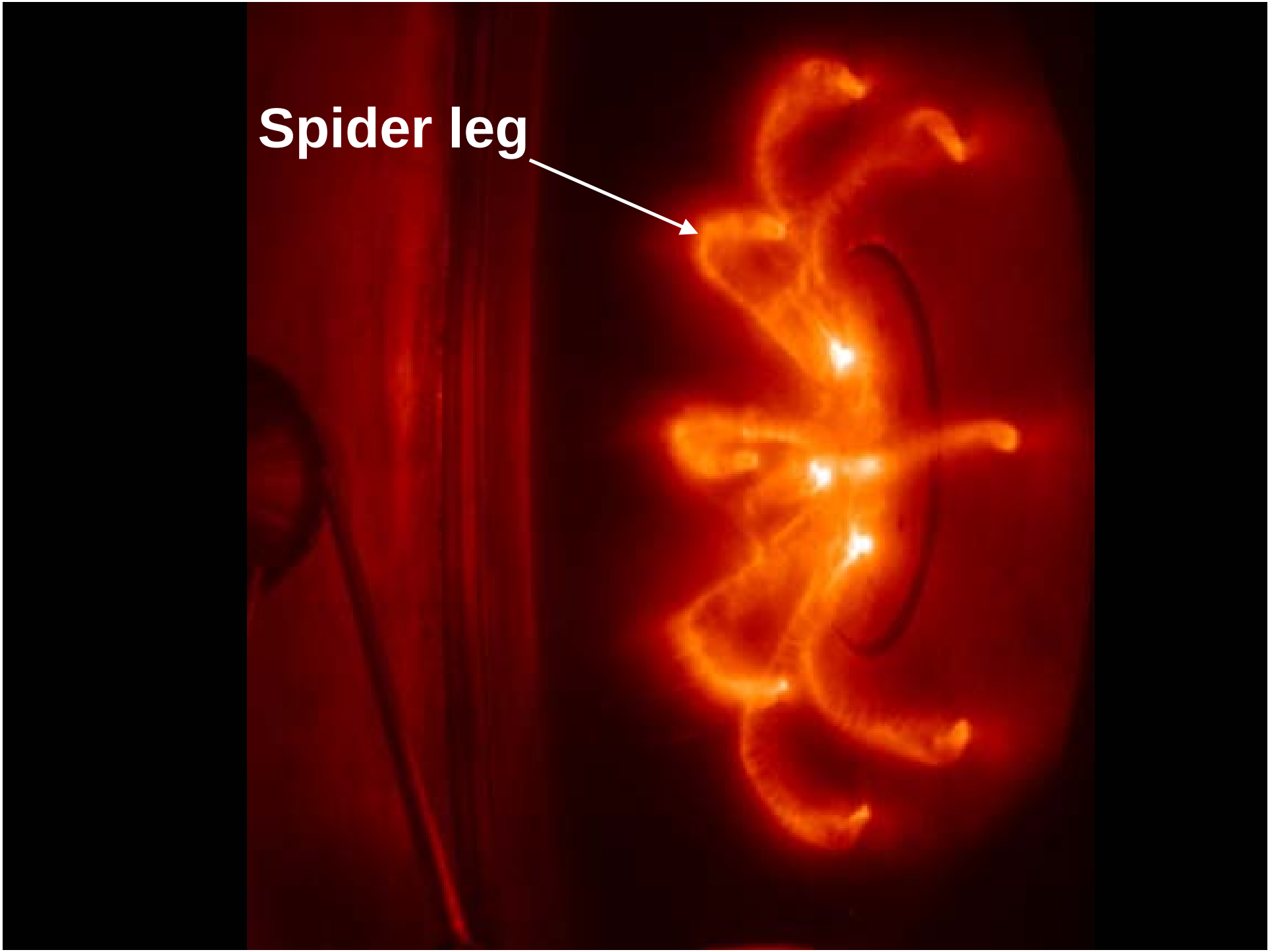
Apply high voltage across gap between disk and annulus

Steps:

1. Distinct, arched filamentary plasma loops
2. Loops merge to form central column
3. Jet-like axial expansion of central column
4. Kink instability of central column

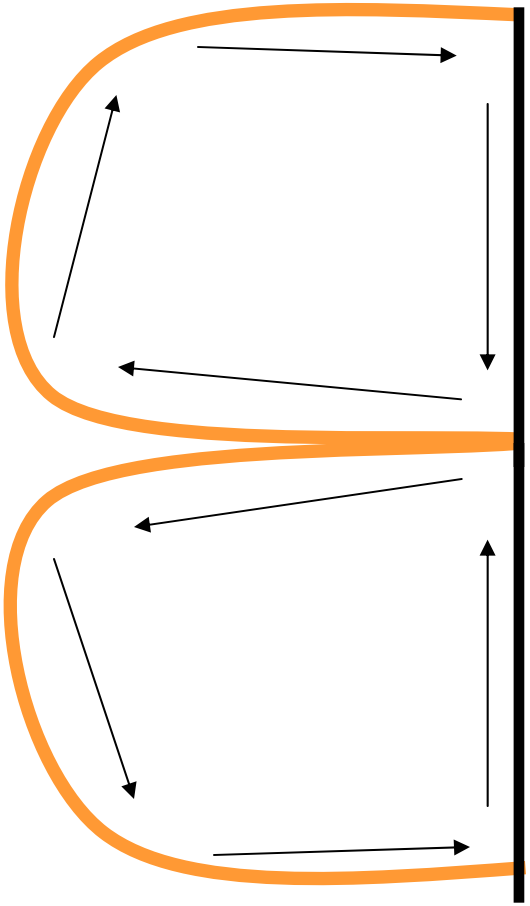
Breakdown, “spider leg formation”



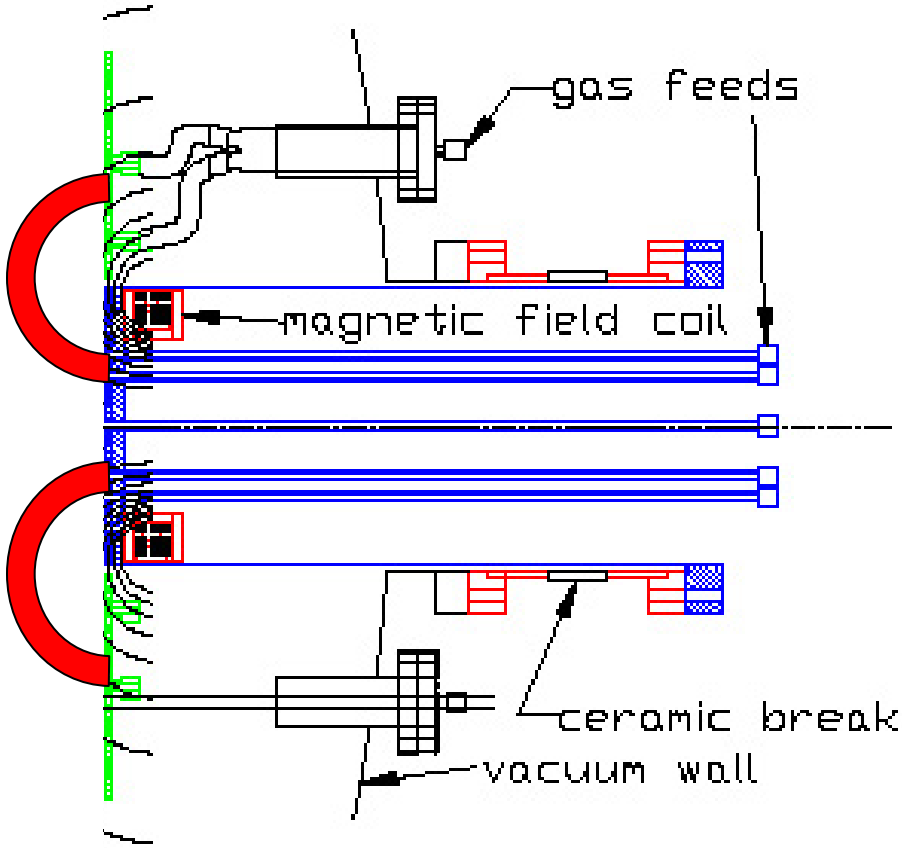

Spider leg

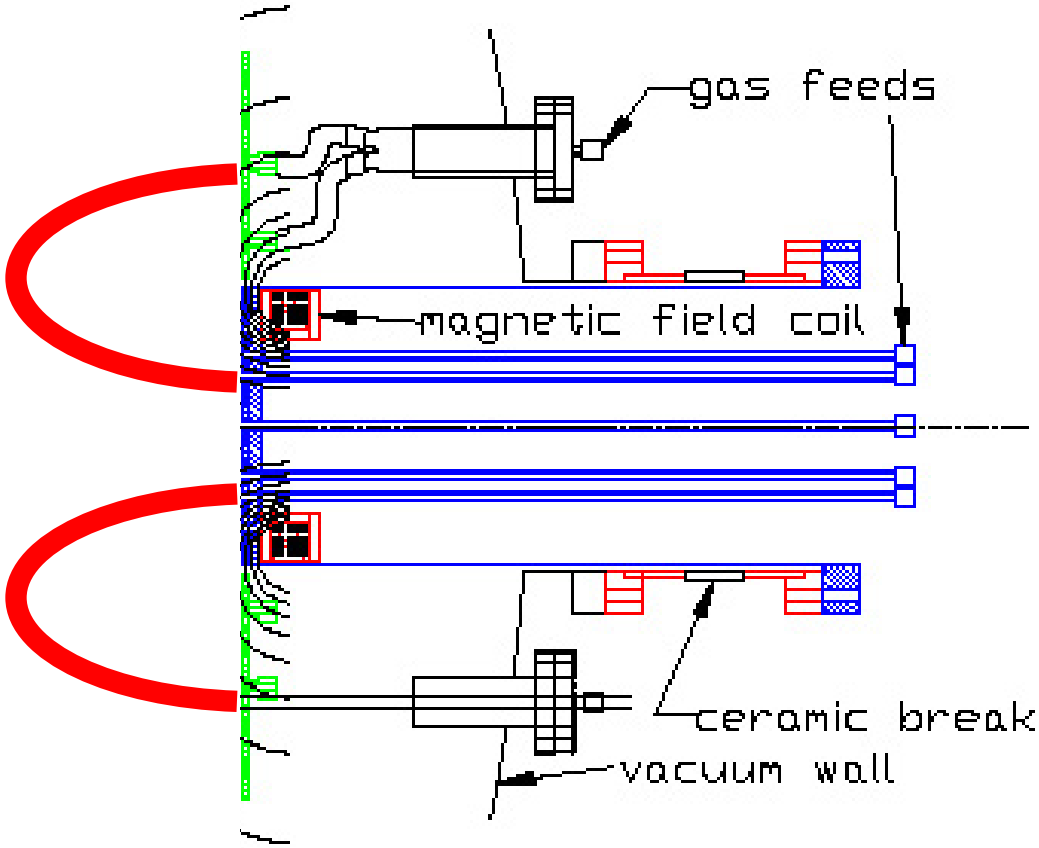
MHD physics

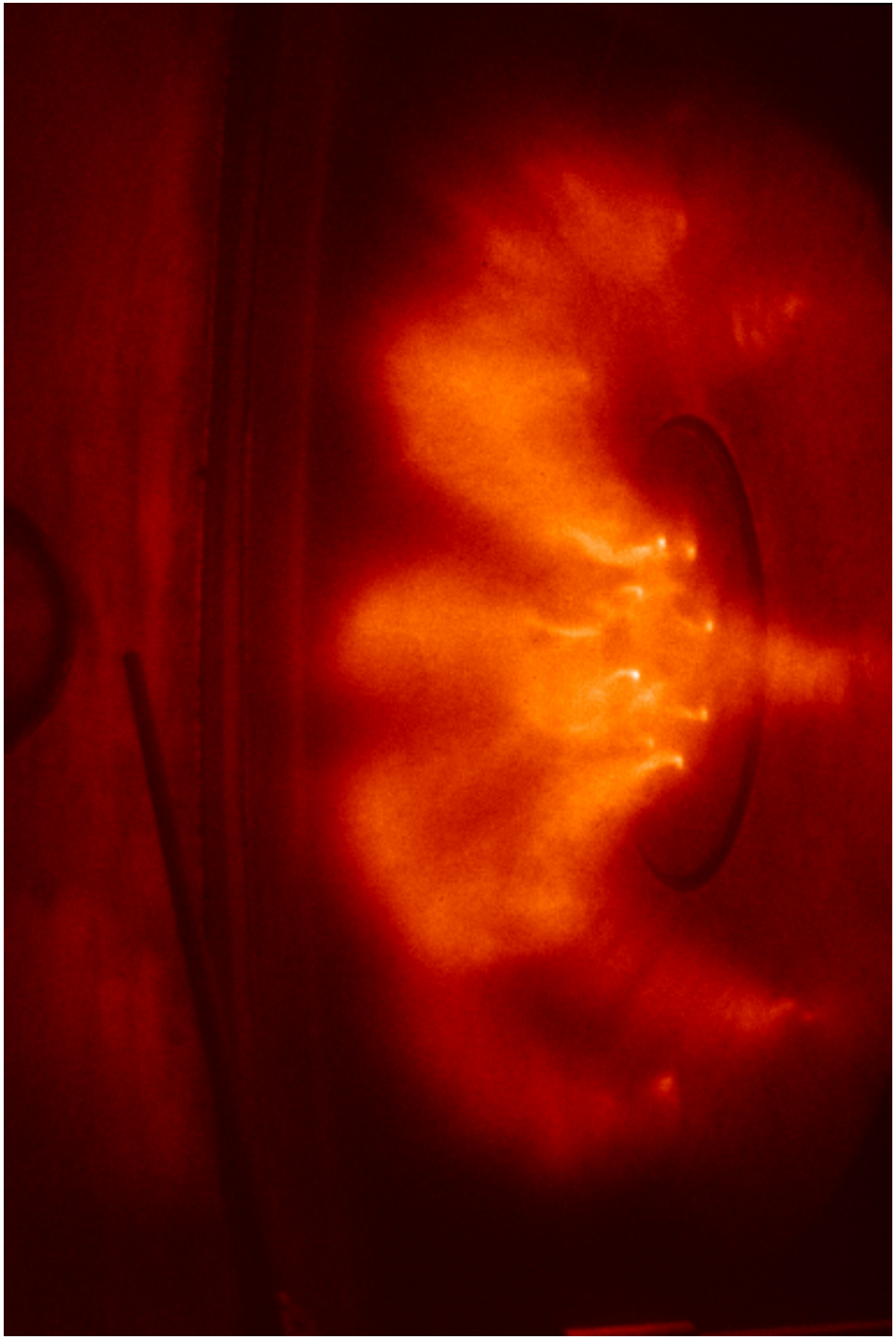
- Anti-parallel currents repel



Spider legs get bigger




gas feeds
magnetic field coil
ceramic break
vacuum wall

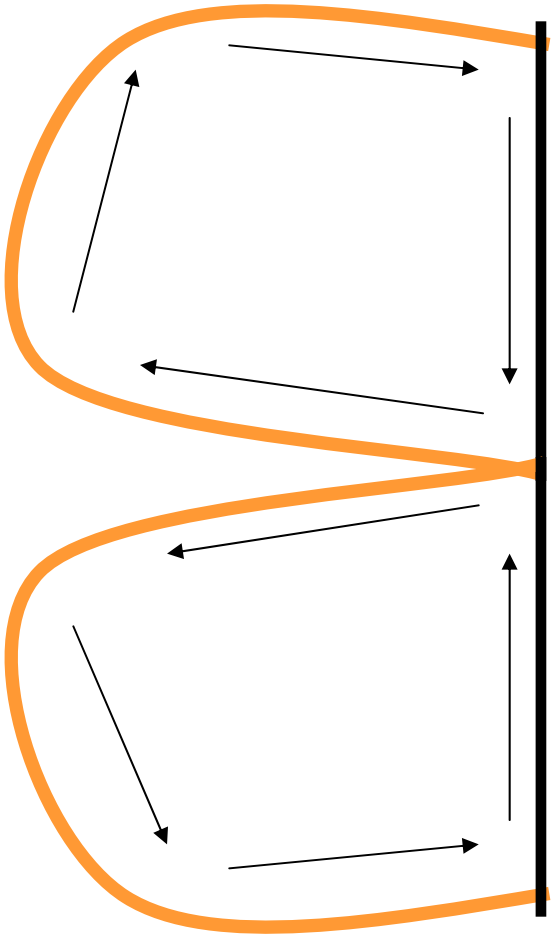


Steps:

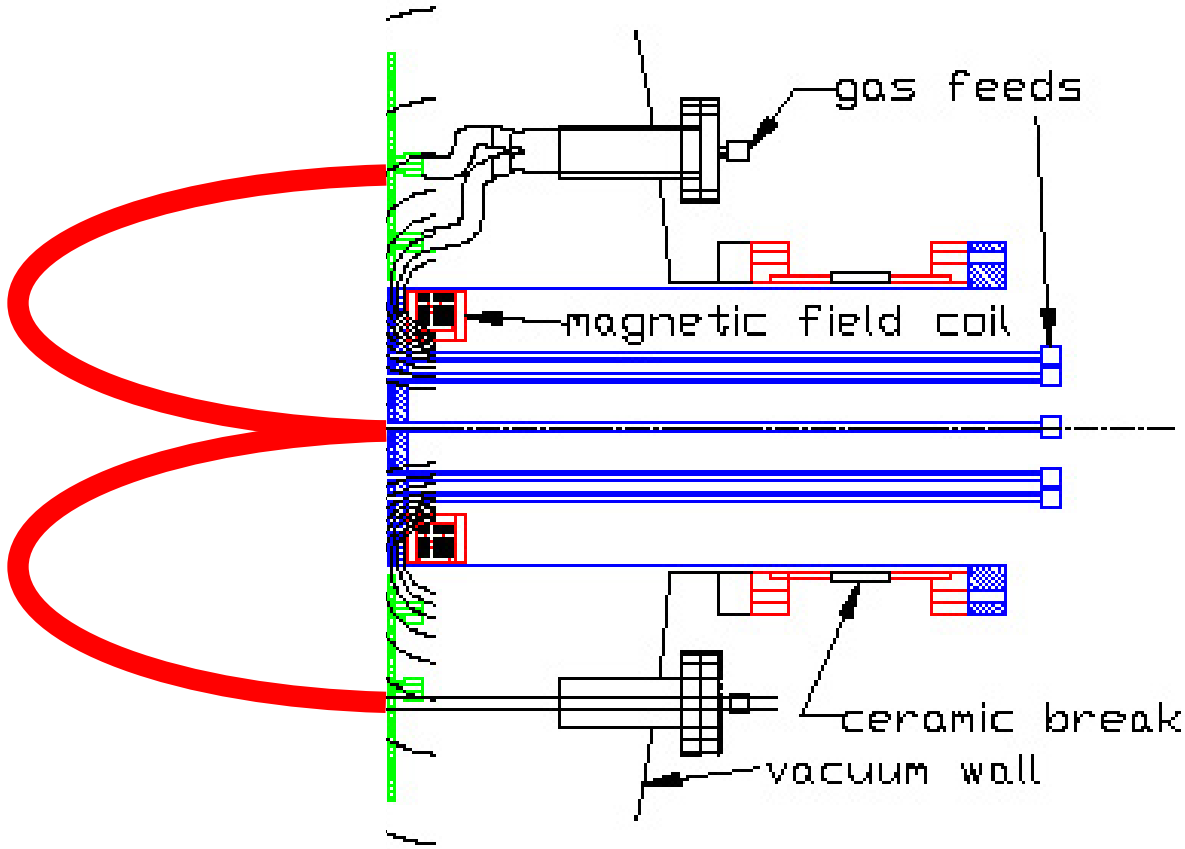
1. Creation of distinct, arched filamentary plasma loops
2. Filaments merge to form central column
3. Jet-like axial expansion of central column
4. Kink instability of central column

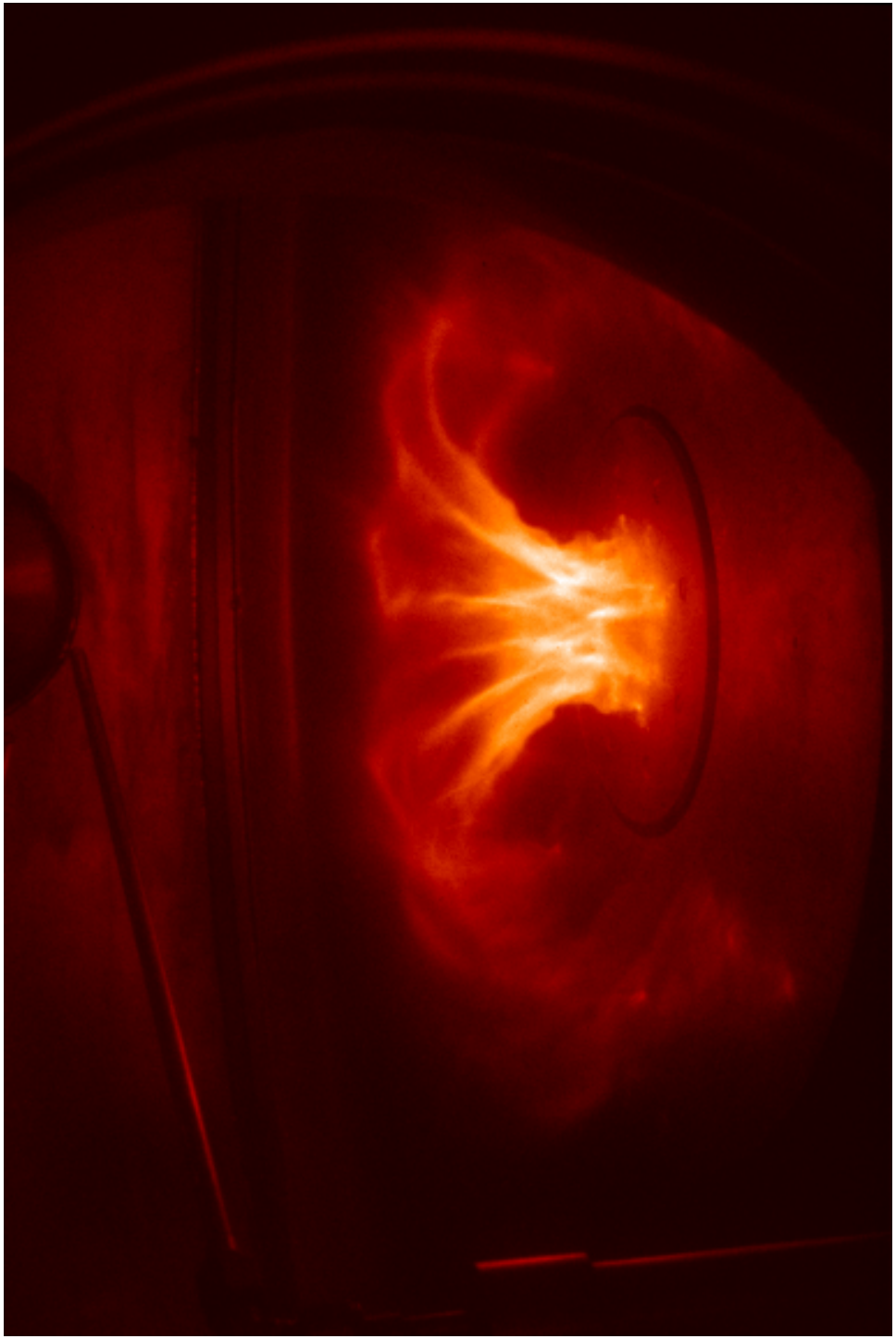
MHD physics

- Parallel currents attract



Spider legs merge to form central column

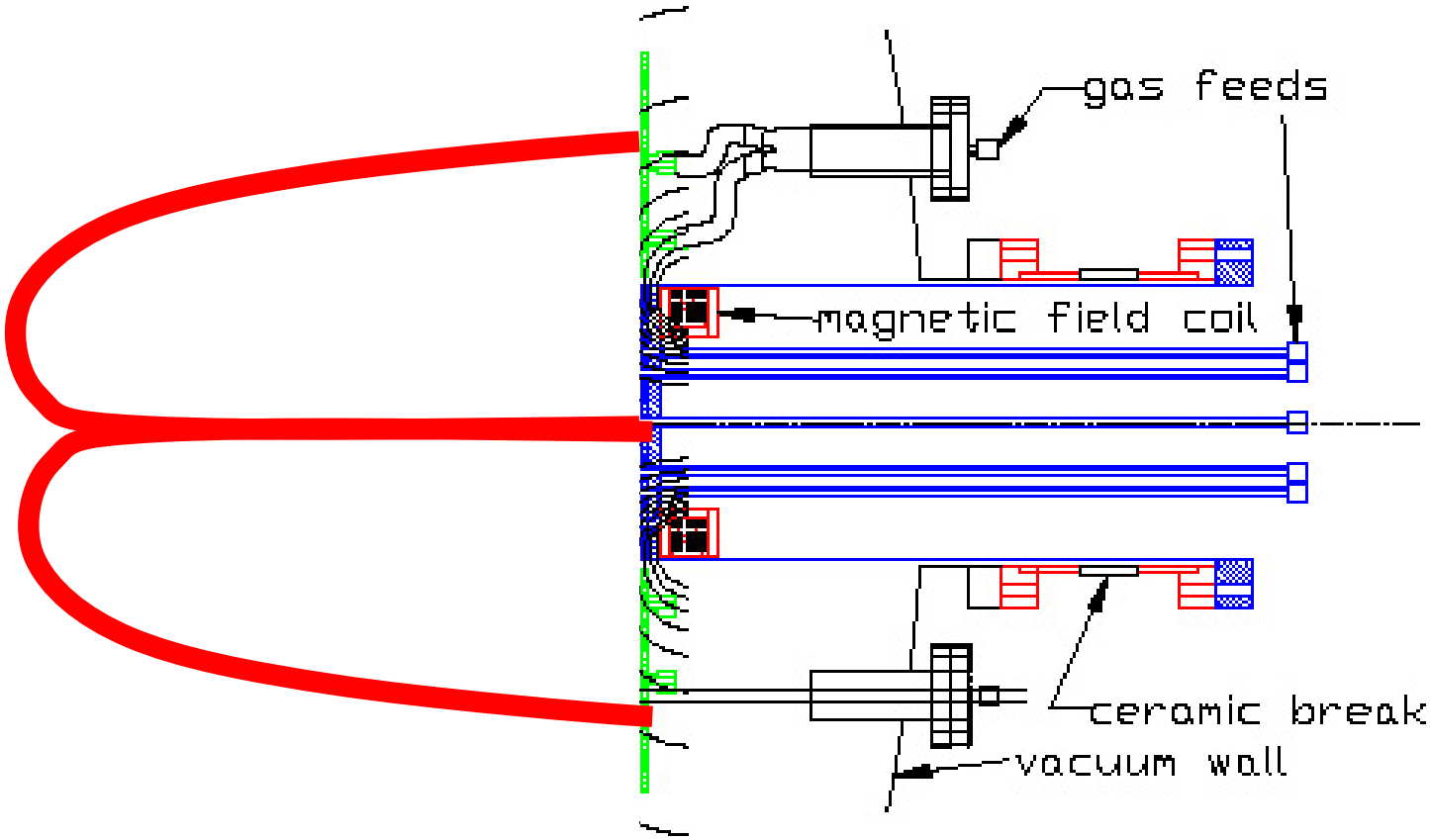




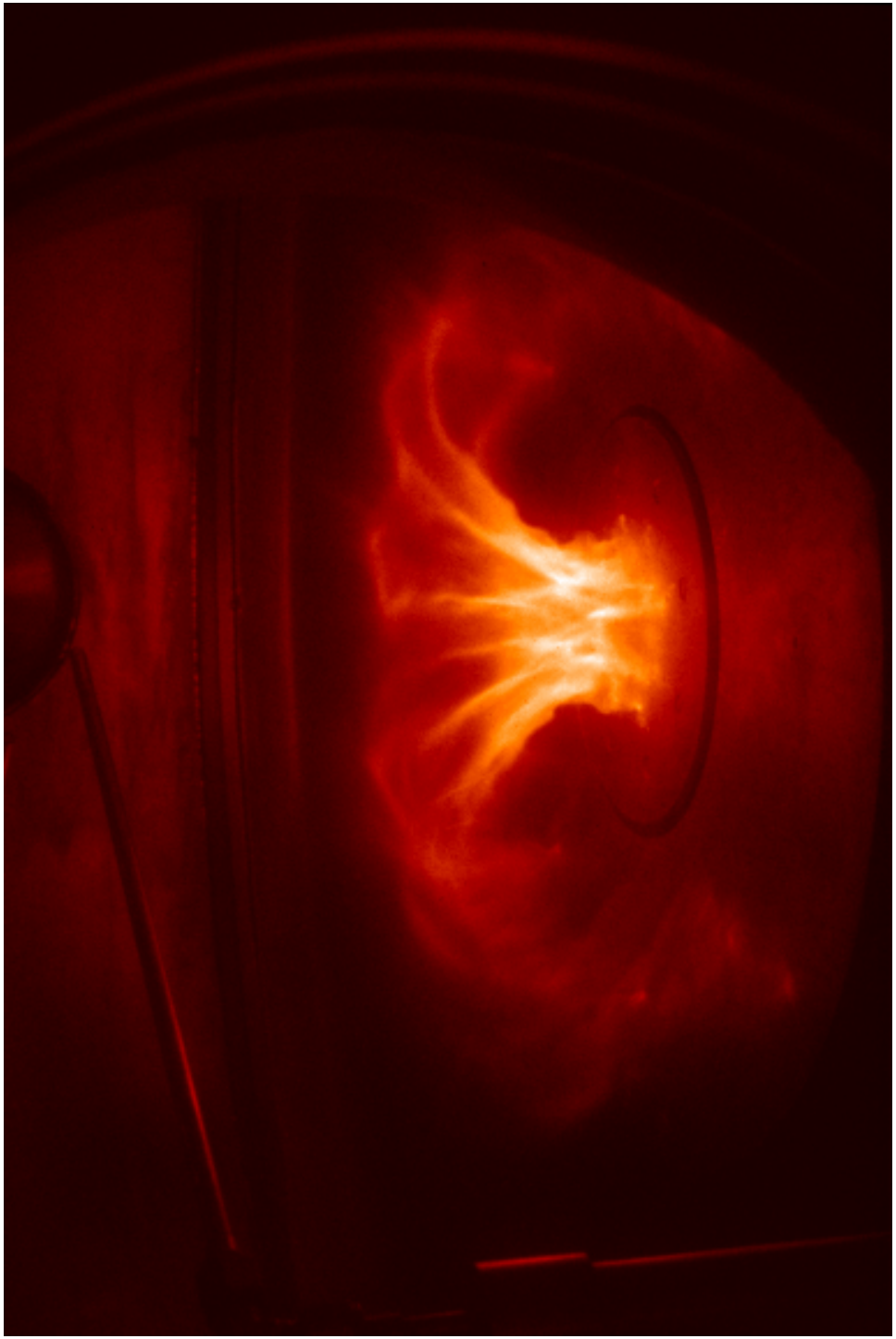
Steps:

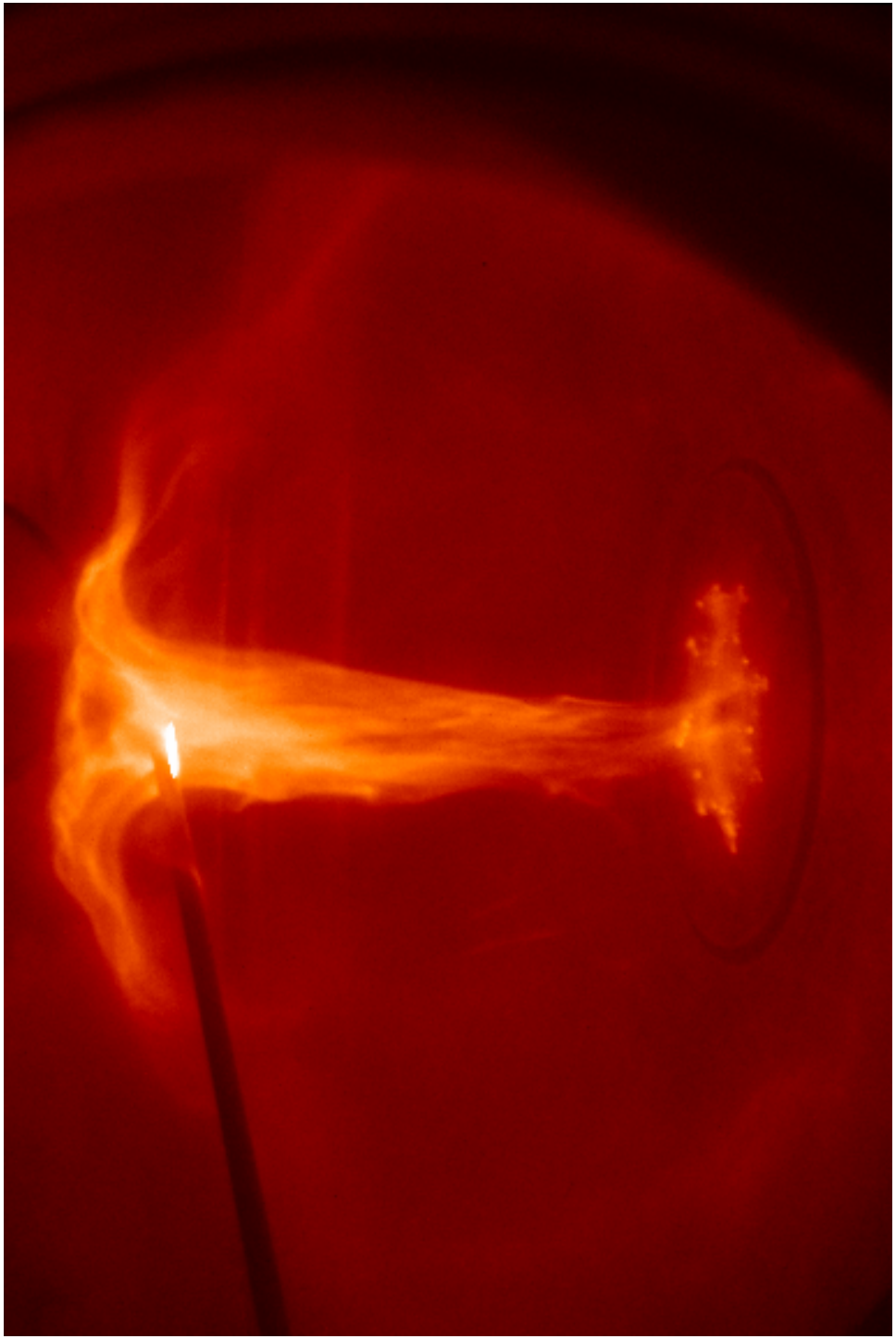
1. Creation of distinct, arched filamentary plasma loops
2. Filaments merge to form central column
3. Jet-like axial expansion of central column
4. Kink instability of central column

Central column lengthens



I ~ 150 kA

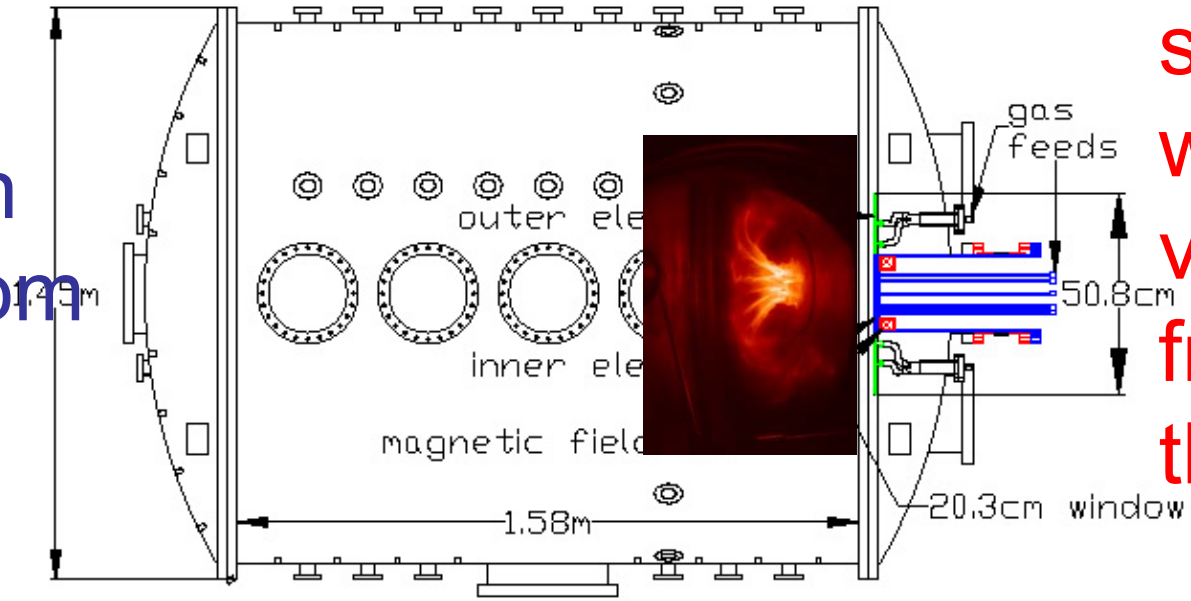




Doppler Shift Measurement

Velocities ~ 10-60 km/s observed

Blue shift seen when viewing from this end

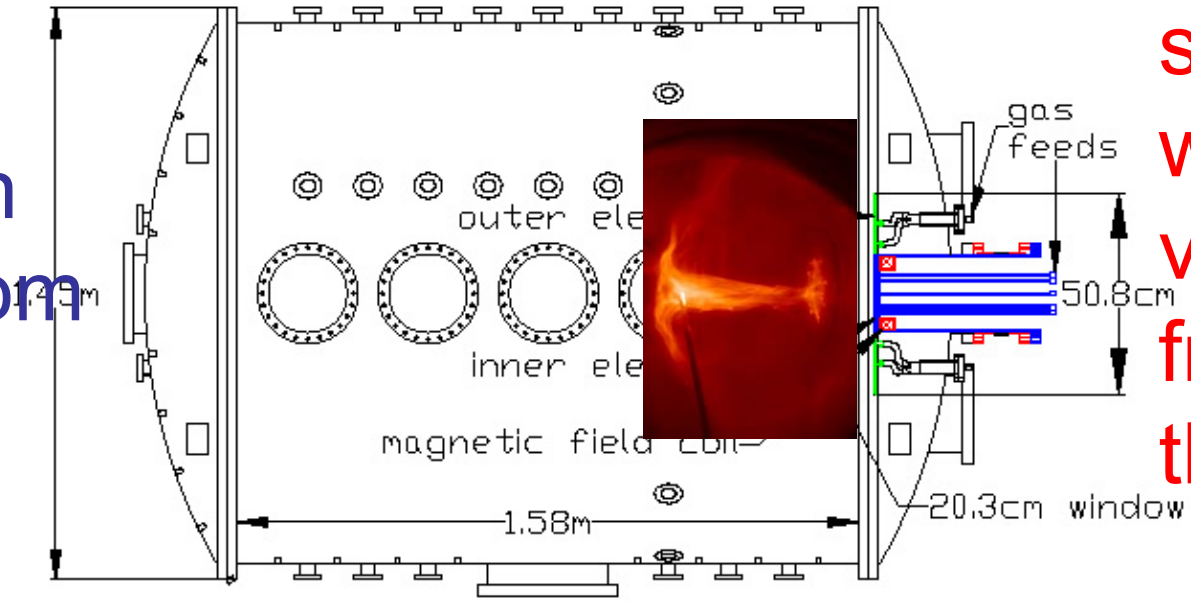


Red shift seen when viewing from this end

Doppler Shift Measurement

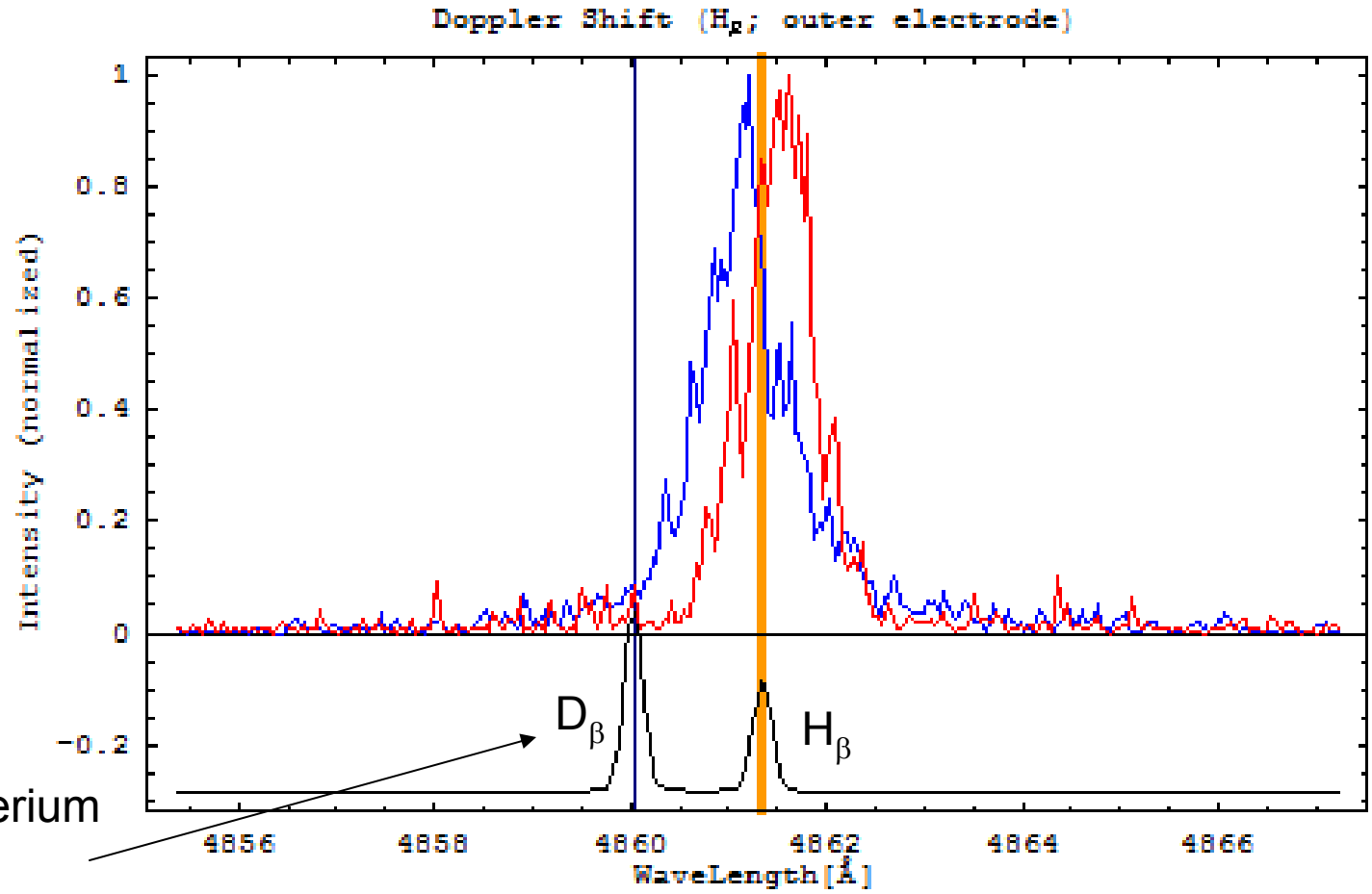
Velocities ~ 15-60 km/s observed

Blue shift seen when viewing from this end



Red shift seen when viewing from this end

Example of Doppler shift data



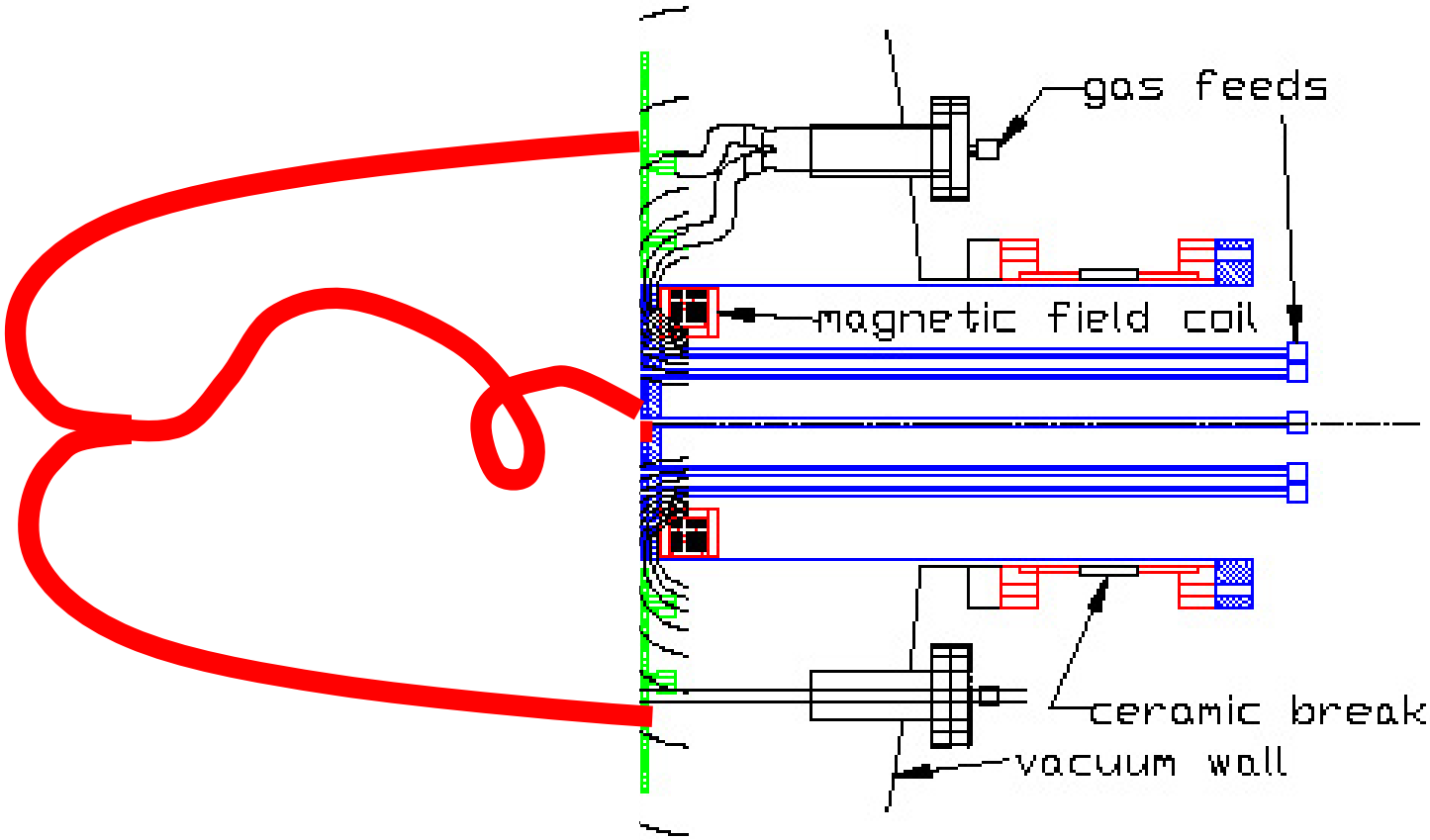
hydrogen, deuterium calibration lines from reference lamp

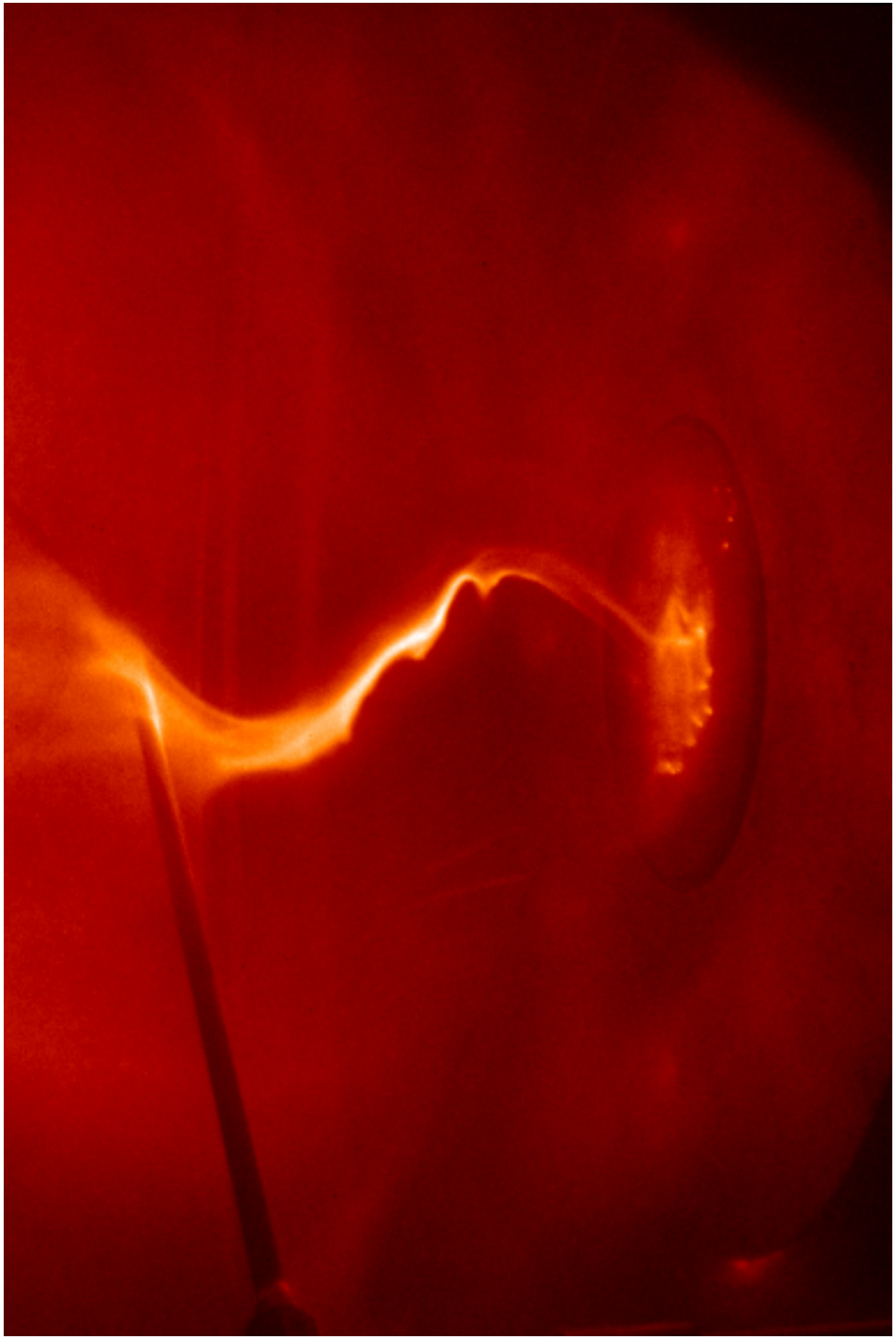
```
Blue : 4861.15 ⟹ -11.3339 [km/s] (blue shift)
Red  : 4861.54 ⟹ 13.165 [km/s] (red shift)
```

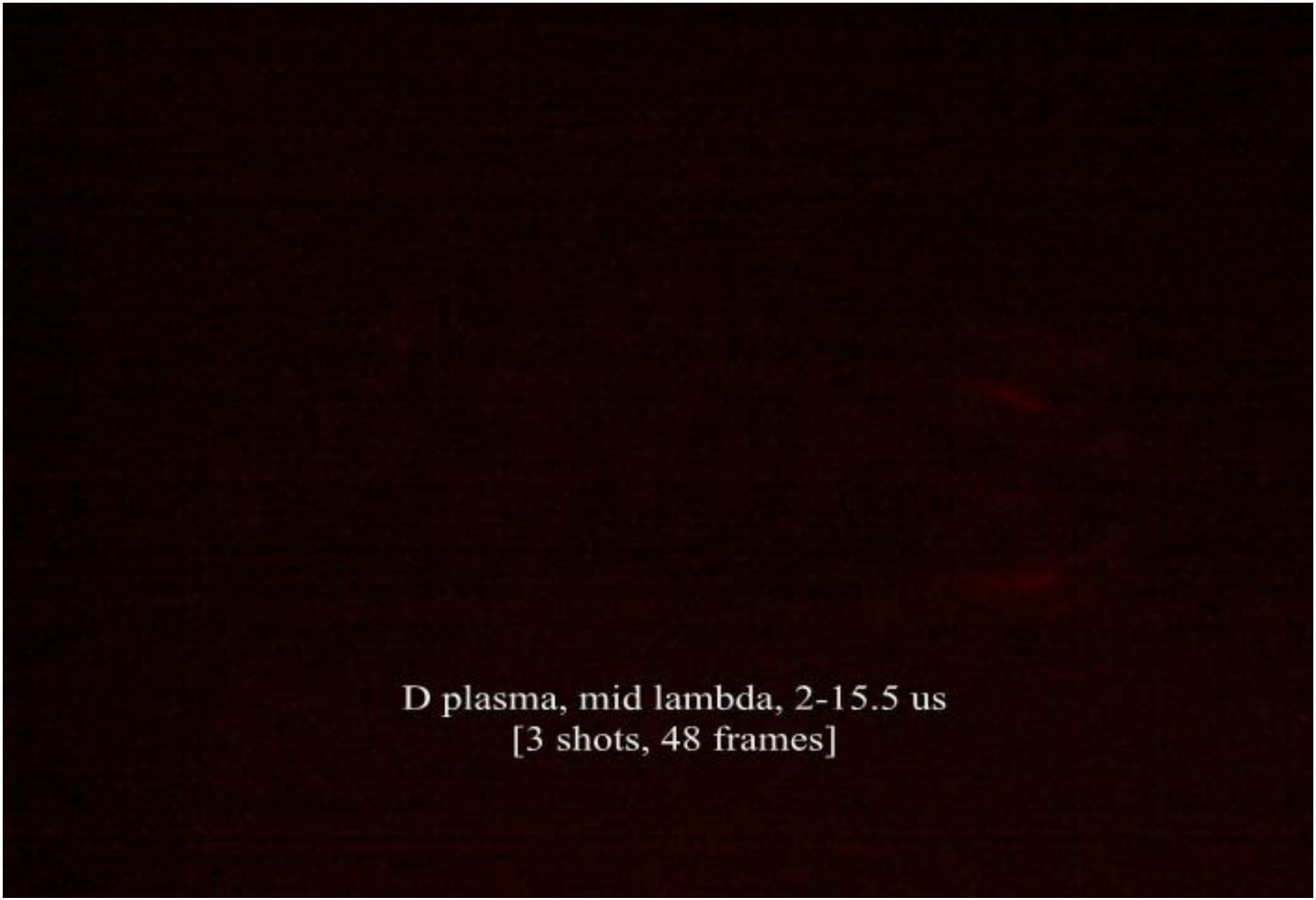
Steps:

1. Creation of distinct, arched filamentary plasma loops
2. Filaments merge to form central column
3. Jet-like axial expansion of central column
4. Kink instability of central column

Kink Instability of Central Column



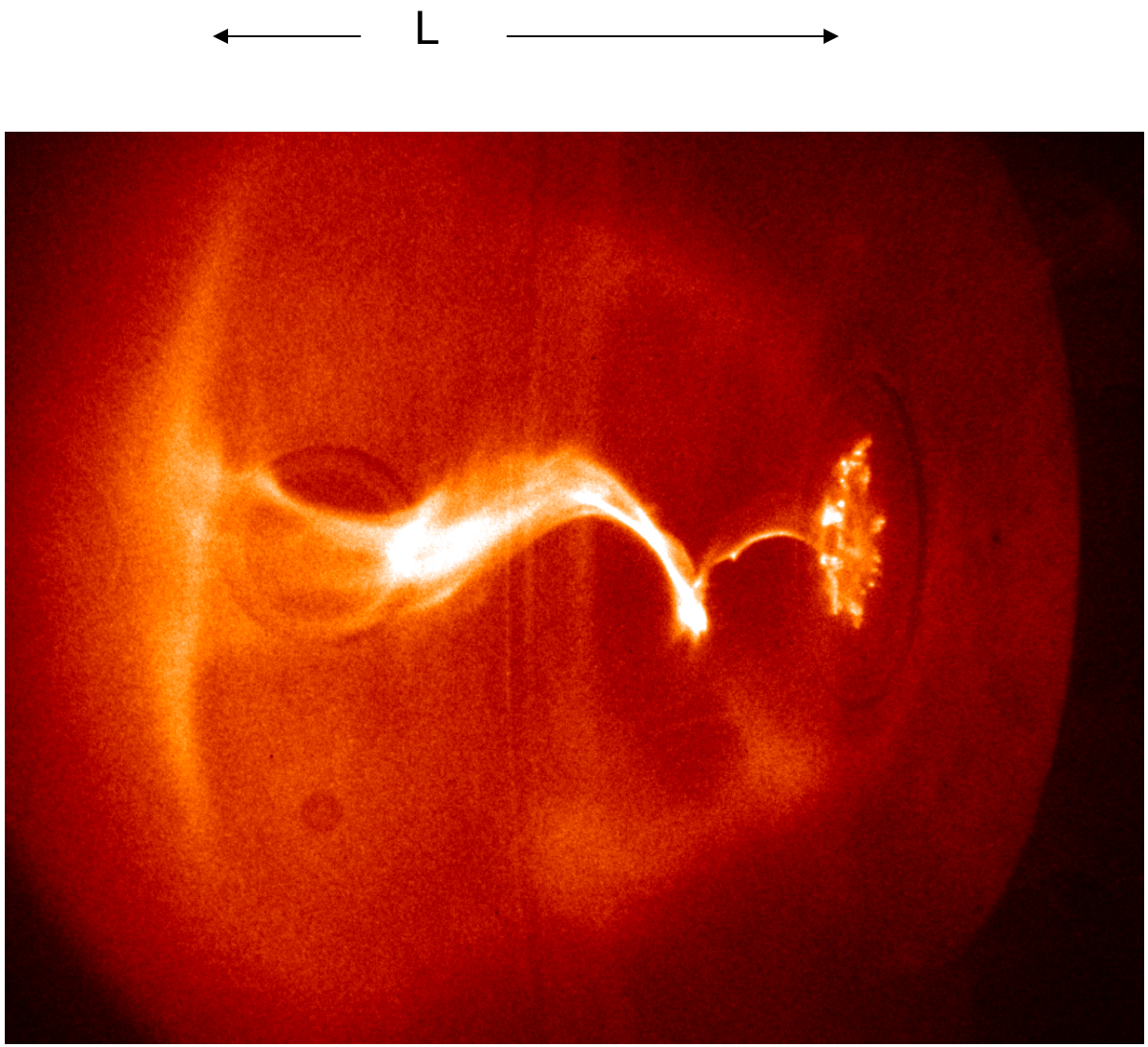



D plasma, mid lambda, 2-15.5 us
[3 shots, 48 frames]

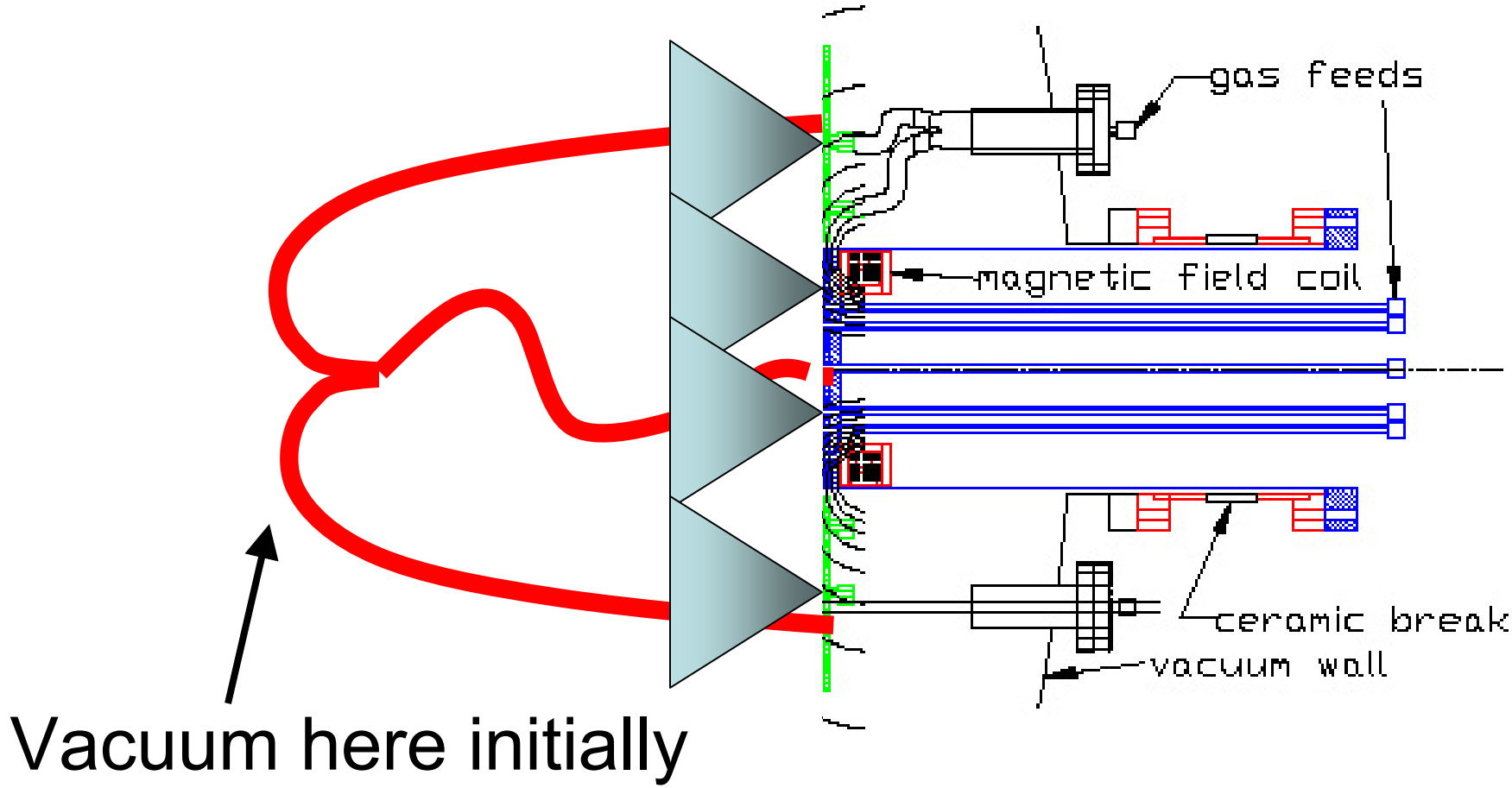
Kink occurs when central column becomes sufficiently long to satisfy instability condition

$$q = \frac{2\pi r B_z}{L B_\phi}$$

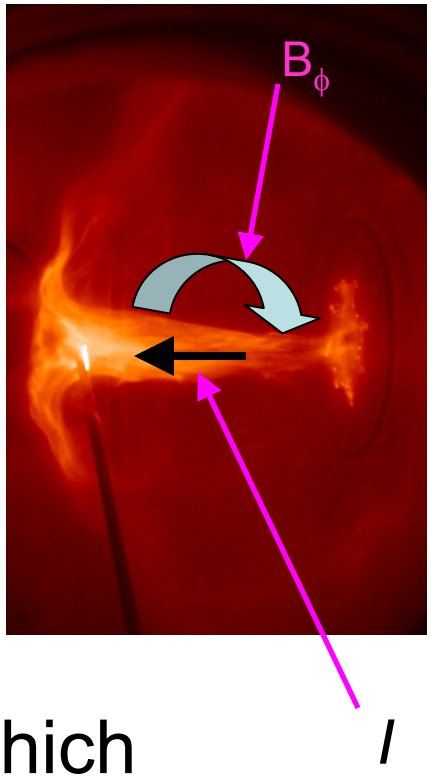
S. C. Hsu & P. M. Bellan
MNRAS 334, 257 (2002)



Where does plasma come from?



Toroidal flux injection



- gun current creates toroidal flux
- voltage across electrodes is rate at which this toroidal flux is injected (Faraday's law)

The need to gobble plasma

- toroidal flux frozen into ideal plasma
  - so toroidal flux injection necessarily involves plasma injection
- need source of plasma: gas nozzle is where ingested plasma comes from
- an MHD-driven ‘pumping-in’

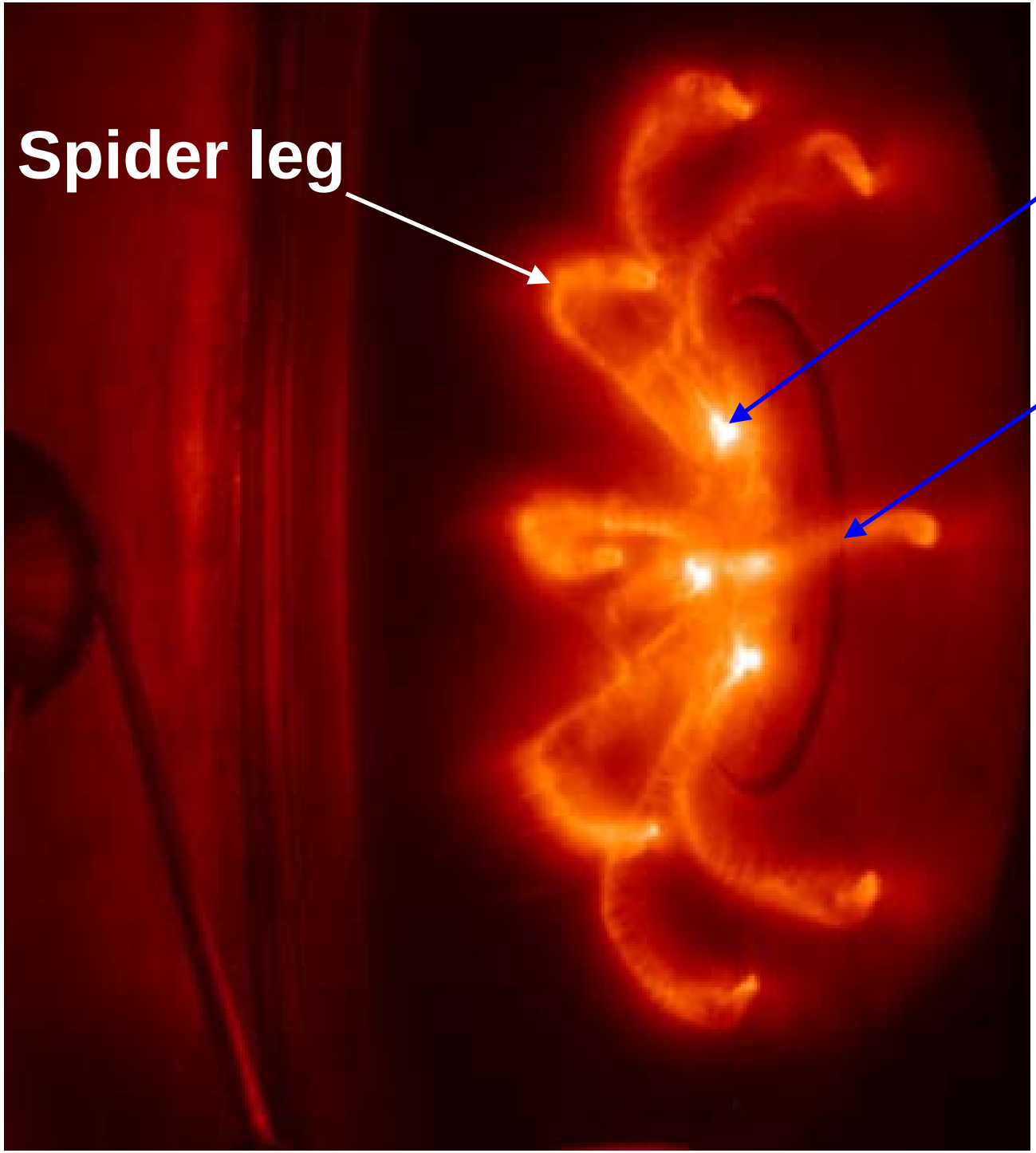
Collimation

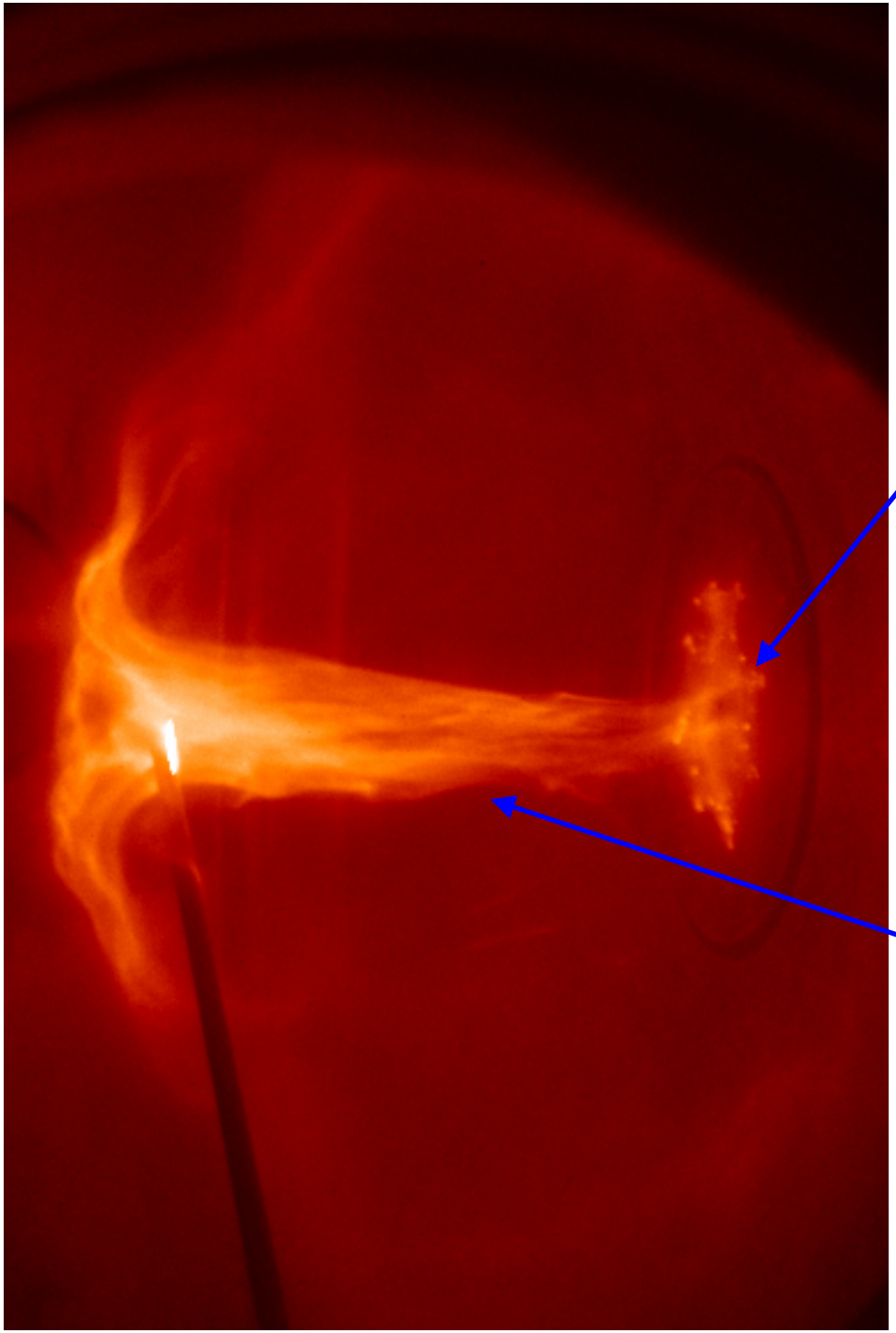
Relevant equations:

Eq. of motion $$\rho \frac{d\mathbf{U}}{dt} = \mathbf{J} \times \mathbf{B} - \nabla P$$

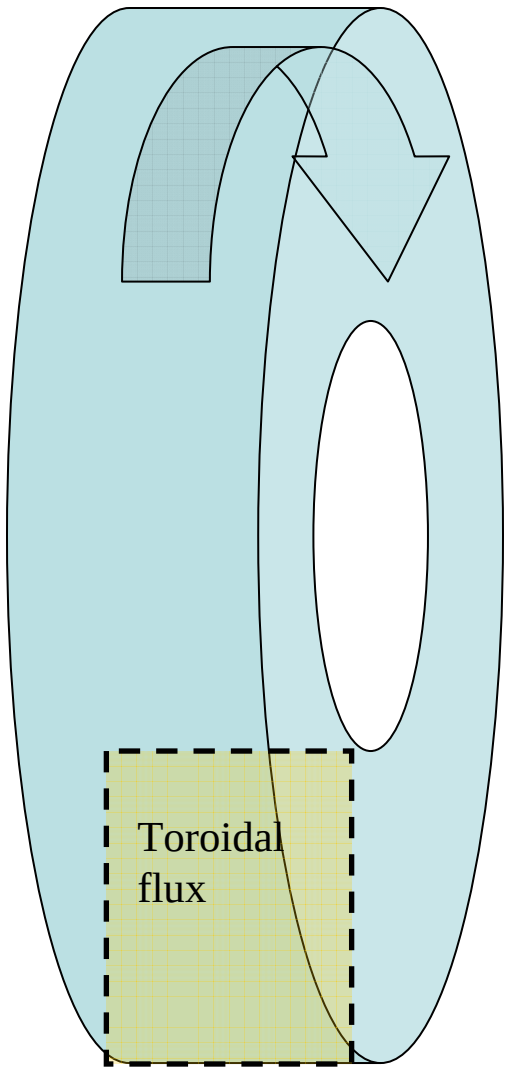
Induction eq. $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B})$$

Mass conservation $$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{U})$$

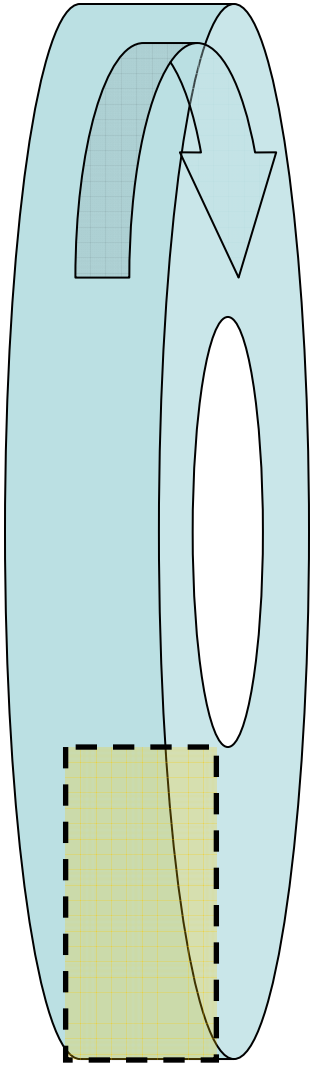

Spider leg
Gas sourc
Collimated
flux tube

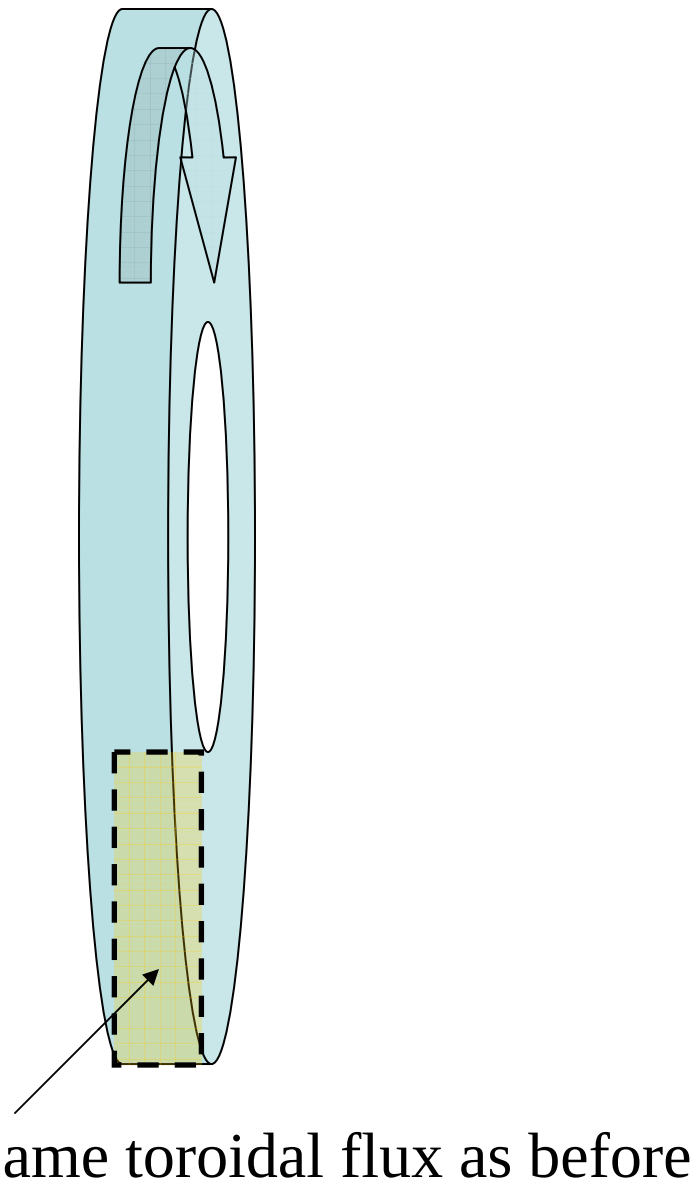

Gas source
Collimated
flux tube

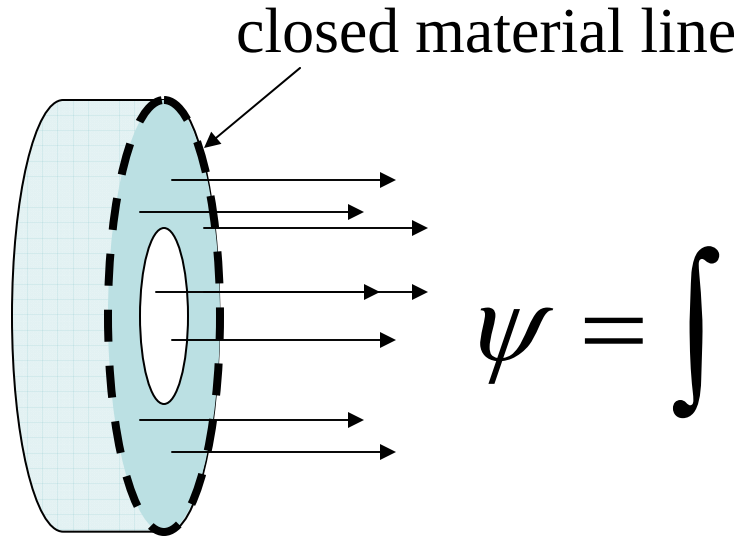
Amplification of convected toroidal flux density due to axial compression



Flux conserved during compression of a fluid element




Same toroidal flux as before



$$\psi = \int \mathrm{B}_{pol} \cdot d\mathrm{s}$$

poloidal flux ψ linked by toroidal fluid element is invariant

Poloidal current I linked by toroid must also be invariant since $I = I(\psi)$

Toroidal component of induction equation (exact)

$$\frac{\partial B_\phi}{\partial t} = r\mathbf{B}_{pol}\cdot\nabla\left(\frac{U_\phi}{r}\right) - r\mathbf{U}_{pol}\cdot\nabla\left(\frac{B_\phi}{r}\right) - B_\phi\nabla\cdot\mathbf{U}_{pol}$$

$U_\phi \approx 0$ since *current* is constant

re-write as

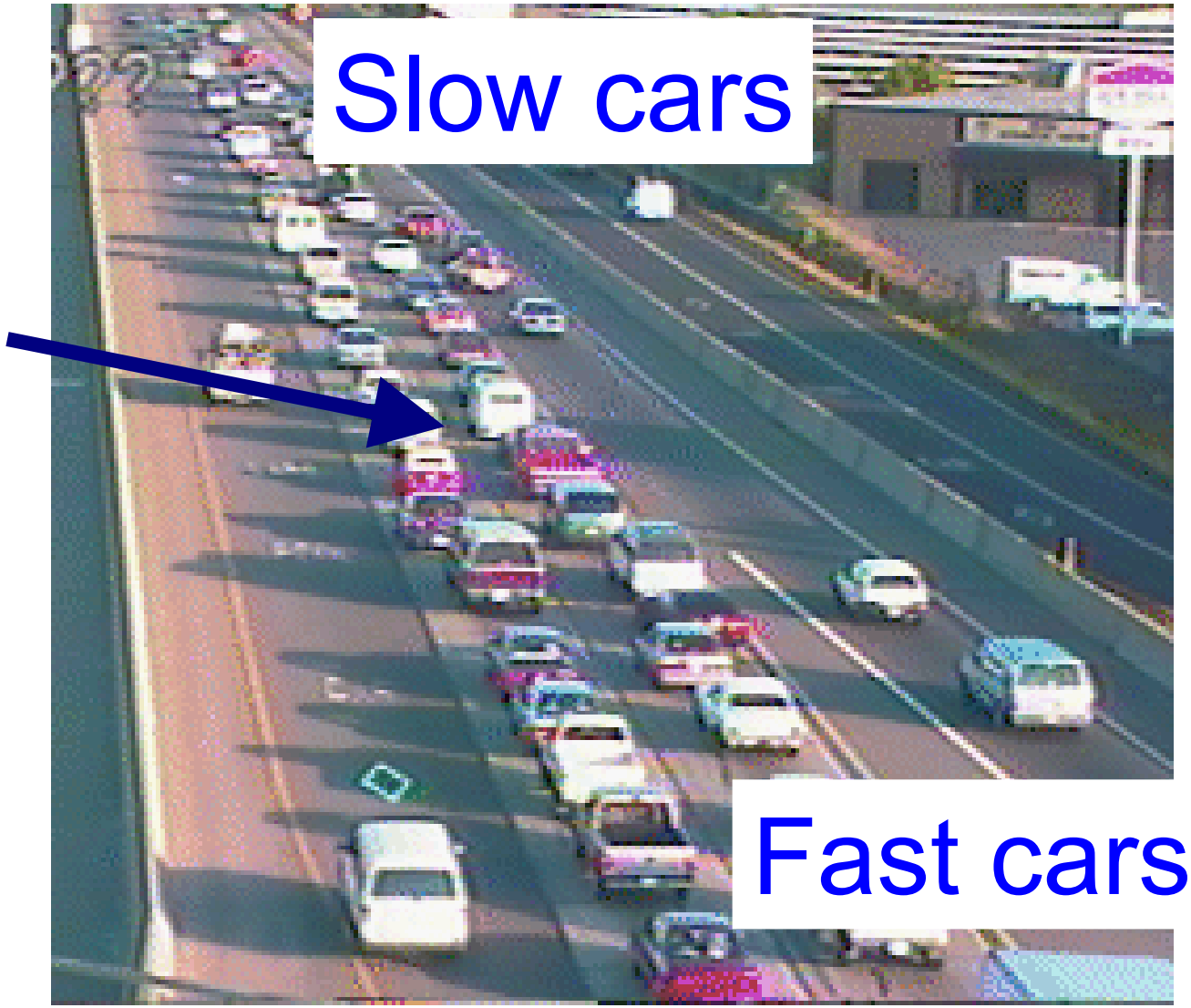
$$\frac{d}{dt}\left(\frac{B_\phi}{r}\right) = -\frac{B_\phi}{r}\nabla\cdot\mathbf{U}$$

<u>Negative divergence</u> implies B_ϕ amplification
i.e., converging flow increases pinching

Traffic jam

$$\nabla \cdot \mathbf{U} < 0$$

Converging flow in moving frame gives pile-up



induction $$\frac{d}{dt}\left(\frac{B_\phi}{r}\right) = -\frac{B_\phi}{r}\nabla \cdot \mathbf{U}$$

continuity $$\rho\nabla \cdot \mathbf{U} = -\frac{d\rho}{dt}$$

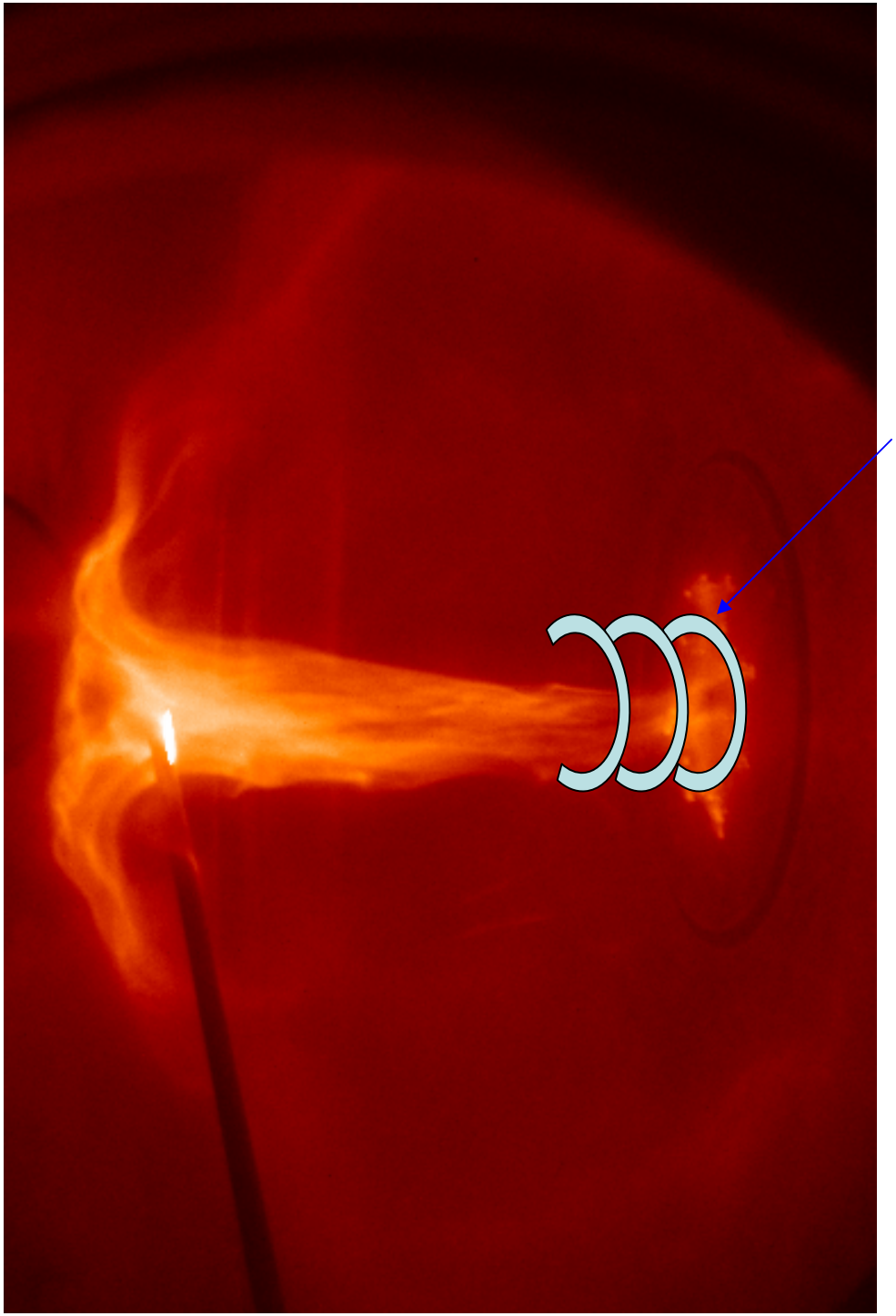
$$\longrightarrow \quad \frac{d}{dt}\left(\frac{B_\phi}{\rho r}\right) = 0$$

Toroidal field <u>grows</u> in proportion to mass accumulation in jet frame

Involves <u>momentum transport (flow)</u>, <u>compressibility</u>, and <u>frozen-in flux</u>

- pile-up of flow amplifies B_ϕ
- Ampere's law gives $2\pi r B_\phi = \mu_0 I$
- since I is fixed, r decreases
- flaring of central column reduced, get <u>collimation</u>

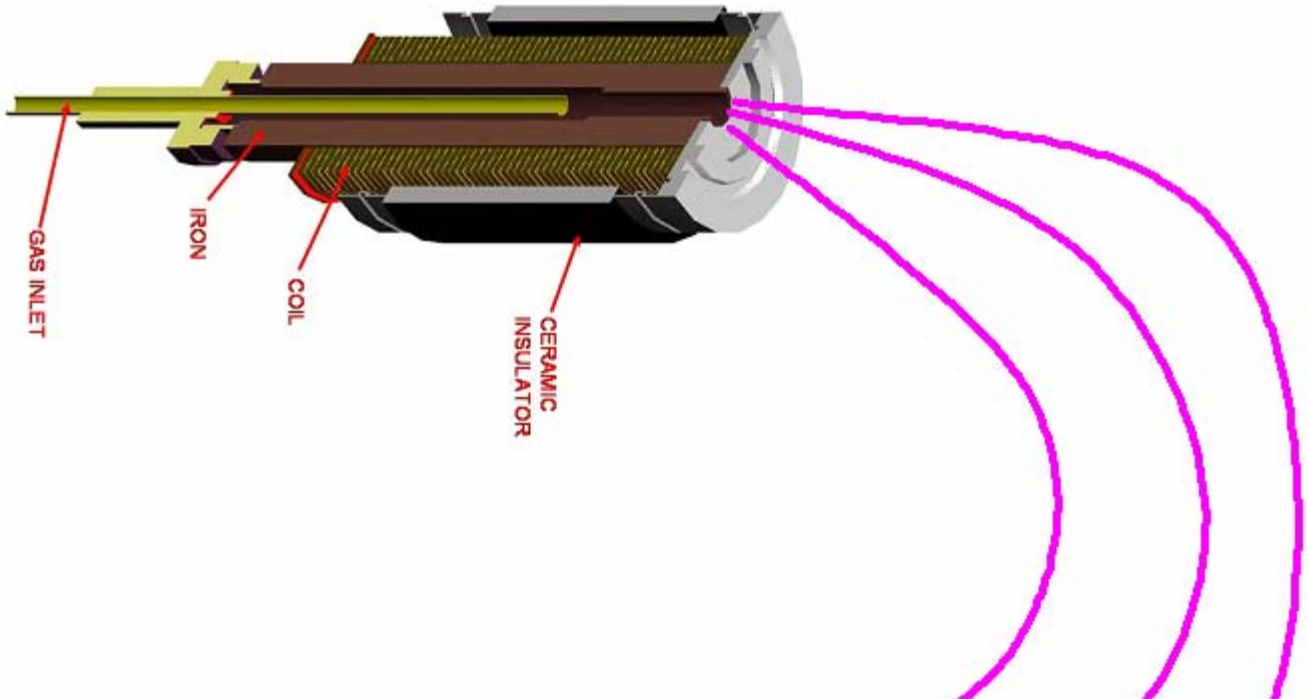
Cartoon showing pile-up of toroidal field lines convected with flow



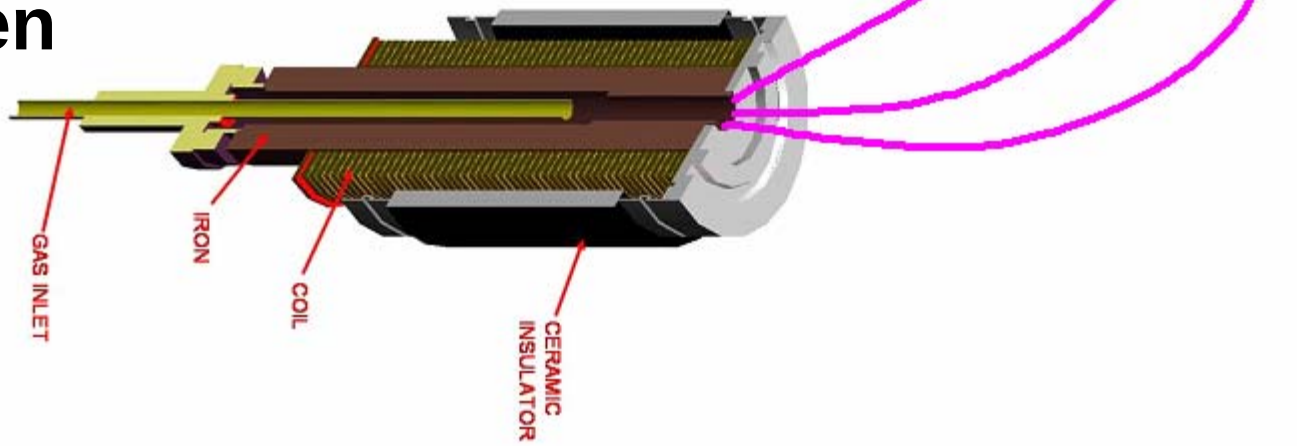
Frozen-in convecting toroidal magnetic field lines

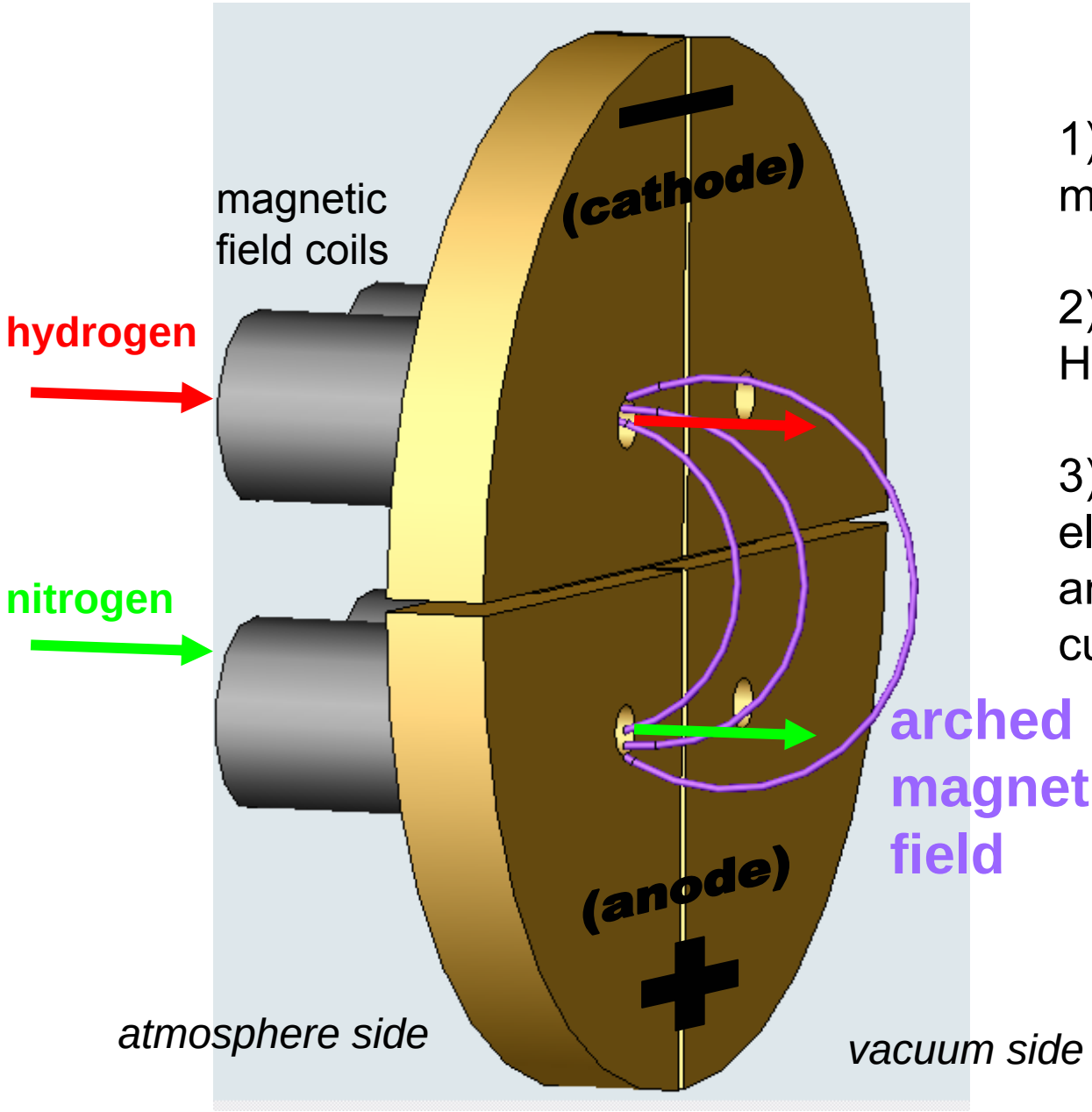
Visualization of colliding jets

Hydrogen



Nitrogen





1) Coil-generated potential magnetic field, up to 0.3 T

2) Fast gas valves inject H_2, N_2 at footpoints

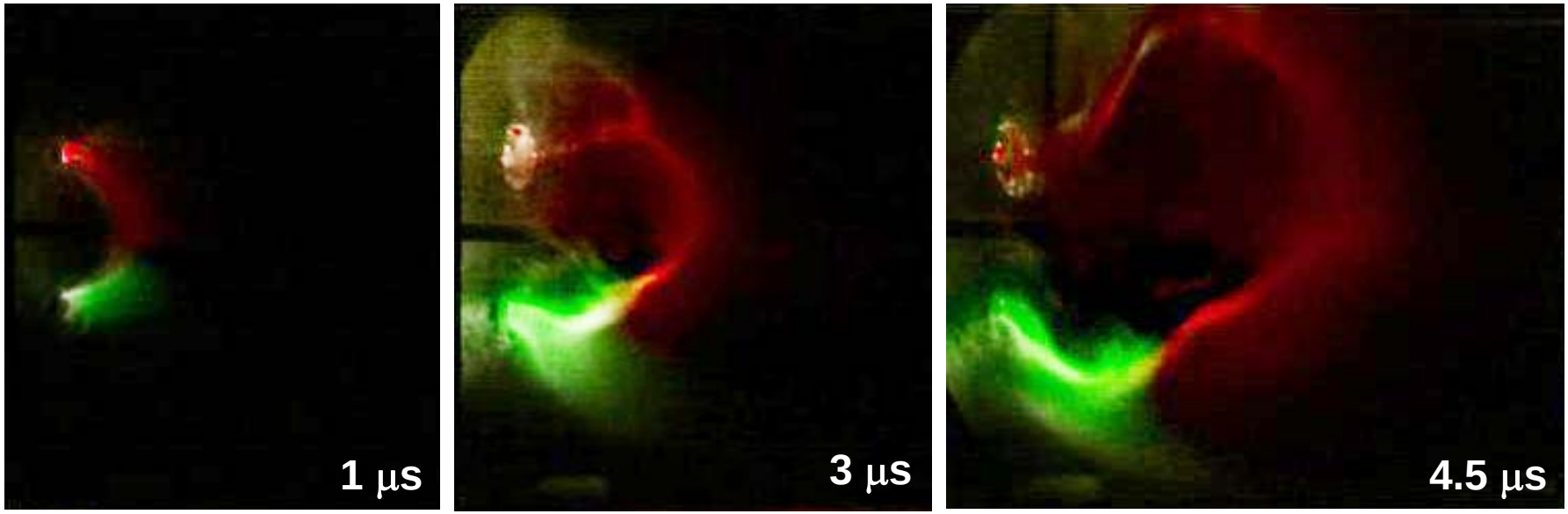
3) 3-6 kV, applied to the electrodes, ionizes the gas and drives a 40-80 kA current

•Dual-gas plasmas <u>visualize</u> plasma flow (momentum transport)

•Hydrogen jet (red) coming from top collides with nitrogen jet (green) coming from bottom

•Jets follow arched expanding magnetic field

•Jets are collimated



.