Report on the Levitated Dipole eXperiment (LDX): An Uplifting Fusion Adventure

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For the LDX Team

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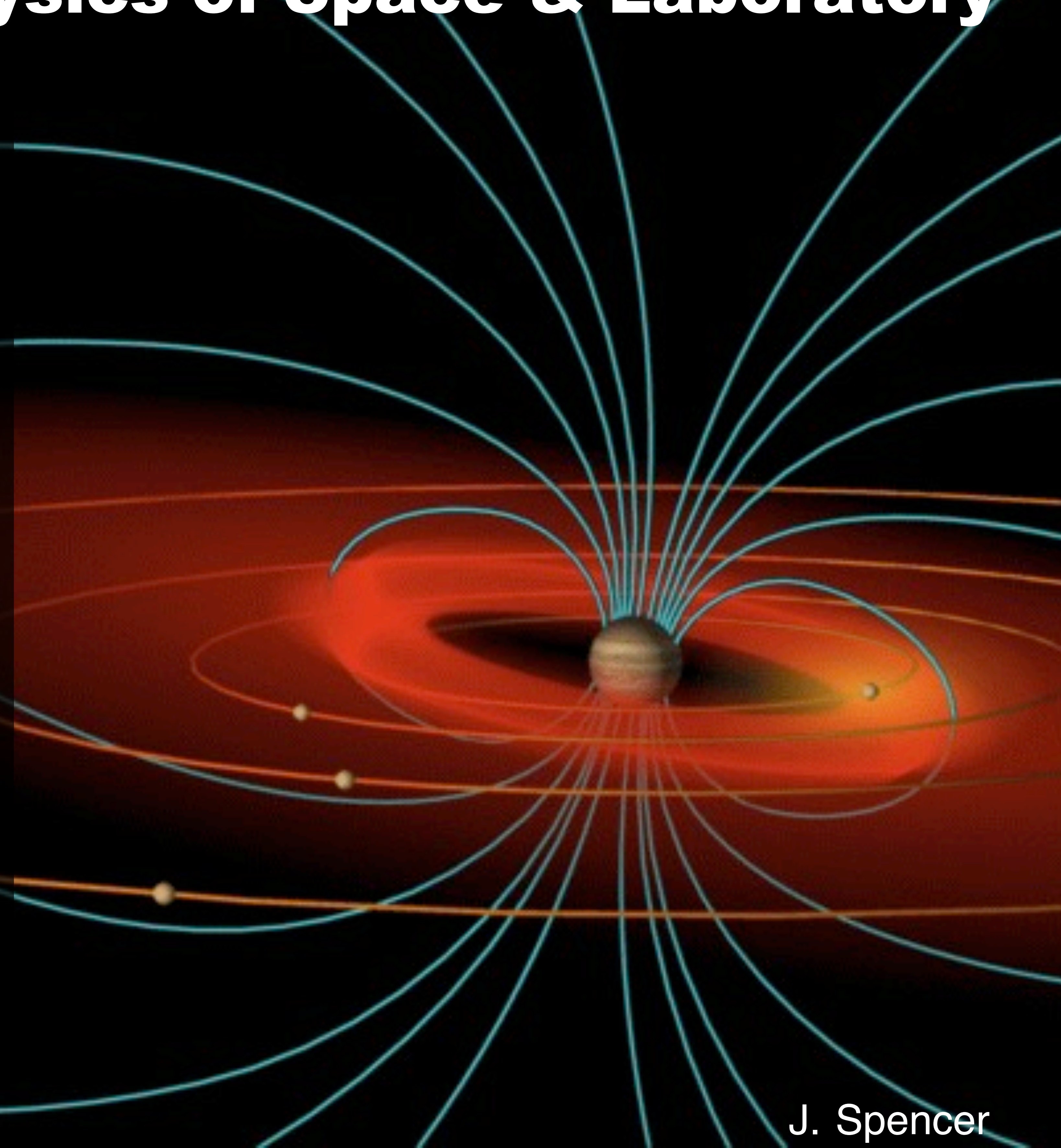
Introduction to Magnetic Dipoles

Why would you build LDX?

Levitated Dipole Confinement Concept: Combining the Physics of Space & Laboratory

- Akira Hasegawa, 1987
- Two interesting properties of active magnetospheres:
  - **High beta**, with ~ 200% in the magnetospheres of giant planets
  - **Pressure and density profiles are strongly peaked**
    - **“Invariant profiles”** turbulent activity **increases** peakedness



J. Spencer

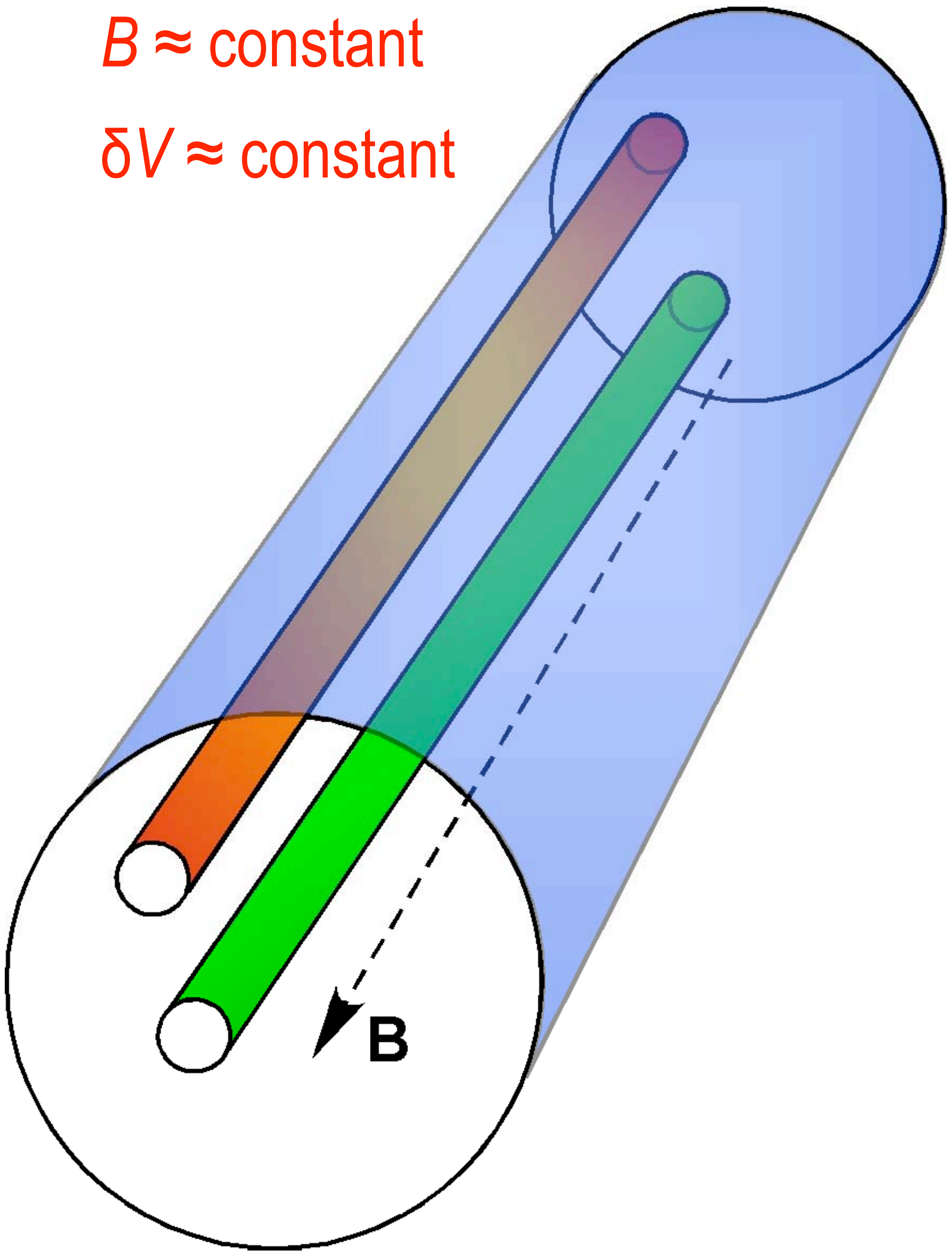
What are Invariant Profiles?

Solenoid, theta-pinch, large aspect ratio torus, …

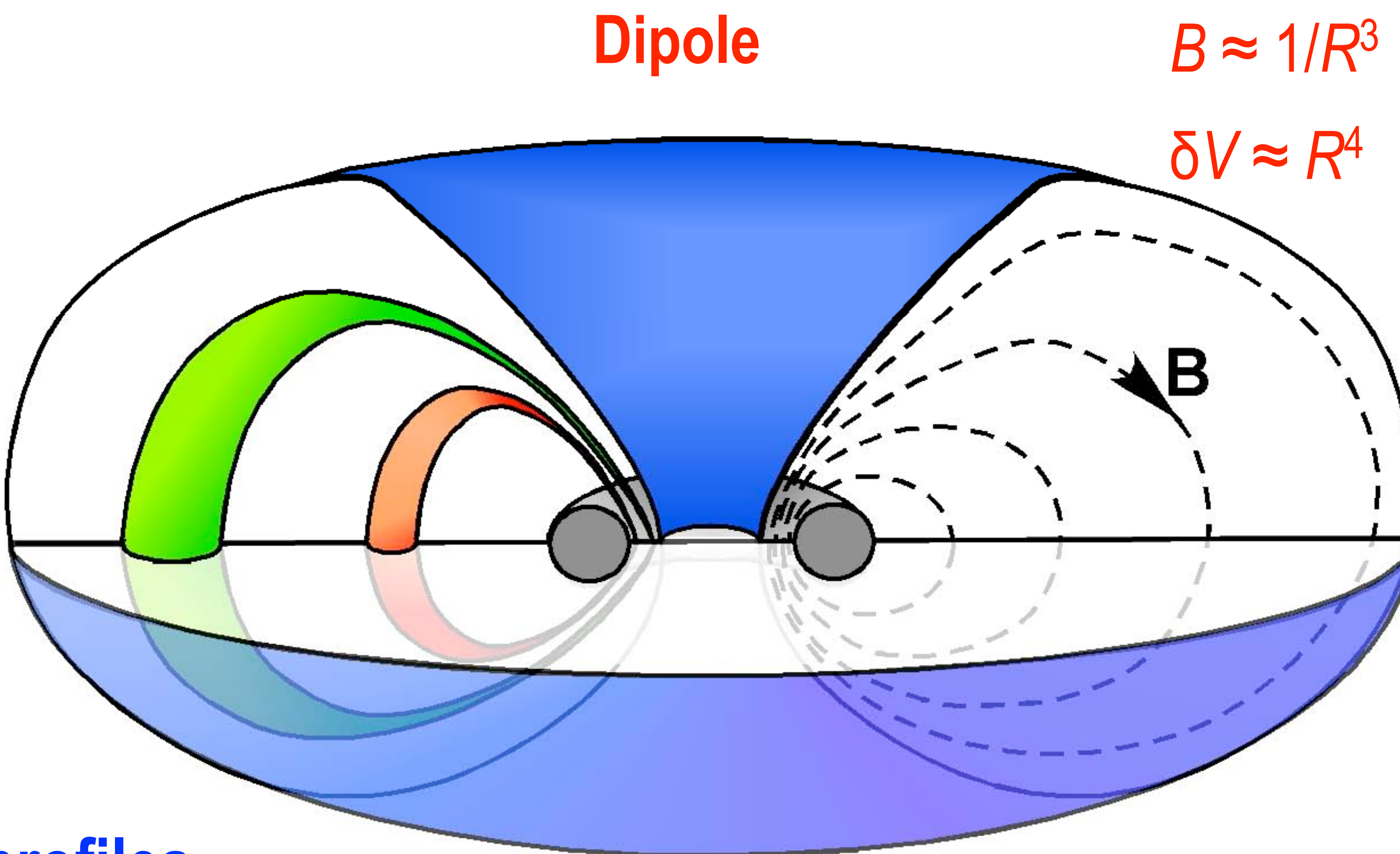
- Invariant to adiabatic interchange of flux tubes
- Flux tube volume:
  - $\delta V = \oint \frac{d\ell}{B} = \text{constant}$
- Invariant profiles:
  - $n\ \delta V = \text{constant}$
  - $p\ \delta V^{\gamma} = \text{constant}$
  - Density and pressure profiles are flat

$B \approx$ constant

$\delta V \approx$ constant



What are Invariant Profiles?

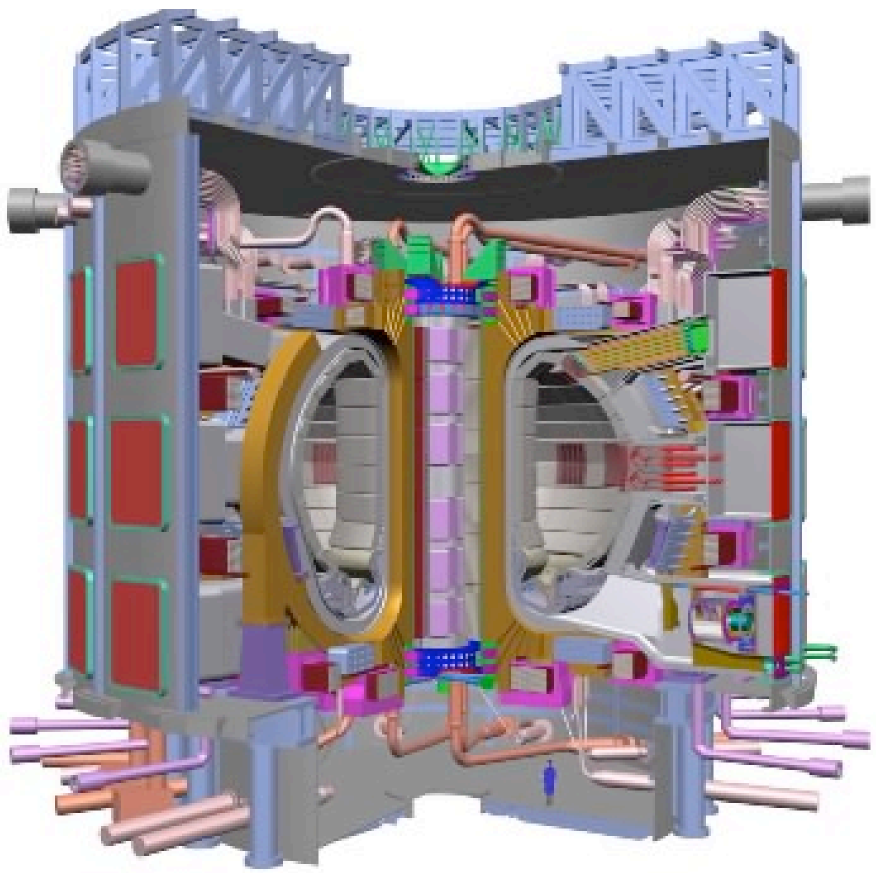
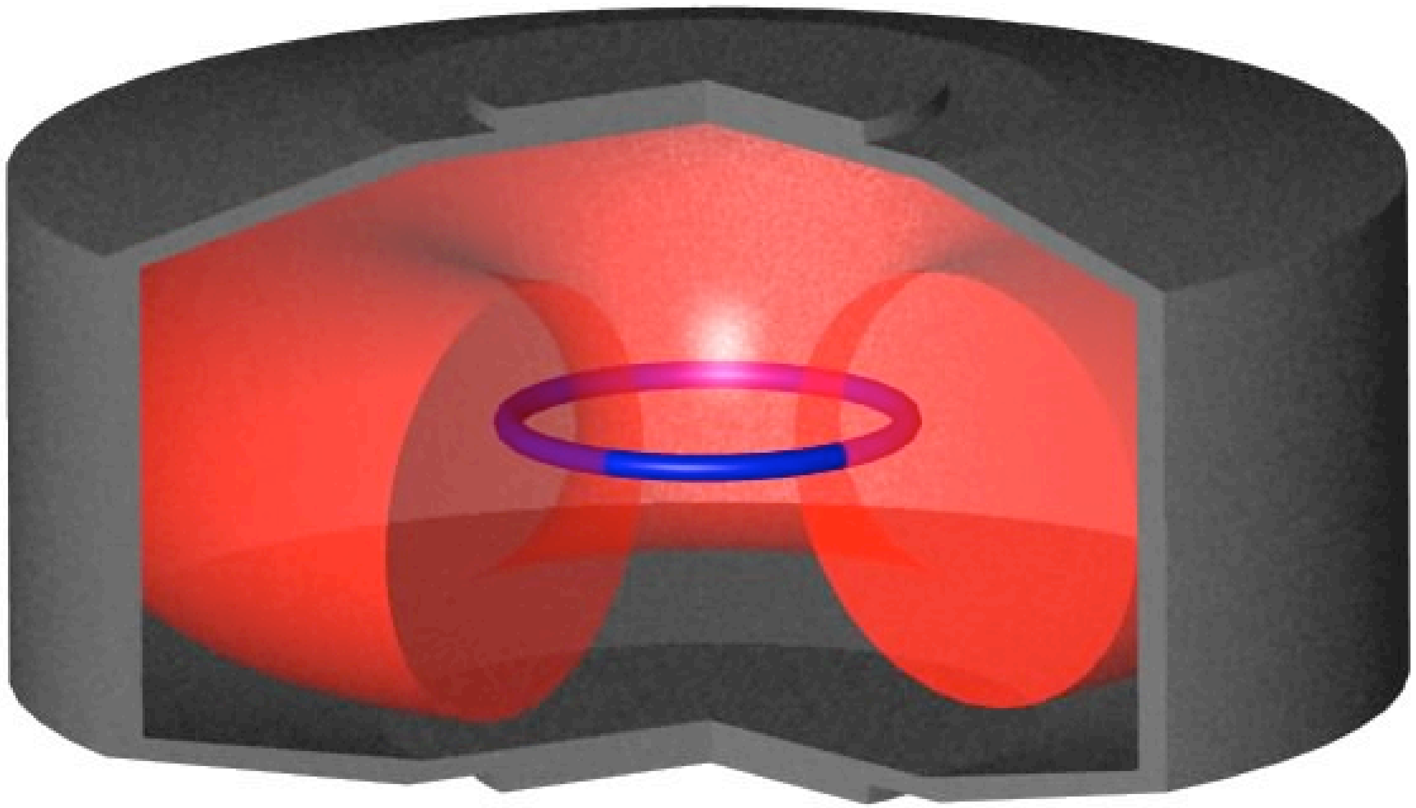


- **Flux tube volume:**
  - $\delta V = \oint d\ell/B \approx R^4$
- **Invariant profiles:**
  - $n\ \delta V = \text{constant}$
  - $p\ \delta V^{\gamma} = \text{constant}$
  - **Density and pressure profiles are strongly peaked!**

"Natural" Profiles in LDX:

$$\delta V_{edge}/\delta V_{core} \approx 50$$
$$n_{core}/n_{edge} \approx 50$$
$$P_{core}/P_{edge} \approx 680$$
$$T_{core}/T_{edge} \approx 14$$

Levitated Dipole Fusion Concept

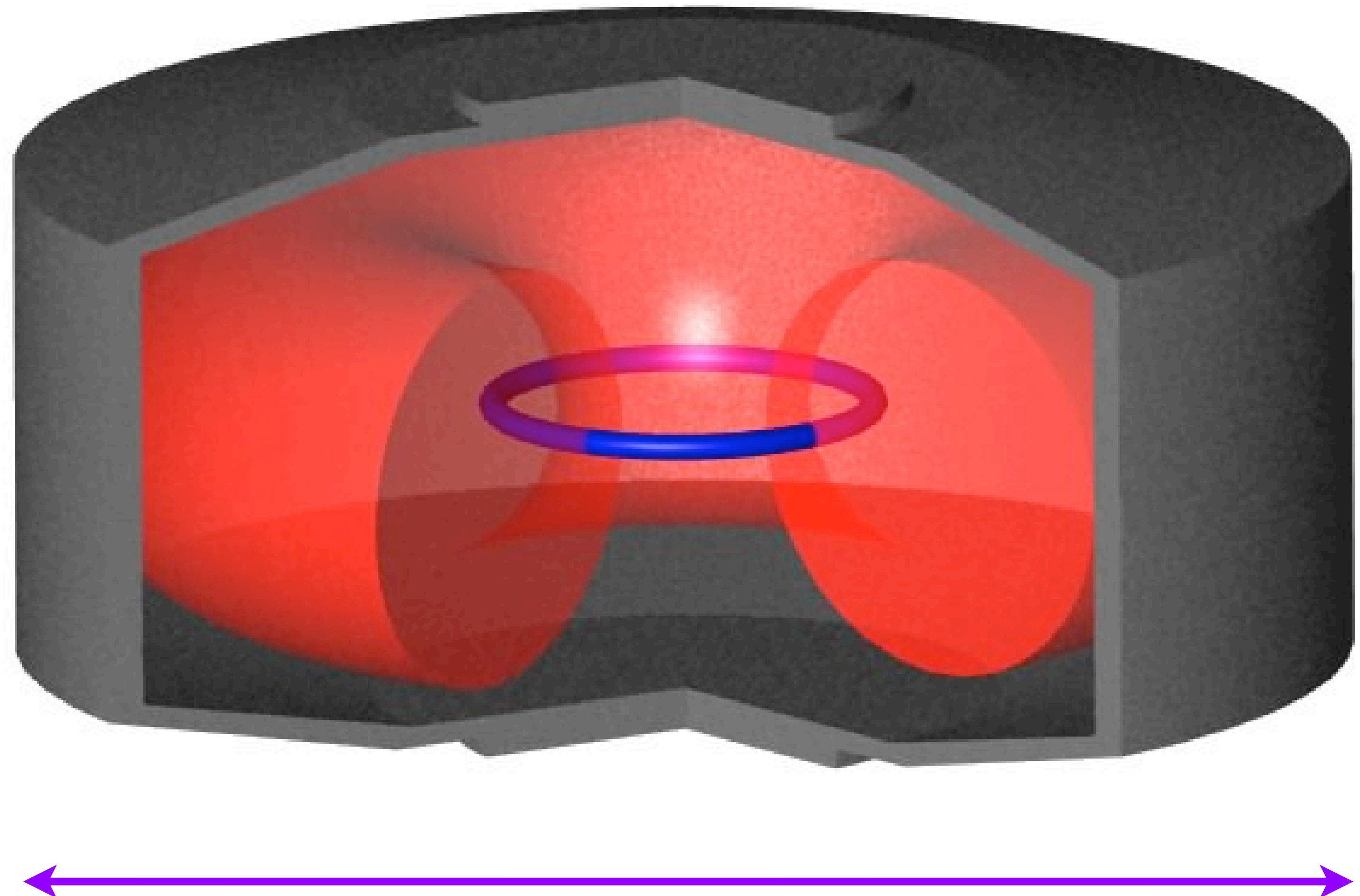
ITER	Levitated Dipole Reactor
	Kesner, *et al.* Nucl. Fus. 2002
	
30 m	60 m
400-600 MW D-T Fusion	500 MW D-D(He^3) Fusion

Levitated Dipole Fusion Concept

- Internal ring
- Steady state
- Non-interlocking coils
- Good field utilization
- Possibility for $\tau_E > \tau_p$
- Advanced fuel cycle

Levitated Dipole Reactor

Kesner, *et al.* Nucl. Fus. 2002

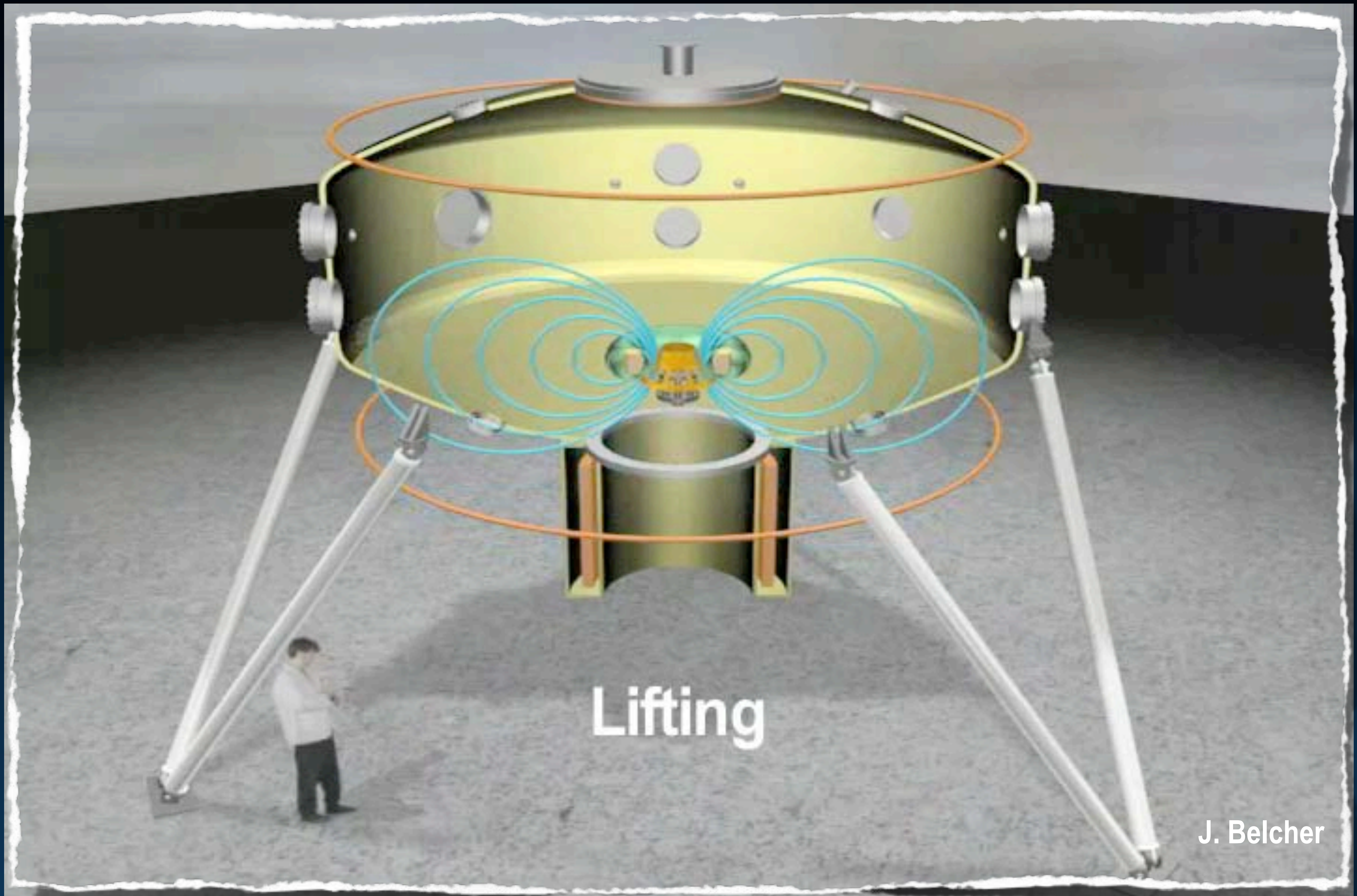


500 MW
D-D(He^3) Fusion

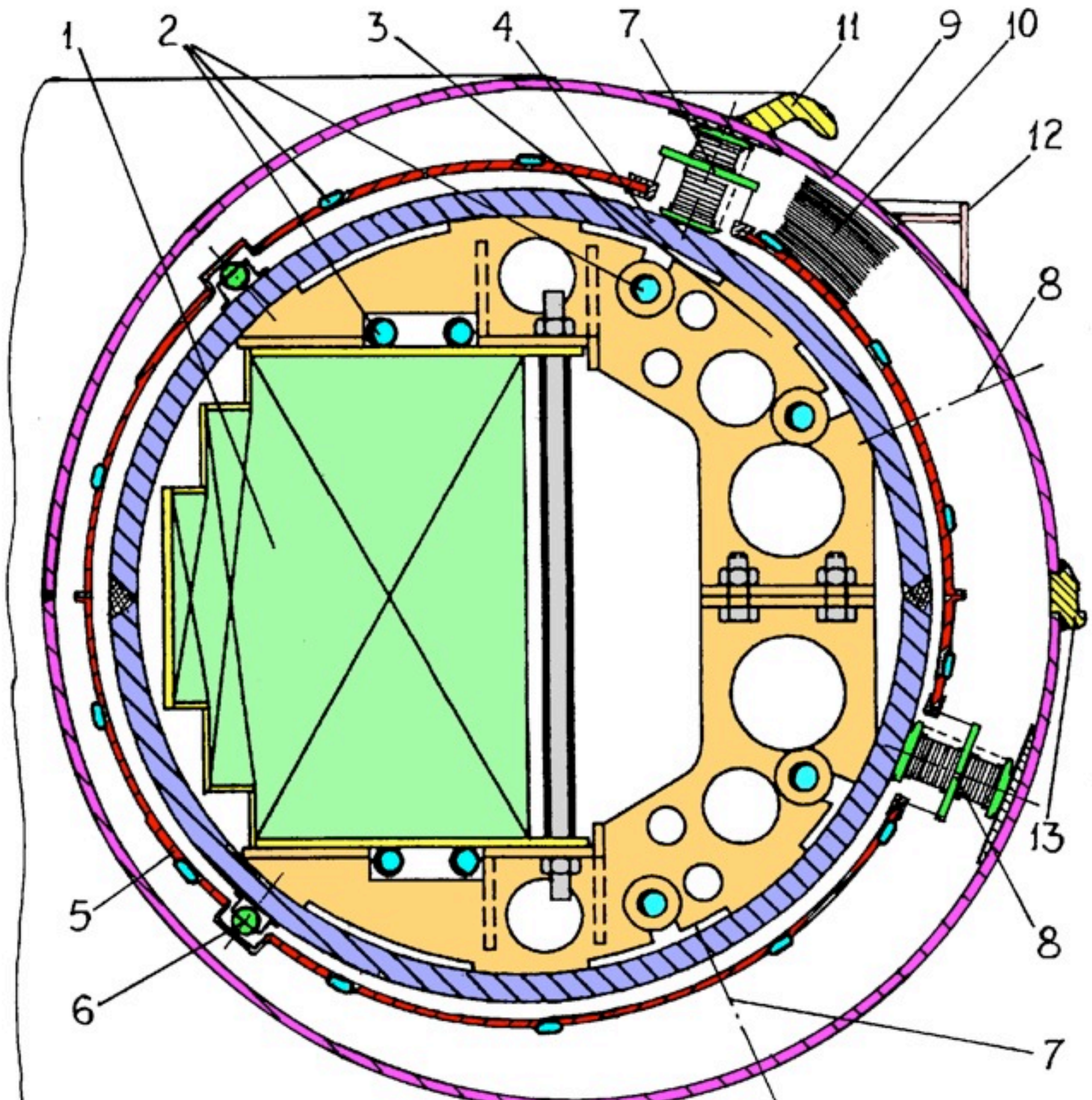
Design and Construction of LDX

Seemed simple enough at the time...

Lifting, Launching, Levitation, Experiments, Catching



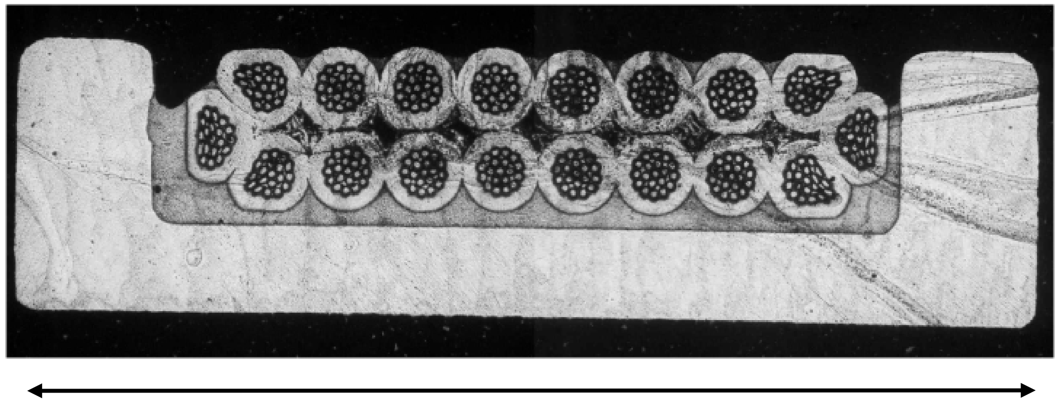
Floating Dipole Conceptual Design



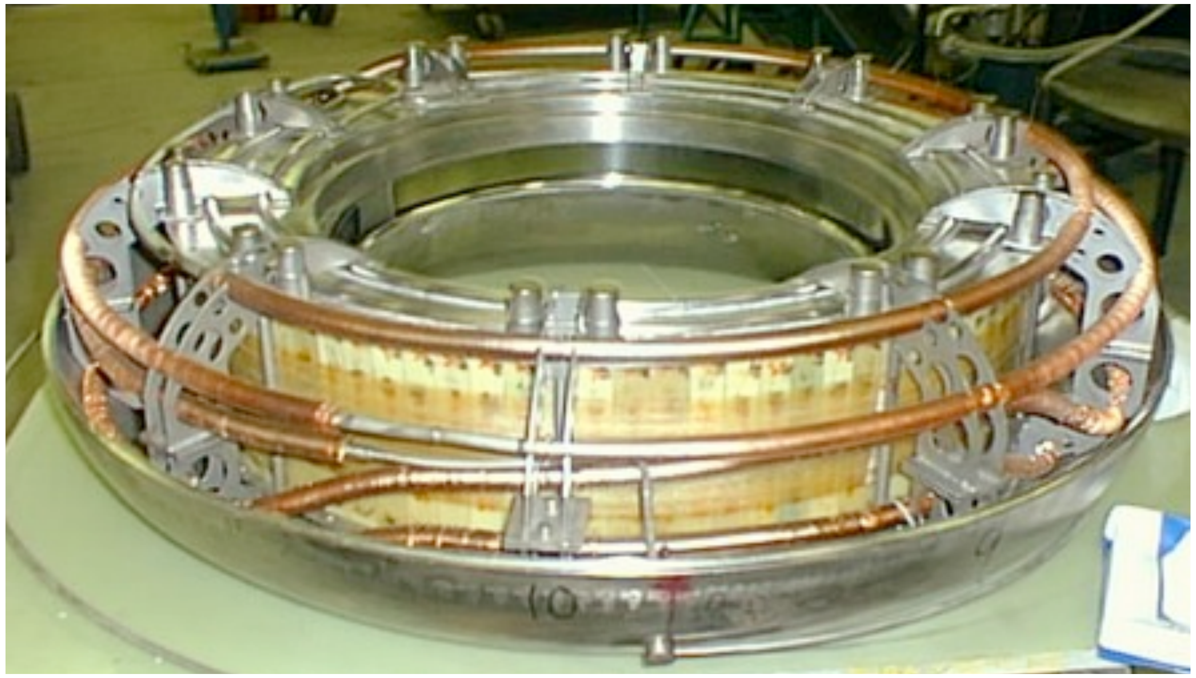
1. Magnet Winding Pack
2. Heat Exchanger tubing
3. Winding pack centering clamp
4. He Pressure Vessel (Inconel 625)
5. Thermal Shield (Lead/glass composite)
6. Shield supports (Pyrex)
7. He Vessel Vertical Supports/ Bumpers
8. He Vessel Horizontal Bumpers
9. Vacuum Vessel (SST)
10. Multi-Layer Insulation
12. Laser measurement surfaces

Winding Pack and He Pressure Vessel

Advanced ITER Nb_3Sn conductor

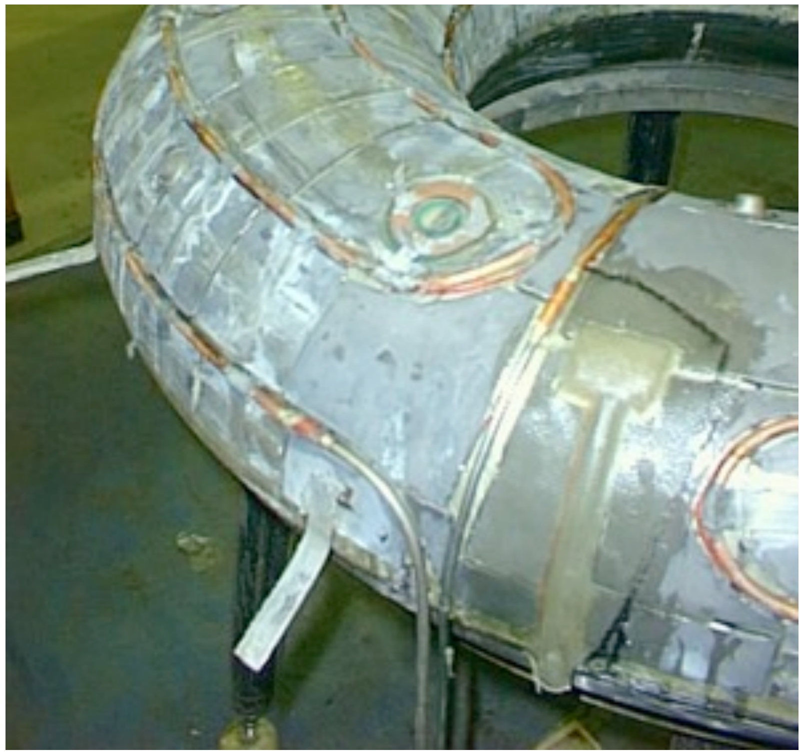


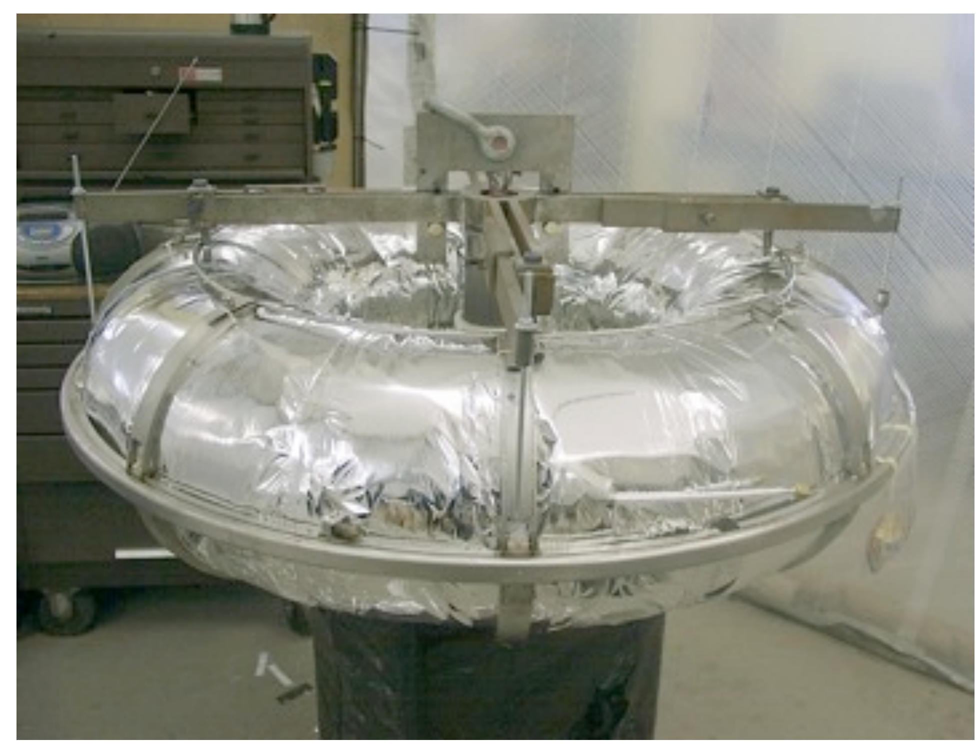
8 mm



… wound very carefully…

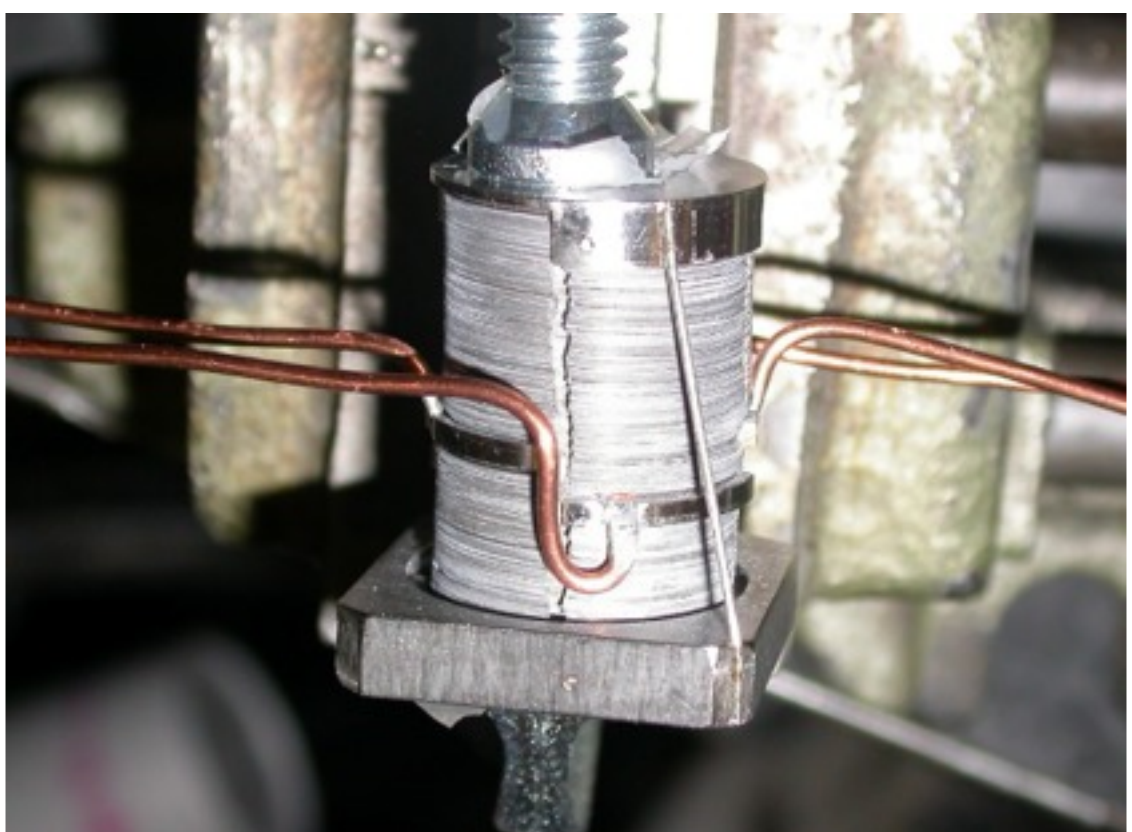
Lead Radiation Shields and Multi-Layer Insulation



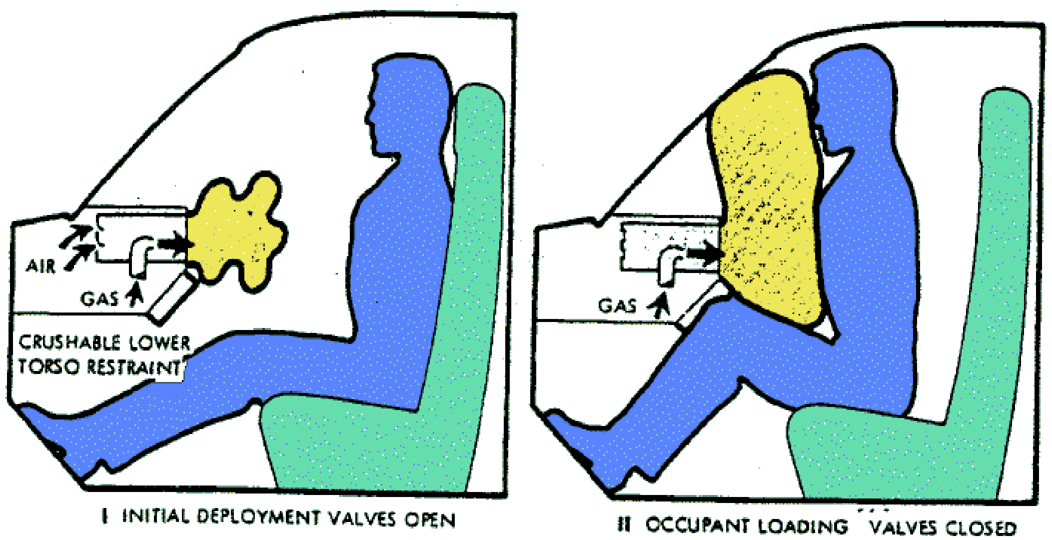


Support Washer Stacks

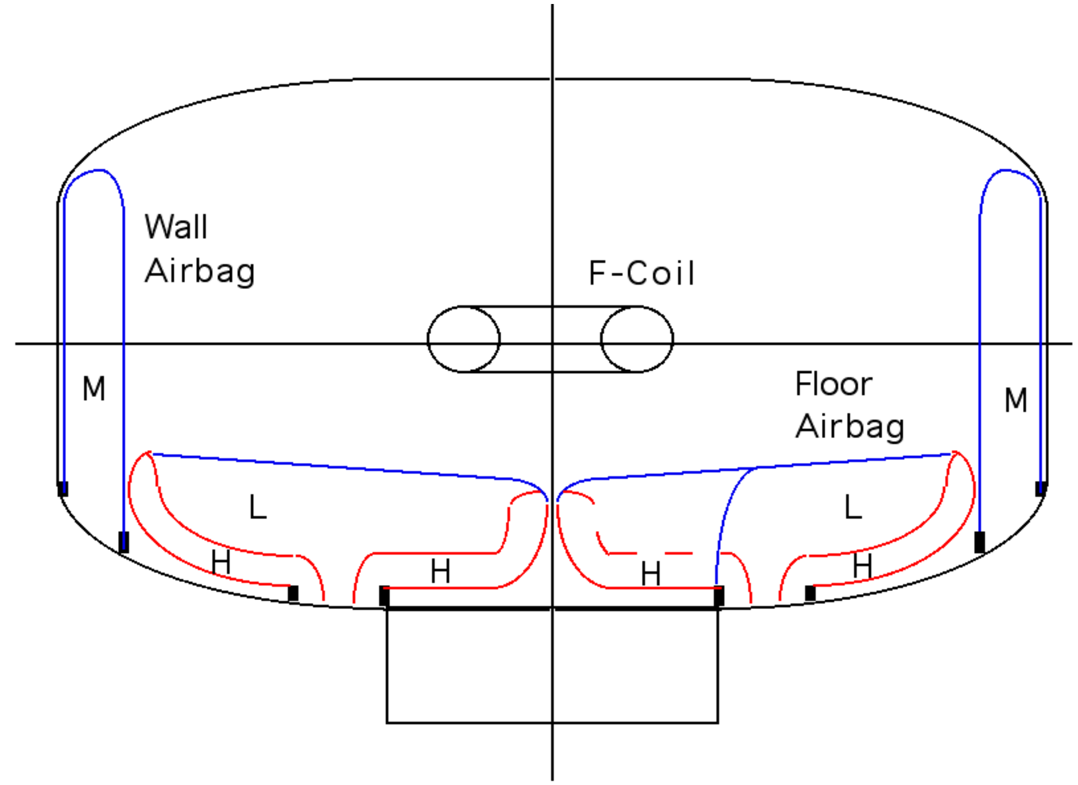
- Specification
  - Hold heat leak to 5 K < 10 mW
  - Withstand 10g crash (5 Tons!)
- Solution
  - Stack of 400 4mil thick washers
- 24 Stacks (~7000 coins) Assembled, Sized and Installed



LDX Airbag Emergency Catcher



W.R. Carey et al, *Society of Automotive Engineers, 2nd International Conference on Passive Restraints*, Detroit, MI, 1972

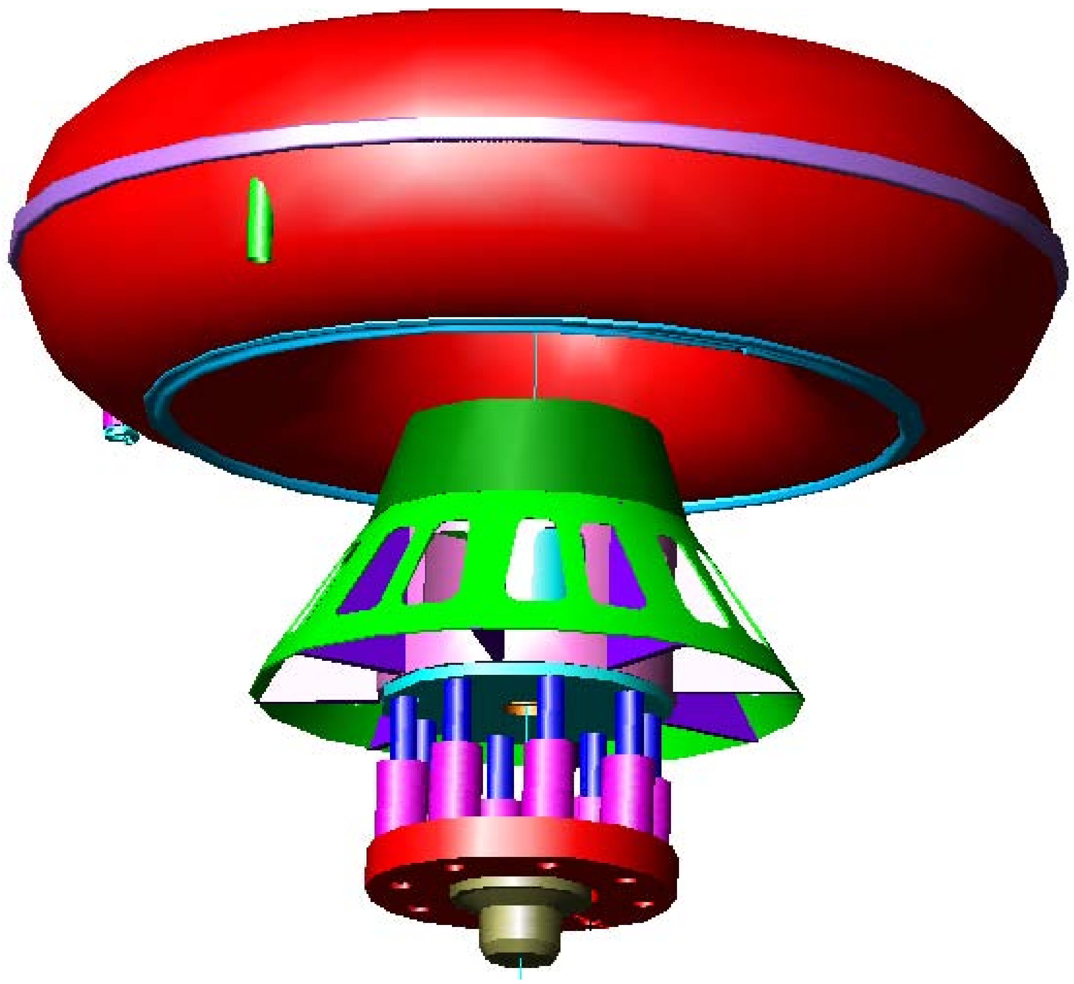


Airbag Catcher (Side View)

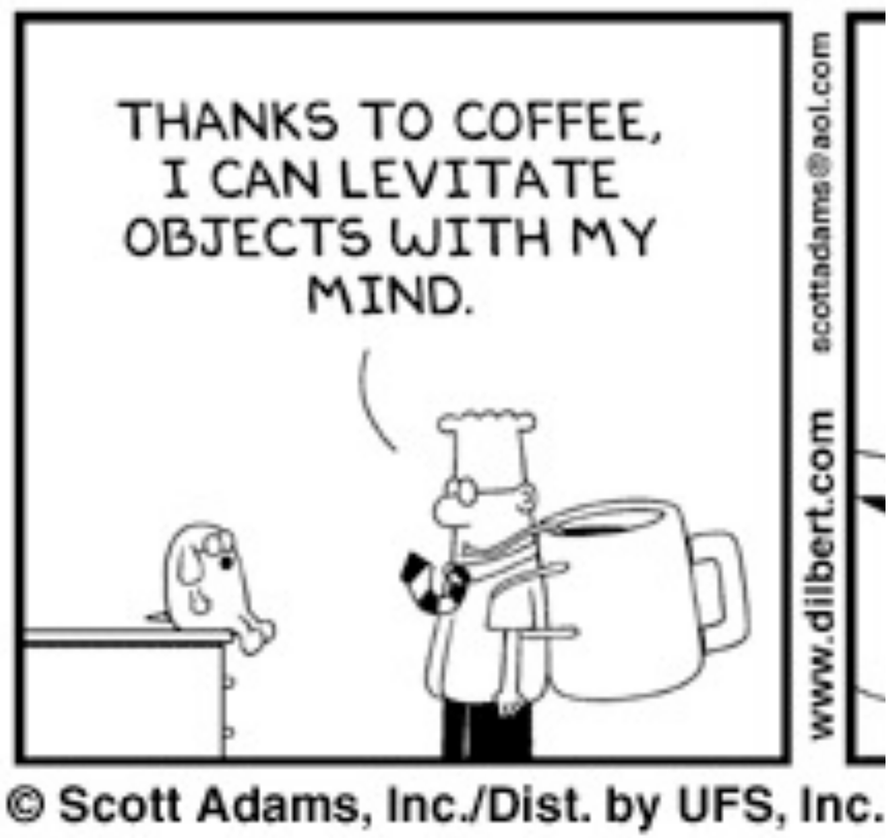
- **NASA Pathfinder application research**
  - **NASA airbag research budget ~ 3 X total LDX budget!**

Launcher / Catcher

- Tested to limit all accelerations to less than 5 g

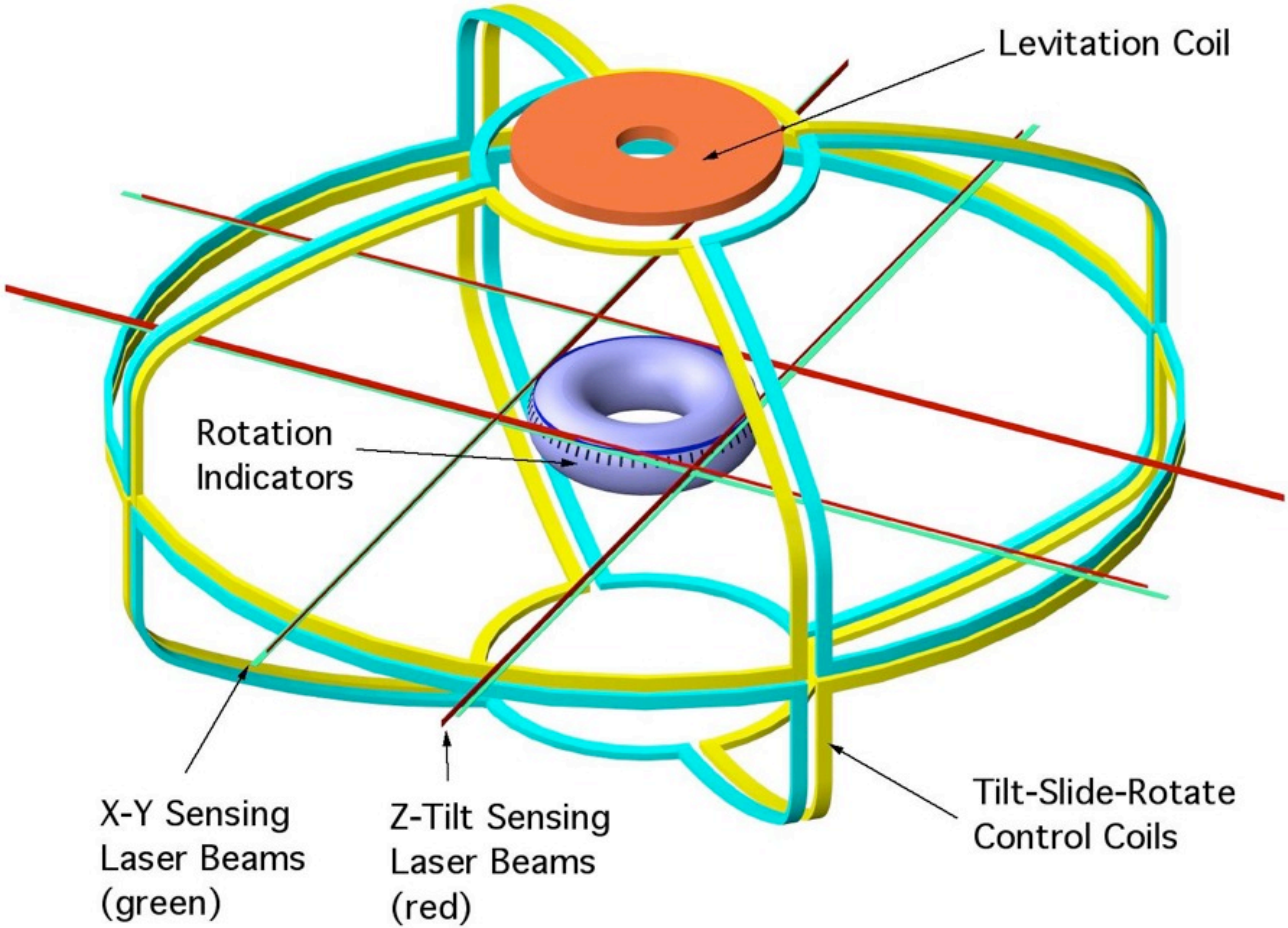


Dilbert Levitation System



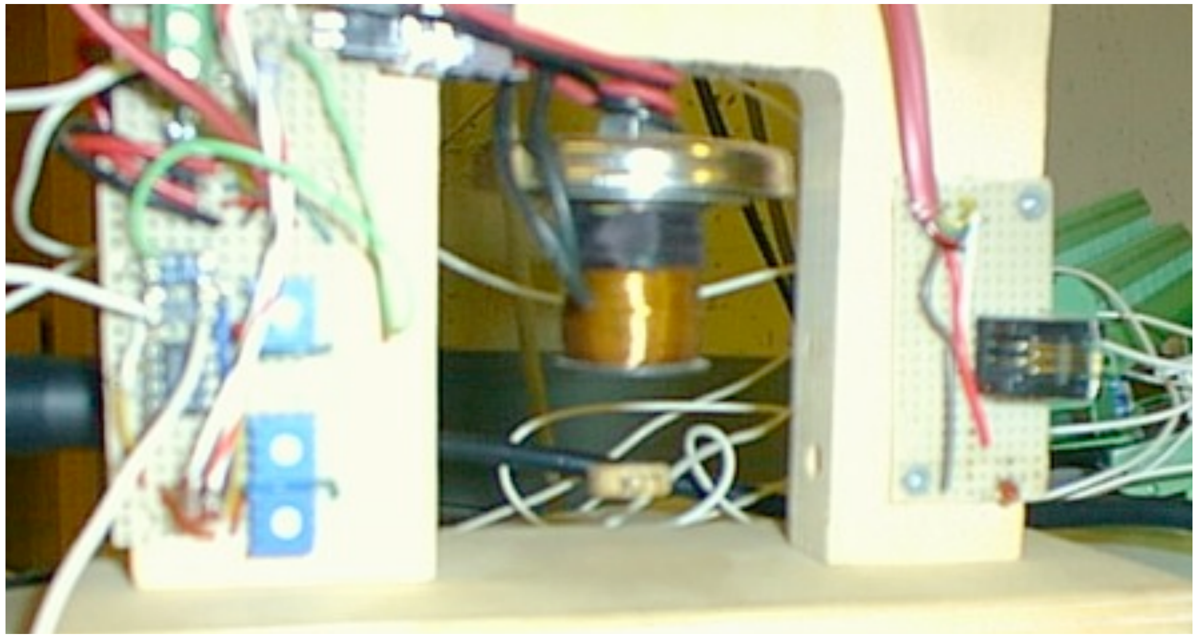
- **Greatly simplified**
  - **Easily manufactured at low cost (even for Starbucks)**
- **Not reliable.**

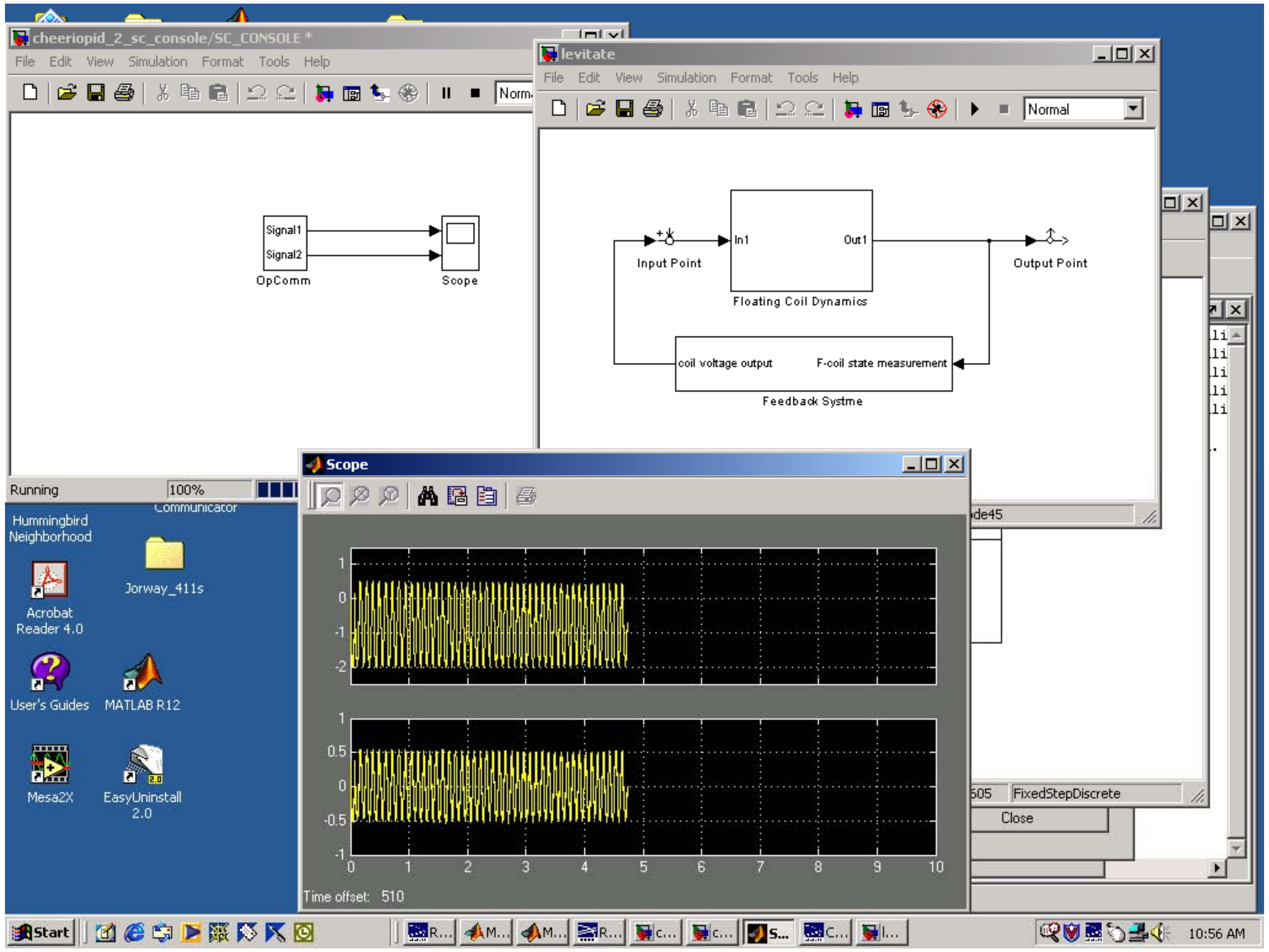
Levitation Control System Schematic



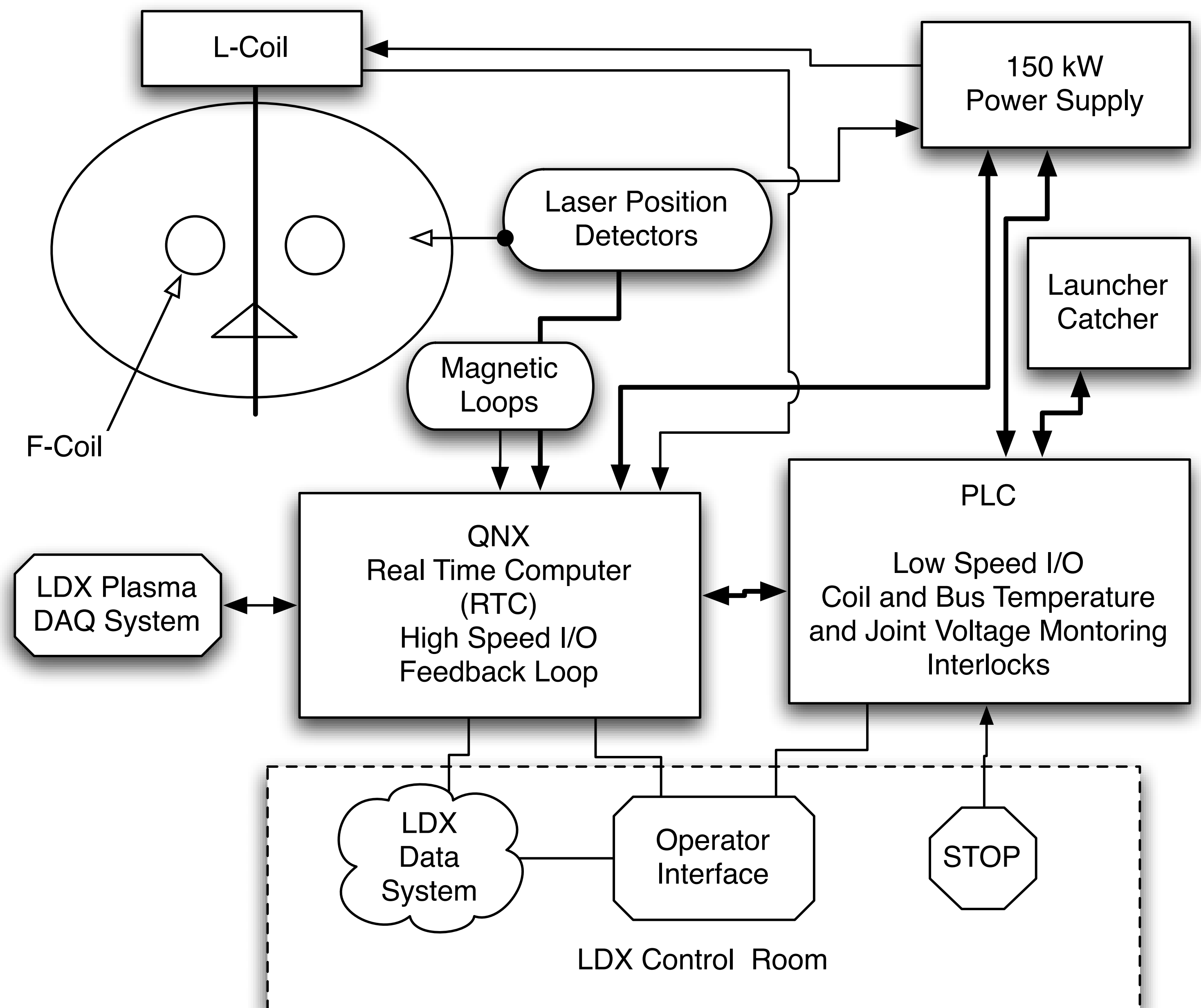
Digitally Controlled Levitation

- Levitated Cheerio Experiment II
- Uses LDX digital control system
- Modified PID feedback system
- Real-time graph shows position and control voltage





Levitation Control System



- Final LDX levitation control system contains added complexity
  - Reliable levitation with over 80 hours of flight time

The Levitated Dipole Experiment (LDX)

LDX Operations and Results

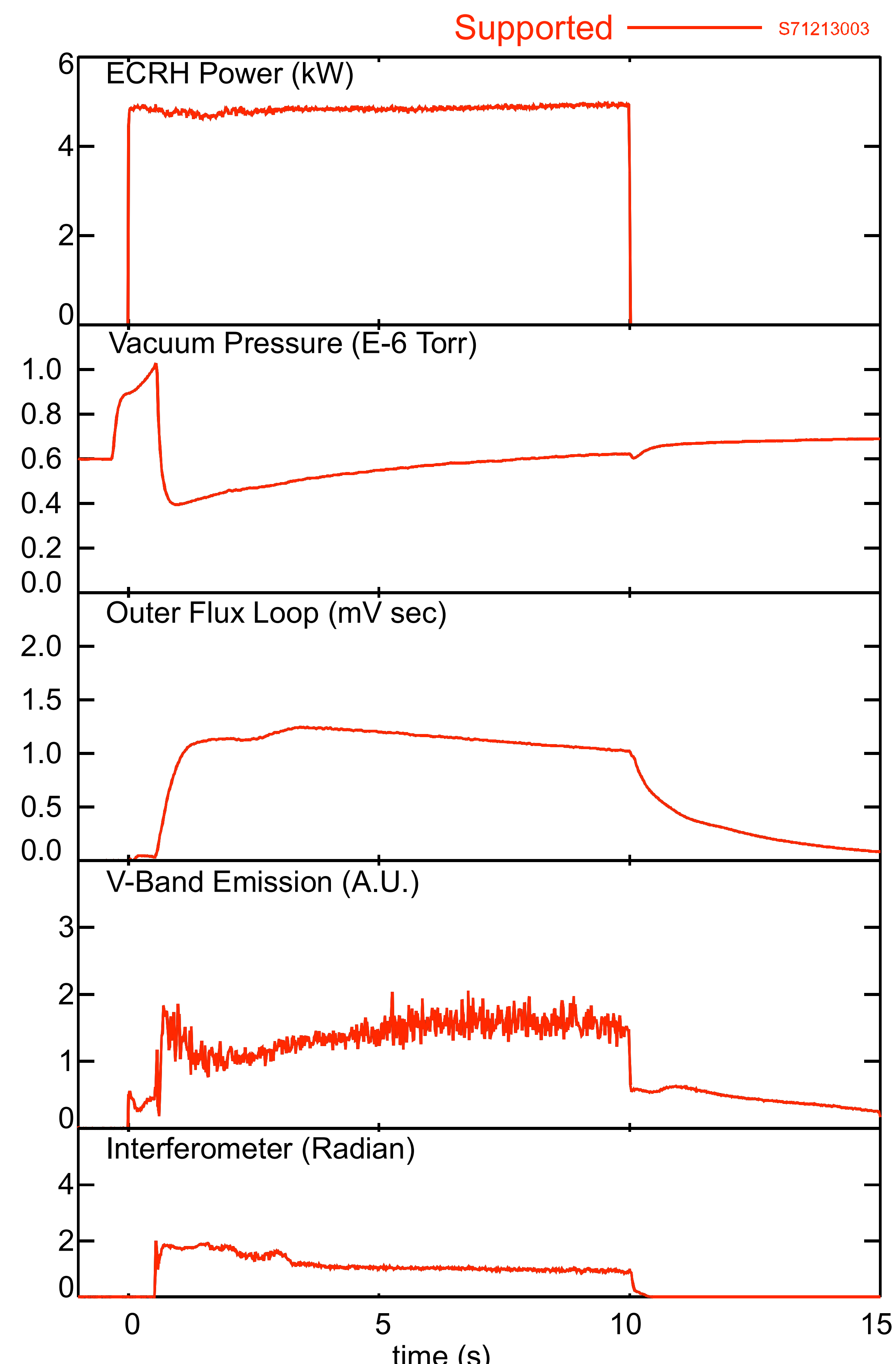
Wow… it really works!

Levitated Dipole Plasma Experiments

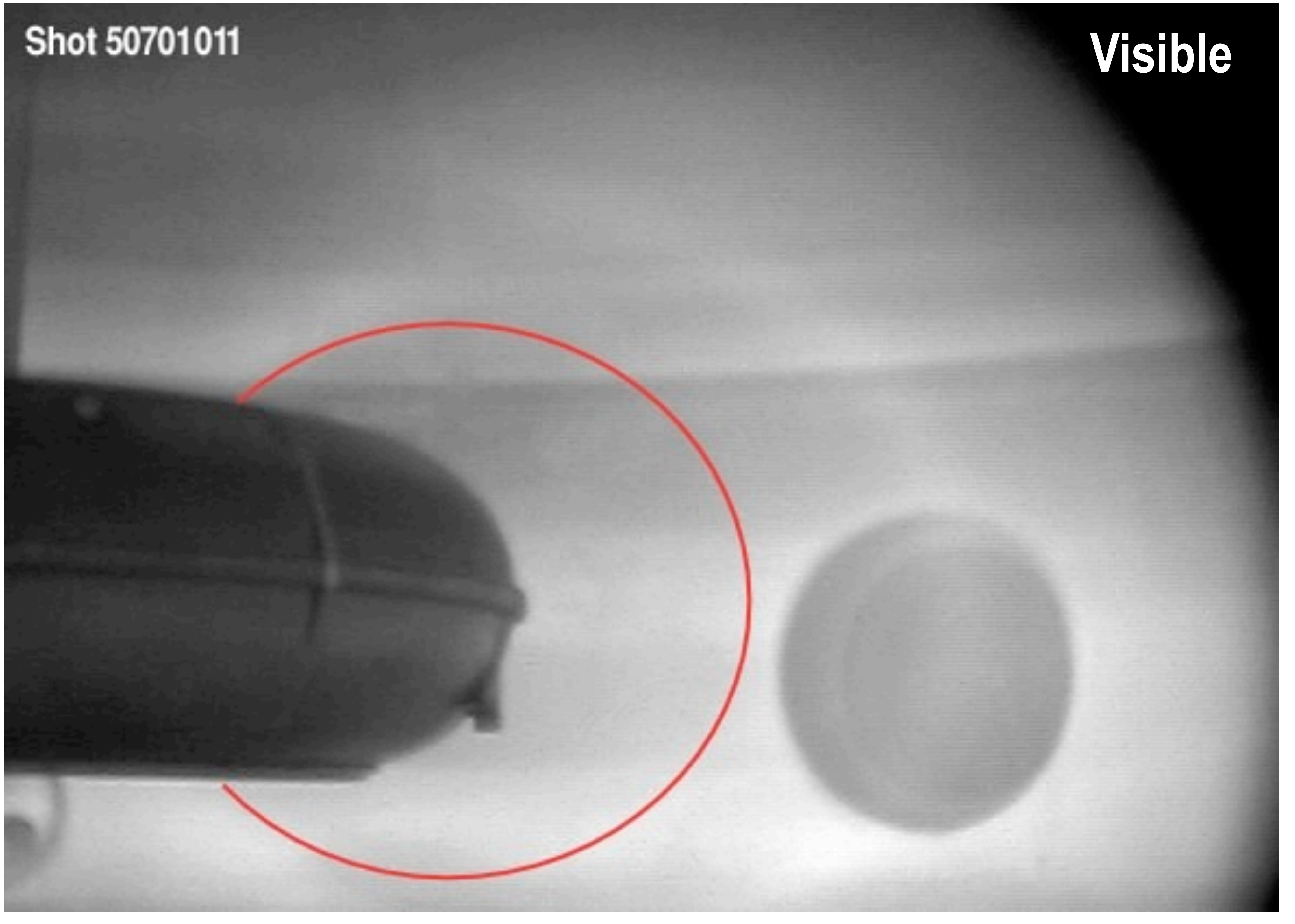
Plasma Confined by a Supported Dipole

- 5 kW ECRH power
- Ip ~ 1.3 kA or 150 J

- Cyclotron emission (V-band) shows fast-electrons
- Long, low-density "afterglow" with fast electrons



Fast Electrons: Anisotropic at ECRH Resonance



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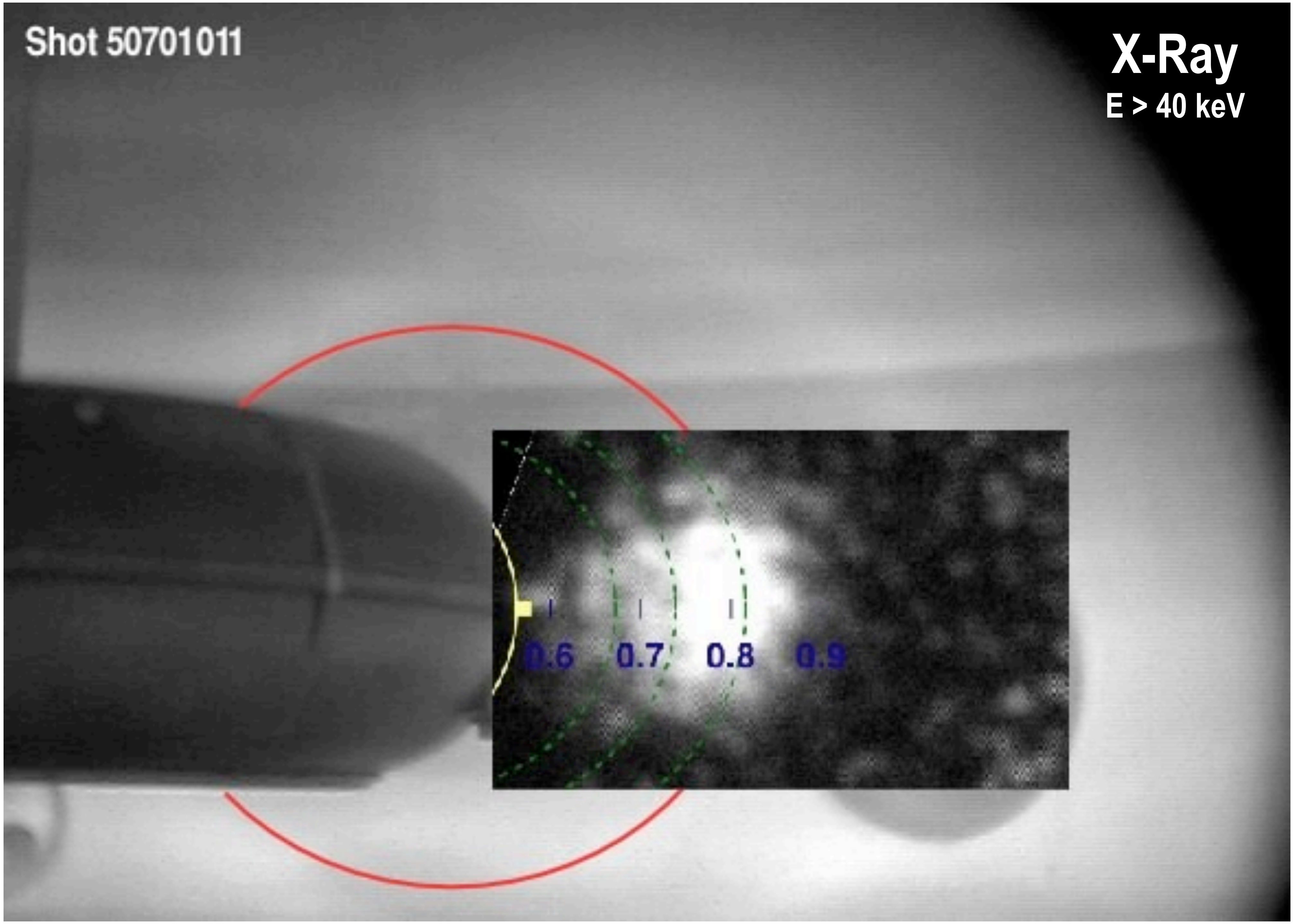
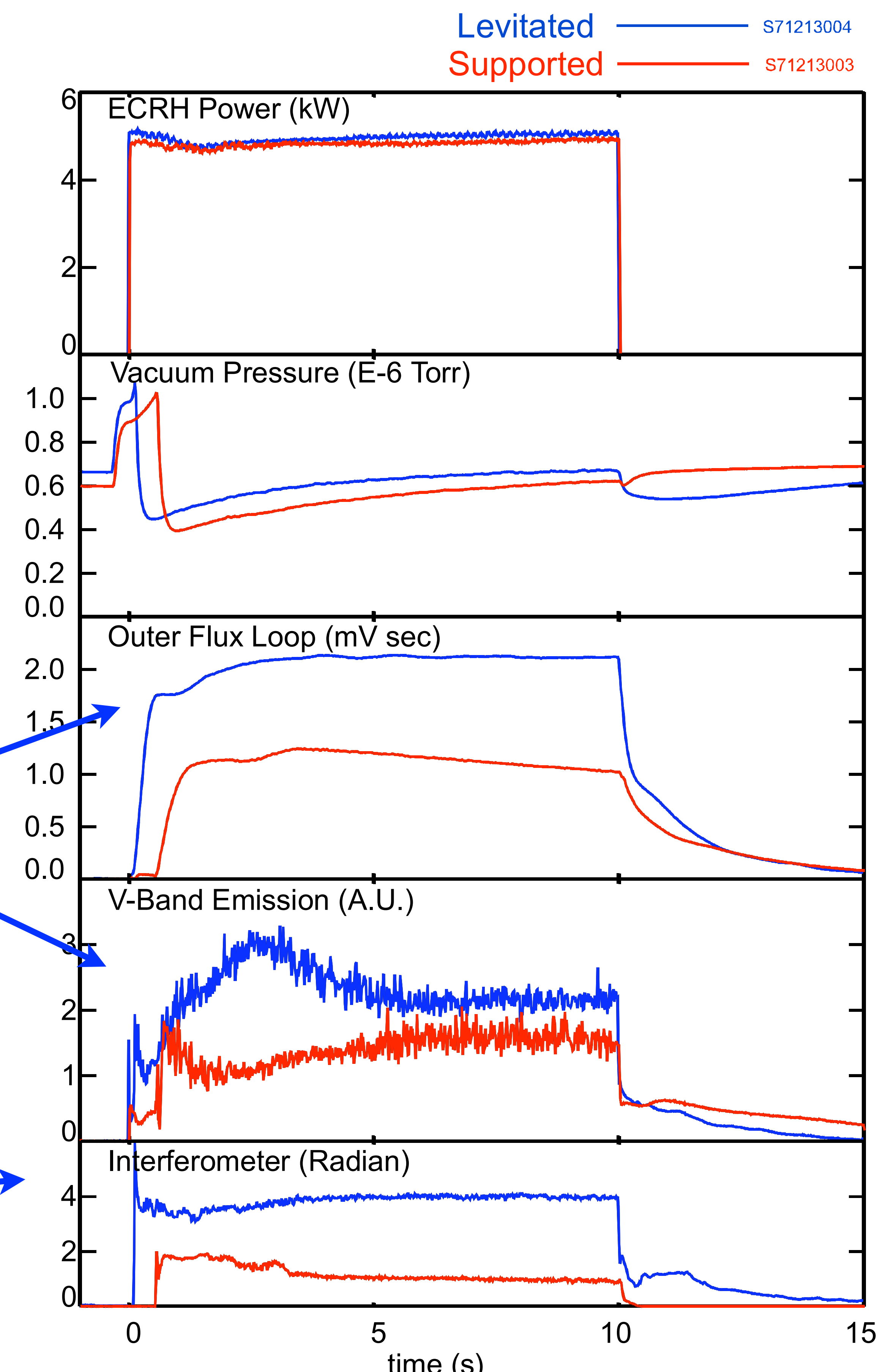


Plasma Confined by a Levitated Dipole

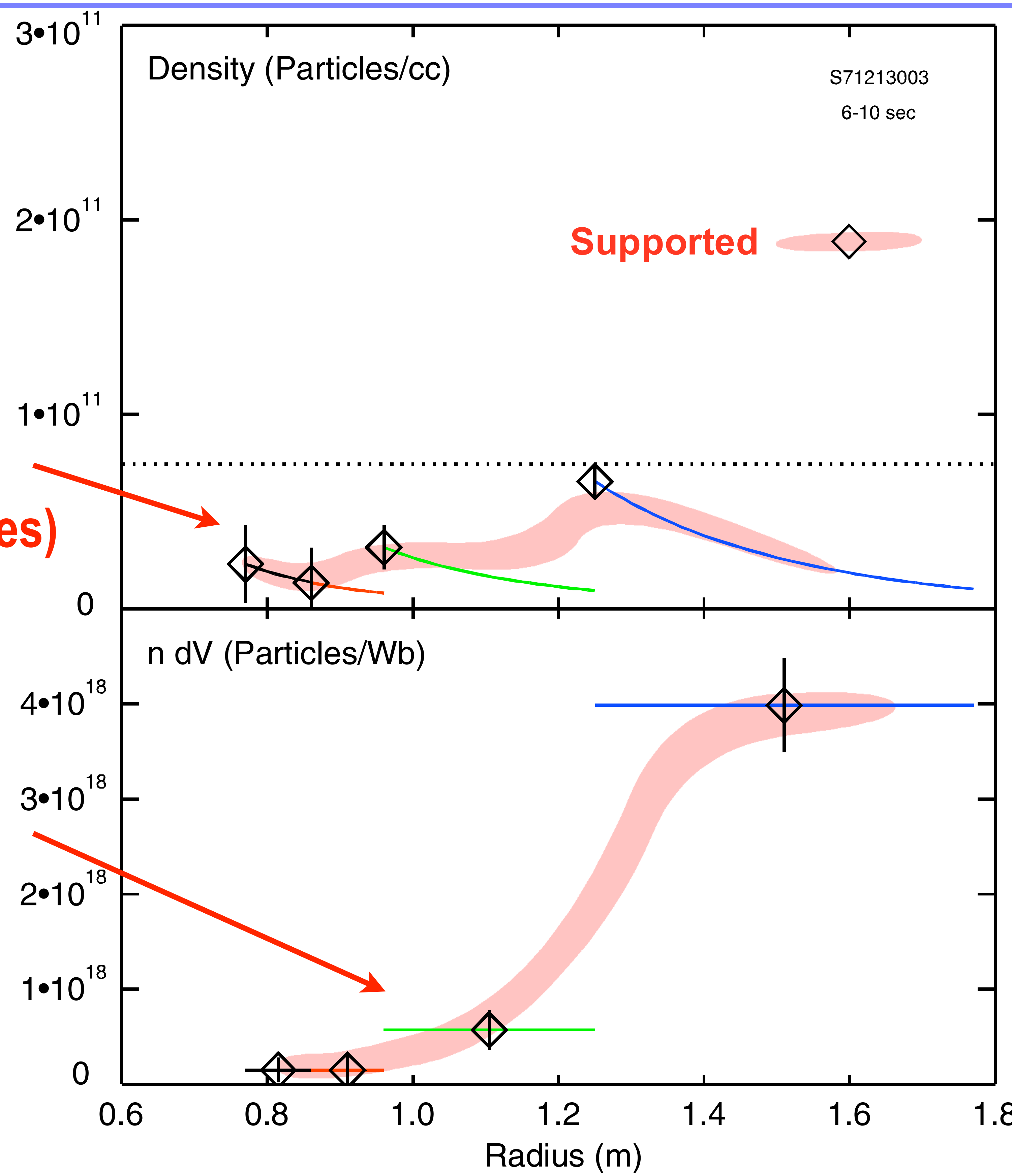
- Reduced fast electron instability
- 2-3 x Diamagnetic flux
- Increased ratio of diamagnetism-to-cyclotron emission indicates higher thermal pressure.
- Long, higher-density “afterglow” shows improved confinement.
- 3-5 x line density



Supported plasmas have flat density profiles

Flat or Hollow Density
(*likely cause*: parallel losses)

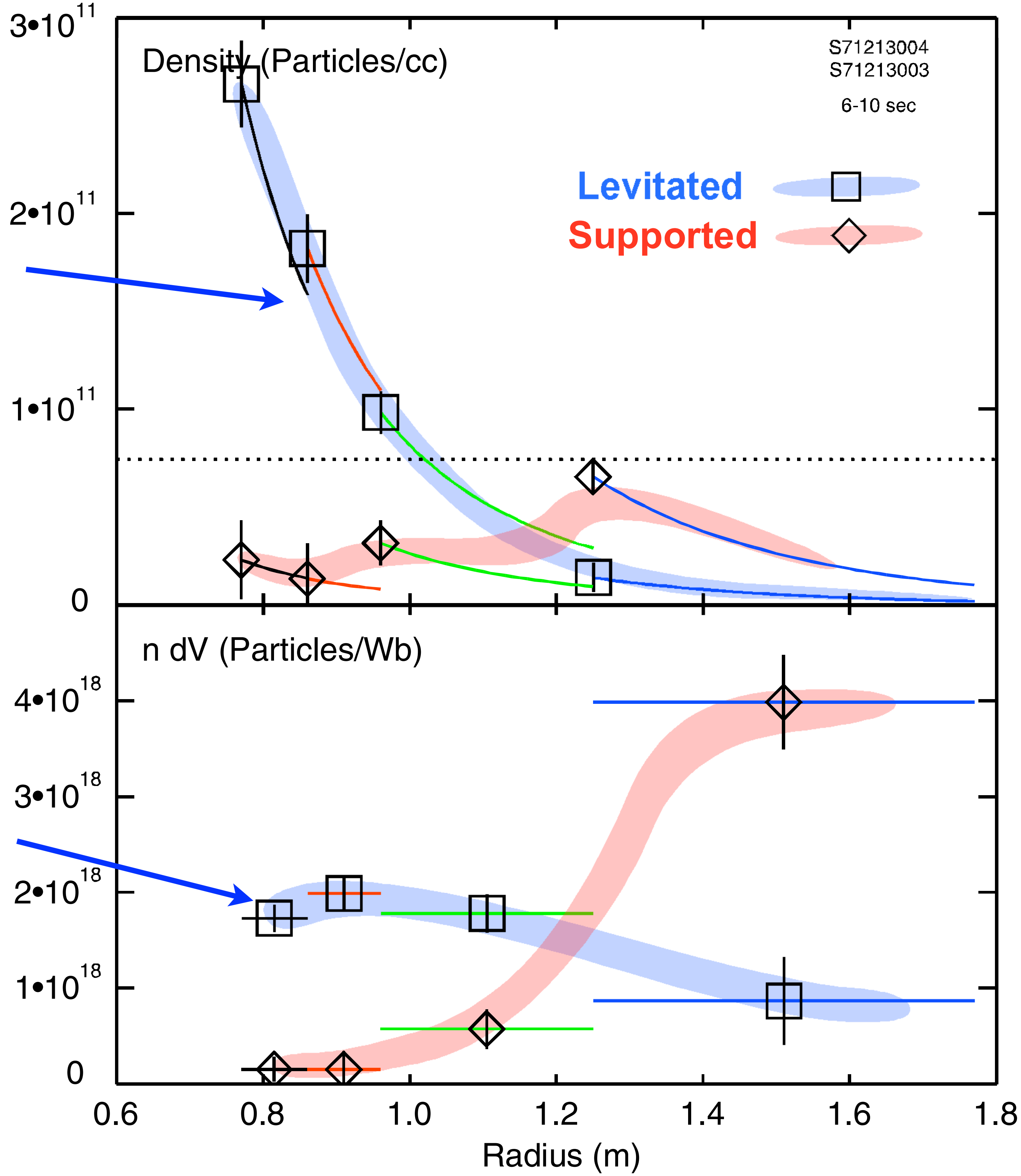
Hollow Number Profile!



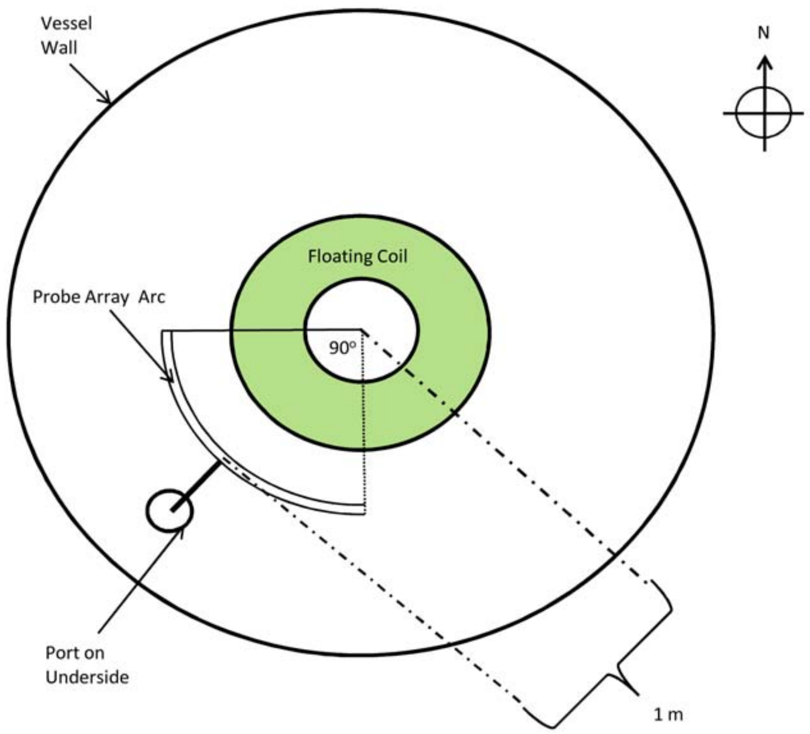
Levitated plasmas show invariant profiles

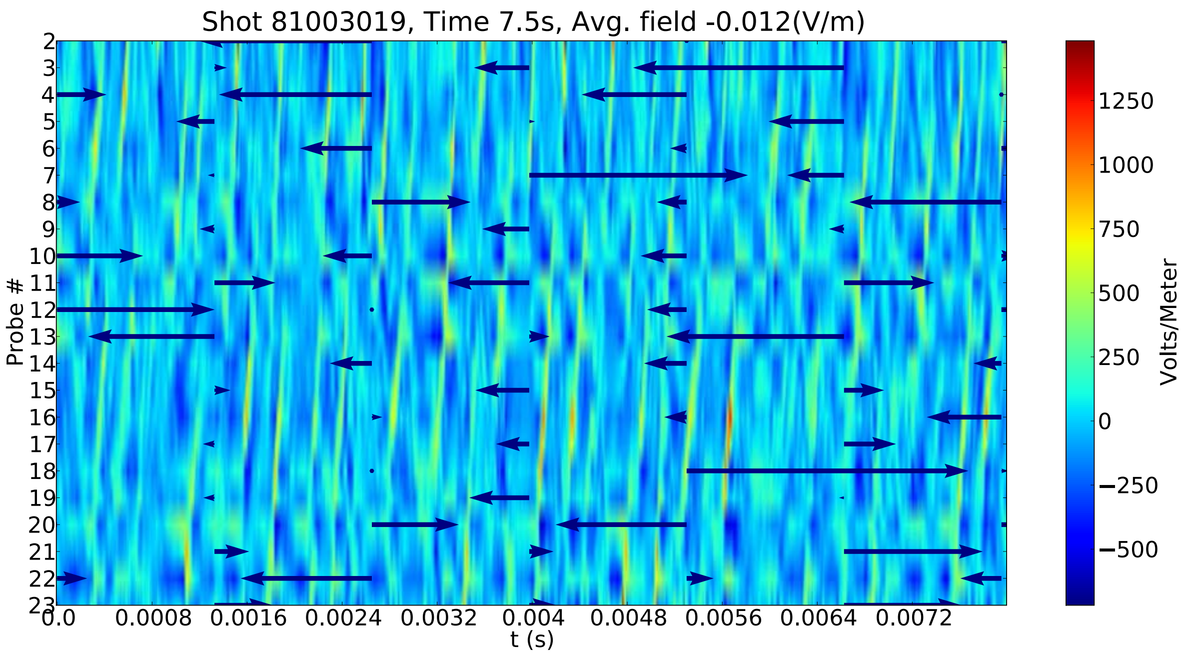
Strongly Peaked Density!

Uniform Number Profile!

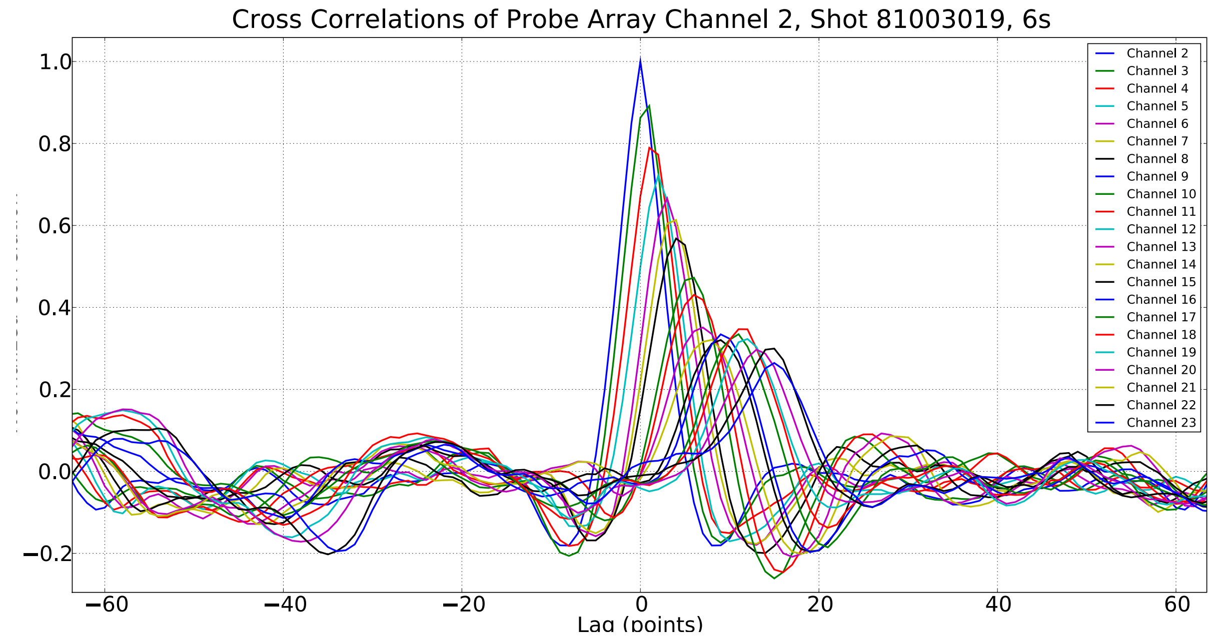


Edge probe array measures low frequency turbulence

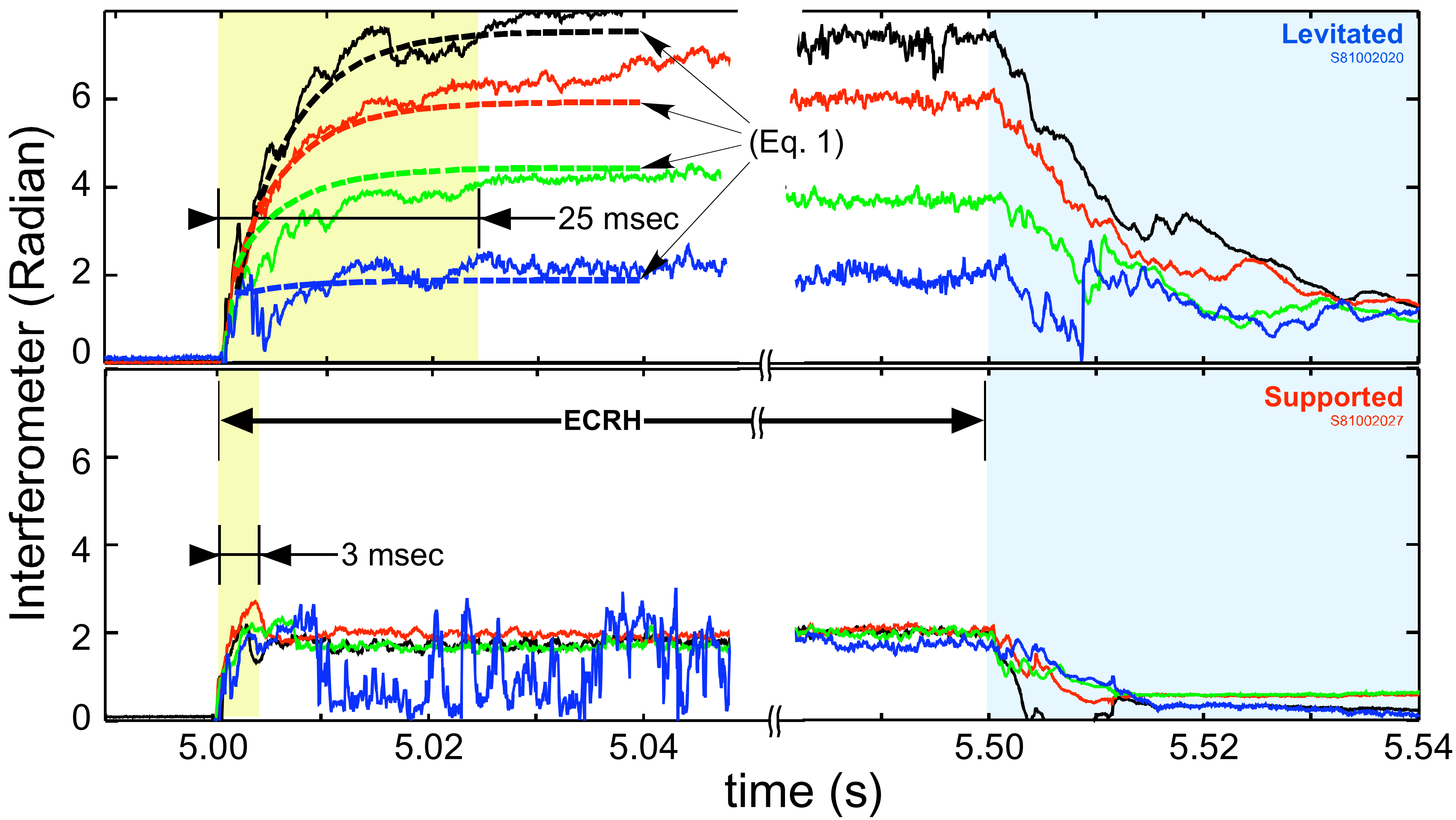




- Array measures low frequency turbulent spectrum (0.1 - 10 kHz)
- Instantaneous ExB radial flow of 35 km/s



Low frequency fluctuations consistent with Turbulent Pinch



$$\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi}\,, \tag{1}$$

where $\langle S \rangle$ is the net particle source within the flux-tube, and the diffusion coefficient is $D = R^2 \langle E_\varphi^2 \rangle \tau_{cor}$ in units of $(\mathrm{V} \cdot \mathrm{sec})^2/\mathrm{sec}$.

Summary

- The dipole concept offers a unique avenue to study magnetic confinement bridging space and the laboratory
- The LDX device is highly innovative, superconducting magnetic confinement device with reliable operation
- LDX is fulfilling its physics mission:
  - Demonstration of stable high beta plasmas
    - Significant plasma stored energy in the bulk plasma has been observed
  - Demonstrated the formation of invariant “natural” density profiles in a laboratory dipole plasma.
    - Peaked profile formation likely the result of low frequency turbulent pinch

Next Steps

- Levitation System upgrades
  - Incorporate magnetic signals
    - remove influence of plasma diamagnetic current on levitation
- Diagnostic upgrades
  - Improved fluctuation diagnostics to study turbulent transport
  - Core temperature diagnostics to test effective adiabatic constant
    - Including Thompson scattering system
- "Scotty, we need more power!"
  - Higher power for higher density and temperatures
  - 10 kW, 28 GHz gyrotron (with U Maryland collaboration)
  - 200 kW ion heating (slow wave ICRH)
    - 1 MW, 3-28 MHz Transmitter donated by GA to be installed with ARRA funding