ICC/1-1Ra
23rd IAEA FEC 11-16 Oct. 2010

Turbulent Particle Pinch in Levitated Superconducting Dipole

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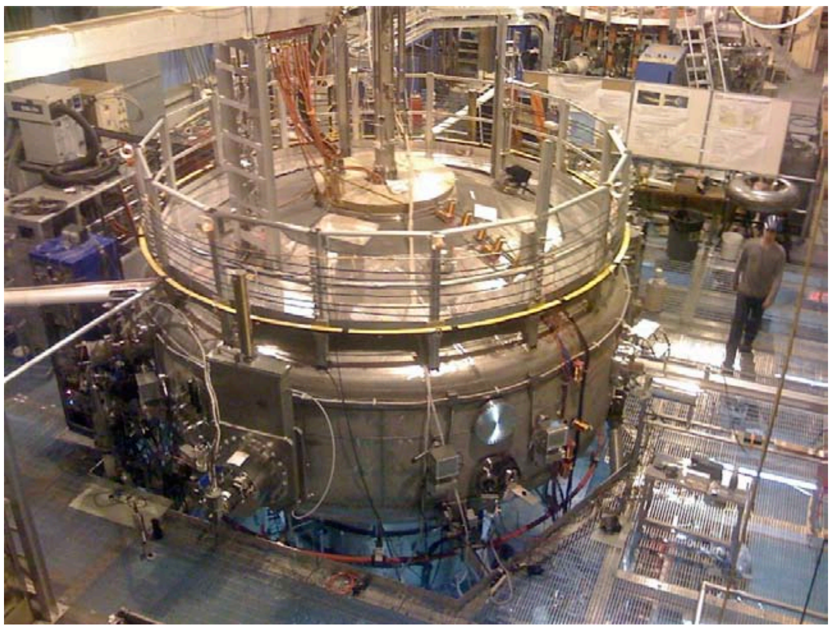
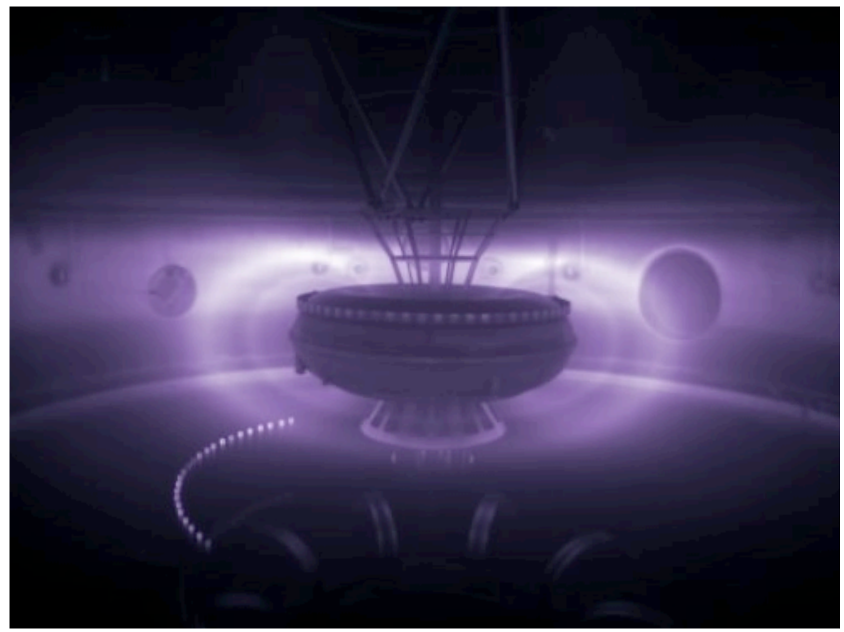


LDX: Superconducting Levitated Dipole



High-β dipole-confined plasma

EXC/9-4Rb
23rd IAEA FEC 11-16 Oct. 2010

High-Beta Plasma Confinement and Inward Particle Diffusion in the Magnetospheric Device RT-1

Graduate School of Frontier Sciences, University of Tokyo, Kashiwa, Chiba, JAPAN

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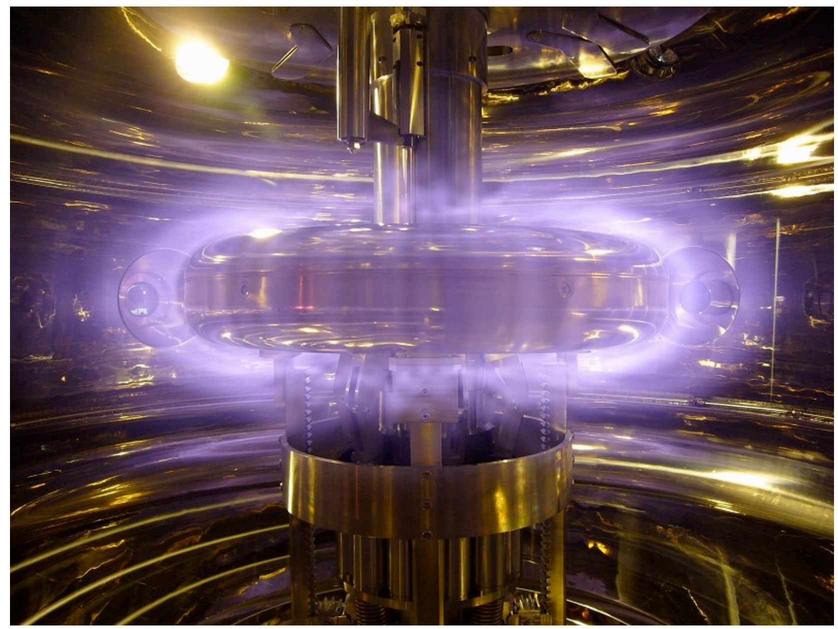
RT-1: Superconducting Levitated Dipole



High-β dipole-confined plasma

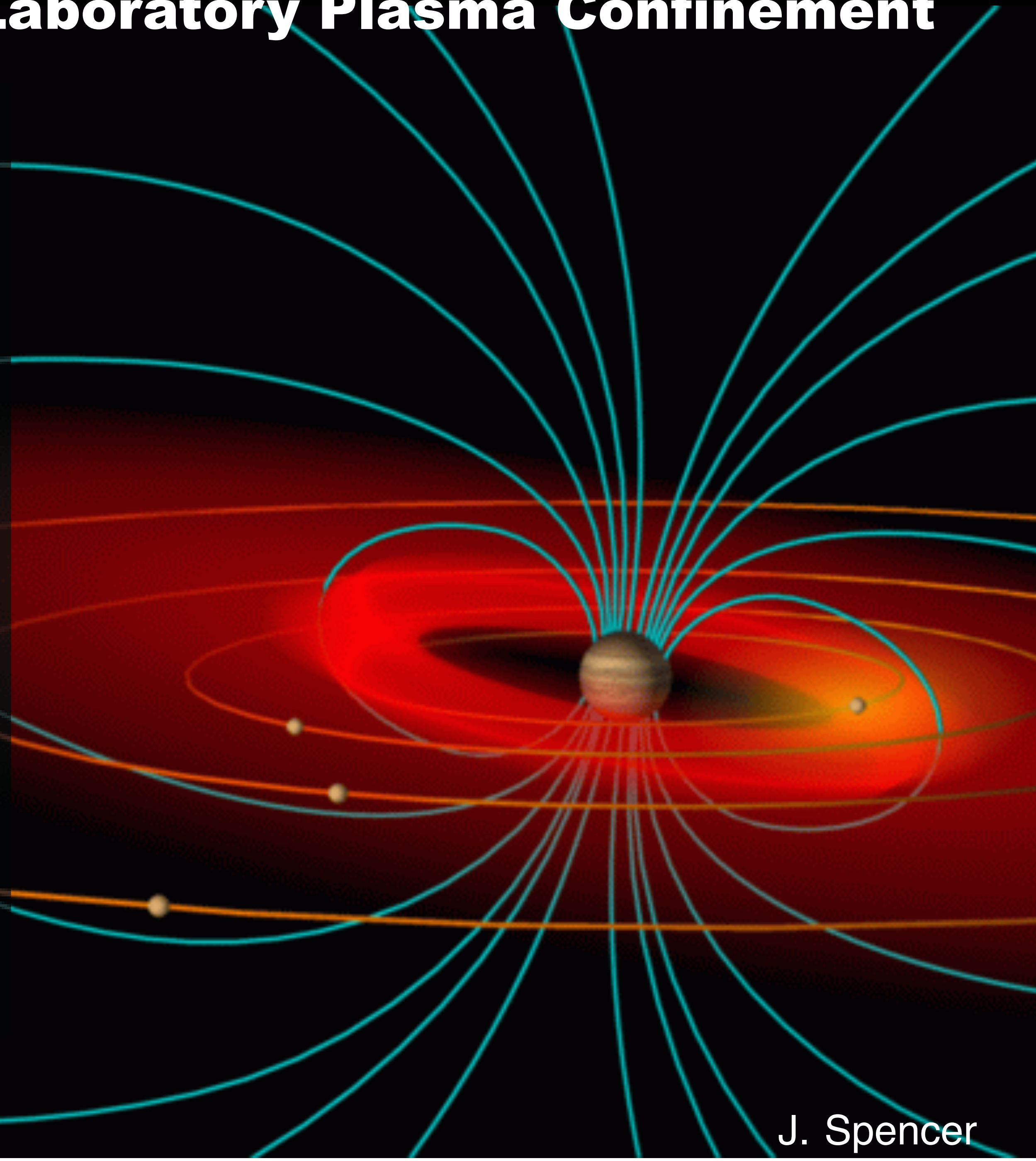
RT-1

Transdisciplinary Sciences, GSFS

東京大学
THE UNIVERSITY OF TOKYO

Magnetospheric Levitated Dipoles: Space Physics for Laboratory Plasma Confinement

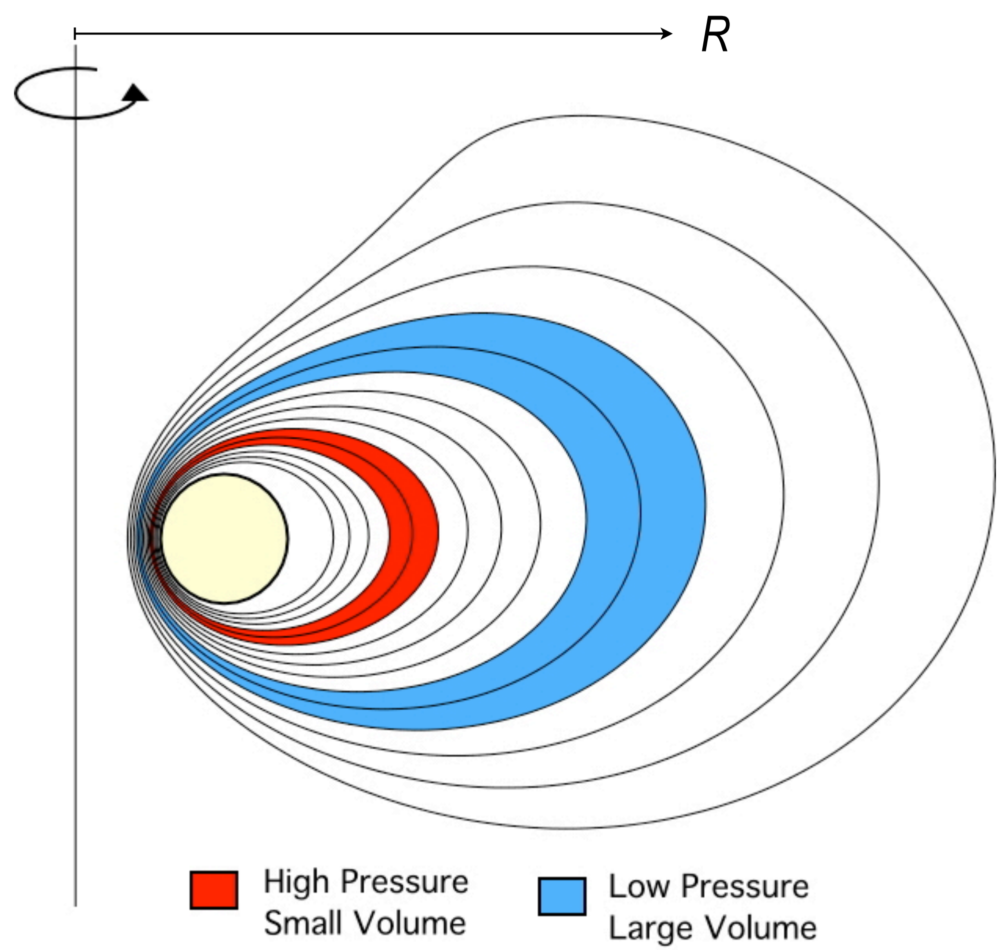
- Akira Hasegawa, 1987
- Two interesting properties of active magnetospheres:
  - **High beta**, (eg. of order unity magnetosphere of Jupiter)
  - **Pressure and density profiles are strongly peaked**
    - **“invariant profiles”** turbulent activity **increases** peakedness



Physics of dipole plasma confinement is now well established

- More than 50 years of magnetospheric exploration: Earth, Jupiter, Saturn, Uranus, and Neptune
- Confinement and stability based on magnetic compressibility
- Gold (1959): Plasma pressure is centrally peaked with $p \sim 1/V^{\gamma} \sim R^{-20/3}$
- Melrose (1967): Plasma density is centrally peaked with $\langle n \rangle \sim 1/V \sim R^{-4}$
- Farley (1970): Turbulence causes strong inward particle pinch (radiation belts)

$$V = \oint \frac{d\ell}{B} \propto R^4$$



Physics of dipole plasma confinement is now well established

- Natural or "Invariant" profiles are stationary solutions to low frequency turbulent mixing that preserve adiabatic invariants

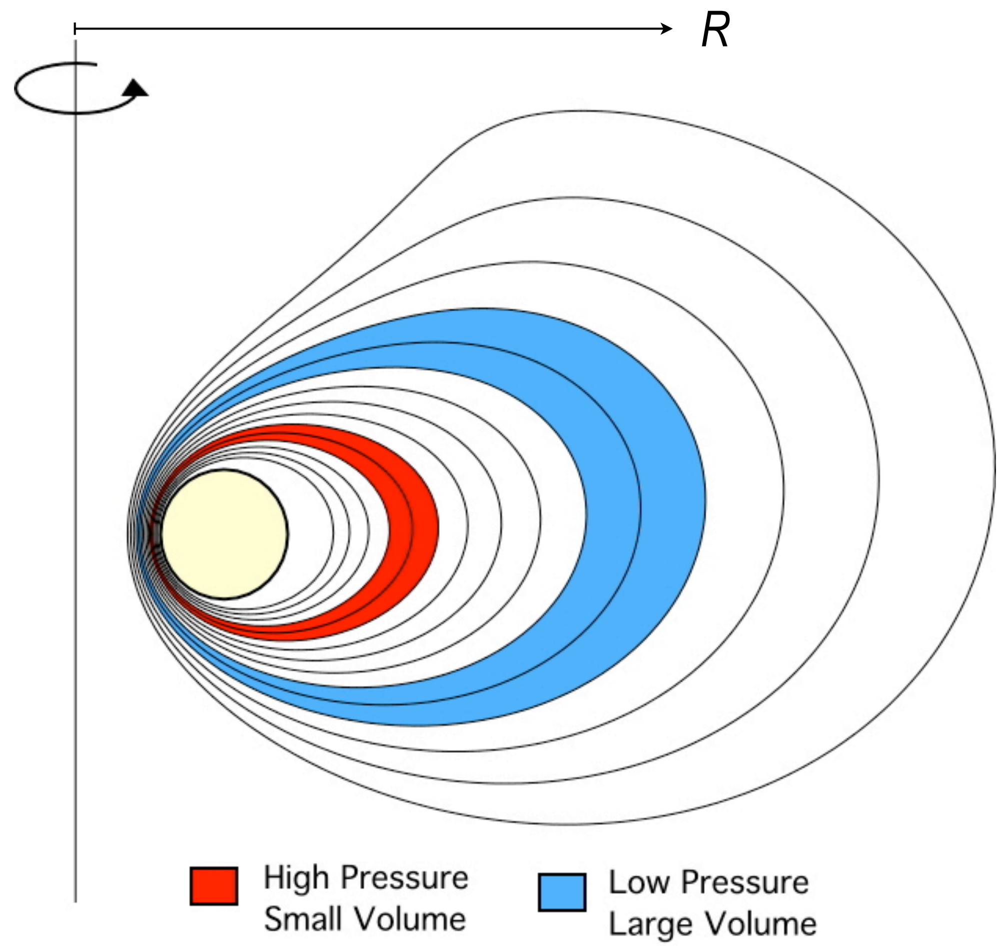
$$V = \oint \frac{d\ell}{B} \propto R^4$$

$$\frac{\partial (nV)}{\partial t} = \frac{\partial}{\partial \psi} D^{\psi\psi} \frac{\partial (nV)}{\partial \psi} + \langle S \rangle$$

$$\frac{\partial}{\partial \psi} \left(D^{\psi\psi} V \frac{\partial n}{\partial \psi} + n D^{\psi\psi} \frac{\partial V}{\partial \psi} \right)$$

dipole geometry has large pinch term

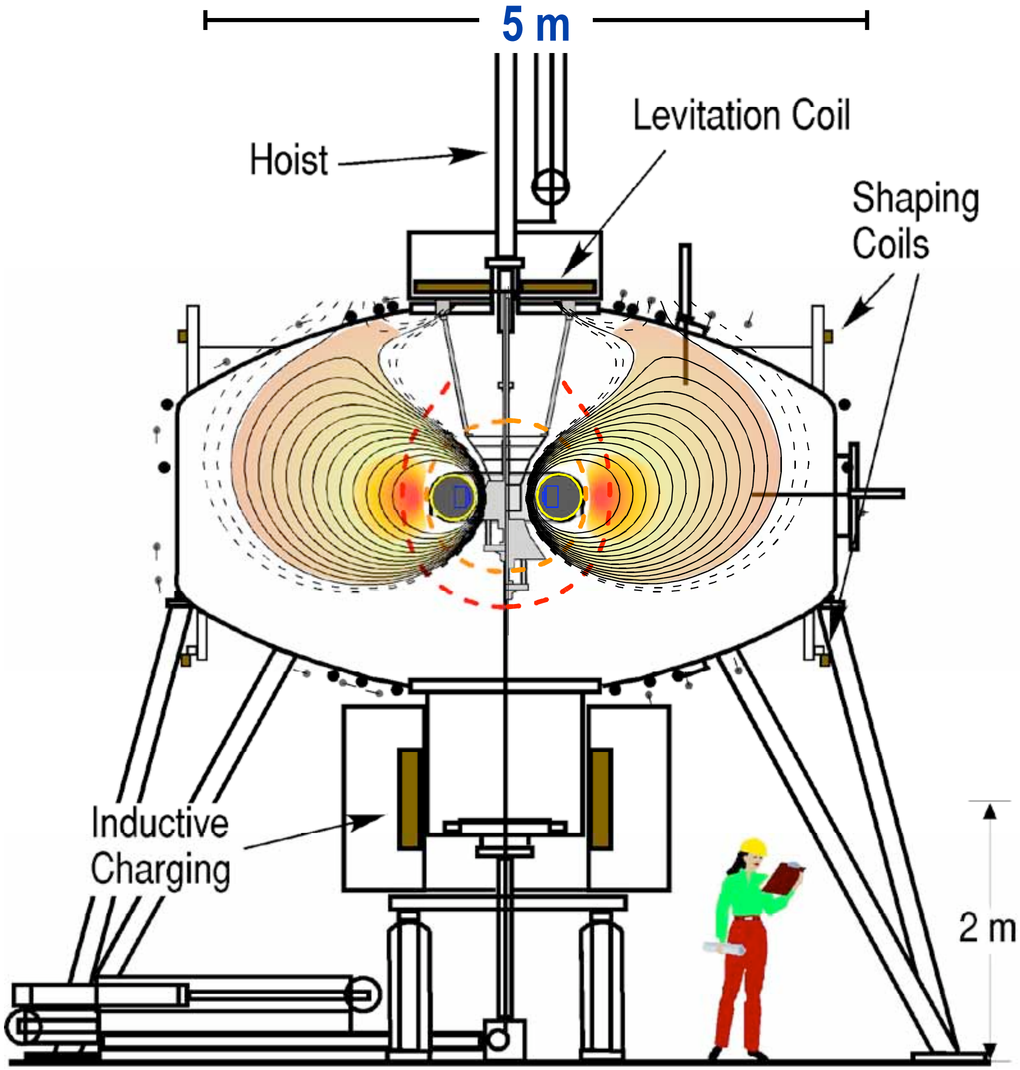
$$\frac{\partial (pV^\gamma)}{\partial t} = \frac{\partial}{\partial \psi} D^{\psi\psi} \frac{\partial (pV^\gamma)}{\partial \psi} + \langle H \rangle$$



Superconducting Levitated Dipole Experiments

LDX (MIT - USA)

Nb_3Sn Dipole 1.2 MA
Inductively Charged
3 Hour Float Time 25 kW CW ECRH



Components of a Levitated Dipole Experiment:

- Strong superconducting dipole for long-pulse, quasi-steady-state experiments
- Large vacuum chamber for unequalled diagnostic access and large magnetic compressibility
- Upper levitation coil for robust axisymmetric magnetic levitation
- Lifting/catching fixture for re-cooling, coil safety, and physics studies
- ECRH for high-temperature, high-beta plasmas

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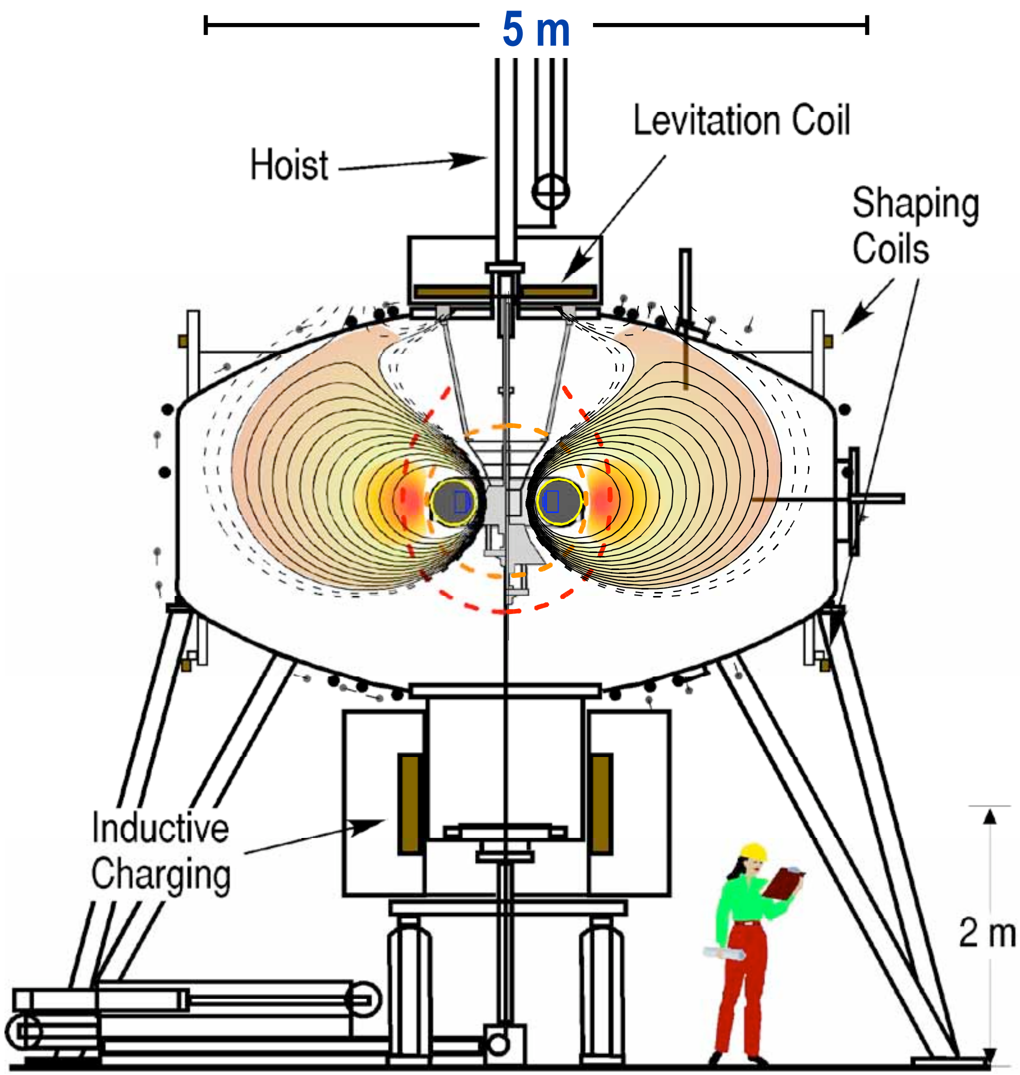
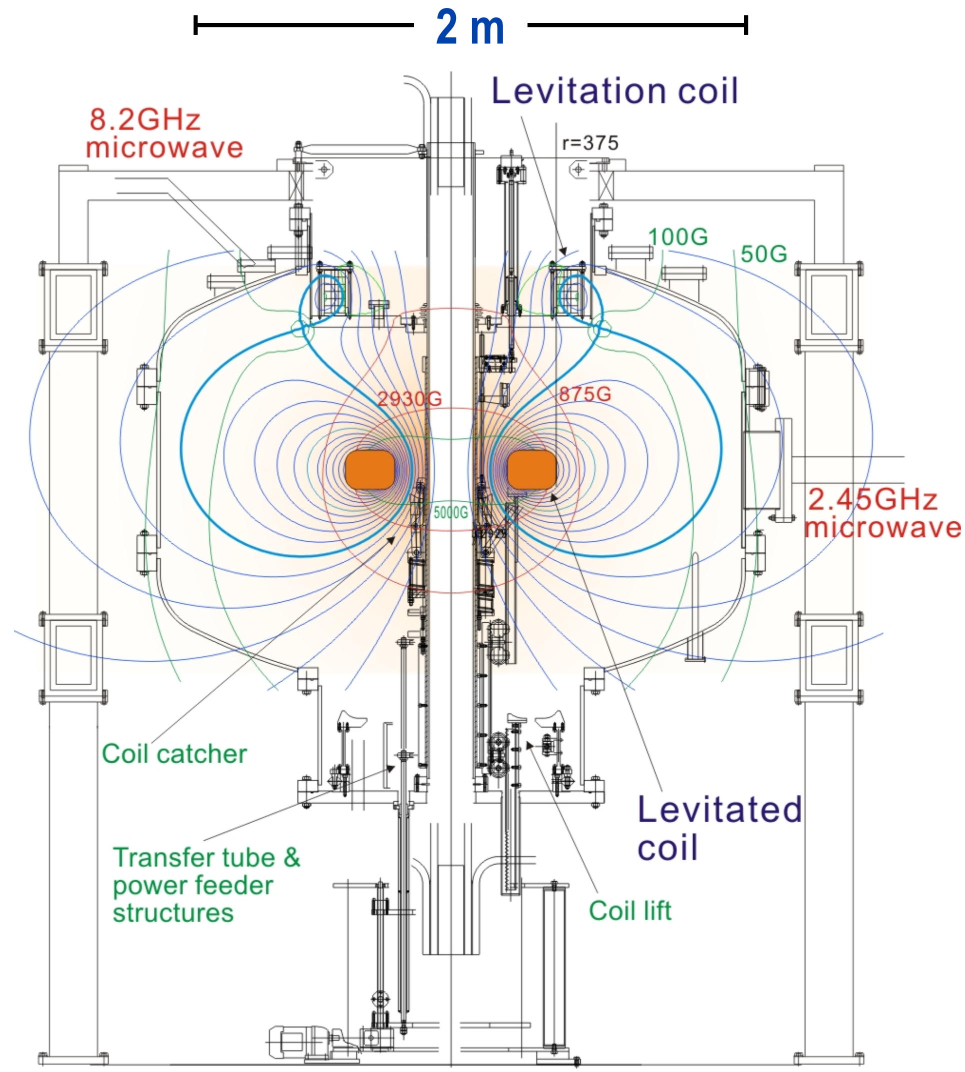


RT-1 (U. Tokyo - Japan)

HTS Bi-2223 Dipole 0.25 MA
Electrically Charged w/SC Switch
6 Hour Float Time 45 kW CW ECRH



LDX & RT-1: Two Key Experimental Results

1. **ECRH generates very high-beta plasmas consisting of centrally-peaked well-confined energetic electrons and warm collisional plasma…**

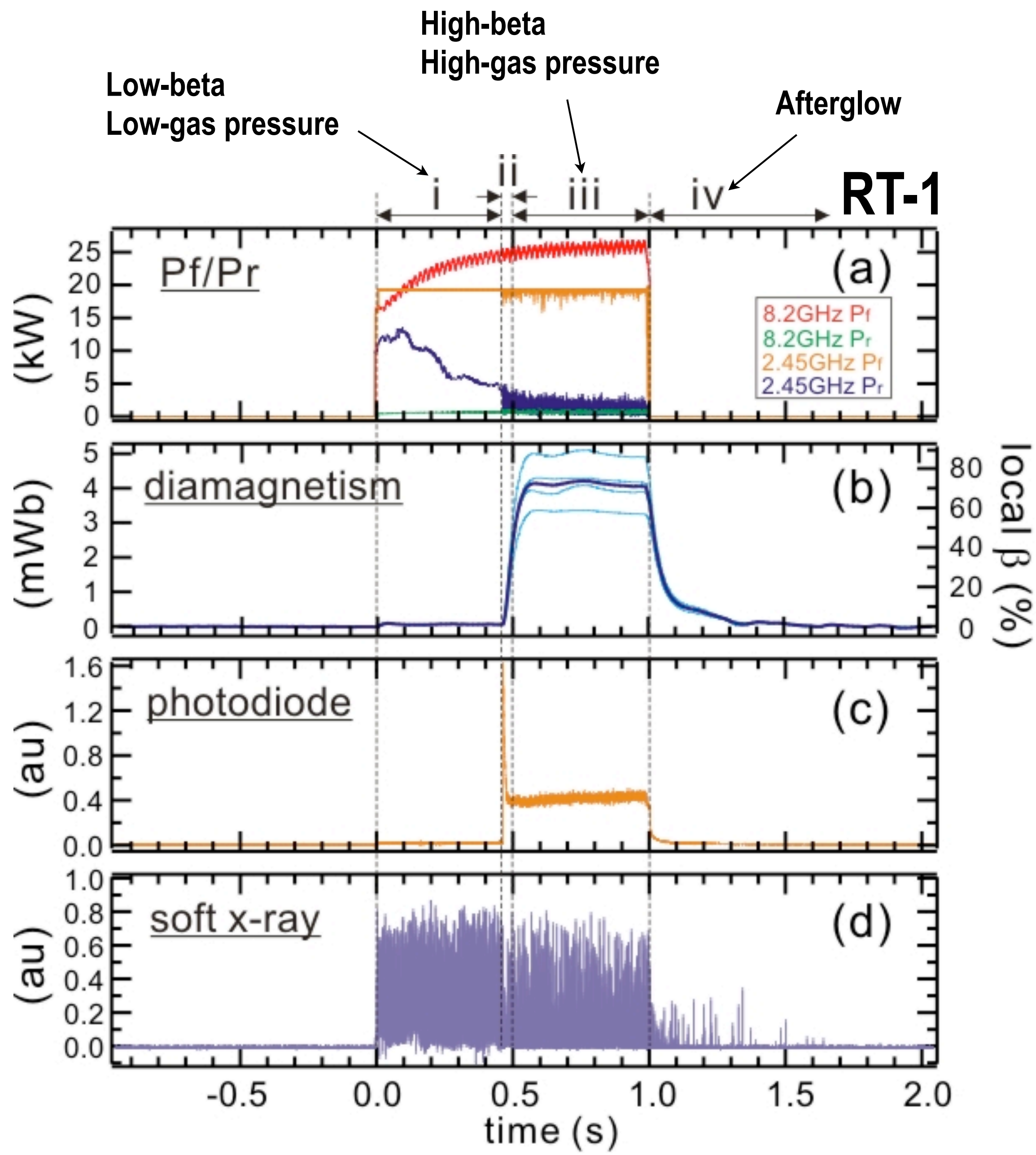
   - Pressure profiles measured with magnetic equilibrium analysis
   - Peak local beta observed in RT-1 reaches 70%
   - Global energy confinement times up to 60 ms. LDX show levitated plasmas contain 40-70% of stored energy in collisional plasma with peak density n ~ 10^{18} m^{-3}.

2. **Plasma density profiles are centrally peaked caused by a strong inward turbulent particle pinch…**

   - Near invariant density profiles measured with multi-chord interferometer
   - Rate of inward pinch (~ 25 ms) observed in LDX to be consistent with fluctuations measurements

High Beta Dipole Plasma with Optimal Gas Fueling

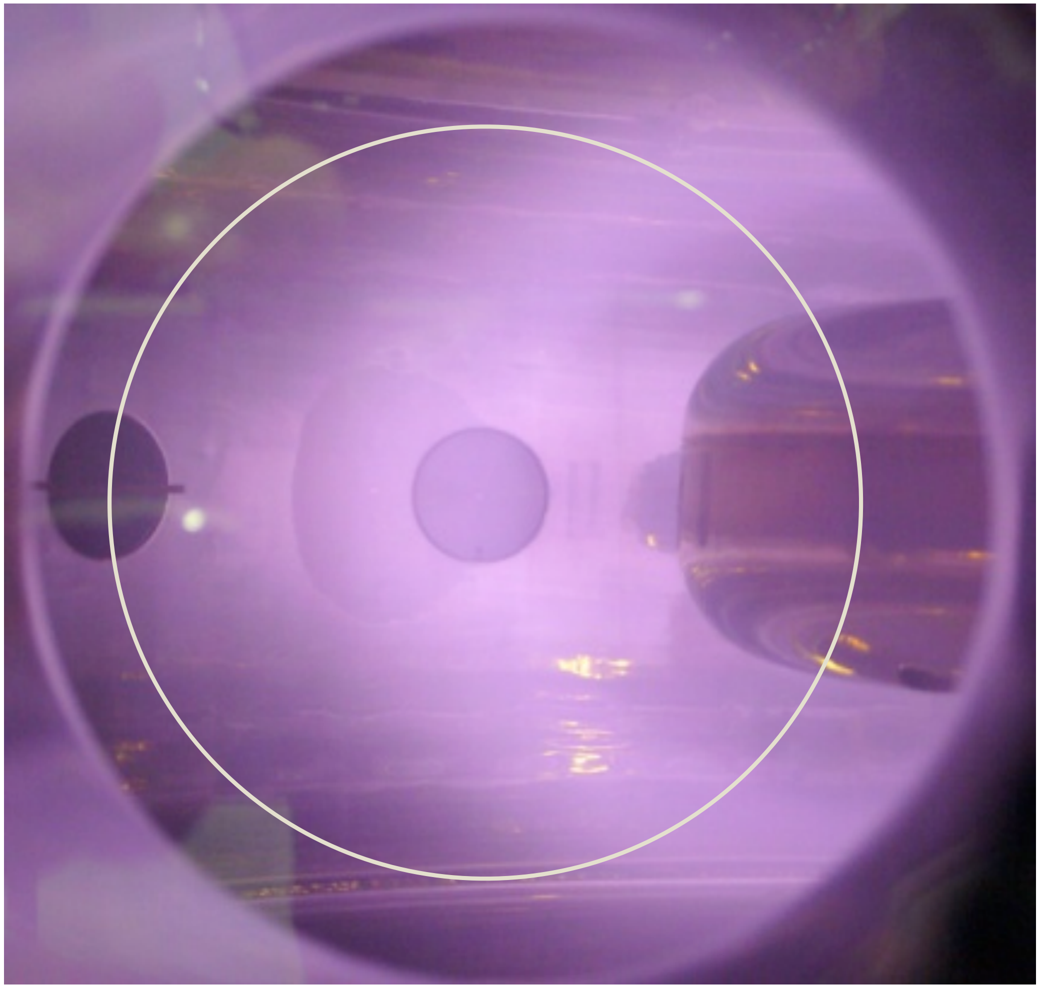
- RT-1 discharge with low gas fueling (also typical of LDX)
- Initial unstable phase with rising neutral pressure
  - When gas pressure exceeds a critical value (~ 1 μTorr), energetic electrons are stable
- Plasma density, plasma stored energy, increase dramatically
  - Peak local beta reaches 70%
  - Removing geomagnetic error field improves confinement
- Two decay times indicate collisional thermal plasma and energetic electron component



Soft X-ray Imaging on RT-1

- RT-1 soft X-ray emission (0.1-10keV) shows isotropic plasma
- Probe target x-rays show energetic electrons near fundamental ECRH resonance zones
  - 2.45 GHz has mid-plane resonance
  - 8.2 GHz resonance crosses coil
- 2.45 GHz heating creates higher stored energy
- LDX hard X-ray (> 40 keV) shows anisotropic mirror trapped fast electrons localized on outer mid-plane

2.45GHz Heating



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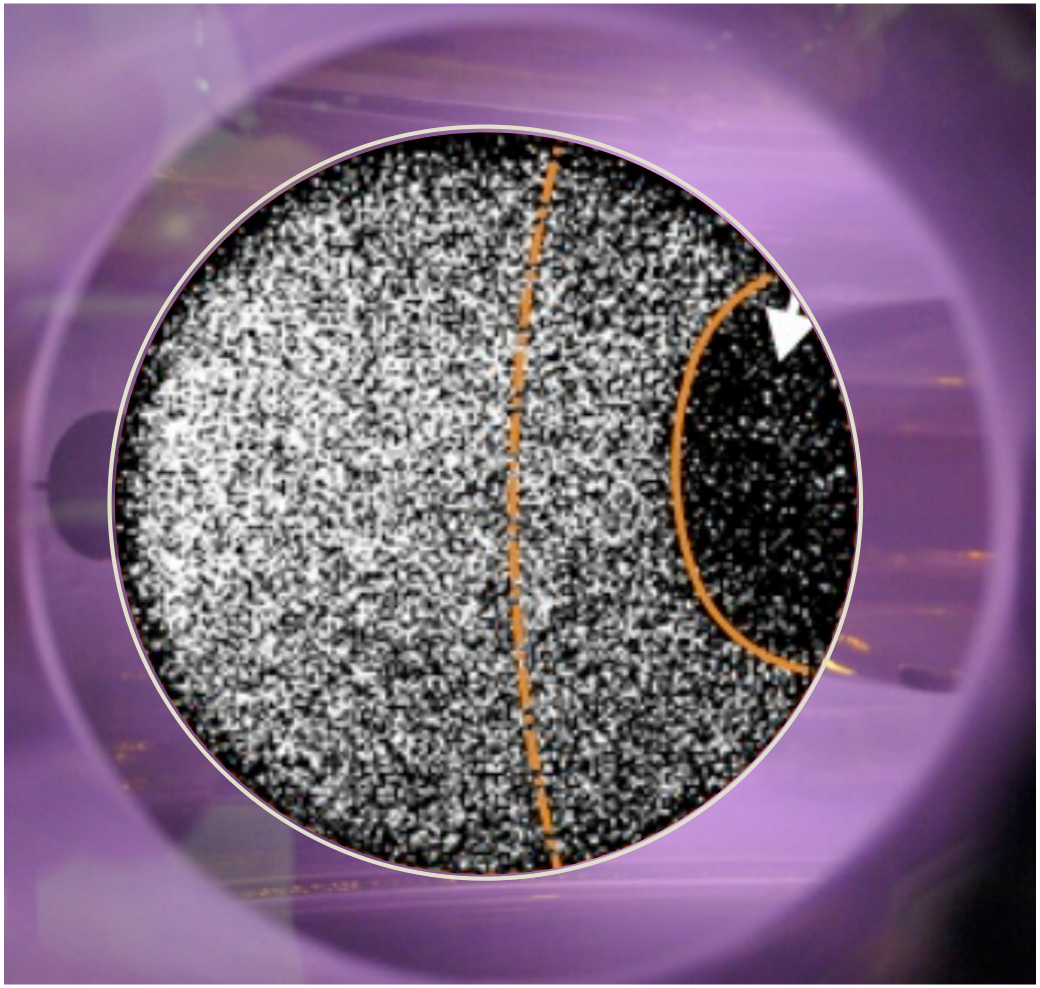

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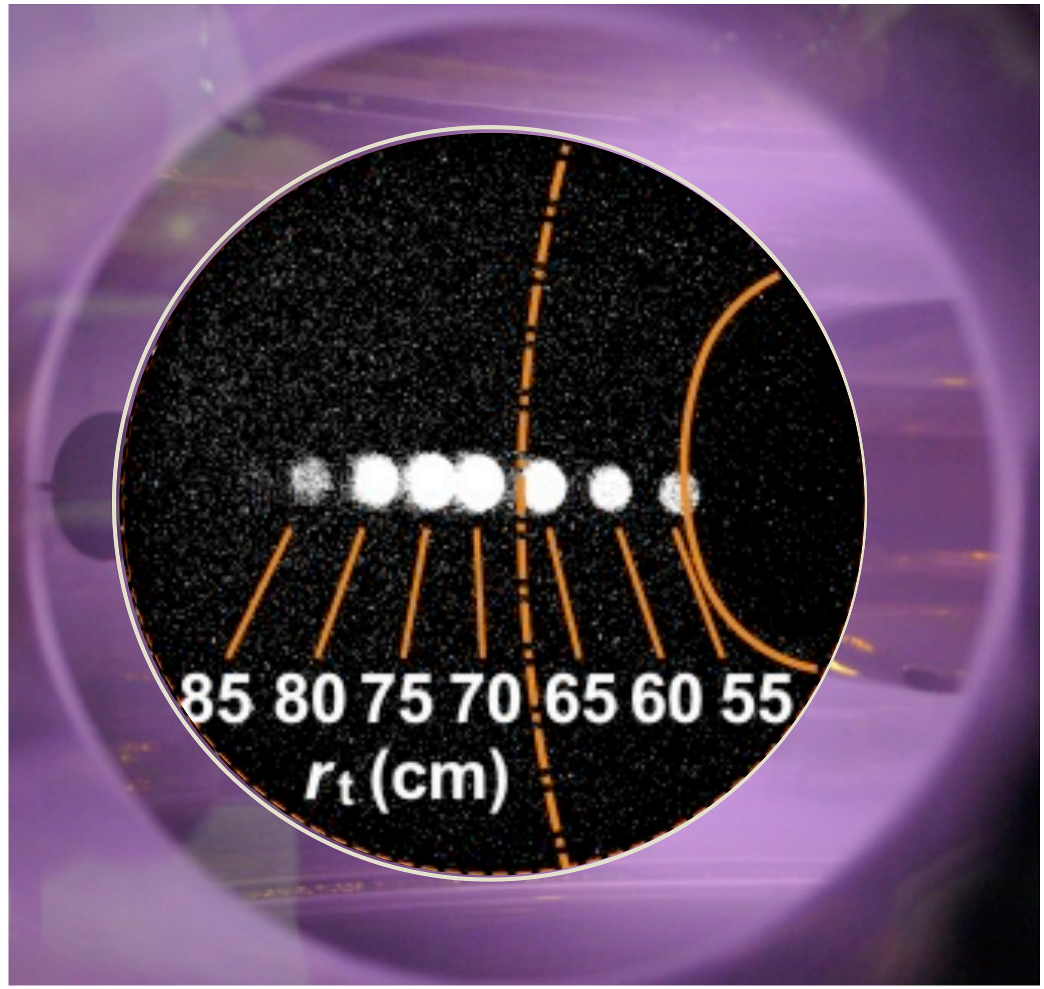
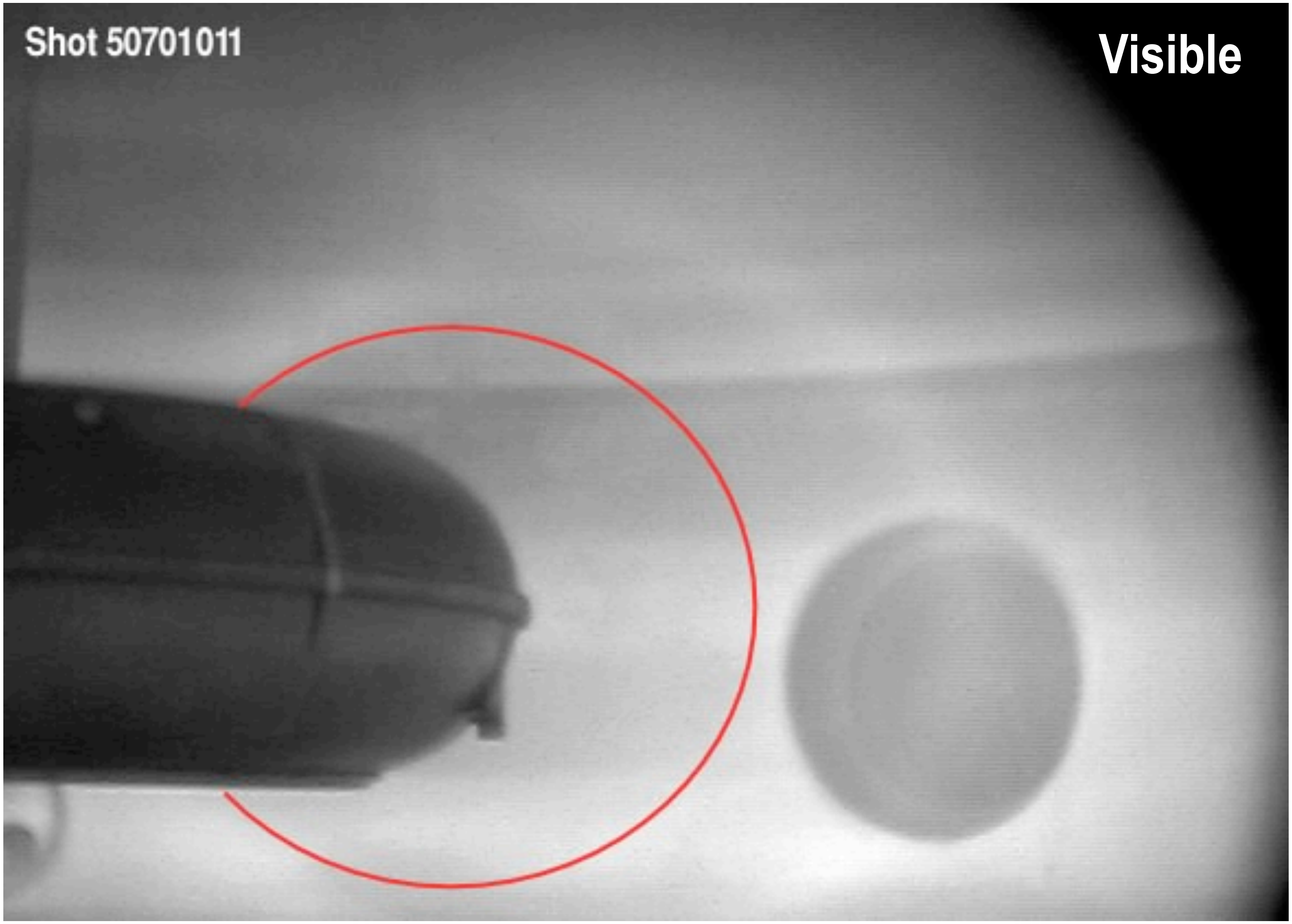


LDX Fast Electrons: Anisotropic at ECRH Resonance



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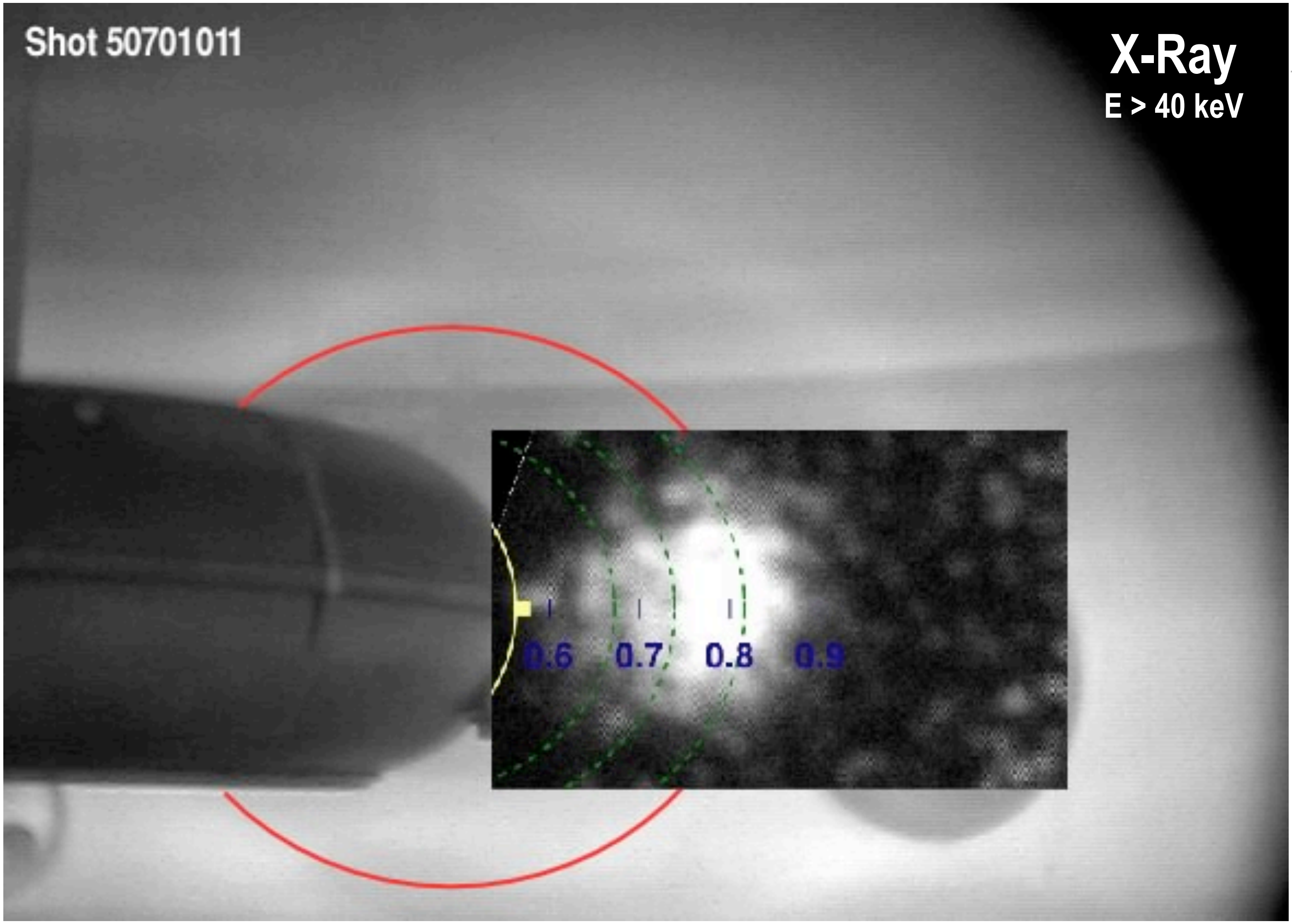
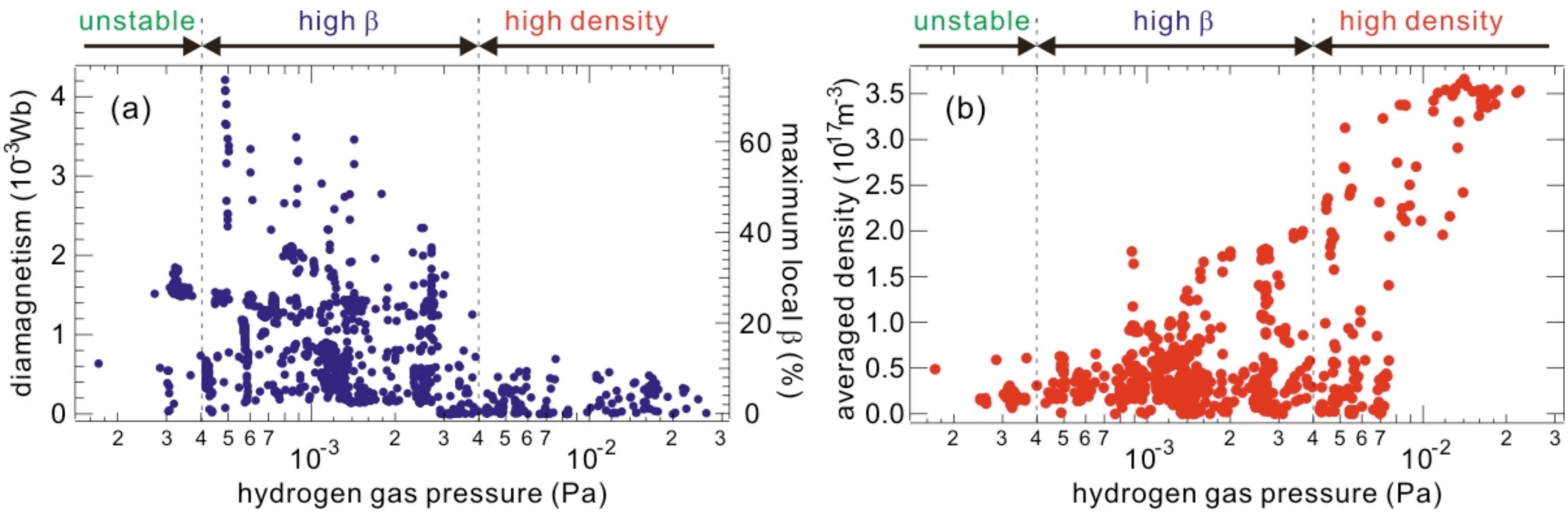


RT-1 Improved plasma properties with increasing gas



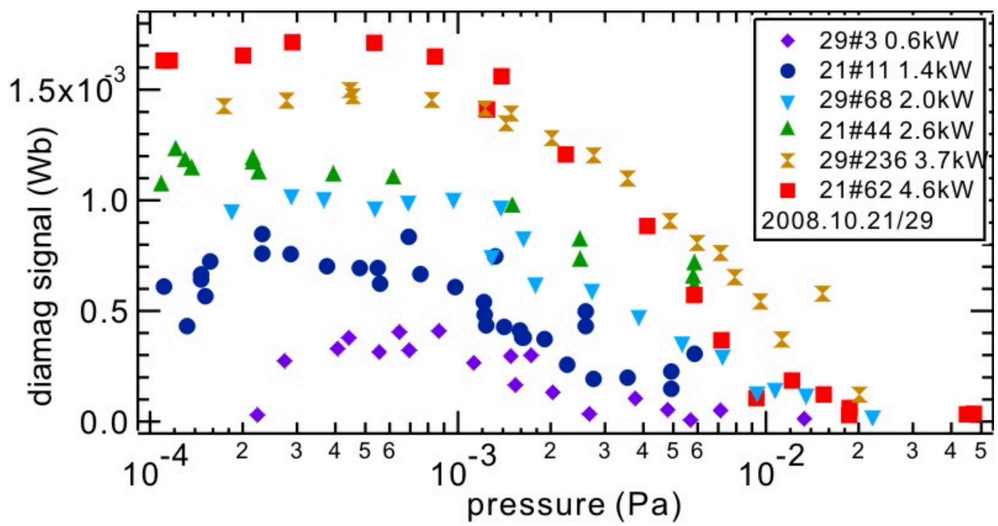
(a) Diamagnetic loop signal and maximum local β estimated from Grad-Shafranov analysis, and

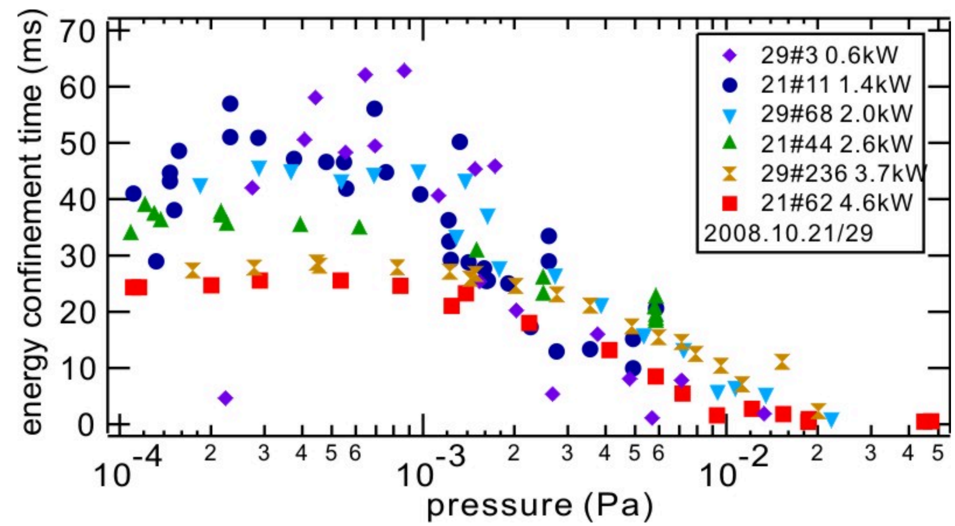
(b) Line averaged density measured with μwave interferometers.

- New geomagnetic field compensation system and optimized operation (coil levitation, discharge cleaning, etc.) realized improvements of the plasma.
- High-β and high density (>n_{cutoff}, possibly due to EBW) plasma is generated, Diamagnetic loop signal ΔΦ=4.2mWb (maximum local β~70%).
- Parameter ranges designated as high-density, high-β, and unstable states, according to the filling neutral gas pressure.
- High-β state is characterized by large stored energy, strong x-ray, and depression of visible light strength and fluctuations.

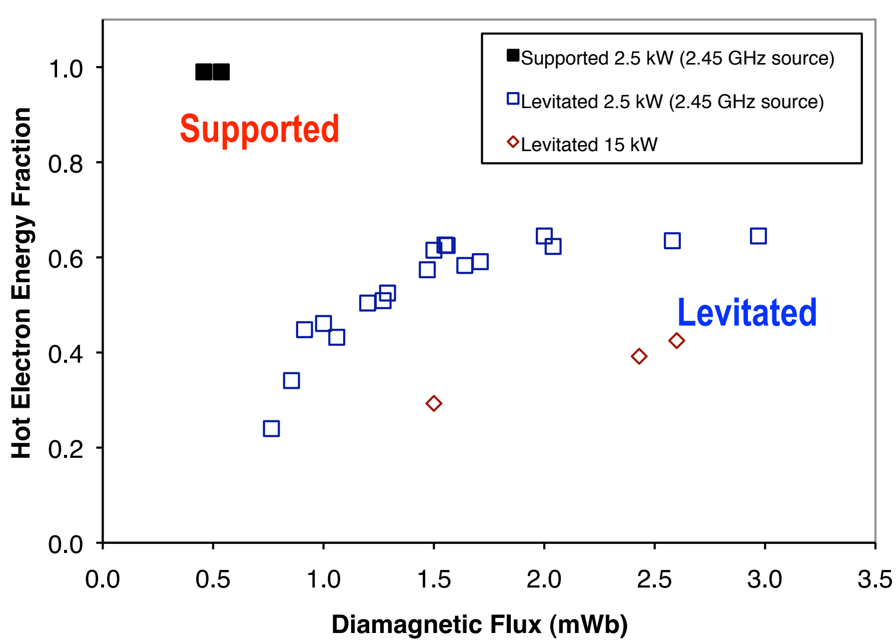
Energy confinement time and β values

Plasma pressure (diamagnetic signal) and energy confinement time in RT-1





Hot Electron Fraction on LDX

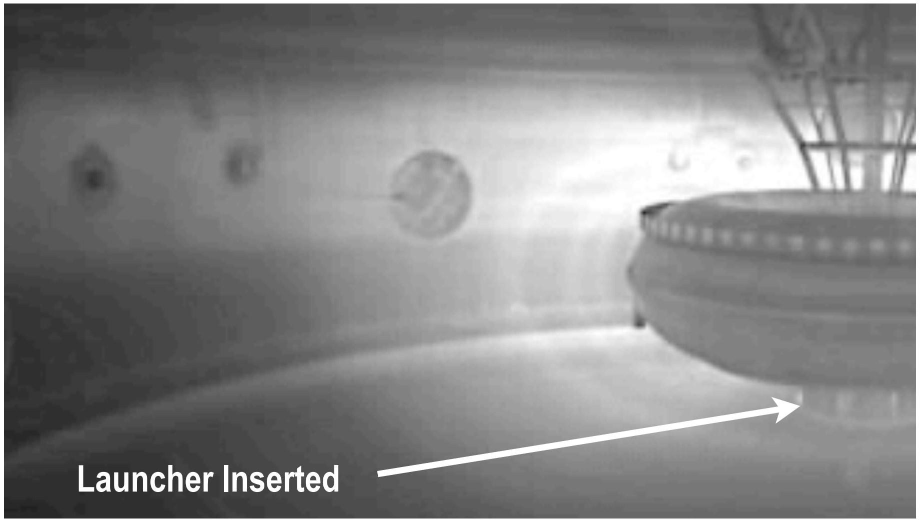


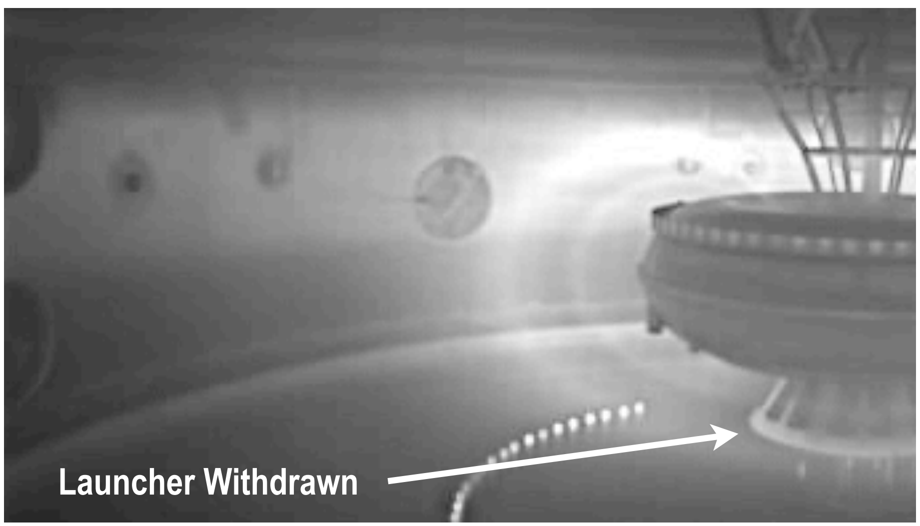
- Energy confinement time estimated from from stored energy and injected RF power
  - $\tau_{E1} \sim 60$ ms.
- τ_{E1} is shorter than that estimated from diamagnetic decay time $\tau_{E2} \sim 500$ms.
  - τ_{E2} up to 10 s on LDX.
- Ratio of fast to slow decay gives estimate of bulk plasma energy content
  - 40-70% stored energy in bulk plasma

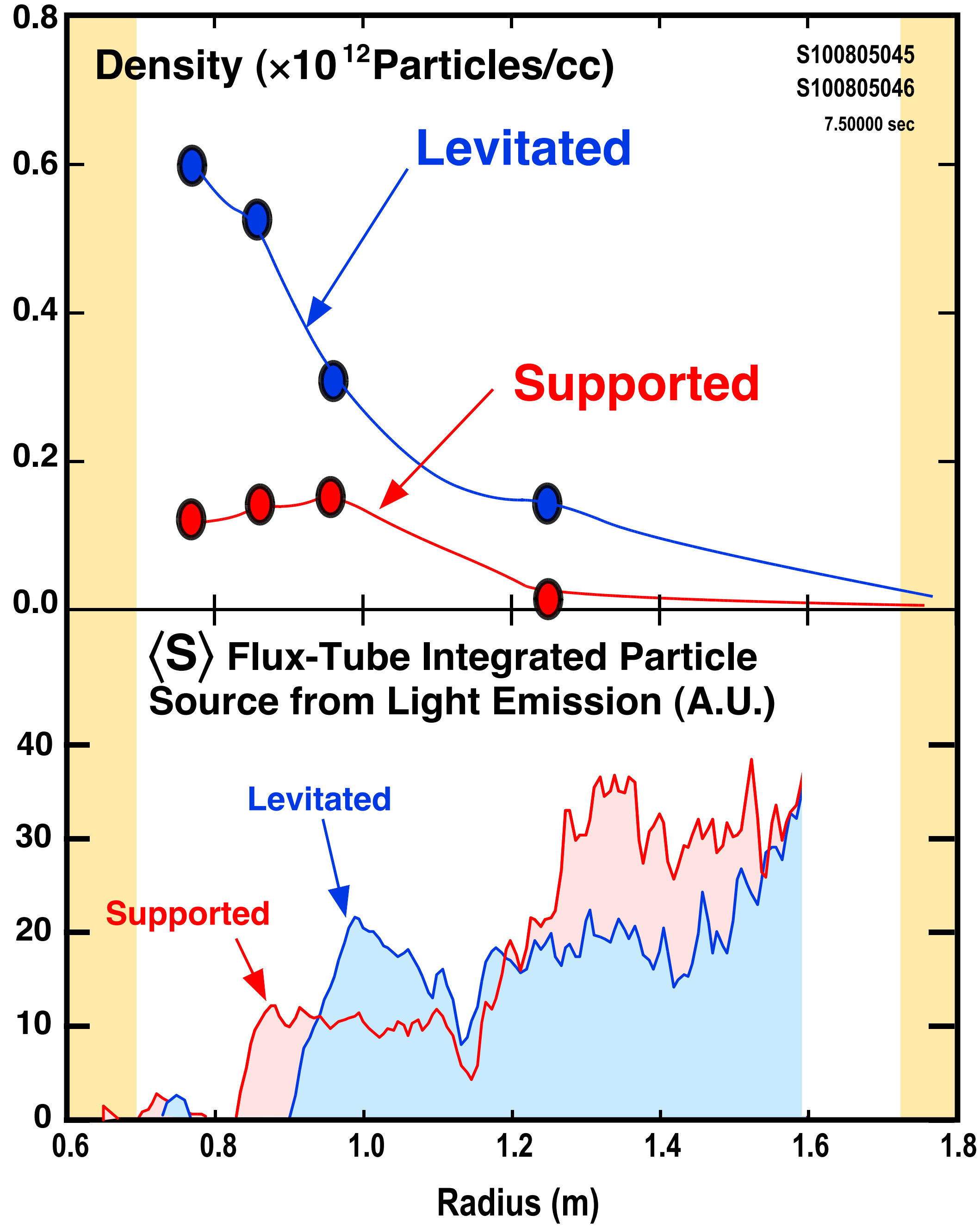
Studies with a Levitated Dipole show Centrally Peaked Density and the Strongest Turbulent Pinch

- Density profiles are centrally-peaked with a levitated dipole
  - Density profiles are "flat" with a supported dipole
- Light emission show the ionization source is NOT centrally-peaked
  - The inward turbulent pinch is directly observed
- The centrally-peaked profile shape is "invariant" with gas and ECRH power modulation
- The strength of the pinch is consistent with measured turbulent fluctuations and magnetospheric physics

Light Emission Shows Outer Gas Fueling

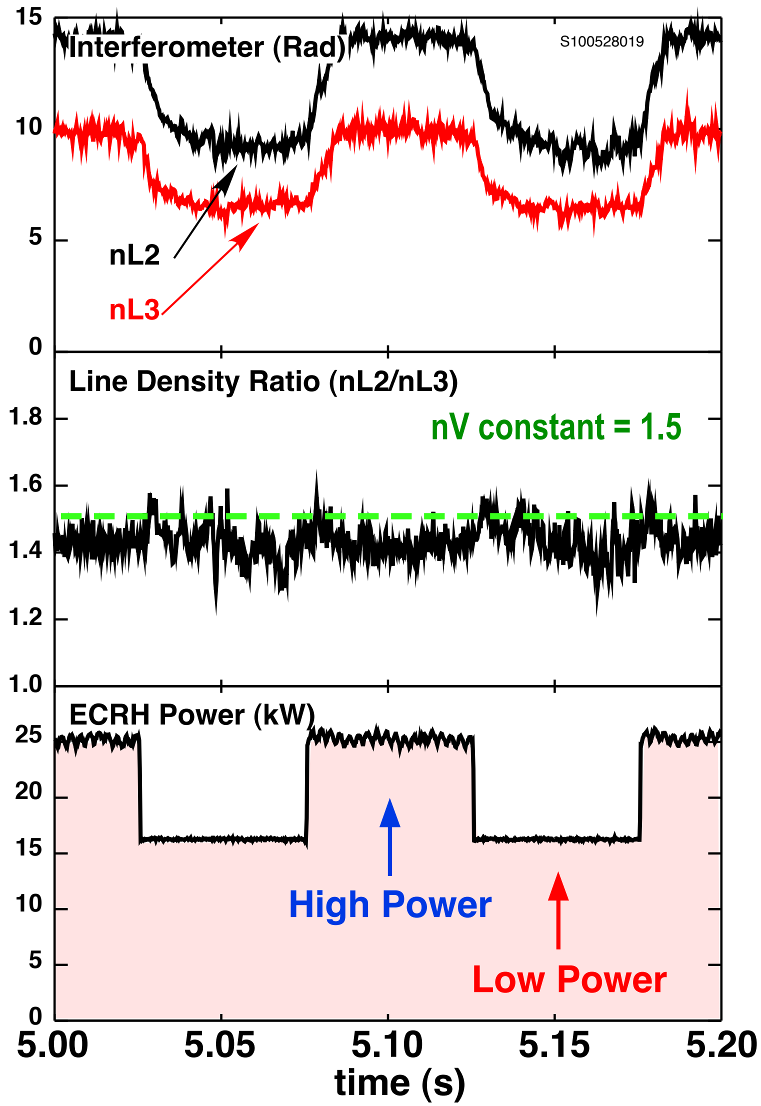


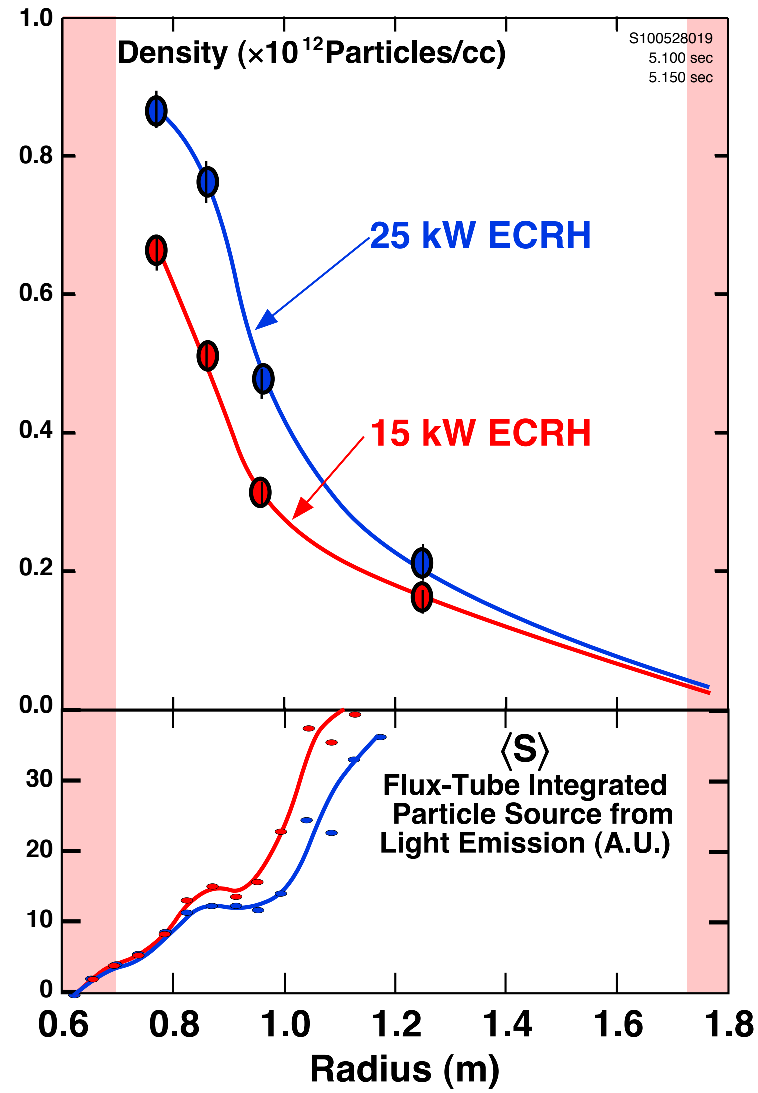




Heating modulation demonstrates existence of inward pinch

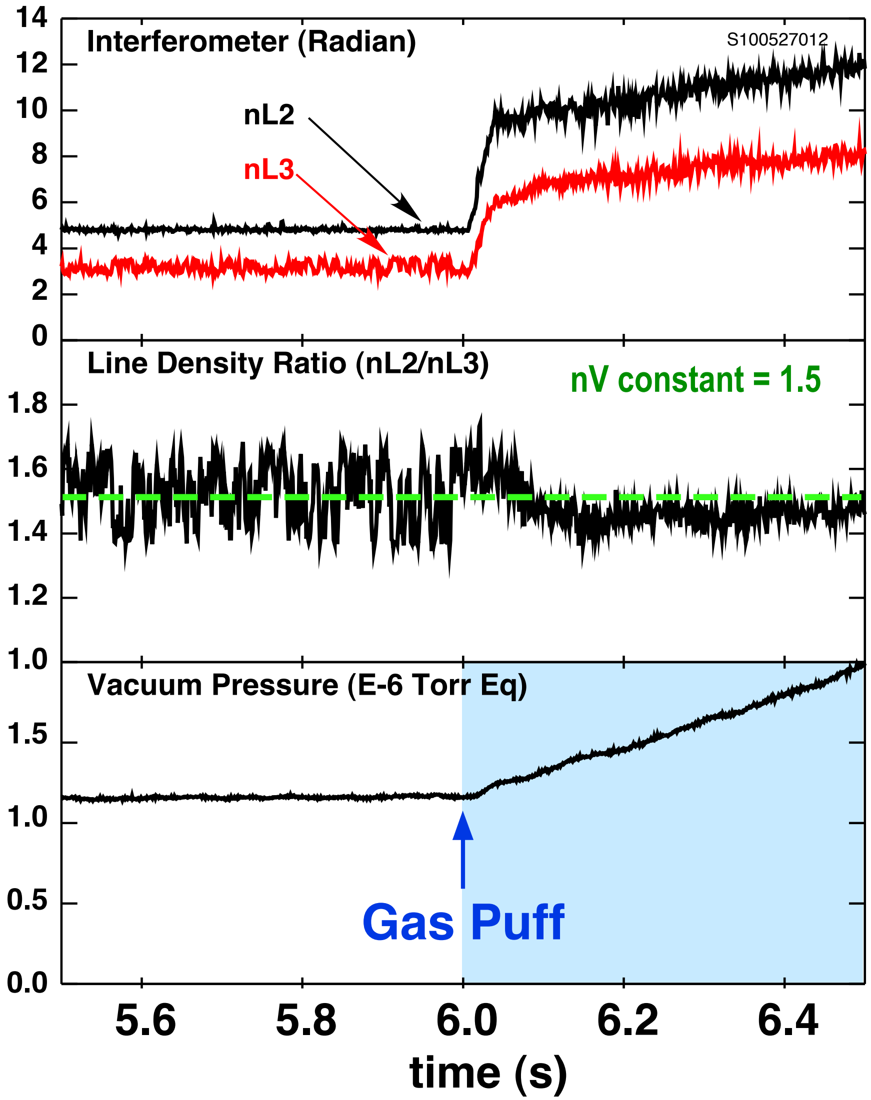
- 10 Hz 10 kW (10.5 GHz) ECH modulation
  - Density modulation follows power: profile shape remains unchanged near nV=constant
  - Source moves radially outward, requiring pinch to create increased central density

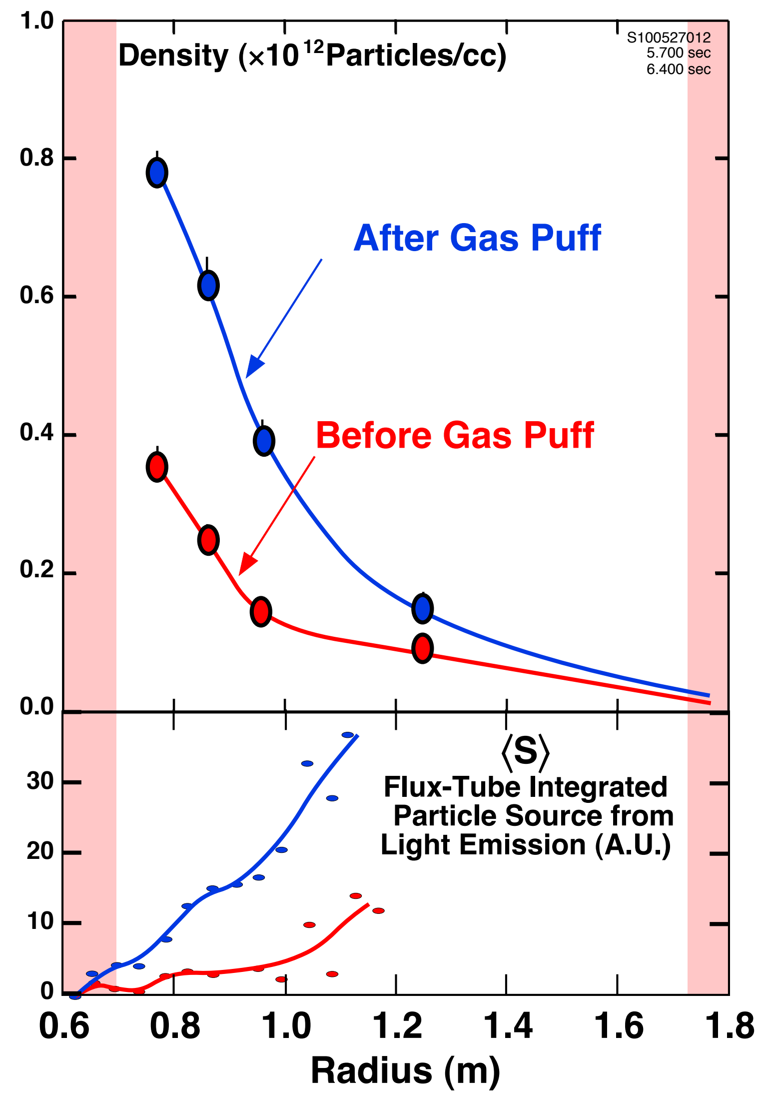




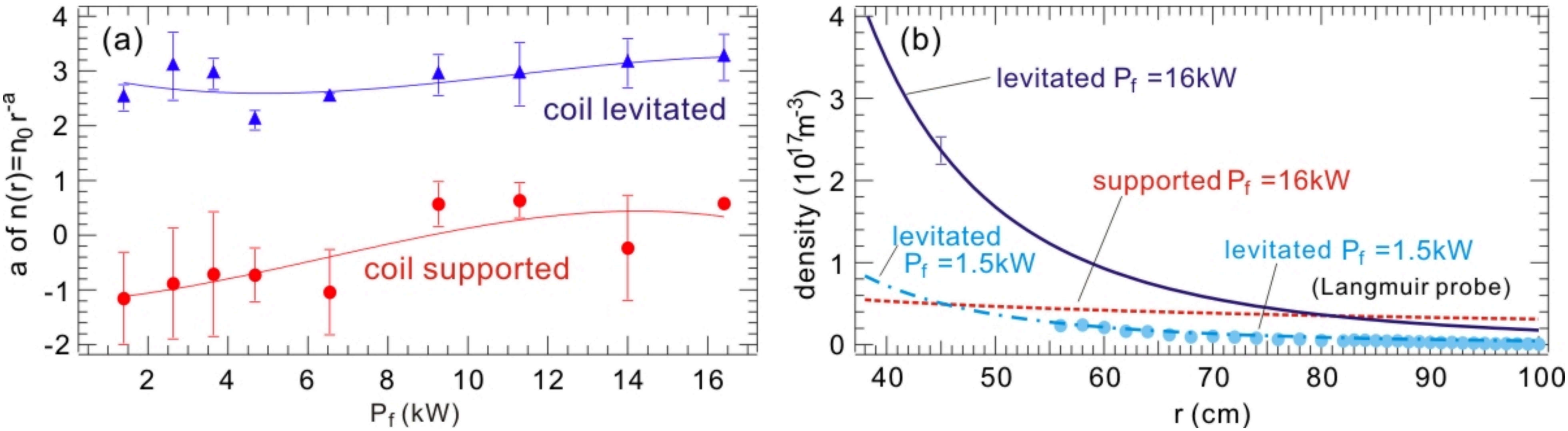
Invariant Profile is Robust: Large Gas Puff

- Fueling experiment: Gas puff at t=6 s
  - Source (particles/flux) from PDA array peaks to the outside, core density doubles





Peaked density profiles on RT-1

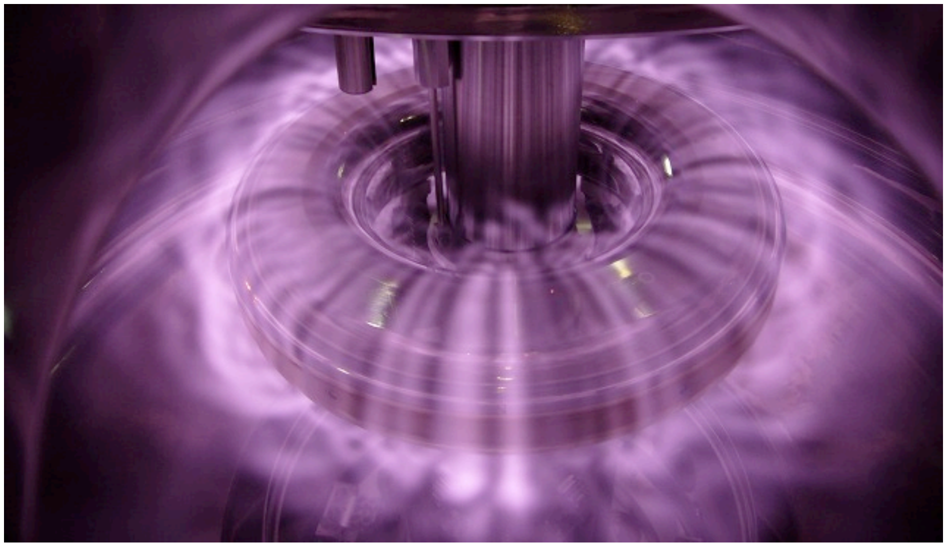


- Similar large increase of peakedness for levitated plasmas
  - 3 chord interferometer fit to radial power law
  - Profiles have consistent shape over all power levels
  - Confirms result of near equal number of particles per flux tube
- Inward diffusion also seen in non-neutral (pure electron) plasmas
  - Pure electron plasma stably confined for 300 s.

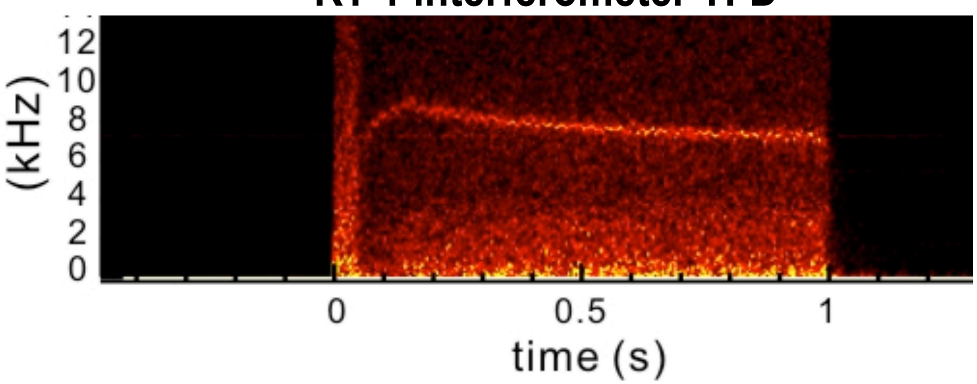
Yoshida *et al.*, PRL 104, 235004 (2010)

Does turbulence match pinch?

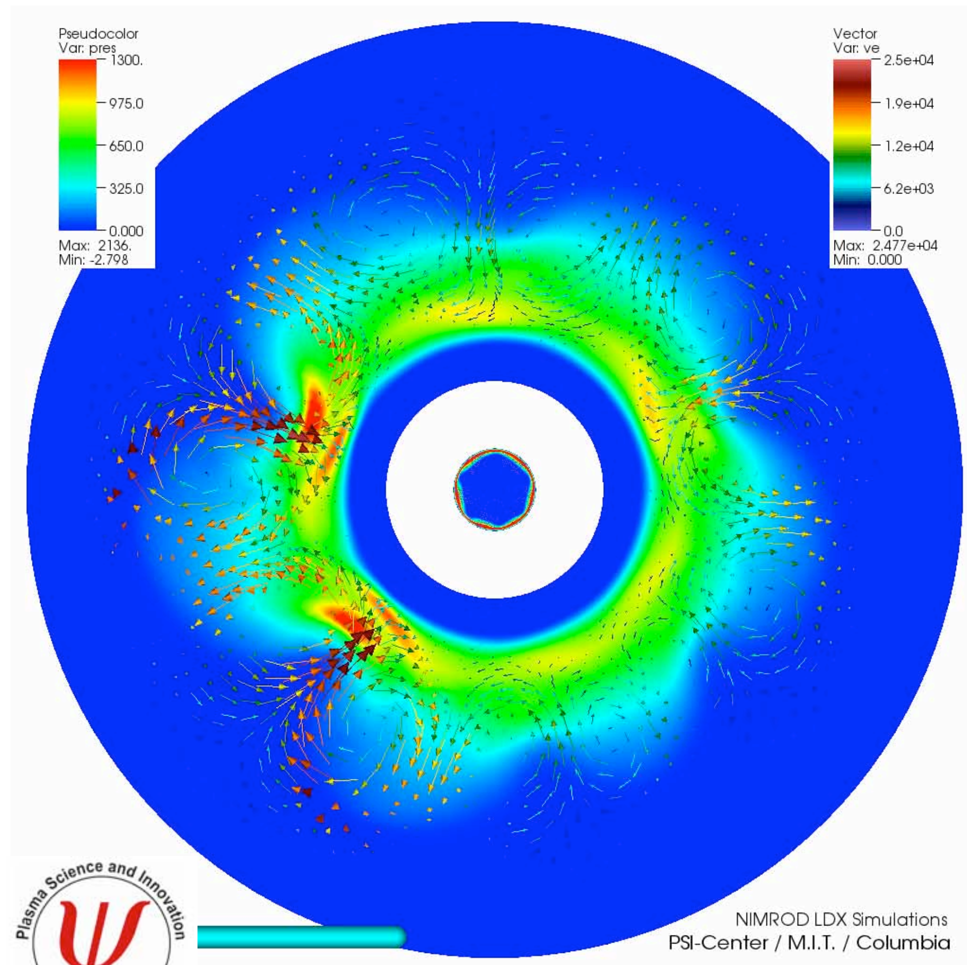
- RT-1 low frequency density fluctuations



RT-1 interferometer TFD

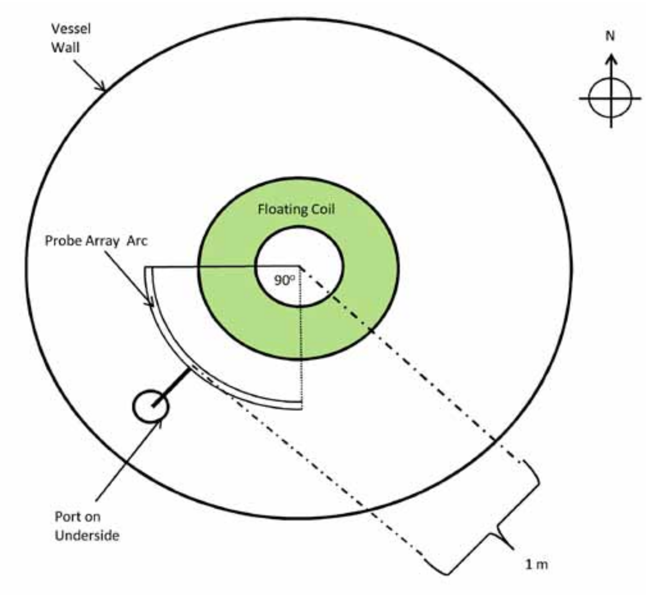


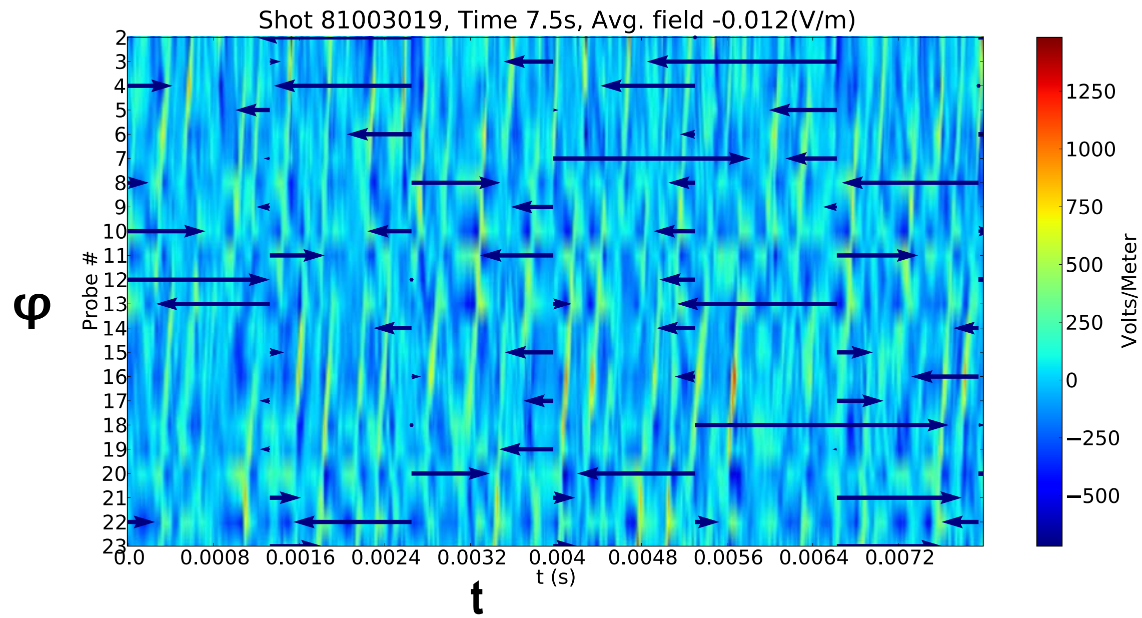
- Nimrod simulation of LDX
  - Central heating with edge fueling



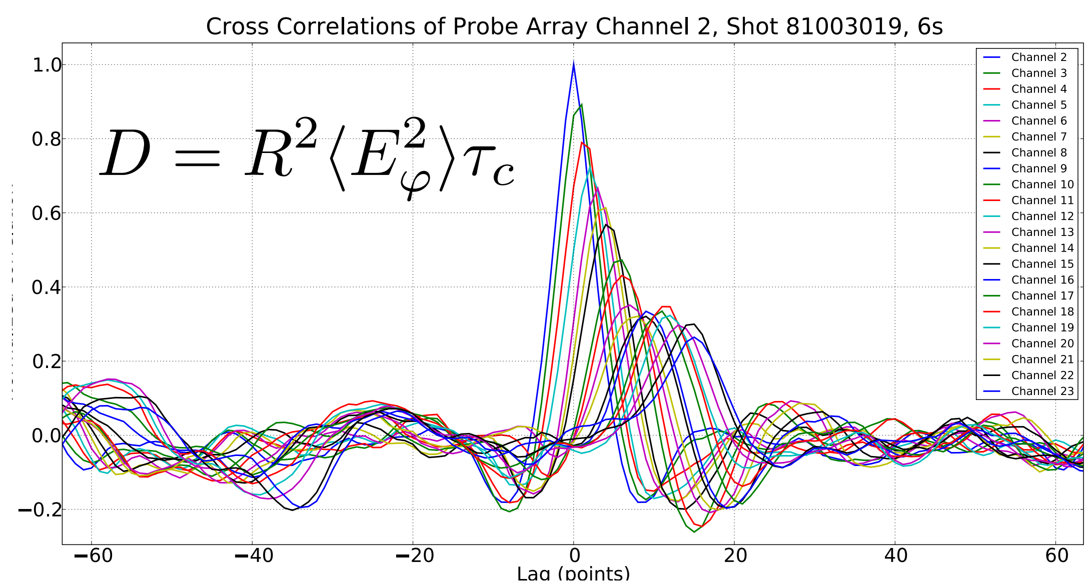
C.C. Kim, B.A. Nelson

LDX: Edge probe array measures low frequency turbulence





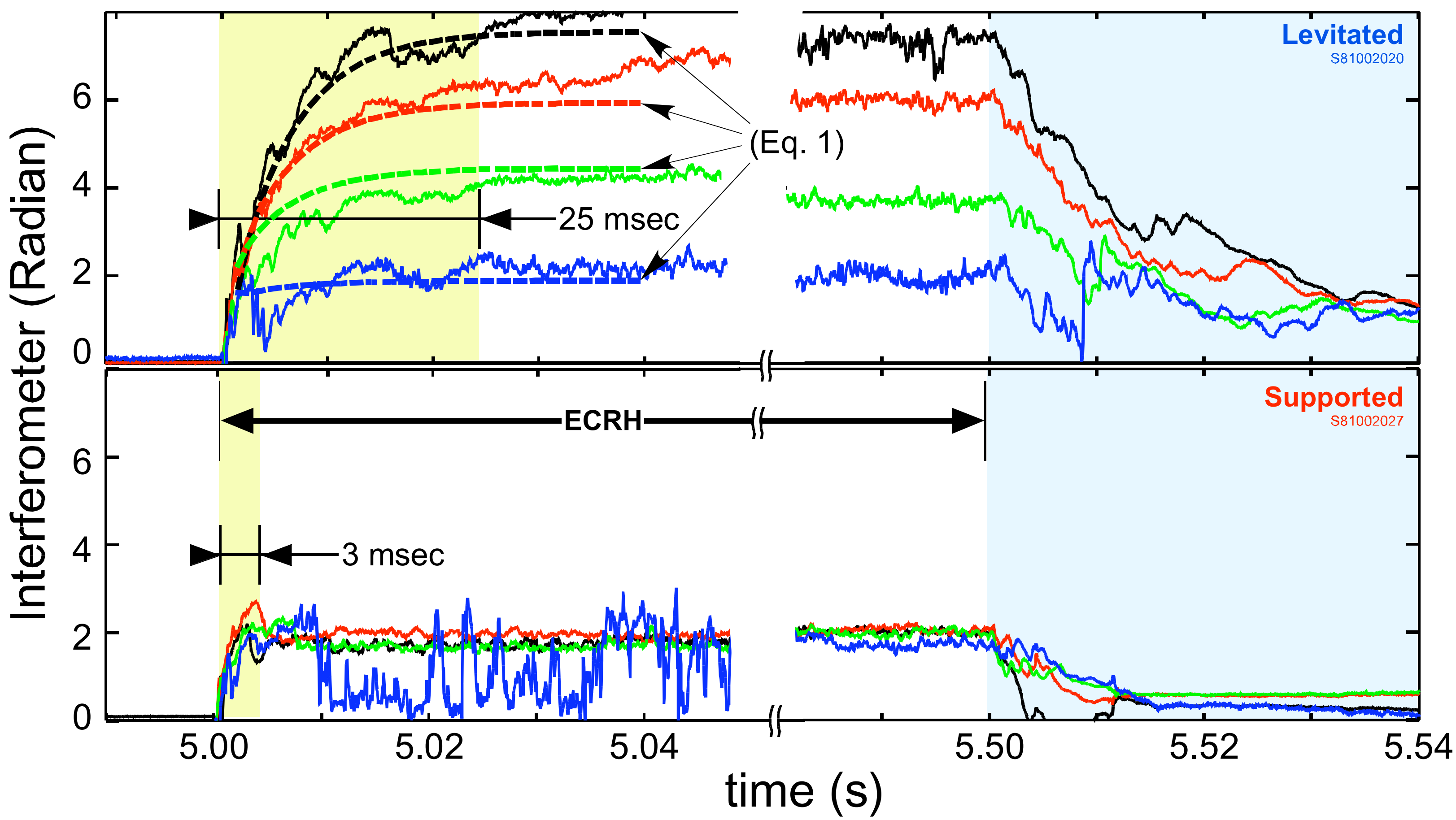
- **Array measures low frequency turbulent spectrum (0.1 - 10 kHz)**
- **Instantaneous ExB radial flow of 35 km/s**



LDX: Low frequency fluctuations consistent with turbulent pinch

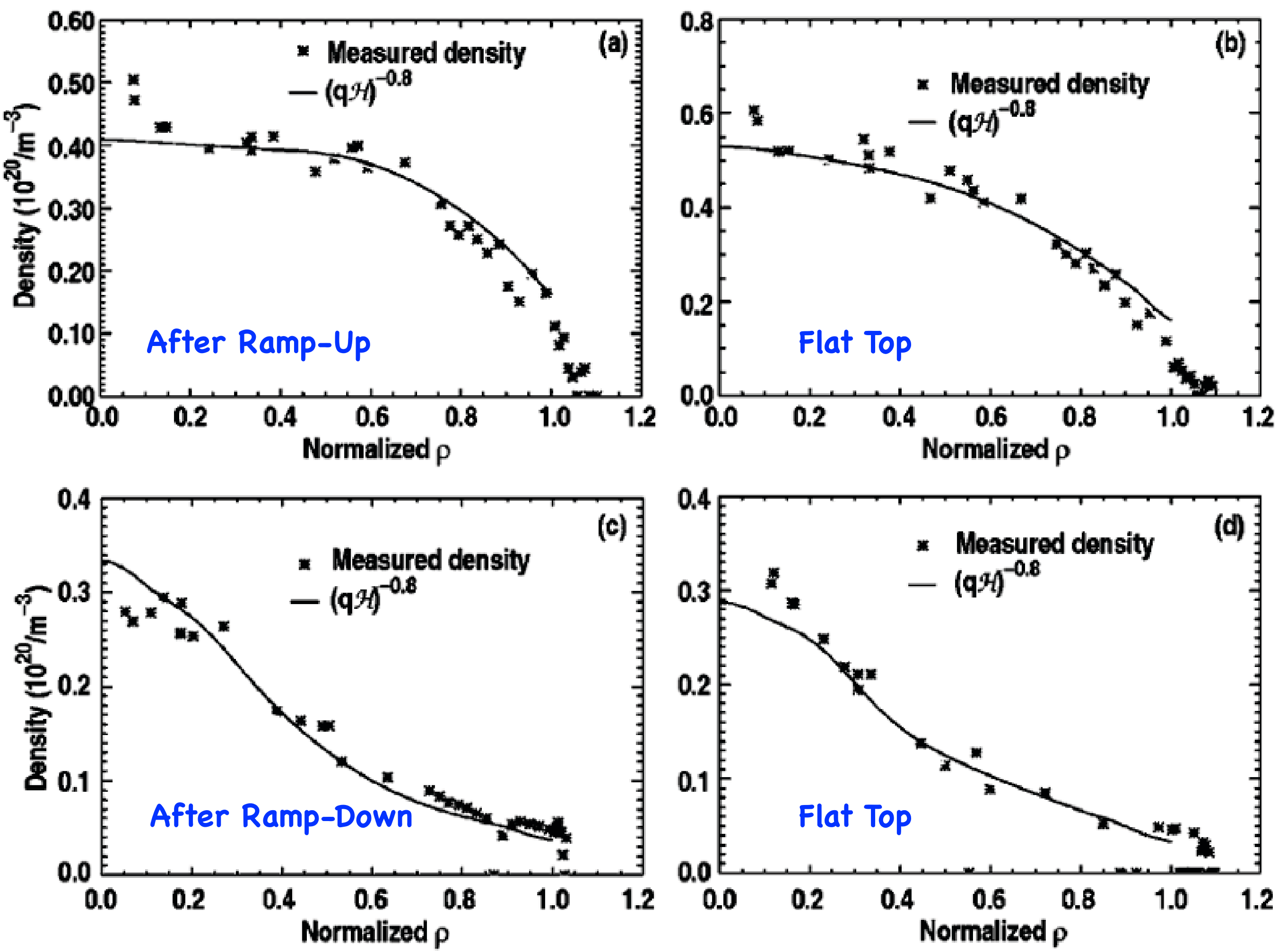
$$\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi} \,, \qquad (1)$$

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 $(\mathrm{V} \cdot \mathrm{sec})^2/\mathrm{sec}$.



DIII-D: L-mode Density Profile Consistency

- Baker and Rosenbluth (1998), Baker (2002)



Lagrangian Transport Description with Preserved Adiabatic Invariants

$$\frac{\partial f_M}{\partial t} = \frac{\partial}{\partial \psi}\left(D^{\psi\psi} \frac{\partial f_M}{\partial \psi} \right),$$

$$\Gamma = -D^{\psi\psi} \int d\mu \, dJ \left.\frac{\partial f_M}{\partial \psi}\right|_{J,\mu}$$

$$\frac{1}{n}\frac{\partial n}{\partial \rho} \approx \xi \left\{ q\mathcal{H} \frac{\partial}{\partial \rho} \frac{1}{q\mathcal{H}} \right\},$$

$$\text{or} \quad n(\rho) \propto (q\mathcal{H})^{-\xi}$$

Summary

- The magnetospheric levitated dipole offers a unique avenue to study magnetic confinement bridging space and the laboratory
  - Large flux expansion allows steep profiles to be formed with turbulent transport
- Superconducting levitated dipoles achieve stable, high-beta, well-confined, plasmas
  - Error field corrected, optimized RT-1 plasmas show peak local ~ 70%.
  - Energetic particle population stabilized with sufficient neutral fueling
  - Global energy confinement time ~ 60 ms. LDX shows 40-70% of stored energy in "warm" collisional electron population
- "Natural" invariant density profiles have been formed in a laboratory dipole confined plasmas
  - Both devices have demonstrated peak profiles near nV = constant
  - Peaked density profile formation shown to be consistent with low frequency turbulent pinch in LDX

Important research ready to be pursued on LDX

- **Measure adiabatic index of turbulent transport:**
  - *i.e.* If $p \sim V^{-\gamma}$ what is γ?
  - Thomson scattering diagnostic planned to measure electron temperature profile
- **Achieve and study high density plasma with warm ions:**
  - Installation of 1 MW, ICRH transmitter planned to increase density and heat ions
  - What is the effect FLR and Ti/Te ratio on turbulence?
  - TOF neutral particle analyzer will measure ion heating
- **Continued study of non-local turbulent transport:**
  - Non-linear studies of drift wave turbulence predict formation of zonal flows. Are predicted zonal flows evident? Do they lead to transport barriers?
  - Reflectometer core fluctuation diagnostic planned
  - High speed fluctuation imaging collaboration

Future tasks for RT-1 project

- **Ion heating**: In the present study, the plasma is generated and sustained by ECH, and T_i<~10eV, while hot-electrons are stably generated. ICRH is in a planning stage including the design of antenna and matching circuit.
- **Beta limit for magnetospheric plasma**: is not experimentally realized and is one of important issues to be studied. Effects of enhanced beta and peaked spatial structures (pressure profiles) of the plasma on the stability properties will be investigated.
- **Investigating two-fluid effects experimentally**: In the parameter range of low-density plasma in RT-1 ($n_e \sim 10^{17} m^{-3}$ by 2.45 and 8.2GHz ECH), ion inertia length $\Delta_i = v_A/\omega_{ci} \sim 1m$ is comparable to or larger than the structure length $L_0 \sim 0.1m$.Thus, plasma equilibria are treated by Hall MHD without neglecting the ion inertia effects. Hall MHD theory predicts diversity of novel plasma structures such as

  - Double Beltrami state*: ultra high-beta (possibly >100%) state, where plasma pressure is balanced by the dynamic pressure of fast flow, and
  - Formation of toroidal ion flow caused by strong diamagnetism**.

* 1998 Mahajan and Yoshida, PRL **81**, 4863; 2002 Yoshida and Mahajan, PRL **88**, 095001.
**2010 Yoshida, PoP, to be published.