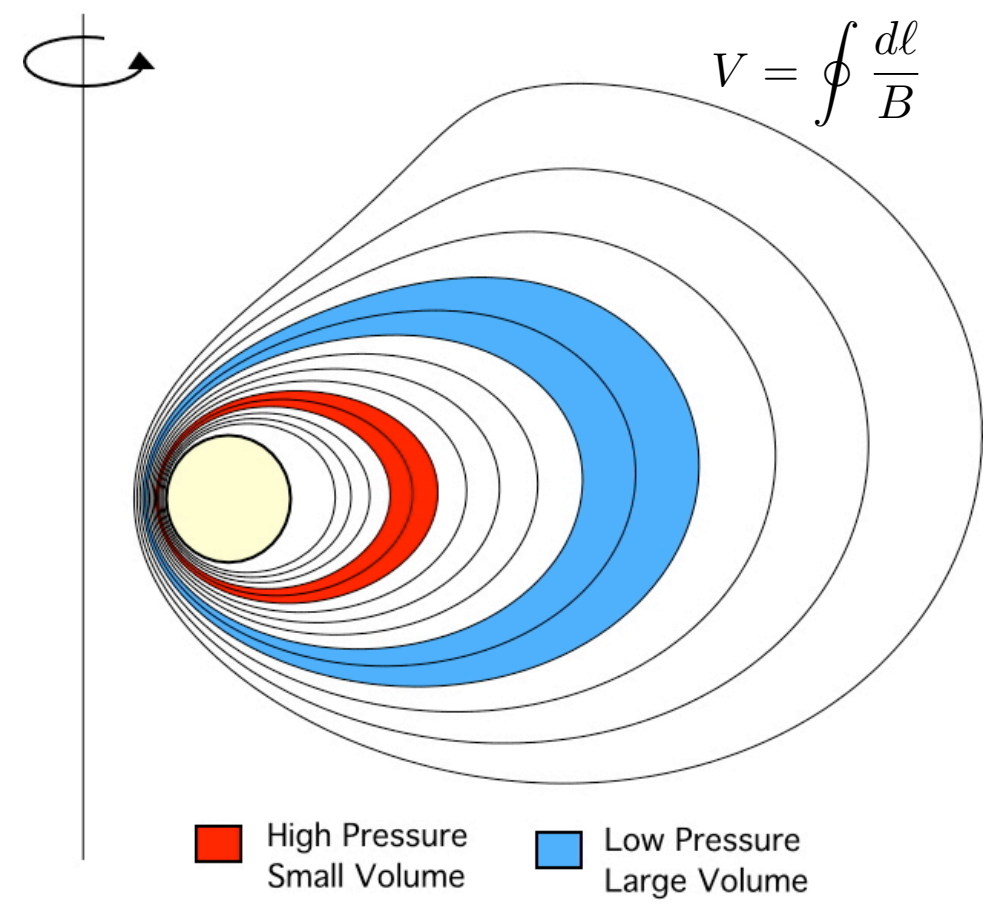
Abstract

We report the first production of high beta plasma confined in a fully levitated laboratory dipole using neutral gas fueling and electron cyclotron resonance heating. The pressure results primarily from a population of energetic trapped electrons that is sustained for many seconds of microwave heating provided sufficient neutral gas is supplied to the plasma. As compared to previous studies in which the internal coil was supported, levitation results in improved particle confinement that allows higher-density, high-beta discharges to be maintained at significantly reduced gas fueling. Elimination of parallel losses coupled with reduced gas leads to improved energy confinement and a dramatic change in the density profile. Improved particle confinement assures stability of the hot electron component at reduced pressure. By eliminating supports used in previous studies, cross-field transport becomes the main loss channel for both the hot and the background species. Interchange stationary density profiles, corresponding to an equal number of particles per flux tube, are commonly observed in levitated plasmas.

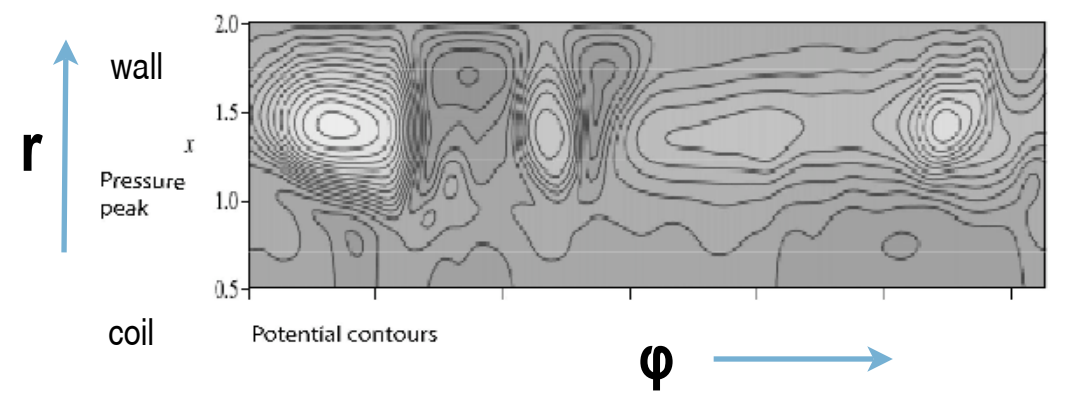
The Levitated Dipole Concept



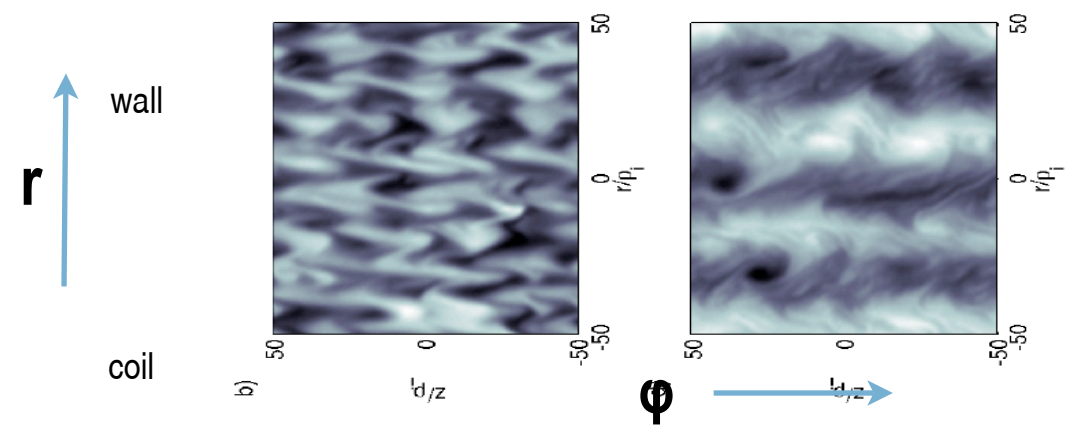
- **MHD stability from plasma compressibility**
  If $p_1 V_1^\gamma = p_2 V_2^\gamma$, then interchange does not change pressure profile.
- **Drift wave stability for interchange invariant profile**
  For $\eta = \frac{d \ln T}{d \ln n} = \frac{2}{3}$, density and temperature profiles are also stationary.
- **Interchange mixing leads to constant entropy peaked profiles**
  $n \propto V^{-1}$ and $p \propto V^{-\gamma}$

Uncommon Plasma Topology

- No magnetic shear
  - ExB convective cells are possible
- Non-linear evolution of interchange may lead to convective cells
  - Explore non-linear evolution of interchange like instabilities
- Near marginal stability, convective cells do not necessarily transport energy



Pastukhov, Chudin, Pl Physics 27 (2001) 907.



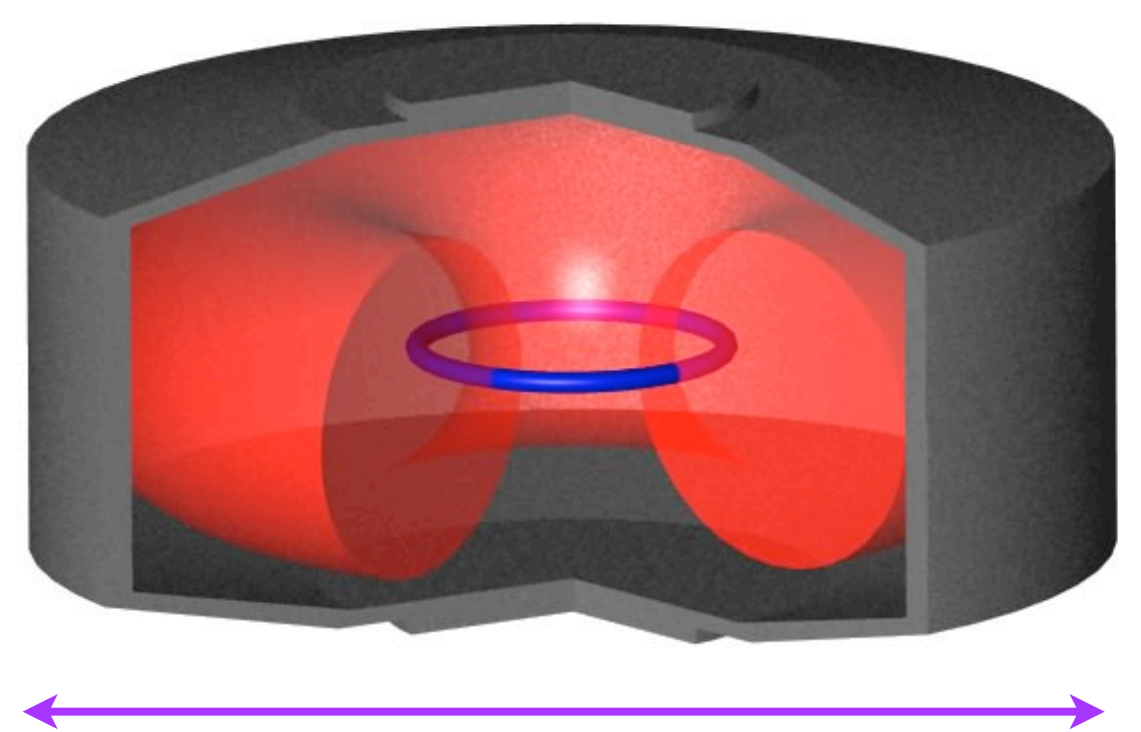
Ricci, Rogers, Dorland, PRL 97, 245001 (2006).

Possible Fusion Power Application

- 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



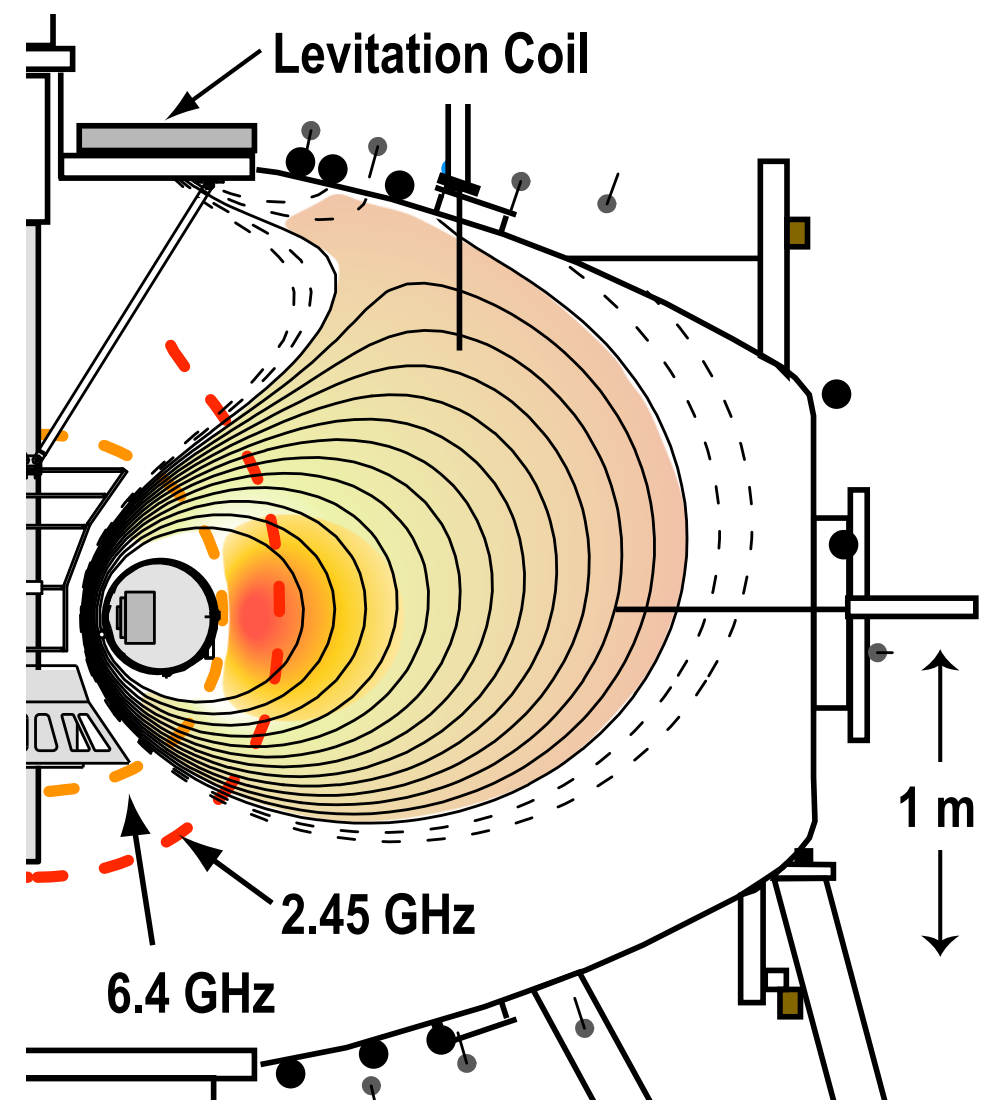
60 m

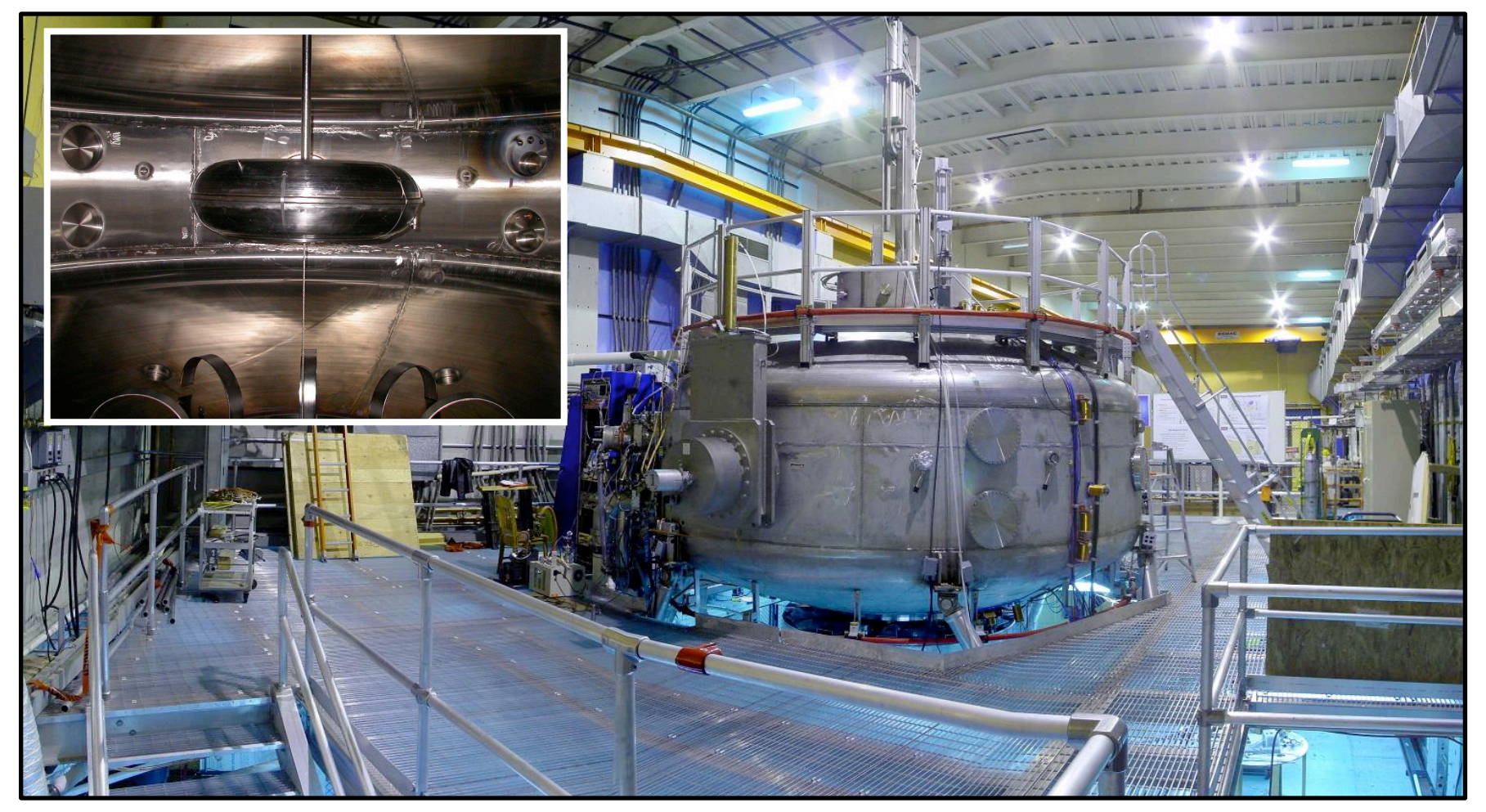
500 MW

D-D(He^3) Fusion

Levitated Dipole Experiment (LDX)

- 1.1 MA Floating dipole coil
  - Nb3Sn superconductor
  - Inductively charged by 10 MJ charging coil
  - Up to 2 hour levitation using active feedback on upper levitation coil
- Two component plasma created by multi-frequency ECRH
  - 2.5 kW, 2.45 GHz
  - 2.5 kW, 6.4 GHz
  - 10 kW, 10.5 GHz





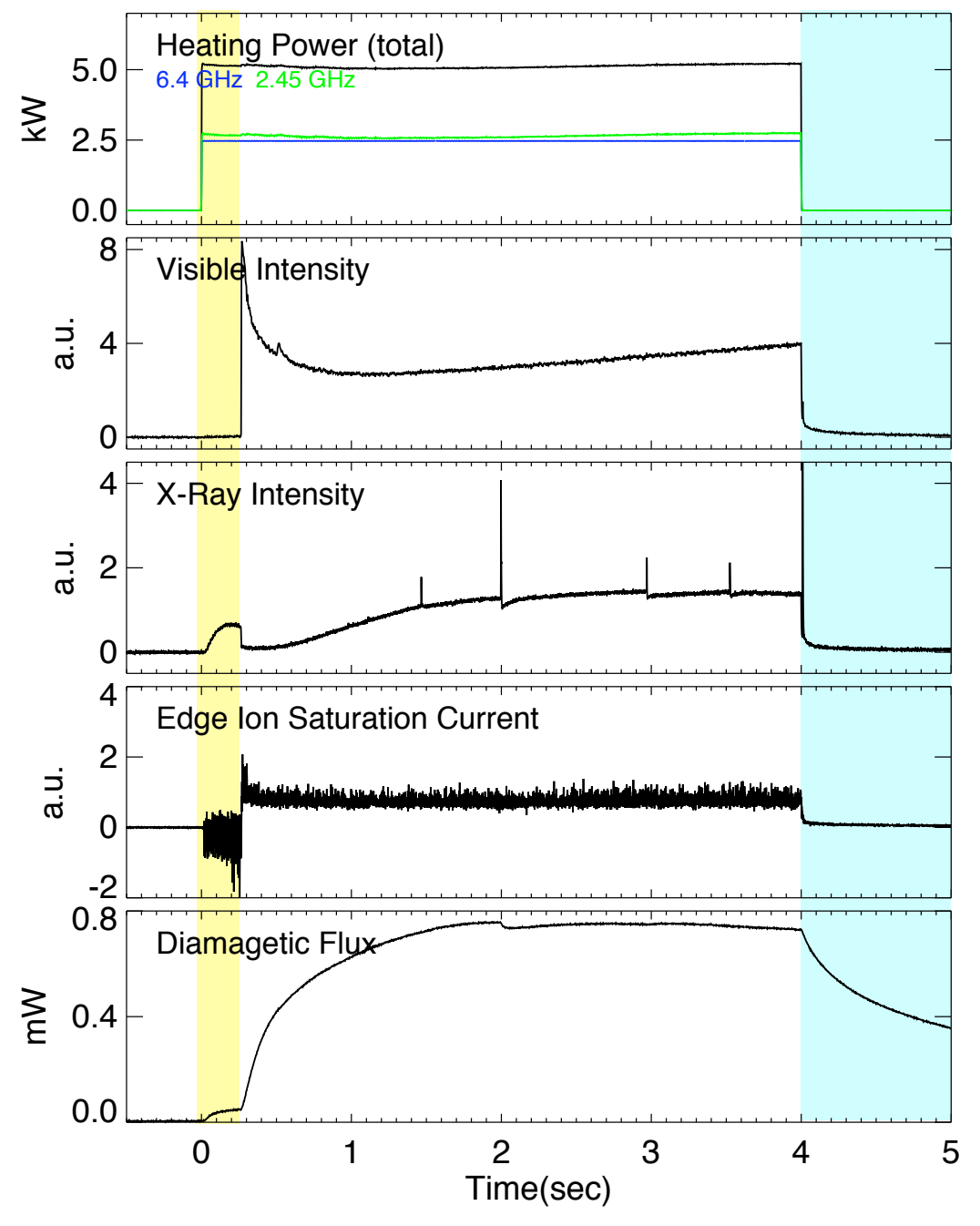
LDX experiment. The vacuum vessel is 5 m in diameter and the 560 kg superconducting dipole coil is 1.2 m in diameter.

Plasma Diagnostic Set

- Magnetic equilibrium
  - flux loops, Bp coils, Hall effect sensors, levitation system trackers
- Fast electrons
  - 4 Channel x-ray PHA, x-ray detector, 137 GHz radiometer
- Core parameters
  - interferometer, visible cameras, visible diode and array, survey spectrometer
- Fluctuations
  - Edge I_{sat} and V_f probes, Mirnov coils, visible diode arrays, interferometer, fast visible camera, floating probe array
- Edge parameters
  - swept and Mach probes

Typical Supported Mode Shot

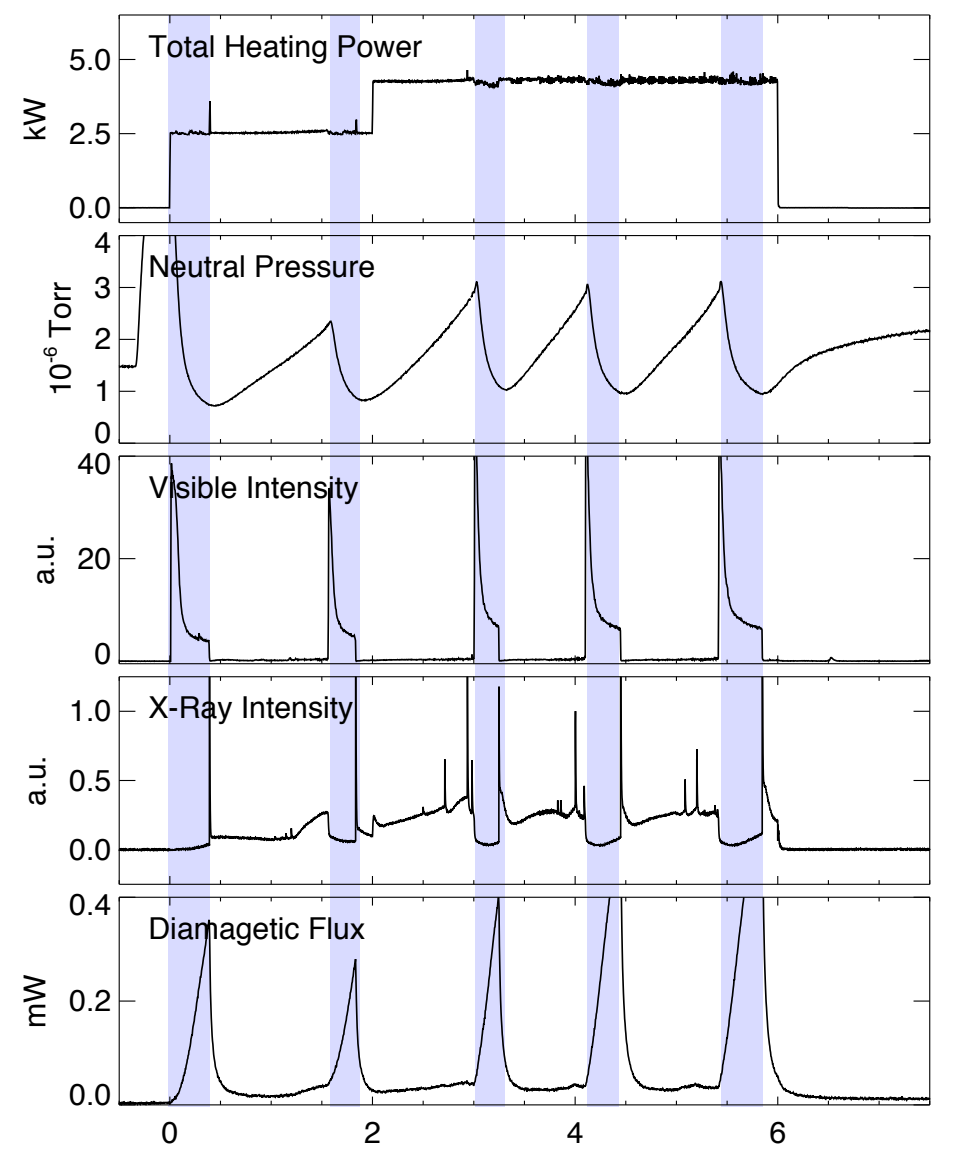
- **Unstable Regime:**
  - Fast electron radial transport
  - Low density
  - Low diamagnetism (low β)
- **High Beta Regime:**
  - Large diamagnetic current
  - Measurable density.
  - β loss events accompanied by xray bursts
  - Low frequency edge electric and magnetic fluctuations
- **Afterglow**: (no input power)
  - Low density
  - Slow diamagnetism decay
  - Quiescent with instability bursts

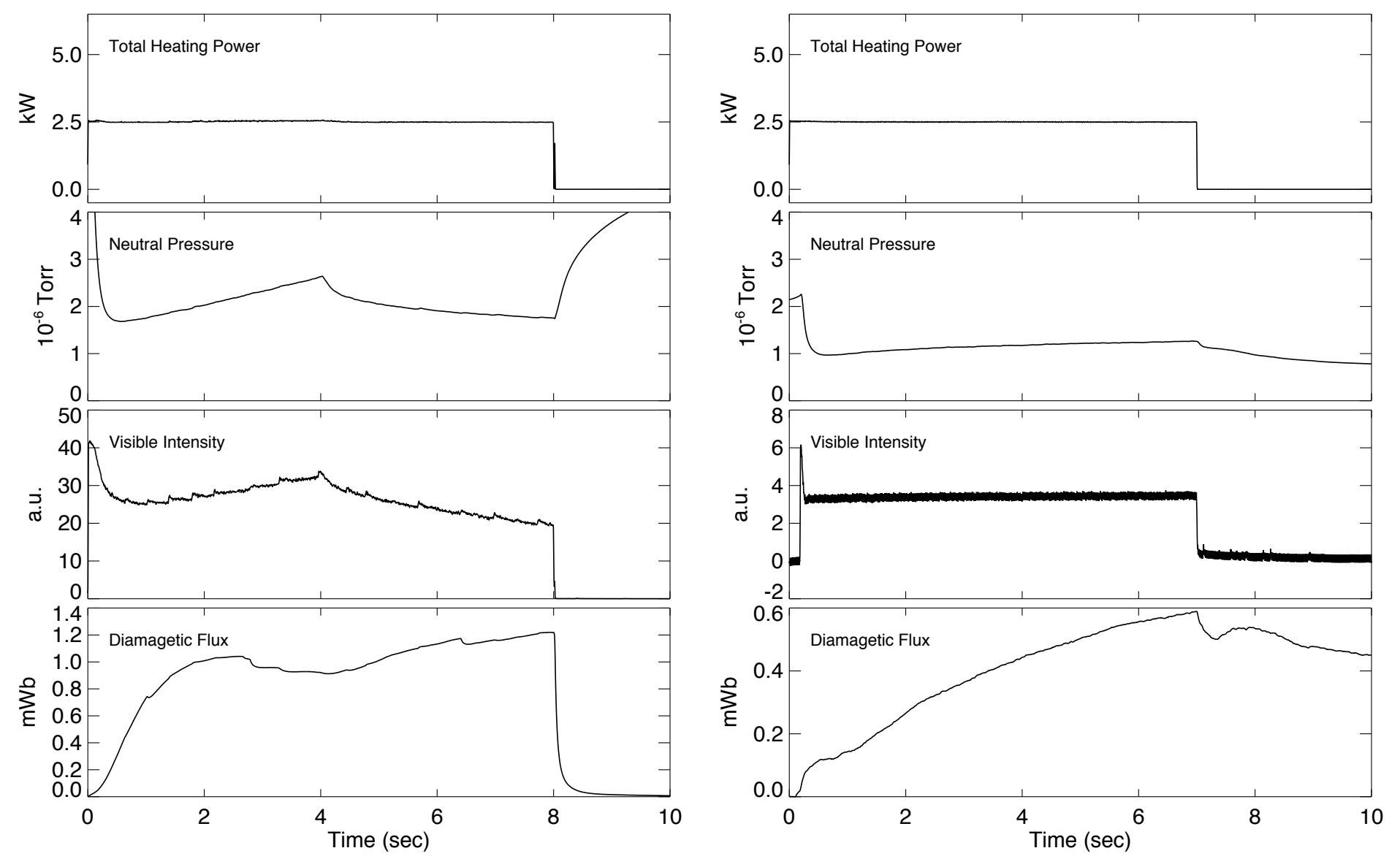


Hot Electron Interchange (HEI)

- With supports, high fueling needed to stabilize HEI, increase density, and increase beta
  - Unstable regime evolves gas from vessel walls by surface heating
- Once stable, less fueling is needed to maintain stability
  - Without continued puffing, plasma pumps required gas from chamber
- Consistent with theory showing background density stabilizing
  - Krall (1966), Berk (1976)...

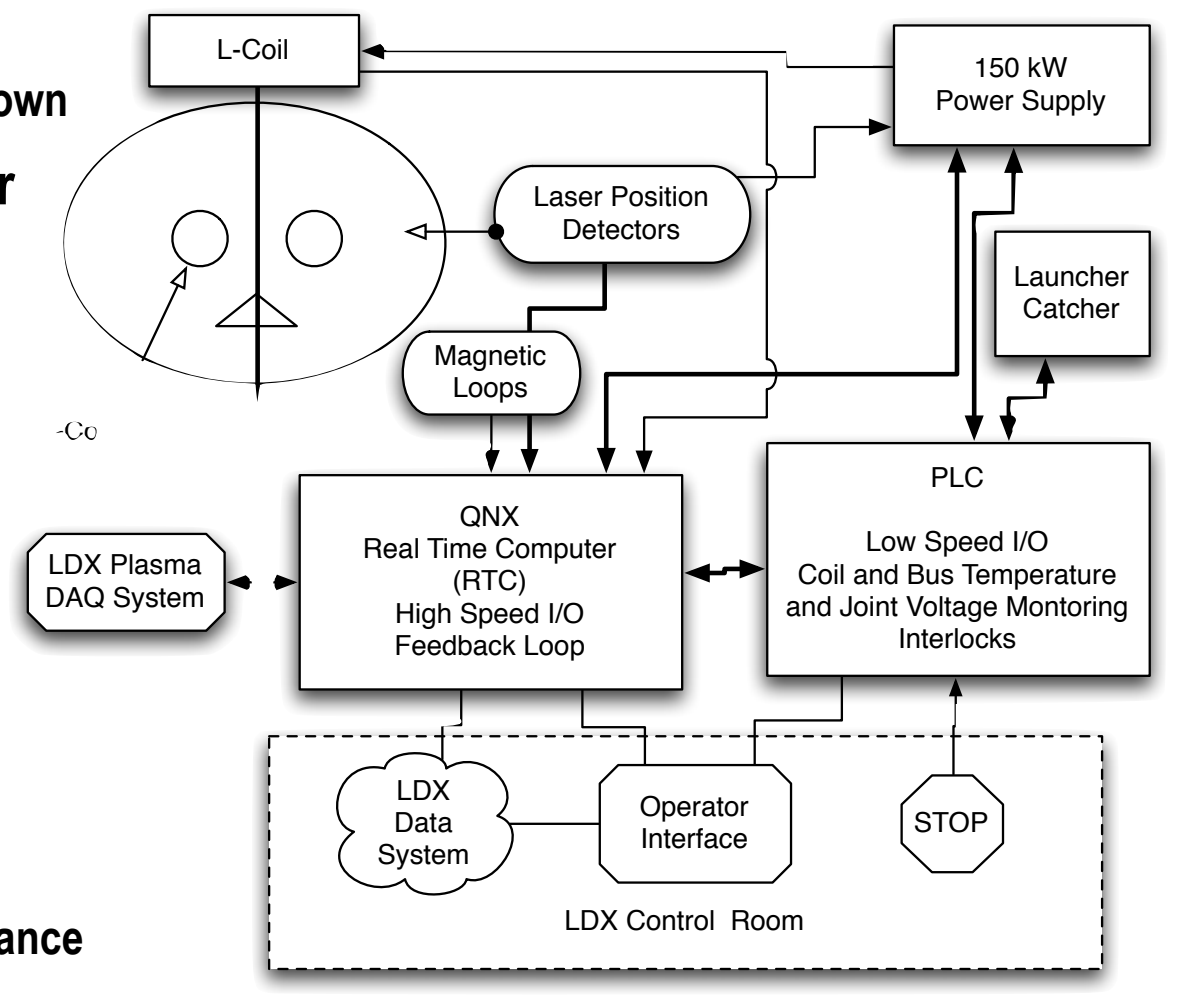
$$-\frac{d \ln \bar{n}_h}{d \ln V} < 1 + \frac{m_\perp^2}{24} \frac{\omega_{dh}}{\omega_{ci}} \frac{\bar{n}_i}{\bar{n}_h}$$



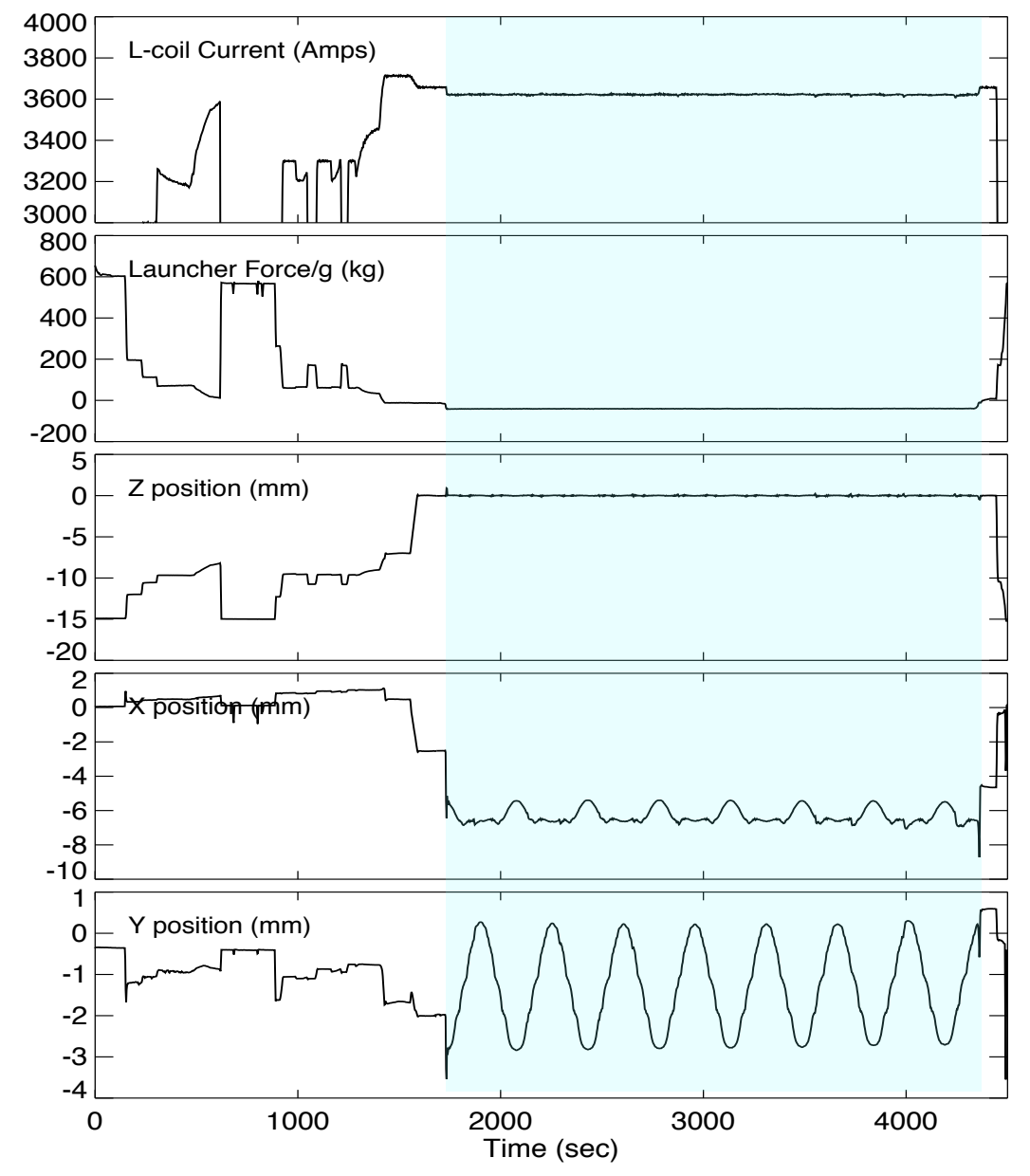


Levitation System

- 4500 A / 50 V Power supply
  - Resistive coil allows for rapid shutdown
- Realtime digital control computer
  - Allows different control methods to be implemented
  - Matlab/Simulink Opal-RT development environment
  - 4 kHz feedback loop
  - Failsafe backup for upper fault
- Programmable Logic Controller
  - Slow fault conditions
  - Interlocks
  - Coil and Bus temperature and resistance monitoring

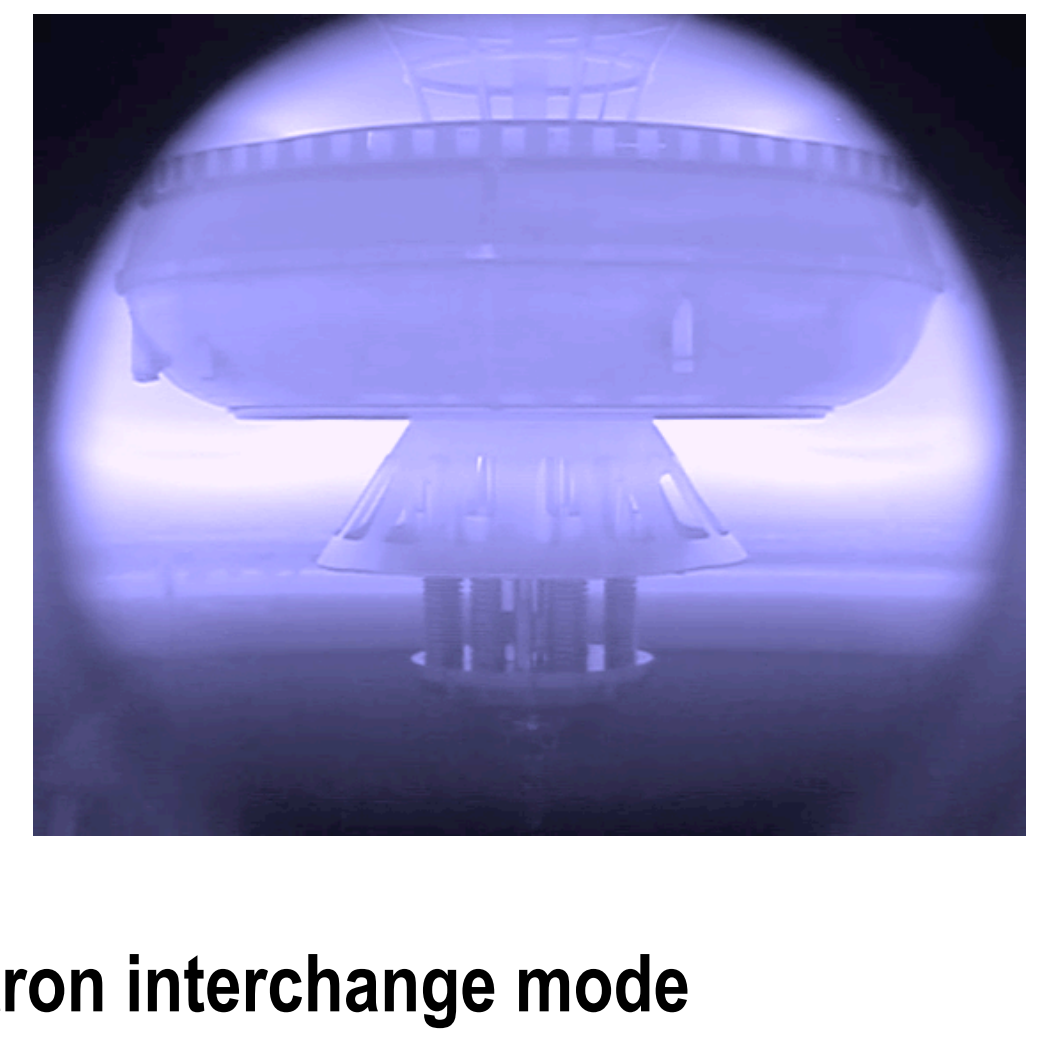


- Well controlled flight
  - After launch, < .2 mm z excursions
  - small effect of ~ 10 plasma shots
  - oscillation in x and y caused by slow rotation
    - gravitational well in toroidal rotation caused by incomplete balance
    - 6 minute period with very small damping
- Control algorithm
  - P - I - D - A control of voltage
    - PS voltage feedback fast
    - Small operating space of reliable gains
  - Full state control under development
    - (Extended) Kalman filter
    - Optimal control
    - Coupling between coils affected by plasma beta!

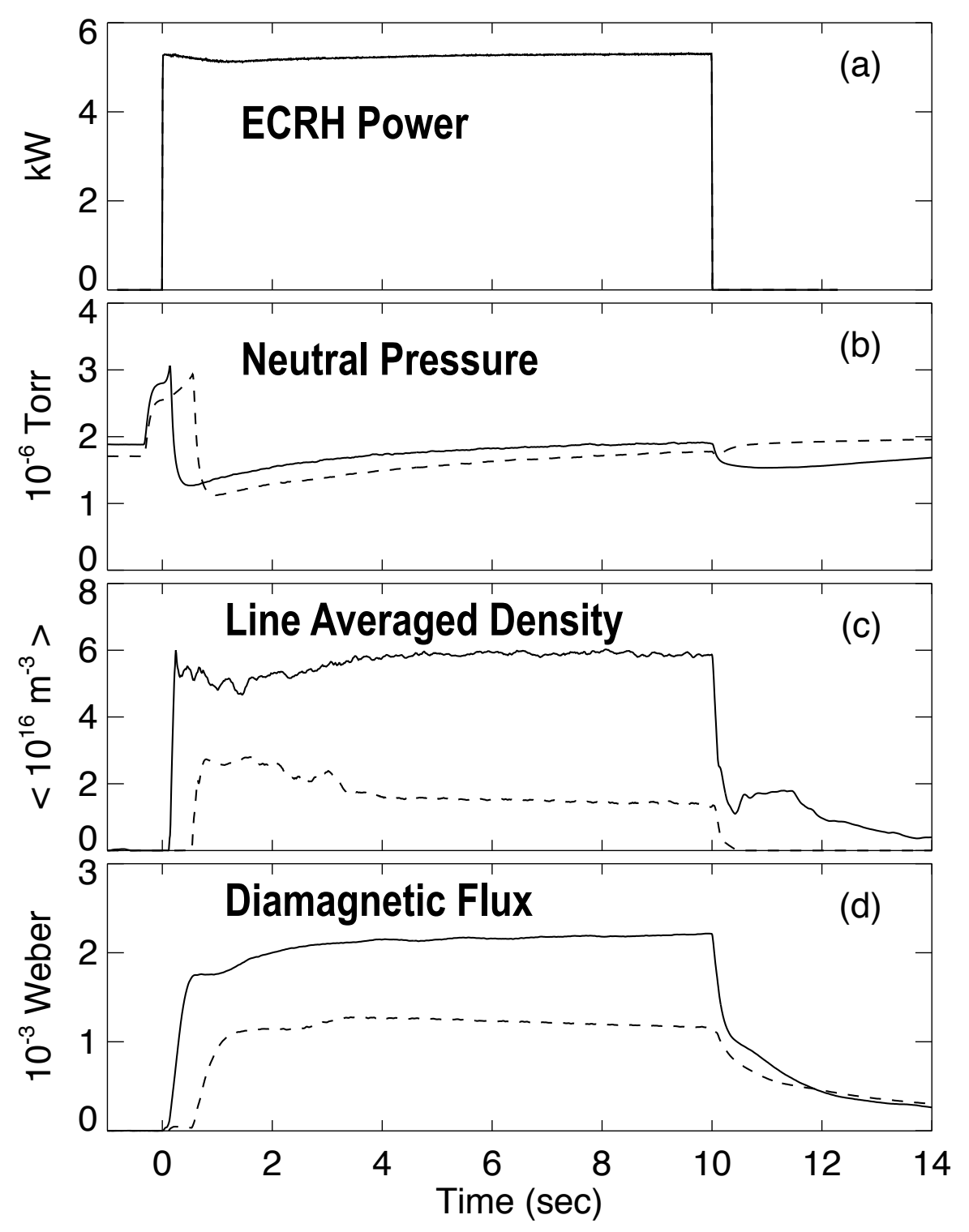


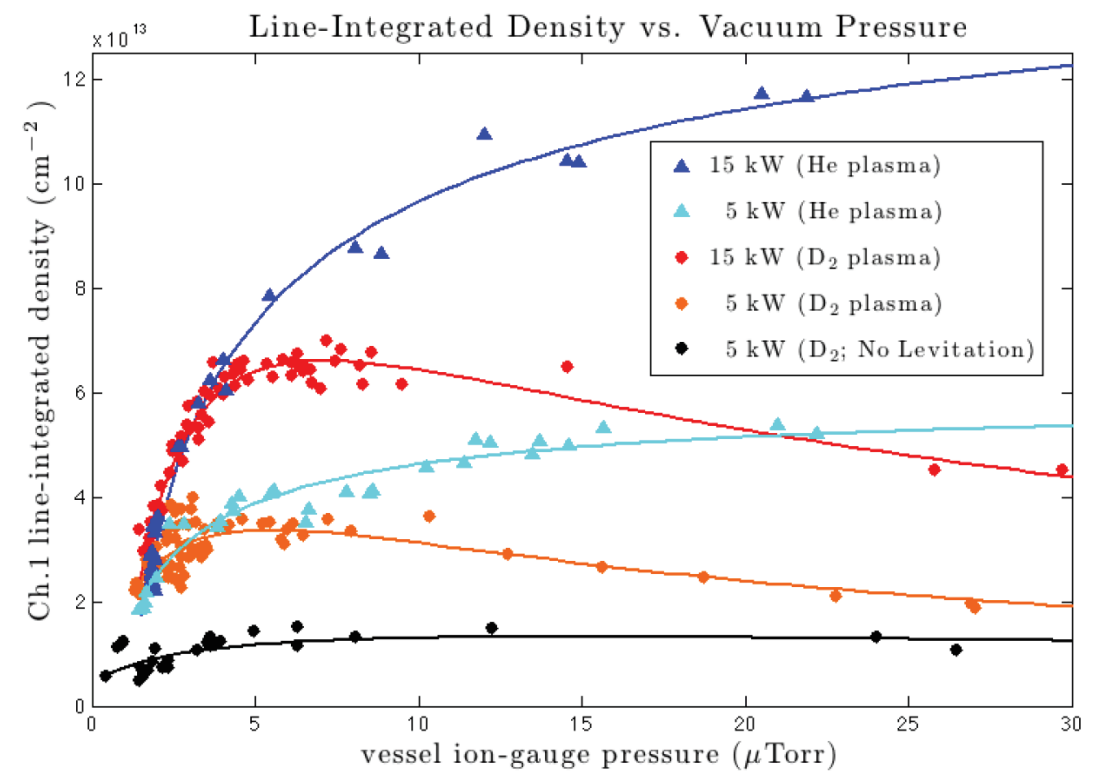
Confinement Improves with Levitation

- Elimination of parallel loss channel
- Improvement of bulk electron confinement
  - Higher bulk density
  - Single peaked profiles with near constant number of particles per flux tube
  - Improved energy confinement
  - Improved stability for hot electron interchange mode

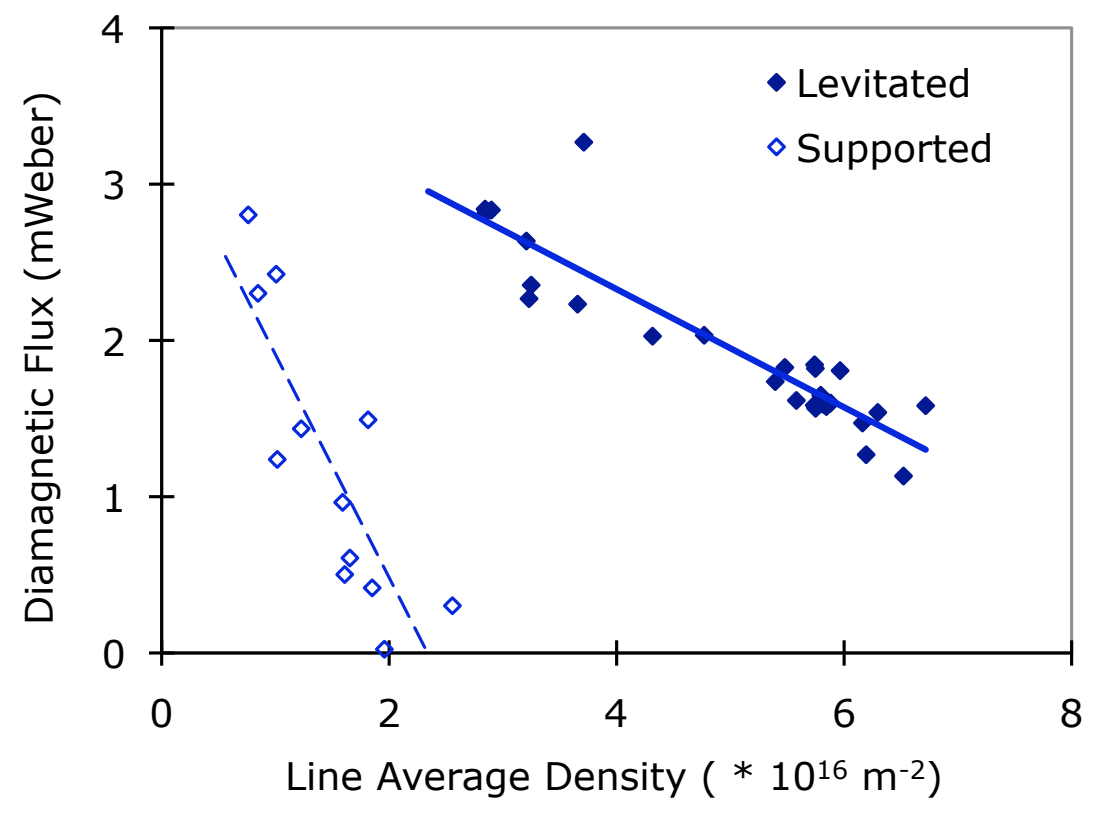


- Similar shots
  - With (solid) and without (dashed) levitation
  - Similar gas fueling
- 3 x density
  - much more peaked profile with levitation
- 2 x stored energy





Steady state central chordal density measurement versus neutral pressure for different conditions. The effect of levitation for deuterium plasmas with 5 kW of input ECRH is shown as increased density by a factor of 2-4. (Also depicted are significant power and species dependencies at high neutral pressure).

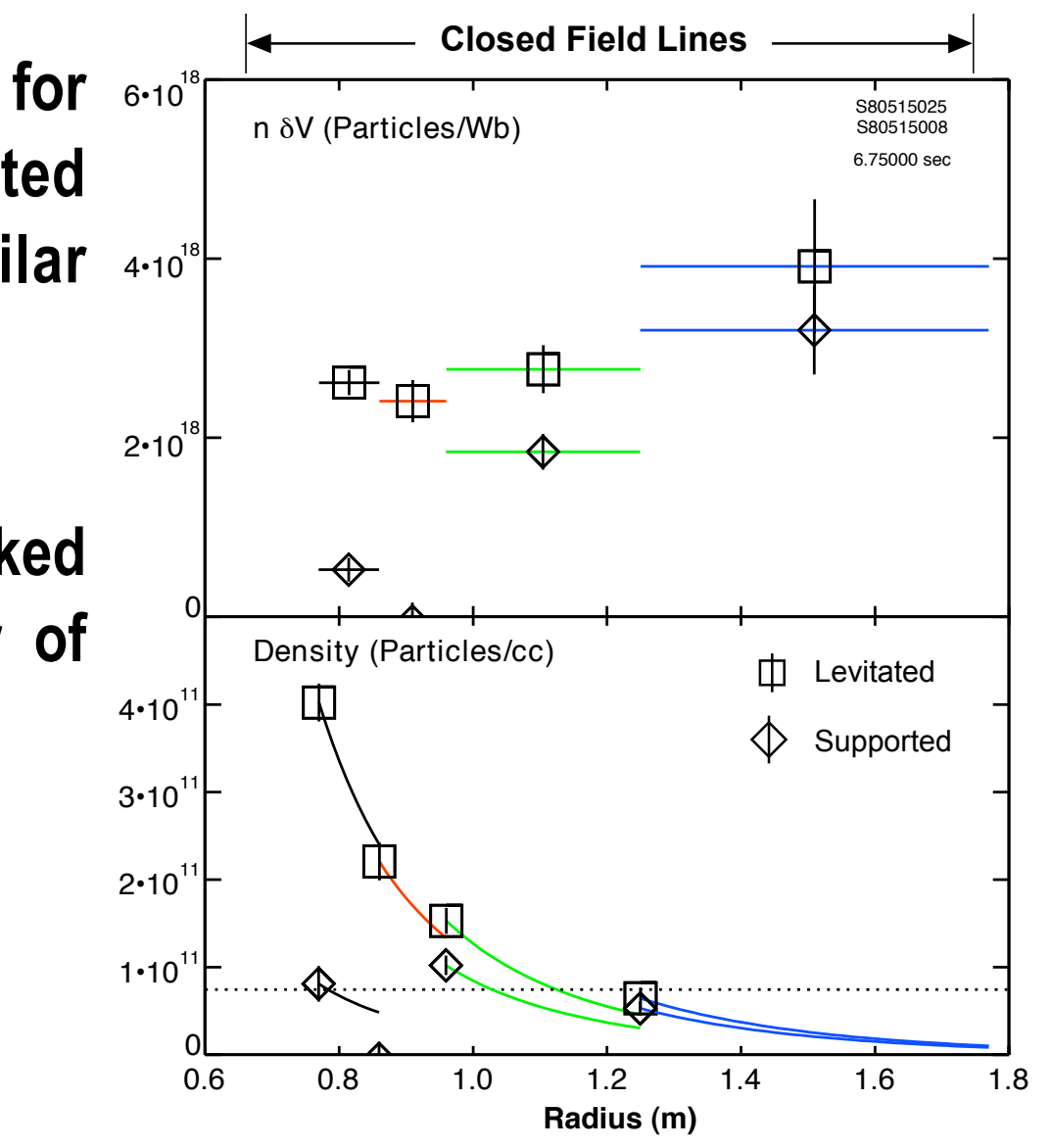


Diamagnetic flux for supported and levitated operation during density scan of run 80321. Both operations show an inverse scaling between fast particle confinement and bulk density.

Levitation allows high beta operation at higher densities.

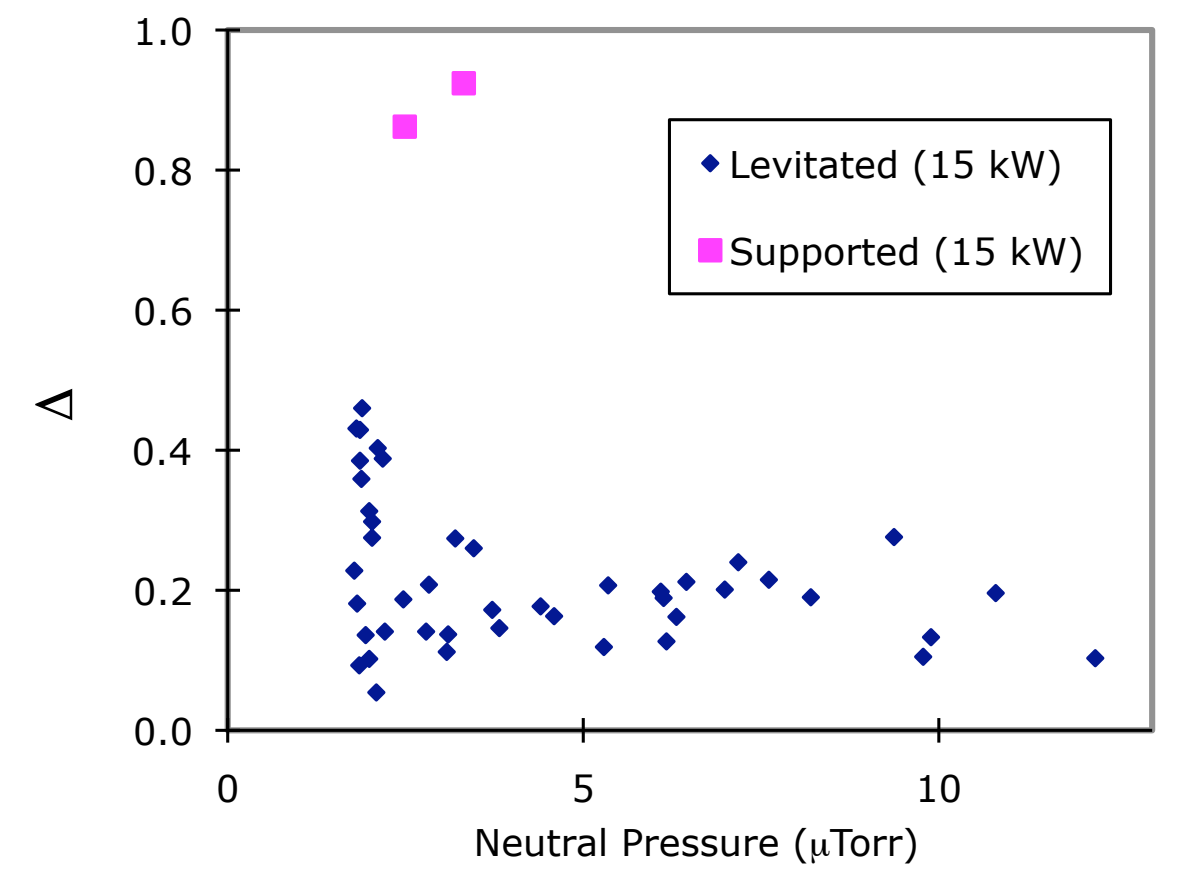
Computation of the density profile for supported (diamond) and levitated (square) discharges under similar conditions with 15 kW of ECRH.

The levitated case has a singly peaked profile with near constant number of particles per flux tube.



Deviation parameter (Δ) from constant number of particles per flux tube profile.

Levitated plasmas with multi-source ECRH and sufficient neutral fueling exhibit density profiles close to the interchange stationary profile.

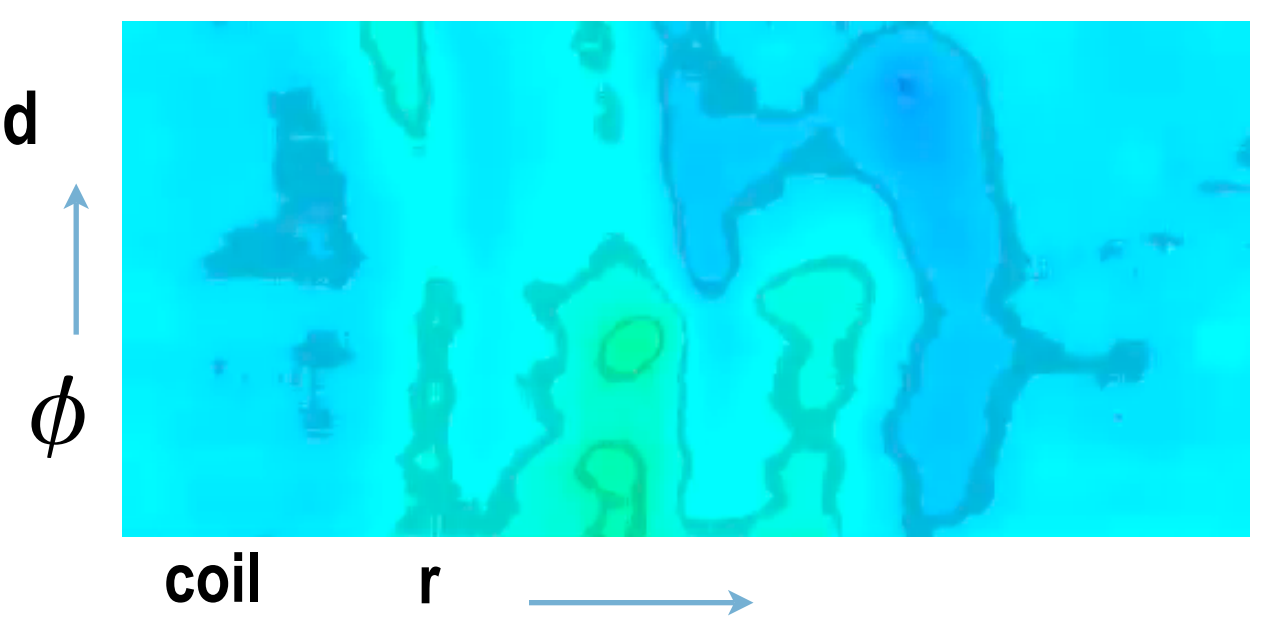


Similar supported (left) and levitated (right) shots. Numerous small hot electron interchanges are followed by a disruptive HEI in the afterglow. In comparison, the levitated shot undergoes no HEI's even though operated well below the unstable limit for supported operation.

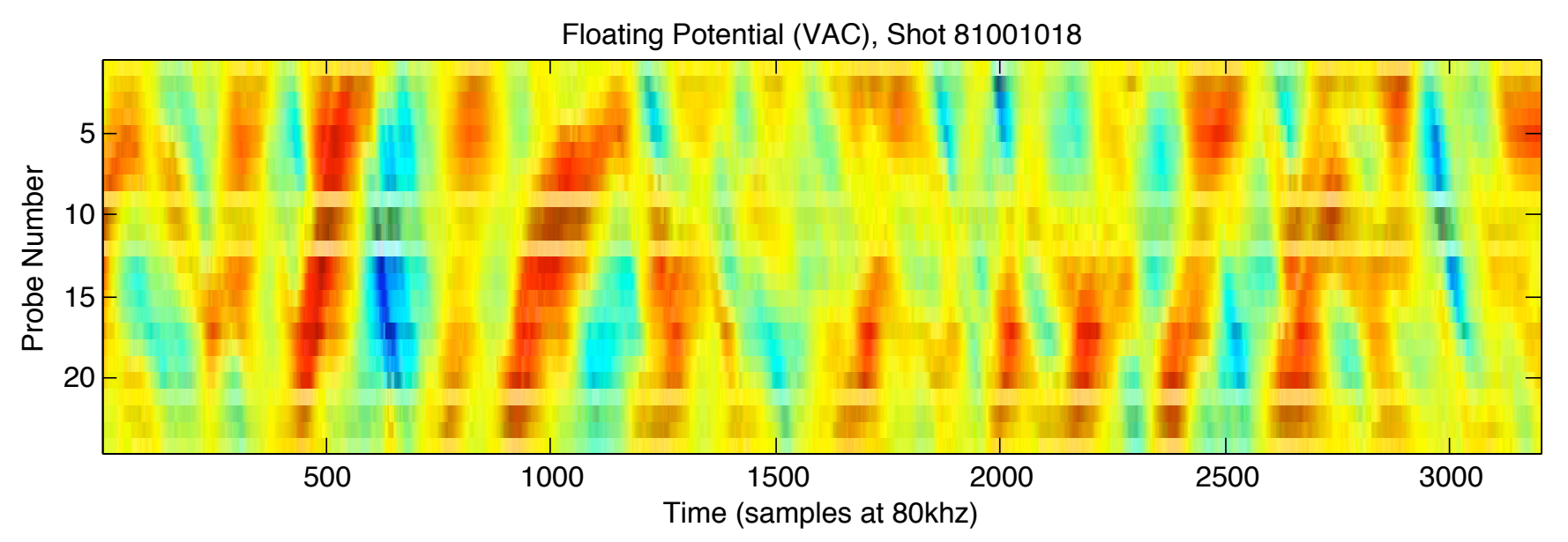
In general, reduced HEI activity are observed when levitated and no major disruptions have been observed in the heated phase when levitated, even while operated at much lower neutral pressures.

Investigating Radial Transport and Turbulence

- With levitation, observed density profile is dominated by radial transport
- Interchange mixing likely cause of profiles with near constant particles per flux tube
- We observe low frequency oscillations, both broadband and quasi-coherent that may be representative of interchange mixing
- Ongoing examination of relationship of observed turbulence with changes in plasma profiles as well as the effect of plasma turbulence on the plasma profiles.



Fast camera showing radial structure of interchange turbulence.



Plot of edge floating probe array, showing quasi-coherent structure of edge turbulence. Dominant is a 2 kHz, m=1 mode, rotating in the electron diamagnetic drift direction. (Which is also the ExB direction.)

Correlation weighted histogram of phase relationship between photodiode array channels during heating phase of levitated plasma. Channels are separated by 90 degrees azimuthally. Same quasi-coherent m=1 mode is observed.