Turbulent Particle Pinch in Levitated Superconducting Dipole

ICC/1-1Ra

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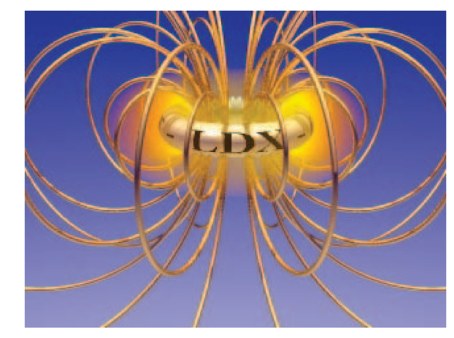
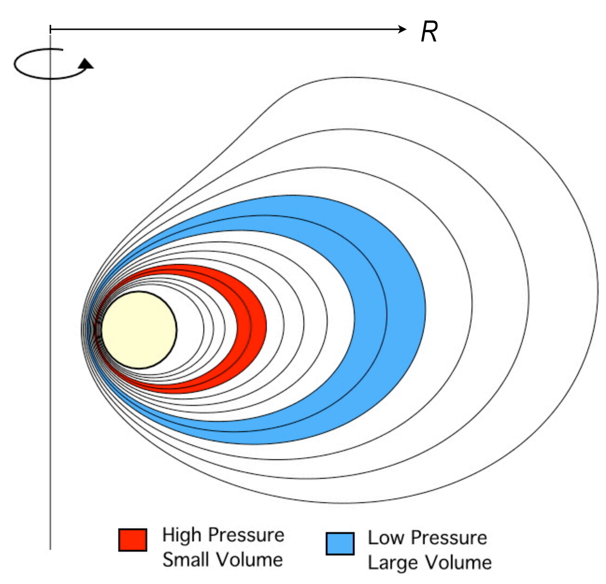


Superconducting Levitated Dipoles

- Levitated superconducting dipole brings the physics of space to the study of plasma confinement in the laboratory
  - Compressibility provides stability with order unity beta
  - Shear-free magnetic field eliminate neoclassical effects
  - Large magnetic flux expansion leads to centrally peaked density and pressure profiles
- Physics of magnetospheric dipole plasma confinement is 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)
  - Strongly peaked "invariant" density and pressure profiles are stationary solution of turbulent diffusion.

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

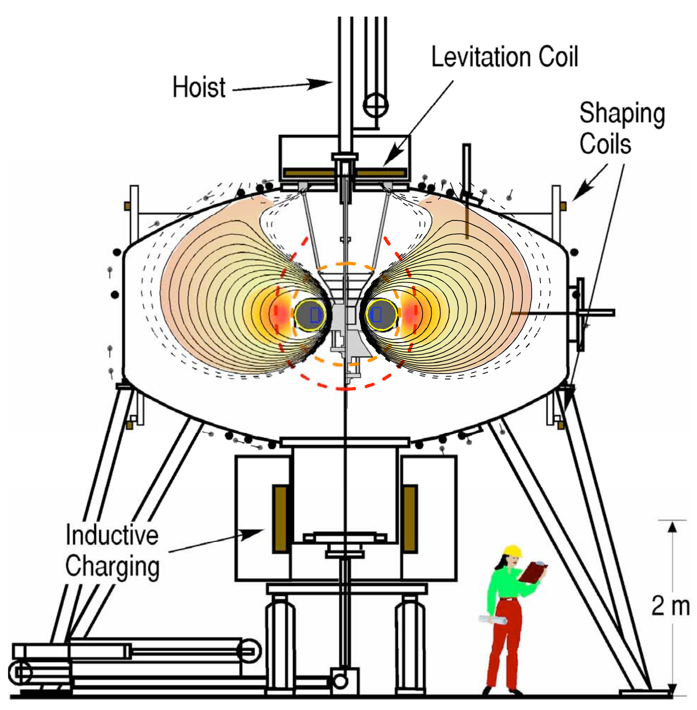


Large pinch term for dipole

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

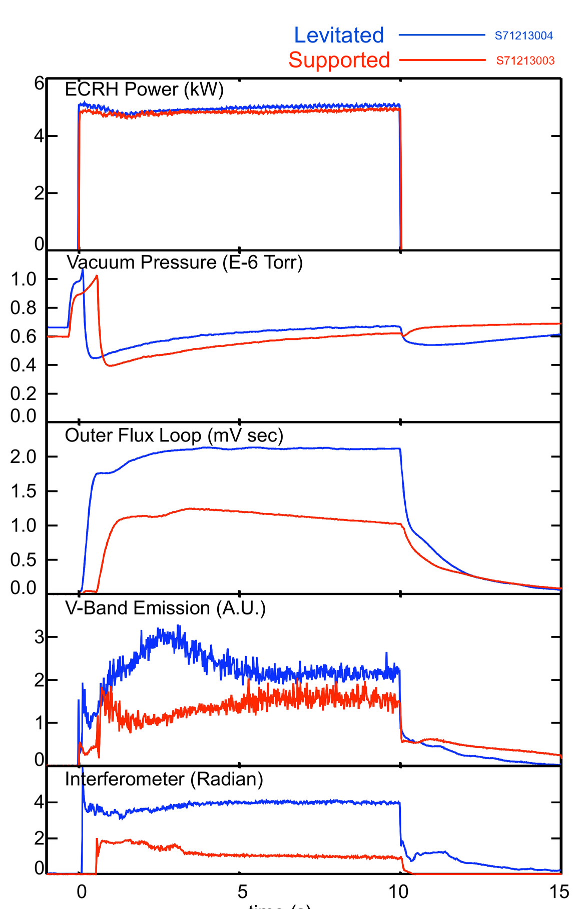
Levitated Dipole Experiment (LDX)

- 1.2 MA Nb3Sn coil allows 3 hour float time for long pulse, quasi-steady state experiments
- Large, 5 m diameter, vacuum chamber with excellent diagnostic access and large magnetic compressibility
- Upper levitation coil for axisymmetric, reliable magnetic levitation
- Lifting/catching fixture for re-cooling, coil safety and physics studies
- 25 kW CW ECRH for high temperature, high beta plasmas

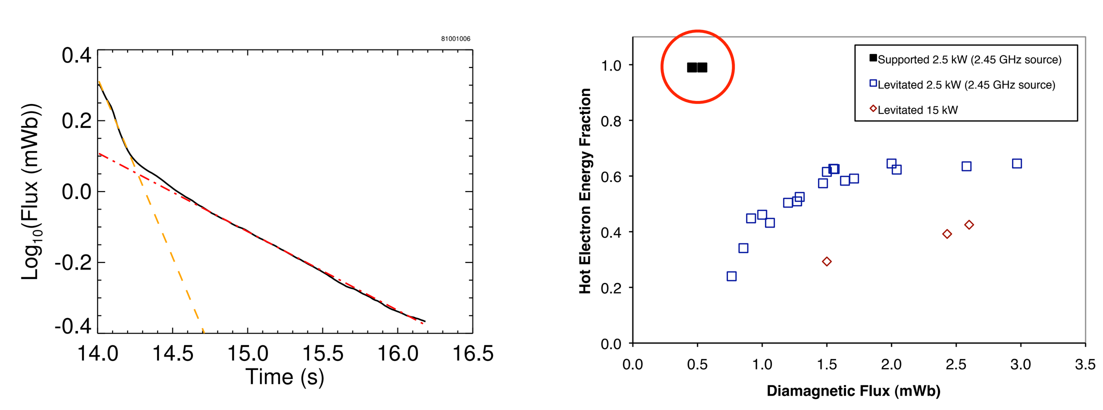


LDX High Beta Levitated Plasmas

- 5 kW ECRH power and ~ 300 J stored energy (levitated)
- Peak local beta ~ 40%
- Supported plasma has stored energy in energetic electron population
- 2-3 x stored energy when levitated
- Levitation increases ratio of diamagnetism-to-cyclotron emission indicating higher thermal pressure.
- Supported long afterglow confinement indicative of energetic particle confinement
- Long, higher-density levitated afterglow shows improved bulk plasma confinement.

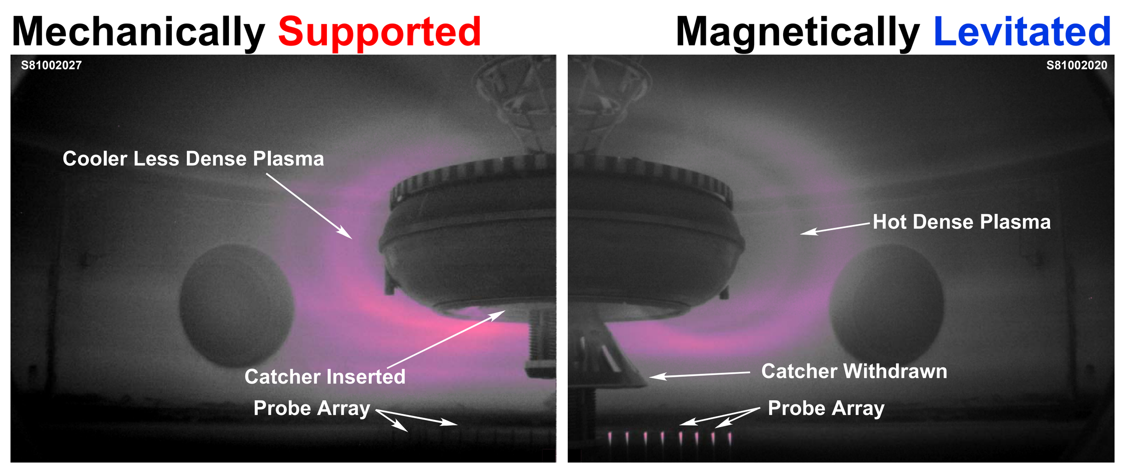


Significant Thermal Plasma Energy with Levitation



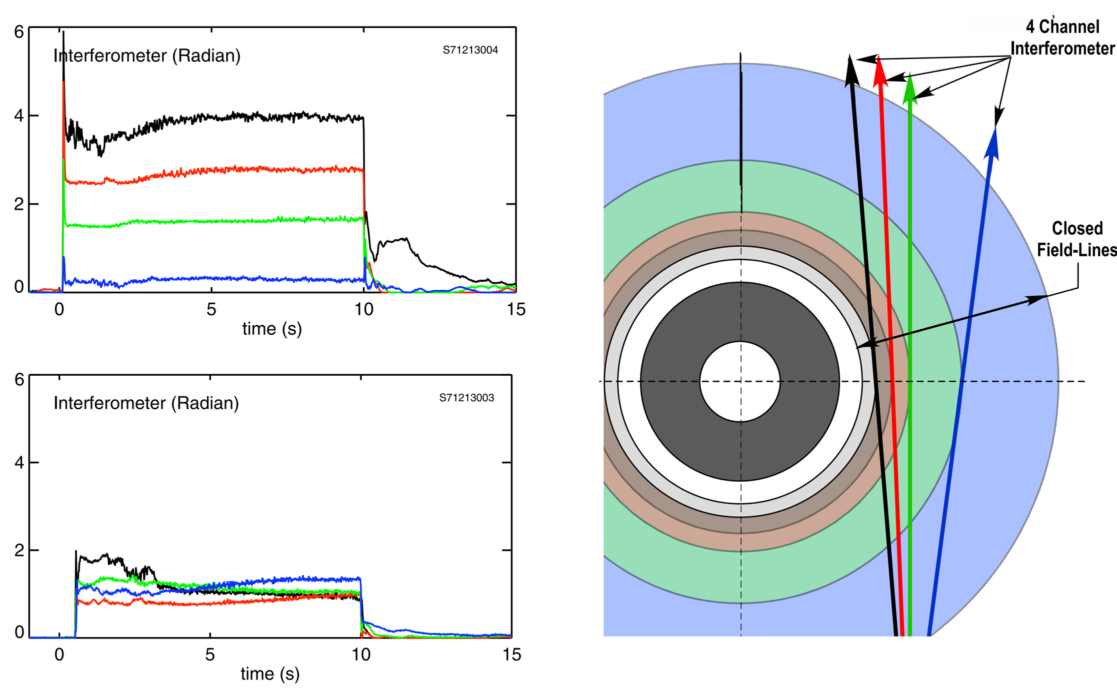
- Dual exponential decay in stored energy as measured by magetics
- Faster decay assumed to be warm bulk plasma
  - Up to 70% of stored energy in bulk

Levitation required to investigate dipole cross-field transport in laboratory



- Removing catcher eliminates mirror losses
  - Source region moves outward, edge probes see plasma losses
- Observed turbulence level is similar in both cases

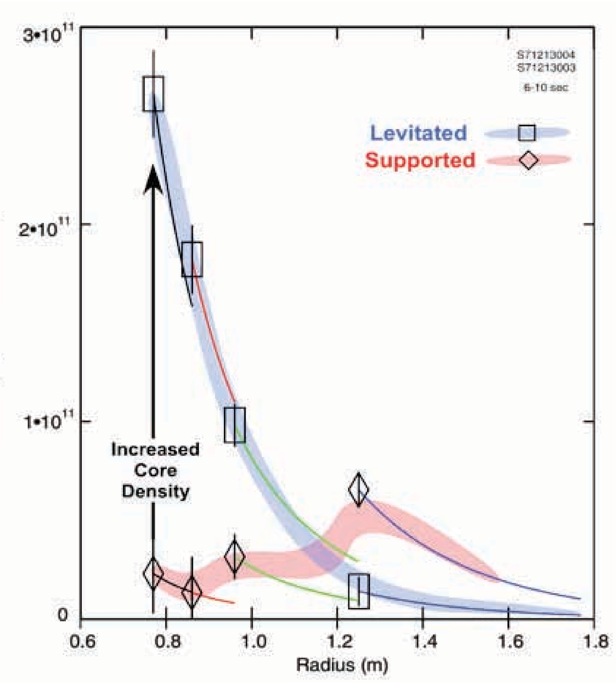
Highly peaked density profiles observed during levitated discharges



Reconstruction of the density profile for supported and levitated discharges under similar conditions with 15 kW of ECRH.

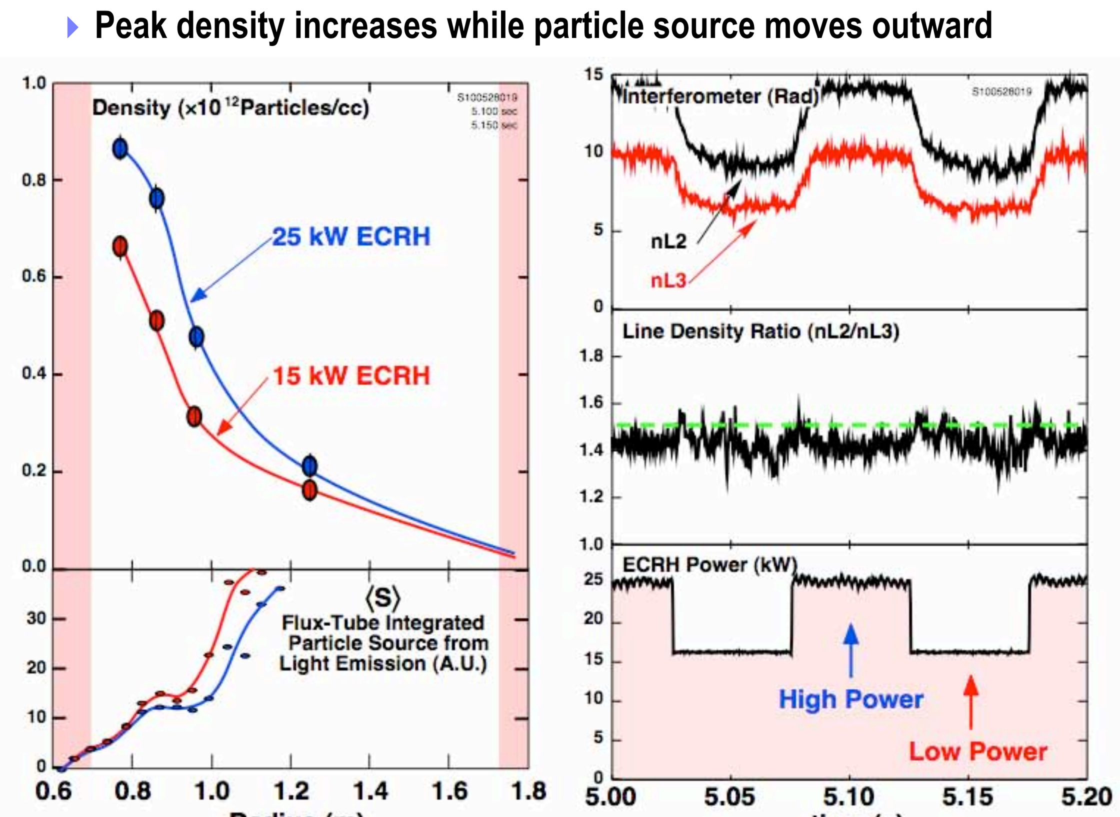
Supported mode has profile consistent with particle sources and parallel losses.

The levitated case has a singly peaked profile with near constant number of particles per flux tube. This "invariant" profile is consistent with interchange mixing and diffusion of total particles per flux tube.

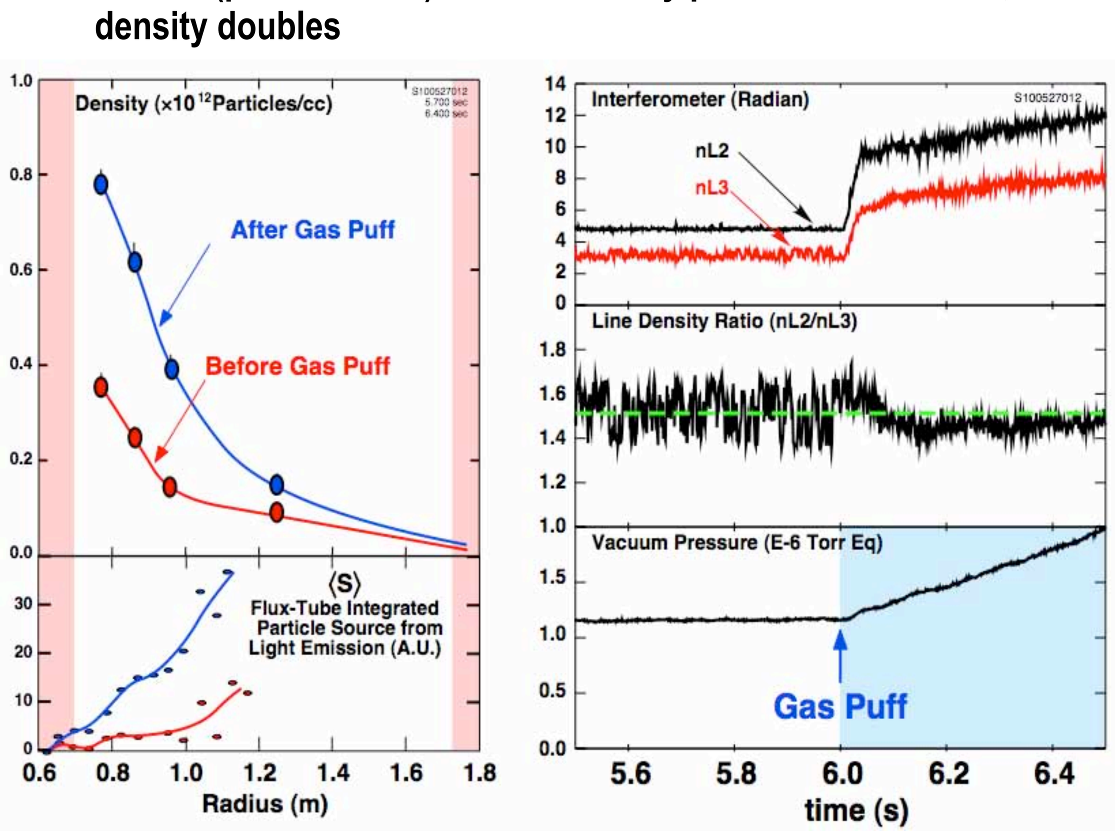


Invariant Profile is Robust to Heating and Fueling Changes

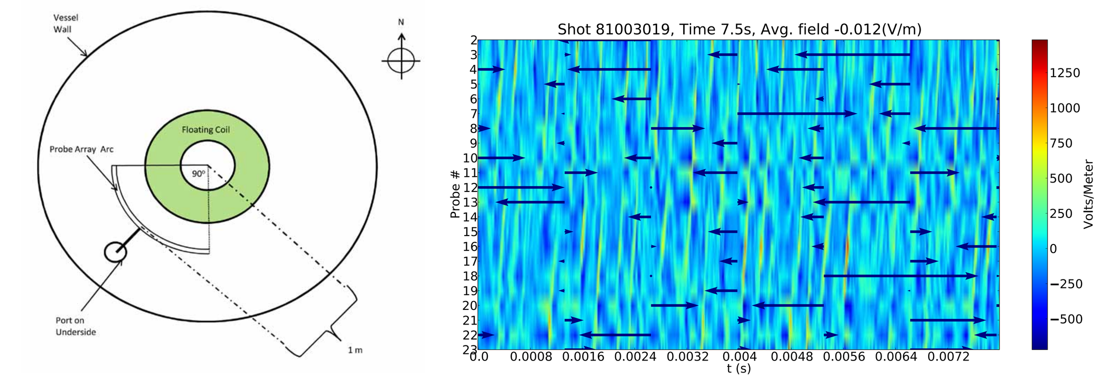
- 10 Hz 10 kW (10.5 GHz) modulation
  - Density modulation follows power: profile invariant and consistant with constant number of particles per flux tube
    - nl2/nl3 = 1.5 for constant nV
  - Peak density increases while particle source moves outward



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

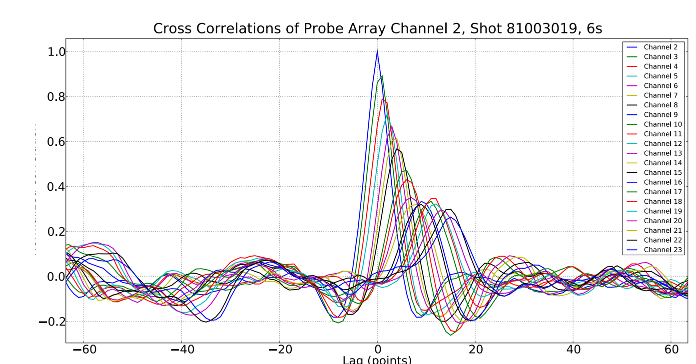


Low frequency fluctuations consistent with turbulent pinch



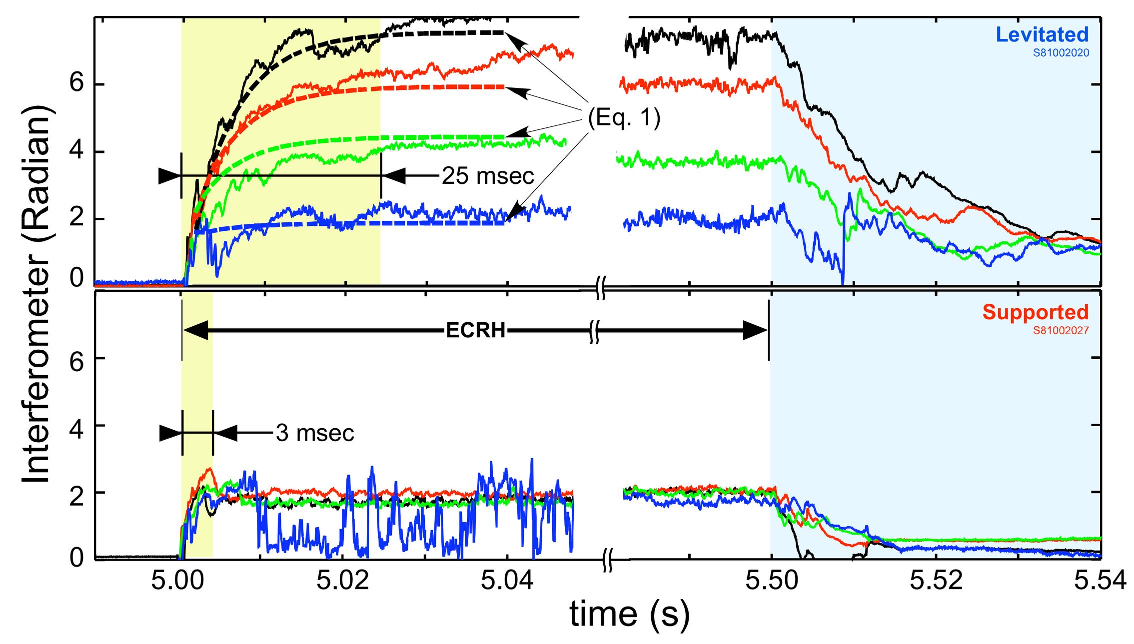
Plot of edge floating probe array, showing quasi-coherent structure of edge turbulence. Dominant is a 2 kHz, n=1 mode, rotating in the electron diamagnetic drift direction. (Which is also the ExB direction.)

- Array measures low frequency turbulent spectrum (0.1 - 10 kHz)
- Instantaneous ExB radial flow of 35 km/s approach the sound speed
- Measure azimuthal electric field fluctuation levels and correlation times



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

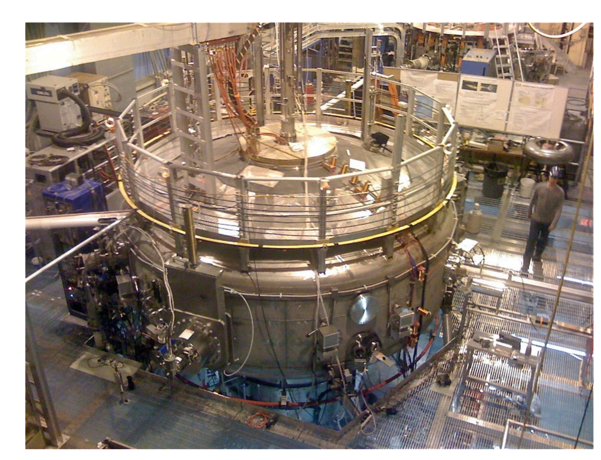
where $\langle S \rangle$ is the net particle source within the flux-tube, and the diffusion coefficient is $D = R^2 \langle E_\varphi^2 \rangle \tau_{cor}$ in units of $(\mathrm{V \cdot sec})^2$/sec.



Turbulent startup of levitated plasma show pinch time consistent with expected diffusion coefficient based on characteristics of edge fluctuations.

The Levitated Dipole Experiment (LDX)

- The LDX device is highly innovative, superconducting magnetic confinement device with reliable operation and long plasma pulses



- LDX has succeeded in reproducing two magnetospheric observations in the laboratory:
  - 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

LDX is ready to investigate important and fusion relevant plasma physics

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