Abstract

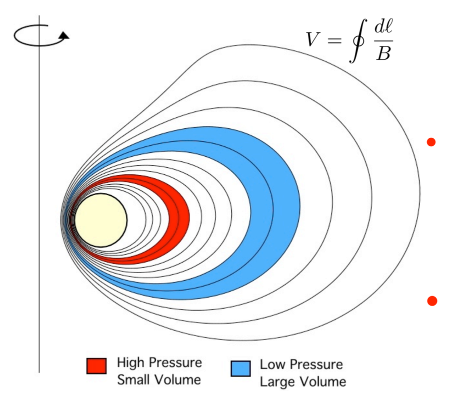
The Levitated Dipole Experiment (LDX) investigates plasmas confined in the closed field line dipole magnetic geometry where the plasma stability is provided by compressibility and where plasma convection leads to peaked profiles and may allow for $\tau_E > \tau_p$. In the past year, we have continued to investigate the improved energy and particle confinement when the supports are removed from the plasma.

Of most significance, we observe that:

- A large fraction of the stored energy in levitated plasmas is contained in the bulk electron population.
- Eliminating plasma losses along field lines allows observations of a strong particle pinch leading to a density profile with near equal number of particles per flux tube.
- The previously observed low frequency fluctuations are consistent with the required turbulent convection to drive the observed particle pinch.

In future experiments, an optimal levitation control system will be implemented, reflectometer and soft x-ray spectrometer diagnostics will be added, and a higher frequency (28GHz) electron cyclotron heating source will be added to increase the density of LDX plasmas. In preparation for installing a 1MW ICRF transmitter, initial ion cyclotron heating experiments will also be performed.

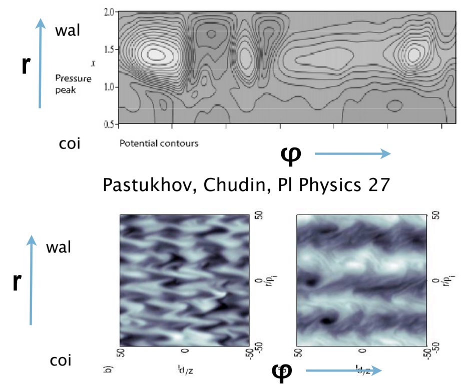
The Levitated Dipole Concept



- 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 Closed Field Line 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

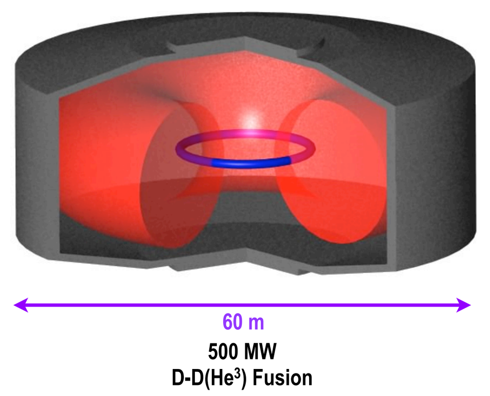
Ricci, Rogers, Dorland, PRL 97,

Possible Fusion Power Application

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

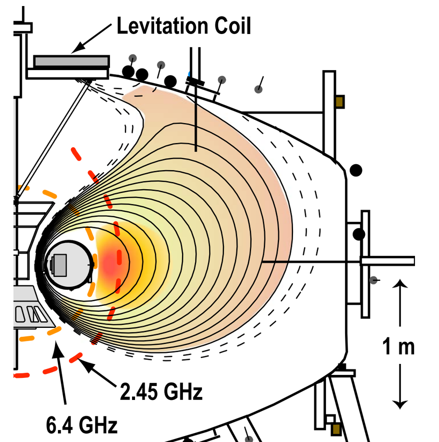
Levitated Dipole Reactor

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



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
  - 10 kW, 28 GHz (FY2010)



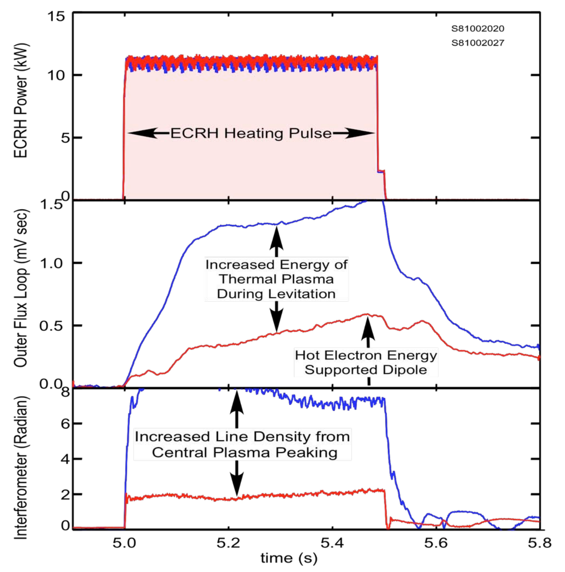
LDX experiment. The vacuum vessel is 5 m in diameter and the 560 kg superconducting dipole coil is 1.2 m in diameter.

Plasma Diagnostic Set

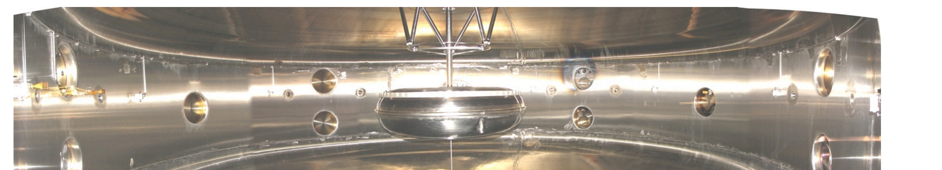
- Magnetic equilibrium
  - flux loops, Bp coils, Hall effect sensors, levitation system trackers
- Fast electrons
  - X-ray PHA, x-ray detector, 60 GHz & 137 GHz radiometers
- Core parameters
  - interferometer, visible cameras, visible diode and array, survey spectrometer
- Fluctuations
  - Edge I_{sat} and V_f probes, Mirnov coils, visible diode arrays, interferometer, fast visible camera, floating probe array
- Edge parameters
  - swept, Isat, and floating potential probes
- In development
  - reflectometer for density profile (peak density) corroboration and internal fluctuations
  - soft x-ray spectral measurements

Improved Confinement with Levitation

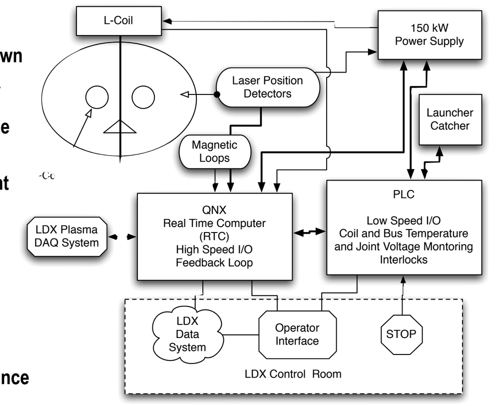
- Similar shots Supported and levitated
  - Similar gas fueling
- 3-5 x line average density
  - much more peaked profile with levitation
- 2-3 x the diamagnetic flux
- Significant stored energy in warm bulk plasma when levitated
- Observed over all operating conditions



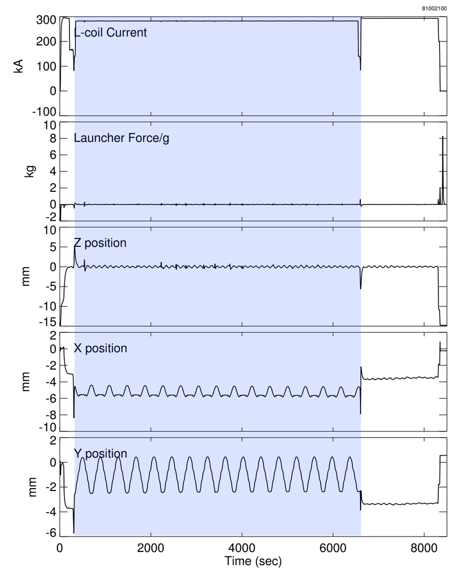
Levitation System



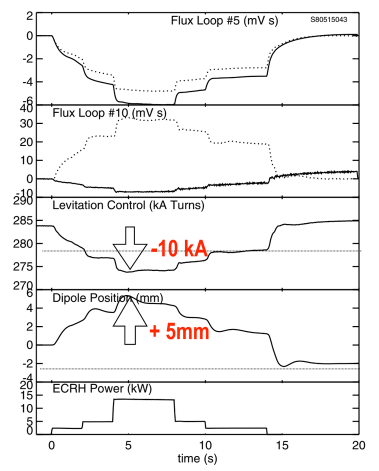
- 4500 A / 50 V Power supply
  - Resistive coil allows for rapid shutdown
- Realtime digital control computer
  - Allows different control methods to be implemented
  - Matlab/Simulink Opal-RT development environment
  - 4 kHz feedback loop
  - Failsafe backup for upper fault
- Programmable Logic Controller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

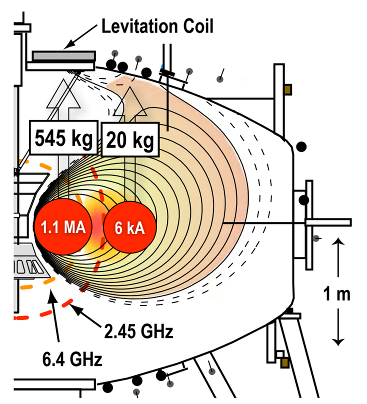


- Well controlled flight
  - After launch, < .2 mm z excursions
  - oscillation in x and y caused by slow rotation
    - gravitational well in toroidal rotation caused by incomplete balance
    - 6 minute period with very small damping
- Control algorithm
  - P - I - D - A control of voltage
    - PS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



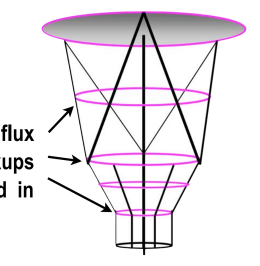
Effect of Plasma on Levitation System





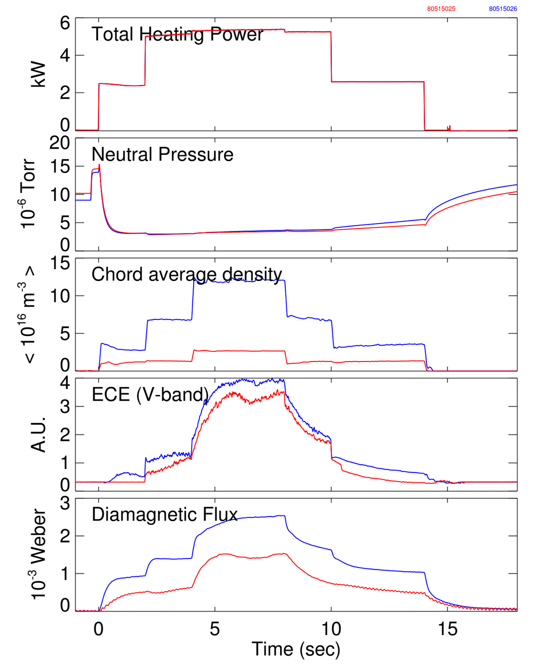
Isolating the Plasma Mutual Inductance

- Diamagnetic plasma increases effective mutual inductance of L and F coils
- Use internal and external flux loops
  - Feedforward on plasma energy from external loop
  - Use coil position sensitive internal magnetic loops for velocity feedback
- Both require calibration for effective use

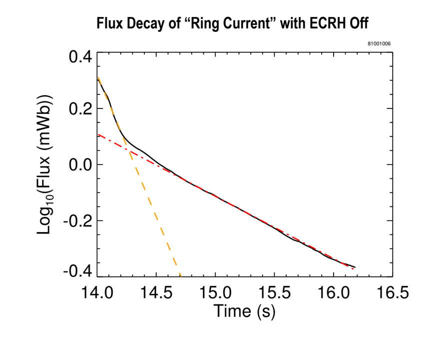


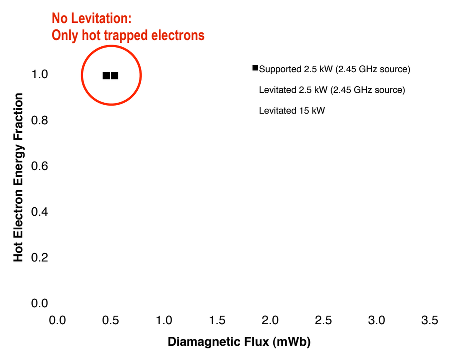
Internal flux loop pickups now used in feedback

Significant Stored Energy in Thermal Plasma



When levitated, a large increase in density and magnetically measured stored energy is seen with only modest increase of ECE emission, which is sensitive mostly to the mirror trapped hot electron population.



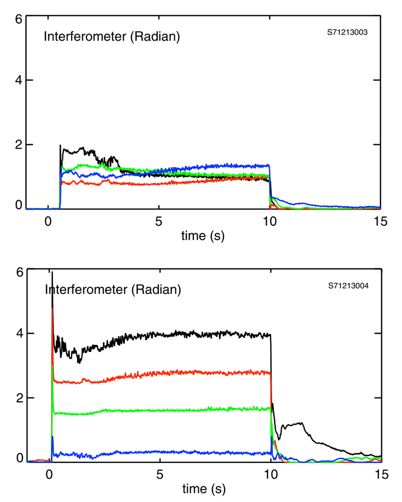


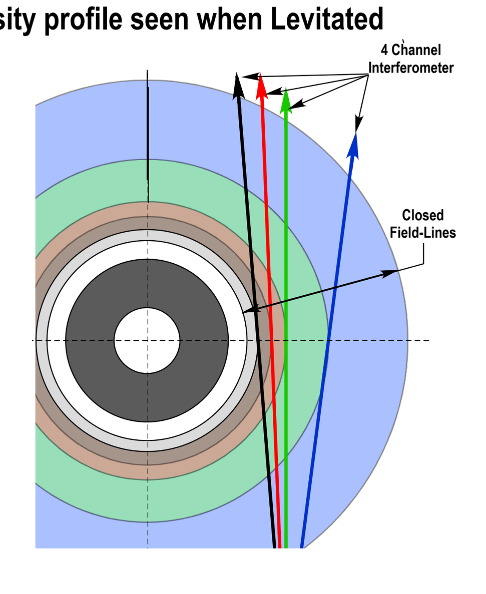
The observation of signficant fraction of bulk plasma beta is determined from the nature of the diamagnetic flux signals which show an initial energy decay of the bulk plasma followed by the long decay of the fast particles as also seen in the supported shots. Furthermore, the radiometer, which sees primarily harmonic ECE from the fast electrons, does not show the marked increase that the diamagnetic loops demonstrate. Thus the increase in beta during levitation is largely in the bulk warm electrons.

The significant bulk beta is roughly consistent with a pV^γ = constant profile starting with the measured edge T_e of ~20 eV. This profile would have core T_e ~ 400 eV.

Inward Particle Pinch Observed during Levitated Plasmas

Dramatic Peaking of density profile seen when Levitated

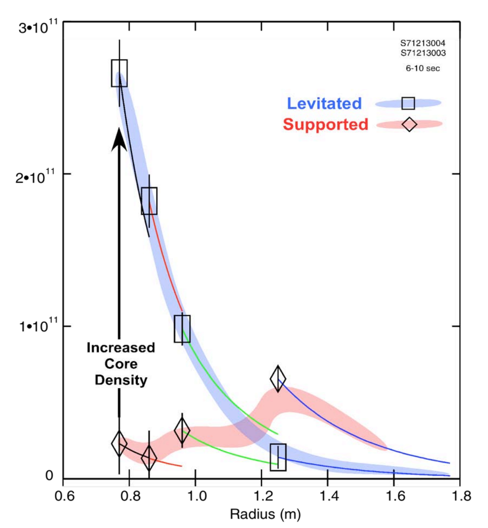




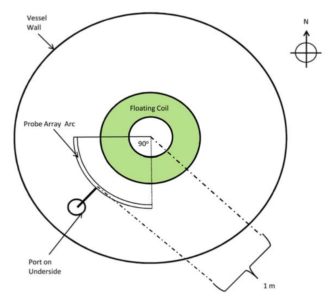
Reconstruction of the density profile for supported (diamond) and levitated (square) discharges under similar conditions with 15 kW of ECRH.

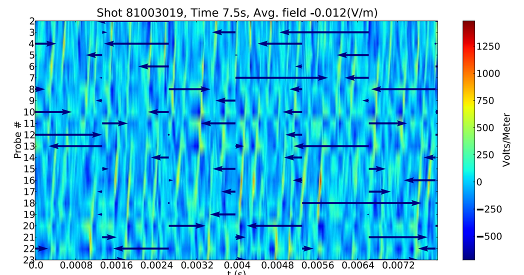
Supported mode has profile consistent with particle sources and parallel losses.

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

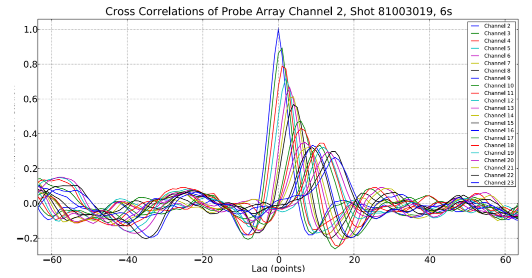


Low Frequency Fluctuations consistent with Turbulent Pinch



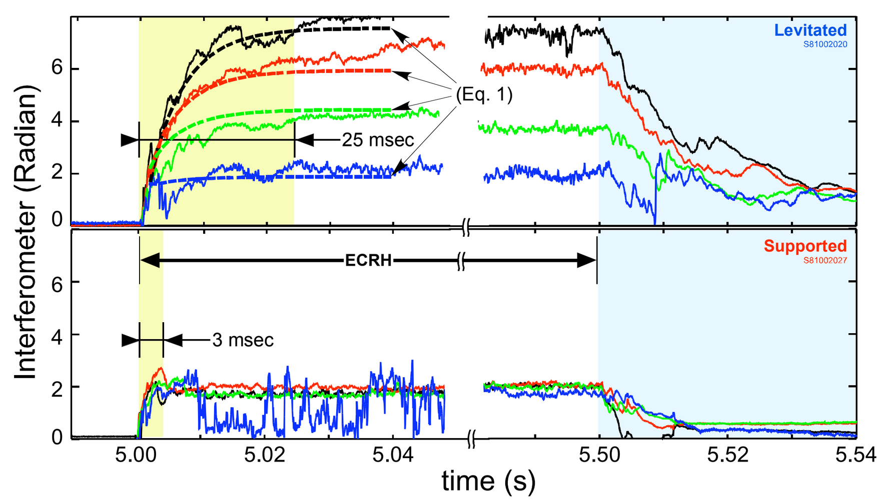


Plot of edge floating probe array, showing quasi-coherent structure of edge turbulence. Dominant is a 2 kHz, m=1 mode, rotating in the electron diamagnetic drift direction. (Which is also the ExB direction.) Assuming the plasma potential is a constant offset from the floating potential gives a measure of the electric field. Instantaneous radial ExB drift speeds of 35 km/s approach the sound speed. Measured azimuthal electric field fluctuation levels and correlation times may be used to estimate turbulent diffusion coefficient.



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

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

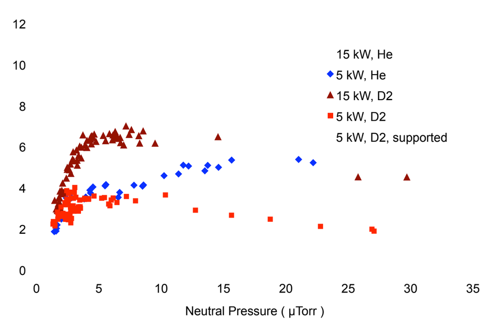


Turbulent startup of levitated plasma show pinch time consistent with expected diffusion coefficient based on characteristics of edge fluctuations. See Mauel, UP8.00051

Towards Higher Density Dipole Confined Plasmas

Dipole Edge Power Balance Scaling

Steady state central chordal density measurement versus neutral pressure for different conditions.

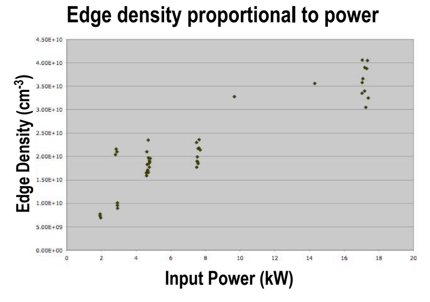


Increasing power increases the core density and there is large mass effect for the optimal fueling. This observation is consistent with the dipole "natural profiles" (nV = constant), where the edge parameters are set by power flow along the scrape off layer (SOL). Here the improved confinement of He is due to the slower sonic flow to the wall in the SOL.

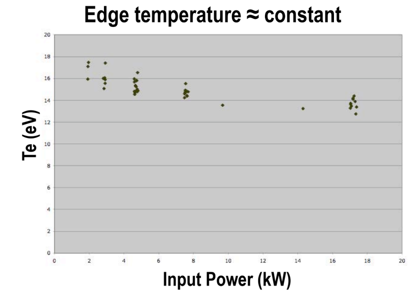
Indeed, probe measurements of density and temperature at the SOL indicate a nearly linear scaling of density with power and a nearly constant edge temperature, as predicted by the notion that the edge power balance determines the edge parameters (see Kesner, et al. UP8.00052).

Thus, assuming the edge scales with power and the natural profiles, we can extrapolate the power levels required to reach the LDX Phase III target plasma conditions.

Edge density proportional to power



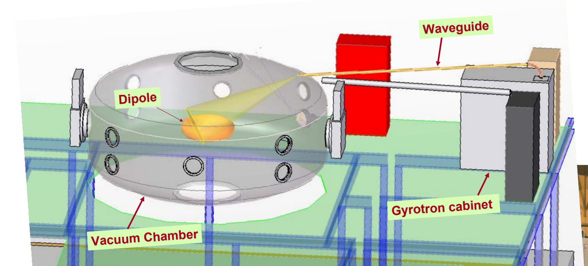
Edge temperature ≈ constant



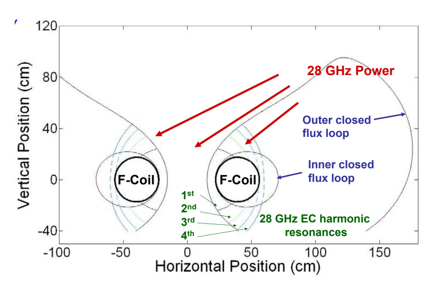
LDX Phase III Target Plasmas

- Original proposal goal for thermal plasma studies
  - ~10^{13} / cm³ density
  - peak β order unity
- Current plasmas ~ 15 kW
  - peak density ~ 0.8 x 10^{12} / cm³
  - edge temp 15-20 eV
  - core temp 400 eV ? (see Davis UP8.00054)
  - thermal peak β ~ 10 %
- FY2010 - University of Maryland 28 GHz gyrotron
  - 10 kW addition power (+ 55 %)
  - peak density ~ 1.5 x 10^{12} / cm³
  - thermal peak β ~ 20 %
- 1 MW 3-28 MHz CW transmitter installation
  - 200 kW ICRF heating
  - ~10^{13} / cm³ density
  - peak β order unity
  - Isotropic, thermal plasma
    - T_i=T_e, 500 eV core

University of Maryland 28 GHz Gyrotron

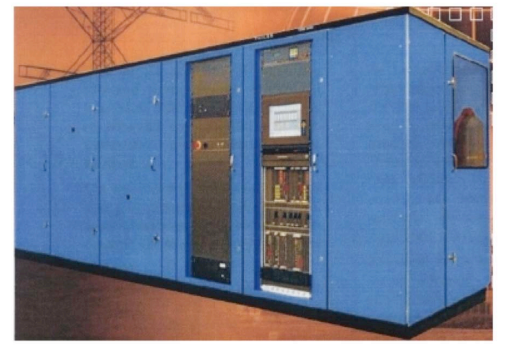


- 28 GHz heating
  - heat with broad profile across plasma in high field region
  - antenna designed for direct beam to resonance zones
- Installation underway
  - Custom vacuum penetration (with very shallow angle to vessel)
  - Vacuum window, beamline, and dummy load fabrication at MIT.
- Initial operation planned for Jan 2010.
  - See Woskov, UP8.00059



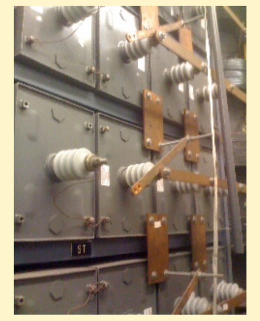
1 MW ICRF Transmitter (3-28 MHz)

- 1 MW, 3-28 MHz CW transmitter
  - From Archimedes isotope seperation project
  - Donated to MIT by General Atomics
  - Will be made available to LDX with DOE ARRA stimulus funding
- Installation underway
  - Structural engineering of penthouse completed
    - OK to install
  - Clearing out old TARA power supplies



Need Capacitors?

- 100 Tara Tandem Mirror pulsed power supply capacitors. "Cadillacs"
- 45 kV, 17 uF
- All must go! Get yours today!



- Slow wave (Stix) heating
  - bulk plasma ICRF heating
  - requires high field launch
- Multiple antenna options
  - Direct heating at plasma axis (21 MHz)
    - similar to Phadreus end cell
  - Nagoya type III loops on upper launcher
  - Other designs
- Antenna coupling studies (FY10)
  - Inital experiments to study plasma coupling using low power (~ 1 kW) ham radio HF amplifier
  - allow multiple designs to be analysed while transmitter is installed