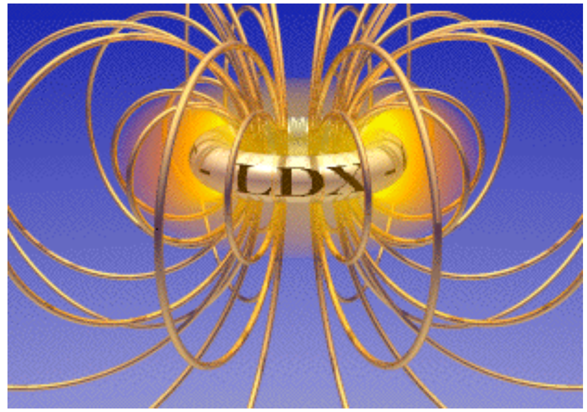


Levitated Dipole Experiment: Overview of First Results and Plans

D.T. Garnier, A.K. Hansen, M.E. Mauel, E.E. Ortiz

Columbia University

A. Boxer, J. Ellsworth, I. Karim, J. Kesner, I. Karim, S. Mahar, J. Minervini, P. Michael, A. Roach, A. Zhukovsky, M. Zimmerman

MIT Plasma Science and Fusion Center

Columbia University

IN LVMINE TVO VIDEBIMVS LVMEN

PSFC

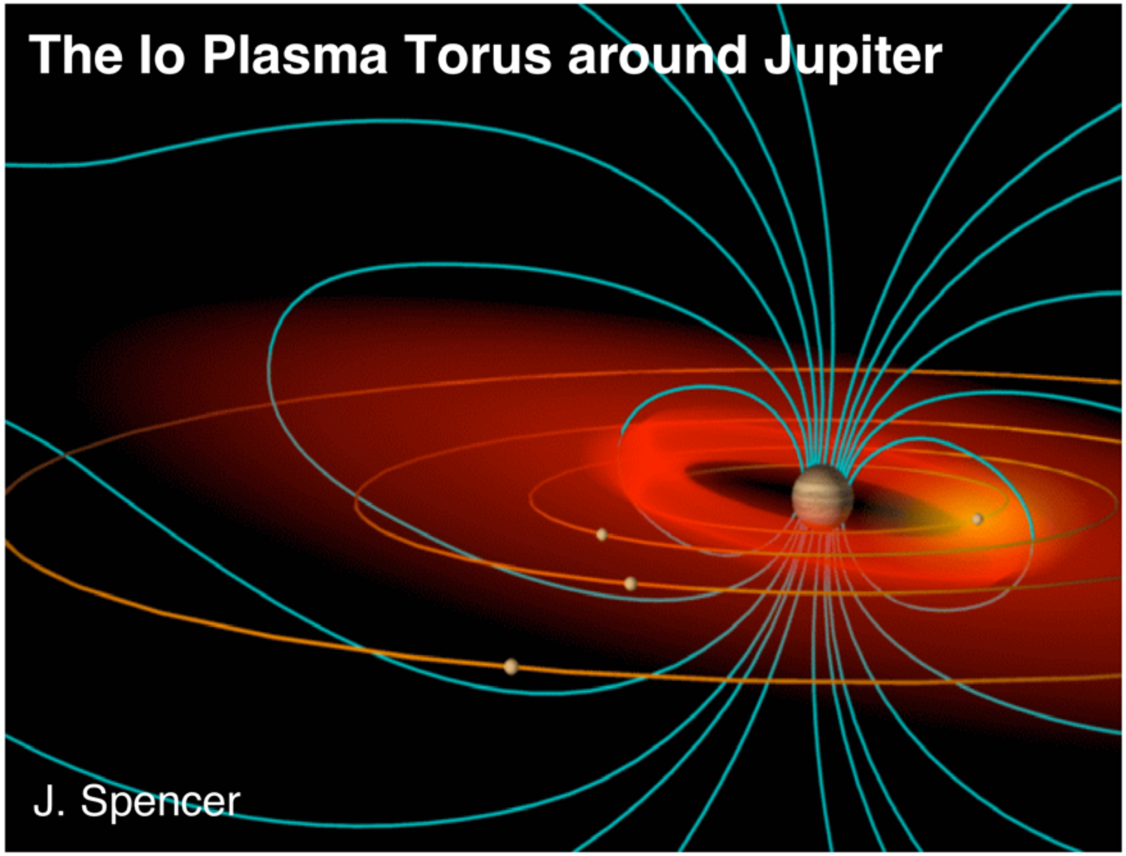
Presented at the

American Physical Society
46th Annual Meeting of the Division of Plasma Physics
Savannah, Georgia
November 15, 2004

Abstract

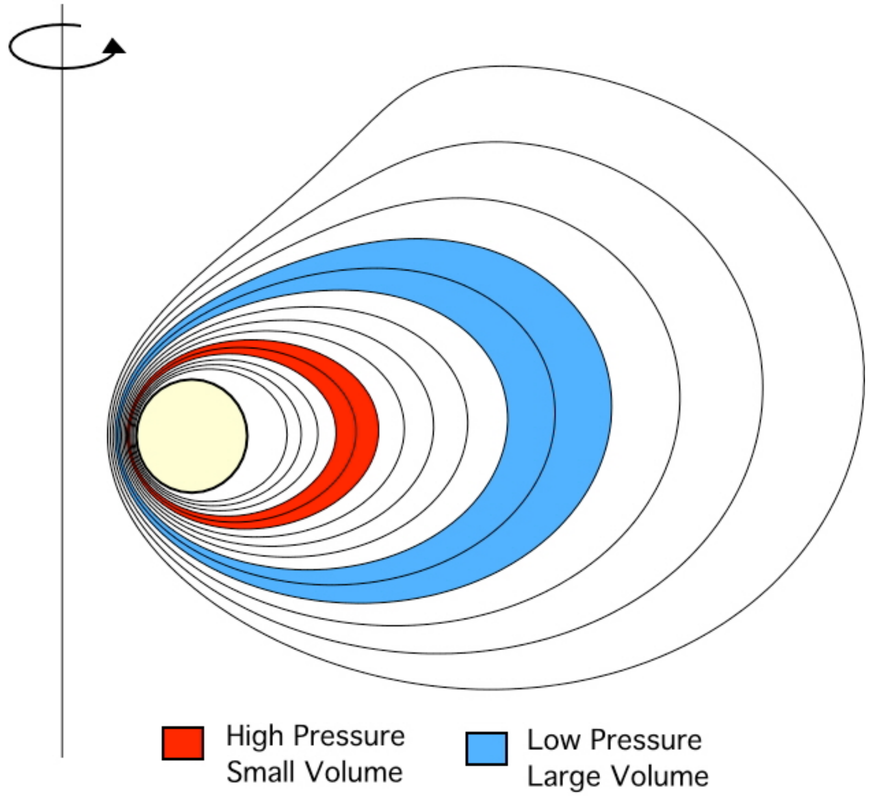
- The Levitated Dipole Experiment (LDX) is the first experiment to investigate the behavior of high-temperature plasma confined by a levitated magnetic dipole.
- LDX will test recent theories that suggest that stable, high β plasma can be confined without magnetic shear. Without shear, the dipole configuration may produce near classical energy confinement with reduced impurity particle confinement.
- LDX consists of three superconducting magnets including the high-field floating coil that is suspended within a large vacuum vessel. The installation and testing of all three superconducting magnets has been completed. The first plasma physics campaigns have begun and will establish reliable operation of the superconducting coils during plasma discharges using a mechanically-supported coil and reveal new insights into the production and stability of high beta plasmas heated by ECRH.
- This poster presents an overview of the LDX experimental results and discusses plans for future physics studies.

Why is dipole confinement interesting?



- Simplest confinement field
- High-β confinement occurs naturally in magnetospheres ($\beta \sim 2$ in Jupiter)
- Opportunity to study new physics relevant to fusion and space science
- Possibility of fusion power source with near-classical energy confinement

Dipole Plasma Confinement



If $p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$, then interchange does not change pressure profile.

For $\eta = \dfrac{d \ln T}{d \ln n} = \dfrac{2}{3}$, density and temperature profiles are also stationary.

- Toroidal confinement without toroidal field
  - Stabilized by plasma compressibility
    - Not average well
    - No magnetic shear
  - No neoclassical effects
  - No TF or interlocking coils
- Poloidal field provided by internal coil
  - Steady-state w/o current drive
  - $J_{||} = 0$ -> no kink instability drive

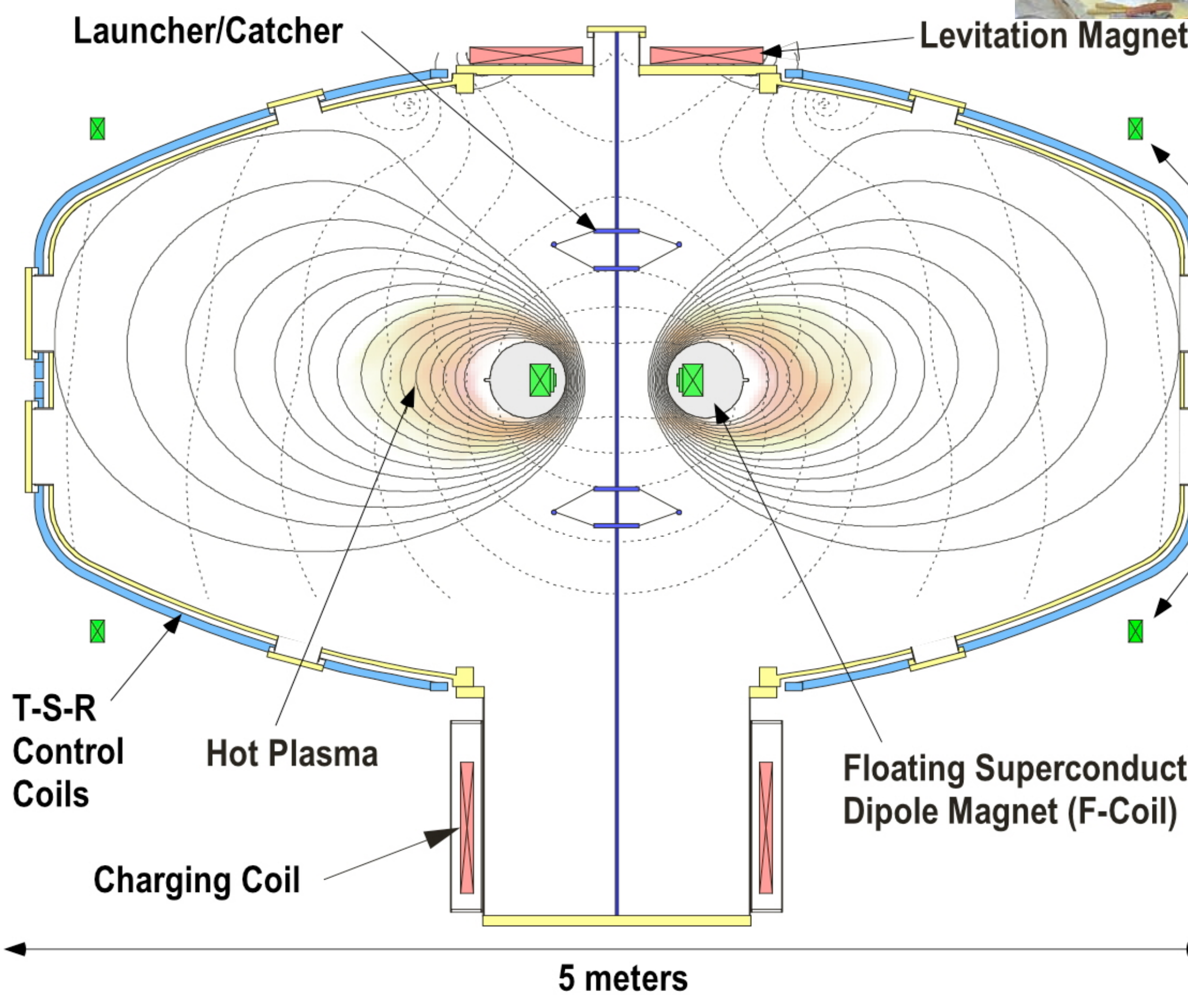
Dipole Confinement continued...

- Marginally stable profiles satisfy adiabaticity condition.
  - M.N. Rosenbluth and Longmire, ***Ann. Phys.*** 1 (1957) 120.

$$\delta(pV^{\gamma}) = 0, \text{ where } V = \oint \frac{dl}{B}, \ \gamma = \frac{5}{3}$$

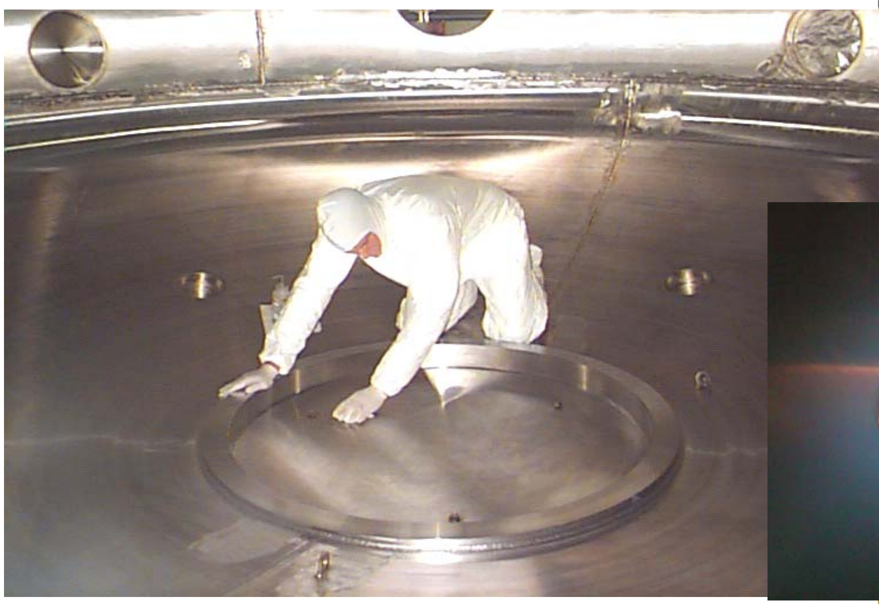
- Equilibria exist at high-β that are interchange and ideal MHD ballooning stable
- For marginal profiles with $\eta = 2/3$, dipoles also drift wave stable
  - Near-classical confinement ?
  - Drift waves exist at other values of η , but with with reduced growth rates
- No Magnetic Shear -> Convective cells are possible
  - For marginal profiles, convective cells convect particles but not energy.
    - Possible to have low τ_p with high τ_E .
  - Convective cells are non-linear solution to plasmas linearly unstable to interchange

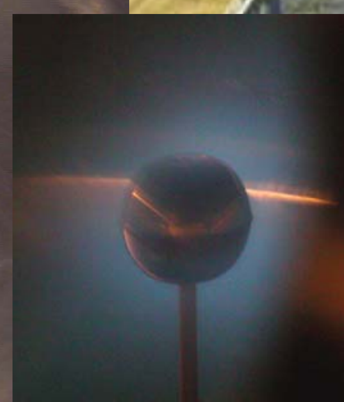
LDX Experiment Cross-Section



LDX Vacuum Vessel

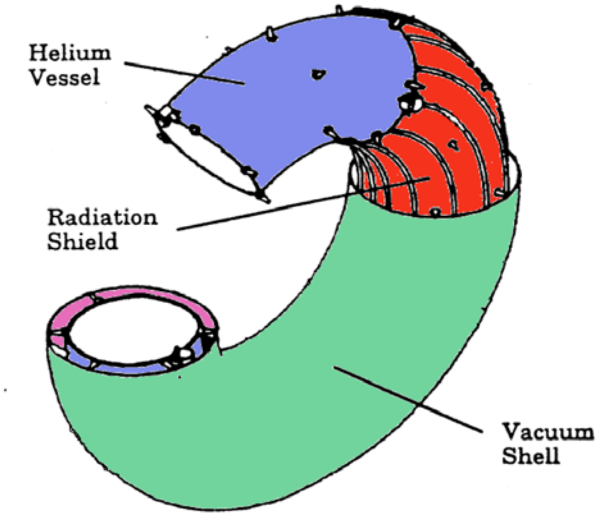
- Specifications
  - 5 meter (198”) diameter, 3 m high, elevated off chamber floor
  - 11.5 Ton weight
  - Manufactured by DynaVac, Inc. (1999)
- Glow Discharge Cleaning
  - Tested March 2004
  - Extensively used for before each run
    - Gaining operation experience...



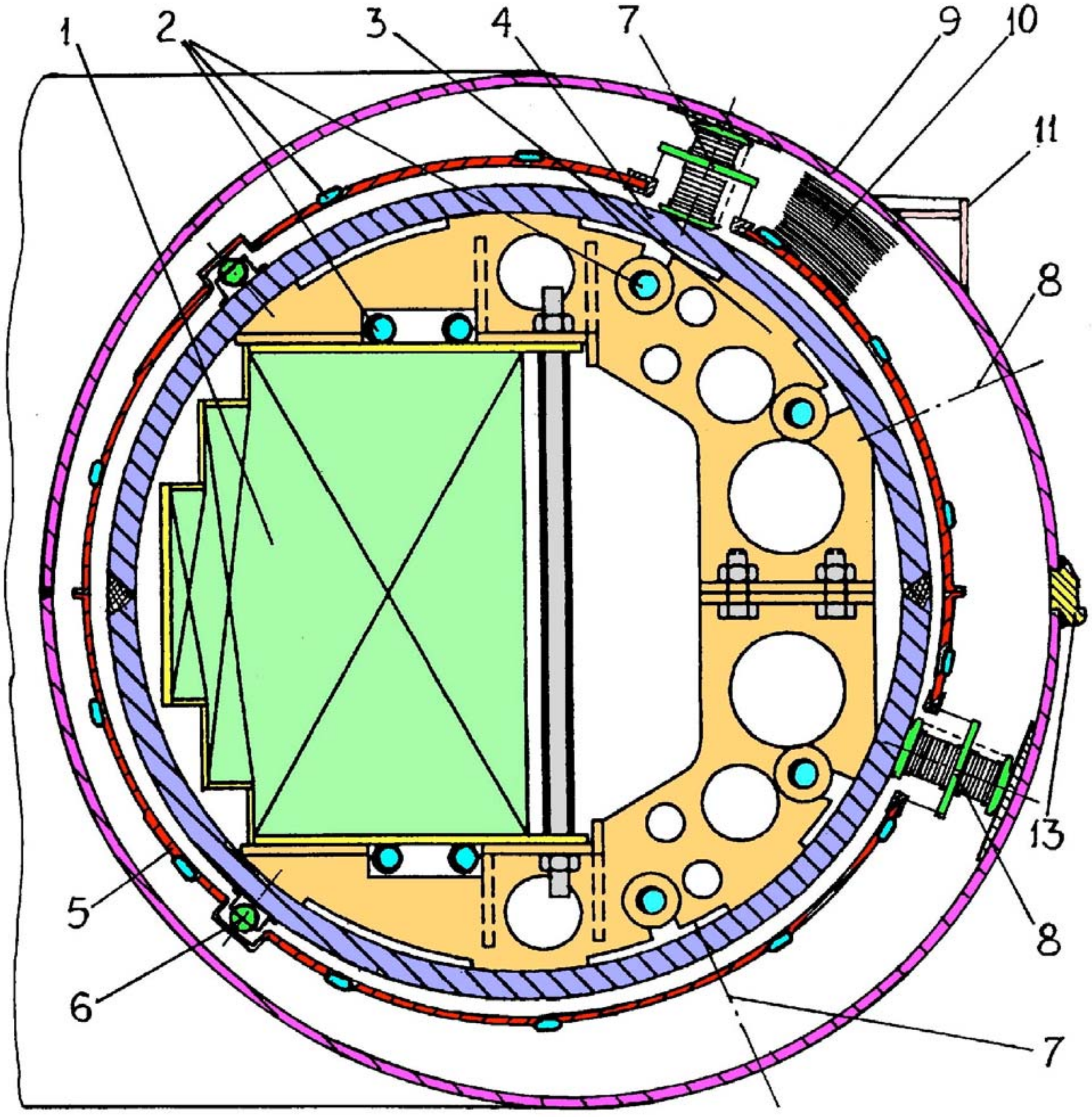


LDX Floating Coil

- Unique high-performance Nb3Sn superconducting coil
  - 1.5 MA, 800 kJ (maximum)
  - 1300 lbs weight
  - Inductively charged
- Cryostat made from three concentric tori
  - Helium Pressure Vessel
  - Lead Radiation Shield
  - Outer Vacuum Shell
- Initial Operations
  - 850 kAT charge
  - ~2 Hour operation time
    - Superconducting to ~13.5 K



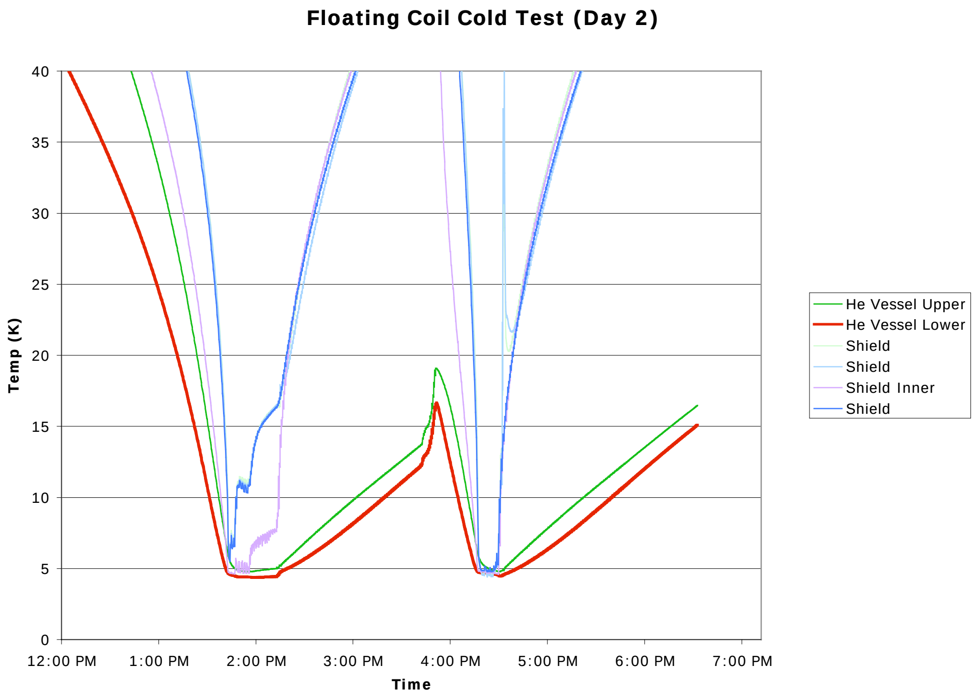
Floating Coil Cross-Section

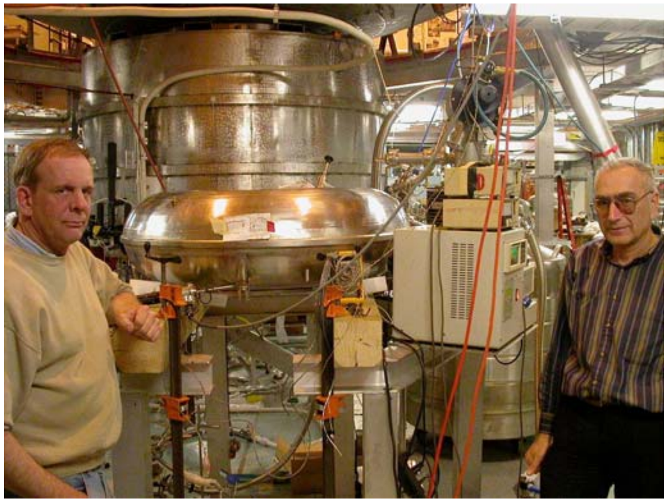


1. Magnet Winding Pack
2. Heat Exchanger tubing
3. Winding pack centering clamp
4. He Pressure Vessel (Inconel 625)
5. Thermal Shield (Lead/glass composite)
6. Shield supports (Pyrex)
7. He Vessel Vertical Supports/Bumpers
8. He Vessel Horizontal Bumpers
9. Vacuum Vessel (SST)
10. Multi-Layer Insulation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

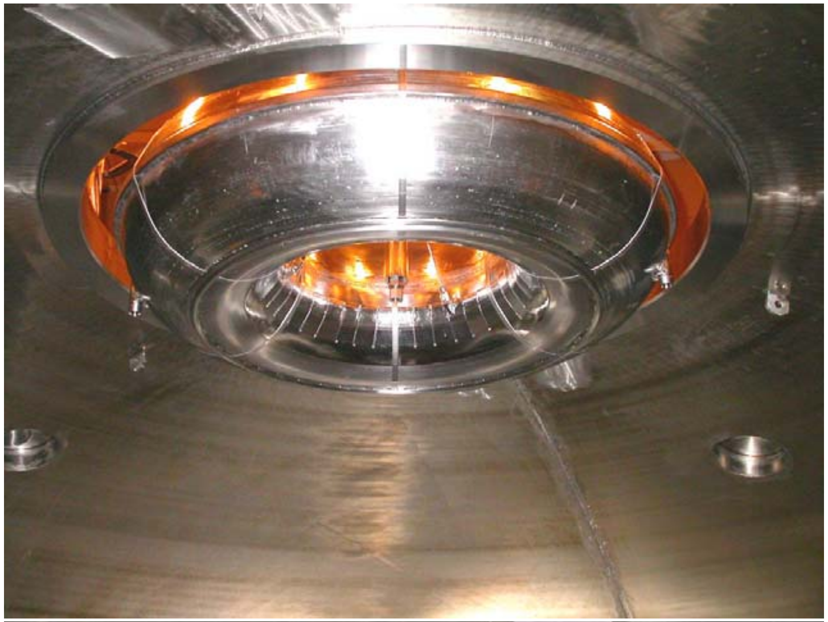
Floating Coil Cryogenic Operations

- 12 Cycles to 5°K completed
  - First Liquid He cold test
    - April 30-May 6, 2004
- 3 Day cooling from RT to LN2 temp
- Cooling from LN2 to LHe in 7 hours
  - Result is better than expected indicating very efficient heat exchanger
- Inner He Vessel reached 4.5 °K
  - Indicates good performance of inlet transfer lines and bayonet connections
- Inner He vessel remained
  - below 10°K for > 1 hour
  - Coil superconducting for > 2 hours
- Initial analyses indicate supports are at fault for extra heat leak
  - Possibly due to over-compression by close out welds
- Operationally
  - Experiment times ~ 2 hrs
  - Rapid recool cycle developed
    - 3 cycles / day possible



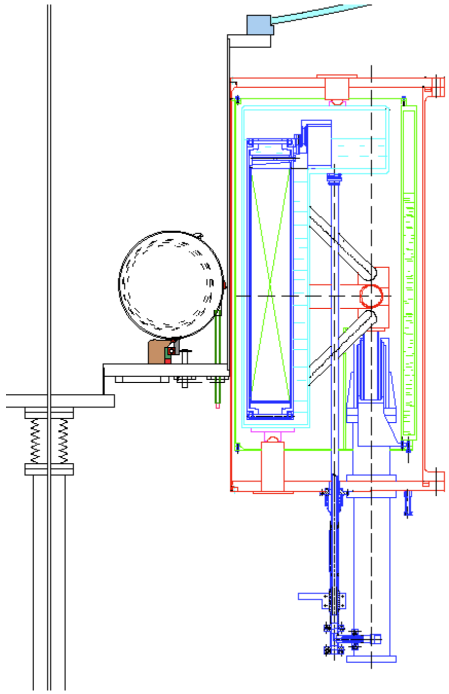


Floating Coil Installation (5/04)

Superconducting Charging Coil

- Large superconducting coil
  - NbTi conductor
    - 4.5°K LHe pool-boiling cryostat with LN2 radiation shield
  - 1.2 m diameter warm bore
  - 4.3 T peak field (tested)
  - Cycled 2X per day
  - Ramping time for F-Coil < 30 min.

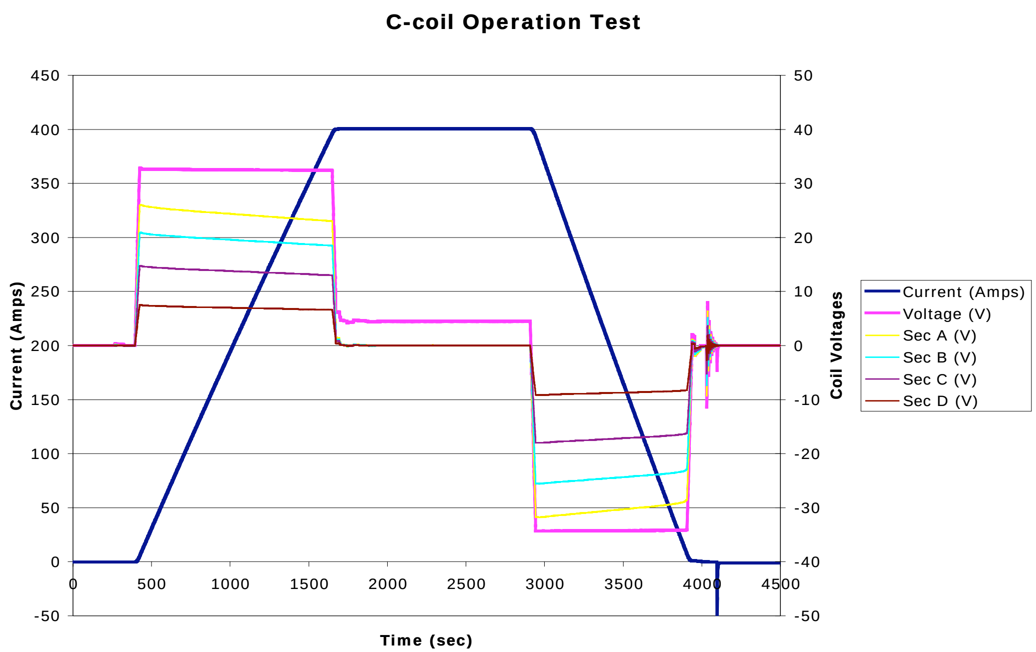


- Built and tested at SINTEZ Efremov Institute in St. Petersburg, Russia
  - Received at MIT 9/03.

Installation and Test of C-coil

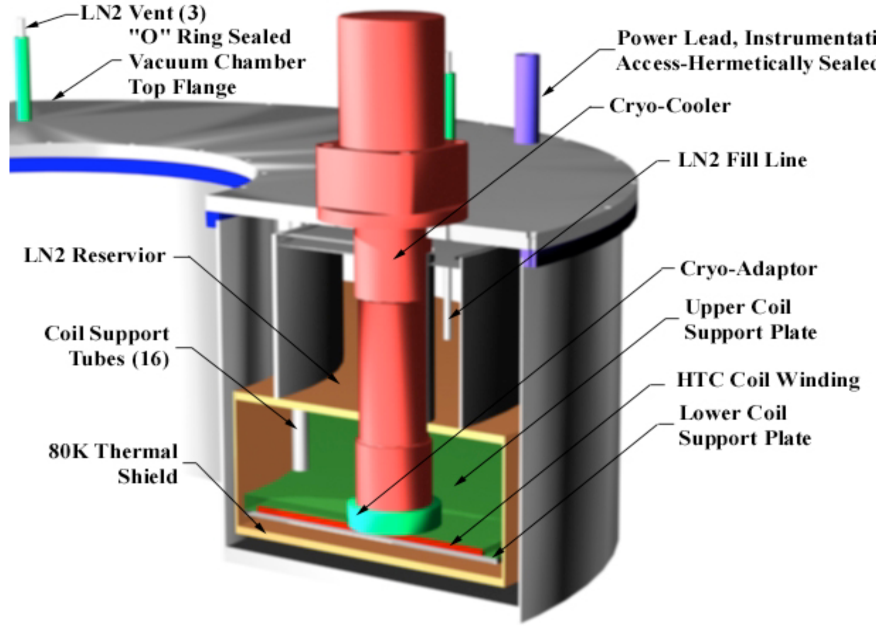
X marks the spot.

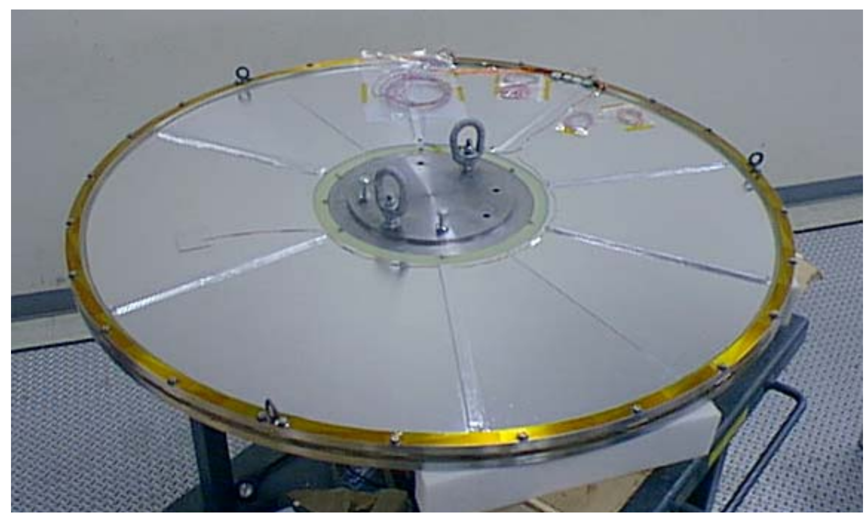
- Rolled under vessel and jacked up
- New support legs installed.
- Cryogenic, electrical, and control systems installed
- Magnet tested to 400 Amps
  - 90% of final operation point



High T_c Superconducting Levitation Coil

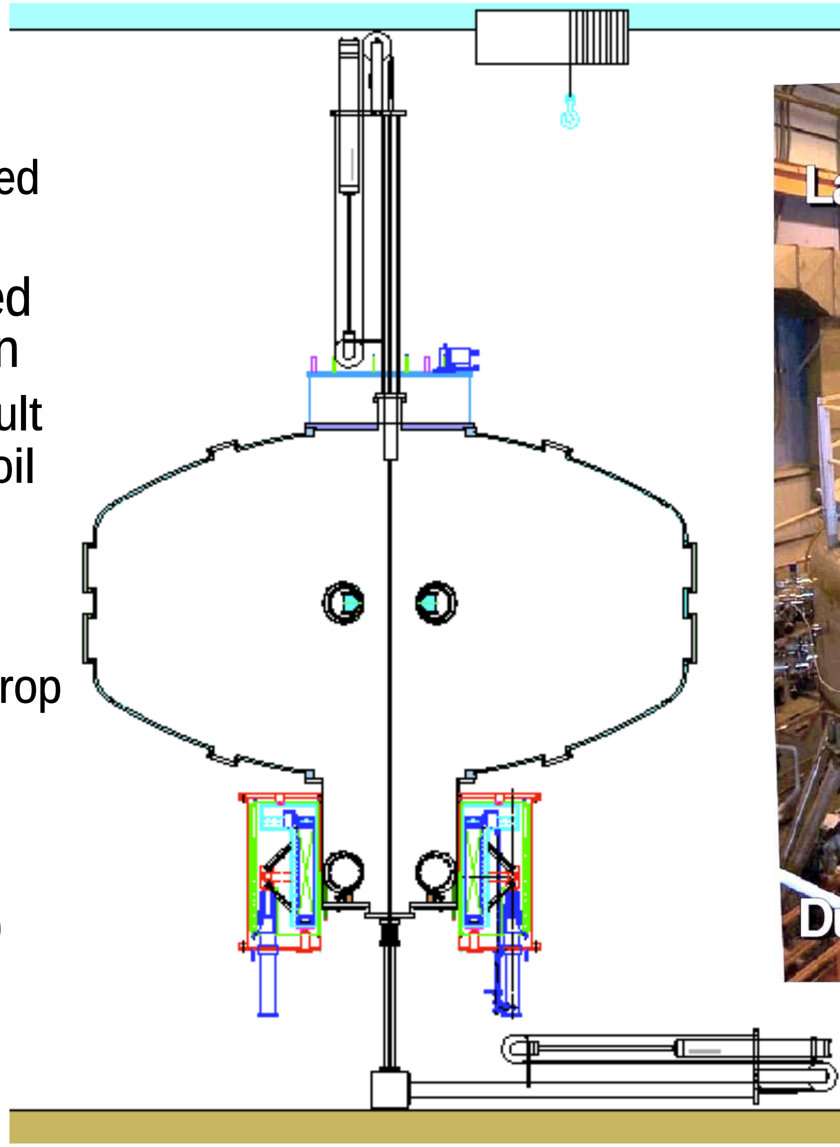
- SBIR collaboration with American Superconductor
  - First HTS coil in the fusion community
  - Uses available BSSCO-2223 conductor
- Operational temp 20-25° K
- Feedback gain selected for 5 Hz mode frequency
  - < 20 W AC loss
- 20 kJ stored energy
  - Emergency dump in < 1 second.
- Coil Completed & Tested
  - 77° K superconducting tests successful
  - 20° K tests complete
  - Preliminary assessment: GOOD!



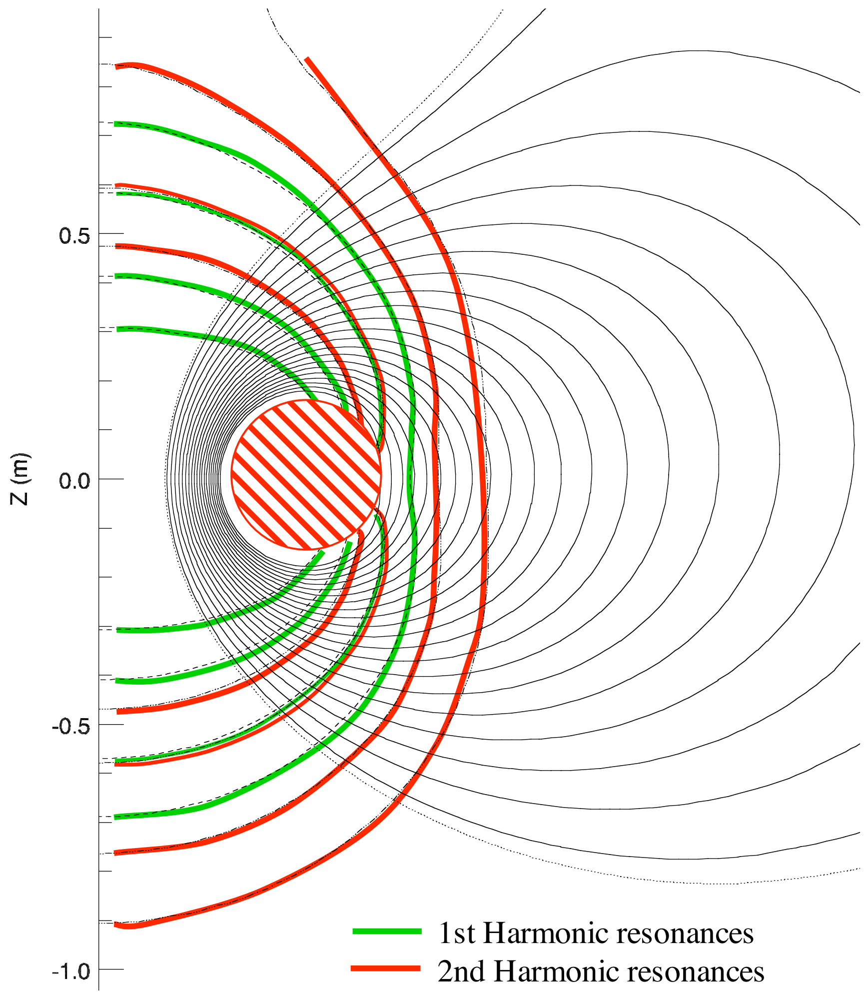


Launcher/Catcher

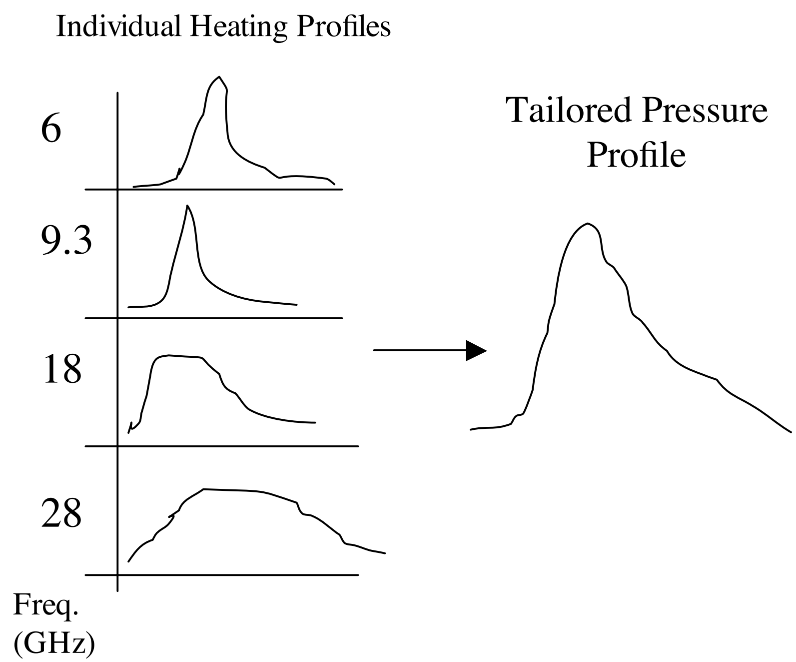
- Bellows feedthrough
  - High vacuum required
  - Long (> 2m) motion
- Used in both supported and levitated operation
  - Central rod limits fault motion of floating coil without interrupting plasma.
  - Integral shock absorbers to keep drop deceleration < 10g
- Status
  - Built and tested for Phase 1 (supported) operations



Multi-frequency ECRH on LDX



- Multi-frequency electron cyclotron resonant heating
  - Effective way to create high-β hot electron population
  - Tailor multi-frequency heating power to produce ideal (stable) pressure profile with maximum peak β.



LDX Experimental Goals

- Investigate high-beta plasmas stabilized by compressibility
  - Also the stability and dynamics of high-beta, energetic particles in dipolar magnetic fields
  - Examine the coupling between the scrape-off-layer and the confinement and stability of a high-temperature core plasma.
- Study plasma confinement in magnetic dipoles
  - Explore relationship between drift-stationary profiles having absolute interchange stability and the elimination of drift-wave turbulence.
  - Explore convective cell formation and control and the role convective cells play in transport in a dipole plasma.
  - The long-time (near steady-state) evolution of high-temperature magnetically-confined plasma.
- Demonstrate reliable levitation of a persistent superconducting ring using distant control coils.

LDX Experimental Plan

- Supported Dipole Hot Electron Plasmas
  - High- β Hot Electron plasmas with mirror losses
  - ECRH Plasma formation
  - Instabilities and Profile control
- Levitated Dipole Hot Electron Plasmas
  - No plasma losses to supports
  - β enhancement
  - Confinement studies
- Thermal Plasmas
  - Thermalization of hot electron energy with gas puffs / pellets
  - Convective cell studies
  - Concept Optimization / Evaluation

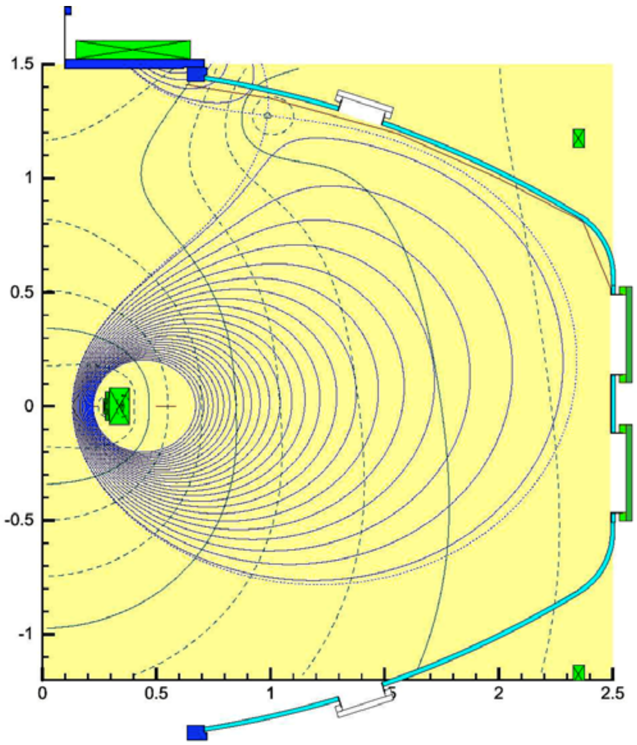
Initial Supported Hot Electron Plasmas

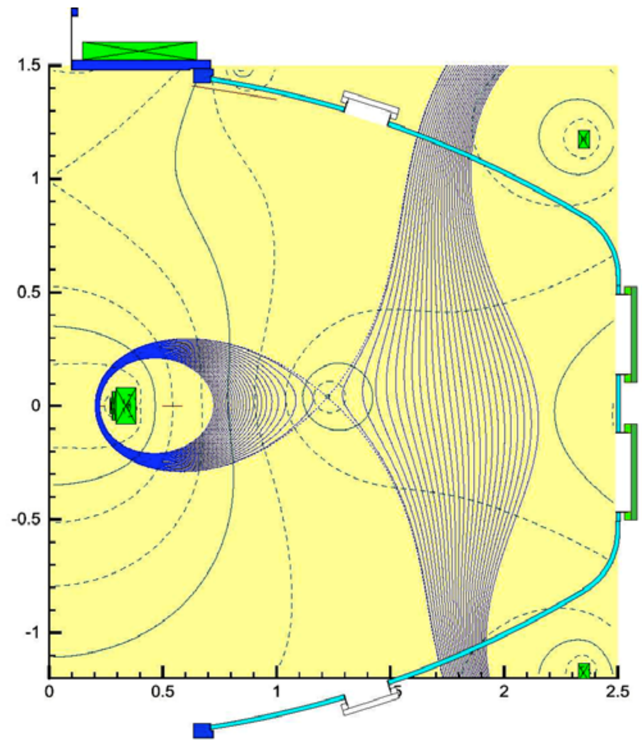
- Low density, quasi steady-state plasmas formed by multi-frequency ECRH with mirror-like losses from supported dipole
  - Areas of investigation
    - Plasma formation & density control
    - Pressure profile control with ECRH
    - Supercritical profiles & instability
    - Compressibility Scaling
    - ECRH and diagnostics development
  - Unique to supported operation
    - B field scaling
    - “Loss cone” effects

Helmholtz Shaping Coils

$$\frac{P_{core}}{P_{edge}} \le \left(\frac{V_{edge}}{V_{core}}\right)^{\gamma} \text{ where } V \equiv \oint \frac{d\ell}{B}, \text{ and } \gamma = {}^{5}\!/_{3}$$

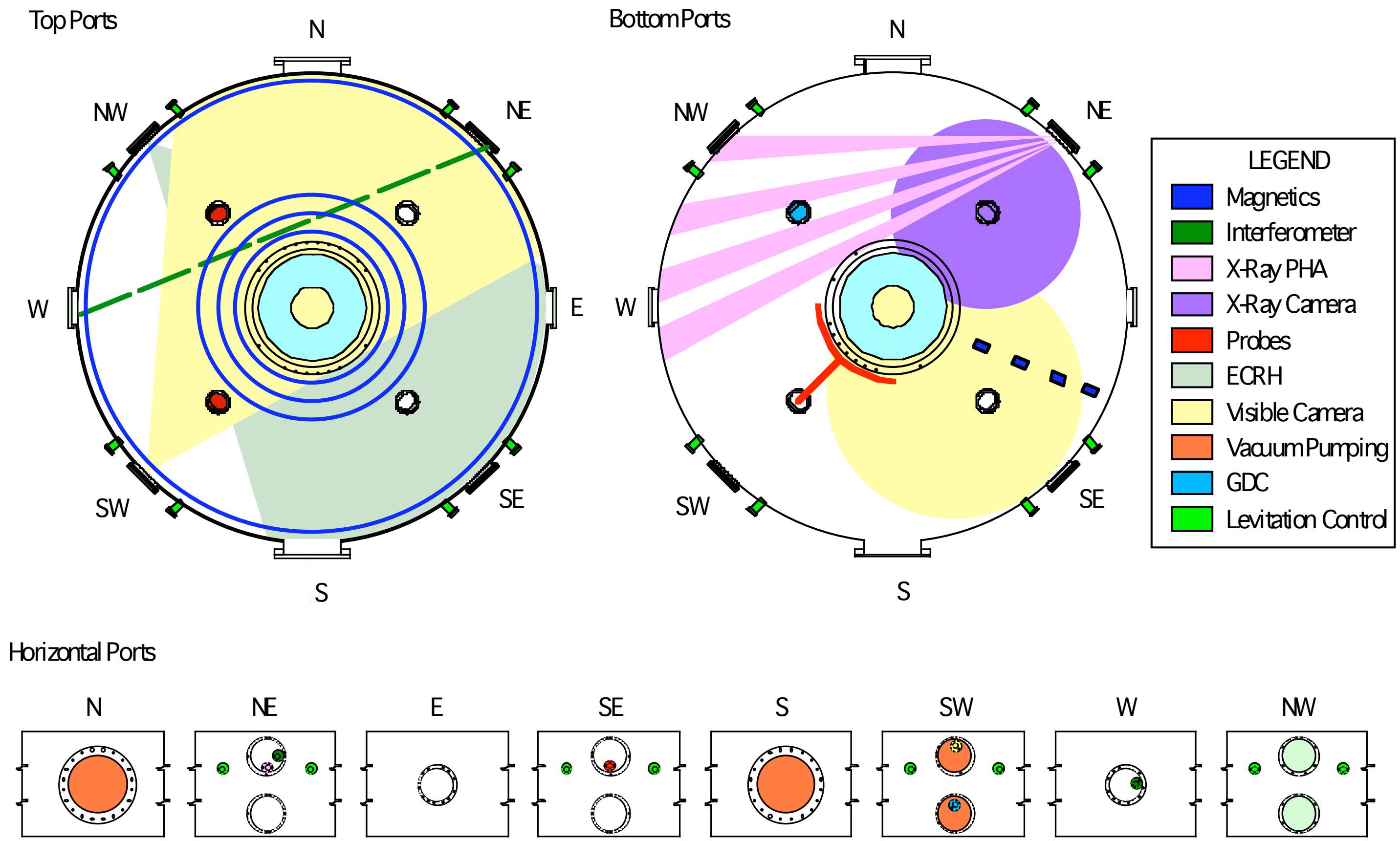
Helmholtz Coil:	0 kA	Helmholtz Coil:	80 kA
Compression Ratio:	228	Compression Ratio:	14
Adiabatic Pressure Ratio:	8500	Adiabatic Pressure Ratio:	85





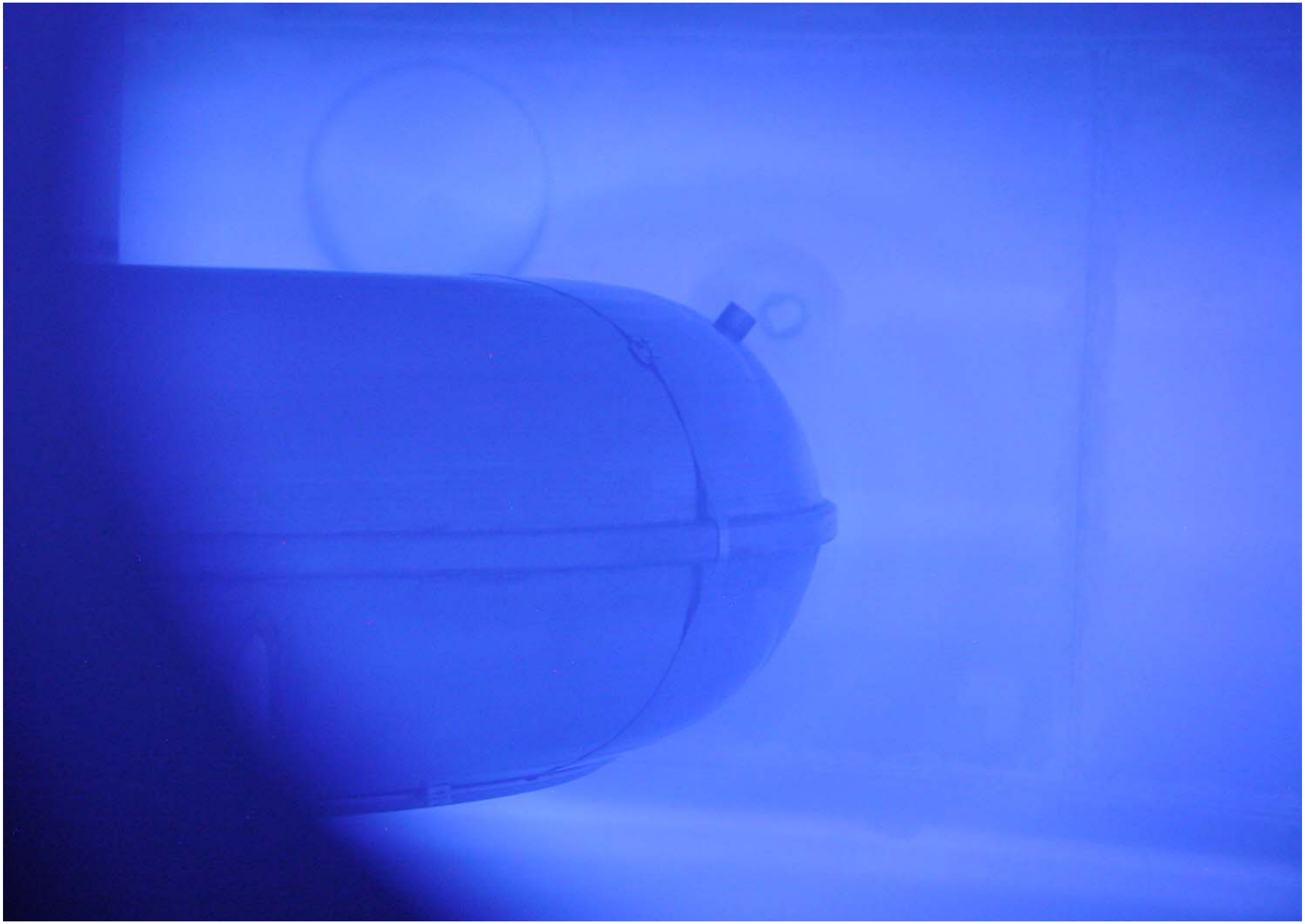
Compressibility can be adjusted to change marginal stable pressure by factor of 100!

Initial Plasma Diagnostic Set

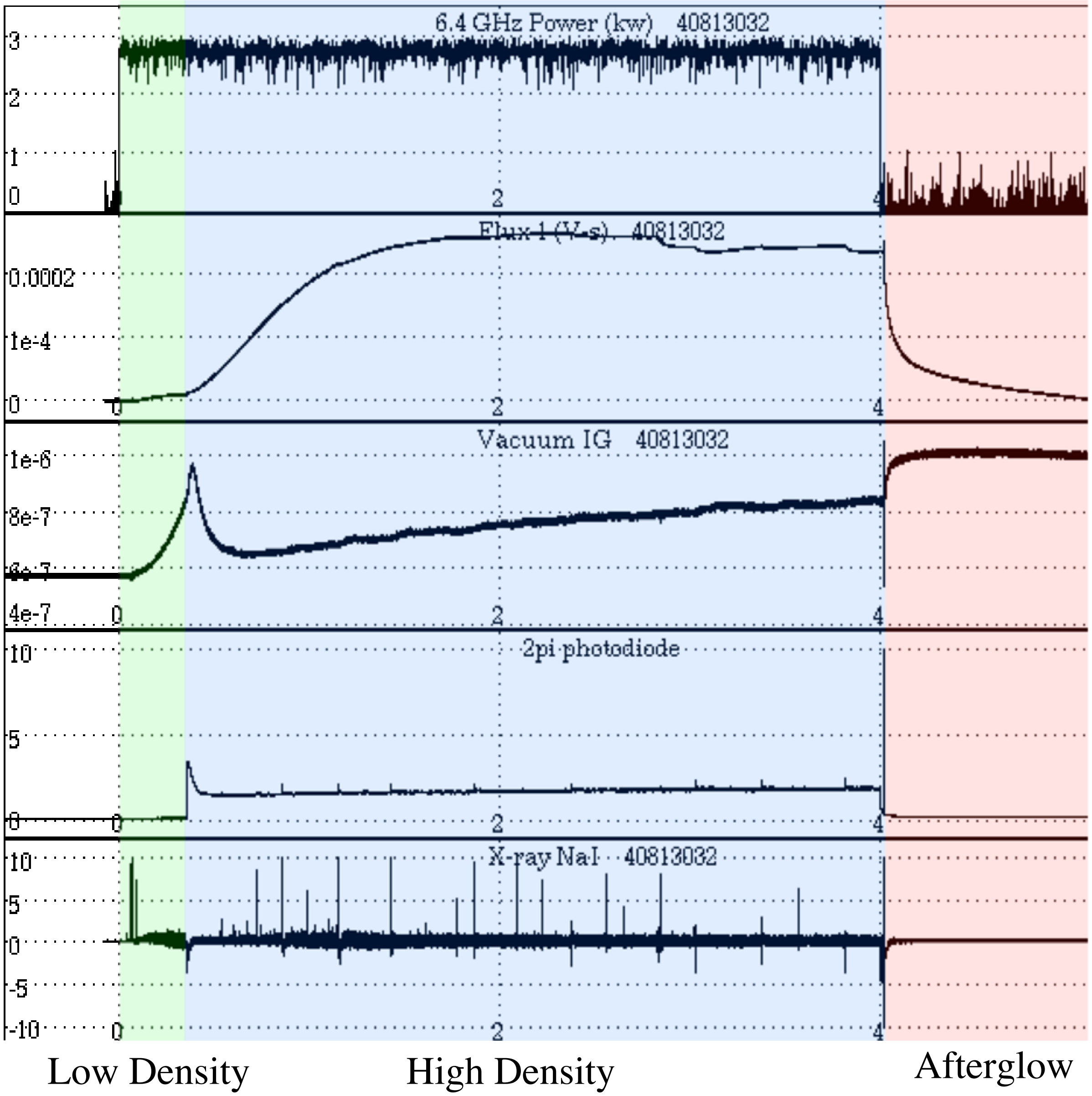


- Magnetics (flux loops, hall probes)
  - Plasma equilibrium shape
  - Mirnov coils for magnetic fluctuations
- Interferometer
  - Density profile and macroscopic density fluctuations
- X-rays diagnostics
  - PHA hot electron energy distribution / profile
  - NaI X-ray power temporal diagnostic
- Visible cameras
- Edge probes
  - Edge plasma density and temperature
  - Fluctuations

First Plasma! (Friday, August 13, 2004)

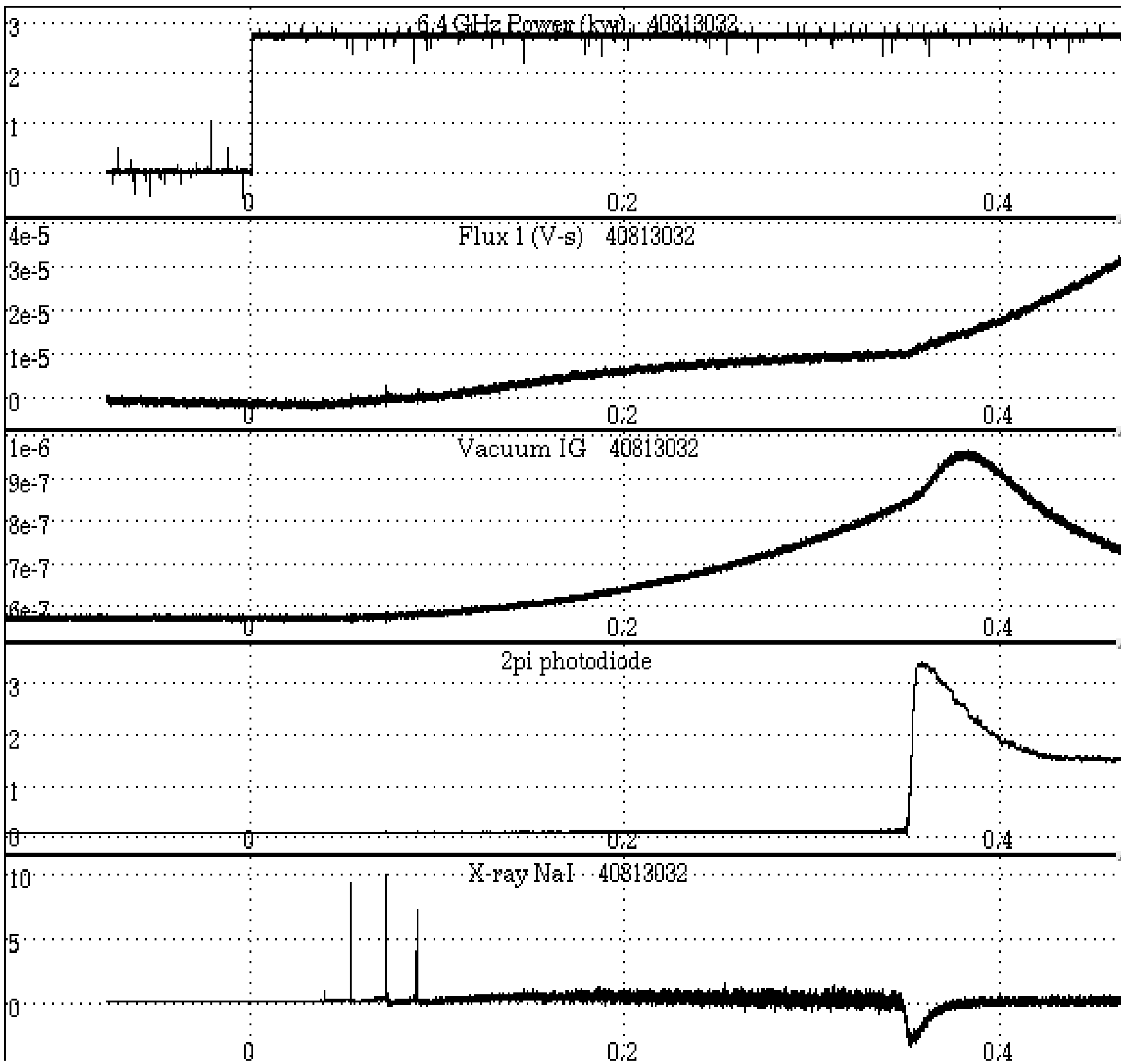


First Plasma Run (8/13/04)



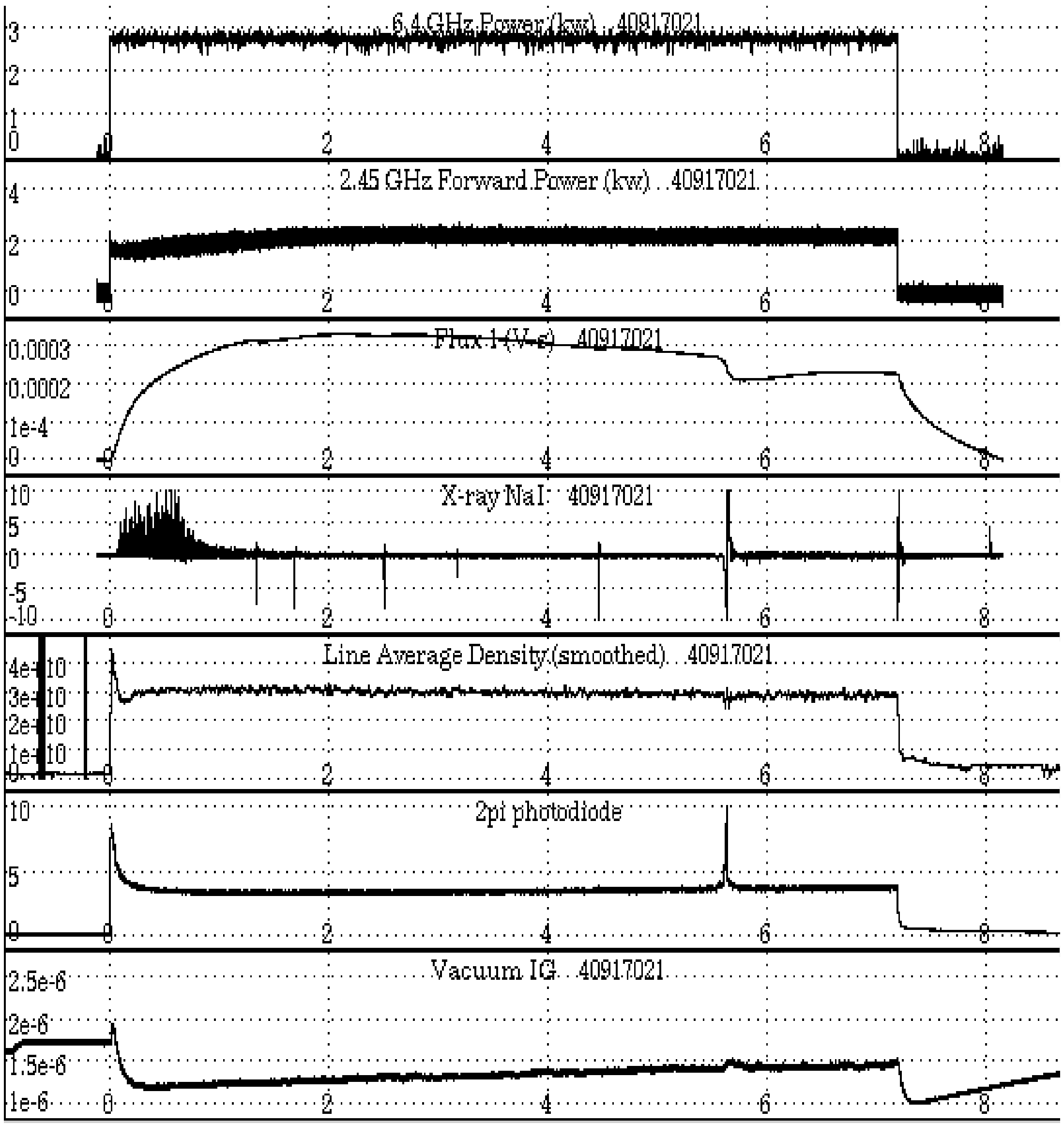
- First run setup
  - Supported Operation
  - 250 A C-coil charge
    - ~700kA in dipole
  - Single 6.4 GHz source
    - 3 kW max
  - Vacuum base pressure 1x10[7] Torr
- Objectives
  - Plasma breakdown
  - Density scan and control
    - D_2 fill 5x10[7] - 1x10[5] T
- Observation
  - 3 operational regimes

Low Density Regime



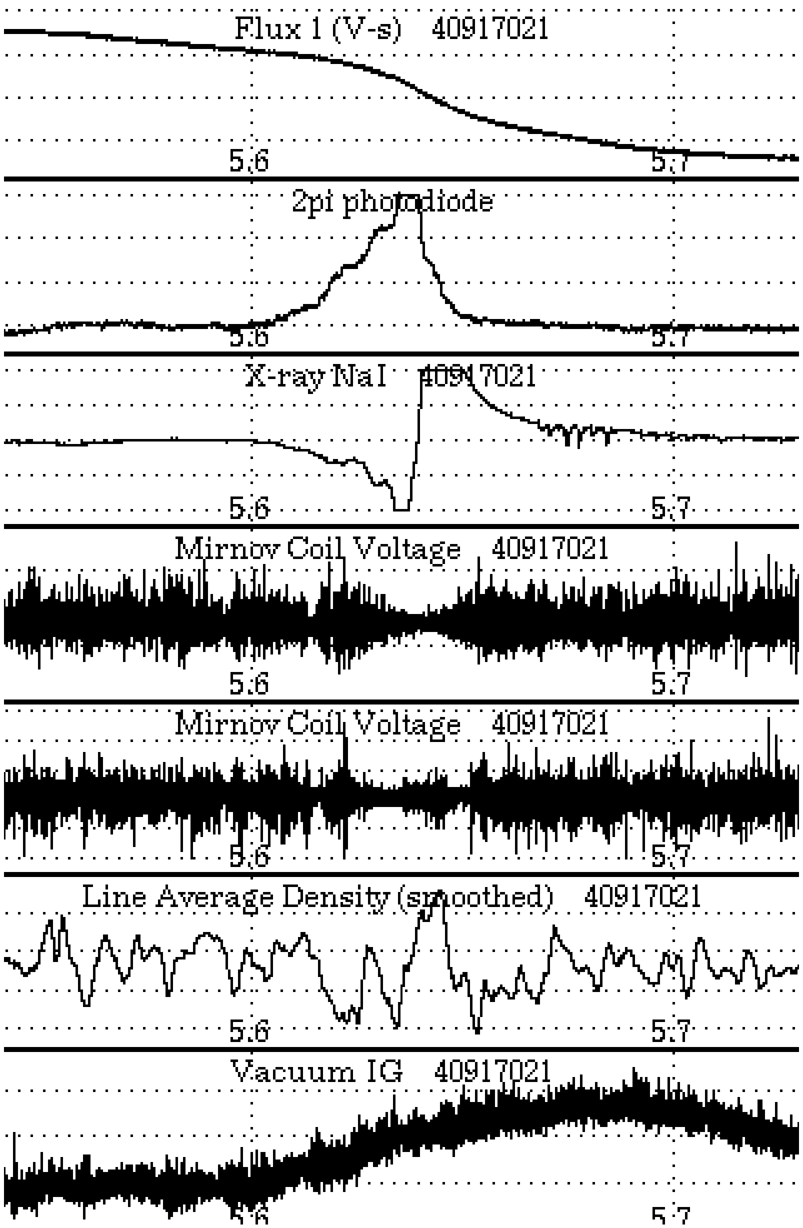
- Low plasma density
  - > 1 x 10^9 / cc
- Requires low fill pressure
  - < 8 x 10^{-7} Torr
- Bursty X-ray emmission
- Possibly higher energy transport
  - Limited growth rate and limit in magnetics diagnostics
- Similar to CTX
  - Columbia's Collisionless Terralla Experiment (CTX) normally operates in this regime
- Limited in time to < 1 sec
  - Wall fueling raises neutral pressure and transition occurs

High Density Regime



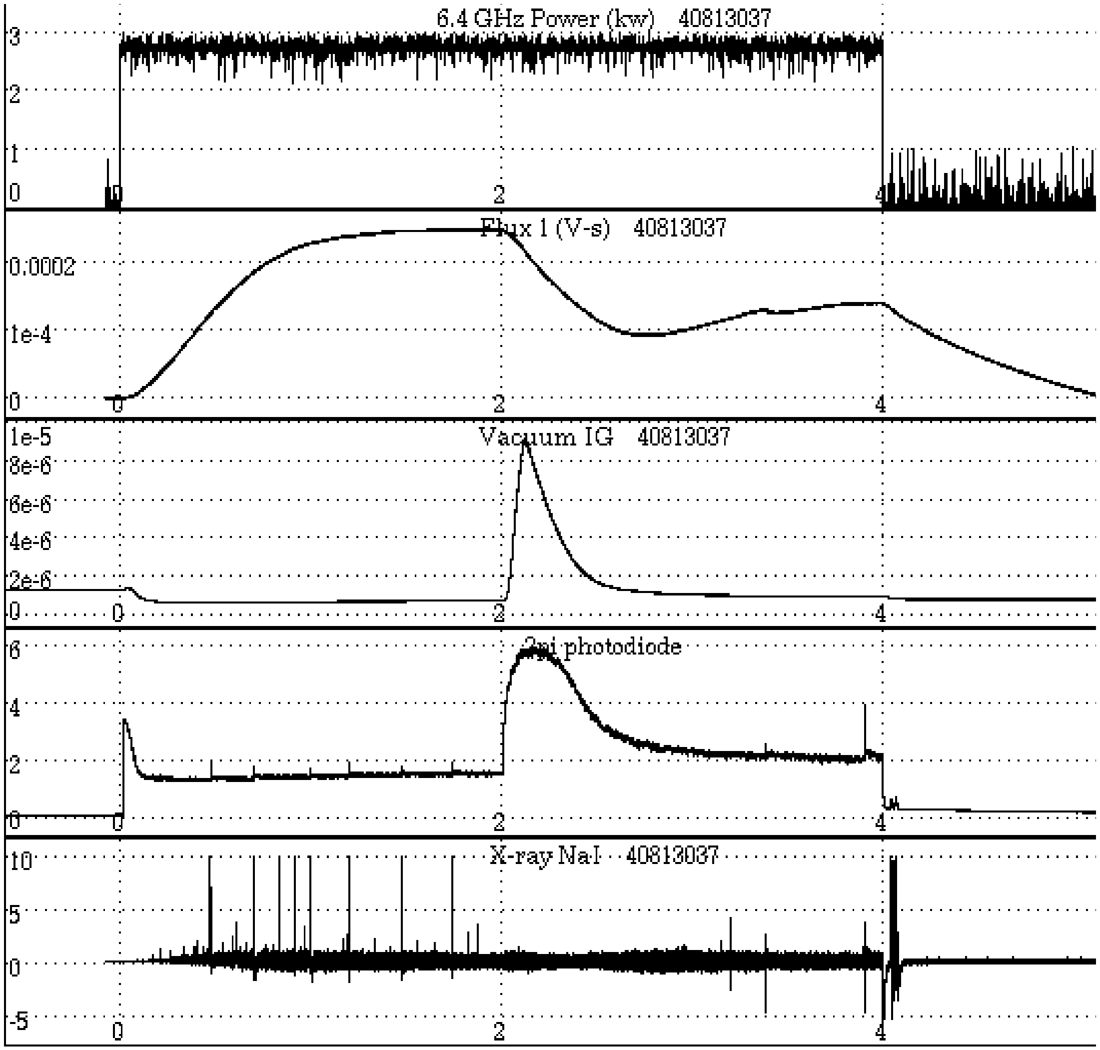
- ECRH heated regime
  - Shot heated with both 2.45 and 6.4 GHz sources
- Higher density
  - Line average density 2-5 x 10^{10} / cc.
  - Peaked density profile
- Higher stored energy
  - Unlike CTX results where diamagnetism drops after transition
  - Profile evolution having effect
- Peak collapsing events

Central Pressure Loss



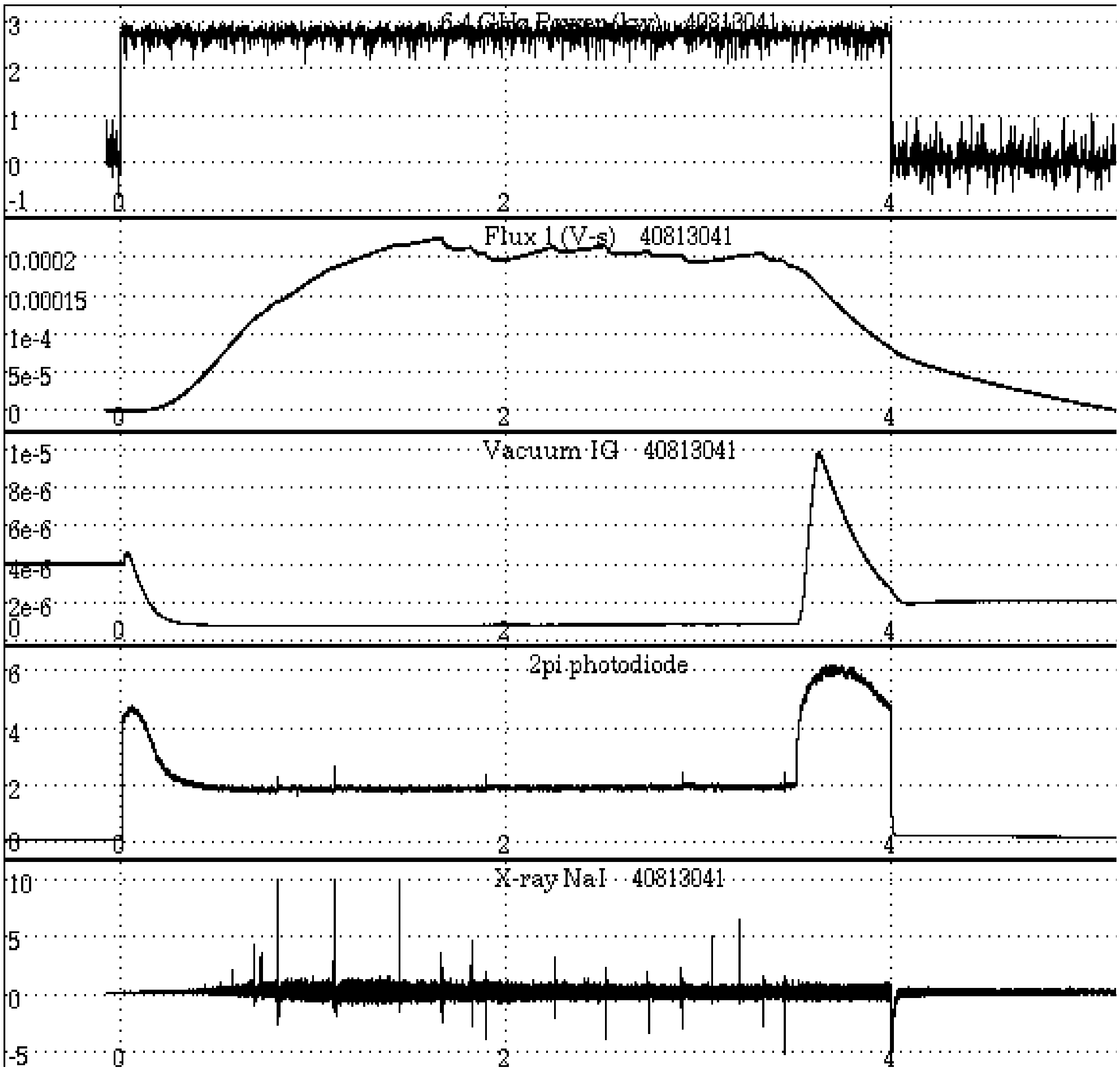
- Core plasma Event
  - Characterized by loss of flux on all external flux loops
  - Reduction of central X-ray flux
    - followed by burst.
  - Burst in visible
- Some edge effects
  - Drop in Mirnov power spectrum in some cases
  - Increase in neutral density
  - Occasional correlation with hot electrons collected on probes
- Occur at highest plasma beta
- Sawteeth like?
  - At highest energy
  - Definite change in profile after event
  - Seemingly not the limit in beta

Big Gas Puff



- Large gas puff
  - Increases density
  - Reduces stored energy
    - Increased scattering of hot electrons into loss cone ?
    - Other ?
  - Quells core collapse events
    - Another puzzle piece.

Afterglow



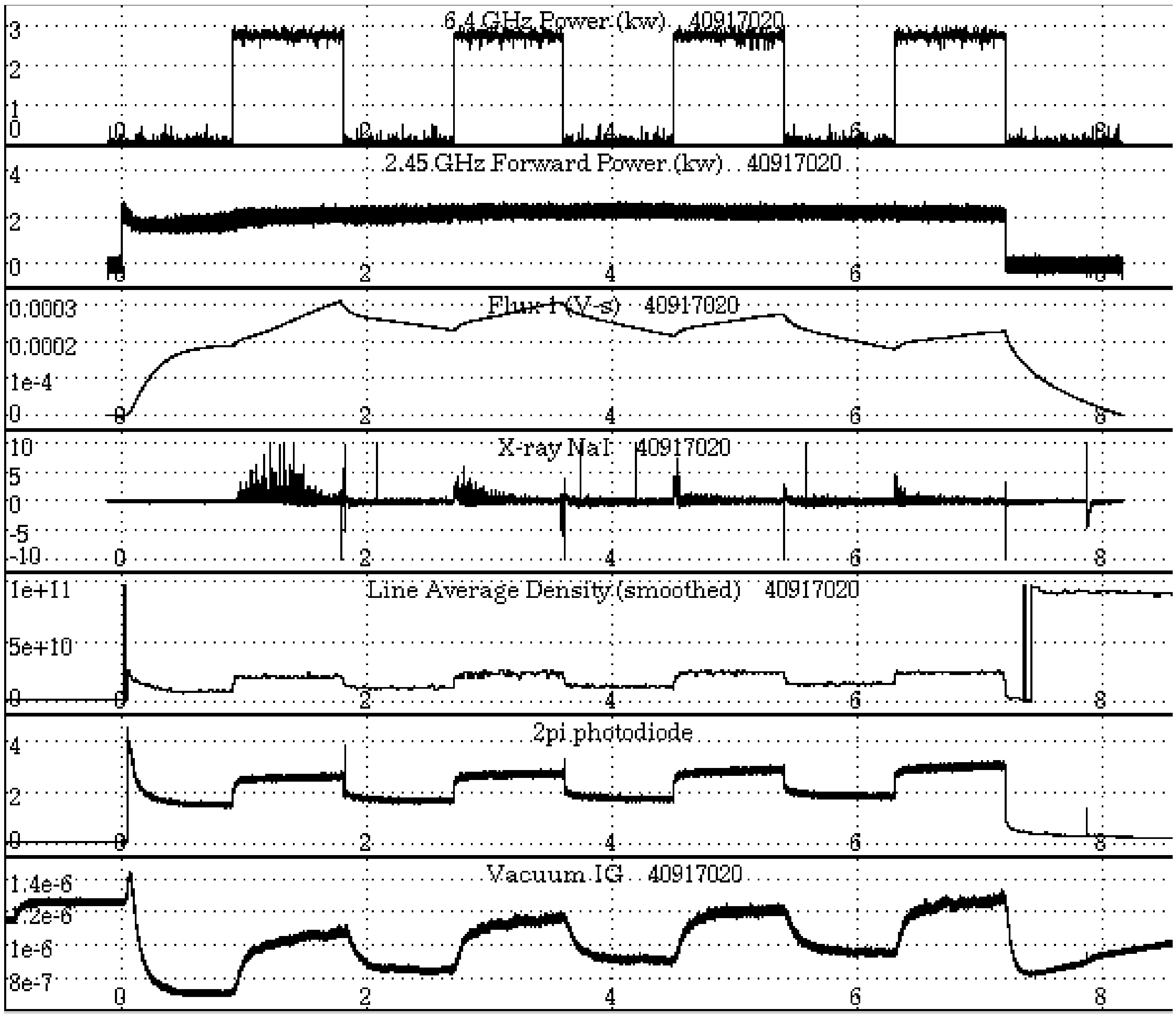
- ECRH Off
  - Warm plasma dissipates in 20 ms
  - Hot electrons confined for ~10 sec
- Transition can be violent
  - Possibly hot-electron interchange mode
    - Unstable after loss of warm plasma?
  - Anisotropy driven mirror instability
- Late Gas Puff Experiment
  - Afterglow inward collapse is controlled

Initial ECRH Profile Control

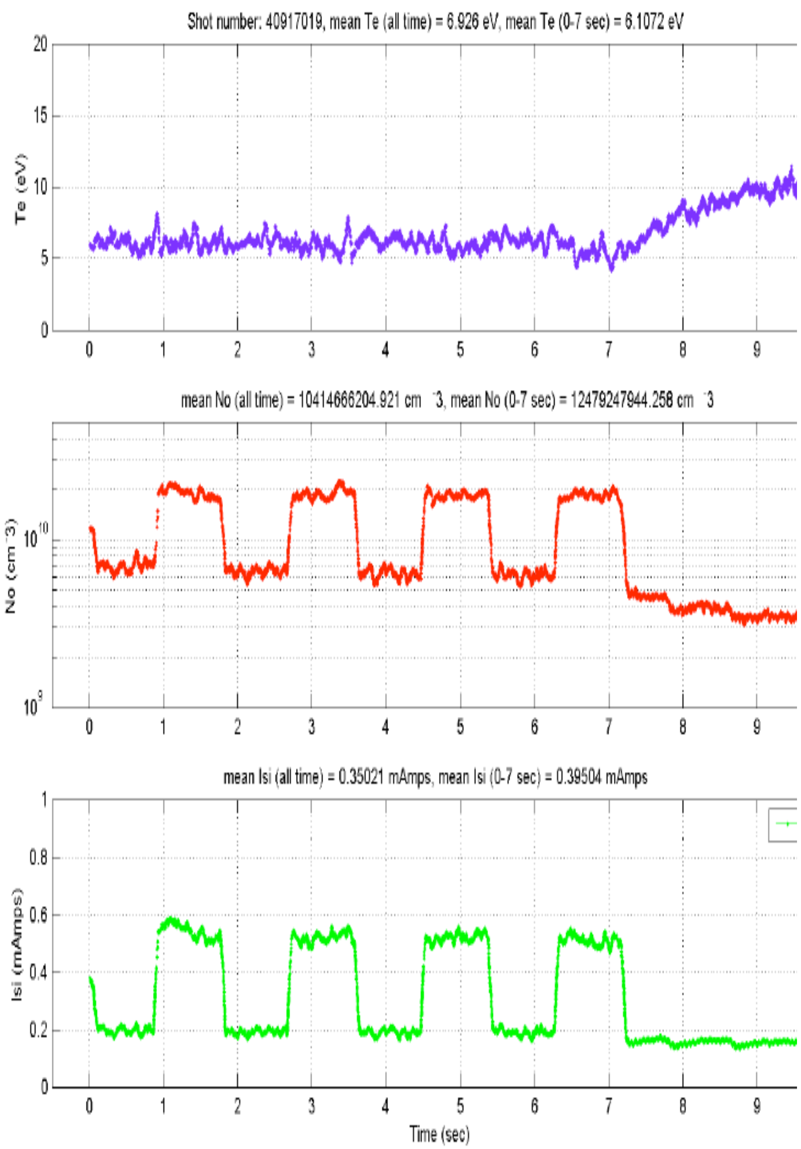
- Constant Power
  - Gradual evolution with constant power
    - Changes in density and pressure profile
    - Changing anisotropy ?
- Modulation
  - Dramatically different energy confinement with different heating profiles
  - Evolution of profiles also important
    - Highest stored energy only occurs in first peak

2.45 GHz Modulation

6.4 GHz Power Modulation

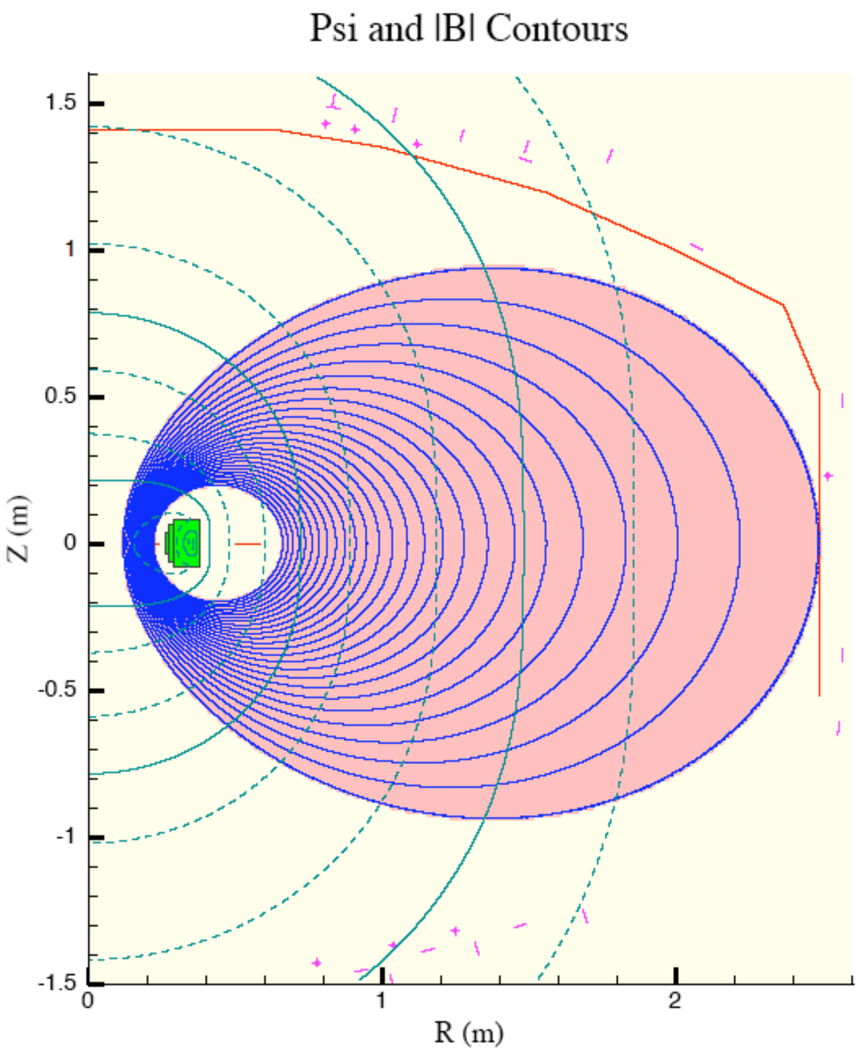


Edge Probes



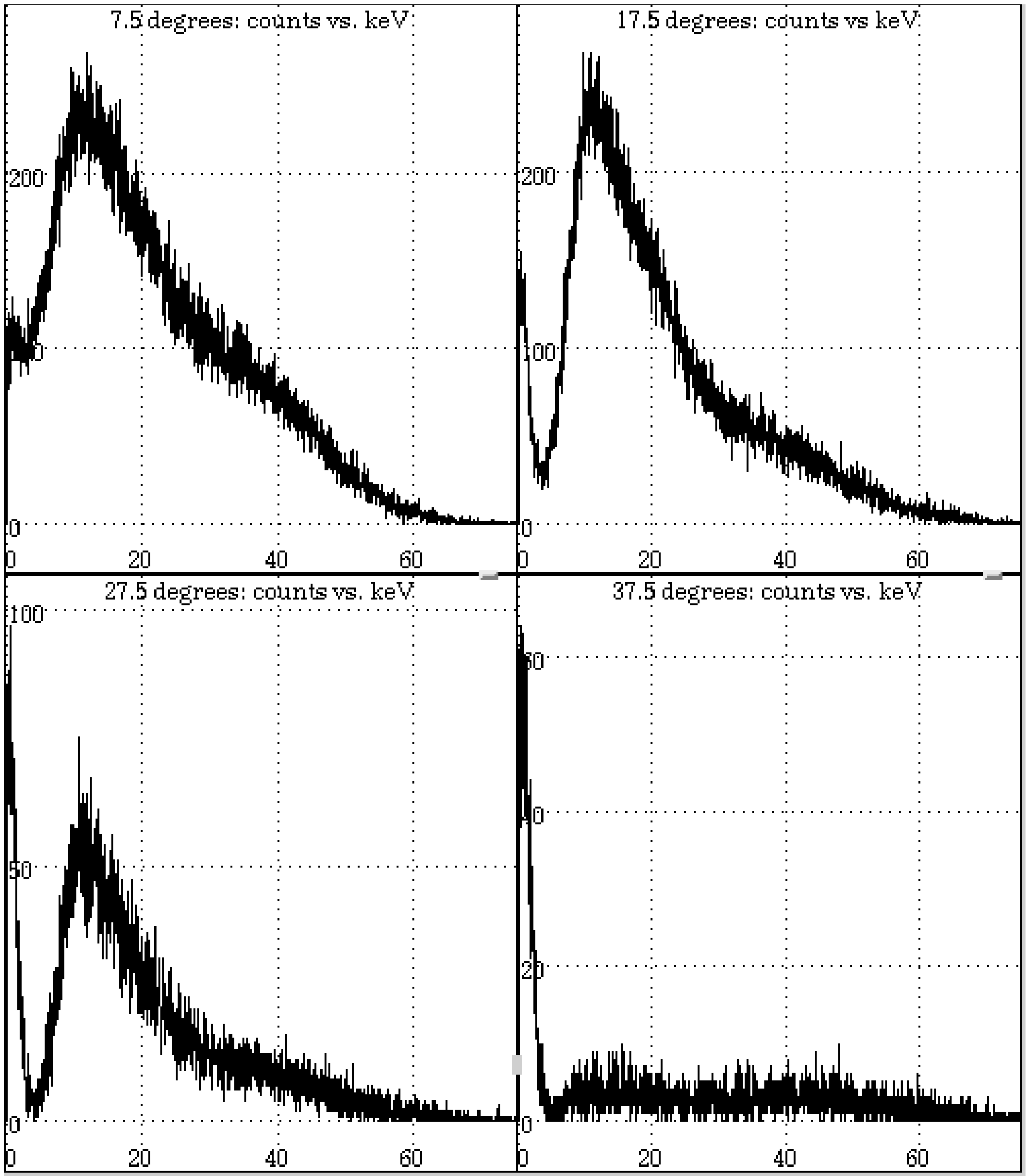
- Two edge Langmuir probes
  - One is Mach probe
- Results
  - Edge density
    - 0.2 - 2 x 10^{10} cm^{-3}
  - Edge temperature
    - 5 - 10 eV
- Roughly consistent with interferometer and magnetics pressure fit

Magnetics Diagnostic



- Fit simple model to measurements
  - 8 Flux Loops
  - 18 B_{pol} Coils
- Results
  - Peak beta 8%
  - Edge pressure matches probe data (~0.01 Pa).
  - Central pressure 200 Pa
    - 20000 Compression ratio

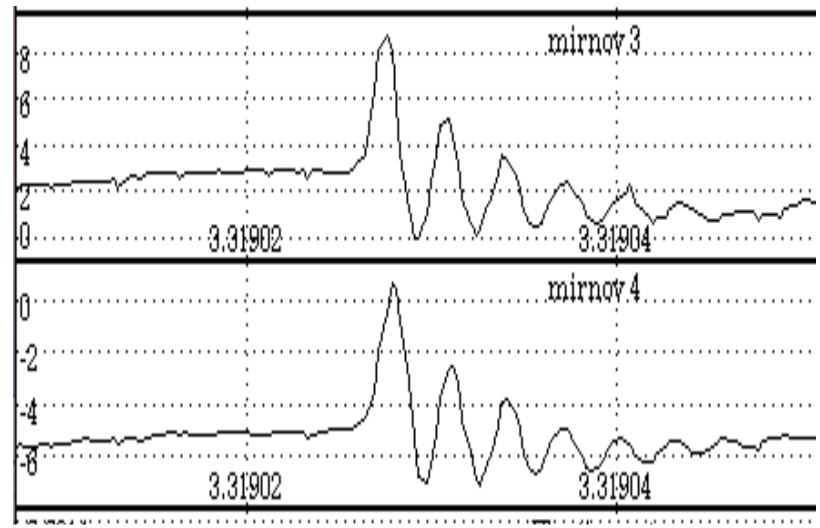
X-Ray Spectra



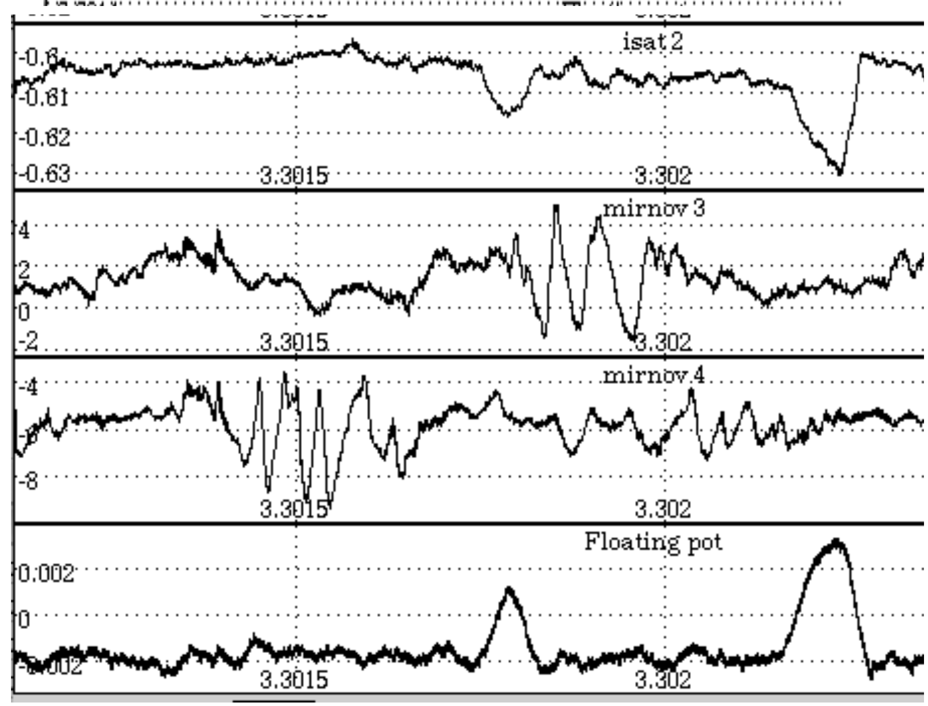
- First run
  - showed ~40 keV temperature
  - Peaks in spectrua
    - Wall Interaction?
    - Scattering in collimator?
- Second run
  - 20 keV temperature
- Future improvements
  - Time resolved spectra
  - Further investigation of peaks

Instabilities at Edge

- 300 kHz “fast edge mode”
  - N=1
  - Electron diamagnetic drift direction
  - Not seen on other diagnostics
  - **$\delta B/B \sim 0.1\%$**



- 30 kHz broadband fluctuations
  - Higher N ?
  - Ion direction?



LDX Basic Plasma Parameters

- "High Density" Regime
  - Density
    - Line average density 1-5 x 10^{10} / cc
    - Edge density 0.1-1 x 10^{10} / cc
  - Temperature
    - Hot-electron energy 20-40 keV (maybe higher)
    - Edge temperature 5-12 eV
  - Pressure
    - Edge 0.01 Pa, Core 200 Pa.
    - Beta (local maximum) 8%

Conclusions

- First Plasma achieved 8/13/04!
  - Major fabrication complete
- Initial Physics Operations
  - Supported operation (Phase I)
  - Focus on stability of high-β hot electron plasmas
    - Plasma formation and control
    - Diagnostic set and experimental plan
    - Peak beta ~ 4-8% achieved
  - Measurement of basic plasma parameters underway
  - Beginning observation of instabilities, transport, and profile control
- Immediate next steps
  - Control of volume profile with shaping coils
  - Increase magnetic field
  - Diagnostic development
- Longer term steps
  - Preparation continues for First Levitation and Phase II operations
- Check www.psfc.mit.edu/ldx/ for updates on progress