Controlling Interchange Instabilities in the Levitated Dipole Experiment

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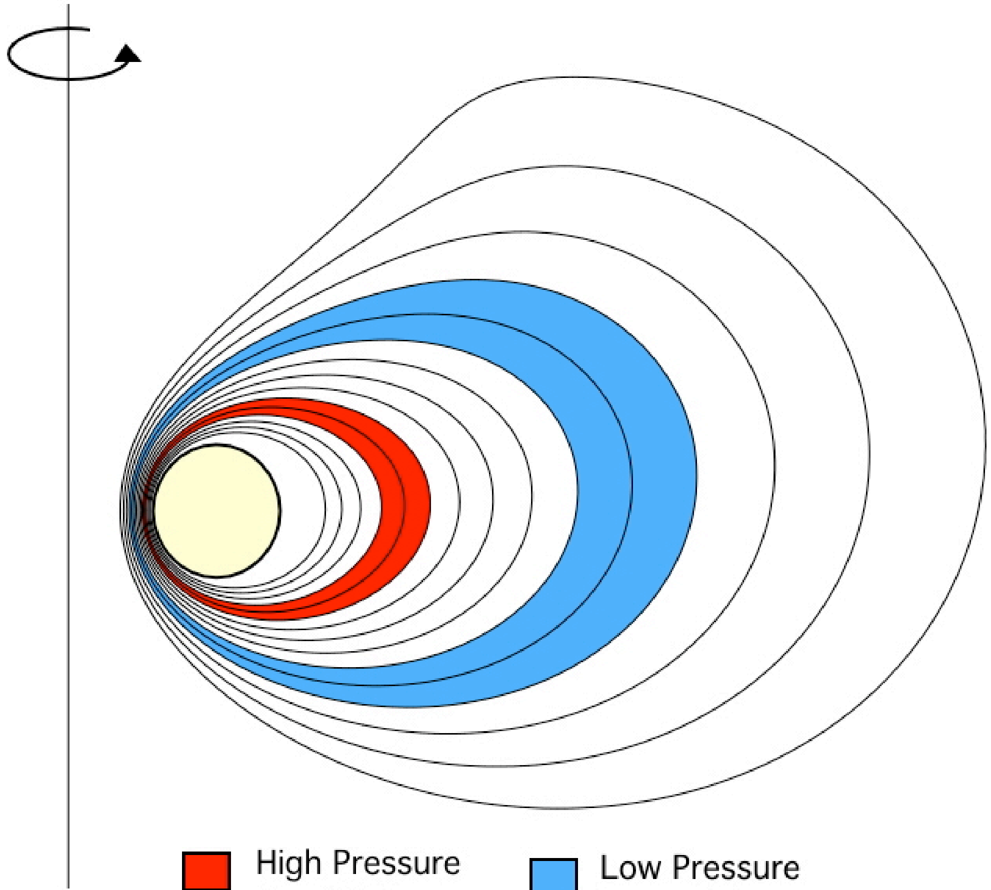
Synopsis

- We observe a fast growing flute-like mode that drives rapid radial transport of plasma particles and energy
  - Identified as the “hot electron interchange” (HEI) mode
  - When stabilized, LDX plasmas reach a high-β operational regime
- The most effective experimental control for the mode is the neutral gas fueling
  - Higher neutral gas pressure stabilizes the mode
  - destabilizes it (sometimes dramatically)
  - Observed hysteresis in required fueling consistent with simplified theory
- Other controls, and other control problems in LDX

Dipole stability derives from plasma compressibility



- **Toroidal system without toroidal field**
- **Closed field lines**
  - **no magnetic shear**
  - **"bad curvature"**
- **Adiabatically invariant pressure profile is marginal to MHD interchange**

$$\delta(pV^\gamma) = 0$$

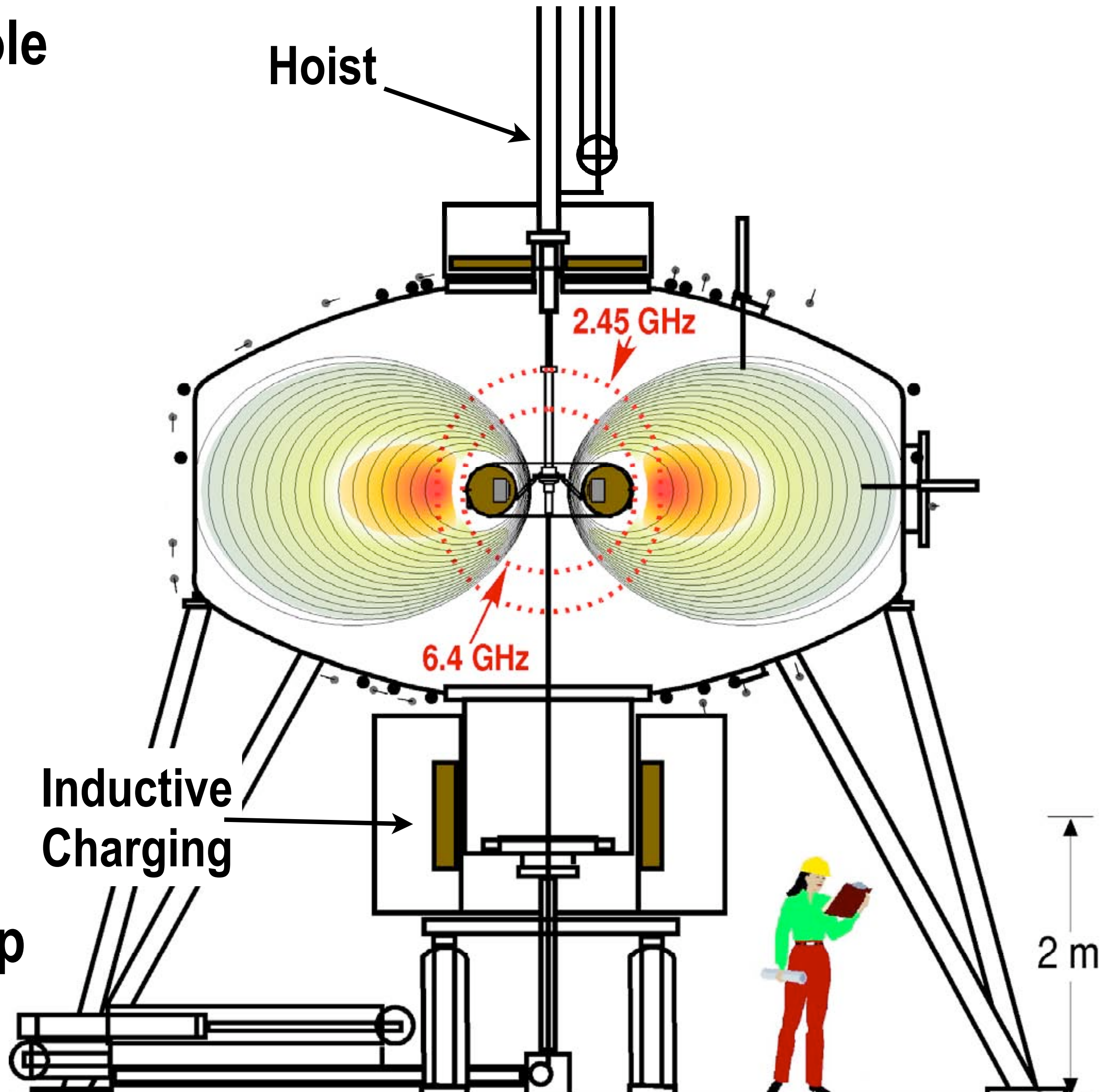
- **Kinetic stability:**

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

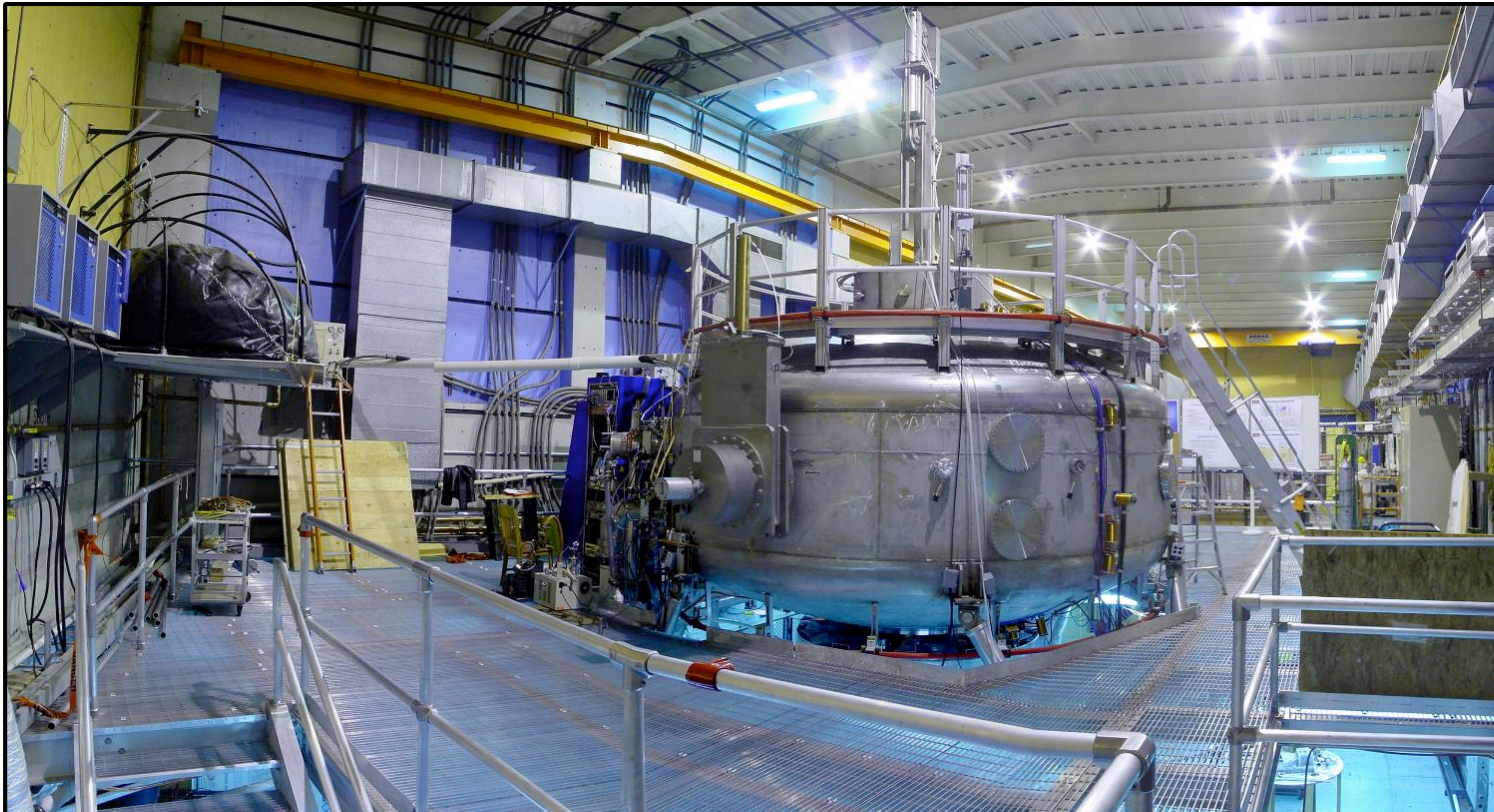
For $\eta = \dfrac{d\ln T}{d\ln n} = \dfrac{2}{3}$, density and temperature profiles are also stationary.

LDX Experiment Cross-Section

- Superconducting dipole magnet I > 1 MA
- Large 5 m diameter vacuum vessel
- Expansive diagnostic access
- Dipole supported by three thin spokes
- Two ECRH heating frequencies provide up to 5 kW power



The Levitated Dipole Experiment (LDX)



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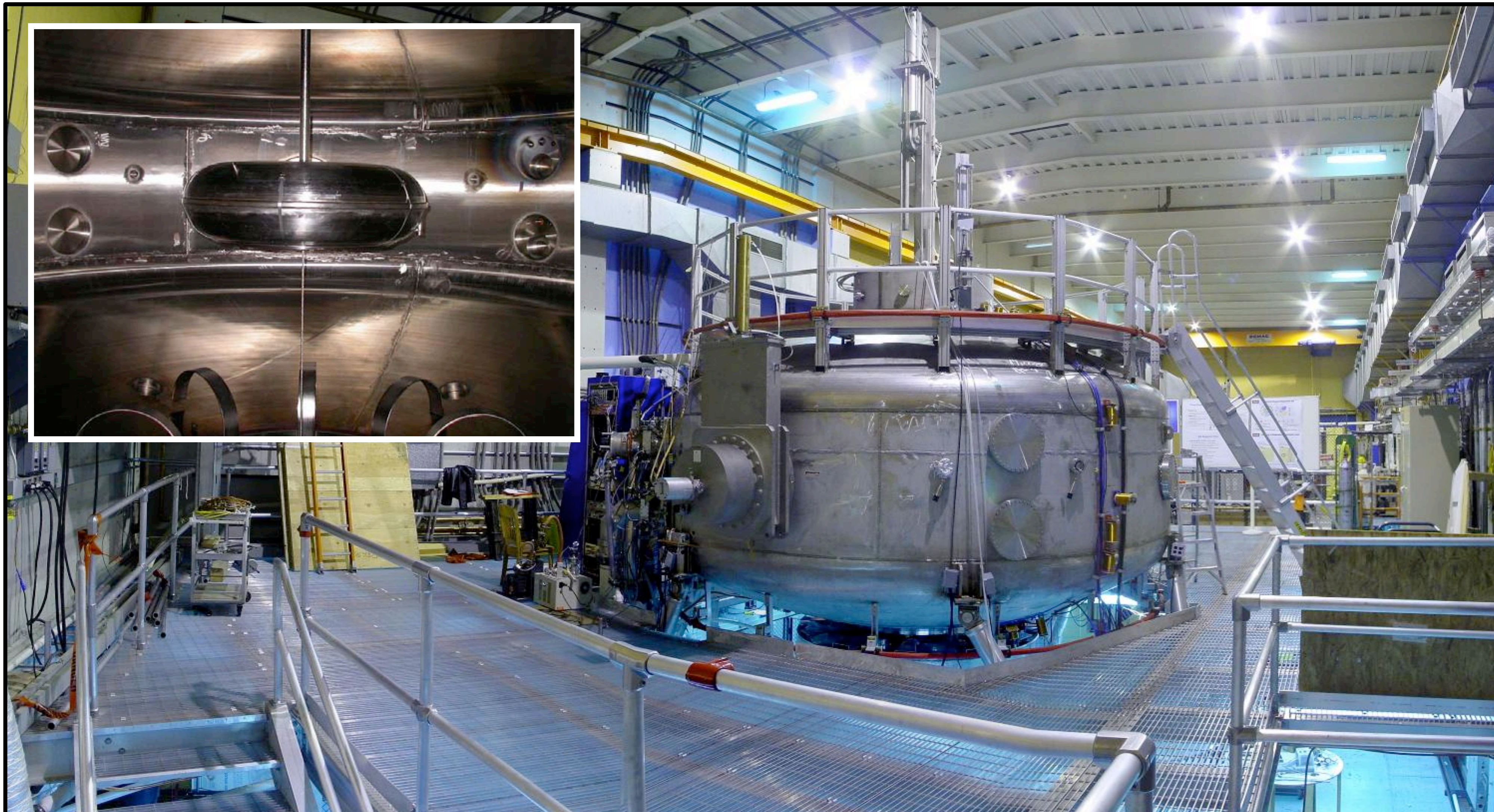


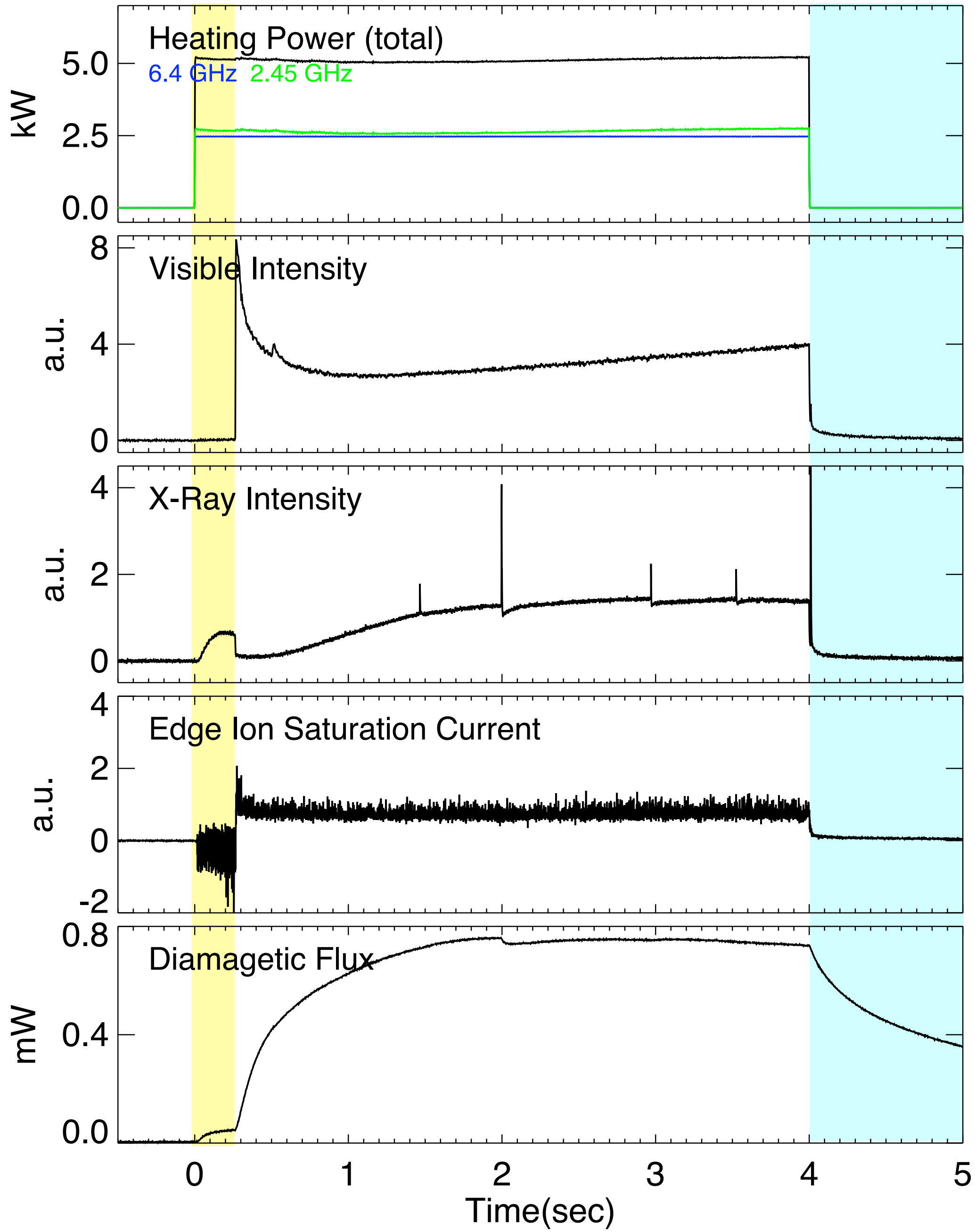
Plasma Diagnostic Set

- Magnetic equilibrium
  - flux loops, Bp coils, Hall effect sensors
- Fast electrons
  - 4 Channel x-ray PHA, x-ray detector, Hard X-ray camera
- Core parameters
  - interferometer, visible cameras, visible diode and array
- Fluctuations
  - Edge I_{sat} and V_f probes, Mirnov coils, visible diode array, interferometer
- Edge parameters
  - swept probes

Typical LDX Plasma

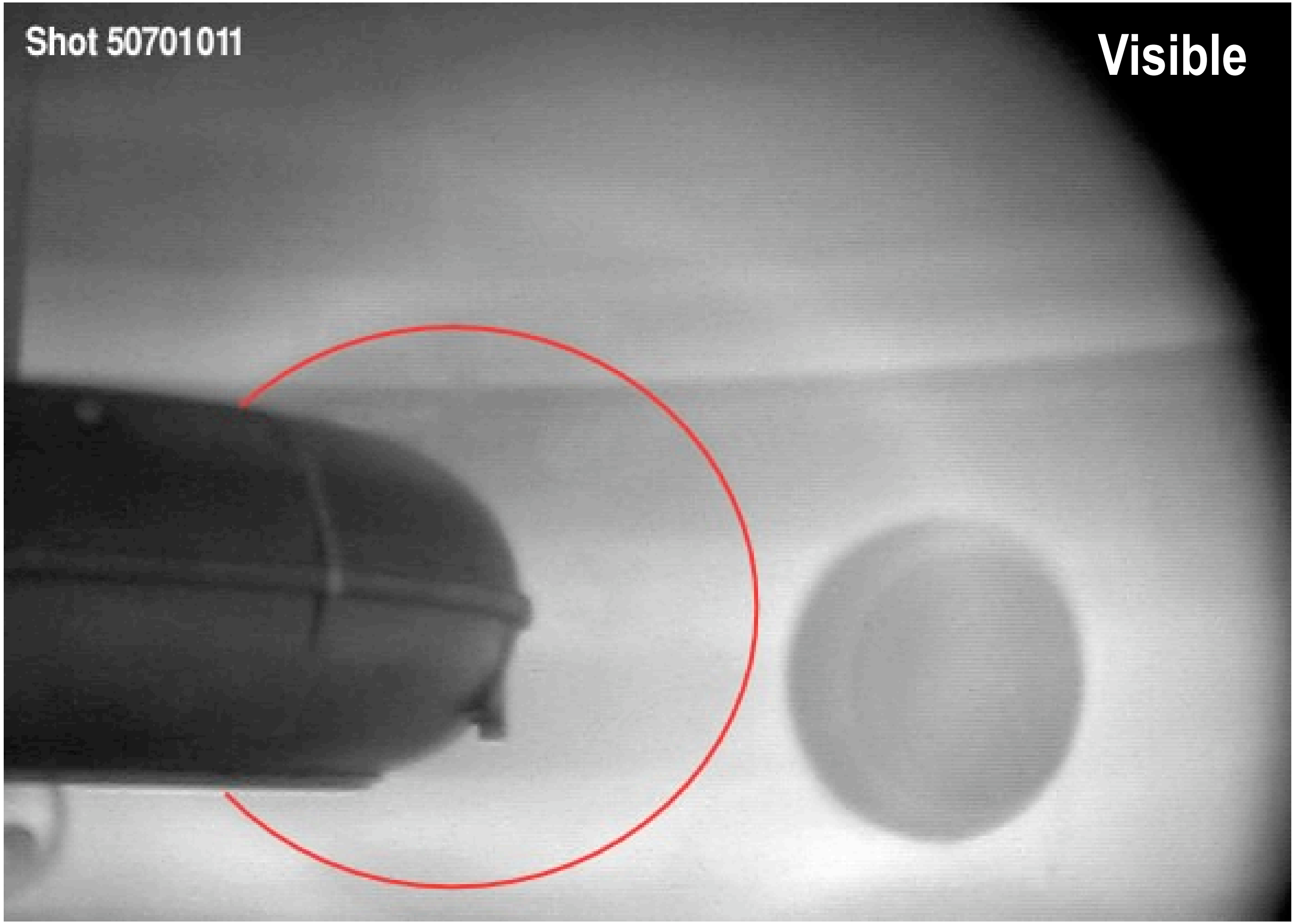
- Setup for Shot 50701014
  - Small D_2 gas pre-fill
  - ECRH power for 12 seconds
- Three regimes observed
  - Short initial unstable
  - Stable high-β
  - Afterglow

Typical Shot: Indicates 3 regimes



- **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

Fast Electrons: Anisotropic at ECRH Resonance



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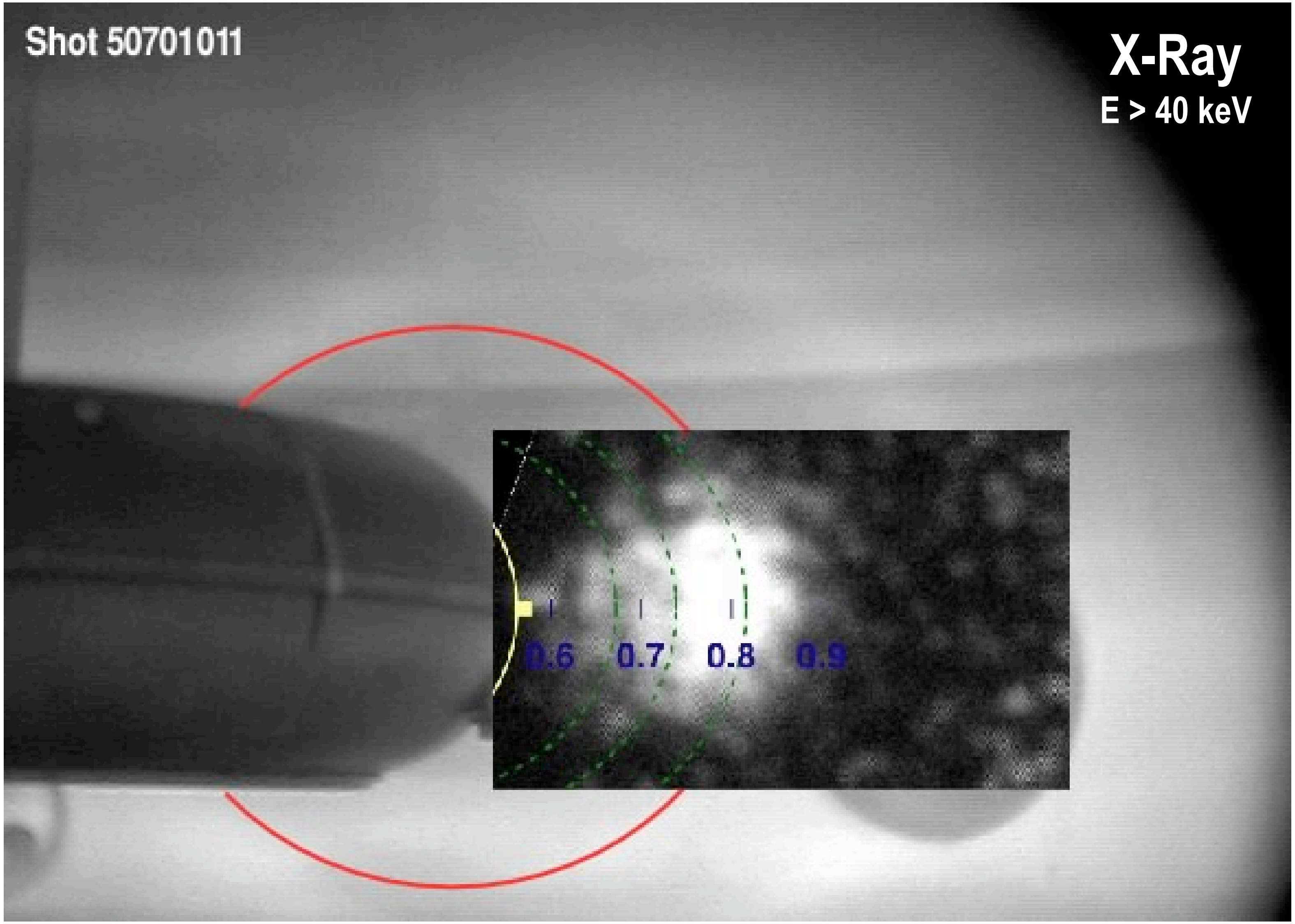


Characteristics of the Stable (High-β) Regime

- Quasi steady state
- Bulk plasma has 10x increased density
  - Edge density ~ 10^{10} cm^{-3}
  - Peak density near ECRH cutoff ~ 10^{11} cm^{-3}
- Fast electron population with 100-200 keV energies
- Significant diamagnetic current > 3 kA
  - Afterglow indicates the current is carried by fast electrons
  - Magnetic reconstruction:
    - Peak local beta: ~ 20%
    - Stored energy: 330 J (with 5 kW of input power ➠)

LDX Parameters in high-β Regime

ECH creates a hot electron component within a background plasma.

Hot Electron Plasma

- **Density: $n_{eh} << n_{eb}$**
- **Temperature: $T_{eh} >> T_{eb}$**
  - **Hot electron energy > 50 keV, ω_{dh}~1-10 MHz**
- **Pressure**
  - **Core 200 Pa.**
  - **β_{max} ~ 20%**
- **Confinement**
  - **Stored energy ~ 200 J, "τ_E" ~ 50 msec.**

Background Plasma

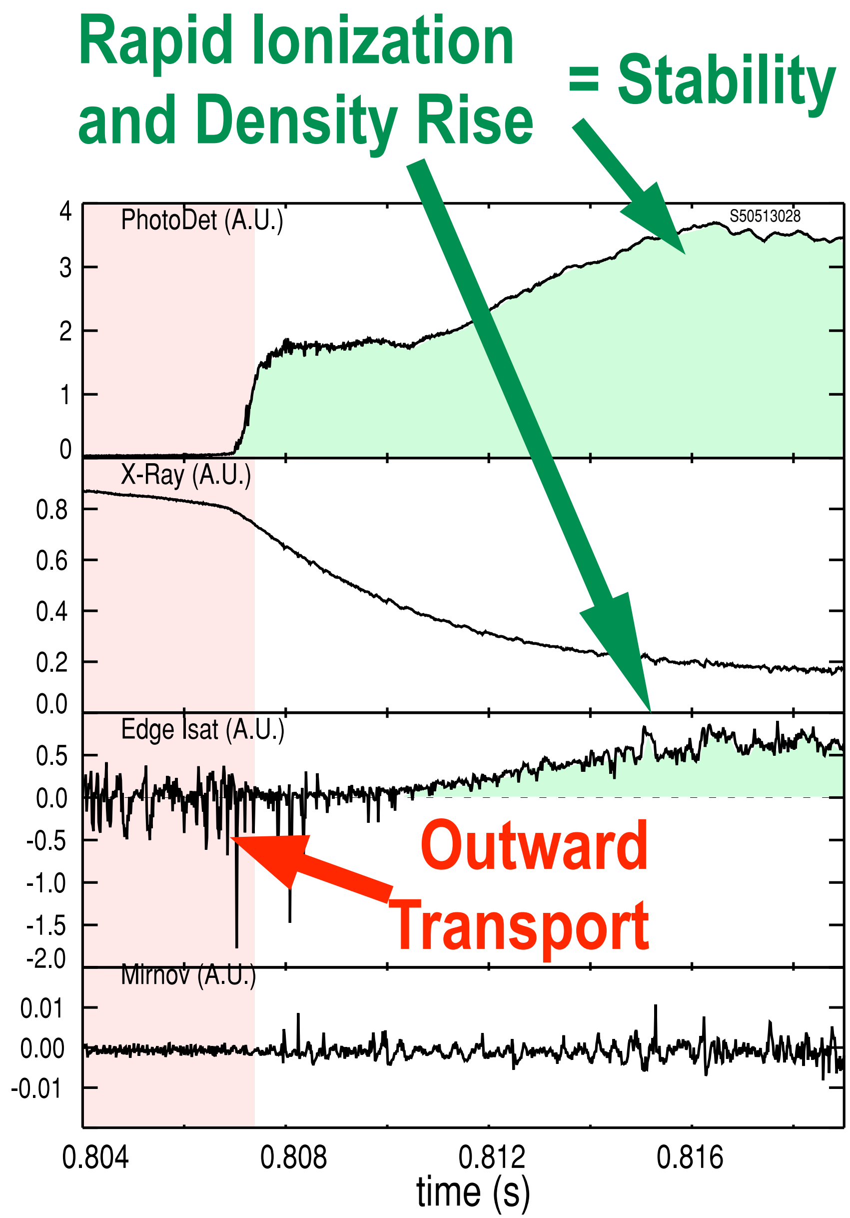
- Density
  - Core: <nl>~1-5 x 10^{16} m^{-3}
    - n_{cutoff}(2.45 GHz)= 7.6e16 m^{-3} @ R_0=0.78 m
    - n_{cutoff}(6.4 GHz) = 5.2e17 m^{-3} @ R_0=0.60 m
  - Edge density 1-2 x 10^{16} m^{-3}
- Temperature:
  - Edge temperature ~10-20 eV, ω_{*b} ~1-10 KHz
- Pressure
  - Edge 0.01 Pa

P_{Core}/P_{edge}~10000

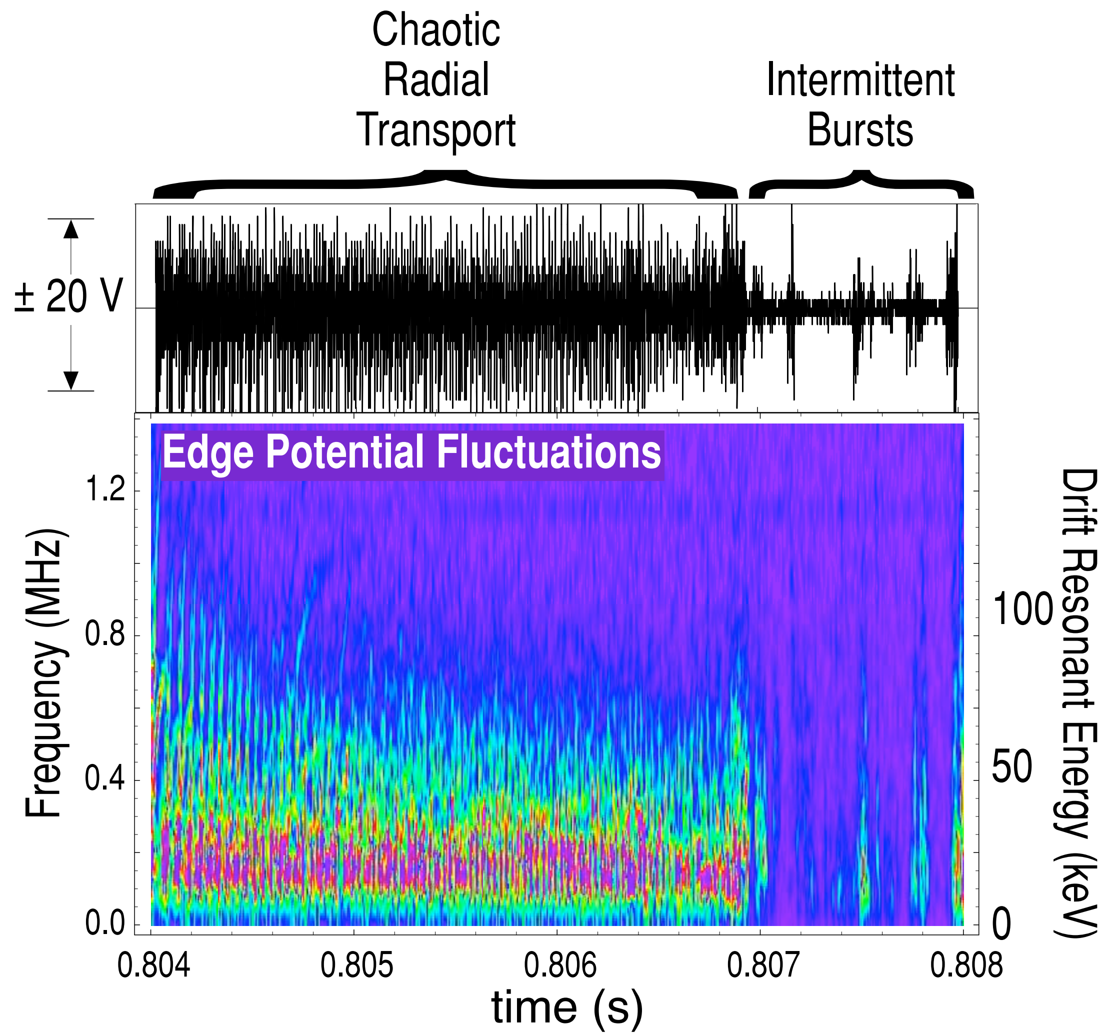
Controlling the High-β with Gas Puffing

- **With sufficient neutral gas pressure, plasma enters high-β regime**
- **With insufficient neutral gas pressure, the plasma will become unstable (sometimes violently)**
- **A hysteresis is the observed thresholds implies the bifurcation of the low density unstable and stable high-β regimes**
- **Qualitatively consistent with theory of the Hot Electron Interchange Mode stability**

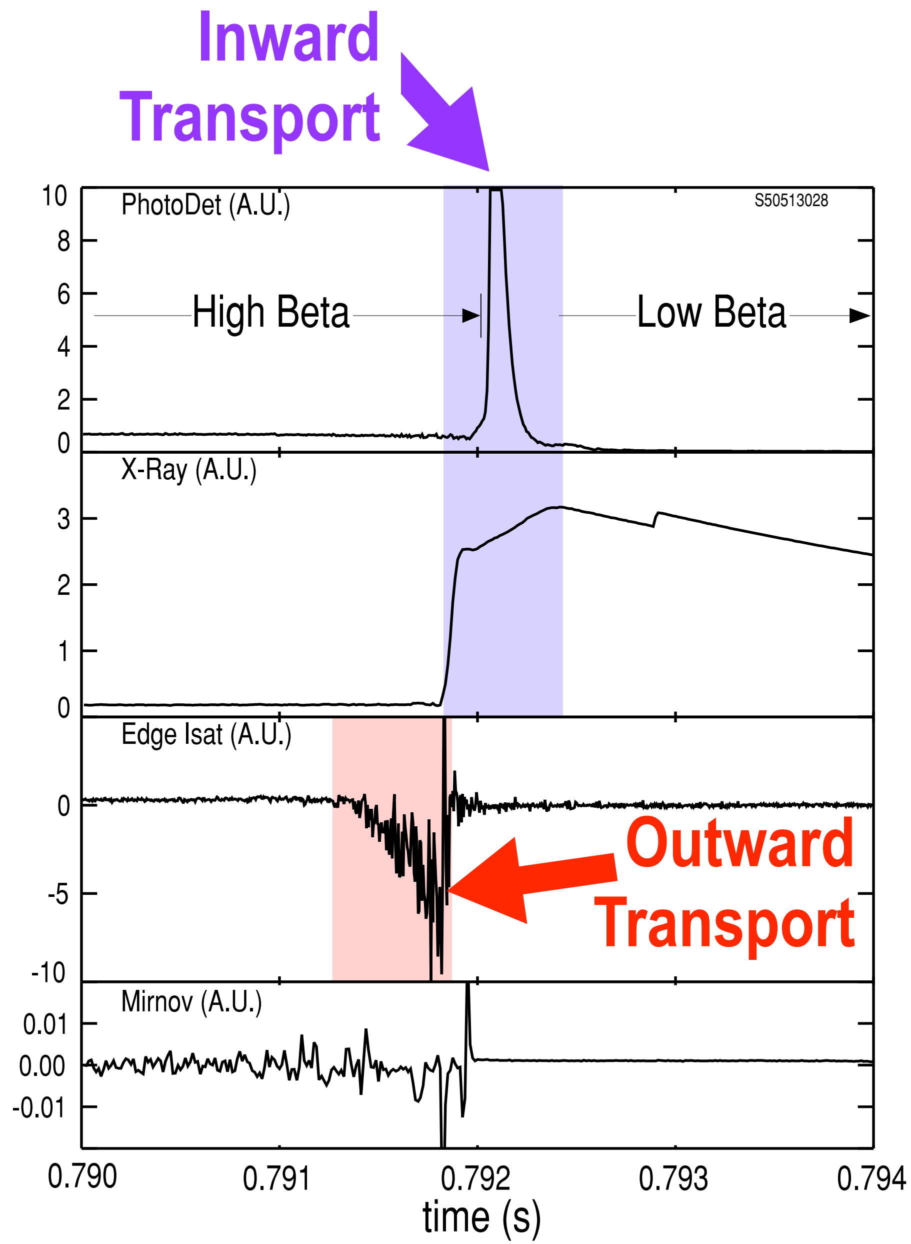
High-β Plasma Begins Upon HEI Stabilization



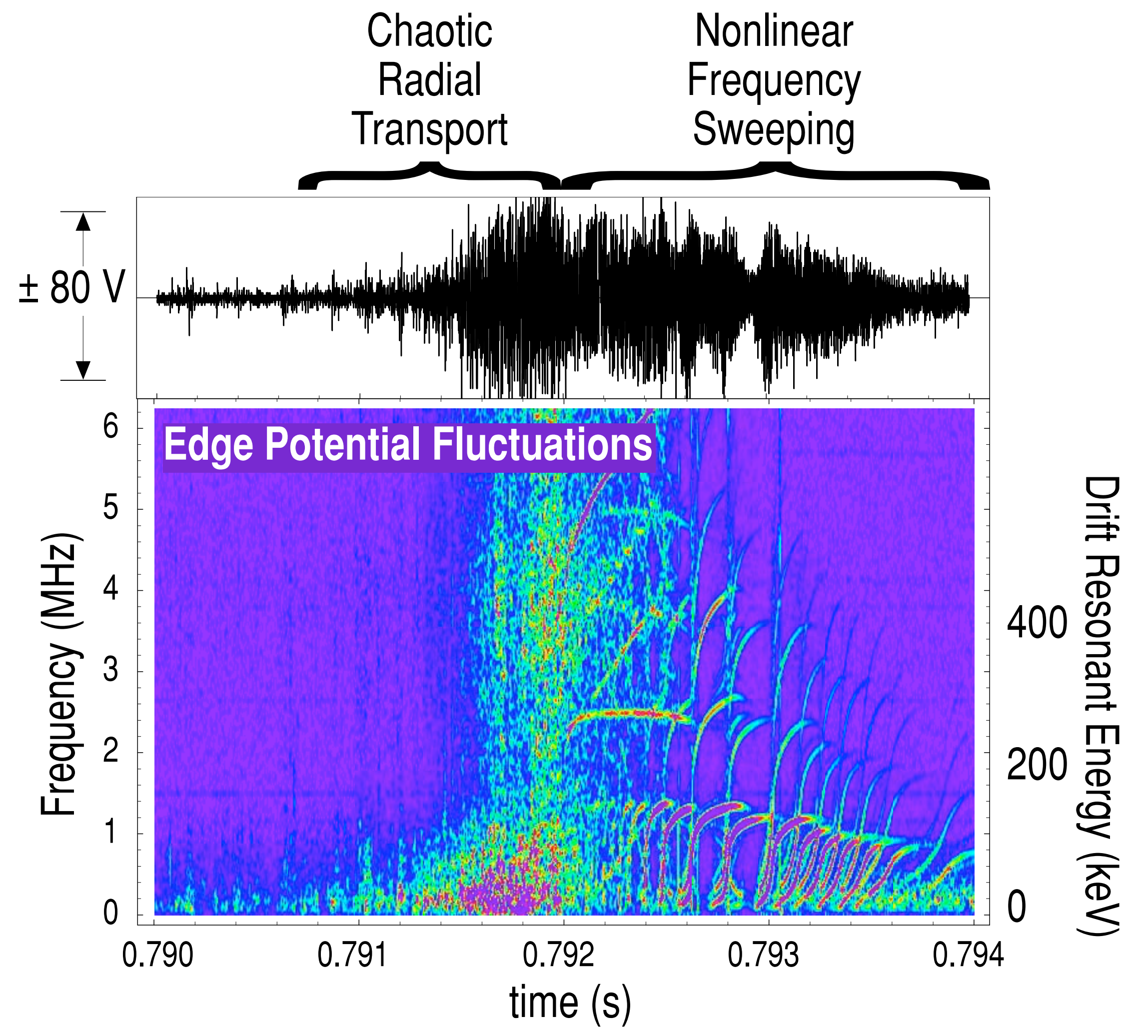
In unstable regime, quasi-continuous HEI instability prevents plasma build-up …



HEI Instability Can Terminate High-β Plasma

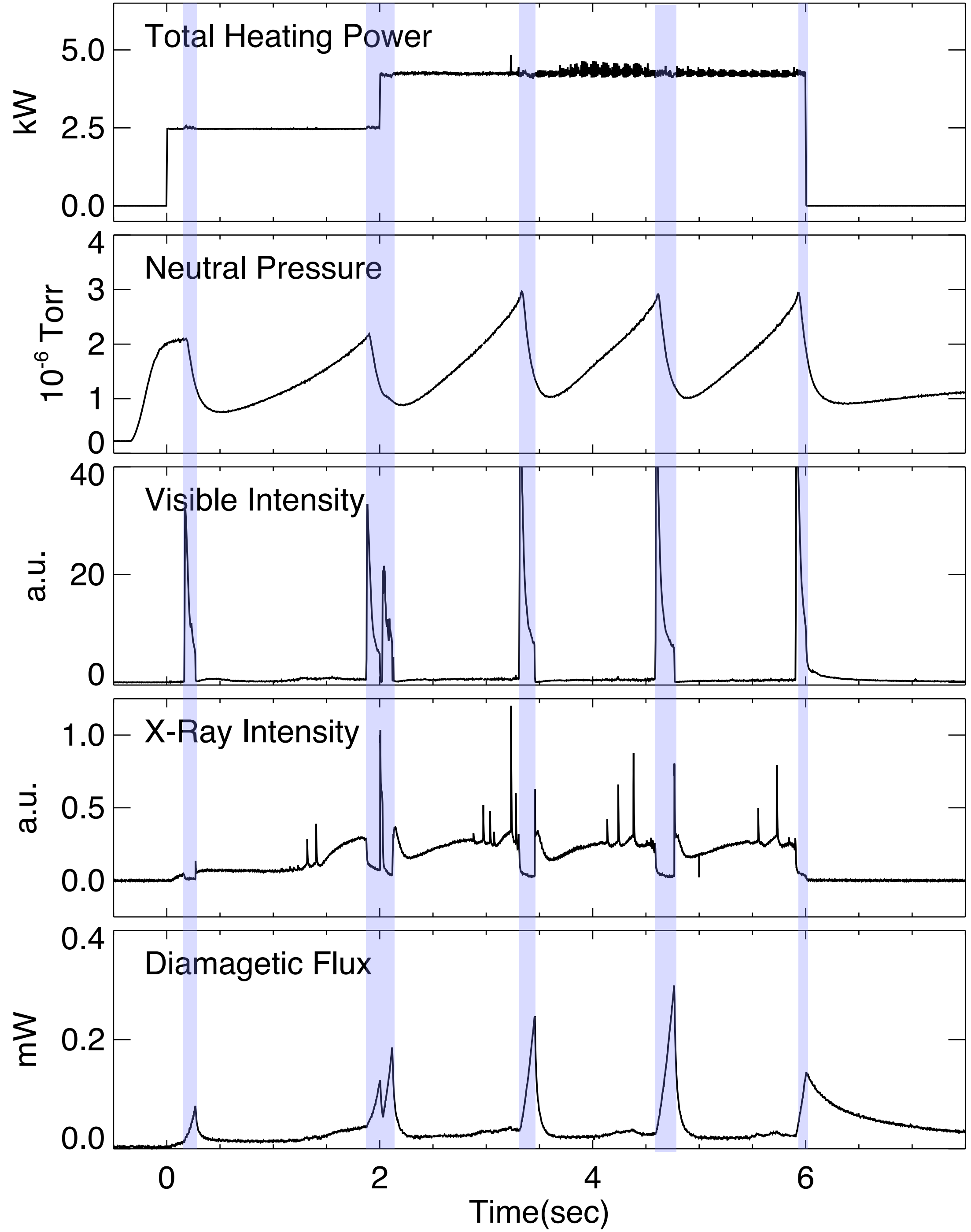


Intense HEI instability resonates with fast electrons causing rapid radial transport…



HEI ⇒ Hysteresis in Gas Requirements

- 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



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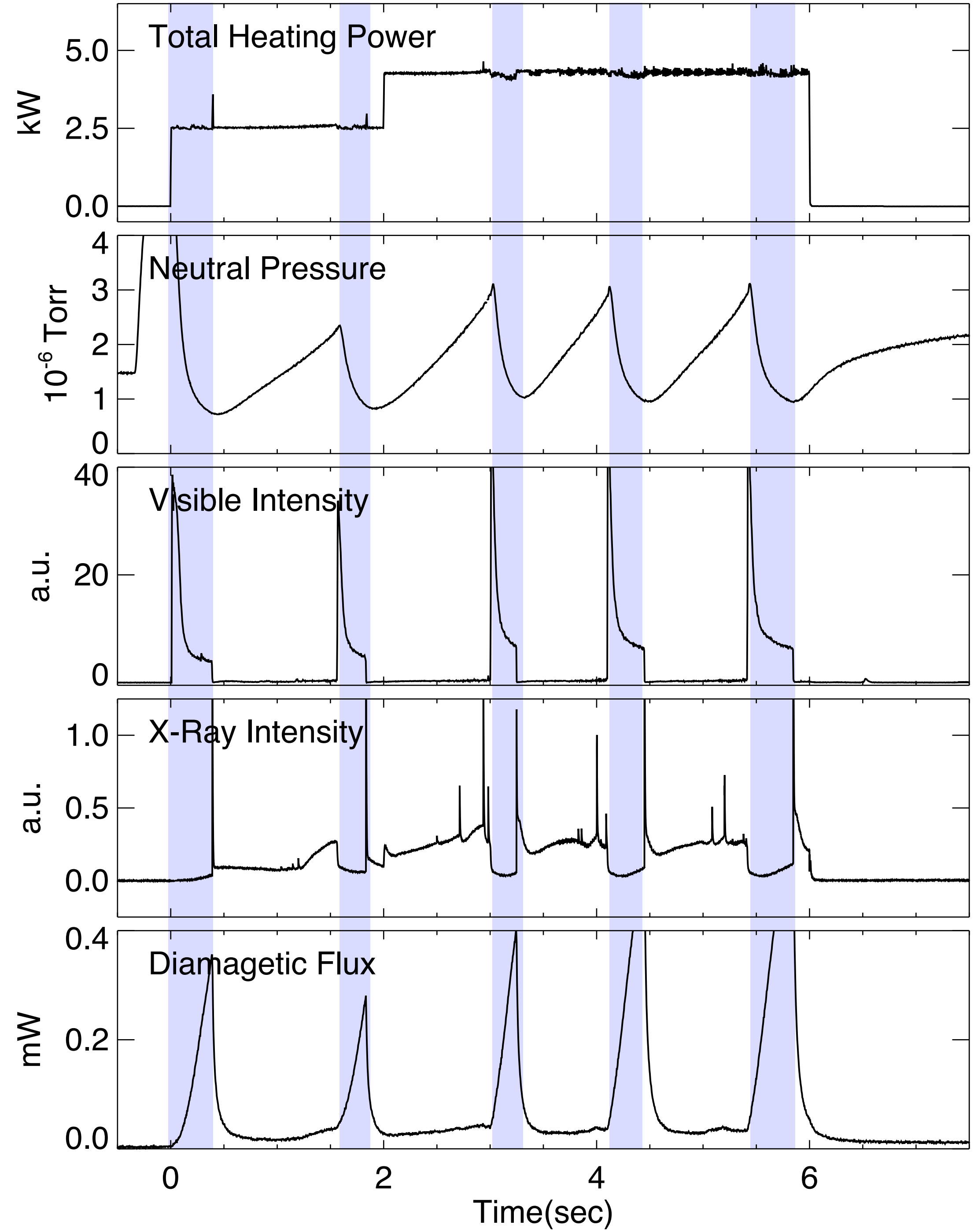
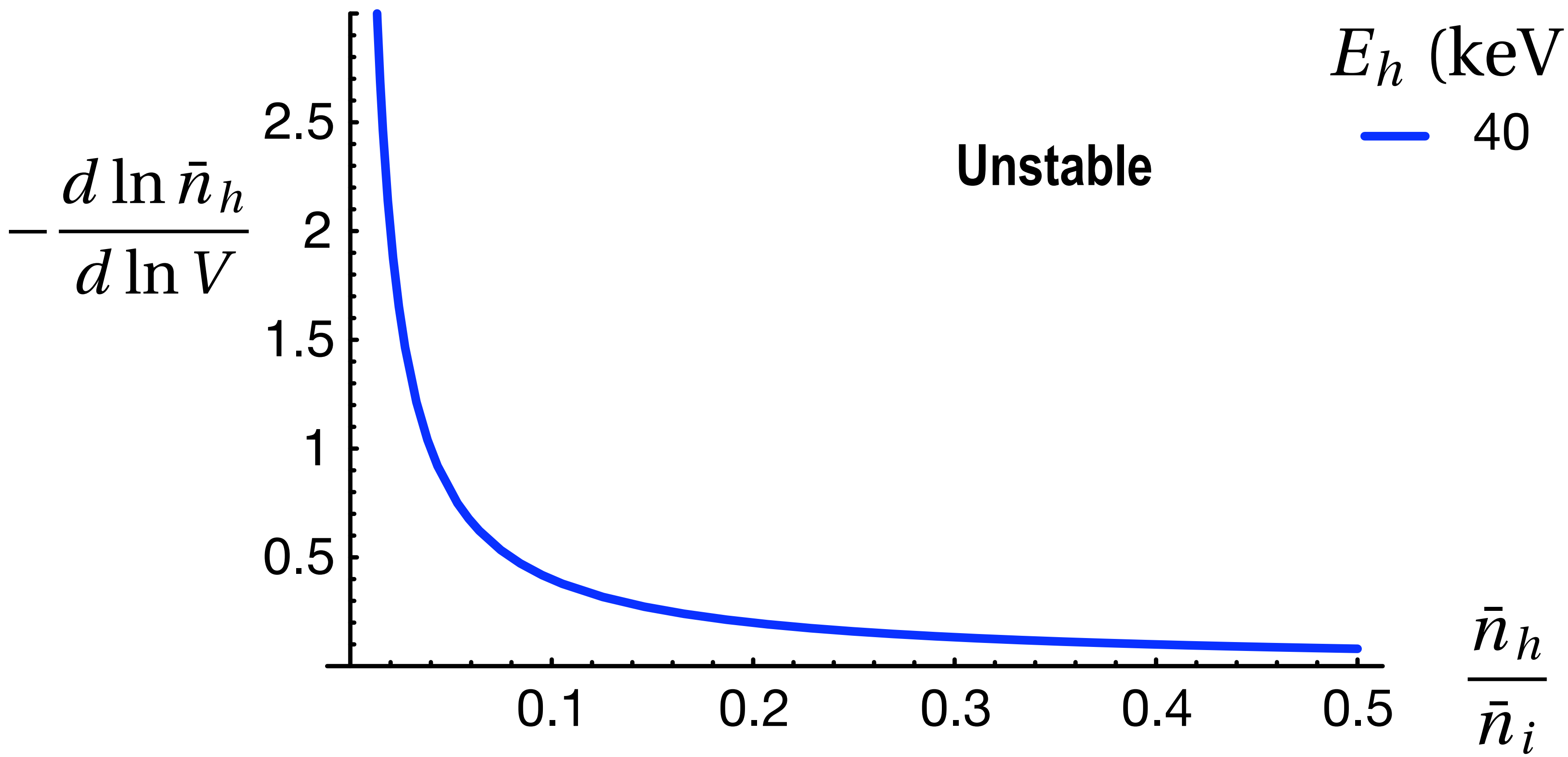
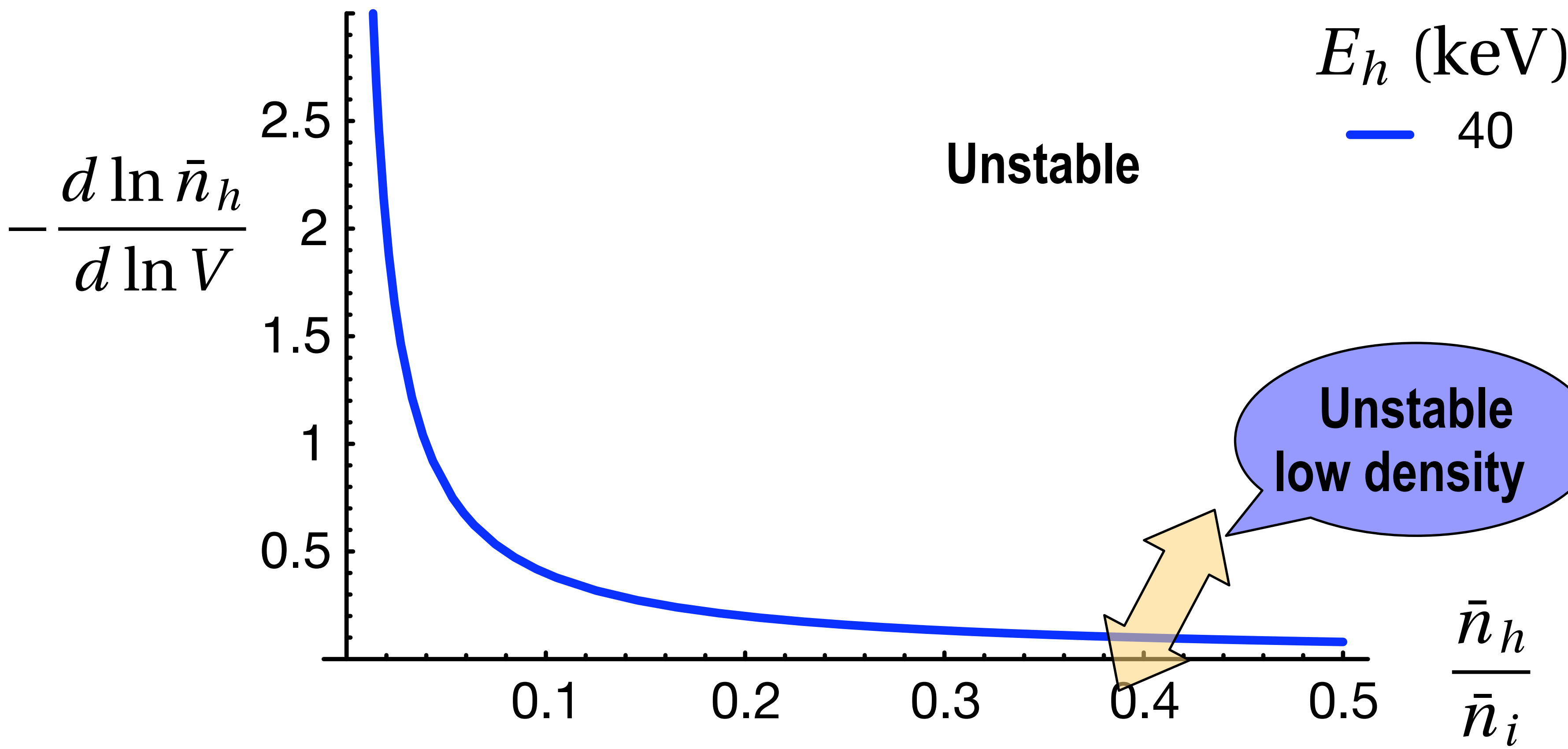


Hysteresis in evolution of stability limit



- **Unstable regime has high f_h and 40 keV electrons**
- **Increased gas fueling ⇒ stabilization ⇒ f_h to drop by 1/10**
- **In high-β regime, fast electrons heat ⇒ higher stability limit**

Hysteresis in evolution of stability limit



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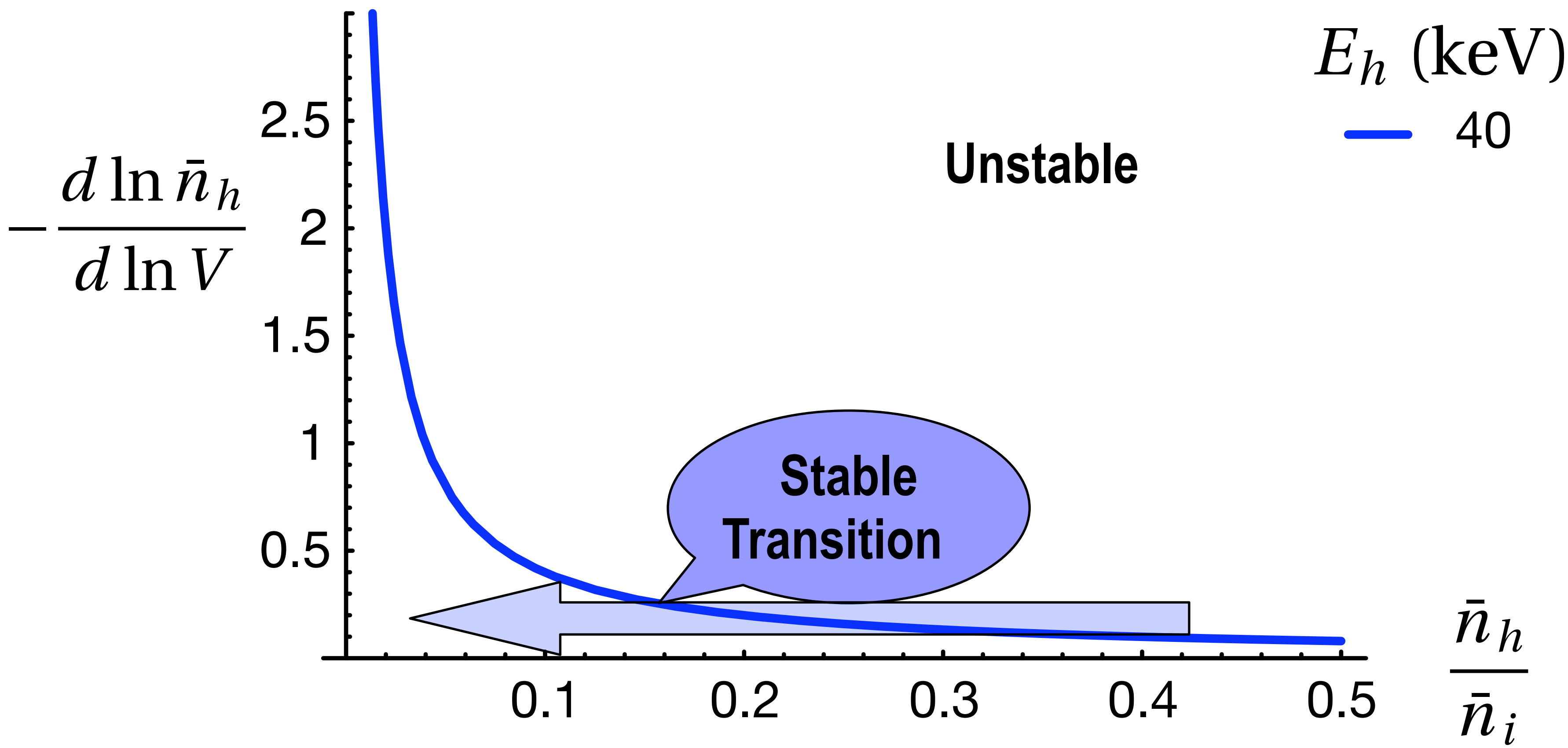

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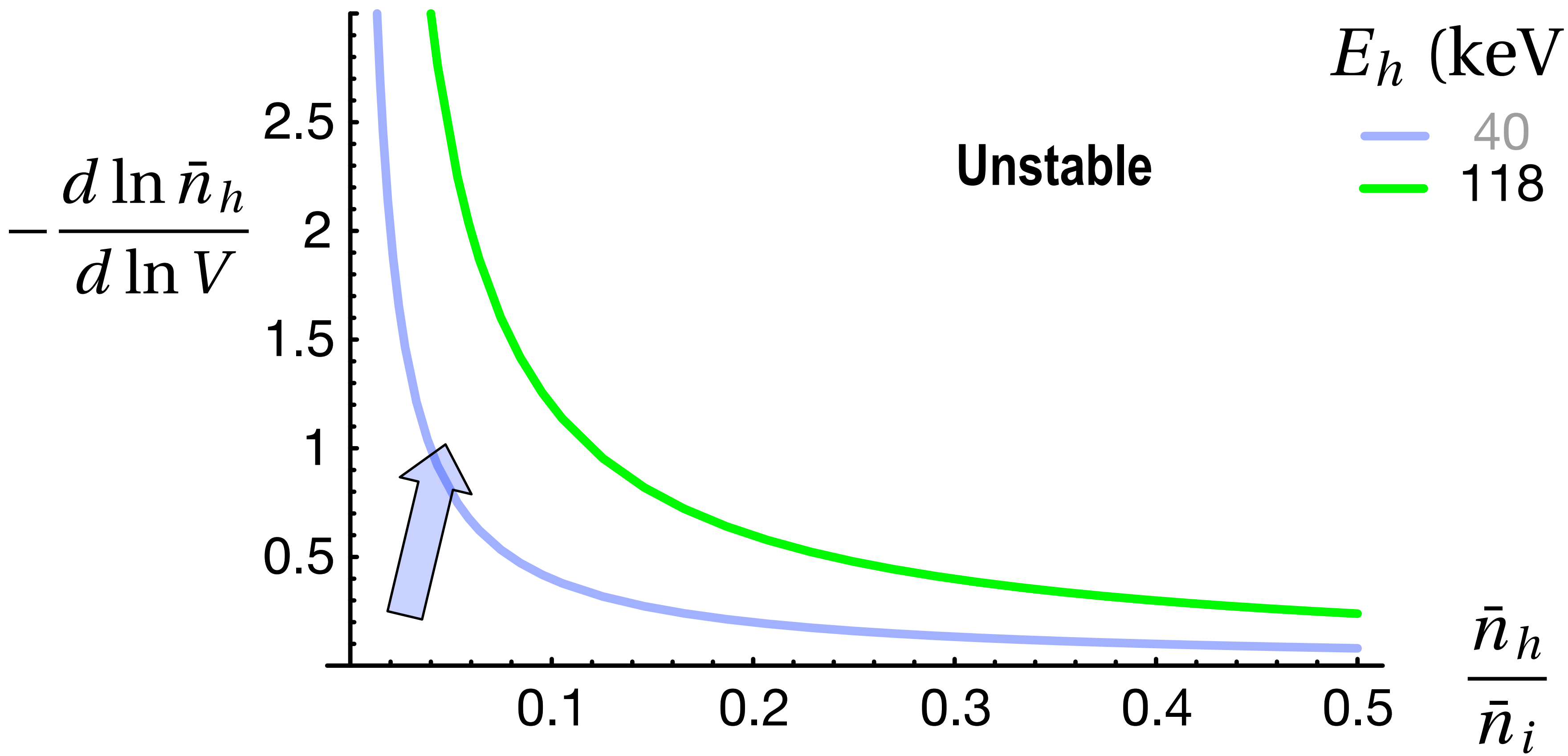

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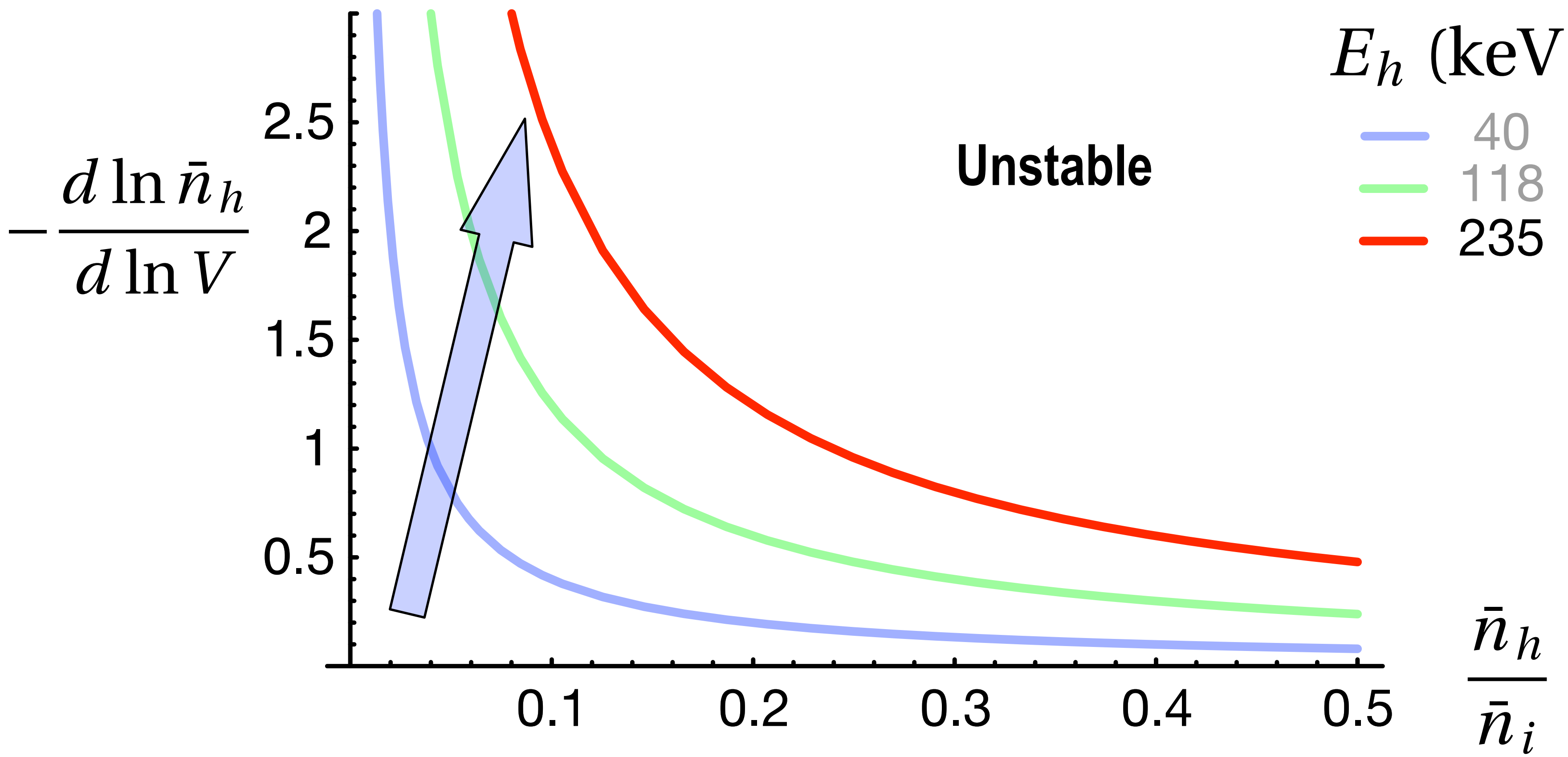

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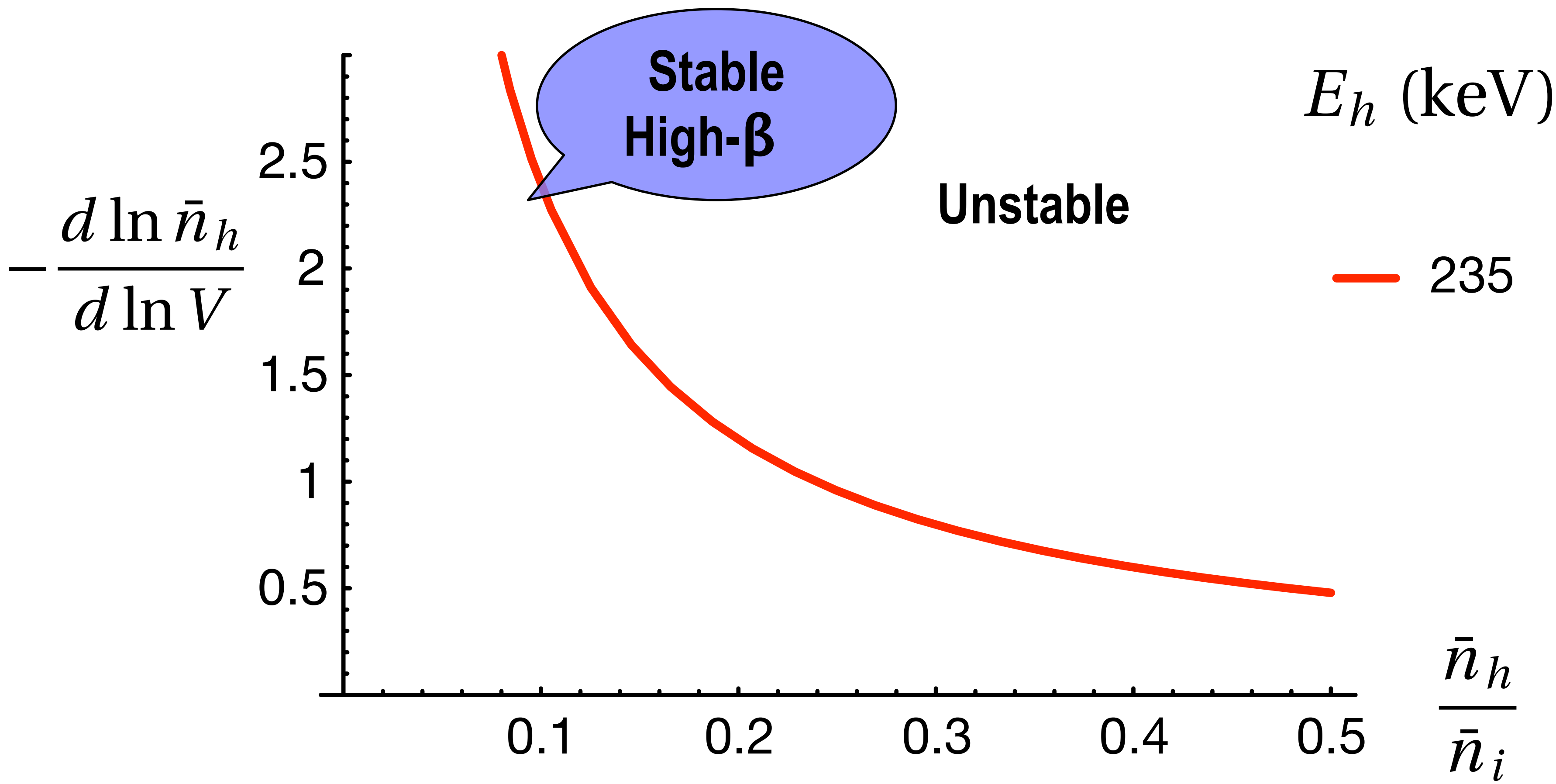

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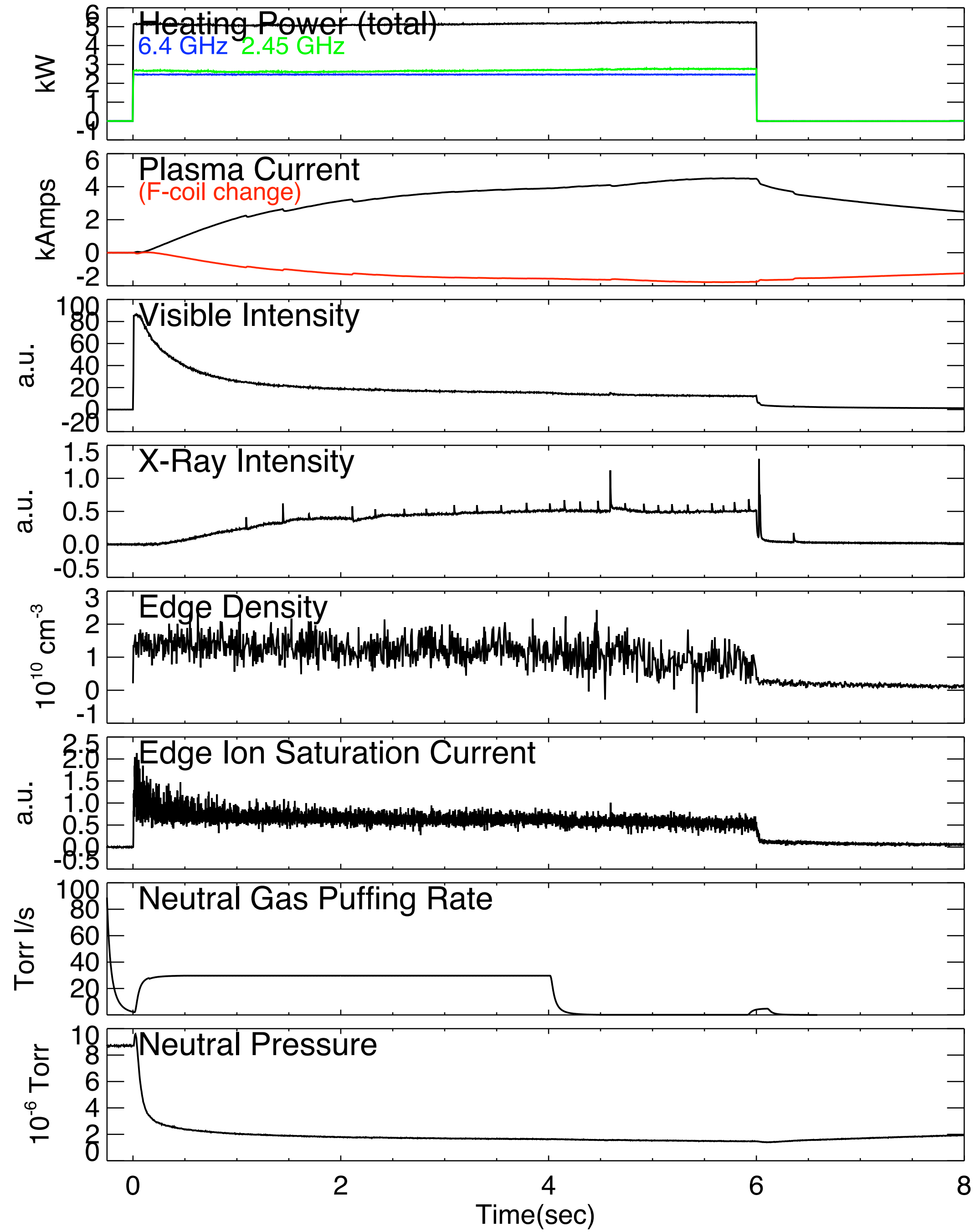
Pre-programmed Optimization

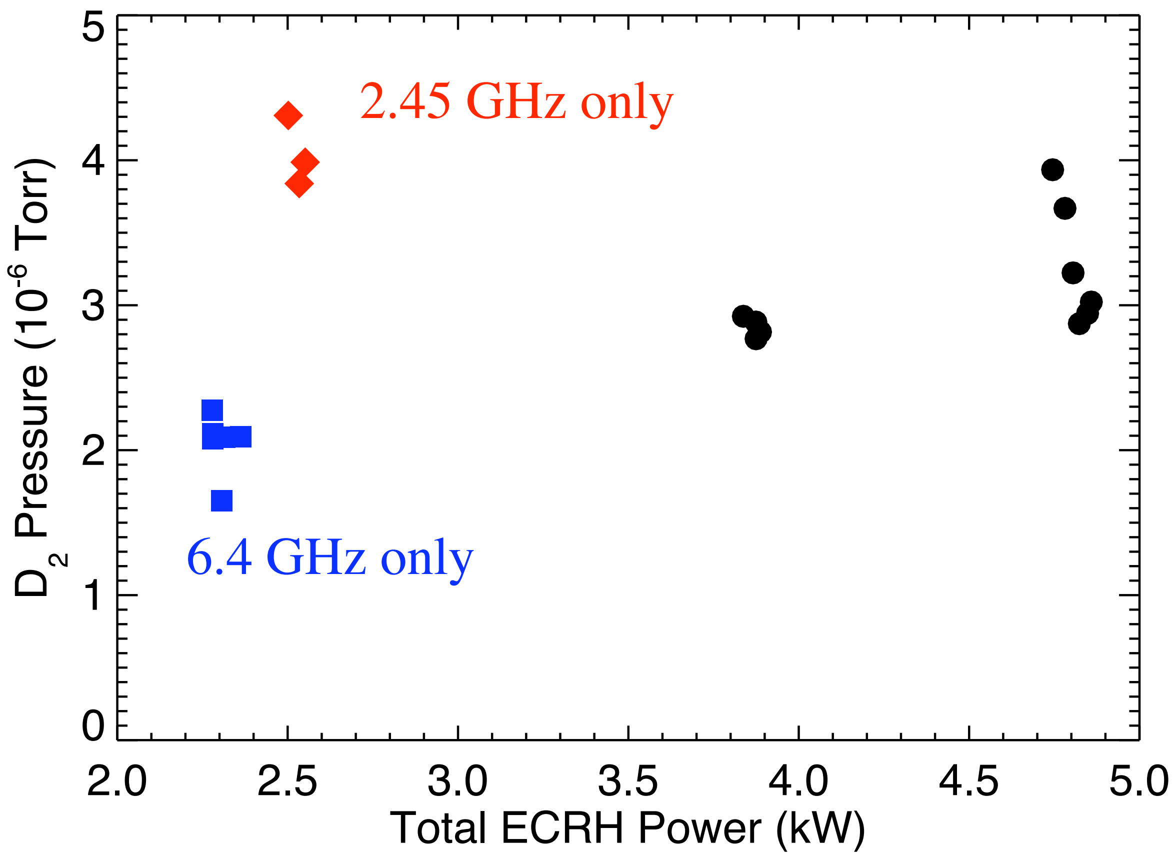
- Careful programming of puffing rate gave highest plasma stored energy
  - Maintain small but stable neutral
- Stored energy increases with less neutrals
  - Less pitch angle scattering of fast electrons
- Small puff before afterglow to (nonlinearly) stabilize initial HEI in afterglow
- Feedback system planned for next run...



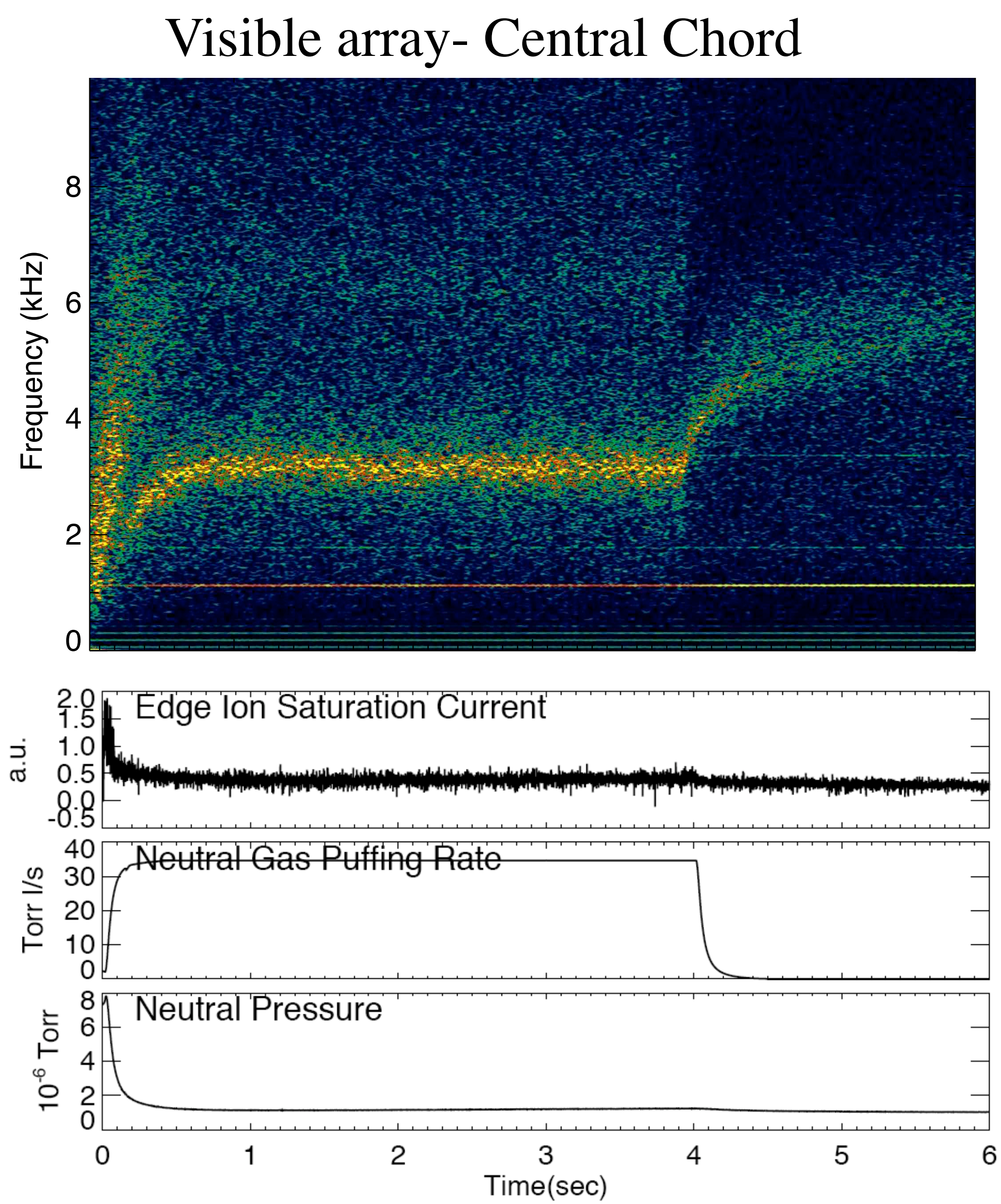
Other Controls on HEI stability

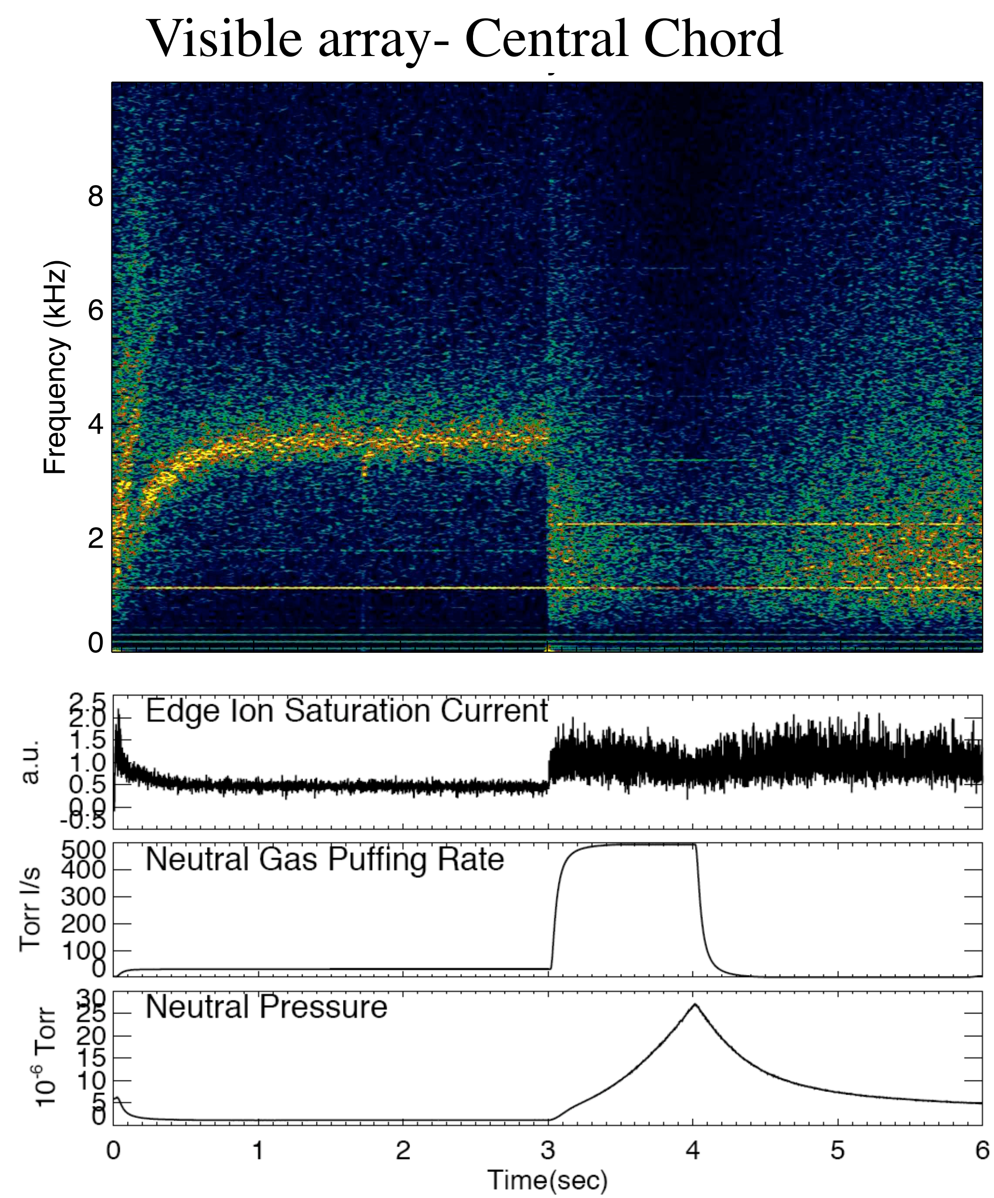
- Weak trend with total ECRH power
  - More power requires more neutrals
- Heating profile has dramatic effect
- Plasma shaping also has dramatic effect
  - Smaller plasmas need higher neutral pressure

Neutral Pressure Required for Stabilization



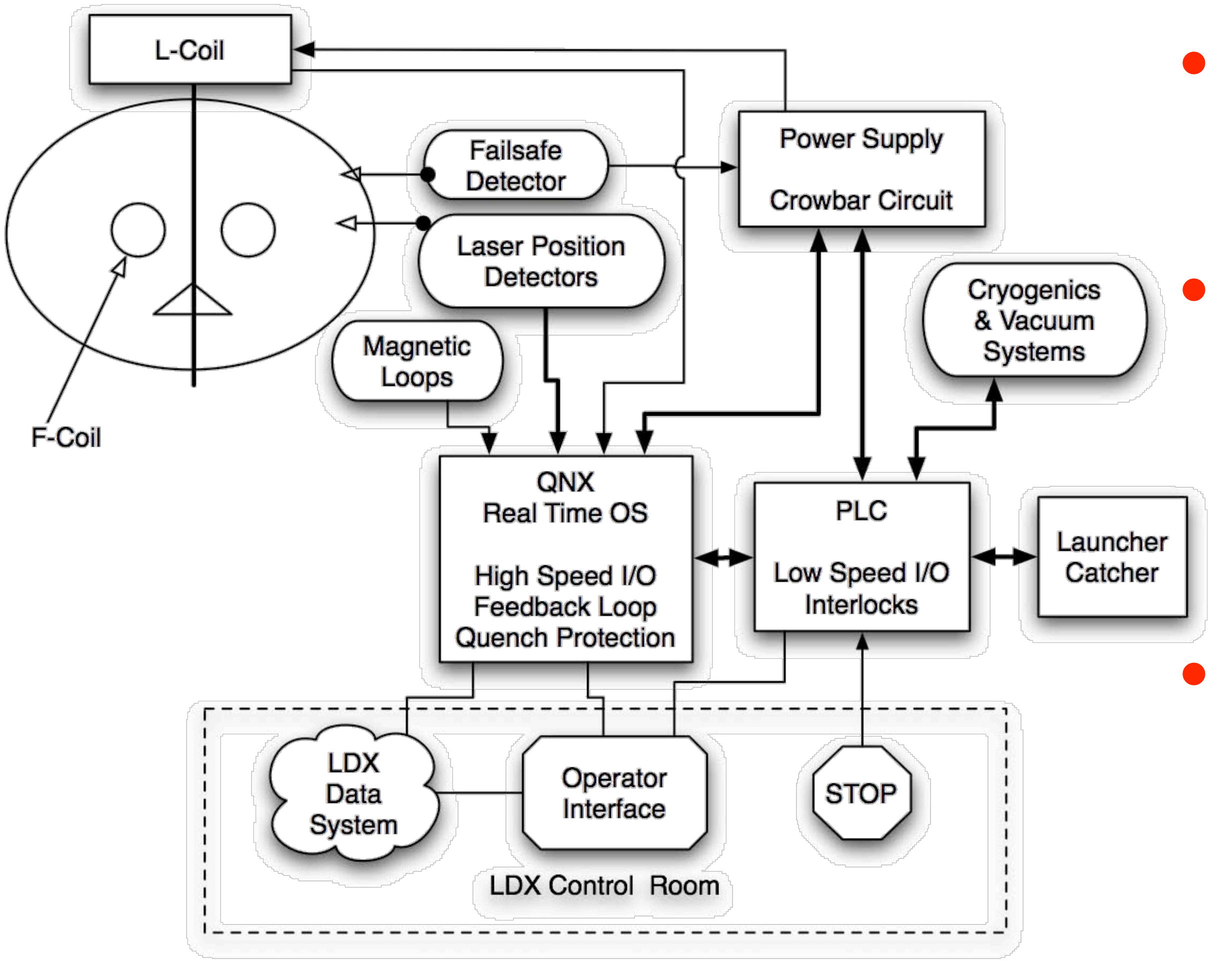
Other control issues: Low frequency mode





- Low frequency (few kHz) core fluctuation also effected by fueling

Levitation Control System

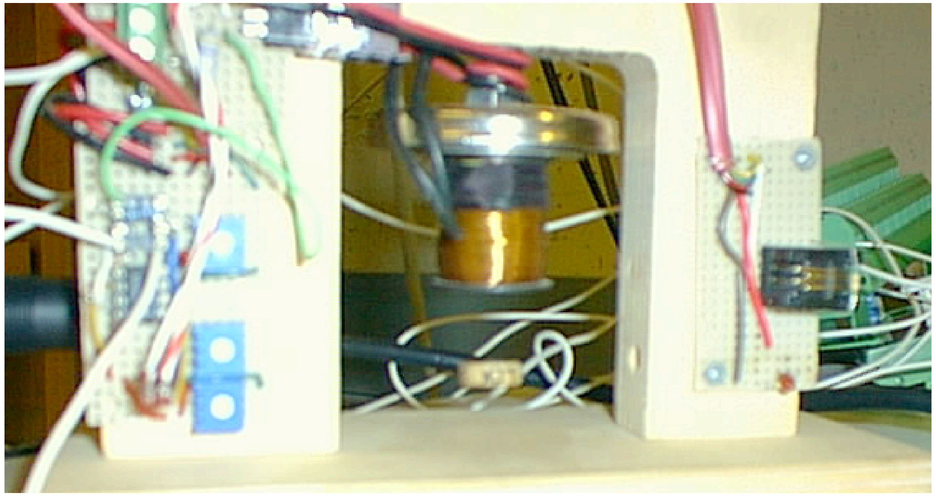


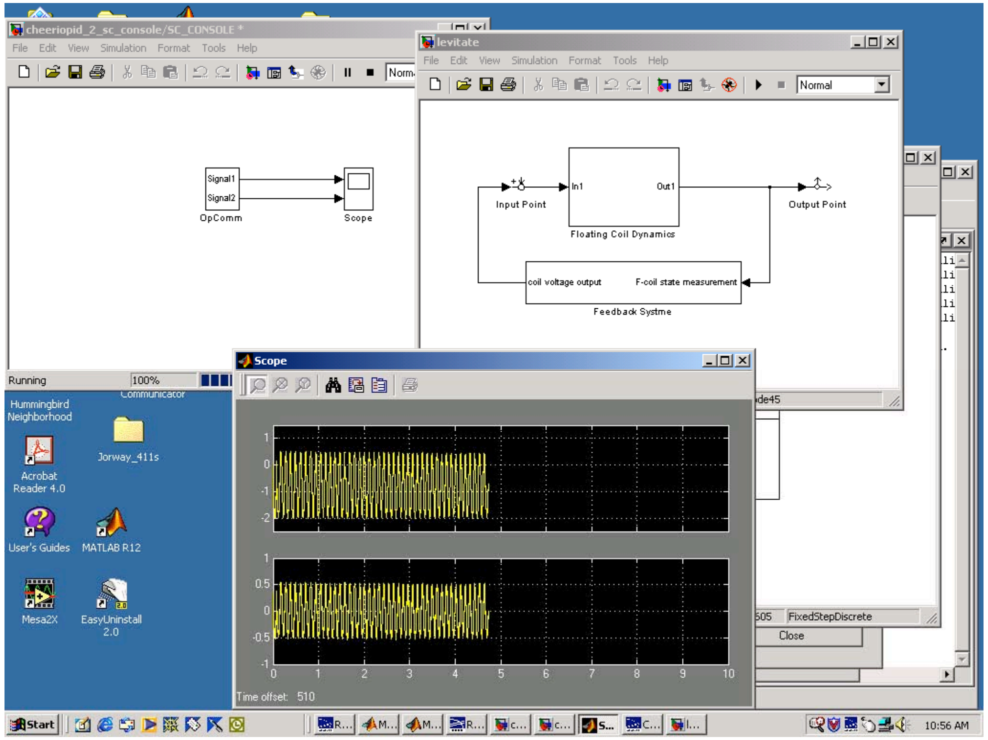
- 150A, +/- 100V Power Supply
  - Integrated dump resistor for rapid discharge
- Realtime digital control computer
  - Matlab/Simulink Opal-RT development environment
  - 5 kHz feedback loop
  - Failsafe backup for upper fault
- Programmable Logic Controller
  - Slow fault conditions
  - Vacuum & Cryogenic monitoring
  - PS user interface
- Optical link to control room
  - User interface
  - LDX data system

Summary

- Stable high-β plasmas are created in LDX in supported operation
  - Plasma energy is carried by fast electrons in a highly localized peak near ECRH resonance
- High requires sufficient neutral gas pressure to stabilize hot electron interchange mode
  - Demonstrable hysteresis in threshold levels for transition to and from unstable regime is consistent with theory
- Plasma confinement is optimized when fueling is controlled
- Other interesting control problems in the near future
  - Including first levitation!

LCX II: Digitally Controlled Levitation





- Levitated Cheerio Experiment II
- Uses LDX digital control system
  - Test at 10 times the frequency required
- Modified PID feedback system
  - Low pass filter added for high frequency roll-off of derivative gain
  - Stimulated work on Kalman filtering system for LDX control
- Real-time graph shows position and control voltage
  - Wiggles indicate non-linearly stable rolling mode…