Production and Study of High-Beta Plasma Confined by a Superconducting Dipole Magnet

Darren Garnier

For the LDX Team

Columbia University

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Results

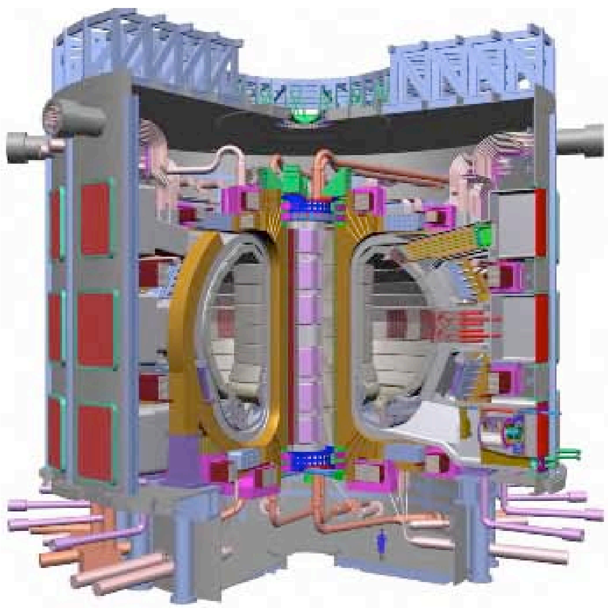
- Stable high beta plasmas are created in LDX
  - Large diamagnetic currents carried by fast electrons
  - Imaging shows a highly localized peak near ECRH resonance
  - Magnetic reconstruction gives ~ 20% peak beta
  - When stable…dominant loss channels to support rods
- High beta requires sufficient neutral gas pressure
  - 3 regimes found: (1) unstable, (2) high-β, (3) afterglow
  - Increasing gas pressure causes: (1) dramatic rise in density, (2) stabilization of the HEI, and (3) transition to high-β regime
  - Hysteresis in gas fueling required to maintain stability

Outline

- Introduction to the Dipole fusion concept
- Description of the Levitated Dipole Experiment (LDX)
- How high beta plasmas are created
- Reconstructing the magnetic equilibrium
- Controlling the high beta state with neutral gas fueling
- Hot Electron Interchange Instability
- Summary and next steps...

Levitated Dipole Fusion Concept

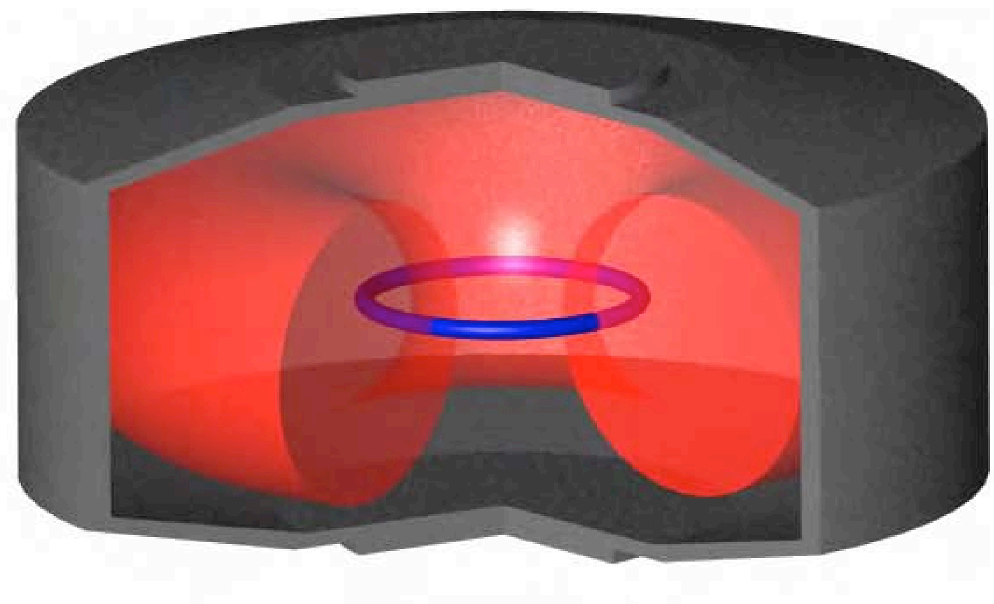
ITER



30 m

400-600 MW
DT Fusion

Levitated Dipole Reactor



60 m

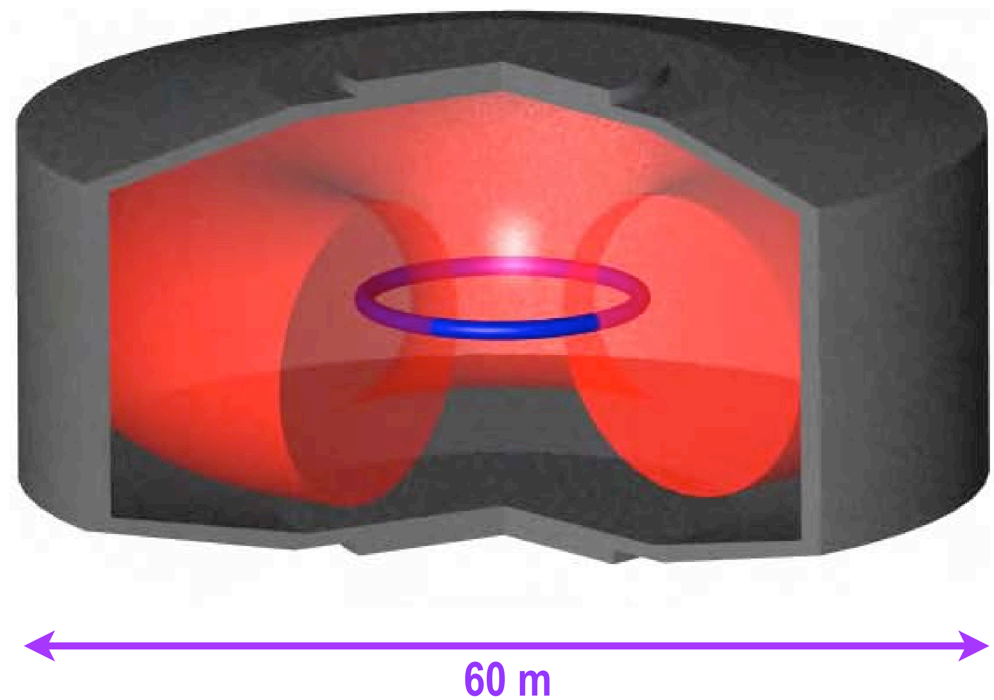
500 MW
DD(He3) Fusion

Kesner, et. al. Nucl. Fus. 2002

Levitated Dipole Fusion Concept

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

Levitated Dipole Reactor



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Investigating the Dipole Concept

- **Stability:**
  - **Can a dipole be stable at high β?**
- **Energy Confinement:**
  - **Sufficient to burn advanced fusion fuels?**
- **Particle Confinement:**
  - **Can convection decouple τ_p and τ_E ?**
- **Engineering:**
  - **Superconducting magnet surrounded by fusion plasma?**

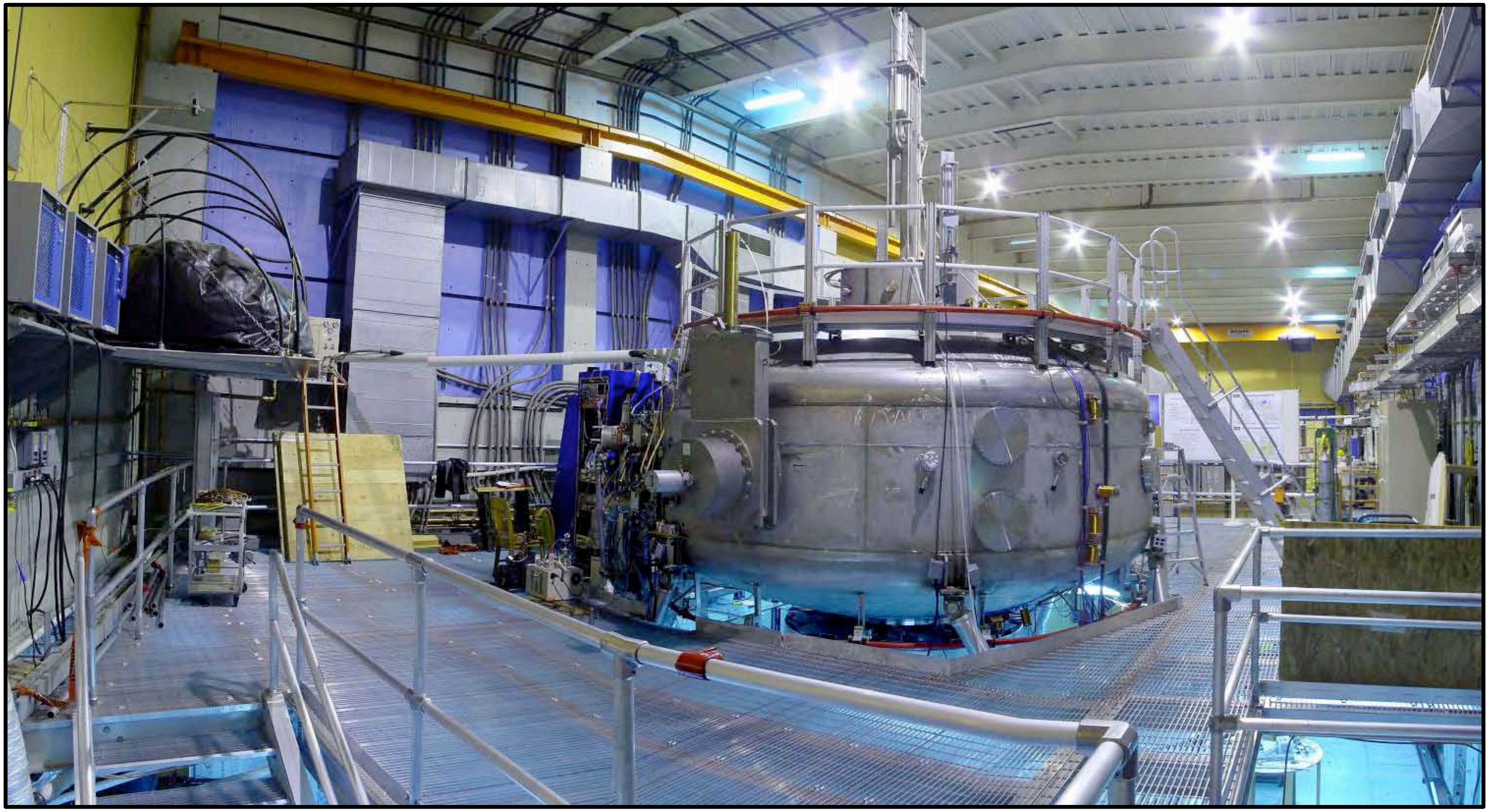
Investigating the Dipole Concept

- **Stability:**
  - **Can a dipole be stable at high β?**

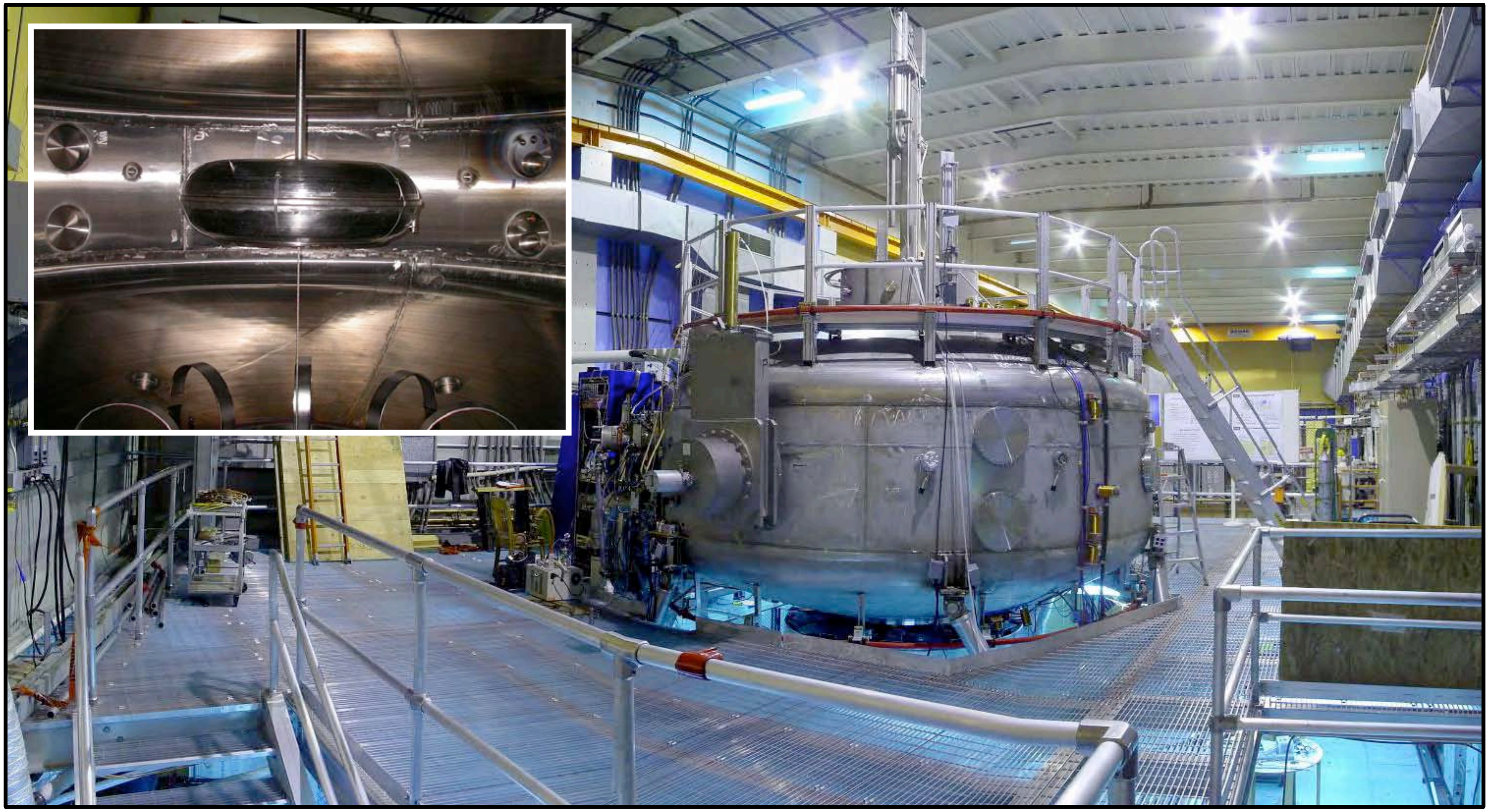
LDX Phase I

- **Energy Confinement:**
  - **Sufficient to burn advanced fusion fuels?**
- **Particle Confinement:**
  - **Can convection decouple τ_p and τ_E ?**
- **Engineering:**
  - **Superconducting magnet surrounded by fusion plasma?**

The Levitated Dipole Experiment (LDX)

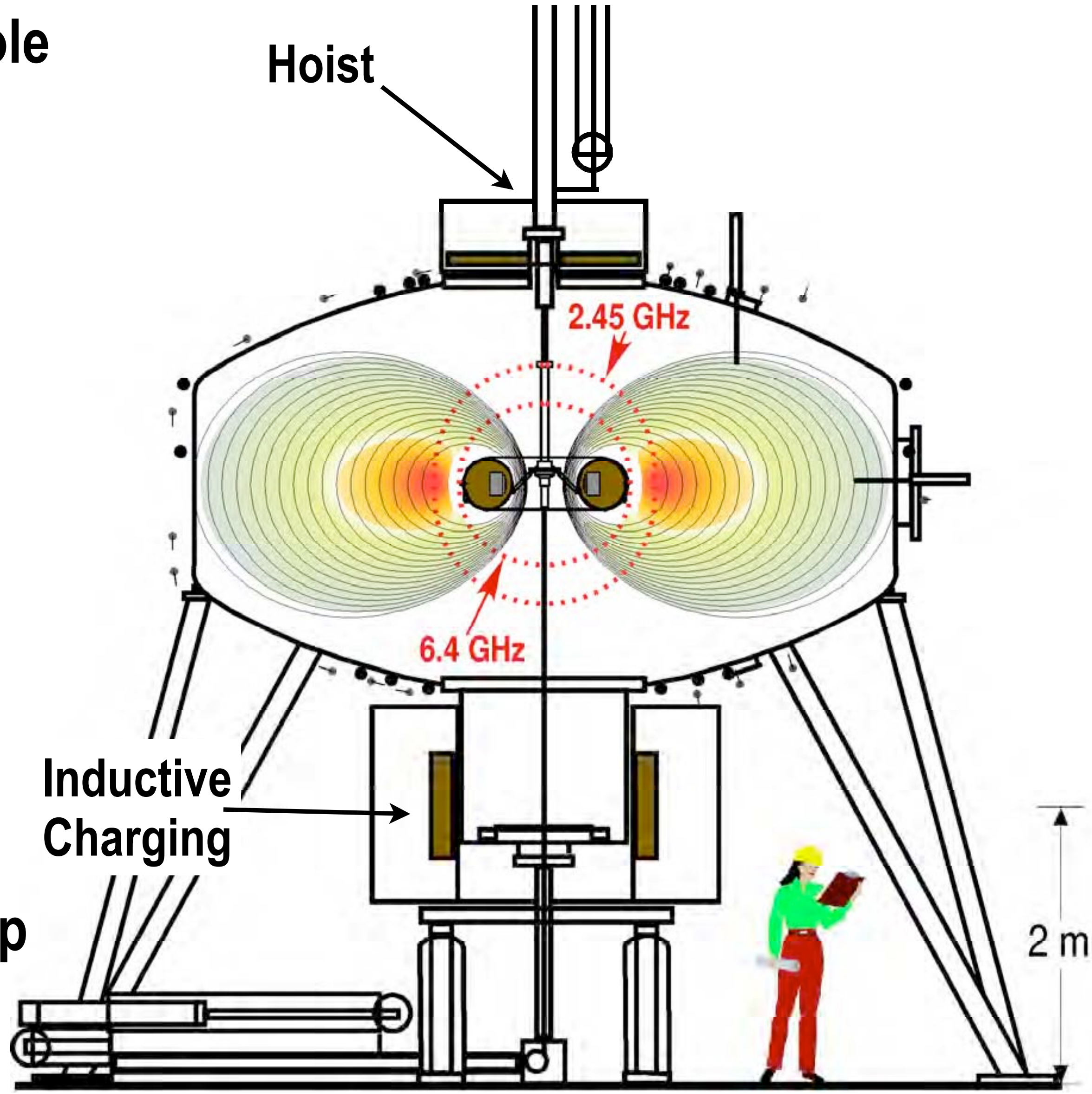


The Levitated Dipole Experiment (LDX)

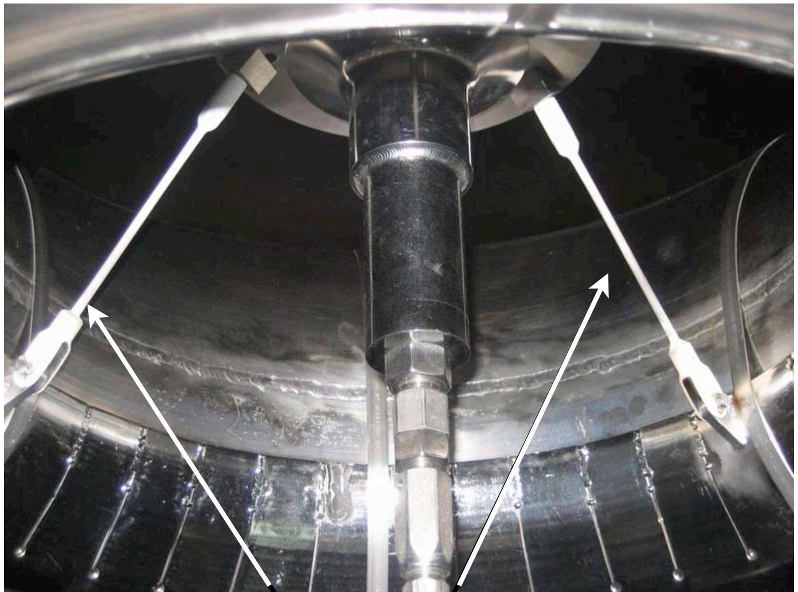


LDX Experiment Cross-Section

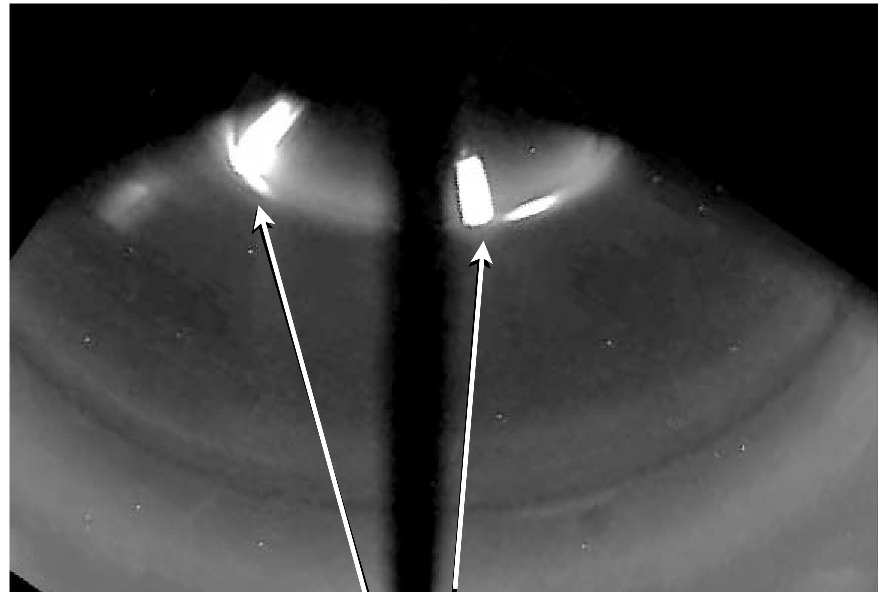
- Superconducting dipole magnet I > 1 MA
- Large 5 m diameter vacuum vessel
- Expansive diagnostic access
- Dipole supported by three thin spokes
- Two ECRH heating frequencies provide up to 5 kW power



Thin Supports Remain a Major Power Loss



Three high-strength, alumina-coated spokes support dipole during Phase I experiments

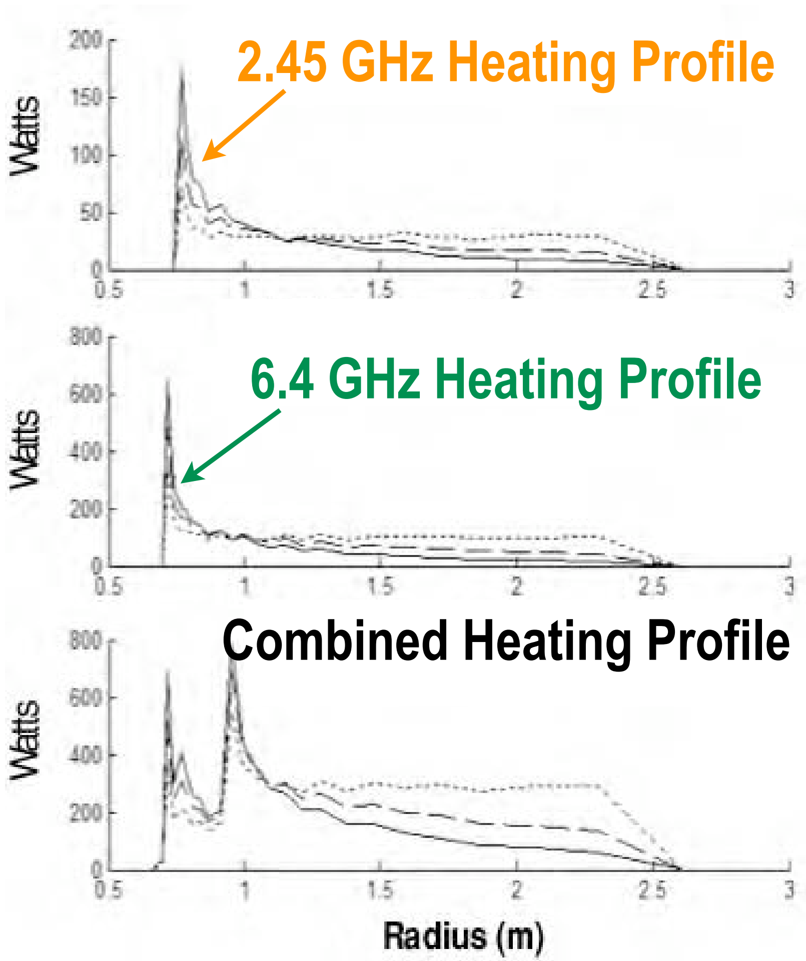


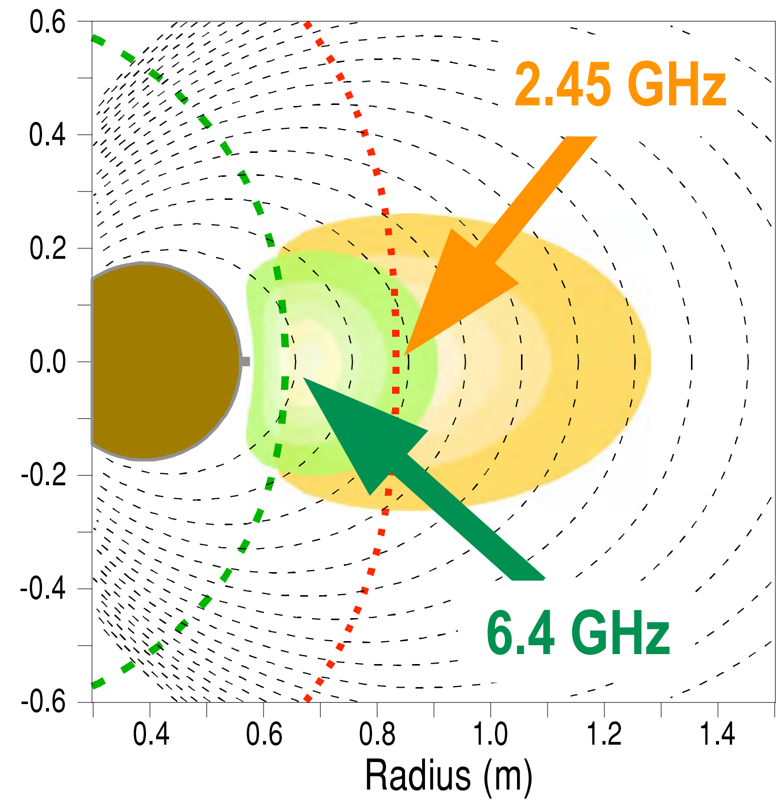
Supports become “warm” during high-beta plasma operation

(Elimination of supports, next step, will further enhance confinement.)

ECRH Strong at Equatorial Resonance

- Up to 5 kW total ECRH power
- 2.45 GHz and 6.4 GHz





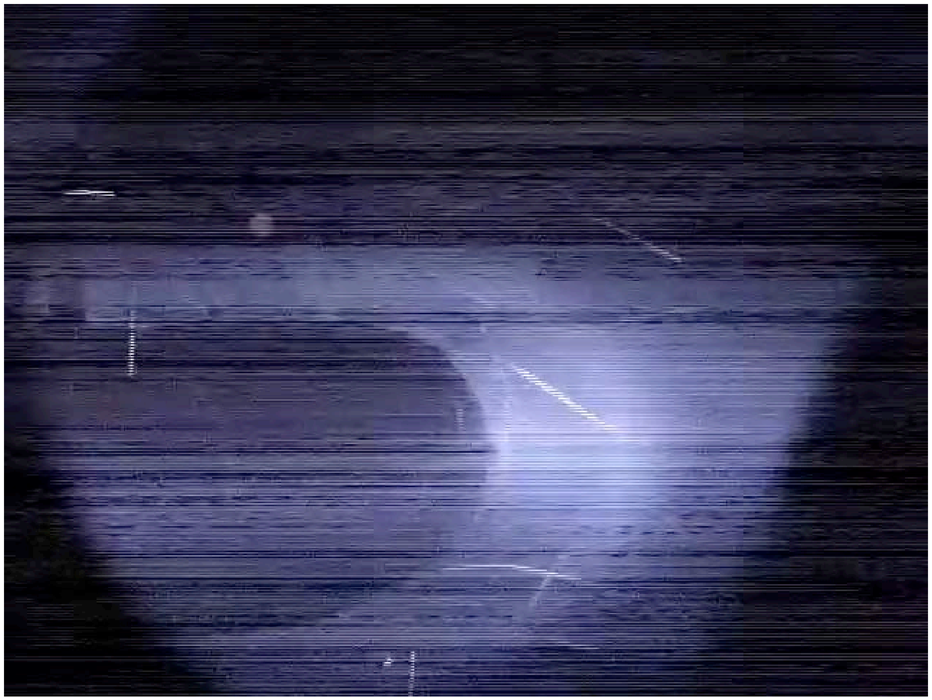
Plasma Diagnostic Set

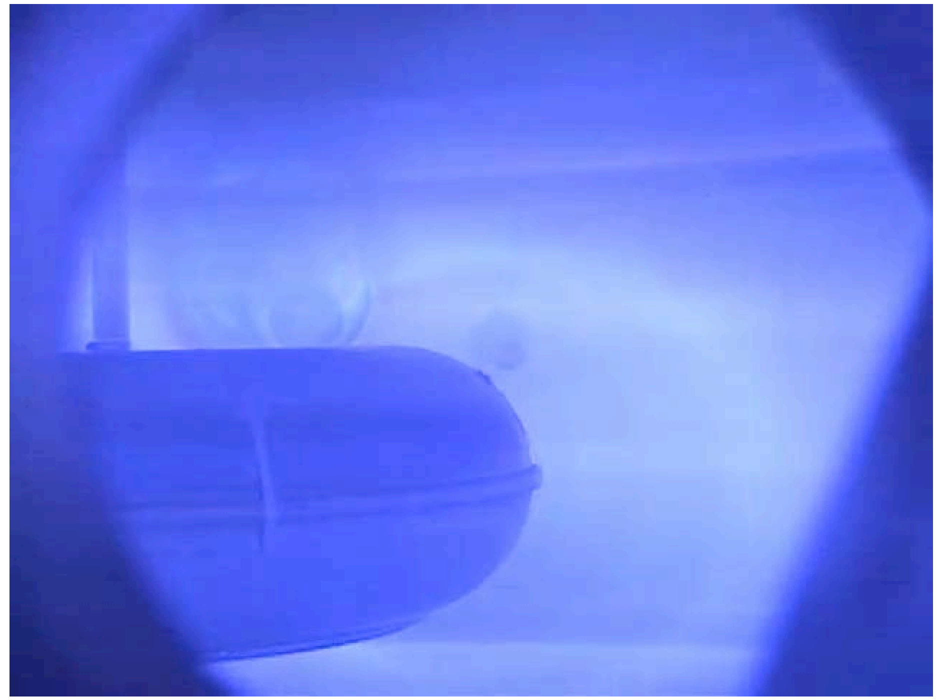
- Magnetic equilibrium
  - flux loops, Bp coils, Hall effect sensors
- Fast electrons
  - 4 Channel x-ray PHA, x-ray detector, Hard X-ray camera
- Core parameters
  - interferometer, visible cameras, visible diode and array
- Fluctuations
  - Edge Isat and Vf probes, Mirnov coils, visible diode array, 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
  - Initial unstable
  - Stable high-β
  - Afterglow

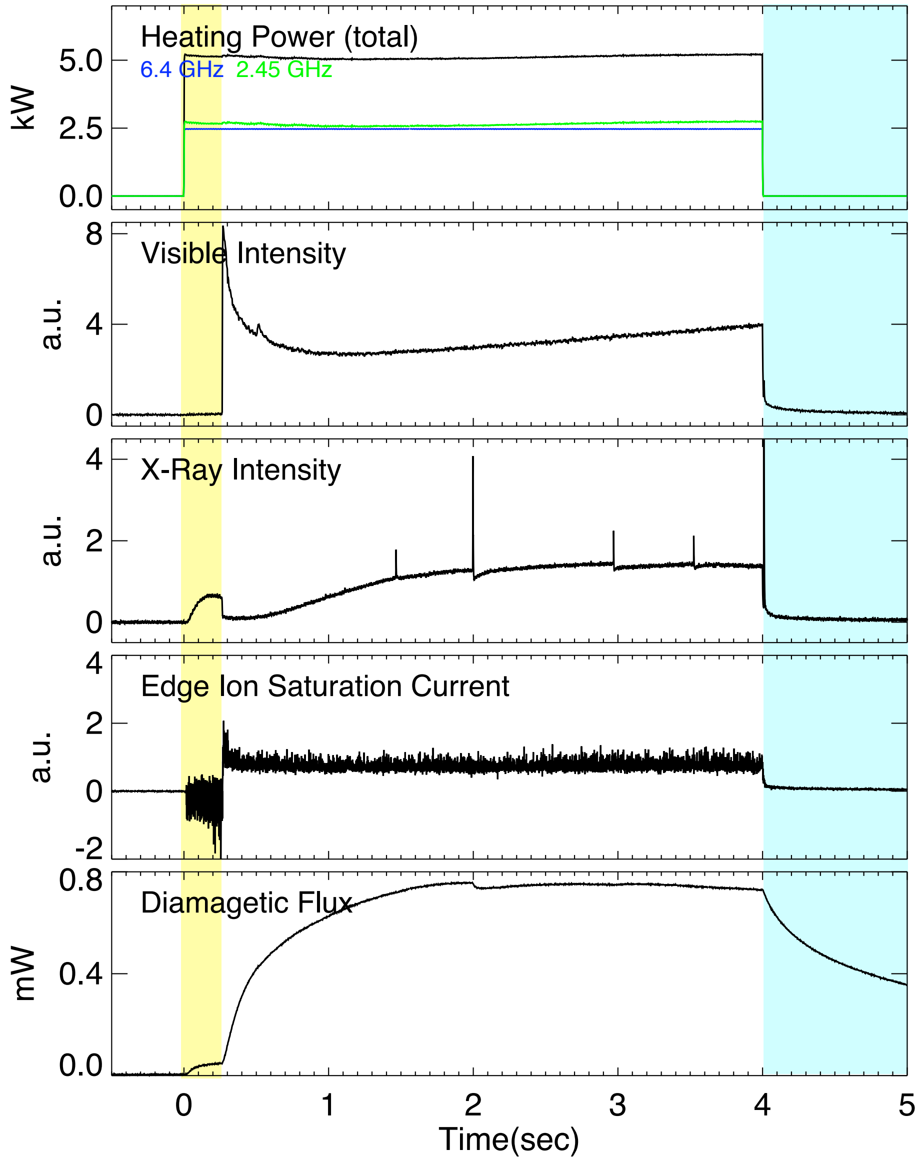
Unstable and Stable ECRH regimes





- Transitory unstable regime with small, localized plasma (anisotropic) and sparks caused by rapid radial loss of hot electrons to coil
- Bright ionization transition followed by steady large plasma with isotropic profile

Typical Shot: Indicates 3 regimes

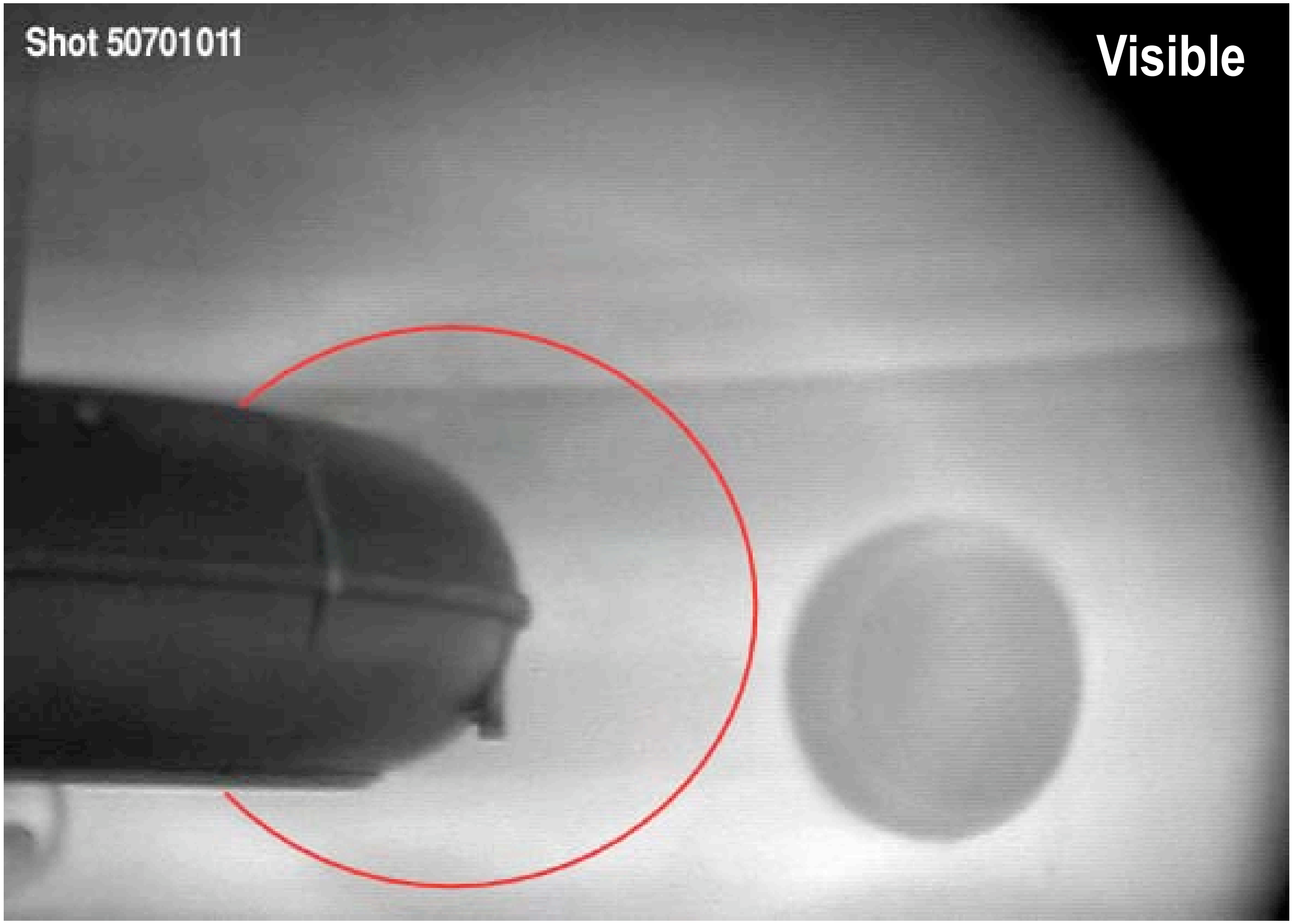


- **Unstable Regime:**
  - Fast electron radial transport
  - Low density
  - Low diamagnetism (low β)
- **High Beta Regime:**
  - Large diamagnetic current
  - Measurable density.
  - β loss events accompanied by xray bursts
  - Low frequency edge electric and magnetic fluctuations
- **Afterglow:**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

Characterizing the High Beta Regime

- Quasi steady state
- Bulk plasma has increased density
  - Edge density ~ 1 x 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

Fast Electrons: Anisotropic at ECRH Resonance



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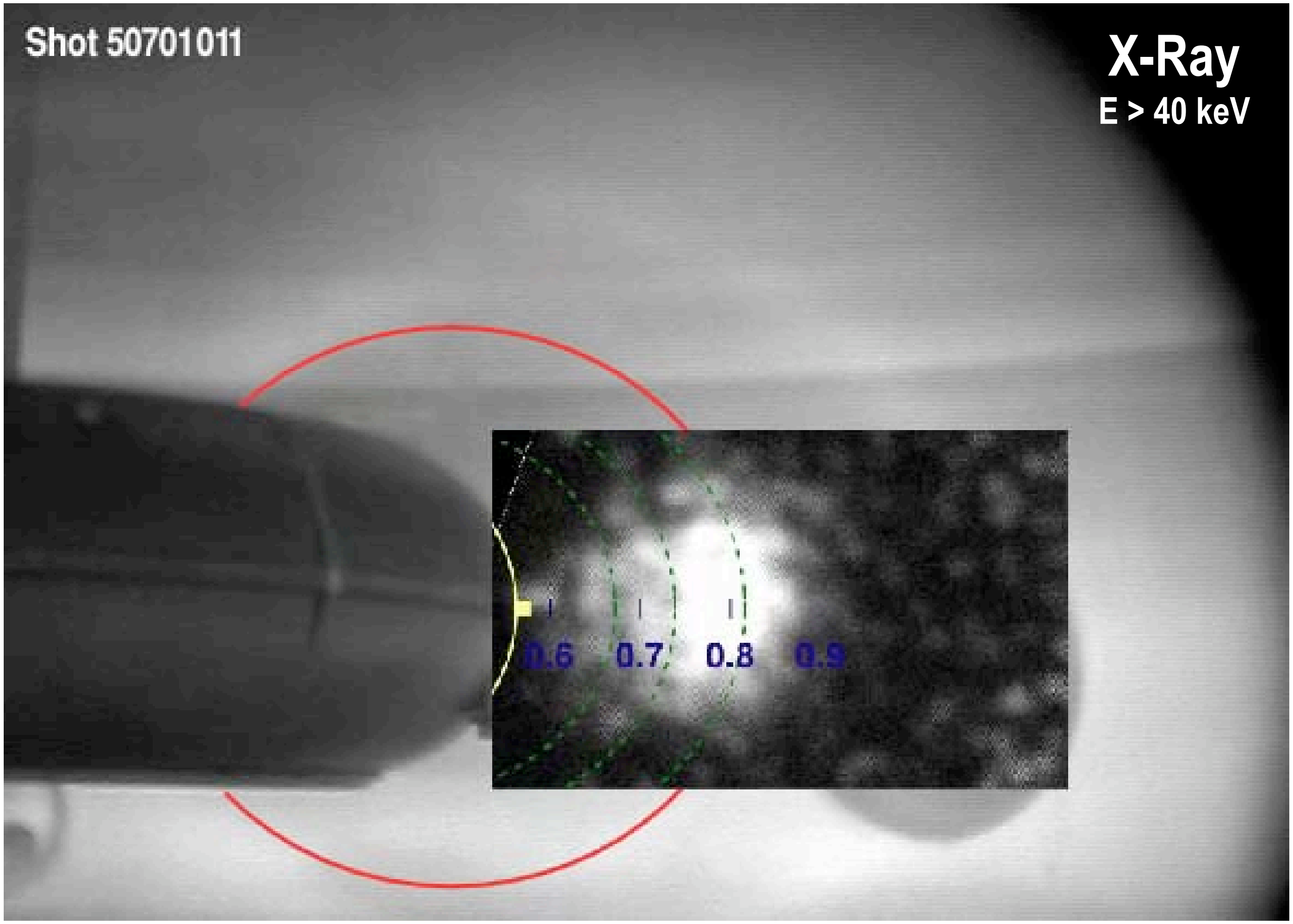
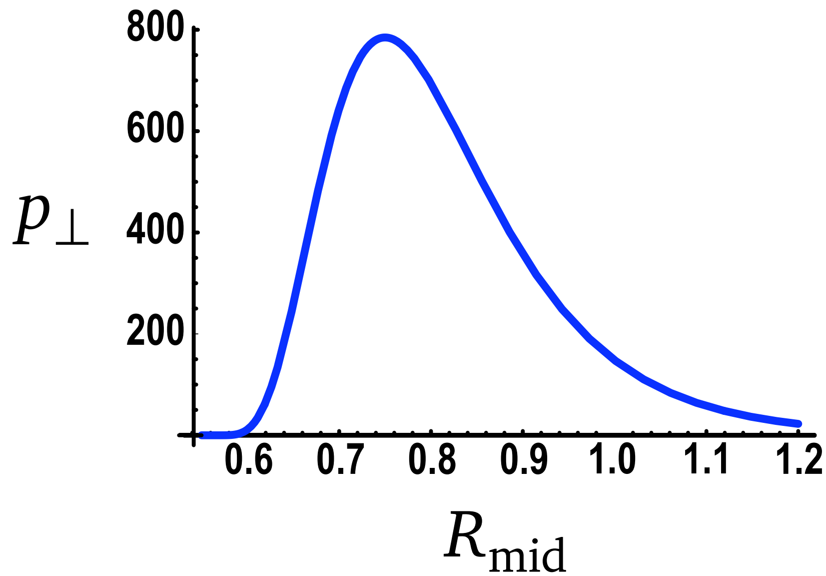


Magnetic Reconstruction

- 26 measurements used to reconstruct pressure profile
- Simple model with 4 unknowns:
  - Peak pressure, p_0
  - Peak major radius, R_p
  - Profile steepness, g
  - Anisotropy, $p_\perp / p_\parallel$
- Flux though superconducting dipole held constant

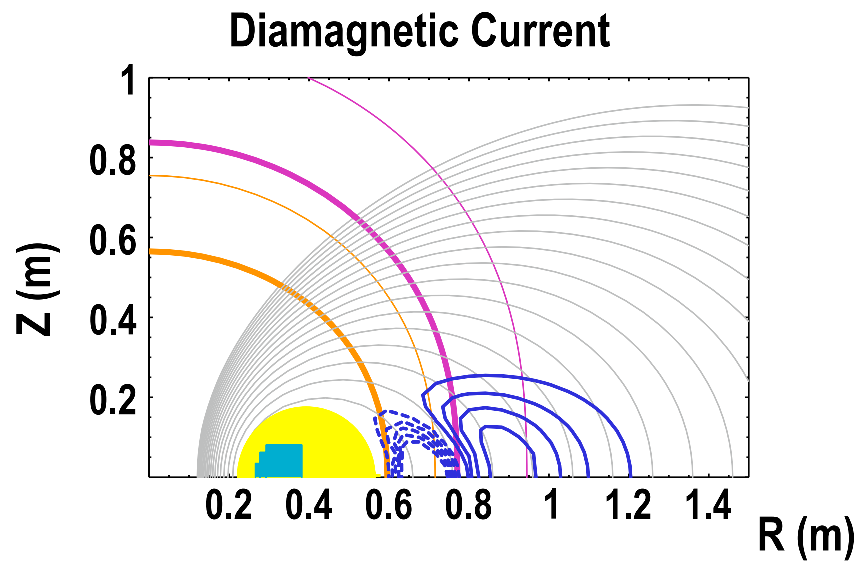
$$J_\phi = \frac{\mathbf{B} \times \nabla p_\perp}{B^2} + \frac{\mathbf{B} \times \kappa}{B^2}(p_\parallel - p_\perp)$$

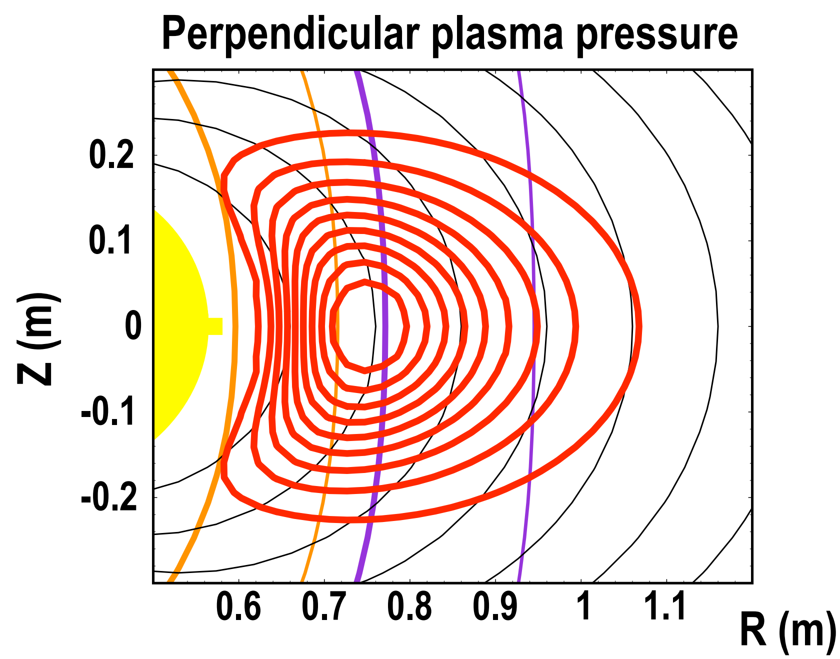
$$p_\perp \approx p_0 \left(\frac{R_p}{R_{\text{mid}}}\right)^{4g} \left(\frac{B_{\text{mid}}}{B}\right)^{p_\perp/p_\parallel - 1}$$



Anisotropic Magnetics Reconstruction

- Shot 50513029
- Fixed from imaging
  - R_{peak} = 0.75 m
  - $p_{\perp} / p_{\parallel} = 5$
- Magnetics fit
  - E_{total} = 330 J with 5 kW input
  - I_p = 3.4kA
  - β_{max} ~ 20%

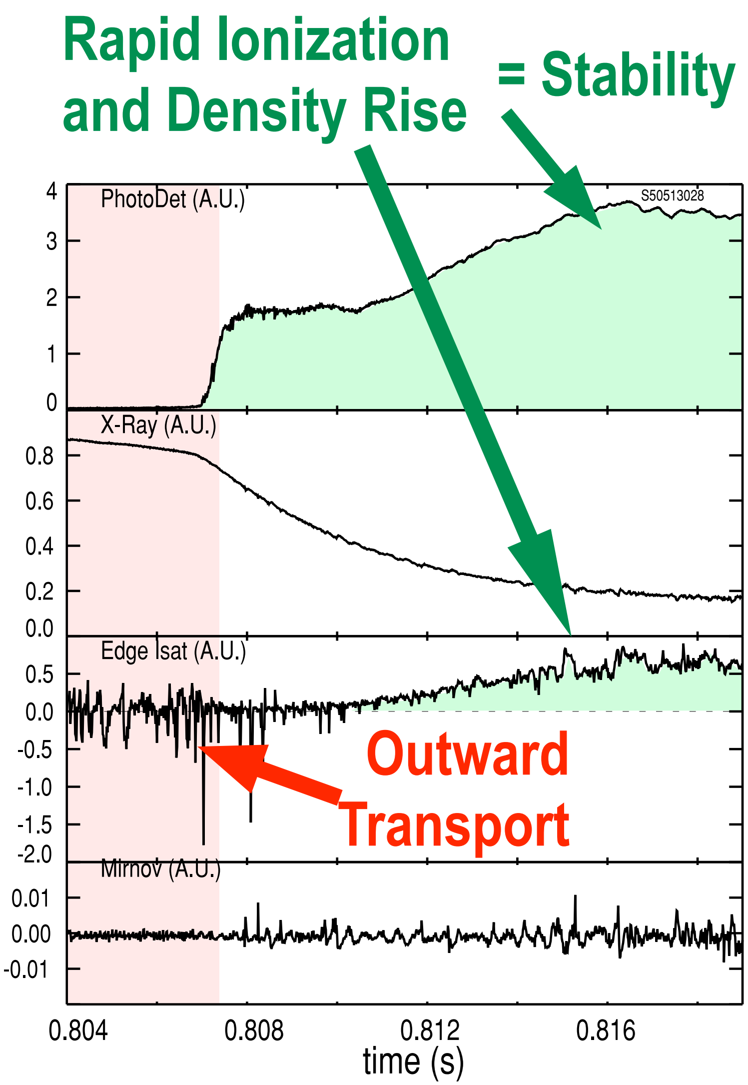




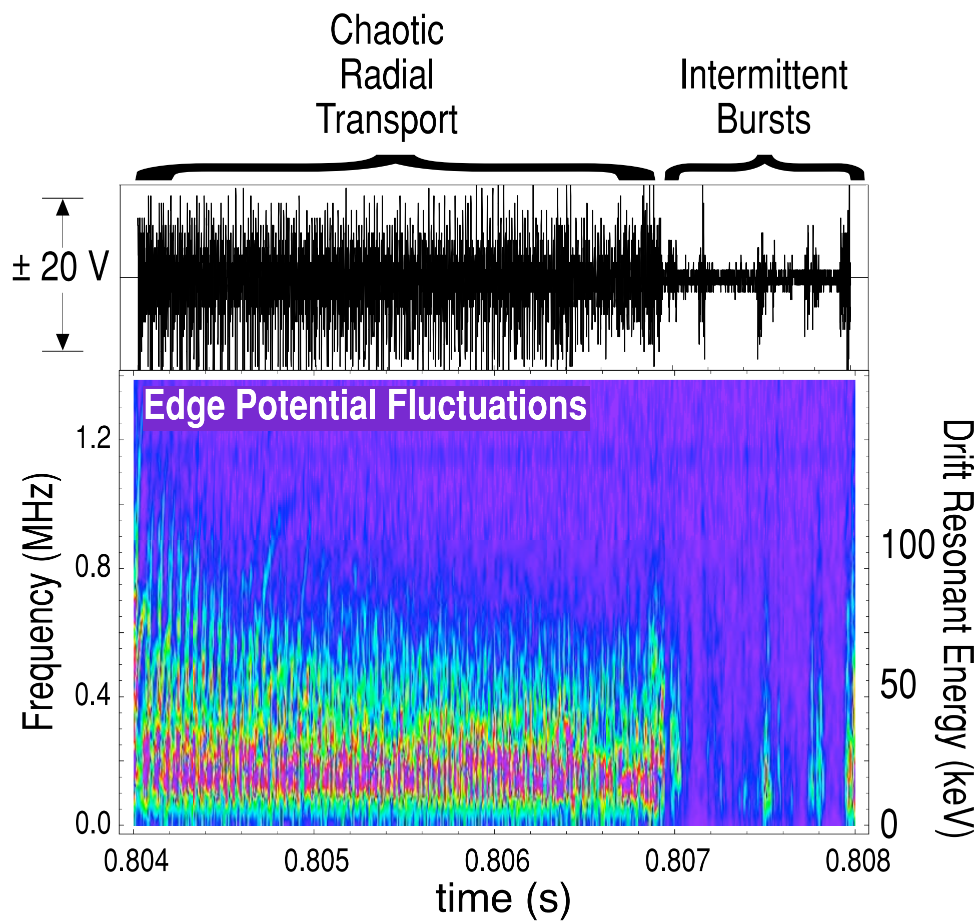
Controlling the High-β with Gas Puffing

- 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

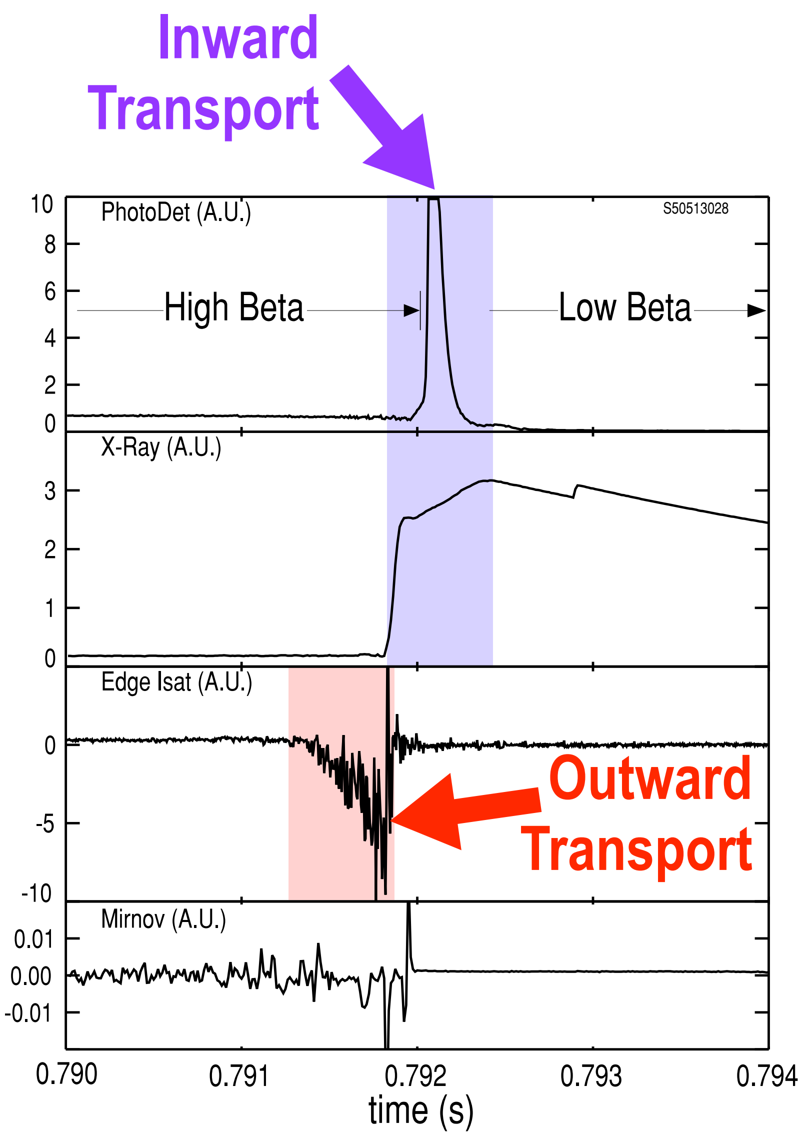
High-β Plasma Begins Upon HEI Stabilization



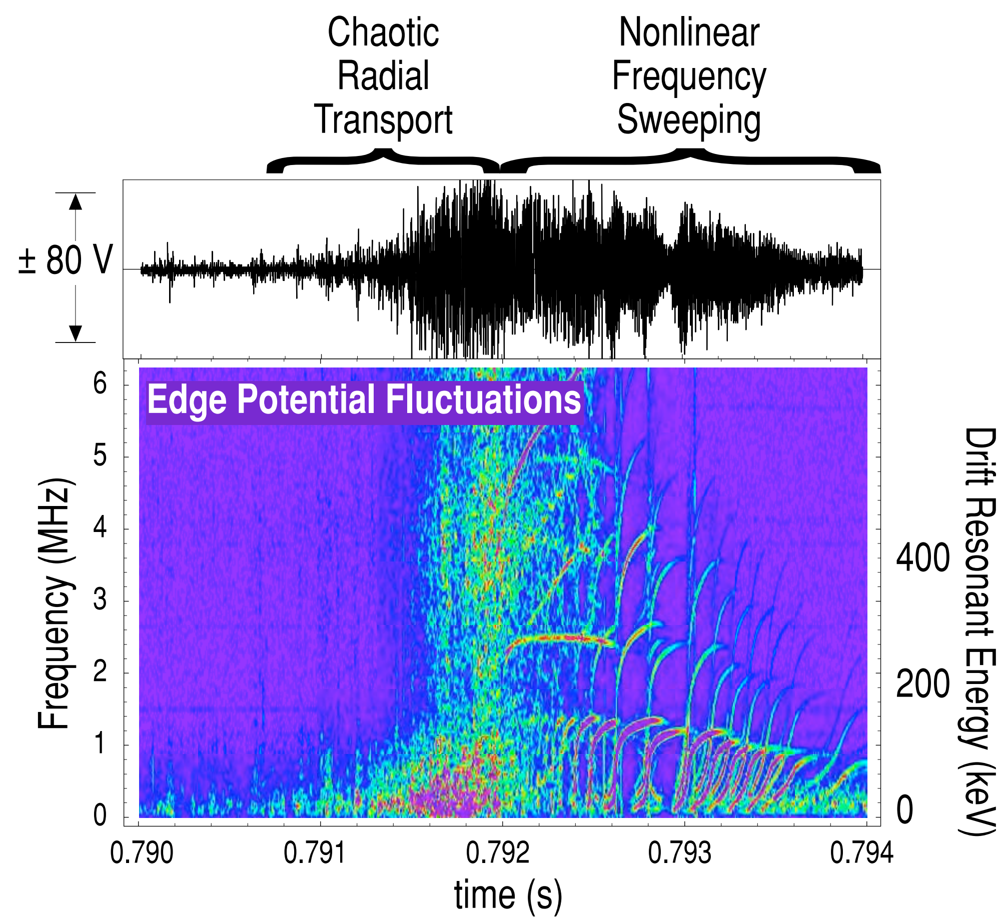
In unstable regime, quasi-continuous HEI instability prevents plasma build-up …



HEI Instability Can Terminate High-β Plasma



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



Insufficient Fueling Leads to Instability

- Plasma attempts to enter stable regime repeatedly

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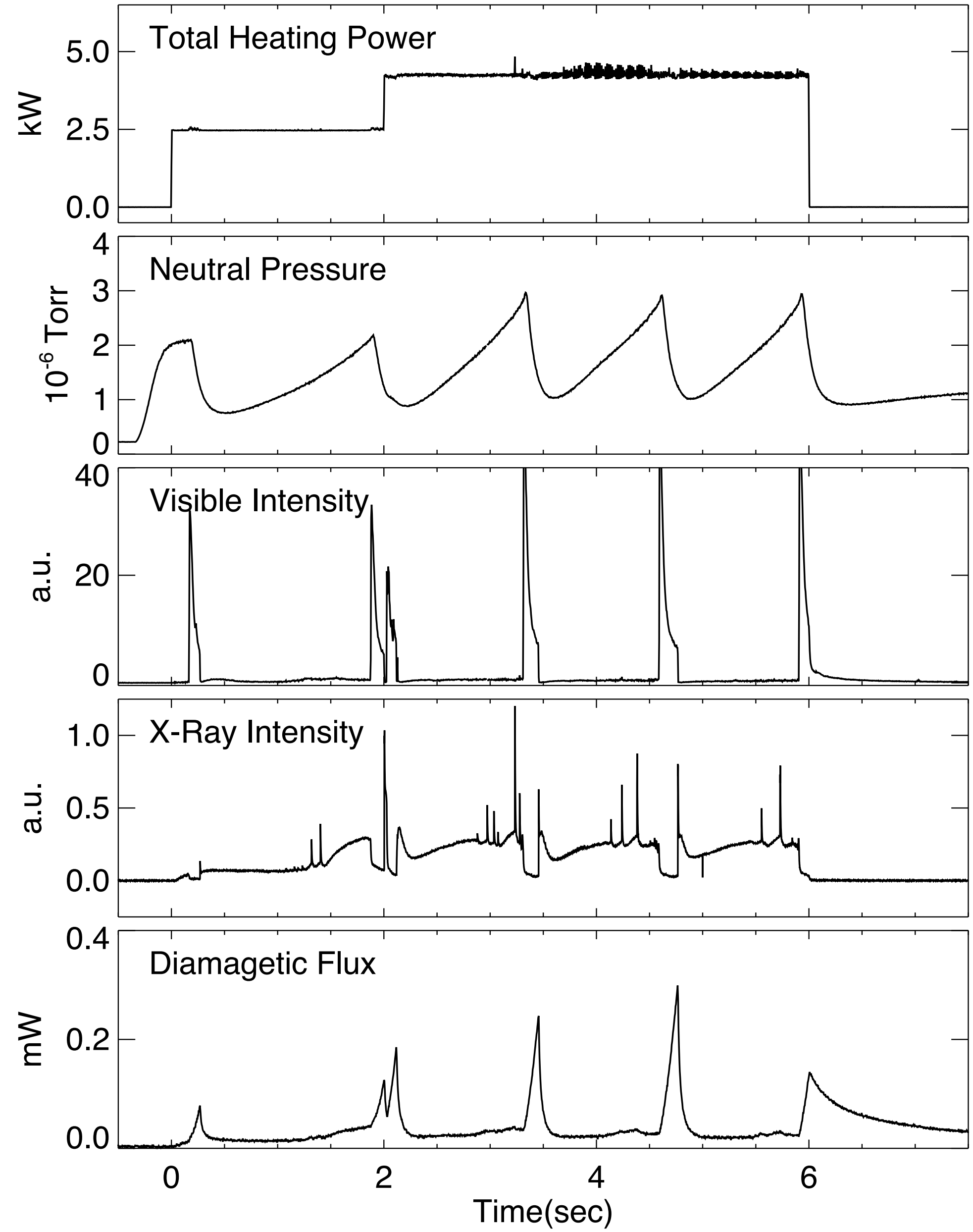
HEI ⇒ Hysteresis in Gas Requirements

- 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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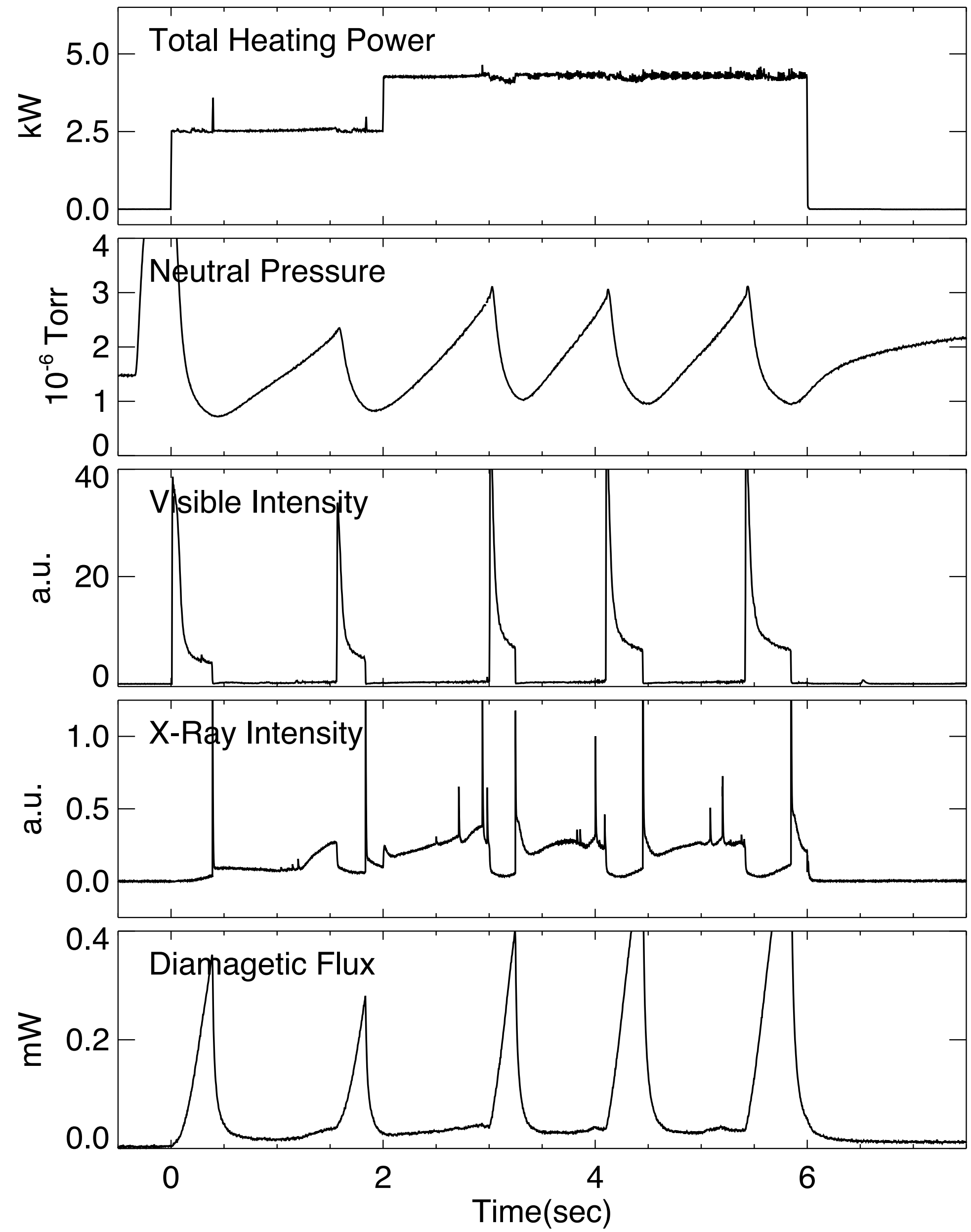


Hot Electron Interchange Stability

- **Bulk plasma must satisfy MHD adiabaticity condition**

Rosenbluth and Longmire, (1957)

$$\delta\left(p_b V^{\gamma}\right) = 0$$

where $V = \oint \frac{d\ell}{B}$

or

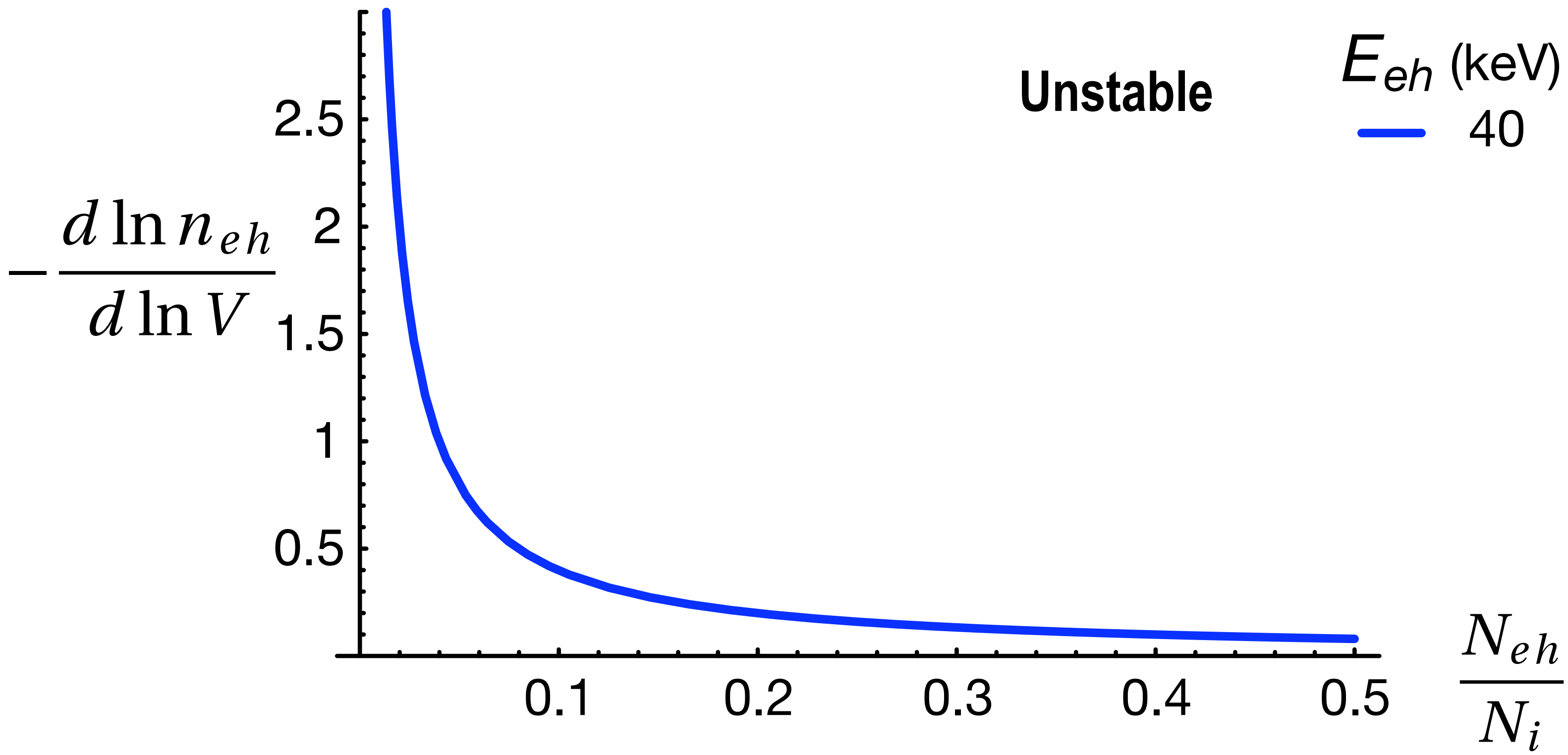
$$-\frac{d\ln p_b}{d\ln V} < \gamma^{-1}$$

- **Fast electron stability enhanced due to coupling of fast electrons to background ions**

Krall, (1966)

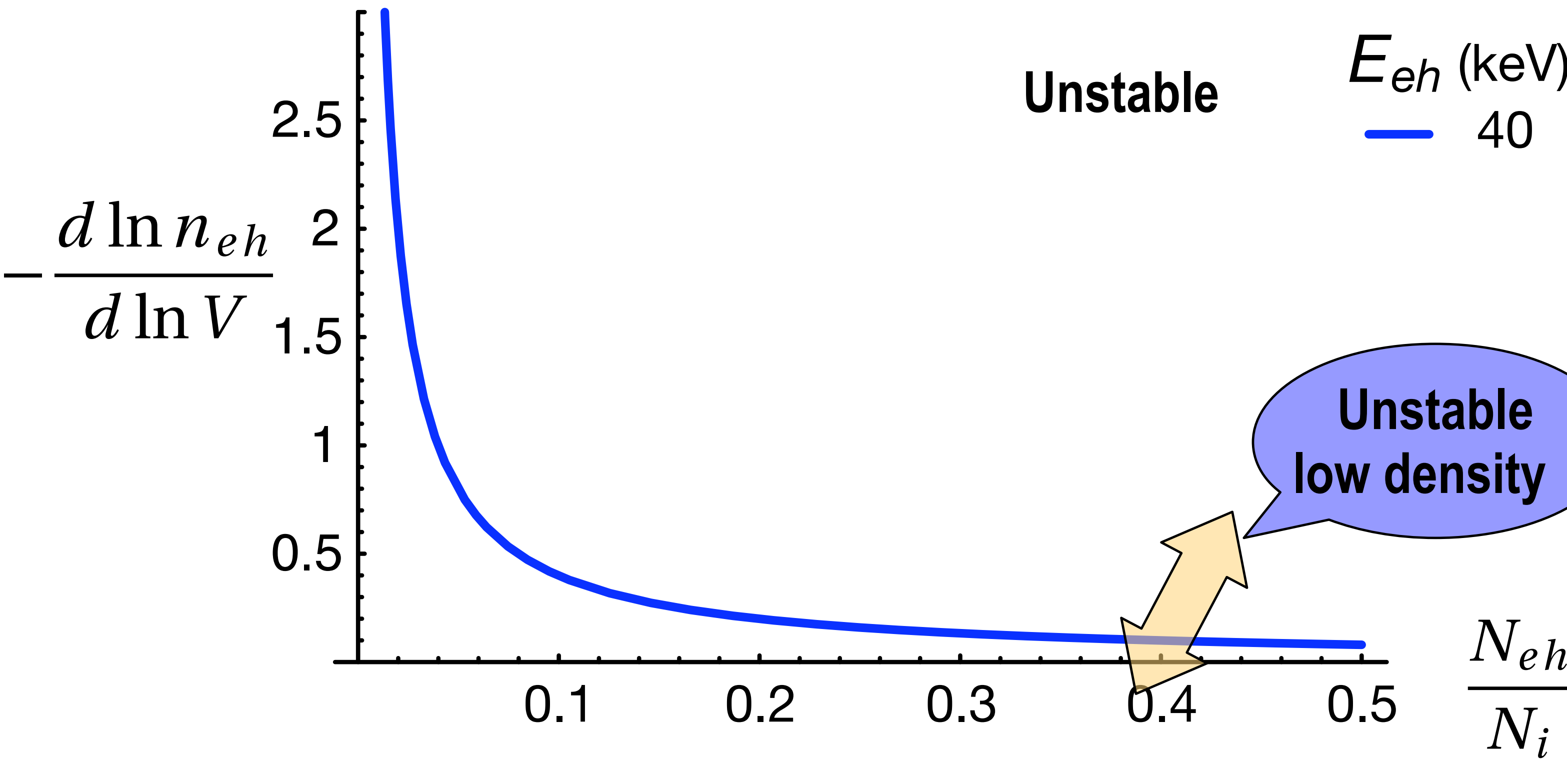
$$-\frac{d\ln n_{eh}}{d\ln V} < 1 + \frac{m_{\perp}^2}{24}\frac{\omega_{dh}}{\omega_{ci}}\frac{N_i}{N_{eh}}$$

Hysteresis in evolution of stability limit



- **Unstable regime has high f_{eh} and 40 kV electrons**
- **Increased gas fueling ⇒ stabilization ⇒ f_{eh} 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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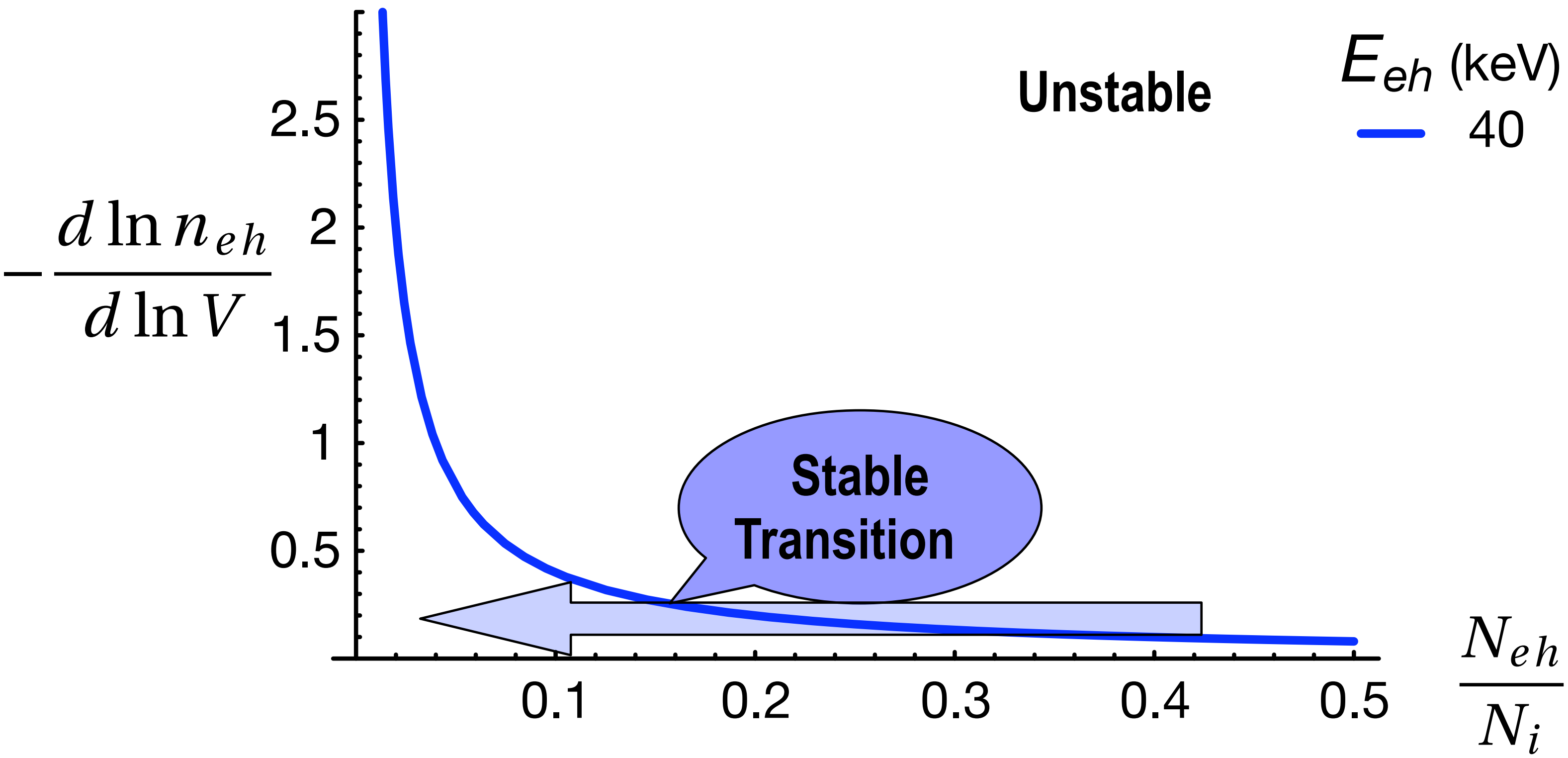

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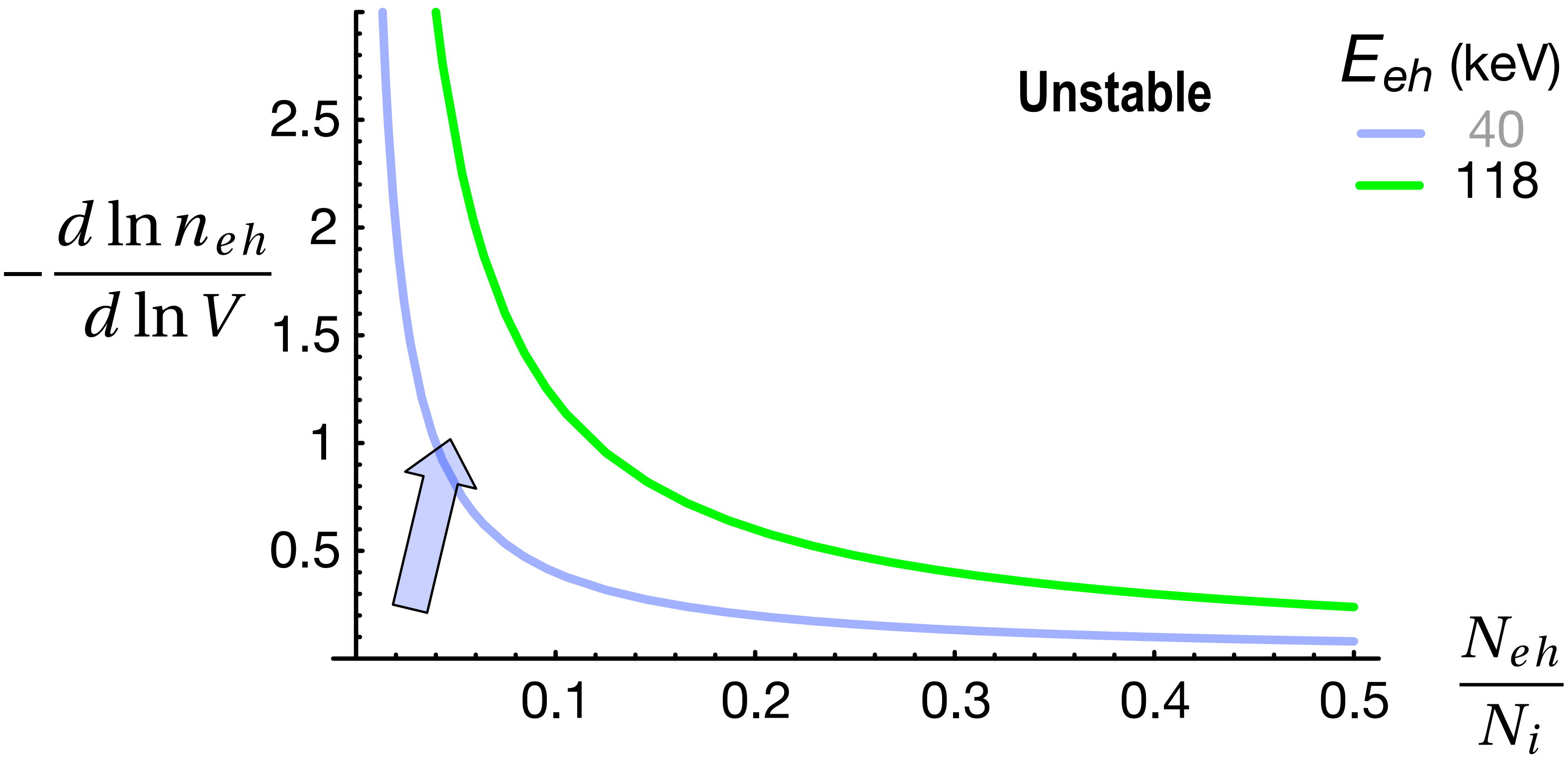

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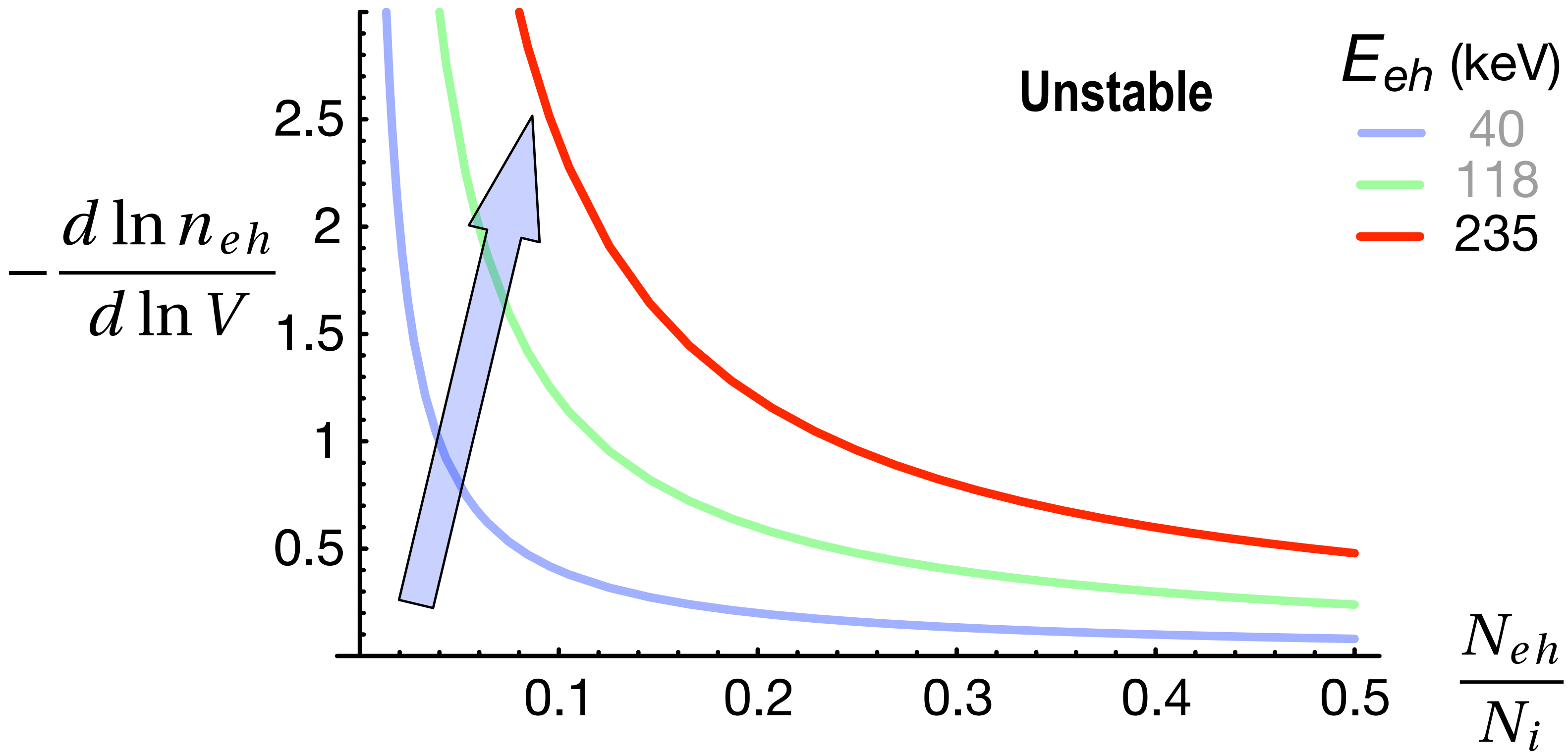

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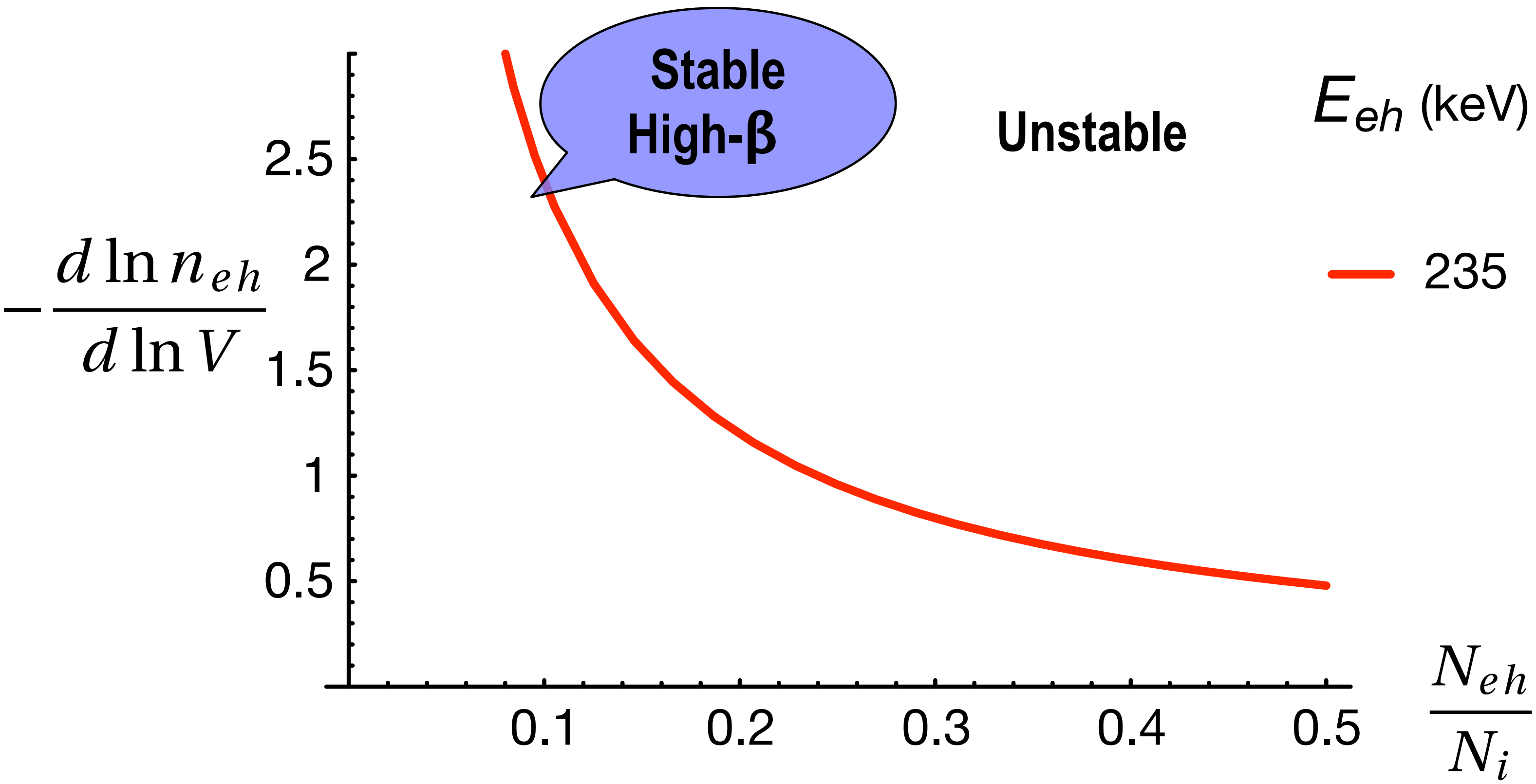

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Next Step: Levitation

- Fast electron losses to supports eliminated
  - Pitch angle scattering reduce anisotropy, not beta
  - Anisotropy driven modes relax plasma without losses
- Bulk plasma confinement also improved
  - Stable fast electron fraction with lower neutral gas fueling ?
- Radial transport driven profiles
  - Single peaked, broader (more stable) profiles

➡ **Expectation of improved stability and confinement**

  - Contrast with supported operation will further understanding of unstable/high-β regime bifurcation.

Summary

- Stable high-beta plasmas are created in LDX
  - Imaging shows highly localized peak near ECRH resonance
  - Magnetic reconstruction gives ~ 20% peak beta
  - Plasma losses are to thin dipole supports
- High beta requires sufficient neutral gas pressure to stabilize hot electron interchange mode
- Demonstrable hysteresis in threshold levels for transition to and from unstable regime

In case you missed the posters...

http://www.psfc.mit.edu/ldx

- Alex Boxer
  - Microwave Interferometer
- Jen Ellsworth
  - X-Ray Measurements
- Alex Hansen
  - Effect of ECRH Location on Confinement
- Jay Kesner
  - Hot Electron Instability in a Dipole
- Emmanual Mimoun
  - Photodiode Array Measurements
- Eugenio Ortiz
  - Probe Measurements of Electrostatic Fluctuations

The End

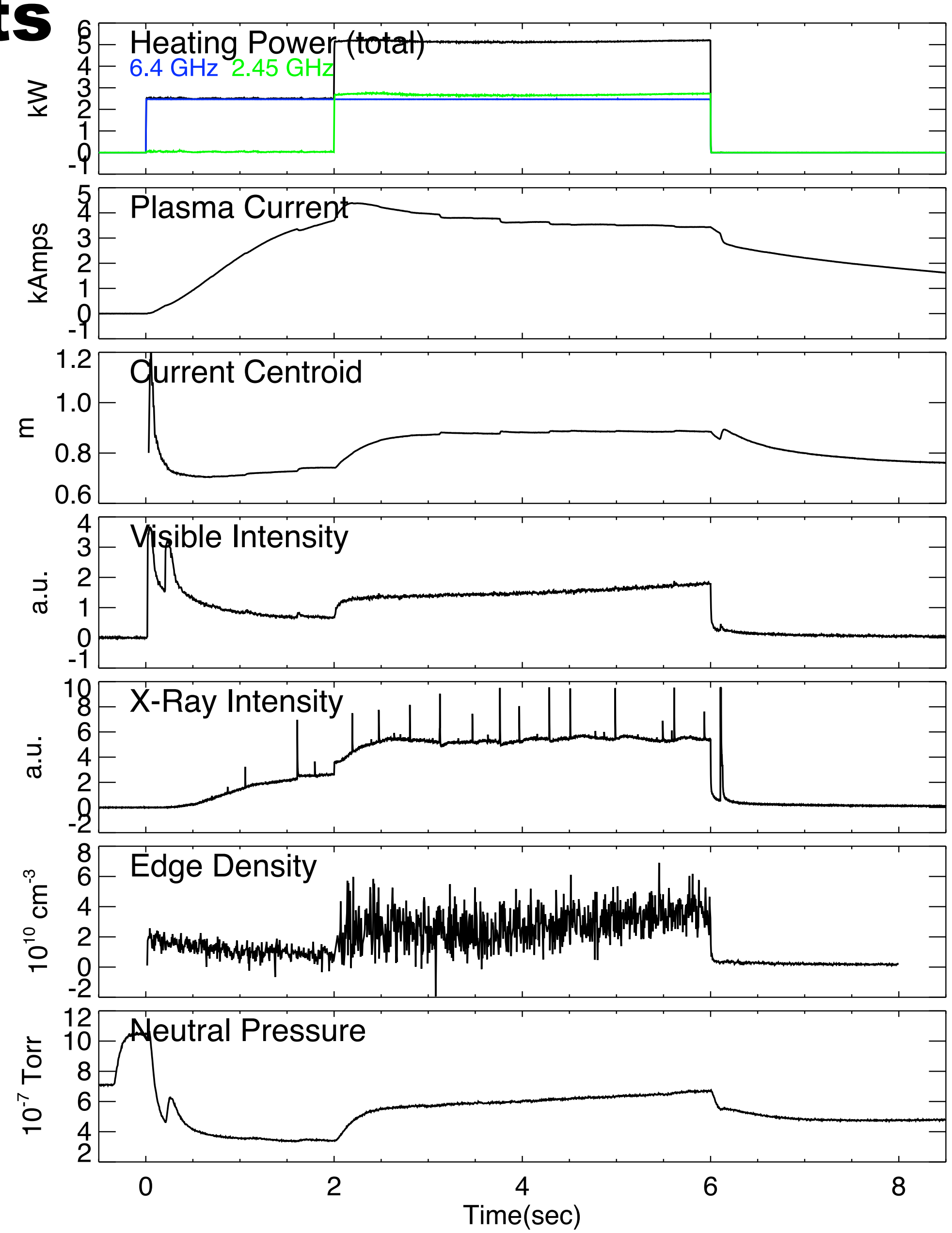
- What follows are extra slides that aren’t making it into the talk....

LDX High-β Plasma Parameters

- Density
  - Line average density 1-5 x 10^{10} / cc
  - Edge density 0.1-1 x 10^{10} / cc
- Temperature
  - Hot-electron energy 100-200 keV (and higher)
  - Edge temperature 10-20 eV
- Pressure
  - Edge 0.01 Pa, Core 500 Pa. --> Ratio ~ 50000
  - Beta (local maximum) ~ 20%
- Confinement
  - Stored energy ~ 400 J with 5 kW input power
  - τ_E ~ 80 msec.

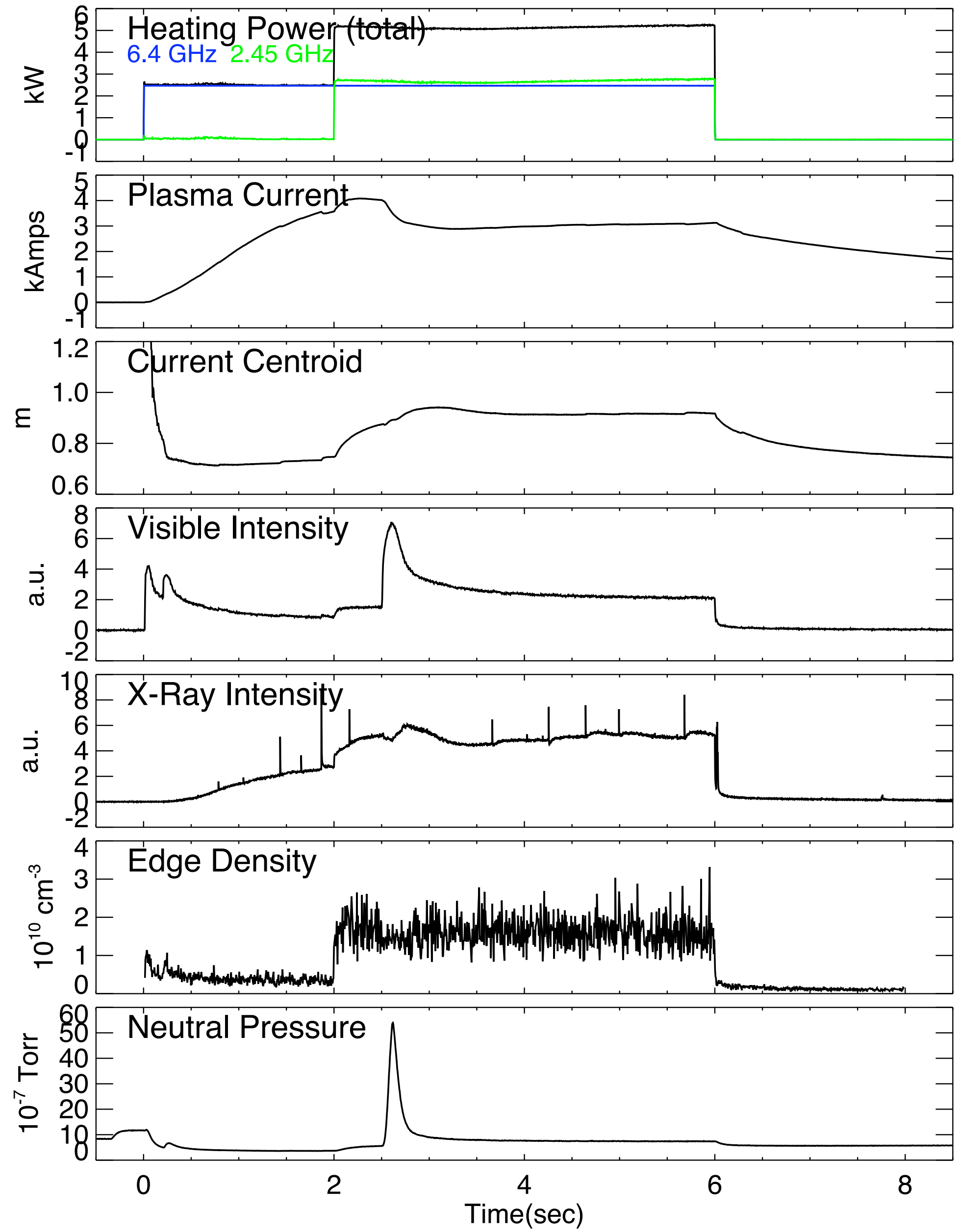
Controlling HEI Bursts

- Different run day
  - Wall conditioning not quite so good
- Typical high beta regime
- Many small HEI modes
  - Does not lead to beta collapse
- Marginal stability?



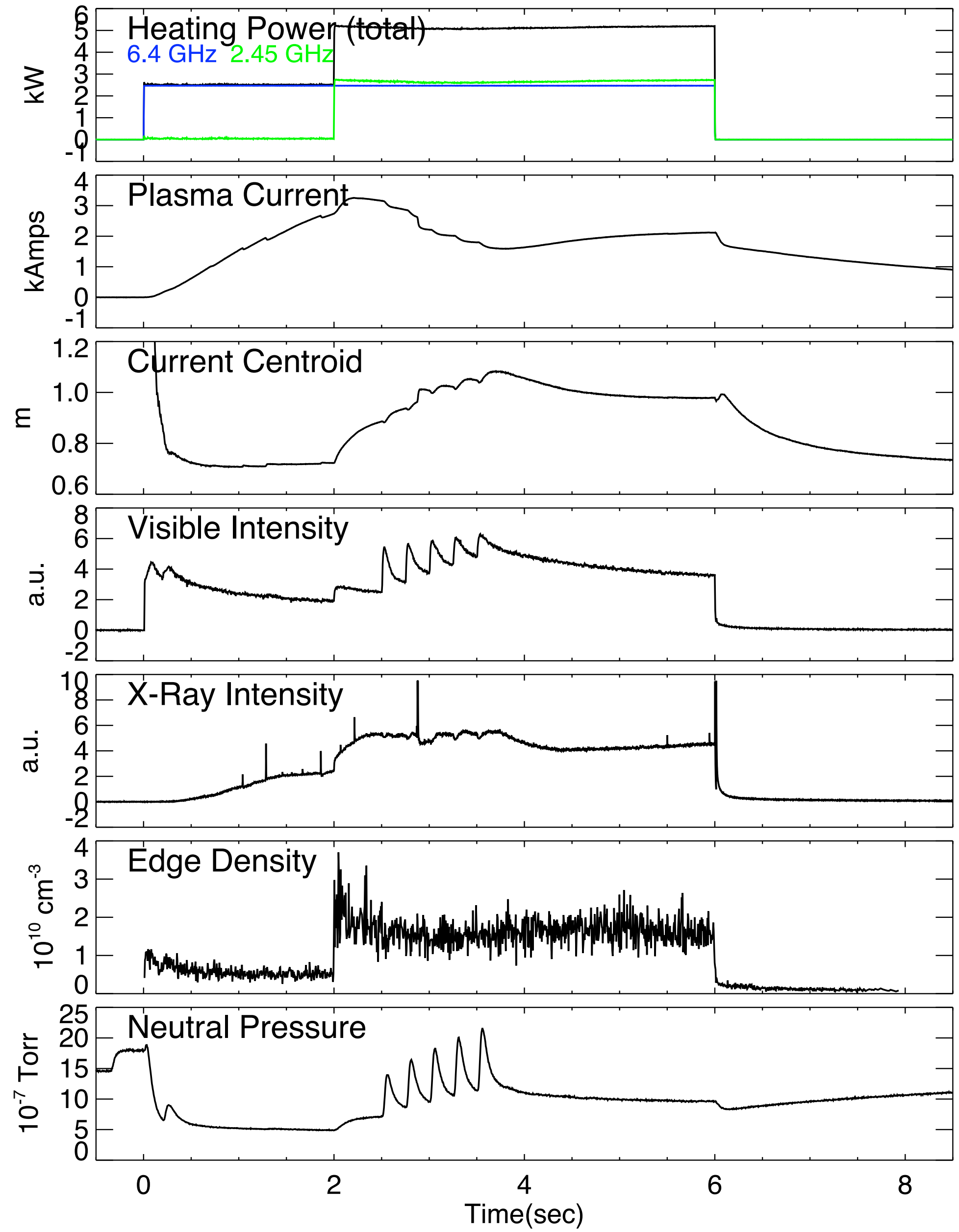
More gas!

- Same conditions as previous shot
- Large puff at 2.5 s
- Stabilizes small HEI
  - More background density

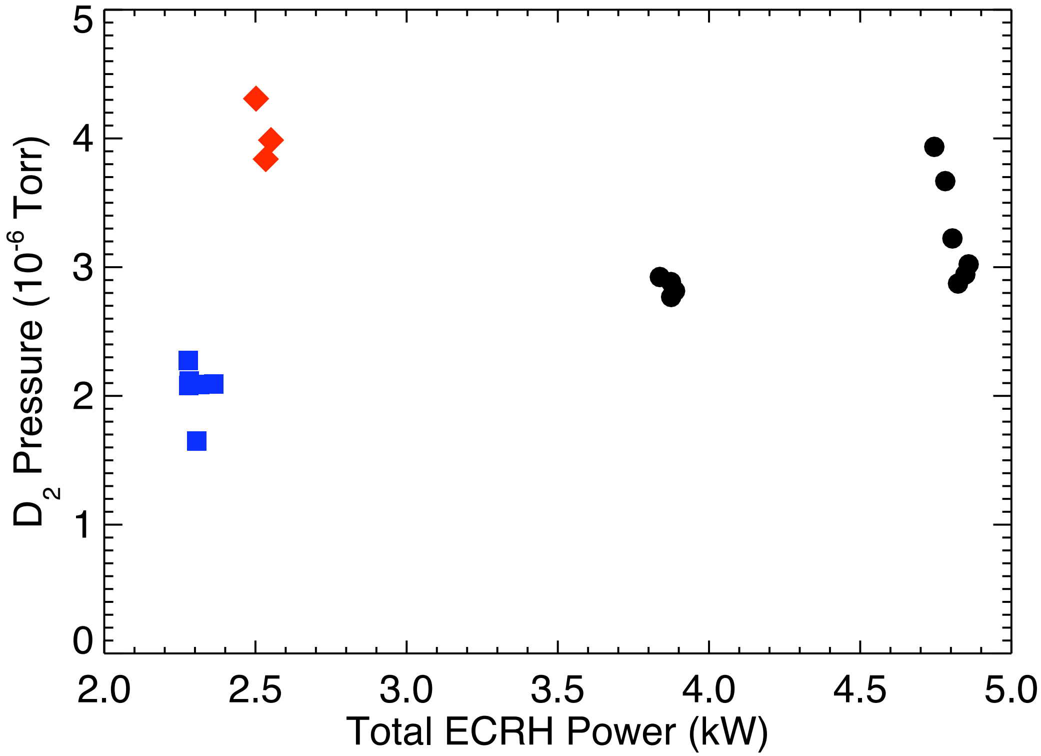


Even more?

- That did it.
  - But stored energy is reduced due to increased pitch angle scattering of fast electrons



Observed hysteresis in gas fueling at transitions



- **Clear separation between stability onset and loss of stability**
- **Trend seen with 6.4 GHz power level**
  - **More power requires more fueling**
- **Not shown: also trend seen with shaping coil current**
  - **Required gas pressure increases with decreasing plasma size**