Effects of the Hot Electron Interchange Instability on Plasma Confined in a Dipolar Magnetic Field

Eugenio Ortiz

For the Levitated Dipole Experiment Team

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Outline

- Motivation for Dipole Fusion Concept
- Levitated Dipole Experiment (LDX)
  - Operation and plasma formation
  - Measurement of anisotropic high beta equilibrium
- Hot Electron Interchange (HEI) Instability
  - Dominant instability in LDX
  - High beta achieved only when HEI is stabilized with fueling
  - New observations of HEI in high beta

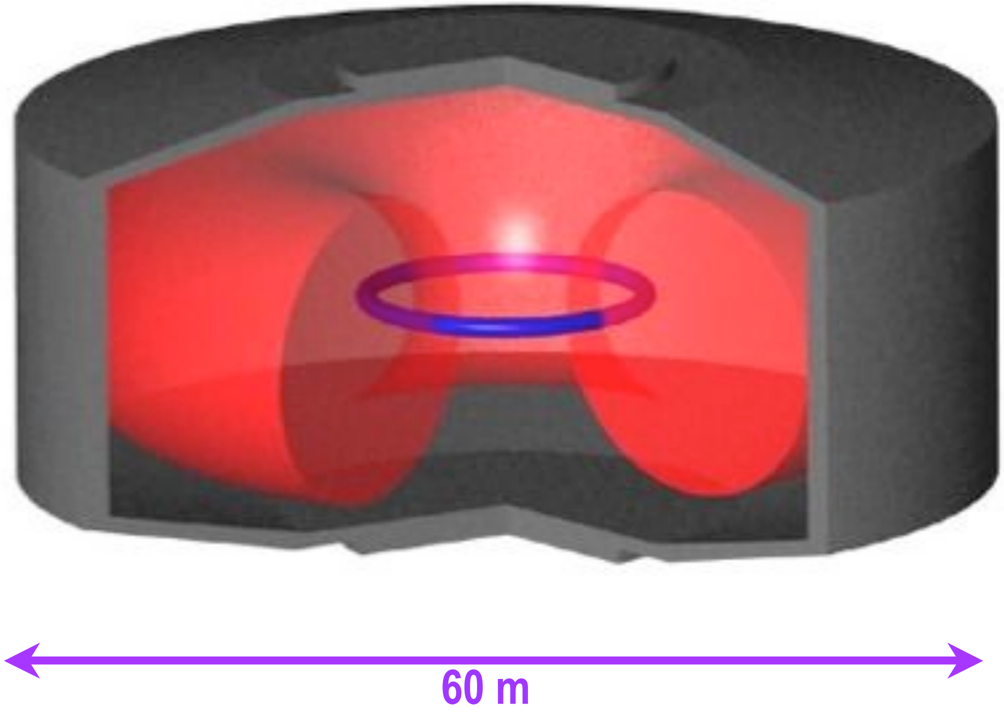
Levitated Dipole Fusion Concept

Key Advantages

- Internal ring with large plasma volume
- Simple non-interlocking coils design; good field utilization
- Steady state; High **beta**
- Theory suggests energy confinement can exceed particle confinement
- Advanced fuel cycle

Levitated Dipole Reactor

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



500 MW
D-D(He^3) Fusion

Investigating the Dipole Concept

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

LDX Phase I

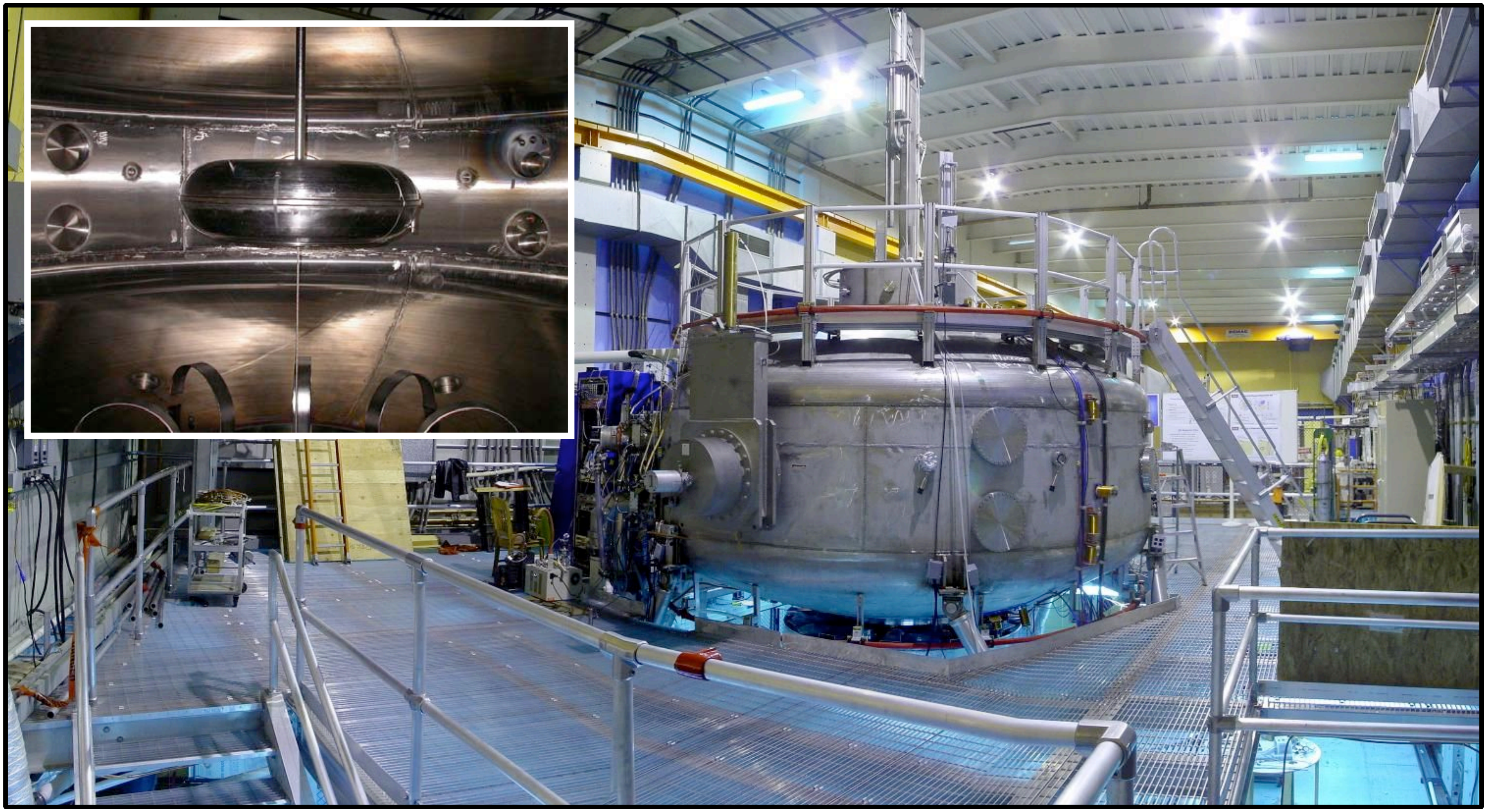
- Energy Confinement:
  - Sufficient to burn advanced fusion fuels?
- Particle Confinement:
  - Can convection decouple τ_p and τ_E ?

LDX Phase II

Levitation

- Engineering:
  - Superconducting magnet surrounded by fusion plasma?

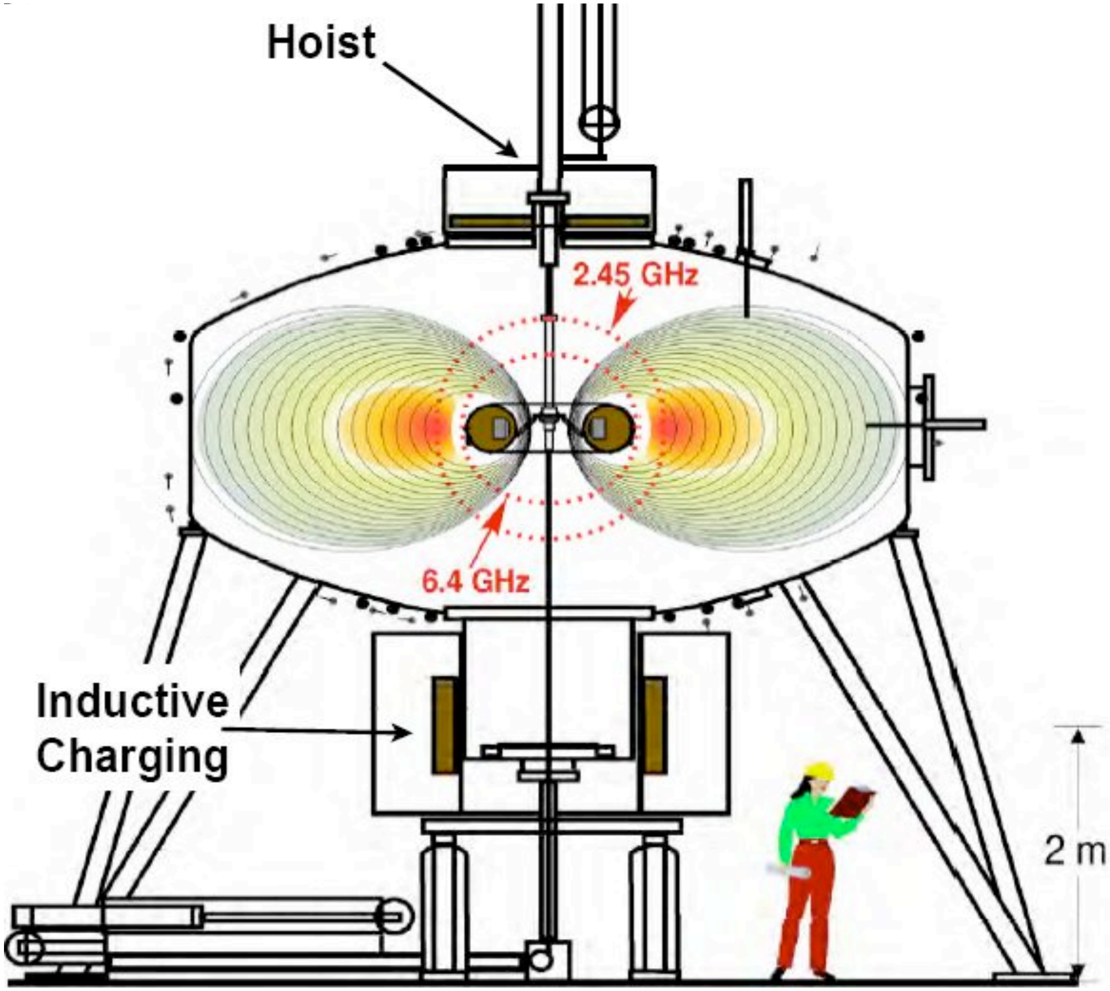
The Levitated Dipole Experiment (LDX)



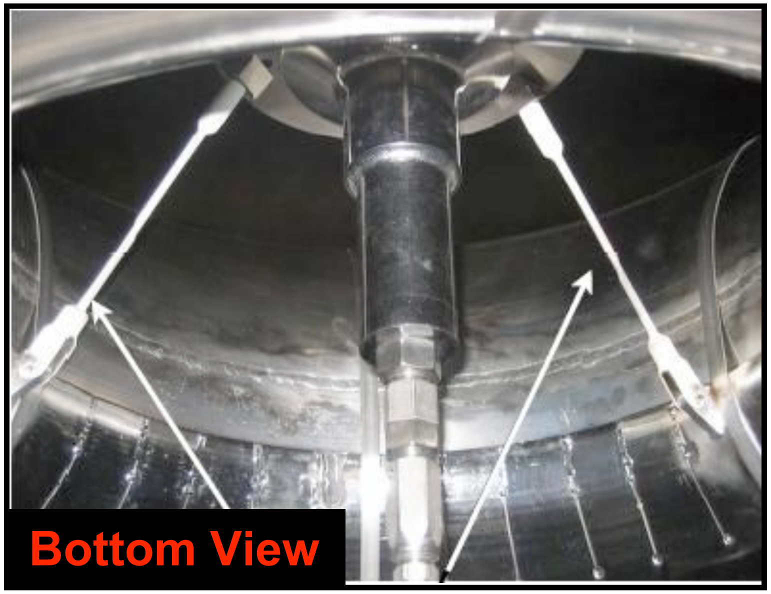
LDX Cross-Section/Operation

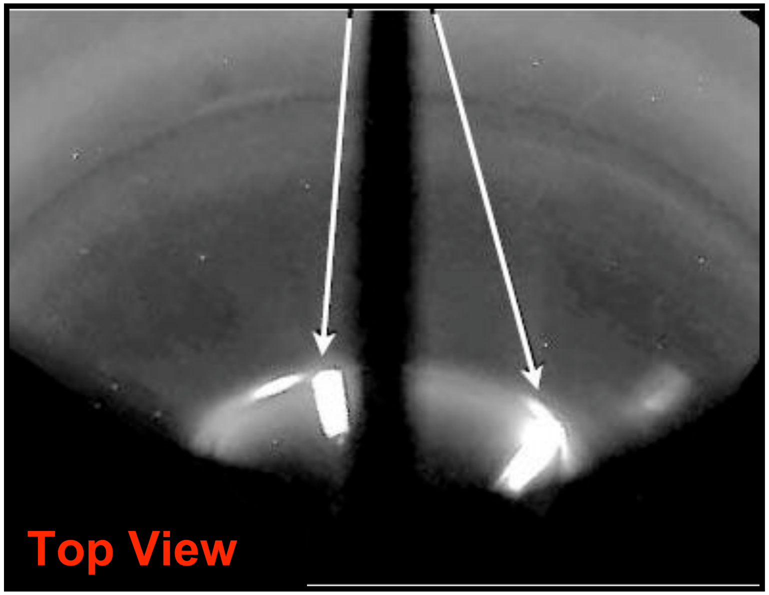
Supported Mode

1) Liquid Helium cools F-coil in charging station
2) Inductively charge F-coil (1 MA), C-coil discharges
3) Lift F-coil into position
4) Use ECRH (5 kW); create plasma
5) Run experiments safely for two hours
6) Lower F-coil back to re-charge or discharge into charging station



Floating Coil Held Up by Thin Supports



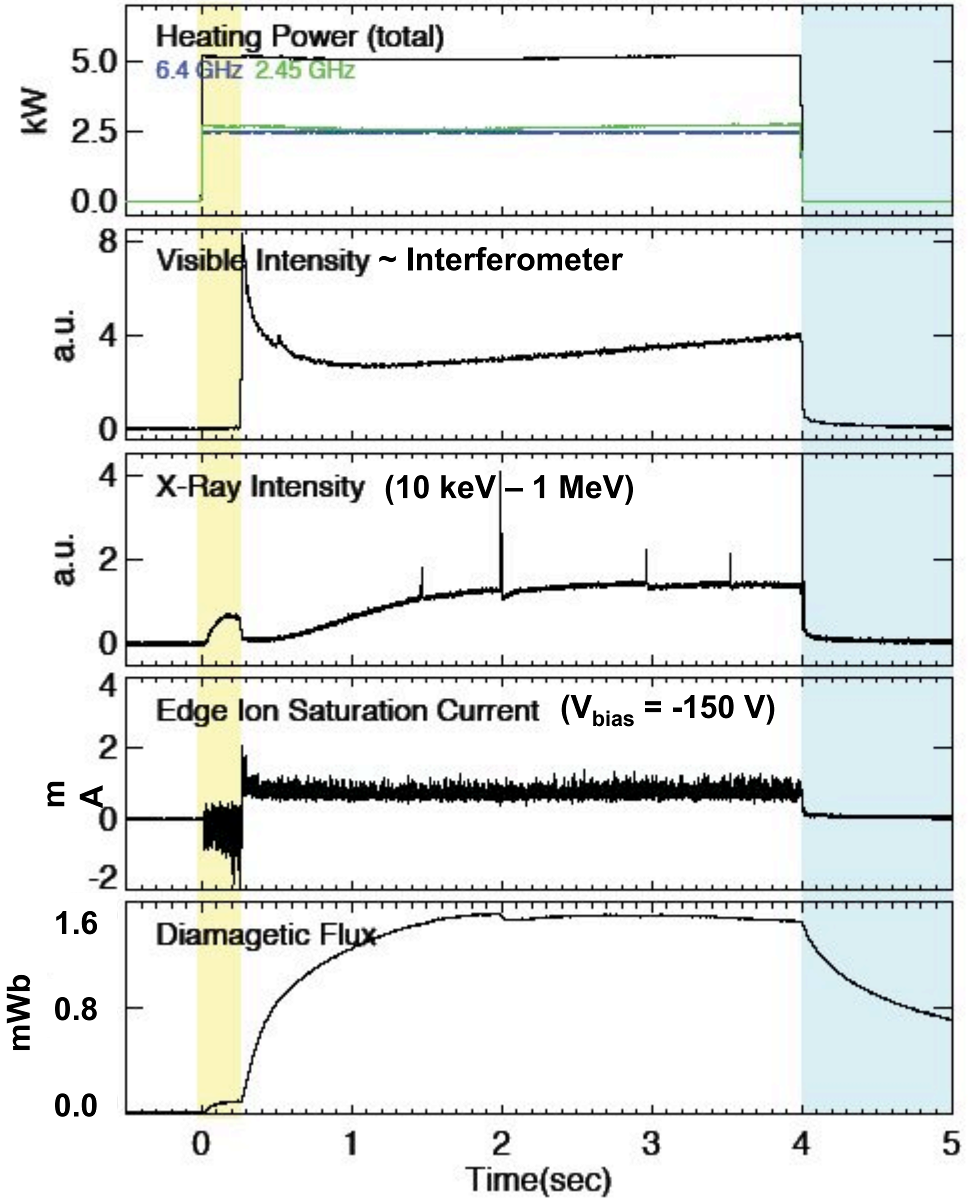


Three high-strength, alumina-coated spokes support the floating coil during Phase I

Thin supports remain a major power loss

Typical High Beta Discharge

- High beta maintained in quasi-steady state
- Plasma diagnostics:
  - External magnetic flux loops, pick-up coils and hall sensors
  - X-ray detectors
  - Visible diode array
  - Fixed & swept Langmuir
  - Interferometer
- HEI observed during three distinct intervals
  1. Unstable plasmas
  2. High beta plasmas
  3. Afterglow plasmas



Magnetic Reconstruction of Plasma Equilibrium

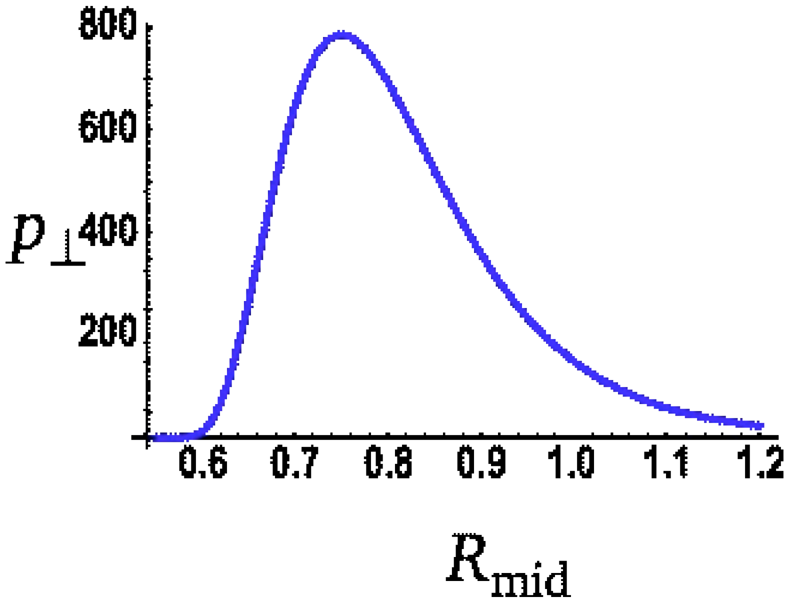
- 26 measurements used to reconstruct pressure profile

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

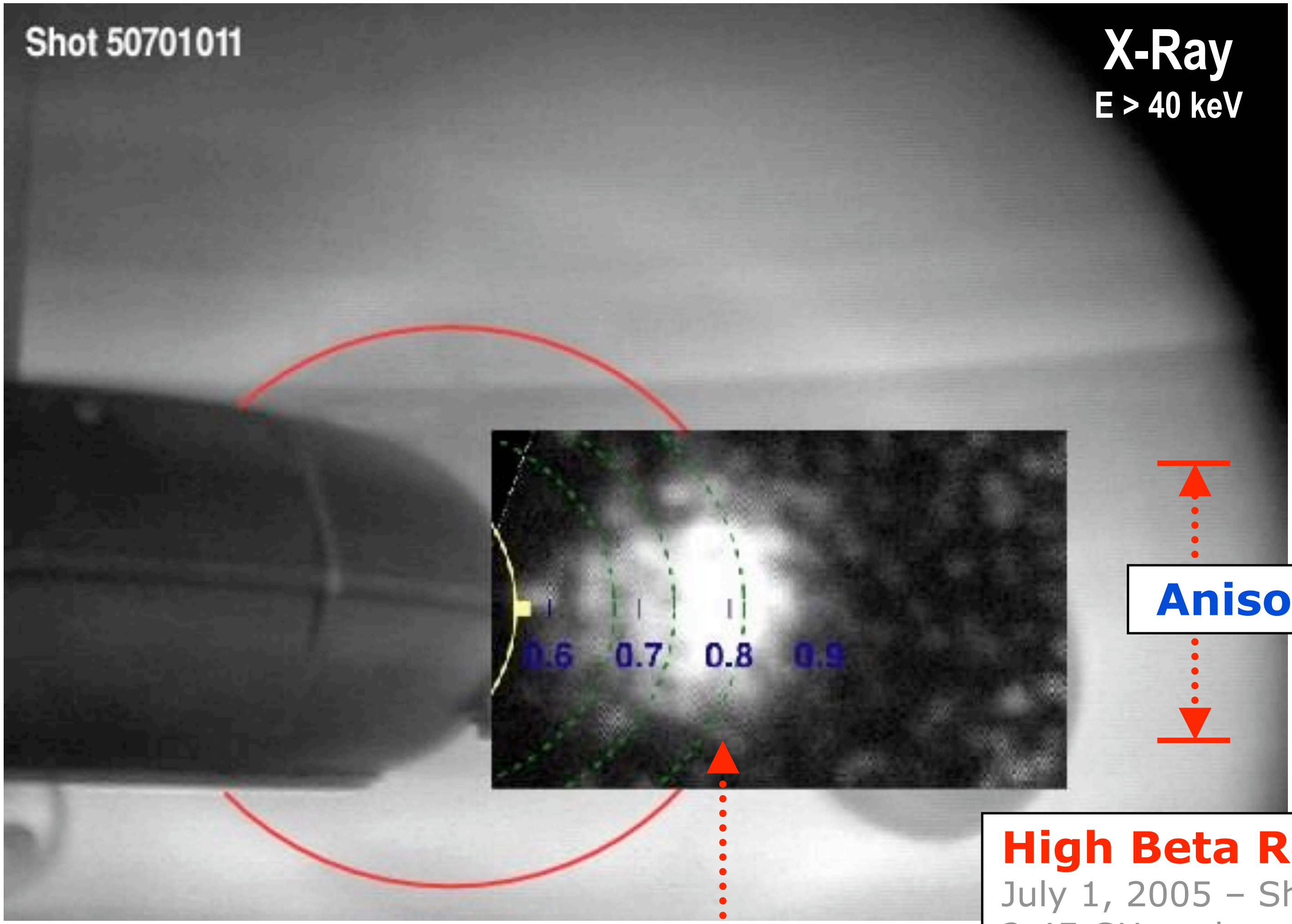
- Simple model with four unknowns:
  - Peak pressure, p_0
  - Peak major radius, R_p
  - Profile steepness, g
  - Anisotropy, $p_\perp / p_{II}$

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

- Constraints:
  - Flux through superconducting dipole held constant
  - R_p determined from X-ray camera image



Anisotropic Fast Electrons Localized to ECRH Resonance



Anisotropic

High Beta Regime

July 1, 2005 – Shot 11

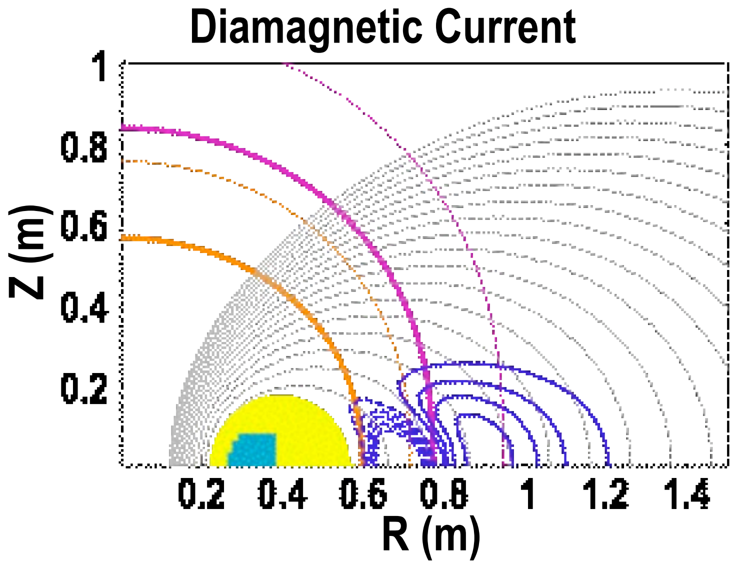
2.45 GHz only

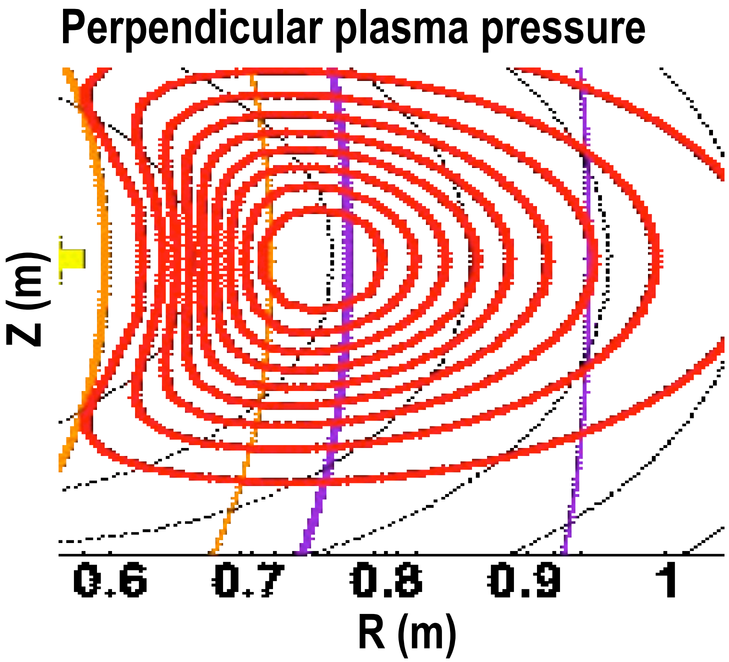
Localized to ECRH

Record High **Beta** Discharge

- Shot 50513029
    - Optimal gas fueling
- Fixed from imaging
    - $R_{\text{peak}} = 0.75$ m
    - $p_{\perp} / p_{//} = 5$
- Magnetics fit
    - $E_{\text{total}} = 330$ J with 5 kW input
    - $I_p = 3.4$kA
    - Peak local **Beta** = 20%
- Equilibrium exceeds ideal MHD limit due to compressibility

$$\frac{-d \ln P}{d \ln V} > \frac{5}{3}$$





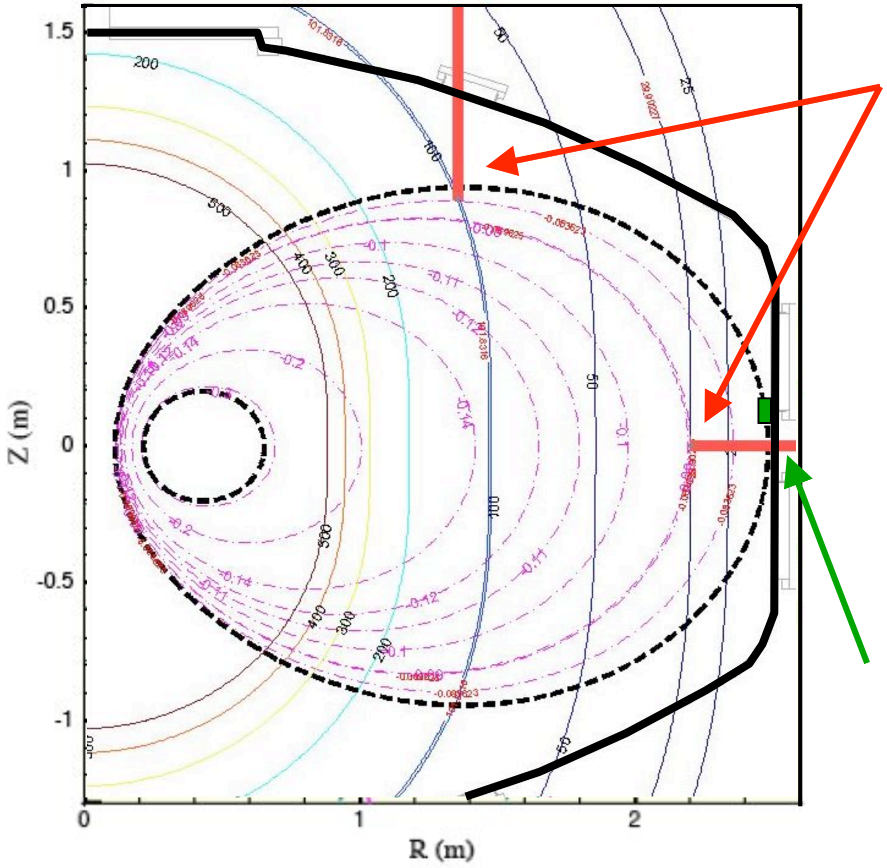
High **Beta** Control with Gas Puffing

- With sufficient neutral gas pressure, plasma enters high **beta** regime
- With insufficient neutral gas pressure, the plasma will become unstable (sometimes violently)
- A hysteresis in the observed thresholds implies the bifurcation of the low density unstable and stable high **beta** regimes
- Consistent with theory of the Hot Electron Interchange (HEI) instability

Physics of Hot Electron Interchange (HEI) Mode

- Interchange instability driven by fast electrons
- HEI instability resonates with the drift motion of fast electrons. Causes a REAL frequency, $\omega \sim m\ \omega_d$
- Stable beyond the usual ideal MHD Limit
- As documented in low **beta** dipole experiment (CTX), HEI has the following characteristics:
    - Rapid outward transport with broad frequency spectrum
    - Dominated by low-m numbers
    - Broad global radial mode structure
    - Nonlinear frequency sweeping corresponds to radial propagation of “phase-space holes”

Measure HEI Fluctuations

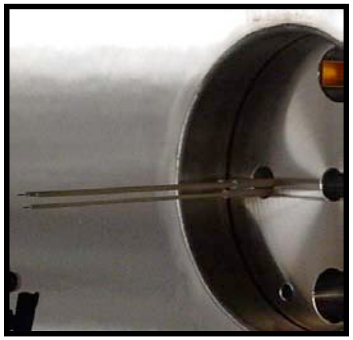


Floating Probes

- Floating potential fluctuations
  - High impedance, 50 K-Ohm
- Two thoriated tungsten probes
  - l=.99 cm, d=.16 cm, As=.3 cm^2
- Wide-band (.5 to 500 MHz) amplifier

Mirnov Coils

- Poloidal magnetic fluctuations
  - On outer wall of equatorial plane
- Boron Nitride core
  - 200 turns of 30 AWG magnet wire
  - Boron Nitride ceramic spray
- Custom amplifier boards



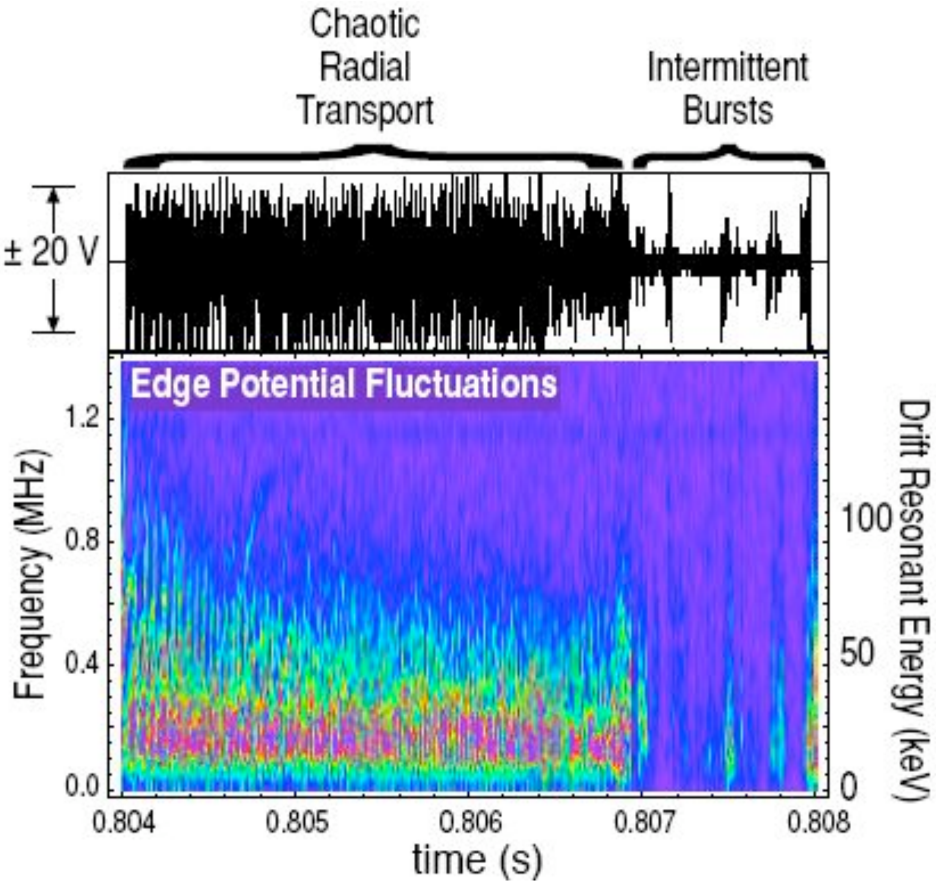
HEI Appear Under Three Conditions

- Continuous Bursts:
  - Unstable plasmas, low beta, low-density
- Minor Relaxation:
  - Short, low-amplitude, remains at high **beta**
- Total Energy Collapse:
  - Intense, large-amplitude, rapid density & fast electron beta loss

Continuous Bursts at Low Gas Fueling

- Unstable plasmas, low β
- Observed outward radial transport of fast electrons
- Coherent modes with low amplitude on edge floating potential, ± 20 V
- Frequency chirping up to 0.6 MHz
- Corresponding to 10-60 keV energetic electrons
- Prevents plasma buildup

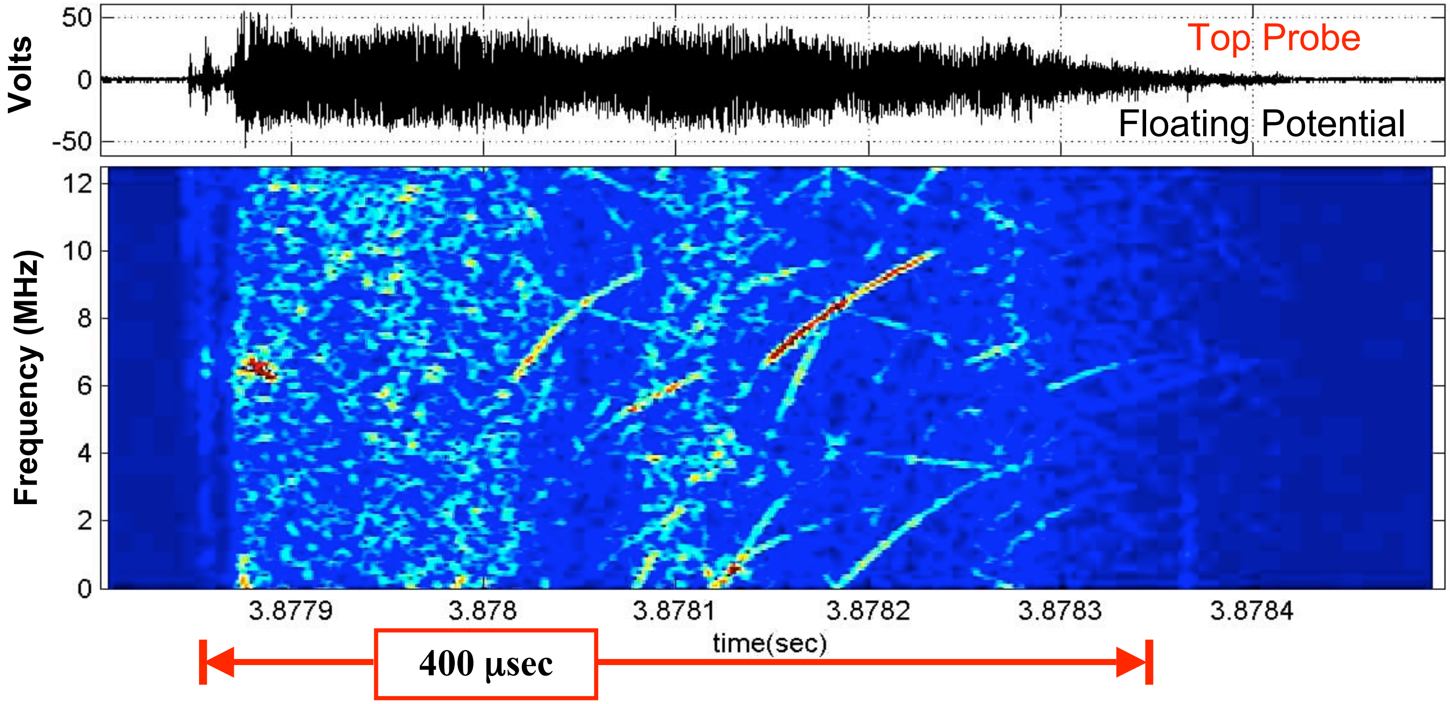
Low Density Regime
May 13, 2005 – Shot 28
Both Sources on
ΔFlux < .1 mWb



Minor Relaxation Burst

- < 2 % **beta** loss
- Short burst duration, < .5 ms
- High frequency, wide-band fluctuations
- Radially localized; detected only on adjustable probe near peak pressure
- Large amplitude fluctuations, ± 50 V

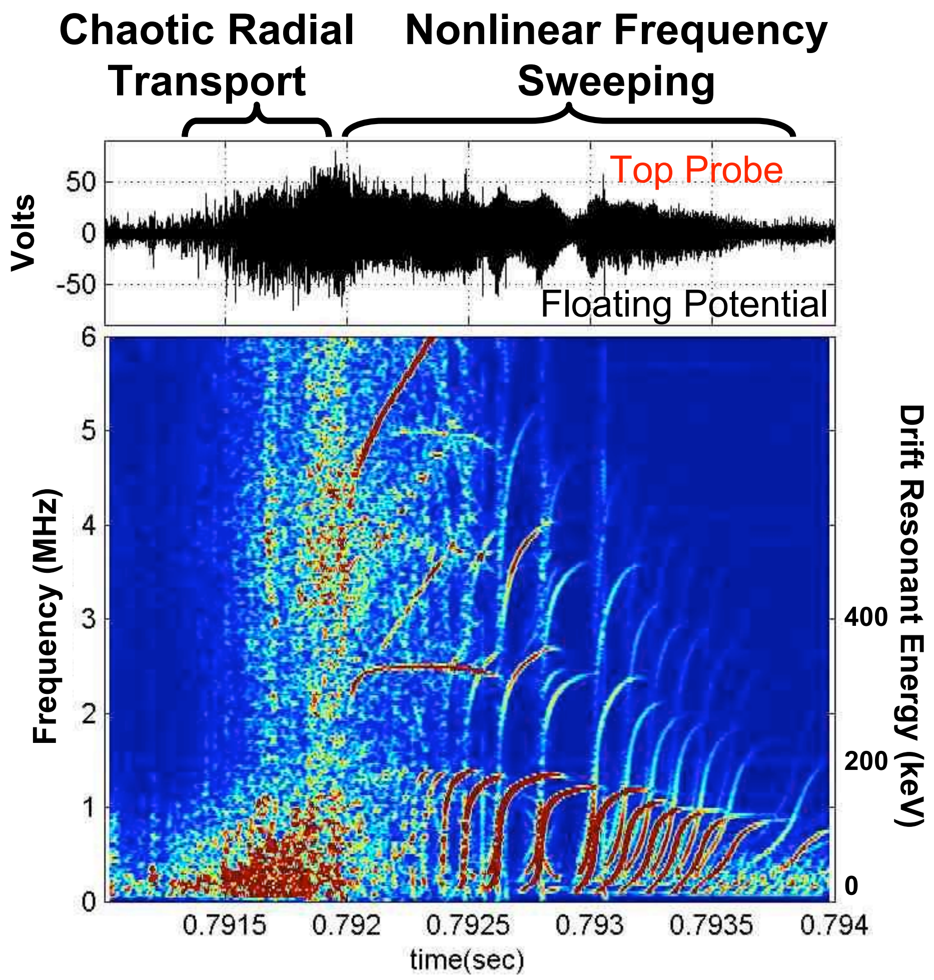
High Density Regime
May 13, 2005 – Shot 35
Both Sources on,
ΔFlux ~ .1 mWb



Total Energy Collapse When Fueling Drops

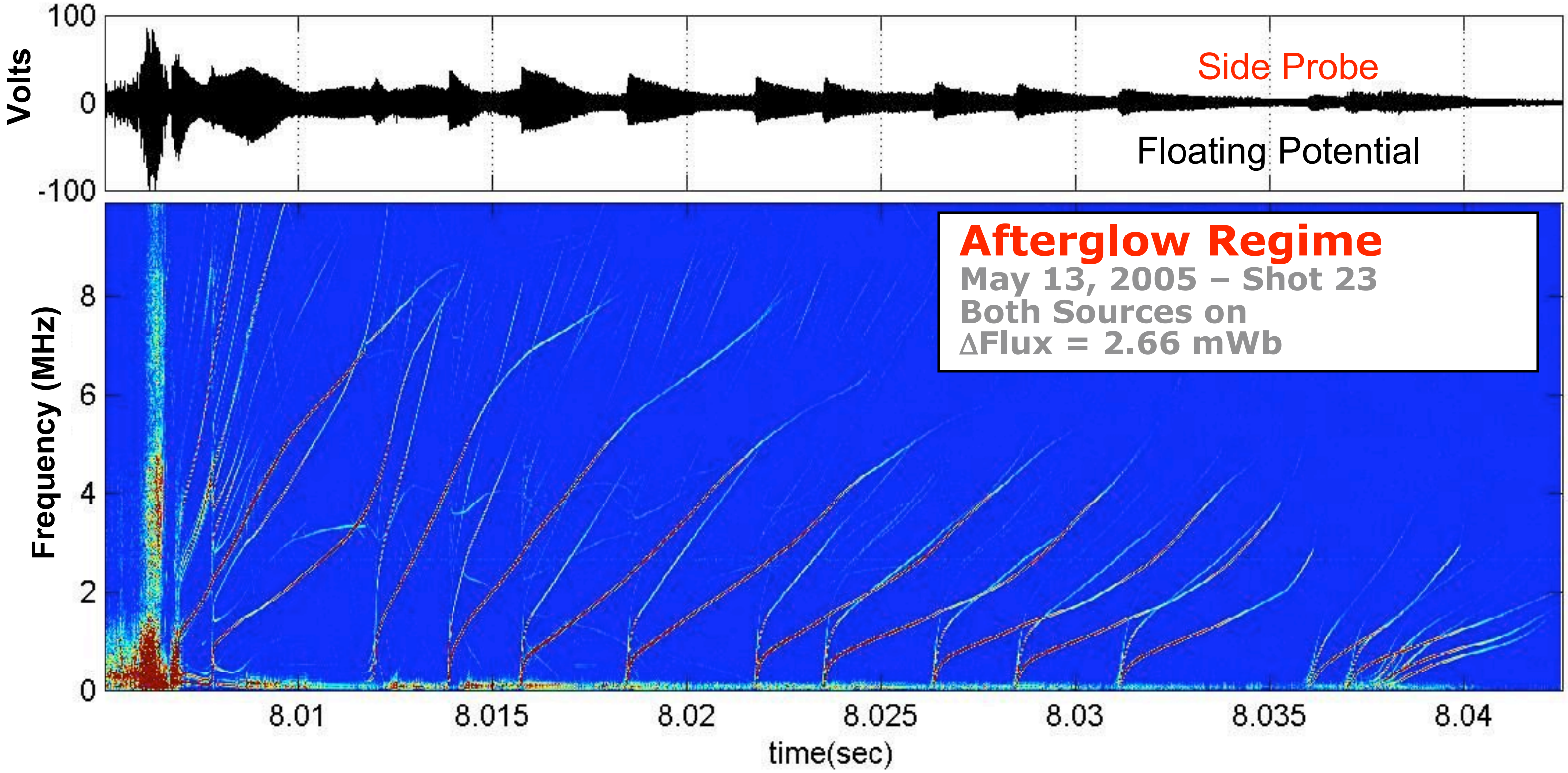
- Total (> 90%) **beta** loss
- Very rapid loss (~100 μs); outward radial transport
- Inward transport as well; spikes in X-ray signal
- Large amplitude (±60V) fluctuations
- Frequency chirping up to 1-5 MHz
- Corresponding to 100-400 keV fast electrons

H-L Density Transition
May 13, 2005 – Shot 28
Both Sources on
ΔFlux = 1.71 mWb



Long Lasting HEI “Burst” in Afterglow

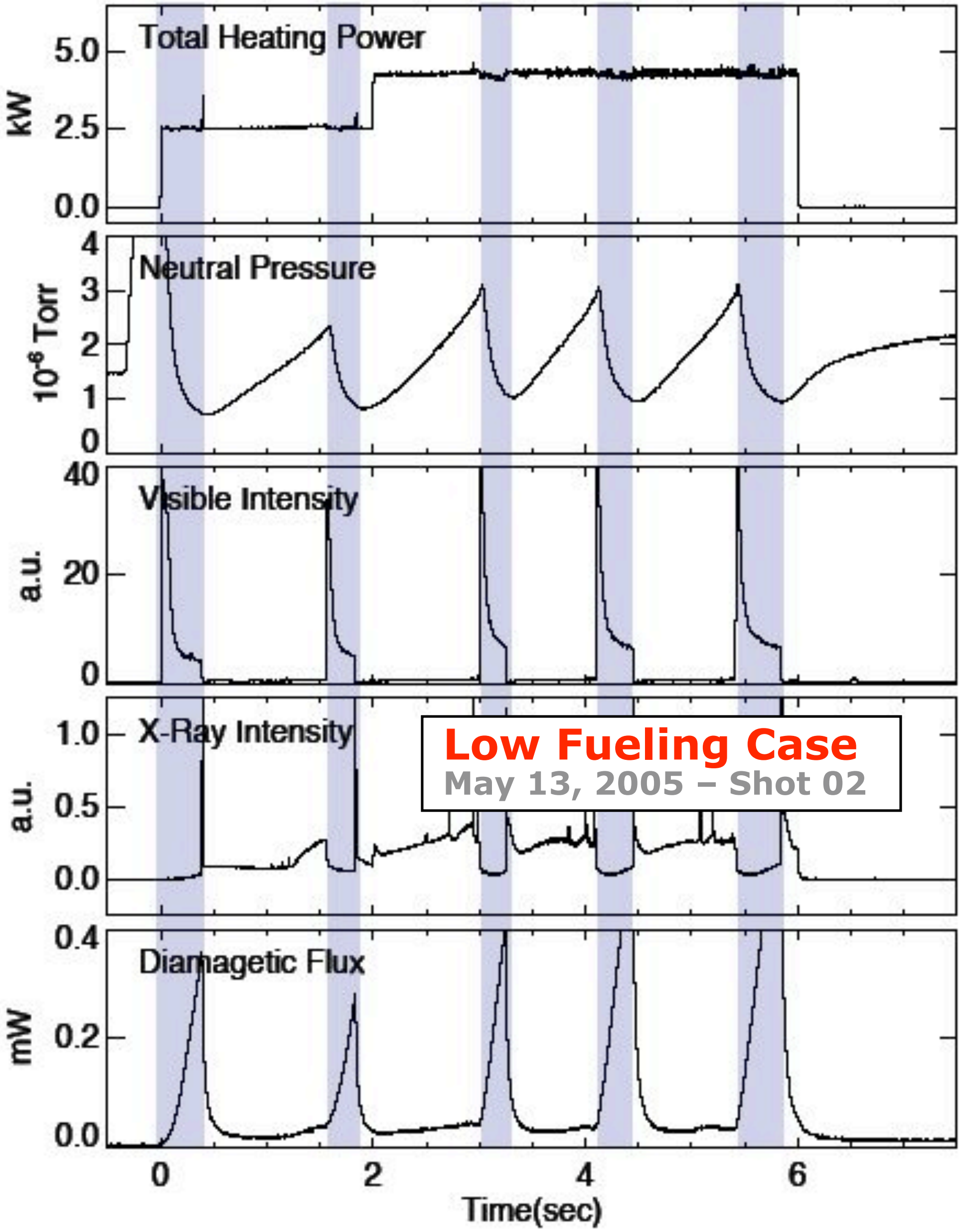
- Excite long instability bursts ≈ 40 ms!
- Complex (beautiful!) frequency spectrum evolves in time
- Largest amplitude fluctuations (±80-100V)



Afterglow Regime
May 13, 2005 – Shot 23
Both Sources on
ΔFlux = 2.66 mWb

HEI → Hysteresis in Gas Requirements

- High fueling needed to suppress HEI
- Increase density ⇒ increase beta
  - Low density regime evolves gas from walls
- Once stable, less fueling needed to maintain stability
- Without continuous puffing the plasma pumps required gas from chamber



Low Fueling Case
May 13, 2005 – Shot 02

Hot Electron Interchange Stability

- Bulk plasma must satisfy MHD adiabaticity condition **Rosenbluth and Longmire, (1957)**

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

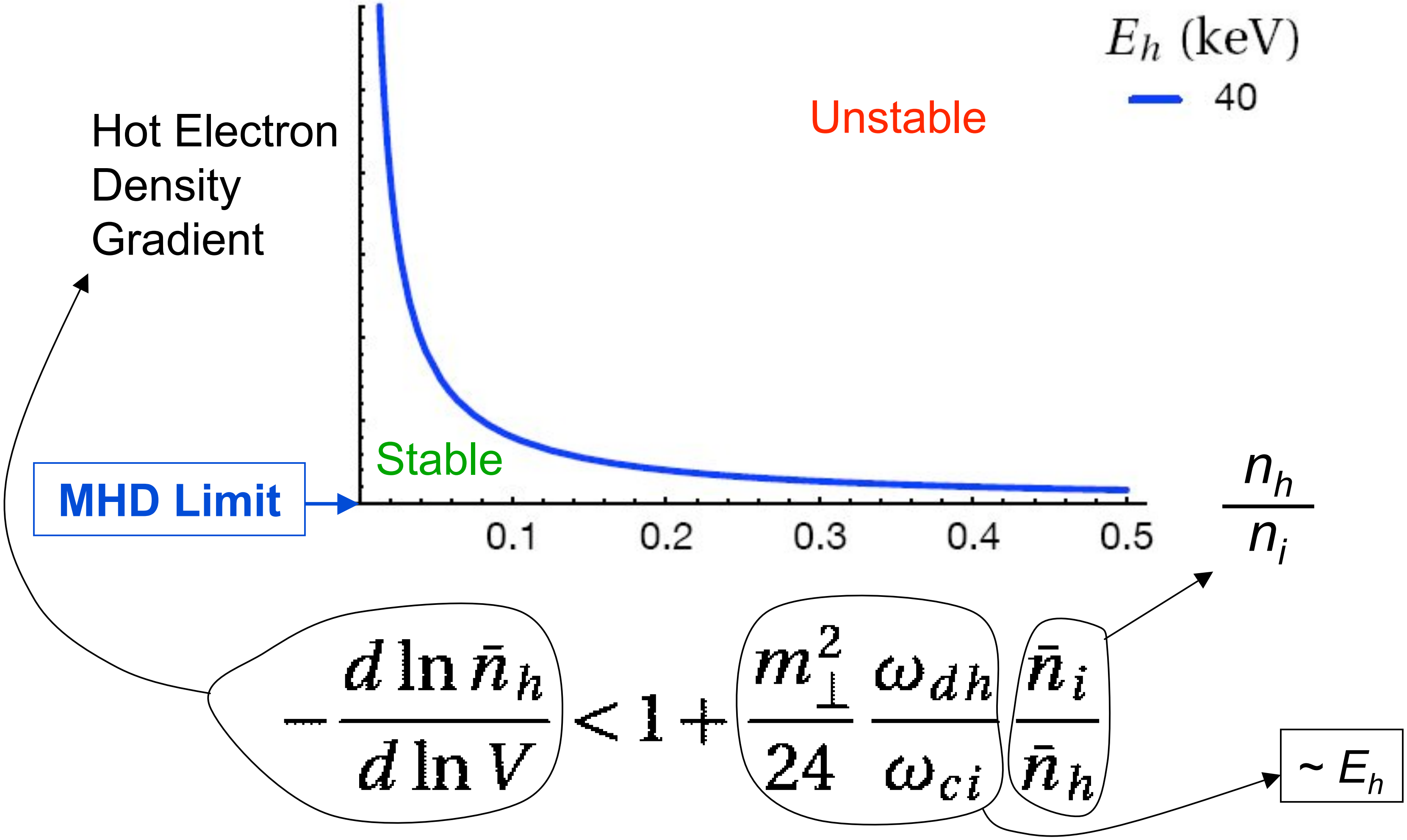
where $V = \oint \frac{d\ell}{B}$ **or** $-\frac{d\ln p_b}{d\ln V} < \gamma^{-1}$

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

$$-\frac{d\ln \bar{n}_h}{d\ln V} < 1 + \frac{m_\perp^2}{24}\frac{\omega_{dh}}{\omega_{ci}}\frac{\bar{n}_i}{\bar{n}_h}$$

Krall (1966), Berk (1976)...

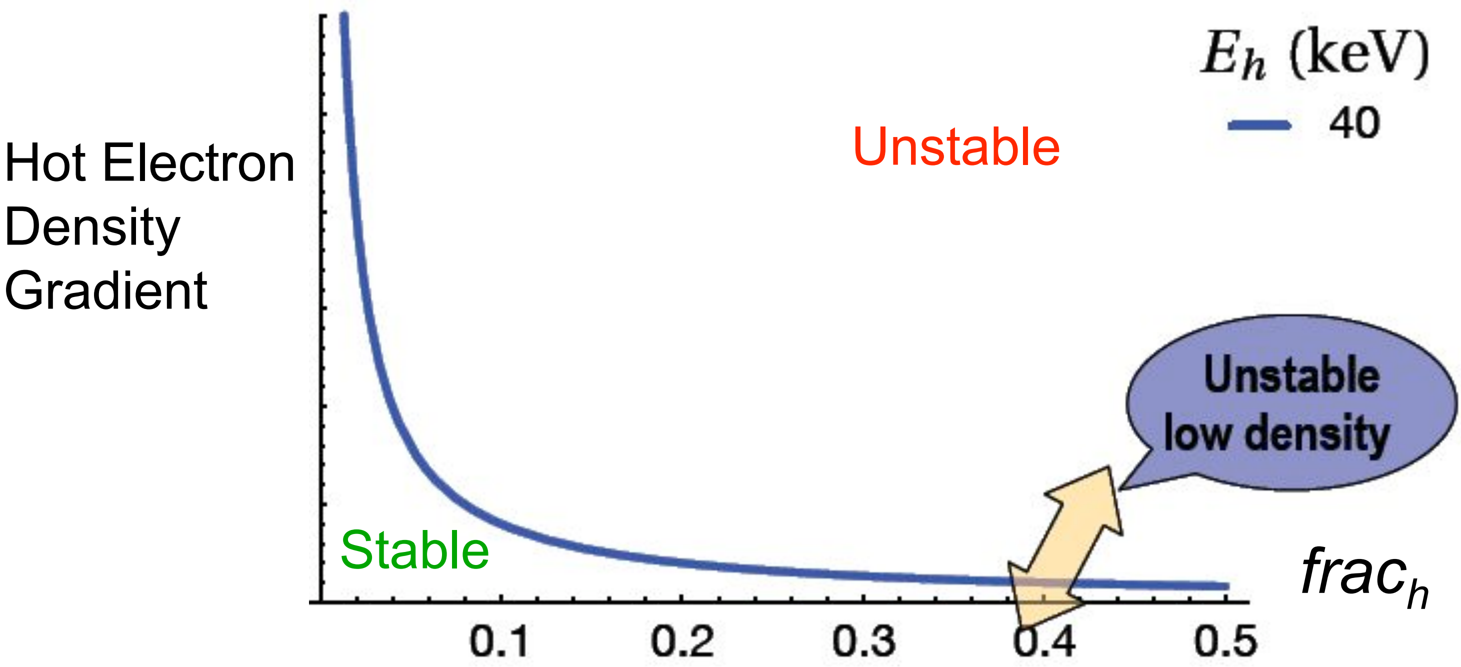
Simple Model: How To Get To High **Beta**



$$-\frac{d\ln\bar{n}_h}{d\ln V} < 1 + \frac{m_\perp^2}{24}\frac{\omega_{dh}}{\omega_{ci}}\frac{\bar{n}_i}{\bar{n}_h}$$

- Qualitative simple model to explain the hysteresis effects and how to get to high beta

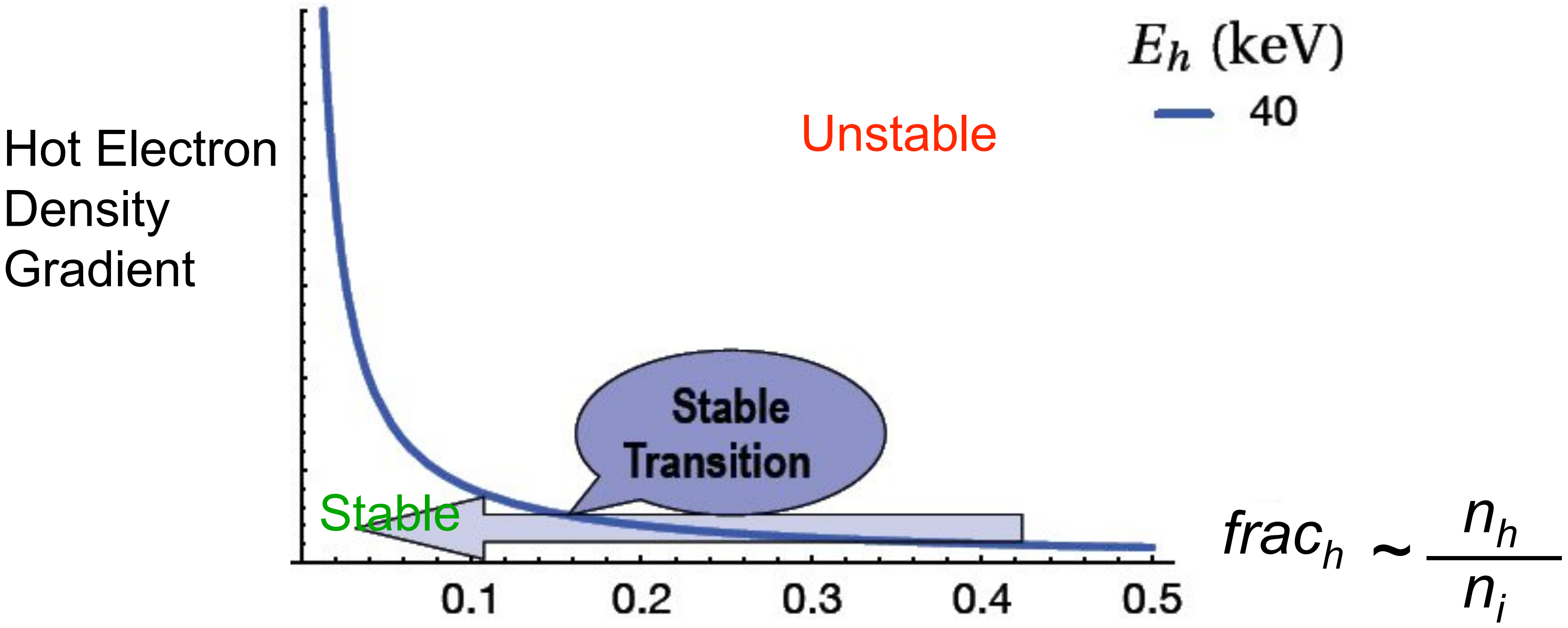
Simple Model Explanation of Hysteresis



$$frac_h \sim \frac{n_h}{n_T}$$

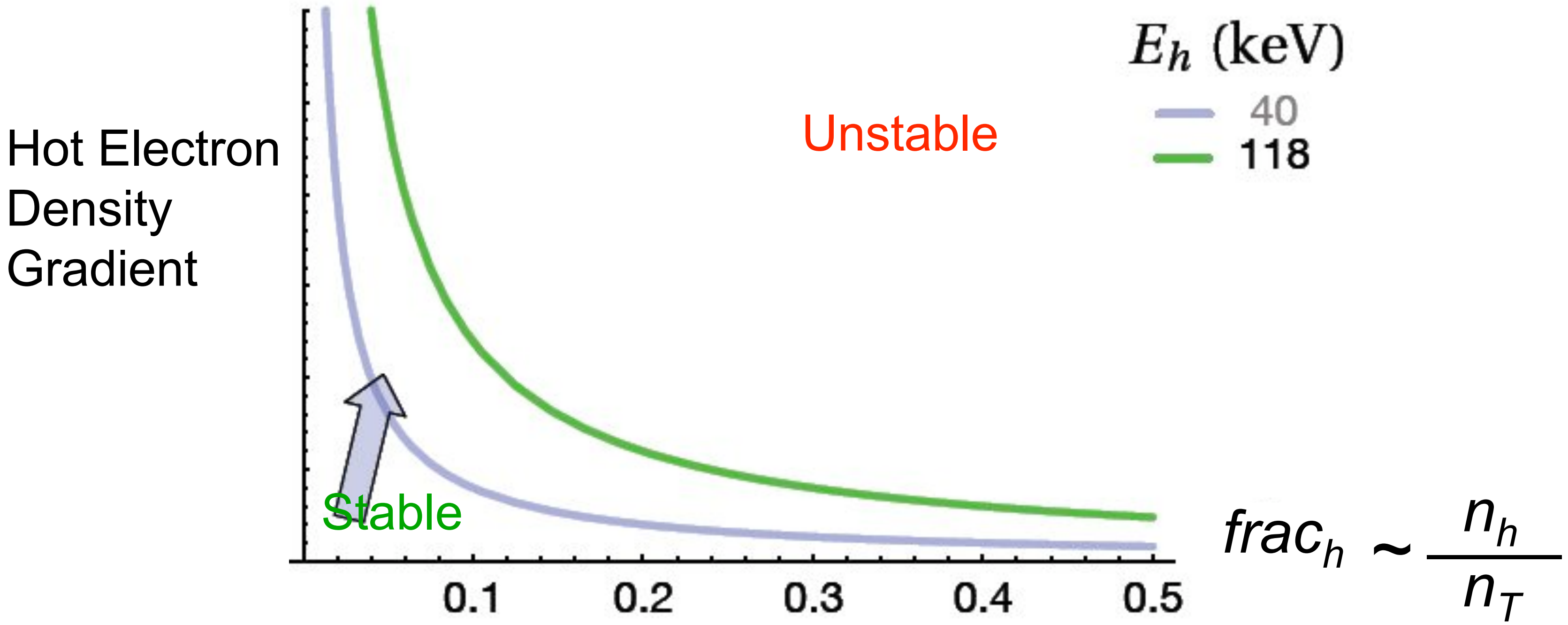
- Unstable regime has high $frac_h$ with 40 keV electrons

Simple Model Explanation of Hysteresis



- Unstable regime has high $frac_h$ with 40 keV electrons
- Increasing gas fueling → $frac_h$ drops → stable transition

Simple Model Explanation of Hysteresis



$$frac_h \sim \frac{n_h}{n_T}$$

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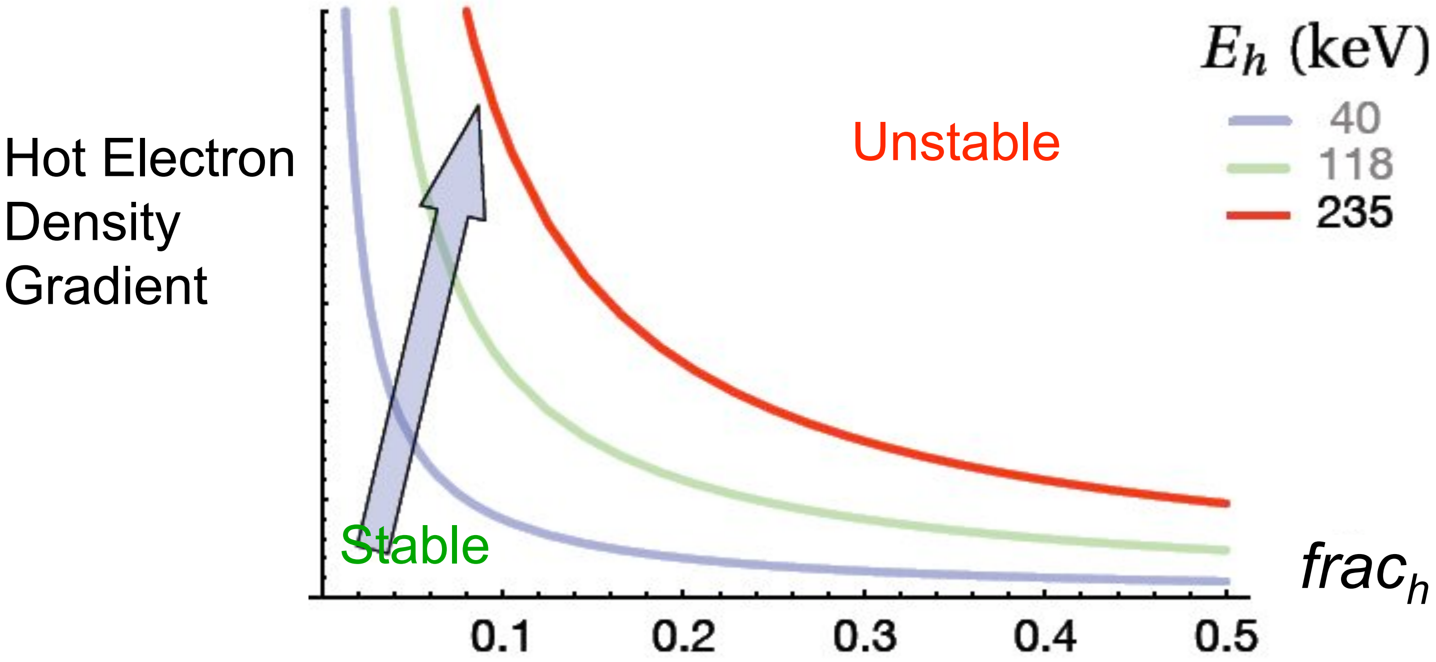
- **Beta** increases free of HEI

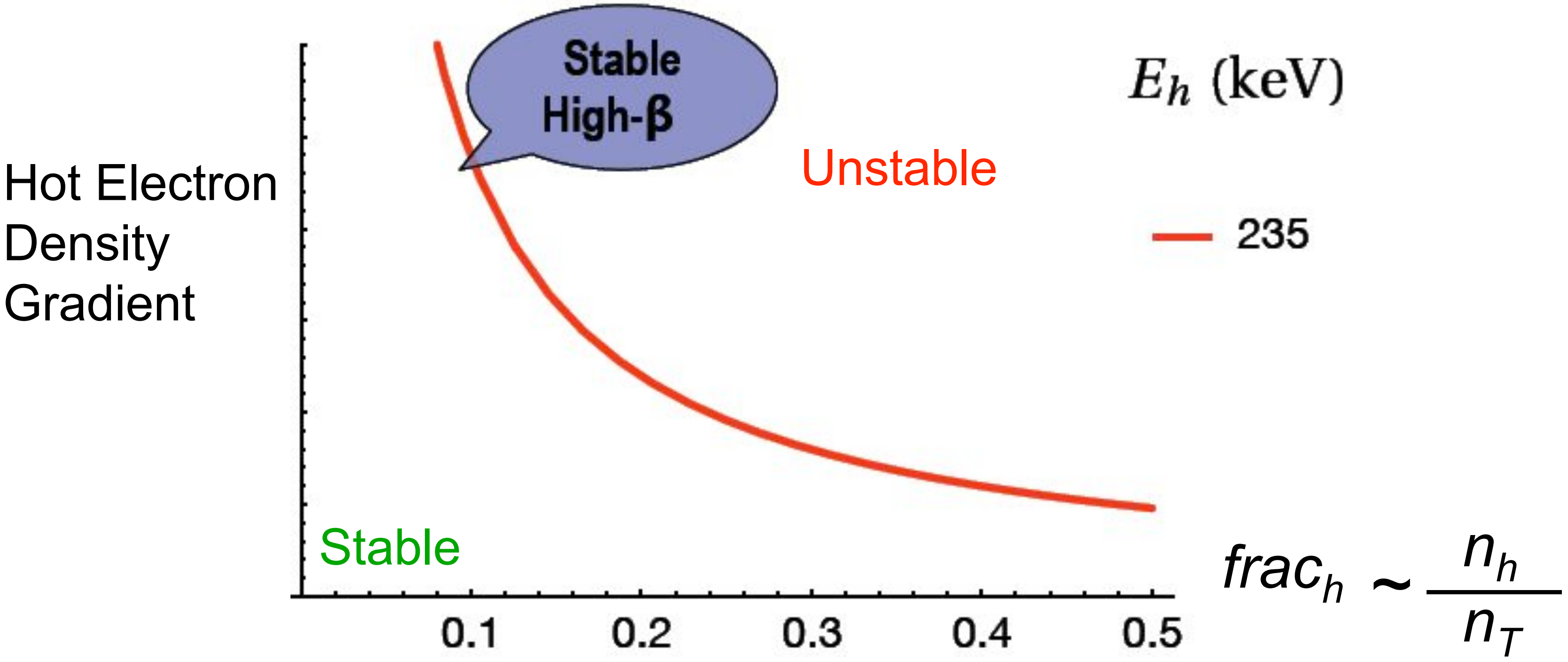
Simple Model Explanation of Hysteresis



$$frac_h \sim \frac{n_h}{n_T}$$

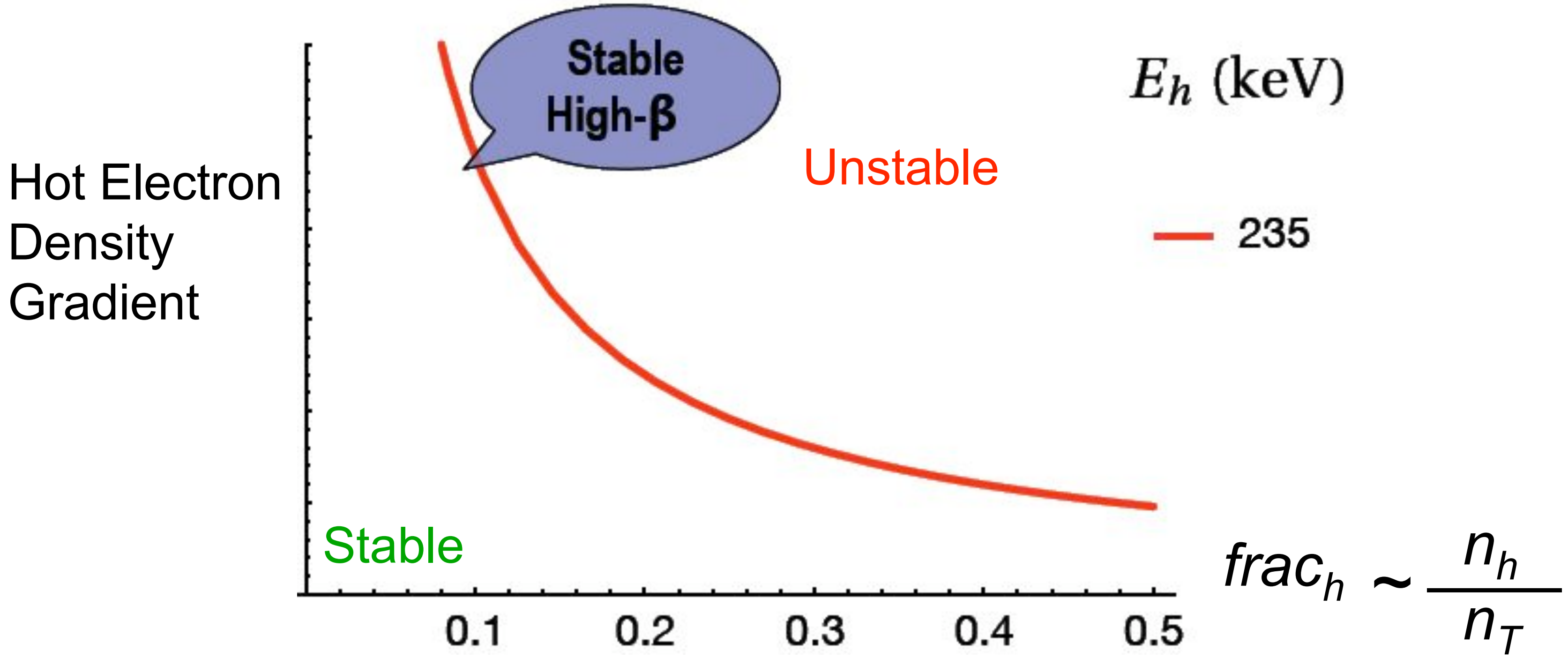
- Unstable regime has high $frac_h$ with 40 keV electrons
- Increase gas fueling → $frac_h$ drops → stable transition
- **Beta** increases free of HEI
- Fast electrons now heat → new higher stability limit

Simple Model Explanation of Hysteresis



- Unstable regime has high $frac_h$ with 40 keV electrons
- Increase gas fueling → frac_h drops → stable transition
- **Beta** increases free of HEI
- Fast electrons now heat → new higher stability limit
- Finally high **beta** regime → stable to HEI so as long as puffing rate balances ECRH heating

Simple Model Explanation of Hysteresis



- As temperature of fast electrons increases so does stability limit
- Hysteresis is observed on the fueling requirements of the HEI because the stability curve shifts outward depending on the state of the hot electrons:
  - High fueling needed to suppress HEI in unstable regime
  - Less fueling required to do the same in high **beta** regime

Comparison of LDX with Nonlinear Code

- Use self-consistent, nonlinear, gyrokinetic simulation code to understand LDX instability behaviors
- HEI saturation level and extent of radial transport depends upon the fast electron fraction, $n_{hot}/n_{total.}$
  - When $n_{hot}/n_{total} \sim 0.35$, low-amplitude "relaxation burst"
  - When $n_{hot}/n_{total} > 0.5$, intense, strong radial transport is predicted
- Computation of perturbed diamagnetic current can be compared with Mirnov measurements:
  - After initial "linear" phase, strong radial transport causes edge magnetic field perturbations to reach levels *greater than* the unperturbed equilibrium fields.

Conclusions

- Phase I has been completed and equilibrium results demonstrate stable operation at high beta (see P1.029)
- Magnetic reconstruction of anisotropic equilibrium (see P1.028) returns peak local beta of 20% and 330 J at 5 kW of ECRH (see P1.031)
- Hot Electron Interchange Instability found to be the dominant instability in LDX Phase I
- High beta achieved only when HEI is stabilized with fueling (see P1.030)
- New observations of HEI in high beta include
  - Hysteresis - stability/instability
  - Large perturbed magnetic fields
  - Rapid (~100 μs) for complete loss of fast electrons

LDX Physics Team

- MIT
  - Jay Kesner
  - **Alex Boxer**
  - **Jennifer Ellsworth**
  - **Ishtak Karim**
  - **Natalia Krasheninnikova**
  - **Alexei Kuznetsov**
- Columbia University
  - Mike Mauel
  - Darren Garnier
  - Alexander Hansen
  - **Eugenio Ortiz**

*** Graduate Students**