High Beta Observations of the Hot Electron Interchange Instability

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Abstract

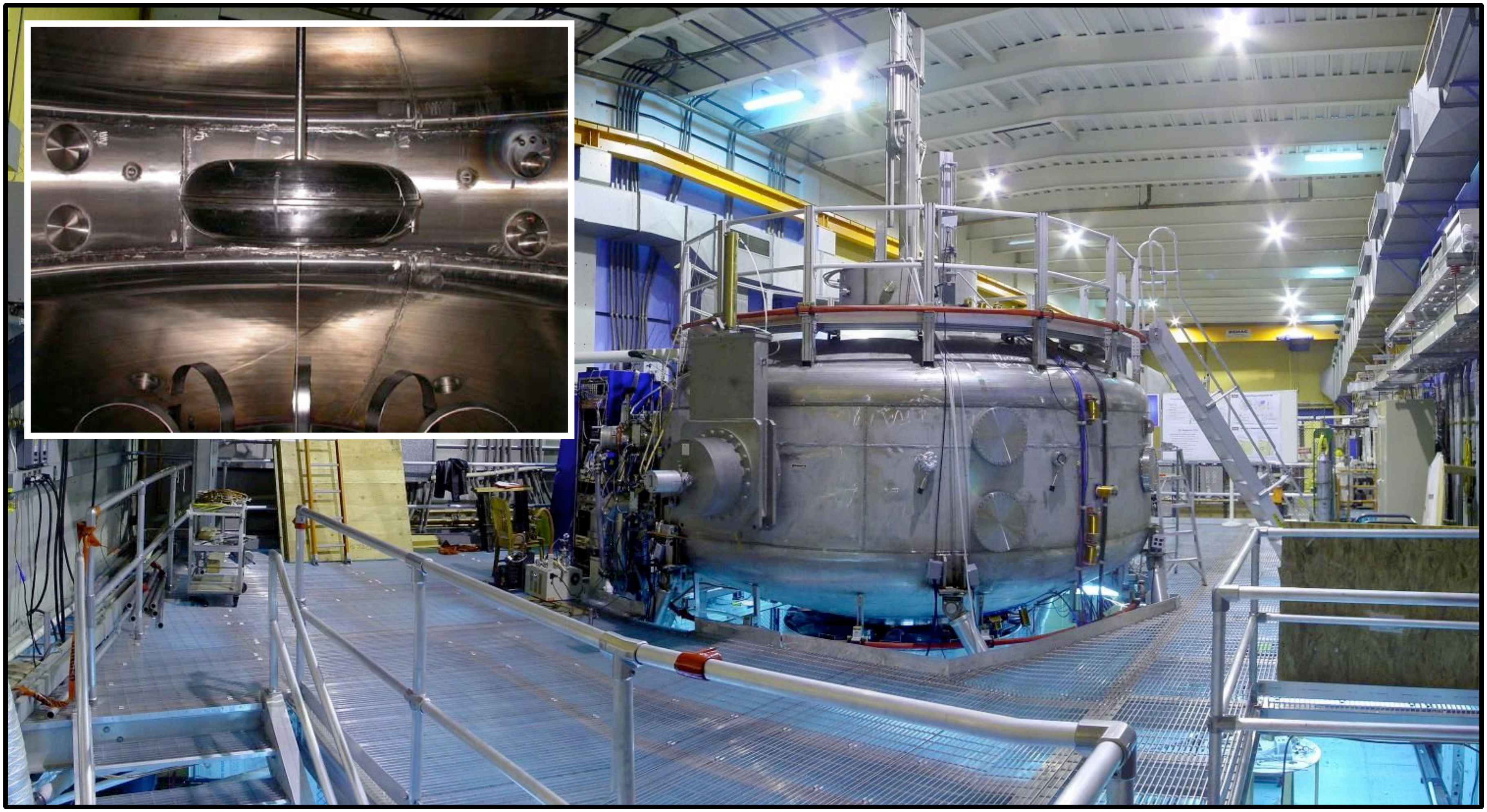
High frequency (f > 1 MHz) electrostatic fluctuations have been observed in high-beta plasma created in the Levitated Dipole Experiment (LDX). We have previously identified these fluctuations as the Hot Electron Interchange (HEI) instability[1]. New observations have been made in the presence of the magnetic levitation fields. We find the HEI mode is characterized by frequency sweeping at the drift-resonance of trapped energetic electrons. The fluctuations often appear with coherent structures that have been detected on fast high-impedance electrostatic probes and edge Mirnov sensors. We observe phase shifts using multiple probes that will enable us to determine the toroidal mode number (m) and a higher sampling rate reveals frequency sweeping as high as 40 MHz. Measurements that characterize these modes now incorporate fast magnetic measurements in an attempt to put together a coherent picture of plasma behavior during these modes, including the consequences of these instabilities on plasma formation and pressure limits.

(1) E.Ortiz to appear in J. Fus. Energy (2006).

Outline

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

The Levitated Dipole Experiment

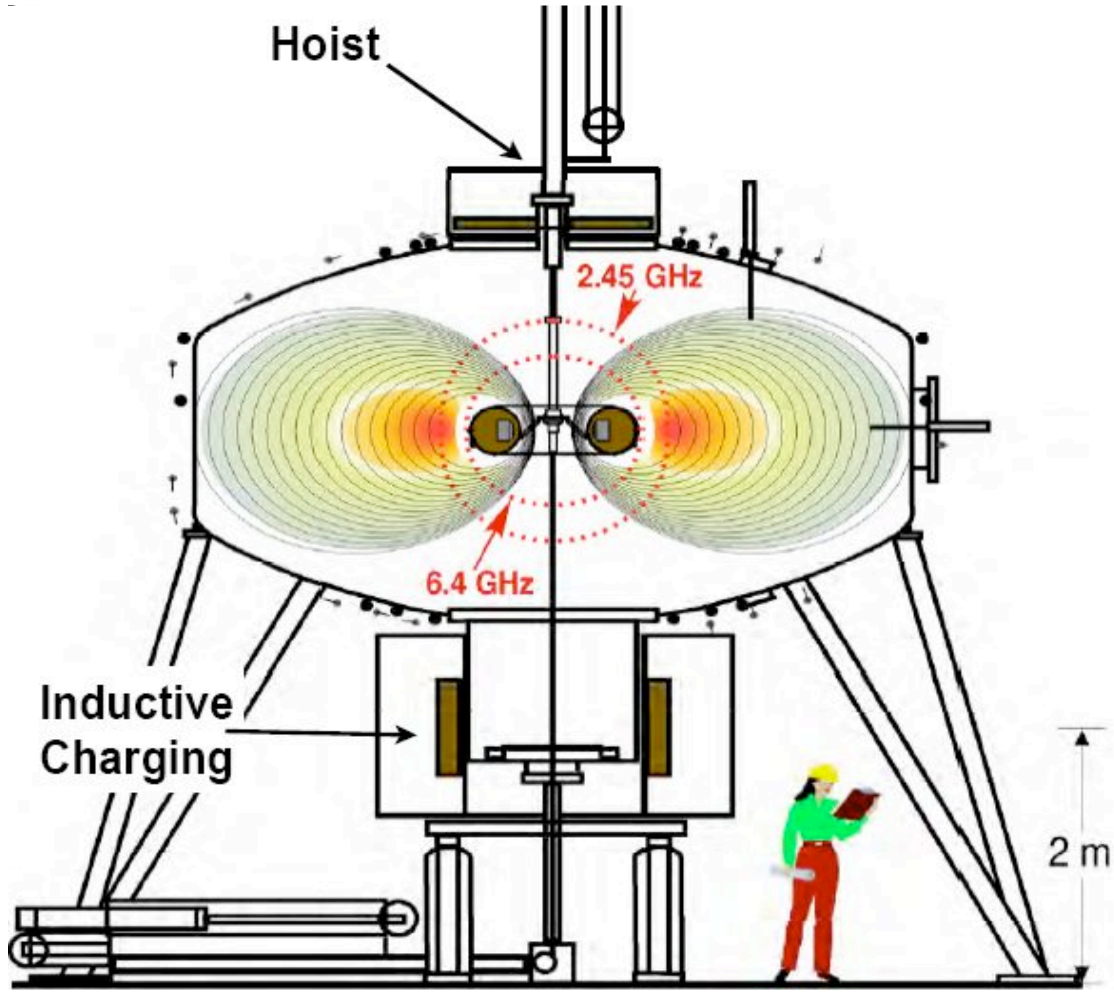


LDX

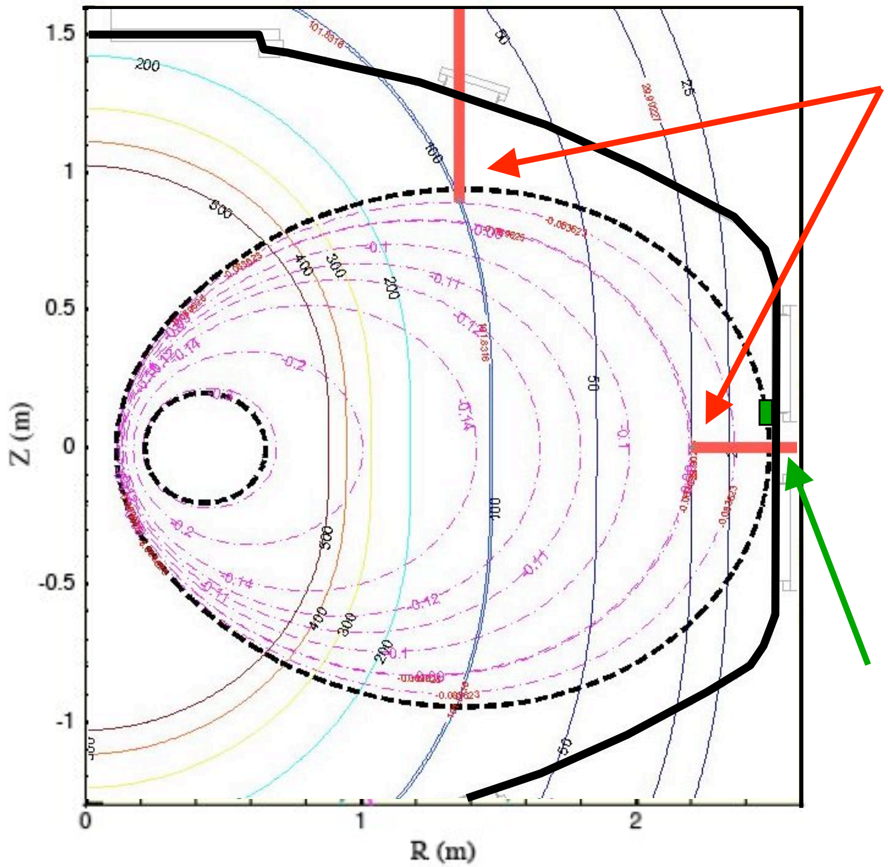
LDX Cross-Section/Operation

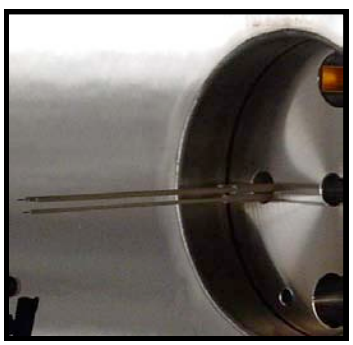
Supported Mode

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



Measure HEI Fluctuations





Floating Probes

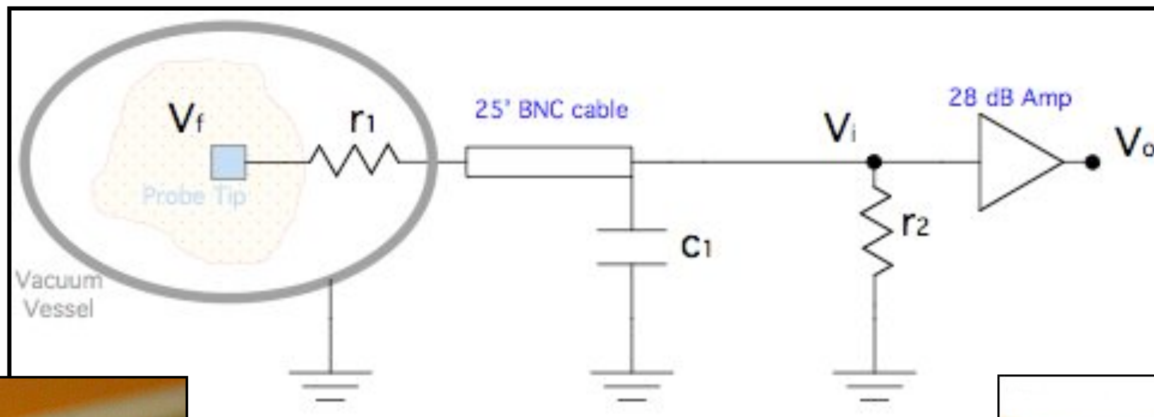
- Floating potential fluctuations
  - High impedance, 50 K-Ohm
- Two thoriated tungsten probes
  - l=.99 cm, d=.16 cm, As=.3 cm^2
- Wide-band (.5 to 500 MHz) amplifier

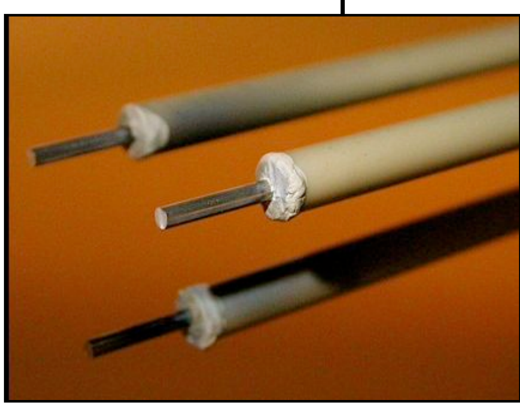
Mirnov Coils

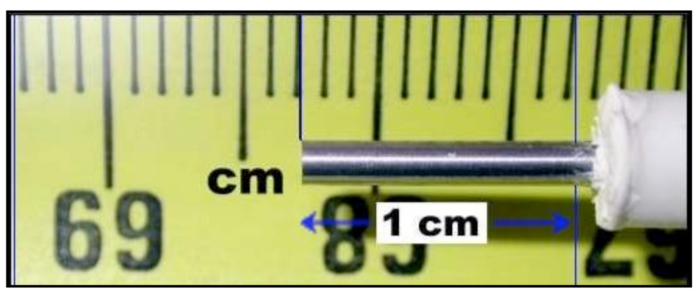
- Poloidal magnetic fluctuations
  - On outer wall of equatorial plane
- Boron Nitride core
  - 200 turns of 30 AWG magnet wire
  - Boron Nitride ceramic spray
- Custom amplifier boards

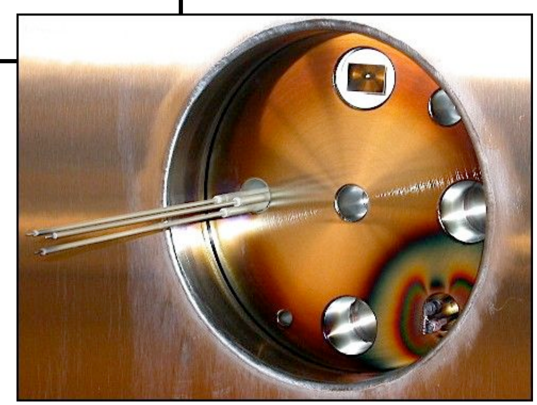
Electrostatic Probes Circuit

- Multiple high impedance probes measure the plasma floating potential
- Localized probe capture fluctuations up to 150 V
- Simple circuit amplifies signal before digitizer

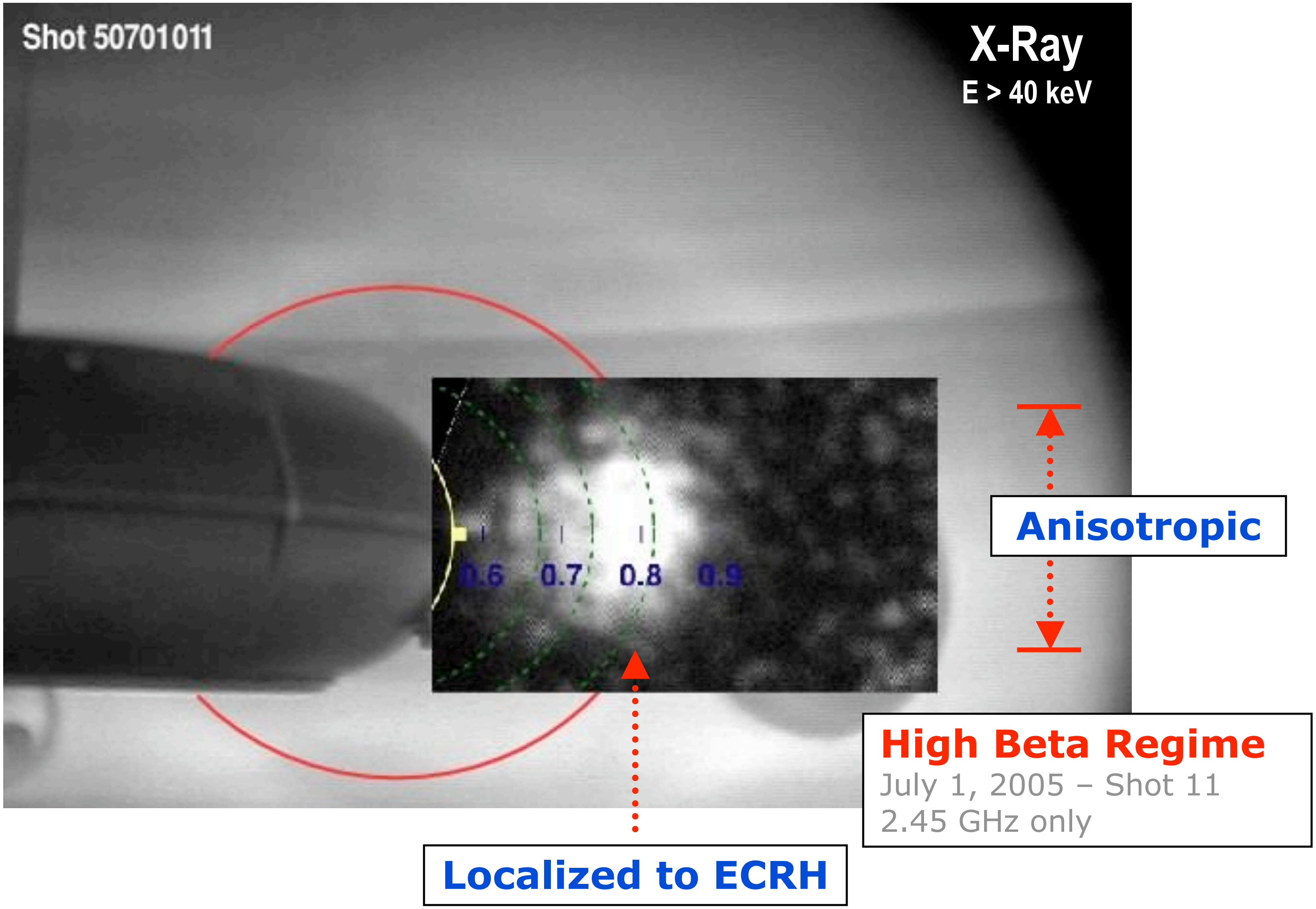








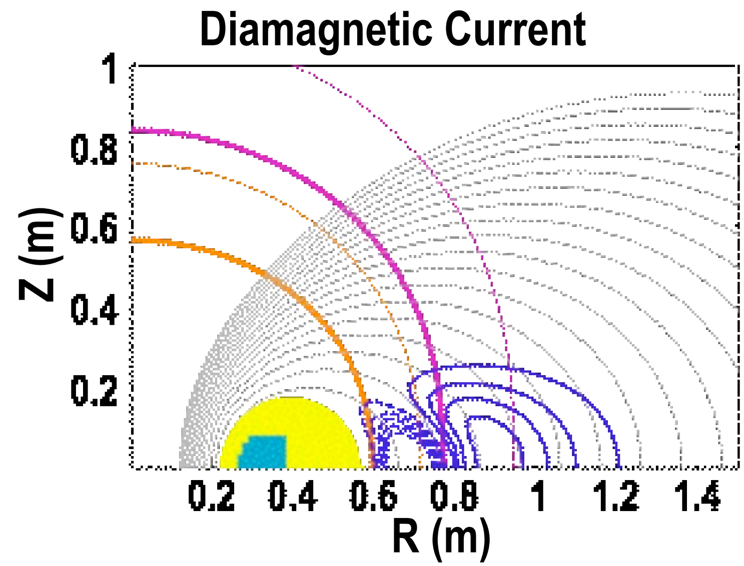
Anisotropic Fast Electrons

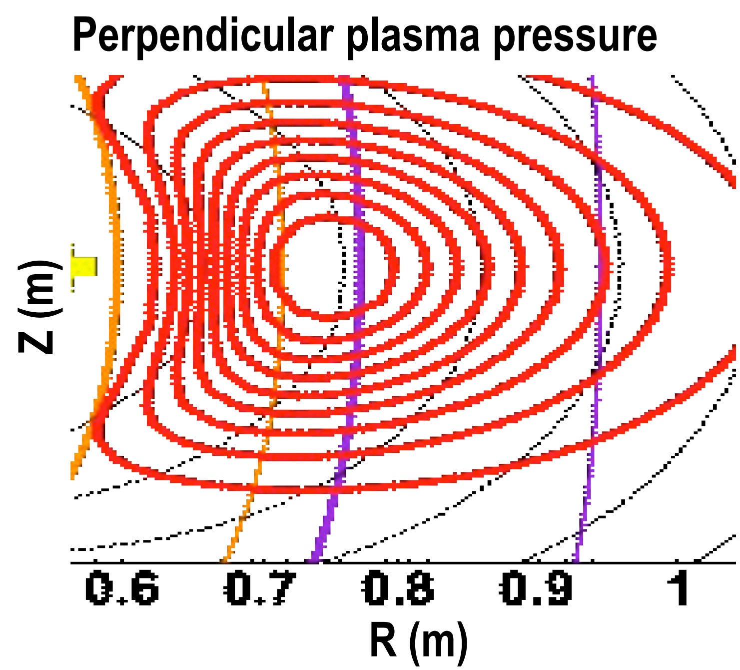


Record High **Beta** Discharge

- Shot 50513029
  - Optimal gas fueling
- Fixed from imaging
  - $R_{\text{peak}} = 0.75$ m
  - $p_{\perp} / p_{\parallel} = 5$
- 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

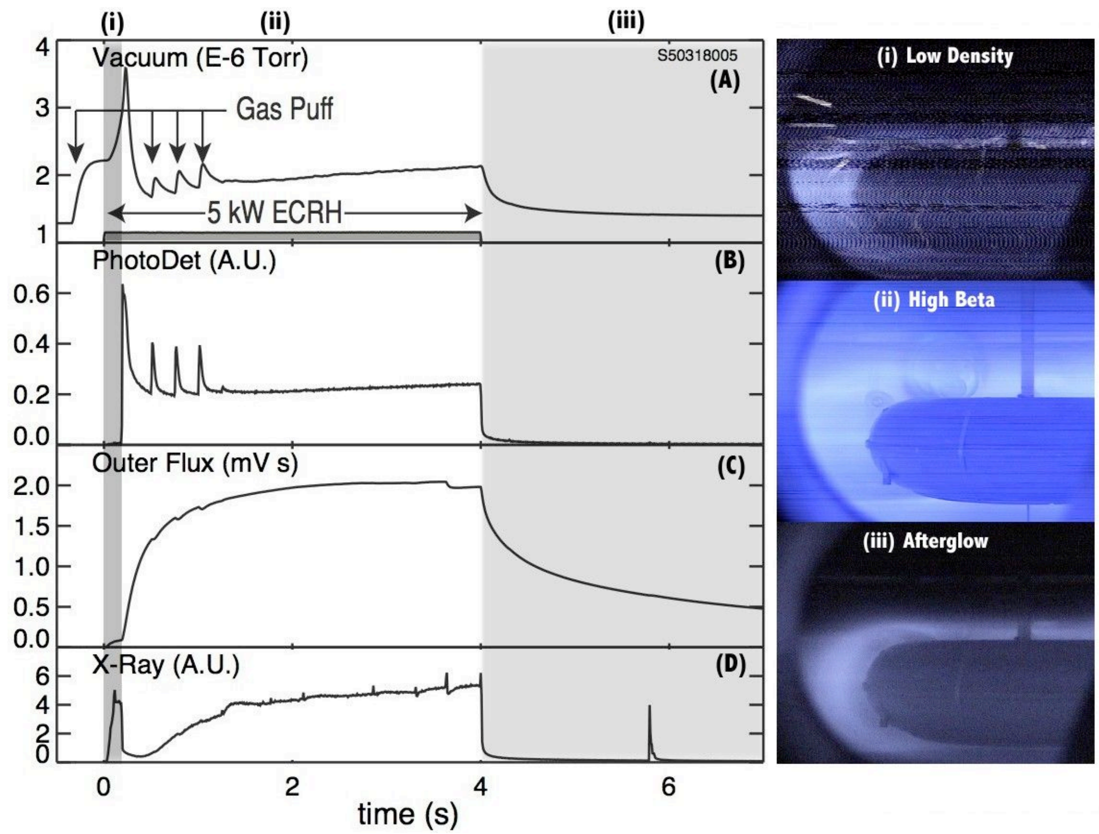
$$\frac{-d \ln P}{d \ln V} > \frac{5}{3}$$





Equilibrium Plasma Regimes

- Low density (also low beta ≤ 0.5%)
- High density (also high beta ≥ 5 %)
- After Glow (high beta, but low density)

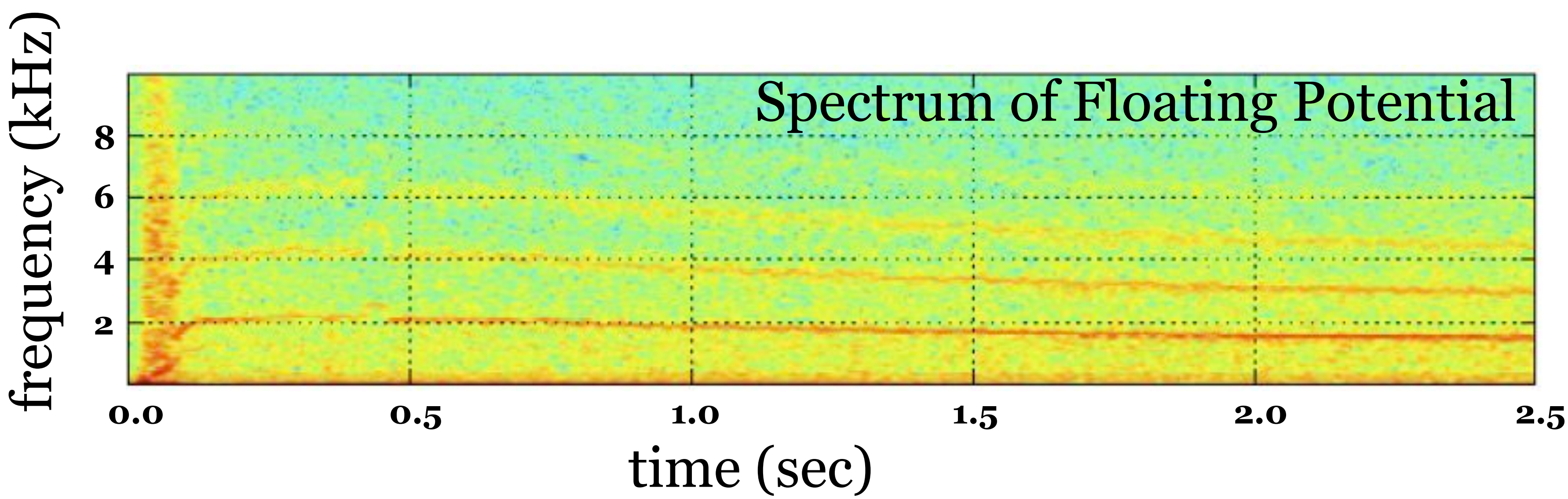


Fluctuations

- Two classes of fluctuations identified
- Low Frequency ~ 5 Khz
  - No observable transport
- High Frequency > 1 Mhz
  - frequency sweeping
  - limits plasma pressure
  - observed electron transport on side probe
  - energetic electron distribution modulates

‘Natural’ mode

- Begins with large broad band burst
- The lowest mode frequency ~ 1.5 kHz
- Frequency depends on gas fuel pressure and magnetic intensity/geometry
- See J. Kesner poster for more details



Physics of the Hot Electron Interchange

- 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”

Hot Electron Interchange Stability

- Bulk plasma must satisfy MHD adiabaticity condition

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

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

Rosenbluth and Longmire, (1957)

- 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)...

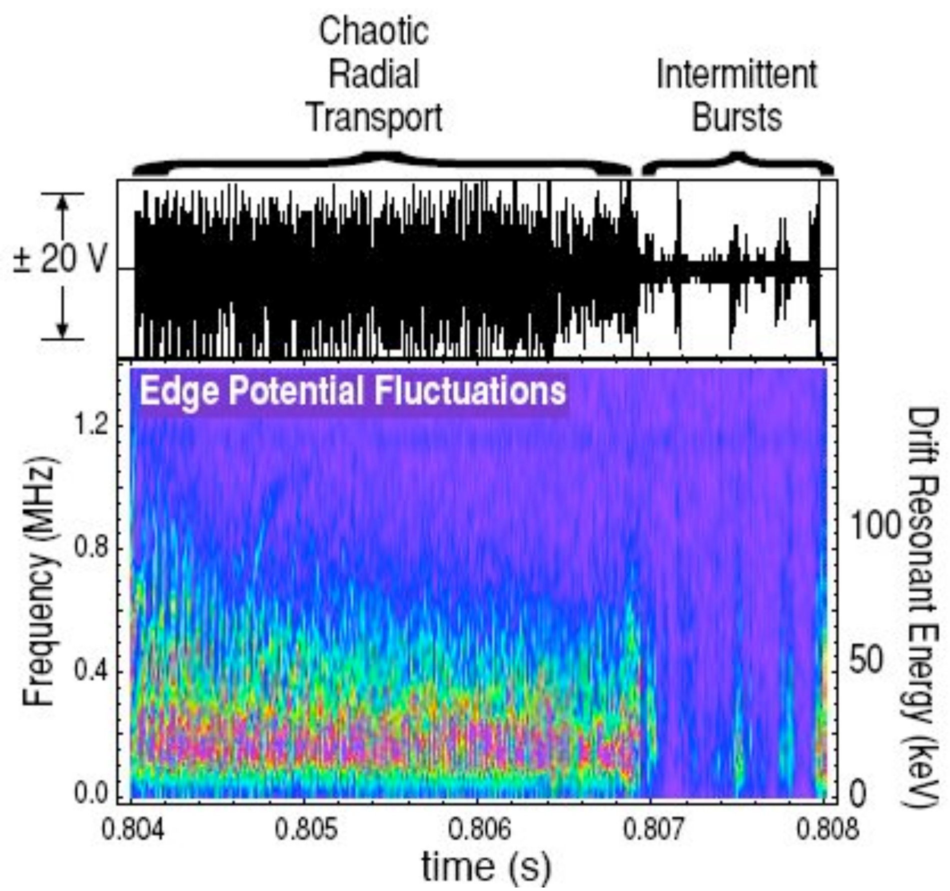
HEI Under Three Conditions

- 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

- 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

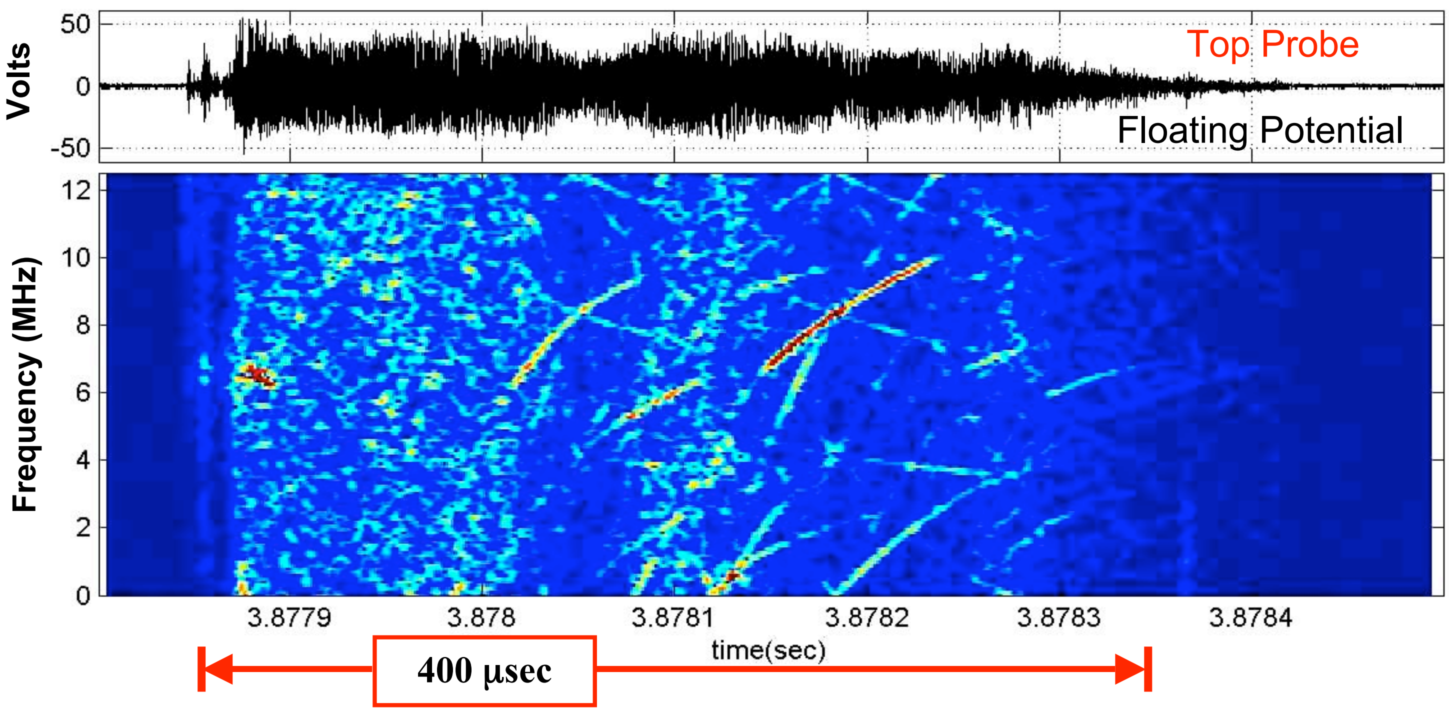
Low Density Regime
May 13, 2005 – Shot 28
Both Sources on
ΔFlux < .1 mWb



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

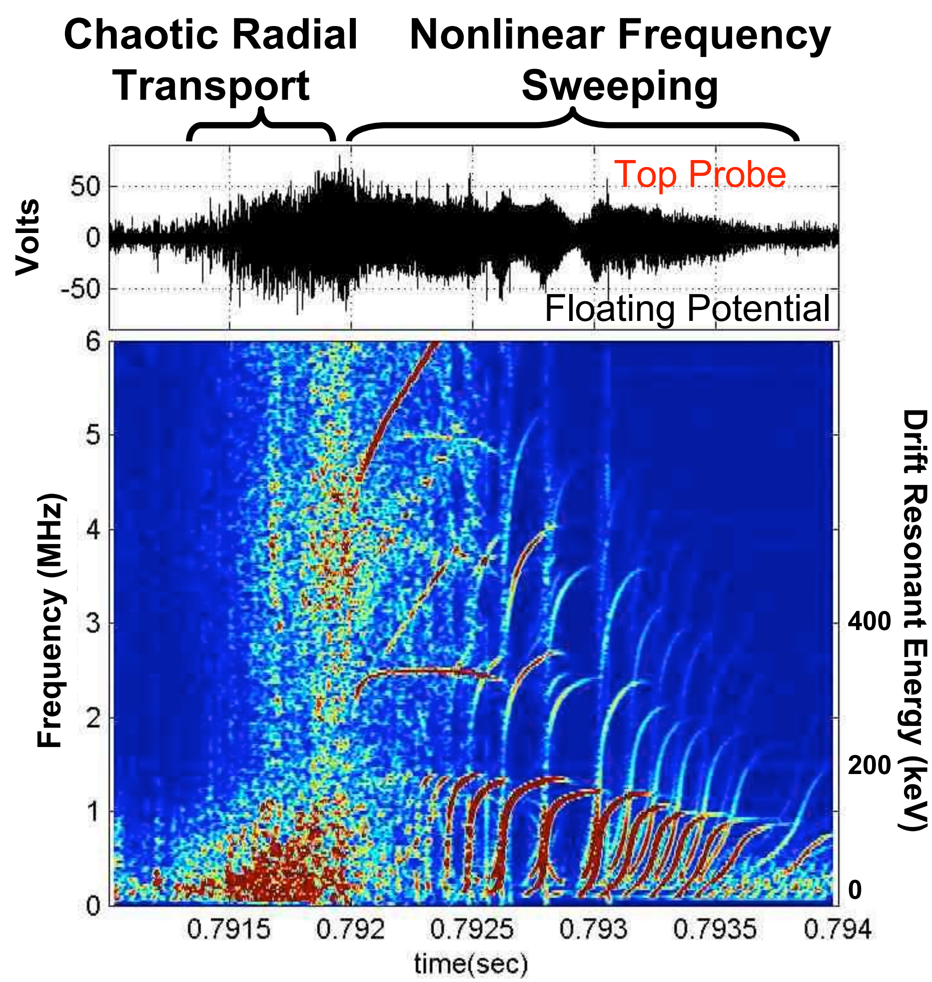
High Density Regime
May 13, 2005 – Shot 35
Both Sources on,
ΔFlux ~ .1 mWb



Total Energy Collapse

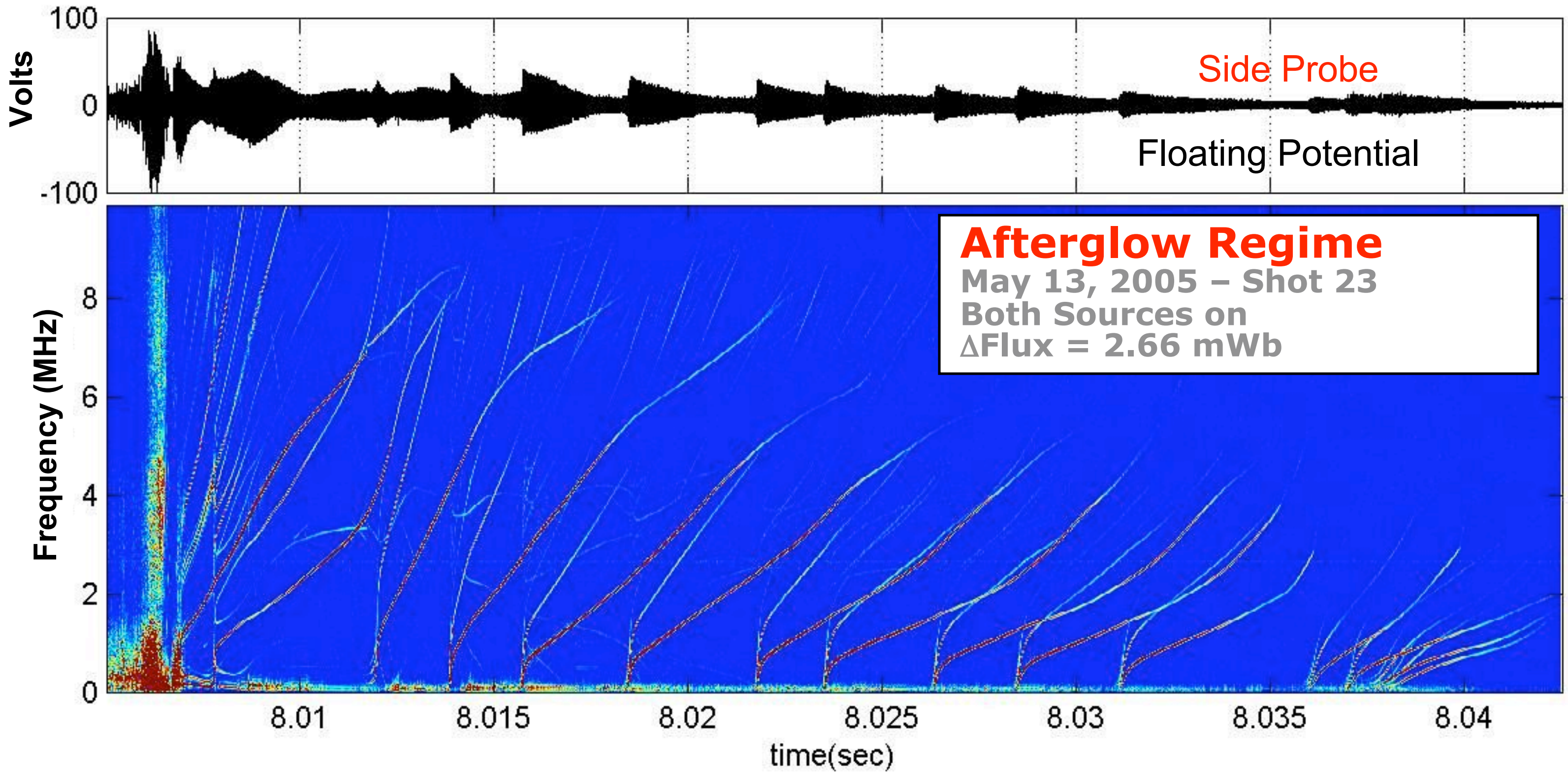
- Total (> 90%) **beta** loss
- Very rapid loss (~100 μs); outward radial transport
- Inward transport as well; spikes in X-ray signal
- Large amplitude (±60V) fluctuations
- Frequency chirping up to 1-5 MHz
- Corresponding to 100-400 keV fast electrons

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



Long Lasting "Burst" in Afterglow

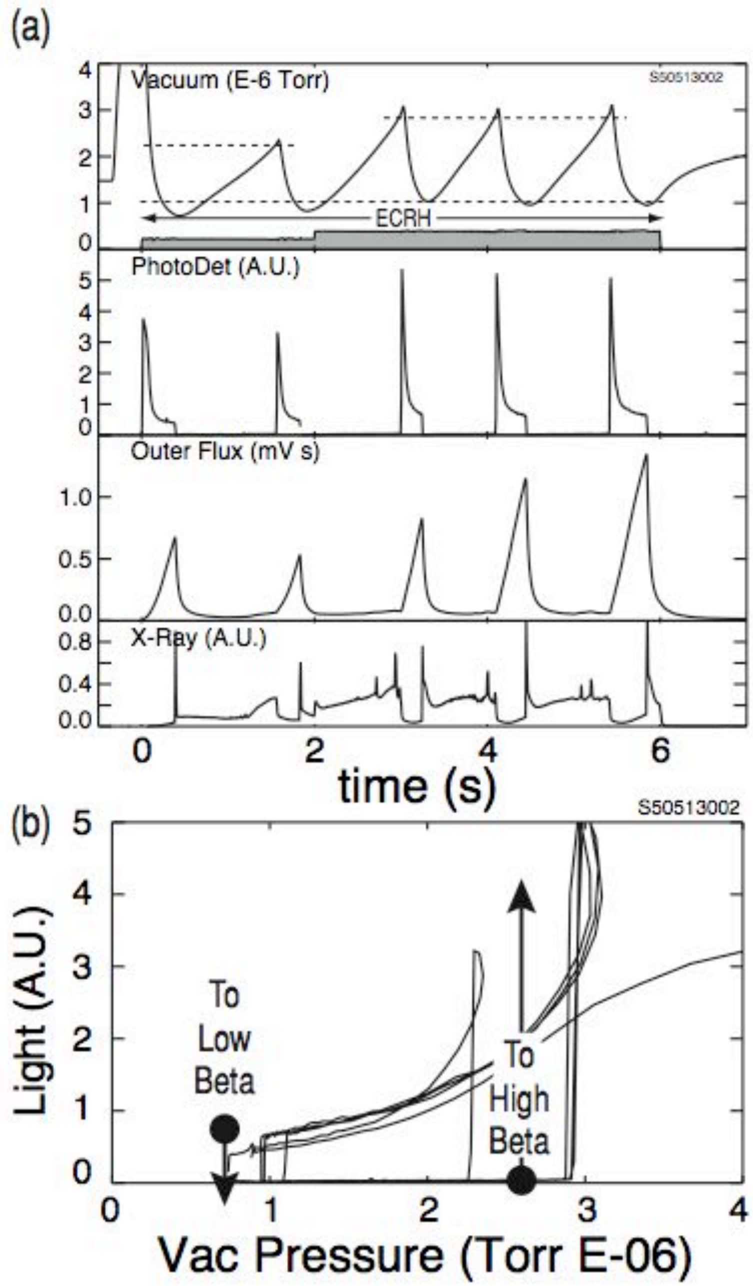
- Excite long instability bursts ≈ 40 ms!
- Complex (beautiful!) frequency spectrum evolves in time
- Largest amplitude fluctuations (±80-100V)



High **Beta** Control with Puffing

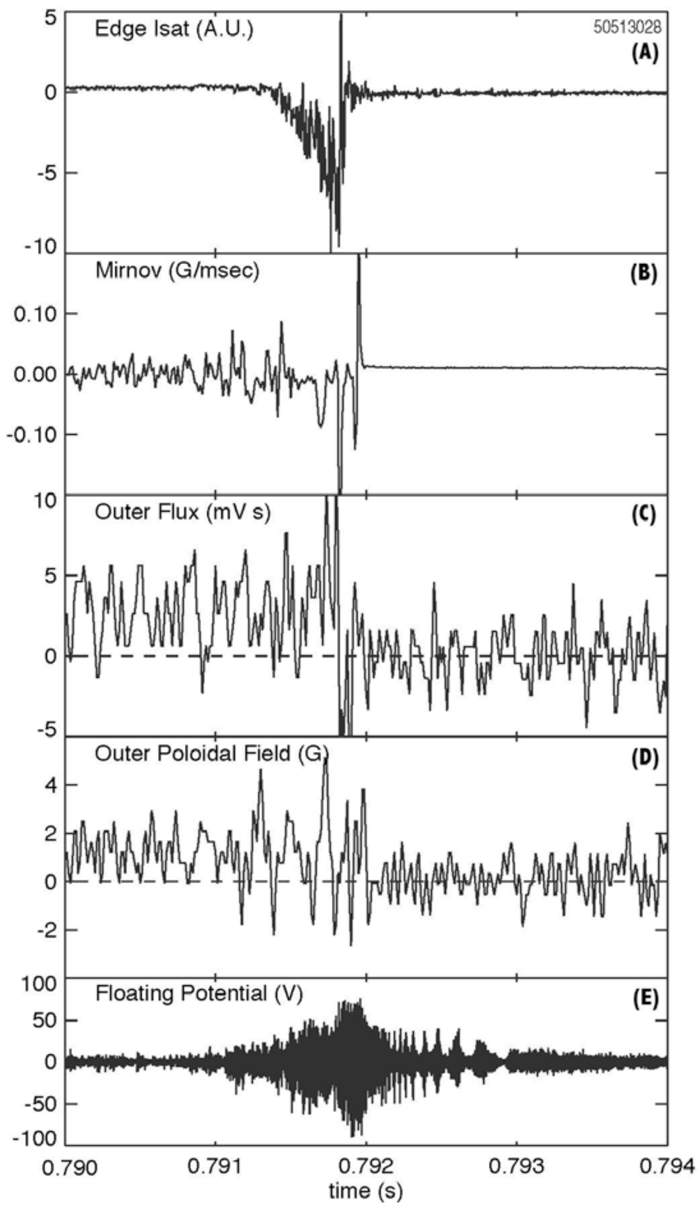
- With sufficient neutral gas pressure, plasma enters high **beta** regime
- With insufficient neutral gas pressure, the plasma will become unstable (sometimes violently)
- A hysteresis in the observed thresholds implies the bifurcation of the low density unstable and stable high **beta** regimes
- Consistent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

Hysteresis in Density Evolution



- Control of neutral gas pressure is essential to achieving and marinating high beta
- When neutral gas pressure is programmed to 1-3 μTorr, HEI instability stable and fast electron pressure increases by factor of ten
- The pressure threshold for transition to high beta depends on heating profile, see figure at 2 kW transition occurs at 2 μTorr and at 4 kW at 2.8 μTorr
- Once high beta established, plasma grossly stable so long as pressure remains above ~ 1 μTorr

Magnetic Fluctuations



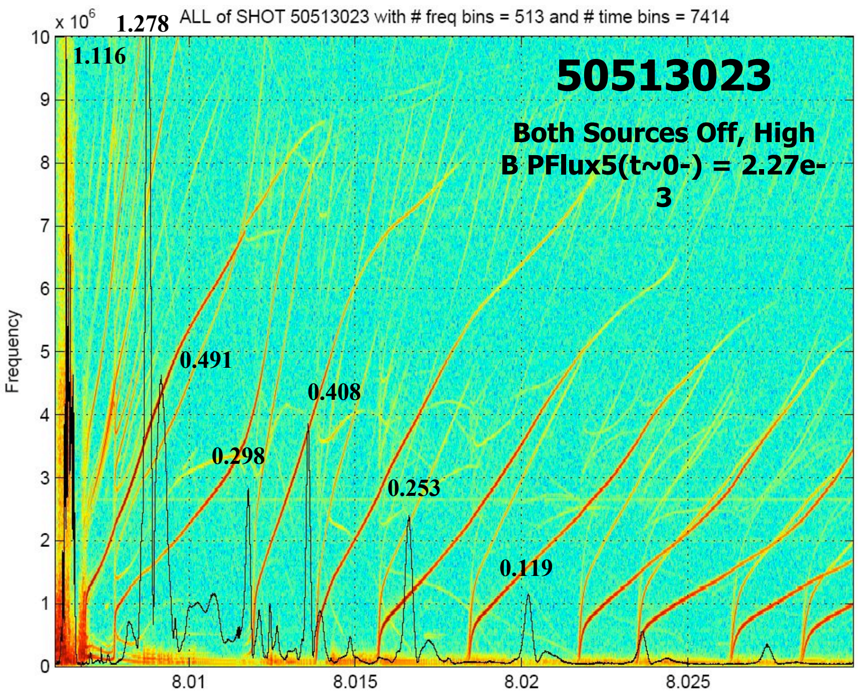
- During HEI, hot electron plasma radially rearranges
- Fast magnetic probe results corrected for eddy currents
- Strong transport of energetic electron to the edge
- Large change in magnetic field at the edge
- Confinement of hot electrons lost in less than 100 micro-seconds

Radiometer Signal and HEI

- A 50 Ghz Radiometer horn peaks significantly during strong multiple (m=1) HEI bursts
  - Max chirp $f_{(m=1)}$> 1.5 Mhz in LD, $f_{(m=1)}$ > 1.0 Mhz in AG & $f_{(m=1)}$ > 4.0 Mhz in HD, depending on Beta
- Temporal occurrence and height of Radiometer peak varies depending on: number of simultaneous bursts, chirp magnitude, and relative frequency
  - Related to multi-mode coupling, constructive/destructive interference?
- Suspect multi-mode coupling leads to enhance particle transport into higher magnetic fields
  - Energetic electrons cyclotron radiate in this region
- Magnitude of Radiometer peaks also depends on operating plasma regime

Radiometer and Spectrum

- Similar Radiometer temporal behavior during high beta and low beta HEI, but amplitudes vary greatly
- Radiometer signal peaks during multiple chirp events
- Fast Mirnov coil signals also evolve during and may help predict when Radiometer peak occur (following pages)



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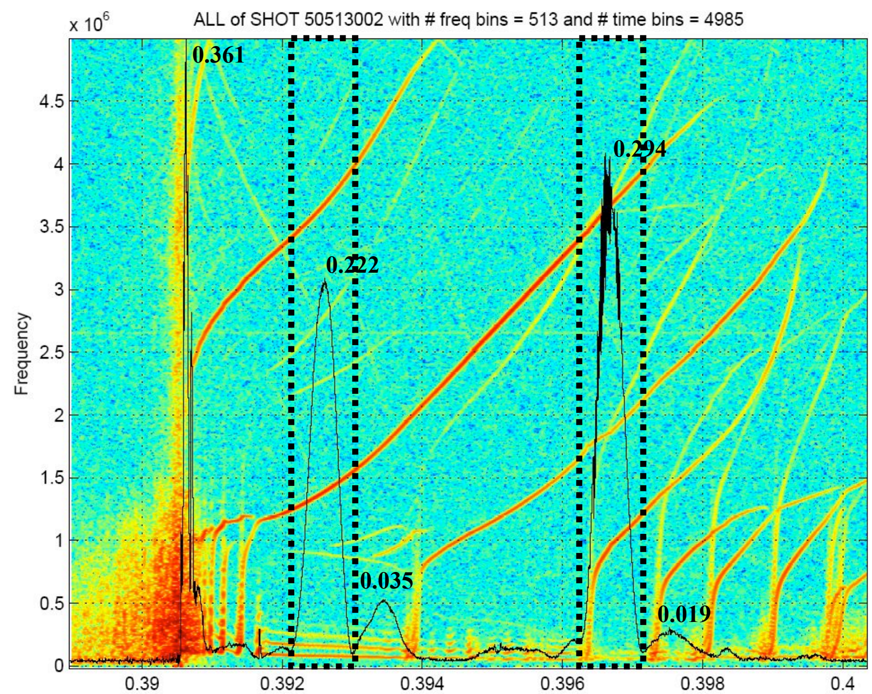
Both Sources On, Lower B PFlux5(t~0-) = 6.29e-4



Xcorr Raw Signals: After Glow

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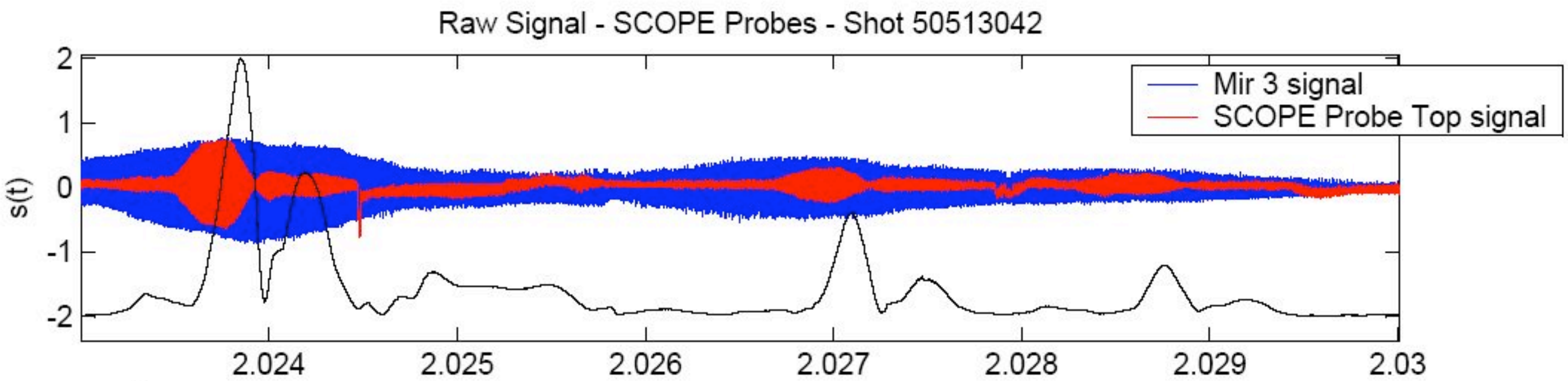

- Cross-correlated magnetic and electric probe signals
  - Plot above shows how the radiometer signal peaks when the both the magnetic and electric probe signal amplitudes are large
- Cross-correlation of these results (on next page) show that these radiometer peaks occur when both signals are most strongly correlated at the HEI frequency
  - A rapid phase shift occurs during the peaks

Xcorr TFD & Phase: After Glow

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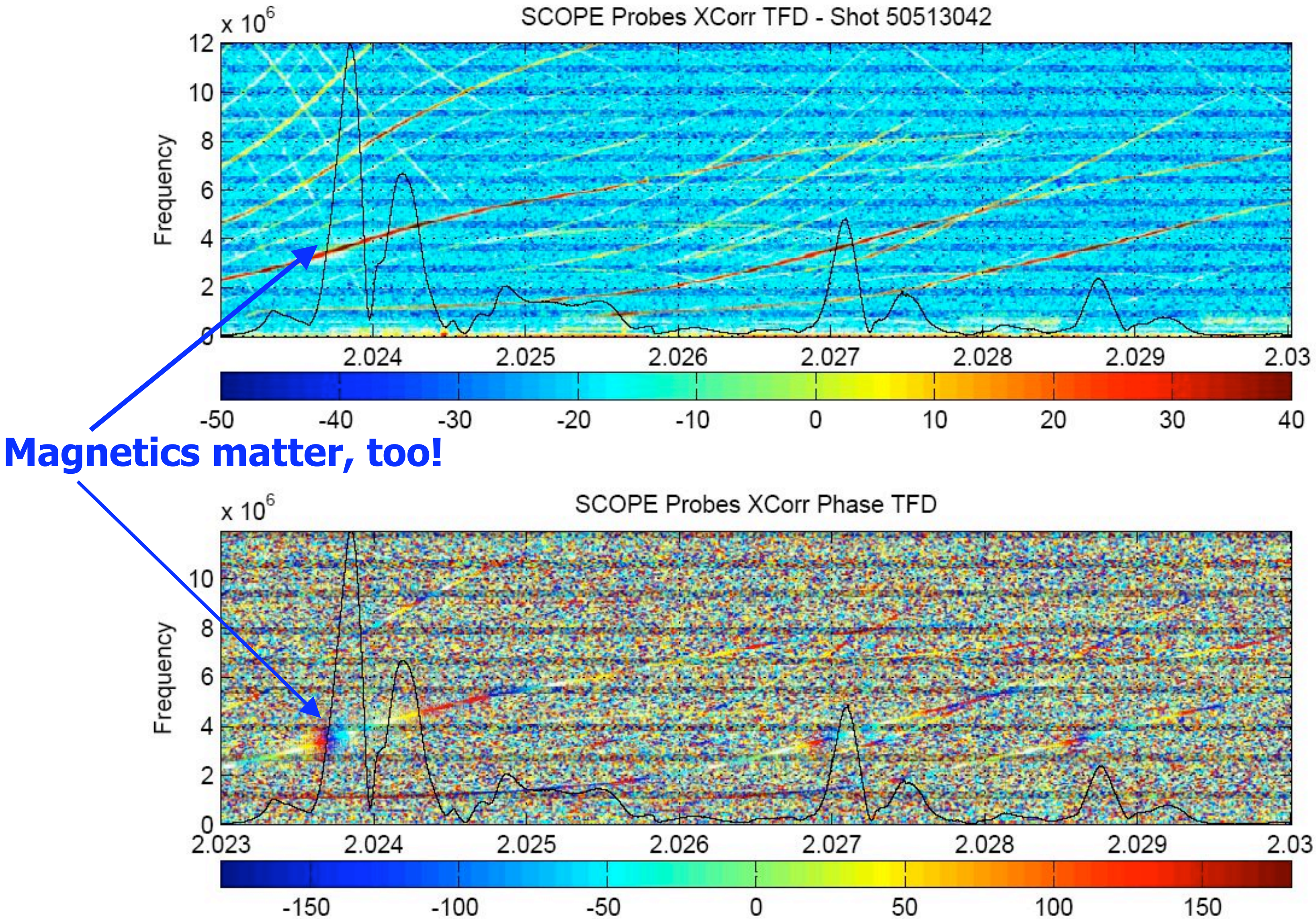

Conclusions

- Equilibrium results demonstrate stable operation at high beta during supported operation
- Magnetic reconstruction of anisotropic equilibrium returns peak local beta of 20% and 330 J at 5 kW of ECRH
- Hot Electron Interchange Instability found to be the dominant instability during supported operation
- High beta achieved only when HEI is stabilized with fueling (see VP1 20)
- New observations of HEI in high beta include
  - Hysteresis - stability/instability
  - Large perturbed magnetic fields
  - Rapid (~100 μs) transport leads to complete loss of fast electrons