Probe Measurements of Electrostatic Fluctuations in LDX

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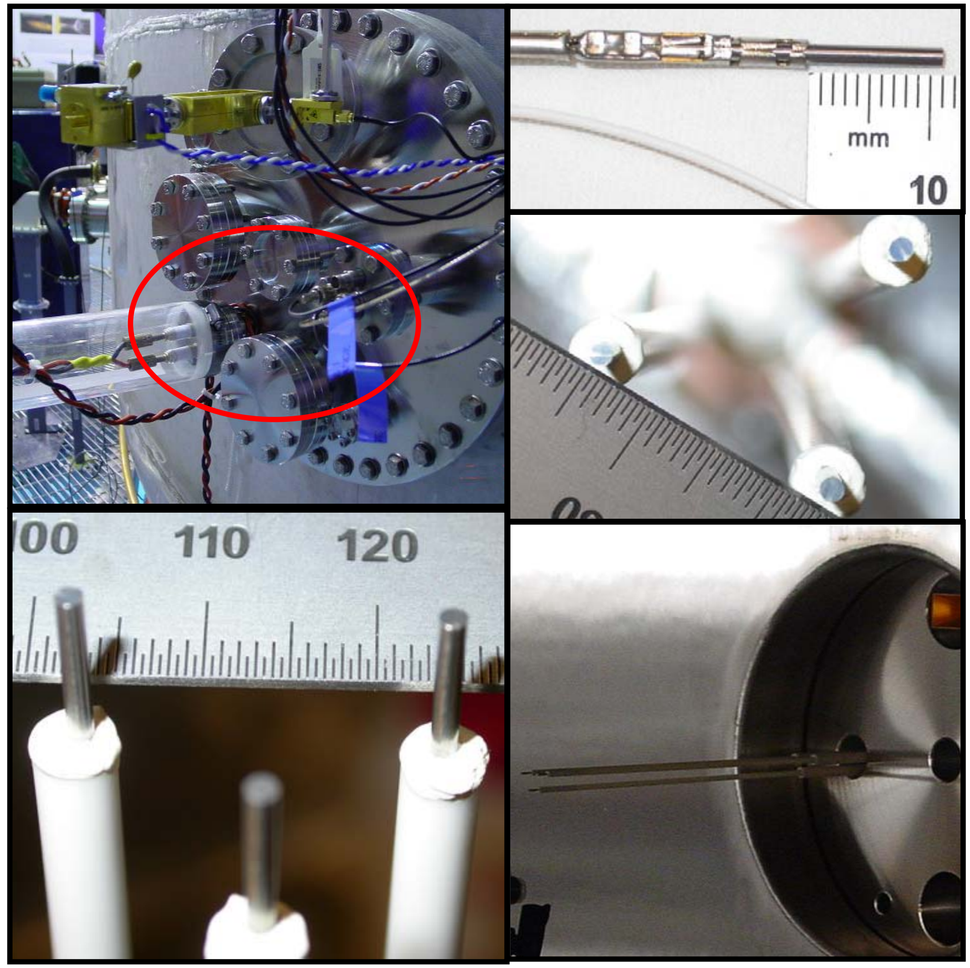
Outline

- Overview of Electric Probes on LDX
- Operational Plasma Regimes in LDX
- Types of Fluctuations Observed
  - High-beta ($\beta \equiv 2\mu_o p/B^2$) low frequency fluctuations
  - Hot Electron Interchange (HEI) instability in various limits (High β, Low β, and/in plasma regimes)
  - Initial work on magnetic fluctuations
- Plasma Images of the HEI instability
- Other High Frequency Instabilities

Hardware: Fixed Electric Probes

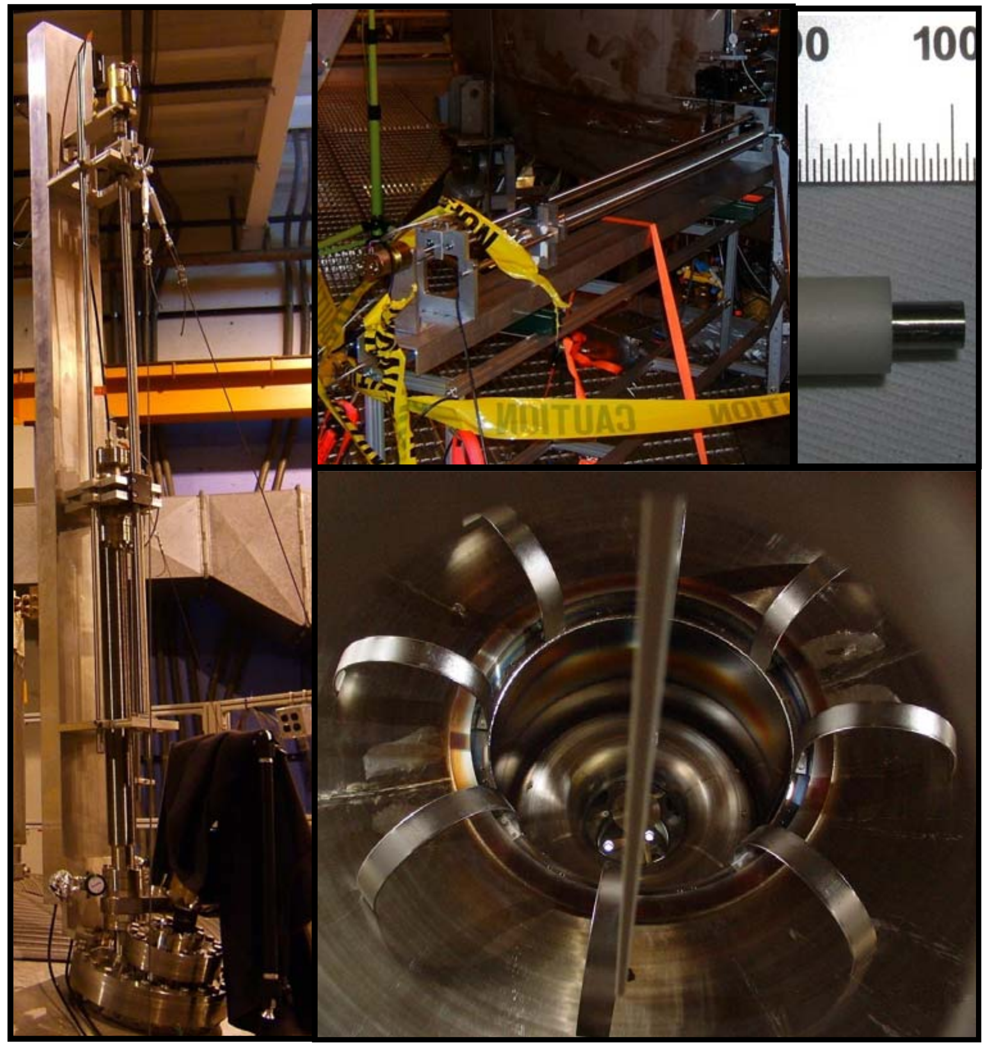
- Measure Ion Saturation current, Plasma edge density & potential fluctuations
- Three equal size **W** (Thoriated) probes
  - *l*=.99 cm, d=.16 cm, As=.49 cm^2
- Ceramic bond sealant (Cotronics, 904 Zirconia)
  - Ultra Hi-temp ceramic adhesive
- On mid-plane (**Z-pos = 0**)
  - **South:** biased to –155 V,
    - ✓ Ion Saturation current
  - **North:** voltage swept probe at 1.127 kHz, –50 to 40 V,
    - ✓ Electron temp & density from IV curve
- Below mid-plane (**Z-pos ~ -1 cm**)
  - **Mid:** high-impedance tip floating probe
    - ✓ Floating Potential & potential fluctuations



* Images by E.E. Ortiz. July 25, 2004. Aug 1..19, 2004. Nov 12, 2004.

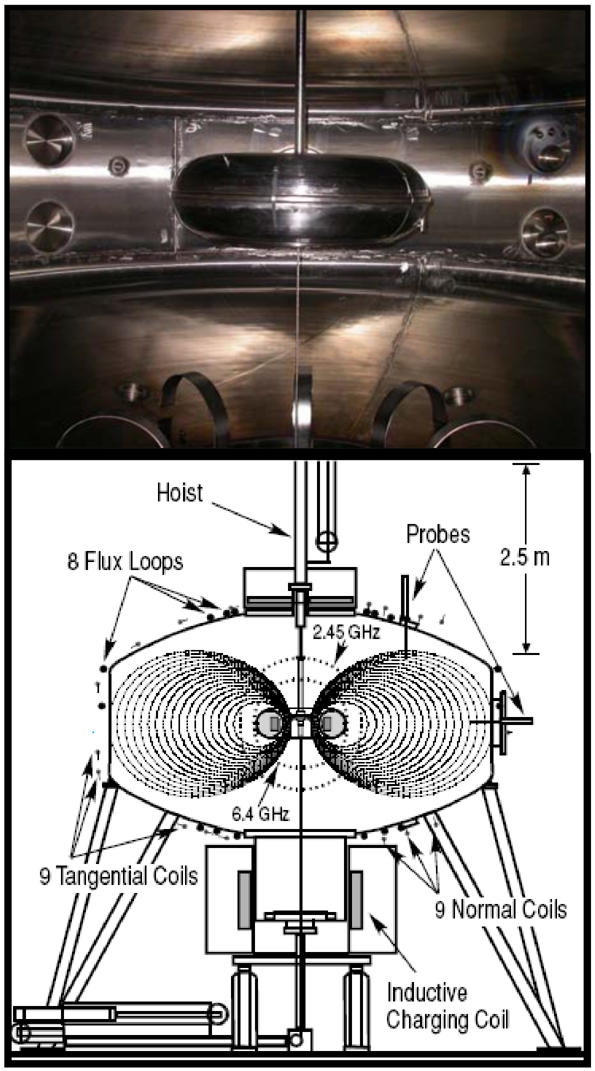
Hardware: Movable Electric Probes

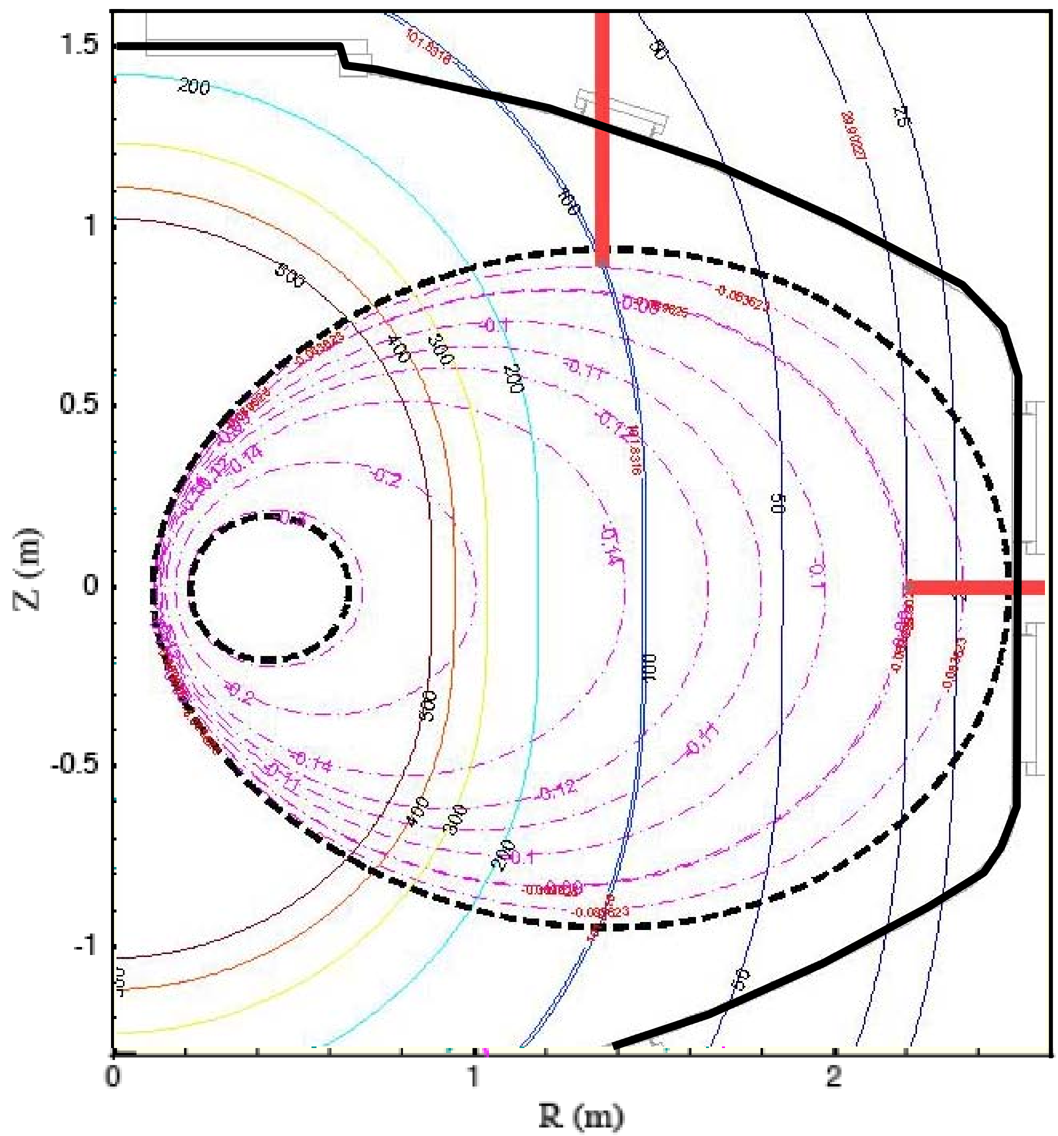
- Measure floating potential of electrostatic fields
  - High (50 K-Ohm) impedance
- Four equal size **W** (Thoriated) probes
  - *l*=.5 cm, d=.3 cm, As=.47 cm^2
  - Three vertical & one horizontal
- Adjustable linear motion // to R or Z-axis
  - Motor positioning controlled with PLC
- VERTICAL PROBES:
  - Z**-pos**: one - two meters off mid-plane
  - θ**-pos**: 45°, 225°, 315° from N
  - **R-pos**: 1.36 m from center
- HORIZONTAL PROBE
  - Z**-pos**: -.4 m
  - θ**-pos**: 45° from N
  - **R-pos**: 1.36 m from center



* Images by E.E. Ortiz. 2004-2005.

Floating Coil Produces Strong Dipole Field

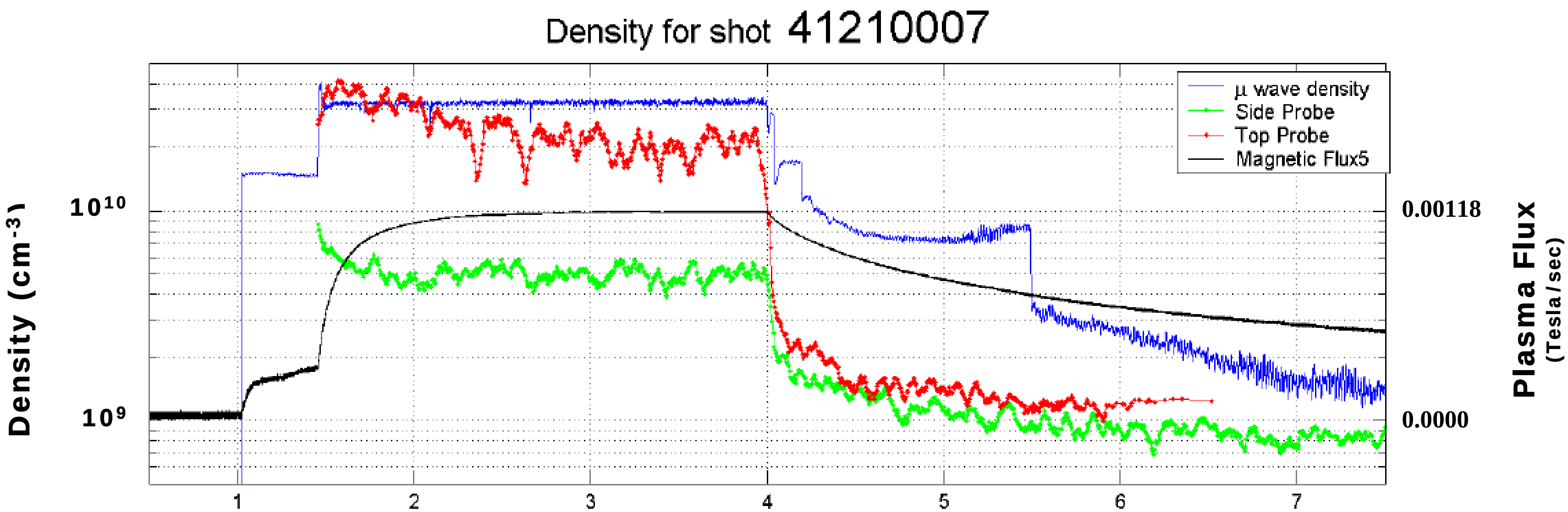




LDX Plasma Regimes

Three operational regimes identified:

- Unstable
  - During ECRH pulse, <u>no</u> measurable edge density, small plasma flux signal, negative spikes in I_{sat}, low $\beta \leq 0.5\%$.
- Stable or High density
  - During ECRH pulse, measurable edge density, high $\beta \geq 5\%$.
- Afterglow
  - ECRH off, high β, low density & decaying edge density.



Electric Fluctuations Overview

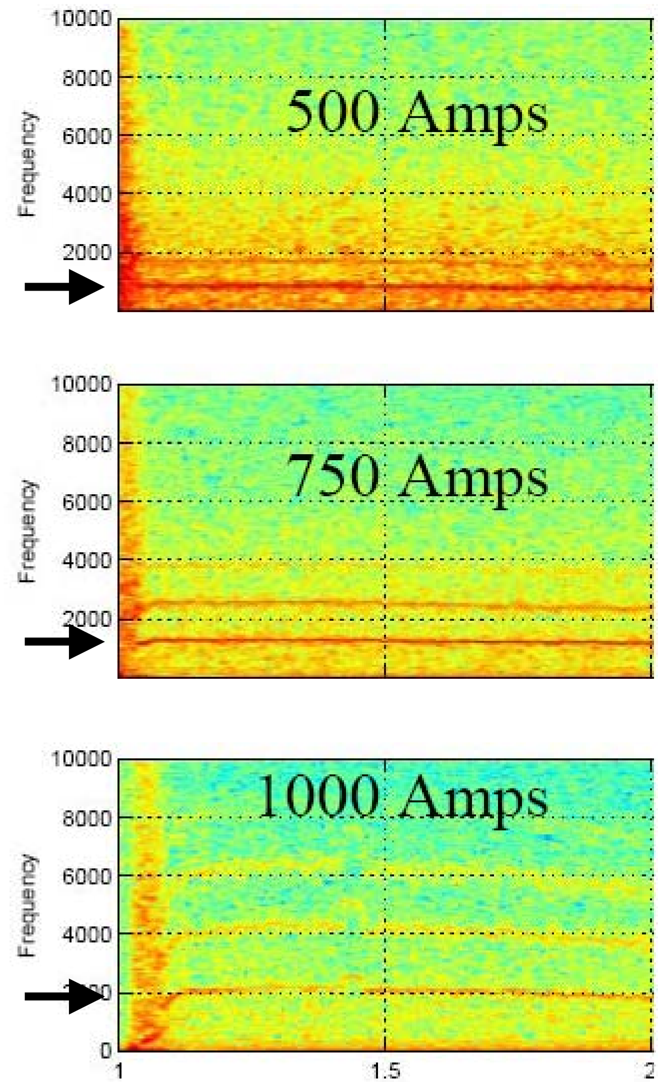
- Mode frequency not always constant, simple fast Fourier transform not enough.
- Need multiple transforms in time to see frequency evolution of fluctuations.
  - Spectrogram or Time Fourier Domain (TFD) plot shows the evolution of frequency over time.
- Low frequency ($\leq$ 5 Khz) fluctuations
  - Detected on all run campaigns, but intensity varies sometimes disappearing in back-ground noise.
  - Fluctuations rise quickly, peak & level off as the plasma β reaches steady-state in the stable regime.
  - Are they convective cells, natural (m=0) bulk plasma phenomena or other more localized plasma behavior?

Electric Fluctuations Overview (continue…)

- High frequency (> 1 Mhz) fluctuations
  - HEI instability again detected in a dipole experiment.
    - Also in the Collisioneless Terrella Experiment [15].
  - Flute instability first described by Krall [6].
    - Kinetic driven instability -- energy exchange between particles & waves electrostatic potential.
    - Conserve μ & J yet break the conservation of ψ & cause wave-induced radial transport.
  - HEI instabilities have time-evolving spectra that resonates with the drift motion of fast electrons, $\omega \sim m\omega_d$.
  - HEI suppressed by increasing the neutral fueling pressure before and/or during heating.

Low Frequency Fluctuations

- Detected by electric, Mirnov B-dot, ion-saturation & photo-diode edge probes.
  - Frequency ~.5-4 kHz.
  - During β stable regime.
  - Rise quickly (<200ms).
  - In sync with plasma flux peak.
- Visible in most plasma shots, yet more sharply visible during Helmholtz pulse. See image series, RHS.
- Helmholtz coils shape plasma & change volume.
  - Higher parallel current in the coils, smaller plasma volume.



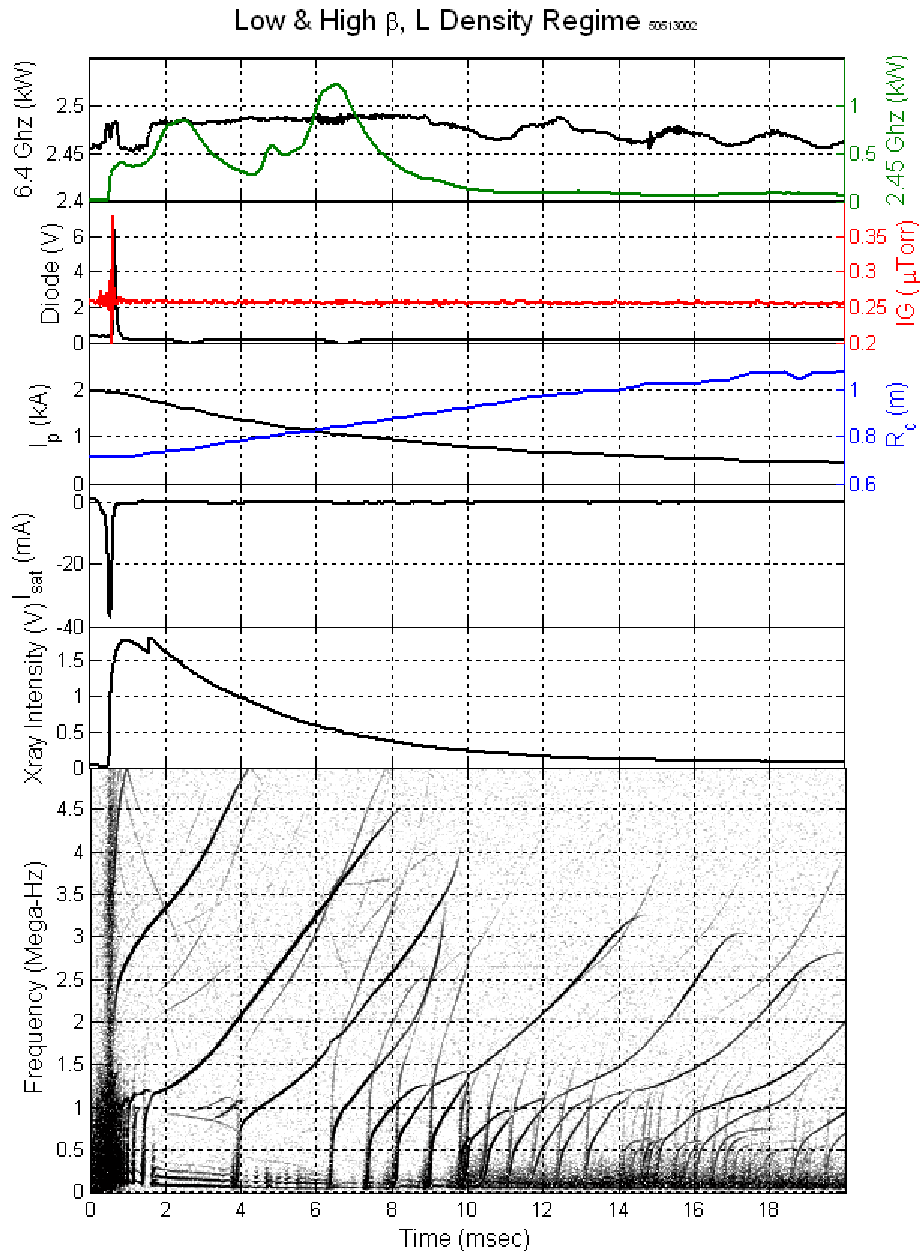
Low Frequency Fluctuations (continue…)

- Image series (above) is for fixed deuterium pressure, Fcoil current, & ECRH power.
  - Fluctuation scales to Helmholtz current & inversely scales with plasma volume.
  - Leads to question >> Where does it come from?
  - Global rotation, radial expansion & contraction or convective cells?
- Levitated Octupole Experiment [4,14,15] identified convective cells in low-density plasma with $f_{cc} < 600$ Hz.
- Edge probe fluctuation frequency not low enough to be convective cells.
  - On the other hand a new camera based diagnostic recently showed fluctuations of frequency ~200 Hz.
- Further analysis & experiments with multiple edge probes needed to pin down the source.

HEI mode - Unstable Regime

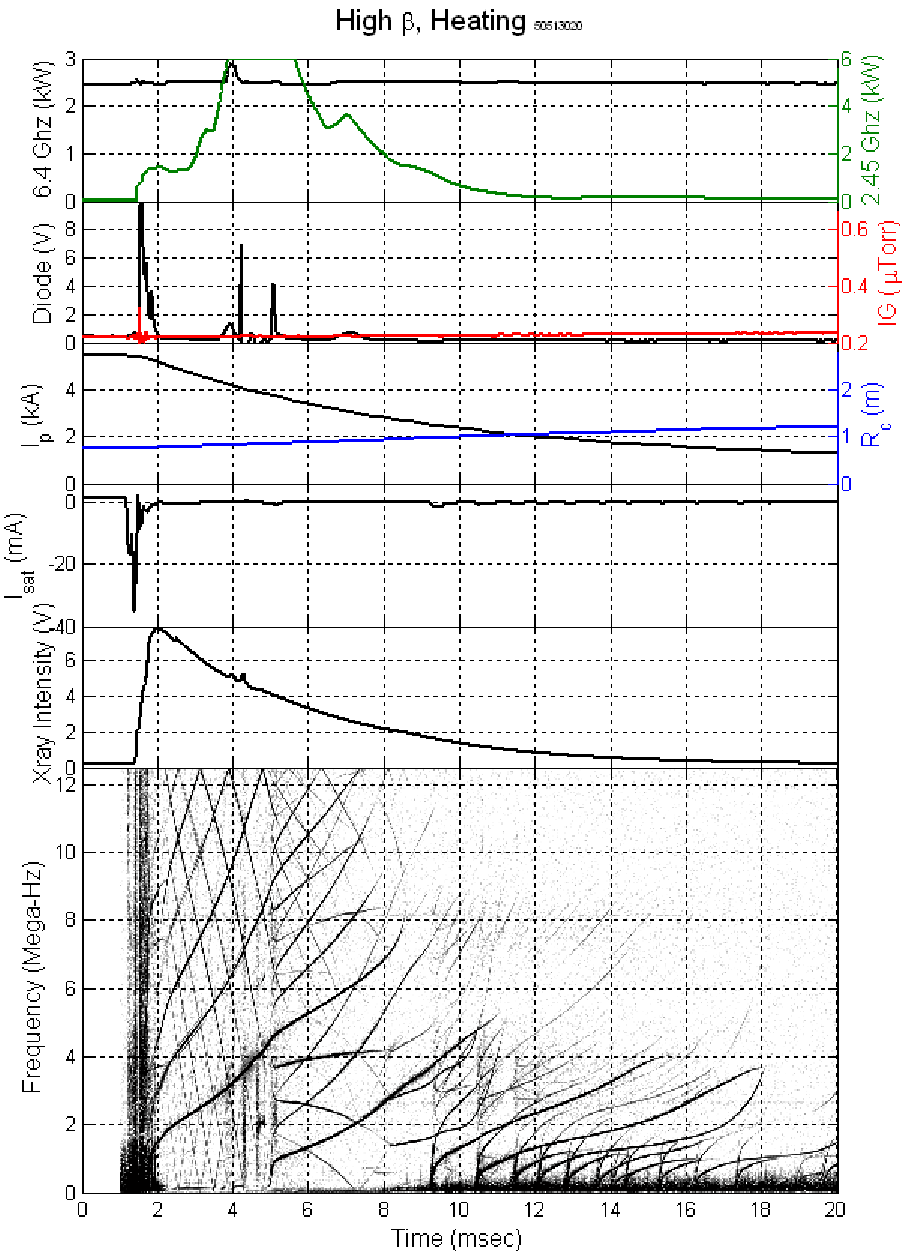
2.45 GHz Only, Full Power

- Magnetic & electro-static fluctuations measured with high speed digitizers F_{sample} = 25MHz.
- ECRH turns on & mode starts with broad band floating potential burst.
  - ECRH forward power diode on 2.45 GHz horn reacts even if source is off.
  - Photo-diode light spikes.
- X-rays intensity signal rises quickly & decays.
- I_{sat} probe dips negative.
- Unstable regime can be compared to CTX in low-β.



HEI mode – Stable Regime

6.4 GHz Only, Full Power

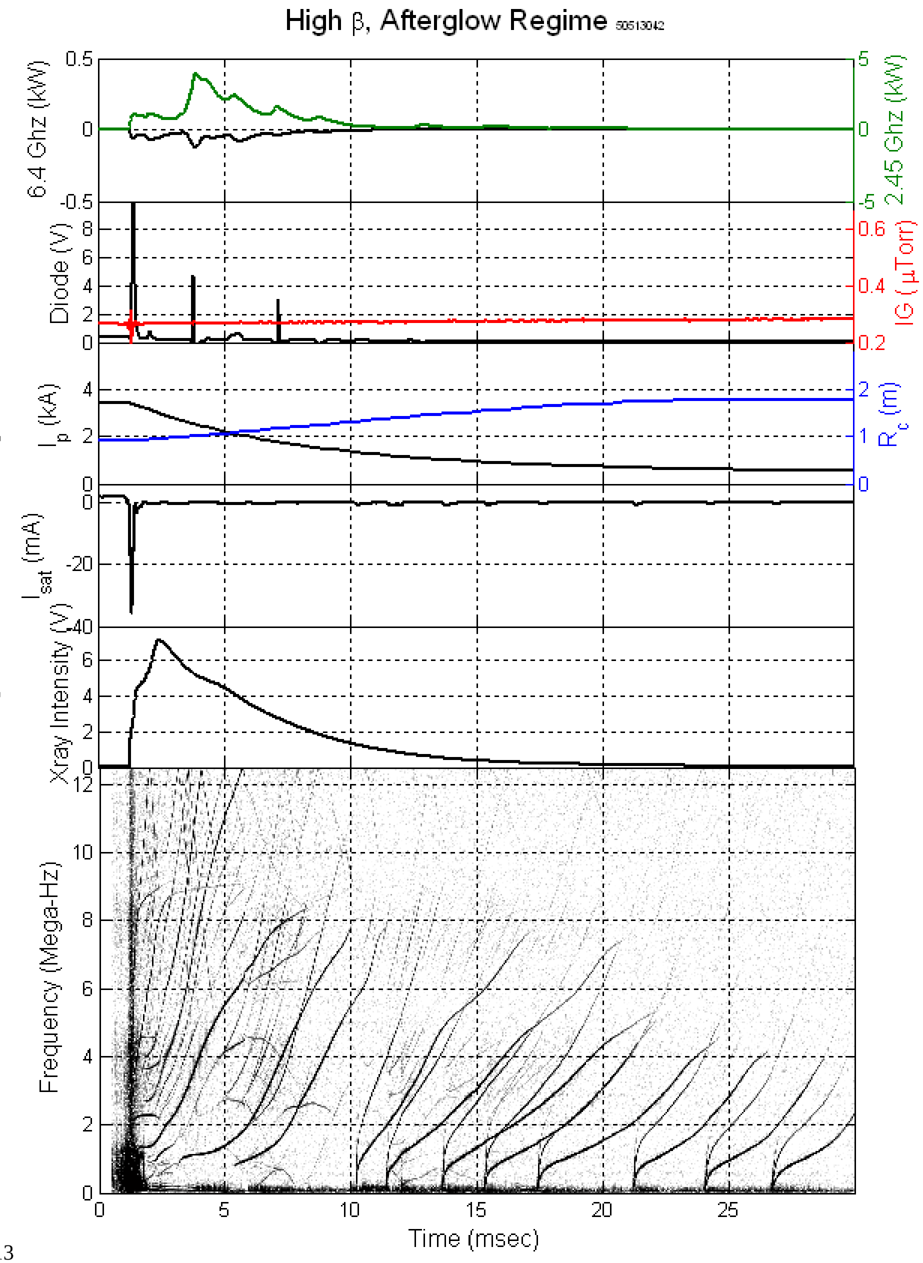


- Multiple spikes on photo-diode signal.
- Larger X-ray intensity peak than in Unstable regime.
- Both ECRH forward power diodes react to mode, especially at resonance point.
- After 15 ms, chirps flatten out at 1 MHz.
- HEI Instability abated by increase of deuterium fuel pressure before or during shot.
- Limit β & relax density gradients.

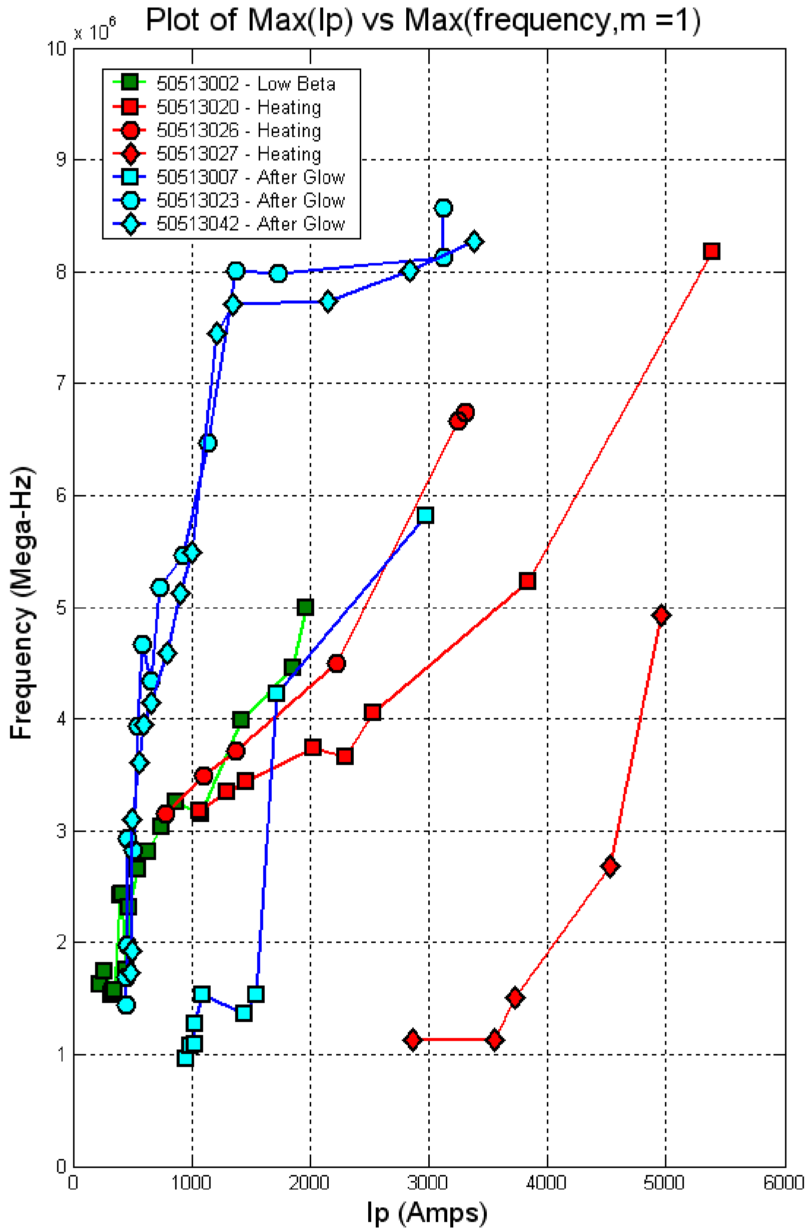
HEI mode - Afterglow Regime

Both Sources, Full Power

- Analogous with Stable regime on initial response.
  - ECRH response ~ 10 ms in both regimes.
  - X-ray intensity peaks around 7 Volts.
  - Similar level on I_{sat} dip for all three regimes.
  - Yet, photo-diode spikes not as intense.
  - Multiple chirps greater than 5 MHz.
- Later response (>15ms) still has single chirps into 3-4 MHz range.
  - In contrast, chirps do not rise as high after early response in Stable regime.



How Fast is the Fast Electron Population?



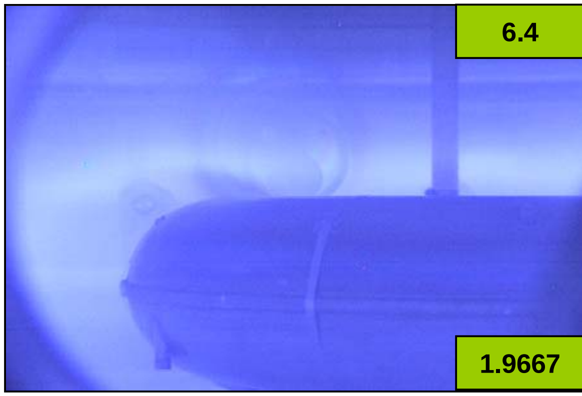
- X-rays detectors measure fast electron population temperature.
  - Not yet definitive for LDX.
- Instead plasma current, $I_p \sim n_{fep} * E_f$, versus lowest mode HEI instability frequency, $f_{m=1} \sim K * Ef$, can be compared.
  - Relates instability to fast electron population, Te.
  - Expect linear relation.
- Population temperature at least 100 keV to produce greater than 5 MHz chirps.

Video: Fast Electrons

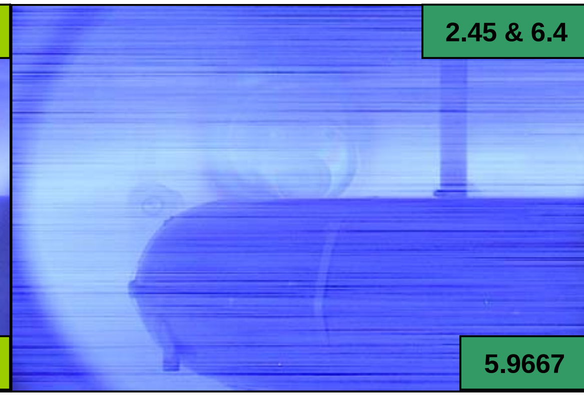
- Visible light emission during ECRH is dominated by the cold electrons as can be seen in the first image below.
- Afterglow equilibrium decay rate on the order of seconds.
  - Represents the collisional loss rate of the trapped electrons.
  - Peak near the equatorial plane [5].
- Cold electrons in Afterglow quickly scatter into loss cone.
  - Leave a nearly completely fast electron plasma.
- Low density plasma visible light emission is dominated by electron de-excitation ($\sim ne*no*<\sigma\nu>$).
  - Hydrogenic plasma electron excitation rate peaks ~ 100 eV.
  - Insensitive to T_e above 100 keV, at which point it has a magnitude ~ 10% of its peak [1].
- Fast electrons in LDX make up most of visible light radiation in Afterglow.
  - According to X. Chen et al. this is proportional to the fast electron density.

Video: Fast Electrons (continue…)

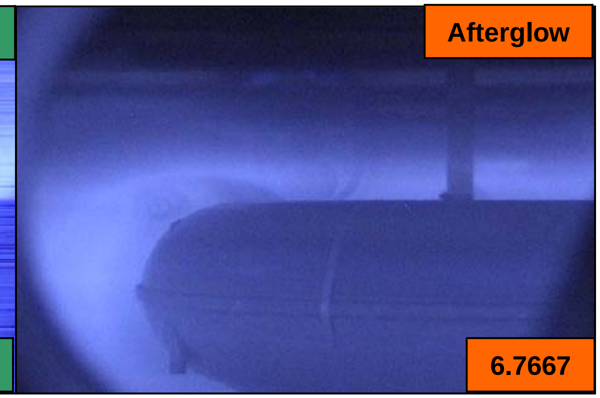
SHOT: **50318020**, I_{fcoil} = 250 A, I_p = 3.4 kA, $IG_{t=0}$ = .75 μTorr



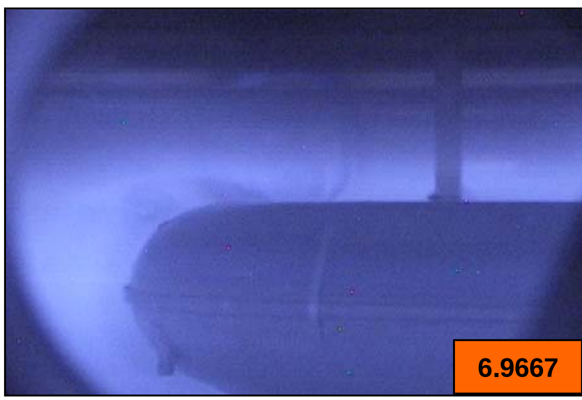
- Cold electrons dominate visible light collected
- No pocket of fast-electrons visible even after 2s heating



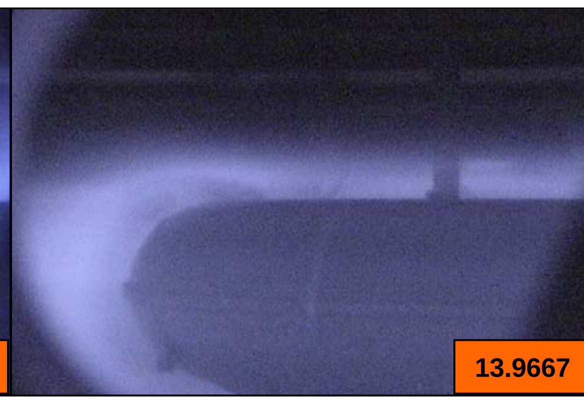
- 2.45 GHz ECRH blurs video
- Hard to tell what's going on



- .77 s into afterglow regime
- Notice formation of bright clump near equatorial plane



- Tiny HEI .97 s into Afterglow
- It also blurs video
- Beta relaxation minor

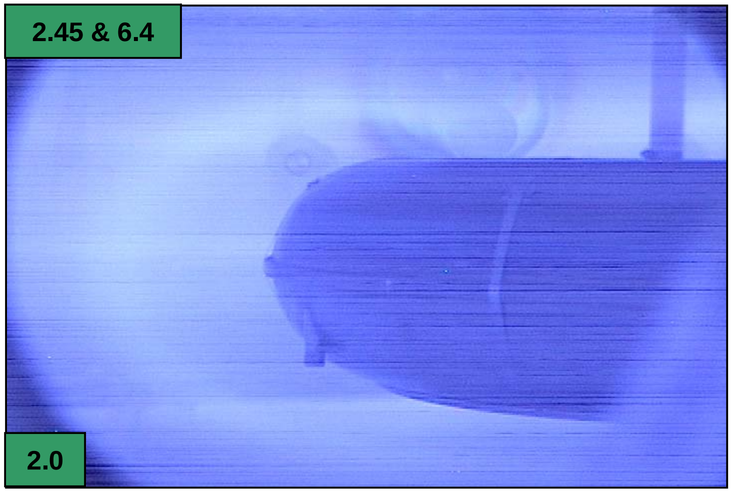


- 7.97 s into Afterglow, stable very slow decay
- Notice image dimming & changing color

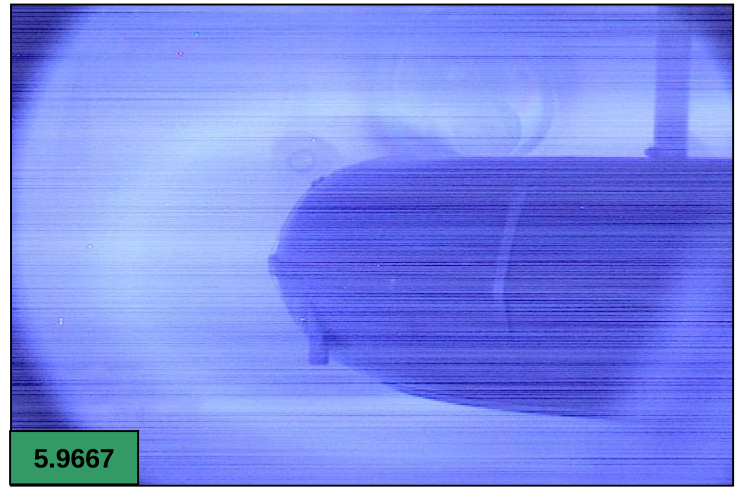
- Large HEI 8.77 s into Afterglow
- Instability signature of X-rays seen above, plasma & beta vanish next frame

Video: Fast Electrons (continue…)

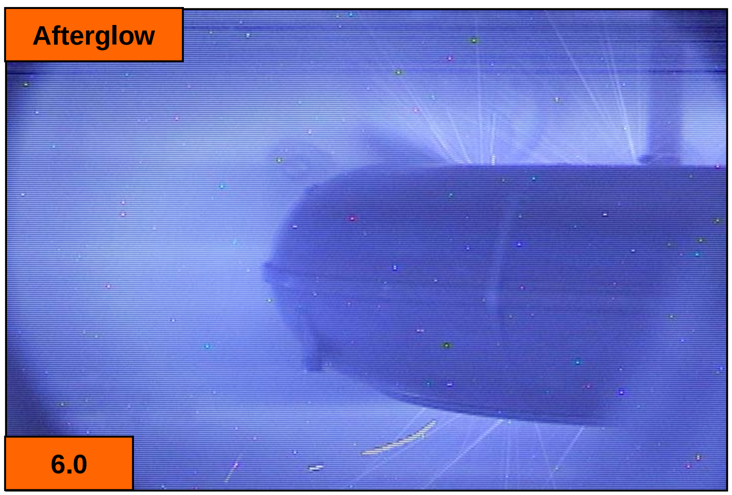
SHOT: **50513029**, I_{fcoil} = 300 A, I_p = 5.1 kA, $IG_{t=0}$ = 1.4 μTorr



♠ 2 s into discharge, plasma current around 4.3 kA before second puff



♠ Last frame before Afterglow, stable 5.1 kA plasma after additional puff

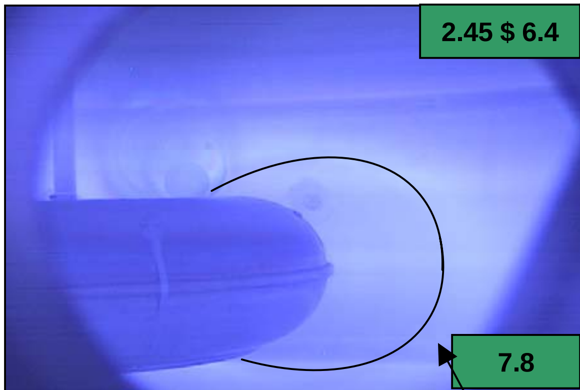


♠ First frame into Afterglow, a very large HEI, flying objects originate inside fcoil as fast electrons scatter off the supports

♠ Plasma current drops by 4 kA in .2 s, the glow is noticeably smaller, yet flying objects still persist

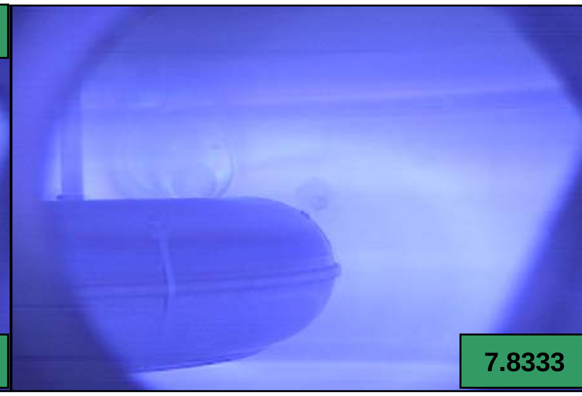
Video: Fast Electrons (continue…)

SHOT: **50701013**, I_{fcoil} = 400 A, I_p = 3.5 kA, $IG_{t=0}$ = 0.6 μTorr



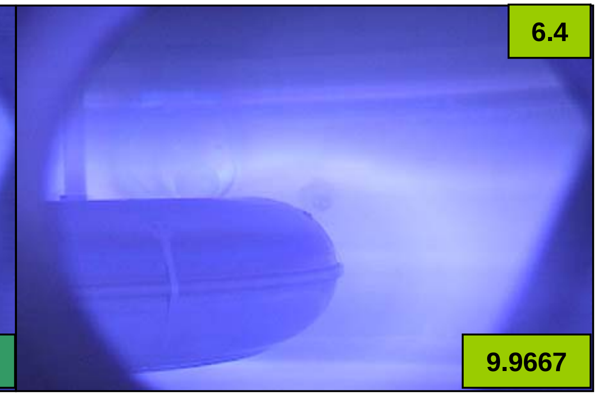
♠ Well into the discharge, both sources are on when …

♠ A tiny HEI goes off at 7.82 s note intensity surface @ ψ_{int}



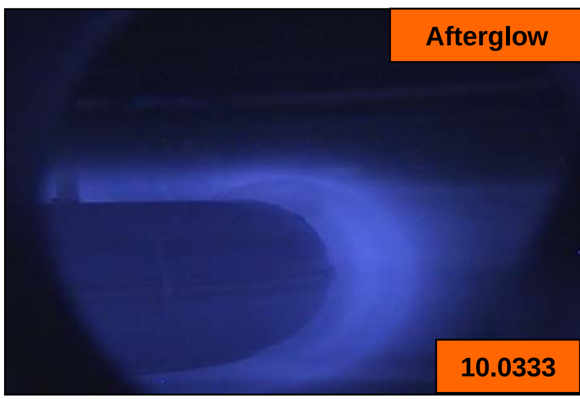
♠ The adjacent flux surfaces exchange plasma moving less cooler, less dense plasma in

♠ Visibly brighter inside ψ_{int}



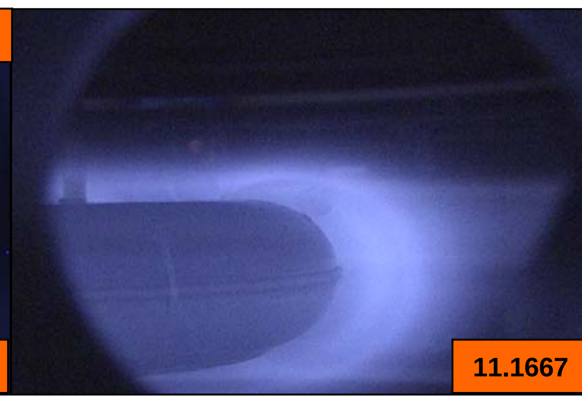
♠ Last frame before Afterglow, notice shifted hue to prior frame

♠ 6.4 only has a different ψ_{int}, shifted inwards



♠ Second frame into Afterglow, clearly see the regions of fast electron density

♠ Overall brightness reduced



♠ 1.17 s into Afterglow & the hue has changed again, probably due to less neutrals off the walls fueling the plasma

♠ But, after an HEI & particles driven to the walls, hue changes back towards a darker color tending toward heating color

HEI Conclusions

- High frequency fluctuations on electrostatic probes have been identified as the hot electron interchange instability & found to limit plasma pressure.
- Frequency sweeping occurs at the drift-resonance of trapped fast electrons.
- Electron population temperature at least 100 keV.
- Plasma regimes exhibit different chirping behavior:
  - Last longest during Afterglow regime.
  - Most intense during Stable regime.
  - Continuous chirps during Unstable regime.
- HEI instabilities have been studied extensively in dipoles with low β [8-12,15-17], yet not con-currently with magnetic fluctuations.
  - LDX provides first look at this in next section.

Magnetic Fluctuations

- Achieved high β values, ~20%, yet no new high frequency magnetic fluctuations.
- Limiting factors:
  - Lack of dependable & high-speed digitizing equipment.
  - Lack of instabilities captured during high β regime.
- Solutions:
  - Add new 10 channel high speed (>20 Mhz) digitizer.
  - Levitate >> higher β and improve instability detection mechanism.
- Important questions:
  - Do magnetic fluctuations limit/modulate the energetic electron distribution driving the HEI or other instabilities?
  - How does high-beta plasma behave in the presence of high frequency magnetic fluctuations, and, do we see pressure limits?
- An unexpected & interesting result related to magnetic fluctuations presented next.

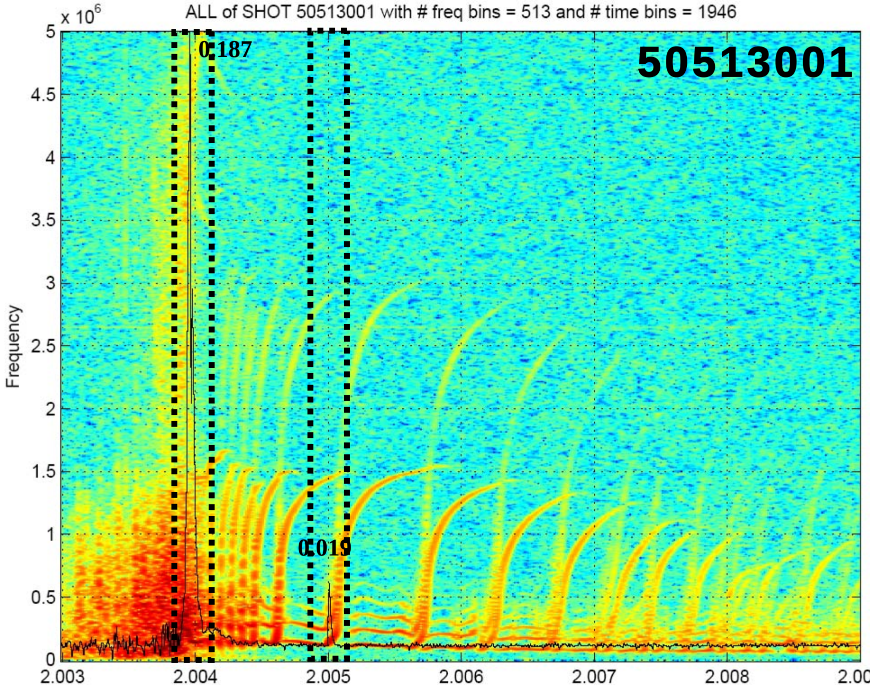
LDX, A giant cyclotron-maser?

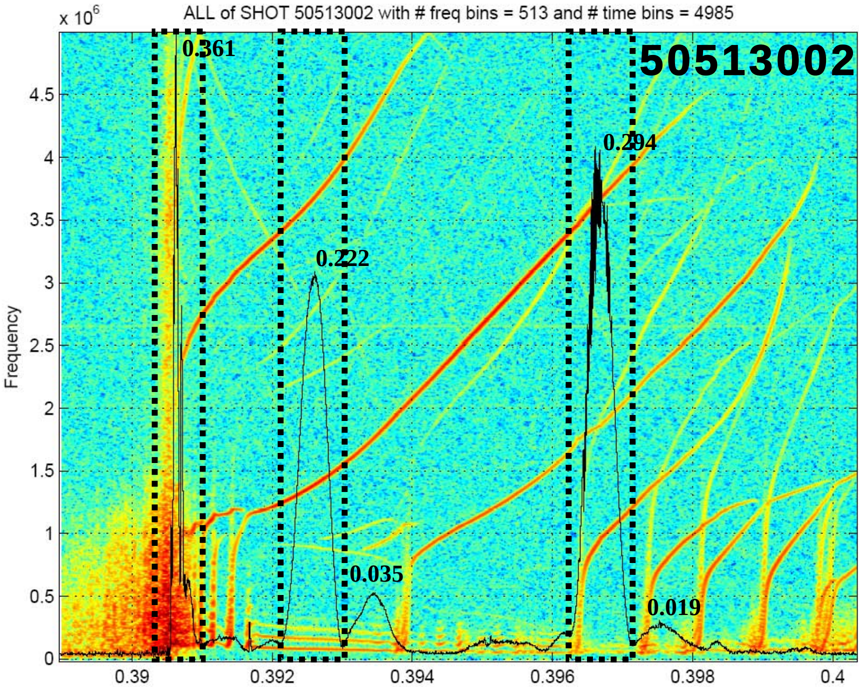
- Very-high frequencies, concurrent with HEI instabilities, are detected by a 50 GHz radiometer.
- Radiation most likely from multi-mode coupling leading to enhance particle transport into higher magnitude (~ 1 Tesla) fields near center of floating coil.
  - Relativistic electrons cyclotron radiate (GHz) in this region.
- The horn peaks significantly only during strong multiple primary mode (m=1) HEI bursts.
- The primary mode chirps up to a max frequency.
  - $f_{(m=1)}$> 1.5 Mhz in Unstable, $f_{(m=1)}$ > 1.0 Mhz in Afterglow & $f_{(m=1)}$ > 4.0 Mhz in Unstable, depending on beta.
  - Define Radiometer Peaks (RP) as those which clearly stand alone & are indirect/directly related to HEI events.
- Location, height & magnitude of RP depend on several factors: # of bursts, magnitude, relative frequency.
  - Constructive/destructive interference between modes?
  - What connection does it have to plasma regimes & β?

HEI vs. Radiometer – Unstable Regime

Both Sources (LHS) :: 2.45 GHz (RHS)

- First radiometer peak (RP) a result of broad spectrum burst related to the onset of the HEI instability.
- Unstable regime plots show RPs in dotted boxes below.
- Second RP occurs within 2 ms.
- Level of RP generally lower during Unstable regime.

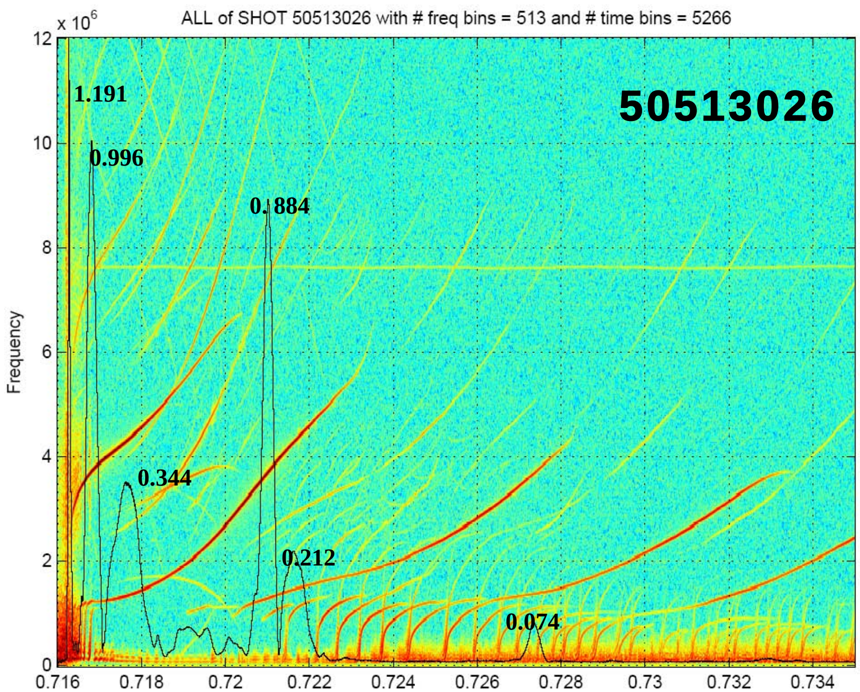


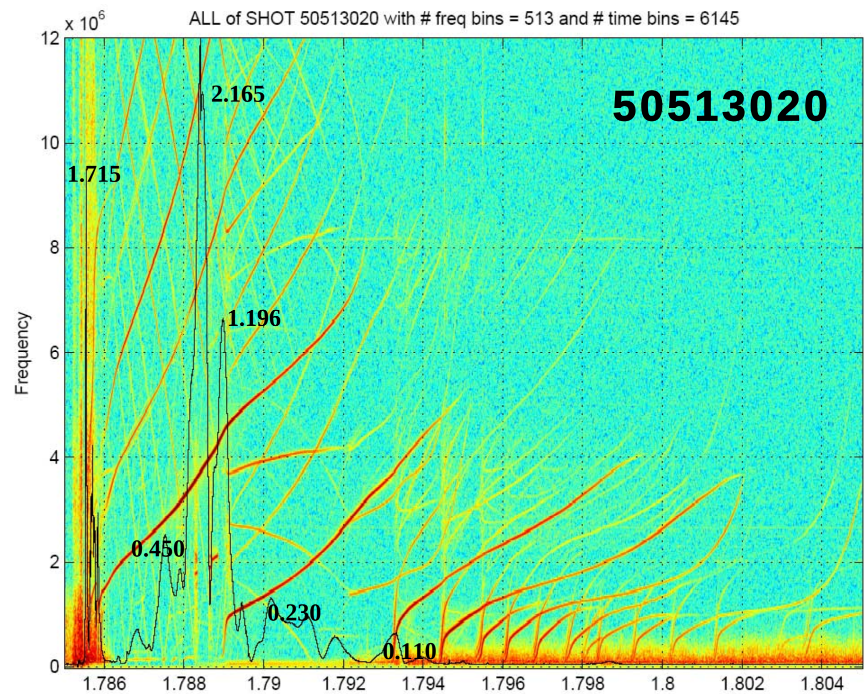


HEI vs. Radiometer – Stable Regime

6.4 Ghz Only

- 6.4 Only plots below show different chirping behavior to Unstable & Afterglow, similar to each other.
- Chirping frequency maximum scales with β.
- Stable regime radiometer peaks have largest signal amplitude (1-2 Volts).

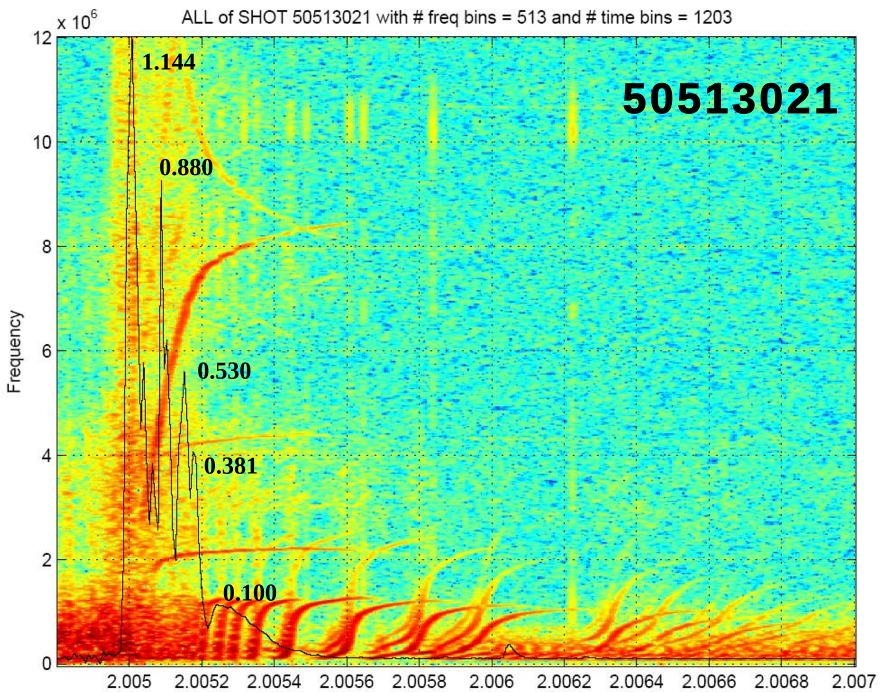


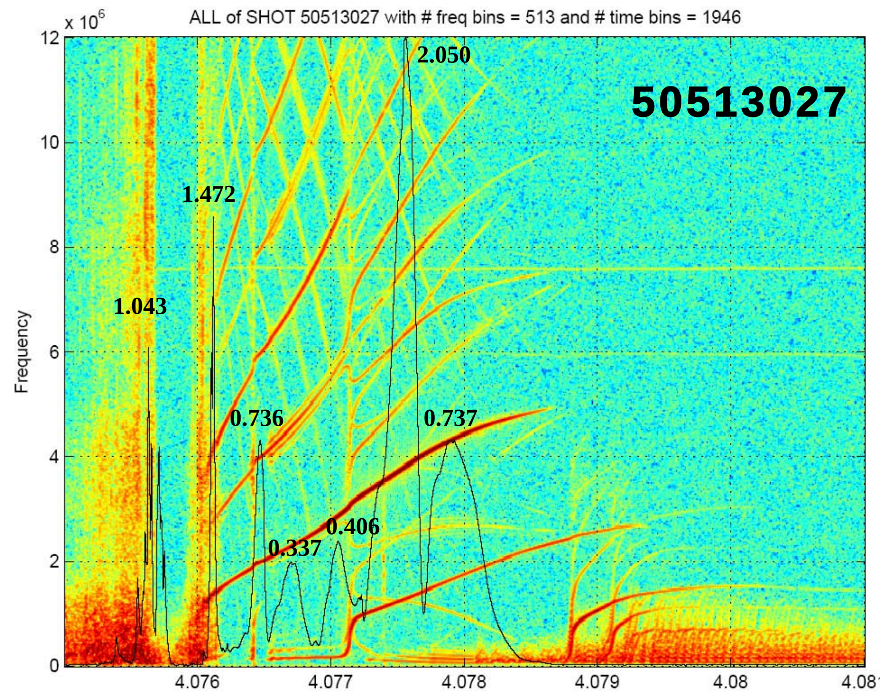


HEI vs. Radiometer – Stable Regime

Both Sources On

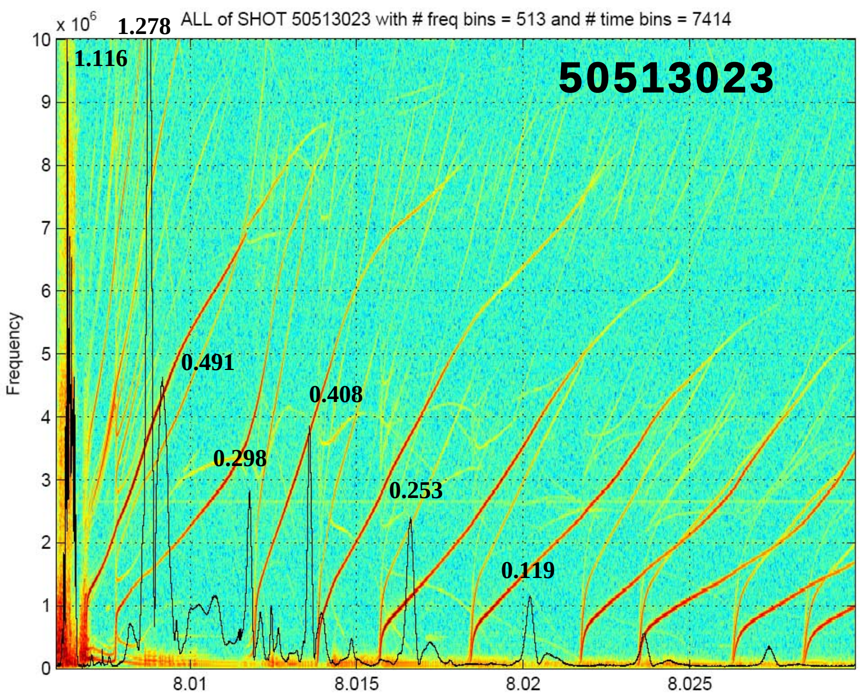
- Both sources on plots below show different chirping behavior than Unstable, Afterglow & Stable regime with 6.4 only, previous page.
- Similar to each other with chirp rollover as HEI stabilizes.
  - Stable regime HEIs w/ $f_{m=1}$< 1 Mhz common, due to ECRH.
- RPs sometimes limited to initial broad band disruption.

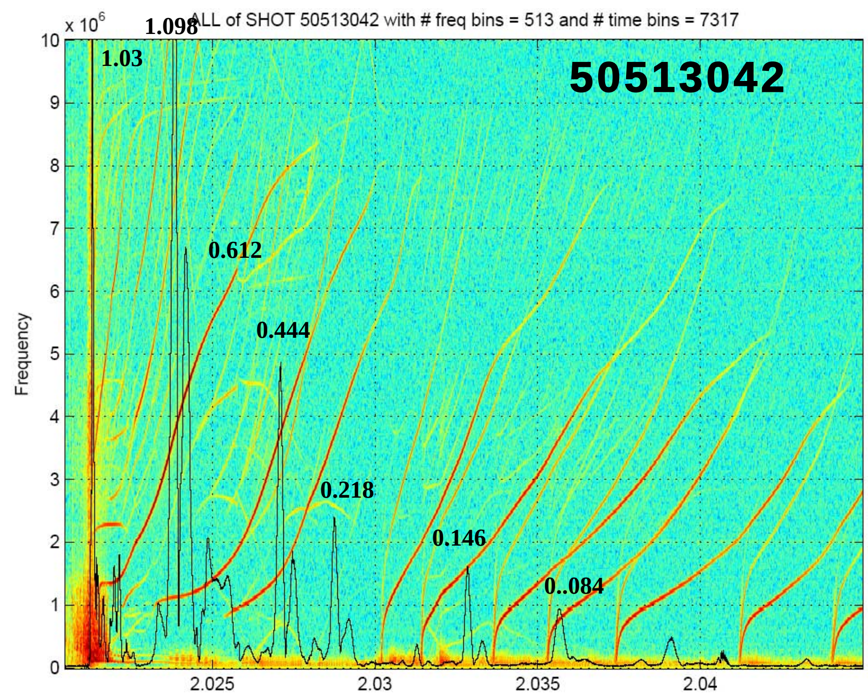




HEI vs. Radiometer – Afterglow Regime Both Sources, ½ power 6.4 GHz (LHS) :: Both Sources, Full Power (RHS)

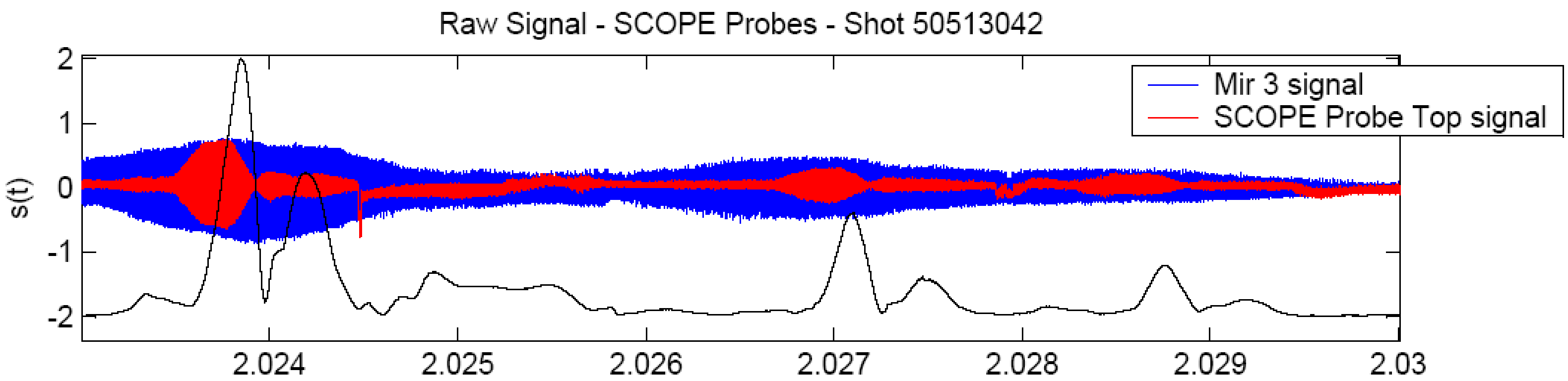
- Multiple radiometer peaks concurrent with individual instability chirps.
- Radiometer peaks (RPs) suffer faster maximum peak decay than HEI instability.
- A cross correlation with magnetic fluctuations show fast phase changes during RPs, next section.





Magnetic & Electric Correlation – Afterglow

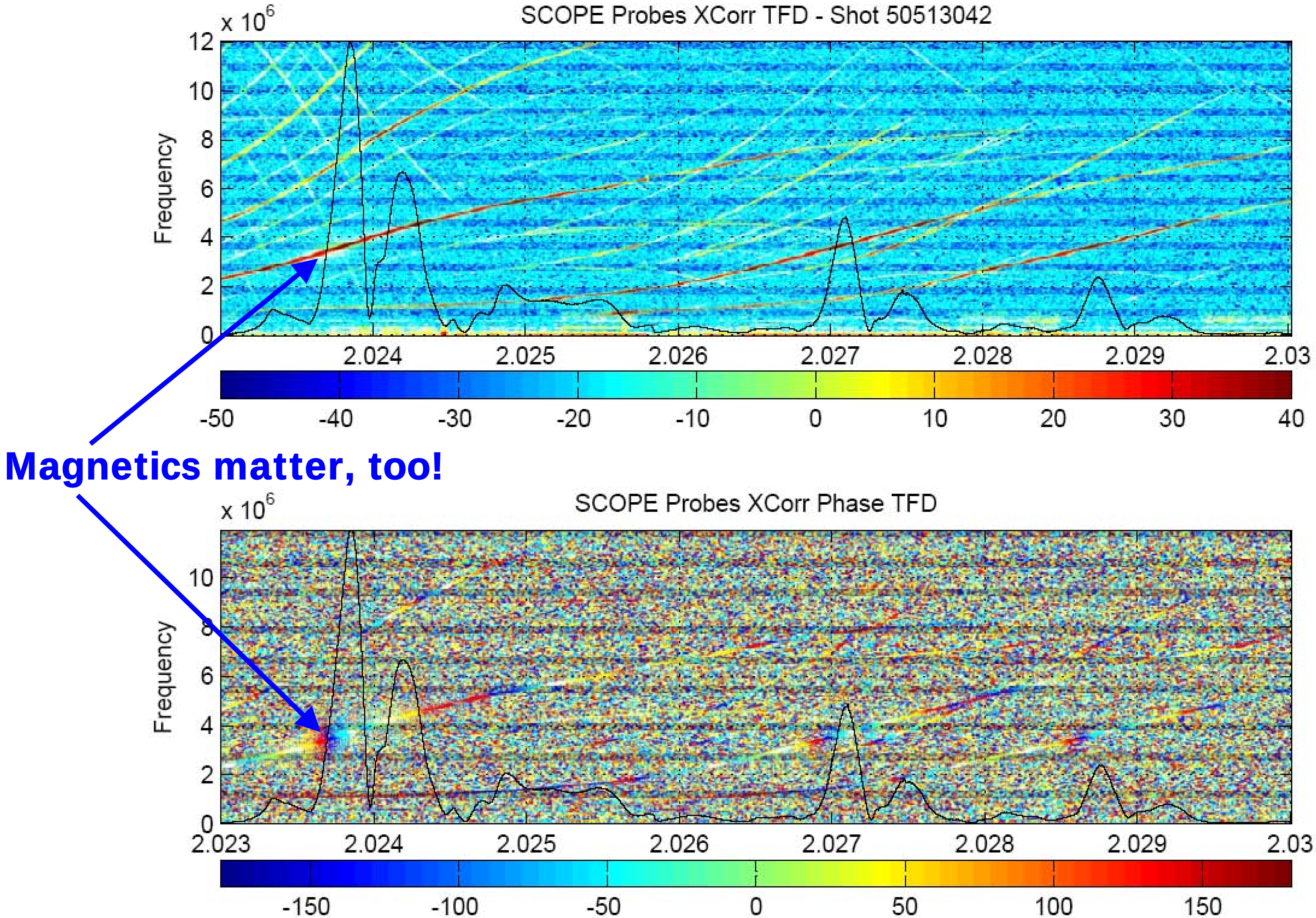
(50513042)



- Three RPs above in an Afterglow shot versus corresponding Mirnov Coil & Floating Potential signals.
  - This close up shows that the magnetic fluctuation modulates the amplitude of the recorded radiometer signal.
  - The electric fluctuation amplitude must grow & maximize in conjunction with the magnetic amplitude before an RP appears.
- A Time Fourier Domain (TFD) Cross correlation & Phase correlation show…
  - That the two signals highly correlate with each others primary mode, the signals phase cycle, the rising edge of a radiometer RP occurs always at the same phase relationship (±180°), & primary mode appears to resonate, next page.

Magnetic & Electric Correlation – Afterglow

(50513042)



Possible Higher Frequency Instabilities

Cyclotron Maser or Whistler Instabilities in LDX?

- Cyclotron Maser Instability (CMI) [4,7].
  - Driven by relativistic bunching mechanism.
  - May occur at frequencies below the nonrelativistic cyclotron frequency, as T_e rises frequency decreases.
- Whistler Instability [4].
  - Electron micro-instability driven by temperature anisotropy.
  - Typically a frequency at or below the ECRH frequency.
- Both can be simultaneously present, may offset one another [2].
- LDX may have none, one or both present:
  - 50 Ghz radiation could be ECE of fast particles as they enter the high field region.
  - If radiometer predicts CMI -> they occur more frequently/ intensely in Stable & Afterglow regime, T_e greater.
  - Whistler mode may be responsible for kicking particles and breaking μ conservation if HEI causes radial inward transport to exceed critical value.

Summary

- Multiple fixed & movable electric probes are used to measure bulk plasma parameters & fluctuations.
- Three operational plasma regimes identified: Unstable, Stable & Afterglow.
- Low frequency fluctuations likely global plasma rotation and/or expansion & contraction.
- High frequency fluctuations on electrostatic probes have been identified as the Hot Electron Interchange (HEI) instability & found to limit plasma pressure.
- Higher frequency instabilities such as Whistler & Cyclotron Maser instability may also be present.
- Magnetic & electric fluctuations highly correlate during the HEI mode. Further studies on their phase-relationship are next phase of determining how the mode modulates fast-electron density.

Abstract

High frequency > 1 Mhz and low-frequency < 5 kHz electrostatic fluctuations have been observed in high-beta plasma created in the levitated dipole experiment. The high-frequency mode is characterized by frequency sweeping at the drift-resonance of trapped energetic electrons and identifies the instability as the hot electron interchange (HEI) mode. The HEI mode limits plasma pressure, but it is stabilized when the rate of neutral fueling exceeds a threshold. The fluctuations often appear with coherent structures that have been detected on fast high-impedance electrostatic probes. Magnetic fluctuations of the HEI in the high-beta LDX have been measured, and the phase-relationship between the magnetic and electric fluctuations help to determine how the mode modulates the energetic electron distribution. Measurements that characterize these modes are compared to 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 are presented.

References

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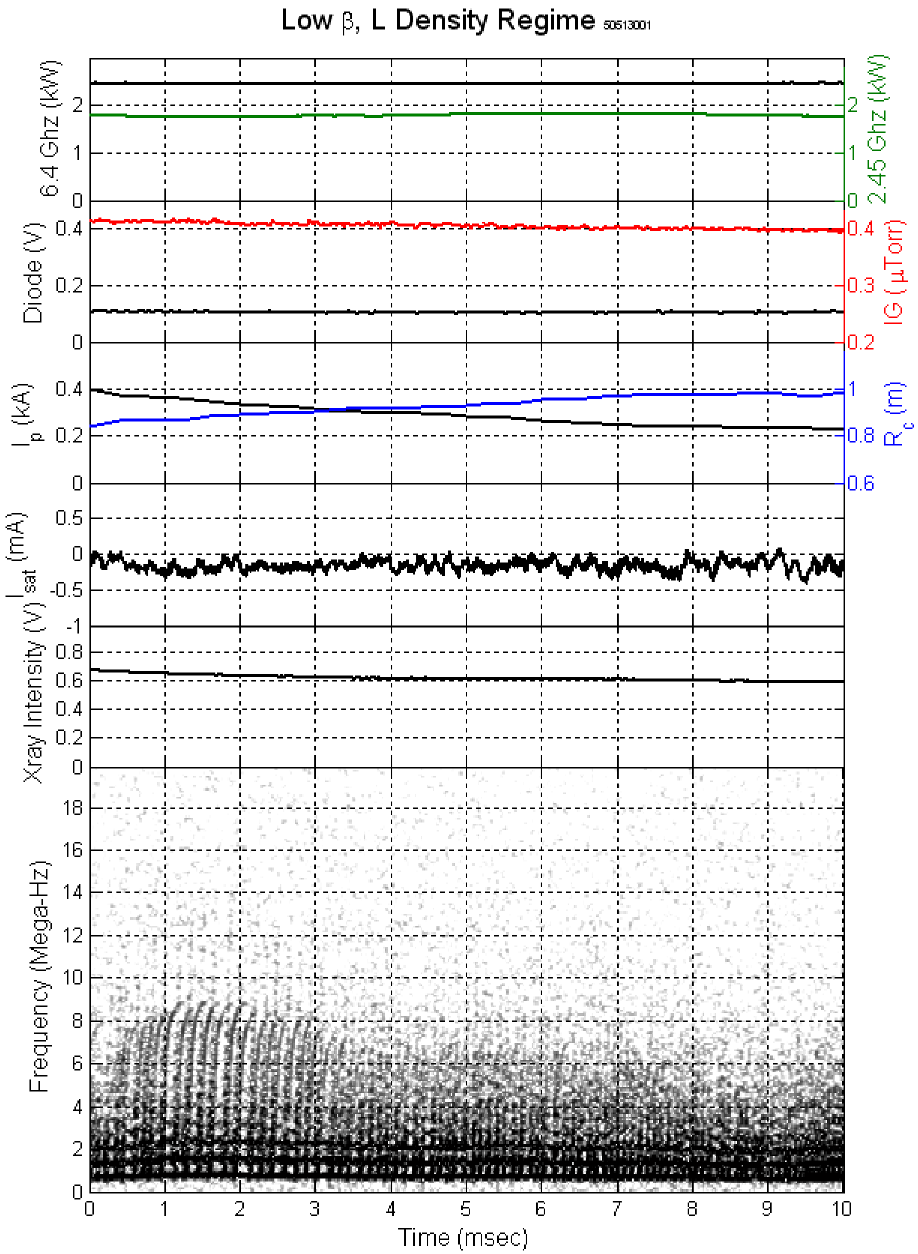
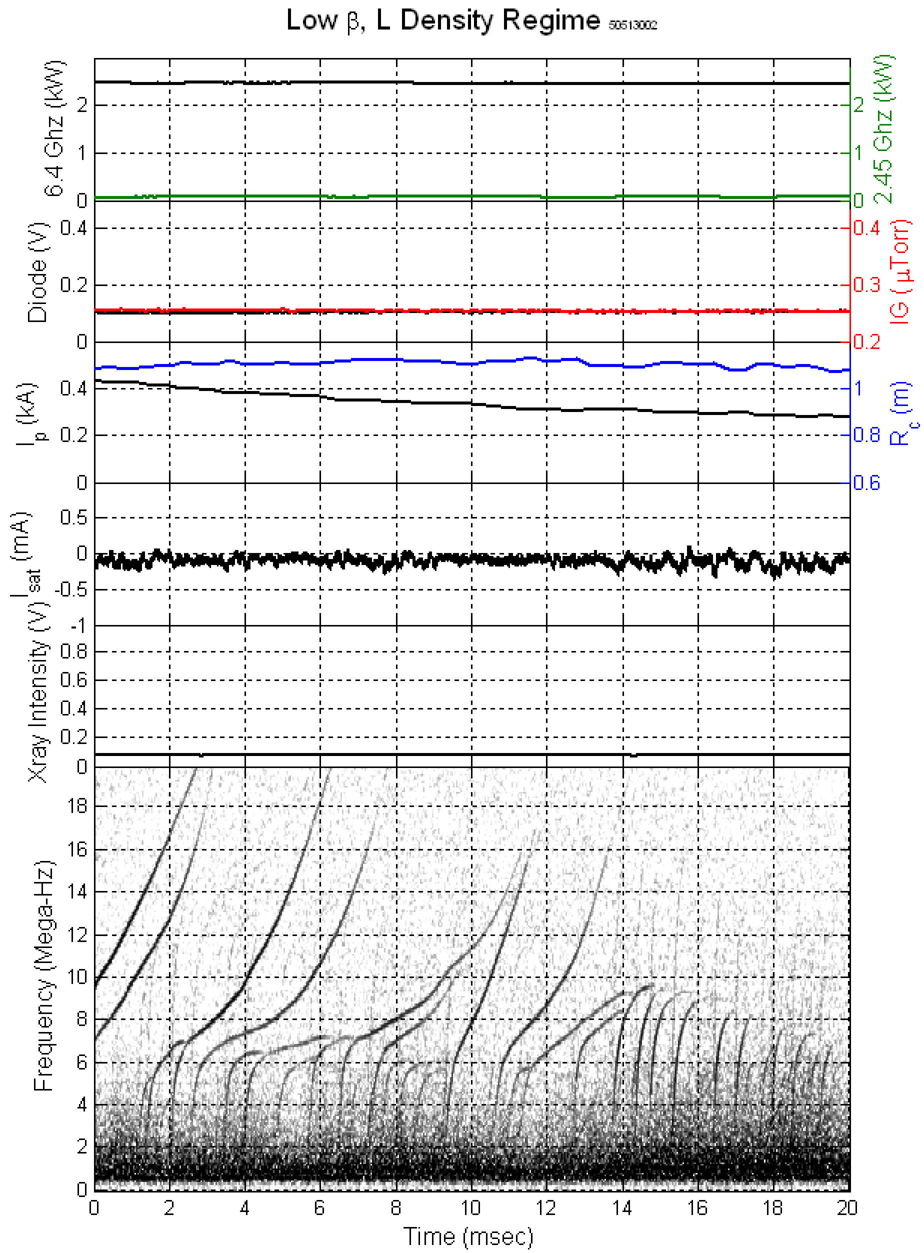
Appendix

Post Burst Behavior - Unstable Regime

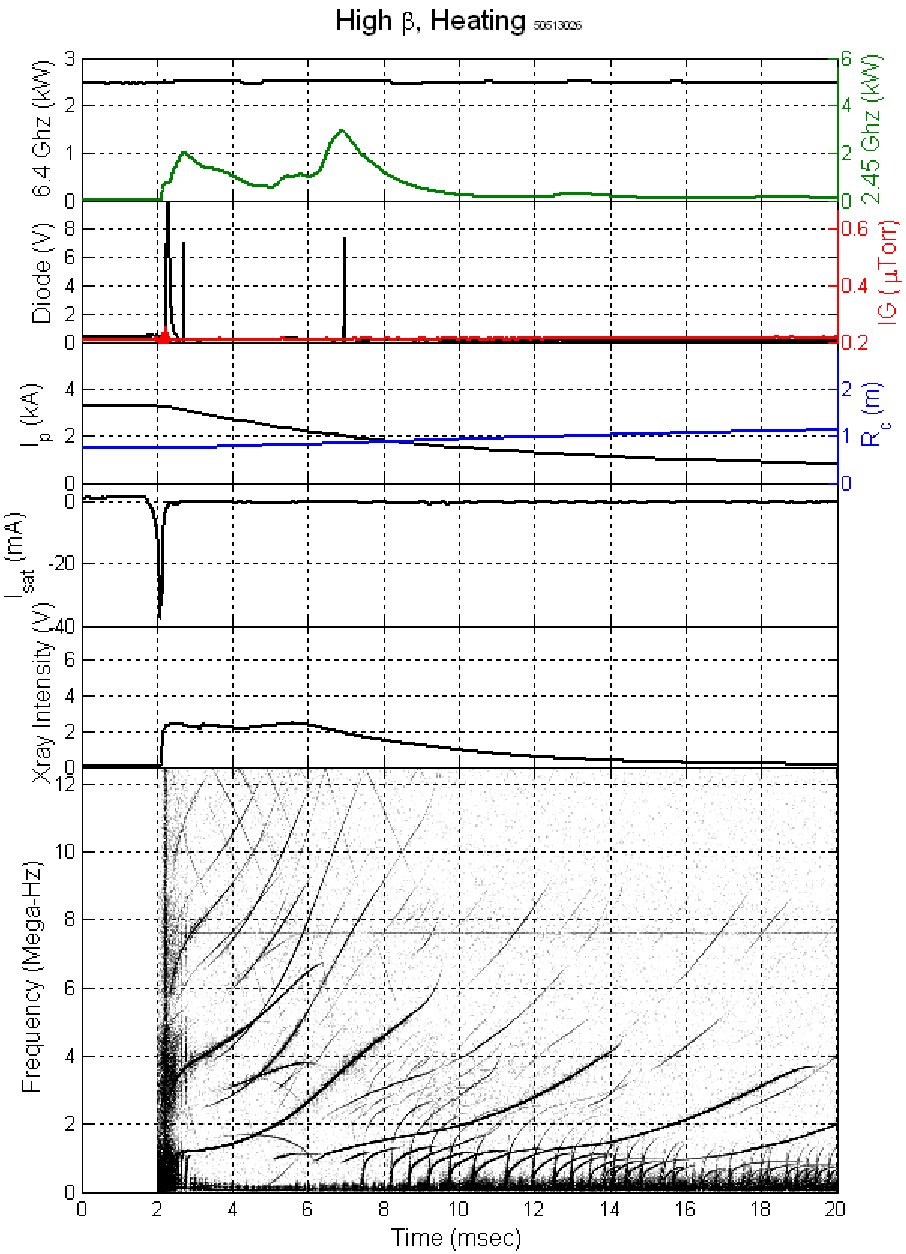
Both Sources (LHS) :: 2.45 GHz (RHS)

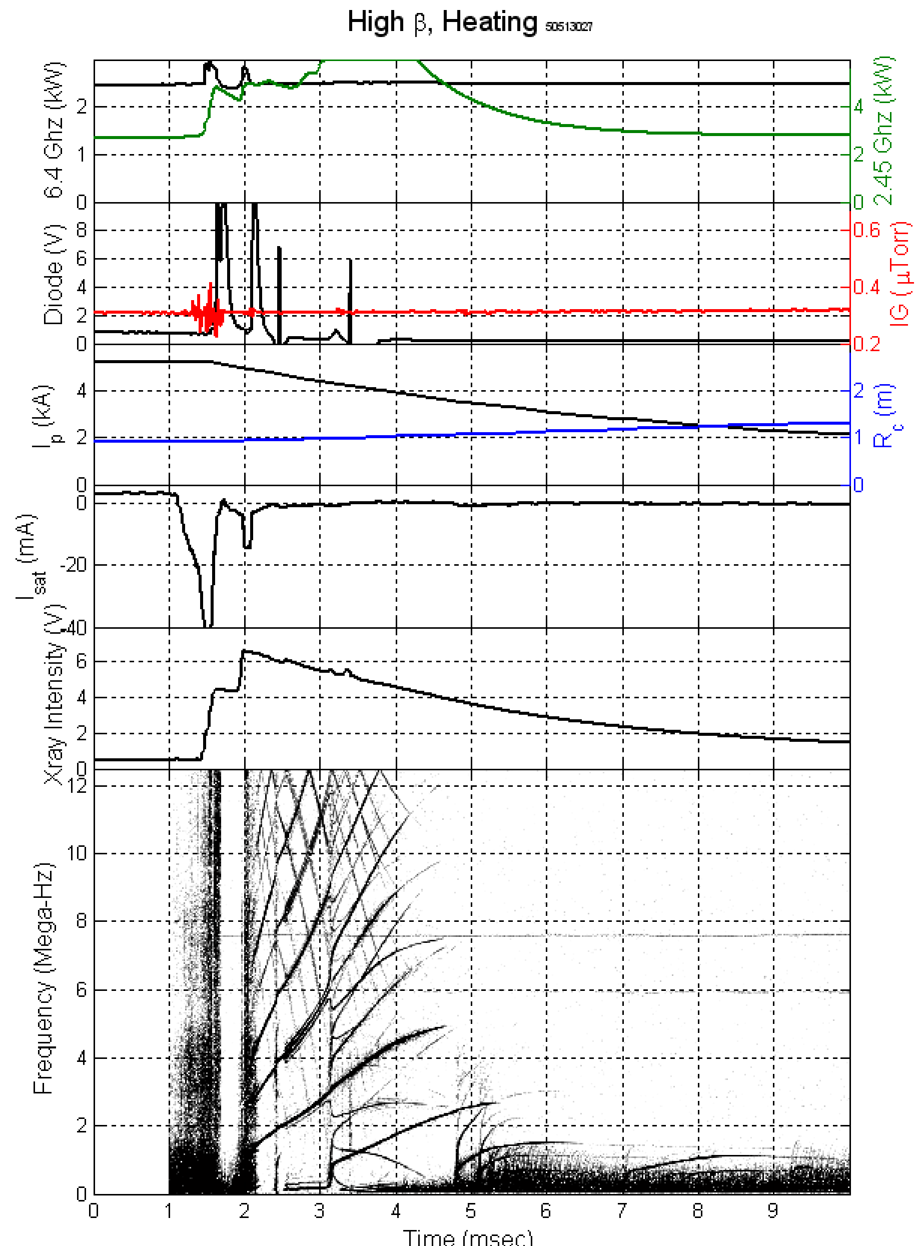




HEI mode - Stable Regime

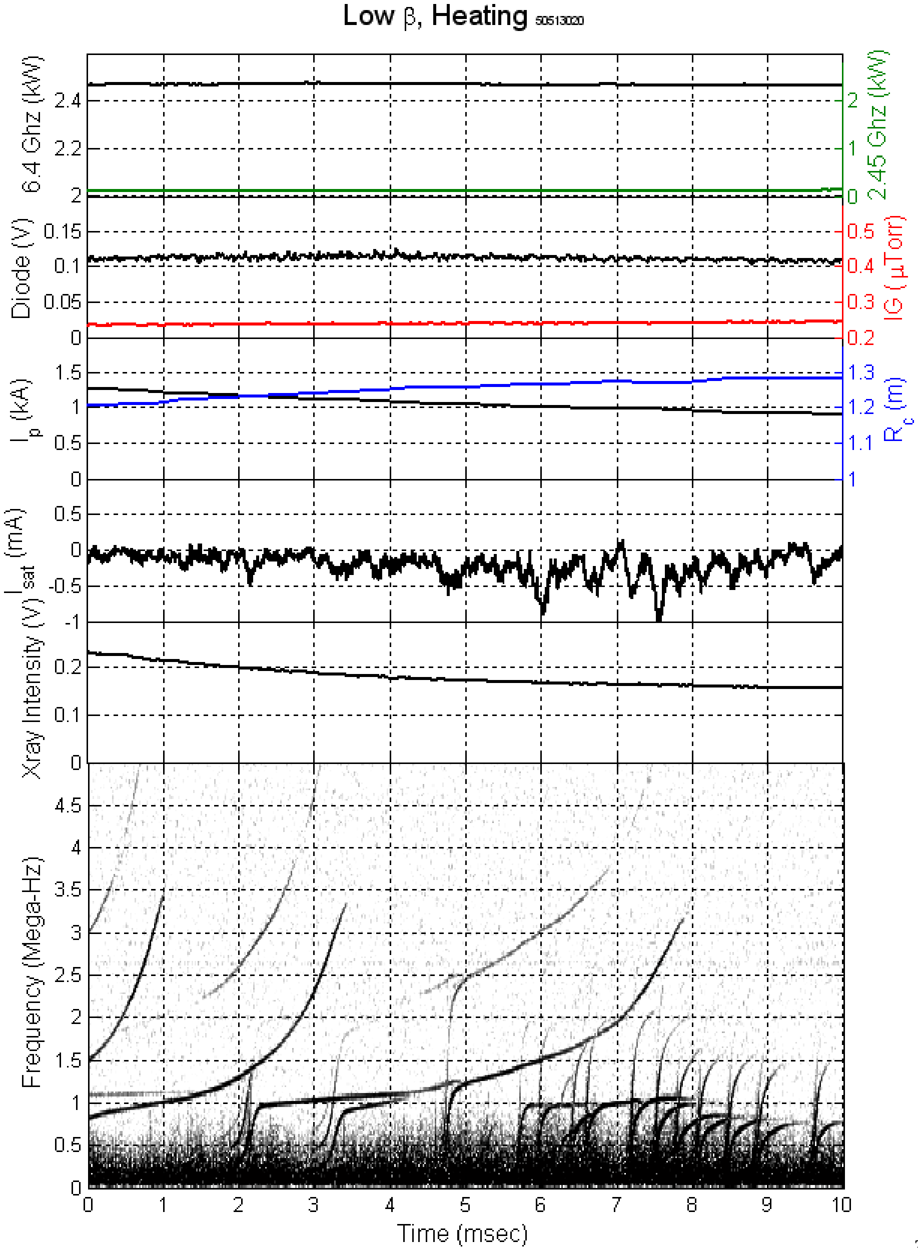
6.4 GHz (LHS) :: Both Sources (RHS)

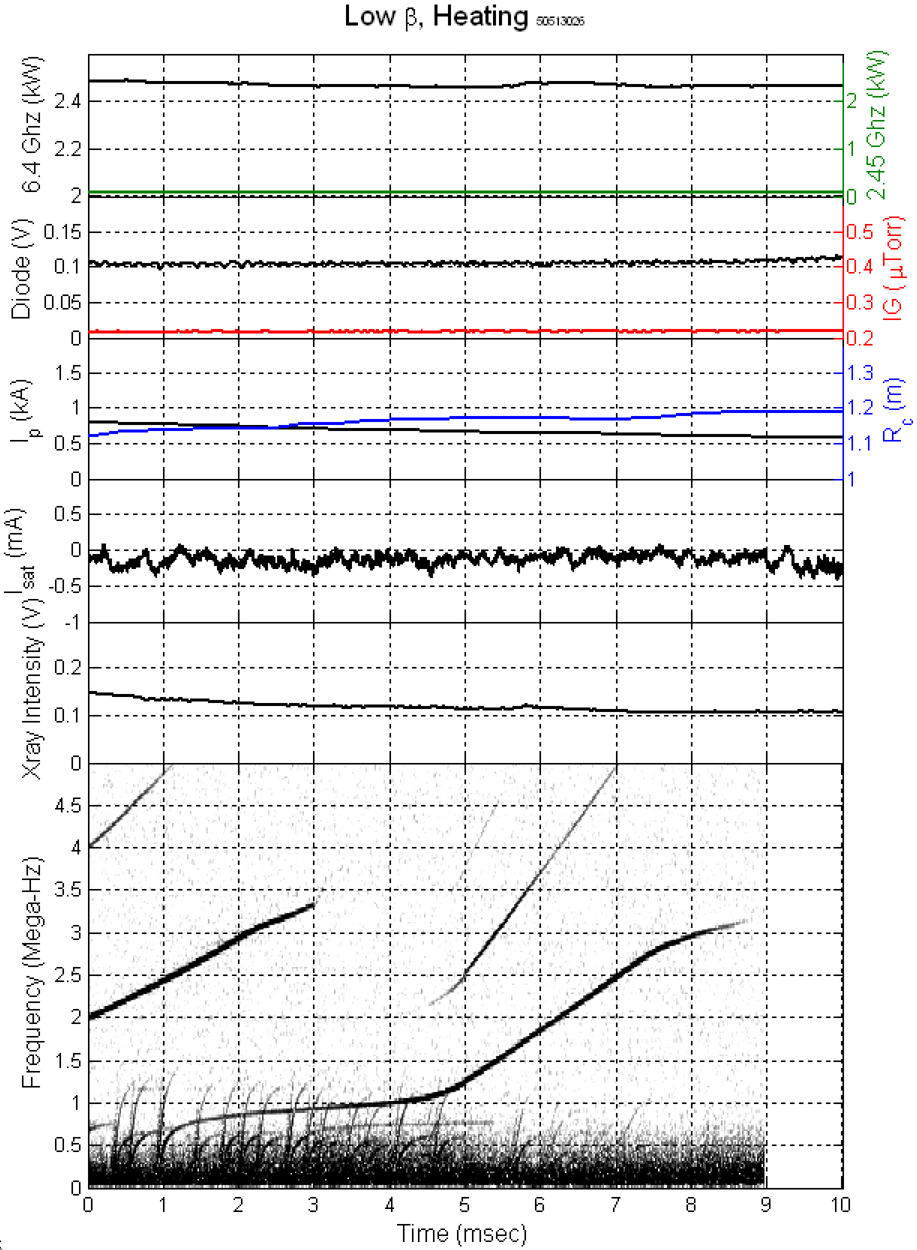




Post Burst Behavior - Stable Regime

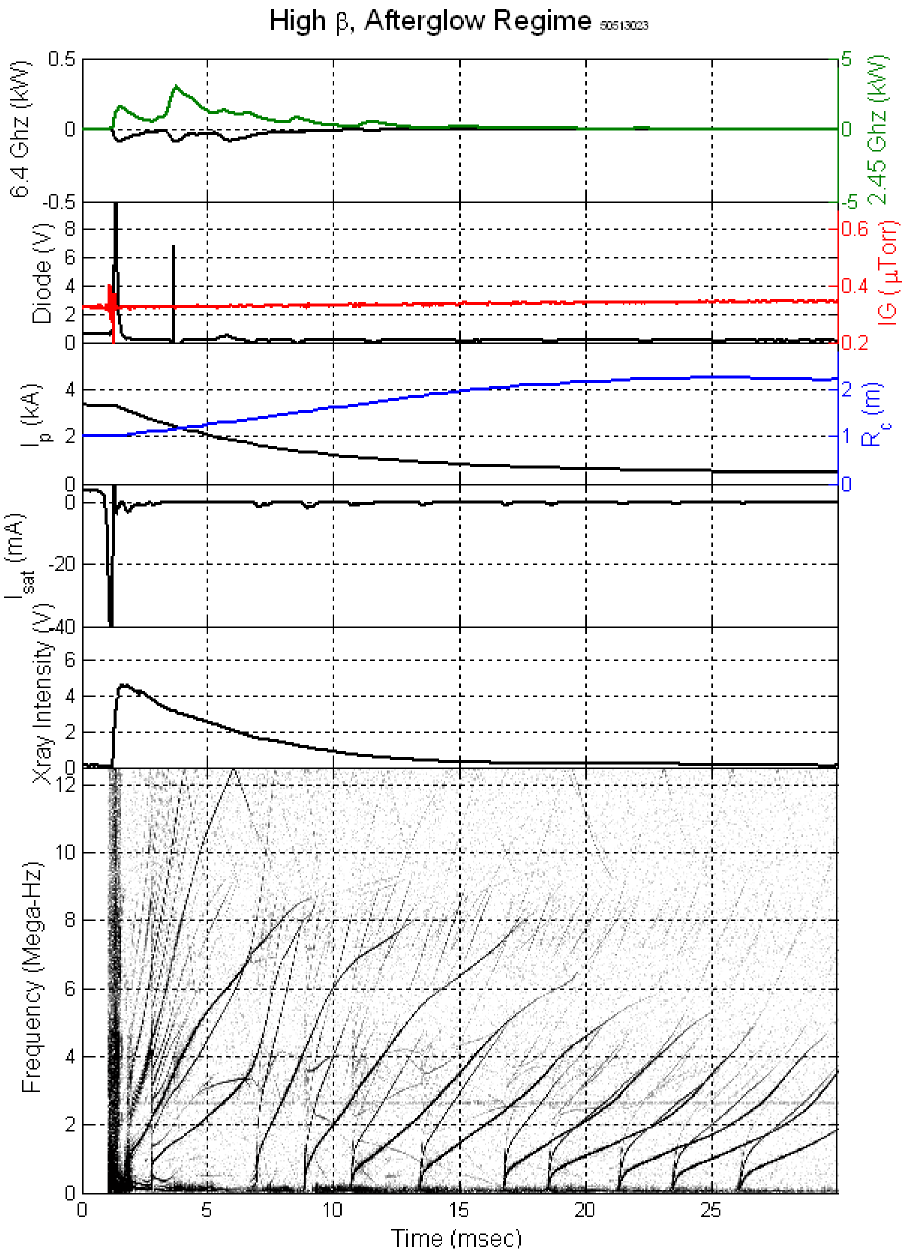
6.4 GHz (LHS) :: 6.4 GHz (RHS)

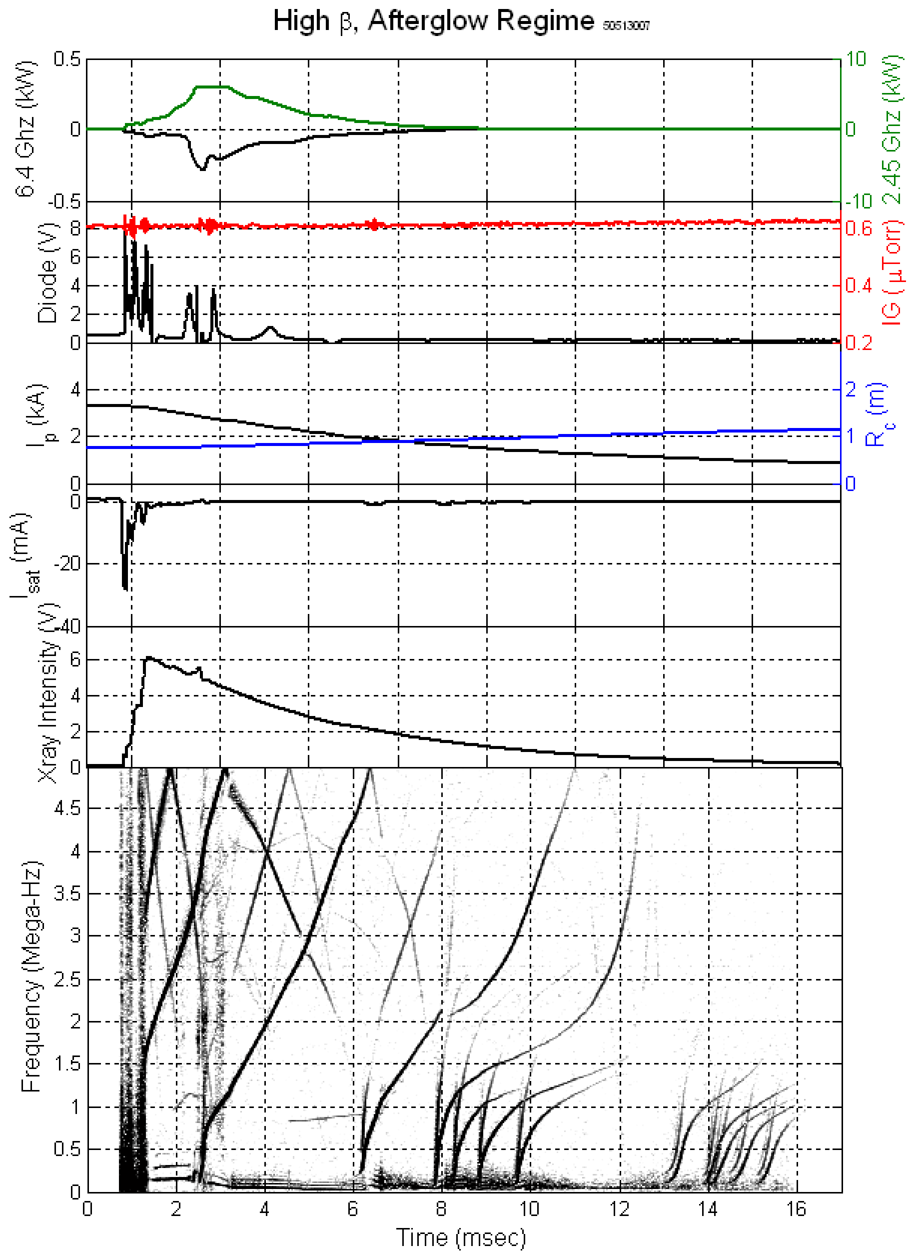




HEI Mode - Afterglow Regime

Both Sources, ½ power 6.4 GHz (LHS) :: 6.4 GHz, Full Power (RHS)





Post Burst Behavior - Afterglow Regime

Both Sources, ½ power 6.4 GHz (LHS) :: Both Sources, Full Power (RHS)