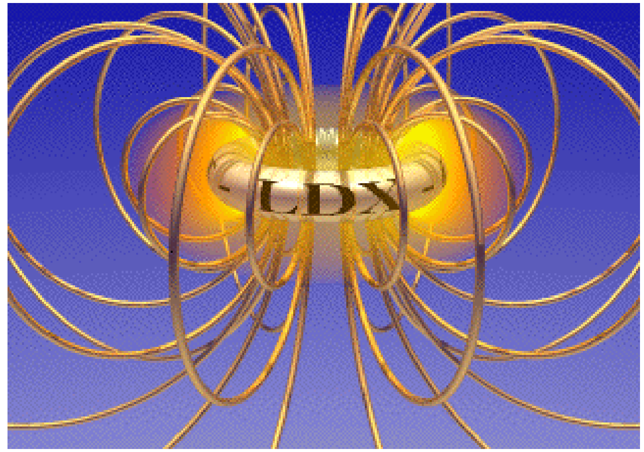

Varying Electron Cyclotron Resonance Heating to Modify Confinement on the Levitated Dipole Experiment

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2006 Innovative Confinement Concepts Worshop

Austin, TX February 13-16, 2006

Abstract

Plasmas in the Levitated Dipole Experiment are formed and sustained currently via two electron cyclotron resonance heating (ECRH) sources: 2.5 kW at 2.45 GHz and 2.5 kW at 6 GHz. An important topic being investigated is how varying the ECRH affects the confinement and stability of the plasma. We report the results of using different operational combinations of our RF sources, such as varying the power levels, sequencing of the onset time, and altering the active duration. We also report results from experiments in which the plasma shape was altered via external coils, which serves to enhance the effects of changes in the RF power on confinement. Results from these studies will be presented and discussed, as well as the status of the next step in our ECRH program: more power at an additional frequency.

- This work supported by grants from the U.S.D.O.E.

Key Results

- The plasma response to the sources differs, even for nominally the same input power
- The relative timing between firing the sources matters.
- When one of the two sources is turned off during a discharge, the configuration evolves slowly toward that which the remaining source would have set up by itself.
- Changing the RF power during discharge can be used to turn plasma instabilities on and off.

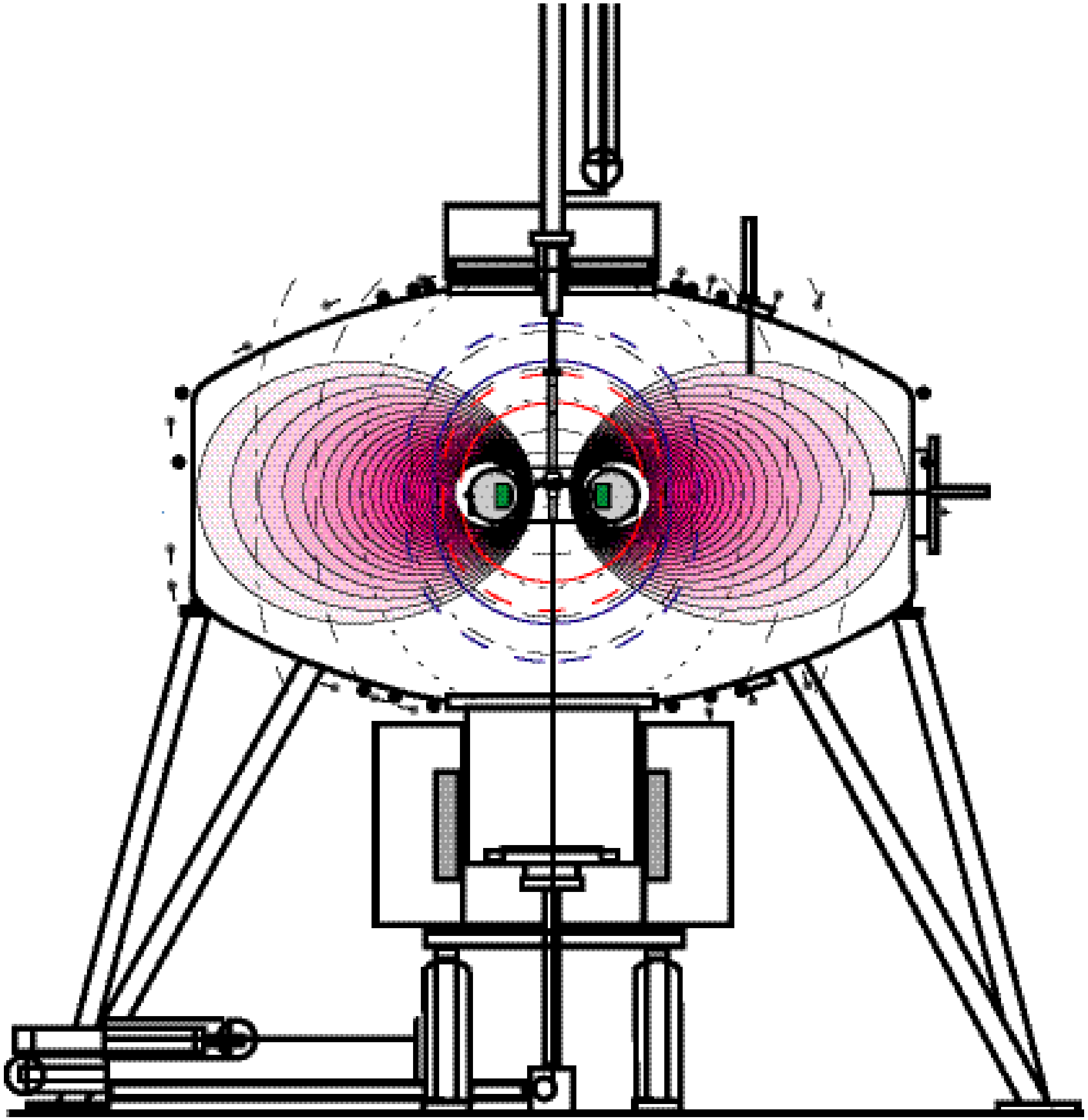
Outline

- Electron cyclotron resonance heating on the Levitated Dipole Experiment.
- All power is not created equal.
- Timing studies.
- Power modulation.
- Using modulated RF and plasma shaping to study the hot electron interchange mode stability transition.
- Next steps.

LDX plasmas are formed and heated via electron cyclotron resonance heating (ECRH).

- No ohmic heating option in LDX.
- Site credits
  - Have sources for several frequencies.
- Easy to make high beta plasmas.
  - Coupling of vacuum electromagnetic waves to plasma is easy.
  - Nothing fancier needed as of yet.
    - Confinement limited by plasma-support interaction.
- Pressure dominated by fast electrons, but density dominated by colder, thermal background.
  - Interesting fast-particle instability studies.

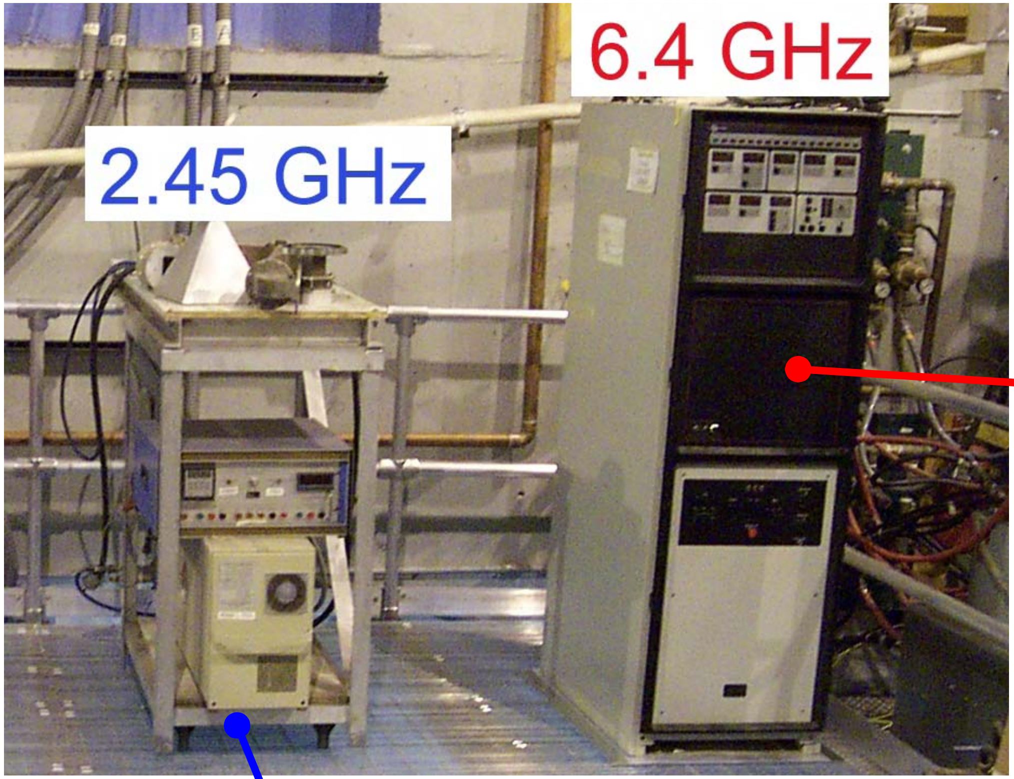
Two frequencies have been used to date.



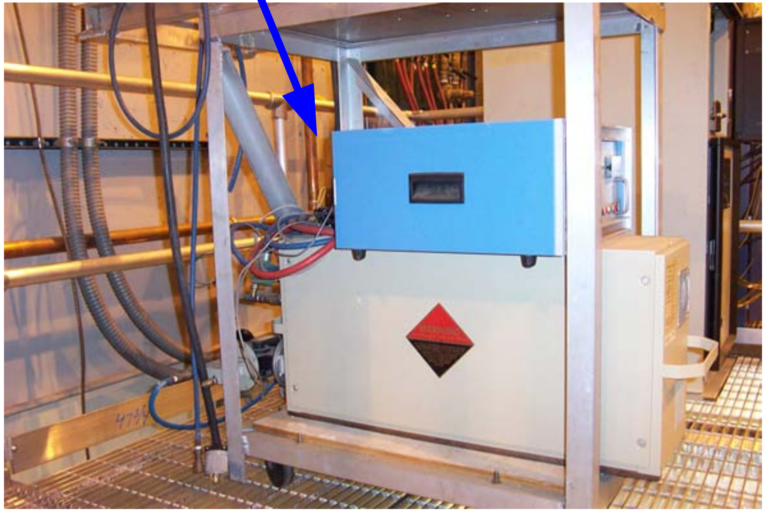
Shown:

- Cutaway of LDX vacuum chamber
- | B | surfaces, with those corresponding to fundamental and first harmonic resonances in color.
  - 2.45 GHz
  - 6.4 Ghz
- Representation of equilibrium for supported coil configuration.

Hardware



Opened to Show Klystron Tube

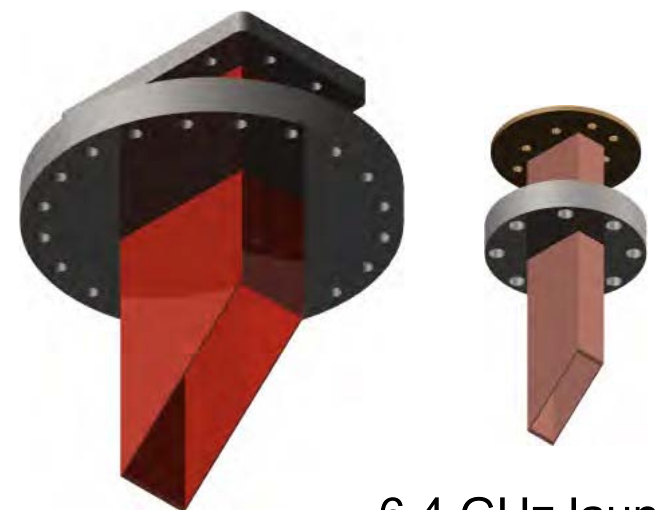


Side View of Controller (top) and Magnetron (bottom)

Tube Detail

LDX uses simple RF launching structures.

- Antennas are cut waveguides.
  - Match waveguide impedance to free space.
  - No need for directivity, because we aren't driving current.
- We use a cavity heating scheme.
  - Small first-pass absorption.
  - Waves reflect from vacuum chamber.
  - Get relatively isotropic heating in spite of toroidally localized launch.



6.4 GHz launcher

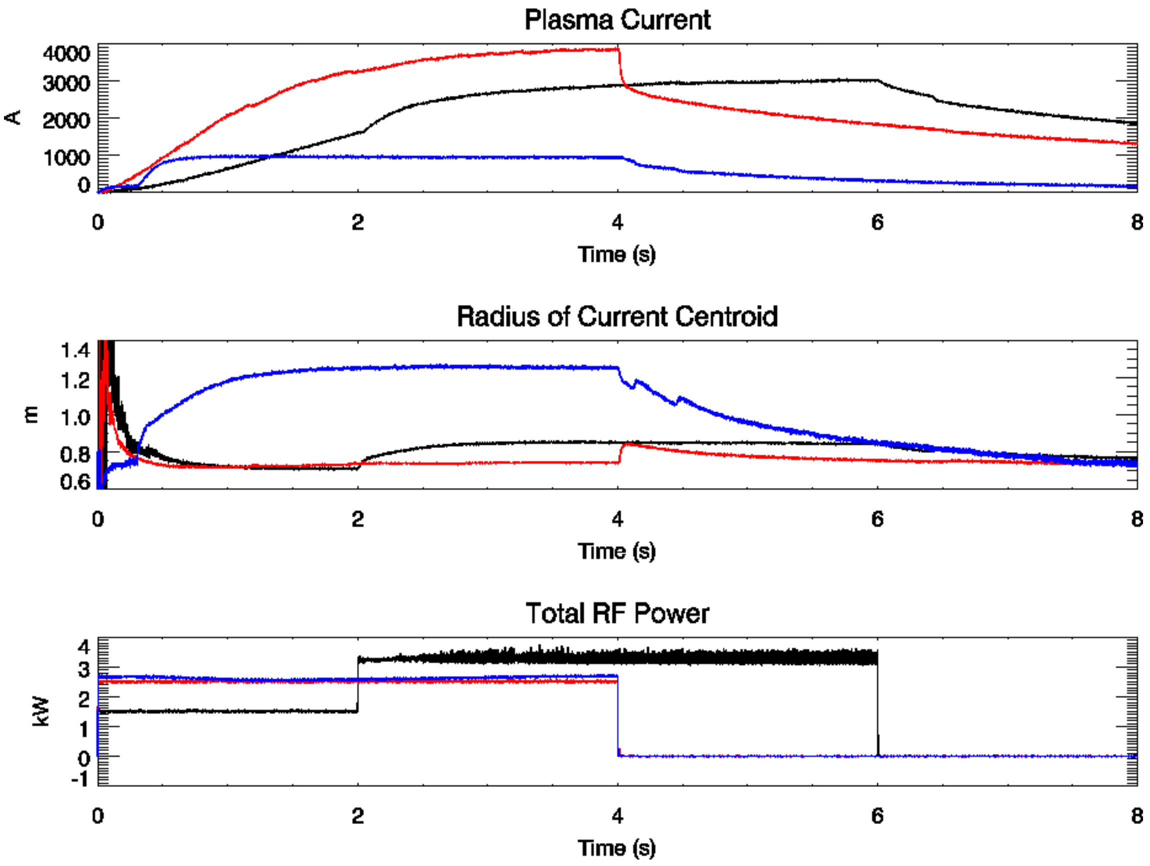
2.45 GHz launcher

Vacuum vessel port with launchers

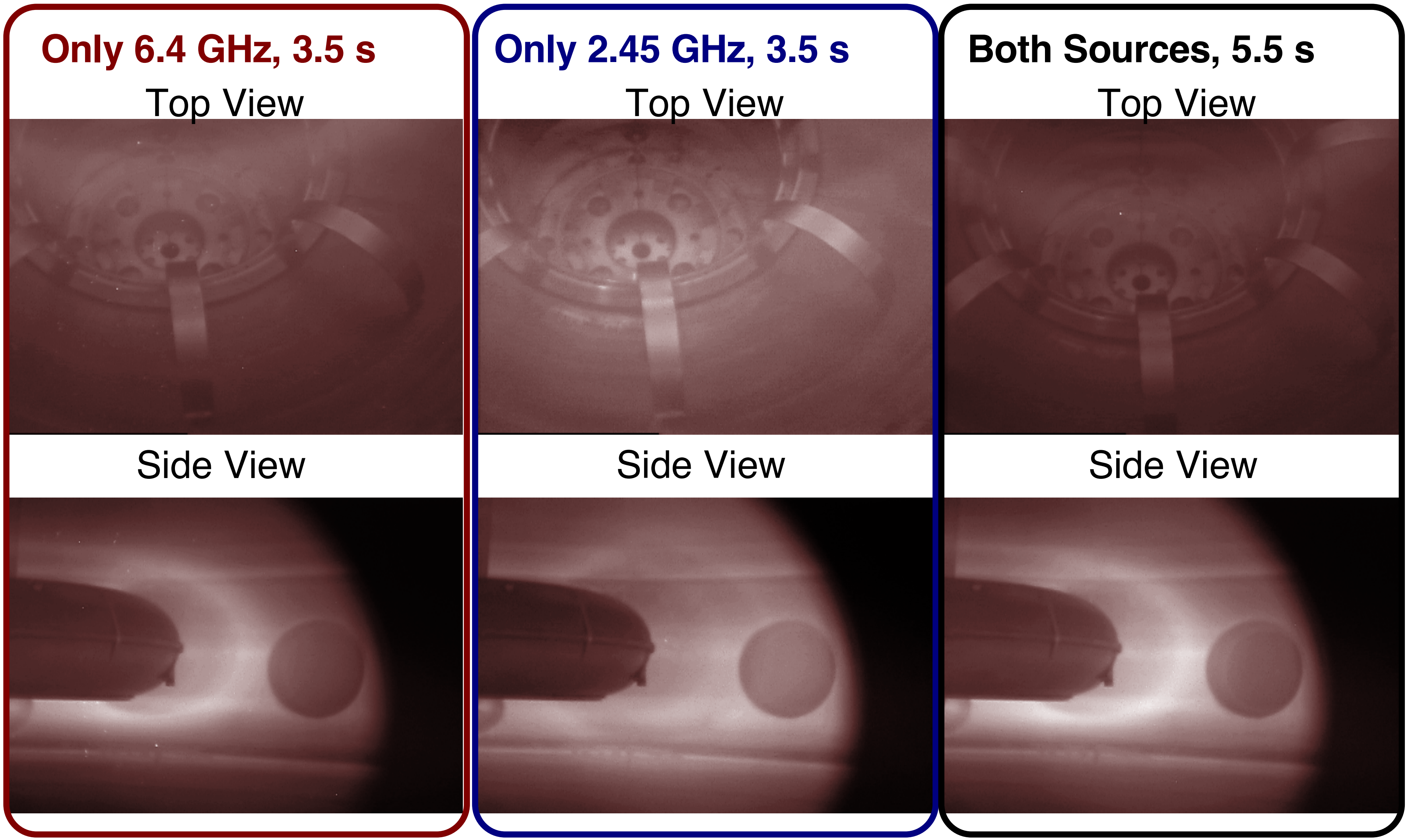
The ECRH sources produce different effects at similar input power.

- Diamagnetic current and centroid calculated via a current filament model constrained by magnetics.
- The 2.45 GHz-only case reaches saturation soonest and has the least current compared to the other scenarios.
  - Larger volume to heat.
- The 6.4 GHz-only case produces more current than even the combined case.
  - Combined case has larger plasma size.

50317015 2.62 kW in 2.45 GHz
50317012 2.46 kW in 6.4 GHz
50318019 3.2 kW both sources combined



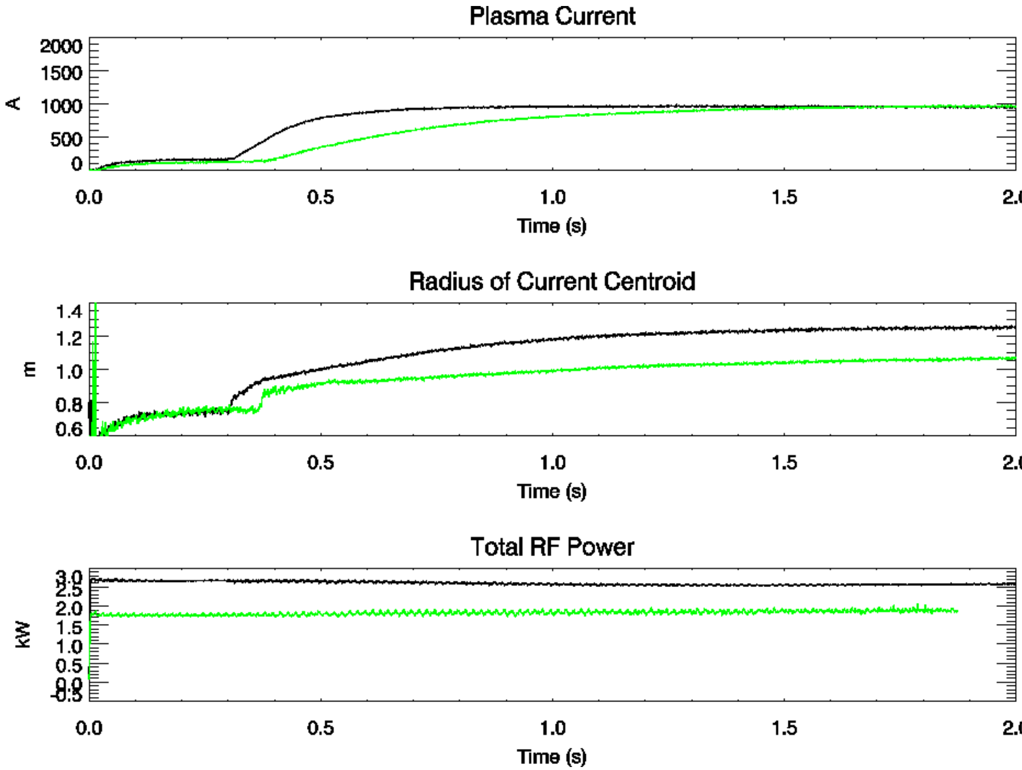
Visible light from the "combined case" appears similar to the 6.4 GHz-only case.



- Note: cameras used auto-gain so intensities can't be compared.

A rollover in the diamagnetic current vs. applied power is observed for 2.45 GHz heating.

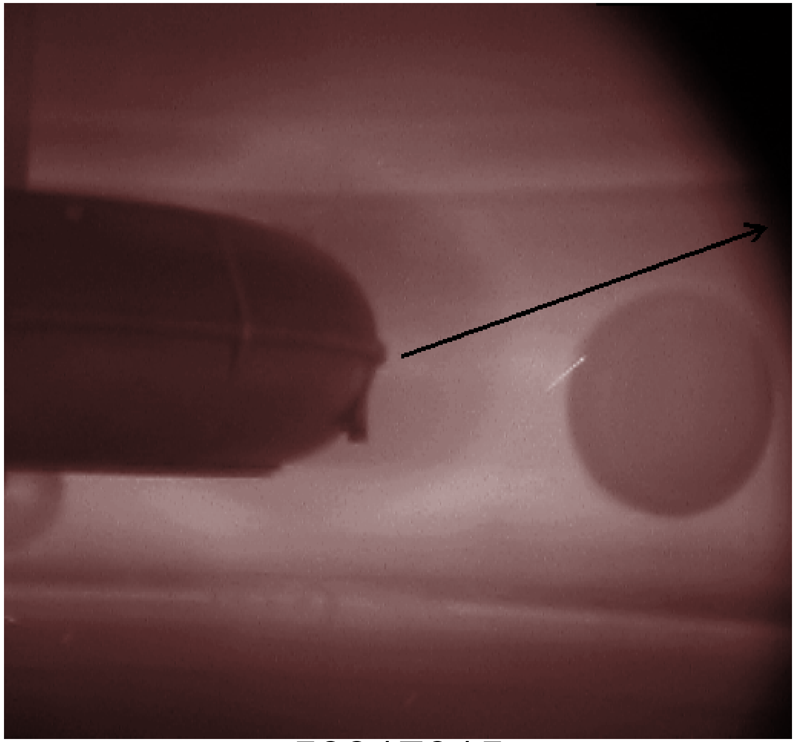
- The current is the same for 2500 W of injected power as for 2000 W injected.
- Current centroid moves outward.
  - An effect shows up in visible light.
  - Difference in stored energy goes into increased plasma size.



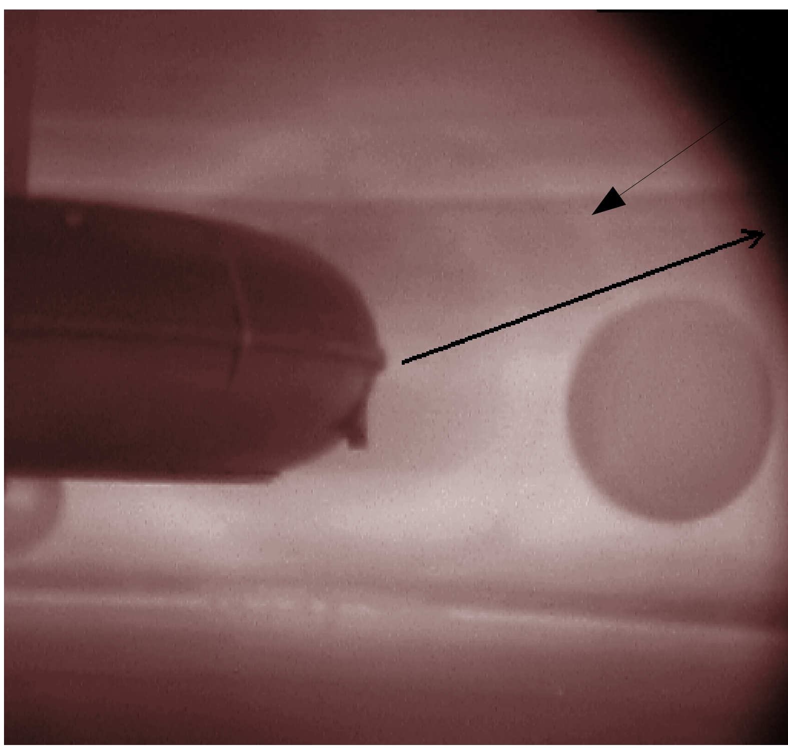
50317015 50317011
All heating via 2.45 GHz

- Possible explanation: observed density is near cutoff.

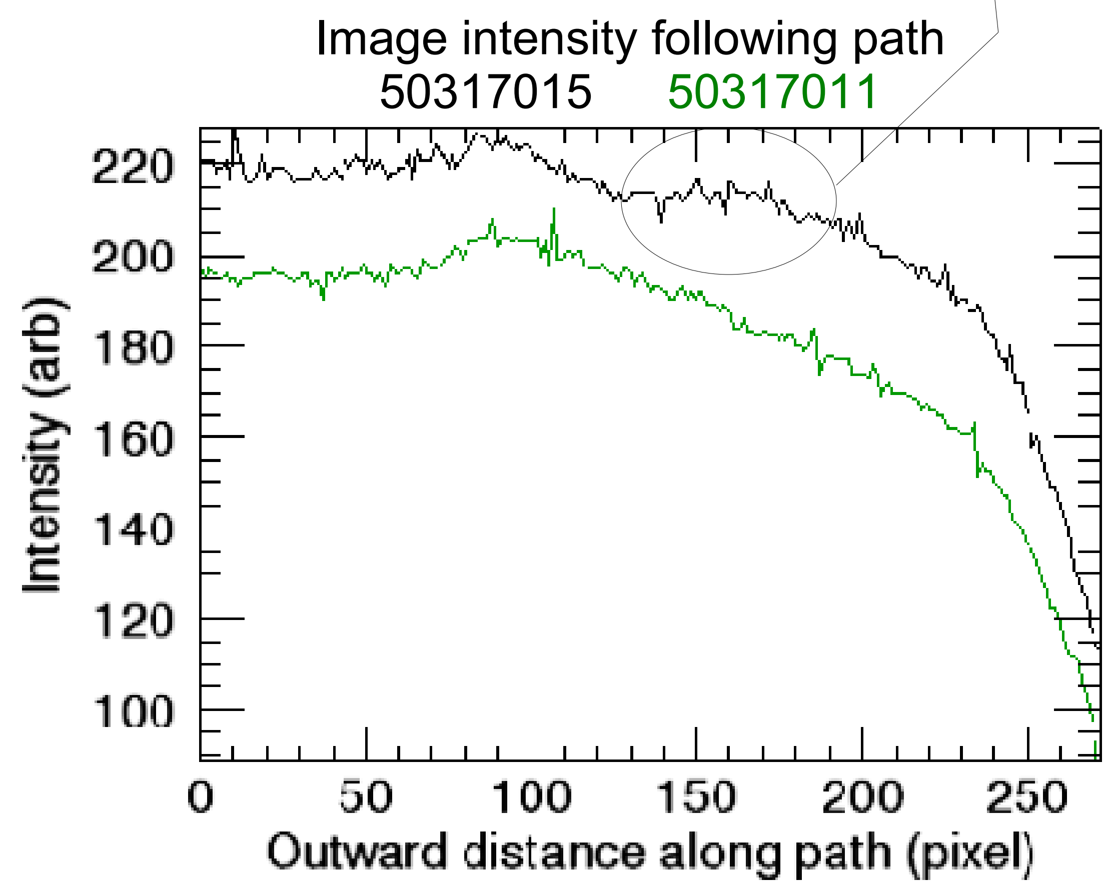
50317011



50317015

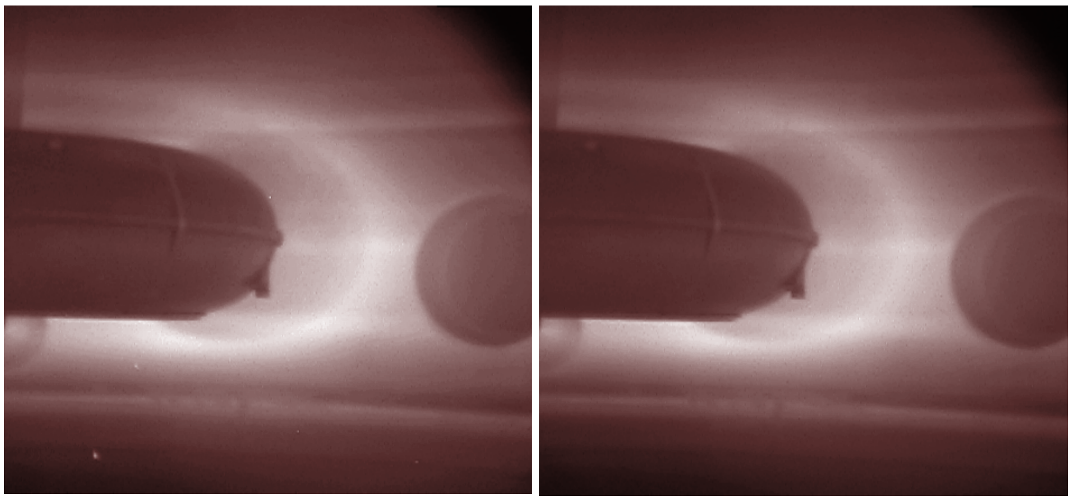


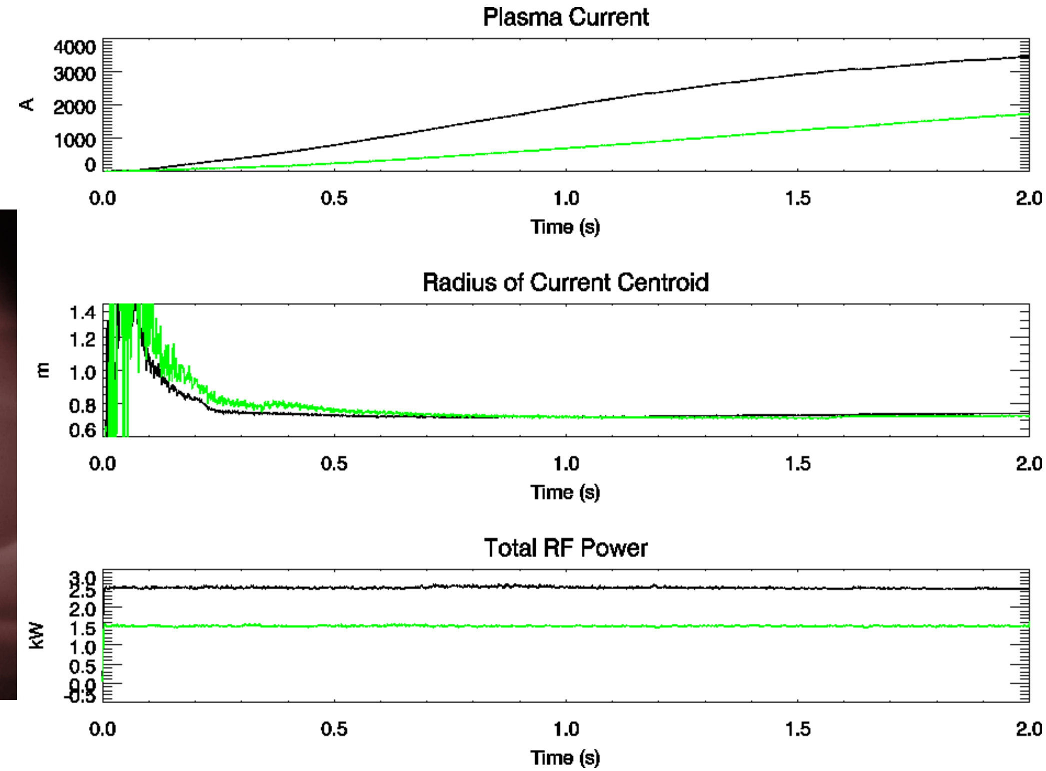
- Light feature visible for 2500 W injected power.
- Related to $2\omega_c$ absorption?



The diamagnetic response to the 6.4 GHz source doesn't show a rollover.

50317017 50317018



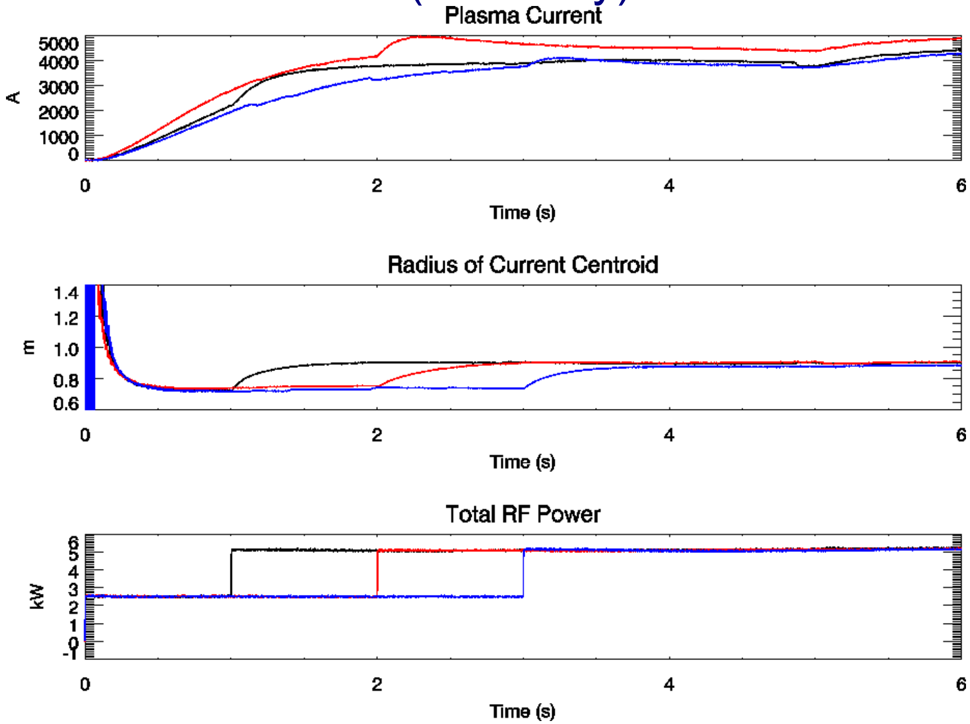


50318017 50318018
All heating via 6.4 GHz

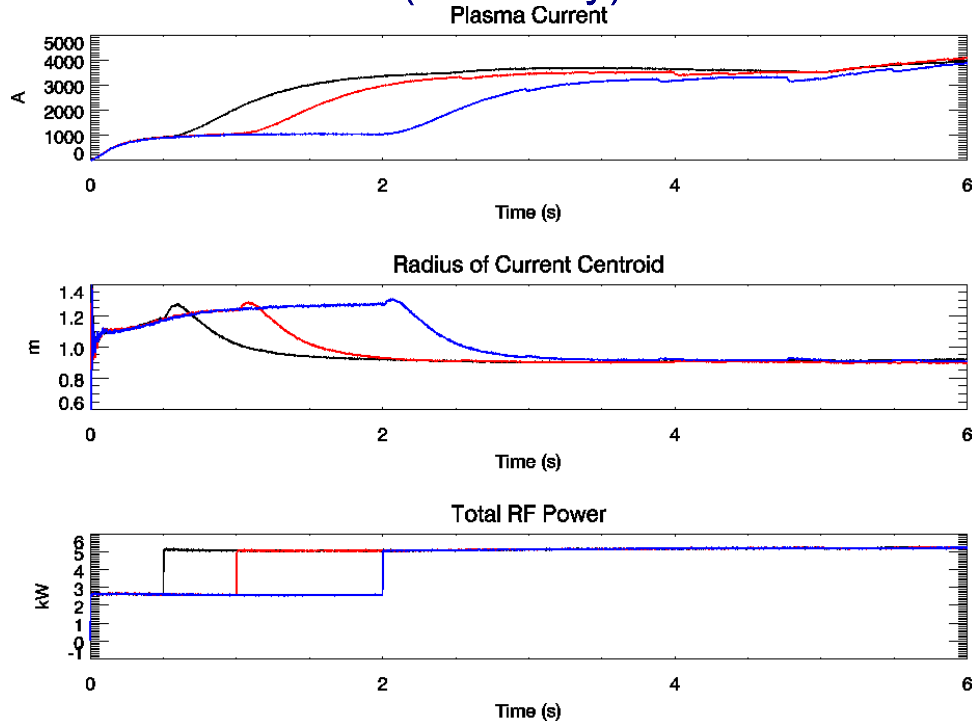
- The diamagnetic current increases.
  - Power level below where a rollover would occur?
- Current centroid stays at about the same position.
  - Stored energy difference goes in to more peaked profile.

The relative firing time of the sources is important.

2.5 kW at 6.4 GHz from t = 0
2.5 kW at 2.45 GHz:
50512020 (1 s delay)
50512018 (2 s delay)
50512021 (3 s delay)



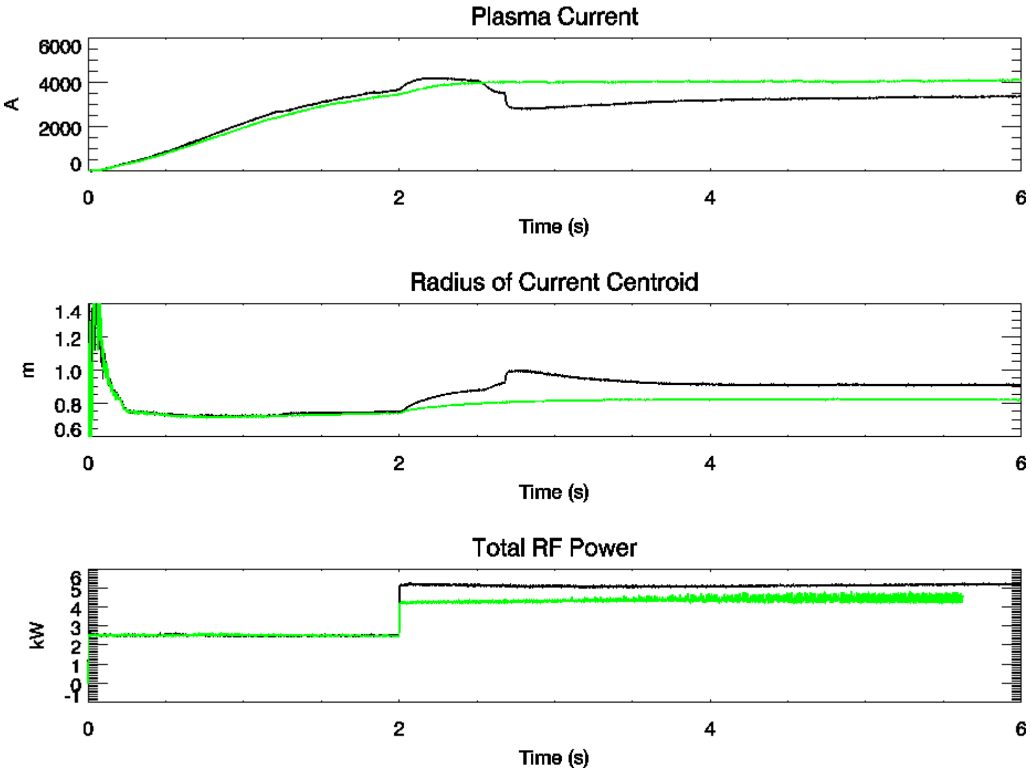
2.5 kW at 2.45 GHz from t = 0
2.5 kW at 6.4 Ghz
50512022 (0.5 s delay)
50512023 (1 s delay)
50512024 (2 s delay)

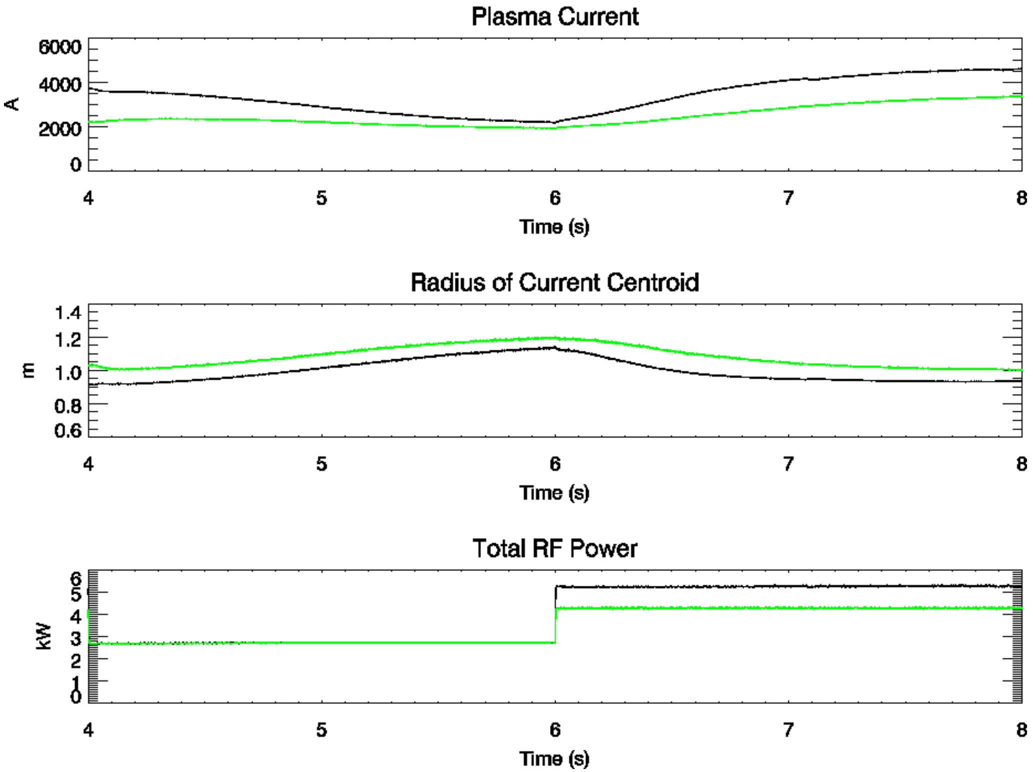


- After sufficient time with both sources on, all three discharges in each set evolve to a similar configuration.
  - Current magnitude and centroid
  - Elapsed time must be long enough for plasma to “forget” about the prior RF programming.

- 2500 kW at 6.4 Ghz, 2.500 kW at 2.45 GHz fired with a delay:
  - For the 2 and 3 s delay cases the current quickly rises to a maximum value and then decreases
    - For the 1 s delay case the current comes to a stationary value.
    - The characteristic time for the 6.4 GHz power to saturate is several seconds, so this occurs before saturation of the response to 6.4 GHz.
- 2500 kW at 2.5 GHz, 2500 kW at 6.4 GHz fired with a delay:
  - The temporal behavior is qualitatively similar regardless of the firing time.
    - Current rises until a stationary state is acheived.
  - Even the 0.5 sec delay (black) still has the 6.4 GHz power injected after the the plasma response to the 2.45 GHz source is saturated.

Varying the input power produces different effects for the two sources.





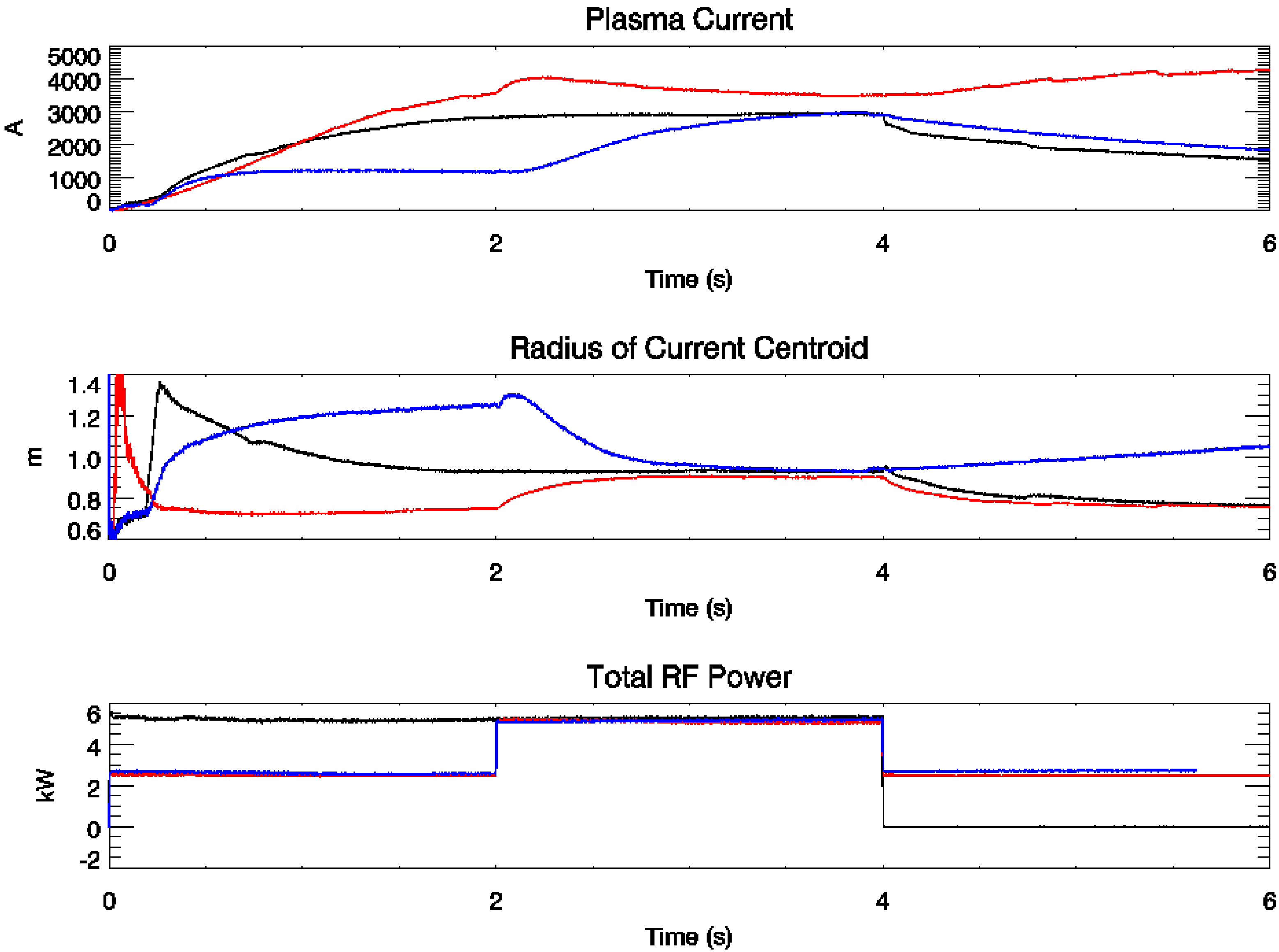
2500W at 6.4 GHz throughout
50318020 2500 W at 2.45 GHz added at 2 s
50318017 1500 W at 2.45 GHz added at 2 s

2500W at 2.45 GHz throughout
50513022 2500 W at 6.4 GHz added at 2 s
50513023 1500 W at 6.4 GHz added at 2 s
(1 prior cycle of power modulation)

- Behavior similar to single-source results.

- Starting with 2500 W at 6.4 GHz and adding power at 2.45 GHz with a 2 sec delay:
  - Adding ~2500 W produces a momentary rise and then a decay in the current, as before.
    - An instability occurs in the depicted
    - discharge.
  - Adding ~1500 W results in a gradual rise in the current with no decay.
    - Closer to an optimum?
- When adding 6.4 kW power to 2500 W at 2.45 GHz the current doesn't exhibit any “overshooting” behavior.
  - Change in current roughly proportional to 6.4 GHz input power.
  - Due to higher cutoff density?

Chopping one source on and off slowly changes the plasma.



50318004
both on for 4 s
50318009
chop 6.4 GHz
50318010
chop 2.45 GHz

- Behavior during initial 4s is the same as for the respective delayed source onset case above.

- For the constant power case (zero delay time) the current comes up to a stationary value.
  - As for delayed 6.4 GHz power, above.
  - Also as for short (1 s) delays in the 2.45 GHz power, above.
- After one source is turned off the plasma evolves toward what is seen in the respective single-source configuration:
  - Current increases and radius of centroid decreases when only 6.4 GHz is on.
    - Evolution timescale is similar to that of discharges which are only heated at 6.4 GHz.
  - Current decreases and radius of centroid increases when only 2.45 GHz is on.
    - Evolution timescale is longer than that of discharges only heated at 2.45 GHz (cf. < 2 sec into this discharge).
  - Characteristic of the fast (current-carrying) electron energy confinement time?
    - Similar to the decay time with no applied RF.

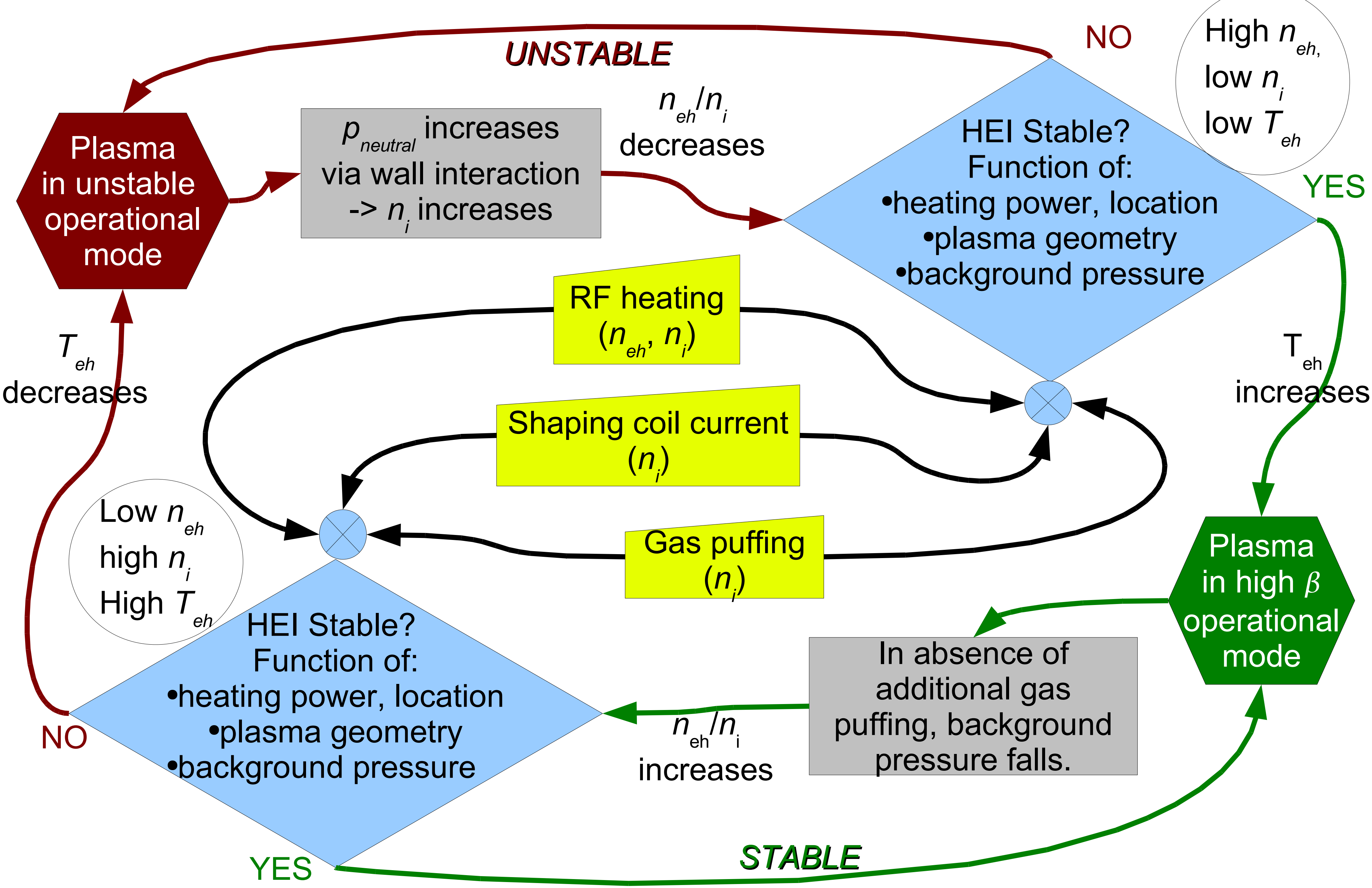
Control of the hot electron interchange mode is important for LDX.

- The hot electron interchange mode (HEI) is observed to be a cause of β loss in LDX discharges.
- Stabilized by coupling to background ions.
  - Stable for $-\frac{d\ln\langle n_{eh}\rangle}{d\ln V} < 1 + \frac{m_\perp^2}{24}\frac{\omega_{dh}}{\omega_{ce}}\frac{\langle n_i\rangle}{\langle n_{eh}\rangle}$, where $\langle\,\rangle$ refers to a field line (flux surface) average, $m_\perp$ is a total perpendicular wavenumber, and ω_{dh} is the drift frequency of the fast electrons.
  - The parameter $\langle n_i\rangle/\langle n_{eh}\rangle$ is an important experimental knob by which the HEI may be controlled.
- Invited talk by E. Ortiz, this meeting.
- Garnier *et al.*, submitted to *Physics of Plasmas* (for publication in 2006).

The high beta threshold can be influenced by modifying the confinement of the bulk plasma.

- The bulk plasma is subject to the MHD stability criterion.
  - $\delta\left(p V^{\gamma}\right) = 0 \rightarrow p_{edge} V^{\gamma}_{edge} = p_{peak} V^{\gamma}_{peak} ; V = \oint \frac{d\ell}{B}$
- The shaping coils run as a Helmholtz pair were used to reduce V_{edge}.
- p_{edge} remains essentially constant.
  - Set by fueling, wall conditioning, etc.
- This sets the bulk pressure profile => the bulk density profile.
- The hot electron density was varied by modulating the RF power.
- Thus, we vary n_{eh}/n_i, and therefore HEI stability.

Stability is influenced by 3 “knobs”.

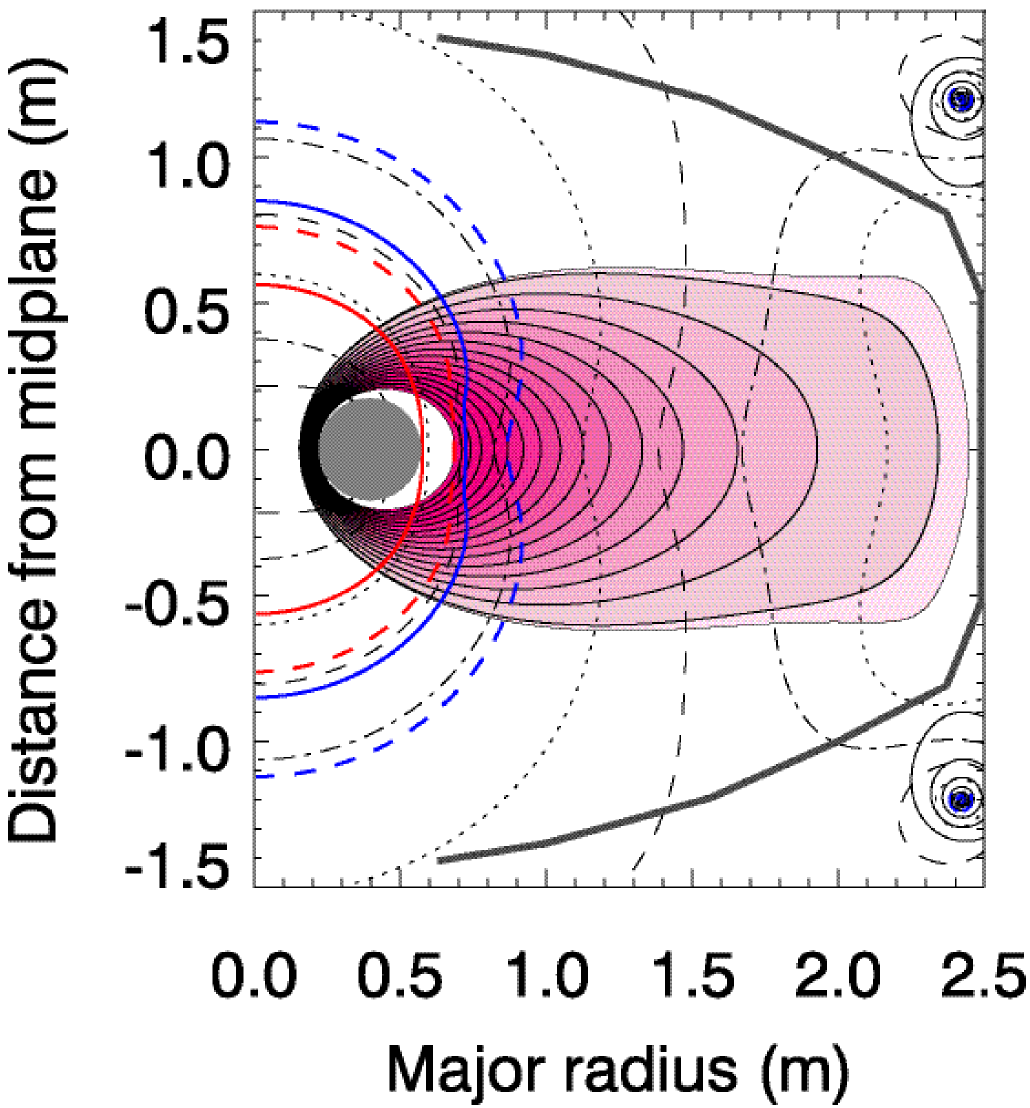


A pair of coils is used to change the plasma shape.

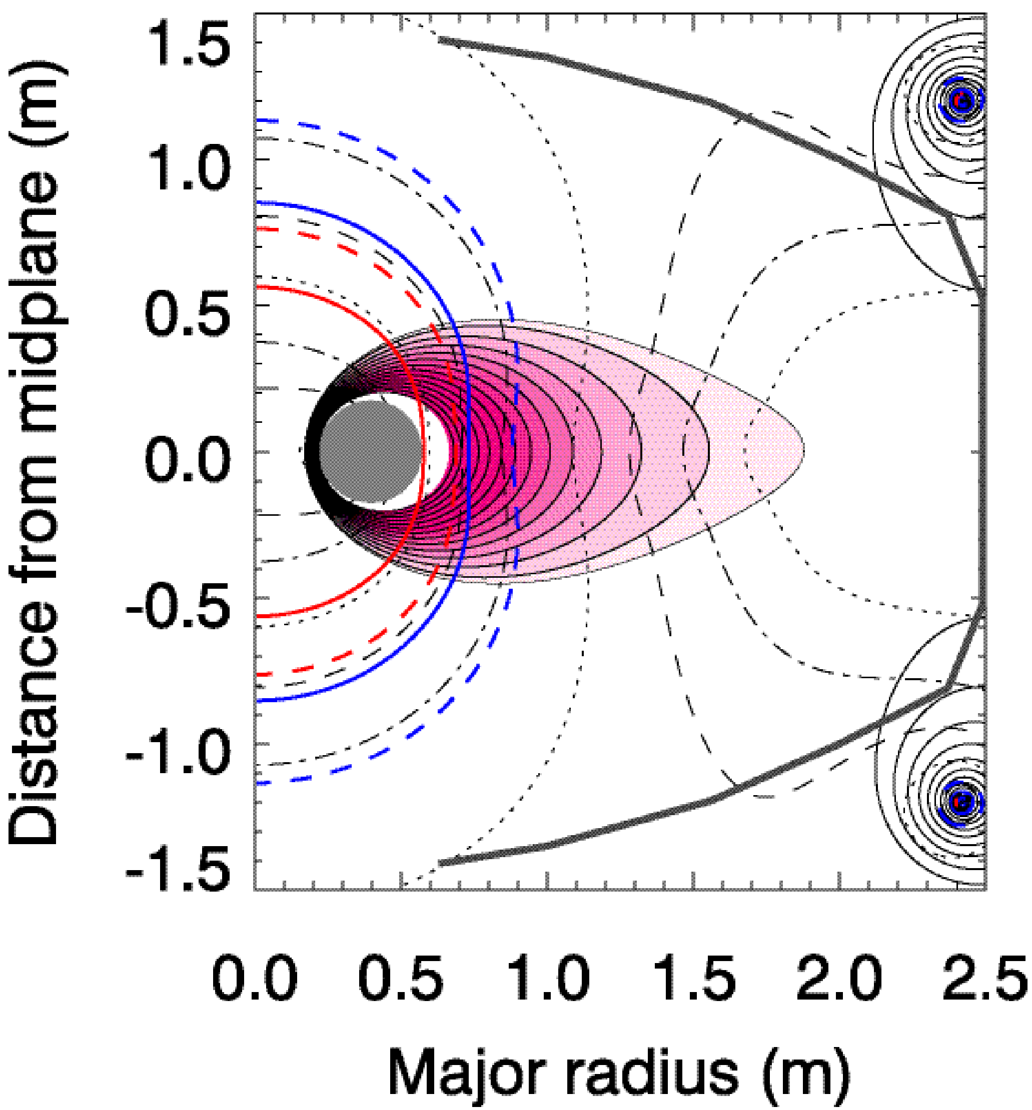
- The coils are arranged in a Helmholtz configuration.
- They are driven via two separate power supplies so that they can have different currents.
  - Not for discharges to be discussed here.
- Changes the area enclosed within the last closed field line.
  - Affects stability of bulk plasma.
    - In turn affects stability of hot electron interchange.

Four discharges are compared.

8 kA-turns shaping coil current

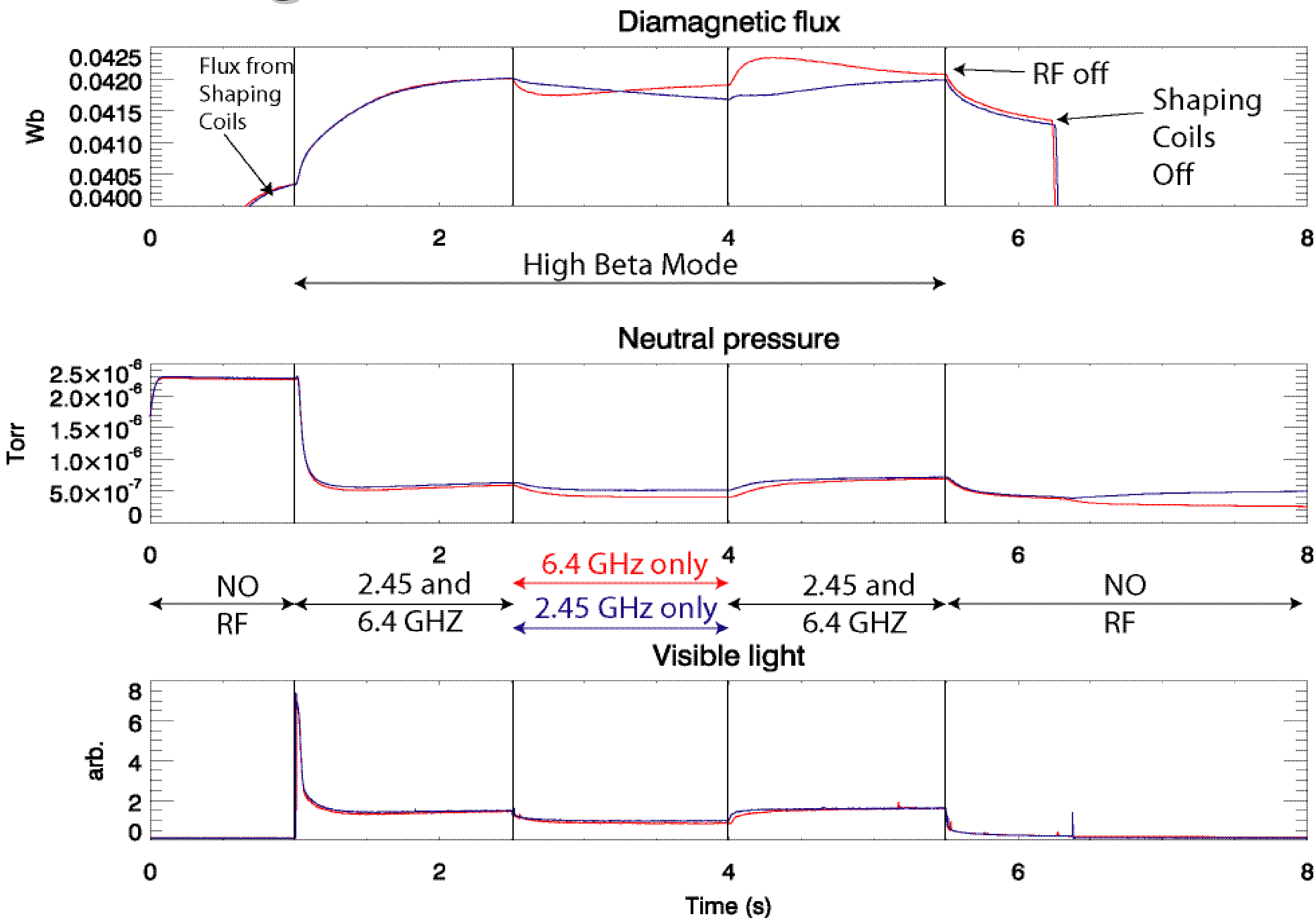


16 kA-turns shaping coil current



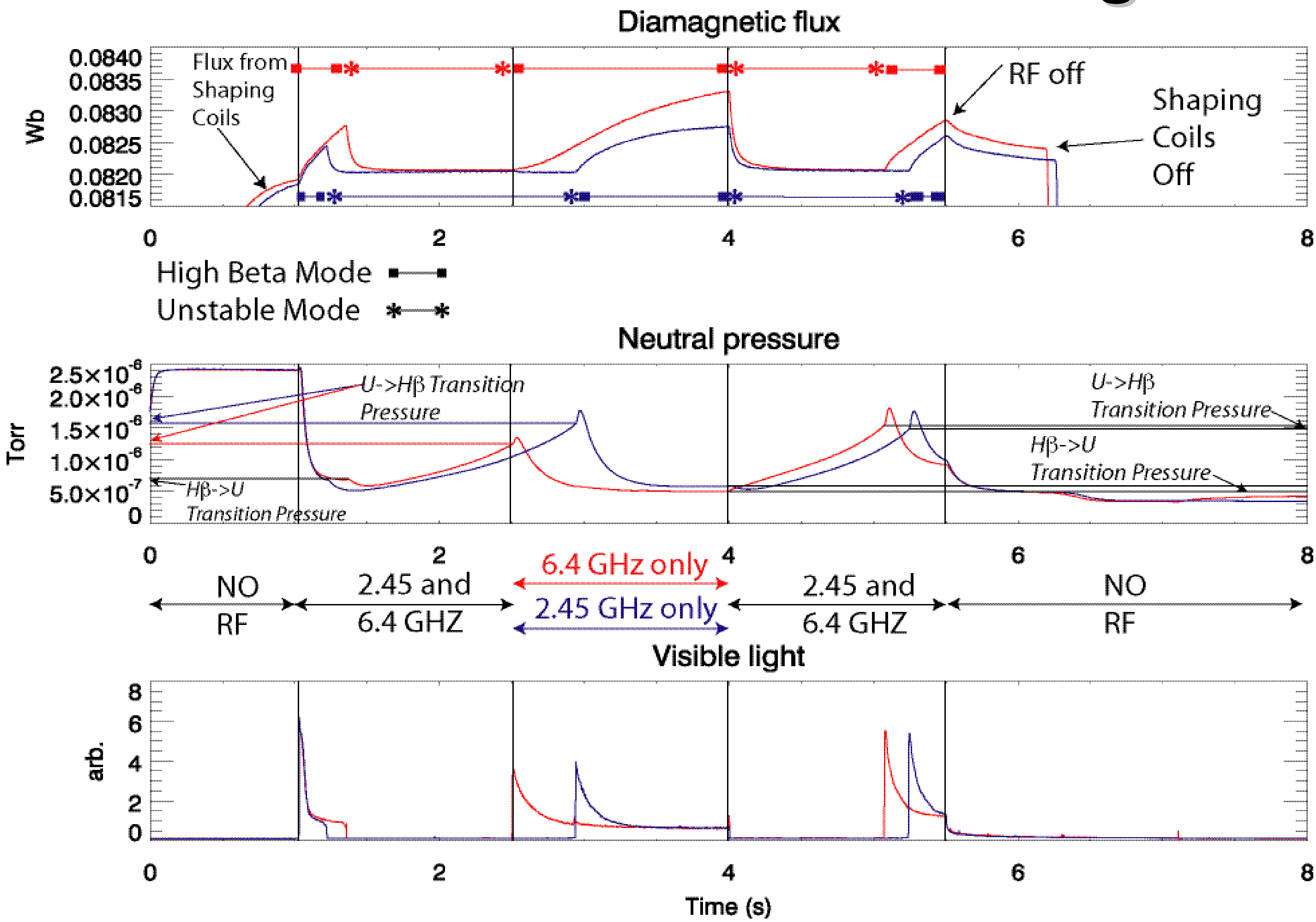
- Two discharges with 8 kA-turns shaping coil current.
  - One with 2500 W of 2.45 GHz turned on and off, 6.4 GHz at constant 2500 W.
  - One with 2500 W of 6.4 GHz turned on and off, 2.45 GHz at constant power.
  - Note: Two X-points in this case.
- 2 with 16 kA-turns shaping coil current.
  - RF programming as above.
  - Single X-point
- Similar fueling for all discharges.

With 8 kA-turns of shaping coil current the high beta mode can be sustained.



- Effects on the diamagnetic flux loop signal are the same as is seen in unshaped discharges.
  - Rise and decay when the 2.45 GHz is chopped on.
  - Slow evolution when a source is turned off.
  - Note: no current modeling for these discharges
- High beta mode throughout the discharge
  - Lower pressure required for HEI stability.
    - Neutral pressure during single-source phase close to level at which the plasma went unstable for 16 kA-turns of shaping coil current.
  - Effects on stability of changing the RF power consequently not visible at this shaping coil current.
    - Heating location
    - Injected power

16 kA-turns of shaping coil current makes it difficult to sustain high beta.



- The plasmas make two transitions out of high beta mode.
  - During phase with both sources on after startup.
    - Heating power constant.
    - Neutral pressure falls below critical level.
  - Upon increase of heating power.
    - Threshold pressure scales inversely with applied power.
- The plasmas make two transitions into high beta mode after the startup transition.
  - During single-source phase.
    - Neutral pressure is lower for 6.4 GHz heating than for 2.45 GHz heating.
  - During phase with both sources.
    - Pressure is essentially the same as in the 2.45 GHz heating case.
  - In either case, pressure is higher than that needed to exit from high beta mode.

An immediate "next step" is to add heating power at a higher frequency.

Cabinet

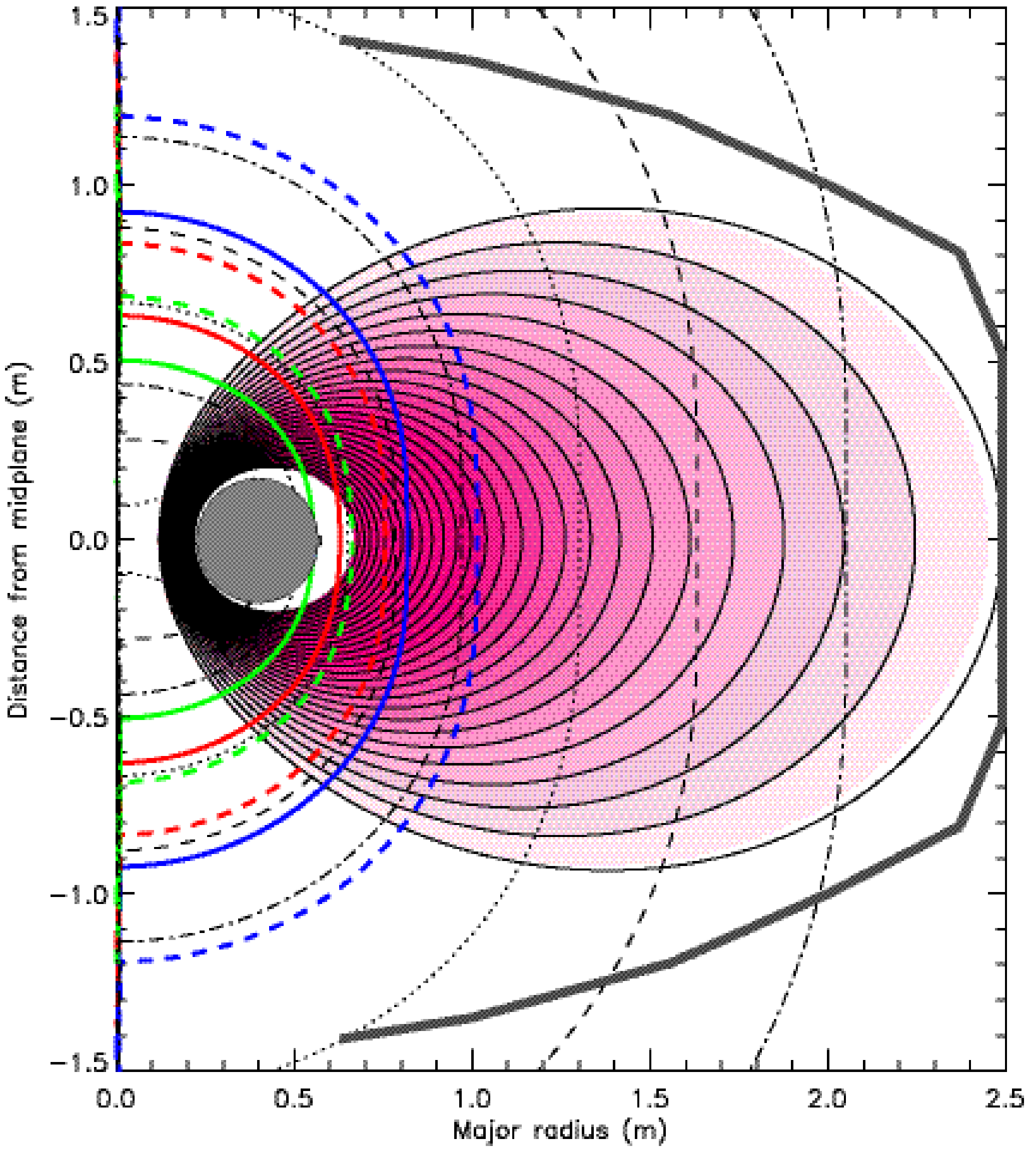
Cabinet with doors removed

Quarter-wave horn /vacuum connection

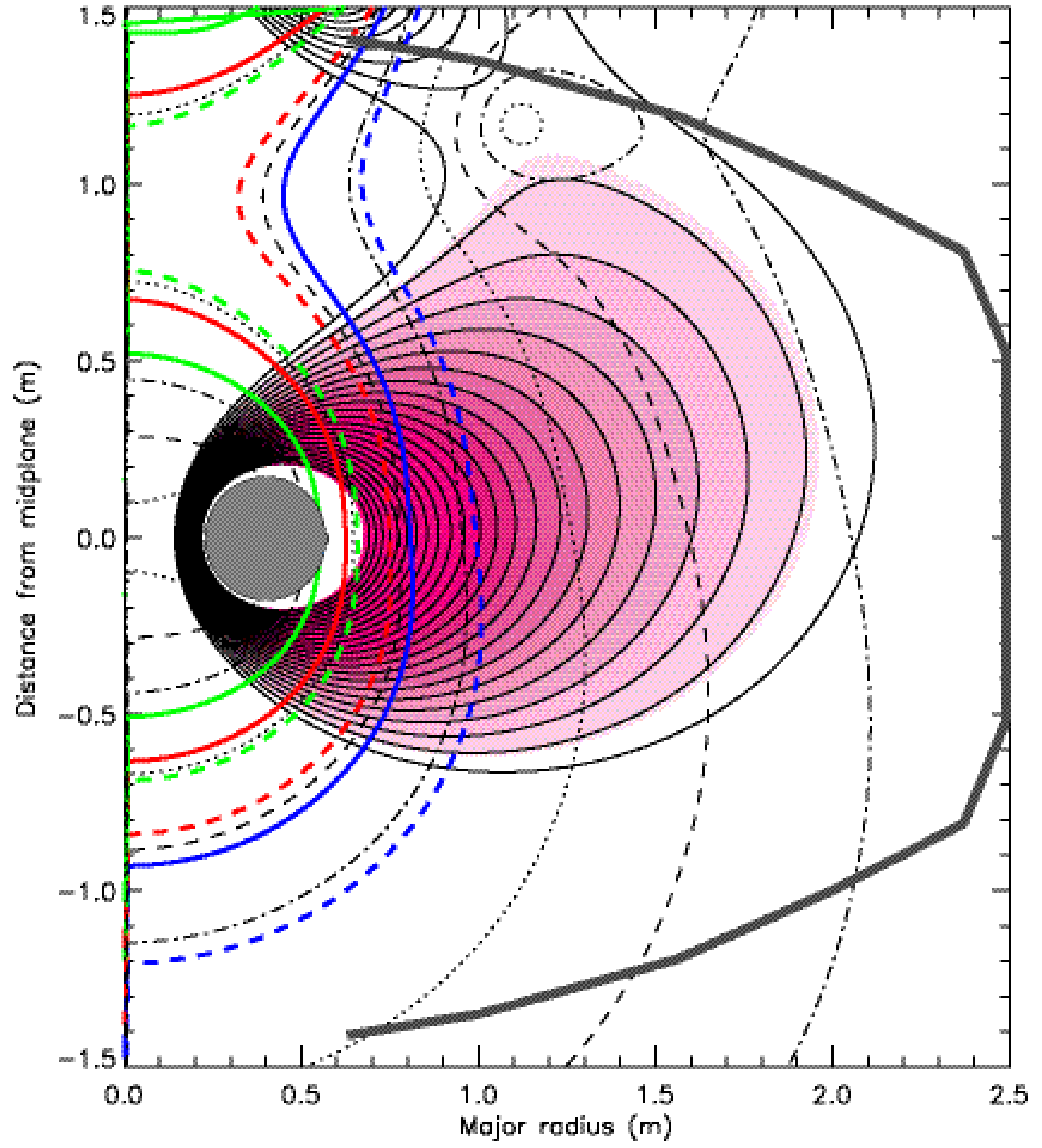
- 10 kW (CW), 10.5 GHz klystron is next in line.
  - Waveguide run is essentially done.
  - Wiring and testing is ongoing
- Allows us nearly to triple the heating power.
- Additional profile control knob.

Heating with the 10.5 GHz source will expand LDX's operational space.

Supported equilibrium showing
2.45 GHz, 6.4 GHz and 10.5 GHz
fundamental and 1st harmonic resonances



Levitated equilibrium showing
2.45 GHz, 6.4 GHz and 10.5 GHz
fundamental and 1st harmonic resonances



- 10.5 GHz can heat to a higher density than the lower-frequency sources.
  - $\sim 1 \times 10^{18}\ m^{-3}$
- Operational characterization needed:
  - Timescale of plasma response.
  - Best firing sequence with respect to other sources.
- Once the dipole coil is levitating all of these studies will need to be repeated.
  - Parallel losses will be reduced.
  - X-point.

Summary

- How the plasma diamagnetic response scales with applied power depends on which source is used.
- It also depends on the relative onset time of the sources.
- Turning one source off results in the plasma evolving slowly to a new configuration.
- Varying the plasma shape alongside modulating the RF power allows the onset threshold of the hot electron interchange mode to be investigated.