We Have Used Two Frequencies of ECRH to Form/Heat our Plasmas

Abstract

An important topic being investigated in the Levitated Dipole Experiment (LDX) is the effect on confinement of varying the deposition profile of the electron cyclotron resonance heating. We report the results of using different operational combinations of our radiofrequency (RF) sources, such as varying the power levels, sequencing of the onset time, and altering the active duration. In addition, we have employed external shaping coils to reduce the plasma volume, which in turn changes the locations of the resonances. Although in the levitated mode of operation the ability to alter the floating coil current, and thereby move the resonances but allow the plasma to occupy its full volume, is severely constrained, the current can be varied in the supported mode, and these experiments have been performed. Results from these studies will be presented and discussed.

- This work is supported by the U.S. Department of Energy.

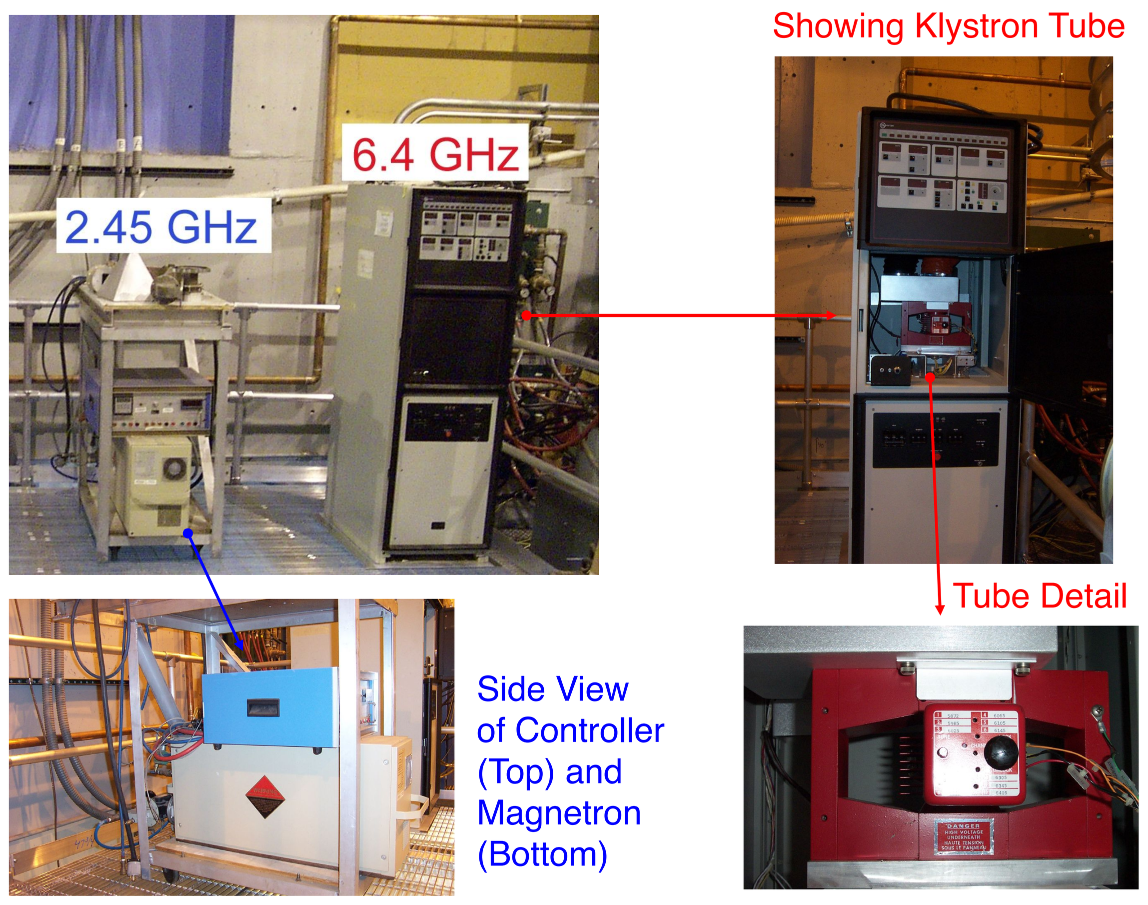
What's New

- Six experimental campaigns have been run.
  - The dipole coil was mechanically supported.
- We have performed a number of experiments in which changing the RF has been an important tool to modify the plasma.
  - Input power levels
  - Timing
  - Resonance locations
    - Plasma shaping
    - Dipole coil current -> magnetic field
- The plasma responds differently to the 2.45 and 6.4 GHz sources when applied at the same power level.
- We have found conditions in which changing the applied RF can cause nearly complete confinement loss.

Outline

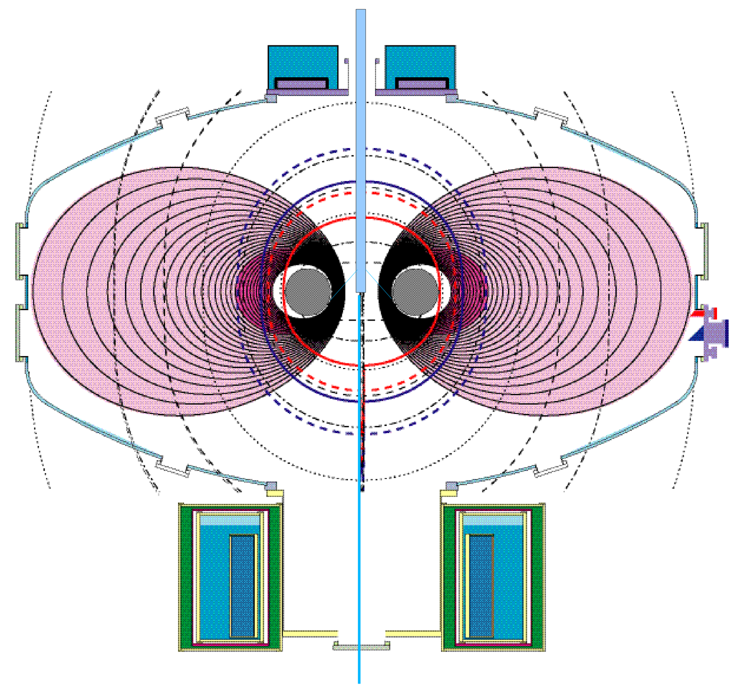
- Overview of electron cyclotron resonance heating (ECRH) on LDX.
  - Why multiple frequencies?
  - Extant sources
  - Implementation
- Modeling
- Experimental results
  - Single discharges
  - Multi-discharge power scans
    - Peak stored energy
    - "Afterglow" (no input power) and connection to confinement during heating.
- Future work

- ECRH is an effective way to create a high β hot electron population.
- We have the following sources online currently:
  - 2.5 kW CW at 6 GHz
    - Klystron
    - Operated for all campaigns
  - 2.5 kW CW at 2.45 GHz
    - Magnetron
    - Operated for second and succeeding runs
  - More on the way
- By heating at more than one frequency, we are able to perform heating profile studies.



The Resonances for the ECRH Sources are Near the Dipole Coil.

- Cutaway of LDX Vacuum Chamber and Magnet Systems
- Modeled Equilibrium
  - Supported Coil
  - Pink region denotes closed field lines.
- ECRH resonances
  - 2.45 GHz
  - 6.4 GHz
  - Fundamental resonances are solid, first harmonic are dashed.

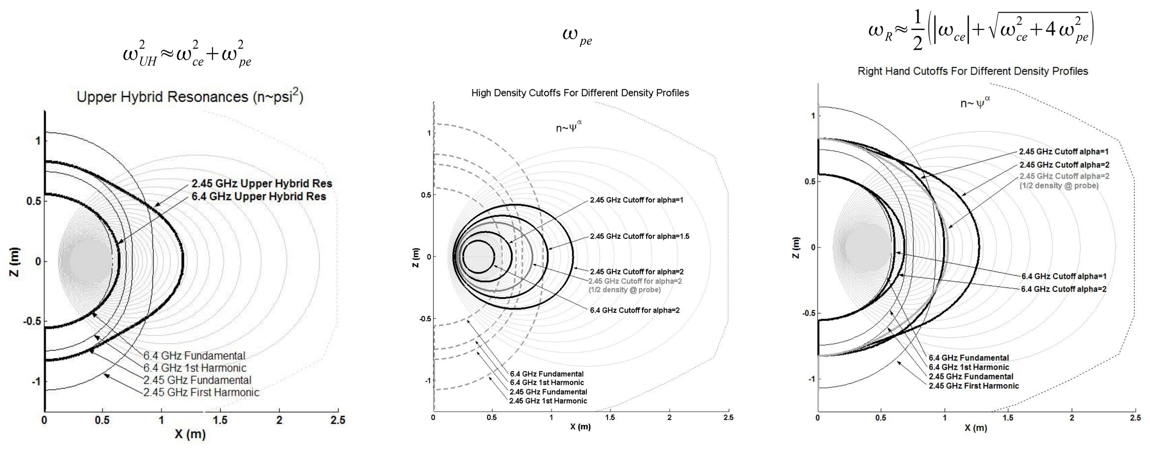


- The antennas are cut waveguides.
  - Match waveguide impedance to free space.
  - No need for directivity, because we aren't driving current.
- Our primary heating method is cavity heating.
  - Small first-pass absorption is expected.
  - Get relatively isotropic heating in spite of toroidally localized launch.

Some Modeling Concerning ECRH in LDX Has Been Performed.

The Locations of the Cold-Plasma Cutoffs and Resonances Have Been Estimated

- The electron density is estimated via a power law model, $n_e \sim n_0 \psi^\alpha$ ($\alpha = 0, 1, 2$), using an edge probe measurement as a constraint.
- Lower hybrid resonances in the range of our ECRH frequencies do not appear in the LDX plasma.
- The other resonances/cutoffs do appear within our plasma, and are density-dependent.
  - Upper hybrid resonance
  - Electron plasma frequency (ω_{pe}) –> O-mode cut off.
  - Right hand cutoff –> affects X-mode propagation.
- It is entirely possible that our density is such that the ω_{pe} and right-hand cutoffs are coming into play.
  - To determine this definitively requires better knowledge of the density profile than we currently have.



Note: only one value of the density profile exponent employed

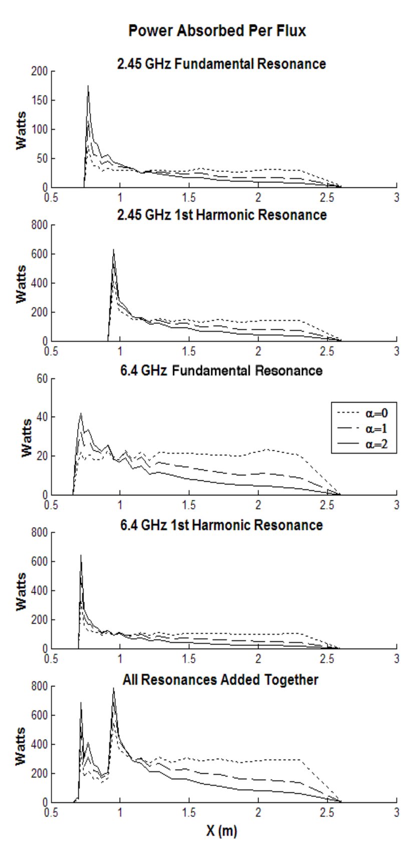
An Estimate of the Power Deposition Has Been Made.

- It can be shown that the power crossing a resonance can be approximated by:

$$P_\perp = \pi |E^-|^2 n_e e \frac{1}{\nabla B}$$

where E^- is the right-hand-circularly polarized component of the wave electric field.

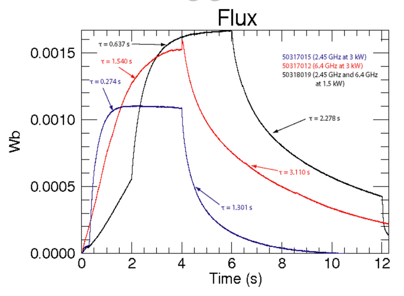
  - Method from Stix.
- Caveat: method ignores finite width of resonance region.
- There is a a strong density profile dependence for the power absorption.
- Caveat: for the values shown, full accessibility of the RF was assumed, which may not always be the case.
  - Cf. the results of the cutoff study
  - Affects the 2.45 GHz absorption.



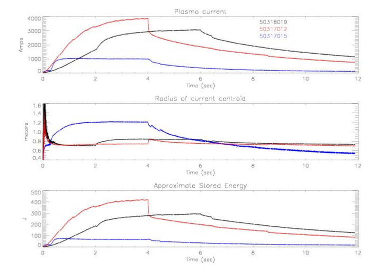
- References:
  - Scott Mahar, Master's Thesis (MIT, 2005).
  - T.H. Stix. *Waves in Plasmas* (2nd edition). American Institute of Physics, 1992.

Reprints of this or other LDX posters will be available at *http:///psfcwww2.psfc.mit.edu/ldx/pubs/*

The Two Sources Produce Different Effects at the Same Nominal Input Power

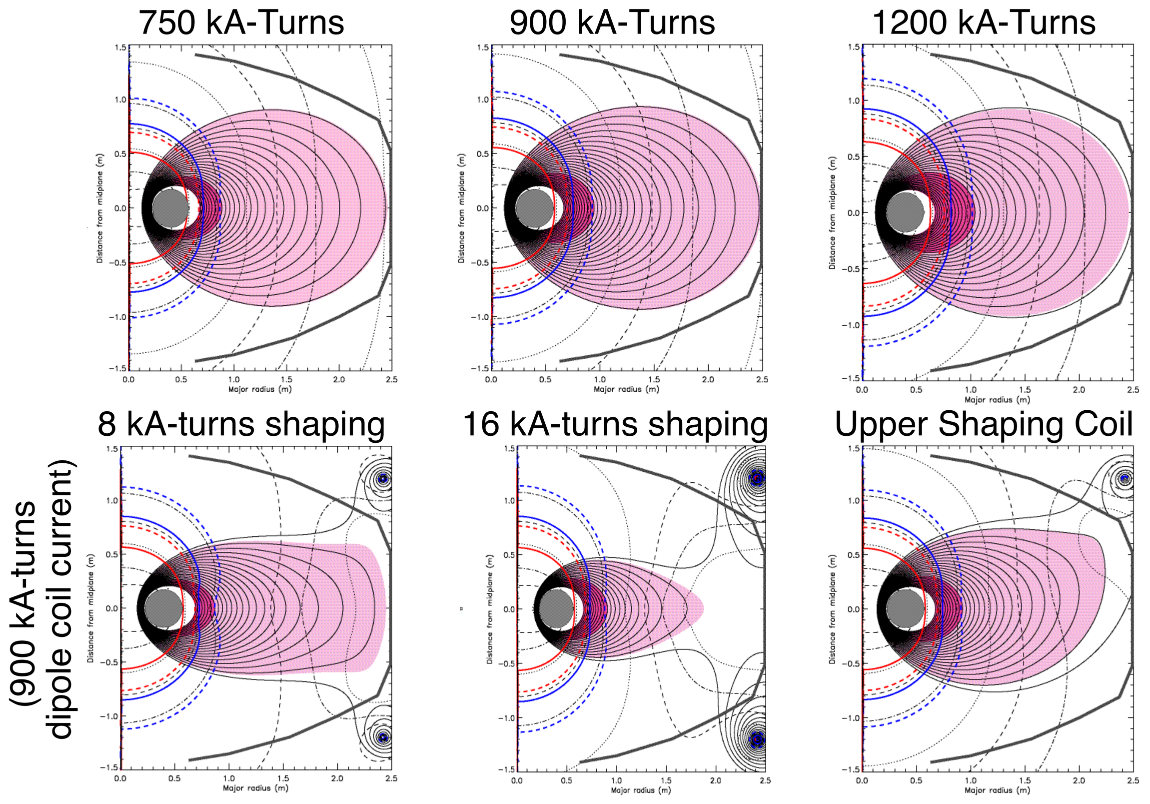


Using Current Filament Model

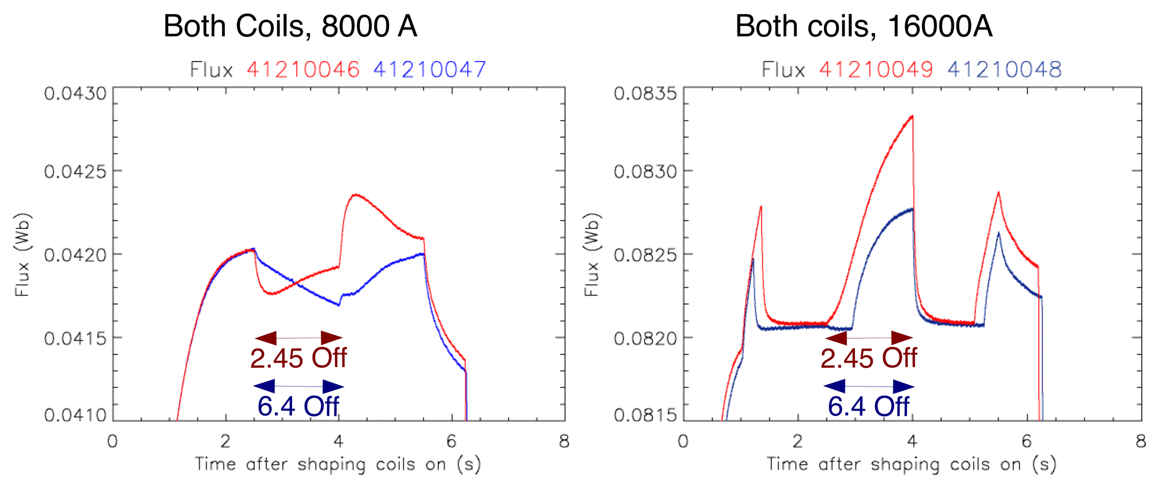


- Similar total power from the ECRH.
  - 2.45 GHz only
  - 6.4 GHz only
  - Both sources at half power
    - Note: the ECRH programming for the discharge with both sources on was different
      - 6 s pulse, w/2.45 GHz fired at 2 s.
      - The other cases used 4 s pulses.
- Timescales:
  - $\tau_{2.45\ only} < \tau_{both\ sources} < \tau_{6.4\ only}$
  - True for rise time as well as decay time.

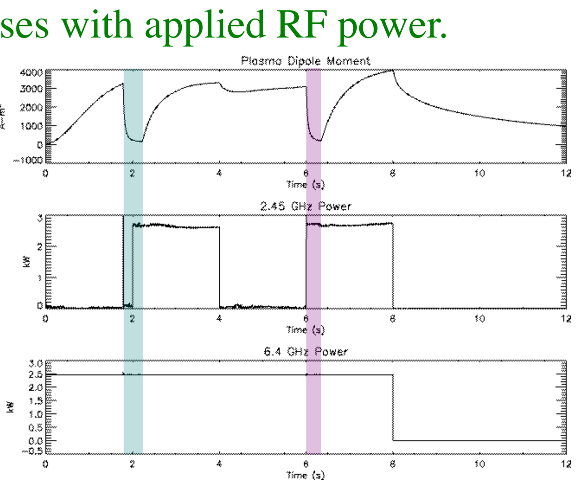
We Have Run in a Number of Different Magnetic Configurations.



The Plasma Can Be Destabilized by Additional Applied RF



- In the 8000 A shaping current case the changes are slow.
  - Flux recovers after 2.45 GHz turned off.
  - Flux decreases steadily after 6.4 GHz turned off.
- In the 16000 A case, the plasma exhibits large changes in the flux with similar results for both flavors of modulation.
  - A drop occurs before the modulated source is turned off.
    - Plasma re-enters a low-beta configuration.
  - There is a recovery after the source is turned off.
    - Delayed when modulating the 6.4 GHz source.
  - Presumably the addional RF power pushes the plasma across the hot-electron interchange stability boundary.
    - Only the fast electrons, not cold bulk plasma.
- This can also occur in the absence of shaping.
  - Seemingly a neutral pressure threshold for transition.
    - Threshold value decreases with plasma volume.
    - Increases with applied RF power.
      - Soı

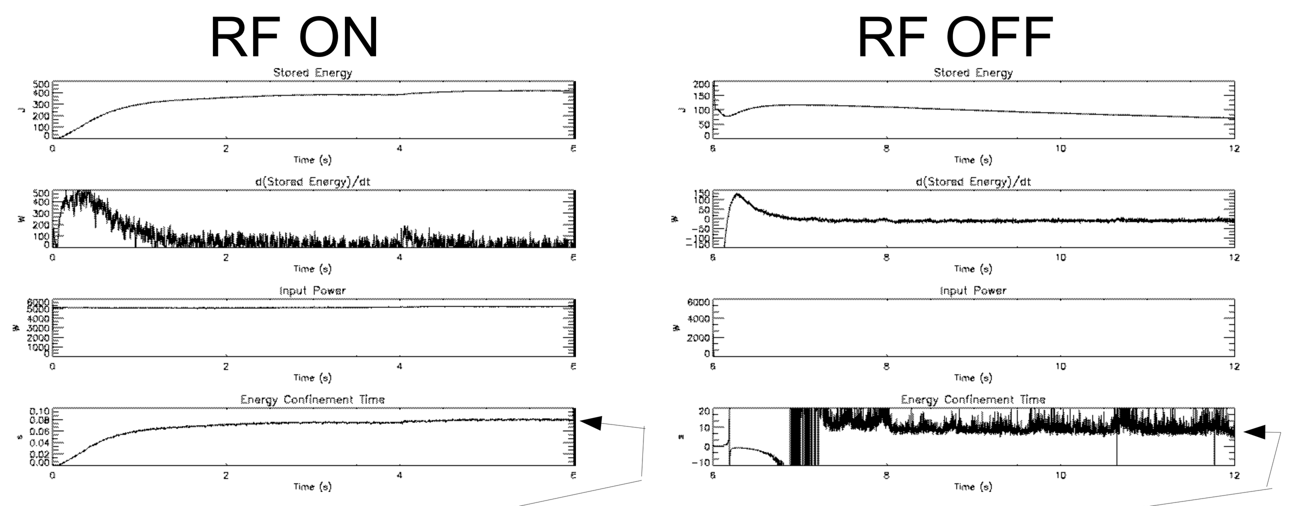


The Energy Confinement Time Is Estimated via a Simple Power Balance

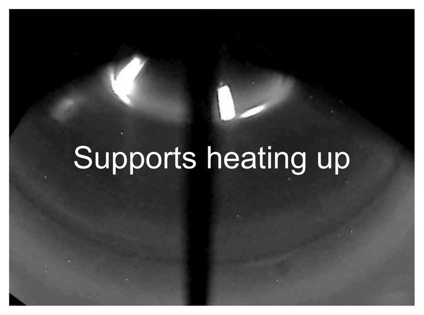
- $\frac{dW}{dt} = P_{in} - P_{out}, \ \tau_E \equiv \frac{W}{P_{out}}$

  $\rightarrow \tau_E = \frac{W}{P_{in} - \frac{dW}{dt}}$
- Use forward power measurements on the RF sources for P_{in}.
- Use a filament model for the plasma current to estimate W and dW/dt.
  - Match to magnetics measurements.
  - Usual equilibrium reconstruction method is at a single point in time.
  - Caveats:
    - The model doesn't include the effects of pressure anisotropy.
    - The model also doesn't include non-monotonic pressure profiles.
      - Less problematic for plasmas that use only a single RF source.

The Inferred Confinement Time is Much Larger when the RF is Off.



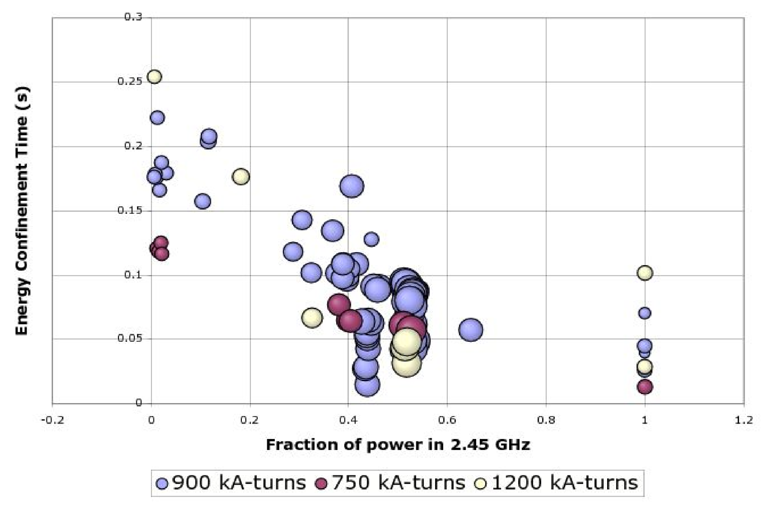
- τ_E ~80 ms for RF on, ~10 s for RF off.
  - In this particular case.
- Uses the simple confinement model above.
- Use forward power measurements on the RF sources for P_{in}.
- Note: the stored energy is dominated by fast (>10 keV) electrons.
- Primary loss mechanism is probably via in the bulk (~10 eV) electrons.
  - Heating at fundamental resonances.
  - Parallel losses to the supports.



- Fast particle loss channels may also play a role.
  - RF-induced diffusion.
  - Non-RF effects
    - Collisions with bulk particles.
- In the "no-RF" case, the confinement time reflects the fast electron confinement.
  - Bulk population goes away when heating turned off.
  - Coil supports are seen to not to be heated.

The Estimated Confinement Time Declines With Increasing 2.45 GHz Power Fraction.

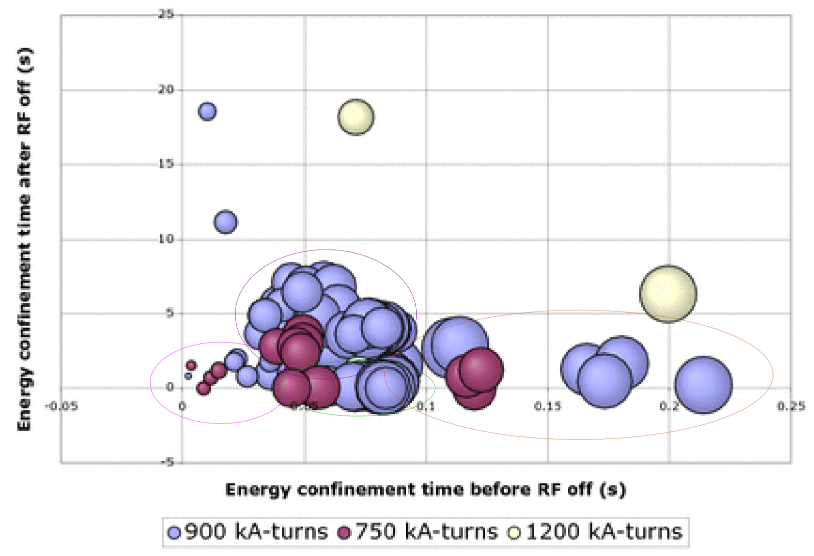
Energy Confinement Time vs. Fraction of Power in 2.45 Ghz (Point Size ~ Total Input Power)



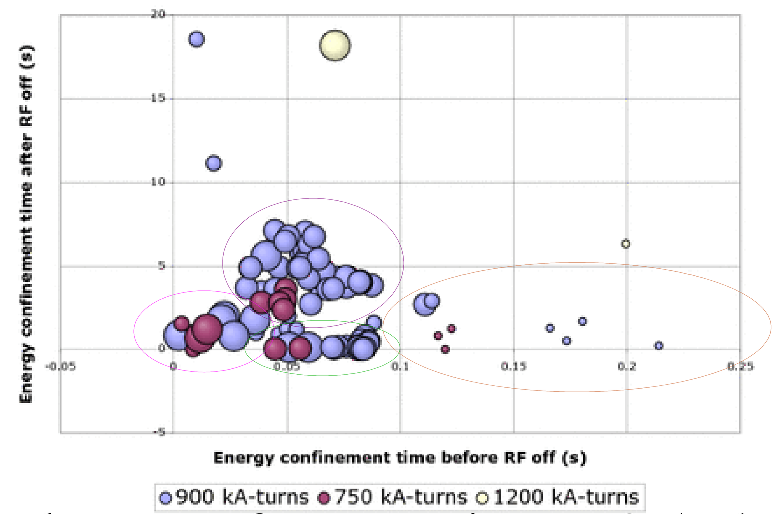
- Not just a power scaling,
  - Discharges with no/very low 2.45 GHz power are at essentially the same power level as those with only 2.45 GHz.
- Caveats:
  - Database doesn't make cuts for "discharge quality".
    - Hence large scatter.
    - Also explains reduced 1200 kA-turn confinement.
  - The limitations of the modeling may play a role in the observed trend.

The Post-RF Confinement Time Depends on the Heating Phase Confinement and the Source Used

Confinement Time After RF Off vs. Confinement Time Prior to RF Shutoff (Point size ~ Stored Energy before RF off)



Confinement Time After RF Off vs. Confinement Time Prior to RF Shutoff (Point size ~ Fraction of Input Power in 2.45 GHz)

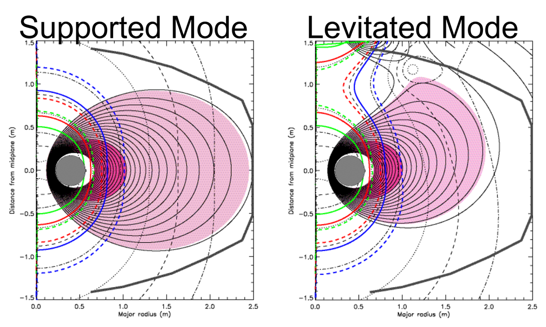


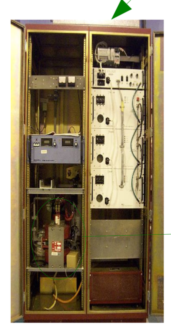
- Method: evaluate confinement time at 0.5 s before and after the RF is switched off.
  - Caveat: minimal "quality control" cuts.
- Cluster of points near (0.05 s, 4 s).
- Inverse relationship for high heating-phase confinement.
  - Higher stored energy before RF off.
  - Low 2.45 heating fraction.
  - These plasmas tend to lose their stored energy violently after heating is removed.
    - Presumably close to stability boundary.
  - Similarly for group below cluster.
- Few points for low heating-phase confinement and high post-heating confinement.
  - The plasmas were puny before the RF went off.
- The points for 2.45 GHz-only plasmas tend to reside near the origin.
- Possible scaling with magnetic field.
  - More points needed.

Future Work

- Additional ECRH frequencies and power.
  - Enhance ability to control the heating profile.
  - 10 kW @ 10.5 GHz is next in line.
  - Resonances for higher frequency (> 6.4 GHz) sources are nowhere tangent to a field line.
    - Absorption will be different.

- Study confinement with levitated dipole coil.





Summary

- Some modeling of electron cyclotron wave propagation in LDX has been performed.
- Under certain conditions, we can destabilize the plasma with an RF pulse.
  - Plasma shaping
  - Neutral pressure
- The plasma responds differently to our two sources, even when applied at the same power level.
- Confinement during the post-RF phase has a complicated relationship to that of the heated phase.