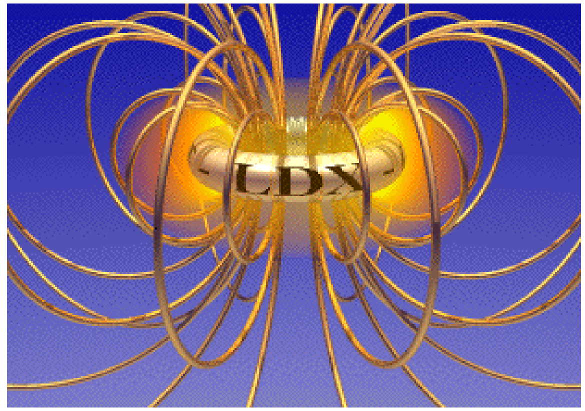

ECRH in the Levitated Dipole Experiment

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Abstract

High β plasmas will be produced in the Levitated Dipole Experiment (LDX) using ECRH. In order to control the pressure profile, the LDX experimental plan calls for the use of multiple frequency electron cyclotron heating (MFECH). MFECH was observed to result in increased pressure for the trapped, high energy electrons in mirror experiments. Initial experiments will establish the parameter regimes for stable plasma operation. We will also study the effects of MFECH on the density and pressure profiles, and the possible formation of convective cells due to non-axisymmetric RF launch. We have several source frequencies available, and we plan for at least two of them, 6 GHz and 10 GHz, to be available for first plasma. To aid our experimental efforts, work is in progress on modifying existing ray tracing codes to include the LDX equilibrium profiles.

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New Results

- **Two ray-tracing codes have been modified for use in dipole geometry (Kesner, Ram).**
  - **Warm Plasma**
    - A. K. Ram and A. Bers, *Phys. Fluids B*, **3**, 1059 (1991).
  - **Relativistic (TREC code modification)**
    - G. Le Clair, I.P. Shkarovsky, Y.Demers, and J.-F. Mercier, Centre canadien de fusion magnétique Report CCFM RI 472e (1997).
- **At least two frequencies should be available early in experimental campaign.**
  - **6.4 GHz is ready now, 10.5 GHz coming online soon, 18 and 28 GHz later**

Outline

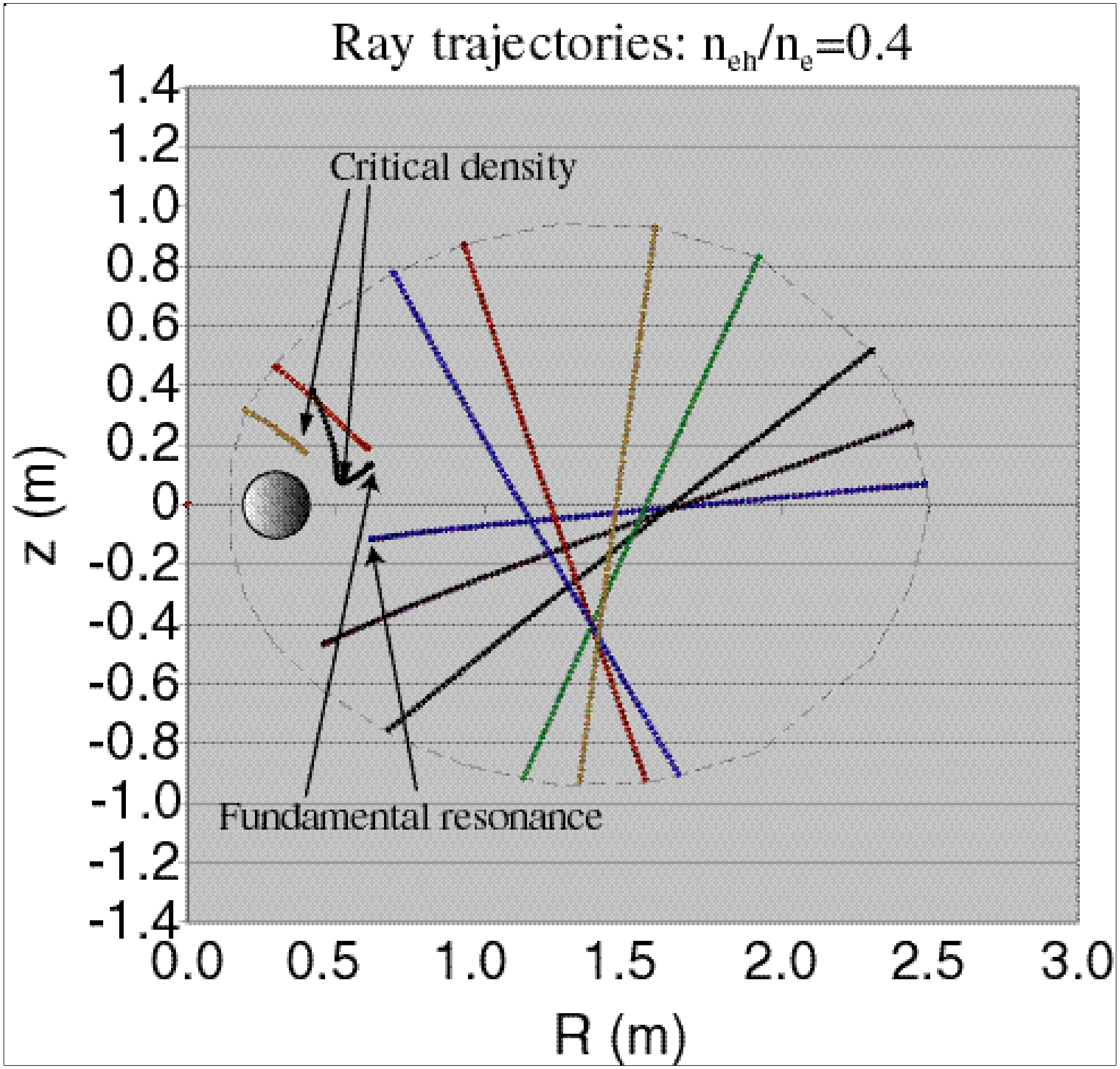
- **Ray-tracing codes for dipole geometry**
  - **Warm plasma with multiple electron distributions (Ram code)**
    - A. K. Ram and A. Bers, *Phys. Fluids B*, **3**, 1059 (1991).
  - **Relativistic (TREC code)**
    - G. Le Clair, I.P. Shkarovsky, Y.Demers, and J.-F. Mercier, Centre canadien de fusion magnétique Report CCFM RI 472e (1997).
- **ECRH in LDX**
  - **Hardware**
  - **Experimental Plan**
- **Future work**
- **Summary**

Warm Plasma Ray Tracing Code

A warm plasma ray-tracing code has been modified to work in dipole geometry.

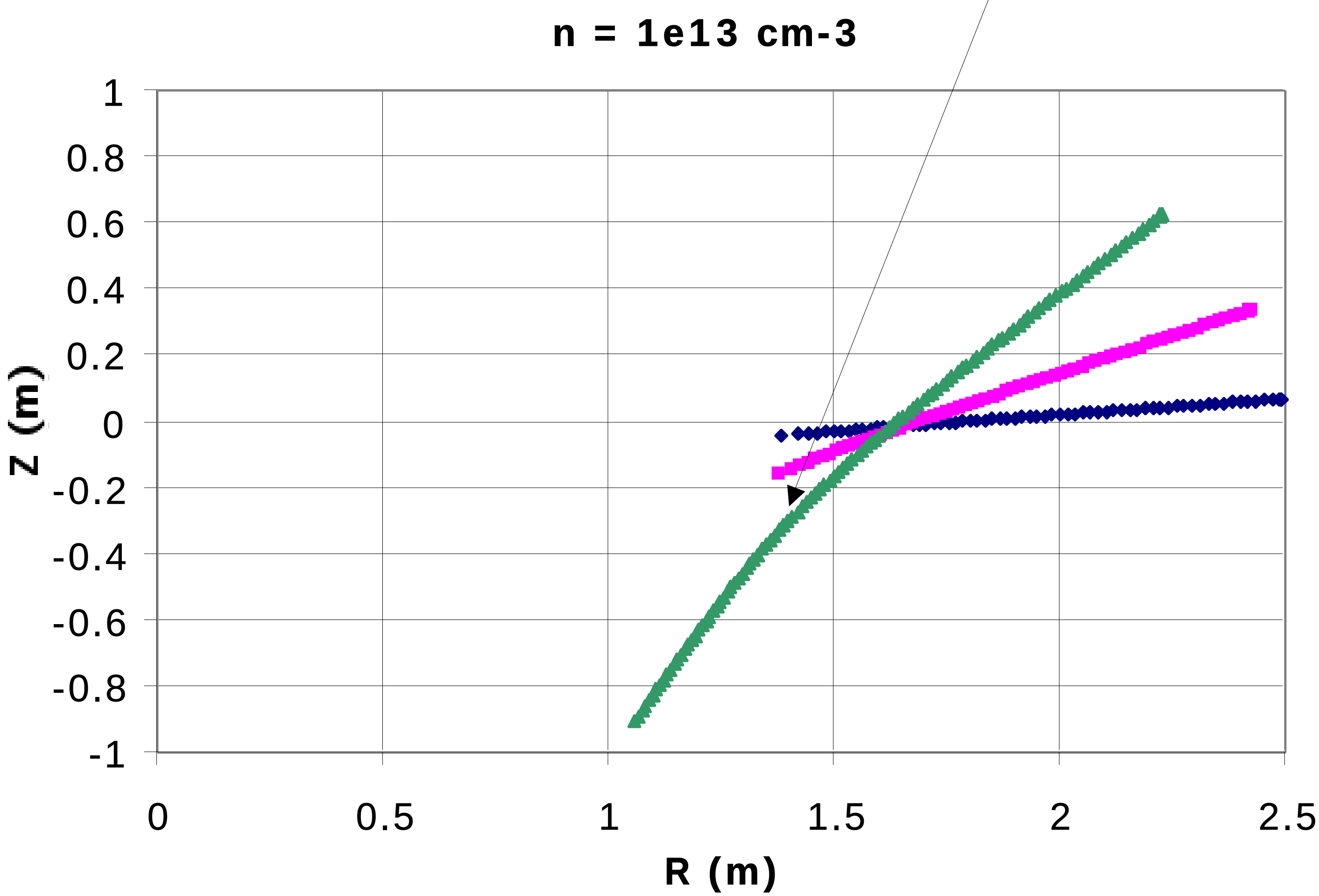
- **Modification of a tokamak code.**
  - A. K. Ram and A. Bers, *Phys. Fluids B*, **3**, 1059 (1991).
- **Caveats:**
  - **Relativistic effects are not included.**
  - **Magnetic field is that of a current ring.**
    - **Model field**
    - **Relevant at low β**
  - **Simple density and pressure profiles.**
  - **Hot electrons are represented by a separate Maxwellian distribution from that of the bulk electrons.**
    - **Rather than a tail.**

Most trajectories show little refraction at LDX-relevant low densities.



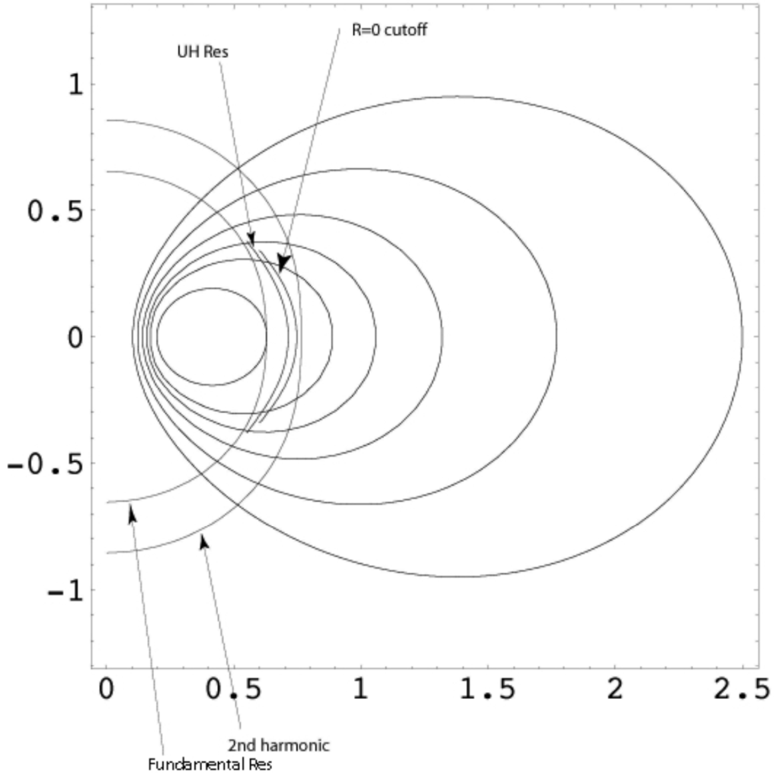
- **Parameters:**
  f = 6.4 GHz, X-mode
  $n_e = 5\times10^{11}$ cm^{-3}
  $n_{e,hot} = 2\times10^{11}$ cm^{-3}
  T_e = 10 eV
  $T_{e,hot}$ = 100 keV
- **Most trajectories follow essentially straight paths.**
- **Exception: those from the high-field side can reflect from a density cutoff.**

At higher densities, refraction occurs.

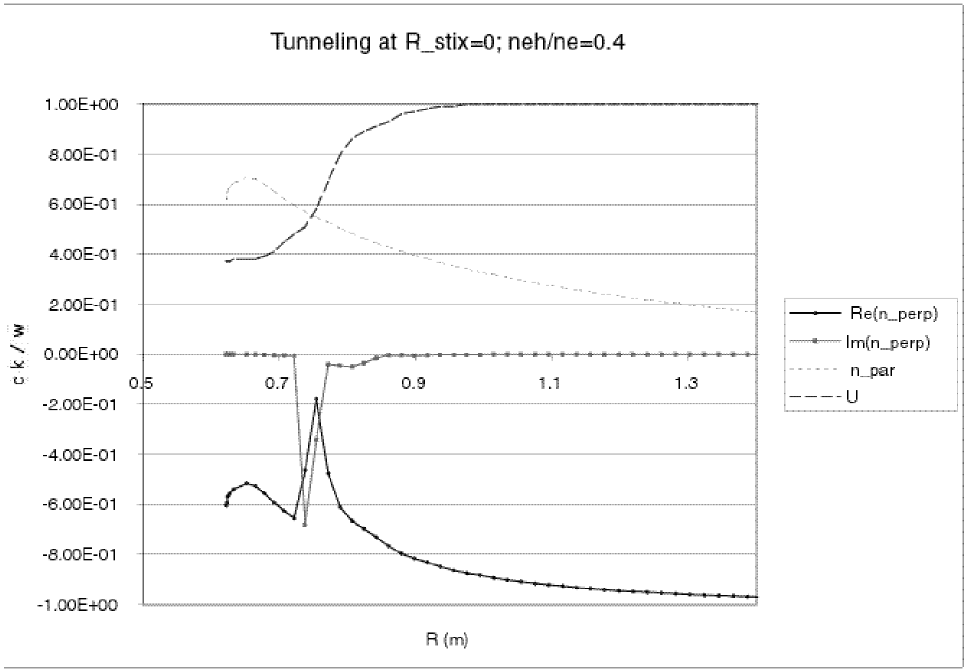


- Plasma parameters other than the peak densities are identical to the previous case.

"Tunneling" of X-mode waves through a cutoff can be seen.



Cutoff-resonance-cyclotron layer are close together.



- **The code continues tracing the ray even when Im($n_\perp$) > Re($n_\perp$)**
  - **WKB approximation may not be valid**
- **The right-hand cutoff, upper hybrid resonance, and cyclotron harmonics can all be close together.**

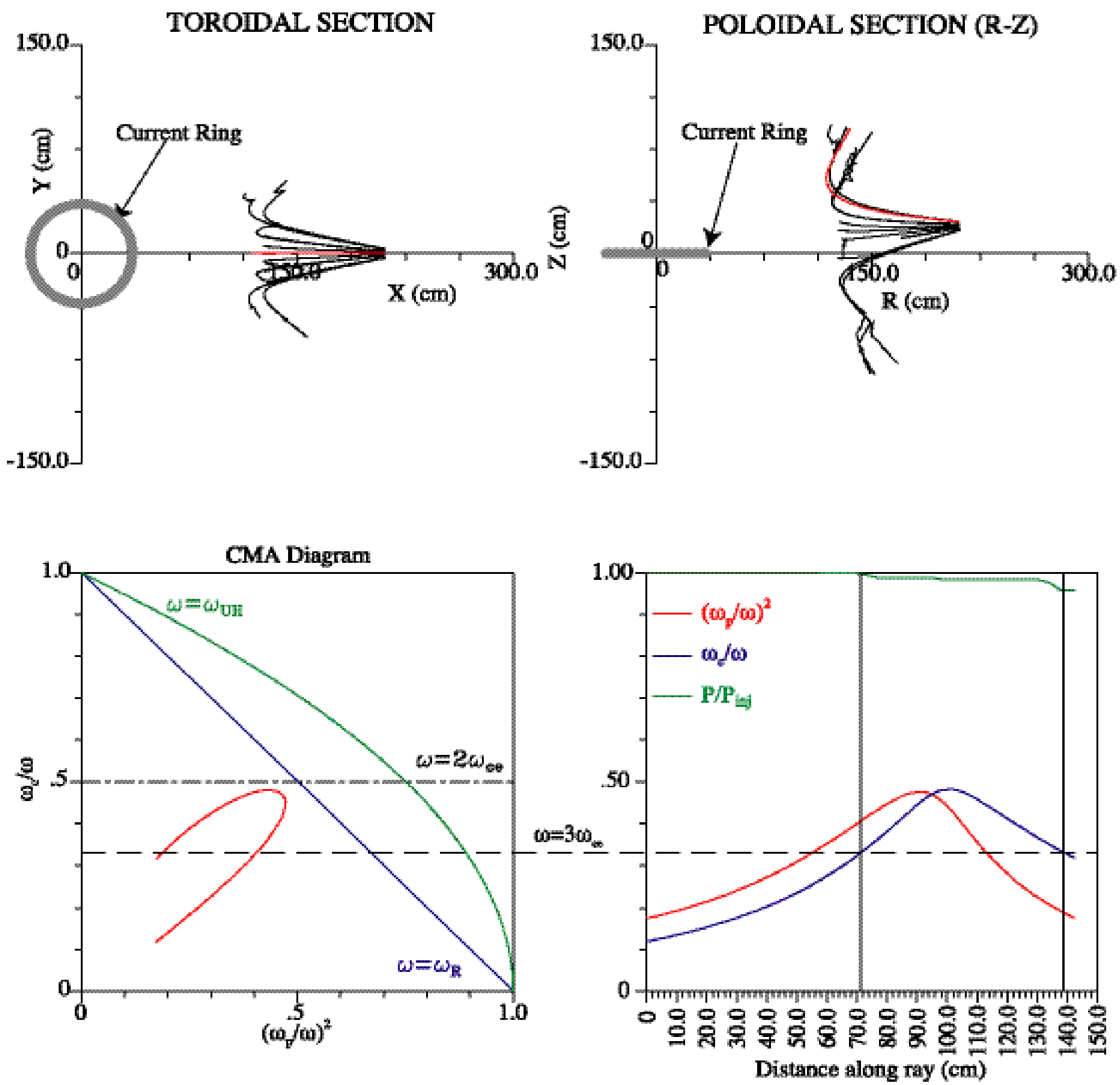
Relativistic Ray Tracing Code

A relativistic code is also being used

- **Motivation: significant relativistic effects in the dielectric tensor can occur even when $\langle U_{thermal} \rangle \ll m_e c^2$.**
  - J. Egedal and H. Bindslev, *Plasma Physics and Controlled Fusion*, **36**, 543 (1994).
- **The code is a modification of the TREC code.**
  - G. Le Clair, I.P. Shkarovsky, Y.Demers, and J.-F. Mercier, Centre canadien de fusion magnétique Report CCFM RI 472e (1997).
- **Uses a "weakly relativistic" approximation**
- **Caveats**
  - **Lacks separate hot and cold populations, as are expected in the experiment.**
  - **Preliminary--there are still some numerical problems to be ironed out for some ray trajectories.**
  - **Magnetic field is a current ring again (i.e. model problem, low β).**

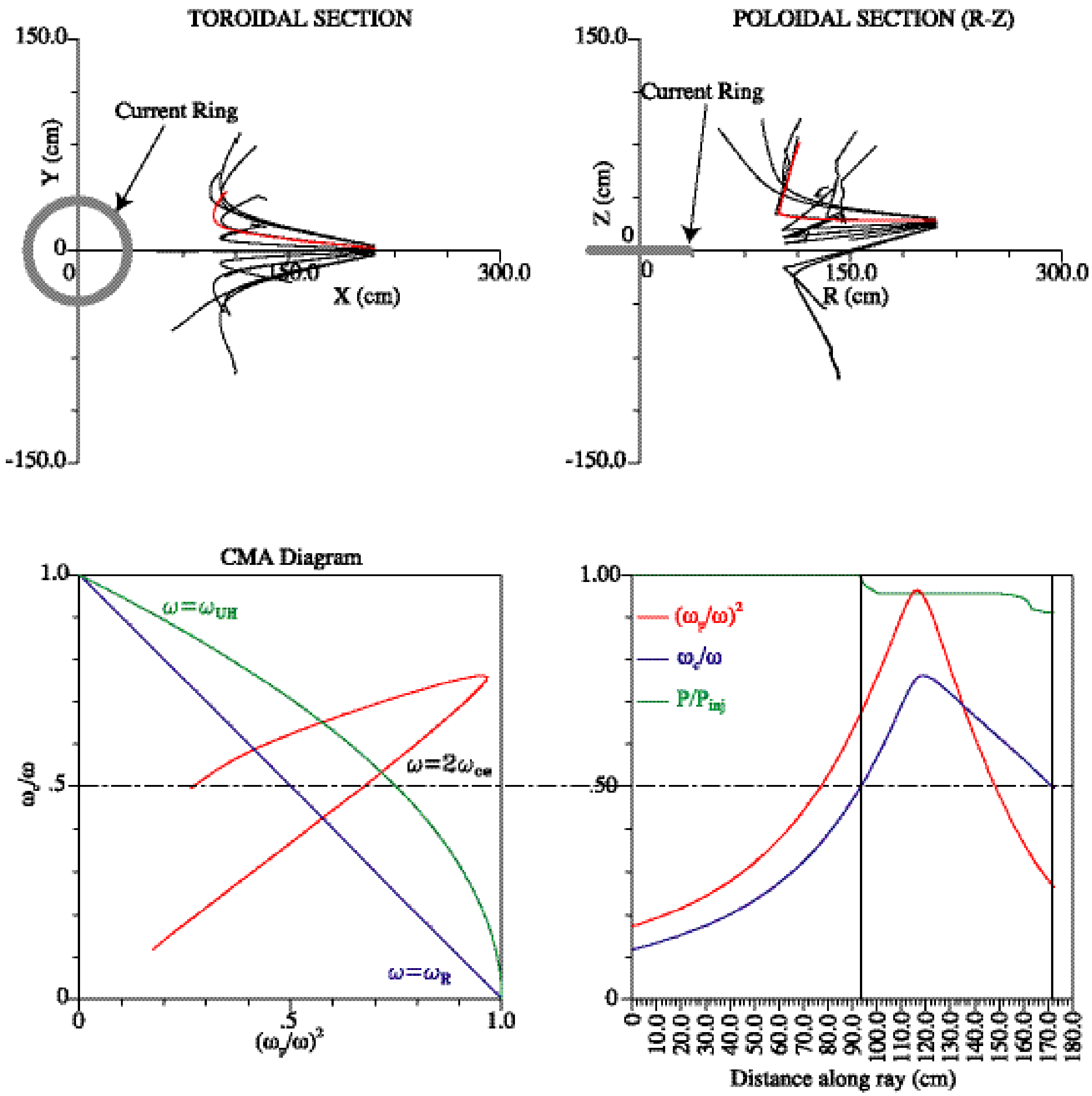
Initial runs from the relativistic code for X-mode show large refraction at the R cutoff.

- **Parameters:**
  f = 4.6 GHz
  n_e=1.5x10^{12} cm^{-3}
  T_{e0}=40 keV
- **X-mode rays refract near the right-hand cutoff**
  - **an example is shown in red (except for the lower right plot).**
- **Some absorption of this ray can be seen at ~ 3ω_{ce}, both before and after refraction.**



Results for O-mode are similar.

- Selected ray in red except for lower right plot.
- Refraction occurs around the plasma frequency.
- Absorption occurs at above $2\omega_{ce}$ each time the layer is crossed.
  - This is expected from relativistic effects.
- Single-pass absorption not as large as for Ram code
  - Temperatures are different

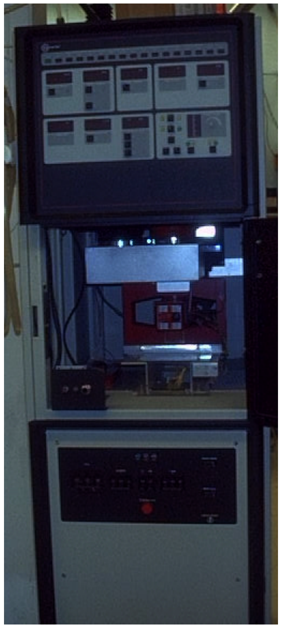


Hardware

We have several klystrons and gyrotrons available.

- Klystrons
  - 3 kW CW at 6.4 GHz
  - 10 kW CW at 10.5 GHz
  - 10+ kW CW at 18 GHz
- 28 GHz Gyrotrons
  - 10+ kW CW
- The 6.4 GHz klystron system is a modified commercial system and is operational.
- The other klystrons and the gyrotrons need parts and labor to be functional.

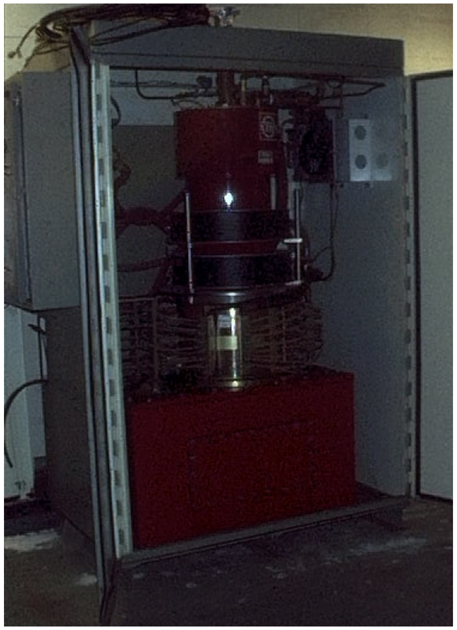
6.4 GHz



10.5 GHz

18 GHz

Gyrotron



Experimental Plan

MFECH provides a mechanism for pressure profile control.

- **Use multiple sources with different resonant zones to tailor the pressure profile to marginal stability.**
- **Results from the SM-1 symmetric mirror (TRW):**
  - **Multiple frequency electron cyclotron heating (MFECH) with large frequency separation.**
  - **Elimination of low frequency fluctuations in cold electron population with multiple sources.**
  - **Order of magnitude increase in stored energy in hot electrons.**
    - B. H. Quon, R.A. Dandl, W. DiVergilio, G. E. Guest, L.L. Lao, N.H. Lazar, T.K. Samec and R.F. Wuerker, *Physics of Fluids* **28**, 1503 (1985).
- **Results from CTX supported dipole (Columbia):**
  - **Hot electron interchange mode "bursts" with only one source.**

MFECH provided profile control and stability in the SM-1 mirror.

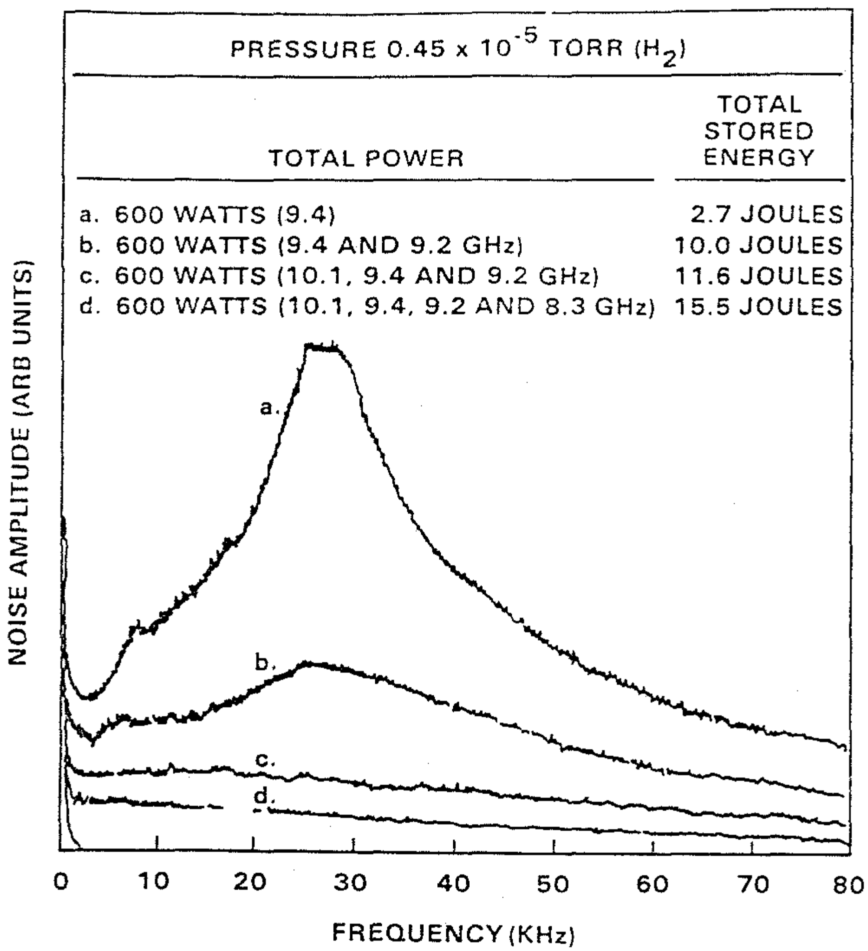


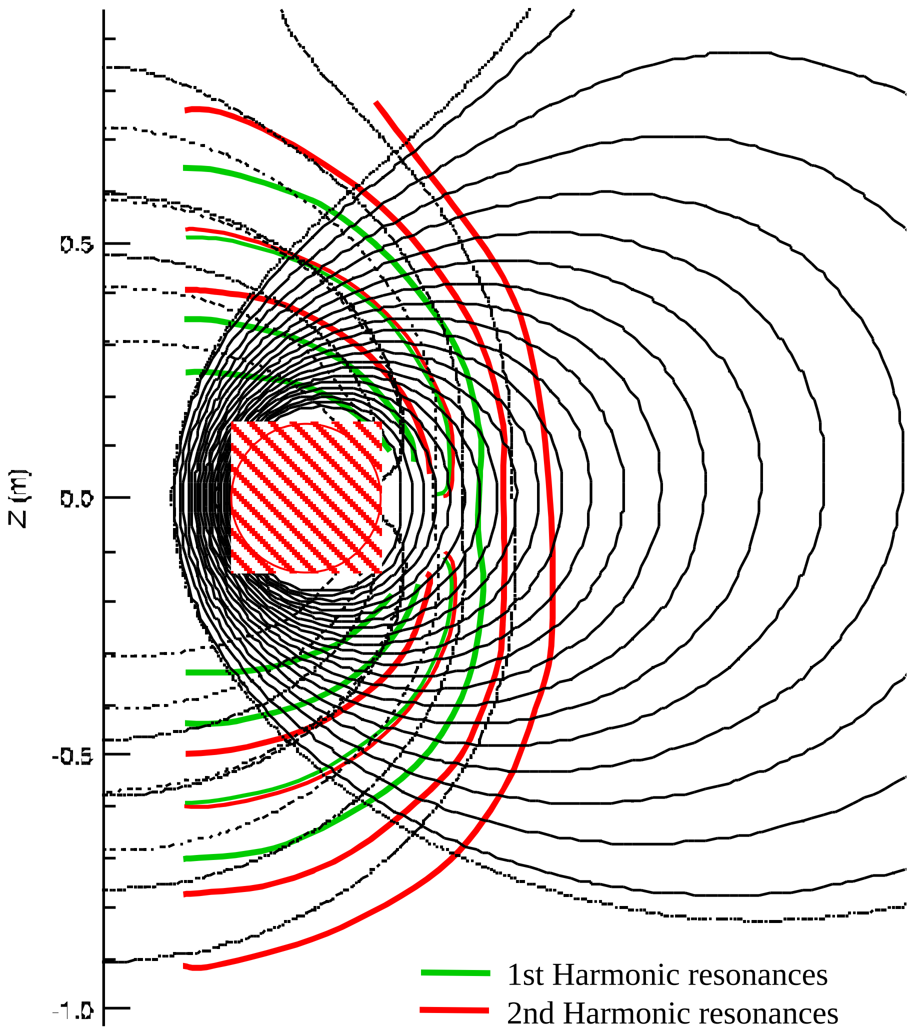
FIG. 11. Spectra of low-frequency fluctuations in the cold-electron end-loss current for four different heating configurations.

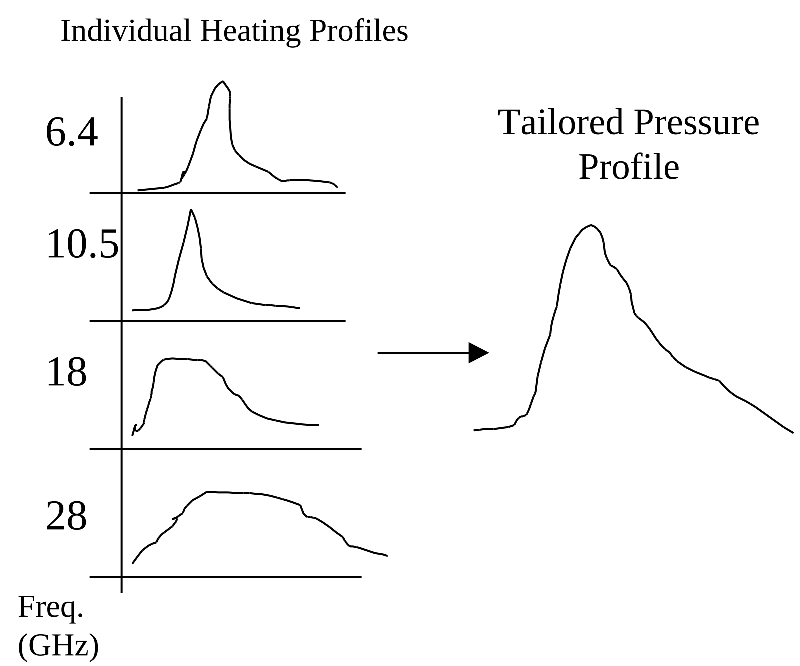
- **Using multiple-frequency ECH in SM-1 symmetric mirror allowed stable operation.**
  - **Reduction of low frequency fluctuation in cold electrons by order of magnitude**
  - **Increase in stored energy in high-β hot electrons**
- **The speculation is that this was due to a more stable hot electron ring profile.**

❖ **B. Quon et al, *Phys. Fluids* 28, (1985) 1503.**

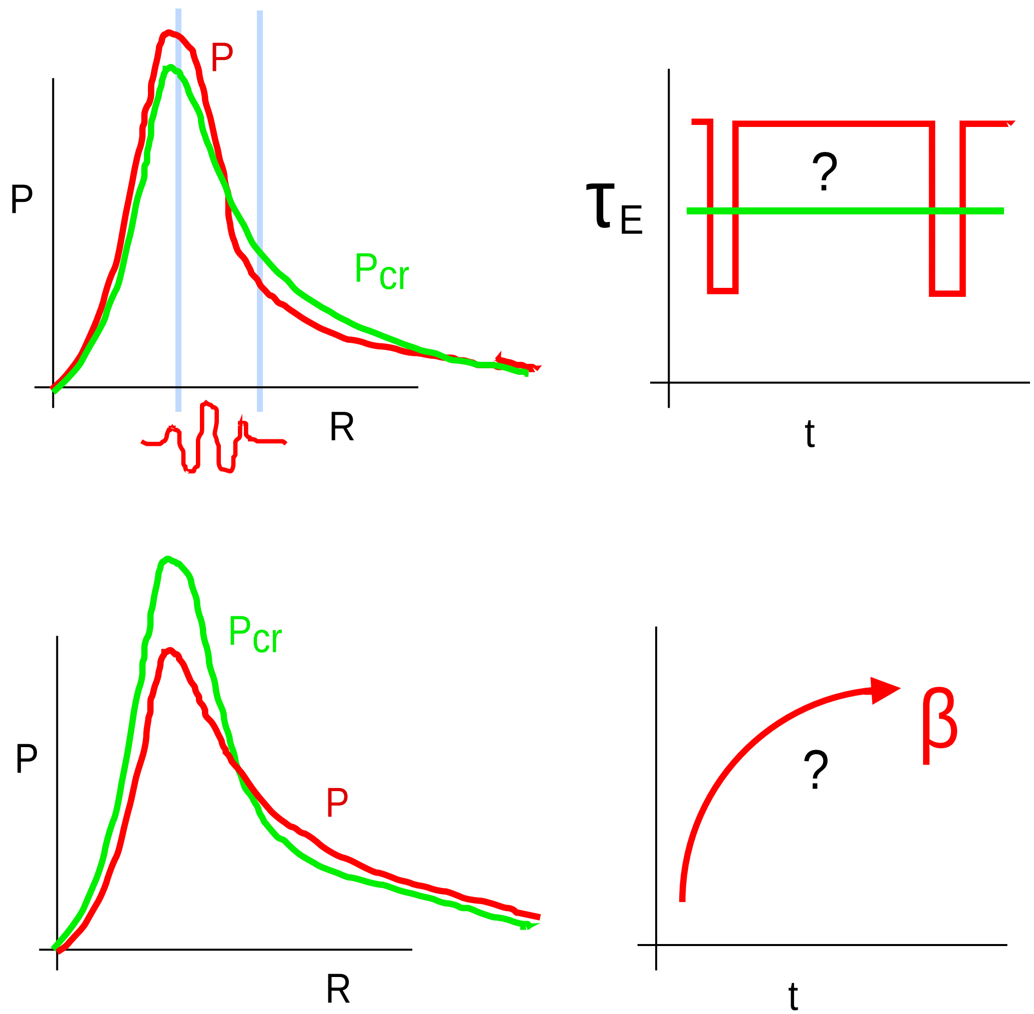
The profile can be controlled via the multiple resonances.

- **Multi-frequency ECRH**
  - **Measure single frequency response.**
  - **Tailor multi-frequency heating to ideal profile.**





Instabilities and confinement can also be investigated with ECH.



- Interchange instability should exist when: $p' > p'_{critical}$.
  - Investigate nature of instability.
    - How does it saturate?
    - How much transport is driven?
- Maximize β when: $p' < p'_{critical}$ everywhere
  - What is maximum attainable β and what is limit?

MFECH can provide enhanced heating

- **Use of multi-frequency ECH has also shown substantial increase in stored energy in hot electron population.**
  - **Probably due to elimination of super-adiabatic effects which create phase-space barriers for heating.**
- **Results from SM-1**
  - **Effect is greatest when frequency separation is equal to bounce time of warm electrons.**
- **Results from EBT**
  - **Increase was not seen, but EBT was believed not to have super-adiabatic effects.**

MFECH efficiency in SM-1 was enhanced by using two closely-spaced frequencies.

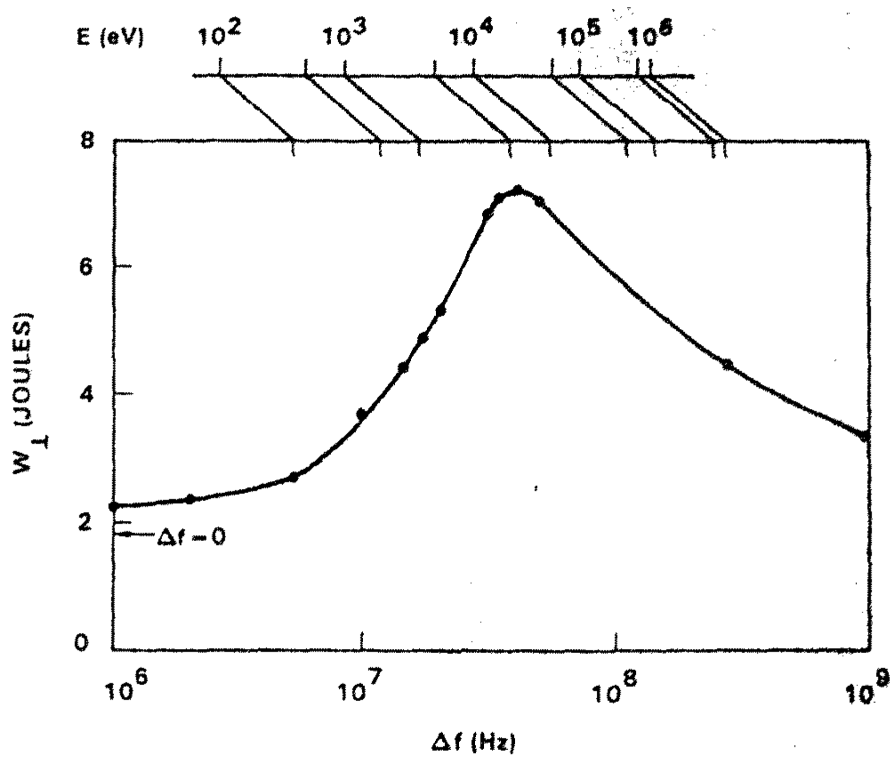
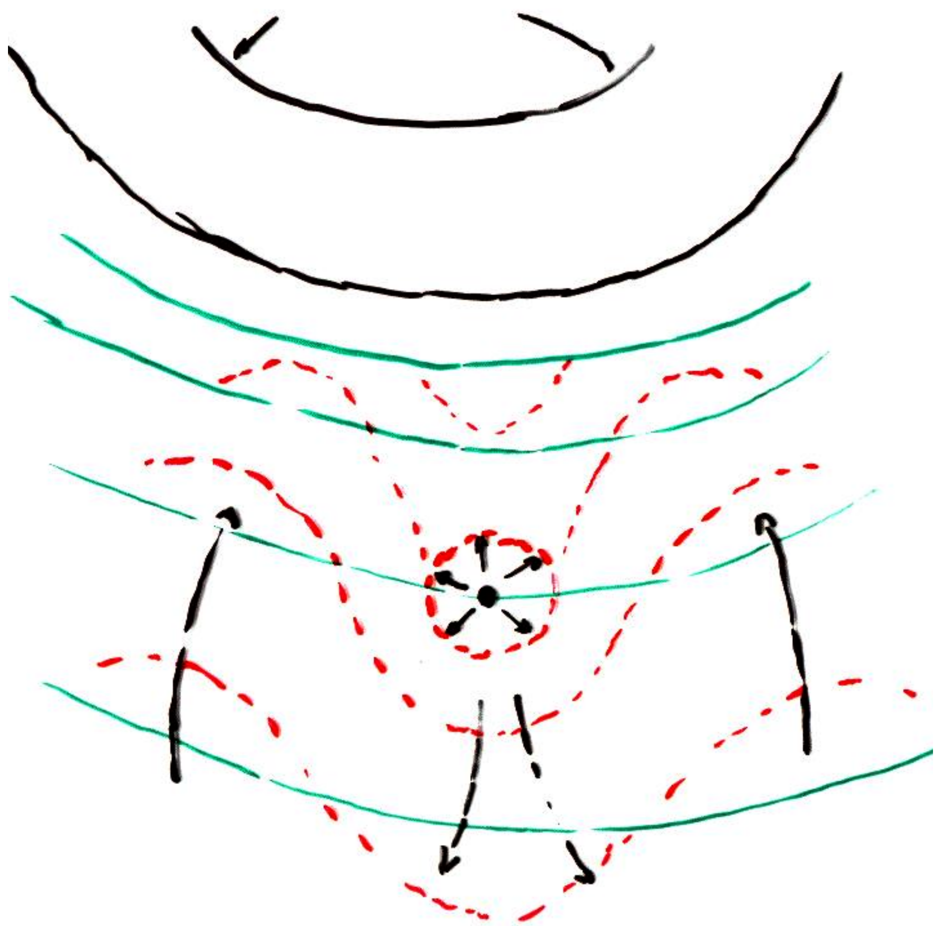


FIG. 9. Total stored energy as a function of frequency separation for two-frequency heating. The scale gives the electron energy for which the bounce frequency is equal to the applied frequency mismatch.

- **Using 2 frequencies with a small spread greatly improved energy confinement in hot electrons.**
  - **Seen when frequency difference equal to warm electron bounce frequency.**
  - **Probably due to elimination of super-adiabatic effects that create phase-space barrier for further heating of hot electrons.**

Convective cells are a wild card.



- Do they exist?
  - Are they the nonlinear saturation of interchange modes?
- Do they degrade energy confinement?
  - Can we have high energy confinement with low particle confinement?
- Explore methods for driving and limiting

Convective cells are affected by single-pass absorption.

- **Currently envisioned system relies on “cavity-heating”.**
  - **Good results seen in CTX supported dipole experiment**
- **If single-pass absorption is high**
  - **Appears likely from ray-tracing code**
  - **Non-axisymmetric heating**
  - **Formation of convective cells**
- **High single-pass absorption + high density gradient**
  - **Poloidal current from ECCD**
  - **Magnetic shear reduces convective cells**
    - **Wisconsin Octopole**
- **Experimental knobs**
  - **ECCD control ?**
  - **Build axisymmetric ECRH launchers ?**
    - **Similar to EBT**

Heating of high-density plasmas requires different techniques.

- **With 28 GHz gyrotron, can heat to densities**

$$n \le 10^{19}\ \mathrm{m}^{3}.$$

- **Methods for heating over-dense plasmas to be explored:**
  - **ICRF**
  - **Mode conversion of ECRF into electron-Bernstein waves**
  - **Launching of whistler waves from the high field region**
  - **Modest-sized neutral beam**
    - **Good beam penetration possible in a reactor to inside of ring**

Future Work

- **Computational**
  - **Include more realistic profiles**
    - **Spline fits between multiple points to produce gradients**
    - **Experimental data could be included.**
  - **Interface with equilibrium solver**
    - **Allow for high-β equilibria**
  - **Combine relativistic effects with realistic electron distribution**
- **Experimental**
  - **Achieve first plasma**
  - **Bring many frequencies on line**

Summary

- **Two ray-tracing codes are now available for dipole equilibria.**
  - **Single-pass absorption is visible in both.**
    - **Small for low T_e (<100keV)**
    - **Large for T_e > 100keV**
  - **Multipass absorption ("cavity heating") is expected to be important in LDX plasmas.**
    - **Particularly for startup**
- **LDX will use multi-frequency ECRH for plasma formation/heating.**
  - **Profile control**
  - **Confinement studies**
  - **Possible convective cell formation**