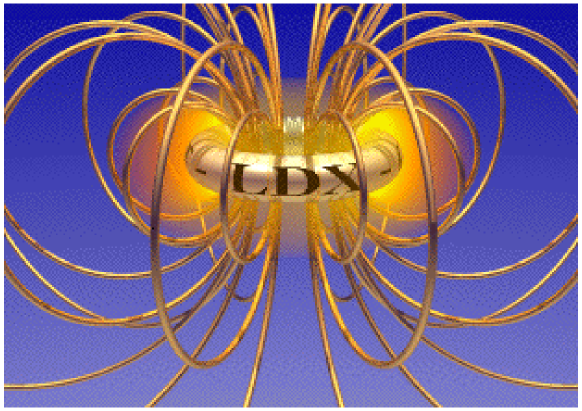

ECRH in the Levitated Dipole Experiment

D. Garnier, M. Mauel

Columbia University

J. Kesner

MIT Plasma Science and Fusion Center

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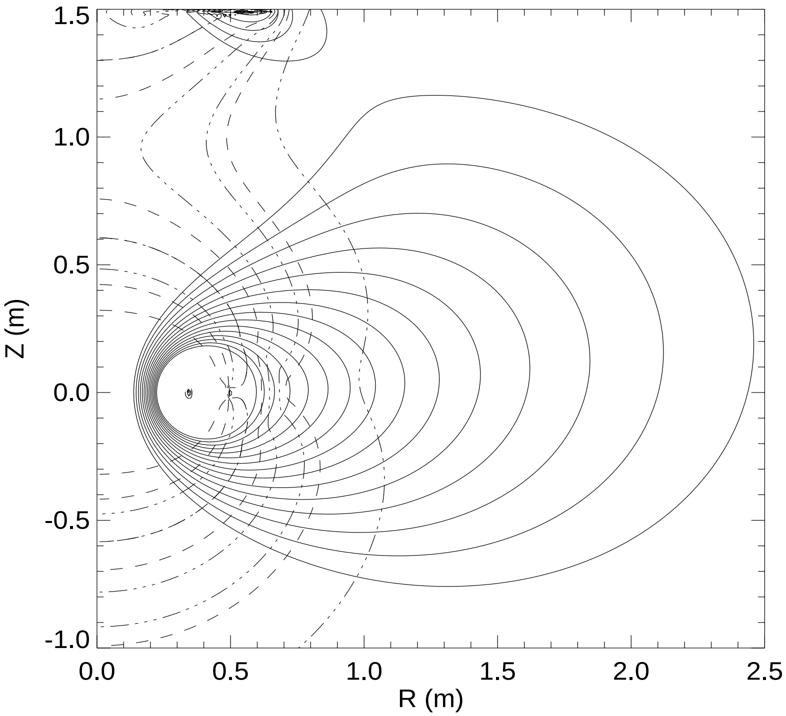
Abstract

In the initial phases of the Levitated Dipole Experiment (LDX), multiple frequency ECRH (with frequencies between 2.45 and 28 GHz) will be used to produce a population of energetic electrons at high–β. Use of multiple frequency ECRH in mirror experiments have shown a reduction in plasma turbulence and increased heating efficiency. The pressure profile will be controlled by adjusting the relative power of the ECRH sources. The effect of the pressure profile on plasma stability and confinement is a principal area of study for the LDX experiment. Other concerns for the use of ECRH within LDX, such as formation and control of convective cells and heating of over-dense thermal plasmas are also discussed.

Dipole Confinement



Computed LDX equilibrim showing plasma flux surfaces and elctron cyclotron resonant surfaces. The Equilibrium has a peak local beta $\beta \sim 2$and a flux tube average beta $<\beta>\sim 1$

- Toroidal confinement without toroidal field (no neoclassical effects)
- Stabilized by plasma compressibility
- Marginally stable profiles satisfy adiabaticity condition.
  - M.N. Rosenbluth and Longmire, *Ann. Phys.* **1** (1957) 120.
- Such plasmas are ideal ballooning stable
  - D. Garnier, J. Kesner and M. Mauel, submitted to *Phys. Plasmas* (1999)
- For $\eta \leq 2/3$ profiles, dipoles are also drift wave stable.
  - J. Kesner, *Phys. Plasmas*, **5** (1998).

Dipole Geometry

- Compressibility Condition
  - Stationary pressure profiles

$$\delta\left(pV^{\gamma}\right)=0$$

$$V \equiv \oint \frac{d\ell}{B}, \gamma = {}^{5}\!/_{3}$$

- Dipole Geometry

$$B \propto r^{-3} \Rightarrow V \propto r^{4}$$

$$\Rightarrow p \propto r^{-20/3}$$

$$\beta \propto \frac{p}{B^{2}} \propto r^{-2/3}$$

$$\eta \equiv \frac{L_n}{L_T} = 2/3$$

- Stationary *n* & *T* profiles

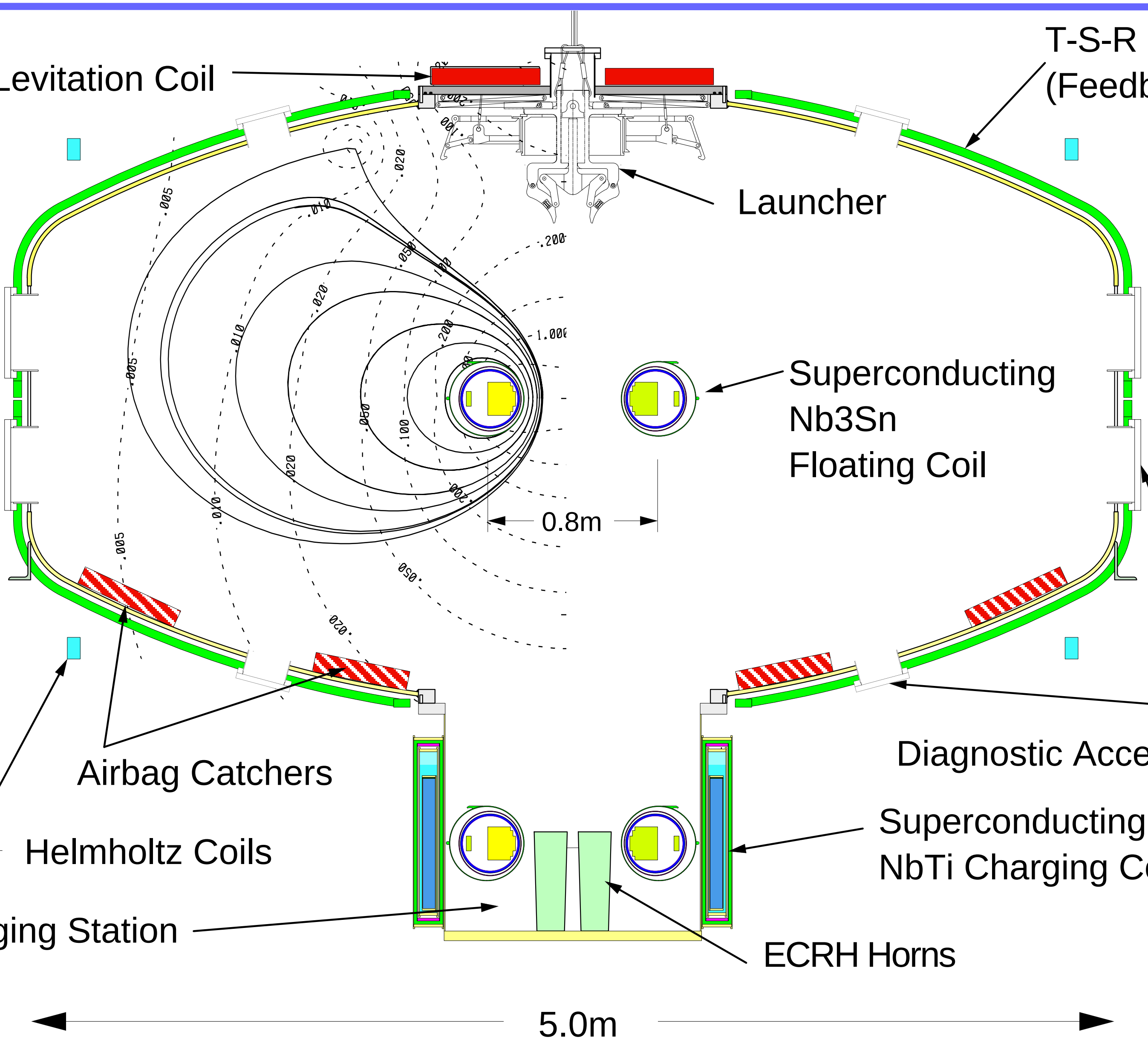
$$n \propto r^{-4},\; T \propto r^{-8/3}$$

- Scale Lengths
  - Dipole
  - Tokamak

$$R_c \approx \frac{r}{2},\; L_n \approx \frac{r}{4} \Rightarrow \frac{R_c}{L_n} \approx 2$$

$$R_c \approx \mathrm{R},\; L_n \approx a \Rightarrow \frac{R_c}{L_n} \approx \frac{R}{a} \approx 3-4$$

LDX Experiment Cross-section



Levitation Coil

T-S-R Coils
(Feedback)

Launcher

Superconducting
Nb3Sn
Floating Coil

Airbag Catchers

Diagnostic Access

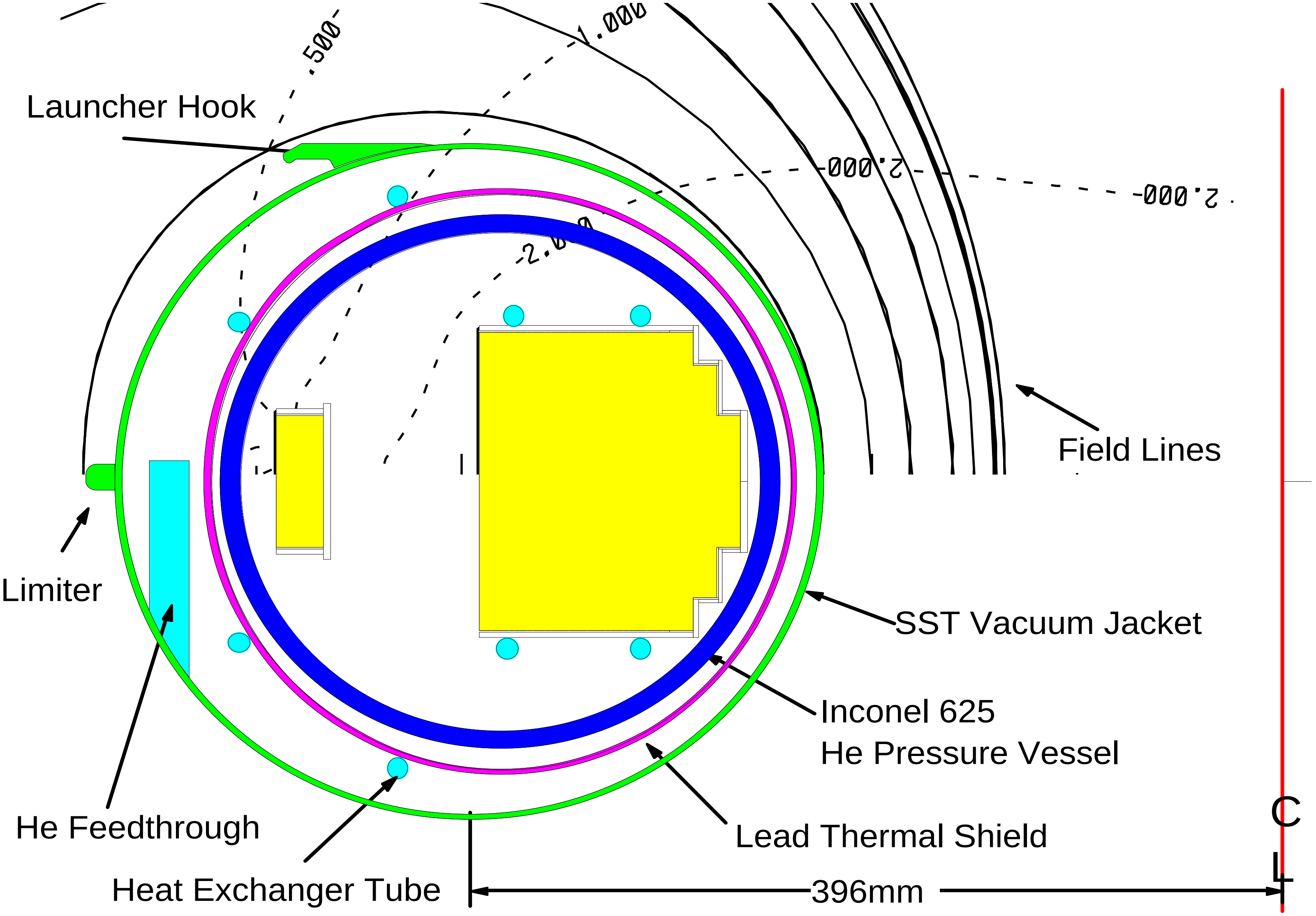
Helmholtz Coils

Superconducting
NbTi Charging Coil

Charging Station

ECRH Horns

LDX Floating Ring Cross-Section



Launcher Hook

Limiter

He Feedthrough

Heat Exchanger Tube

Field Lines

SST Vacuum Jacket

Inconel 625
He Pressure Vessel

Lead Thermal Shield

396mm

LDX Experimental Plan

- 3 Major Campaigns
- Supported Dipole Hot Electron Plasmas
    - Summer 2000
  - High- β Hot Electron plasmas with mirror losses
  - ECRH Plasma formation
  - Instabilities and Profile control
- Levitated Dipole Hot Electron Plasmas
    - Summer 2001
  - No end losses
  - β enhancement
  - Confinement studies
- Thermal Plasmas
  - Concept Optimization / Evaluation

Hot Electron Plasmas

- Supported Dipole Campaign
  - Low density, quasi steady-state plasmas formed by multi-frequency ECRH with mirror losses
  - Areas of investigation
    - Plasma formation
    - Density control
    - Pressure profile control
    - Supercritical profiles & instability
    - Compressibility Scaling
    - ECRH and diagnostics development
- Levitated Dipole Campaign
  - No end losses
  - Areas of investigation
    - Global Confinement
    - β enhancement and scaling

MFECH for Profile control

- Use multiple sources with different resonant zones to tailor the pressure profile to marginal stability
- Results from the ST-1 symmetric mirror
  - 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. Quon et al, *Phys. Fluids* **28**, (1985) 1503.
- Results from CTX supported dipole
  - Hot electron interchange mode “bursts” with only one source

Profile Control and Stability in ST-1

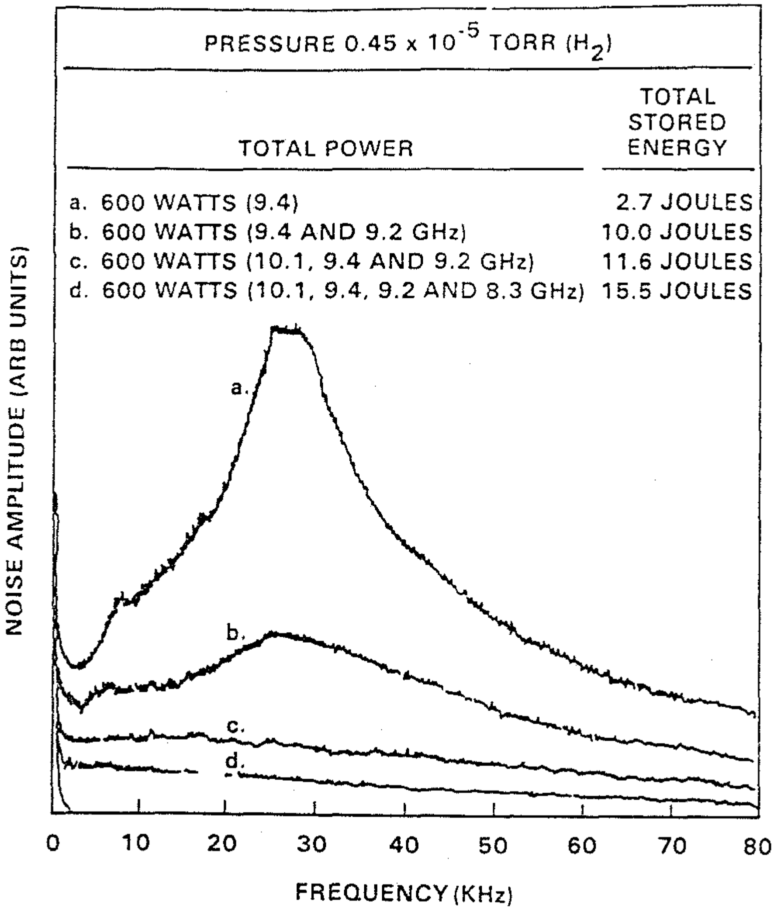
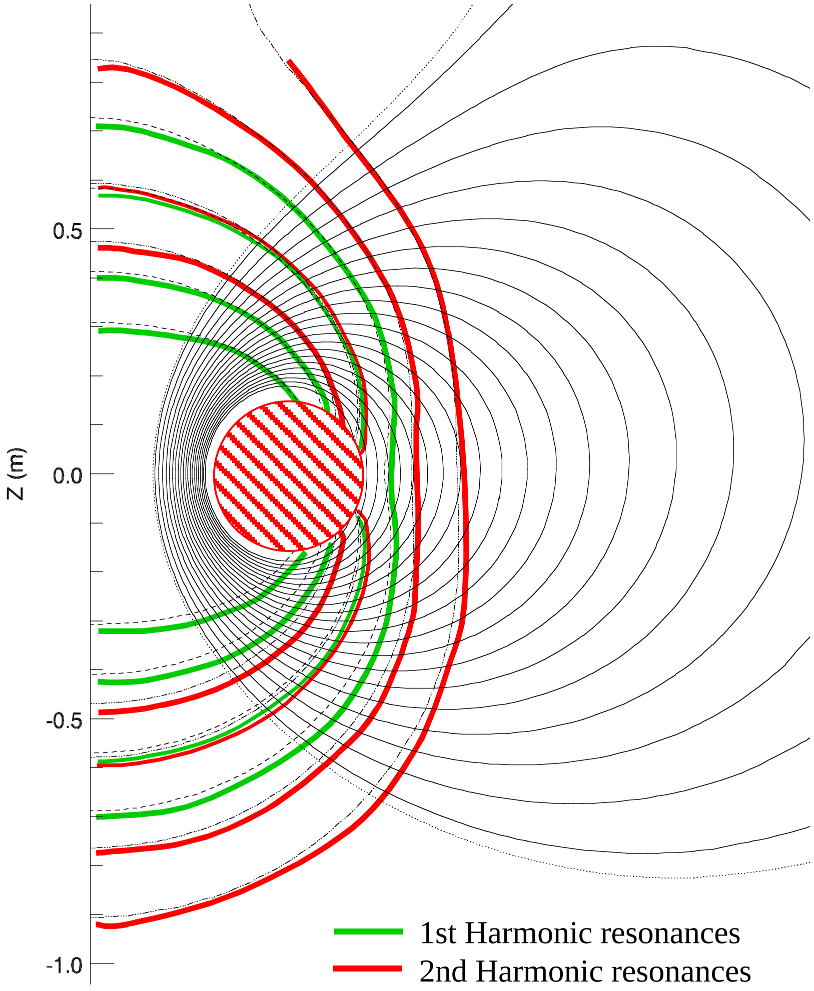


FIG. 11. Spectra of low-frequency fluctuations in the cold-electron end-loss current for four different heating configurations.

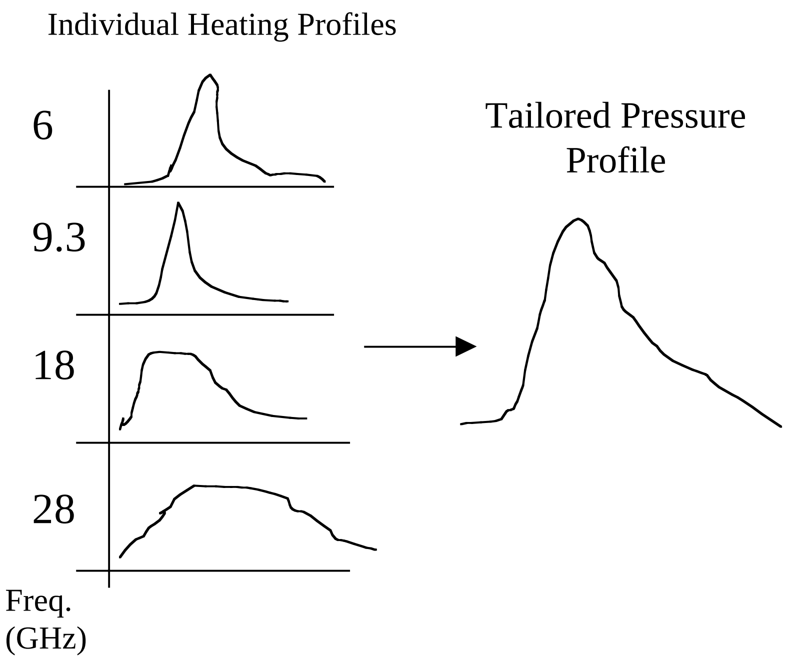
- Using multiple-frequency ECH in ST-1 symmetric mirror allowed stable operation
  - Reduction of low frequency fluctuation is cold electrons by order of magnitude
  - Increase in stored energy in high-β hot electrons
- Speculation that this was due to more stable hot electron ring profile

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

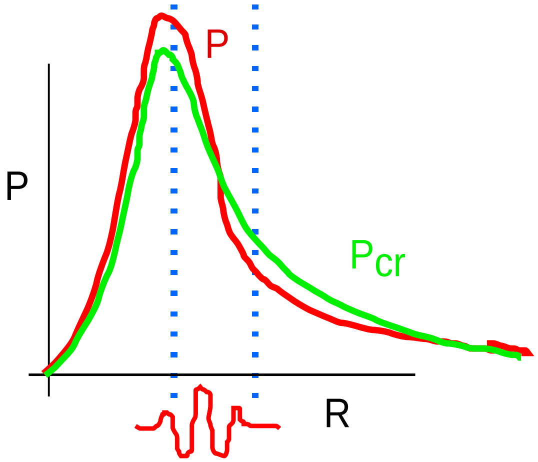
Profile Control

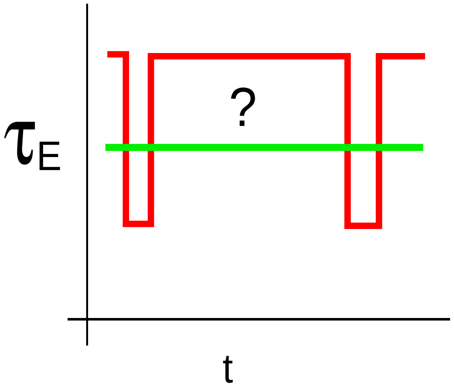


- Multi-frequency ECRH
  - Measure single frequency response
  - Tailor multi-frequency heating to ideal profile.

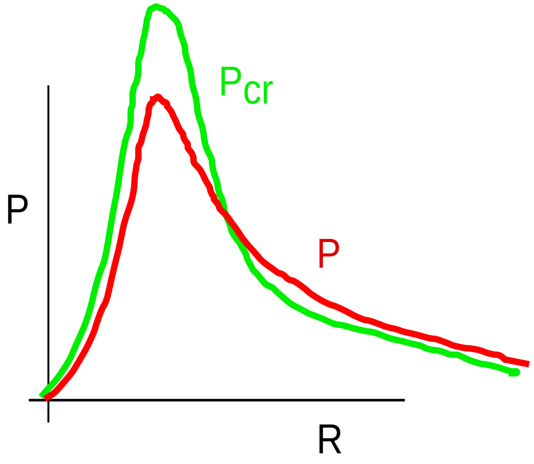


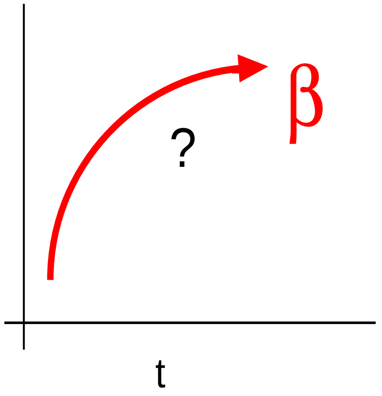
Instabilities & Confinement





- 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 for 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 ST-1
  - Effect greatest when frequency separation is equal to bounce time of warm electrons
- Results from EBT bumpy torus
  - Increase not seen, but EBT was believed not to have super-adiabatic effects.

MFECH efficiency in ST-1

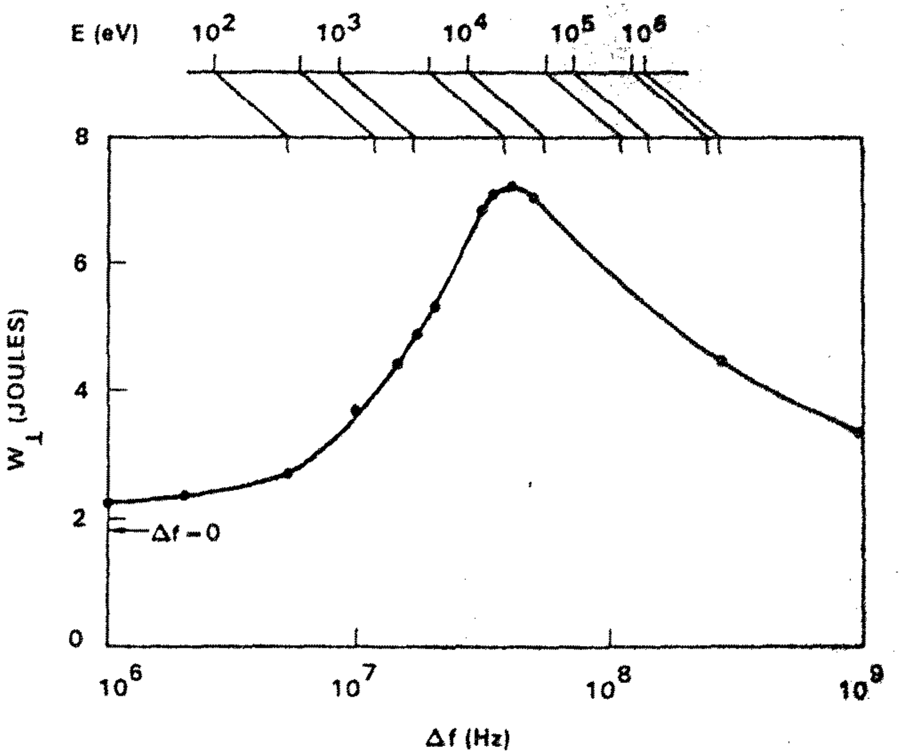


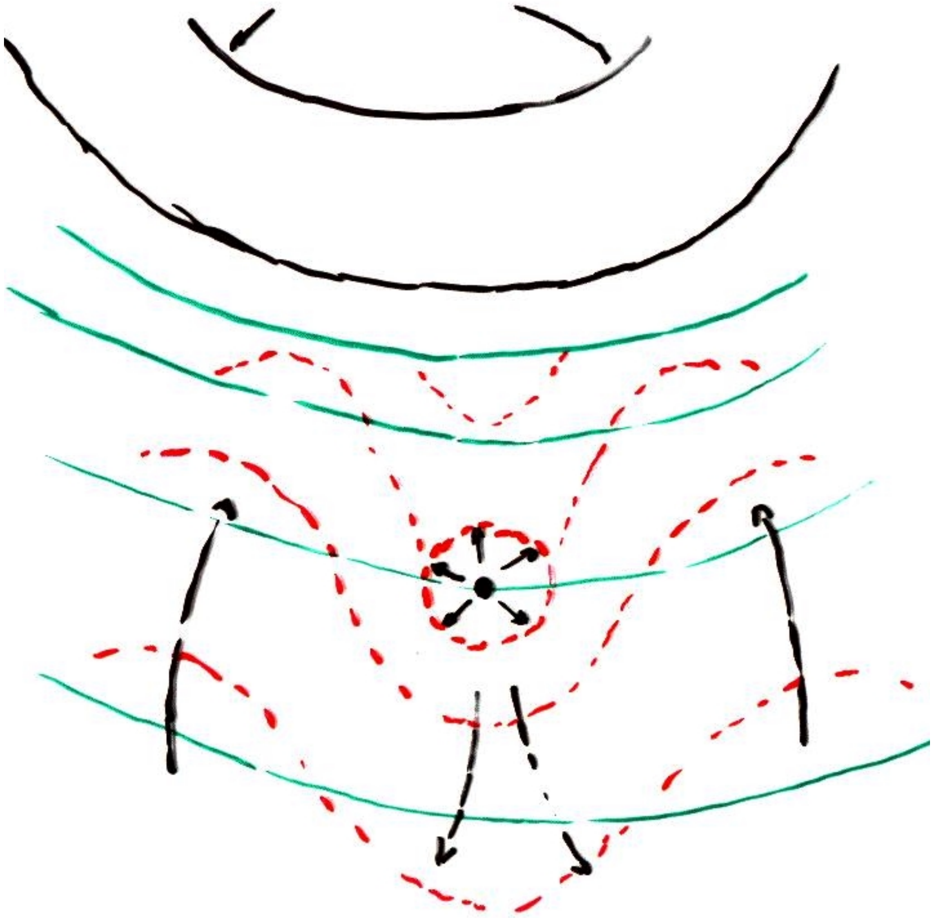
FIG. 9. Total stored energy as a function of frequency separation for two-frequency heating. The scale gives the electron energy for which the bounce frequency is equal to the applied frequency mismatch.

- Using 2 frequencies with small spread in frequencies 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.

Thermal Plasmas

- Transient thermal plasmas produced by gas puff or lithium pellet injection into hot-electron plasma
- Areas of Investigation
  - Thermalization of hot-electron β
  - Transient Transport
    - Instability driven transport during profile relaxation
  - Convective Cells
    - Investigate possibility of $\tau_p << \tau_E$
  - Heating of Over-dense Plasmas
  - Confinement of thermal plasmas
  - Concept Evaluation

Convective Cells



- 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 and Single-pass Absorption

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

Heating of high-density plasmas

- With 28 GHz gyrotron, can heat to densities

$$n \leq 10^{19}\ \mathrm{m}^{3}$$

- 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