ECRH in the Levitated Dipole Experiment[1]

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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 overdense thermal plasmas are also discussed.

INTRODUCTION

The Levitated Dipole Experiment (LDX), a joint Columbia/MIT project, is currently under construction at MIT. LDX will be the first concept exploration experiment to study the physics of plasmas confined by a levitated magnetic dipole. Such a plasma, stabilized by compressibility, should have near classical confinement with $\beta \sim 1$.

From ideal MHD, marginal stability for interchange modes results when the pressure profile, p satisfies the adiabaticity condition, $\delta(pV^\gamma) = 0$, where V is the flux tube volume ($V \equiv \oint d\ell/B$) and $\gamma = 5/3$ [1]. For a point dipole, this condition ($p \propto V^{-\gamma}$) leads to pressure profiles that scale with radius as $r^{-20/3}$. LDX equilibria that satisfy marginal stability for interchange are also stable to ideal ballooning modes at high β [2]. Furthermore, plasma that obeys this condition of a "gentle" profile compared to the magnetic curvature should also be stable to drift

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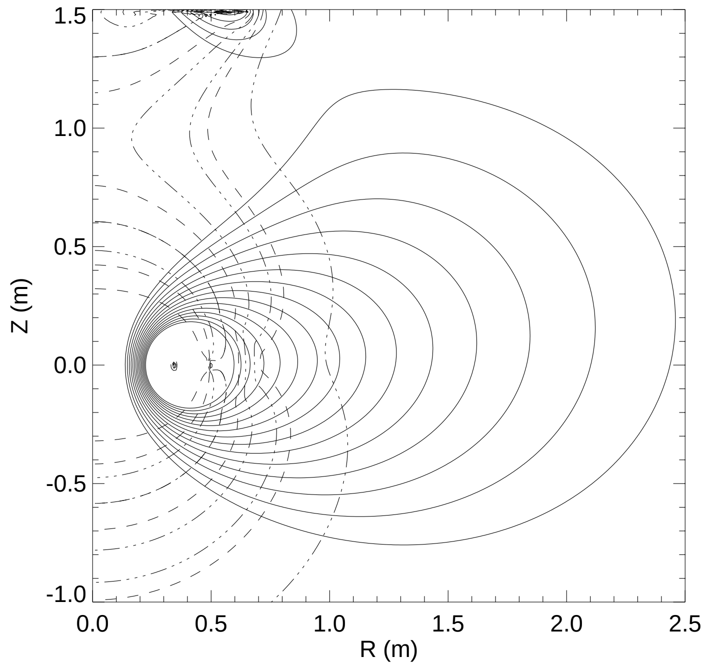

FIGURE 1. Computed LDX equilibrium showing plasma flux surfaces and electron cyclotron resonant surfaces. This equilibrium has a peak local $\beta_{local}^{peak} \approx 2$ and a peak flux tube average beta, $< \beta >^{peak} \approx 1$

wave turbulence [3,4]. Studying the effect of the pressure profile on plasma stability and confinement is a principal goal of the LDX experiment.

ELECTRON CYCLOTRON HEATING ON LDX

LDX has been designed to be a low cost experiment able to investigate the key physics of high-beta dipole confinement while simultaneously maintaining high confidence of its technical success. After careful consideration of several options for plasma formation and heating, we have chosen to use multiple frequency electron cyclotron heating (MFECH) which will allow greater control of the pressure profile and increased heating efficiency.

The combination of closed field lines and high beta makes the dipole an ideal geometry for creating a high beta, hot electron plasma by the application of MFECH. Such plasmas have been demonstrated in mirror machines with open field lines as well as in levitrons [5] and in the non-levitated dipole CTX experiment [6,7] at Columbia University.

The buildup of hot electron stored energy in CTX is observed to be limited by both the application of strongly localized heating which results in the pressure gradient exceeding a critical value as well as by the scrape-off of hot and warm electrons on the dipole's mechanical supports. These limitations should be eliminated when the dipole is levitated and when multiple frequency heating (in the range of 2.45 to 28 GHz) is able to broaden the pressure profile.

Radial Pressure Profile Control

In the SM-1 axisymmetric mirror, MFECH with widely separated frequencies ($\Delta f/f \sim 10\%$) greatly reduced the low frequency fluctuations in the cold electron population and increased stored energy in the hot electrons [10]. It was speculated that these results were due to improvements to the hot electron ring profile yielding an improvement in stability. Similarly, LDX will utilize MFECH to tailor the plasma pressure profile to enhance hot electron β and study instability and transport in super-critical profiles.

As shown in Fig. 1, in the dipole each resonant surface crosses nearly all field lines. The absorption of power into the plasma depends in detail on how a resonance surface crosses the flux surfaces. For example, one would expect that high frequency resonance surfaces (*e.g.* 28 GHz) intersecting the plasma near the "hole" of the dipole where the flux surfaces are compressed would show fairly uniform heating on all field lines. This would then lead to a pressure profile inversely proportional to the volume of each field line ($p \propto V^{-1}$) which is significantly less steep than allowed by the adiabaticity condition.

On the other hand, consider the lower frequency 6 GHz Ω_{ce} resonance where it crosses the midplane. One would expect preferential heating where the resonance surface is tangent to the flux surface due to the larger volume in the resonance zone. Thus, heating at lower frequencies will tend to steepen the pressure profile.

Therefore, by varying the power levels of the different frequency heating sources, we can adjust the pressure profile to maximize hot electron β.

MFECH for improved heating efficiency

Experiments in SM-1 [10] indicated that a substantial increase of stored energy was obtained in a hot electron plasmas when multiple frequencies were applied ($\Delta f/f \sim 0.1\%$). This result was seen when the frequency separation was an odd multiple of the warm electron bounce frequency, and was probably due to the elimination of superadiabatic effects [11] which can create phase space barriers during single-frequency heating. In LDX we will use this approach with our broad band klystron to improve heating efficiency and allow a control on the hot electron population.

Single-pass absorption and convective cells

Currently, we plan to couple the microwave power into the vacuum chamber through quartz windows using single mode waveguide relying on "cavity heating" to maintain axisymmetric heating. If the single-pass absorption is high, using this simple coupling method may lead to nonaxisymmetric heating and driving of convective cells. While the dipole may be a configuration where convective cells do not lead to enhanced energy transport [8], we may decide to construct a more uniform microwave radiator, perhaps like the manifold used on EBT.

Another consequence of high single pass absorption, coupled with the steep density profile of the dipole plasma, could be a significant amount of electron cyclotron current drive (ECCD). In the dipole, ECCD would drive poloidal currents generating a toroidal magnetic field. Since a small toroidal magnetic field suppressed convective cells in multipole experiments [9], poloidal current drive in LDX may provide a mechanism to switch off (and on) large-scale convective flows.

EXTENDED OPERATIONS

In the third phase of the LDX experimental plan, we intend to study higher density thermal plasmas with $T_e \sim T_i$. To achieve these higher density plasmas, we plan to use fast gas puffing and/or pellet injection to raise the density and thermalize the energy of the high-β hot electron population. These techniques will give a transient high density plasma whose β will depend on the efficiency of the thermalization process and the severity of the transient transport processes brought on by the cold neutral injection.

These thermal plasmas are too dense to allow heating by multiple-frequency ECRH, although 28 GHz heating of the high-field plasma will allow densities up to $\leq 10^{19}$ m^{-3}. To achieve higher densities, we are exploring other plasma heating techniques. These include ICRF, mode conversion of ECRF power into electron-Bernstein waves, launching of whistler waves from the high field region [12] and using a modest-sized neutral beam. Neutral beam heating may be ideally suited for a levitated dipole reactor since good beam penetration is possible from the edge to the core plasma in the high field region in the inside of the dipole ring.

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