Initial Results of Multi-Frequency Electron Cyclotron Heating in the Levitated Dipole Experiment

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Abstract. The Levitated Dipole Experiment (LDX) has created high-beta, hot-electron plasmas that are confined by a strong dipole electromagnet via multiple-frequency electron cyclotron resonance heating (ECRH). Multiple frequency ECRH is used to investigate how variation of the power deposition profile may be used to adjust the plasma density and pressure profiles. The initial experiments have been performed using up to 3 kW at 2.45 GHz and 3 kW at 6.4 GHz. Variations included switching on and off a single source while injecting constant power with the other source. We have also investigated the role of magnetic shaping, using external coils, on ECRH phenomena and plasma profile control. The preliminary results of these experiments will be presented.

Keywords: dipole confinement, electron cyclotron heating, superconducting magnet
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INTRODUCTION

The Levitated Dipole Experiment (LDX), a joint Columbia/MIT concept exploration experiment sited at MIT, has begun experimental operations (the first plasma was in August 2004), though the dipole coil has heretofore been supported mechanically rather than levitated.

Plasmas confined by a dipole field are stabilized by compressibility. From ideal MHD, it is expected that marginal stability for interchange modes will occur when the pressure, p, satisfies an adiabaticity condition: $\delta\left(pV^{\gamma}\right)=0$, where $V \equiv \oint \frac{d\ell}{B}$ is the incremental flux tube volume and $\gamma=\frac{5}{3}$ is the ratio of specific heats.[1] In addition, equilibria satisfying this criterion are also stable to ballooning modes.[2] For marginal profiles with $\eta \equiv \frac{d\ln T}{d\ln n}=\frac{2}{3}$, drift waves are stable as well.[3, 4] Other experiments, but not fusion-oriented, that confine plasma in dipole geometry are the CTX supported dipole[5] and the Mini-RT levitated dipole.[6]

A major goal of research on LDX is to study the effect of the pressure profile on the stability and confinement of the plasma. One of our main “knobs” to do this is electron cyclotron resonance heating (ECRH) at multiple frequencies. This has historically proven to be an effective means to create high β hot-electron plasmas in mirror machines,[7] levitrons,[8] and CTX.[5, 9]

ECRH SOURCES ON LDX

There currently are two ECRH sources in use for LDX. One is a Gerling magnetron, which delivers 3 kW of CW power at 2.45 GHz. The other is a Varian klystron, with a CW power output of 3 kW at 6.4 GHz.

The microwaves from each source are transmitted to the experimental vacuum chamber via waveguide runs of about 6 m. The antennae are inside the vacuum chamber, and are segments of waveguide that are cut an appropriate angle as maximize the transmission and minimize the directivity. LDX relies on a “cavity heating” scheme, i.e. small first-pass absorption and multiple reflections of microwaves from the vacuum chamber walls, which has the benefit of making the heating somewhat isotropic.

EXPERIMENTAL RESULTS

We will present initial results from two areas of investigation. One was to hold the nominal input power fixed and vary the amount put out by each source. The other involved chopping the power in one source on and off while the other source was held fixed, with and without an applied vertical field to change the plasma compressibility. We will focus on the gross macroscopic changes that are visible in a poloidal flux loop.

Fixed input power

Three cases were chosen for this experiment: (1) 3 kW on the 2.45 GHz source, (2) 3 kW on the 6.4 GHz source, and (3) 1.5 kW on both sources together. Data from one of the poloidal flux loops is shown in Fig. 1(a) for the three cases. Note that the firing time of the two sources was different for the case where both sources were used–the 2.45 GHz source was fired at 2 s into the discharge. Clearly, the amplitudes are different between the cases, with the 2.45 GHz-only case having the smallest value, and the combined case having the largest. Rise and decay time constants are shown as well; these were calculated via a nonlinear fit to the data assuming exponential behavior. The time constants in both the rise and decay phases satisfy $\tau_{2.45} < \tau_{2.45+6.4} < \tau_{6.4}$.

Modulation experiments

For these experiment, there are again three cases: (1) both sources are turned on together, (2) the 2.45 GHz source is held constant through the whole discharge with the 6.4 GHz source being chopped on and off, and (3) the 6.4 GHz source held constant throughout the discharge with the 2.45 GHz being chopped on and off.

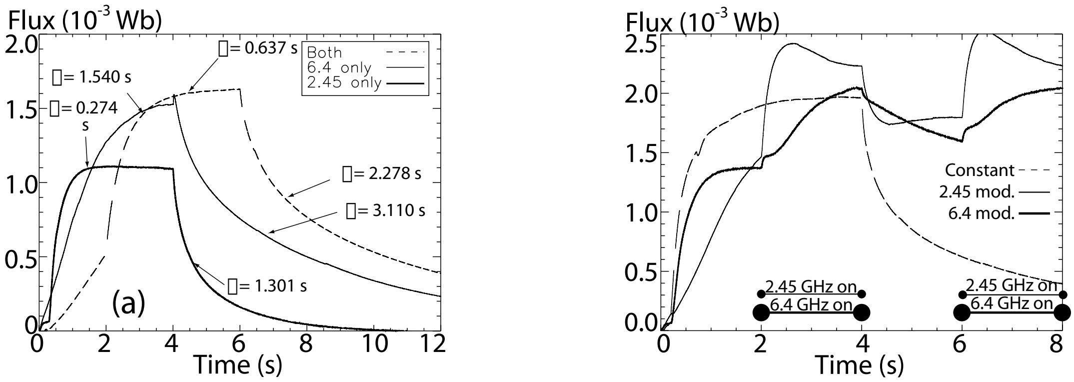

FIGURE 1. (a) Diamagnetic flux for discharges at nominally identical power. Exponential rise and decay time constants are shown (b) Diamagnetic flux for modulations of each source plus a control case. The periods when the modulated source are chopped on and off are shown below in the same linestyle.

No vertical field

Data from the 3 cases are plotted plotted in Fig. 1(b), with indicators in the same linestyle as each trace. Note that the programming for the discharge where both sources were fired concurrently had both switch off at 4 s, while the modulated cases switch off at 8s. Firing the 2.45 GHz source after the 6.4 GHz source results in a higher maximum flux than firing the two sources concurrently, and much higher than firing the 6.4 GHz source after the 2.45 has been on. It appears that the 3 traces are converging toward a similar value at t=4 seconds, at which time whichever source being modulated is shut off, so possibly if the 6.4 GHz were kept on longer than 2 s the flux might reach the same value as in the unmodulated case.

Vertical field applied

By applying an external field via a set of Helmholtz coils, we can dramatically change the volume encompassed by the last closed field line (Fig. 2 (a)), i.e. the confined plasma volume, which should change the plasma compressibility. The general behavior in such discharges is qualitatively similar to the prior results (Fig. 1(b)) until the applied external field is large enough, at which point the behavior shown in Fig. 2(b) occurs. Note that drops in the flux (1.5 s, 4 s) occur during the period in which both RF sources are on. This suggests that the pressure profile has crossed a stability boundary, and the sudden rise at 5 s presumably indicates crossing back to stability.

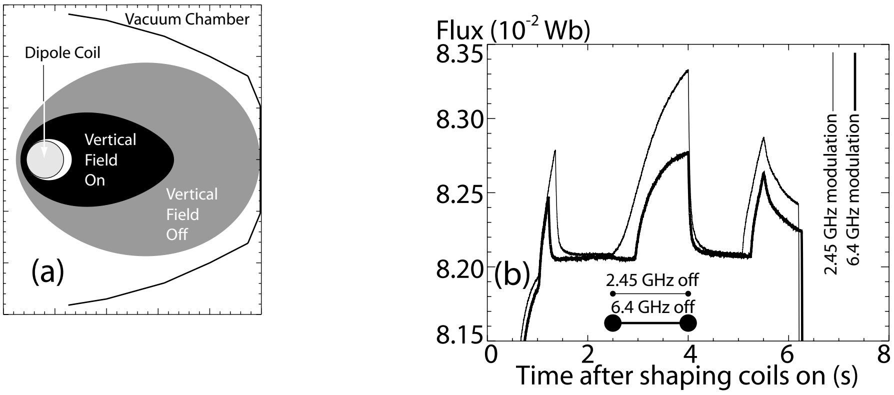

FIGURE 2. (a) Area within last closed field line without (gray) and with (black) applied vertical field. (b) Diamagnetic flux for plasma with a large shaping coil current and modulated RF input power (both sources). The periods when the modulated source are chopped on and off are shown below in the same linestyle.

FUTURE WORK

Our next immediate goal is to get an additional source (10 kW @ 10.5 GHz) online. Once that is done further optimization studies can be performed.

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