Observations and modeling of the electron cyclotron emission background in the Levitated Dipole Experiment

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Abstract. Hot electron cyclotron emission (ECE) measurements and modeling calculations have been carried out for the Levitated Dipole Experiment (LDX)⁵. Heterodyne radiometers at 110, 137 and 165 GHz have been used to view the plasma from bottom and midplane locations. An intense environment of harmonic ECE of up to 1 keV at 110 GHz and afterglow decay times of up to 6.9 seconds were observed at lower pressures. Interpretation of the emission levels in terms of hot electron parameters requires integrating modeled emission over a large magnetic field range of 0.09 to 3.2 Tesla and a k to B angular view range of 0 to 90° within the field of view of each receiver as the hot electron density peak is followed around a given flux contour. Hot electron temperatures of the order of 100 keV, depending on knowledge of the electron density peak location, were determined by taking the ratio of radiometer signals at different frequencies. Abrupt radial movements of the highly peaked hot electron density where evident, particularly with ECRH turn on and turn off.

1. Introduction

Hot electrons are a characteristic feature of electron cyclotron resonance heated (ECRH) plasmas [1-3]. The intense harmonic electron cyclotron emission produced can be exploited as a diagnostic of the hot electrons, but also presents a significant background for active probe aided diagnostics in the affected frequency range. Interest in developing such diagnostics is motivated by recent research of the magnetic dipole field configuration, like that observed around planets, as an alternative confinement concept for fusion energy. A magnetic dipole based fusion reactor would use a He³ catalyzed D-D fuel cycle that would minimize the power by neutrons and would not require external tritium production [4]. Levitated coil remote power refrigeration may be feasible in a reactor size levitated device. Free floating superconducting magnetic dipole experiments are operating at MIT/Columbia, LDX [5], and University of Tokyo, RT-1 [6].

LDX uses a free floating 1.1 MA, 68 cm mean diameter, 560 kg superconducting coil (F-coil) in a large 5 m diameter vacuum chamber [7]. The plasma is confined on the outside of the current carrying coil rather than inside a set of coils as in most other magnetic confinement devices. The F-coil is routinely floated by a for up to 3 hours between cryogenic recoolings by a 280 kA lifting coil (L-coil)

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⁵ http://www.psfc.mit.edu/ldx/
during which time plasmas are pulsed by ECRH. Up to a total of 17 kW power from four sources: two at 2.45 GHz (2.5 kW and 1.9 kW), one at 6.4 GHz (2.5 kW), and one at 10.5 GHz (10 kW) are pulsed to sustain plasmas for up to 14 s with a slowly decaying afterglow that can be detected for up to 25 s at lower densities after all plasma sustaining sources are off. Line averaged electron densities of up to 2 \times 10^{11} \text{ cm}^{-3} with highly peaked profiles (~1/r^4) are diagnosed with a diagnostic set that includes a 4-channel 60 GHz interferometer.

2. Analytical Basis

It is assumed that the hot electron ECE can be represented by blackbody intensity $I_{BB}$ at a single temperature even if the electron distribution is not Maxwellian in which case the temperature is then specific to the ECE measurement parameters. If the radiation transport is also optically thin, then emission intensity $I_\omega$ detected by each radiometer with frequency $\omega$ over path length $s$ can be expressed by [8]

$$I_\omega \approx I_{BB} \alpha_\omega s$$

(1)

where $\alpha_\omega$ is the ECE absorption coefficient that is a function of frequency, magnetic field vector amplitude and direction, and electron density and temperature. Here we use the expression for $\alpha_\omega$ given by Nassri and Heindler equation (2) [9]. In interpreting ECE in the present experiment it is necessary to integrated over a wide range of harmonics and view angles observed simultaneously by each fixed frequency radiometer. This is different from previous ECE diagnostic experience where typically only one harmonic at one view angle is observed at a time. The viewing geometries used in LDX are illustrated in figure 1 showing the diffraction limited 1/e^3 Gaussian beam antenna views at 137 GHz superimposed on the flux contours. A highly peaked plasma, limiting $s$ to a few cm, follows along an inner flux contour going through the outer midplane at < 80 cm horizontal. Along this flux line the B field strength can vary from as low as 0.09 on the outside to as high as 3.2 Tesla on the inside. The angle of B to the view $k$ varies from being parallel to perpendicular. A partial obstruction of the vertical view by the bottom F-coil catcher is not shown [7].

Figure 2 shows a calculated ECE harmonic spectrum for the bottom view at 137 GHz summed over both x and o components and weighted by the Gaussian receiver antenna pattern. The lower harmonics dominate the emission even when they occur in the outer fringe region of the radiometer field of view. This is particularly true at the midplane where the upper and lower edges of the view contribute most.

![Figure 1. 137 GHz millimeter-wave radiometer fields of views in LDX from the bottom and midplane (F: F-coil).](image1)

![Figure 2. Calculated ECE spectrum at 137 GHz viewing from the bottom in LDX for several electron temperatures.](image2)
3. Experimental Setup
The ECE background in LDX was explored over several plasma campaigns using heterodyne radiometers at 110, 137, and 165 GHz singly and in combined pairs for the two viewing geometries shown in figure 1. The receivers had double sideband noise temperatures (DSB) of 2000 to 3000 K and the same 3 GHz DSB IF electronics. Small signal calibration was accomplished with liquid nitrogen and room temperature blackbody sources (eccosorb) and the IF detector and dc amplifier calibrated response was extended to a 40 dB dynamic range using a microwave source that was measured by an Agilent E4418B Power Meter. Figure 3 shows how pairs of radiometers were combined on one view port to have an identical field of view within the limit of diffraction. The scalar horn output of the receivers was combined in wide bandwidth 20 mm diameter circular corrugated waveguide with a quartz beamsplitter. Then the waveguide diameter was expanded to either 29 mm or 35 mm for launching the HE_{11} mode view into LDX through calibrated fused quartz windows over a free space distance of the about 2.5 m to the plasma. The plasma does not fill the radiometer views so the reported temperatures here are lower limits of the local emission.

4. Results
An example of the ECE observed vertically from below LDX at a horizontal radius of 28 cm in a D_{2} plasma with a line averaged peak plasma density of 0.8 x 10^{11} cm^{-3} is shown in figure 4. A total of 15 kW of ECRH was applied as indicated by the bars in the lower left corner. The ECE increases with ECRH power and peaked at radiometer detected temperatures of 300/135 eV for 137/165 GHz, respectively. A long afterglow after all sustaining power is turned off was detected for over 25 s with a 1/e decay time of 6.9 s. Background pressure was 3.6 x 10^{-7} Torr. This afterglow decay is similar to that observed in the levitated spherator [1] and also depends exponentially on background pressure in LDX.

The ECE was observed to peak at 900/330 eV for 110/137 GHz, respectively for both radiometers paired at the midplane view as shown in figure 5 for a D_{2} plasma with a line average density of 1.6 x 10^{11} cm^{-3}. In this case it was possible to determine the hot electron temperature by taking the ratio of the two radiometer signals to cancel out the dependence on electron density and path length s. However, knowledge on which flux contour the density peaks is required. Two assumptions are shown in lower figure 5. The absolute temperature is sensitive to location, but the transient features do not change. For the plotted inner position, the hot electron density initially increases to about 130 keV in the first second and then decreases as the density builds up with more ECRH power. Transient displacements of the radial position of the hot electron peak are evident, particularly with ECRH switch on and off, supporting the assumption that the hot electron profile is highly peaked. In the
afterglow the apparent increase in hot electron temperature to 200 keV could be explained by both the preferential loss of cold electrons and the inward radial displacement of the density peak.

The contribution of internal reflections to the measured signals is an important question that can affect the interpretation. Measurements made by two near identical 137 GHz radiometers from below and at the midplane are shown in figure 6. The ratio of the calibrated signals from these two radiometers is in not 1 as would be expected for uniform reflective emission distribution. The contrast goes as high as a factor of 5 during plasma transients. The vertical view radiometer sees the inner dipole region, which is blocked from the midplane view. The increasing ratio at turn on is due to the warming up of the electrons. At turn off, the much higher ratio increase may be an indication of an additional transient imbalance in the electron distribution between inner and outer regions.

This investigation of the harmonic ECE in LDX shows that an intense background is present in levitated magnetic dipole plasmas, and that useful localized interpretation of the hot electron parameters are possible despite the large magnetic field gradient and orientation variation present. Active millimeter-wave and terahertz probe diagnostics would need to consider this radiation.

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