CHARACTERIZATION OF THE MICROWAVE COUPLING TO THE PLASMA CHAMBER OF THE LBL ECR ION SOURCE

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Abstract

The characteristics of the microwave coupling of the 6.4 GHz LBL ECR ion source were measured as a function of frequency, input power, and time dependence. The time dependence of the plasma diamagnetism and plasma loading of the ECR chamber were compared. The cavity modes in the LBL ECR plasma chamber are fairly widely spaced which makes it possible to locate frequencies, where a single RF mode is predominately excited. For one of these modes we were able to demonstrate that with no plasma in the cavity it is over-coupled. As the power is increased, the plasma density and the plasma loading both increase and the cavity becomes under-coupled. The experiments demonstrate that even for this low frequency, low plasma density source, the plasma loading strongly lowers the Q and the RF stored energy as the plasma builds up.

INTRODUCTION

The LBL ECR plasma chamber, which has a diameter to wavelength ratio of only 2, is not as over moded as many higher frequency ECR ion sources. This makes it possible to locate frequencies, where a single RF mode is predominately excited. In Table 1 the mode distribution between 6.2 and 6.5 GHz for the source is shown. This is approximate since it is based on a model with cylindrical geometry and the LBL ECR has a sextupole shaped chamber.[1] Using model calculations and accounting for dipole and multi-pole modes there are about 94 modes between 6 and 7 GHz or an average mode spacing of 10 MHz. In contrast a large high frequency source such a VENUS at 28 GHz has a mode spacing of roughly 26 kHz, which means no possibility to see quasi single mode excitation.

Table 1: Calculated Modes in the LBL ECR Plasma Chamber

Mode	**Frequency in GHz**
TM$_{01,16}$	6.236
TE$_{4,1,9}$	6.317
TM$_{0,2,8}$	6.325
TE$_{1,2,9}$	6.330
TE$_{3,1,13}$	6.339
TE$_{2,1,10}$	6.353
TE$_{0,1,14}$	6.362
TM$_{1,1,14}$	6.362
TE1$_{,1,17}$	6.374
TM$_{0,2,9}$	6.496
TE$_{4,1,10,}$	6.507

The LBL ECR can be analyzed as a transmission line terminated by a single port resonant cavity. The measurable variables are the frequency, incident power level, and the reflected signal. In this analysis, we treat the case of a single mode cavity or, equivalently, a multi-mode cavity where the modes are sufficiently separated with respect to their frequency response that they can be treated as a single mode cavity over a small delta in frequency.[2] This approximation works best at zero or low plasma densities in the source when the cavity Q is high. At higher plasma densities where the plasma loading increases the modes overlap and the approximation breaks down.

In a single port cavity the incident and reflected power can be measured. These data can be used to compute the adsorbed power and the coupling coefficient, β, which can be expressed as

$$\beta = \frac{\sqrt{P_i} \mp \sqrt{P_r}}{\sqrt{P_i} \pm \sqrt{P_r}} \tag{1}$$

where P_i is the incident power and P_r is the reflected power. The choice of sign depends on whether the cavity is under coupled (upper sign) or over coupled (lower sign).

The coupling coefficient can be written alternatively as

$$\beta = \frac{Q_0}{Q_{ext}}, \tag{2}$$

where Q_{ext} is the external Q-value of the cavity. For a single mode Q_{ext} is a constant dependent on the geometry of the coupling port and the electromagnetic distribution of the mode. In this paper, the calculation of the Q_0 includes all of the power adsorbed inside the cavity, whether it is due to the resistive walls or plasma adsorption.

The electromagnetic energy stored in the cavity (EM-fields), U, can be calculated from

$$U = \frac{Q_0 P_a}{\omega} = \frac{Q_{ext}}{\omega} \beta P_a, \tag{3}$$

in which P_a is the absorbed power (reflected power P_r subtracted from the incident power P_i) and ω the microwave (angular) frequency. It follows that the energy stored in the EM-fields at any given time (plasma density), normalized with respect to the empty cavity value, can be written as

$$\frac{U_t}{U_{t=0}} = \frac{\beta_t\left(1-\left(\frac{P_r}{P_i}\right)_t\right)}{\beta_{t=0}\left(1-\left(\frac{P_r}{P_i}\right)_{t=0}\right)} \qquad (4)$$

Equation 4 is written as a ratio because in these measurements it was not possible to directly measure or calculate Q0 although it can be estimated from the band width of the modes observed when dependence of the reflected power is plotted versus frequency.

EXPERIMENTAL MEASUREMENTS

For these measurements an adjustable microwave oscillator was used to drive a Varian klystron over the bandwidth of one of its channels, which are roughly 40 MHz wide. A small region of frequency between 6.34 and 6.37 GHz was measured in detail in the vicinity of the normal operating frequency for the source. In Fig. 1 the ratio of reflected to incident power is plotted without plasma and for 1, 2, 3, and 5 Watts of incident power. At these low powers, which are just enough to initiate a low density plasma, the effects of the plasma loading on the coupling coefficient can be observed. For example for the mode at 6.346 GHz, the reflected power at resonance first decreases between no plasma and 1 W, then increases. This indicates that with no plasma the cavity is initially over coupled and β is greater than 1. At 1 W it is close to unity coupling and it becomes more and more under coupled (β <<1) as the power is increased to 5 W. Two other changes occur as the plasma density increases with power. First the width of the resonance increases indicating increased plasma loading and the center frequency shifts up roughly 2 MHz, due to the change in the dielectric coefficient of the plasma.

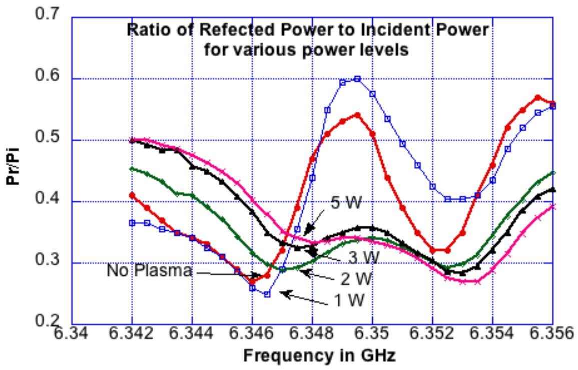

Figure 1: The reflected power ratio versus frequency at low RF incident power.

In Fig. 2 the reflected power ratio is shown for various powers between 40 and 250 W. Here the modes begin to overlap as the loading increases, but still the reflected power ratio continues to increase with incident RF power indicating that both Q_0 and β are decreasing.

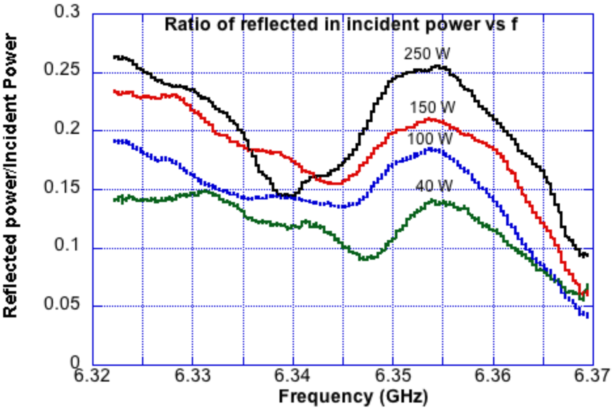

Figure 2: The reflected power ratio versus frequency for P_i from 40 W to 250 W.

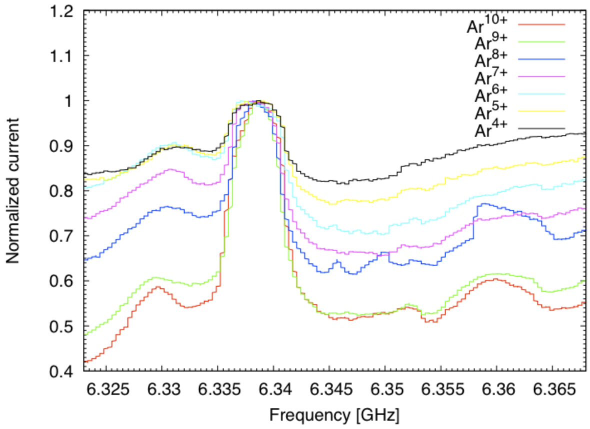

Figure 3: Ion currents for argon, normalized to their maximum value, as a function of frequency at 250 W incident power.

Figure 3 illustrates that for 250 W of incident power the production of high charge states is optimized at 6.337 GHz. For each charge state, the currents were normalized to1.0 at 6.337 GHz. For $Ar^{9+}$the beam current increases by a factor of two at the optimum frequency. This illustrates that outside a narrow frequency range of 5 MHz, the coupling efficiency between the RF modes and the plasma electrons decreases rapidly.

The response of the reflected to incident power ratio was measured as a function of time to study how the plasma build up affects the coupling microwave power to the plasma chamber cavity. The RF was switched on and the reflected power versus time was measured. The Q of this ECR chamber is relatively low and the microwave filling time is on the order of a µs, which is much faster than the times needed to build up plasma. The t = 0 time used below is a few µs after the RF is switched on when the RF field reaches its maximum value without plasma.

This is illustrated in Fig. 4 where the reflected power and the signal from the plasma diamagnetism loop are plotted versus time. The initial high reflected power drops to a minimum at 2ms as the coupling approaches unity and then increases as the plasma density grows. It reaches approximate equilibrium at roughly 3 ms. As the cavity goes from over coupled to under coupled the reflected power does not go quite to zero at unity coupling indicating an imperfect coupling network. However, it is clear from Fig. 4 that the loading increases quasi-monotonically with time and the Q decreases out to at least 3 ms. The diamagnetic loop signal on the other hand is proportional to the rate of change of the plasma diamagnetism (rate of change of plasma energy content), which peaks at about 3 ms. The integral of the loop signal is proportional to the plasma diamagnetism (plasma energy content) and following an apparent saturation in plasma density at 3 ms it continues to increase slowly implying that the hot tail of the electron energy distribution increases. This has little effect on the RF adsorption.

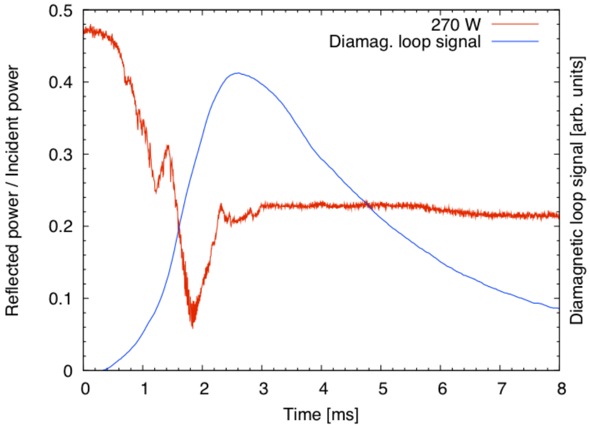

Figure 4: Reflected power ratio and the diamagnetic loop signal after RF turn on.

In Fig. 5 the electromagnetic energy of the microwave fields, normalized to the field at t=0, is plotted vs. time for slightly different conditions than Fig. 4. To compute the relative stored energy vs. time the measured values of Pr and Pi were used to compute the quantities in Eq. 4. The rapid drop at 5 ms is an artifact of the calculation of β near unity coupling where, as noted earlier, imperfections in the coupling network prevent the reflected power from going to zero at unity coupling. Fig. 5 shows the microwave stored energy reaches a maximum at turn on when there is no plasma loading and then decreases rapidly as the plasma density rises and loads down the cavity. Since the microwave electric field strength is proportional to the square root of the stored energy, it also decreases as the plasma builds up. A similar analysis showed that at 3 ms the Q_0 with plasma has decreased to only 10% of the initial Q_0 with no plasma.

A rough estimate of the Q_0 without plasma was made by using the full width half maximum values for the resonance width without plasma in Fig. 1. The Q_0 without plasma is 3000 to 5000 and as described above the Q_0 with plasma drops to one tenth that value.

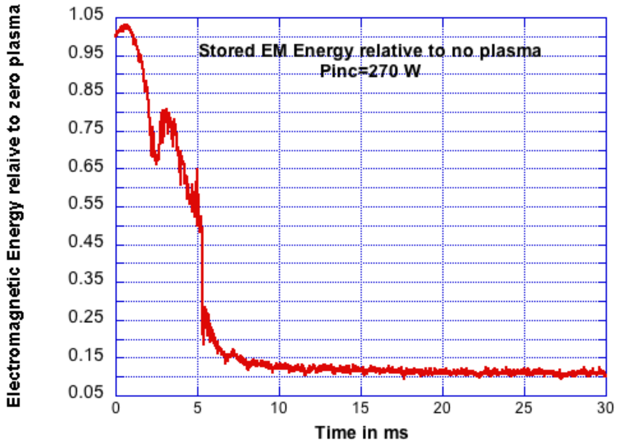

Figure 5: Relative stored power versus time calculated using Eq (4).

DISCUSSION

There are a number of models used to simulate the ECR heating of electrons in the plasma.[3] The two poorly understood inputs to these simulations are the microwave field distribution or mode and the strength of the RF electric fields. While the method described here is not applicable for highly over moded cavities, it is a reasonable approximation for the LBL ECR. With further effort and cold testing on the bench it would be possible to identify the modes excited, the zero plasma Q and then make very solid estimates of the RF electric fields. In any case, these measurements demonstrate that there are high RF fields only at the onset of an RF pulse and these fields are rapidly reduced by the plasma loading. For higher frequency sources, where the plasma density is much higher, the plasma loading will be even stronger and further damp the electric field strength.

Finally, these measurements indicate that the LBL ECR microwave coupling could be improved by using a waveguide directly inserted in the plasma chamber to increase the coupling strength, thereby making it similar to the coupling used on the AECR-U and VENUS sources.

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