MEASUREMENT OF THE DIAMAGNETIC CURRENT ON THE LBNL 6.4 GHz ECR ION SOURCE

J. Noland#, J. Benitez, M. Kireeff Covo, D. Leitner, C. Lyneis, LBNL, Berkeley, CA 94720, USA.
J. Verboncoeur, Department of Nuclear Engineering, UC Berkeley, Berkeley, CA 94720, USA.
O. Tarvainen, Department of Physics, University of Jyvaskyla, Jyvaskyla 40500, Finland.

Abstract

A method of measuring the diamagnetic current on the LBNL 6.4 GHz ECR ion source is described. The diamagnetic signal is proportional to the rate of plasma formation and decay. Furthermore, the integrated signal can be used to estimate the total plasma pressure, or energy density, and can thus be used to study the warm and hot electron populations in an ECR plasma.

INTRODUCTION

ECR ion source (ECRIS) plasmas are capable of creating large amounts of high energy x-rays[1]. These x-rays present hazards to personnel and can add a substantial heat load to the cryostat of superconducting ECRIS's. As the heating frequency is increased, the problem will only worsen. In order to understand the production of x-rays in ECRIS plasmas, it is important to understand the electron heating mechanism, as it is the high energy electrons that are responsible for the creation of penetrating x-rays.

One common, non-invasive, high temperature plasma diagnostics that can be used to study high energy electrons is measurement of the plasma diamagnetic current. This diagnostic has been successfully applied to ECRIS plasmas previously[2]. Plasma diamagnetism is related to the energy density of all charged particles in the plasma. In a typical ECRIS plasma, though, the diamagnetic currrent is dominated by warm and hot electrons[3].

This paper describes the methods used to record diamagnetic signals on the LBNL 6.4 GHz ECRIS[4]. First,the theory of plasma diamagnetism is briefly discussed. In the second section of the article we discuss the diamagnetic loop experimental setup. Finally, examples of typical diamagnetic current measurements made over the course of our study are shown.

PLASMA DIAMAGNETISM

Charged particles orbit around magnetic field lines in such a way that the magnetic field created by their motion opposes the externally applied magnetic field. If a plasma is uniform, i.e., no density or temperature gradients, then the currents created by neighboring charged particles will cancel, and no net current will exist. If, on the other hand, gradients are present in a plasma a net current can arise. This macroscopic current creates a magnetic field that acts to decrease any external magnetic field, and is thus called a “diamagnetic” current. A common method of

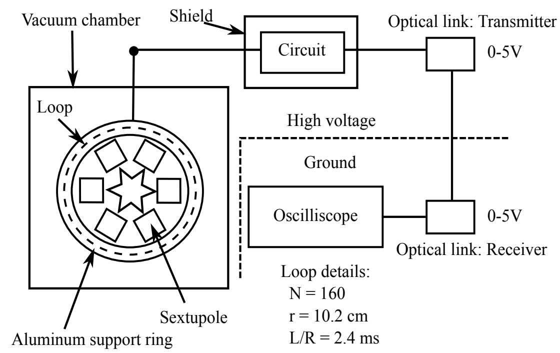

Figure 1: Experiment setup of diamagnetic loop used for plasma energy density measurements.

measuring the diamagnetic current is to use a loop of wire that is wrapped around the plasma chamber.

As the plasma in an ECR ion source forms or decays, the changing diamagnetic current creates a time varying magnetic field that opposes the steady, external magnetic field. By Faraday's law, an electric field is created. The electric field is responsible for creating a voltage across the leads of the diamagnetic loop, which is what is ultimately measured.

The electromotive force (emf) in the diamagnetic loop can be written:

$$\epsilon = -N \frac{d\phi}{dt}, \qquad (1)$$

where N is the number of turns in the diamagnetic loop, and Φ is the total magnetic flux passing through the loop. Starting with Eq. 1, the following equation relating the integrated diamagnetic signal to the plasma pressure can be derived [5]:

$$\int^{t} \epsilon_P \, dt = \frac{\pi \mu_0 r_0^2}{B_0} nkT, \qquad (2)$$

where r_0 is the plasma radius, and nkT is the plasma pressure due to all particles in the plasma. To arrive at this equation it is assumed that the velocity distribution is isotropic so that the pressure tensor reduces to a scalar, that the plasma can be represented by the ideal MHD equilibrium equation, and that the density profile is given by:

$$n = n_0 \exp\left(-(r/r_0)^2\right). \qquad (3)$$

#jdnoland@lbl.gov

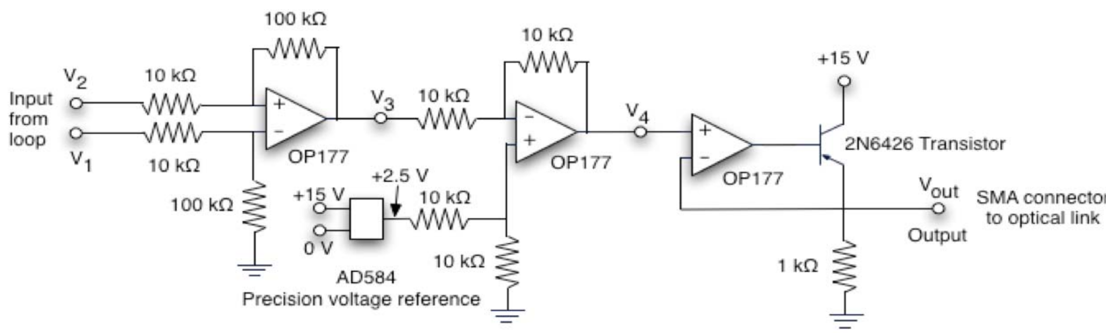

Figure 2: Diagram of circuit used to process diamagnetic loop signal.

EXPERIMENTAL SETUP

The experimental setup used to measure the diamagnetic signal is shown in Fig. 1. The diamagnetic loop is located within the vacuum chamber of the ECR. It is wound upon an aluminum support ring, which is, in turn, placed onto the sextupole structure. The leads of the diamagnetic loop are brought out of the vacuum chamber with a feed through. The loop and aluminum support ring are in electrical contact with source, and so float up to high voltage as the extraction voltage of the source is increased.

The raw signal from the loop is processed by a circuit, described in greater detail in the following section. Both the external portion of the feed through and the circuit are contained in an aluminum enclosure to prevent pick up of external noise.

To bring the diamagnetic loop signal outside of the high voltage cage that surrounds the ECR, a fiber optic cable is used. The processed signal from the circuit is first sent to an optical transmitter through an SMA cable, and then to the optical receiver through the fiber optic cable. Finally, the signal is sent to an oscilloscope where it is saved to a Compact Flash card. To reduce noise in the signal the averaging feature of the oscilloscope is used. For each data point, 128 microwave power on/off cycles are averaged. The data is processed on a PC using a simple Mathematica notebook. We can estimate the plasma energy density using Eq. 2.

Figure 3 shows the approximate location of the aluminum support structure upon which the diamagnetic loop is wound. The loop itself is made of magnet wire and is circular with an approximately square cross section (1.27 cm by 1.27 cm). It has a mean radius of approximately 10.2 cm and has 160 turns. The resistance of the loop is approximately 4 ohms, and its inductance is approximately 9.7 mH. The time constant of the loop (L/R) is thus approximately 2.4 ms. We expect, then, the diamagnetic loop will be able to follow changes in plasma energy density that occur on time scales greater than approximately 10 ms.

Loop circuit

Figure 2 shows a diagram of the circuit used to process the diamagnetic loop signal. The circuit consists of three major sections: a differential amplifier, a level shifter, and, finally, a driver section, required to power the analog optical link transmitter. The circuit does not have an analog integrator, as we have chosen to perform the integration on a PC.

The final output voltage of the circuit is given by:

$$V_{out} = -10(V_2 - V_1) + 2.5$$

The offset of 2.5 V is required because the optical link transmitter and receiver used both require a voltage between 0-5 V. The loop signal, though, is both positive and negative, depending on whether the plasma is forming or decaying. The final voltage signal is sent to the optical link transmitter through an SMA cable.

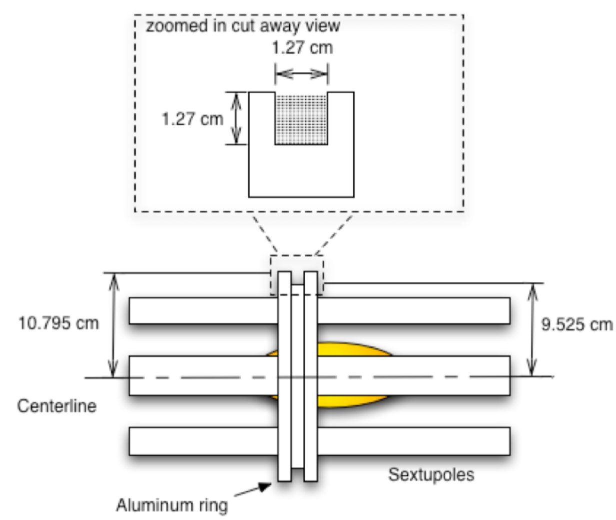

Figure 3: Approximate position of aluminum support ring. Drawing not to scale.

RF pulsing circuit

In order to measure a diamagnetic signal, which relies on changes in plasma density, an ECRIS must be operated in pulsed mode. Figure 4 shows a schematic of the pulsing method used in this study.

A signal generator is used to create the desired microwave pulse pattern. The signal is then sent to the Gunn Diode Modulator (GDM). The GDM is needed to provide the correct voltage and current values to drive the Pin Absorptive Modulator (PAM). When the output signal from the GDM is greater than zero, the PAM does not attenuate the oscillator signal. If the output signal from

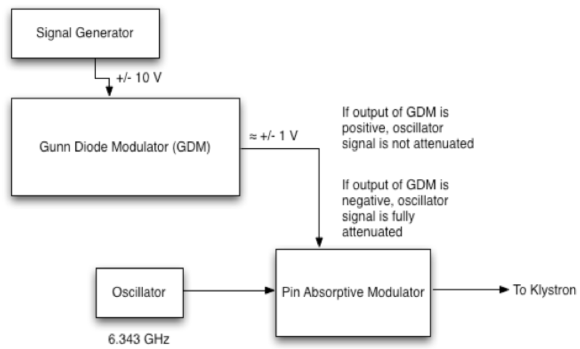

Figure 4: Diagram of klystron pulsing circuit.

the GDM is negative the PAM fully attenuates the oscillator signal, and the klystron power output is zero. Delays introduced with this method are on the order of microseconds. Plasma formation and decay time scales, though, are on the order milliseconds, and so the delays are ignored.

EXAMPLES OF EXPERIMENTAL DATA

Figure 5 shows an example of an unintegrated diamagnetic signal. The large, positive spike occurs when the microwave power is turned on. The smaller, negative spike occurs when the microwave power is turned off. Because the induced voltage is proportional to the rate of plasma formation, Fig. 5 indicates that the plasma forms at a faster rate than it decays.

The relative plasma energy density as a function of microwave power is shown in Fig. 6. The plasma energy density is calculated by integrating the initial, positive

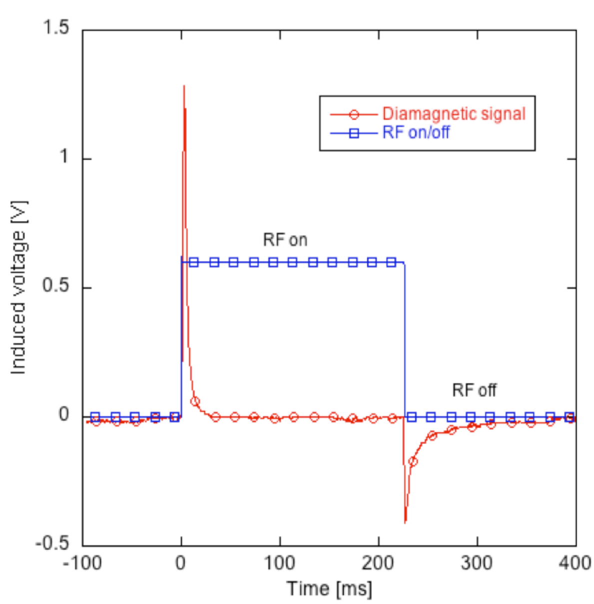

Figure 5: Diamagnetic loop signal. Argon plasma.

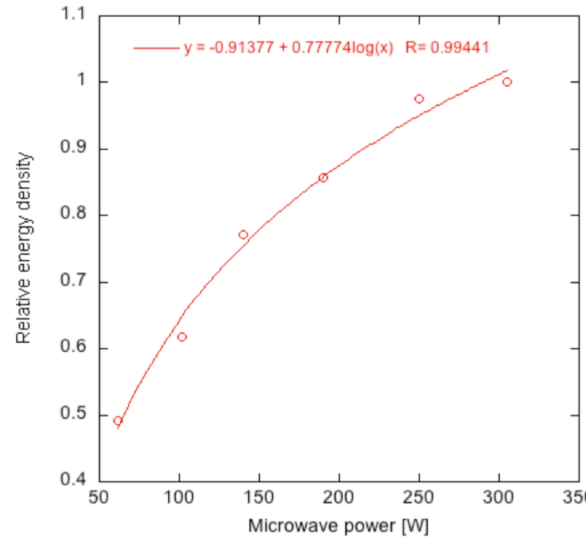

Figure 6: Relative plasma energy density versus microwave power. Argon plasma

spike and using Eq. 2. The relative plasma energy density is seen to increase logarithmically with microwave power.

SUMMARY

In this paper we have described a method of measuring diamagnetic signals on the LBNL 6.4 GHz ECR. This diagnostic is useful for understanding the behaviour of the warm and hot electrons confined in the plasma as source operating parameters are varied.

It is seen that the plasma energy density, as estimated using the integrated diamagnetic signal, increases logarithmically with the microwave power, and that the plasma forms at a faster rate than it decays at.

We will make a similar set of measurements on the LBNL 14 GHz AECR-U in a future experiment. More detailed explanations of the results and experimental setup discussed in this paper will be available in future articles [6,7].

REFERENCES

[1] D. Leitner, J. Benitez, C. Lyneis, D. Todd, T. Ropponen, J. Ropponen, H. Koivisto, and S. Gammino, Rev. of Sci. Inst. 79 033302 (2008)

[2] C. Barue, M. Lamoureux, P. Briand, A. Girard, and G. Melin, Journal of Applied Physics 76 2662 (1994)

[3] G. Melin, F. Bourg, P. Briand, J. Debernardi, M. Delaunay, R. Geller, B. Jacquot, P. Ludwig, T.K. Nguyen, L. Pin, M. Pontonnier, J.C. Rocco, and F. Zadworny, Rev. of Sci. Inst. 61 236 (1990)

[4] C. Lyneis, "Operating experience with lbl ecr source," International Conference on ECR Ion Source and their Applications, p. 42-56 (1987)

[5] F. Chen, Introduction to Plasma Physics and Controlled Fusion, 2nd ed. Plenum Press (1984)

[6] To be submitted to Plasma Sources Science and Technology.

[7] To be submitted to Journal of Instrumentation.