ECR ION SOURCE PLASMA RELATED RESEARCH AND DEVELOPMENT AT JYFL

H. Koivisto[1], P. Frondelius[1], T. Ropponen[1], P. Suominen[1], O. Tarvainen[1] and R. Vondrasek[2]
1) Department of Physics, Accelerator Laboratory, University of Jyväskylä, P.O.Box 35, FIN-40014, Jyväskylä, Finland

2) Argonne National Laboratory, Physics Division, 9700 S. Cass Ave, IL 60439, USA

Abstract

A device for the plasma potential measurement [1] has been developed at JYFL (University of Jyväskylä, Department of Physics). The device can be used to obtain information about the temperature of ions, plasma potential and the structure of the plasma potential of ECR ion sources. Initially the main focus of the research will be to find information about the temperature of the ions. In this article we will present the results of these measurements. A new plasma chamber for our 6.4 GHz ECRIS will be constructed in order to study the idea of modified multi-pole structure (MMPS) [2]. With this structure a very high local multi-polar magnetic field can be achieved. With the aid of the new chamber the magnetic field at the magnetic pole can be increased continuously from 0.4 T to 0.9 T. At the same time the plasma volume and the azimuthal component of multipolar field remains unaltered.

INTRODUCTION

Numerous attempts (for example [3, 4, 5]) to model and understand the plasma or the ion extraction of ECR ion sources have been performed. The ion and electron temperatures and the plasma potential are often required as input parameters. It has generally been accepted that three different electron populations can be found within the ECRIS plasma: 1) cold / thermal electron population ($T_e \leq 50$ eV), 2) a warm electron population, which is responsible for the ionization ($T_e \approx$ from about hundred eV to few keV) and 3) a hot electron population which is well confined and practically collisionless. It has also been suggested that the ion temperature is very low – less than 1 eV. We have developed an instrument, which can be used to measure the energy distribution (beam current decay) of ion beams by applying a stopping voltage [1]. With the aid of the decay curve the plasma potential and the temperature of ions can be determined. In this article we will present some results related to the ion temperature. We will also give the status of the development work related to a new modified plasma chamber.

ION TEMPERATURE

The plasma potential measurement instrument developed at JYFL measures the energy of the ion beam by applying a decelerating voltage to a mesh located in the beam line after mass analysis. The voltage of the mesh can be adjusted with a voltage regulated power supply, which is floating on the high voltage of the ion source ($V_{mesh} = V_{source} + V_{adjustable}$). This arrangement makes the measurement independent of the source voltage and therefore the plasma potential can be determined in a single measurement without changing the source voltage or disturbing the plasma. The plasma potential is determined by measuring the ion beam current at the grounded electrode situated behind the mesh as a function of this adjustable voltage. By analyzing the ion beam decay curve, information about the ion temperature and the plasma potential can be obtained. The plasma potential instrument and the method of determining the plasma potential are presented in ref. [1].

The shapes of the plasma potential curves measured with different charge states were observed to be different in the case of 14 GHz ECR ion sources, which can be explained to be an effect of the ion temperature. In order to distinguish the effects of the plasma potential (V_p) and the ion temperature (T_i) on the measured voltage-current curves, a simple computer simulation code was developed with the Mathematica 4.1 program. The input parameters of the code are: adjustable potential profile along the plasma chamber axis, spatial distribution of different charge states relative to the potential profile, ion temperature and ion properties (charge state and mass). The ions were assumed to have Maxwellian velocity distribution in the ECRIS plasma. According to our simulation results, the shape of the measured curve at low stopping voltages (lower than the value of the plasma potential) mainly depends on the potential profile and the spatial distribution of the ions while the ion temperature determines the shape of the curve with higher stopping voltages.

Figure 1 shows the simulation results compared with the measured plasma potential curve corresponding to the JYFL 14 GHz ECRIS operating at 630 W for O^{7+}. In this case the plasma potential was determined to be 19.8 volts and the ion temperature of O^{7+} ions 23 eV when the simulated curve matched the measured curve with a correlation of 0.999. Because the effect of the ion temperature on the measured curves is more severe for low charged ions, the most reliable plasma potential values are obtained in measurements with high charge states. The value of the plasma potential is a characteristic of the plasma and it does not depend on the charge state. Therefore the ion temperatures of different charges states of oxygen were determined as follows: at first the potential profile and the maximum value of the potential were determined with the aid of the curve measured with O^{7+} ion beam. The same profile and plasma potential value were used in the simulations with different charge states while the ion temperature was varied in order to match the simulated curves with the measured curves for voltages exceeding the value of the plasma potential.

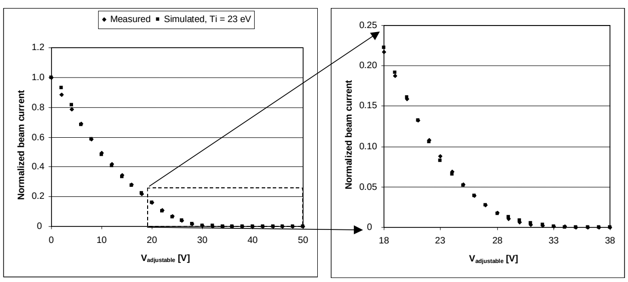

Figure 1: The measured and the simulated plasma potential curves.

The error related to the ion temperatures was estimated by comparing the correlation between simulation results and measured curves. It was observed that the error is about ± 2 eV for high charge states and about ± 1 eV for low charge states (O^{+} and O^{2+}). In practice this means that the other parameters of the simulation (for example the potential profile) cannot be changed so that the simulated curves match the measured curves if the ion temperature was changed ± 2 eV.

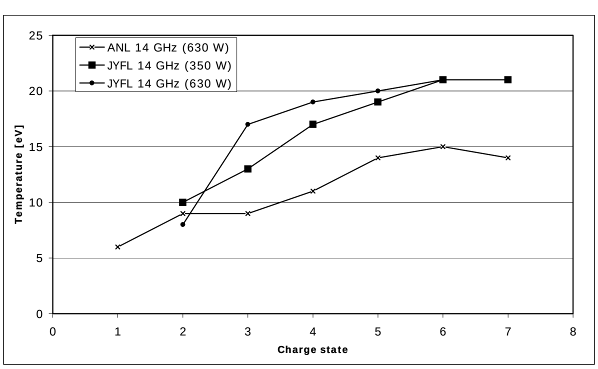

Figure 2: The temperature of oxygen ions as a function of the charge state.

Fig. 2 shows the temperature of oxygen ions as a function of the charge state in three different cases: two have been measured with the JYFL 14 GHz ECR ion source with a microwave power of 350 W (18.8 V) and 630 W (19.8 V) and one has been measured with the ECR2 at ANL (14 GHz) with a power of 630 W (6.5 V) corresponding plasma potential values shown in parenthesis. The only significant difference between these sources is the radial mirror ratio (B_{rad}/B_{ECR}) being over 10 % higher for ECR2 at ANL. Both sources are modified versions of the AECR-U at LBNL.

In ref. [3, 5] it has been stated that the temperature of the ions are of the order of 1 eV or less. In addition it has been assumed that due to the high collision rates of ions, different charge states of the ions have the same temperature i.e they are at the thermal equilibrium. According to our measurements with the plasma potential instrument the temperature of the ions is much higher than 1 eV as shown in Fig. 2. In addition, the temperature is different for low and high charge states. As figure 2 shows, the temperature of oxygen ions is between 8 (O^{2+}) and 22 eV (O^{7+}) in the case of the JYFL 14 GHz ECR ion source being slightly lower in the case of ANL 14 GHz ECRIS. No satisfying explanation for the difference was found. In both cases the temperature increases first as a function of the charge state ($q < 5$) and starts to saturate in the case of higher charge states ($q \geq 5$). A possible explanation for this behavior will be given later in the discussion. Figure 2 also shows that the saturation temperature does not strongly depend on the microwave power – in both cases (350 W and 630 W with the JYFL 14 GHz ECRIS) saturation temperature is about 22 – 23 eV. The energy spread of the ion beams corresponding to the results shown in Fig. 2 was observed to be 8-23 q eV.

MODIFIED PLASMA CHAMBER

The idea of the modified multipole structure (MMPS) for the ECRIS plasma chamber has been presented earlier in ref. [2,6]. In this structure the multipole field is increased only at the magnetic pole with the aid of a high permeability material like iron. A new plasma chamber for the JYFL 6.4 GHz ECRIS is being constructed [7] in order to test the idea (Fig. 3). The magnetic field at the magnetic pole can be varied approximately from 0.4 T to 0.9 T. The plasma chamber will be completed by the end of the year 2004 and the first tests will be started in early 2005.

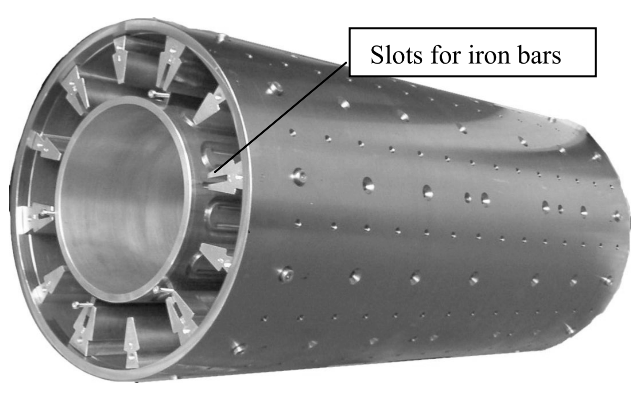

Figure 3: The new plasma chamber for the JYFL 6.4 GHz ECRIS to test the idea of MMPS.

DISCUSSION

The ion temperatures reported in this article are remarkably higher (10-20 eV) than generally accepted values. However, they are in good agreement with the results presented in ref. [8] in which the ion temperature in oxygen plasma was determined by measuring the Doppler shifts of different charge states. In ref. [3] valuable work has been done to increase the knowledge about the ion distributions and confinement times of ions inside the ECR ion source plasma. In that work an equation to calculate the confinement time for different charge states has been given. The equation does not include the potential dip because an ion temperature of 1 eV or less would give too long confinement time in that case. Using the equation the calculated ion confinement times were observed to be in good agreement with the measured confinement times presented in that work (1.5 ms and 2.7 ms for Ar^{9+} and Ar^{12+} ion beams, respectively). The confinement time would increase far beyond the observed results if the potential dip was included in the model. Consequently, the authors suggested that the potential dip does not possibly exist in the ECRIS plasma. That may be accurate if the temperature of the ions is of the order of 1 eV or less as was assumed. On the other hand, the ion temperature being higher than 10 eV necessitates the existence of the potential dip due to the fact that the confinement times calculated from the afore mentioned model would be too low (0.047 ms and 0.087 ms) without it. Hence, the ion temperatures measured with the new plasma potential device strongly supports the existence of the negative potential dip in the ECRIS plasma.

According to our results, the lower charge states of the ions are not in thermal equilibrium with each other (see Fig. 2). This observation leads to interesting speculations. The electron-ion collision frequencies in a fully ionized plasma [9] can be calculated with the aid of eq. (1).

$$\langle \nu_{ei} \rangle = \frac{\sqrt{2} n_i q^2 e^4 \ln(\sqrt{\varepsilon_0 k T_e / (n_e e (1 + q T_e / T_i))})}{12 \pi^{3/2} \varepsilon_0^2 \sqrt{m_e} (k T_e)^{3/2}} \qquad (1)$$

As Eq. (1) shows the collision frequency increases with the square of the ion charge state. As a consequence, more energy is transferred from the thermal electron population to the highly charged ions, which increases their energy. However, the energy transfer from electrons to ions is a slow process because of the remarkable mass difference between ions and electrons. The ion-ion collision frequency can be calculated using eq. (2).

$$\langle \nu_{ii} \rangle \approx \left(\frac{m_e}{m_i} \right)^{1/2} \left(\frac{T_e}{T_i} \right)^{3/2} \langle \nu_{ei} \rangle \qquad (2)$$

Also in the case of ion-ion collisions the collision frequency increases as the square of the ion charge state. However, in this case due to the lower mass differential less than 10 collisions are needed to reach thermal equilibrium [10]. According to the tendency shown in Fig. 2 the confinement times of low charge states are too short to experience enough collisions and therefore to reach thermal equilibrium in the ECRIS plasma. The confinement times of high charge states are longer as has been shown for example in ref. [3] and the collision frequency of high charge states is higher, hence equilibrium can be reached. And Fig.2 indicates that only the highly charged ions are in thermal equilibrium with each other. Now the natural question is: are the cold electros and the highly charged ions approaching thermal equilibrium with each other? This would mean that in the case of the measurements performed with ANL 14 GHz ECRIS and the JYFL 14 GHz ECRIS the cold electron population has the equilibrium temperature of about 15 eV and 23 eV, respectively. This also indicates that the temperature of cold electron population is close to the decelerating energy provided by the plasma potential.

ACKNOWLEDGMENT

This work has been supported by the Academy of Finland under the Finnish Centre of Excellence Programme 2000-2005 (Project No. 44875, Nuclear and Condensed Matter Programme at JYFL).

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