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ECR plasmas and ECR Ion Sources

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Abstract

This article presents recent results, both experimental and theoretical, obtained in the field of Electron Cyclotron Resonance (ECR) Ion Sources. The shape of the Electron Distribution Function, the dependence of the electronic and ionic confinement times on the plasma parameters were studied. These experimental results are summarized, and they are compared with theoretical results, which, for the first time, explain how ECR Heating itself determines the ultimate parameters of the plasma, and consequently the performances of ECR ion sources.

1 Introduction

Mirror-confined ECR heated plasmas have proved to be very efficient for the production of Multiply Charged Ions (MCI). When used for ion injection into accelerators, these plasma devices are called ECR Ion Sources (ECRIS). To produce MCI, some criteria have to be fulfilled:

1. Electrons should reach energies larger than the ionization potential of the desired ion. For example producing fully stripped argon requires 4 keV electrons.

2. Ions should be confined for a time sufficient to reach the desired charge state.

3. To minimize charge exchange the neutral pressure should be kept as low as possible.

These criteria are well achieved in a mirror-confined ECR heated plasma. A schematic drawing of an ECRIS is presented in Figure 1. Coils (1) and (2) create the mirror field and permanent magnets (3), or Ioffe bars, are used for the multipole field (usually hexapolar). The superposition of these fields leads to a minimum-$\boldsymbol{B}$ structure. The electrons interact resonantly with the wave close to the resonance surface (4) which is shaped like an ellipsoid. The High Frequency (HF) wave is injected along the magnetic field, and the whole chamber is biased at typically +20 kV. Then ions are extracted through a grounded extraction electrode. In §2 recent experimental results are presented. In §3 a new theory of ECR plasmas is presented, which explains limitations of the devices, in particular with respect to frequency. In §4 some important conclusions concerning ECR heated plasmas are drawn.

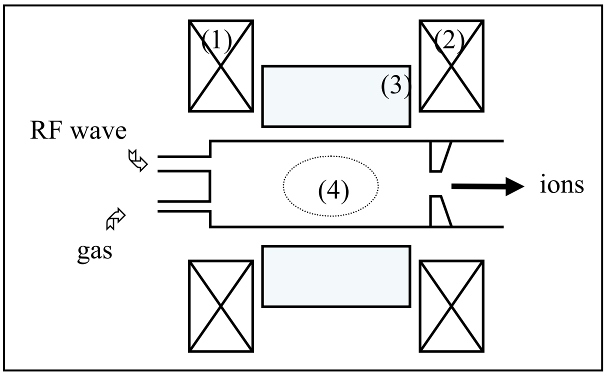

Figure 1: Principle of an ECRIS.

2 Experimental results

2.1 Characterization of the electron population

Experiments were undertaken in the Quadrumafios source [1]: electron energy, density were measured, including the plasma potential [2]. The confinement time of the electrons τ_e is, as usually, defined by the ratio between the losses (current I_e) and the density n_e:

$$\tau_e = \frac{1}{2}\frac{n_e e S}{I_e} \tag{1}$$

where S is the section through which the current I_e is measured. The Electron Distribution function (EDF) is very far from a maxwellian since the plasma potential is of a few tens of Volts (typically 30 V), while the EDF has a mean energy of a few tens of keV (up to 100 keV in some conditions)! This shows that collisional effects are of importance only for low energy electrons. Hot electrons are governed by their interaction with the HF wave. The electron confinement time is shown in Figure 2: this time depends on the neutral pressure and also of the HF power. Hot electrons as those observed in the Quadrumafios source were also observed in the Caprice source [3]. These electrons play a major role to build the high density, high confinement time plasma, required for the production of MCI.

2.2 Characterization of the ionic population

The ion population was studied through X-ray spectroscopy, in Argon gas, in the Caprice source, which has much higher performances that the Quadrumafios source [3]. The K_α line of the different charges is observed between 3 and 4 keV with a high resolution spectrometer. It is possible to identify all the lines corresponding to charges between 9 and 16, and then to relate these lines to the ionic densities in the plasma. When both densities and currents are known it is possible to derive the ionic confinement time τ_q of the charge state q. This is shown in Figure 3, which suggests that the confinement time increases linearly with the charge q. This conclusion is fully consistent with the following confinement scheme. The ions are cold (typically the ion temperature $T_i = 1$ eV) and highly collisional; as they are much heavier (mass m_i) than the electrons, they are expelled from the plasma through an ambipolar electric field E. This scheme leads to

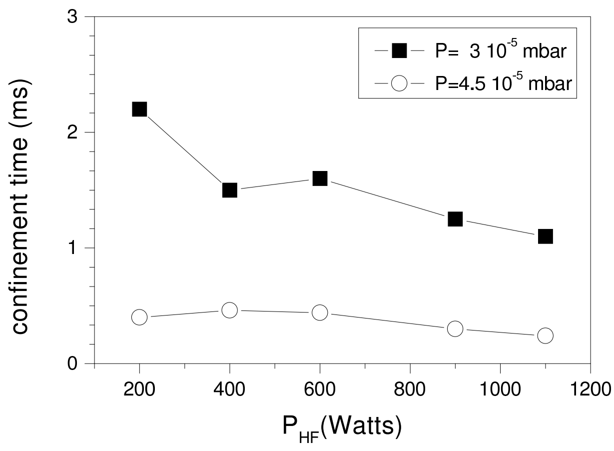

Figure 2: Electron confinement time.

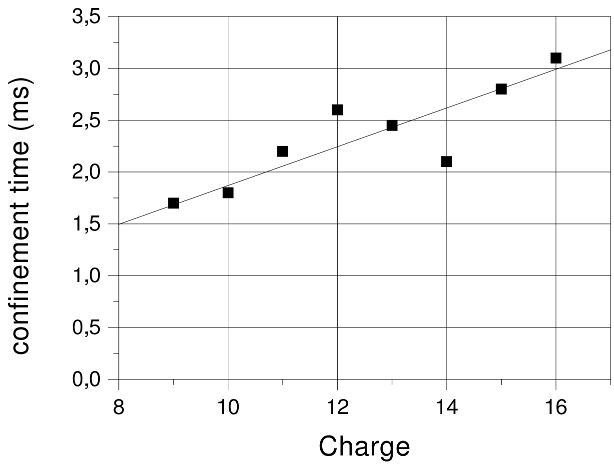

Figure 3: Ion confinement time versus charge.

the following law of confinement:

$$\tau_q = 7.1 \times 10^{-20} Lq\, ln\Lambda \sqrt{A} \frac{n_{\mathrm{e}} Z_{\mathrm{eff}}}{T_{\mathrm{i}}^{3/2} E} \tag{2}$$

From these experiments we conclude that in order to get a significant amount of multiply charged ions it is necessary to have a density above $10^{12} cm^{-3}$, a confinement time in the range of 1-5 ms for the electrons, which may be significantly higher for highly charged ions, due to the linear dependence of the ionic confinement times with the charge. However some other constraints are present, in particular related to HF frequency. This is analyzed in the following section.

3 Theoretical and numerical results

In a recent publication [4] a Fokker-Planck code was presented, which calculated the EDF built by the ECR Heating, including the full collision term. The HF term was however slightly simplified but a much clearer understanding arose from this study. The influence of the mirror ratio was verified, the influence of the neutral density on the confinement time was the same as observed experimentally. Moreover it was demonstrated that there is a saturation of the performances of the source with the HF power. Another important effect is the influence of the phase velocity of the wave: the higher this phase velocity, the lower the losses, and the higher the density and electron mean energy. The phase velocity v_ϕ is a function of the parameters of the plasma [4] (density n_{e}, thermal velocity v_T):

$$v_\phi^3 \approx \frac{\omega^2}{\omega_p^2} v_T c^2 = \frac{n_c}{n_{\mathrm{e}}} v_T c^2, \tag{3}$$

where

$$n_c = \frac{\omega^2 m_{\mathrm{e}} \epsilon_0}{\mathrm{e}^2}$$

is the so-called cutoff density, that is proportional to the square of the HF frequency ω. Equation (3) shows that the larger the density (as compared to the cutoff density), the smaller the phase velocity. Therefore, in order to reach a high density, it is necessary to have a large cutoff density (i.e. a large frequency). Using equation (3) it is possible to plot the plasma density and confinement time versus the frequency of the wave: this is presented in Figs.12 and 13 of [4], which show that only high frequencies can produce high plasma densities with high confinement times, and consequently high charge states. This explains why the performances of the ion sources are enhanced when the frequency is increased (cf Fig. 3 of [5]).

4 Conclusion

Experiments are in excellent agreement with theory. The confinement times necessary to produce MCI are shown to lie in the range 1 - 5 ms. As in the experiments, we have found that the electron density and the electron mean energy saturate with the incident HF power. Moreover, we have proved that the phase velocity strongly affects the electron density and therefore the performances of ECRIS: the smaller this velocity, the smaller the density and the smaller the currents. In ECR heated plasmas it is therefore necessary to increase the frequency in order to enhance the performances. This shows how the performances of the sources can be improved: existing ECRIS work at frequencies below 18 GHz; a considerable enhancement will be obtained with 28 GHz gyrotrons and superconducting solenoids, as is under development [5].

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