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The Quadrumafios electron cyclotron resonance ion source: Presentation and analysis of the results[a]

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The Quadrumafios electron cyclotron resonance ion source (ECRIS) has been especially designed to permit physical studies of the plasma; this paper describes the source itself (which has been operated at 10 GHz in a first step), its preliminary performances, and the different diagnostics involved, which mainly concern the electron population (ECE, x rays, diamagnetism, microwave interferometer, and electron analyzer). The results are presented and discussed: There is of course a close relationship between the parameters of the plasma and the performances of the source; this point will be discussed in the article.

I. INTRODUCTION

The performances of the electron cyclotron resonance ion sources (ECRIS) in the production of highly charged ions is strongly correlated to the high-temperature electron population which is generated by the ECR heating mechanism. Different measurements were already performed[1,2] involving various types of ECR sources. However, the available diagnostics were always limited; in particular the total electron density could not be directly measured.

This paper describes the first results obtained with the Quadrumafios ion source which is the first ECRIS totally dedicated to basic plasma physics related to the production of multicharged ions. Section II presents the source itself and the operating conditions; in Sec. III diagnostics are described: the electron endloss analyzer, microwave interferometer, diamagnetism and x-ray detector; Sec. IV presents a few results obtained with all these diagnostics; these results are discussed and a few important conclusions concerning the confinement of electrons in ECR discharges are drawn.

II. DESCRIPTION OF THE QUADRUMAFIOS SOURCE

A. Magnetic configuration

Although the Quadrumafios source was initially designed to run at 18 GHz we worked in a first step at 10 GHz. Figure 1 shows the magnetic configuration which gave the results presented in Fig. 2; the corresponding resonance surface diameter is 3 cm. It is worth mentioning that this configuration does not lead to the highest achievable energy of the hot electron population. Optical ports are available for plasma diagnosis, which are located between the four poles of the quadrupolar minimum B structure.

B. Performances at 10 GHz

The usual operating conditions were the following: 10-kV extraction voltage, 700-W rf injected power. However, the performances presented in Fig. 2 were obtained at higher microwave power (up to 2 kW injected); the injected gas was argon and a mixture of argon and oxygen was tested. The gas mixing effect is modest in these conditions.

III. DESCRIPTION OF THE DIAGNOSTICS

A. X ray measurements

The collimated x rays are detected through a NaI(Tl) scintillator located perpendicularly to the main axis of the source. For a Maxwellian electron population of temperature T_e the spectral power emitted through Bremsstrahlung per unit frequency scales like

$$j(E) \sim \exp(-E/kT_e),$$

where E is the photon energy. A linear fit of the logarithm of the spectrum is achieved between 100 and 300 keV. However the fit becomes less and less accurate when increasing the energy interval, which clearly shows that the distribution is not Maxwellian at all. However, the "temperature" derived with this method provides a rough estimate of the mean energy of hot electrons.

A Michelson interferometer[2] is also available, which measures the ECE spectrum. The results are qualitatively in agreement with those derived from the x rays.

B. Electron endloss analyzer

An electron endloss analyzer can be installed on the main axis of the source; it is located at the same place as the plasma electrode which of course has to be removed; an ion-repelling voltage is first applied, then a variable negative repelling voltage is applied to analyze the electrons. Analyzing the electrons stemming from a mirror machine—like an ECR source—needs much care; in particular it should be remembered that the electrons that *can* be analyzed *cannot* be confined in the plasma. In other words only unconfined electrons can be analyzed. Therefore it is necessary to make assumptions on the confining mechanism (or the deconfining mechanism): In the following we will assume that electrons are diffused into the loss cone mainly through e/i collisions. In order to derive the temperature of the electrons in the

[a]The abstract for this paper appears in the Proceedings of the 5th International Conference on Ion Sources in Part II, Rev. Sci. Instrum. 65, 1090 (1994).

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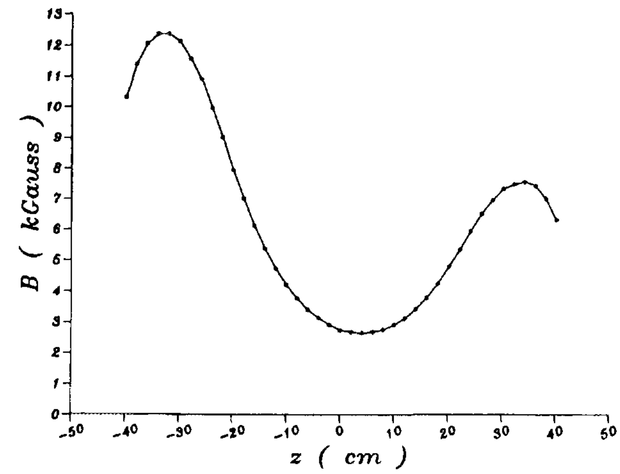

FIG. 1. The magnetic configuration of the source which leads to the performances of Fig. 2.

plasma we first differentiate the characteristic curve; then we take into account the loss mechanism, which is a function of the electron velocity (Spitzer scattering rate); we fit the curve obtained with a Maxwellian of temperature $T_{\perp}$. The result is a perpendicular temperature, as defined in an earlier publication.[3]

C. Microwave interferometer

A polar interferometer[4] has been installed to directly measure the line-averaged density over the ray path. An emitting horn with high gain launches the millimeter waves (4-mm wavelength) into the plasma; a receiving horn gathers the signal which has experienced a phase shift along its path through the plasma. In order to get complementary information on the confinement of the plasma we switch the rf off for a short duration (typically 200 ms) and observe the decay of the density. This decay can be compared with the decay of the diamagnetism of the plasma (the diamagnetism is measured with a conventional loop[4] surrounding the plasma), which gives information on the electron confinement time.

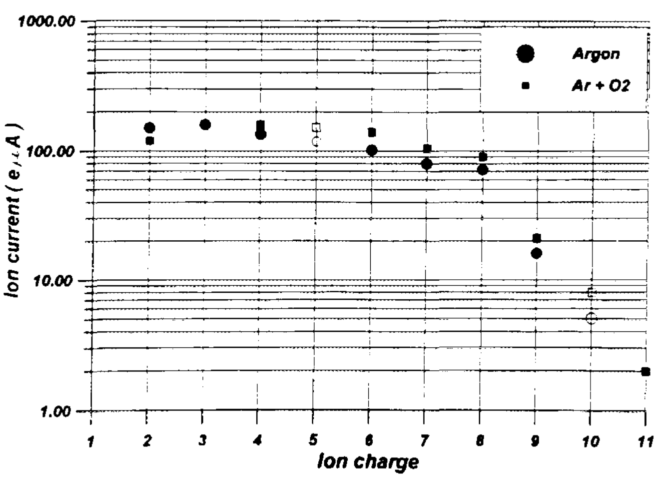

FIG. 2. Preliminary performances in argon (pure and with oxygen as a support gas) at 10 GHz; Ar^{5+} and Ar^{10+} currents are extrapolated.

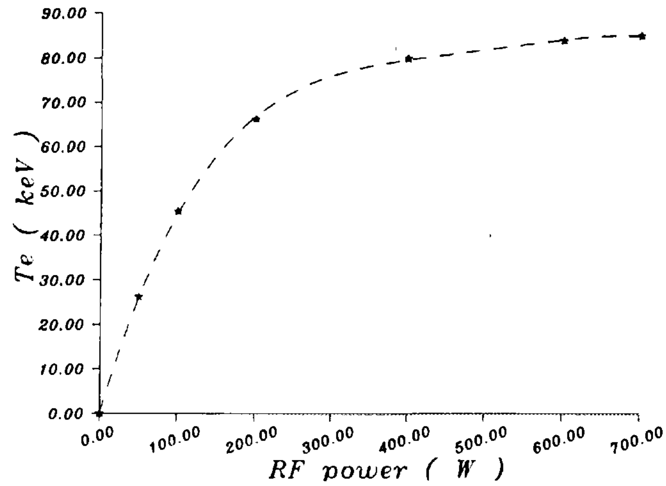

FIG. 3. Evolution of the hot electron temperature with the rf power.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Except when using the electron analyzer—where no ions can be extracted—we run the source at the maximum available rf power (700 W), optimize the current of Ar^{8+} (pure argon gas), and progressively decrease the power; at each intermediate point we measure the density, diamagnetism, ECE, and x rays. When we use the electron endloss analyzer we try to reproduce the operating conditions that occur when ion extraction is available.

A. Hot electron studies

The temperature of the hot component, derived from the Bremsstrahlung emission, is plotted vs incident rf power (Fig. 3). Whereas this temperature was almost constant above 100 W on the 18-GHz Minimafios source,[2] it can be seen here that this temperature is more dependent on the injected power: From the shape of the curve the saturation is expected to take place at a value of 90 keV but the available rf power was too low to reach this value.

The total kinetic pressure of the plasma is measured through diamagnetism (Fig. 4): Dividing the total energy content of the plasma by the decay time of the diamagnetism one obtains the rf absorbed power, which is presented in Fig.

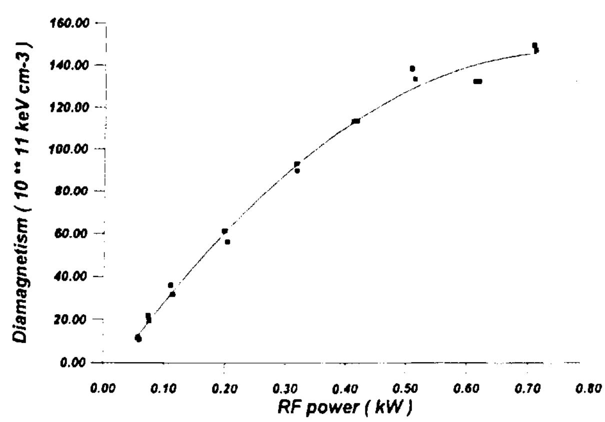

FIG. 4. Volume energy of the plasma vs injected rf power, derived with the diamagnetism.

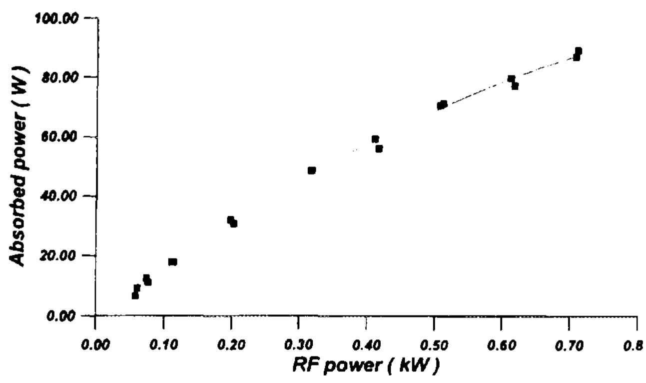

FIG. 5. Evolution of the absorbed power, defined as the ratio of the diamagnetism and its decay time, with the rf power.

5. Only a reduced part (less than 15%) of the rf power is absorbed. That point will be discussed in the following.

B. Lower energy electrons: Electrostatic analyzer

Figure 6 presents the perpendicular temperature of the electrons which leave the magnetic trap. It is of course abusive to call it a temperature for the same reasons as above but again this permits a very simple characterization of the mean energy. This energy seems to increase linearly with the rf power. This temperature is of course much lower than the hot electron temperature since the main electron losses occur at lower energy; therefore the net contribution of the hot electrons to the total loss current is negligible.

C. Electron density: Microwave interferometer

Figure 7 shows the density of the plasma as a function of the rf power: The plasma is supposed to be homogeneous over its whole cross section, whose diameter is estimated to be 3 cm (which is the diameter of the resonance surface). In a first step (below 200 W) the density rapidly increases; in a second step it remains constant and then it seems to decay beyond 500 W; however this decay might be due to instrumental errors (differences of less than 10% are difficult to

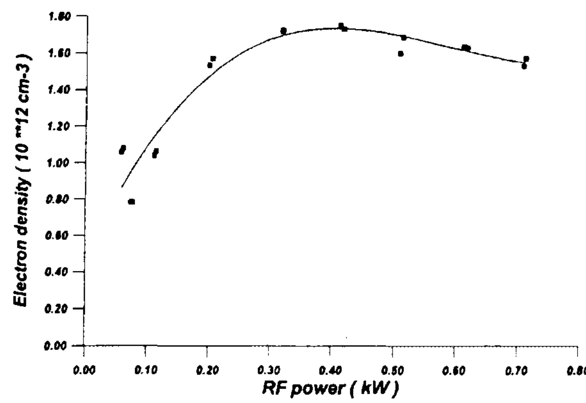

FIG. 7. Evolution of the electron density with the rf power.

see) and this has to be confirmed by other measurements. The density is not far from the so-called cut-off density which is 1.24×10^{12} cm^{-3} at 10 GHz.

This density can be compared to the estimated hot electron density, derived from the diamagnetism and the x rays. The total density is ten times greater than this hot electron density, which is presented in Fig. 8.

D. Discussion

These results can give us a more accurate idea of the electron population. Of course the main result of this study consists of the experimental evidence that the distribution is far from Maxwellian: This distribution function can be approximated by a Maxwellian only over a limited energy range. However, this result was already demonstrated theoretically.[4]

1. Radio-frequency absorption

Only a small part of the rf power seems to be absorbed, as derived from diamagnetism; however this result should be carefully interpreted: The diamagnetism is closely related to the hottest electron population, so that the measured absorbed power is the rf power absorbed essentially by the *hot* electrons. Cooler electrons have a reduced energy but also a reduced confinement time (as demonstrated by the electron endloss analyzer) and can therefore contribute to the total energy balance.

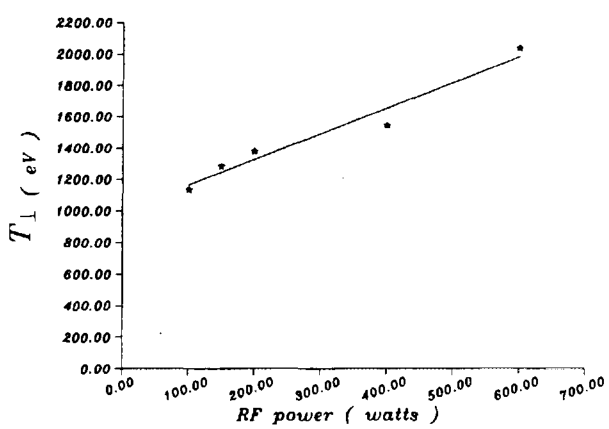

FIG. 6. Evolution of the electron temperature, derived with the electron endloss analyzer, with the incident rf power.

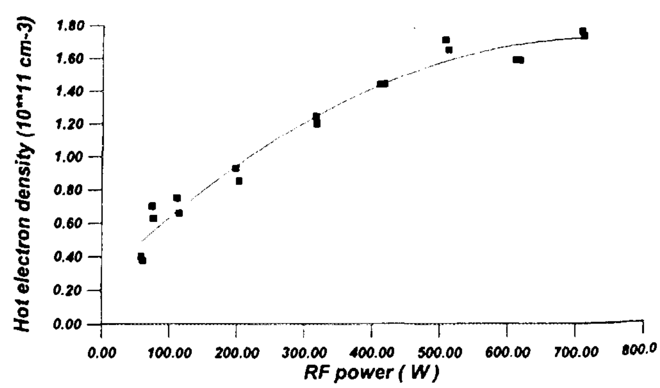

FIG. 8. Evolution of the hot electron density with the rf power.

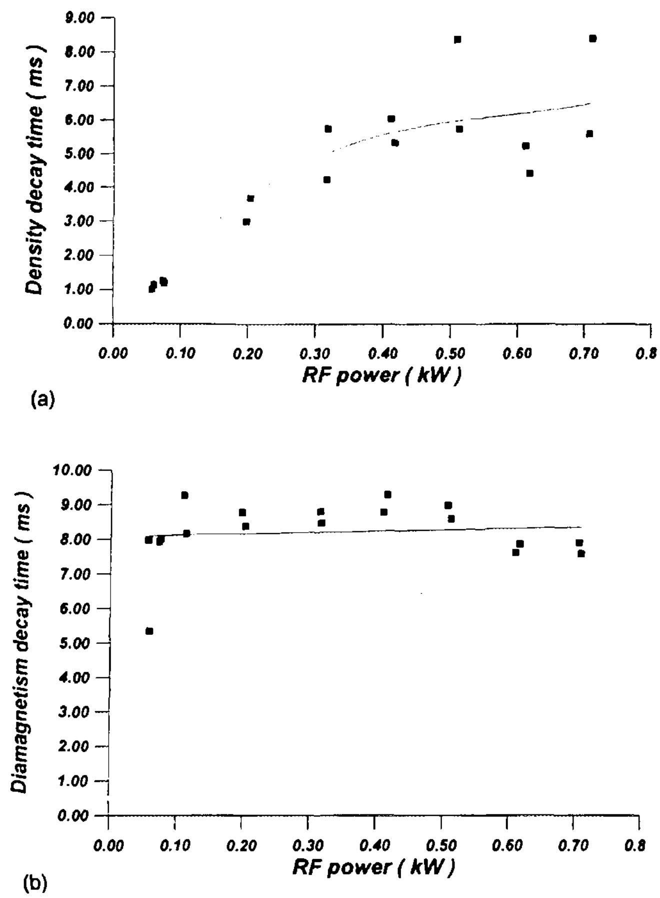

FIG. 9. Decay time of the diamagnetism (a) and of the density (b) vs rf power.

2. Description of the electron population

The electron population can be considered as a "bulk" of mildly heated electrons, which are the dominant population, and a smaller (10%) hot electron population of very high energy (mean energy 80 keV at 700 W). This description of the electron population is confirmed by other measurements: We are able to plot the decay time of the diamagnetism vs rf power [Fig. 9(a)]: This time is approximately constant over the range of available rf power. This is theoretically predicted (see for instance Ref. 5), since Coulomb scattering of hot electrons off ions and colder electrons only depends on the energy of the hot electrons and the colder electron density:

$$\tau \sim T^{3/2}/n,$$

where T is the temperature of the hot electrons (Spitzer time); since the colder electron density n and the hot electron temperature T do not change much above 200 W, the confinement time of the hot electrons has a very limited variation above this energy, as experimentally found.

3. Confinement of the electrons

The total density of the electron population is very close to the cut-off frequency (perhaps higher?). Unfortunately it was not possible (because our transmitter was limited in power) to analyze the behavior of the density at higher rf power. The relaxation time of the total density increases linearly with the rf power in a first step [see Fig. 9(b)] and then saturates. It is important to note that the decay time of the density is always smaller than the decay time of the diamagnetism, which confirms that the bulk electrons are less confined than the hot electrons, which are far less collisional. The slight decrease of the total electron density above 500 W (see Fig. 7), if it is confirmed, would suggest that the confinement time of the electrons decreases, which is not clear from Fig. 9(b). As a possible explanation one should remember that the decay time (relaxation time) is not necessarily the same as the confinement time during rf (transport time).

It is the first time that the presented diagnostics are used together to measure the parameters of an ECRIS. Therefore comparison with existing sources is hard to perform. However, the hot electron population was sufficiently well diagnosed in the Minimafios source to make a few comments: The *temperature* and *density* of *hot* electrons are comparable on both sources; however, whereas the hot electron confinement time decreased with increasing rf power in the Minimafios this time remains constant in the Quadrumafios ion source. This suggests that the *total* electron density may vary with the rf power in the Minimafios source, while it remains approximately constant in Quadrumafios, so that the *total* electron density could be higher in Minimafios than in Quadrumafios. That could explain why the two sources exhibit different performances. However, an important question remains open: Which building parameter makes it possible to the Minimafios source to fully strip argon gas while the Quadrumafios source is so far unable to do so?

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