High current density production of multicharged ions with ECR plasma heated by gyrotron transmitter

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In order to study the possibilities to produce high currents of pulsed heavy ion beams dedicated to synchrotron injection, two new approaches of ECR devices are now underway. The basic principle consists in maintaining a functioning point of the source with the highest density as possible and a minimum confinement time for the production of a given charge state. It means that for a constant $n_e \tau_i$ product we try to maximize n_e and minimize τ_i. For this purpose two experiments are in progress at ISN/Grenoble[a] and IAP/Nizhny Novgorod.[b] The first one consists of using a minimum $|B|$ magnetic structure with a 1.8 mirror ratio characteristic value with a 28 GHz frequency injection. In this case we explore different functioning points up to 10 kW of UHF power. The second one consists of a simple mirror magnetic system (simple mirror ion source, SMIS) working at 37.5 GHz with a mirror ratio up to 3 (2.5 T) where we study discharges with a peak power up to 100 kW. We will show that, in spite of a very short rising time of the current, we can maintain the production of multicharged ions and that we can observe very high current densities. In the future, the challenge will be the design of an extraction geometry matching theses current levels.

I. INTRODUCTION

The two main parameters that measure the capability of a plasma to produce multicharged ion are the electronic density n_e and the confinement time of the ions τ_i especially if we assume that the suitable electronic energy can be achieved in any case due to the efficiency of the ECR heating.

The product $n_e \tau_i$ is a rough measurement of the collision rate so it is roughly proportional to the $\langle Z \rangle$ of the ion in the plasma. The ratio n_e / τ_i is roughly proportional to the flux of particles arriving to the wall so the current density of a given charge state.

The aim of this project consists in multiplying the density by a factor of 3, that seems achievable with a 28 GHz discharge and optimizing the confinement time with a division by a factor of 3. In this case the $n_e \tau_i$ product remains constant and only the ratio n_e / τ_i is multiplied by a factor of 10. The current is multiplied by a factor of 10 and the $\langle Z \rangle$ remains constant so we look for a modification of the charge state distribution as illustrated by Fig. 1. We think that this functioning point could be achieved in a quite simple 28 GHz classical source working with a mirror ratio around 1.5. Finally, if we plan to work with high density and low confinement it means that the loss rate of the particles will be very high so that will need of a strong UHF power density in order to maintain the electronic density.

II. PHOENIX 28 GHz

A. General layout

The purpose of this project consists of using a very high density plasma in a quite medium confinement device in order to generate very high current density beams for the generation of high currents.

[a]Under grant CERN/GSI/CEA/IN2P3 K598/PS and EU Contract No. HPRI-1999-50019.
[b]Under Grant IAP/IN2P3-2/2001.

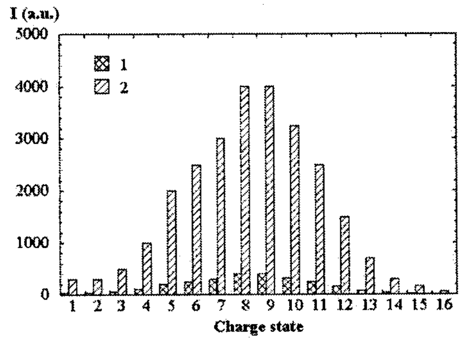

FIG. 1. Low flux and high flux charge state distribution with constant ⟨Z⟩.

It is the reason why PHOENIX is a compact machine matched to a 10 kW, 28 GHz gyrotron. The plasma chamber is a 74 mm in diameter and 300 mm in length tube with a direct and axial injection of the wave. The waveguide is a TE01 oversized for the 28 GHz frequency and it has a diameter of 32 mm (Fig. 2).

An important point is the introduction of a thick insulator (3 mm) between the coils and the inner part of the source in order to achieve an insulation up to 60 kV for the extraction of high current density. The axial magnetic profile is just matched to a 28 GHz ECR frequency for a mirror ratio of roughly 1.5. In this case the maximum axial field is 1.6 T at the injection of the wave and 1.4 T at the extraction for a 1300 A current inside the coils. The electrical consumption is roughly 200 kVA in this case. The radial field is done with a classical 80 mm in diameter FeNdB hexapole delivering 1.5 T on the pole.

B. High current density measurements

In a first step we only try to identify the possibility of production of very high current densities (above 20 mAe/cm^2). We have started the source at the present maximum extraction voltage of 48 kV and with a 2 mm extraction. We have easily extracted 4 mAe of total current with nitrogen corresponding to 3 mAe of total current arriving on the Faraday cup (75% of transmission and 0.9 mAe of N^{3+}; Fig. 3). In this case it means that we can reach a density close to 100 mAe/cm^2 at least in a 2 mm hole.

In this case we have switched the extraction hole to 6 mm (gap 35 mm) and study the production and transmission at 45 kV (Fig. 4). We can see the currents delivered by the high voltage power supply, measured in a Faraday cup placed just at the exit of the puller, the sum of all the ionic

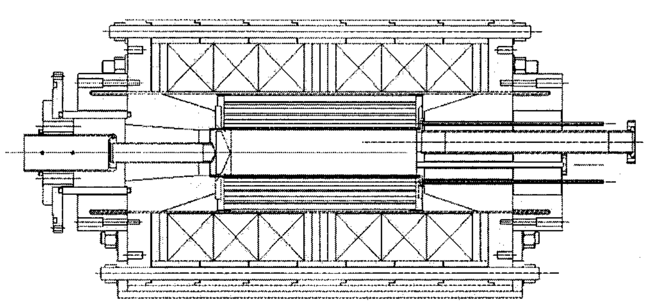

FIG. 2. The source PHOENIX 28 GHz.

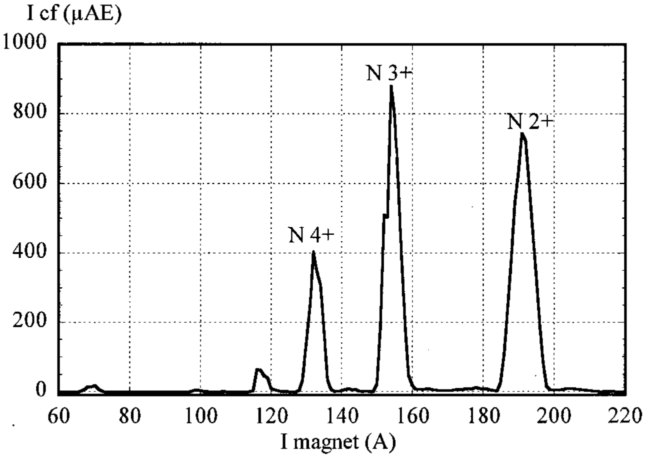

FIG. 3. N^{3+} up to 900 μA with ∅ 2 mm extraction hole at 48 kV.

currents arriving in the Faraday cup placed after the bending magnet and the current of 0^{4+} as a function of the UHF power.

We can see that at a low extracted current of 3.5 mAe after the puller (12 mAe/cm^2) we have a very good transmission. All the drain current arrive at the exit of the puller and are transferred through the bending magnet. But around 6 mAe after the puller (21 mAe/cm^2) we observe a saturation of the current after the bending magnet (4.4 mAe) indicating a clear space charge limitation through the beam line. Now around 7 mAe after the puller we began to see a major difference between the drain current and the Faraday cup current indicating the beginning of current losses and generation of the secondary electrons directly on the puller. Now it is the extraction gap that is space charge limited.

The conclusion of the present experiments are that we can easily produce high current densities of multicharged ion

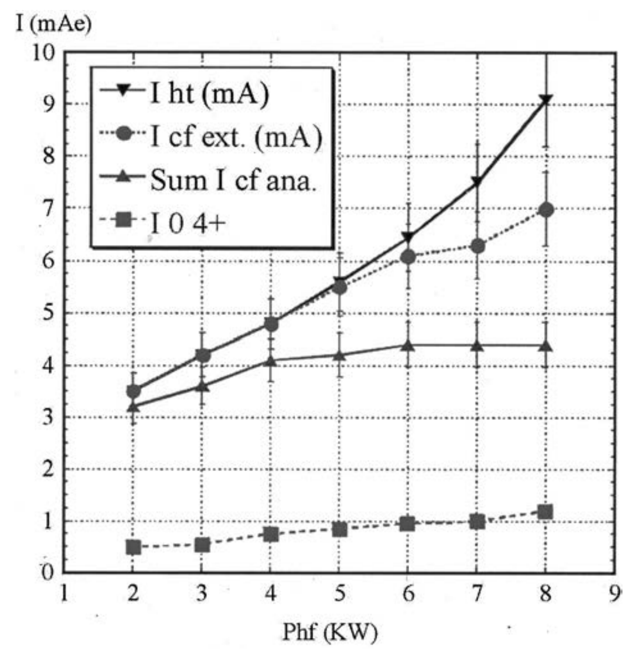

FIG. 4. Power dependence of the drain current (I_{ht}), the Faraday cup current at the exit of the puller ($I_{\mathrm{cf\ ext.}}$) and the total current of the spectrum at the exit of the bending magnet ($\Sigma I_{\mathrm{cf\ ana.}}$).

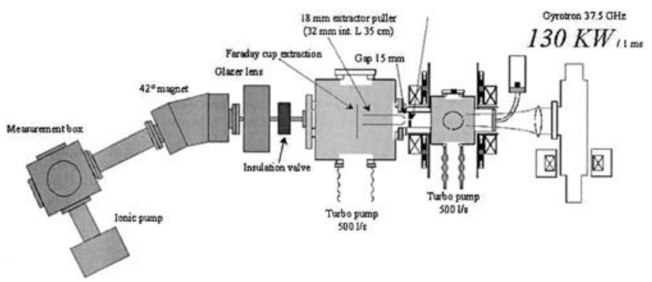

FIG. 5. SMIS 37.5 GHz experimental setup.

but we have to match the extraction voltage to each value in order to get a good transmission. In a near future an upgrade of the voltage and the acceptance of the beam line will be done.

III. SMIS 37 GHz

A. General layout

In parallel with the PHOENIX experiment a second device developed at the IAP of Nizhny Novgorod (Russia) and called simple mirror ion source 37.5 GHz is used to study the production of very high current density of multicharged ions.

Here a new step in the reduction of the confinement is done. The source is reduced to a simple axial magnetic mirror placed around a simple stainless steel plasma chamber[1] (Fig. 5). There is no hexapole and the pulsed UHF power is injected on the axis of the source through a glass window. In this case the extraction hole is reduced to 1 mm only. Due to technological limitations the magnetic field is pulsed and has a maximum value of 2.5 T during roughly 10 ms. The pulsed duration of the UHF power is limited by the high voltage power supply and has a maximum duration of 1 ms with a peak power of 130 kW. Another specificity of this device is the use of a quasi-optical coupling for the UHF injection. The power extracted from the gyrotron is a Gaussian beam that is refocused by a dielectric lens before the injection under vacuum through the glass window of the source. In this case there is no physical connection between the transmitter and the source, so there is no problem of insulation and power density transmission.

The source can presently be biased only up to 15 kV and the analyze of the beam is done with the former charge breeding beam line of ISN/Grenoble that has been transferred to Nizhny Novgorod.

B. Preliminary result

We can see in Fig. 6 a first result obtained for nitrogen (with C from outgassing). Here we show the spectrum during the 1 ms pulse of the UHF power and at five steps of 200 μs. We see that a full spectrum of multicharged ions of nitrogen can be produced in an opened trap. Here we have a clear illustration of the compensation of the reduction of the confinement time by a very strong power density used to maintain the electronic density. The peak power is 60 kW for a 1

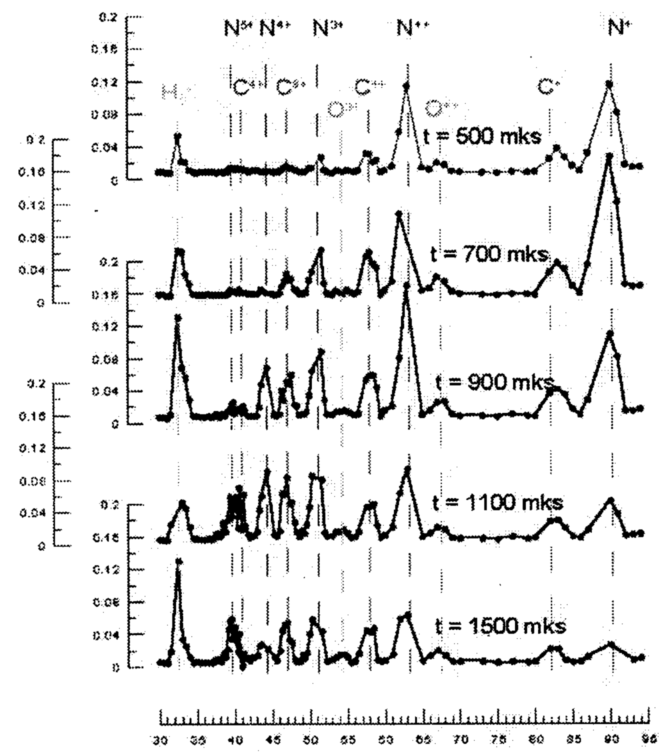

FIG. 6. Charge state distribution of N obtained with SMIS and with 200 μs steps.

l plasma chamber and the rising time of the current of N^{4+} or N^{5+} is only some hundreds of μs. In this case the total current extract from the source is around 5 mAe with roughly 3 mAe measured at the level of the extraction Faraday cup. The current density reaches more than 400 mAe/cm^2 that is roughly 10 times more than with PHOENIX and 100 times than a classical source. Of course, the transmission is very poor because of the low extraction voltage and the poor acceptance of the beam line. This aspect will be upgraded in a near future but the purpose of this first experiment consists in showing the possibility to produce multicharged ions inside a ion source without radial magnetic field.

IV. CONCLUSION

We start new compact devices working with high frequency and high power density and we clearly observe a drastic increase of the current density of multicharged ions. These currents densities can be produced in a minimum $|B|$ structure with a power density in the range of 5 kW per liter or in an open magnetic trap with a power density in the range of 50 kW per liter. The next step is now the control of the beam formation in the characteristic environment of an ECR ion source for the production of multi-milliamperes multicharged ion beams.

[1] V. G. Zorin, S. V. Golubev, and S. V. Razin, Rev. Sci. Instrum. **69**, 634 (1998).