Electron Cyclotron Resonance Sources of Multiply Charged Ions Last Developments at Grenoble

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Abstract

The behavior of compact electron cyclotron resonance ion sources (ECRIS) is emphasized in this article, and more specifically the Caprice ECRIS concept: a high B field ($\geq$ 1 T) source offering good performances both in extracted ion charge states and intensities, in a rather small volume, a source easy to handle and to operate. This concept like the ECRIS concept itself originated from the Grenoble group; it is quite attractive to continuous regime cyclotrons requiring high stability ion beams, but it is also well suited to delivering very high intensity particle pulses (today a few pμA of Pb^{28+} or Au^{27+} ion beams, a few ms long) of interest for synchrotron bunching. Finally the developments and activities in the field of ECRIS at Grenoble, are shortly surveyed while giving some trends and prospects.

I. INTRODUCTION

The ECRIS are now widely used by the accelerators. The Grenoble group which developed the first high charge state ECR source [1], although not directly associated with an accelerator facility, keeps on strongly working on ECRIS development for improving their performances, and on other plasma applications where radiofrequency waves–plasmas interactions are very important.

The ECR ion sources, an outgrowth of the fusion plasma studies in the so called open-ended mirror machines [2] can be shortly described as follows. It is made of a magnetic configuration able to trap hot electrons heated by a resonant rf wave–electron interaction; as a consequence, in order to satisfy the charge neutrality condition, the ions get electrostatically trapped and undergo successive ionizations; the extracted ion beams out of an ECRIS are actually the losses of this magnetic configuration. This is why tuning an ECR ion source in order to obtain high charge state and high intensity ion beams, results in a difficult compromise owing to opposite requirements: (i) confining a high density plasma for ionizing high charge states, but consequently having low losses and offering low intensity ion beams, (ii) having high plasma losses and possibly high intensity ion beams, which evidently does not allow the plasma density to build up, and may seriously jeopardize the ionization efficiency for high charge states !

Various concepts of ECR ion sources have been constructed, while trying to overcome this contradiction as well as other difficulties both from the technology and from the plasma physics. The Grenoble group built Minimafios, one of the most performant sources as to the 16-18 GHz prototypes [3] for delivering special ion beams; Neomafios [4], a source using only permanent magnets for its magnetic configuration; and Caprice, a compact source which got gradually improving [5].

II. THE CAPRICE CONCEPT

Although the Caprice source is not the best today source as to the performances of the multiply charged ion beams it can deliver, nevertheless it offers an outstanding compromise between the so many desirable characteristics of a multiply charged ion source that physicists of modern accelerators may wish to work with: high charge states, high intensities, high stability, wide range of ion species, reliability and longevity (no cathode, no filament), simplicity and modularity in the design (easy change of parts), a source easy to handle and to operate.

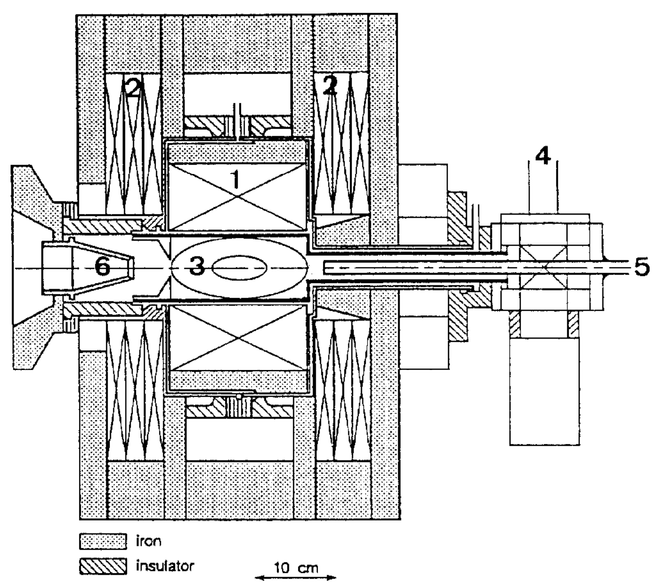

Figure 1: Caprice source, 1-permanent magnet hexapole, 2-solenoid coils, 3-closed mod-B surfaces, 4-rf power input, 5-gas inlet, electric oven feedthroughs, 6-ion extraction.

A. Description and main features

A sketch of the source is given in figure 1. The source is characterized by a small plasma chamber (16 cm long, 6.6 cm diameter) highly magnetized (i) by using electrical coils for the axial field, ~1.2T at the mirror throat owing to a strong and thick iron yoke and to other iron parts such as the puller electrode, (ii) by a high remanent induction

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permanent magnet hexapole for the radial field, ~0.9T at the plasma chamber radius.

The rf power is launched by a coaxial feeder, and the source equally works at 10 GHz and 14 GHz (at a higher axial field) with quite similar performances.

The measured emittances at a constant extraction voltage vary in between 80 to 150 πmm.mrad (for 80% of the beam intensity) for charge states below 10; at higher charge states the emittance gets better not only because of the increased ion beam velocity, but also because the high charge state ions are actually originating from the plasma center along the main axis (electrostatic confinement).

B. Results in continuous regime

This is one of the main advantages of the Caprice concept: it behaves exceptionally stable for long runs, i.e. tens of hours of continuous operation, with usually no more than 1 kW of rf power. The data set shown in figure 2 gives the optimized results with a few gases obtained with a Caprice source at 10 GHz.

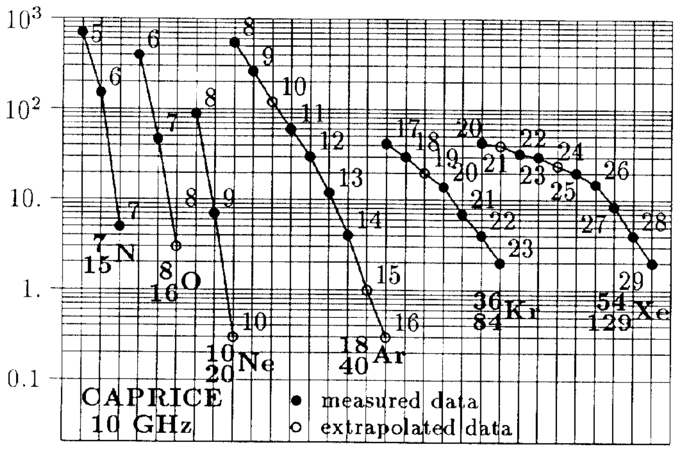

Figure 2: Optimized ion currents (eμA) for some gases.

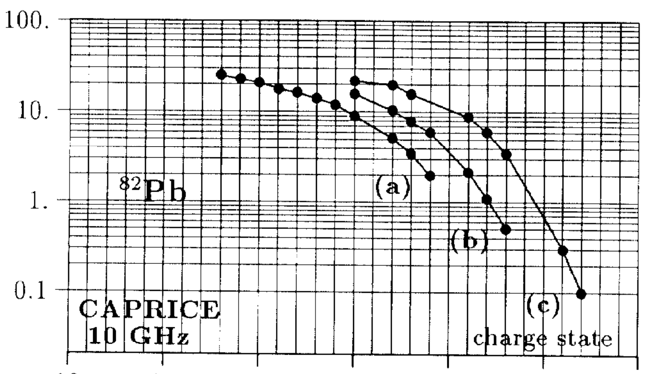

Figure 3. Optimized lead ion currents (eμA) from Caprice (a)4kG hexapole,Pb plasma-vaporized, (b)8kG hexapole, Pb plasma-vaporized, (c)9.3kG hexapole, Pb oven-vaporized

Recently for atomic physics studies, the Caprice source proves its capability of delivering Ar^{17+} ions in the 1 enA range, and Ar^{18+} ions in the 20 epA range, which ranks it well above other sources.

The figure 3 illustrates how much progress has been made with optimized lead ion beams, as an example, when increasing the hexapole magnetic field and varying the technique of production of the metal vapor. The technique of independently heated micro-oven considerably improved the capability of the source for delivering high charge state high intensity ion beams, as compared to the former technique of metal/oxide samples directly heated by the hot electron plasma; the main drawback of this former technique was to kill some hot electrons, and then to reduce the ionization efficiency of the source, as well as not to separate the functions of (i) vaporizing the metal and controlling its pressure, from (ii) the ionization and plasma formation. A few instantaneous charge state distributions are shown for lead and gold in figure 4, both obtained by this specific high temperature oven technique.

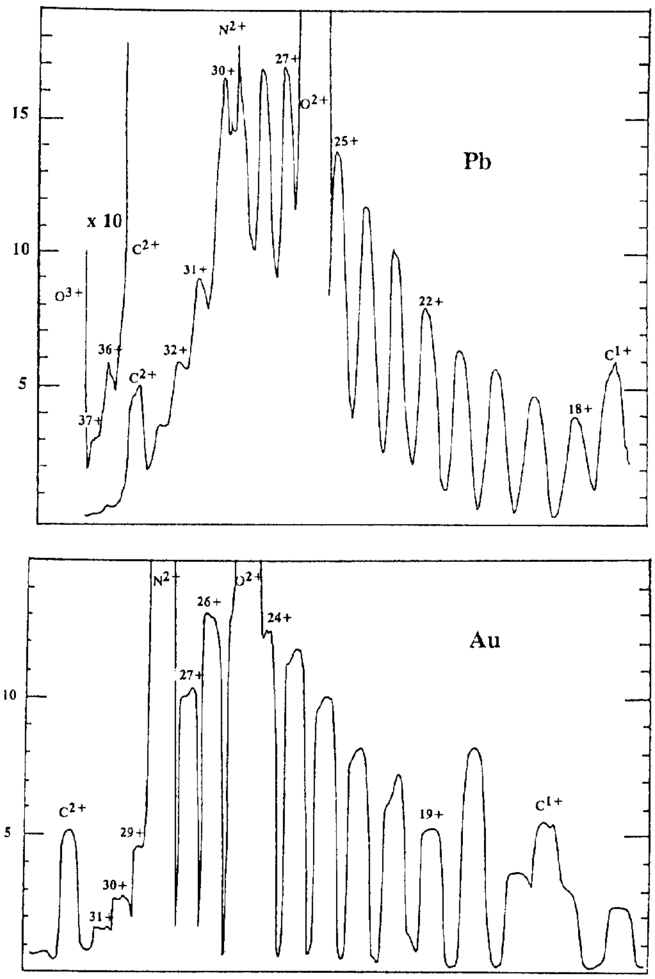

Figure 4: Charge state distributions from a 10 GHz Caprice source for lead (optimized on Pb^{31+}) and gold (optimized on Au^{26+}), vertical scale in eμA.

C. Results in pulsed mode: the afterglow effect

The pulsed mode of operation of the Caprice source is even more impressive than the cw mode; this specific afterglow mode, which the Grenoble group was first to investigate [3], is a consequence of the electrostatic confinement of the ions in the space charge well of the magnetically confined hot electrons within the source, that makes it similar to the EBIS. Once the ECR discharge has reached a steady state regime, turning the rf power off causes the electron population to collapse: the cold electrons leave the trap faster than the hot ones, and as the discharge is no longer sustained by the rf field, i.e. not refuelled by new cold electrons, the confined ions are compelled to leave the trap because of the charge neutrality condition. This effect occuring in the afterglow plasma is quite impressive; it may be optimized so as to obtain a few particle μA pulses of charge state ~30, a few ms long, at a frequency ~ a few tens of Hz: so far 2 pμA pulses of Pb^{28+} ions, 1 pμA pulses of Au^{27+} ions (see figure 5); the pulse intensity is essentially limited by the metal vaporization process (here the oven technique), it should be possible to reach ~3 pμA for these ions.

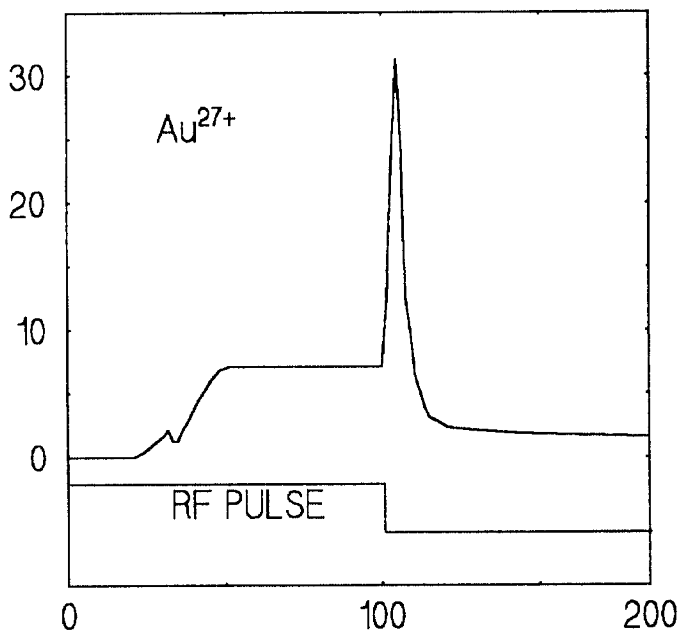

Figure 5: Afterglow pulse of Au^{27+} ion current (eμA), horizontal scale in ms.

III. ECRIS R&D AND PROSPECTS

As already mentioned above the Grenoble group has developed other sources, among which the only permanent magnet built ECRIS Neomafios 8 & 10 GHz [4] and soon 2.45 GHz are quite interesting because of their reduced power consumption, however offering lower performances than the Caprice source.

Today the main activity in Grenoble concentrates on the following efforts, which will hopefully give new orientations to the ECRIS.

A. The Quadrumafios facility

This facility specially designed for plasma measurements, and evidently not a compact one, aims at featuring and understanding the multiply charged ion production. Plasma and atomic physics diagnostics are developed in order to measure and control the most important plasma parameters: microwave interferometry for the electron density, bremsstrahlung and line X-ray spectrometry for the electron energy and the ion characterization, diamagnetic loops for the plasma energy content, electron cyclotron emission for the electron energy, electron and ion losses electrostatic analyzer, visible light and VUV light spectrometry, etc... The first data obtained at the frequency of 10 GHz are currently being processed.

B. Superconducting ECRIS

In a joint venture INFN-LNS-Catania/CEA-DRFMC-Grenoble, the building of a superconducting source for the K-800 cyclotron has just started. The source is designed so as to reach the highest magnetic fields so far used in an ECRIS: 1.4 T radially at the chamber wall and 2.2 T axially at the mirror throat. This facility is expected to deliver at high charge states the highest extracted ion currents,

(i) because of its capability of trapping a higher electron density, and thus of delivering larger intensity ion beams, than the today ECRIS;

(ii) because of its large plasma volume, that should enhance the plasma losses and the extracted ion currents (assuming a constant rf power per unit volume).

C. Prospects for Caprice

When considering the question how to get enhanced performances with Caprice, it seems like, partly from observations and partly from speculations, that turning the knob up for the rf power is not the solution. Thus the only serious possibility would be to increase the plasma volume, while keeping constant the other parameters. Nevertheless this leads to increase the input rf power, so as to maintain the same rf power per unit volume. But may Caprice be upgraded in size without ruining the concept itself and its compromise ? This is actually another challenge the Grenoble group is facing with.

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