HYBRID ION SOURCES FOR THE PRODUCTION OF HIGHLY CHARGED ION BEAMS FROM METALS

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Abstract

The ECLISSE experiment proved in 2002 the possibility to couple a Laser Ion Source (LIS) with an Electron Cyclotron Resonance Ion Source (ECRIS) in order to obtain ion beams from refractory metals with a cw beam structure. The use of a LIS inside the ECRIS plasma chamber may permit to increase the beam current and the ion charge state. The use of 3rd generation ECRIS may extend the capabilities of this method, as the denser plasma may catch the ions extracted from the LIS with energies up to about 1 keV per charge state, much higher than it is possible for sources operating at lower frequency, as it was verified with the SERSE source. The perspectives opened by the availability of the MS-ECRIS source operating at 28 GHz will be described along with some details on the proposed experiments, to be carried out in 2008.

THE ECLISSE EXPERIMENT

Accelerators for nuclear physics demand higher current and charge states as well as the extension of the variety of species, especially to metal ion beams and heaviest species. The low cross sections of interesting reactions for nuclear and particle physics make the availability of mA beams mandatory. The improvements of ion sources have permitted up to now a significant increase of the available current, that is particularly important for the research programmes with radioactive ion beams, and of the available charge states, that increase the final beam energy (linearly for linac and quadratically for cyclotrons), thus making possible to extend the programmes with stable beams [1]. In particular, the demand of metal ion beams have increased and it exceeds often the ability of ECR ion sources that are the typical injector for cyclotrons and linear accelerators in nuclear research facilities. Moreover the oven that are used for the production of vapours inside the ECRIS fails with refractory elements and the sputtering method is not adequate for the production of beams with intensity above few tens of μA.

For all these reasons a novel method for the production of intense beams of highly charged metal ions was proposed in 1998 at INFN-LNS. The concept of the hybrid ion source is the following: the first stage consists of a Laser Ion Source (LIS) which gives intense currents of electrons and multiply charged ions (q/m = 1/10 or lower) by means of metal laser ablation, then the plasma of an ECR ion source acts as a charge state multiplier [2]. The ECLISSE experiment (ECR ion source Coupled to a Laser Ion Source for charge State Enhancement) aimed to obtain intense beams in dc and pulsed mode, mainly from refractory elements. The SERSE source was preferred to other ECRIS because of its high plasma density, which guarantees a good trapping of LIS-generated ions.

The negative bias of the laser-irradiated target can be used to decrease significantly the ion velocity. This feature is particularly relevant as the coupling efficiency between LIS-generated beams and the ECR plasma is rapidly decreasing with the increase of the energy of the incoming beam. The major points to be investigated appeared to be the coupling efficiency of the ion beam produced by the LIS to the ECR plasma, as well as the possibility to enhance the available charge state by an ECRIS. A pulsed Nd:YAg laser has been used at INFN-LNS for the tests and its main features are described in Tab.1.

Table 1: Main features of the laser used for ECLISSE.

Laser Type	Nd:YAG
Wavelength	1064 nm (1ω)/532 nm (2ω)
Pulse Width	9 ns
Maximum Energy	0.9 J
Maximum Fluence	450 J/cm^2
Maximum Intensity	5 x 10^{10} W/cm^2
Beam Diameter	1 cm (non focalized)
Min. Beam Diam.	0.05 cm (focalized beam)
Beam Divergence	< 0.7 mrad
Mode	Single Shot / 30 Hz / 1 Hz
Most used mode	1Hz, 300 mJ, 10^{10} W/cm^2
Target bias	-0.5 to -3 kV

Preliminary studies have been carried out to determine: the efficiency of the coupling process of ions from the LIS beam to the ECRIS plasma; the energy distribution and charge state distribution (CSD) produced by the LIS at different laser power density; the etching rates and the amount of ions and neutrals extracted from the target; the magnetic field effect on LIS output; the effect of biasing the metal target. A full description of these studies is presented in [2,3,4].

The ion component of the plasma plume is generally investigated by using different ion collectors (IC) and an electrostatic ion energy analyzer (IEA), in order to obtain information about the integral ion emission and the energy distribution for each charge state. IEA measurements have shown that the ion energy distributions are Boltzmann-like and they have a regular energy shift that increases with the charge states, probably due to a very high electric field, self-generated inside the non-equilibrium plasma [5]. At laser power density of the order of 10^{10} W/cm^2, in the case of heavy metal target, high charge states up to 10^+ and kinetic energies up to 10 keV have been obtained. In the ECLISSE experiment configuration, the laser output axis was perpendicular to the beam-line axis and an infrared mirror deflected the laser light and sent it to the target. The laser repetition rate was 30 Hz and 1 Hz. Ta and Au targets were placed in a rotation system, permitting to have new surface available for the ablation; the normal to the target was coincident with the ECRIS magnetic axis. The target has been connected to a power supply placed on a high voltage insulated box, with the possibility to vary the voltage between 0 and -3 kV, in order to decelerate the energetic ions that could not be caught by the ECR plasma. The presence of the magnetic field (2.7 T in the region where the target was placed) acts as a focusing length for the plasma expansion, as KOBRA3D simulation code predicted.

A full description of the experiment carried out in 2002 at INFN-LNS is given in [4]. It was obtained that the charge state distribution (CSD) by laser can be increased of two charge states with respect to a similar CSD produced by oven evaporation at the same microwave power rate; the highest peak was 32^+ or 33^+ for gold. More than 3 μA of Au^{36+} were obtained as well as 16 μA of Au^{29+} and 12 μA of Au^{32+}. By decreasing the laser energy, more than 16 μA of Au^{30+} have been produced and the current of high charge states was quite high, up to Au^{41+} in spite of the pressure increase ($1.8 \cdot 10^{-7}$ mbar). Preliminary experiments using the pulsed regime were carried out only for a laser repetition rate of 30 Hz and without biased target; different laser energy, different width and time delay of rf pulses were tested. In addition, a 6 mm collimator and 10 kV extraction voltage were used, that limited the total current from the source.

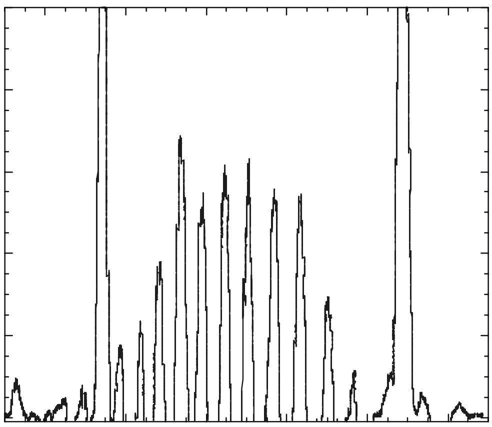

Figure 1**:** Typical charge state distribution for Au.

The maximum current of Ta^{28+} in this condition was only 2 μA and about 10 μA of Ta^{24+} were obtained. The rf power was 1.5 kW and the laser energy was 600 mJ. The rf pulse lasted 4 ms and the 9 ns laser pulse relative phase could be changed continuously. By operating this phase change we found a maximum of 14 μA for Ta^{24+}. Fig.1 shows a typical CSD for gold optimized for the highest charge states. It must be considered that the current may be increased by a factor three or four without the collimator and even more by operating at higher voltage.

MS-ECRIS DESCRIPTION

The production of intense beams of highly charged ions imposes the use of higher frequency (28 to 37 GHz) than it is used for the 2nd generation ECRIS (operating between 14 and 18 GHz). The 3rd generation ECRIS make use of superconducting magnets for the confining trap, B-minimum type, as the resonance field B_{ECR} = 1 T at 28 GHz. According to the ECRIS standard model a radial confinement with values at the chamber wall above 2.2 T is ideal, along with an axial confinement mirror with the two maxima respectively above 4 T and above 3 T. The MS-ECRIS source [6], funded by the European Union in the framework of the EURONS JRA07-ISIBHI initiative, has been designed to fulfil all these requests. Its magnetic trap has the highest design values to date, to get an optimum confinement for 28 GHz or higher frequency. Its design is open to be adapted to the major accelerators in Europe; the main parameters are given in Tab.2 and compared to the ones of the SERSE source, which is the parent project. Its plasma chamber provides a better accessibility and a higher pumping speed than the SERSE one, due to its higher diameter (180 mm instead of 130 mm). Another advantage is the high microwave power available, up to 10 kW, that may permit the production of intense beams even for charge states above 40^+.

Table 2: Main features of SERSE and MS-ECRIS.

Source Type	**SERSE**	**MS-ECRIS**
Frequency	18 GHz	28 GHz
$\mathbf{B_{radial}}$	1.55 T	2.7 T
$\mathbf{B_{inj}}$	2.7 T	4.5 T
$\mathbf{B_{ext}}$	1.6 T	3.2 T
$\mathbf{\Phi_{chamber}}$	130 mm	180 mm
$\mathbf{L_{chamber}}$	550 mm	650 mm
$\mathbf{\Phi_{cryostat}}$	1000 mm	1100 mm
$\mathbf{L_{cryostat}}$	1310 mm	1347 mm
$\mathbf{V_{extr}}$	20-25 kV	40 to 60 kV
O^{8+}	~7 pμA	~20 to 50 pμA
$\mathbf{Xe^{20+}}$	----	~50 pμA
$\mathbf{Pb^{27+}}$	----	40 pμA

SIMULATIONS OF "ECLISSE" EXPERIMENT WITH MS-ECRIS

In order to have higher currents of metal ion beams it is mandatory to improve the efficiency of the coupling between LIS and ECRIS, i.e. the capture probability. The main requirement for multicharged ion loading in an ion source is that the flow of ions produced by the laser pulse hitting the sample is slowed down and trapped by the ECR plasma.

The effective interaction of heavy ions beams with this plasma occurs mostly as the result of long-range elastic Coulomb collisions. In order to evaluate the capture probability, some simulation have been carried out according to the method described in [7].

Fig.2 shows the coupling probability for some species, for typical parameters of the LIS and for the plasma parameters of MS-ECRIS.

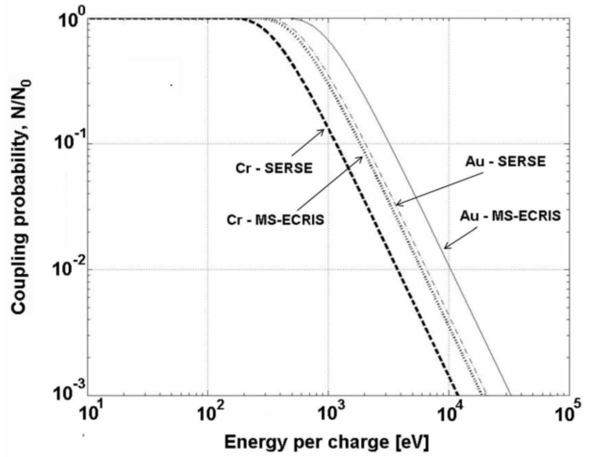

Figure 2: Coupling probability for O plasma with Cr and Au as injected ions, vs. the energy per charge.

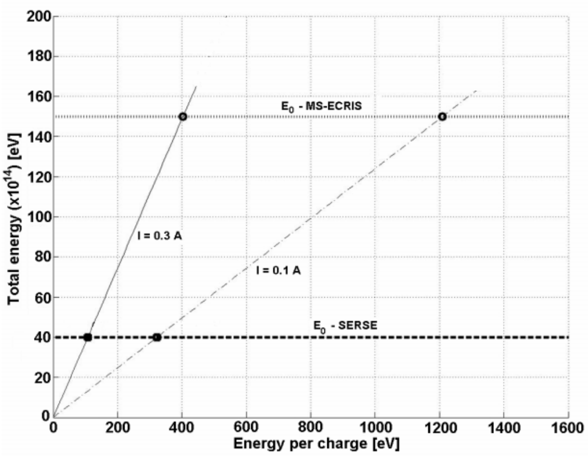

Figure 3: Comparison of total LIS beam energy and plasma energy content.

In particular, chromium (A_i = 52) and gold (A_i = 197) ion beam absorption in the oxygen plasma, with average charge state 6, length 12 cm, electron density $4 \cdot 10^{12}$ cm^{-3} for the SERSE source plasma, and $1 \cdot 10^{13}$ cm^{-3} for the MS-ECRIS one, have been considered. It must be underlined that the trend is quite similar for different ion species and that high coupling efficiency is obtained only for energy lower than 300 eV per charge state for the SERSE source and 1 keV for the MS-ECRIS source. The coupling efficiency is close to zero for energies per charge state higher than 10 keV for any case.

In order to avoid that the beam perturbs the plasma, the amount of transferred energy, E, should be lower than the initial total ion energy in the unperturbed plasma, E_0. Fig. 3 shows the total beam energy, E, in terms of the ion beam energy per charge ε_i (the two lines are corresponding to a relevant beam current, i.e. 0.1 A and 0.3 A) in comparison with the total energy of ions, E_0, in the plasma. A current of 100 mA can be tolerated up to energies of 300 eV for the case of SERSE and 1200 eV for the case of MS-ECRIS. The advantage of a 3rd generation ECRIS like MS-ECRIS is then clearly demonstrated. Even from the technical point of view, the advantage of MS-ECRIS is evident. In fact the larger plasma volume will permit higher beam current and the better vacuum will permit to extract higher charge states. Finally the presence of an additional port on the injection plug may permit to better focus the laser beam.

CONCLUSION

The proof-of-principle test of this method have shown that a cw regime is obtained for the highest charge states, that is particularly relevant for cyclotron–based facilities. The main results are here summarized: (i) the coupling between the LIS ions and the ECRIS plasma is effective; (ii) given a certain charge state, the ECLISSE method may permit a current increase and an improvement of CSD with respect to the conventional method (oven, sputtering, sample insertion); (iii) the efficiency of the high charge states buildup is limited by the high pressure in the plasma chamber due to outgasing, but it can be improved with MS-ECRIS.

These results are certainly satisfactory, but they could be even better, provided that the target is better cooled (thus limiting the outgasing). In addition, the 2nd harmonic of the laser frequency may be applied, that option not being available during previous tests.

Finally we expect that over the long term period the 3rd generation ECRIS with higher plasma energy content will make possible the production of 1 mA peak current for q > 25^+ that is a challenge of particular interest for many accelerator facilities. For cyclotrons, it will be possible to increase the charge state and then the energy, providing cw currents of some tens or even hundreds μA, exceeding by one order of magnitude the currents available with classical methods, as resistive oven or sputtering.

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