STUDY OF CHARGE STATE ENHANCEMENT BY MEANS OF THE COUPLING OF A LASER ION SOURCE TO THE ECR ION SOURCE SERSE

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Abstract

The possibility to produce intense ion beams from solid elements, by using a pulsed Laser ion source as the first stage of the superconducting ECR ion source SERSE is discussed in the following. The Laser ion source may be used to produce negative or positive ions and electrons that are injected into the plasma of SERSE.

The design of the experimental setup and the study of the extraction of ions from a target by means of Nd:Yag laser irradiation are briefly described. This Laser ion source will be located in the plasma chamber of the source SERSE, in presence of its magnetic field.

A simple evaluation of the charge state enhancement inside the ECR plasma is also presented in the following.

1 INTRODUCTION

The superconducting electron cyclotron resonance (ECR) ion source SERSE [1,2] has been designed and built for the axial injection of the Superconducting Cyclotron [3], yet operational at the Laboratori Nazionali del Sud in Catania.

The source tests have given excellent results for gaseous elements, in terms of extracted currents of high charge states, such as 2.6 eμA of Ar^{17+}, 2 eμA of Xe^{36+} and more than 200 eμA of O^{7+}.

Metallic ions will be produced with a high temperature oven, yet tested off-line up to an operational temperature of 2000°C [4], but for some elements the oven is not able to provide the correct vapor pressure to feed adequately the ECR plasma created by a support gas. For these elements the ion sputtering method may be used, but it is not the best solution for a few elements, as the refractory ones (Tantalum, Tungsten, Rhenium, etc.) and we plan to use a laser-based system to evaporate metals from a target.

The target will be negatively biased with respect to the plasma chamber so that electrons and negative ions are guided towards the ECR plasma. This procedure has already been used in a room temperature ECR ion source [5] with satisfactory results. In principle it allows to obtain the same charge state distribution (CSD) than in the case of production of ions from a gaseous element.

Considering that the laser beam, impinging onto a target, creates not only neutrals and negative ions but even positive ions, depending on the available laser power density [6], we are also investigating the possibility to obtain high charge state ion beams from a pulsed laser ion source (LIS).

The laser produced ion beam will be injected in the main ECR plasma, from which a pulsed or continuous beam of very high charge state ions will be extracted.

Two different experiments will be carried out with this setup: the former will focus on the production of the negative ions and electrons by means of a laser beam of moderately high power density and on the following coupling of such ions (and eventually of neutrals) to the ECR plasma produced in the SERSE chamber by the support gas. This experiment will follow the main guidelines of the investigations already carried out elsewhere [5,6] with the advantage of using the SERSE plasma as a powerful ionization tool (its plasma density is above 10^{12} cm^{-3}, the confinement time is in the order of some tens ms).

The latter experiment will consist of the production of ion beams with a relatively high charge state by means of a higher laser beam density [7,8] and of the further ionization in the ECR plasma. In this case two main issues are to be investigated:

1) the optimization of the coupling of the fast ions expulsed from the LIS, which entails that the ions from the target, placed at negative potential, are decelerated in order to have a good interaction with the plasma;

2) the use of a pulsed source as injector of a CW source could lead to high beam noise, if the repetition rate of the laser is not much higher than the inverse of the ion lifetime in the plasma (typical ion lifetimes for a high confinement ECR plasma are in the range of tens ms).

This limitation appears to be very critical, because our experimental setup is based on a laser with a repetition rate of 30 Hz, which hardly fulfill this condition, but the operation of this setup in pulsed mode can be taken in consideration for pulsed beam accelerators.

2 INJECTION OF NEGATIVE IONS IN THE ECRIS PLASMA

The ECR ion source SERSE is described in [1,2]. Because of the cryostat, there is no radial accessibility to the plasma chamber and even the axial accessibility is poor because of the extraction system on the left side and the biased electrode, the microwave and gas inputs on the right side. Therefore the easier solution is to inject the laser beam from the extraction hole, because laser optics cannot be used inside the ECR plasma chamber. The laser beam will be injected from the 0° port of the 90° analysis magnet (fig. 1), on-axis with the extracted beam.

In fig. 2 a lateral view of the experimental setup is also shown. The plasma electrode with a 8 mm hole (located 250 mm inside the cryostat, on right side in fig. 2) will be replaced by another with a 12 mm hole, to prevent any damage to the extractor because of the erosion caused by the halo of the laser beam. The sketch in fig. 3 shows the target and the plasma chamber. The target will be located in place of the existing negatively biased electrode.

A 4 mm removable shield, cylindrically shaped, will be used inside the chamber to collect the cluster emission from the target. They will be changed periodically to maintain the plasma chamber clean, which is mandatory for a good production of high charge states ion beams (charge exchange processes can reduce substantially the yield of the highest charge states). We expect to pump the target holder chamber with the same turbomolecular pump which is used now for the injection side of SERSE, with the vacuum in the low 10^{-8} mbar.

The Nd:YAg laser (λ=1064 nm) will be aligned onto the target, by means of a He-Ne laser, and a focusing lens will be placed at about 20 cm from the 0° flange of the magnet, in order to have a beam spot dimension variable from 0.5 to 8 mm at the target position. The Nd:YAg laser will be operated at some hundreds mJ up to a maximum of 0.8 J energy, with a repetition rate of 30 Hz or lower, in order to produce a plasma on the target. According to literature [5,6], neutrals and negative ions can be produced with a rate of 10^{13} to 10^{17} atoms/s, which is an appropriate feed rate for the ECR plasma. The positive ions should have not enough energy to surpass the barrier of few kV and they would be lost. In our experimental setup, for a power of the laser beam of 0.1 GW, on a target area of 1 cm^2 to 1 mm^2, the power density is W/d=10^8 to 10^{10} W/cm^2, in good agreement with [6], which foresees a maximum negative ion ejection for a laser density of 10^8 to 10^9 W/cm^2.

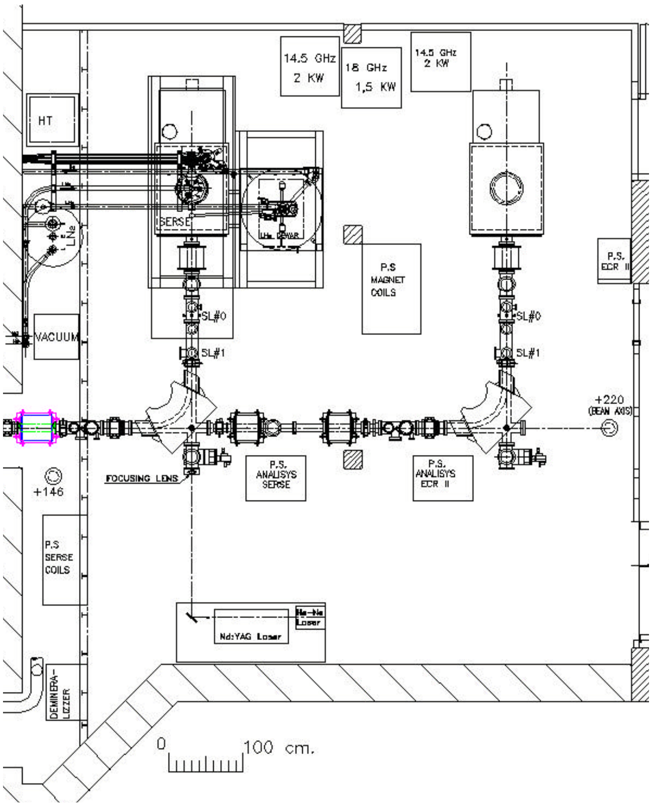

Fig. 1 - A plan view of the experimental room.

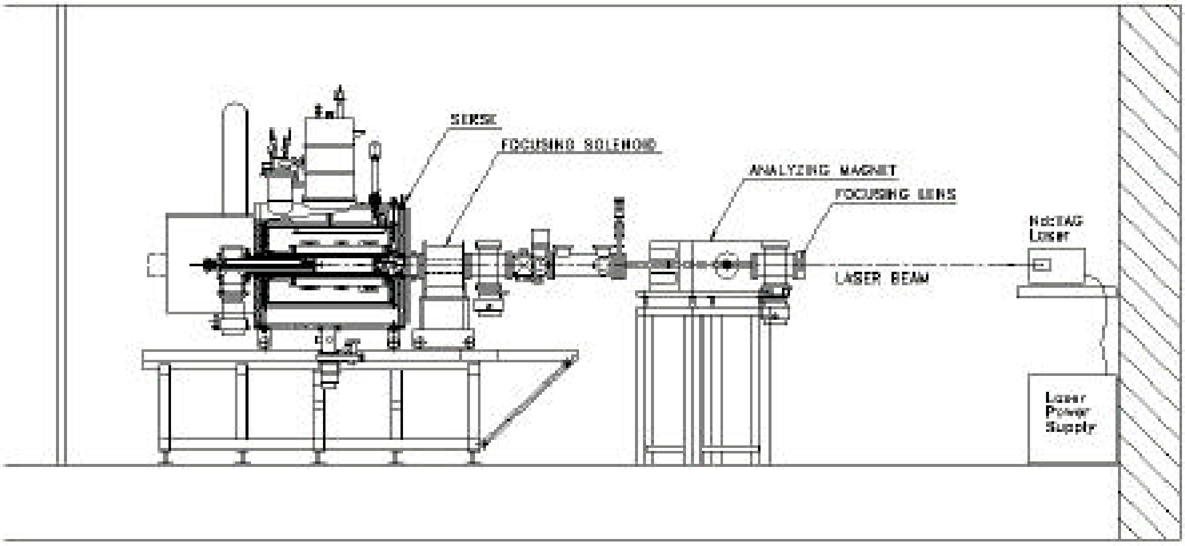

Fig. 2 - A side view of the experimental setup.

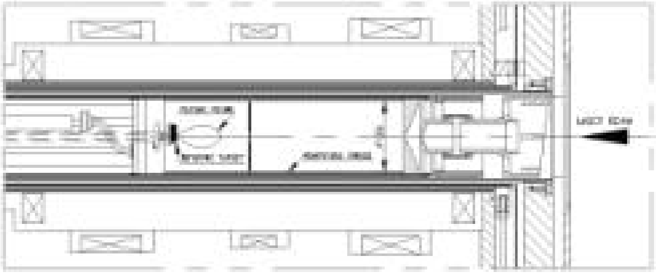

Fig. 3 - A cross section of the plasma chamber.

3 ECLISSE PROJECT (ECR COUPLED TO LASER ION SOURCE FOR CHARGE STATE ENHANCEMENT)

The second and the most interesting part of the experiment is devoted to the production of intermediate charge states ions with the LIS and to the charge state enhancement in the ECR plasma. The experience with infrared Laser ion sources [7,8] have shown that a laser beam with power density in the range from 10^{13} to 10^{15} W/cm^2 produces highly charged positive ions and electrons when it hits a target of high Z material [9].

This regime could be produced by the available 0.3 GW Nd:YAG laser only if the beam is focused in a spot smaller than 0.1 mm. Unfortunately such a spot cannot be obtained with our setup (minimum spot size is about 0.5 mm) and then only medium charge states can be created (e.g. q=10 or 15+ for the heaviest ions). The dependence of the average charge state on the laser power density is already known for some elements [9] and for a power density in the order of 10^{12} W/cm^2 the average charge state for Lead is about 10.

If the Laser Ion Source provides multiply charged ions to SERSE, the ions will be subject to ionizing interactions inside the ECR plasma and the average charge state extracted from the source will be higher than the one obtainable with ion sputtering or evaporation methods, provided that the ions from the LIS have an energy not so high to pass through the plasma with negligible interactions. If the ion energy is of the order of few hundreds eV, the coupling is effective, as demonstrated in [10,11] and shown in fig. 4.

Here the currents of Xe^{14+} extracted from an ECR source are given versus the potential between the 1^+ source and the ECR source, for a constant ion feed rate. This experience puts in evidence the capability of ECR plasma to further ionize, provided that the energy of ions injected is quite low.

If ΔV is the voltage of the target holder with respect to the potential of the ECR ion source and q is the charge state of the ion, all the ions with energy $E_{\mathrm{fast\ ion}}$ fulfilling the condition:

$$(E_{\mathrm{fast\ ion}} - q\, e\, \Delta V) \leq 500 \text{ eV}$$

will have a relatively high probability to be further ionized. In case of energies lower than qe ΔV the ions are decelerated to thermal energies and they will be neutralized when getting to the plasma. In this case the ECR plasma will ionize neutrals rather than ions and the enhancement mechanism will not occur. According to [10] the ionization is optimized for the ions whose energy allows not only the transit through the deceleration potential, but also through the plasma potential. On the other hand, if the energy of the ions is too high, the interaction with the plasma is poor and further ionization is not favored even if the occurring probability is still not zero.

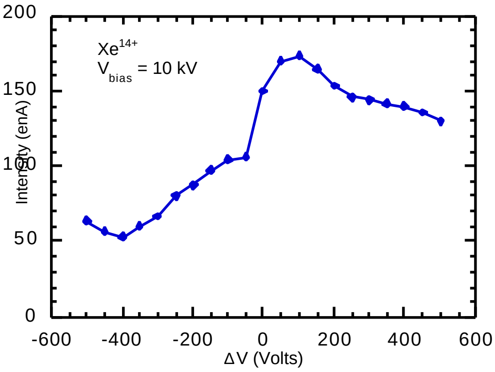

Fig. 4 - Xe^{14+} current from an ECR source vs. the potential between the two sources [10].

Considering that ion energies in the order of 20 to 50 keV per charge state have been observed for ions extracted from LIS working at power densities above 10^{13} W/cm^2 [7] and that in our experiment the power density of the laser is lower, we expect a <q> value lower than 20 and ion energy of few keV per charge state.

In order to optimize the coupling with a large range of variability, the target will be then biased up to -30 kV or less with respect to the ECR plasma chamber.

The following ECR ionization will depend on the quality factor $n_e\, \tau_i$ (where n_e is the electron density and τ_i is the ion confinement time) and on the electron temperature T_e of the ECR plasma. The characteristic values of the electron temperature are some keV and the densities above 10^{12} cm^{-3}.

If the calculations are carried out with a population of highly charged ions, rather than on a population of neutrals, as starting point, the average charge state <q> increases, provided that the vacuum is low enough. Being fixed the plasma density, the injection of medium charge state ions should work as the increase of ion confinement time.

The calculation with a numerical code based on the balance equation of the plasma have shown [12] that the injection of highly charged ions has a poor effect if the beam is not compensated at the beginning of the interaction with the plasma. In fig. 5 the currents for Uranium ions are reported vs. the charge state for three different cases:

1) neutrals created by ion sputtering process, with oxygen as mixing gas, for rf power above 3 kW and high mirror ratio, in order to have a plasma density close to cutoff (curve 1);
2) the same plasma density and rf power, but with injection of Uranium ion beam (rate equal to 10^{16} pps) with <q>=20 not compensated (curve 2);
3) the same as in case 2), but with space charge compensation (curve 3).

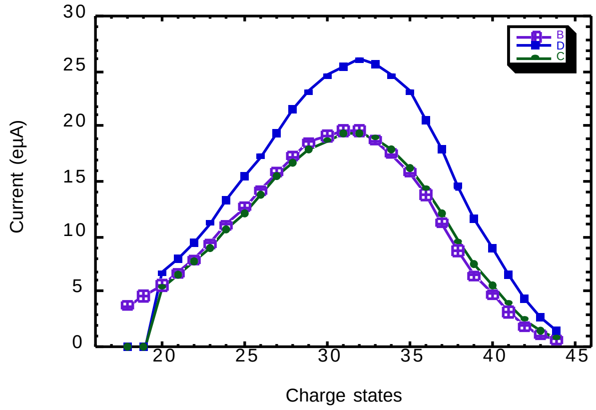

Fig. 5 - Intensity of different charge states of Uranium for injection of neutrals (curve 1), of ions (curve 2) , of ions and electrons (curve 3).

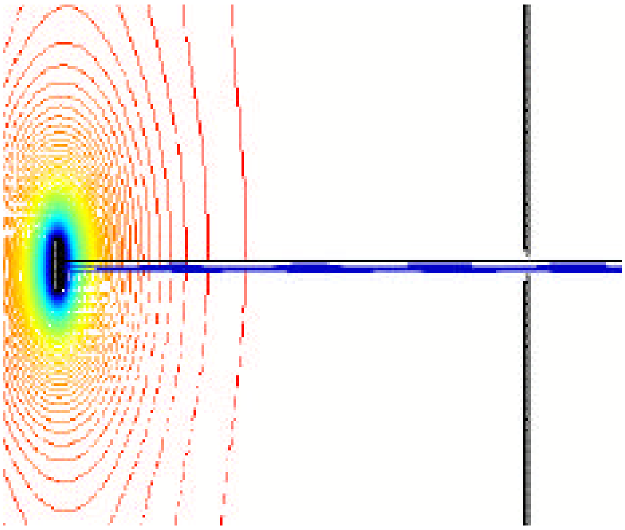

Fig. 6 - Beam transport from the Laser source target to the ECR plasma chamber (2 mm spot).

In order to evaluate the transport efficiency, we have carried out some simulations with the code KOBRA3D [13]. The magnetic field guides the plasma plume towards the ECR plasma with an efficiency of 100% (the plasma diameter is quite large, between 50 and 70 mm), if the magnetic field is parallel to the plasma expansion, as it is for a laser beam coincident with the magnetic axis and a target surface perpendicular to them. In the case of SERSE the axial magnetic field is in the range of 2 to 2.7 T which maintains the plume very narrow (about 1 to 2 mm). In fig. 6 the calculations were carried out for a 100% neutralized beam with <q> = 20, leaving the LIS in a volume where B=2.5 T along the axis and B=0 perpendicular to the axis. The electric potential between the LIS and the plasma chamber is 30 kV and the energy of the beam at the LIS exit is 32 keV per charge state. The initial spot represented in fig. 6 is 2 mm and the final one is 1.4 mm.

4 CONCLUSIONS

The possibility to increase the capability of the source SERSE, by enhancing the average charge state <q> and the currents of the extracted beams with the injection of moderately high charge beams, seems to be realistic and a test stand is under construction. The crucial point of the experiment is the minimization of the energy spread of the ions extracted from the laser ion source, which will be studied off-line, and systematic evaluation of the energy spread and charge state distributions will be carried out with the diagnostic developed at IPPLM in Warsaw [14]. Once that all the parameters of the laser ion source will be optimized, the laser ion source will be coupled to the ECR ion source. Meanwhile, the modeling of ECR plasmas in presence of beam injection will be investigated theoretically, in order to minimize the time needed for the commissioning.

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