

R&D of ECR ion sources: news and perspectives

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Abstract The future accelerators need ion beams with higher charge state and higher current. This demand will be met by the “third generation Electron Cyclotron Resonance Ion Sources” (ECRIS) which will make use of improved plasma confinement by means of higher magnetic field and of higher microwave frequency, thus boosting the performance of nowadays ECRIS operating at the frequency of 14 and 18 GHz. The possibility to obtain confining fields exceeding 4 tesla, by means of special design of NbTi superconducting magnets, open the way to a new operational domain, at the typical frequencies of gyrotrons, above 28 GHz, with plasma densities never achieved before in ECRIS (10^{13} cm^{-3} and higher). The test of SERSE at 28 GHz, confirming the theoretical frame on which the third generation ECR sources design is based, will be presented; a synthetic review of the new generation ECRIS is carried out, with a particular emphasis on the design of the GyroSERSE source. Finally, the scheme of an innovative hybrid source will be outlined and a short description of the ECLISSE (Electron Cyclotron Resonance ion source Coupled to a Laser Ion Source for charge State Enhancement) experiment is hereinafter presented.

Key words ion-source • plasma

Introduction

At many large accelerator facilities there is a strong need of higher currents of highly charged ions, both pulsed and cw mode. At INFN-LNS the ultimate goal for nuclear science is to produce between 0.5 and 2 μA of U^{60+} (cw mode) and other heavy ions to increase the energy of the beam extracted from the superconducting cyclotron (the advantage of coupling a 3rd generation ECRIS to an accelerator is clearly shown in Fig. 1). A similar advantage can be obtained by any other accelerator facility based on a linac or a cyclotron, and particularly relevant is the gain for the future accelerator facilities as LHC in Europe and RIA in USA which needs currents of a few hundreds μA or even thousands (over a longer time period, the next project of GSI needs 6 mA of highly charged heavy ions as Pb^{25+} (private communication – N. Angert).

Another requirement of the future radioactive beam facilities based on a linac or cyclotron post-accelerators is to have an efficient $1+/N+$ charge breeding process in order to obtain high charge states ($Q > 20+$) with an ionisation efficiency higher than 20% on a single charge state.

In 1999, a research project called “Innovative ECRIS” was established to meet all these requirements. Some tests were carried out with a high frequency–high power (28 GHz – 10 kW) microwave transmitter coupled to the superconducting source SERSE at INFN-LNS [5, 10]. The results were outstanding and beam intensities never obtained before were measured. Nevertheless, it was evident that more intense beams can be obtained with an adequate source design by means of a powerful plasma confinement system of higher RF power density and of a higher extraction voltage. This is the aim of the GyroSERSE source, a high

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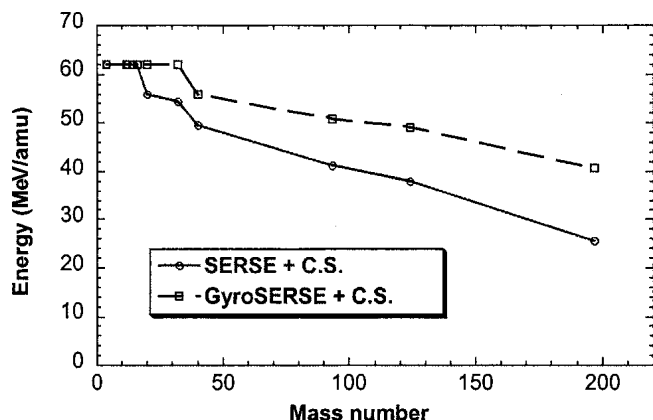


Fig. 1. Maximum energies achievable from the K-800 superconducting cyclotron of INFN-LNS with the best existing ECRIS and the 3rd generation ECRIS, GyroSERSE.

confinement superconducting source optimised for 28 GHz and designed following the scaling laws [8] and the high B mode concept [1], described in the next paragraph.

Test of scaling laws from 2.45 GHz to 18 GHz

In 1987, from the results of the MINIMAFIOS source at 10 and 16.6 GHz, Geller inferred the scaling laws [8] which were for a few years the guiding line for ECRIS designers and users:

$$(1) \quad q_{\text{opt}} \propto \log B^{3/2}$$

$$(2) \quad I^{q^+} \propto f^2 M_i^{-1}$$

where q_{opt} is the optimal charge state, B is the peak field of the magnetic trap, f is the microwave frequency, I^{q^+} is the intensity of the charge state q and M_i is the ions' mass.

In 1993, different sources gave results which put in discussion the statement that simple scaling laws exist and a more complicated framework was revealed. In particular, a series of experiments carried out on the SC-ECRIS at MSU working at 6.4 GHz changed the ECRIS scenario, because this source was able to deliver ion currents exceeding at best 10 and 14 GHz sources at that time. These results have been explained by the so-called High- B mode concept [1, 3] which states that by increasing the confining field the ECR sources work better because of higher electron densities and temperature. This concept, which can be summarized by the formula:

$$(3) \quad B/B_{\text{ECR}} > 2$$

where B_{ECR} is the magnetic field corresponding to the ECR frequency, does not conflict with frequency scaling, but it limits the benefits of frequency scaling to the sources with a very high confining field.

In 1998 and 1999, extensive tests to validate the scaling laws have been performed on the SERSE ion source at INFN-LNS [4] and the results of these tests are shown in Fig. 2, where the beam currents obtained at different levels of radial confinement for frequencies between 2.45 and 18 GHz are compared. Except for the lower frequency,

the curves are quite similar, but all of them obey to formula (3). These results show the rules which an efficient ECRIS must follow to produce intense beams of medium and high charge states and that have been recently defined as the ECRIS standard model [14]:

- the last closed surface must be $B_{\text{last}} \approx 2B_{\text{ECR}}$;
- the radial magnetic field value at the plasma chamber wall must be $B_{\text{rad}} \geq 2.2B_{\text{ECR}}$;
- the axial magnetic field value at injection must be about $B_{\text{inj}} \approx 3B_{\text{ECR}}$ or more;
- the axial magnetic field value at extraction must be about $B_{\text{ext}} \approx B_{\text{rad}}$;
- the axial magnetic field value at minimum must be in the range $0.30 < B_{\text{min}}/B_{\text{rad}} < 0.45$.

Summary of the tests of SERSE with a 28 GHz gyrotron

In order to define the best parameters for the design of 3rd generation ECRIS, experiments have been performed with SERSE, the fully superconducting source installed at LNS in Catania, coupled to a 28 GHz gyrotron-based generator. It was the first time that this high frequency has been launched into a minimum- B structure and the first part of tests was devoted to the study of the RF coupling to the plasma. This parameter has a paramount role on the high charge states buildup, as the electron temperature is dependant on the RF power and the injection of a few kW (about 1 kW/l) in the chamber is needed to boost the electron temperature to the order of magnitude of keV.

For the tests of SERSE at 28 GHz, a 10 kW gyrotron was available, but only 2 to 4 kW were used in cw mode. The maximum power launched into SERSE was limited by the plasma chamber cooling power which was originally calculated for a maximum RF power of 2.5 kW at 18 GHz. In the afterglow mode, 6.5 kW has been launched at 10 Hz repetition rate (maximum duty cycle was 50%). A more detailed presentation of the RF propagation and coupling is given in [5].

According to [11], the optimum RF power launched into an ECRIS per volume unit is about 800 W/l in cw mode and 1.2 kW/l in the after-glow mode. Then, the performance at 28 GHz were limited by the RF power, as well as by the

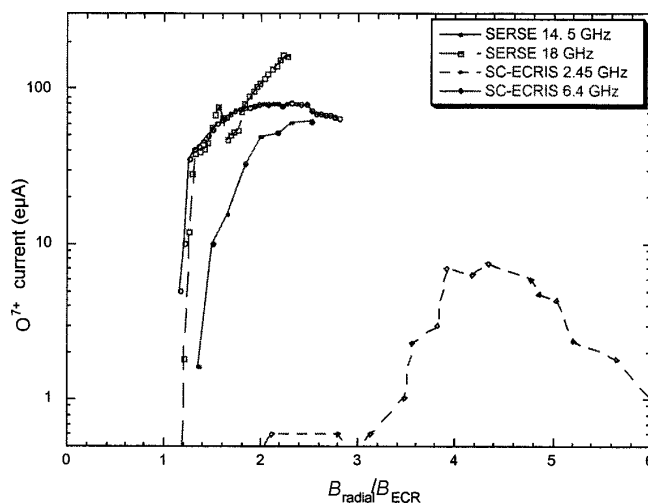


Fig. 2. A comparison of ECRIS performance at different frequency vs. the magnetic field.

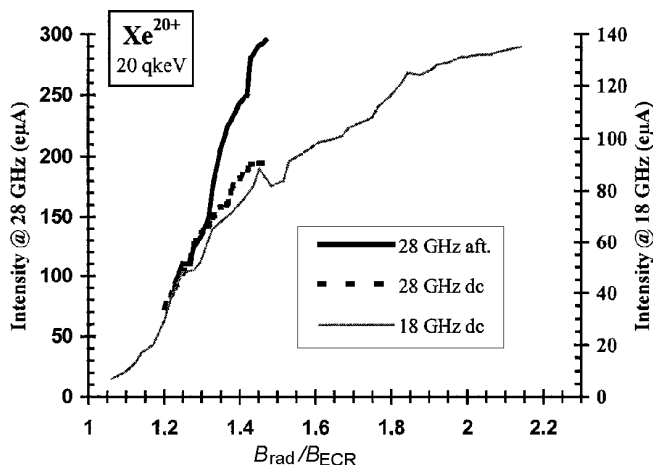


Fig. 3. Effect of radial magnetic field scaling on Xe^{20+} current.

poor magnetic confinement and by the low extraction voltage. Nevertheless, the 28 GHz operation permitted to get currents exceeding half mA of Xe ions with charge states up to 25+, as well as some μA of charge states between 38+ and 42+, the results which have been never obtained by any other source [5, 10].

The radial confinement had a major influence on the beam production for medium and high charge states as well, thus confirming the ECRIS standard model even at 28 GHz [3, 5]. Figure 3 presents Xe^{20+} intensity variation with the radial mirror ratio ($B_{\text{rad}}/B_{\text{ECR}}$) at 18 GHz and 28 GHz. The left Y-axis is proportional to the right Y-axis (multiplied by the square of the frequencies ratio), then one can notice the remarkable superimposition of both curves in dc mode. Being the technological limit for the SERSE radial magnetic field 1.45 T, one can easily extrapolate that a further 75% gain is possible with a higher magnetic field, while keeping the other parameters constant.

The state-of-the-art

In 1994, at INFN-LNS a design study of an ECRIS operating at 28 GHz was carried out. This project was suspended because the technology needed to the construction of a 3 T hexapole was not available at that time. In 1995, a proposal of a similar source has been done from LBNL, but with a significantly lower magnetic field, because of technological limits [19]. This project started in 1997 and after a long construction phase, it got its first plasma on May 2002 at 18 GHz only [13]. In 1999, after the successful exploitation of the SERSE source at a frequency of 14 and 18 GHz the GyroSERSE project was reconsidered, because the possibility to obtain confining fields above 3 tesla became realistic. In the meantime, the “Innovative ECRIS” collaboration was established with the aim to enhance the performance of ion sources. In this framework, the tests at 28 GHz with the sources SERSE and PHOENIX [17] were carried out. In particular, the PHOENIX tests confirmed the validity of a different approach, well suited for pulsed operations and for the production of high intensity of medium charge state ions, but not for the production of highly charged beams.

Some other innovative sources have been commissioned or built recently. The RIKEN 18 GHz source with hybrid

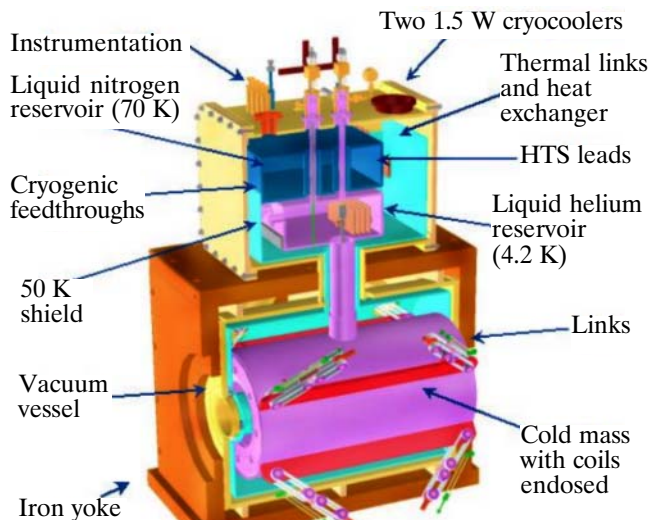


Fig. 4. An artistic view of the VENUS source at LBL.

magnets have given good results (1.6 emA of Ar^{8+}) [16] and even better results are expected from the above-cited VENUS source at the Berkeley National Laboratory (Fig. 4, [13, 14, 19]). This source is the first 3rd generation ECRIS to be completed, being able to operate in High- B mode at 28 GHz (the frequency upgrading is scheduled for summer 2003). Because of its excellent magnetic trap design, VENUS is deemed to get a leading role in the ECRIS field for the coming years, together with the Lanzhou source (Fig. 5, [20]), at least for a few years, which are needed for the construction of the GyroSERSE source. Other elegant and promising developments have been carried out in Nizhny Novgorod [21], Munster [15] and Grenoble [9], but none of these sources is expected to get the best results in terms of very high intensity–very high charge state ion beams production. The first source (Fig. 6) consists of a simple mirror trap able to produce high current, moderately charged ion beams, by means of huge power density at high frequency (up to 130 kW, pulsed mode, at 37 GHz); in spite of a complicate mastering of microwave power. This method looks to be interesting for applications, even if not immediately applicable for accel-

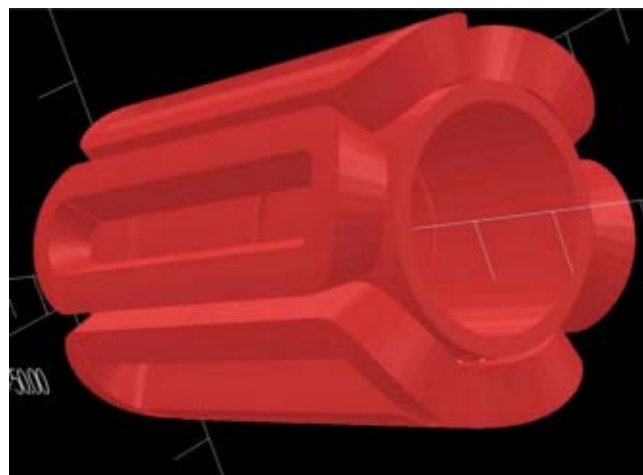


Fig. 5. The innovative design of the SECRAL source magnets at IMP, Lanzhou.

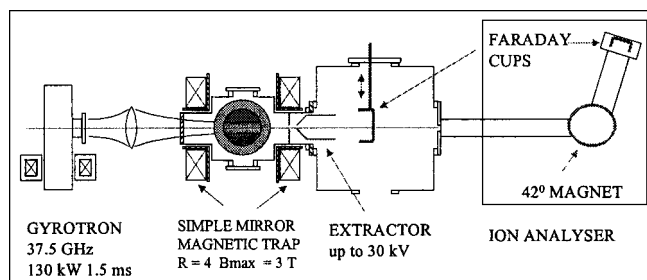


Fig. 6. The SMIS (Simple Mirror Ion Source) set-up at IAP in Nizhny Novgorod.

erators' operation. The second source is based on a B -minimum trap with a flat field and it is really promising in terms of medium charge state production. The last one, at CEA Grenoble, represents an extreme application of conventional techniques and it features the interesting possibility to inject 10, 14, 18 and 29 GHz microwave in the same plasma chamber.

This summary is not exhaustive and more developments in the ECRIS field are under way but are not considered here for limits of space. More information can be found in Ref. [12].

GyroSERSE: magnets and general design

The main features of the magnet design of the GyroSERSE source are given in Table 1. Figure 7 shows a model of the magnetic system with the solenoids and the hexapole surrounded by an iron yoke and followed by the focusing solenoid which is the first element of the beamline. The mechanical constraints have obliged to choose a well larger inner bore than for SERSE, because of the boundary conditions for the hexapole (the stored energy exceeds 300 kJ). The plasma chamber inner diameter is 180 mm, 50 mm larger than the one of SERSE.

Figure 8 shows the B -mod lines in the plasma chamber, featuring a value of the last closed surface of about 3 T. Then, the magnetic field will permit to operate in High- B mode, i.e. with a mirror ratio greater than 2, at any frequency between 28 and 37 GHz, or even at higher frequencies but with a more modest confinement.

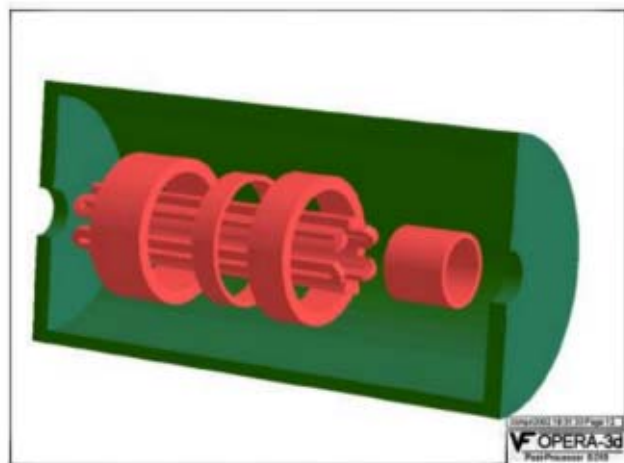


Fig. 7. The OPERA-3D model of the GyroSERSE magnetic system.

Table 1. Comparison between the main parameters of SERSE and GyroSERSE.

	SERSE	GyroSERSE
Frequency	14 GHz + 18 GHz	28–37 GHz
Maximum RF power P_{\max}	2 kW + 2 kW	10 kW
B_{radial}	1.55 T	3 T
B_1 (injection)	2.7 T	4.5 T
B_2 (extraction)	1.6 T	3.5 T
ϕ_{chamber}	130 mm	180 mm
L_{chamber}	550 mm	700 mm
ϕ_{cryostat}	1000 mm	1000 mm
L_{cryostat}	1310 mm	2150 mm
V_{extr}	20–25 kV	40–50 kV
$L_{\text{He consumption}}$	~4 l/h (100 l/day)	0

The coils of the magnetic system will be wound from NbTi superconducting composites and cooled by immersion in a liquid helium bath. The electrical connection to the power supply at room temperature will be made by high critical temperature superconducting current leads. The use of one or two cryocoolers will permit to operate the cryostat without external supply of liquid helium.

The mechanical design is aimed at reliable operations at 50 kV extraction voltage and at the achievement of a vacuum pressure of 10^{-8} mbar. In Fig. 9, a sketch of the GyroSERSE is presented. The 28 GHz RF coupling to the plasma will follow the guidelines of the one used for the SERSE 28 GHz experiment line [5] and a similar 28 GHz 10 kW gyrotron (TE_{02} output mode) will be used.

More information on the GyroSERSE source design can be found in [6].

The extraction optics and LEBT

The major difference between the existing ECRIS and the GyroSERSE source consists in the need to get rid of the space charge effects. By increasing the RF heating from 18 GHz to 28 GHz, one then had to face with extracted beams in the range of tens mA, which lead to larger emittances. This obstacle will be common to any 3rd generation ECRIS and the tests described before have demonstrated that the extraction voltage should be at least 40 or 50 kV to avoid the beam blow-up due to space charge forces.

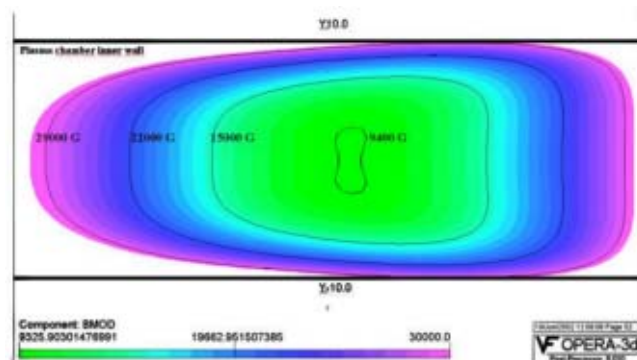


Fig. 8. The B -mod lines inside the GyroSERSE plasma chamber.

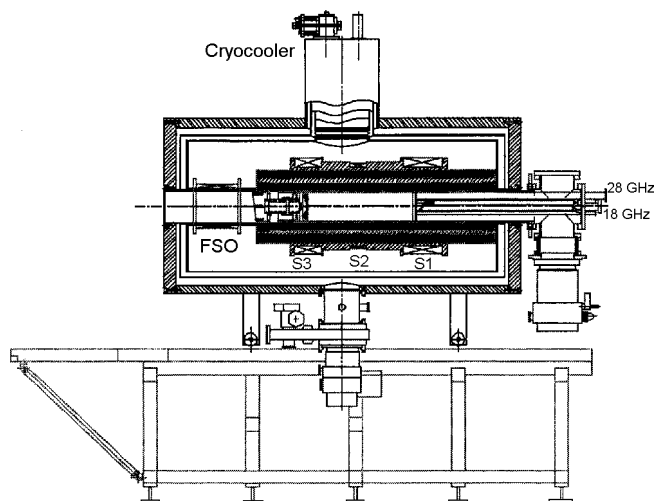


Fig. 9. A sketch of the GyroSERSE source.

A standard triode topology was chosen for GyroSERSE because of its simplicity, but a larger voltage and a smaller gap are considered. The calculated emittance ranges between 120 and 200π mm-mrad at 40 kV extraction voltage. An extraction voltage higher than 40 kV may further decrease the emittance. The different design options and the preliminary beamline simulations are described in more detail in Ref. [2].

Expected performance

The GyroSERSE expected performance for uranium and xenon beams compared with the ones of other sources are shown in Fig. 10.

These data show that the best (or at least a conservative and convenient) solution to provide very high charge states ion beams is the design of a third generation ECRIS, with an appropriate magnetic trap for 28 GHz operation, according to the ECRIS standard model.

Thus, the possibility to build a multipurpose source, able to provide one or two milliampere of medium charge state beams as Pb^{25+} and $e\mu A$ -level intensity of Pb^{50+} without major modifications (just by changing the gas and RF power knobs), is interesting for many laboratories and a Joint Research Project will be submitted soon.

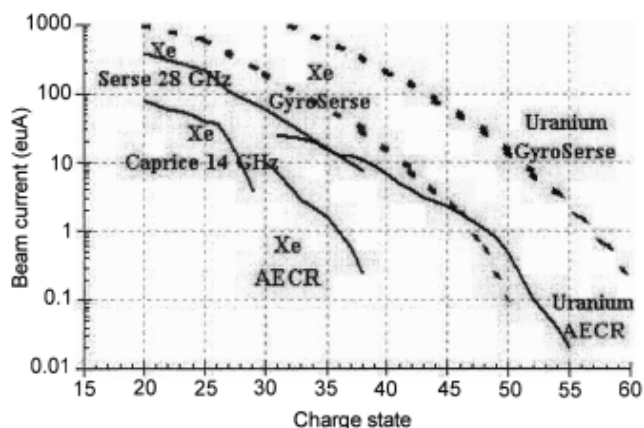


Fig. 10. The GyroSERSE expected performance compared with other sources' performance for uranium and xenon beams (cw mode).

The ECLISSE project

A novel approach to highly charged ions production was proposed at INFN-LNS. The ECLISSE method (ECR ion source Coupled to a Laser Ion Source for charge State Enhancement) is based on the coupling between a Laser Ion Source (LIS) and ECRIS. The theory suggests that this concept may be effective provided that the ion energy from the LIS is of the order of a few hundreds eV, i.e. sufficiently low to permit the trapping and further ionisation in the plasma region of ECR ion source [7].

Preliminary experiments carried out at IPPLM in Warsaw and at LNS have demonstrated the feasibility of such hybrid ion source. An extensive description of the ECLISSE method and of the preliminary experiments can be found in [7, 18].

The aim of the experiments consisted mainly in the minimization of the multiply charged ions energy of the emitted ion current maximization and in the study of etching rates at high repetition rates of the laser. A 900 mJ/9 ns Nd:YAG laser was used in the experiments; single pulse regime and 30 Hz repetition rate regime were used and the maximum power density was in the range of 10^{10} W/cm³.

Preliminary measurements indicate that near the ion production threshold, the ion energy has an average value of around 100 to 300 eV per charge state. These conditions

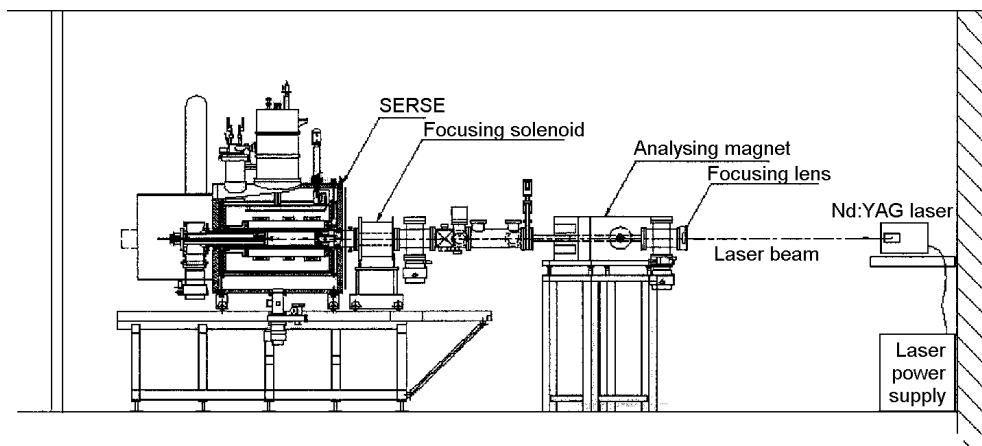


Fig. 11. A side view of the ECLISSE experimental set-up.

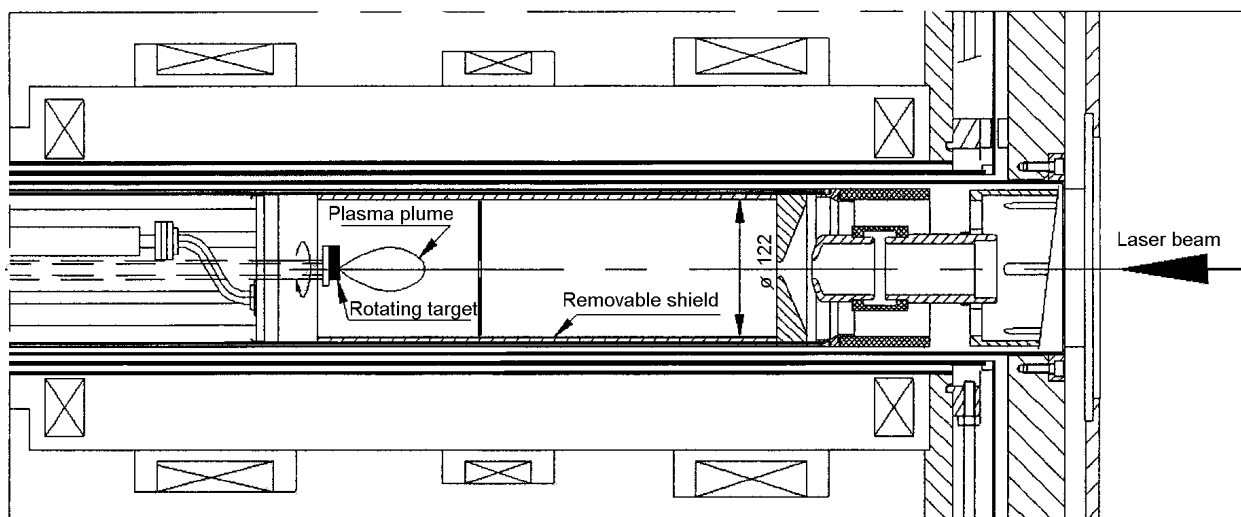


Fig. 12. A cross section of the SERSE plasma chamber, modified for the ECLISSE experiment.

are favorable for injection of these ions in the ECRIS. The amount of LIS-produced ions was also in good agreement with our expectation, as we have measured a yield of the order of 1 to 5×10^{12} ions/pulse/cm² with the maximum flux directed along the normal to the target surface. At 30 Hz repetition rate, it is possible to extrapolate a number of particles around 10^{14} pps/cm², i.e. an average current of the order of $15 \mu\text{A/cm}^2$. However, these values were obtained without magnetic focusing; the strong magnetic field of SERSE is expected to focus all ions ejected from the irradiated target, then such amount should be increased by one order of magnitude.

Figure 11 shows a scheme of the ECLISSE experiment at INFN-LNS; the assembly of the hybrid ion source has been carried out recently according to this scheme and the tests are going to begin. In Fig. 12, the cross section of the SERSE plasma chamber is shown with the metal target placed on a rotating rod in the injection side of the chamber. A displacement system has been prepared and tested to irradiate a sample on a fresh surface following an annular shape. The Nd:YAg laser has been aligned onto the target, by means of a He-Ne laser, and a focusing lens is placed at about 20 cm from the 0° flange of the magnet, in order to have a beam spot dimension variable from 1 to 8 mm at the target position.

The 3rd ECRIS generation offers attractive opportunities for the ECLISSE method, because of their larger plasma length and of the higher plasma density which will make less critical the limits on the LIS-produced ion energy, as demonstrated in [7]. Moreover, the larger plasma energy content $n_e kT_e$ will be much higher and higher beam currents injected by the LIS may be tolerated by the plasma.

Conclusions

The development of ECR ion sources have permitted in the recent years to improve significantly the performance of accelerators in general, and of cyclotrons in particular. The investment has been relevant in many laboratories, but the advantages have overwhelmed the costs and now many laboratories in Europe, USA and Asia have planned

the construction of innovative ECRIS or they are going to follow this road. New concepts are still going to be studied and a large increase of currents is expected, thus confirming that this type of research is still in its youth.

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