# ADVANCED ECR SOURCES FOR HIGHLY CHARGED IONS

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*Abstract*

New technologies for next generation Electron Cyclotron Resonance Ion Sources (ECRIS) are under development in many laboratories in the world, in order to achieve higher charge states and higher currents, especially for heavy ion beams. In particular, in the last few years the efforts have been concentrated on the coupling of high power high frequency microwaves (e.g. 10 kW, 28 GHz), on the study and the development of complex magnetic systems for an adequate plasma confinement, on the design of extractors able to minimize the emittance of heavy ion beams at high current level (tens of milliamperes).

The first injection of a high power (6 kW) of a 28 GHz wave in a B-min ECRIS was achieved in the SERSE superconducting source at INFN-LNS, Catania in 2000. High currents of ions were produced, both in pulsed and dc modes. Since then, other relevant improvements in the ECR source technology have been carried out. The talk will describe the major developments of ECRIS science and technology in Europe, Asia and US.

The conceptual design of a high magnetic field superconducting ECR ion source, named GyroSerse will be also described. This multipurpose ECR ion source aims to:

- the production of very high charge states of heavy ion beams (i.e. up to 1 eμA of $U^{60+}$ and 5 pμA of light ions up to $Ar^{16+}$ in cw mode).

- the production of high current of highly charged ions both in cw and pulsed mode such as 1 emA of $Xe^{20+}$ beams or 0.3 emA of $U^{30+}$ beams in dc mode and 6 emA of $U^{28+}$ in pulsed mode (with a pulse duration of 200 μs).

For injection into the accelerator, all these beams should fulfill the following requirements: energy from 2.5 to 5.0 keV/nucleon, emittance lower than 200 π mm.mrad and high reliability.

## 1 INTRODUCTION

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 increased plasma density 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).

A similar ECR ion source is useful for any accelerator facility based on a linac or a cyclotron, and particularly relevant is the gain for the future accelerator facilities (LHC and GSI in Europe and RIA in US) which needs currents of a few hundreds eμA or even thousands [1, 2, 3].

Even if relevant improvements were obtained by some conventional ECRIS in the recent past, the highest performance from ECRIS can be obtained only at higher frequencies and with higher confining fields, so that the B-minimum trap must be realized with superconducting magnets.

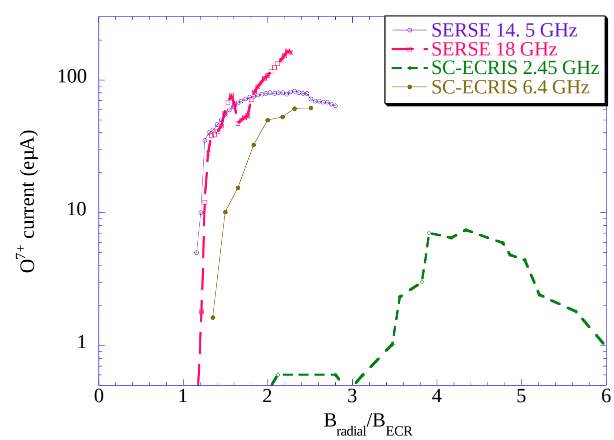


Figure 1: The comparison of ECRIS performance at different frequency versus the magnetic field.

## 2 EXPERIENCE AT LOWER FREQUENCIES

A large number of experiments have permitted to establish the rules that link the ion source performance to magnetic field strength and shape as well as to the frequency [4]. In particular systematic tests have been carried out with two superconducting magnets ECRIS, at

MSU-NSCL in 1993-95 [5,6] and at INFN-LNS in 1998-99 [7], in order to validate the scaling laws and the High B mode concept. The results of these tests are summarized by Fig. 1, which shows the beam currents as a function of the radial confinement for frequencies between 2.45 and 18 GHz. Already in 1995 we proposed [8] some 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 [9].

## 3 PIONEERING 28 GHZ OPERATIONS AND STATE OF THE ART OF ECRIS

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 3T hexapole was not available at that time. In 1995 the proposal of another fully superconducting magnets 28 GHz ECRIS, called VENUS, was presented from LBNL, with a lower magnetic field, according to the existing technology [10]. The construction of the source started in 1997 and its first plasma was obtained on May 2002 at 18 GHz [11].

In the meantime at INFN-LNS, after the successful exploitation of the SERSE source at 14 and 18 GHz and the validation of the High B mode concept, the GyroSERSE project was reconsidered, even because the possibility to obtain fields above 3 T became realistic.

In order to define the best parameters for the design of 3rd generation ECRIS, experiments have been performed with SERSE, coupled to a 28 GHz gyrotron-based generator [12,13,14]. 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, in order to achieve the cutoff density and the maximum electron temperature at the same time.

For the tests of SERSE at 28 GHz, a 10kW 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 have been launched at 10 Hz repetition rate (maximum duty cycle was 50%).

Even if the performance at 28 GHz were limited by the RF power, as well as by the poor magnetic confinement (the last closed iso-B surface being $B_{last} \approx 1.5\ B_{ECR}$) and by the low extraction voltage (26 kV maximum), the 28 GHz operations permitted to get currents exceeding half mA for Xe ions with charge states up to $25^+$, as well as some eμA of charge states between $38^+$ and $42^+$, results which have been never obtained by any other source.

The full set of results at 28 GHz, complementary to the ones in fig. 1, are reported in refs. [12,13,14]. The experiments performed at 18 and 28 GHz gave more detailed rules for the magnetic confinement:

a) the last closed surface must be $B_{last} \approx 2\ B_{ECR}$, i.e. the so called High B mode [4, 10], customary used by the Caprice source [16];

b) the radial magnetic field value at the plasma chamber wall must be $B_{rad} \geq 2.2\ B_{ECR}$;

c) the axial magnetic field value at injection must be at least $B_{inj} \approx 3B_{ECR}$;

d) the axial magnetic field value at extraction must be about $B_{ext} \approx B_{rad}$ ;

e) the axial magnetic field value at minimum must be in the range $0.30 < B_{min}/B_{rad} < 0.45$.

The ideal ECRIS should have the highest frequency as possible to reach the highest electron density as possible (cutoff density is about proportional to the square of the frequency) and its magnetic field should obey to all these rules.

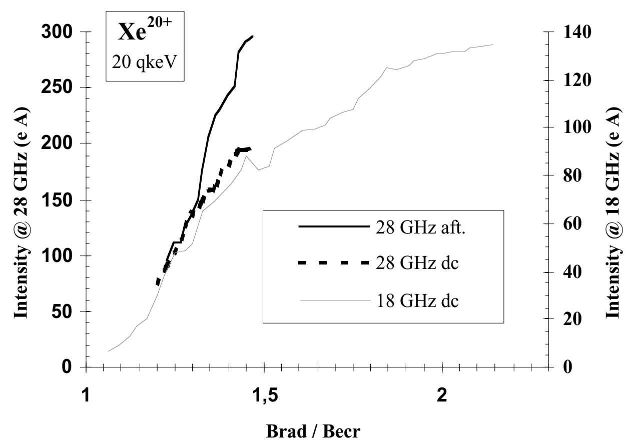


Figure 2 : Effect of the radial magnetic field on $Xe^{20+}$ current [13].

The radial confinement had a major influence in the beam production for medium and high charge states as well, thus confirming the ECRIS standard model even at 28 GHz. Fig. 2 presents $Xe^{20+}$ current increase with the radial mirror ratio ($B_{rad}$ / $B_{ECR}$) at 18 GHz and 28 GHz. The left Y-axis scale is obtained from the right Y- axis scale by multiplying it for the square of the frequency 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. Additionally, a higher extraction voltage increases the extracted currents according to the $V^{3/2}$ law [13,14]. Therefore we concluded that a SERSE-type source scaled for 28 GHz operations can be the ideal source for high charge states and high current beam production.

Some other innovative sources have been commissioned or built more recently. In particular the liquid-He-free RAMSES 18 GHz ECRIS with hybrid magnets have given good results at RIKEN, Tokyo, already almost as good as the previous room temperature 18 GHz source. The source is shown in fig. 3. The superconducting set of coils permits to get an axial magnetic field of 3 T and the NdFeB hexapole produce a radial field of 1.2 T at the plasma chamber wall radius. As reference for high current production, about 2 emA in dc mode of $Ar^{8+}$ are produced at RIKEN [17].

However, because of the cost of superconducting ion sources, source development could be achieved on room temperature devices. The room temperature GTS source at CEA Grenoble [18,19] represents an extreme application of conventional techniques and it features the interesting possibility to inject 10, 14, 18 and 29 GHz microwave at the same time in the plasma chamber, that will permit to deepen the knowledge of the ECRIS science and technology. In single frequency operation (18 GHz) beam current above 1 mA of $Ar^{8+}$ has been obtained and world record intensities have been broken for higher charge states like 420 µA of $Ar^{11+}$, 110 µA of $Ar^{14+}$ . On the other hand, 2.1 µA of $Ar^{17+}$ have been produced (two sources only are able to produce such high currents of H-like Argon, i.e. the superconducting SERSE source at INFN-LNS and the conventional AECR-U source at LBNL [20]). Beam intensities given by GTS confirm the necessity for any ECRIS to be operated with a confinement as presented in paragraph 3. With a reasonable extrapolation up to 28 GHz, one can think in reaching the 1 mA level for $Ar^{12+}$.

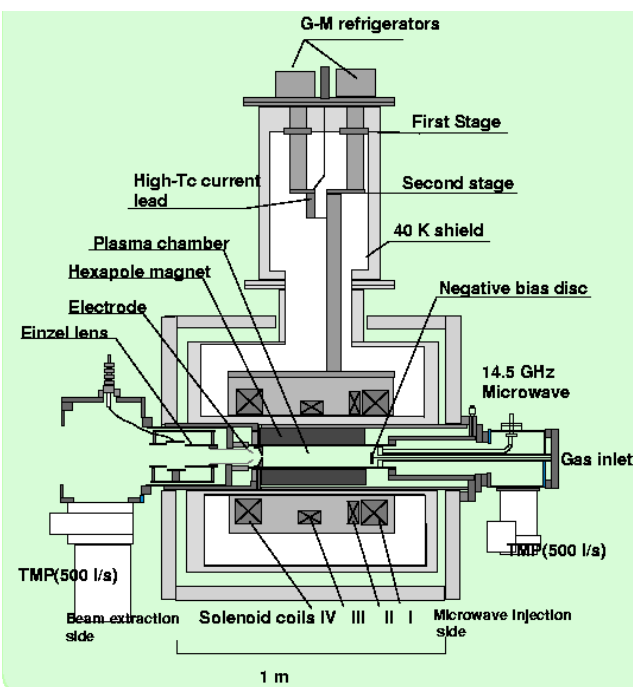


Figure 2: The RAMSES 18 GHz ECR ion source.

This summary of the ECRIS technology state of the art is certainly 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 [21].

It is worth mentioning in the next pages three appealing source designs based on fully superconducting magnets, as the SECRAL source of IMP, Lanzhou, the VENUS source of LBNL, Berkeley, and the GyroSERSE source.

## 4 SECRAL

The SECRAL source (fig. 4) has an innovative magnet design, which realizes a B-minimum trap by means of an hexapole external to the three solenoids, i.e. the contrary of what is usually done in any ECRIS. In this way the magnetic field is not so high as for VENUS and GyroSERSE design, and a much more compact source can be built, with a plasma chamber of 125 mm diameter and a total length of the source of the order of 1 m only.

The maximum radial field at the plasma chamber wall is expected to reach 2 T, which is almost the optimum field for 28 GHz operations.

The source construction is now under way and the magnets will be ready in summer 2003. As it is the case for VENUS, a preliminary series of tests at lower frequency will be carried out. More details on the SECRAL source are available in [22].

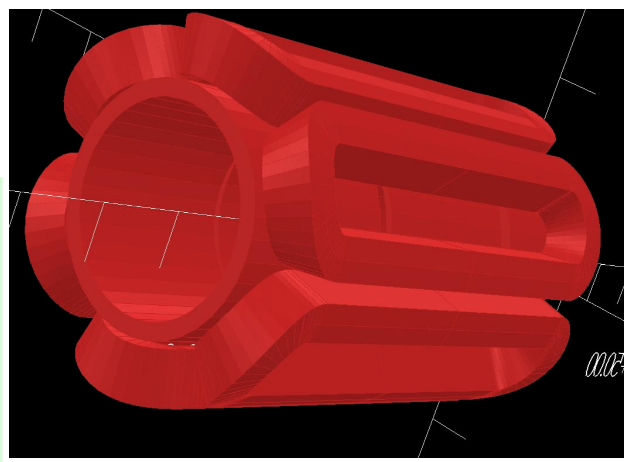

Figure 4 – The innovative design of the SECRAL source magnets at IMP, Lanzhou.

## 5 VENUS

VENUS source at the Lawrence Berkeley National Laboratory (fig. 5) is the first 3rd generation ECRIS to be completed. At this moment it is operating at 18 GHz, but it is able to operate in High B mode even at 28 GHz. Because of its excellent magnetic trap design, VENUS is deemed to get the leading role in the ECRIS field for the coming years and it is expected to fulfil the largest part of the requirements of the RIA project [3,9].

Some relevant improvements to the existing ECRIS technology were made to obtain large beams.

The plasma chamber has been designed to be able to handle 15 kW of RF power and inner surface is not round, as it presents cut-out at the location of plasma flutes. This original feature can improve the capability to withstand a large RF power which is needed to get the best results.

Special attention has been paid to the design of an adequate beam transport system, able to handle intense

beams. The experience of SERSE tests at 28 GHz has put in evidence the need to minimize the emittance growth and the solution chosen by the LBNL group is effective.
A detailed description of the VENUS design and its state of the art is presented in ref. [23].

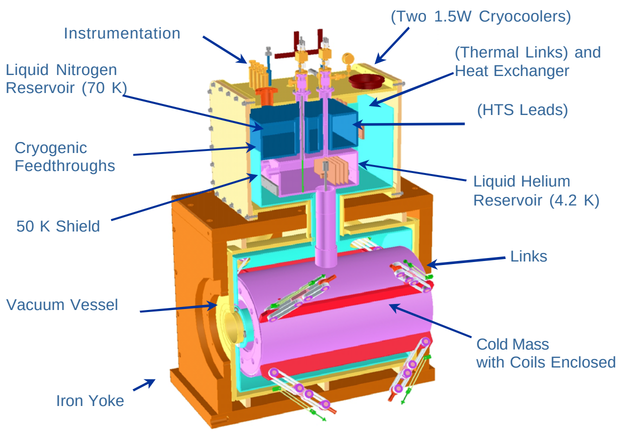


Figure 5 – An artistic view of the VENUS source.

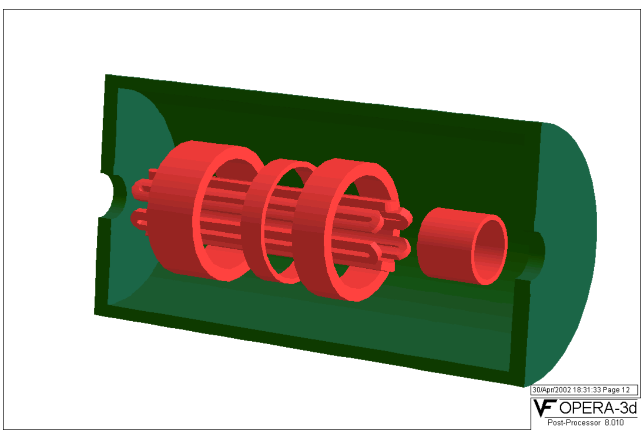


Figure 6: The OPERA-3D model of the GyroSERSE magnetic system.

## 6 GYROSERSE

The GyroSERSE project [24,25] was completed in 2001 and it was approved for funding in 2002-04. Unfortunately the construction was stopped because of budget limitations at INFN. Anyway further developments (study of the beamline, stray fields, etc.) continued, as there is a strong interest to install a 3rd generation ECRIS at LNS.

The main features of the magnet design of the GyroSERSE source and the comparison with the ones of SERSE, SECRAL and VENUS are given in tab. 1. Fig. 6 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 plasma chamber inner diameter is 180 mm, 50 mm larger than the one of SERSE, and total volume will be doubled with respect to that source.

The B-mod lines in the plasma chamber features 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.

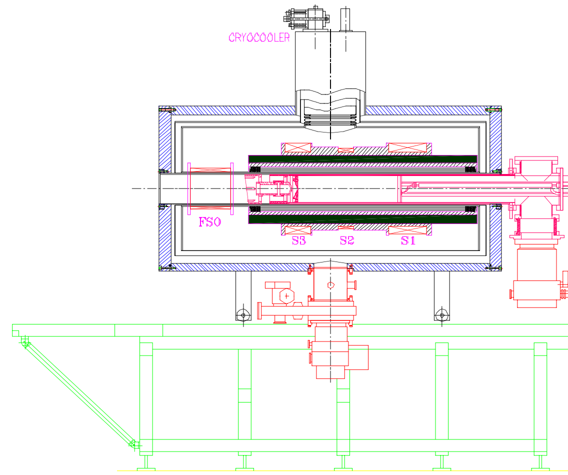


Figure 7: A sketch of the GyroSERSE source.

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 currents leads.

The use of two cryocoolers will permit to operate the cryostat without external supply of liquid helium. The mechanical design is aimed to reliable operations at 50 kV extraction voltage and to the achievement of vacuum pressure of $10^{-8}$ mbar. In fig. 7 the 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 [13] and a similar 28 GHz 10 kW gyrotron ($TE_{02}$ output mode) will be used.

One of the major difference between the existing ECRIS and the 3rd generation ECRIS consists of the need to get rid of the space charge effects. By increasing the RF frequency heating from 18 GHz to 28 GHz, one had to face with extracted beams in the range of tens mA, which lead to larger emittances. Then the extraction voltage should be at least 40 kV to avoid the beam blowup due to space charge forces. 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 200$\pi$ 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 details in ref. [26].

More information on the GyroSERSE source design can be found in [24,25].

## 7 CONCLUSIONS

In the next three or four years a significant increase in the ECRIS performance is expected, as soon as the VENUS and SECRAL sources will be operating at 28 GHz.

In general, the trend to higher currents of multiply charged ions is expected to steadily continue. As an increase of one order of magnitude per decade was obtained over last twenty years, we are confident that multi-mA production can be possible by the end of this decade. As for the highest charge states, up to now achievable by Laser Ion source (with poor reproducibility and bad emittance) and by Electron Beam Ion Sources (with low currents), we expect that technology improvements can allow to increase the competition, with the production of intense dc beams with good emittance and reproducibility, up to $60^+$ charge state and even more.

## 8 ACKNOWLEDGEMENTS

We acknowledge the support of the European Community – Access to Research Infrastructure action of the Improving Human Potential Programme, contract HPRI-1999-50014.

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Table 1: Comparison between the main parameters of SERSE, SECRAL, VENUS and GyroSERSE.

| | **SERSE** | **SECRAL** | **VENUS** | **GyroSERSE** |
|---|---|---|---|---|
| Frequency | 14 GHz +18 GHz | 18 – 28 GHz | 18-28 GHz | 28-37 GHz |
| Maximum RF power $P_{max}$ | 2 kW + 2 kW | 10 kW | 10 kW | 10 kW |
| $B_{radial}$ | 1.55 T | 2.0 T | 2.0 T | 3 T |
| $B_1$ (injection) | 2.7 T | 4.0 T | 4.0 T | 4.5 T |
| $B_2$(extraction) | 1.6 T | 2.0 T | 3.0 T | 3.5 T |
| $\phi_{chamber}$ | 130 mm | 126 mm | 140 to 152 mm | 180 mm |
| $L_{chamber}$ | 550 mm | 804 mm | 1030 mm | 700 mm |
| $\phi_{cryostat}$ | 1000 mm | 900 mm | 1060*970 mm | 1000 mm |
| $L_{cryostat}$ | 1310 mm | 1000 mm | 1070 mm | 2150 mm |
| $V_{extr}$ | 20 kV (25 max) | 40 kV | 30 kV | 40-50 kV |
| LHe consumption | ~4l/h (100 l/day) | 1 l/h | 0 | 0 |