INTENSE HEAVY ION BEAM PRODUCTION WITH ECR SOURCES

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Abstract

An average increase of about one order of magnitude per decade in the performance of ECR ion sources was obtained since the time of pioneering experiment of R. Geller at CEA, Grenoble; this trend is not deemed to saturate at least in the next decade, according to the increased availability of powerful magnets and microwave generators. Electron density above 10^{13} cm^{-3} can be obtained by 28 GHz microwave heating, but only an adequate plasma trap may allow to exploit that plasma for heavy elements ionization. The optimization of the magnetic field and of the other different parameters affecting the ECRIS plasma has been carried out in the past and more recently a special emphasis was given to the coupling of microwaves to plasma.

The state-of-the-art of ECR ion sources will be presented along with long-term perspectives related to the possibilities opened by higher frequency generators, as 60 GHz gyrotrons, even in case of moderate confinement trap, by combining the large plasma density with larger escape rates in order to get very high ion beam currents.

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 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 new generation of ECRIS will be useful for any accelerator facility based on a linac, and particularly relevant will be the gain for some facilities (LHC, SPIRAL2 and FAIR in Europe, RIA in US, RIBF in Japan) which needs currents of a few hundreds eμA or even mA [1-5].

The operation scheme of the ECR Ion Sources is usually described by the so-called Standard Model, namely the model that considers both the Scaling Laws [6] and the High-B Mode [7]. However further improvements are possible not only with more powerful hardware according to these laws but also with a better comprehension of phenomena related to the interaction between microwaves and electrons in the plasma, that is still far from optimization.

The experiments in the last twenty years [8,9] have clearly demonstrated that the ideal magnetic confinement trap is made of a mirror field exceeding 3 times the resonance field (which is 0.5 T for 14 GHz and 1 T for 28 GHz) and of a radial field of hexapolar type, exceeding 2 times the resonance field. If a similar B-minimum trap is provided, the scaling of the beam current with the square of the frequency occurs, according to Geller's law [6], as shown in fig. 1 for the currents obtained from the SERSE source at INFN-LNS at three different frequencies, that follow the same trend. Further details are given in [8,9].

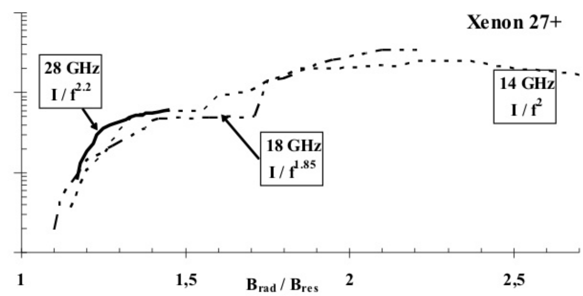

Figure 1: Xe^{27+} current obtained at three different frequencies according to the frequency scaling.

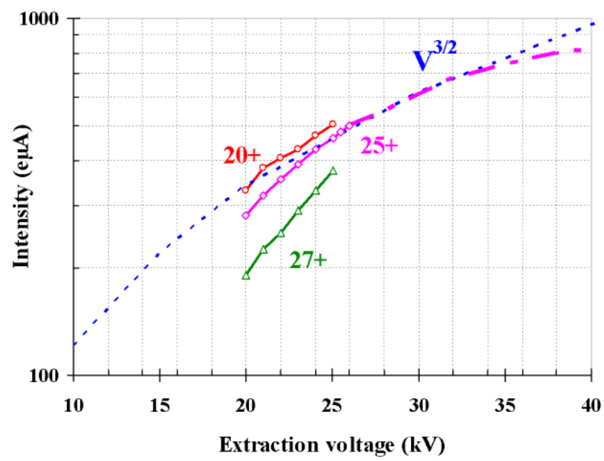

Figure 2: Increase of the beam current with the voltage for three charge states of Xenon.

Anyway other experiences [10] have shown that the ability to provide high electron temperature is crucial for highly charged ion beams production and the coupling of about 0.6 to 0.8 kW/l is mandatory to get optimum results. Once that enough rf power is coupled to ECRIS (and that the confinement is good enough to not allow to warm electrons to get lost) it has been shown that the current extracted from ECRIS is not plasma-limited but space-charge-limited, in the domain experienced up to date. In fig. 2 the results of a test with 28 GHz-6 kW microwaves is shown: it can be observed that the increase follows a V^2 law, i.e. not simply following the Child-Langmuir law; in fact the source voltage increase affects positively the beam transport in the LEBT. For this reason

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the most of the recent projects of ECRIS use high extraction voltages (30 to 60 kV).

As for the management of space-charge dominated beams, it is well known that a carefully designed accel-decel extractor [11] is needed (fig. 3), along with a quiet and uniform plasma with low ion temperature; homogeneity in the plane of the plasma electrode is obtained through a large plasma cross section and an adequate uniformity of the magnetic trap. The position of the plasma electrode is relevant for the total beam current.

Whilst a significant comprehension of the science and technology of ECRIS is available for the above cited process, the ECR heating process and the establishment of high electron temperatures are subject of study. For example, the use of a traveling-wave tube (TWT) generator in place of a klystron-based generator has permitted a relevant increase of current of highly charged ions for the same rf power [10], as shown in fig. 4.

This result indicates that the energy absorption is not optimized and in fact the plasma energy content may be even one order of magnitude lower than the value expected, according to theoretical clues.

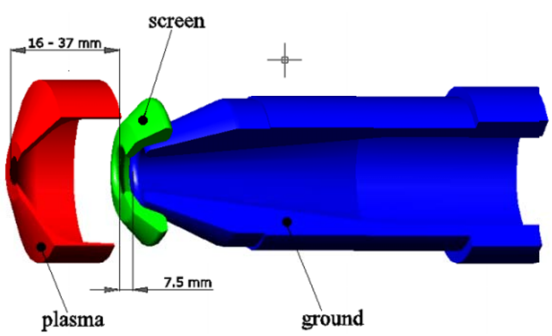

Figure 3: A typical accel-decel extractor for intense beams.

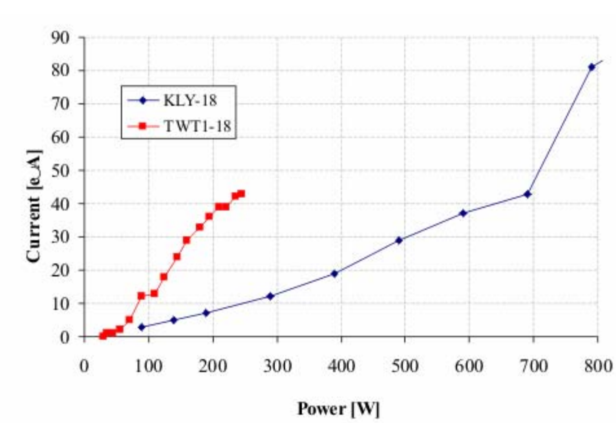

Figure 4: Comparison of the O^{7+} current produced with klystron and TWT, both operating at 18 GHz.

STATE OF ART AND NEW PROJECTS

ECR ion sources are commonly named according to the 'generation' i.e. according to the operating frequency, magnetic field and total output current; now a phase of transition is under way between the 2nd generation ECRIS (14 to 18 GHz, 1 to 2 T, mA current) and the 3rd generation ECRIS (28 GHz, 3 to 4 T, >10 mA extracted current). The source SERSE developed at INFN-LNS [9] and the source GTS developed at CEA, Grenoble [12], represent the bridge over the two generations, while VENUS [4] and SECRAL [13] are the first 3rd generation ECRIS to be built, even if the second still works at 18 GHz. For the next future MS-ECRIS [14] will use the best availabile magnet technology to create an optimum trap for frequency higher than 28 GHz. Some original tests with 75 GHz pumping on a simple mirror trap have been also carried out at IAP, that gave interesting information for future upgrades [15].

Figure 5: The SERSE source at INFN-LNS.

Table 1: Main features of SERSE and MS-ECRIS

	SERSE	*MS-ECRIS*
f	18 GHz	28 GHz
B_{radial}	1.55 T	2.7 T
B_{inj}	2.7 T	4.5 T
B_{ext}	1.6 T	3.2 T
$\Phi_{chamber}$	130 mm	180 mm
$L_{chamber}$	550 mm	650 mm
$\Phi_{cryostat}$	1000 mm	1100 mm
$L_{cryostat}$	1310 mm	1700 mm
V_{extr}	20-25 kV	40 to 60 kV
LHe	~4l/h	0
O^{8+}	~7 pμA	~20 to 50 pμA
Ar^{12+}	15 pμA	100 pμA
Au^{41+}	~10 pnA	~0.1 pμA
Xe^{20+}	----	~50 pμA
Pb^{27+}	----	40 pμA

SERSE and GTS

The SERSE source (fig. 5) was the first ECRIS able to operate in High B mode at the frequency of 18 GHz. The source was installed in 1998 at INFN-LNS and since then it has provided highly charged heavy ions (up to charge state 41^{+}) for the K-800 Superconducting Cyclotron. In table 1 some typical values of beam current are given, along with its main characteristics. In 2000 a series of tests at 28 GHz either in cw mode and in afterglow mode were carried out, demonstrating the ability of the ECRIS to produce mA beams of high charge states (up to 25^{+}).

In 2002 the magnetic structure of SERSE was reproduced with conventional magnets by the source GTS, that achieved very high currents for highly charged ions, for a few cases exceeding the SERSE ones, but its reproducibility and stability were less good, because of a smaller size of the plasma chamber, as shown by Girard et al. [16], who demonstrated that a large size plasma chamber can be helpful, especially for the highest charge states, affecting the confinement time of warm electrons.

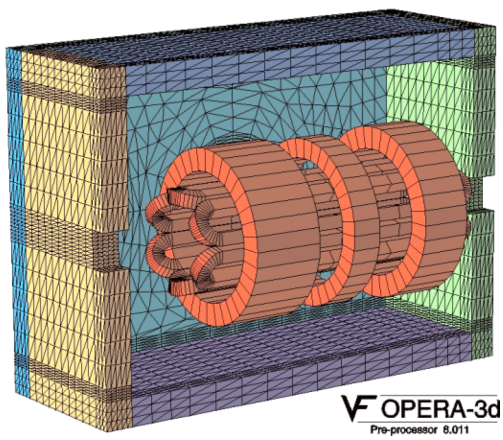

Figure 6: Sketch of the VENUS magnets.

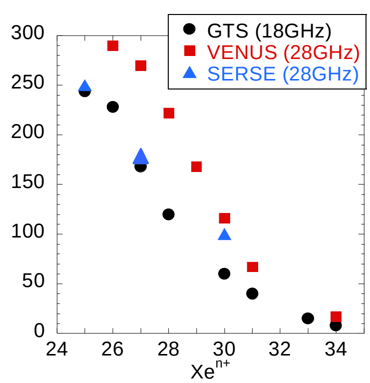

Figure 7: Comparison of the current for some charge states of Xenon for SERSE, GTS and VENUS.

VENUS

VENUS is now the only ECRIS that works routinely at 28 GHz and its characteristics as for magnetic trap (fig. 6) and as for microwave input are the most relevant. The maximum radial field exceeds 2 T and the maximum axial field is well higher than 3 T, the ideal value for High B mode operations at 28 GHz. This optimum field has permitted to couple up to 10 kW and to produce the highest current for many ion species; the best performances for some charge states of xenon are compared in fig. 7 with the best ones obtained by SERSE and GTS. Relevant results have been obtained for Ar^{16+} (133 eμA) and U^{34+} (110 eμA), a factor two below the requirements of the next generation of RIB facility [4].

SECRAL

The goal of the SECRAL source, under commissioning at IMP, Lanzhou (China) is the production of intense beam of Xe^{31+}, U^{41+} (dc beam of 50-100 eμA and pulsed beam of 100 to 200 eμA are requested for the Radioactive Beam Factory [13]). The goal was already reached for Xe^{31+} with operations at 18 GHz (68 eμA), but for heavier ions a 28 GHz upgrade must be considered, still possible for the available magnetic field. For lower charge states as Ar^{14+} (220 eμA) and Xe^{27+} (280 eμA) the SECRAL source exceeded the values of other 18 GHz sources and approached the values obtained by VENUS at 28 GHz.

The innovative feature of this source is the relative positioning of hexapole and mirror coils. Usually the hexapole is mounted inside the coils to limit the maximum field in the conductor, but that increases the size of the magnetic system. Smaller magnets have been built for SECRAL, with magnetic field close to the one of VENUS, but the maximum magnetic field reached by the hexapole is certainly a limitation for further scaling.

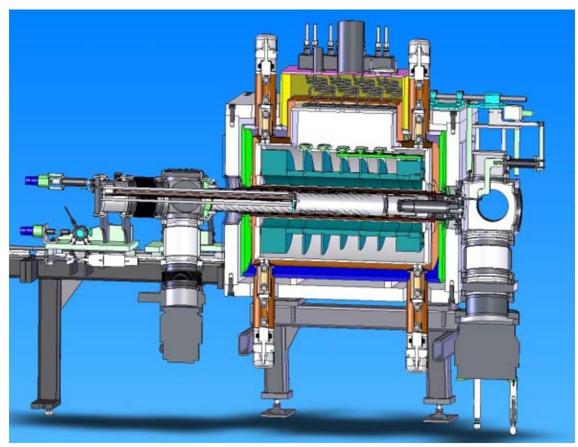

Figure 8: Sketch of the SUSI source.

The SUSI Source

The SUSI source (fig. 8) under construction at MSU-NSCL has been designed to fulfil the needs of intense beam for the Coupled Cyclotron Facility. Its maximum magnetic field was increased during the construction phase from the 2.6 T axial field, 1.5 T radial field of the original design to the final values measured in February 2006 of 3.6 T axial field, 2 T radial field. This upgrade will permit to operate in High B mode not only at 18 GHz, but also at 28 GHz. The plasma chamber diameter is one of the smallest among the new sources (100 mm) which may be a limit for microwave power injection. High voltage is designed to attain 60 kV (ion source at +30 kV, beamline at –30 kV), but the most original issue of the project is the tunable plasma chamber length, as the relative distance between the resonance zone and plasma electrode, the distance between the two magnetic maxima, the "depth" of the minimum can be varied by changing the current in the six axial coils.

RIKEN 3rd Generation ECRIS Project

A new 3rd generation ECRIS has been designed at RIKEN for 28 GHz operation with values similar to the ones of SECRAL and VENUS (axial 3.8 T, radial 2.0 T at the inner surface of the plasma chamber), but a large size of the chamber was chosen (150 mm). The source will be built for the RIKEN radioactive beam factory [5] and the goal is the production of a large variety of heavy ion beams with currents in the order of hundreds eμA (e.g. 525 eμA of U^{35+}). Its design follows the scheme proposed by SUSI with six axial coils to have a flexible profile.

High Frequency Mirror Trap

A simple mirror trap was used at IAP, Nizhny Novgorod, to study the beam production in presence of high density plasma ($1*10^{13}$ cm^{-3}) by means of high frequency microwave (37.5 and 75 GHz). The scheme described in [15] was used for 37.5 GHz, a more complicate magnet has been used for 75 GHz operations (up to 5 T), but in both cases the short pulse (150 μs) with high peak power (up to 200 kW) was able to generate ion current density of the order of some A/cm^2 from 1 mm extraction hole. Obviously the lack of radial confinement did not allow to get high charge states, and the calculated electron temperature was quite low, about 50 eV; anyway this proof-of-principle experiment has given information about the management of high microwave power and about the possibility to generate high energy content plasmas with different regimes than the High B mode.

MS-ECRIS

The MS-ECRIS source [14] has been designed in the frame of the EURONS initiative, funded by the European Union. Intense beam production for highly charged heavy ions will be obtained by an ECR plasma confined by a B-minimum magnetic trap with the highest design values up to date. Such characteristics will permit to use 28 GHz or higher frequency to heat the plasma, by keeping the optimum confinement, according to the High B mode concept. The MS-ECRIS source commissioning at GSI Darmstadt is expected for the spring of 2007; its design is open to changes in order to be adapted to the major accelerators in Europe, and tests will be carried out either in dc mode and in pulsed mode. The main parameters of its design are given in table 1 compared to the ones of the SERSE source, which is the parent project; a sketch of the magnetic system is presented in fig. 9. With respect to SERSE it will have the advantage of a LHe-free cryostat (served by two cryocoolers) and of a much more complex plasma chamber, designed for 60 kV insulation, for the management of 10 kW microwave power and including also a X-ray shield of tantalum to prevent the LHe boil-off experienced in previous experiments [9].

As for the case of SERSE, a particular care was paid to the design of the hexapolar coils, not only in terms of stability versus quench, but also in terms of uniformity for different azimuth, that is very important to avoid preferential loss paths for the electrons and to keep the plasma stable. Optimization of the beam extraction and transport has been carried out by taking into account the previous experience [9,11]. In order to operate such a source effectively a vacuum in the order of 10^{-8} mbar is needed, to minimize the recombination. The large size plasma chamber should minimize the thermal increase and then the outgasing, and adequate conductance is ensured for vacuum.

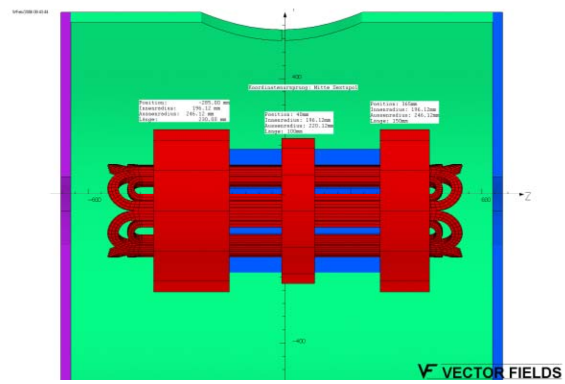

Figure 9: Sketch of MS-ECRIS magnetic system.

4TH GENERATION ECRIS' SCENARIO

Up to now the technical development for ECRIS was mostly linked to the availability of higher frequency generators and higher field magnets. This trend has not yet achieved a saturation, and in perspective Nb_3Sn magnetic traps may exceed NbTi performances. This type of conductors can be used for solenoids with higher field in the conductor (15 or 20 T) but the technological improvements seems to make possible even the design of complicate magnets as hexapoles within the next years. The availability of more powerful magnets may permit to rise the operational frequency to 60 or 75 GHz, that will be the typical frequency for the 4th generation ECRIS, but higher rf power will be then necessary for the achievement of higher electron temperatures. In fact

$$P_{RF} = n_e kT_e V / (\tau_e \eta_{ECRH})$$

where $\eta_{ECRH} = P_{absorbed} / P_{RF} = \eta_{waveguide} \eta_{coupling} \eta_{plasma}$.

If we get $n_e \approx 10^{13}$ cm^{-3} and electron temperature of 10 keV, for plasma volume of the order of a few liters and electron confinement times of the order of 10 ms, the coupling efficiency η_{ECRH} plays a major role, by reducing the needed power from tens of kW to 5 or 10 kW. Moreover new schemes of microwave coupling to plasma may be advantageous for a better focusing of the electromagnetic wave towards the chamber axis that improves locally the density of warm electron population.

The MS–ECRIS source may be an important testbench for the use of a higher frequency in view of the 4th generation ECRIS. In fact, its magnetic field is 4.5 T for the axial mirror and 2.7 T for the radial trap so that electron cyclotron resonance up to 60 GHz is possible, even in presence of a modest level of confinement. This scheme may result useful for the production of very high current beams of moderate charge state; in fact the same quality factor $n_e\tau_i$ is reached if n_e is four times larger because of frequency doubling and τ_i is four times shorter. In addition $I^{q+} \propto n_e/\tau_i$, so that an order of magnitude may be gained for the extracted current by decreasing the B/B_{ECR} ratio (and then τ_i) and by increasing the resonance frequency (and then n_e), but by keeping $n_e\tau_i$ unchanged. In this case the shorter electron confinement time makes necessary a much larger microwave power, up to 30 or 40 kW. It is clearly demonstrated that the use of TWT (and gyro-TWT operating at higher frequency) rises the beam current with a much smaller rf power, because of their improved rf coupling. Then preliminary tests with a 60 GHz-25 kW gyroTWT can be done already with MS-ECRIS. For the long term, the scaling laws suggests that no limitations to higher frequencies exist, so it is possible to think to a 60 GHz 'dream machine' (B_{ECR}> 2 T), with an axial field of 6 to 8 T and a radial field of 4 T generated by Nb_3Sn magnets.

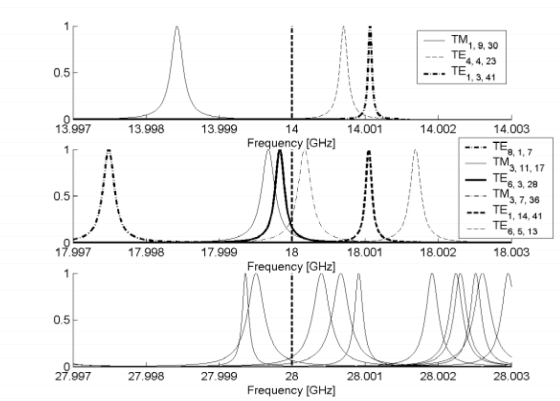

Figure 10: Increase of the modes coupled to ECR cavity.

Finally the availability of powerful codes may permit a precise modeling of the plasma by taking into account a huge number of variables. Even if the complex structures of the injection and extraction flanges together with the large dimensions of the chamber and the high frequencies employed make impossible an analytical solution and also makes difficult to implement a model with state-of-art electromagnetic simulators (CST, HFSS), a study of coupling mechanism and RF technology has been carried out at INFN-LNS [17]. The simulation of the mode transmission in the ECRIS cavity is shown in fig. 10, that demonstrated an increase of the modes inside the cavity which in turn increased the coupling efficiency [18].

A precise model of the effect of DC break and ancillary equipment, measurements with network analyzer and other diagnostics tools, the characterization in terms of S parameters of the plasma chamber have set important landmarks to model ECR heating process. The study of plug-in effect, the analysis of two frequency heating and the coupling of a broadband microwave generator was begun, that will be essential for the future experiments.

The simulation codes developed recently are versatile and allowed to reproduce electron confinement and heating in presence of different electromagnetic field distributions in the cavity [17,18]. However further improvements are necessary in order to correctly simulate collision rates and electron energy distribution function; the phase correlations between electromagnetic field and electrons' acceleration will be also subject of study.

CONCLUSION

In conclusion, the plasma technology has permitted up to now relevant advances in the production of intense beams of highly charged ions and further ones are expected. On the other way the beam extraction and transport issues will be limiting factors in the next future, as well as technological problems, related to the availability of larger field magnets, higher microwave power, higher extraction voltages. Issues that have been considered as negligible up to now, i.e. the watercooling of the plasma chamber, the matching of the beam emittance to the acceptance of the LEBT, the charge exchange caused by the residual vacuum in the extractor, the outgasing, the large emission of X-ray from the plasma will deserve in the future an increasing role and they may determine the final performances of the ion source and then of the whole accelerator chain.

These limitations have not discouraged the design of more powerful ECR ion sources, because the perspective gain that can be originated by larger beam current and higher charge states largely overcomes the investment in money and manpower that remains anyway modest with respect to the ones of the accelerators.

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