SUPERCONDUCTING ECR ION SOURCES: HIGH INTENSITY BEAMS EXTRACTION AND TRANSPORT

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Abstract

In the last decade a relevant step forward in the design of Electron Cyclotron Resonance Ion Sources (ECRIS) have been obtained and some high performance sources have been built, at the operating frequency of 14,18 and 28 GHz. In particular, the total extracted current exceeds 5 mA in cw mode for some of them, at voltage between 10 and 40 kV. A potential drawback of such intense beams consists of the large emittance growth originated from the space charge forces acting on slow heavy ions, but some solutions have been found and they are described in the following, with particular care to the 3rd generation ECRIS that will provide mA beams of highly charged heavy ions in cw and afterglow mode. Total beam current in the order of tens of mA will be extracted and transported through the analysis magnet with minimum beam losses and emittance growth.

THE ECRIS STANDARD MODEL

Electron Cyclotron Resonance Ion Sources (ECRIS) have successfully provided highly charged ion beams (up to 50^+) with moderate intensity (from nA to hundreds of eμA) for cyclotron facilities. A steady increase of the maximum achievable current has been obtained during last twenty years as the effect of the higher plasma density obtained through the application of increased microwave frequency, of larger rf power and of the improved confinement [1]. The perspective to achieve higher charge states has been recently confirmed [2,3] and the key rules have been determined by Geller [4]. The need of intense beams of highly charged ions for RIB factories and for applications [5] fostered the R&D for the development of such beams.

In principle, there is no limit to the production of higher beam intensities because the ion current scales with the ion density in the plasma and with the square root of the electron temperature T_e. The electron density in the plasma n_e rises with the square of the microwave frequency f^2 and T_e increases wi[1]th the microwave power P_{rf}, provided that electrons are not lost because of a poor confinement. This condition means that an increasing field is needed; the most performant ECRIS have radial and axial mirror ratios high, according to the high-B mode (HBM) concept [6], based on the magnetohydrodynamical condition for quiet plasma, which for typical ECRIS parameters can be written as:

$$B/B_{ECR} > 2 \qquad (1)$$

The HBM concept has been confirmed from experimental results between 2.45 and 28 GHz [2,7,8], which outlined the rules that an efficient ECRIS must follow to produce intense beams of high charge state ions, summarized with the statements, known as ECRIS standard model, reported for the first time at the 14th Cyclotron Conf. in 1995 [9]:

a) the last closed surface must be $B_{last} \approx 2\, B_{ECR}$;
b) the radial magnetic field at the plasma chamber wall must be $B_{rad} \geq 2\, B_{ECR}$;
c) the axial field at injection must be above $B_{inj} \approx 3 B_{ECR}$;
d) the axial field at extraction must be $B_{ext} \approx B_{rad}$;
e) the axial magnetic field value at minimum must be in the range $0.30 < B_{min}/B_{rad} < 0.45$.

Once that all the above conditions are met, it is valid the frequency scaling law:

$$n_{cutoff} = \varepsilon_0 m_e \omega^2 / e^2 \qquad (2).$$

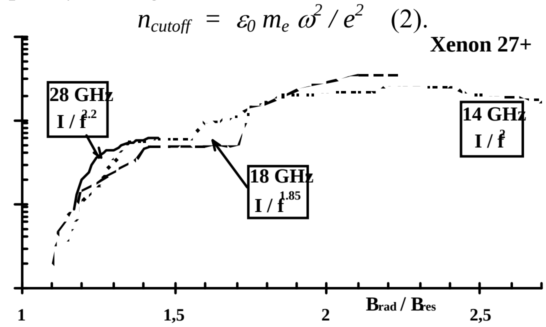

Figure 1: Effect of radial field scaling on Xe^{27+} current, normalized to f^2 (arbitrary units for intensity on y-axis).

The increase of the plasma density (10^{13} cm^{-3} and higher above 28 GHz) by means of higher magnetic field and of higher microwave frequency makes necessary the use of high field superconducting magnets, representing the only option available for any accelerator facility based on a linac or a cyclotron, particularly for the future accelerator facilities (LHC and GSI in Europe, HIRFL in China, RIKEN in Japan and RIA in US) which needs currents of a few hundreds eμA or even thousands. Fig. 1 shows that the experimental data for the same source at different frequencies are close to the ones expected from the HBM concept and from the Geller's laws.

Limitation to the scaling comes only from technology, in terms of rf power and extraction voltage that can be

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applied to plasma chambers; according to the Child-Langmuir law, the maximum current density from a source at voltage V is:

$$j \approx 5.44 \bullet 10^{-8} \sqrt{\frac{Z}{A}} \frac{V^{3/2}}{d^2} \quad [A/m^2] \qquad (3)$$

where Z is the charge state, A the mass number and d the extraction gap in m. A higher voltage V or a smaller gap increase the current, but insulation is hard to be obtained and in addition, cyclotron's central region sets a severe limit to the maximum energy.

Higher microwave frequencies give higher beam current but they oblige to increase the power provided by the generator P_{RF}. In fact, the absorption of power by the plasma is:

$$P_{RF} = n_e \, kT_e \; V / (\tau_e \; \eta_{ECRH}) \qquad (4)$$

where η_{ECRH} is the heating efficiency. For typical values of 3rd generation ECRIS ($n_e = 10^{13}$ cm^{-3}, kT_e = 20 keV, B_{axial} =4T, B_{rad} = 3 T, electron lifetime τ_e = 50 ms) and efficiency of 90%, a value of 6 to 10 kW is obtained for typical ECRIS chamber volumes (6 to 12 liters).

The achievement of the conditions a) to e) is then necessary but not sufficient, as the injection of such a huge power is a technological challenge. Moreover to sustain a high plasma density a high gas load is needed and high voltage sparks may occur; the beam divergence entails huge beam losses at extraction and generates outgassing that finally damages the plasma electrode, as observed in many ECRIS.

Anyway the major problem that is met by 3rd generation ECRIS is the extraction and transport of high intensity highly charged beams and only a few studies about this problem have been carried out up to now [10,11]. Useful know-how is available from the field of high current proton sources or ion implantation sources [12] but some solutions successfully applied to proton sources, as the gas injection in the beam line to help the space charge compensation with the electrons of residual gas, cannot be extended to highly charged heavy ions because of their high charge exchange cross section. The presence of different charge states and of contaminants complicate the emittance pattern and make the beam extraction and transport a difficult task.

SC-ECRIS: PAST, PRESENT AND FUTURE

The history of superconducting ECRIS begun in 1983 with ECREVIS built for CYCLONE at Louvain-la-Neuve [13] that was really a pioneering device, much more advanced with respect to the available technology at that time. After a short period, it was replaced by a conventional ECRIS, but the way it opened was not abandoned. At the same time in Karlsruhe [14] the first source with hybrid superconducting/permanent magnets (SC/PM) was built.

The first fully SC ECRIS that worked with excellent results in terms of produced beams (after a long commissioning) was the Julich one [15], able to provide charge states above 20^+ for Krypton. Anyway its magnetic trap was not sufficient for effective operations at 14 GHz and then the next SC magnet ECRIS built at MSU-NSCL [16] in 1987-90 was designed to get a field above 1.5 T either in axial and radial directions, for frequencies between 6.4 and 28 GHz; unfortunately only the lowest frequency worked well because of the poor hexapole performance that attained only 1/3 of the design field. At 14 GHz its value of B/B_{ECR} was lower than 1.2 and no stable operation was possible. In spite of the limitations, after the demonstration of the HBM concept [7], the MSU SC-ECRIS source has been able to run successfully at 6.4 GHz for 12 years.

The next step was carried out at LNS with the fully SC ECRIS named SERSE [2,8], designed in 1991 and completed in 1997; it was the first SC ECRIS able to run at the nominal design field, that permitted to achieve excellent results in terms of high charge states ion beams production, operating at 14 GHz and 18 GHz. A successful test at 28 GHz permitted to open the way to the production of high intensity beams and many of the results here reported are based on these experiments [2].

The recently completed VENUS source at LBNL is the first 3rd generation ECRIS. Its magnetic field, dimensions, rf power are larger than the ones of SERSE, but they also follow the ECRIS standard model, so it can be expected that the yet relevant results obtained up to date [3]) will be further improved soon. Special attention has been paid to the design of an adequate beam transport system, able to handle intense beams [11], and the solution of a large dipole magnet gap proved to be effective.

Three remarkable SC/PM hybrid ECRIS have been recently built in Japan (RAMSES and SHIVA, which produce mA beams [17]) and India (PKDELIS, with innovative high temperature SC magnets [18]). They cannot attain the same plasma parameters of fully SC magnet ECRIS but produced as well a remarkable series of results.

The SECRAL source at Lanzhou [19] 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 inside the conductor is not so high and a more compact source can be built. The maximum radial field at the plasma chamber wall is 1.9 T, still acceptable for 28 GHz operations. The source construction is now under way and the first results should be obtained in 2005.

Other innovative projects of fully superconducting ECRIS at RIKEN [17] and at MSU-NSCL (SUSI [20]) has been proposed recently, as well as a few other hybrid sources based on SC/PM magnets.

The highest design field has been proposed for the GyroSERSE source which design [21] was completed in 2001 and approved for funding in 2002. Unfortunately the construction was stopped because of budget limitations at INFN, but further developments (study of the extractor and beamline, stray fields, etc.) continued and the know-how was made available to the EURONS collaboration for the construction of the MS-ECRIS source.

Its magnetic field will permit to operate in High B mode at any frequency between 28 and 37 GHz (B_{axial} above 4 T, B_{radial} up to 3 T). The plasma chamber inner diameter will be 180 mm and the volume will be doubled with respect to SERSE. Extraction voltage up to 40 kV will permit an optimum beam management. The multipurpose ECR ion source MS-ECRIS, recently approved by UE, will be simplified with respect to the GyroSERSE design in order to decrease the cost (e.g. a smaller cryostat will not permit an embedded superconducting solenoid for the beam focusing). The collaboration aims to build by 2008 a prototype able to fulfill the request of the accelerators of the involved laboratories (CERN, GANIL, GSI, HMI, JYFL, KVI, LNL, LNS, TSL), as e.g. 1 eμA of U^{60+} and 5 pμA of light ions up to Ar^{16+} in cw mode, or 1 emA of Xe^{20+}, 0.3 emA of U^{30+} (dc mode) and 6 emA of U^{28+} (200 μs pulse).

For injection into the accelerator, all these beams should have energy from 2.5 to 5.0 keV/nucleon, emittance lower than 200 πmm.mrad and high reliability.

HIGH CURRENT PRODUCTION

The ionization in ECRIS is a step-by-step process and a large confinement time for electrons and ions is obtained with a steep magnetic trap; the beam intensity I_{ext} depends on the ion density n_i^q

$$I_{ext} \approx k \frac{n_i^q \, q e}{\tau_i^q} \qquad (5)$$

A rough but effective picture can be derived: if we are looking for high current of medium charge states, we need that the plasma density is high and the electron confinement time is relatively low, to get a high flux of ions from the extraction hole; if we are looking for highly charged ions, a very good trap is needed, and high frequency and high magnetic field at the same time are needed, according to HBM concept. The first strategy has been used not only by sources developed for industrial applications, but also by the first two ECRIS operated at 28 GHz with a modest confinement, SERSE in 2000 [2] and PHOENIX in 2001 [22]. In the first case more than half mA for some charge states above 20^+ was produced and extracted currents were in the order of 10 mA. The extraction process was not well matched and the transmission was below 60%: in addition the high beam noise due to the rf noise and to the poor confinement limited the space charge compensation.

Secondary electrons generated in the residual gas are normally trapped by the beam potential well, which decreases; a partial (and substantially high) space charge compensation occurs, unless the beam is so ‘noisy’ that the potential changes rapidly and the shielding of the beam space charge is not completely achieved. If one describes the beam and secondary electrons coming from the residual gas in terms of a plasma [23] the shielding can work even on 90% of the beam current. Following these basis, a countercheck with the experimental data has permitted to refine the codes and a quite acceptable reproduction of the beam behavior is now obtained. Beam extraction simulations here reported have been performed with the code KOBRA-3D [24]. Further information is given in [10]. The simulations confirmed that the SERSE tests at 28 GHz were far from the optimisation, as the production was almost easy but extraction and transport were poorly efficient. In fact the beamline acceptance is just 150 π mm mrad and in the case of the tests reported in [2] the beam emittance was much higher, even 900π. The small gap (54 mm) - large curvature radius (ρ = 500 mm) magnet permits a transmission close to 100% for beams of emittance below 100π mm.mrad.; but as soon as multi-mA beams are extracted, the transmission was below 60%.

In the case of the PHOENIX source, a transmission of 85% was obtained by means of higher extraction voltage (40 kV) and of a large acceptance magnet. A third experience at 28 GHz is under way at LBNL with the VENUS source, which beamline acceptance is very high (the magnet gap is about four times larger than the one used in [2]).

BEAM EXTRACTION

The development of a model describing the phenomena taking place in the extraction system was undertaken by GSI and LNS; the importance of the spatial distribution of the ions in the radial dimension (related to the influence of the hexapole) was demonstrated. Electrons with arbitrary energy (in the order of tens to hundreds eV) are used in our simulations to compensate the positive space charge of the ions at the plasma boundary and that explains the observed emittance decrease due to the residual gas. In order to get rid of the space charge effects the extraction voltage of 40 kV was considered in the simulations. A higher voltage would be convenient, but it would be hardly matched to a cyclotron or a RFQ. A standard triode topology with accel-decel geometry is the most convenient option because of its simplicity. Smaller gap permits to decrease significantly the calculated emittance. A flat plasma boundary is a desirable operating condition in order to decrease the coupling of the radial electric field with the longitudinal magnetic field. A homogeneous particle distribution in front of the plasma electrode would be necessary to decrease the coupling of an azimuthal electric field component with the B-field.

Both requirements strongly influence the emittance, which means that the position of the plasma electrode is a key parameter for the source optimisation, as shown in [17]. A quiet and uniform plasma must be created inside the ECRIS, as the emittance increases with T_i; the large plasma cross section and the uniformity of the magnetic trap that are required for this reason are consistent with the standard technology of superconducting coils. The ray tracing of the trajectories has been performed up to the

chosen interface between the extractor and the beamline. The emittance at 40 kV changed with the current within the range 120 to 200π mm.mrad. for a total current up to 50 mA. An optimum distance between the plasma and the puller electrodes was calculated for each current value (a puller inclined at 80° with respect to the axis was used as a standard). The emittance decreased with the charge state increase, because of the higher ion energy [10].
According to these results, a new mechanical design of the extractor has been adapted to the different constraints, as the cryostat length have obliged to design a complicate system to move the extractor. The need of a water-cooled puller electrode made much more complex this design which is presented in fig. 2 and described in [10]. The ball screw has been used to avoid blocking. The puller and the ground electrodes consist of a fixed part and of a nose which can be easily replaced, following the experience of high current proton sources. The ability to adapt the puller position to the plasma condition will reduce the trend of the beam to triangular shapes, observed in the real space and reproduced by simulations as soon as the proper modelling of the hexapolar field and of the particle distribution is carried out. In the past the effect of hexapolar field (tens or hundreds gauss) was often neglected and that was not crucial for low intensity beams, but it cannot be discarded for intense beams. Finally it should be remarked that V_{puller} has a relevant effect, as it determines the minimum beam size before the analyzing magnet. Just 1 kV differences may lead to an increase of the final emittance larger than 10%.

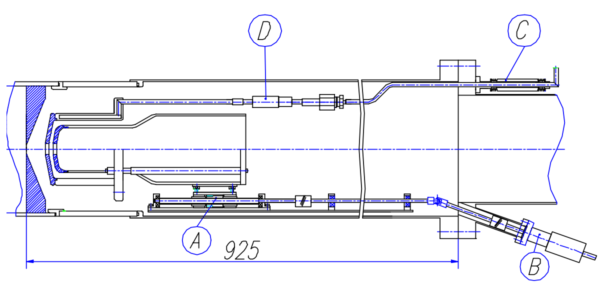

Fig. 2 – The GyroSERSE extractor (A- ball screw, B - rotary drive, C - bellow, D - insulated water tube) [10].

LOW ENERGY BEAM TRANSFER LINE

We have investigated different designs of analysing systems for 3rd generation ECRIS [10]. Calculations were performed using the computer codes GICO, GIOS (to handle the space charge effects) and TRANSPORT. Ion-optical calculations were performed assuming an initial beam phase space of $x_0 = y_0 = \pm 6$mm and $x'_0 = y'_0 = \pm 25$mrad, which is consistent with the results of KOBRA simulations. Calculations were done for a $^{208}Pb^{27+}$ beam and for a $^{129}Xe^{20+}$ beam, as these species are particularly relevant for many accelerators. Extraction voltage of 40kV and magnetic rigidity of 0.080 Tm were used.
A simple system which consists only of a superconducting (SC) solenoid integrated in the source cryostat and of a 90° dipole magnet was considered at first. The length of the solenoid is 300mm only. The 1st order resolving power was just 80. The influence of higher-order image aberrations was also investigated (beam energy spread of 1‰) and no effect of higher-order aberrations was observed. The beam envelopes in x- and y-direction for current of 30mA compensated to 90% (I_{eff}=3mA) fill the dipole gap (±70mm). The size of the beam drastically increases with the current and the resolving power is then decreased. A longer system with normal conducting solenoid before the 90° dipole magnet was also considered. The distance between the object point and the solenoid is therefore increased to 500mm. The 1st order resolving power for the system is almost as good as before, as the focusing power of the solenoid acts later on the beam and a larger area of the dipole magnet is illuminated; space charge effects soon deteriorate this value.
One of the best possible option is given by a more complicate system, consisting of a SC solenoid followed by a quadrupole doublet before the 90° dipole magnet and of a quadrupole after. The quadrupole doublet prepares the beam optimally for the dipole magnet and the third quadrupole enables to get a small spot size at the image plane and a high resolving power. The system achieves a 1st order image (for I = 30mA, 90% compensated) of approximately ±3.5mm (x-direction) and ±48mm (y-direction), which leads to a 1st order mass resolving power of ≈140. The overall flight length of the system is approximately 4.2 m. The beam is kept rather narrow in the dipole magnet [10].

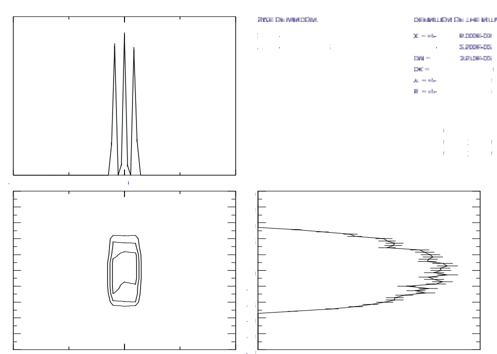

Fig. 3 – GIOS simulation for the optics of the compact analysis section, featuring a poor resolution.

A compact 90° dipole magnet with 500mm deflection radius only (entrance and exit boundary $\varepsilon_{1,2}$=25°) and a quadrupole doublet arranged between the dipole and the image plane was studied finally. This solution is ideal for small injector rooms or for sources operating over a platform. The dipole is directly coupled to the ion source so its resolving power (about 56) is fixed. The quadrupole doublet allows to build a compact system and it gives the possibility to shift the final image plane away if needed, but beam losses may occur inside the quadrupole aperture (±50mm). The space charge generated halos, which are only partially cut in the beam transfer line and that may deteriorate the performance of the cyclotrons' inflector or RFQs' entrance gap; the large beam dimensions limit the resolving power of the 90° magnet. The different peaks easily overlap (fig. 3) showing that this is the crucial problem for intense beam production.

CONCLUSIONS

The current increase from ECRIS is not to be deemed to saturate soon, but the extraction and transport issues are the limiting factor for the next future.

A new concept of extraction and transport system must be used, which maybe sacrifices some issues as the resolving power (questionable for intense beams) but that allows to have a large acceptance and a good flexibility. In particular, the extraction system here described is able to manage different currents, different q/m ratios and can be movable and watercooled at the same time. The experimental data and the simulation has given important information for the future: an accel-decel system is necessary for space charge compensation behind the extractor. The influence of the solenoid is relatively weak in spite of its huge strength, as the ions are generated with small transversal and azimuthal velocity. The azimuthal electric field component together with the solenoidal magnetic field will increase the emittance, then the plasma electrode must be placed at a location with a homogeneous plasma density distribution. Space charge forces are important but compensation occurs through the beamline, unless the beam is too noisy or a narrow focus is produced.

The analysis magnet must have a large gap and a large curvature radius, if the site allows it; quadrupoles help to accomplish all the demands of intense beam transport. A high beam power is to be managed (up to kW), so electrodes and beam diagnostics must be watercooled.

It is to be considered that some interesting perspectives are opened by the availability on the market of generators at frequencies between 35 and 60 GHz. At the lowest frequency a current density in the order of A/cm^2 has been generated for short pulses, and the operation with B-minimum structures seems not so unrealistic. At 60 GHz already two proposal are under way for charge breeding, by using a modest B/B_{ECR} ratio. In all these cases the ability to master a intense beam from the ECRIS will determine the success of the equipment. On the other way the fast improvements of the SC magnet technology permit to imagine the possibility of a 60 GHz-HBM (B_{rad} > 4.5 Tesla) cw ECRIS in the next 10-15 years, so that the solutions here proposed will be not sufficient and further innovation will be needed.

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