

# ECR PLASMA PHYSICS AND PRODUCTION OF HIGHLY CHARGED HEAVY ION FROM MS-ECRIS

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## Abstract

The 3<sup>rd</sup> generation electron cyclotron resonance (ECR) ion sources may permit a significant increase of the available beam current for cyclotrons, that is particularly important for research programmes with radioactive ion beams, and of the available charge states, that increases the accelerated beam energy. Some 3<sup>rd</sup> generation ECR ion sources (i.e. sources with operational frequency above 20 GHz and magnetic field above 2 T) have been built recently. The first ECRIS operating in High B mode (HBM) at the frequency of 28 GHz was VENUS at LBNL, producing now the highest charge states and currents worldwide; recently the MS-ECRIS source has been built by a European collaboration team, within the framework of EURONS/ISIBHI initiative, and it is now close to the commissioning phase. Its magnetic trap makes possible to extend in the future the operating frequency from 28 to 37 GHz, with significant increase of plasma density and of beam current. The description of the source will be given along with a schedule of the forthcoming development. A discussion about the long-term perspective that may be opened by the experiments with MS-ECRIS will be outlined, with a particular remark on the relationship between a deeper knowledge of the plasma physics processes in ECRIS and the performance in terms of highly charged ion beam production.

## INTRODUCTION

Up to recent times, the improvement of the ion sources was strictly linked to the improvement of the magnetic confinement (i.e. higher confinement time [1]), and to the increase of the frequency which, under good confinement conditions, takes to higher plasma density [2]. The beam formation issue has also grown up in importance, because of the emittance deterioration due to space charge forces acting on intense heavy ion beams at low energy, before the injection into cyclotrons [3]. Only in the last few years the application of microwave technology to the consolidate ECR sources with B-minimum field have permitted to improve the microwave coupling to plasma and to increase the amount of energy which is actually transferred from the microwave field to the warm electrons, responsible of the ionization process [4,5,6]. Unfortunately other mechanisms permit to transfer some energy to the electrons above the so-called adiabatic limit [7], that is in the order of a few hundreds keV for the most of ECR ion sources. These high energy electrons are not useful for ionization and moreover they generate an unwanted flux of brehmstrahlung X-rays and deteriorate the plasma stability [8,9,10]. The minimization of this phenomenon play a major role to enhance the highly

charged ions production either for the existing sources and for the upcoming ones; it is a subject of study in different laboratories, e.g. at INFN-LNS and at LBNL [11]. It will be underlined in the following that for MS-ECRIS and even more for the next generation of ECR sources it will be necessary to master many critical issues of plasma physics to fully exploit the ECRIS potentiality, and that even relevant technological achievement that may provide higher confining field and higher power/frequency microwave generators will be not useful without the competent understanding of non-linear effects arising in the ECRIS plasma [12].

## Historical notes

Some historical notes are needed to understand the above statement. Twenty years ago, R. Geller proposed the scaling laws [13] which have been for long time a guideline for the ECRIS community:

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

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

where  $q_{\text{opt}}$  is the optimum 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 mass of ions. Some years later, results from different sources put in discussion the statement that simple scaling laws may be useful. In particular, a series of experiment carried out in 1993 with the SC-ECRIS at MSU working at 6.4 GHz changed the ECRIS scenario, because this source was able to deliver ion currents exceeding the best 10 and 14 GHz sources at that time [14]. These results have been explained by the so-called High-B-mode concept [15,16] which state that, by increasing the confining field (particularly the radial field), higher electron density and temperature is obtained. This concept can be summarized by the formula:

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

where  $B_{\text{ECR}}$  is the magnetic field corresponding to the ECR frequency; this formula does not conflict with the frequency scaling rule, but it limits the benefits of frequency scaling to the sources with a very high confining field. In 1998-2000 tests with the SERSE ion source have confirmed this simple statement [17,18].

Fig. 1 shows the beam current for  $\text{Xe}^{27+}$  obtained at different levels of radial confinement for frequencies between 14 and 28 GHz. The picture obtained by these data was coherent with the so-called ECRIS standard model [1] proposed in 1995 which states that:

- the radial magnetic field value at the plasma chamber wall must be  $B_{\text{rad}} \geq 2 B_{\text{ECR}}$ ;
- the axial magnetic field value at injection must be  $B_{\text{inj}} \approx 3 B_{\text{ECR}}$  or more;

- c) the axial magnetic field value at extraction must be about  $B_{ext} \approx B_{rad}$  ;
- d) the axial magnetic field value at minimum must be in the range  $0.30 < B_{min}/B_{rad} < 0.45$ .

The electron density is dependent not only on the frequency, but it depends on the interplay with frequency, magnetic field and electron temperature. By increasing  $B$ ,  $n_e$  approaches  $n_{cutoff}$  and the magnetic field increase is not useful anymore. Instead in [1] there was an important statement that has proven to be completely wrong:

- “the CSD improves with the RF power but the amount of power that can be coupled to the plasma increases with the confining field and decreases with the base pressure”.

The relation between RF power and magnetic field is not so simple. Some authors studied the RF coupling to the plasma in terms of the maximum power rate per unit volume and of its relationship with the beam intensity produced by different ECR ion sources [19]; only recently it was understood that the efficacy of the microwaves injection in the plasma is related to the geometry of injection plug and plasma chamber [5,20,21]. The modes excited in the multimodal cavity represented by the chamber determine the maximum field over the resonance surface. The changes in the magnetic field profile cannot optimize the coupling completely as they have to follow the constraints coming from the confinement requests.

An argument against the ‘brute force’ use of microwave power can be obtained by fig. 1, that features a higher current for the 28 GHz case than it could be expected by a simple application of the scaling laws [22,23]. This anomaly was explained in terms of a better ECR heating provided by the smaller wavelength, but this consideration would have come to a dead end, if the step towards the 3<sup>rd</sup> generation ECRIS would have not required the mastering of high power - high frequency waves. Already in 1998, when the ECRIS generations were defined [24], it was evident that the amount of microwave power requested by the application of scaling laws would be not affordable for technological reasons for any generation after the 3<sup>rd</sup>.

### MICROWAVES AND ECR HEATING

In order to increase the performance of B-minimum ECRIS, the study of microwave feeding started in 2002 by using electromagnetic fields having large spectral content or obtained by the superimposition of a discrete set of microwaves at different frequencies. In addition, experiments at LNS aimed to investigate the coupling mechanism between the electromagnetic field present in the source chamber and the plasma there confined [21]. The first evidence that significant improvements can be obtained was given by the different performance observed for the SERSE and CAESAR ion source when fed by a klystron based or a travelling-wave-tube (TWT) based generator [4,5] either at 14 and 18 GHz.

It can be seen in fig. 2 that TWT generators permit to obtain the same charge state at a power rate three times lower than a klystron; moreover the different behavior of ECRIS fed by two frequency heating suggested that a

more or less efficient energy transfer is determined by the plasma chamber geometry. Other interesting results came from experiments performed at ORNL and at JYFL [25]. A final confirmation has been obtained by measurements performed with the SUPERNANOGAN sources now installed at CNAO, Pavia [26] and more recently with two experiments performed with the CAPRICE ion sources at GSI testbench [27]. In the first case the frequency was changed in the range 14.44 to 14.53 GHz with a step of 1 MHz and it was observed that changes of a few MHz changed the  $C^{4+}$  current even of 70% (fig. 3). In the latter case, remarkable changes of intensity and beam shape have been observed during the sweep in a narrow range of frequency ( $14.5 \text{ GHz} \pm 40 \text{ MHz}$ ). The beam shape evolution has been observed by means of a viewer located 25 cm far from the extraction electrode without any optical element in between [28].

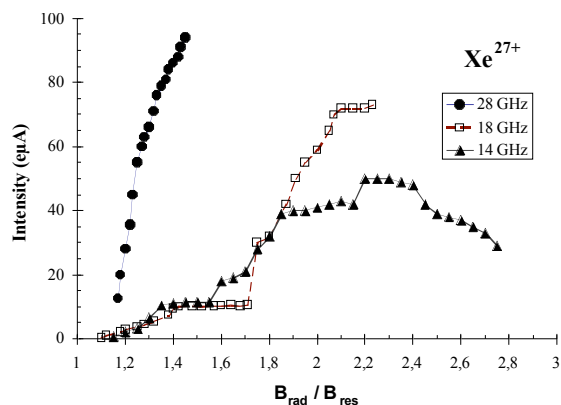


Fig. 1 -  $Xe^{27+}$  currents from the SERSE source at 14,18 and 28 GHz vs.  $B/B_{ECR}$  [18].

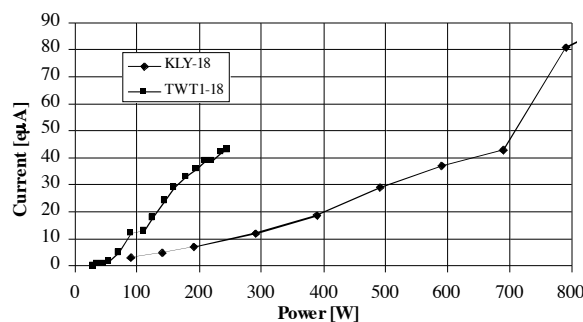


Fig. 2 –  $O^{7+}$  current from the SERSE source vs. the RF power for TWT and klystron both operated at 18 GHz.

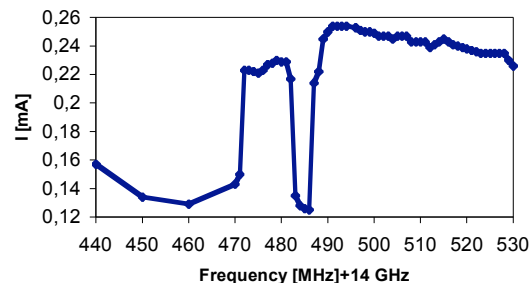


Fig. 3 – Current of  $C^{4+}$  vs the microwave frequency.

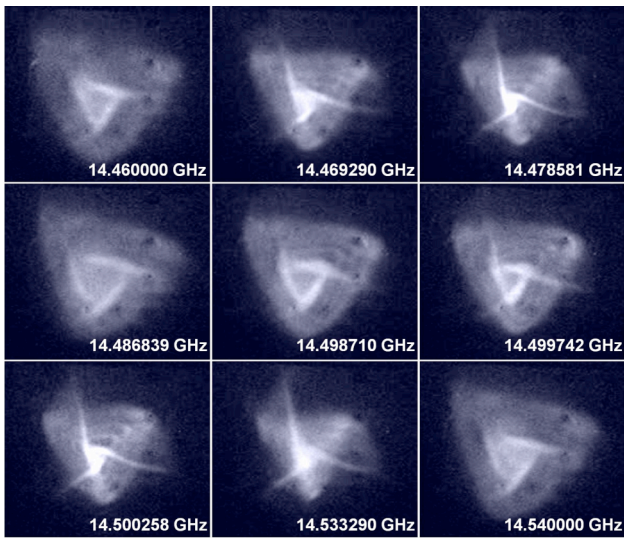


Fig. 4 – Evolution of the beam shape with the frequency [27].

Fig. 4 shows a Helium beam during an acquisition lasting 150 sec (500 W microwave power, fixed magnetic field, injection pressure of  $4.3 \cdot 10^{-6}$  mbar). A change was observed for the  $\text{He}^{2+}$  beam current during the sweep, along with a change of the total current extracted by the ion source (not reported here for sake of brevity but similar to the one in fig. 3). Since the microwave frequency was the only parameter to be changed, the previous observations clearly reveal the role of the electromagnetic field distribution inside the plasma chamber that changes with the frequency affecting the final structure of the extracted beam, and therefore the amount of current that can be injected into the accelerator. Some simulations, based on a single particle motion model, have shown that a remarkable improvement of the electron confinement and heating occurs in the case that the electric field distribution has a similar pattern to the one of the plasma as determined by the magnetic field. More explicitly it is important to have a high value of electric field on the surface where the resonant interaction takes place and not over the entire plasma chamber [21,28]. Within the modes excited in the multimodal cavity, only a few are useful for ECR heating process and a selective excitation is more convenient than a power increase. According to simulations without plasma, the maximum accelerating field may change even by two order of magnitude and the effect is relevant just for changes of a few MHz. Hence an explanation of the so called “Frequency Tuning effect” can be given, explaining the results obtained in many ECR ion sources. On the other way, it is very difficult to give a rigorous description of what happen in the source in presence of plasma. We expect that the presence of the plasma in the chamber damps the difference but a smoother pattern is still sufficient to explain the changes reported in fig. 2, 3 and 4. This picture is certainly not complete; further tests are now planned with TWT amplifiers and with

appropriate microwave diagnostics, in order to get information over a broader bandwidth.

Some other experimental data may find their explanation in terms of non-ECR heating. The observation that many electrons reach an energy higher than the stochastic barrier (even above 1200 keV) cannot be described on the basis of a single particle approach and different injection schemes may be considered for the plasma heating, as the Electron Bernstein Waves (EBW) excitation [12]; overdense plasmas and high accelerating field may be generated in this case as the EBW can propagate into the plasma without density cutoff. The higher densities allow a higher collisionality and then a more effective ion production is possible over limited volumes inside the plasma. As the EBW does not allow propagation outside of the plasma, the conversion from other externally launched modes is needed to obtain this mode inside the plasma; the so-called OXB mode conversion proposed in 1973 [29] may do that inside the ECRIS plasmas even if their B-minimum magnetic field structure is different than the toroidal configurations used so far for EBW excitation. This study can be rewarding as Bernstein waves offer an attractive possibility to create “overdense” plasmas and to explain the presence of unwanted hot electrons, helping to reduce their amount by appropriate source tuning.

### 3<sup>RD</sup> GENERATION ECRIS AND MS-ECRIS

The first ECR ion source able to operate at 28 GHz was the SERSE source at INFN-LNS in 2000 [18,19] which was anyway unable to properly confine the plasma as its maximum radial field is 1.55 T and the resonance field for 28 GHz is 1.0 T. The results were excellent for medium charge states, but for the highest its poor confinement was a limit; the wall outgassing for RF power exceeding 3 kW did not permit the production of charge states above  $40^+$  for Xenon and moreover the production of high energy X-rays was observed [8] that resulted in LHe boil-off. This observation was confirmed by the tests of VENUS at LBNL [9, 11], which started in 2004 the operation at 28 GHz with results much better than the SERSE ones, as its magnetic field fulfils the High B mode conditions.

Table 1: Characteristics of 3<sup>rd</sup> generation ECR ion sources

	VENUS	SECRAL	SuSI	MSECRIS
$B_{\text{radial}}$	2.1 T	2.0 T	2.0 T	2.7 T
$B_{\text{axial}}$	4.0 T	3.6 T	3.6 T	4.5 T
$V_{\text{ext}}$	20 kV	20-30 kV	60 kV	40-60 kV
$\phi_{\text{chamber}}$	150 mm	126 mm	100 mm	180 mm

In 2002 the PHOENIX source was operated at 28 GHz at LPSC Grenoble, but the results in cw mode were not satisfactory because of the low level of confinement. About 600 eμA of  $\text{Pb}^{25+}$  were obtained in afterglow mode [30], but at 55 kV. Some other 3<sup>rd</sup> generation ECR ion

sources have been designed or built in last few years. SECRAL at IMP [31] has the unique characteristics of an hexapole external to the solenoids, A-PHOENIX at LPSC [32] uses HTS solenoids and room temperature hexapole (but with the field enhanced by iron pieces), SUSI at MSU presents a set of six solenoids to produce flat field at the resonance [33]; all these devices have reached the design field, but only SECRAL up to now has obtained remarkable results in terms of highly charged ion beam production, not far from the ones of VENUS, and at 18 GHz only, the other sources being still in the commissioning phase.

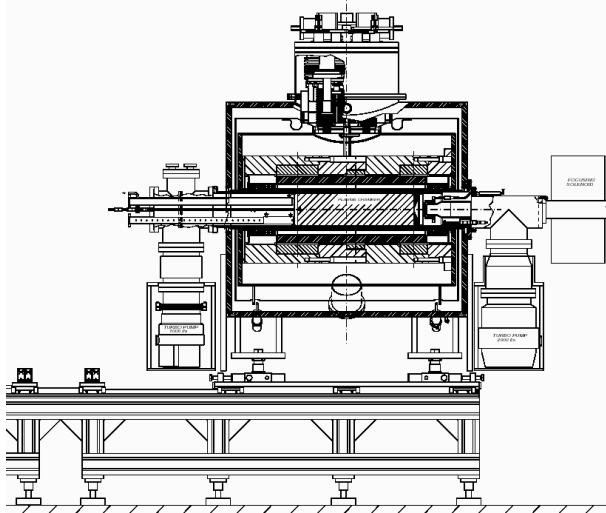


Fig. 5 – The layout of the MS-ECRIS source.

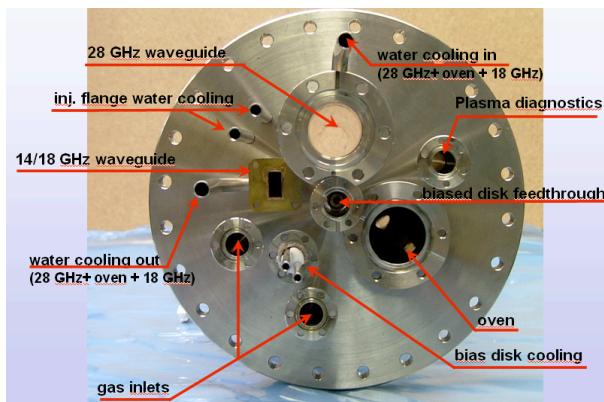


Fig. 6 – The injection flange.

There is only one source that has been designed to operate at higher frequency than 28 GHz fulfilling the High B mode, i.e. the MS-ECRIS source, built by an European collaboration (EURONS/ISIBHI initiative) and now in the phase of the commissioning of subsystems. The minimum B magnetic trap of MS-ECRIS is generated by three coaxial solenoidal coils and a radial hexapole, coaxial with the mirror coils. The front ends of the cryostat are made of soft iron. The field of the central coil is opposite to that of the two outer mirror coils. The magnetic field maxima are 4.5 T for the injection side, 3.2

T for the extraction, with a minimum axial field variable between 0.3 and 0.9 T. The maximum value of radial field is 2.7 T. The cryostat includes six high temperature superconductor (HTS) current leads and two 1.5 W cryocoolers, in order to operate in stand-alone mode. In fig. 5 the layout of the source is presented. The cryostat and magnets are described with more details in [34,35]. In spite of the troubles coming from short circuits between the hexapole coils' wires and delays caused by the implementation of additional safety keys, the magnetic system is now ready and during the preliminary cold mass tests the hexapole (the most complicate component) was energized up to 78% of the nominal current with two quenches only. All the other components of the source are now available and the assembly is expected by November 2007. Functional tests of some parts have been successfully done; the design of the MS-ECRIS chamber has been complicate as it is the result of compromises among the requirements of RF power dissipation, of the X-rays shielding and of electrical insulation with respect to the grounded wall of the cryostat warm bore. The chamber tube has a length of 1162 mm and it is made of AISI 316L stainless steel; inner diameter is 180 mm and thickness of 1.7 mm. A dig of 2.6 mm is made at the position of maximum X-ray emission to fit a 1.5 mm thick tantalum tube. A 4 mm thick PEEK tube will be mounted between the plasma chamber and the warm bore.

Numerical calculations have been undertaken to define the optimum location of the waveguide in the injection flange (fig. 6) to minimize the losses; an optimum position around 0.5 times the radius was found. The biased disk is located on the axis of the injection flange and the oven is placed on the lower part that is not much affected by electrons coming from the plasma. Room for plasma diagnostics is left on the right side, separated from the area of plasma leakage. It is a new feature for ECRIS as a consequence of the importance now recognized to the comprehension of ECR plasma physics, after two decades of impetuous upgrade of the underlying technologies.

The box at the injection side contains all the services for biased disk, oven, microwaves and gas input. It is pumped by means of a 1000 l/s turbomolecular pump. The box at the extraction side contains all the services for the movable extractor, either for motion, for water cooling and for high voltage connections. It is pumped by means of a 2000 l/s turbomolecular pump (large pumping speed is available to reduce the effects of residual gas on the highly charged ions). The cryostat will be movable over rails to get full accessibility to the inner parts and to keep safe the services and the cabling.

The 28 GHz microwave system will follow exactly the same design as the one used for the experiments with the SERSE source [18]; the maximum available power from the gyrotron is 10 kW and the system is protected vs. reflected power up to 2 kW; a dc break designed for 60 kV insulation is placed, and a watercooled window separates the part in air from the part under vacuum. The extraction voltage is set at 40 kV because the current from a 3<sup>rd</sup> generation ECRIS is strongly limited by the space

charge forces and the ability to run at higher voltage is rewarding according to the Child-Langmuir law, with positive effect on the beam emittance. Such an increase of the extraction voltage in turn means that more attention must be paid to the high voltage sparks. In the case of cyclotron there is an additional limitation coming from the injection process, and the possibility to accelerate up to 60 kV and then to decelerate in order to fit the cyclotron requirements has been considered [33].

Particular attention was paid to the mechanics and watercooling of the accel-decel extractor; the plasma electrode is fixed to the chamber and cooled by contact with the wall, the puller and ground electrode may be shifted over 80 mm to optimize the position. The puller is water-cooled with demineralised water. The electrodes can be replaced only after source venting. The extraction hole diameter is 12 mm.

Relevant R&D have been carried out for the design of resistive and inductive oven, because the MS-ECRIS experimental programme will be largely based on the optimization of metal ion beams. The resistively heated foil oven permits already to exceed 2000°C. The inductive oven has reached the same temperature but its durability is still not satisfactory for ECRIS operating with cyclotrons. More details can be found in [36].

## DIAGNOSTICS

An important part of the experimental programme of MS-ECRIS and other 3<sup>rd</sup> generation ECRIS will consist of the tests with different magnets and microwaves set-up, in combination with adequate diagnostics. RF diagnostics can be used in ECRIS but this kind of measurements are often neglected because of their difficulties and of the high cost of the experimental setup. In the past electron cyclotron emission (ECE) was used to determine the profiles of electron temperature, while other kind of RF diagnostics have not been applied, as e.g. the microwave interferometry. In fact complicate set of transmitters and receiving antennas cannot be easily placed in the ECRIS plasma chamber. The measurements with probes connected to a network analyzer are easier and useful but clean signals can be obtained seldom, so their utility to understand what happens inside the plasma is limited.

The information on the X-ray emission are particularly important as they permit to get information on the amount and energy of the electrons. These measurements are difficult as to distinguish the amount of brehmstrahlung X-rays generated inside the plasma and the flux coming from electrons hitting the electrodes or the chamber wall is not simple. Anyway the changes in the X-ray spectra may be related to changes in the electron energy distribution function (EEDF) and may give an hint about the optimum source setup. The final goal will be the enhancement of the so-called ‘warm population’ of the EEDF, between 1 and 100 keV, and the minimization of the ‘hot population’ (above 100 keV).

Soft X-rays diagnostics may be also used to monitor the plasma vs. magnetohydrodynamical instabilities.

Vacuum ultraviolet (VUV) and optical diagnostics either in the visible region and in other regions of the spectrum is used in plasma physics devices but it has not been used so frequently in ECRIS [37], because it requires a careful setting of the device and a relevant manpower and time. VUV spectroscopy gives information on the production of highly charged ions. Optical diagnostics can replace the Langmuir probe for measurements with a high density high temperature plasma, that is ‘optically thin’; precise measurements for ion and electron density in the regions of the plasma can be performed. Finally the evolution of selected emission lines is a signature of ionization and recombination process inside the plasma (the CSD inside the plasma may be different from the one of the extracted beam).

The beam noise and the beam emittance measurements are the typical diagnostics that permit to improve the beam extracted from ECRIS before the injection into the cyclotron. Their role is not to be neglected because of the increasing weight of plasma instabilities at higher RF frequency and power and because of the space charge forces dominating the high intensity beams.

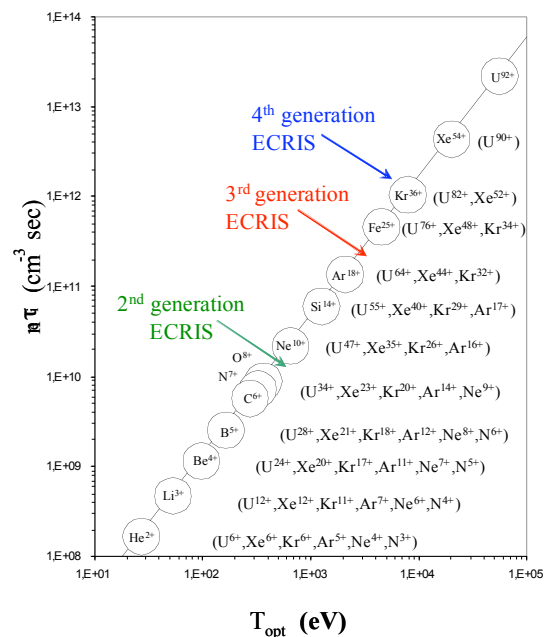


Fig. 7 – The Golovanivsky plot shows the possibility to get higher charge states for the next ECRIS generation.

## 4<sup>TH</sup> GENERATION ECRIS

The increasing cost for the construction of accelerators has been the major reason for the development of new ECRIS. The cost of complex superconducting magnets for ECRIS and of high frequency generators is still small if compared to any kind of accelerator upgrade. Moreover the ECRIS present the advantage of higher reproducibility than other ion sources and they can work either in cw mode and in pulsed mode. The increase of current for highly charged ions in the period 1980-2007 amounted to a factor 100 to 1000 but a further increase is possible, as

proposed in literature [26,38]. The possibility to get a last closed ECR surface of 3 T inside the plasma chamber of MS-ECRIS may permit in future the coupling of higher frequency microwave generators, up to 37 GHz, or even 56 GHz, with a modest confinement.

The design of a 4<sup>th</sup> generation ECRIS is based on magnetic traps with axial field above 6 or even 8T and radial field above 4T, to operate at frequencies between 56 and 75 GHz. Anyway, if the advantages are clear in terms of higher achievable charge states (fig. 7) and in terms of higher currents (due to higher plasma density), it is not yet clear if it will be possible to overcome the technical difficulties. The ability to design complex magnetic systems based on Nb<sub>3</sub>Sn wires is still questionable whilst it is clear that NbTi magnets are not able to run at so high fields. The plasma chamber watercooling will be also complicated by the need of tens of kW of RF power. According to the formula

$$P = V E_e n_e / \tau_e \quad (4)$$

the increase of electron energy of a factor two, of electron density of a factor four (by doubling the frequency) and of the volume, will increase the power of about one order of magnitude for the 4<sup>th</sup> ECRIS generation. Therefore a consistent reduction is to be obtained by frequency tuning and by the magnetic field optimization. The requirements of good vacuum for the high charge states buildup is also conflicting with high RF power. Finally the beam transport of multi-mA beams will be a major problem as well as the injection into the cyclotron of beams with larger energy, that will oblige to redesign the central region of existing cyclotron.

The relevant work needed by a 4<sup>th</sup> generation ECRIS will be balanced by the ability to produce eMA beam for each charge state up to Q=30<sup>+</sup> or 35<sup>+</sup>. These figures are adequate for some of the accelerator facilities to be operated in the next decade, as LHC, FAIR, SPIRAL2, RIBF, RIA, EURISOL, etc. Even for smaller facilities, the investment of money and manpower remains anyway modest with respect to the gain that can be originated by larger beam current and higher charge states, up to 60<sup>+</sup>.

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