3rd and 4th Generation ECRIS: Some Possible Scenarios

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Abstract Since the end of '70s the Electron Cyclotron Resonance ion sources (ECRIS) allowed to increase both the energy and intensity of the beams available from different types of accelerators; perspectives for the future are still optimistic. It is commonly agreed that only some ECRIS parameters have been fully exploited, whether some others are still not efficiently used, or not understood. The developments in the last 20 years have followed the so called Standard Model and the availability of higher frequency generators and higher field magnets have permitted relevant increase; the use of Nb_3Sn may extend the range. The availability of new schemes of microwave coupling to plasma is promising, and the focusing of the electromagnetic wave towards the chamber axis may improve the density of warm electron population. The paper will also describe some critical point of the 3rd generation ECRIS (including technological troubles and limits) and the scenario for future 4th generation ECRIS, operating at f=56—75GHz, to be built in 2010s.

Key words ECR ion sources, plasma, microwaves, ion beams, superconducting magnets

1 Introduction

The increasing cost for the construction of ion beams accelerators has been the major reason for the development of new ECRIS, along with their ability to provide intense beams of highly charged heavy ions with high reliability, stability and low emittance. Even if it is difficult to obtain multi-mA current on each charge state, because the current is distributed over different charge states, the ECRIS present the advantage of a higher current and reproducibility than other ion sources and moreover they can work either in cw mode or in pulsed or afterglow mode, by maintaining their characteristics. Following the roadmap defined by the Geller's scaling laws[1] and the High B mode concept[2], the evolution of ECRIS has been steady. The increase of current for highly charged ions in the period 1980—2005 has amounted to a factor 100 to 1000 (e.g. O^{7+}current increased from 2 to 600eμA); if we consider that the world Gross Domestic Product (GDP) increased of a factor fourty over 40 years and the Wall Street index took 64 years to increase by two orders of magnitude, the added value of ECRIS is appreciable. A further increase is possible according to the Standard Model of ECR sources[3] unless technological problems occur and mA beams of highly charged heavy ions will be soon possible. As for the magnetic field, the optimum parameters are well known. A number of experiments have demonstrated that a good and stable plasma is created in ECRIS if the magnetic trap field is $B/B_{\rm ECR} > 2$, which is called "High B mode condition"[2], that takes to a quiescent plasma and easy source tuning even if non-linear instabilities and charge exchange processes limit the performances (vacuum is one of the major hurdles for 3rd generation ECRIS and will be even worse for the 4th). The increase of microwave power and frequency is necessary but not sufficient. It can be observed[4] in Fig. 1 that the increase of frequency from 14 to 18GHz increased

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the current of Xe^{27+} of 50% only, while for 28GHz operations, in presence of modest confinement, the better microwave matching boosts the performances.

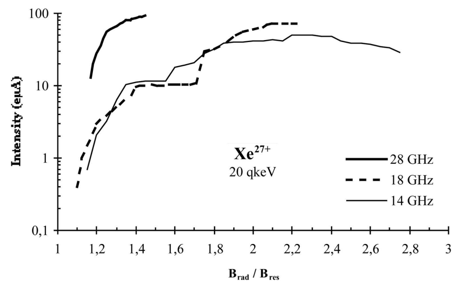

Fig. 1. Increase of Xe^{27+} beam current with the ratio of the radial field to the resonance field B/B_{ECR}.

The plot is given in terms of the B/B_{ECR} ratio (B_{ECR} is 0.5T, 0.63T and 1T for 14, 18 and 28GHz). The 28 GHz curve in Fig. 1 does not show any saturation, and the highly charged ions production was mainly limited by technological constraints[4], as the available magnetic field and the microwave power that can be safely injected in the chamber. Similar current increase for increasing B/B_{ECR} was observed more recently for other sources[5].

2 Magnetic confinement and microwaves

The experience have shown that the dependance of performance and behaviour on the magnetic field topology and strength has been fully understood, but it is not the case for the microwave coupling and the ECR heating mechanism is not fully optimized. Experimental facts show that additional improvements may be obtained: the observation that traveling wave tubes (TWT) generators permits to obtain the same charge state at a power rate three times lower than a klystron[6]; the two frequency (or multiple frequencies) heating mechanism; the fact that the best ECRIS operate with an RF power per volume unit up to 0.8W/cm^3 in cw mode and more than 1W/cm^3 in afterglow mode, without plasma instabilities[7]. These facts suggest that ECRIS improvements may come from a more efficient transfer of energy.

The RF power is determined by $P=V\ E_{\mathrm{e}}\ n_{\mathrm{e}}/\tau_{\mathrm{e}}$ which means that the increase of electron energy of a factor two (to get higher charge states), of electron density of a factor four (by doubling the frequency), of the volume increase for technological reasons, leads to an increase of the power of about one order of magnitude for the next generation of ECRIS, the 4$^{\mathrm{th}}$, to be operated at 56 to 75GHz, and tens of kW will be needed, unless the energy transfer between electromagnetic wave and free electrons is maximized.

We can state that up to now the magnetic field was adapted to the RF modes distribution in the multimode cavity consisting of the plasma chamber and of ancillary equipments, while in the future we may adapt the coupling of microwaves to maximize the ECR heating, then we shall adjust the magnetic field to get a quiescent plasma. Microwave diagnostics and simulation tools are still to be developed. Experimental data feature that not many electrons reach an energy close to the stochastic barrier (even 300keV) but even if theoretical forecast[8] done on the basis of a single particle approach are in good agreement with experimental X-ray measurements in the range of hundreds keV, the electron leakage lowers the temperature so that the temperature of warm electrons T_{e} is far from this theoretical limit[8, 9].

3 Simulation codes

The Particle In Cell (PIC) codes are in principle able to perform the 3D plasma simulation taking into account the presence of magnetostatic, electrostatic, as well as electromagnetic fields. They can describe the plasma properties (ECR electron heating, ionization and particles confinement processes in the magnetic trap) during time, including also the magnetic confinement and the space charge effects. The PIC method is presently not able to give adequate and complete results in stationary conditions, but the potentiality of this method are high. Another fruitful approach to a statistical description of the plasma properties in stationary regime is the 0D model employing the balance equations. Many implementations of the balance equations analysis method have been developed[10, 11]. In all of them the use of some input parameters is required to properly adapt the model to the source characteristics. Starting from the balance equations method[10], a proper resolution of the system of nonlinear algebraic equations is obtained, satisfying the quasi neutrality plasma condition and the flow condition

$$\sum_{s=0}^{S}\sum_{z=1}^{Z_s}\frac{zn_{s,z}}{\tau_{s,z}}-\sum_{k=0}^{K}\frac{n_{e,k}}{\tau_{e,k}}=0\ . \qquad (1)$$

where $n_{s,z}$, $\tau_{s,z}$, $n_{e,k}$, $\tau_{e,k}$ are density and confinement time of ions and electrons and Z_s is the maximum charge state achievable for each ion specie S. An estimation of the total power delivered to the external environment in terms of lost particles can be performed. The numerical method described in Ref. [9] calculates the output charge state distributions (CSD) and the estimated power flow from the plasma that can be compared with the available experimental results.

In Fig. 2 simulations and experimental data are compared for a plasma of pure oxygen. The electron density function was modeled as the superimposition of two maxwellian distributions, with a temperature $T_{e,c}$=100eV for the cold electron component and $T_{e,h}$=5keV, for the warm one. The best fitting for both the charge states and the power is achieved by the C case, showing again that the useful amount of RF power is much lower than the power provided by the generator.

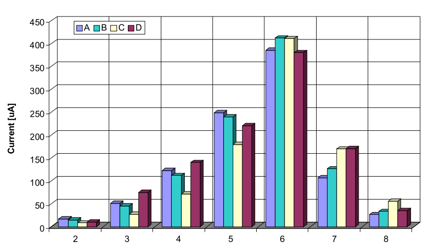

Fig. 2. A) CSD calculated for Oxygen. n_e=8.2 10^{11}cm^{-3}, P=0.4kW; B) n_e=9.7 10^{11}cm^{-3}, P=0.6kW; C) n_e=1.2 10^{12}cm^{-3}, P=1.1kW; D) Measured CSD-P=1.5kW.

4 Some possible scenarios

The conventional solution of microwave frequency increase to obtain higher electron density and larger quality factor by operating in High B mode can be continued by using high field Nb_3Sn magnets. Nb_3Sn have already been used to increase the range of values attainable for accelerator magnet[12], e.g. for LHC dipoles the maximum field of 9.7T for NbTi magnets was increased to 15.3T with Nb_3Sn magnets. Even for the ECRIS' B-minimum traps of a relevant increase may be expected (even a factor 2 for magnets and 1.5 for the hexapole), so it is possible to think to a 56÷60GHz 'dream machine' ($B_{\rm ECR}$ >2T), with an axial field up to 8T and a radial field of 4.5T. Up to now only magnets of dipolar type or solenoidal type has been built, but technology seems mature enough to be applied to complicate shapes in the coming years. High Temperature Superconductors (HTS) are not expected to give a solution in the mid-term, as their critical current is not so high and industrial design is not easy; materials like Bi-2212 or MgB_2 are the preferred candidate for developments in the long-term.

The experience of SMIS at Nizhny Novgorod with 37 and 75GHz heating[13] shows the potentiality of dense plasma created by high frequency microwave in presence of a modest confinement. This scheme may be useful for the production of very high current of medium charge state ions; in fact the same quality factor $n_{\rm e}\tau_i$ is reached if $n_{\rm e}$ is four times larger because of frequency doubling and τ_i is four times shorter. In addition it is about $I^{q+}\propto n_{\rm e}/\tau_i$ so that an order of magnitude may be gained for the extracted current by decreasing the $B/B_{\rm ECR}$ ratio (and then τ_i) and by increasing the frequency (and then $n_{\rm e}$), but by keeping $n_{\rm e}\tau_i$ constant. The only condition is to have enough RF power to sustain a lossy plasma, even considering that the reflection and transmission coefficients of electromagnetic waves for a lossy plasma are different with respect to a lossless plasma. If we relax the trapping constraints, the lost electrons are replaced by other electrons if they are heated in a short time (i.e. electric field at resonance has to be large).

Another scenario is based on the ECLISSE method i.e. on the coupling between a Laser Ion Source (LIS) and ECRIS. The coupling efficiency of the ion beam produced by the LIS to the ECR plasma was demonstrated[14], as well as the possibility to enhance the CSD from ECRIS with respect to the standard methods used for metal ion beams (i.e. evaporation and sputtering). The 3rd generation ECRIS and even better the 4th generation ECRIS may offer the ideal condition for an optimum capture of the ion beams produced by the LIS, because of a higher density plasma (the ECRIS plasma energy content $n_e kT_e$ should be larger than the energy content of the injected beam in order to not drive instabilities). Simulations made show that the mA range may be obtained for afterglow operation with an appropriate tuning of the laser and of the microwave pulse.

The last scenario is based on the consideration that plasma chamber is a resonant structure and the RF field energy depends on resonant modes of the cavity, along with the presence of insulators and coupling structures. It was shown that a minimum amount of power at the right frequency takes to improved production of highly charged ion beam[7]. The ideal microwave pattern for coupling to the ECRIS plasma must have a three-fold symmetry and must feature a higher field close to the axis. In conclusion, preferential transmission modes exist[7] for which smaller changes in frequency take to large changes in performances, as shown in Fig. 3 for the SUPERNANOGAN source. In this case the frequency was changed in the range 14.44 to 14.53GHz with a step of 1MHz and it was observed that changes of a few MHz changed the C^{4+} current even of 70%.

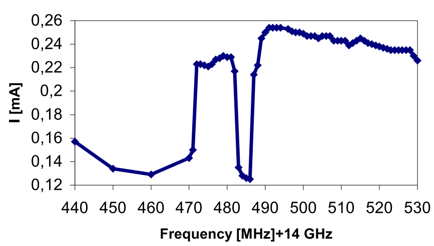

Fig. 3. Current of C^{4+} vs the microwave frequency.

Different injection schemes may be even considered, that include the use of electron cyclotron resonance and of Bernstein wave excitation at the same time, as demonstrated in Ref. [15], thus producing overdense plasmas in some region of the plasma chamber. The EBW (Electron Bernstein Waves) can propagate into the plasma without density limits. The higher densities allow a higher collisionality and then a more effective ion production is possible over limited volumes. 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. This process called OXB mode conversion was described in 1973[16] and it was shown that the OXB mode conversion might be optimized in terms of Ordinary-mode (O-mode) insertion angle with respect to the external magnetic field direction. In the case of ECRIS plasmas the study of the mode conversion is not so simple as the direction of propagation of the O-mode and Extraordinary-mode (X-mode) with respect to the B-min magnetc field structure is much different than in the case of toroidal configurations used so far. But this study can be rewarding as Bernstein waves offer an attractive possibility to heat “overdense” plasmas.

5 Limits and perspectives

The design of 3rd generation ECRIS have obliged to take into account some technical issues that are usually not evaluated for conventional ECRIS, either in terms of microwave power management and in terms of stray magnetic field that is detrimental for beam optics, for pumping system lifetime (a thick shield is necessary for the pumps of the MS-ECRIS source[17]) and for the gyrotron tube. The presence of intense X-ray fluxes generated by the ECRIS plasma, observed by many experiments[4, 5], generates a heat load upon the superconducting ECRIS cryostat. For VENUS and MS-ECRIS the solution was found in the use of about 2mm Tantalum cylinders between the plasma chamber and the insulator, but for the 4th generation ECRIS this problem will be much bigger, because of the higher electron energy. The lifetime of the insulator located between the cryostat and the plasma chamber also affects the reliability of ECRIS. An increase of the extraction voltage from 30kV up to 60kV is mandatory to shift the Child-Langmuir limit, but high voltage sparks are a major problem. A review of technological problems is given in Ref. [18]; beam extraction and transport is described in Ref. [19].

The perspectives for the future will be significantly addressed by the study of ECRIS plasma with VENUS and MS-ECRIS. The measurements of brehmstrahlung X-rays may give useful information. In particular, a systematic study will be carried out in the next few months with the VENUS source[20] at different level of microwave power and of magnetic field. Charge state distributions, reflected power and beam emittance may help to follow the plasma evolution with the variation of gas input, of microwave power and of confining field. A similar set of measurements will be carried out in the next year with the MS-ECRIS source[17].

In conclusion, the effectiveness of the scaling laws and High B mode at 28GHz suggests that no limitations to higher frequencies exist except for the availability of adequate magnets and RF generators. The need of larger currents for the forthcoming accelerator facilities will push in the direction of the 60GHz 'dream machine' but the decrease of trapping may give also important results if the lost electrons can be replaced by electrons which are heated in a short time. As it was done for SERSE at 28GHz[4] that was a bridge to the 3$^{\rm rd}$ generation ECRIS, even MS-ECRIS, that is a 3$^{\rm rd}$ generation ECRIS, may be operated as a bridge to the 4$^{\rm th}$.

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