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Study and modelling of a high current ECR Ion Source

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In the next future the development of ECR (Electron Cyclotron Resonance) ion sources with higher performances superconducting magnets will open new fields of investigation. Following the Geller's scaling laws [1] and the High B mode concept [2], the ECRIS evolution during these years has been stable and it led to an increase in terms of high charge states current of about one order of magnitude per decade. The main goal of the most performing sources, actually in commissioning or in construction phase, is to get milliamperes currents of highly charged heavy ions. These performances require the use of high confinement magnetic fields, together with a proper power rate and higher frequencies microwaves. It involves several technological problems, included those related to the large power requirements and to the consequent high heating of the plasma source chamber [3]. In order to have a better insight about the phenomena involving ECR heating in the superconducting source of INFN-LNS in Catania the "Classical Model of Ion Confinement and Losses" [4,5], based on the balance equations and on the charged particle confinement in the open magnetic trap has been applied with some improvements and modifications. The results obtained by this approach have been compared with available experimental data, for the estimation of the electron density and effective energy distribution in the plasma source.

ECRIS modelling

The superconducting ECR source (SERSE) present at INFN-LNS [6] has been modelled by the dynamic set of balance equations in stationary conditions ($dn_{i,z} / dt = 0$, where $n_{i,z}$ is the concentration of ions with charge state z) [4,5]. One of the main subjects when using this kind of approach is about the electron distribution modelling [7]. In the present work it is considered as the superimposition of three Maxwellians distributions, each of them represented by a characteristic electron temperature. In stationary conditions, cold electrons (T_e up to some hundreds eV) concentration is usually small because of confinement losses (their small energy and mass lead to pour confinement times) and of ECR heating, generating higher temperature electrons; this is electron component mainly causing the first ionization degrees. Warm electrons (T_e about some keV) have better confinement because of the higher energy, and they are those mainly responsible for higher ionizations. Hot electrons have very good confinement, they stabilize the plasma, regulate the ion losses, allowing to achieve even higher ionizations. Ions temperature is very small, and here it is considered equal to the typical 0.1 eV value. The source chamber is 48 cm long, it has 13 cm diameter and an extraction hole diameter of 1.1 cm. The mirror ratio is about 6.5 at injection and about 4 at extraction, for the 18 GHz frequency optimized operation mode. When the source works in stationary conditions the flow of negative and positive charges have to be equal. Therefore, by neglecting the radial losses respect to the longitudinal ones:

$$\sum_{z=1}^{Z_s} \frac{z\, n_{i,z}}{\tau_{i,z}} - \sum_{j=1}^{3} \frac{n_{e,j}}{\tau_{e,j}} = 0 \qquad (1)$$

where $n_{i,z}$ is the concentration of ions of charge state z, $\tau_{i,z}$ is the corresponding ion confinement time and Z_s is the maximum charge state; $n_{e,j}$ is the concentration of electrons of the j type and $\tau_{e,j}$ is the corresponding electron confinement time. The *quasi-neutrality* condition for the plasma in the source imposes that $\sum_{z=1}^{Z_s} z\, n_{i,z} - \sum_{j=1}^{3} n_{e,j} = 0$. A value of $10^{-7} \div 10^{-8}$ for this difference is enough to generate potential peaks of tens or hundreds volts within the confined plasma. An approach commonly adopted for the determination of the extracted currents was proposed by West [4]. It takes into account the confinement losses, but not the limitations due to the space charge effects. In order to consider them, we normalize the currents following the $z^{0.5}$ law, characteristic of the Child-Langmuir formula [8]. Therefore:

$$J_z = \sqrt{\frac{z}{Z_s}}\, \frac{qVa}{2S}\, \frac{z\, n_{i,z}}{\tau_{i,z}} \qquad (2)$$

where q is the elementary charge, a is the electrode surface, V and S are the effective plasma volume and surface, that we determined by Montecarlo method. For an ECR ions source the energy balance in stationary regime may be written as:

$$P_{fw} - P_r = P_m + P_{rad} + P_{tr} \qquad (3)$$

In this expression P_{fw} is the power supplied by the microwave generator (Klystron, TWT, Gyrotron…), and P_r is the power reflected by the chamber towards the microwave supply; these two quantities can be experimentally measured in order to know the net power flowing to the chamber. P_m is part of the microwave power dissipated on the chamber surface; when the confining magnetic field is switched off it is the main power sink for the chamber. P_{rad} is the power irradiated by the plasma (Bremstralhlung and Synctrotron radiation); it can be supposed to be negligible respect to the other components, and it is confirmed by the simulations. P_{tr} is the power associated to particles losses from the magnetic trapping. By the balance equations it is possible to determine the ions and electron concentrations, together with the corresponding time heating and the plasma potential and potential dip. Thus:

$$P_{tr} = qV\left(\phi + T_{e,c}\right)\frac{n_{e,c}}{\tau_{e,c}} + qV\sum_{k=1}^{2}\frac{n_{e,k}\,T_{e,k}}{\tau_{e,k}} + qV\sum_{z=1}^{S}\left(z\Delta\phi + \sum_{i=1}^{z} I_z\right)\frac{n_{i,z}}{\tau_{i,z}} \qquad (4)$$

where ϕ is the plasma potential, $\Delta\phi$ is the potential dip [7], I_z is the potential of *z*-ionization for the ions. The first two terms deal with the energy associated to the electrons (the first for cold and the second for k = 1 warm and k = 2 hot), while the third component is related to the ions losses. Plasma potential and potential dip are determined by the flow and charge equalization. Some preliminary results are shown in Figure 1a and 1b for pure ^{18}O. In particular, in Figure 1a the results of the simulations are compared with the experimental data obtained when P_{fw} = 1400 W. It is shown how the space charge effects limit the extracted currents, leading to results closer to the experimental data for pure ^{18}O. The contributions to the total calculated power (equal to 1466.2 W) are given by warm and hot electrons (1396.6 W), followed by ions (68.3 W) and cold electrons (1.3 W). The Bremsstrahlung emitted power results negligible (it is in the order of tens of mW respect to the others. Figure 1b shows the calculated charge states distributions when different electron temperatures are considerated for the warm and hot electron components, and also when different times heating for the cold-to-warm and for the warm-to-hot electron transition are taken into account.

Conclusions

The set of balance equations in stationary regime has been considered on the superconducting ECR source (SERSE), determining plasma potential and potential dip by the equalization of the charge flows and by the plasma *quasi-neutrality* condition. A formula taking into account the limitations due to the space charge effects was used for the extracted ions currents, following the Child-Langmuir principle. The presented approach to the problem of the ions source modelling is versatile and can describe the working principles of the source quantitatively. It takes into account all the main physical phenomena involving ECR heating and ion confinement. The preliminary calculated results properly fit the experimental data.

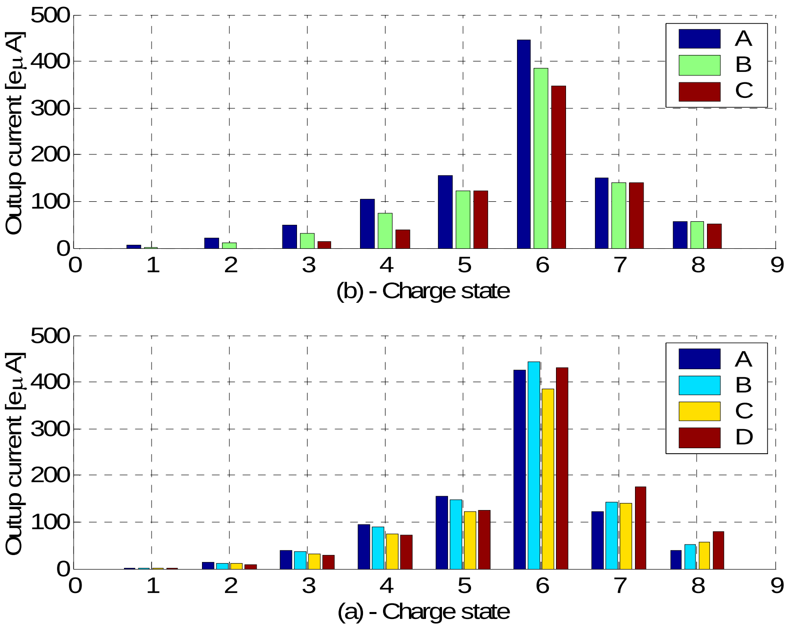

Figure 1: (a) Comparison between: A) Simulation with West [4] formula for extracted currents: n_e = 2.3 10^{12} cm^{-3}, $T_{e,c}$ = 100 eV, $T_{e,w}$ = 5 keV, $T_{e,h}$ = 15 keV, P_{tr} = 1466.2 W, $\tau_{h\ c\text{-}w}$ = 10^{-7}s, $\tau_{h\ w\text{-}h}$ = 10^{-8}s; B) the same simulation but with formula (2) for extracted currents; C) Experimental results for P_{fw} = 1400 W. (b) Comparison between simulations (employing formula (2) for extracted currents) with different times heating and hot electron temperatures. For times heating $\tau_{h\ c\text{-}w}$ = 10^{-7}s, $\tau_{h\ w\text{-}h}$ = 10^{-8}s: A) n_e = 1.8 10^{12} cm^{-3} ,$T_{e,c}$ = 100 eV, $T_{e,w}$ = 5 keV, $T_{e,h}$ = 8 keV, P_{tr} = 937.8 W; B) n_e = 2.1 10^{12} cm^{-3}, $T_{e,c}$ = 100 eV, $T_{e,w}$ = 5 keV, $T_{e,h}$ = 10 keV, P_{tr} = 1157.8 W; C) n_e = 2.3 10^{12} cm^{-3}, $T_{e,c}$ = 100 eV, $T_{e,w}$ = 5 keV, $T_{e,h}$ = 15 keV, P_{tr} = 1466.2 W. For times heating $\tau_{h\ c\text{-}w}$ = 10^{-9}s, $\tau_{h\ w\text{-}h}$ = 10^{-10}s: D) n_e = 2.5 10^{12} cm^{-3},$T_{e,c}$ = 100 eV, $T_{e,w}$ = 5 keV, $T_{e,h}$ = 15 keV, P_{tr} = 1852.8 W.

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