NEW TOOLS FOR THE IMPROVEMENT OF BEAM BRIGHTNESS IN ECR ION SOURCES *

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Abstract

According to the model that has driven the development of ECRIS in the last years, a large variation of the pumping microwave frequency (order of GHz) along with the proportional increase of the magnetic field boosts the extracted current for each charge state because of a larger plasma density. Recent experiments have demonstrated that even slight frequency's changes (of the order of MHz) considerably influence the output current, and what's more important, even the extracted beam properties (beam shape, brightness and emittance) are affected. A number of tests have been carried out in the last few years and they will be reviewed along with the results of numerical simulations which are able to explain the observed phenomena. The frequency has been systematically changed and the beam output has been recorded either in terms of charge state distributions and beam emittance. The detected bremsstrahlung X-rays are additionally analysed: they give insights about the electron energy distribution function (EEDF). An overview about the possible future improvements of ECR ion source will be given.

INTRODUCTION

Forthcoming projects aiming to radioactive beams production will be very demanding by the point of view of primary beam intensities and charge states. In this context the ion sources, being the first ring of the accelerator chain, will play roles of growing importance. ECRIS (electron cyclotron resonance ion sources) are largely used on these purpose, because of their ability to produce, in CW and pulsed operations, intense currents of multicharged ions.

However the improvement of ECRIS performances, based on the increase of either microwave frequency (it enhances the plasma density, then the output current) and mirror ratio of the magnetic trap (it confines ions for longer times in order to obtain higher charge states), is now close to saturation, limited by the reliability of the magnets and by the costs.

Concerning the generators, the limitations come not by technology but by the basic principles of plasma heating in multi-mirror devices. Experiments carried out on last generation sources, in fact, have revealed that at frequencies of the order of 28 GHz (with power levels of few kW) suprathermal electrons, with energies of the order of 1-2 MeV, are largely produced. According to theoretical and empirical estimations [1, 2], their number grows with the pumping frequency, and at 28 GHz it is already close to the limits which ensure the safety of the magnetic system. These particles in fact produce large amounts of hard X-rays, which are then partially absorbed inside the cryostat surrounding the superconducting magnets, leading to the boil-off of the liquid helium. Deterioration of the high voltage insulators was also observed. Suprathermal electrons are also useless because their ionization rate vanishes at so high energies. Their nature is still not explained by the current theories describing the ECR heating mechanism, which do not predict electron energies larger than 200-300 keV. Anyway, considering experimental data shown in [3], their production mechanism appears to be strongly related to the magnetic gradient at the ECR, and more generally to the mirror trap profile (taking into account also the distance of the resonance from the minimum field position).

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ALTERNATIVE PLASMA HEATING SCHEMES

The necessity to overcome models based on semi-empirical approaches was enunciated already in the last decade of XX century by Richard Geller in order to make advances in terms of extracted currents and production of highly charged ions. For this reason several alternative heating schemes were proposed, by different teams spread over the world. The first one appeared in 1994 and it was named Two Frequency Heating (TFH): it consists in the use of two waves at different frequency instead of one [4], both carrying a total amount of power that is approximately the same of a single wave. It has been observed that the charge state distribution (CSD) peak shifts to higher charge states, and a current increase of a factor 2–4 can be obtained for the highest charge states.

Other variants on plasma ignition schemes were brought at ORNL, using a broadband generator or a flat-B field configuration [5] (i.e. shaping the magnetic field with a quasi-constant profile at the ECR position), but they did not provide remarkable benefits. In some cases they even worsen the performances, producing huge amount of hot electrons.

In the years 2001 – 2004 some controversial results were obtained at INFN-LNS of Catania [6], where the plasma was alternatively heated by TWT or Klystrons: using the first generator the current of each charge state increased considerably, and/or operations at much lower power levels than klystrons were possible, obtaining the same performances. These results finally led to the so-called "Frequency Tuning Effect", which permits to optimize the source performance easily and in affordable way. It has been demonstrated that the different behaviour of the source when using TWT or Klystrons was due to the different -although very close – pumping frequencies used for the plasma ignition. If the pumping frequency is slightly tuned (few MHz over the several GHz used in modern devices) the average charge state and the output currents – especially for the highly charged ions– change remarkably. This effect can be also coupled to TFH, providing huge benefits to the source performances: when the TFH was tested with the SERSE source at INFN-LNS for the first time the importance of tunable frequency generators, like TWT, to fully exploit the potentialities of the double frequency heating was put in evidence.

Since 2005 several efforts have been paid to the modelling of this phenomenon, and main results are reported in [7, 8, 9, 10].

In TFH the two frequencies usually differ of about 3–4 GHz, but anyway not less than 1 GHz. It is a common idea that in the TFH mode the two frequencies have to be well separated. However, analytical calculations and numerical simulations presented in [7] showed that very close frequencies (of the order of few hundreds of MHz) could help to heat the plasma electrons more rapidly, thus improving the ionization rate, providing that a proper phase shift holds between the two waves. This effect can be denominated Two Close Frequency Heating Effect, and appropriate tests with the SERSE source of LNS is scheduled.

MODELLING OF ELECTRON AND ION DYNAMICS

We developed a numerical code implemented in MATLAB in order to follow the electron and ion dynamics by means of a MonteCarlo collisional approach. More details are available in [8, 9, 10]. We performed fully 3D collisional simulations of ECRIS plasma, splitting the electron and ion dynamics, and looking separately to their time evolution. A SERSE-like device has been implemented in our code, assuming a plasma chamber length of 45 cm, and radius 6.5 cm.

In a fully 3D MC simulation the B-min field can be correctly reproduced, in Cartesian coordinates, by using the following formulas:

$$B_x = -B_1 xz + 2Sxy$$

$$B_y = -B_1 yz + 2S(x^2 - y^2)$$

$$Bz = \begin{cases} -B_0 + B_{inj} z^2 & \forall z < 0 \\ -B_0 + B_{ext} z^2 & \forall z > 0 \end{cases}$$

The magnetic field for 14 GHz (B_{ext}=1.2 T, B_{inj}=2.2 T, B_{min}=0.3 T, B_{hex}=1.2 T) is correctly reproduced with B_0=0.3 T, B_{inj}=25 T/m^2 , B_{ext}=36.5 T/m^2 and S=360. The collision probability is calculated according to a well known Monte-Carlo technique, once known the characteristic time of Spitzer collisions for particles moving at velocity v:

$$P(t) = 1 - \exp\left(-\frac{t}{\tau_{coll}}\right) \qquad \tau_{coll} = \frac{M_{i,e}^2 2\pi\varepsilon_0^2 v_{i,e}^3}{n_e z^4 e^4 \ln\Lambda}$$

Where z is the ion charge state (it is z=1 for electrons) and ln Λ the so called Coulomb logarithm. The MonteCarlo hybrid code solves the relativistic Landau equation [11] for electrons and a non relativistic equation for ions:

$$\frac{d\vec{v}}{dt} = \frac{q}{M}\left[\vec{v} \times \vec{B} + \vec{E}_s\right] \qquad (i)$$

$$\frac{d\vec{v}}{dt} = \frac{q}{m}\left(1 - \frac{v^2}{c^2}\right)^{3/2}\left[\vec{v} \times \vec{B}_S + \vec{v} \times \vec{B}_{em} + \vec{E}_{em} - \frac{1}{c^2}\left(\vec{E}_{em} \cdot \vec{v}\right)\vec{v}\right] \qquad (e)$$

where E_s the electrostatic field over the resonance surface of the plasma, which can be perturbed by eventual fluctuations of the electron density [8, 10].

The crucial assumption of our model is that the source chamber works as a resonant cavity even when filled by the plasma, which just shifts the resonance frequencies proportionally to the electron density, and introduces an absorption term in the eigen-field equation of the cavity. Experiments performed so far demonstrate that mode patterns still persist in high density absorbing plasmas [12].

THE FREQUENCY TUNING EFFECT

After the experimental evidences which confirmed the effectiveness of frequency tuning on the improvements of ECRIS performances, it was argued that the FTE was based on the coupling properties between the microwave generator and the plasma chamber. Several experiments were carried out in order to measure the reflection coefficient of the plasma chamber fed by rectangular waveguides [10, 12]. Resonant modes can be identified in correspondence to the minima of the reflection coefficient. From the experimental data generally appeared that the current signal was peaked on frequencies corresponding to modes, because of a better coupling. However this is not a strict rule: in some cases, although the matching of the microwave line with the source (cavity plus plasma) is optimal, the extracted current remains low. Therefore we must distinguish between the microwave generator-to-plasma chamber coupling and the excited mode-to-plasma coupling. In the latter case, as formerly explained in [8, 9, 10], the mode spatial structure plays the main role.In ECRIS the conditions for the electron cyclotron resonance are fulfilled over a characteristic egg-like structure defined as ECR surface. According to simulations, the heating rapidity is strongly regulated by the electromagnetic field pattern over the resonance surface. The structure of the electromagnetic field is regulated by the triplet of numbers which identifies each mode at a given frequency: $TE_{n,m,r}$ or $TM_{n,m,r}$.

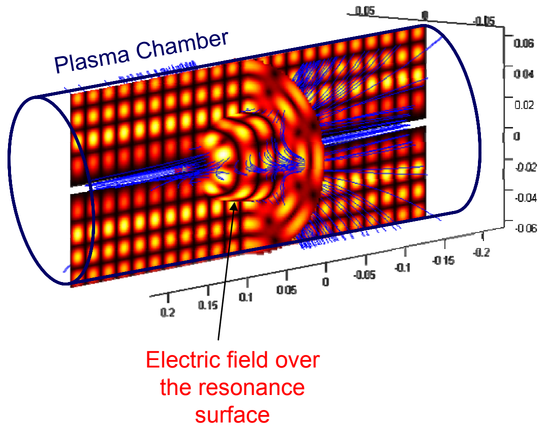

Figure 1: example of electromagnetic field distribution inside the plasma chamber for $TE_{4,4,23}$ mode excited at 14.05 GHz (light areas correspond to high field). The structure of the magnetic field lines is also shown.

Modes with high values of the triplet of integer numbers n, m, r have many maxima and minima inside the plasma chamber, and several of them intercept the resonance surface (see figure 1).

The heating process depends on the matching between areas characterized by high values of electric field with the electron fluxes, which at first approximation follow the magnetic field lines. According to simulations [9] a more or less efficient matching affects mostly the heating rapidity from the cold (1-1000 eV) to the warm (1-100 keV) population. Considering a SERSE-like device after 10-15 passages through the resonance, corresponding to about 50 ns, when the pumping frequency is varied within 50 MHz around 14 GHz, electron mean energy fluctuations are about a factor 5 to 6, (for some modes electrons reach 2-3 keV of average energy, for others up to 15-18 keV, keeping constant the RF power and the Q factor of the cavity). More recent simulations reveal that the energy gain for electrons saturates after 200-300 ns: then electrons are lost because of pitch-angle scattering into the loss cone. In order to correctly reproduce the real energy of electrons we used a high Q (10^4) factor for the cavity. Therefore the frequency tuning regulates the final temperature of the warm electron component. The suprathermal electrons are not influenced by the tuning of the frequency, as confirmed also by experimental results reported in figure 2. These measurements were done with the CAESAR source at LNS, by detecting X-rays and by collecting the corresponding Charge State Distribution at a given frequency. Note that the slope of the high energy part does not change with the frequency, meaning that the temperature of the hottest plasma component was unchanged.

Up to now we have considered the frequency tuning influence on the electron dynamics, and more specifically on the heating rapidity. However, the experimental results put in evidence that this picture is not exhaustive, and it

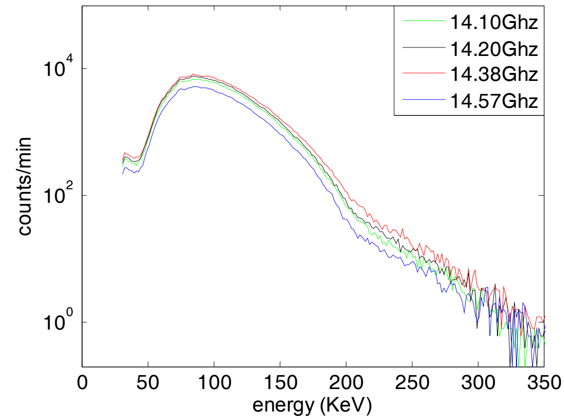

Figure 2: X-ray spectra obtained at different pumping frequency with the CAESAR source at LNS.

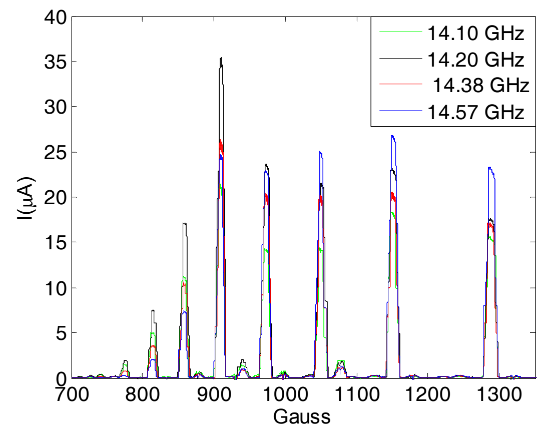

Figure 3: charge state distribution for Kr obtained at different frequencies (tests with CAESAR at LNS).

does not explain all the consequence of the heting scheme.

Figure 3 shows that the highest charge states are more influenced by FTE, as observed in previous experiments. Figure 4 shows the trend of detected X-rays integrated over fixed energy intervals, and plotted versus the pumping frequency. At 14.38 GHz the maximum number of counts was revealed, but the same frequency produces relatively low currents and even a lower mean charge state. Considering the relation $<q> \propto n_e \tau_i$, being n_e the electron density and τ_i the ion lifetime, and assuming that the number of X-ray counts is somehow linked to the electron density, the results in figure 3 and 4 can be explained only by taking into account a possible influence of FTE on the ion dynamics (τ_i changes more than n_e). Interesting data on the ion dynamics were taken already in 2008: strong variations of the beam shape were observed when changing the pumping frequency in the CAPRICE source of GSI [13]. Since then, a plenty of data have demonstrated the influence of the frequency tuning on the beam dynamics (e.g. at JYFL of 2009 and 2010 [14, 15]).

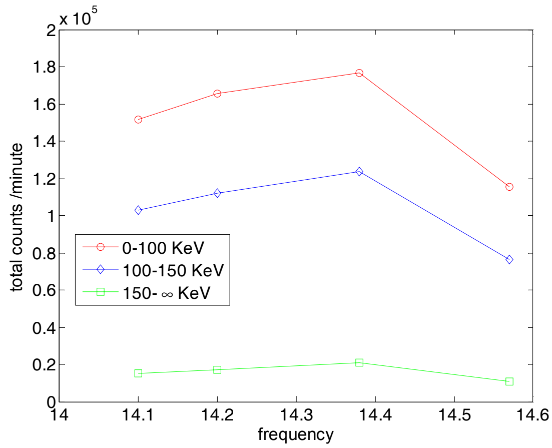

Figure 4: total counts of detected X-rays at different energy ranges versus the pumping frequency (tests with CAESAR at LNS).

The very recent experiments at JYFL have revealed that the crucial game in the next future will be played in the phase space: the transmission through the cyclotron was measured at different frequencies; it came out that the transmission coefficient depends more on the mismatch in the phase space (emittance of the source versus acceptance of the cyclotron) rather than on the beam current.

Results presented before, and largely discussed in [8, 10], put in evidence for the first time the strong relationship between electron and ion dynamics, which usually have been considered uncoupled because of the different timescales.

Several items are explained in such a way:

- ECRIS beams triangular-three arm shape can be explained assuming that the ions are magnetized in their last path towards the extraction hole, whereas they are collisional in the inner resonance region;
- The electromagnetic field pattern concerning a given excited mode changes the plasma structure in such a way that the ion motion is influenced strongly by density fluctuations.
- Inner plasma scattering mechanisms, due to non-homogeneities in the plasma structure, characterize the beam emittance.

According with our simulations, the ions are affected strongly by any fluctuation of plasma density in correspondence of the resonance surface. Looking to data presented in [10], it can be noticed that the plasma is almost completely confined inside the resonance surface. Only poorly populated fluxes of plasma particles are evident, close to the plasma chamber axis. This additional confinement provided by the electromagnetic field inside the ECR enclosed volume is due to the rapid increase of the electron perpendicular velocity (with respect to the magnetic field lines), which expels the particle from the mirror loss cone. Many of the low energy electrons reach energies on the order of keV after a single resonance crossing, then they begin to oscillate in the mirror, turning at the resonance value of the magnetic field. This mechanism has been observed also by PIC simulations: a steady state structure of the electron density appears after few tens of ns and lasts for times longer than tens or even hundreds of μs. The inner resonance plasma reaches densities at least three times larger than the outer one. More recent results [10] demonstrated that this accumulation of plasma electrons inside the ECR volume is regulated by the strength of the electromagnetic field over the resonance surface: where the electromagnetic field is higher, there will be a denser plasma. This characteristic plasma distribution influences the ion dynamics. The surface of the inner resonance plasma no longer coincides with the egg-shaped resonance area, because of density fluctuations, and the plasma surface corrugates, according to figure 5. This corrugation has remarkable consequences:

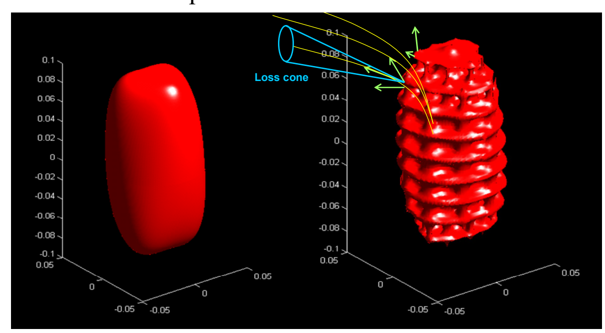

Figure 5: Smooth (left) and corrugated (right) isodensity surface of the primary plasma: the corrugation depends on the particular pattern of the electromagnetic field.

In order to preserve the quasi-neutrality, ions are accelerated when crossing the boundary between the high-density inner resonance plasma and the low density-outer resonance plasma. In fact, the electron density drops quite rapidly outside the volume enclosed by the ECR. Ions are then partially reflected, partially accelerated when passing from inner resonance plasma to the outer one, fitting the shape of the electron density distribution. Ions are dynamically confined by collisions in the inner resonance-high density plasma; in the outer-resonance plasma, because of the lower density, the number of collisions drastically decreases and the ions feel the magnetostatic field. Localization of density perturbs the ion trajectories and the plasma surface corrugation originates the ions' scattering along their path towards the extraction hole. The ambipolar electric field is directed towards the density gradients, i.e. everywhere perpendicularly to the corrugated surface (see the coloured arrows in figure 5 – right). Corrugation of the inner resonance plasma surface can introduce more or less ions into the lateral loss cones, thus decreasing the axial output current.

Therefore the following situation may be conceived: a given mode is able to rapidly move the electrons from the cold to the warm population (effect on heating rapidity – electron dynamics) but the configuration of the inner resonance density scatters the ions mostly laterally.

Therefore the number of highly charged ions in the output current will be very low and the source performances will be worse (the influence on ion lifetime is enhanced). For some other modes, the scattering may be less pronounced (thus producing high current beams) but the ions may still have large perpendicular components (with respect to the plasma chamber axis) that results in a higher emittance.
In addition, simulations put also in evidence a depletion of plasma density in the near axis region: this may be at the basis of hollow beams. The only way to reduce the around axis accumulation of plasma, flattening the density, is the excitation of modes with maxima even in the region close to x=y=0.

DISCUSSION AND PERSPECTIVES

Our modelling demonstrates that different modes excited into the plasma chamber produce different shapes of the output beam. This relationship between the mode structure and the beam emittance is confirmed by experiments on simpler devices like the microwave discharge ion sources working at 2.45 GHz. Low order modes are excited, and the extracted beam is not hollow at low currents, becoming hollow at large intensities because of space charge effects. In ECRIS, high order modes are typically excited, due to the physical size of the plasma chamber which is much higher than the operating wavelength. The main consequence is that the first two index of the excited mode are generally greater than one, resulting in electric fields having the maxima off-axis and low values in regions close to the plasma chamber axis.

Studies with the state-of-art electromagnetic simulators will start quite soon, trying to find some solutions to this problem. Non-cylindrical shapes of the plasma chamber may be tested, in order to better adapt the structure of the electromagnetic field to the resonance surface shape.

The above presented model well explains the frequency tuning effect as a consequence of the mode structure. FTE helps to improve ECRIS performances without any modification to the hardware of the source, permitting to overcome the limitations of the current semi-empirical scaling laws for the frequency (over GHz range) and the magnetic field. Therefore it could permit to fully exploit the potentialities of already existing devices, operating in a frequency range 6.4 – 28 GHz. Variable frequency microwave generators are needed; TWT amplifiers are preferable because of their versatility in changing the output frequency. For third generation sources, which make use of Gyrotrons at 28 GHz, Gyro-TWT should be employed, conjugating the requirements of high frequencies (Gyrotron) devices with the easy tuning ensured by TWT-based amplifiers.

Any further step forward, made by increasing the pumping frequency (and the magnetic field accordingly), will be possible only when problems coming from the very energetic electrons will be solved. Some tools are under investigation at LNS on this subject. Active electron donors, like carbon nanotubes based electron guns, have been successfully tested with the CAESAR source of LNS [16]: they allowed to damp the hot electron component by means of the injection of electron beams (some mA of electron currents) into the plasma.

Theoretical investigations aiming to the comprehension of the generation mechanisms of hot electrons will be continued at LNS. The magnetic field profile, and especially the gradient at the resonance point, is the main parameter affecting the electron energy distribution function (EEDF), and simulations will be improved to determine the time evolution of EEDF at different field profiles.

On this purpose, the theoretical approach will include also self-consistent interactions between electrons and ions in order to correctly determine the inner plasma ambipolar potentials. Some efforts will be devoted to the computing time: the present version of the code is really time-consuming, requiring one week of calculations for 2500 particles (ions or electrons) over 5 microseconds (for electrons) or 200 (for ions). We plan to migrate on a GRID computing environment, in order to get the availability of about 180 CPUs in the next months, taking advantages also of the code parallelization.

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