STUDY OF THE FREQUENCY TUNING EFFECT 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) boosts the extracted current for each charge state because of a larger plasma density. Recent experiments have demonstrated that even slight frequency changes (of the order of MHz) considerably influence the output current, and also the beam properties after the extraction (beam shape, brightness and emittance). In order to investigate how this fine tuning affects the plasma heating, a set-up for the injection of variable microwave frequency into the ECRIS cavity has been prepared. The microwave power is fed by means of a Travelling Wave Tube amplifier with a broad operating frequency range. The frequency can be systematically changed and the beam output is 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). Then the results have been compared with simulations and data coming from previous preliminary experiments.

INTRODUCTION

ECRIS are high performance ion sources able to provide intense beams of multiply charged ions. They are able to operate in cw or pulsed mode, for very long times with small ripple and sufficient reliability to be used for accelerator facilities and for hadrontherapy. In ECRIS the ion beam is extracted from a high density plasma generated by means of microwaves (with frequency ranging from 6.4 to 28 GHz) in a plasma chamber filled with a gas or vapour. The plasma chamber consists of a metallic cylindrical cavity, where the plasma is confined by a magnetostatic multi-mirror field (B-minimum trap) ensuring a confinement time long enough to permit the multiple ionization of atoms. The maximum attainable charge states and currents depends on the plasma density and confinement time, according to the relations:

$$< q > \propto n_e \tau_i \qquad (1)$$

$$I_q \propto \frac{n_e}{\tau_i} \qquad (2)$$

being n_e the electron density and τ_i the ion lifetime. A semi-empirical model was developed in the last decade of XX century, conjugating the requirements of larger microwave frequencies (to increase the electron density) with stronger magnetic field (to effectively confine the plasma) [1,2]. This model is now close to saturation, because of technological limitations in magnet manufacturing, and of scientific constraints connected to the use of larger and larger frequencies, which produce a plenty of high energy electrons useless for the ionization. In order to overcome the limitations imposed by semi-empirical models, we need to investigate more deeply the ECR heating mechanism, finding alternative ways to improve the performances of existing sources.

In the years 2001 – 2004 some controversial results have been obtained at INFN-LNS [3], when the plasma was alternatively heated by TWT or Klystrons: using the first generator the current of each charge state increased considerably, and/or operations with much lower power than klystrons were possible, with 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. Since 2005 several efforts have been paid to the modelling of this phenomenon, and main results are reported in [4,5,6,7].

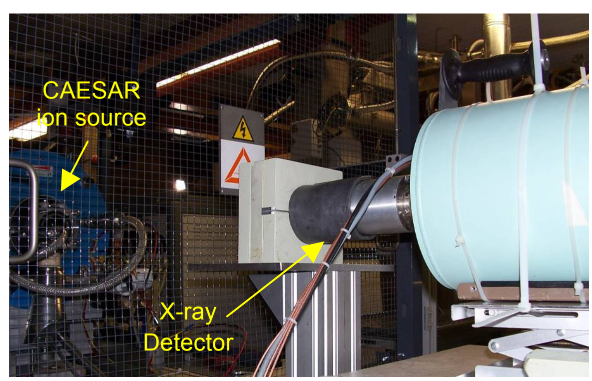

Figure 1: The X-ray detector and collimator on axis with the CAESAR source.

Here we will present the experimental results collected with the CAESAR source at INFN-LNS which show how the frequency tuning influence either the charge state distribution (CSD) and the X-ray spectra. X-rays come out from bremsstrahlung radiation, produced by electrons inside the plasma core because of interactions with the ion

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component. An additional source of X-ray production is the particles collision with the plasma chamber metallic walls. In order to avoid that X-rays generated on chamber walls reach the detector (we are interested only to the interactions of electrons in the plasma core) we used an appropriate lead bricks collimator with a small square window of 1 mm^2. The HPGe detector (High Purity Germanium) detector was placed on the source axis, at 1.5 m from the input flange of the plasma chamber. A Kr plasma has been produced, by keeping constant the background pressure ($2 \cdot 10^{-6}$ mbar) and the input RF power (150 W). The frequency was varied in the range 14 – 14.6 GHz. The magnetic field profile remained the same during all the experimental activity.

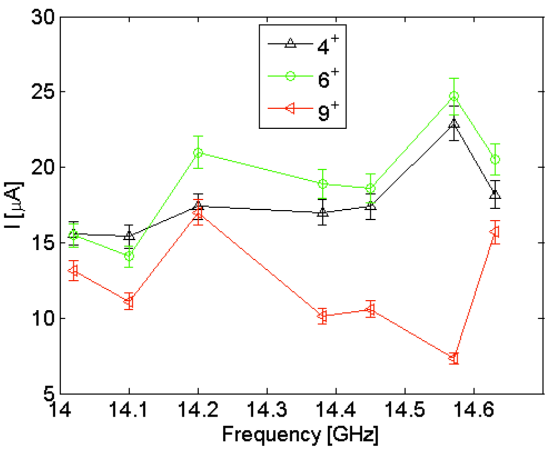

Figure 2: Trend of different charge states versus the pumping wave frequency (the power, the pressure and the magnetic field were kept constant).

EXPERIMENTAL RESULTS ABOUT THE FREQUENCY TUNING EFFECT

While the measurements featured the charge state distributions be strongly influenced by the frequency, as in ref. [3], the analysis of the X-ray generated within the plasma triggered a more detailed view of the processes involved with the frequency tuning effect (FTE). Figure 2 shows that the highest charge states are more affected than the lower ones, which is a signature of FTE influence on plasma heating rate. A more detailed investigation of CSD, in fact, points out that the charge state on which the CSD is peaked changes with the frequency. Since the temperature of warm electrons (that are responsible of most of ionizations) it is approximately given by three times the ionization energy of the charge state on which the CSD is peaked, we can conclude that the temperature of the warm electrons population is mostly regulated by the frequency used for plasma heating. Let us define this evidence as 'influence on electron dynamics', because the electrons are the only species which is strongly affected the electromagnetic field.

ECRIS plasmas are also characterized by other two electron populations, named cold and hot. The former is made by low energy electrons, which are rapidly scattered into the loss cones because of their quite large collision frequency. The latter are instead produced by diffusion of warm electrons in the velocity space, especially for low values of the magnetic gradient [8]. Optimal conditions for ECRIS operations are established when electrons move rapidly from cold to warm population, and only few of them transit till the hot one.

X-ray measurements helped to determine how FTE influences the electron diffusion in phase space, till extremely high values of energy. In [9] it is shown that the number of energetic electrons (i.e. the ones populating the spectrum tail) slightly changes passing from one frequency to another, mostly because of variations in warm population density. However the slope of the X-ray spectra is observed to remain unchanged, meaning that the temperature of hot electrons is constant.

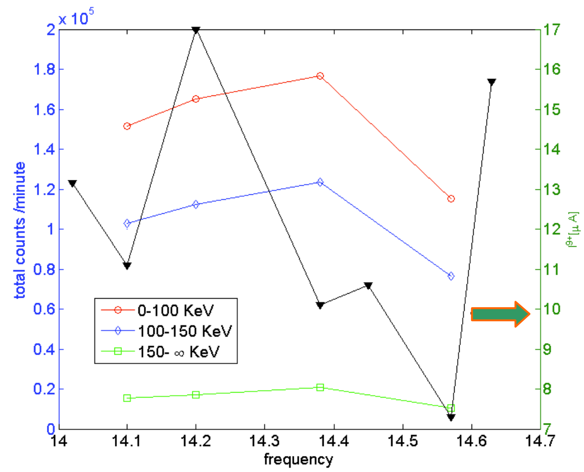

Figure 3: Comparison between number of X-rays at different energy ranges with the current of Kr9+, for different pumping wave frequencies.

Therefore, the heating rate from warm to hot population is not affected by the FTE. At first approximation we can assume that the number of X-ray counts at intermediate energies (1-100 keV) is connected with the warm electrons density. Therefore, according to equation (1), a large number of X-rays corresponds to higher $<q>$ and more intense output current, which is not the case for the experimental results above shown.

Figure 3 shows that the number of X-rays in the energy range 1-100 keV (warm electrons) reaches the maximum value near 14.4 GHz, but this not correspond to the largest output current for the Kr^{9+} charge state (describing how the impact of frequency on the highest charge states obtained at the given power level is not simply defined). We can even state that a mere influence of FTE on heating rapidity is not exhaustive and that the influence on ions must be taken into account, somehow (especially their lifetime). Evidently, for some frequencies, although the heating process is efficient and moves many electrons from the cold to the warm population, the plasma dynamics is not appropriate for the extraction of intense currents of highly charged ions.

Additional experimental data collected in the last years [10,11] confirmed that even the ions are strongly influenced by the frequency tuning, because the shape of the extracted beam changes remarkably when changing the pumping wave frequency and hollow beams are generated for some values of frequency. Then a more general theory which entails the effects of FTE on either electrons and ions dynamics is required.

MODELLING OF PLASMAS UNDER THE FREQUENCY TUNING EFFECT

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 [5,7].

The simulations have put in evidence that if we assume the plasma chamber working as a resonant cavity, then the excited mode-to-plasma coupling mechanism 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. Resonant modes are excited inside the chamber and their shape depends on the triplet of integer numbers which identifies each mode at a given frequency: $TE_{n,m,r}$ or $TM_{n,m,r}$.

Modes with high values of the triplet numbers have many maxima and minima inside the plasma chamber and several of them intercept the resonance surface. The heating process depends on the matching between areas characterized by high values of electric field with the electron fluxes, which follow the magnetic field lines. This matching regulates the heating rapidity (defined as energy gain per time unit) which fluctuates even of a factor 5 to 6 when varying the frequency. Anyway this effect is evident only during the electron heating from cold to warm population, whereas suprathermal electrons are unaffected, as confirmed also by experimental results reported in Fig. 3.

The ions are affected strongly by any fluctuation of plasma density in correspondence of the resonance surface. Looking to data presented in [7], it can be noticed that the plasma is almost completely confined inside the resonance surface. Only poorly populated fluxes of plasma electrons are present outside, close to the plasma chamber axis. This strong confinement inside the ECR surface is due to the perpendicular acceleration of initially low energy electrons passing one time through the ECR surface: this mechanism expels the electrons from the mirror loss cone and confines them into the volume enclosed by the ECR. Therefore the accumulation of plasma electrons inside the ECR volume is regulated by the strength of the electromagnetic field over the resonance surface: where it is higher, there will be a denser plasma. This characteristic plasma distribution influences the ion dynamics because of the plasma quasineutrality. Additionally, the surface of the inner resonance plasma no longer coincides with the egg-shaped resonance area, because of density fluctuations, and it shows a quite particular corrugation. This corrugation has remarkable consequences, as it perturbs the ion trajectories and it originates the ions' scattering along their path towards the extraction hole. The nature of the corrugation can guide more or less ions into the lateral loss cones of the magnetic configuration, thus decreasing the axial output current. Therefore the following situation may be expected: a given mode is able to rapidly move the electrons from the cold to the warm population but the configuration of the inner resonance density scatters the ions mostly laterally. Therefore the number of highly charged ions in the output current lowers and the source performances be worse (the influence on ion lifetime is enhanced). For 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 chamber axis) resulting in higher emittances.

On the basis of experimental results and theoretical modelling, the FTE appears as a powerful technique even to improve the ECRIS performances of existing sources. Evidently, the design of future sources will take advantage by the modelling of the electron energy increase: on this perspectives, the use of non-cylindrical chambers [9], in order to adequately match the electromagnetic field with electrons and ions density distributions, or the use of the gyro-TWTs (that could allow some versatility to get FTE at large frequencies, above 24 GHz) will be mandatory to continue the trend of the previous decades, which have seen the increase of the beam intensity by a few orders of magnitude.

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