Increase of beam brightness by means of improved ECR heating in ECRIS - Electron Cyclotron Resonance Ion Sources

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Abstract

The improvement of Electron Cyclotron Resonance Ion Sources' performances, that has been steady during last 30 years, is now close to saturation because of technological limitations. For this reason additional theoretical studies have been carried out in the framework of the HELIOS experiment of INFN. It has permitted, during last two years, to optimize ECRIS plasma heating, globally improving either electron and ion dynamics. Experimental and theoretical efforts have been able to increase not only the maximum current and mean charge state produced by the source, but also to optimize the beam brightness especially for high intensity beams, by minimizing the beam halos. Simulations helped to determine the shape of the electron energy distribution function. They also revealed that not only the tuning of the pumping frequency (Frequency Tuning Effect – FTE) influences the plasma heating, but also it affects the ion dynamics and beam formation, which is mediated by the electrons through the formation of corrugated isodensity surfaces, thus explaining the different beam shapes measured under different conditions. An improvement in beam transmission through the application of FTE was observed at CNAO, Pavia, where the LINAC transmission is much better with respect to the facility of HIT, Heidelberg, where the FTE is not employed..

Fundamentals of ECRIS' Physics and Frequency Tuning Effect

In ECRIS a dense plasma is formed by means of electromagnetic waves in the GHz range interacting with a gas or vapour filling a metallic (cylindrical) cavity of few litres of volume; the plasma ignition takes place in presence of a strong magnetostatic field, shaped in such a way to realize a B-minimum trap for the confinement of the plasma's charged particles. The conditions for the electron cyclotron resonance are fulfilled over a characteristic egg-like structure defined as ECR surface.

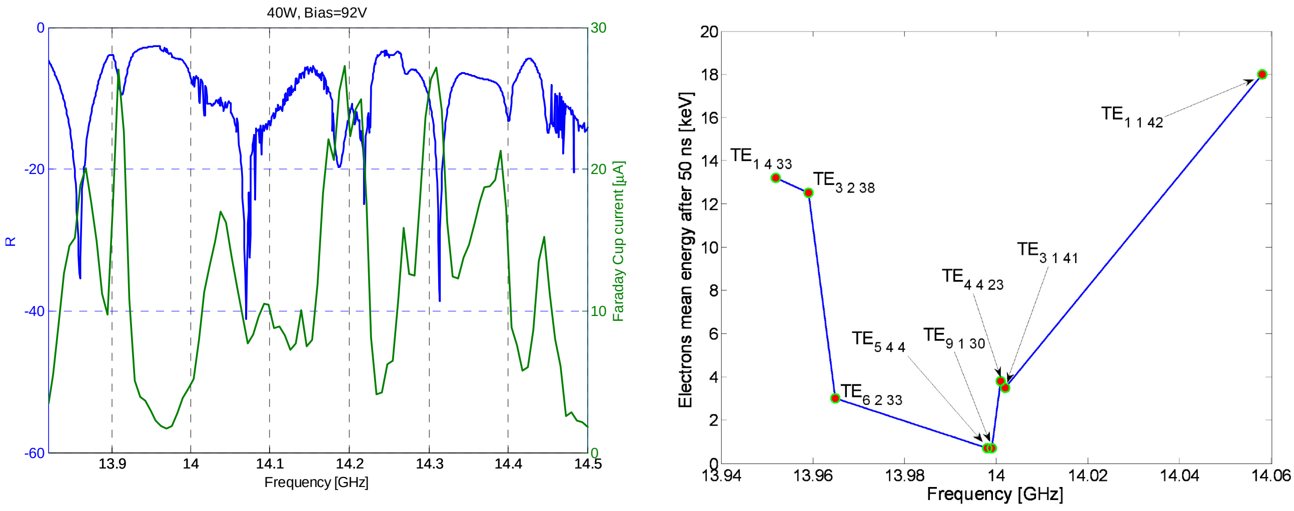
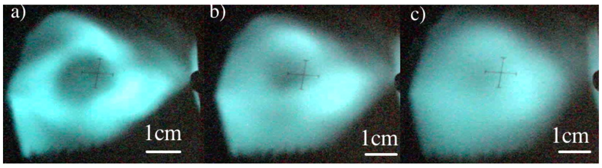


Figure 1: (left) Measured C^{4+} output current at different pumping frequency for the ECRIS at CNAO, Pavia; (right) Simulated electron heating rapidity at different frequencies: Montecarlo tecniques have been used, in a fully 3D model which takes into account the cavity modes structures: strong fluctuations for small changes of the frequency are evident.

The currently accepted model for the increase of the ECRIS performances is based on global scaling laws involving either the magnetic field and the microwave frequency: the use of increased frequencies takes to larger plasma densities and beam currents, as long as the plasma trap is adequately designed to ensure the suppression of magnetohydrodynamical instabilities. Under the conditions requested by the High-B mode concept [1] (i.e. $B_{max}/B_{ECR}>2$) the extracted currents scale with square of the pumping frequency. However this trend is now limited by technological issues, because modern sources working at 28 GHz require magnetic fields much larger than 3 T. Alternative methods of plasma heating, like the fine tuning of the pumping wave frequency (i.e. the FTE) have been explored in order to overcome the limitations imposed by the current design. Tests about the FTE have been recently carried out at Jyvaskyla University Physics Laboratory (JYFL), and with the ECR ion source of CNAO, Pavia. At CNAO a net increment of the transmission along the LEBT has been evident. In particular, the coupling of the source with the RFQ, during its commissioning phase, has given much better results with respect to the “twin” accelerator of HIT (Heidelberg, Germany). Keeping constant all the other elements and parameters of LEBT, in Pavia the transmission efficiency is around 50-70% thanks to the FTE, that is much better than the 30% obtained at HIT without the FTE. This results permits to CNAO accelerator to largely exceed the design current out of the Linac. The data collected from numerical simulations confirm that the frequency tuning effect is correlated with the electromagnetic field distribution in a region close to the ECR surface. The field pattern, which depends upon the particular electromagnetic mode excited into the chamber, regulates the rapidity of the electrons heating [2]. Modes with high field values where the magnetostatic field lines intercept the ECR surface are the best candidate to provide strong and efficient heating of cold electrons.

Already in 2006 an experiment carried out at GSI [3] revealed that the FTE influenced also the beam formation mechanism. These results were confirmed recently with the ECR ion source of JYFL. Ar^{9+} beam shape is shown in figure 2 (left) for different plasma heating frequencies: 14.050 GHz, 14.090 GHz, 14.108 GHz; for some frequencies (e.g. 14.108 GHz) the characteristic hollow beam shape partially disappears, which has beneficial effects on the accelerator performances, increasing the beam transmission. Additional measurements have shown that the higher charge states, in presence of hollow beams, mostly populate the beam halo, meaning that a strong ion scattering (driven by self-generated, inner plasma electric fields) affects the beam formation mechanism. Particle-in-Cell and single particle simulations permit to explain this mechanism [4].



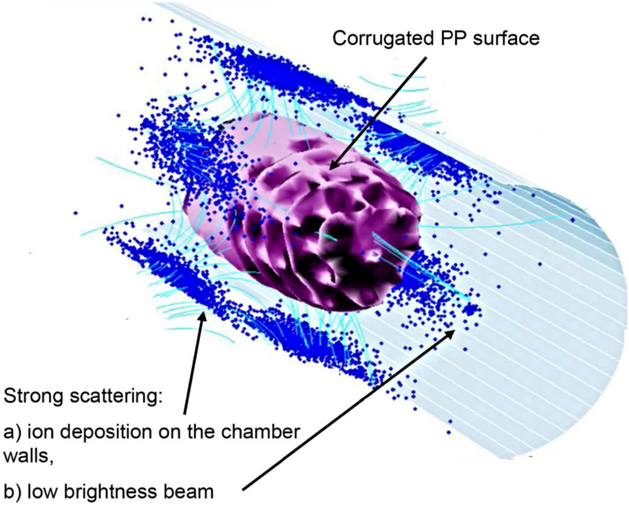


Figure 2: Left: Ar^{9+} beam shape at different plasma heating frequencies - 14.050 GHz, 14.090 GHz, 14.108 GHz. Right: simulation of the ion dynamics in presence of a strongly corrugated isodensity surface in proximity of the ECR corresponding magnetic field.

A characteristic structure of the plasma contained inside the ECRIS cavity is evident from calculations: the inner resonance plasma (Primary Plasma, PP) is much denser than the outer one (Secondary Plasma, SP). This characteristic distribution influences the ion dynamics: ions are accelerated when crossing the PP to SP boundary because of a positive potential existing over the resonance surface. The amplitude of the corrugation and the surface of the corrugated areas depend on the particular mode excited inside the plasma chamber. For smooth surfaces, the ions have a longer lifetime and reach the extraction flange producing the characteristic three cusp plasma “star”. Conversely, strongly corrugated surfaces produce large electric fields which scatter the ions during the crossing of the PP-SP boundary; the scattering reduces the ion lifetime (then the production of highly charged ions) and increases the ion beam divergence. Ions are mostly lost laterally, on the chamber's walls, and the extracted ones produce a large emittance beam, so the source performances globally worsen.

Discussion on hot electrons and conclusions

The same simulations have been employed for the investigation of the build up of the electron energy distribution function. Experiments with third generation ECRIS put in evidence the existence of extremely hot electrons[5], whose energy raises well above the adiabatic barrier predicted by the stochastic heating theory [6], and often exceed 1 MeV. Their presence is detrimental because they worsen the reliability of the source, leading to the L-He heating in the source's cryostat (superconducting magnets are employed in modern sources), to high voltage insulator aging and moreover they are useless for the ionization, since their cross section is close to zero. Either experiments and simulations confirm that the global reduction of the magnetic gradient at the resonance triggers the heating mechanism which produces the electrons above the so called adiabatic barrier E_b. This increment becomes particularly evident when increasing B_{min} [2]. Particle-in-Cell simulations additionally demonstrated that the closer the resonances are to the bottom of the magnetic field trap, the higher will be the electron temperature. For resonances close to B_{min} the adiabatic invariants, which stop the electron heating, activate quite late, thus allowing the particles to diffuse in the phase space rapidly.

Data collected and theoretical developments takes to the conclusion that ECRIS performances are still far from their full exploitation. The fine tunings of pumping frequency and magnetic field profile may produce better results than the expensive use of larger magnetic fields and microwaves amplifiers. New plasma heating schemes may provide further improvements.

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