RF heating for ECR Ion Source plasmas

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ECRIS – Electron Cyclotron Resonance Ion Sources are nowadays the most powerful devices able to feed accelerators with highly charged ions in a reliable and efficient way. They typically produce several tens or hundreds μA of multiply charged ion beams (e.g. Ar^{14+}, Xe^{34+}, etc.), which can be obtained either from gaseous or solid elements and are extracted from a high density and temperature plasma ($n_e \sim 10^{10}$-10^{12} cm^{-3}, $T_e \sim 0.1$-100 keV) generated by means of the Electron Cyclotron Resonance. The plasma is excited inside a cylindrical metallic chamber by microwaves (2.45-28 GHz) and there confined by a Magneto-Hydro-Dynamically stable B-min configuration (an hexapole superimposed to a simple mirror system), characterized by closed and quasi-ellipsoidal constant B surfaces. The density measurements reveal that plasma mostly accumulates inside the closed ECR surface (the so-called 'plasmoid'). Simulations and modelling demonstrate that this strong non-homogeneity is due to the action of RF field at the resonance surface: cold electrons ($T_e<10$ eV) are probably confined by the ponderomotive quasi-potential, while the hot ones ($1<T_e<100$ keV) are confined by the deterministic electron acceleration after a single pass through the resonance.

The monotonic increase of ECRIS performances with the frequency and with the mirror ratio, in terms of extracted current and average charge state, was originally interpreted just on the basis of larger plasma cutoff densities and of the better confinement, but now it is clear that the RF scattering plays the main role: the rate of electrons injection into the loss cones gradually increases with the frequency as well. Crucial, to determine the timescale of the plasma heating and the upper boundary of the EEDF (Electron Energy Distribution Function), is the fine tuning of the pumping frequency and especially of the magnetic field profile. Experiments, in fact, demonstrate that possible non-linear pumping wave - to - plasma interactions generate, even if with low efficiency, high frequency electrostatic modes and ion acoustic waves, leading to turbulent heating and boosting of the perpendicular ion transport [1]. The turbulence produces many hot electrons ($E>W_B$, with W_B stochastic barrier), and consequently hard X-rays [2] whose number gradually increases when reducing the B gradient.

In the last years the RF heating investigation has increased its importance and many advances has been triggered by the research performed at INFN-LNS, where a 20-years long tradition exists about the design, development and modelling of innovative ECRIS. E.g. the influence of the cavity mode structure on the output current and on the beam shape and brightness has been recently explained either experimentally and theoretically [3]. The correlation between the magnetic field profile and the pumping wave frequency has been also deeply investigated. Additional studies on alternative heating schemes, based on a multi-frequency approach, or, more recently, on possible mode conversion and electrostatic wave excitation, have been carried out. A short review on the state of the art and on the perspectives will be given in the paper.

[1] A. A. Ivanov et al., 2002 *Europhys. Lett.* **59** 841;
[2] S. Gammino et al., 2009 *Plasma Sources Sci. Technol.* **18** 045016;
[3] D. Mascali et al., *Rev. Sci. Instrum.* 2010 **81**, 02A334.