ECR ION SOURCES DEVELOPMENTS AT INFN-LNS FOR THE PRODUCTION OF HIGH BRIGHTNESS HIGHLY CHARGED ION BEAMS*

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Abstract

The design of future high-performing ECRIS will require alternative approaches in microwave-to-plasma coupling, in order to maximize the electron density at relatively low frequency and to reduce the hot electrons formation and their consequences on beam stability and on source reliability. On these purposes, different activities have been carried out at INFN-LNS in the recent past, including advanced modelling, diagnostics, and studies about alternative methods of plasma heating based on electrostatic-waves generation. A description of these activities will be presented, with special emphasis to the microwave to plasma coupling and to the plasma diagnostics. Some of the already collected results have been a basis for the design of the new AISHa source (for hadrontherapy purposes) and for the construction of an innovative prototype named Flexible Plasma Trap: on this machine we will search for new schemes of microwave launching, in synergy with the full-wave plus kinetic calculations of the wave-to-plasma interaction mechanism.

INTRODUCTION

Among the various types of ion sources developed since 1950s, Electron Cyclotron Resonance Ion Sources (ECRIS) are the best candidate to support the growing request of intense beams of multicharged ions coming from both fundamental science (nuclear and particle Physics, especially) and applied research (neutrons spallation sources, subcritical nuclear reactors, hadrotherapy facilities, material treatments, ion implantation).

Inside an ECRIS machine [1] a dense and hot plasma, made of multicharged ions immersed in a dense cloud of energetic electrons, is confined by multi-Tesla magnetic fields and resonantly heated by some kWs of microwave power in the 2.45-28 GHz frequency range. The ECRIS development path has been traced – since the years of general scaling laws definition (1980-1995) [2,3]– on the philosophy of magnetic field and microwave source frequency and power boosting. This trend is now deemed of approaching saturation due to technological constraints.

While until 2004-2005 the output currents and charge states were deemed to depend only on major plasma parameters (density and temperature), more recently some unexpected issues have come to the attention of the ECRIS community: plasma instabilities [4], local fluctuations and/or non uniform distribution of the plasma density [5], non linear response of the electron heating to the pumping wave frequency, or sensitivity to slight adjustments of the magnetic field, have been correlated with the intensity and emittance of the plasma-generated beams, showing that the parameters' space has not been fully explored, as well as the wave-to-plasma interaction in a closed resonant cavity (i.e. the ECRIS plasma chamber) with small size-to-waveguide ratio is still not fully exploited [6,7].

PLASMA HEATING IN ECRIS

The development of new generation ECRIS requires a more detailed comprehension of plasma heating processes. Recent research activity has shown that the heating process is critically dependent not only on the RF power level, but also on the fine tuning of the pumping wave frequency (frequency tuning effect [8]). Fine adjustments of the magnetostatic field profile also play a relevant role [9]. In a long-term perspective, in addition, we have considered the option of a radically different heating method of ion sources plasmas, that could be based on Electron Bernstein Waves [10].

Tuning of Frequency and B-field Profile

At INFN-LNS additional studies about frequency tuning effect have been carried out. Recently, a campaign of measurements has been carried out in collaboration with GSI-Darmstadt ion sources team [11]: it has been shown a critical variation of the plasma energy content (defined as the product of electron density and temperature $\varepsilon=n_e kT_e$) versus slight adjustments of the pumping wave frequency and magnetic field profile. Measurements about plasma spectral energy were done by means of an hyper-pure Germanium detector (HpGe) sensitive in the 30-400 keV energy range (energy resolution around 200 eV at 40 keV). The average charge state extracted from the source, namely <q>, was simultaneously evaluated: it came out that <q> was roughly connected to fluctuations of ε, the latter being so sensitive to the frequency tuning. By modifying the extraction coil current of less than 10% we slightly changed the magnetic field profile at the

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resonance zone: this in turn changed the overall deposition of energy into the plasma, but <q> fluctuations were once again mostly dominated by the frequency.

In other situations, like in [9,12], the variation of the extraction field produced a "phase-transition" like response: it happened that the temperature of the hot electrons grew smoothly to some extent, then undergoing to some jumps once critical magnetic profiles were established.

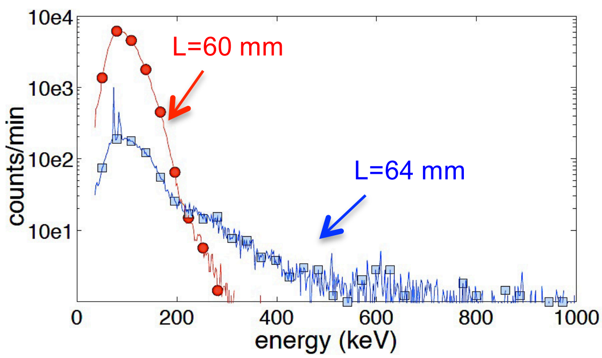

Figure 1: X-ray spectra emitted by CAESAR ion source plasma for two different magnetic field profiles

Fig. 1 illustrates one of these situations. It was obtained with the CAESAR source, where plasma electrons bounce in a B-min trap with an axial magnetic field of parabolic form: $B=B_{min}(1+z^2/L^2)$. Here L is a crucial parameter, since it fixes the gradients of the field and its "characteristic scale-length" of variation. We performed measurements of plasma emitted X-rays using the above mentioned HpGe detector. *L* was varied of only 4 mm by modifying the current flowing in the second (extraction) solenoid. The setup with L=60 mm produced an endpoint energy below 300 keV, while at L=64 mm more energetic electrons were generated, up to 550 keV. This non linear behaviour has been observed several times in other machines, and tentatively explained in [12] as based on an interplay between density distribution and magnetic profile; in the same paper a method for energetic electrons damping (they are detrimental for the ion source safety, other than useless for plasma ionisation) was also proposed. In [13] a possible connection with cyclotron instability onset was also invoked.

This non-linear response of the plasma heating to frequency and magnetic field has imposed a different approach in the design of new ion sources: the new projects AISHa (for hadrontherapy) and ASIA (candidate for the ECOS-LINCE facility) will be based on very flexible RF and magnetic systems. The same research outputs have also influenced the design of new high intensity proton sources, like PS-ESS [14], now ongoing for the forthcoming European Spallation Source.

Innovative Plasma Heating Methods

Plasmas heated by electromagnetic waves (ECR heating mechanism) are density limited due to the presence of the well-known cut-off effect. Aimed to solve this limitation, different heating mechanisms were theoretically argued, then demonstrated in nuclear fusion plasmas [10]. The new mechanism is based on a "modal conversion" scenario in which the pumping electromagnetic waves ("X" type waves) propagate in a magnetized plasma with a suitable angle to drive the generation of longitudinal plasma modes (named "Electron Bernstein Waves", EBW) able to deposit energy into an overdense plasma core. The incoming electromagnetic wave propagates into the plasma until reaching the UHR (Upper Hybrid Resonance) region, that is a resonance given by the interplay between the plasma density and the magnetic field, occurring at $B<B_{ECR}$. A similar scenario has been produced as a proof-of-principle at LNS by launching an electromagnetic wave above 3 GHz inside a small-size plasma reactor equipped with a simplified magnetostatic field (B<0.1 T, ECR at 2.45 GHz). Due to the formation of an UHR layer inside the plasma, the wave was efficiently absorbed at very low power levels (<100W), possibly converted into an EBW then absorbed at the ECR sub-harmonics. The normalized (with respect to the cutoff value) density profile is shown in Fig. 2 (here measured by means of a Langmuir probe).

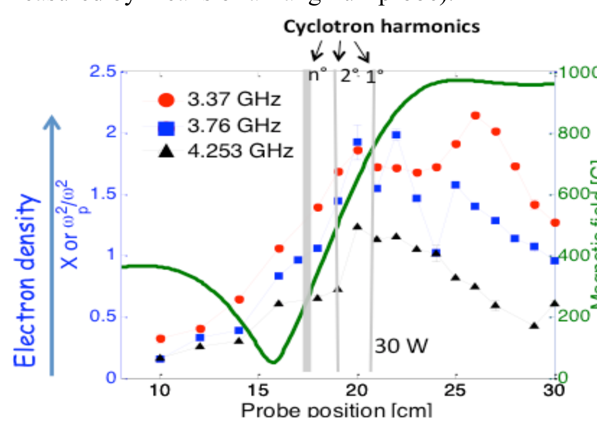

Figure 2: Plasma density profiles in case of far-from-resonance heating at three different frequencies above 3.3 GHz (ECR at 2.45 GHz).

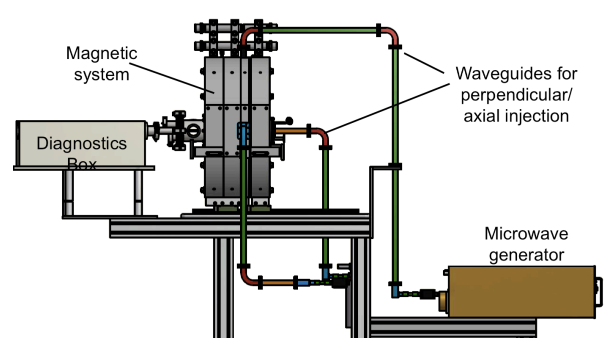

Figure 3: Final design of the new Flexible Plasma Trap now under installation at INFN-LNS.

These results (the plasma is up to two times denser than the cutoff at only 30 W of input RF power) are very encouraging for future ion sources design based on this new heating scheme. In order to carry out more advanced

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studies on this subject, we have designed a new test-bench machine named "Flexible Plasma Trap" (see Fig. 3) which will operate from 2 to 7 GHz with an adjustable magnetic field, allowing axial/radial injection and a microwave absorption oriented design of the RF system.

NUMERICAL MODELLING

Several efforts have been paid to the modelling of plasma heating and plasma formation. We are now moving towards self-consistent solution of Maxwell equations inside the plasma chamber of an ECRIS (playing the role of a resonant cavity), when the dielectric tensor of a magnetized, non-homogeneous plasma is taken into account. Fig. 4 shows the 3D electromagnetic field solution obtained by means of a FEM method, considering a plasma-filled cavity in "cold plasma" approximation (full permittivity tensor used into the equations) [15]: the electric field increases up to almost one order of magnitude when approaching the resonance; moreover, a "cavity effect" and a field amplification in the inner plasmoid region (plasma resonant effect) also appears, both due to the electromagnetic discontinuity at ECR layers. The modelling is revealing that the plasma shape and the electrons/ions distributions into the plasma are strongly affected by the electromagnetic field shape, also affecting the ion beam properties. This implies that self-consistent evaluation of the ions dynamics into the plasma will allow to predict beam quality, thus optimizing the ECRIS performances well beyond the brightness achievable nowadays, with evident advantage for beam dynamics of the future accelerators.

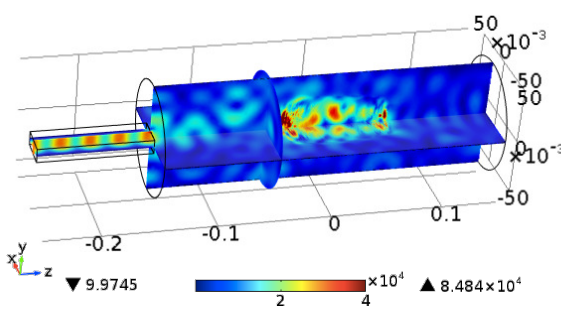

Figure 4: Simulated electromagnetic (electric field component) field distribution on a multislice plot for an 8GHz ECRIS, including the plasma at n=0.7 n_{cutoff}.

ADVANCED DIAGNOSTICS

Microwave-to-plasma coupling optimisation requires diagnostics tools spanning the entire electromagnetic spectrum, from microwave interferometry to X-ray spectroscopy; these methods can be implemented in advanced forms including high resolution X-ray spectroscopy and spatially-resolved X-ray spectroscopy made by quasi-optical methods (pin-hole cameras).

Fig. 5 shows a proof of what can be obtained by means of an X-ray pin-hole camera setup: on the left-hand side a plasma image in the optical domain is shown, while the right-hand picture shows the emission in the soft-X ray region (0.7-10 keV), thus putting in evidence the areas of the plasma containing the most energetic electrons. The imaging also helped to investigate the electron dynamics in the magnetostatic field: the bright strip on the bottom-right side of the picture, in fact, is made by electrons guided by the magnetostatic field towards the chamber walls. This kind of diagnostics will be also very useful tools for benchmarking the numerical modelling, supporting the beam characteristics optimisation.

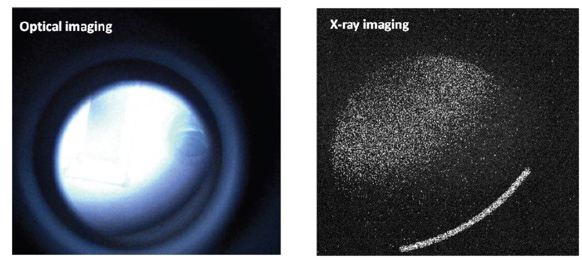

Figure 5: Optical and X-ray observation of the plasma.

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