INNOVATIVE SCHEMES OF PLASMA HEATING FOR FUTURE MULTIPLY-CHARGED IONS SOURCES: MODELING AND EXPERIMENTAL INVESTIGATION

G. Castro*[1], D. Mascali[1], G. Torrisi[1], L. Celona[1], O. Leonardi[1], M. Mazzaglia[1,2], D. Nicolosi[1],
R. Reitano[1,2], G. Sorbello[1,3], C. Altana[1,2], F. P. Romano[1,4], and S. Gammino[1]
[1]LNS-INFN, Catania, Italy
[2]Università degli studi di Catania, dipartimento di Fisica, Catania, Italy
[3]Università degli studi di Catania, DIEEI, Catania, Italy
[4]CNR, Istituto per i Beni Archeologici e Monumentali, Via Biblioteca 4, 95124 Catania, Italy

Abstract

The application of plasma heating methods alternative to the direct Electron Cyclotron Resonance coupling, such as the Electron Bernstein Waves heating, is already a reality in large-size thermonuclear reactors. The heating driven by these plasma waves gives the unique opportunity to largely overcome the cut-off density. The downsizing of tools and methods needed to trigger EBW in compact traps such as ECRIS devices is still a challenge, requiring advanced modeling and innovative diagnostics. At Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud (INFN-LNS), the off-ECR heating (driven by Bernstein waves) has produced a highly overdense plasma. Interferometric measurements say the electron density has overcome by a factor ten the cut-off density at 3.76 GHz. More advanced schemes of wave launching have been then designed and implemented on the new test-bench called Flexible Plasma Trap, operating up to 7 GHz – 0.5 T, in flat/simple mirror/beach magnetic configuration. The paper will give an overview about modal-conversion investigation by a theoretical and experimental point of view, including the state of the art of the diagnostics developed to detect plasma emitted radiation in the RF, optical, soft-X and hard-X-ray domains.

INTRODUCTION

The Electron Cyclotron Resonance Ion Sources (ECRIS) and the Microwave Discharge Ion Sources (MDIS) are currently the best devices worldwide to feed effectively high-energy accelerators [1]. Plasma is produced by microwaves typically in the range 2.45-28 GHz by means of the so-called “Electron Cyclotron Resonance (ECR)”. Most of the parameters of the extracted beam, such as the intensity, the emittance and the shape in the real space depend on the characteristics of the plasma from which the beam is extracted [2]. Any further development of ECR-type ion sources is thus intrinsically limited by physical properties of the plasmas. In microwaves-sustained plasmas, the density increases with RF power and stabilizes around a value below the critical density $n_{cut-off}$. An option to overcome this limitation consists in the use of ElectroStatic (ES) waves, showing no cut-offs within the plasma. An ES wave is a rarefaction-compression wave whose electric field is parallel to the wave propagation direction. Most of ES waves do not suffer any resonance within a plasma; however, Electron Bernstein Waves (EBW) [3] can be strongly absorbed by the plasma at cyclotron harmonics [4] . Due to their electrostatic nature, EBWs must be generated within the plasma from electromagnetic waves. EBWs are excited at UHR via the decay of a large-amplitude electromagnetic wave, propagating perpendicular to ambient magnetic field in the X-mode, into a short-wavelength electron Bernstein. Three main mechanisms of EM to EBW coupling have been studied and characterized in plasma fusion devices, as schematically depicted in Fig. 1:

- **High field side launch:** X waves are launched by regions where $B/B_{ECR} > 1$. X waves are here not screened by the R cut-off, reach the UHR crossing the ECR from the high field side, then being converted into EBWs.
- **Directed FX-B conversion:** The fast X-mode (FX) tunnels through the evanescent region between the R-wave cut-off and the UHR and couples to the slow X-mode (SX) that, in turn, mode converts to EBWs at Upper Hybrid Resonance (UHR).
  If the UHR layer is enclosed by R and L cut-offs, the X wave can be reflected back and forth passing through the UHR, then leading to the establishment of the Budden-type conversion scenario. The module of the conversion efficiency of a FX wave into a B-mode in these conditions is [5]:

$$|C_{XB}| = 4e^{-\pi\eta}\left(1 - e^{-\pi\eta}\right) \tag{1}$$

η is the Budden parameter, obtained by expanding the wave potential around the UHR. If the length scale of magnetic field variation $L_B = B/(\partial B/\partial x)$ is larger than electron density variation length-scale $L_n = n_e/(\partial n_e/\partial x)$, η can be written as:

$$\eta = 294\,|BL_n|^{UHR} \tag{2}$$

Direct FX-B conversion heating is used in experiments with relatively low magnetic field, where the normalized gradient length $k_0 L_n$ is ~ 0.3 (k_0 being the wave number of the incident wave in vacuum) and $\eta \sim 0.22$ [6, 7].

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* Castrog@lns.infn.i

- **O-SX-B conversion:** in such a case, the R cut-off is crossed by the O wave that, if the conditions for O-SX conversion are valid at the O cut-off, is converted into SX waves which are, in turn, converted into Bernstein waves at UHR. The efficiency of O-SX transition process is maximized for $k_0 L_n \sim 1-20$, i.e. for flattened density profiles.

EBWs have been already generated in large devices for fusion, and the studies have shown that EBW heating could be a valid alternative to the ECR heating. At WEGA stellarator of Greifswald, for example, EBW heating allowed to reach densities up to 10 $n_{cut-off}$ [8].

In the experiments here described, EBWs are generated and absorbed in a small plasma reactor characterized by an axis-symmetric magnetic field, aimed to the generation of beams for accelerators.

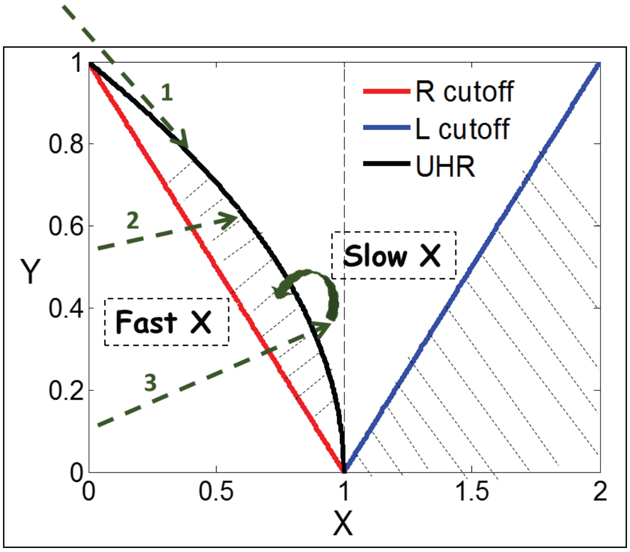

Figure 1: Main mechanism of conversion from the X wave to the EB waves: 1) High field side launch; 2) FX-B conversion; 3) O-SX-B conversion; X and Y are the dimensionless density and magnetic field respectively.

DIAGNOSTICS FOR HIGH DENSITY PLASMAS

High density plasmas require the development of "ad hoc" diagnostics (see Fig. 2) able to investigate the electron energy distribution function of the different electron populations and their distribution in the plasma chamber [9].

- **Langmuir Probe (LP) diagnostics** still represent the easiest way to perform plasma density measurements of bulk electrons (10-100 eV). However it features some limitations: i) the density measurement is “model-dependent”; ii) the probe undergoes to plasma damage, especially when density overcomes 10^{12}cm^{-3}; iii) the probes perturb the plasma chamber especially by an electromagnetic point of view.
  The development of a multimodel software to cross-check the Langmuir probe (LP) data by means of several “self-consistent” models validated for high density ($1 \cdot 10^8$ to $1 \cdot 10^{12}$ cm^{-3}), strongly magnetized plasma (see Ref. [10] for more details) allowed to obtain more and more reliable information from the resistivity curve.
- **Microwave interferometry** is a non-invasive method for plasma diagnostics for the whole plasma density measurements. Interferometry in ECR Ion Sources is a challenging task due to the very small λ/L ratio (with λ microwaves' wavelength and L typical size of the plasma chamber).
  At INFN-LNS a new interferometer, based on the so-called “frequency sweep” method has been developed for small size ion sources [11]. The measurements shown in [11] demonstrate the absolute plasma density can be measured in a non-intrusive way.
- **X-ray based systems**: X-ray volumetric measurements can be a powerful method for measuring the plasma density at medium-high energy ranges. the techniques developed in past years [12] allow to know the temperature and density of the electron population emitting X rays.
- **Plasma imaging and space-resolved analysis** is performed by using the Photon Counting (PhC) technique, provided by the X-ray pinhole. This technique allows to investigate both dimensions and geometry of the plasma source as well as the spatial distribution of X-ray energies in the plasma, allowing to distinguish hot regions from the cold ones .
- **Optical Emission Spectroscopy** may represents a powerful diagnostics for the low energy (1-10 eV) plasma electron population. It permits to distinguish different ion populations and identify them directly within the plasma.

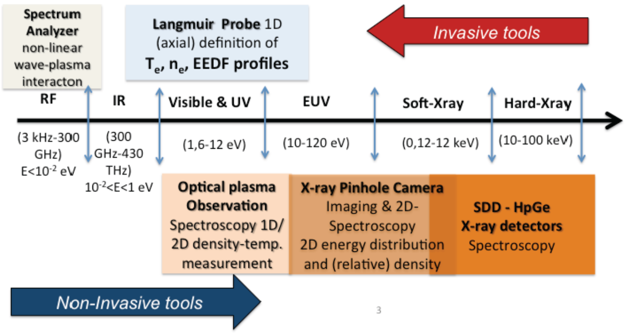

Figure 2: Diagnostics used and related electromagnetic spectrum.

EXPERIMENTAL EVIDENCES

The experimental apparatus has been already already shown in details in reference [10, 11]: A plasma reactor surrounded by permanent magnets generating a (maximum magnetics field ~ 0.1 T) is fed by microwaves at 3.76 GHz, generated by a Traveller Wave Tube (TWT). This frequency has been chosen after a fine tuning of the machine. The magnetic field strength is too low to permit ECR resonance, but it is able to sustain the UHR. A plasma has been excited at $1.5 \cdot 10^{-4}$ mbar with increasing microwaves' power from 20 to 200 W. Experimental results, detailed in [10, 11], show that a largely overdense plasma has been obtained when microwaves' power overcomes 80 W. These results have been confirmed by measurement performed with both interferometry and LP diagnostics. In particular, interferometry gives an averaged plasma density value equal to: $n_e = 2.1 \pm 1 \cdot 10^{12}$ cm^{-3}. This value is four times larger than the average value measured - in exactly the same operative conditions - by means of the Langmuir probe, that resulted $n_e = 5.5 \pm 1.5 \cdot 10^{11}$ cm^{-3} (averaged value along the same line of sight). The discrepancy is probably due to the electromagnetic perturbation that the Langmuir probe (a metallic rod introduced in a compact resonator) generates within the plasma chamber, modifying the plasma features. Anyway, the values measured by interferometry and LP diagnostics are respectively ~ 10 times and~ 5 times larger than $n_{cut-off}$ at 3.7576 GHz, equal to $1.275 \cdot 10^{11}$ cm^{-3}. Table 1 summarizes the results of plasma density measurements.

Table 1: Results of Electron Density Measurements

	Electron density (cm^{-3})
Interferometry	$(2.1 \pm 1) \cdot 10^{12}$
LP diagnostics	$(5.5 \pm 1.5) \cdot 10^{11}$
$n_{cut-off}$ (at 3.76 GHz)	$1.75 \cdot 10^{11}$

Measurements of microwave power within the chamber [10] have shown EM waves do not propagate within the plasma bulk accordingly to measurements of plasma density (in overdense plasmas EM waves are reflected). However, selfconsistent simulations shown that plasma can be fed by EM waves propagating from the chamber walls towards the center, and thus orthogonal to the magnetic field lines (i.e. X and O waves). The plasma 2D imaging technique permitted to describe the radial plasma profile, by calculating the number of detected x-rays versus the chamber radius. This information enables us to calculate the η coefficient, in the hypothesis of wave propagating from the walls towards the plasma bulk.

Figure 3 shows the η coefficient, calculated by means of Eq. (2) and the normalized radial density, versus the plasma chamber radius. At the radial position of 35 – 50 mm, the η coefficient is in the range 0.20-0.25 (dark strip in the figure), a value which maximize the Budden conversion coefficient (Eq. (1)). These results lead to the conclusion that plasma is generated by the directed FX-B conversion, in Budden type scenario.

The fine tuning of the microwave frequency permit to find the best configuration in term of modal configuration within the chamber, favoring the conversion of larger amount of RF power, in the form of X waves, to Bernstein waves (modal dependent conversion). From a self-tuning point of view, also the density gradient assumes the value which maximizes FX-B conversion.

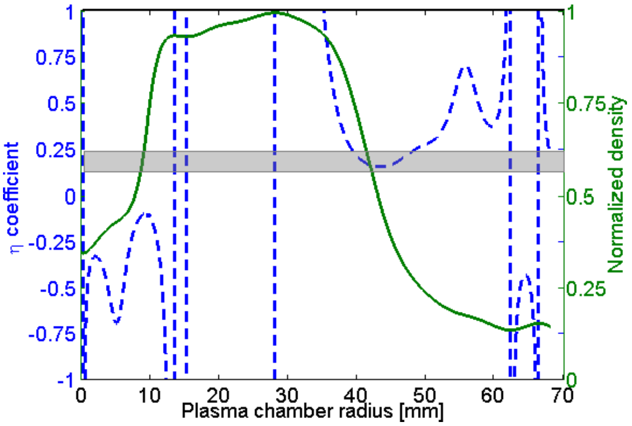

Figure 3: η coefficient and normalized density vs chamber radius.

The next goal of our research group is to force the conversion from EM to Bernstein waves without any influence of the plasma chamber modal behavior (modal independent conversion). The Flexible Plasma Trap (in commissioning at INFN-LNS) has been thought, developed and constructed with the aim to generate high density plasmas by means of novel plasma heating schemes. It is constituted by three coils generating different magnetic field profiles (maximum magnetic field is ~ 0.5 T). It is fed with microwaves in the range 3 – 7 GHz. A microwave launcher has been developed for a controllable (directional) launching of the pumping wave inside the plasma chamber, having specific angles with respect to the external magnetostating field. The launcher is placed orthogonally to the chamber axis, so it allows feeding O/X waves within FPT. The goal is to launch high frequency (14 GHz) microwaves inside a pre-formed plasma at 7 GHz or so, attempting to establish a high efficiency conversion scenario such as the OXB one. The first results of the new experimental campaign are expected in the next autumn.

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