Multi-diagnostics investigation of an ECR plasma confined in a simple mirror trap

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Abstract. This work presents the multi-diagnostics characterization of the plasma in an axis-symmetric simple mirror trap as a function of magnetic field profile (mirror ratios and magnetic field gradient), neutral gas pressure and microwave power. The simultaneous use of Optical Emission Spectroscopy, Langmuir Probe and X-ray diagnostics allows the characterization of the whole electron energy distribution function from a few eV to hundreds of keV, investigating how the electron heating is affected by magnetic gradients, RF power and neutral pressure. In hydrogen plasmas, the use of the optical emission spectroscopy has permitted to simultaneously evaluate the plasma and electron density and the relative abundances of H and H_2 also. The latter being a key parameter when plasma traps are used such as sources of intense proton beams. Results show non-linear behaviours under small variations of even one source parameter only.

INTRODUCTION

Over the last years, the requirements set for positive and negative ion sources devoted to feeding particle accelerators have increased steadily. The ions are typically created in the source within a low pressure plasma. In order to perform a detailed source optimization, knowledge about the plasma parameters is inevitable. Therefore, dedicated efforts concerning the characterization of the plasma parameters have been carried out. For sake of compactness (mechanical constraints limit ECRIS ion source dimensions), historically only a limited number of diagnostics have been applied to ECRIS plasmas. Therefore, in most of the cases, plasma properties were only estimated from semi-empirical considerations. However, a detailed knowledge of the electron energy distribution function (EEDF), resolved over the plasma chamber, is mandatory for any improvement of existing or future devices.

In this paper, a comprehensive diagnostic characterization of an ECR-coupled ion source plasma is carried out. At the Flexible Plasma Trap (FPT) test-bench [1], a hydrogen discharge is investigated by means of a movable Langmuir Probe (LP), optical Emission Spectroscopy (OES) and X-Ray spectroscopy. The simultaneous use of these different diagnostics allowed characterizing various plasma parameters as a function of the applied external magnetic field, of microwave power and of gas pressure.

EXPERIMENTAL SETUP AND DIAGNOSTIC METHODS

The FPT experiment has been designed, developed and commissioned at INFN-LNS with the specific aim to enclose in a simple and flexible ECRIS-relevant device all instruments required for the plasma characterization [1]. The external magnetic field used for ECR heating and plasma confinement is generated by means of three solenoids which also allow tuning the magnetic profile. In this work, we focused to the investigation of the plasma generated in simple mirror (but with varying B_{min}/B_{max} ratio) configuration. Microwaves are generated by a Travelling Wave Tube (TWT) operating in the range 4-7 GHz.
Hereinafter, a brief introduction to the diagnostics used during the experimental campaign is given.

- **LP diagnostics:** Plasma immersed electrostatic probes represent the easiest way to perform the measurements of density and temperature of low energy plasma electrons. Although LP is an invasive diagnostics, it enables to gain information about the EEDF in the low energy range. The evaluation of plasma parameters by the resistivity curve depend on the theoretical model applied. In this work, electron density has been obtained by following references [2].
- **OES diagnostics:** A method for determining discharge parameters in a non-invasive way is provided by optical emission spectroscopy (OES). However, this diagnostics has the drawback that only line-of-sight-integrated results are obtained. The measured emissivities have been evaluated with the collisional radiative (CR) models Yacora H and Yacora H2 [3]. These models balance all relevant population and depopulation processes for the particular states in the hydrogen atom or molecule respectively, thereby yielding steady state population densities.

- **X-ray diagnostics:** The X-ray volumetric measurement is a powerful method for determining the plasma density and temperature of the warm/hot (i.e. above 500 eV and up to the hard-X ray spectrum, lying in the hundreds of keVs domain) component of the EEDF. It requires a proper collimation of the X-ray flux for fixing the solid angle covered by the X-ray detector and an adequate emissivity model for the data evaluation. Although ECRIS plasmas are characterized by non-isotropic EEDFs, for sake of simplicity, we follow the approach described in references [4], which assumes fully isotropic emission. During the experimental campaign, we used two different X-ray detectors: a Silicon Drift Detector (SDD) and a High Purity Germanium (HpGe) detector. The SDD is sensitive in the energy range 1-30 keV while The HpGe detector is sensitive up to several hundreds of keV.

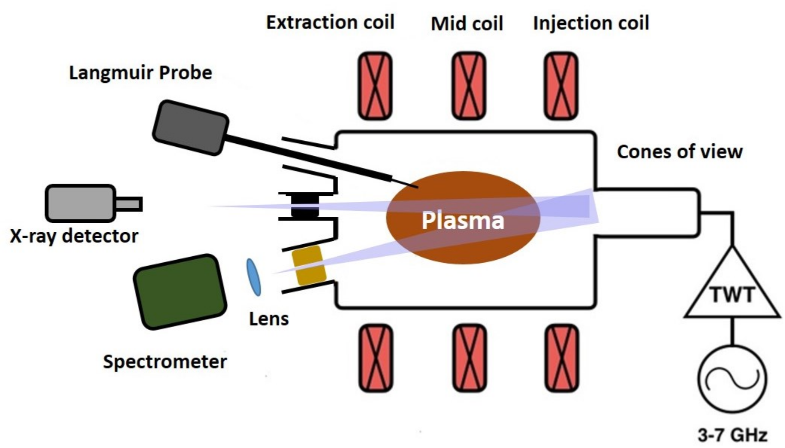

Figure 1: Sketch of the FPT setup including the different diagnostics used during the experimental campaign: OES, LP and X-rays diagnostics.

EXPERIMENTAL RESULTS AND PERSPECTIVES

During the experimental campaign, input microwave frequency has been set at 6.83 GHz, a value which was proved to optimize the wave-to-plasma coupling. The injection and extraction coil currents have been fixed at 440 and 411 A respectively, while the one in the mid coil has been changed from -88 A (the minus means that current flows inversely to that of injection and extraction coils) to +60 A. The change in mid coil current allowed to modify the B_{min}/B_{ECR} ratio along the chamber axis from 0.56 to 1.04.

Figure 10 shows preliminary results from Multidiagnostics for two different pressures ($1.5 \cdot 10^{-4}$ and $2 \cdot 10^{-3}$ mbar). Figure 10a shows the average electron density, measured by OES and LP diagnostics versus B_{min}/B_{ECR}, while Figure 10b shows X-ray emission rate and temperature for SDD and HpGe versus B_{min}/B_{ECR}. Both SDD and HpGe show a strong increase of electron temperature and X-ray emission rate when $B_{min}/B_{ECR} > 0.8$, in the same conditions in which OES and LP diagnostics detect a decrease of electron density. In other words, plasma energy content is transferred from cold electrons (temperature in the order of few eV) to warm and hot electrons (temperature > 1-10 keV). This phenomenon is probably due to the gradual change of the magnetic gradient at ECR, from strong gradient profile to a gentle gradient, as modelled by Canobbio [5].

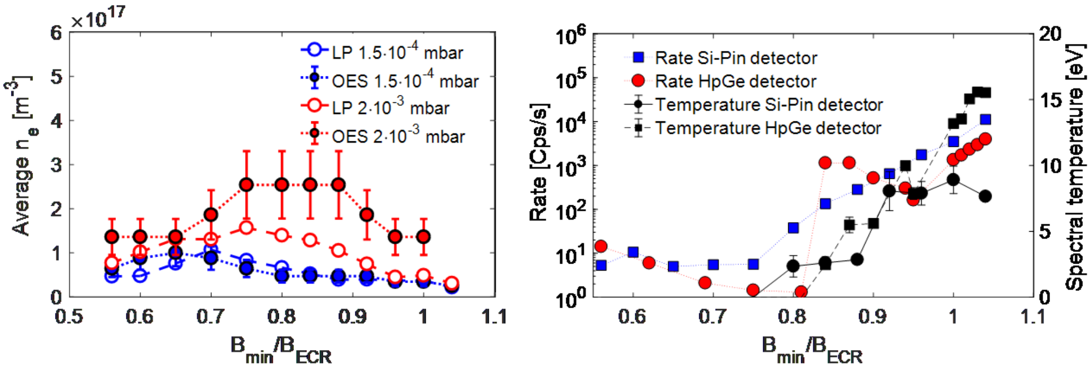

Figure 2: a) Electron density and temperature calculated by means of LP and OES diagnostics versus B_{min}/B_{ECR}. b) X ray emission rate and electron temperature for SDD detector (energy range 1-25 keV) and HpGe detector (energy range > 10 keV) versus B_{min}/B_{ECR}.

The preliminary results shown in this paper put in evidence how the multiple diagnostics approach permits a more sophisticate plasma investigation. The B_{min}/B_{ECR} ratio represents a key parameter for ECRIS sources and its influence on EEDF has relevant importance for the development of future devices. Multidiagnostics studies are currently in progress and a comprehensive characterization of FPT plasma is going to be published.

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