RESULTS OF THE OPTICAL EMISSION SPECTROSCOPY DIAGNOSTICS OF THE ESS PROTON SOURCE*

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Abstract

The evaluation of the electron density and proton fraction of hydrogen plasmas has a relevant importance for plasma traps used as sources of intense proton, H2+ or H3+ beams. Optical Emission Spectroscopy (OES) enables to evaluate simultaneously and on-line the H/H2 relative abundances together with plasma and electron temperature. In this work, the experimental results of the OES measurements on the Proton Source of the European Spallation Source plasma has been related to the properties of the ion beam extracted by the source (proton fraction and beam intensity, in particular). Benefit of the diagnostics and the further improvements foreseen in next future will be highlighted.

INTRODUCTION

The Proton Source for the European Spallation Source (PS-ESS) is a Microwave Discharge Ion Source (MDIS) operating at 2.45 GHz microwave frequency for high intensity proton beam generation. PS-ESS has been designed and assembled at INFN-LNS as injector for the European Spallation Source (PS-ESS); it produces pulsed proton beams (14 Hz, 2.84 ms puls) from 40 mA to 90 mA nominal current, at 75 keV energy and 2.25 π mm mrad maximum normalized emittance [1]. The source has been characterized by means of a Faraday Cup, an Emittance Measurement Unit and a Doppler shift measurement unit. The standard beam diagnostics allows the measurement of the beam characteristics (as the extracted current, the species fraction and the RMS emittance). However, the beam properties depend on the characteristics of the plasma which generates it. Good performances of a proton source are obtained only if a homogenous, stable, dense and cold plasma is generated within the proton source. Therefore, the knowledge of the plasma parameters represents a fundamental information for the full comprehension of the source performances, but also an essential information for any further improvement of proton sources and ECRIS.

Among the different plasma diagnostics tools, Optical Emission Spectroscopy (OES) is the only diagnostics which is not affected by the plasma generation and does not affects the plasma itself during measurements. Since OES requires just the light emitted by the plasma, a small quartz window is sufficient for the evaluation of the plasma parameters and of the relative abundances of the neutral species. In this work, the results of the OES characterization of PS-ESS, performed in the best machine operative conditions, will be described.

EXPERIMENTAL SET-UP

Figure 1 shows a schematic diagram of the PS-ESS OES experimental set-up. It includes the RF power injection system, the three magnetic coils and the OES diagnostics system. PS-ESS is fed by microwaves at 2.45 GHz generated by a Magnetron, while the magnetic field is obtained by means of three solenoids which permit different magnetic configurations, from off-resonance configurations to simple mirror or magnetic beach (see Fig. 2). In this work, OES measurements has been carried out in best PS-ESS experimental performances, obtained in flat magnetic field configuration. The OES diagnostics system consists of a spectrometer ImSpector V8E, coupled to an ACA2040 CMOS camera. The spectrometer resolution is 2 nm and it is sensitive in the spectral range of 380 - 1000 nm. The whole system is connected to the PS-ESS by means of a 1500 μm diameter fiberglass that is, in turn, properly connected to a quartz window, which "looks" towards the centre of the PS-SS plasma chamber.

The whole OES experimental set-up has been properly calibrated and commissioned by using another plasma device, the Flexible Plasma Trap [2]. Preliminary measurements has been already published in reference [3]. The experimental measurements have been carried out at $2.7{\cdot}10^{-5}$ mbar pressure, measured in low energy beam transport. simulations performed by Comsol permitted to evaluate the pressure as ~ $3{\cdot}10^{-3}$ mbar within the plasma chamber. Microwave power has been increased from 120 to 1200 W.

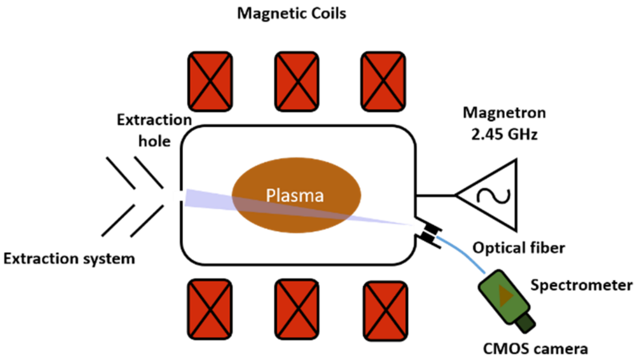

Figure 1: Schematic of the PS-ESS experimental setup at the INFN-LNS.

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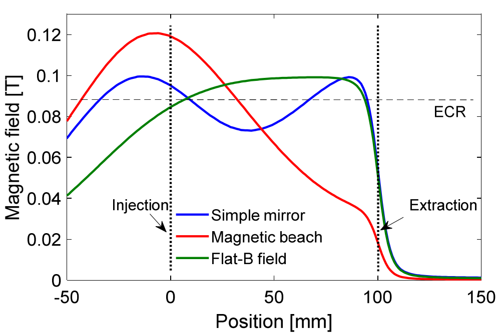

Figure 2: Magnetic field profiles that can be generated by the PS-ESS.

The analysis method is based on the line-ratio method, well-described in references [4-5]. Spectroscopic measurements have been carried out for the Balmer series of atomic hydrogen (H_α to H_γ) as well as for the Fulcher-α transition of the H_2 molecule (d3Π_u → a3Σ_u+). We compared experimental results with theoretical line ratios obtained by applying a collisional radiative (CR) model. In particular, we compared experimental and theoretical H_β/H_γ and H_α/H_β line ratios to simultaneously determine electron density and temperature. Relative abundance between atomic and molecular hydrogen n_H/n_{H_2} ratio can be determined by comparing the H_γ/H_{Fulch} with theoretical data from CR model.

EXPERIMENTAL RESULTS

Figure 3 shows the electron density as a function of the microwave power. Electron density increases with RF power, but it saturates around $1 \cdot 10^{18}$ m^{-3} above 800 W. OES density is around 10 times the density cut-off at 2.45 GHz, that is $8.75 \cdot 10^{16}$ m^{-3}. This implies that probably heating mechanisms other than Electron cyclotron resonance contribute to the plasma heating. The electron temperature is shown in Fig. 4. It lies in the range expected for proton sources and measured by means of other diagnostics (≈ 10 eV). In particular, electron temperature shows a slightly decreasing trend of electron temperature with microwave power. This trend has been already found in other measurements performed by Langmuir probe [6], and it is probably due to the gradual decrease of the mean free path of electrons during the acceleration process as the density becomes higher and higher.

Finally, Fig. 5 shows the n_H/n_{H_2} ratio as a function of the microwaves' power. n_H/n_{H_2} is around 0.5 at lower power and approaches 2 around 800 W. Unfortunately, it has been not possible to determine the n_H/n_{H_2} ratio above 800 W because the signal to noise ratio of the Fulcher band (necessary for evaluate n_H/n_{H_2}) becomes too low and a huge experimental error arises.

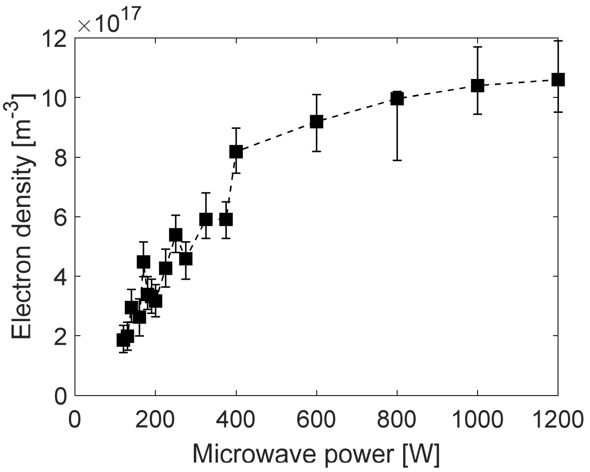

Figure 3: OES electron density as a function of the microwaves' power.

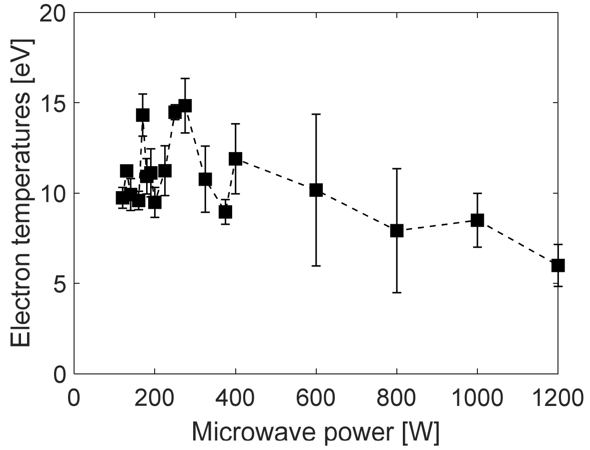

Figure 4: OES electron temperature as a function of the microwaves' power.

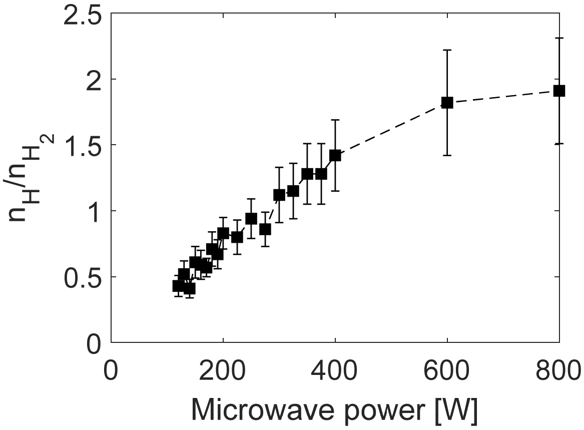

Figure 5: n_H/n_{H^2} ratio as a function of the microwaves' power.

CORRELATION BETWEEN PLASMA AND BEAM PARAMETERS

One of the goal of the current research in plasma physics applied to ECRIS is to relate the plasma parameters to the beam parameters. The commonly used approach is to find a solution of the particle balance equations in a plasma [6-8]. The exact solution of the system of balance equation would enable to foresee the properties of the extracted beam. However, the solution of the balance equations require the knowledge of a huge number of parameters, as the properties of the chamber surface, diffusion coefficients in plasma, motion in the sheath and a lot of other parameters which make balance equations approach very difficult to be practically applied.

An option to reduce the number of balance equations, simplifying the approach, is to use the plasma parameters calculated by OES as input parameters. The simultaneous knowledge of n_H/n_{H^2} and neutral pressure permits to estimate the absolute neutral population within the plasma chamber. Furthermore, electron density and temperature permit to evaluate the reaction rate coefficients of the main reactions occurring in a hydrogen plasma. In this way, balance equations can be reduced to 4 equations in 4 unknowns, namely the H^+, H_2^+ and H_3^+density and the ion confinement time. Once properly solved, the balance equations give information about the density of the different charged particle in the plasma, and therefore they give an evaluation of the properties of the extracted beam. Unfortunately, two free parameters must be taken into account during the study, the ion and neutral temperature, whose values has been fixed on the basis of the available literature. Figure 6 shows the cross sections of the main reaction taken into account to solve the reduced balance equations in a hydrogen plasma. Cross sections lower than 10^{-18} cm^2 have been neglected.

The results show a very strong correlation between the estimation of the reduced balance equations and experimental measurements of the extracted beam performed by means of a Doppler shift measurement unit and of an ACCT.

Figure 7 shows the comparison between the extracted current measured by the ACCT and the extracted current expected after solving the reduced balance equations. As it is evident, estimation and measurements are very close each other, this representing a first benchmark of the used approach. More details about the procedure of analysis together with a general discussion about correlation between plasma and beam parameter will be given in reference [9].

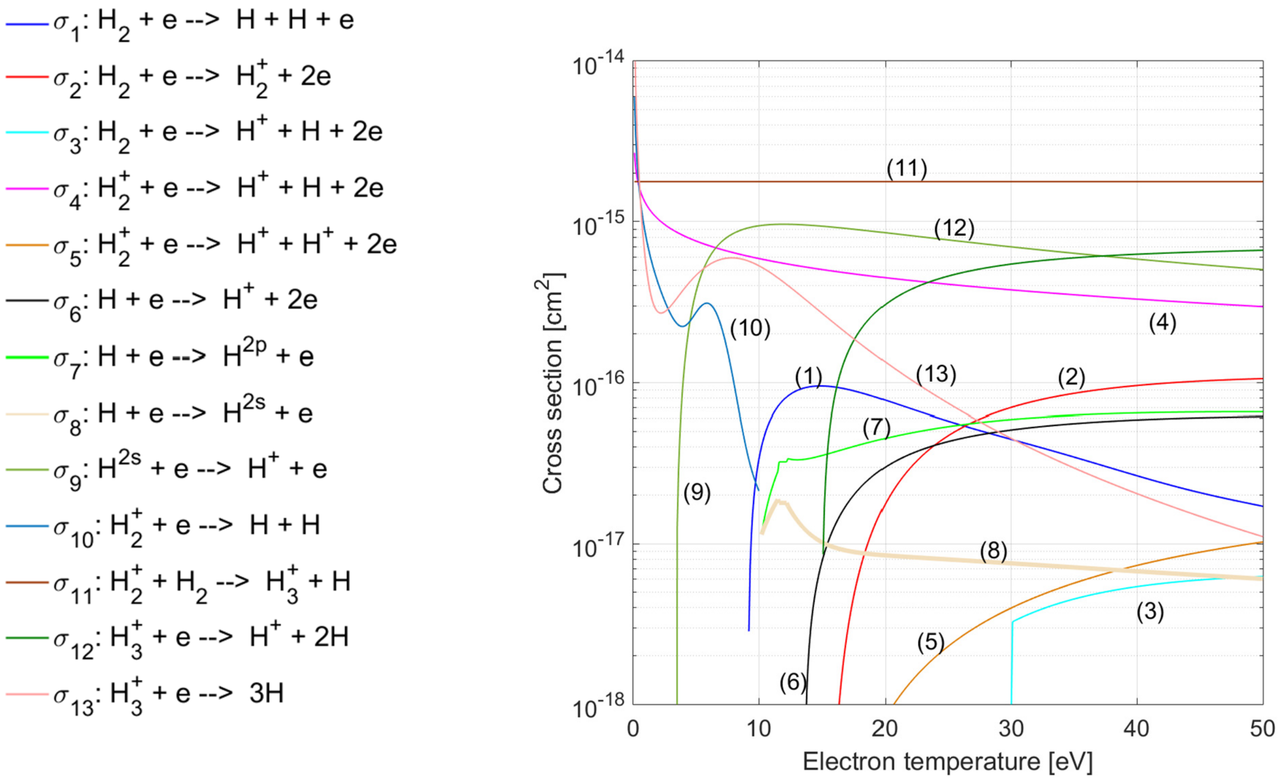

Figure 6: Cross sections of the main reactions occurring in a hydrogen plasma. σ_{11} depends only on ion temperature. σ_1 has been calculated for ion temperature equal to 0.1 eV)

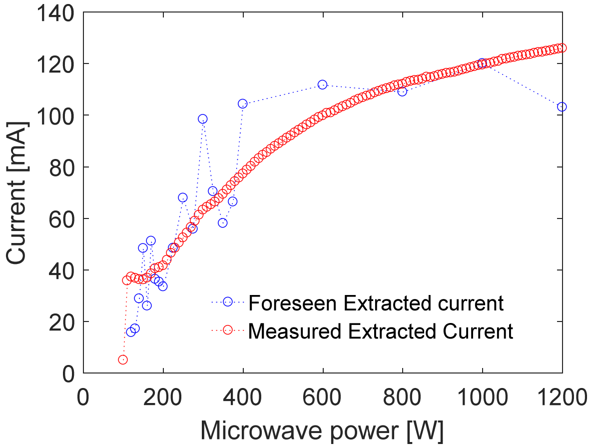

Figure 7: Comparison between extracted current measured by the ACCT and extracted current.

In the next months, the OES diagnostics equipment will be further enhanced after the commisioning of two different instruments for OES. The first one is a 15 µm monocromator detector. Its resolution is enough to characterize molecular rotational temperature and to obtain higher resolution emission lines, needed for extending OES to other plasmas. The second one is SARG, a powerful spectropolarimeter formerly installed at TNG, Telescopio Nazionale Galileo, Canary Islands. SARG allows to reach very high resolution: R = 160:000 in the range: 370-900 nm, suitable for ion temperature measurements and/or on-line discrimination of the ionisation states of the ions inside the plasma. First results are expected within the end of this years.

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