Application of Optical Emission Spectroscopy to Hydrogen plasmas for proton rich plasmas generation

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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, H_2^+ or H_3^+ beams. Optical Emission Spectroscopy (OES) enables to evaluate simultaneously and on-line the H/H_2 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 designed and assembled at INFN-LNS as injector for the European Spallation Source (PS-ESS) produces pulsed proton beams (at 14 Hz, 2.86 ms pulse duration) with nominal current in the range 2-74 mA, 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 allow measurements of the proton fraction of a beam only after beam extraction, while they do not give any information about plasma composition and relative abundances of in-plasma neutrals and ions components. The limits of these diagnostics have been overcome by means of Optical Emission Spectroscopy. OES enables direct “in plasma” measurements, evaluating not only the electron density and temperature, but also the relative concentration of the different neutral species. OES has been applied to characterize the hydrogen plasma generated inside the PS-ESS source and hereinafter the results obtained will be described.

EXPERIMENTAL SET-UP

OES measurements have been carried out on the PS-ESS. Preliminary tests of OES have been carried out on the Flexible Plasma Trap (FPT), a test bench for plasma diagnostics and development of new sources, installed at INFN-LNS [2]. Figure 1(a) shows a schematic diagram of the PS-ESS, including the RF power injection system, the three magnetic coils, and 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 figure 1(b)). In this work, OES measurements has been carried out in best PS-ESS experimental performances, obtained in Flat magnetic field configuration.

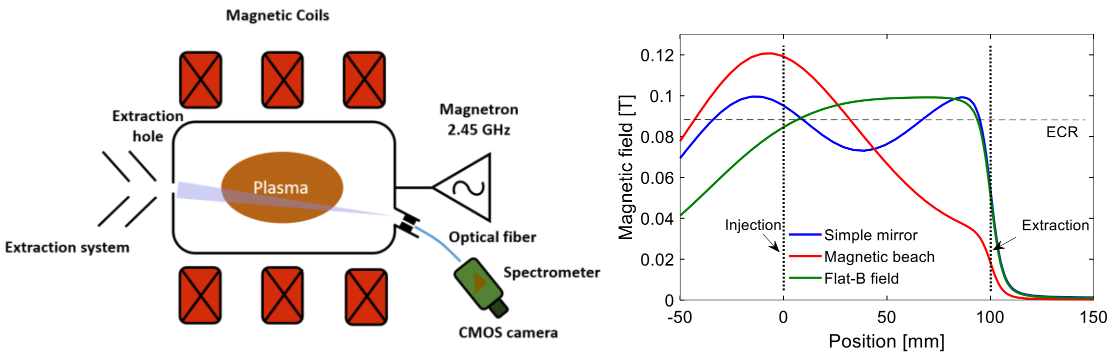

Figure 1: (a) Schematic of the PS-ESS experimental setup at the INFN-LNS; (b) Magnetic field profiles that can be generated by the PS_ESS.

The OES diagnostics system consists of an ImSpector V8E spectrometer, 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. The experimental measurements have been carried out at $2.7 \cdot 10^{-5}$ mbar pressure in low energy beam transport (pressure simulated in plasma chamber ~ $3 \cdot 10^{-3}$ mbar) and a microwave power increasing from 120 to 1200 W.

EXPERIMENTAL RESULTS AND PERSPECTIVES

The analysis method is based on the line-ratio method, well-described in references [3] [4]. Spectroscopic measurements have been carried out for the Balmer series of atomic hydrogen ($H_\alpha$to H_γ) as well as for the Fulcher-α transition of the H_2 molecule ($d^3\Pi_u \rightarrow a^3\Sigma_u^+$). 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 $H_\gamma/H_{Fulch.}$ with theoretical data from CR model.

Figure 2 shows the results of the electron density and temperature versus microwave power.

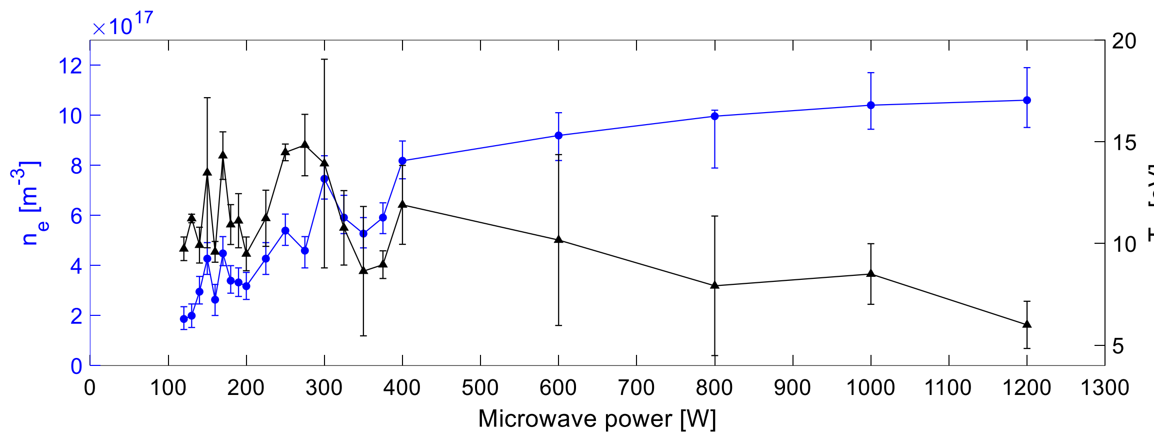

Figure 2: Density and temperature obtained from the OES evaluations for varying power.

Electron density increases with RF power from ≈ $1{\cdot}10^{17}$ m^{-3} at 120 W to ≈ $1{\cdot}10^{18}$ m^{-3} above 800 W. The temperature lies in the range expected for proton sources and measured by means of other diagnostics (≈ 10 eV). In particular, figure 2 shows a slightly decreasing trend of electron temperature with microwave power. A characterization of the extracted beam (extracted current, species fraction and emittance measurements) has been performed in the same experimental conditions. Figure 3 shows extracted current from PS-ESS versus microwave power. Electron density follows the same trend of extracted current, showing that the general behavior of the PS-ESS can be foreseen and followed on-line by OES measurements.

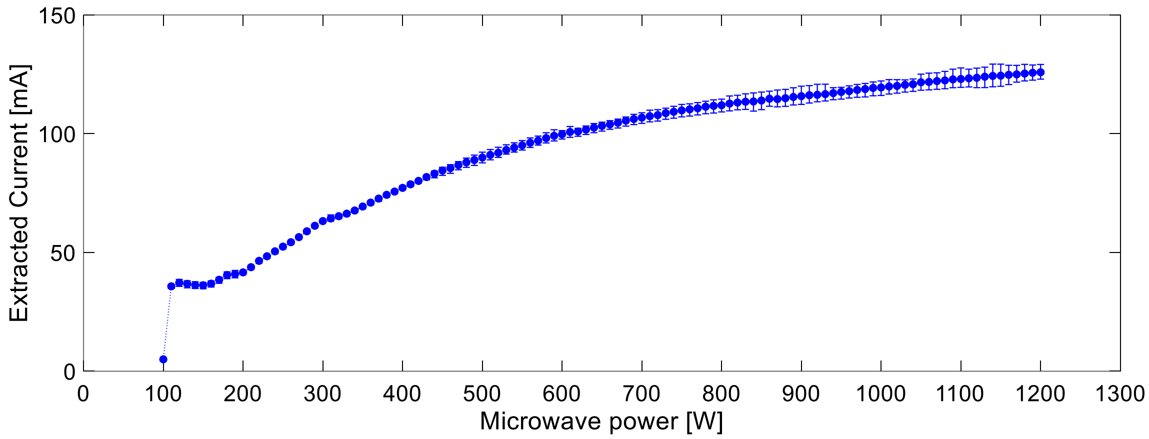

Figure 3: Extracted current from PS-ESS

Next step is to find a close relationship between plasma parameters and beam parameters. This could permit to monitor, on-line and in a non-invasive way, beam parameters by OES diagnostics. More information is expected after two new OES detectors (currently in commissioning phase) will be available. The first one is a 15 μm monocromator detector. Its resolution is enough to characterize molecule rotational temperature [5] and to obtain higher resolution emission lines, needed for extend 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.

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REFERENCES

[1] L. Neri et al., *Journal of Physics*: **874**, 012037 (2017).
[2] S. Gammino et al., Rev. *Jurnal Instrum*. **12** (2017).
[3] U. Fantz, *Plasma Sources Sci. Technol*. **15**, S137 (2006).
[4] U. Fantz et al., *Nuclear Fusion* **46**, S297 (2006).
[5] Briefi S, Rauner D and Fantz U 2017 *Journal of Quantitative Spectroscopy & Radiative Transfer* **187** 135-144