APPLICATION OF OPTICAL EMISSION SPECTROSCOPY TO HIGH CURRENT PROTON SOURCES*

G. Castro†, M. Mazzaglia[1], D. Nicolosi, D. Mascali, R. Reitano[1], L. Celona, O. Leonardi, F. Leone[1], E. Naselli[1], L. Neri, G. Torrisi, S. Gammino, INFN-LNS, Catania, Italy
[1]also at University of Catania, Catania, Italy; INFN-LNS, Catania, Italy
B. Zaniol, consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy

Abstract
Optical Emission Spectroscopy (OES) represents a very reliable technique to carry out non-invasive measurements of plasma density and plasma temperature in the range of tens of eV. With respect to other diagnostics, it also can characterize the different populations of neutrals and ionized particles constituting the plasma. At INFN-LNS, OES techniques have been developed and applied to characterize the plasma generated by the Flexible Plasma Trap, an ion source used as "testbench" of the proton source built for European Spallation Source. This work presents the characterization of the parameters of a hydrogen plasma in different conditions of neutral pressure, microwave power and magnetic field profile, along with perspectives for further upgrades of the OES diagnostics system.

INTRODUCTION

In recent years, different projects have requested the ability to produce intense proton and H_2^+ beams. A 74 mA proton current is requested by the European Spallation Source [1]), while up to 50 mA H_2^+ by the Daeδalus and ISOdar experiments [2, 3]. The fraction of proton and H_2^+ constituting the extracted beam depends on the source parameters such as magnetic field profile, neutral pressure, microwave power and frequency and also on the dimensions of the plasma chamber [4]. Up to now, the proton fraction of a beam is known only after beam extraction; furthermore, some important information, such as the vibrational states of the H_2^+ molecule, can not be measured in any way by standard beam diagnostics by means (higher H_2^+ vibrational states are detrimental for H_2^+ acceleration [3]). The limits of the actual diagnostics can be overcome by means of Optical Emission Spectroscopy. It enables direct “in plasma” diagnostics measuring not only the electron density and temperature, but also the relative concentration of different neutral species, vibrational temperature of the molecules, and concentration of the different charges states in case of plasma of multicharged ions. At the INFN-Laboratori Nazionali del Sud (INFN-LNS), OES has been applied to characterizing the hydrogen plasma generated by a plasma trap (described in the next section) as a preliminary test for further development on other ion sources (in particular for the proton source of ESS). Hereinafter the first results obtained will be described.

* Work supported by INFN in the framework of ESS MIUR activities
† Castrog@lns.infn.it

EXPERIMENTAL SET-UP

OES measurements have been carried out with the Flexible Plasma Trap (FPT), a test bench for plasma diagnostics and development of new sources, installed at INFN-LNS. FPT is fed by microwaves in the range 4-7 GHz generated by a TWT, while the magnetic field is obtained by means of three coils, which permit different magnetic configurations. The most interesting magnetic configurations, presented in Figure 1, have large importance for ion sources. Flat magnetic field is the typical magnetic field used in a microwave discharge ion source for proton generation; simple mirror configuration increases ion lifetime for multicharged ion generation; finally, magnetic beach configuration allows exploring new mechanisms of plasma heating such as EBW heating [5]. An overall characterization of the FPT can be found in reference [6].

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 a spectral range of 380 - 1000 nm. The whole system is connected to the FPT 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 FPT plasma chamber. The cone of view of the fiberglass is around 22 degree wide and can integrate the plasma light over a well-determined volume. The whole OES experimental set-up has been calibrated by comparison with a calibrated lamp. Figure 2 shows a view of the FPT and of the experimental set-up for OES.

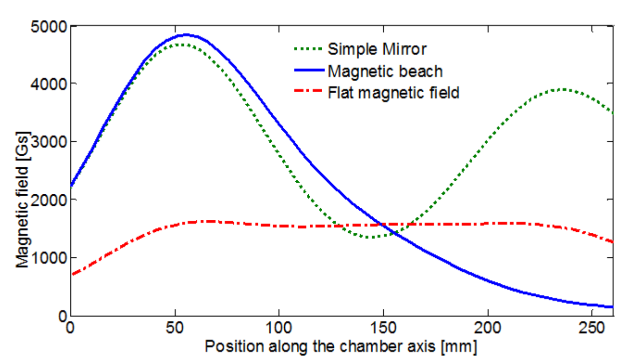

Figure 1: Magnetic field profiles that can be generated by the FPT.

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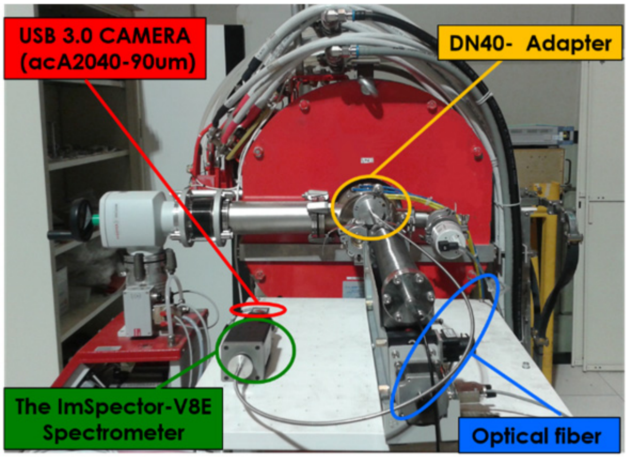

Figure 2: A view of the FPT and the OES set-up.

The low resolution of our instrumentation (2 nm) makes impossible any attempt to search for vibrational lines of H_2^+ (a few tens of pm needed); however, the resolution is enough for studying the dependence of the H/H_2 ratio and of electron density on the source parameters.

EXPERIMENTAL RESULTS

The determination of plasma parameters from emission spectra is still a challenging question. An interesting summary can be found in references [7, 8]. The intensity of emission I depends on the particle density in the excited state, which, in turn, depends strongly on plasma parameters, such as electron temperature t_e, electron density n_e and density and temperature of all neutral and ionized particles n_n and t_n. Such a dependence is described by the effective emission rate coefficients X^{eff}, calculated by means of opportune population and depopulation models [7]. The intensity of the emission line, for the transition *l-->m,* is proportional to $X_{lm}^{eff}(n_e, t_e, n_n, t_n)$ and to the particle density in the ground state n_g [7]. The ratio between two emission lines I_{pk}^1 and I_{lm}^2 is therefore:

$$\frac{I_{pk}^1}{I_{lm}^2} = \frac{n_{g1}}{n_{g2}} \frac{X_{pk}^{eff}(n_e, t_e, n_n, t_n)}{X_{lm}^{eff}(n_e, t_e, n_n, t_n)} \quad (1)$$

If one knows the $X_{pk}^{eff}/X_{lm.}^{eff}$ ratio, Eq. (1) allows calculating n_1/n_2 from I_{pk}^1/I_{lm}^2. This is called the "line ratio method".

We applied this method to calculate the relative abundance n_H/n_{H_2} of atomic and molecular hydrogen in plasma. It can be shown [8], in fact, that the ratio between the H_γ Balmer line (434.1 nm) and the Fulcher band (600-640 nm) is almost independent of electron temperature and assumes a value ~1 for the values of electron density typical of FPT, i.e. $n_H/n_{H_2} \approx I_\gamma/I_{Fulch.}$

The determination of the n_H/n_{H_2}ratio has large importance for proton sources, because it identifies the conditions that favour the H or H_2 presence in plasma. An H-rich plasma favours proton generation, while an H_2-rich plasma favours H_2^+ generation.

Together with the n_H/n_{H_2}ratio, the total intensity of the spectral emission has been calculated. Total intensity gives information about the energy content of the electron population responsible for the optical transitions in plasma, i.e. in the range 1-20 eV.

First, we characterized the n_H/n_{H_2}ratio and total intensity as a function of the RF power and neutral pressure.

For experimental measurements, a very stable configuration of FPT has been chosen: the microwave frequency has been fixed at 6.82 GHz and operated in simple mirror magnetic configuration. The hydrogen pressure was fixed at $0.8 \cdot 10^{-4}$ mbar, a value minimizing the reflected power.

Figure 3 shows the dependence of the n_H/n_{H_2}ratio and the total intensity on the microwave power from 20 W to around 120 W. At 20 W, n_H/n_{H_2} is indeterminate, since the experimental error is too high. From 40 to 80 W, n_H/n_{H_2} increases up to 0.5 and then decreases again. A similar behaviour can be found in the total intensity of the signal. Since the total intensity is related to the cold electron population, this means that $n_H/n_{H_2}$is maximized when the electron energy is high enough for the H_2 molecule break up. Further increase in the electron energy content, however, is detrimental for H generation, probably because the cross section for H_2 break up decreases above 15 eV [9].

This means that either too low or too high RF power could be detrimental for proton generation in a proton source. Furthermore, since higher RF power favours the increase of the emittance, proton beam should be generated by using RF power as low as possible.

Figure 4 shows the dependence of n_H/n_{H_2}ratio and total intensity on neutral pressure. Microwave power has been fixed at 60 W, while the other parameters remained unchanged. The neutral pressure was increased from 1 to $8 \cdot 10^{-4}$ mbar. The highest values are comparable with the typical operating pressure of proton and H_2^+ sources ($5 \cdot 10^{-4}$-$1 \cdot 10^{-3}$ mbar [1]). Total intensity increases strongly with the pressure, indicating an increase of the electron energy content of cold electrons, while the n_H/n_{H_2}ratio decreases because of the continuous addition of H_2 molecules. This means that for higher values of pressure, higher and higher RF power is needed to improve the proton fraction of the extracted beam.

Finally, Figure 5 shows the dependence of the n_H/n_{H_2} ratio and total intensity on the mirror ratio of the magnetic field, i.e. on the ratio $B_{max}/B_{min.}$ The mirror ratio is an important parameter because it allows modifying the ion confinement time within the plasma.

To have a stable plasma for any value of the magnetic field profile, microwave' frequency and power have been fixed respectively at 5.63 GHz and 60 W, with neutral pressure at $2 \cdot 10^{-4}$ mbar. In this case, both the n_H/n_{H_2}ratio and the total intensity increase with B_{max}/B_{min} and, consequently, with confinement time.

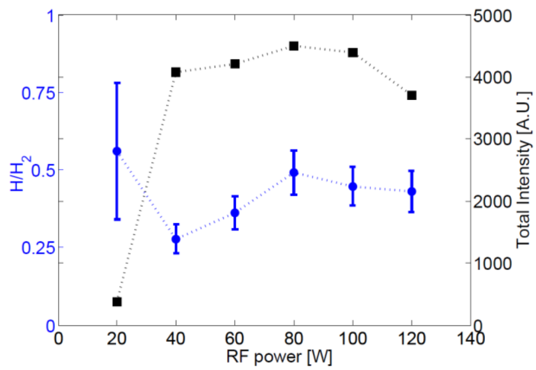

Figure 3: Dependence of the n_H/n_{H_2}ratio on RF power.

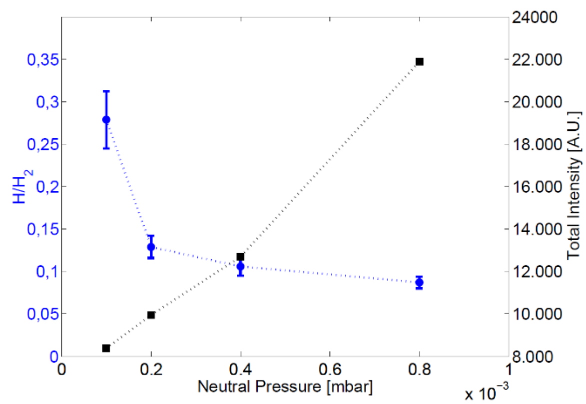

Figure 4: Dependence of the n_H/n_{H_2}ratio on the pressure.

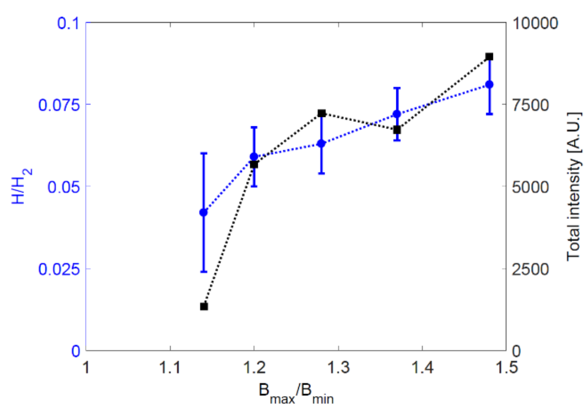

Figure 5: Dependence of the n_H/n_{H_2}ratio on the B_{max}/B_{min} ratio.

This means that, for larger confinement times, the chance that H_2 molecules are broken into H atoms by electrons is increasing. Furthermore, for lower values of B_{max}/B_{min}, the density of RF power absorbed by plasma decreases, so a strong increase of RF power is needed to guarantee a larger value of the proton fraction.

CONCLUSIONS AND NEXT STEPS

Preliminary OES measurements carried out with the FPT permitted the "in plasma" characterization of the relative abundances of the neutral component of a hydrogen plasma and indeed the identification of the source parameters that favour the proton or the H_2^+ generation within the plasma. New studies, based on the radiative collisional model, are expected to permit also the electron density calculation from the ratio between $\mathbf{H_\beta}$ and $\boldsymbol{H_\gamma}$ Balmer lines. The OES technique will be also applied to the PS-ESS source in order to relate, for the first time, the proton fraction to the $\boldsymbol{n_H/n_{H_2}}$ratio and electron density measured by means of the line ratio method. In perspective, we expect that all new proton sources will be equipped with multi-line of sight OES diagnostics, in order to evaluate, during the tuning phase of the source, the best operating conditions for high-stability, high current, proton (or H_2^+) beams.

The low-resolution spectrometer will be supported soon by a high-resolution spectrometer, SARG. SARG is an advanced spectropolarimeter with a resolution of $\lambda/\Delta\lambda$=160000 in the range of 370-900 nm (~3 pm at 400 nm), to be installed at INFN-LNS in late spring in the PANDORA experiment [10]. The new spectrometer will also allow discriminating, "in plasma", the vibrational and rotational states of H_2^+. In the case of plasmas composed of multicharged ions, the determination of the charge state distribution before of the beam extraction will also be possible.

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