

## Overview of the optical emission analysis of the hydrogen gas puff experiments in the linear plasma device PSI-2

V Kotov, M Sackers, M Reinhart, O Marchuk, G Sergienko, A Kreter and S Brezinsek

*Forschungszentrum Jülich GmbH, Institute of Fusion Energy and Nuclear Waste Management  
- Plasma Physics, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany*

The linear plasma device PSI-2 [1] is actively used for material-plasma interaction research in the field of magnetic fusion. This experiment is equipped with a variety of diagnostics and can be applied as well for studies of atomic and molecular kinetics in magnetized plasmas with high degree of ionization [2, 3]. The plasma chemical processes relevant for divertor detachment produce hydrogen atoms in specific excited states. They can be detected by means of optical emission spectroscopy (OES), and the individual contributions can be isolated by Balmer lines analysis [4, 5]. In the present paper application of this technique in PSI-2 is discussed.

The study was made for dedicated pure hydrogen experiments with plasma limited only by neutralizer plate far away from the measurement cross section. The electron temperature  $T_e$  and density  $n_e$  resolved over the plasma radius were measured by the movable Langmuir probe. Their profiles (piecewise least square fits of the processed data) are presented in figure 1. Two sets of measurements were performed, one in November 2024 and another one in March 2025, after renewal of the plasma source. The  $H_2$  pressure in the target chamber is controlled by gas puff. One can see good reproducibility of the plasma parameters and of the trend between the low (0.02 Pa) and high (1 Pa) pressure cases.

The spectra were taken with the imaging spectrometer Acton SpectraPro-750 which provides integrals along lines of sight spatially resolved over the height of the plasma column with spectral resolution sufficient to integrate over individual Balmer lines. The OES measurements were absolutely calibrated against integrating sphere (USS 600, Labsphere) with known spectral radiance. The ratio of the radiation intensities of the  $H_\alpha$  and  $H_\beta$  lines which correspond to the plasma profiles of figure 1 is shown in figure 2. The OES data demonstrate good

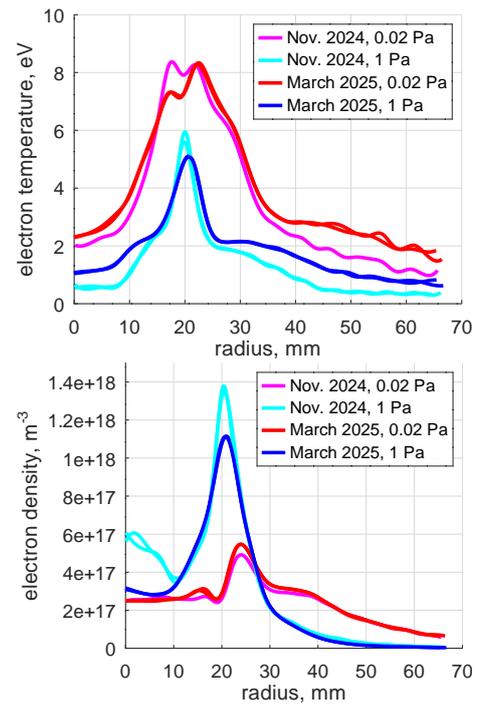


Figure 1: Plasma parameters without (0.02 Pa) and with (1 Pa) extra  $H_2$  gas puff in the target chamber

reproducibility as well. At the same time, one can see that axial symmetry of the discharges in question is only approximate.

In optically thin plasma the intensity of each line is determined by the number density  $n_n$  of upper states  $H(n > 1)$  which can be expressed as a sum over excitation channels [6]:

$$n_n = R_{H(n=1)}^n n_e n_{H(n=1)} + R_{H^+}^n n_e n_{H^+} + R_{H_2^+}^n n_e n_{H_2^+} + R_{H_2}^n n_e n_{H_2} \quad (1)$$

Here  $R_X^n(T_e, n_e)$  are population factors calculated in quasi static approximation with help of collision radiative models,  $n_X$  are the number densities of the corresponding species. In the present study  $R_X^n$  provided by the model ‘‘YACORA on the Web’’ [6] and by the data collection AMJUEL [7] are used. The factors  $R_{H(n=1)}^n$  and  $R_{H^+}^n$  express, respectively, electron impact excitation of the atomic ground state and recombination of  $H^+$ ;  $R_{H_2^+}^n$  is the contribution of the processes  $e + H_2^+ \rightarrow e + H(n \geq 1) + H^+$  and  $e + H_2^+ \rightarrow e + H(n \geq 1) + H(n = 1)$ ;  $R_{H_2}^n$  is the dissociation  $e + H_2 \rightarrow e + H(n \geq 1) + H(n \geq 1)$ . The  $H^+$  channel is almost negligible for the parameters in question, but is kept in the model for consistency.

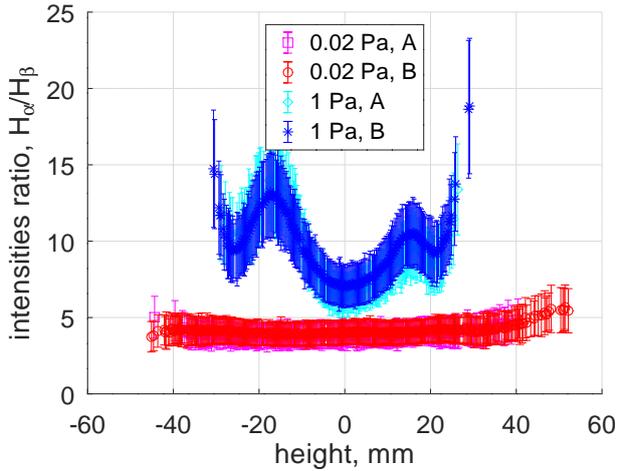


Figure 2: Ratio of the line intensities obtained from the imaging data, A is ‘November 2024’, B is ‘March 2025’ (see figure 1)

works via Abel inversion of the line of sight integrals to the plasma radius and then solving locally a minimization problem based on equation (1). The procedure is applied to the left and right halves of the spatial intensity profiles separately to assess the effect of the actual non-symmetry. The plasma parameters  $T_e$ ,  $n_e$  are taken from the Langmuir probe data, the density  $n_{H_2}$  for the last term of (1) is determined from the pressure gauge measurements (assuming gas temperature 300 K). The  $n_e$  is calculated from the ion saturation current self-consistently for

The OES data are analyzed by applying equation (1) to fit the experimental radiation intensity of two (or more) Balmer lines simultaneously. The basic principle is illustrated in figure 3 which shows the ratios of the  $H_\alpha$  and  $H_\beta$  intensities calculated theoretically using tabulated  $R_X^n(T_e, n_e)$ . One can readily see that the experimental  $H_\alpha/H_\beta$  ratio obtained in 0.02 Pa case, figure 2, would be best matched if  $H_2^+$  channel dominates, figure 3b.

A more elaborate fitting procedure has been developed which automatically adjusts the radial profiles of  $n_{H(n=1)}$  and  $n_{H_2^+}$  to the measured  $H_\alpha$  and  $H_\beta$  intensities. The fitting

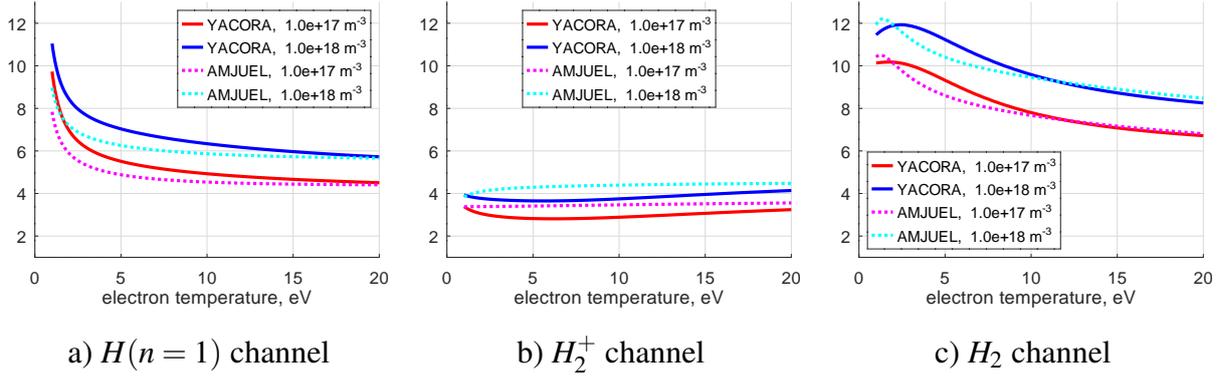


Figure 3: Theoretical  $H_\alpha/H_\beta$  intensities ratio for two selected values of  $n_e$  as function of  $T_e$

the obtained  $H^+/H_2^+$  content. To estimate the impact of the uncertainty of the measured  $T_e$ ,  $n_e$  a sensitivity assessment is performed by varying the nominal value of  $T_e$  by  $\pm 25\%$ , and  $n_e$  by  $\pm 50\%$ . Also,  $n_{H_2}$  is varied by  $\pm 30\%$  according to the specified pressure gauge accuracy.

In the 0.02 Pa case the fitting routine is shown to be able to match both  $H_\alpha$  and  $H_\beta$  within error bars for the nominal  $T_e$ ,  $n_e$ ,  $n_{H_2}$ , as well as for a wide range inside the boundaries given above. The fitting leads to the conclusion that the major part of Balmer radiation is due to  $H_2^+$  and  $H_2$  channels, see figure 4a. It also confirms that the contribution of  $H_2^+$  channel is always significant, figure 4b. For  $H_\beta$  and higher lines the contribution of  $H_2^+$  is even larger than that for  $H_\alpha$  shown in figure 4. The concentration  $n_{H_2^+}/n_e$  obtained by the fitting is very sensitive with respect to the variation of plasma parameters and location, it can vary from  $\sim 10\%$  to  $100\%$ . The results obtained with YACORA and AMJUUEL are close to each other.

The consistency of the reconstruction was checked by comparing with the experimental  $H_\gamma$ ,  $H_\delta$  intensities whose match is not enforced by the algorithm. This comparison shows that the  $H_\delta$  is nearly matched, but the calculated values have very large variation, and the calculated  $H_\gamma$  is always below the experimental values. The situation is worse for the discharges with extra gas puff. In 1 Pa case the 2-parameter fitting routine always fails to even match simultaneously  $H_\alpha$  and  $H_\beta$ . The discrepancy for  $H_\delta$ ,  $H_\gamma$  gets very large, in case of  $H_\delta$  reaching an order of magnitude for local emission near the plasma axis. This result indicates that in the model of equation (1) a process is missing which populates predominantly  $n = 5, 6$  states. The candidate is mutual neutralization  $H^- + H_2^+ \rightarrow H(n \geq 1) + H_2$ , see [8].

The outcome of the reconstruction for 0.02 Pa case demonstrates that this experiment and the OES measurements can be used as a benchmark for the models of  $H_2^+$  plasma chemistry. Moreover, the Fulcher- $\alpha$  line measurements required for reconstruction of the  $H_2$  vibrational temperature which may have large impact on the  $H_2^+$  production are already available in the same

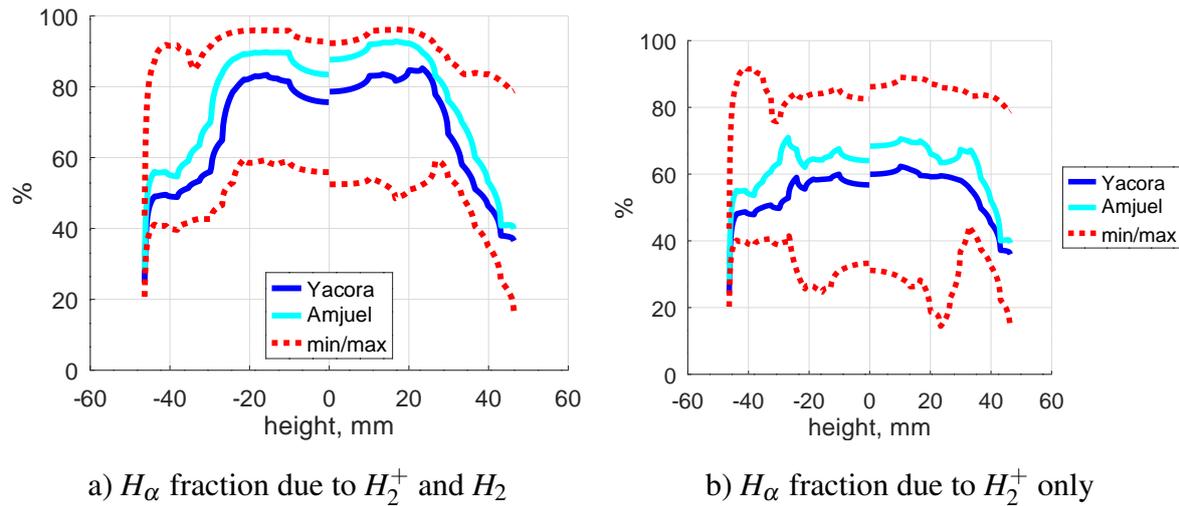


Figure 4: Fraction of the  $H_\alpha$  intensity (integrals over lines of sight) in 0.02 Pa case emitted due to different channels. Solid lines correspond to the nominal  $T_e$ ,  $n_e$ ,  $n_{H_2}$ , dashed lines is the maximum and minimum obtained by the sensitivity assessment

imaging data set. At the same time, the fitting technique applied here is apparently not suitable as quantitative diagnostic because the result is very sensitive to the uncertainty of plasma parameters.

The contribution of  $H_2$  and  $H_2^+$  to the Balmer spectra in PSI-2 can be further isolated with better accuracy by the measurements performed with the High Resolution Spectrometer [9]. They show that the hydrogen line always consists of at least two components, cold and hot, and the hot component has rotational shift which indicates its ionic origin. This observation agrees very well with the analysis of the imaging data. The cold component can be associated with dissociation of  $H_2$ , and the hot component with the  $H_2^+$  channel [5].

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