

Spectroscopic Investigations of the Ion Source at BATMAN Upgrade

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Abstract. The steady improvement of the analysis of atomic and molecular hydrogen emissivities together with the possibility to apply a high-resolution spectrometer motivated repeating at BATMAN Upgrade the detailed optical emission spectroscopy investigations performed at the BATMAN test facility in 2006. Although the test facility as a whole was upgraded, the RF-driven prototype source for the ITER NBI systems basically remained the same. The measurements were carried out in the first operation phase of BATMAN Upgrade i.e. in hydrogen in the volume operation mode of the negative ion source. The previously measured gas temperature of 1000 K in the driver, increasing to about 1200 K towards the grid is now determined to be 630 K in the whole source. Moreover, by evaluating now 12 rotational lines of the molecular Fulcher- α radiation instead of five, the presence of a two-temperature rotational distribution is demonstrated, revealing a hot ensemble with a temperature of about 4300 K. For the line of sight through the driver and the one parallel to the grid, the evaluation of the electron density and temperature showed similar values and trends as in the campaign of 2006. The third line of sight observes the expansion region and gives access, for the first time, to the plasma parameters in this region. Dependencies on the variation of the magnetic filter field strength and its topology are observed. The density ratio of atomic to molecular hydrogen is about 0.3 in all source regions, revealing no pronounced dependence on the filter field; however, due to the complex analysis procedure, the uncertainties are quite high for this parameter.

INTRODUCTION

Recently, an upgrade of the BATMAN test facility for RF-driven H^- ion sources for NBI systems has been realized. While the RF prototype ion source remained the same, the extraction system was modified having now an aperture geometry similar to the ones at the ITER NBI H^- ion source. Focus was also laid on improving the beam diagnostics providing together with the improved beam optics more insights into the beam physics of large ion beams. Furthermore, the magnetic filter field can be generated by a current flowing through the plasma grid as it is foreseen for the ITER sources. In addition, several technical improvements concerning the electrical circuits and the cooling systems were carried out. More details on the test facility BATMAN Upgrade (BUG) can be found in [1, 2].

One of the standard diagnostic methods for determining the parameters of the ion source plasma is optical emission spectroscopy (OES). From the emissivities of the atomic Balmer line radiation as well as the molecular Fulcher- α band various plasma parameters can be evaluated applying collisional radiative models for H and H_2 : the electron temperature T_e , the electron density n_e and the density ratio of atomic to molecular hydrogen. The latter is especially of importance as the flux of atomic hydrogen onto the plasma grid surface directly influences the amount of negative hydrogen ions created there. From the evaluation of the Fulcher- α spectrum, the rotational and vibrational population of H_2 can be determined. As the rotational population in the electronic ground state takes place via heavy particle collisions, the rotational temperature corresponds to the gas temperature of the discharge which means that T_{gas} can also be obtained. Detailed investigations on the ion source plasma were already carried out in 2006 providing valuable insights in the ion source physics [3]. Over the years, the analysis methods improved considerably and the diagnostic equipment has been upgraded. A newly available high-resolution spectrometer has a factor of two better spectral resolution compared to the previous investigations, allowing for a clear identification of more rotational lines of the Fulcher- α emission band and thus giving a more detailed picture of the rotational distribution of H_2 [4]. Additionally,

the expansion chamber of the prototype ion source was equipped with diagnostic flanges such that this plasma region can be investigated bridging the gap between the driver plasma and the plasma close to the plasma grid, determined in the campaign of 2006.

The OES measurements were carried out in hydrogen and in pure volume mode, i.e. with no caesium present. The source was operated at the ITER relevant pressure of 0.3 Pa and with a typical RF power of 70 kW. Focus was laid on determining the plasma parameters of the driver, of the expansion region and close to the plasma grid (PG) for a variation of the filter field strength, i.e. for varying the current I_{PG} flowing through the PG. A current of 2 kA roughly corresponds to a peak value of 3 mT at 4 cm distance to the PG [1]. In order to allow for a comparison to the former BATMAN setup, measurements were also carried out without PG current but with installing the previously used magnet frame equipped with permanent magnets in the $z = 9$ cm position [5].

EMISSON SPECTROSCOPY AT BATMAN UPGRADE

Figure 1 shows the ion source of the BATMAN Upgrade test bed. The driver in which the plasma is generated has an inner diameter of 24.5 cm and a length of 14 cm; the expansion chamber is 59 (length) x 32 (width) x 23 (depth) cm³. Measurements were carried out at three different lines of sight (LOS): axially through the driver, and parallel to the plasma grid in a distance of 2.6 cm (labelled as PG in the following) and of 18 cm (labelled as expansion). The yellow lines in figure 1 indicate the corresponding lines of sight. For the analysis of the emissivities a length of the LOS of only 14 cm was assumed for the driver as the radiation originating from the expansion chamber is estimated to be less than 10% compared to the radiation generated in the driver itself. This means that the plasma parameters determined from this LOS represent the ones of the driver region. For the two other lines of sight, the full width of the source was taken into account. The viewing cones of the LOS have a diameter of roughly 1 cm. An intensity calibrated high-resolution spectrometer (focal length 0.75 m, grating 1800 grooves/mm, $\Delta\lambda_{FWHM} \approx 15$ pm @ 600 nm) equipped with a CCD camera (1024 pixels, pixel size 13.5 x 13.5 μ m) was used; the high resolution being a prerequisite for the extended Fulcher- α evaluation described below.

It should be noted that the LOS in the expansion region and the one close to the grid are both vertically centered with respect to the source geometry. In order to identify effects of the plasma drift on the plasma parameters and thus vertical asymmetries, LOS through the diagnostic ports in the top and the bottom part of the source are planned to be used in a subsequent measurement campaign.

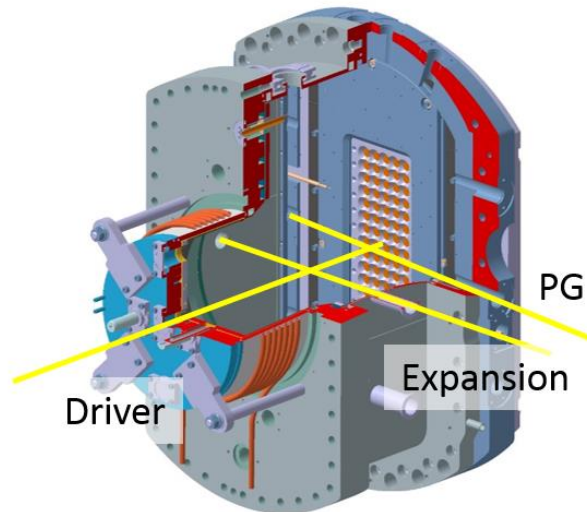


FIGURE 1. View of the RF driven prototype ion source used at BATMAN Upgrade. The yellow lines depict the lines of sight for the optical emission spectroscopy measurements. The arrangement of the apertures in the plasma grid is shown as well.

The OES measurements covered the atomic Balmer lines (H_α to H_δ) as well as the molecular Fulcher- α transition ($d \ ^3\Pi_u \rightarrow a \ ^3\Sigma_g^+$, located between 590 and 630 nm). In order to obtain plasma parameters from the measured

emissivities, the collisional radiative (CR) models Yacora H for atomic and Yacora H₂ for molecular hydrogen are applied [6]. These CR models balance all relevant population and depopulation processes for the particular states of H or H₂ yielding population densities, which depend on the plasma parameters. As the excited state population of atomic hydrogen does not only depend on the atomic hydrogen density, coupling of the CR model to the hydrogen molecules, the atomic and molecular ion species as well as to the negative hydrogen ion is provided. Thus, the models require the densities and temperatures of neutral (H and H₂) and charged particles (electrons and H⁺, H₂⁺, H₃⁺, H⁻) as input parameters. Together with the electron density and electron temperature these densities are varied until the absolute emissivities (and consequently also the line intensity ratios) of the measurements are matched by the model results. In the ion source different regions with different plasma parameters exist: in the driver the plasma is mainly in an ionizing state as the RF power is deposited there heating the electrons to temperatures of more than 10 eV. Here, the dominating population processes arise primarily from excitation by atomic hydrogen and by the dissociative excitation process of molecular hydrogen. Via the expansion region, the plasma undergoes a transition to a recombining state close to the plasma grid because the magnetic filter field cools down the electrons by almost one order of magnitude. In the recombining state, dissociative recombination mainly via the H₂⁺ molecule and the mutual neutralization of H⁺ and H⁻ play an important role.

The rotational and vibrational population of the hydrogen molecule as well as the gas temperature are determined from the Fulcher- α transition. In the previous measurement campaigns [3], the first five emission lines (rotational quantum numbers $N = 1, \dots, 5$) of the Q branch ($\Delta N = N' - N'' = 0$) arising from the first four diagonal vibrational transitions (vibrational quantum number $v' = v'' = 0, \dots, 3$) were recorded, which is referred to as standard method in the following. The resulting rotational temperature of the $v'=2$ level was then transferred into the ground state by taking the respective rotational constants into account. However, in low-pressure hydrogen discharges a non-Boltzmann rotational distribution is typically present [7], which can be approximated by a two-temperature distribution [4]. The low-lying rotational levels are described by the cold part of this distribution according to the temperature $T_{\text{rot},1}$ reflecting the population via heavy particle collisions. The hot part of the rotational population describes the high- N levels according to $T_{\text{rot},2}$. The respective share of these two distributions is described by the weighting factor β . There are several possible reasons behind the hot population: recombinative desorption of hydrogen atoms at the wall of the discharge vessel where a part of the binding energy is converted in rotational excitation, dissociative recombination of H₃⁺ with electrons, or direct electron impact excitation [7]. In order to probe also the hot part of the rotational distribution at the ion source plasma, the Fulcher- α evaluation was extended to the first 12 states ($N = 1 \dots 12$) of each vibrational level for the current campaign. It should be noted that the unambiguously identification and separation of the individual rotational lines in the spectra requires a high resolution of the spectrometer as the one used for this study.

In this improved analysis the ground state rovibrational population is calculated and projected via the respective electron excitation rate coefficients into the excited states. In order to match the measured population in the rovibrational levels of the excited state, this ground state population is varied yielding not only the above described rotational distributions but also the vibrational temperature. Finally, knowing both the rotational and vibrational distributions of the d³ Π_u state, the integrated emissivity of the Fulcher- α transition can be calculated which is required determining the density ratio of atoms to molecules via the two CR models.

RESULTS

Rotational population of H₂ and its relation to the gas temperature

Figure 2 shows the Boltzmann plot of the rotational population in the ground state of the molecule evaluated from the Fulcher- α transition. In such a Boltzmann plot, the population density of a rotational level is divided by the statistical weight and plotted in logarithmic scale against the respective energy. A linear fit yields the rotational temperature. In previous measurement campaigns [3], it was observed that the gas temperature increases from about 1000 K measured in the driver to around 1200 K determined close to the plasma grid. When only the first five rotational states are analyzed, a similar increase is also present for the measurements of the current campaign (see figure 2 a). The absolute values are slightly lower: $T_{\text{gas}} = 820$ K in the driver whereas 1100 K are obtained at the LOS close to the PG. Performing the improved Fulcher- α evaluation for the current measurement campaign reveals several aspects: first, one can see in figure 2 b) that a two-temperature distribution of the rotational states is clearly present. Fitting the distribution accordingly leads to a reduction of the determined gas temperature to 630 ± 25 K, a value that is obtained

at the driver LOS as well as at the one of the expansion region and close to the PG. This means that the gas temperature is constant in the whole volume of the ion source. One can see that the increasing share of the hot population i.e. the parameter β , towards the PG causes the previously measured apparent gas temperature increase towards the PG. The hot ensemble of the particles reveals a temperature of about 4100 – 4500 K which can be considered as being the same for all LOS within the error bars of ± 300 K. Among the above mentioned possible reasons for this population, a clear identification of the process is a point of further investigations.

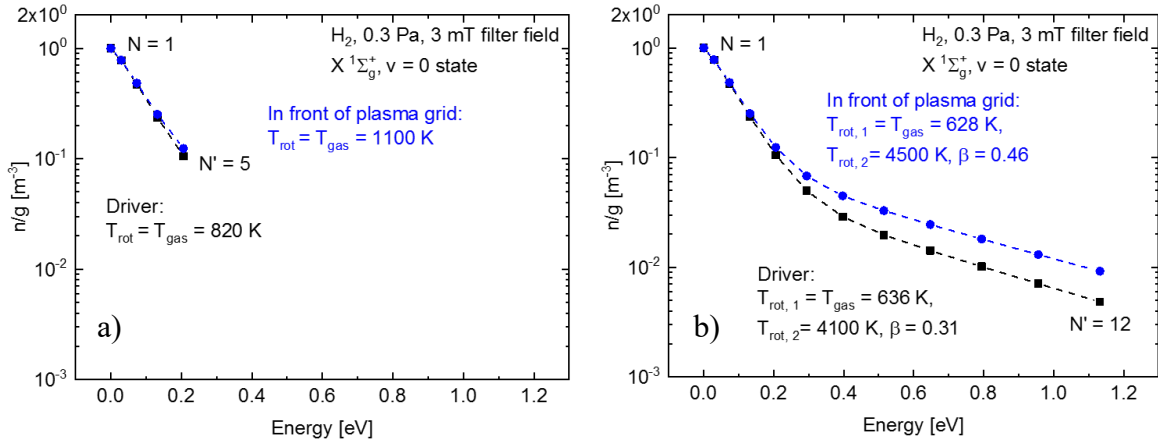


FIGURE 2. Boltzmann plot of the rotational states within the X ¹Σ_g⁺, v = 0 state of H₂. Part a) shows the first five rotational states which are evaluated in the standard Fulcher- α analysis whereas part b) shows the improved analysis where the first 12 lines are considered. The measurements were carried out for an RF power of 70 kW at a pressure of 0.3 Pa and I_{PG} = 2 kA.

From the measured four vibrational bands of the Fulcher- α system, the vibrational temperature in the ground state of the hydrogen molecules is determined to be 3000 ± 500 K revealing no dependencies on the filter field strength. It should be noted, that with this method, only the first four vibrational levels in the ground state of the molecule are accessible.

An important aspect of an NBI system are the losses of H⁻ ions in the extraction system due to collisions with the background gas stripping the second electron. As the gas density cannot be measured reliably in between the single grids of the extraction system, the gas temperature determined in the plasma region in front of the PG is used for calculating those densities (see for example [8]). Calculations are either carried out for a gas at room temperature, i.e. 300 K or at the temperature of 1150 K taken from the measurements of the campaign of 2006. The latter needs now to be replaced by the 630 K for the filling pressure of 0.3 Pa. This leads to an increase of the gas density and therefore of the stripping losses but also the gas conductance of the grid system is influenced. However, measurements carried out at the half-size ITER source at the ELISE test facility indicated that the calculations overestimate the stripping losses in general [9].

Electron temperature and density

The electron density and temperatures evaluated from the OES measurements are summarized in figure 3 for a variation of the magnetic filter field strength. For these measurements, the PG current I_{PG} has been varied from 0 to 3 kA what corresponds to a filter field strength in front of the PG between 0 and 4.5 mT. In order to allow for a comparison to the BATMAN measurements from 2006 [3], data points obtained with the permanent magnets and without I_{PG} are also included. However, it should be kept in mind, that in the original prototype source the permanent magnets are housed inside the source at the axial distance of z = 3 cm from the PG. For the measurements here the magnet frame mounted outside the lateral walls of the source [5] located at z = 9 cm was used. Concerning the driver LOS, an electron temperature of 10.5 eV and an electron density of about 7×10^{17} m⁻³ is obtained virtually independently of the filter field strength and topology. Thus, the plasma parameters averaged along the driver axis are not influenced by the low magnetic filter field strength which is less than 1 mT in these cases [1]. At the LOS going through the expansion region, the T_e and n_e values are reduced compared to the driver to just below 8 eV and to about

$1.5 \times 10^{17} \text{ m}^{-3}$ due to the expansion of the plasma. Again, the variation of the filter field strength does not affect the obtained electron temperature and density values. This is explained by the fact that the magnetic filter field strength is still rather low: the expansion LOS is located at roughly 18 cm distance from the PG whereas the peak of the fields is at 4 cm for the PG current variation or at 8 cm for the permanent magnets. In contrast, the parameters evaluated for the PG LOS react on the filter field: T_e decreases from 7 eV to below 3 eV for increasing PG current and n_e decreases from $9 \times 10^{16} \text{ m}^{-3}$ to $6 \times 10^{16} \text{ m}^{-3}$. The plasma cooling sets in at a current between 0.5 – 1 kA corresponding to a field strength of 0.8 – 1.5 mT. At these strengths, the electrons are considered to be magnetized, i.e. the Larmor radius is in the centimeter range or lower. Similar values for the electron temperature and density are obtained for the ELISE source in which the filter field is also generated by a PG current [10].

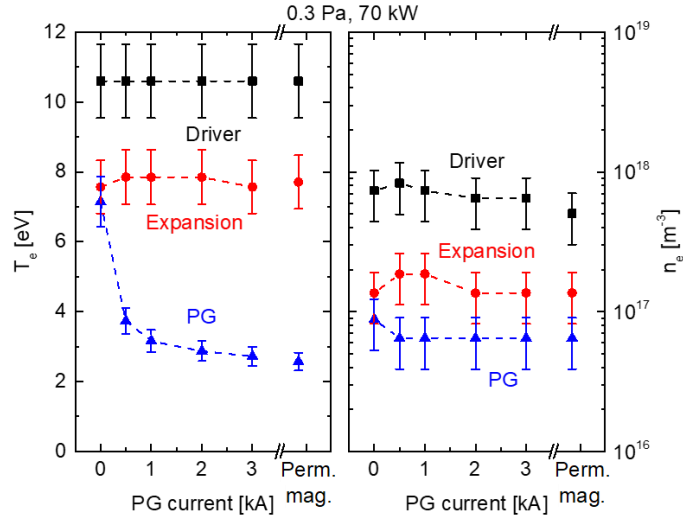


FIGURE 3. Electron temperature and density for the variation of the PG current and for the configuration using permanent magnets at a pressure of 0.3 Pa and an RF power of 70 kW.

The robustness of the analysis for the evaluation of electron temperature and density for an ionizing plasma, i.e. in the driver, is demonstrated for the results for the permanent magnets at the pressure of 0.6 Pa. In the measurements from 2006, an electron temperature of 6 eV compared to the now measured 8 eV is obtained whereas for both cases the electron density is determined to $2 \times 10^{18} \text{ m}^{-3}$. Taking into account the relatively large error bar of $\pm 1 \text{ eV}$ for T_e in this temperature range, the results match well. An agreement is observed as well for the recombining plasma in front of the PG but one should keep in mind that the contributions from H_2^+ and H^- to the Balmer line radiations are not negligible and thus their densities are relevant as well.

Density ratio of atomic to molecular hydrogen

The results for the density ratio of atomic to molecular hydrogen are shown in figure 4 for all three LOS. The analysis of the ionizing plasma, i.e. the plasma in the driver is more or less straightforward as the radiation of the atomic hydrogen originates to more than 80% from excitation and de-excitation processes within the hydrogen atom and represents thus dominantly the atomic hydrogen density. In the expansion chamber, the dissociative recombination of the H_2^+ molecular ion becomes relevant but the contribution is still minor compared to the one from atomic hydrogen. Therefore, the uncertainty in the atomic to molecular density ratio is increased only slightly. In the recombining plasma, i.e. the plasma close to the PG, the dissociative recombination is dominating the emission of the Balmer lines such that the uncertainty of the determined density ratio of atomic to molecular hydrogen becomes higher. In addition, the emissivity decreases drastically from the driver to the PG. Very difficult to analyze was the data point for the permanent magnets and represents thus only an estimate.

Taking this into account, the results for the driver and the expansion chamber are considered to be the same and indicate, if at all, a tendency to increase with the magnetic filter field strength and topology. The values for the PG region are interpreted to follow this behavior. Hence, a density ratio of 0.3 ± 0.1 is obtained in average. Due to the

high electron temperature and density in the driver the dissociation of molecular hydrogen primarily happens in this region. In the region close to the PG, the formation of atomic hydrogen is negligible to the one in the driver because of the reduced electron density and temperature. Therefore, the constant density ratio with varying filter field can be explained by the constant T_e and n_e values in the driver.

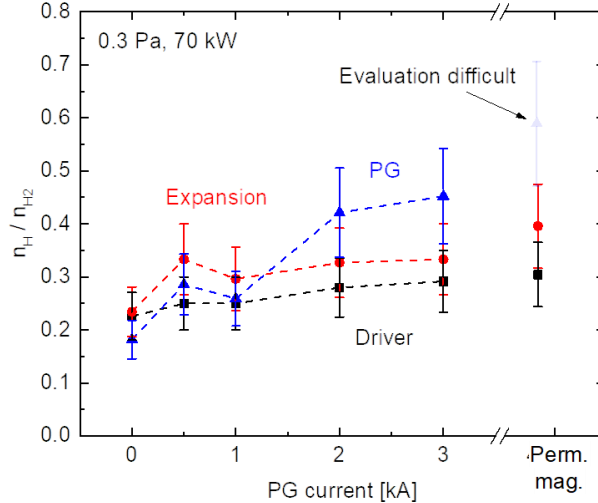


FIGURE 4. Density ratio of atomic to molecular hydrogen for varying PG current and for using permanent magnets.

The atoms are produced in the driver and flow into the expansion chamber towards the grid. If caesium is evaporated into the source and distributed by the plasma, the work function of the molybdenum coated plasma grid is reduced and the atoms are converted into negative ions and extracted. As the flux of atomic hydrogen is thus an important parameter influencing the amount of negative ions emitted from the surface, a precise knowledge of the atomic hydrogen density is highly desirable. In particular, as the results from this campaign give higher values close to the plasma grid as the campaign from 2006 where a ratio of 0.2 is reported. Preferably, the atomic hydrogen density should be measured directly and independent from the analysis by the CR model. The method providing this quantity would be the two photon absorption laser induced fluorescent method (TALIF) which, however, needs viewports perpendicular to each other, precise alignments opportunities and requires a complex calibration procedure [11]. Such a method was not applied to ion sources yet but might be considered in future.

SUMMARY AND CONCLUSIONS

At the BATMAN Upgrade test facility, improved spectroscopic investigations have been carried out motivated by the availability of a high resolution spectrometer, new diagnostic access which reveal plasma parameters in the expansion region and improved analysis methods. Several new insights are gained: (i) the analysis of the rotational distribution of the hydrogen molecule in its ground state revealed a two temperature distribution in which the cold part represents the gas temperature. The hot part is determined by other processes, most likely recombining hydrogen atoms at the wall. (ii) It could be clarified, that the apparent increase of the gas temperature in previous investigations was caused by the increasing importance of the hot part from the driver towards the plasma grid. (iii) A gas temperature of 630 K is observed for the driver, the expansion chamber and the plasma region close to the plasma grid. This is roughly a factor of two lower than the values obtained in the campaign in 2006. As this has direct consequences on the stripping loss calculations for H^- NBI systems new calculations are highly desirable. (iv) Electron temperature and density values are similar to the 2006 results demonstrating the robustness of the evaluation for these parameters. (v) Additional insight could be gained to the plasma in the expansion region, showing slightly reduced parameters compared to the driver. No dependence on the magnetic filter field configuration was observed, which is attributed to the fact that the filter field peak occurs closer to the PG. (vi) The plasma close to the PG reveals a dependence on the filter field, the onset being at a similar field strength as the one obtained at the half-size ITER source at the ELISE test

facility, where the filter field is also generated by the PG current. (vii) The atomic to molecular density ratio is at a value of 0.3 for the whole source but it has high uncertainties for the recombining plasma in front of the PG. An independent and direct measurement of the atomic hydrogen density is highly desirable for the precise quantification of the negative ion emission rate from the caesiated plasma grid. This might be addressed in future by using the TALIF method.

This campaign focussed on the variation of the magnetic filter field at the ITER relevant pressure of 0.3 Pa and at the typical RF power of 70 kW in a non-caesiated source. Consequently, the parameter range will be extended. Having the option to use LOS in the top and in the bottom part of the expansion chamber and close to the plasma grid allows for investigating the consequences of the strength of the filter field on the plasma symmetry. Due to the improved reliability of the results, measurements in caesiated source might give new insights as well. Of utmost importance however, is the comparison with a deuterium plasma, in which the reason for the increased amount of co-extracted electrons and their temporal stability is still unclear.

Last but not least, it should be mentioned that the underlying CR models Yacora H and Yacora H₂ have been made recently available for the community via a web-interface in the project “Yacora on the Web”. Please visit www.yacora.de!

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