Spectroscopic study of hydrogen particle behaviour in island divertor of W7-X

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1. Introduction

In fusion devices, the recycled hydrogen particles are released from the plasma-facing components (PFCs), such as walls, limiters and divertors, in the form of atoms and molecules [1]. The probability of the different released particle species is related to the temperature and the material of PFCs. For the graphite material under high ion flux conditions, it has been found that at low surface temperature mainly hydrogen molecules are desorbed while above about 1100 K the majority of the released particles are hydrogen atoms [2]. In addition, the incoming protons could induce chemical erosion and release hydrocarbon molecules without threshold energy [3]. The process plays a role in impurity production as well as re-fueling of the plasma. Once hydrogen atoms and molecules or hydrocarbon are released from PFCs, they are subsequently dissociated or ionised according to the local plasma conditions. Neglecting in the first order of the chemical erosion, then the total hydrogen atom influx is $\Gamma_{total} = \Gamma_H + 2\Gamma_{H2}$, if we suppose all molecules dissociates to atoms and not during the dissociation chain directly to H^+. Here, Γ_H represents the flux of hydrogen atoms which includes energetic hydrogen atoms resulting from reflection of protons and thermal atoms by desorption. One typical way to determine these particle fluxes in edge plasma is the measurement of the integral photon flux of spectral lines or molecular bands emitted by the released particles. The photon fluxes of the line emission can be transferred into particle fluxes by means of inverse photon efficiencies S/XB in case of atoms and D/XB in case of molecules [4]. This S(D)/XB values can be obtained from collision radiative models for hydrogen embedded in EIRENE or ADAS for given electron density and temperature, or experimentally from a dedicated gas injection with a known influx. The gas injection influx should be high enough to get adequate photon fluxes for spectrometers and low enough to minimize local plasma disturbances. In section 2, H_2 gas injection experiments on W7-X are presented in details.

In order to quantify the hydrogen particle flux, Balmer lines from hydrogen atoms and Fulcher band ($d^3\Pi_u \rightarrow a^3\Sigma_g^+$) from hydrogen molecules are widely used. Fig.1 shows part of

Fulcher band measured by divertor spectrometers on W7-X [5]. Rotational lines from the Q-branch of the diagonal vibrational transitions ($\nu' \rightarrow \nu''$: $0\rightarrow0$, $1\rightarrow1$, $2\rightarrow2$, $3\rightarrow3$) are indicated.

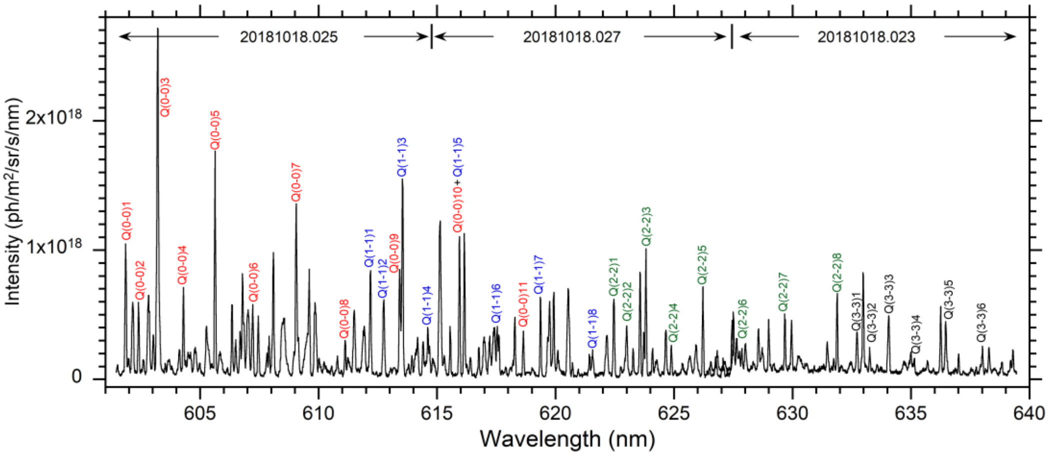

Fig.1 Survey of H_2 Fulcher lines measured by divertor spectrometer in attached divertor plasma on W7-X.

2. H_2 gas injection experiments

In Operation Phase 1.2, W7-X run in island divertor configurations with ten divertor units made of graphite. Five He-beam nozzles were installed in the horizontal divertor plate located at HM51 as shown in Fig.2, and they could inject H_2, H_e, N, N_e and CH_4 for different research studies. These five nozzles are located at the scrape-off layer with a connection length of the magnetic field of less than 200 m, which is far away from the plasma heat deposition area to avoid the overheating of the nozzles. The distance between the five nozzles and the last closed flux surface is larger than 9 cm. Two divertor spectrometers were installed to observe the He-beam gas injection. One is a mult-channel input spectrometer with high spectral resolution. The line of sights are parallel to the horizontal divertor plate and the spatial resolution is 5 mm. This spectrometer is used to measure the penetration of atomic and molecular lines via their emission. The other one is an overview spectrometer with a tangential line of sight which covers most of the divertor plasma. The details of these two spectrometers could be found in [5].

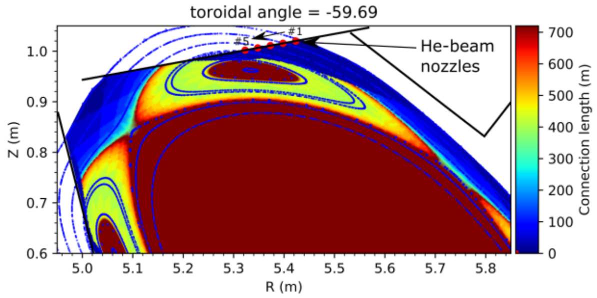

Fig.2 Connection length and Poincare plot of magnetic fields (standard divertor configuration) at cross section with He-beam nozzles (HM51).

In discharge #20181010.013 (Fig.3), H_2 was injected using different He-beam nozzles with a gas injection duration length 0.5 s at two heating power steps, i.e. $P_{ECRH} = 3.8$ MW and 1.9 MW. The injected H_2 gas influx is 2.5×10^{20} molecules/s. The penetration depth of injected H_2 visualised by Fulcher line emission (Q_3 (0-0)) from nozzle #3 is 2 cm, while it is less than 1 cm for the recycled H_2 molecules as shown in Fig.4. Both penetration depths for two ECRH powers are nearly identical. Fig.5(a) shows the increase of the line integrated density during H_2

gas injection. At P_{ECRH} = 1.9 MW, the line integrated density increase is $\Delta n_e = 0.11 \times 10^{19}$ m^{-2} for nozzle #2 while it increases to 0.18×10^{19} m^{-2} for nozzle #5 meaning a higher fuelling efficiency in the case of the nozzle close to the magnetic island. At higher heating power P_{ECRH} = 3.8 MW, all nozzles have better particle fuelling efficiency. The increased line integrated density is $\Delta n_e = 0.18 \times 10^{19}$ m^{-2} for nozzle #2 and 0.25×10^{19} m^{-2} for nozzle #5. The corresponding fuelling efficiencies are around 16% and 23%. Fig. 5(b) shows the intensity ratio H_γ/H_2 (Q_3 (0-0)) which are separately from hydrogen atoms and molecules during H_2 gas injection. This value shows an increase tendency when the nozzle position approaches to the island. At higher heating power, it also increases slightly. Fig.6 shows the time evolution of the line emissions from hydrogen atoms and molecules. During H_2 gas injection, the H_γ and H_2 (Q_3 (0-0)) line intensities have a significantly increase. The line intensity ratio H_δ/H_γ and H_γ/H_2 (Q_3(0-0)) have a decrease during H_2 injection as shown in Fig.6(b). During the H_2 gas injection, the electron temperature on the same flux tube measured by neighbouring M51 Langmuir probes decreases slightly due to the minor local perturbation causing by local cooling effect, while the electron density increase less than 20% as shown in Fig.7.

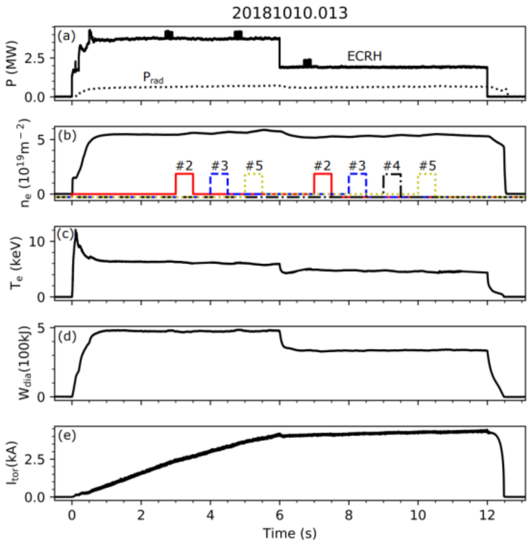

Fig.3 Time evolution of plasma parameters and H_2 gas injection from He-beam nozzles

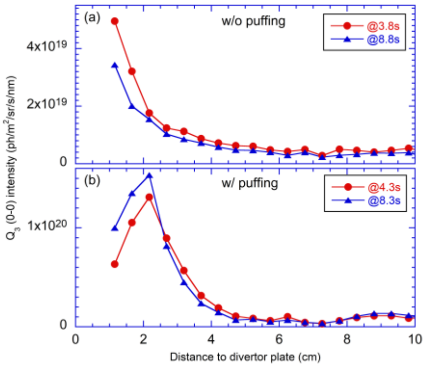

Fig.4 Measured intensity of H_2 Fulcher line (Q_3 (0-0)) as functions of the distance from divertor plate (a) without and (b) with H_2 puffing from He-beam nozzle #3.

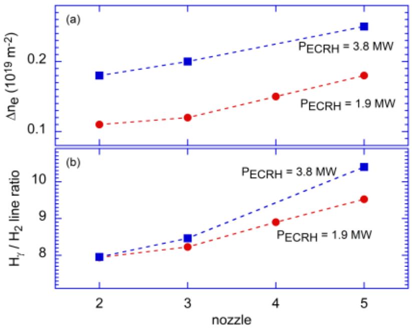

Fig.5 (a) Increase of line integrated density measured by interferometer system, and (b) intensity ratios of H_γ/H_2 (Q_3 (0-0)) during H_2 injection from He-beam nozzles.

Without H_2 injection, the measured Balmer lines, e.g. H_δ and H_γ, come from the directly reflect H atoms and released H atoms. In addition, desorbed H_2 molecules contribute part of H atoms by different dissociation channels. These dissociation channels depend on the local plasma conditions as well as the ground state population of the molecules. Here, we assume that the recycled H_2 molecules and the injected H_2 molecules follow the same dissociation processes. Since the Fulcher band intensity is proportional to the H_2 gas influx. Then, the calculated recycled H_2 molecule influx from divertor plate is 4.5×10^{19} molecules/s, i.e. the averaged influx density is 1.7×10^{21} molecules/m^2/s at $P_{ECRH} = 1.9$ MW. At $P_{ECRH} = 3.8$ MW, the recycled H_2 molecule influx is 5×10^{19} molecules/s and influx density is 1.9×10^{21} molecules/m^2/s. Here, the used area on dviertor plate to calculate particle influx and influx density is indicated by the tangential line of sight as shown in Fig.2 in [5]. In further, if we assume that the Fulcher band line intensity is also proportional to the Balmer lines emitted from H atoms dissociated from H_2. Then, in the measured H_γ without H_2 puffing, there are 30% from the H atoms dissociated from H_2 and 70% from directly reflect H atoms and released H atoms.

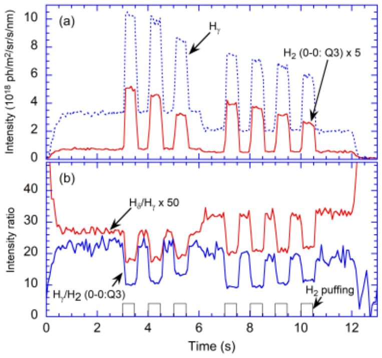

Fig.6 Time evolution of (a) H_γ and H_2 Fulcher line intensity (Q_3 (0-0)) and (b) H_δ/H_γ and H_γ/H_2 (Q_3 (0-0)) intensity ratios.

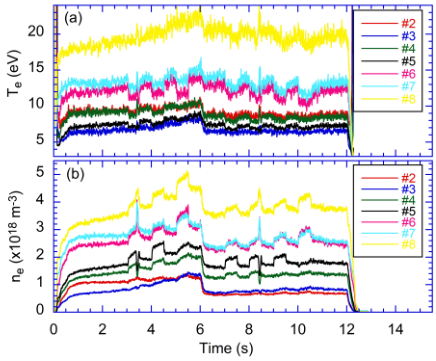

Fig.7 Electron temperature and density measured by HM51 divertor Langmuir probes.

3. Summary

Hydrogen recycling plays a key role in the steady-state operation on W7-X. In OP1.2, the H_2 gas injection through He-beam nozzles installed on divertor plates has been applied to calibrate the recycling flux measured by the divertor spectrometers. The results show that the nozzle position close to the O-point of the island has better fuelling efficiency. And at higher heating power, the fuelling efficiency is also better. The recycled H_2 molecules influx from divertor plate is estimated in W7-X in front of the graphite target plate. Meanwhile, in the H_γ intensity, there are about 30% contributed from hydrogen atoms dissociated from H_2 molecules.

Acknowledgements

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