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Study of the plasma driven permeation of hydrogen through a nickel membrane in RF and ohmic plasmas in the spherical tokamak QUEST

Sanjeev K. SHARMA[1], Hideki ZUSHI[2], Ikuji TAKAGI[3], Yuki HISANO[1], Mizuki SAKAMOTO[2], Yuta HIGASHIZONO[2], Taichi SHIKAMA[3], Sigeru MORITA[4], Tetsuo TANABE[1], Naoaki YOSHIDA[2], Kazuaki HANADA[2], Makoto HASEGAWA[2], Osamu MITARAI[5], Kazuo NAKAMURA[2], Hiroshi IDEI[2], Kohnosuke N. SATO[2], Shoji KAWASAKI[2], Hisatoshi NAKASHIMA[2], Aki HIGASHIJIMA[2], Yousuke NAKASHIMA[6], Nobuyuki NISHINO[7], Yuji HATANO[8], Akira SAGARA[4], Yukio NAKAMURA[4], Naoko ASHIKAWA[4], Takashi MAEKAWA[3], Yasuaki KISHIMOTO[3], Yuichi TAKASE[9] and QUEST Group

[1]IGSES, Kyushu University, [2]RIAM, Kyushu University, [3]Kyoto University ,[4]NIFS,[5]Kyushu Tokai University, [6]University of Tsukuba,[7]Hiroshima University,[8]Toyama University,[9] University of Tokyo

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Particle retention and recycling are still major issues for the long pulse fusion devices. Plasma driven permeation (PDP) is one of the main reason behind the particle retention/recycling in these devices. To enhance the understanding of the particle retention under various discharge parameters, the PDP of hydrogen through a 30 μm thick Ni membrane heated at 523 K has been studied in RF and ohmic plasmas in the spherical tokamak QUEST. The permeation has been allowed by reflected neutral atoms by using a baffle before the Ni membrane to avoid any impurity deposition. The baffle before the Ni membrane also provides a way to simulate the particles retention behind plasma facing components (PFC) inside the tokamak chamber. It has been observed that the PDP fluence (Q_{PDP}) increases linearly with RF power (P_{RF}) and the chamber pressure. A linear relationship with scattered data between Q_{PDP} and H_α fluence (Q_α) is found in all discharges, which suggests the fundamental proportionality of Q_{PDP} to the incident atomic fluence. For the longer discharge pulse, the PDP flux (Γ_{H2}) tends to saturate at $\tau \approx 30$ s, though the incident ion flux to the chamber wall is $\sim 5\times10^{21}$ m^{-2}s^{-1}. Q_{PDP} is also found proportional to the plasma discharge widths ($\tau > 5$ s).

Keywords: plasma driven permeation, PDP, recycling, retention, tritium

1. Introduction

The particle retention and recycling are still one of the crucial problems to be resolved for the safe and trouble free operations of the next generation fusion devices especially for the long pulse discharges [1-5]. The particle retention in the plasma facing components (PFCs) is mainly concerned with the safety point of view from the tritium inventory, which is related with the long term retention of the hydrogen isotopes. The long term retention is basically related to the deep implantation, trapping and co-deposition of particles [1]. On the other hand, a short term retention process, due to the shallow implantation of particles is responsible for the release of the gas during the recycling. The recycling is another threat in achieving steady state plasma density operations due to the uncontrolled fueling rate.

The particle retention in PFCs has already been discussed in terms of gas driven permeation (GDP) as well as plasma driven permeation (PDP) [5, 6]. Actually PDP flux (Γ_{PDP}) is several orders of magnitude higher as compared to GDP flux (Γ_{GDP}) and is mainly responsible for the particle retention in plasma based devices. The PDP is mainly caused by the diffusion of the low energy Frank-Condon atoms (2-5 eV) or sub eV (< 1eV) atoms through the materials [7]. A fraction of the incident atomic flux is reflected back. The atoms absorbed in the material are either diffused into the deep material or recombine at the incident surface and released back into the plasma in form of molecules. The diffusive atoms may also be trapped in various trap sites inside the materials and lead to the long term retention.

The plasma driven permeation has been measured in numerous small size plasma devices and ion beams [8 -10]. There are only very few studies on the PDP using tokamak plasma except in Heliotron E and TEXTOR [11-12]. In these references, the permeation measurements had been used for monitoring the atomic flux on the wall and it was also proposed to measure the D/T ratio in a fusion reactor using this technique [12]. In order to enhance the database on the PDP in terms of various operating parameters, the PDP of hydrogen through a 30

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author's e-mail: sksharma@triam.kyushu-u.ac.jp

μm thick Ni membrane heated at 523 K has been studied in RF and ohmic plasmas in the spherical tokamak QUEST. The permeation has been allowed only by the scattered neutral atoms by using a baffle in front of the Ni membrane to avoid impurity deposition on it. It is noted that the permeation probes may be affected by impurity deposition or oxidation on the Ni membrane. The observed permeation due to the baffle before the Ni membrane also simulates the particle retention behind PFCs which may cause a significant contribution to the total retention. This paper describes a parametric study on the plasma driven permeation measurements in the spherical tokamak QUEST.

This paper is organized as follows. In section 2, the experimental conditions are presented. In section 3, the experimental results and a parametric study of PDP are discussed. Finally a conclusion is given in section 4.

2. Experimental setup

QUEST is a medium sized spherical tokamak device, whose chamber radius and height are ~1.4 m and ~2.8 m, respectively. The vacuum chamber is made of stainless steel 304L having a wall thickness of 8-12 mm. The total surface area is 35.8 m^2 and volume is ~13 m^3 including the extension ports. The temperature of the chamber has been kept within 40 – 70 $^{\circ}$C. Hydrogen plasma was initiated by the microwaves using electron cyclotron resonance using two kinds of RF sources 2.45GHz and 8.2GHz. During the ohmic plasma, ohmic coils along with the 8.2 GHz RF system have been used to produce the plasma current (~47 kA). Γ_{PDP} has been measured during various types of plasma discharges.

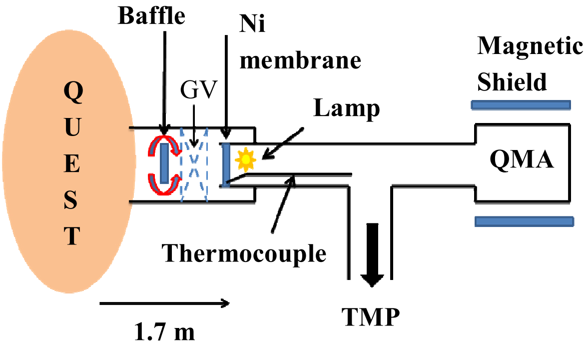


Fig.1. Schematic of experimental setup

The PDP system is shown schematically in Fig. 1. The PDP system (or permeation probe) is installed to view the plasma horizontally 0.20 m below the mid plane. The PDP system consists of two vacuum chambers, upstream and downstream, separated by a nickel membrane. The pressures at the upstream and downstream before the plasma discharges are kept typically < 10^{-5} and ~2×10^{-6} Pa, respectively. The nickel membrane used for the permeation has thickness and surface area of 30 μm and 2×10^{-4} m^2 respectively. A radiation lamp directly heats the rear surface of the Ni membrane. The temperature of the Ni membrane is kept fixed at 523 K, which is monitored by a thermo couple attached to the rear surface. The total and partial pressure of H_2 in the downstream is measured by a quadrupole mass analyzer (QMA). The atomic (Balmar series) and molecular (Fulcher α) line spectra are used to monitor the incident and re-emitted fluxes from plasma facing components by a spectrometer (200 to 800 nm). The Fulcher line intensities ((v = 0 - 0) Q1-Q5) from H_2 molecules are also separately measured by a high resolution visible spectrometer. OII spectral lines are also being measured for the monitoring of the wall conditions.

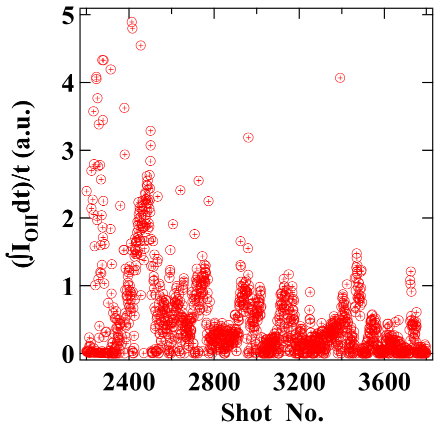


Fig.2. Gradual reduction of averaged OII intensity during experimental campaign

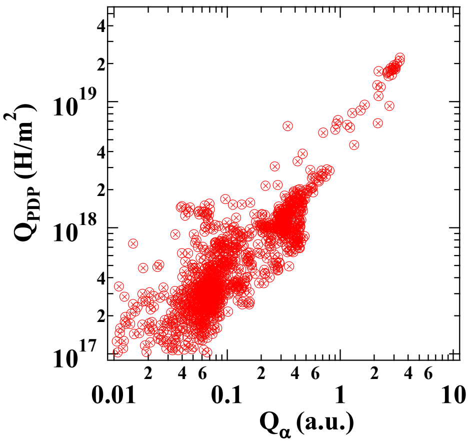


Fig.3. Linear relationship between Q_{PDP} and Q_α

3. Results and Discussion

3.1 Global measurement of PDP

During the two months long experimental campaign (2009), the measurement of PDP flux has been carried out for more than 1200 discharge shots. The measurement of PDP starts from the initial wall conditions to the improved one during the whole campaign. OII spectral lines are used for monitoring of the wall conditions. A gradual reduction of the averaged OII intensity shows a wall conditioning during the experimental campaign (fig.2). Here, OII intensity signal is averaged over the discharge widths.

The experimental campaign includes various types of plasma discharges including short pulse conditioning, high power (~100 kW, 8.2 GHz, 70 - 250ms) RF current drive, Ohmic plasma (~ 47 kA), low power long pulse (4.5 kW, 2.45 GHz, ~30 s) discharges. The permeated fluence Q_{PDP} is obtained by integrating Γ_{PDP} over 120s, when Γ_{PDP} reduces to its background level. The measured Q_{PDP} varies from ~10^{17} to ~ 4×10^{19} H/m^2 over a large dynamic range of discharge parameters. As H_α flux indirectly measures the incident atomic flux on the first walls, the incident particle fluence has been inferred by integrating H_α signal over the discharge widths. Fig. 3 shows a summary of Q_{PDP} and H_α fluence (Q_α) for more than 1200 discharge shots. It has been observed that Q_{PDP} follows Q_α. A linear relationship with scattered data between Q_{PDP} and Q_α is found in all the discharges, suggesting the fundamental proportionality of Q_{PDP} to the incident atomic fluence (fig. 3). It is important that the linear relationship has been established over a wide range of discharges. Long term working of the permeation probe without any cleaning procedure is one of the important results of the present work.

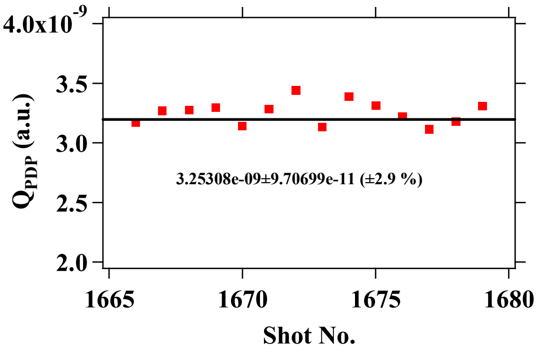
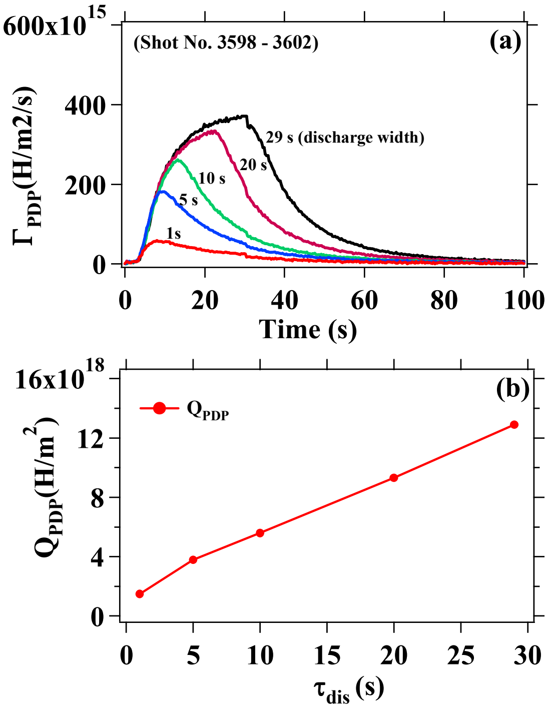


Fig.4. Reproducibility of Q_{PDP} during the plasma discharges with similar operating parameters.

3.2 Reproducibility in PDP measurements

The reproducibility of Q_{PDP} has been checked during the plasma discharges having similar experimental conditions i.e. magnetic configuration, gas puff, P_{RF} and discharge widths (fig. 4). During these discharges, the plasma was produced by 4.5 kW RF power (2.45 GHz). The discharge widths were kept at 29 s. A gas puff of 80 ms (~1.3×10^{18} m^{-3}) was applied prior to the discharges. Two more gas puffs at 10 s and 20 s during the discharge are also applied. The reproducibility of Q_{PDP} is found within ±3% variation. On the other hand, Q_α shows a ±6% variation during these discharges (not shown). Even in the similar kind of discharges, it is observed that both signals i.e. Q_{PDP} and Q_α follow each. It could be noted that the observed scattering during the large range of operating conditions, as shown in fig. 3, is quite large as compared to the calculated reproducibility of ±3%. The scattering from the linearity may be attributed to the localized variations in plasma parameters like density/electron temperature or to the fact that Q_α may not be representing the actual incident neutral fluence. Without sufficient plasma, a less H_α intensity could be expected; even though there are plenty of neutrals (sub eV).



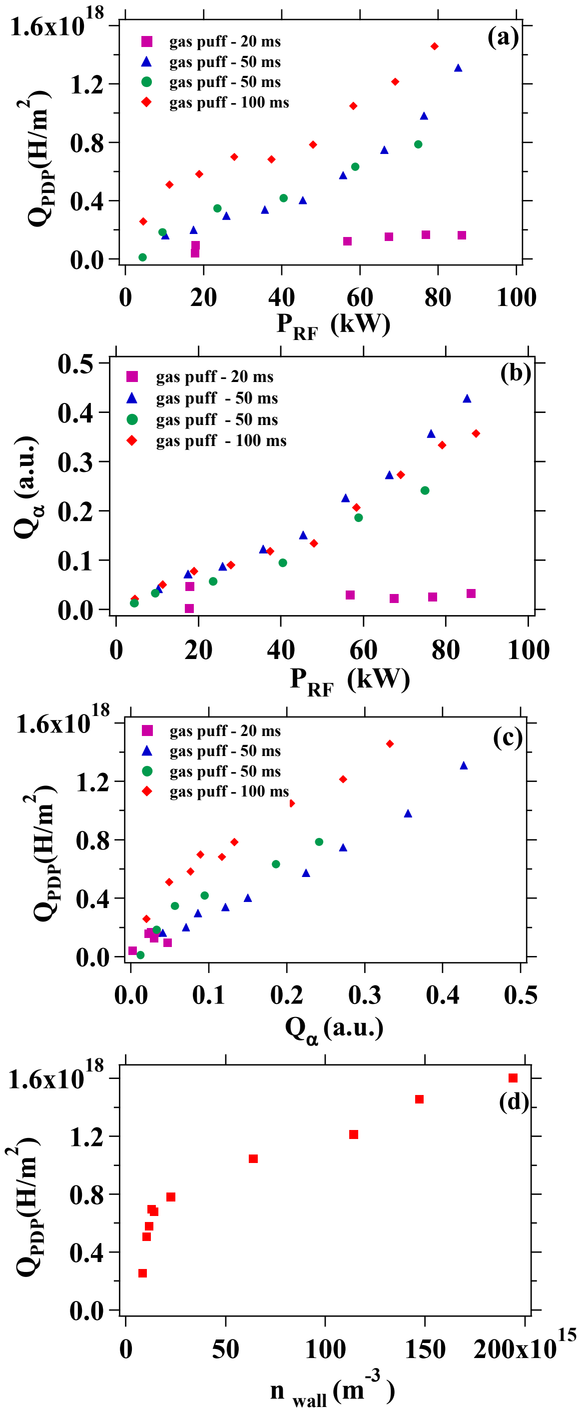
Figs. 5 (a) Γ_{PDP} measurements during the discharge width scan (b) Q_{PDP} vs. τ_{dis}

3.3 Parametric study of PDP

The measured Γ_{PDP} and Q_{PDP} are being studied as a function of various operating parameters like plasma discharge width (τ_{dis}), RF power (P_{RF}), gas puff width (τ_{gas}) and the magnetic field configuration specially vertical magnetic field strength (figs. 5 – 8). During these studies, only one operating parameter is scanned and rests of the parameters are kept constant.

3.3.1 Discharge width scan

For the discharge width scan, the PDP measurements have been carried out from τ_{dis} = 1s to 29s. The plasma, during these discharges, was produced using the 2.45 GHz RF system. The RF power was kept fixed at 4.5 kW during all these discharges. A gas puff of 80 ms was applied only once before each discharge. It is found that Γ_{PDP} does not saturate completely even until 29 s. In the discharge width scans, the time to achieve the peak value of Γ_{PDP} increases with τ_{dis} (fig. 5(a)). Q_{PDP} also shows a linear dependence with τ_{dis} (fig. 5(b)). This suggests a successive increment in the particle retention in the plasma facing components during the longer discharges.



Figs. 6 (a) Q_{PDP} vs. P_{RF} (b) Q_{α} vs. P_{RF} (c) Q_{PDP} vs. Q_{α} (d) Q_{PDP} vs. n_{wall}

3.3.2 RF power scan

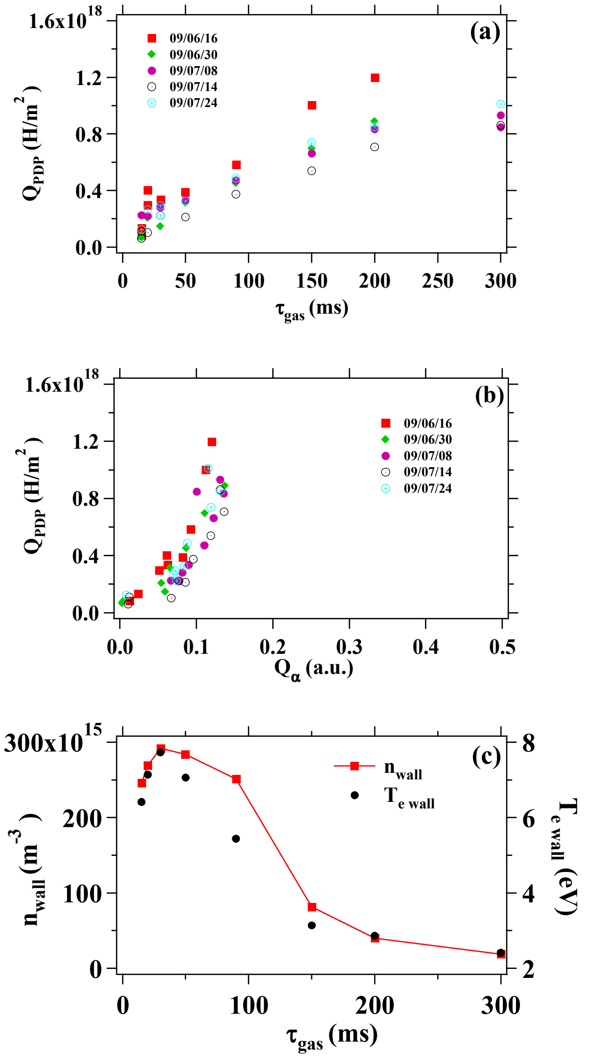
During the RF power scan, P_{RF} has been varied from 5 to 90 kW using the 8.2 GHz RF system. τ_{dis} is kept constant at 250 ms. The gas puff widths have been fixed at 20, 50, 100 ms for each set of power scan, which corresponds to the particle densities from 3×10^{17} to 1.5×10^{18} m^{-3} (H_2). It is observed that Q_{PDP} increases with P_{RF} (fig. 6(a)). Initially Q_{PDP} increases slowly with P_{RF}. However after P_{RF} = 50 kW, Q_{PDP} increases more rapidly. Here P_{RF}=50 kW seems to be some threshold value. The similar thresholds at P_{RF}=50 kW have also been observed in various spectral fluences like H_{α} (fig. 6(b)), H_2 (Fulcher α band), Lyman-α and edge plasma density n_{wall} measured by a Langmuir probe near the wall (not shown). Here Q_{PDP} shows an offset linear relationship with Q_{α}, n_{wall} (figs. 6(c) and 6(d)), H_2 (Fulcher band), and Lyman-α (not shown). The offset in linear relationship is due to the fact that even when the density of ions or excited atoms is comparatively low, Q_{PDP} is quite large. It strongly suggests that Q_{PDP} is mainly caused by a large number of sub eV neutral atoms. It is important that Q_{PDP} shows such correspondence with various spectral fluences as well as n_{wall} even though the PDP measurement is an offline measurement. Such phenomena make this method an important tool for measuring atomic hydrogen in the edge region.

3.3.3 Gas puff scan

Similarly during the gas puff scan, the P_{RF} was kept constant at 70 kW using 8.2 GHz RF system. τ_{dis} was fixed at 70ms. The gas puffs having fixed amplitudes, were applied in the range of τ_{gas} =15 to 300 ms before each plasma discharge. During the gas puff scan, the external pumping was stopped by closing the gate valve. Various data sets of τ_{gas} scan have been recorded keeping the similar operating conditions. The initial gas pressure P_{gas} just before the plasma production in the chamber was varied from ~1×10^{-3} to ~1×10^{-2} Pa during these scans. Γ_{PDP} increases with P_{gas}. Q_{PDP} is found linearly proportional to P_{gas} (or τ_{gas}) below a critical pressure after which Q_{PDP} tends to saturate (fig 7(a)). The saturation in Q_{PDP} is possibly due to the reduction of atomic flux caused by the low dissociation rate of molecules due to the low electron temperature. The linearity of Q_{PDP} with Q_{α} and other spectral fluences is relatively poor for the longer gas puffs (fig 7(b)). Q_{PDP} is found increasing more rapidly as compared to Q_{α} and other spectral fluence i.e. H_2 (Fulcher band) and Lyman-α. This may be due the reduction of H_{α} emission itself, however the low energy hydrogen atoms might be in enough numbers, causing the rise in Γ_{PDP}. It could be understood by the reduction of ion flux at the wall ($\propto n_{wall} \sqrt{(T_{e\ wall})}$ with increasing of τ_{gas} (fig 7(c)).

3.3.4 Effect of magnetic field on Q_{PDP}

In the magnetic field configuration scan, a variation of about ±13% in Q_{PDP} has been observed (fig. 8). In these scans, mainly the vertical magnetic field was varied using various poloidal magnetic field coils. Other operating parameters like P_{RF}, τ_{gas} and τ_{dis} were kept fixed. The variation of Q_{PDP} during the configuration scan is quite large as compared to the reproducibility level of ±3% observed in the discharges having the similar operating conditions. It may be due to the variations in the local plasma wall interaction (PWI) caused by the change in the magnetic field configuration. This suggests a high sensitivity of Q_{PDP} towards the local PWI.



Figs.7 (a) Q_{PDP} vs. τ_{gas} (b) Q_{PDP} vs. Q_α (c) n_{wall} vs. τ_{gas}

4. Conclusion

Hydrogen permeation flux Γ_{PDP} through the 30 μm thick Ni membrane heated at 523 K has been measured during more than 1200 plasma discharges in QUEST. The linear relationship with scattered data between Q_{PDP} and Q_α is found in all type of discharges, suggesting the fundamental proportionality of Q_{PDP} to the incident atomic fluence. Since reproducibility of Q_{PDP} is found about ±3 % in the discharges under the constant operational conditions (P_{RF}, τ_{dis}, τ_{gas} and magnetic configuration), the study of single parameter scan with keeping others constant is carefully carried out for the case exceeding this reproducibility as a reference. The following conclusion is achieved.

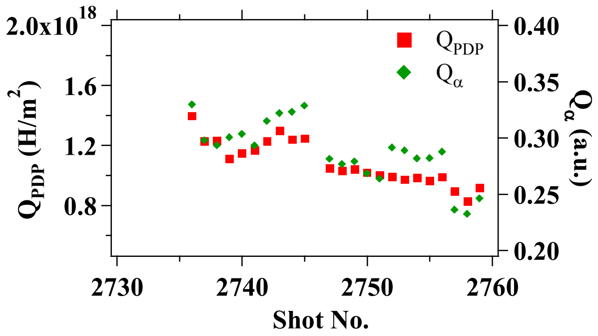


Fig.8 Variation in Q_{PDP} during vertical magnetic field scan.

First, Q_{PDP} increases with P_{RF} and the linearity factor is raised at 50 kW. Similar dependence of Q_α on P_{RF}, other spectral fluencies (Fulcher-α and Lyman-α), and the ion flux to the wall are observed, and then it is concluded that Q_{PDP} has a similar sensitivity with respect to the incident fluence normally measured by spectroscopic methods or ion flux. Secondly, Q_{PDP} shows a linear relationship with P_{gas} or initial total number of hydrogen particles. A lack of the linearity of Q_{PDP} with Q_α and other spectral fluences is found as a consequence of reduced T_e at higher P_{gas}, suggesting an advantage of PDP on the direct measurement of neutral atomic hydrogen. Thirdly, although Γ_{PDP} could not show a clear saturation until τ_{dis} = 29 s, at n_{wall} of several times of 10^{17} m^{-3}, Q_{PDP} increases linearly with τ_{dis} (>5s). The variation of ±13 % in Q_{PDP} is found in the magnetic configuration scan, which is much larger than ±3 % standard uncertainty. This also guarantees the higher sensitivity of Q_{PDP} on the local plasma wall interaction via variations in the neutral atoms.

[1]. T. Loarer, Journal of nuclear materials, **390-391**, 20 (2009).
[2]. J. Roth et al, Plasma Phys. Control Fusion, **50**, 103001 (2008).
[3]. T. Loarer et al, Nucl. Fusion, **47**, 1112 (2007).
[4]. H. Zushi et al, Nucl. Fusion, **49**, 055029 (2009)
[5]. R. A. Cauchy, Journal of nuclear materials, **300**, 91 (2002).
[6]. R. A. Kerst et al, Journal of nuclear materials, **122 & 123**, 1499 (1984).
[7]. J. Winter et al, Journal of nuclear materials, **111 & 112**, 243 (1982).
[8]. I. Takagi et al, Journal of nuclear materials,**258-263**, 1082 (1998).
[9]. T. Tanabe, Journal of nuclear materials, **103&104**, 483, (1981).
[10]. R. A. Causey et al, Journal of nuclear materials, **145 – 147**, 284 (1987).
[11]. I. Takagi et al, Fusion Technology, **25**, 137 (1993).
[12]. W. T. Shmayda et al, Journal of nuclear materials, **145-147**, 201 (1987).