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GAS-FUELING STUDIES IN THE PD. TOKAMAK

By

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Gas-Fueling Studies in the PDX Tokamak

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Abstract

The characteristics of gas-fueling of high power discharges in the PDX tokamak have been investigated using gas-flow, neutral pressure, plasma density, and $H\alpha$ emission measurements. The efficiency of gas-fueling was measured for various plasma configurations by comparison of the measured gas-influx rates to the particle exhaust rates inferred from particle decay time measurements. We observe that the fueling efficiency decreases significantly with increasing plasma density as the ionization length for thermal neutrals becomes shorter than the width of the boundary plasma. Gas fueling rates required to maintain a given plasma density are considerably higher (by factors of 5-10) for diverted discharges compared to limiter discharges. This result is attributed to a lower effective recycling coefficient for diverted plasmas. We discuss the dependence of the particle balance on the following experimentally measured parameters: the particle containment time, system-pumping speed, and neutral pressure in the vicinity of the active pumps.

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I. Introduction

The primary means of fueling plasma in present generation tokamaks is via gas injection. To initiate a discharge in a tokamak, the vacuum vessel is usually filled to a gas pressure of the order of 10^{-4} Torr. In order to maintain or increase the plasma density during the course of the discharge period, additional gas injection is usually needed. The gas injection requirements (quantity and rate) will vary depending on the discharge configuration, plasma behavior and wall conditions. Gas injection systems on operating tokamaks have become increasingly sophisticated in recent years in order to program the gas input in response to measured plasma parameters and to monitor the gas-flow characteristics.¹⁻³ Additional methods of fueling tokamaks include neutral beam injection and pellet injection.⁴ Both methods become advantageous for tokamak-based reactor designs where the increased plasma size and density decrease the effectiveness of gas-fueling. However, gas-fueling will most likely remain as the simplest method for initiating the plasma and preparing a target plasma for auxiliary fueling and heating.

In this paper, we discuss measurements of hydrogen and deuterium gas fueling in the PDX tokamak. The gas-fueling efficiency and behavior of the plasma-edge neutral density were studied for several discharge configurations: (1) the standard "dee"-shaped and (2) 4-null divertor configurations; and circular configurations limited by a (3) rail limiter, and a (4) toroidal bumper limiter. In addition to gas-flow measurements, these studies made use of neutral pressure measurements using ionization gauges, plasma density measurements using microwave interferometry and plasma-edge probes, and $H\alpha$ emission measurements.

In Sect. II.A of the paper, we describe the experimental parameters of the studied discharges and the important physical characteristics of the

vacuum vessel internal hardware. In Sect. II.B a brief description of the measurement techniques and the methodology of extracting fueling efficiencies are given. In Sect. III, we present the experimental results and in the final Sect. (IV) we discuss our present understanding of the data.

II.A Plasma Configurations

The PDX tokamak is a versatile device that is capable of studying numerous plasma configurations. These studies investigate the gas-fueling characteristics of four different plasma configurations, all with a nominal 40 cm minor radius (see Fig. 1). A standard "dee"-shaped diverted plasma is formed at a major radius of 138 cm. By shifting the major radius to 144 cm a symmetric 4-null diverted plasma is formed. Conventional circular discharges can be formed at $R = 135\text{--}155$ cm using vertically-adjustable graphite rail limiters. By shifting the major radius inward (to 125 cm) the plasma is limited by a toroidal bumper limiter constructed of TiC coated graphite tiles on the vacuum vessel inner wall.

The studied discharges were ohmically-heated, D or H fueled, with plasma currents of 300 kA, and a range of (line-averaged) plasma densities from $(1\text{--}4) \times 10^{13} \text{ cm}^{-3}$. The reader is referred to the companion paper by Fonck, et al.⁵ on the previous general device papers⁶⁻⁸ for details on PDX plasma characteristics. An important parameter for gas-fueling studies is the net vacuum vessel pumping speed. The PDX vessel is pumped by four turbopumps with a net speed of 3.0 kiloliters/sec for H_2 as measured from the decay time for a pressure transient in the torus. Additional pumping is provided by titanium gettering from 1-10 sublimation sources in the divertor chambers. Typically 4-6 sources are used at an evaporation rate of 0.5 g/hr/source. The sources operate continuously during an experimental run so that thick Ti films are

deposited to minimize H_2 -gas loading effects. The H_2 pumping speed obtained per source is 30-40 kiloliters/sec at the thick-film limit. The measured pumping speeds for D_2 are smaller than the H_2 speeds by a factor of $1.65 \pm .05$ due to conductance restrictions between the plasma volume and divertor chambers. The pumping speeds show no decrease with molecular gas-inputs at quantities which are five-times larger than the largest gas-fills used in these studies.

II.B Measurement Techniques

Gas is injected into the PDX vacuum vessel at four locations on the vessel midplane using piezoelectrically-controlled injection valves. The injection valves are instrumented with two upstream capacitance diaphragm manometers (0-100 Torr, 0-1000 Torr) which measure the integrated gas flow through the valves. Differentiation of this signal yields the instantaneous gas flow. Neutral pressure measurements at various locations around the torus are made using ionization gauges. For these studies, data were obtained from a magnetically-shielded Bayard-Alpert type ionization gauge (P_1) located 15° below the vessel midplane at the toroidal position of the rail limiters, and from a similar gauge (P_2) located on the lower divertor chamber, 180° toroidally from gauge P_1 . Detailed specifications of the gas-flow and pressure measurement instrumentation are given in Ref. 2.

Plasma density measurements were obtained from an 2 mm microwave interferometer system which spanned the main plasma volume. The scrape-off plasma density was measured using an 8 mm interferometer which spanned the divertor throat. Additional information on the density characteristics of the scrape-off plasma was obtained from Langmuir⁹ and calorimeter probe¹⁰ measurements taken at the midplane. Finally, an eight-channel array of H_α/D_α

light emission monitors was used to look at the toroidal variation in edge-neutral flux.

Gas-fueling measurements were obtained by measuring the gas injection rate, Q , necessary to maintain a steady-state plasma density, $\langle n_e \rangle$, for a fixed plasma current, loop-voltage, and radial position. The fueling efficiency was obtained by comparing the measured steady-state gas injection rates to the particle outflux $N = \int \langle n_e \rangle dv / \tau_p^*$ obtained by extracting a time constant τ_p^* from the decay of the line average density following termination of the gas input. A simple model for the particle balance in the plasma is useful for quantifying the fueling measurements.¹¹ The plasma is maintained by ionization of neutral particles flowing into the discharge against the losses represented by the intrinsic particle confinement time, τ_p :

$$dN/dt = fQ_0 - N/\tau_p \quad (1)$$

where f , the fueling efficiency, is the fraction of the neutral influx, Q_0 , ionized. In steady-state $dN/dt = 0$ and just after the gas injection is terminated $dN/dt = -N/\tau_p^*$ where the decay-constant τ_p^* differs from the intrinsic τ_p because of recycling neutrals. Assuming that all particle flows except the gas injection are continuous, Eq. (1) can be used before and after gas feed termination to give

$$N/\tau_p^* = f(Q_0 - Q_0') \quad (2)$$

where Q_0' is the neutral influx after gas feed termination and represents recycling neutrals. The assumption that all flows are continuous yields

$$Q_o - Q_o' = Q \quad (3)$$

so that the fueling efficiency is:

$$f = N/\tau_p * Q. \quad (4)$$

III. Results

Figure 2 shows hydrogen fueling efficiency measurements for two diverted plasma configurations, the dee and 4-null, over a range in plasma density. At low densities, $\langle n_e \rangle \approx 1 \times 10^{13} \text{cm}^{-3}$, the fueling efficiency of the dee configuration is ≈ 0.5 and this value decreases to 0.1-0.15 at higher densities, $\langle n_e \rangle \approx 4 \times 10^{13} \text{cm}^{-3}$. The fueling efficiency for the 4-null configuration is greater by a factor of 1.3-1.4 over the density range investigated.

Fueling efficiencies have not been measured for limiter discharge configurations. In general, considerably less external gas input (by a factor of 5-10) is required to maintain a given plasma density in the presence of the increased recycling from the limiter. To illustrate the parametric trends of gas fueling with discharge configuration, gas species, and vessel pumping speed, the steady-state gas injection rate required to maintain a steady-state plasma density is plotted in Figure 3 for several cases. For comparison the H-fueling curve for the dee configuration from Fig. 2 is replotted in Fig. 3, and this configuration is seen to require the largest gas injection rate. The required gas injection rate for the dee configuration appears to be insensitive to the divertor pumping speed for molecular H_2 . Two data points

taken with a measured pumping speed of 12 kl/s fall along the more complete fueling curve which was obtained at a measured pumping speed of 200 kl/s. The deuterium fueling data in the dee configuration are similar to the hydrogen values at low density, but significantly less D_2 (by $\sim 40\%$) is required to maintain higher density plasmas. The fueling rate drops by an additional 30-40% for the 4-null configuration. The smallest gas injection rates are required for the circular discharge configuration limited by a rail limiter.

The fueling of the circular discharge configuration using the toroidal bumper limiter represents an intermediate case between the fueling of the rail-limited discharges and the diverted discharges. Figure 4a shows the change in steady-state flow and total gas fill required to maintain a constant plasma density, $\langle n_e \rangle = 2.5 \times 10^{13} \text{cm}^{-3}$, as a 40 cm radius discharge is moved inward from the rail limiter to the toroidal bumper limiter. The gas flow requirements increase by 60%. During the transition there is a striking change in the steady-state neutral pressure distribution measured external to the plasma volume. Fig. 4b shows that the pressure, P_2 , measured in the lower divertor chamber for the rail limiter configuration is below 10^{-7} Torr (the detection limit for the wide band detection circuits which are used in these gauges), and increases to 2×10^{-6} Torr as the plasma contacts the bumper limiter. No significant change is seen in the pressure, P_1 , measured just below the plasma midplane at the rail limiter position. The pressure remains high (2×10^{-5} Torr) indicating that significant local recyc'ing occurs at this position for both configurations.

The time behavior of the P_1 and P_2 signals during a discharge sequence are shown for the two limiter configurations in Fig. 5. Both pressure signals show similar behavior for the prefill for initiation of the discharge (-0.03s to $+0.03\text{s}$) and for the outgassing behavior after termination of the discharge

(> 0.8s). The pressure obtained during the discharge depends on the local neutral flux in the vicinity of the gauge. During a rail-limited discharge because of the small required gas input and localized recycling at the limiter, insignificant pressure signals are seen in the divertor chamber. As the recycling delocalizes in the transition to the toroidally-limited configuration, a larger gas input is needed and a significant fraction flows to the divertor chambers contributing to the observed pressure rise.

When the divertor coils are energized, a directed flow of plasma particles into the divertor chamber causes a significant rise in the P_2 signal. Figure 6 shows the dependence of P_2 for the dee configuration over the same range in density investigated for the fueling curves. Pressures greater than 10^{-4} Torr are measured for densities $\langle n_e \rangle > 4 \times 10^{13} \text{cm}^{-3}$. Although, the interaction of neutral beam injection with gas-fueling is out of the scope of this paper, an interesting result relating to Fig. 6 is relevant. With high power neutral beam injection the average densities of the dee configuration could be doubled. At a density $\langle n_e \rangle = 8 \times 10^{13} \text{cm}^{-3}$, gas flows as high as 500 Torr liters/sec contributed to steady-state pressure levels in the divertor chambers greater than 10^{-3} Torr.⁵ Table 1 summarizes the gas-flow and pressure data for the four different discharge configurations.

Measurements of the variation of $H\alpha/D\alpha$ radiation with discharge configuration are consistent with the gas input and edge-neutral pressure measurements. Fig. 7 shows the toroidal variation in $H\alpha/D\alpha$ intensity as measured at the plasma midplane for the four different plasma configurations under study. The $H\alpha$ intensity is proportional to the flux of H_0 through the detector line-of-sight, and thus is expected to be high in regions where the recycling is high and at the gas injection ports. Consistent with the

pressure measurements, the $H\alpha$ intensity peaks at the rail limiter, and this variation delocalizes in the transition to the bumper limiter. The $D\alpha$ measurements in the diverted configurations show significant peaks at the gas injection ports due to the larger injection rates. The ratio of intensities for the dee and 4-null configurations at positions removed from the gas injection ports are consistent with the difference in fueling curves for the two configurations. The variation of the toroidally-averaged $H\alpha/D\alpha$ intensity with plasma density is shown in Fig. 8.

IV. Discussion

A detailed understanding of the gas fueling process for the plasma configurations studied is not possible with this limited set of presented data, considering the complicated atomic physics and particle surface interactions which affect the process. However, considering the composite of gas-flow, pressure, and $H\alpha$ measurements, with measurements of the edge-plasma conditions,⁹⁻¹⁰ a number of conclusions can be drawn concerning the variation of fueling efficiency and recycling behavior for the different configurations.

We consider, first, the fueling efficiency curve shown in Fig. 2. The gas fueling efficiency at very low densities, $\int \langle n_e \rangle dl \approx 1 \times 10^{15} \text{cm}^{-2}$, is high for both diverted configurations, because the edge-plasma is relatively transparent to incident neutrals. The line-integral density of the edge-plasma is measured to be less than 10^{13}cm^{-2} under these conditions,⁶ and is, thus, insufficient for complete ionization of incident neutrals.¹² At higher main-body plasma densities, the edge-plasma density and ionization efficiency rise rapidly. If an incident neutral is ionized within the edge-plasma, the ion has a much higher probability of being transported to the divertor plate and removed from the discharge, thus lowering the fueling efficiency. The

higher fueling efficiency observed for the 4-null in comparison to the dee configuration is consistent with the measured characteristic lengths of the edge-plasma. Magnetic flux contours of the dee configuration exhibit a double separatrix,⁷ and Langmuir probe measurements⁹ show that the line-integral density of the edge-plasma is $4 \times 10^{13} \text{cm}^{-2}$ when the central plasma line-integral density is $\approx 2.5 \times 10^{15} \text{cm}^{-2}$. For the 4-null, a single separatrix is evident and the line-integral density of the edge-plasma is considerably shorter, $\approx 4 \times 10^{12} \text{cm}^{-2}$.

The greater fueling efficiency of the 4-null in comparison to the dee configuration can also be understood in terms of the observed changes in recycling behavior. The measured $H\alpha$ intensity (plotted in Figs. 7 and 8) is proportional to a flux of atomic hydrogen, $F_{H\alpha}$. In the simplest approximation, this flux can be related to the external gas injection rate Q via a globally-averaged neutral recycling coefficient, R :

$$F_{H\alpha} = Q/(1 - R) \quad (5)$$

Thus, $R = 1 - Q/F_{H\alpha}$. (6)

The recycling coefficient also relates the measured density decay-time in the fueling experiments, τ_p^* , to the intrinsic τ_p via

$$\tau_p^* = \tau_p/(1 - R) \quad (7)$$

Comparison of the $H\alpha$ intensities (from Fig. 8) with the Q values for the two diverted configurations (Fig. 2) shows that $F_{H\alpha}$ decreases by a smaller

fraction (0.2-0.3), than Q (0.7-0.8). Thus, from Eq. 6, there is less recycling in the 4-null configuration, and from Eqs. 7 and 4, the fueling efficiency f should be higher. For the diverted configurations, the predominant recycling is expected as back-flow of particles through the divertor throats and open ducts separating the divertor chambers from the main plasma chamber, since P_2 pressures are high. The above argument for the smaller recycling coefficient of the 4-null configuration can be understood physically as the result of blocking of the outer divertor throat with plasma and reducing the back-flow conductance.

For the limiter configurations, the predominant recycling occurs on the limiter surfaces (as shown by the H_g and P_1 intensities). Since the limiters are located within the main plasma volume, recycling is much more effective for fueling the plasma, and the considerably smaller gas injection rates for limited in comparison to diverted discharges can be understood simply in terms of the differing geometry for the recycling surfaces.

Finally, we consider the observed variations in fueling behavior with torus pumping speed. The insensitivity of the H -fueling curve with molecular pumping speed may indicate that the relevant pumping speed for this measurement is the speed for non-thermal atomic or molecular particles. The latter pumping speed may be far less sensitive to the surface conditions of a sublimated titanium film than the pumping speed for thermal hydrogen molecules. This interesting effect warrants further investigation. In particular, fueling measurements should be obtained at densities higher than the two indicated data points at low pumping speed, to investigate possible saturation effects.

In summary, gas fueling shows high efficiency only at low plasma densities, $\langle n_e \rangle \lesssim 10^{13} \text{ cm}^{-3}$, where the edge-plasma is transparent to incident

thermal neutrals. Gas fueling efficiency varies with discharge configuration, dependent on the edge-plasma line-integral density and the contribution of recycling. The increase in required gas flow as the discharge configuration is varied from rail limiter to bumper limiter to poloidal divertor is evidence for the change in recycling behavior for these different configurations.

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Figure Captions

- Fig. 1 Plasma configurations of the PDX device that were investigated in this study: (a) rail limiter, (b) toroidal bumper limiter, (c) dee-shaped, and (d) 4-null.
- Fig. 2 Gas-fueling efficiency curves: steady-state gas flow rate required to maintain a constant plasma density compared with the plasma particle decay rate N/τ_p^* , where $N = \int \langle n_e \rangle dv$ for the dee and 4-null divertor configurations.
- Fig. 3 Gas-fueling curves: steady-state gas flow required to maintain a constant plasma density for various discharge configurations. The H-fueling data for the dee configuration are measured at two different values of the vessel pumping speed for molecular H_2 , 200 kℓ/s (□) and 12 kℓ/s (x).
- Fig. 4 (a) Change in steady-state gas flow and total gas fill required to maintain a plasma density of $\langle n_e \rangle = 2.5 \times 10^{13} \text{ cm}^{-3}$, as a 40 cm minor radius discharge is moved inward from the rail limiter (at $R_0 = 144$ cm) to the toroidal bumper limiter ($R_0 = 125$ cm). (b) Corresponding changes in the torus neutral pressure as measured with a midplane ion gauge at the rail limiter position (P_1), and a similar gauge located in the divertor chamber (P_2).
- Fig. 5 Time variation of the P_1 and P_2 torus pressure measurements during a circular discharge sequence. The dotted P_2 curve shows the behavior

during a rail-limited discharge. The solid curve shows the P_2 behavior with the toroidal bumper limiter. The behavior of P_1 is essentially the same for both cases. The plasma density behavior is shown in units of 10^{13}cm^{-3} .

Fig. 6 Variation of the divertor chamber pressure, P_2 , with plasma density.

Fig. 7 Toroidal variation of the intensity of $H\alpha/D\alpha$ radiation measured at the vessel midplane for various discharge configurations.

Fig. 8 Variation of the toroidally-averaged intensity of $H\alpha/D\alpha$ radiation with plasma density for various discharge configurations.

Table 1

Plasma Configuration	Total Gas Fill (Torr-liters)	Gas Flow ($\bar{Q}$) [(Torr-liters (sec))]	Pressure P_1 limiter (Torr)	Pressure P_1 divertor chamber (Torr)
circular	5-7	10-12	$(1-2) \times 10^{-5}$	$< 10^{-7}$
bumper limiter	8-10	18-20	$(1-2) \times 10^{-5}$	$2 \cdot 10^{-6}$
dee	39-41	45-50	—	$(0.8-1) \times 10^{-4}$
4-null	35-35	35-40	—	$(0.4-0.6) \times 10^{-4}$

Comparison of gas-flow and torus pressure measurements for various discharge configurations. The average gas flow rates ($\bar{Q}$) and pressures are listed for steady-state values for plasma discharges with line-integral densities $\langle n_e \cdot dl \rangle \approx 2.0 \cdot 10^{15} \text{ cm}^{-2}$.

Fig. 1

Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5

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Fig. 6

Fig. 7

Fig. 8