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Observations of macroscopic oscillations of the detachment front for injection of H_2, He, and Ne into the simulated baffled divertor

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Abstract

Oscillations of the position of the detachment front have been observed in a linear machine with a simulated baffled divertor with a He plasma for various species of injection gas, i.e., helium, neon, and hydrogen. The oscillation, with a back-and-forth motion, of the detachment front along field lines, accompanies a significant oscillation of the neutral gas pressure in the divertor region. This is due to the fact that plasma plugging depends on the position of the detachment front. The amplitude and period of the oscillation of the gas pressure are largest for neon and smallest for hydrogen, which can be closely related to the plasma pressure at the entrance of the divertor region for the particular gas species.

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1. Introduction

One attractive way to mitigate the heat load focused on the divertor plate in magnetic fusion devices is to dissipate the heat energy on neutral particles using the so-called ‘gas-target divertor’ method [1]. The plasma-gas interaction enhances plasma momentum loss along the field lines, and finally results in plasma detachment from the divertor plate. A number of studies on linear plasma devices concerning plasma detachment have been performed [2–5]. There is a potential issue that the gas-target divertor method may have negative effects on the high-confinement modes (H-modes) of core tokamak plasmas. Neutral particles leaking from the gas-target region (or divertor region) into the main chamber weaken the radial pressure gradient at the edge of the core plasma [6]. Reduction of the neutral leakage is an important subject for simultaneously achieving both plasma detachment and H-modes. In order to reduce neutral leakage, baffle plates have been located between the divertor plate and the main chamber [7]. In this configuration, denoted herein as a baffled/closed divertor, the neutral leakage through the opening of the baffle is reduced by friction due to ion-neutral collisions. The friction effectively decreases the gas conductance of the opening, which is the so-called ‘plasma plugging’ effect [2,3]. This effect depends on the upstream plasma pressure at the opening of the baffle. Therefore, the position of the detachment front, z_f, is critical to the plugging, since if z_f is outside the divertor region, the plasma

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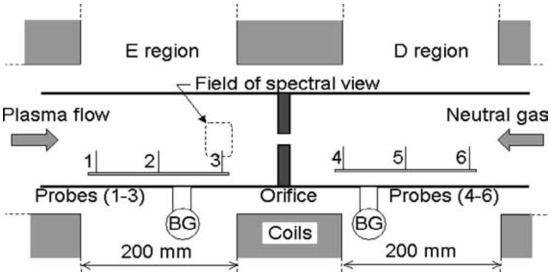

Fig. 1. Schematic diagram of the experimental region and divertor region of the linear machine TPD-II. The plasma is formed to the left of the edge plasma region (labeled 'E') and flows through the baffle orifice to the divertor region (labeled 'D').

pressure at the inlet is lost and along with the friction holding the neutrals back. However, so-called *x*-point MARFEs make the control of the detachment front more difficult [8].

The stability of the detached plasma was experimentally investigated in a linear machine with a baffle [9]. The baffle plate partitioned the experimental space into two regions: a low-neutral-pressure region and a high-neutral-pressure region, labeled the edge plasma (E) and divertor (D) regions, respectively in Fig. 1. It was observed that when helium gas was injected into the D region, z_f oscillated between the D and E regions (typically, the extent of movement was ~0.5 m, and the period was ~8 s). The back-and-forth motion of z_f was accompanied by a significant oscillation of neutral gas pressures in the E and D regions. In addition to helium gas as ash, gases of other species, for example, hydrogen as a recycling gas and neon as a cooling gas, would also be contained in the divertor region in fusion devices. Thus, the effect of the gas species on the z_f-oscillation is of great interest. In this article, we report z_f-oscillations for different species of gas, namely, helium, neon, and hydrogen. The amplitude and period of the oscillation of the gas pressure were largest for neon and smallest for hydrogen. The effect of gas species on the oscillation is discussed herein.

2. Experimental apparatus and setup

Fig. 1 shows the main experimental part of the linear machine TPD-II (Test Plasma by Direct current) at the National Institute for Fusion Science [9–11]. A helium plasma is continuously generated by a dc discharge between the LaB_6 cathode and the anode in the plasma source region located on the left hand (E region of Fig. 1) side 1.2 m from the orifice. The He plasma enters the E region first and then the D region. The orifice (15 mm in length and 15 mm in diameter somewhat larger than the plasma diameter) between the D and E regions is the equivalent of divertor opening in magnetic confinement devices. All the results presented in this paper were obtained for the axial magnetic field of 0.2 T and the discharge current of 95 A. The electron plasma density was $10^{19}\,m^{-3}$ and the electron temperature was 6 eV, which was obtained by a Langmuir probe located in the E region at 0.2 m from the orifice under the condition without gas injection into the D region.

One of several neutral gases, helium, neon, or hydrogen was injected to cause plasma detachment 1.4 m from the orifice into the D region. The neutral gas flows against the He plasma through the orifice, and is pumped at the E region (the effective pumping speed was $0.3\,m^3\,s^{-1}$ for helium gas). The neutral gas pressures at the D and E regions, P_D and P_E were measured using baratron gauges (BGs) located in the corresponding regions. In the E and D regions, 6 probes for monitoring ion saturation current were placed as shown in Fig. 1. In order to reduce the influence of the probes on the oscillation, the probes were located at radial distances of 15 ± 2 mm and 10 ± 2 mm in the E and D regions, respectively.

3. Experimental results and discussion

Fig. 2 shows the appearance of the oscillation for each gas. When the gas rate, Q_D is increased as shown in frame (iii), P_D and P_E monotonically increase before their oscillations. The ion saturation current I_4 of the probe 4 in the D region simultaneously decreases, reflecting the detachment front and thus the value of z_f moving toward the E region. The value of P_D is saturated at $t \sim 350$ s for helium injection ($t \sim 410$ s for neon and $t \sim 400$ s for hydrogen). At the same time, the detachment front, z_f, appears to reach the position of the orifice. We observe experimentally when the z_f enters the E region, and it starts to oscillate between the E and D regions. Simultaneously the values of P_D, P_E, $I_{1,4}$ and spectral intensities oscillate. Oscillations are stopped for a sufficiently higher value of Q_D, since z_f remains in the E region; this appears for hydrogen and helium, but does not appear for neon in the present range of Q_D. The amplitudes of oscillations are largest for neon and smallest for hydrogen.

More details of these oscillations can be seen in Fig. 3, which shows an enlarged part of the beginning of the oscillation depicted in Fig. 2. As can be seen from Fig. 3(ii), there are two parts in each cycle of P_D-oscillations for all gases: the slow rise and the rapid fall. The first part begins after z_f suddenly changes to the D region. The movement of z_f into the D region appears as the rise in I_4 shown in frame (iv). The increase in P_D is a transient; we postulate that P_D increases toward the saturation value, P_{DS} given by $P_{DS} = P_E + Q_D/C_{eff}$, where C_{eff}

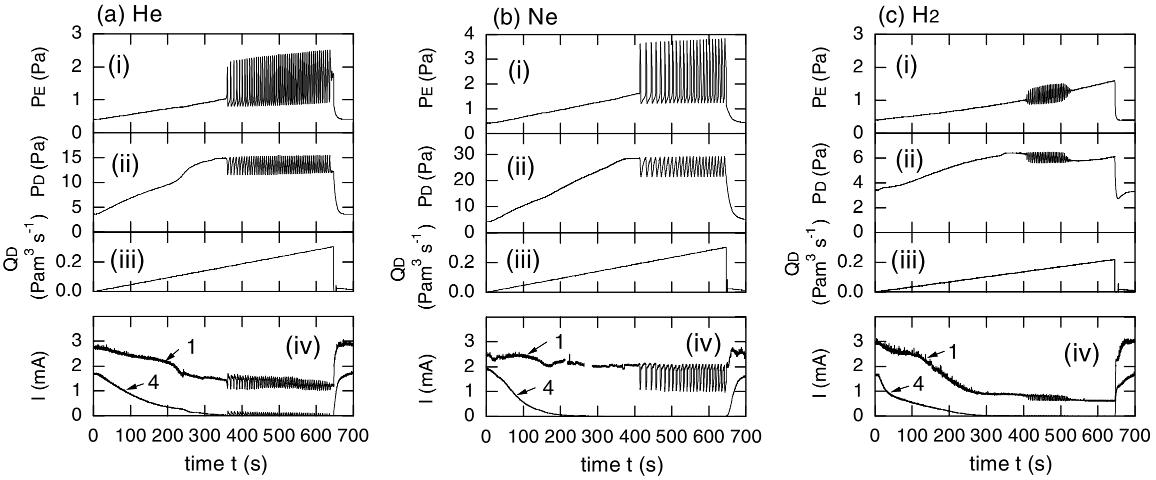

Fig. 2. Long time-series showing oscillations of gas pressures and ion saturation currents accompanied by z_f-oscillation for helium (a), neon (b), and hydrogen (c).

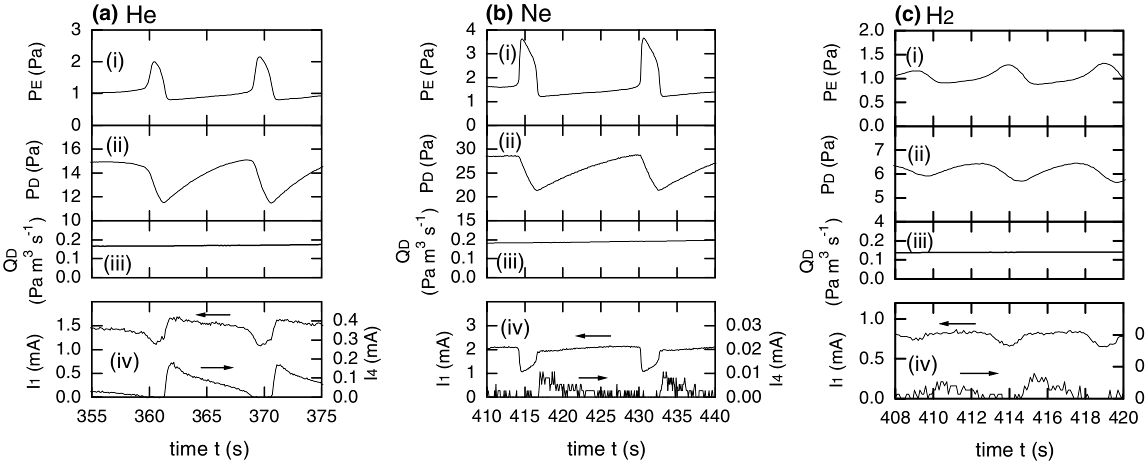

Fig. 3. Enlarged part of Fig. 2, showing details of the beginning of oscillation for helium (a), neon (b), and hydrogen (c).

is the effective orifice-conductance decreased by the plasma flow coming into the D region at the beginning of the first part of the oscillation. If the transient waveform is described simply as $P_D = P_{DS} - (P_{DS} - P_{D0})\exp\{-(t - t_0)/\tau\}$ (where P_{D0} is the initial pressure for $t = t_0$), the mean time-constant τ is given by $\tau = V_D/C_{eff}$, where V_D (=0.084 m^3) is the volume of the D region. The inferred values of C_{eff} for helium, neon, and hydrogen using corresponding τ values drawn from each waveform are 0.017 m^{3}s^{-1}, 0.0068 m^{3}s^{-1}, and 0.038 m^{3}s^{-1}, respectively. The second part of the oscillation begins after z_f enters the E region. The entrance of z_f into the E region can be seen from the sudden reduction of I_1. In this part, P_E experiences a sudden increase and decrease, and P_D decreases rapidly. This clearly shows that the neutral gas accumulated in the D region flows into the E region, which is due to the enhancement of C_{eff}, i.e., the disappearance of plasma plugging when z_f changes to the E region. The difference of durations between the various gas species during this part of the oscillation cycle is much smaller than that of the first part of the cycle, suggesting that durations of the second part of the oscillation are influenced strongly by vacuum conductance.

We should mention that the period of the oscillation decreases as Q_D is increased (see Fig. 2). Because C_{eff} does not significantly vary with Q_D (except the transition between first and second parts of the oscillation cycle), large Q_D leads to a large value of P_{DS} as described above. According to the equation describing transient, the increase in P_D becomes faster for the large P_{DS}. As can be seen in Fig. 2, however, P_D saturates for large quantities of Q_D. Thus, as Q_D is increased, the time required for P_D to saturate becomes shorter.

Fig. 4 shows the pressure difference $\Delta P(=P_D - P_E)$ as a function of Q_D for each gas. The reciprocal of the mean slope, $\langle \partial \Delta P / \partial Q_D \rangle$, (before the oscillation) corresponds to the effective gas conductance of the orifice C_{eff}. Values of C_{eff} drawn from the slope for helium, neon, and hydrogen are $0.014\,m^3\,s^{-1}$, $0.0074\,m^3\,s^{-1}$, and $0.045\,m^3\,s^{-1}$, respectively; these values are comparable to those obtained from time constants as mentioned above, ensuring that the period of the oscillation depends on C_{eff}.

One important characteristic in ΔP behavior is the upper limit, ΔP_{max}, during its oscillation. Whenever ΔP reaches ΔP_{max}, z_f is on the verge of changing to the E region, as mentioned in the explanation for Fig. 3. This leads us to consider that ΔP_{max} can balance the plasma pressure on the inlet of orifice, P_P: $\Delta P_{max} \approx P_P$ which seems to be similar to that mentioned in Refs. [1,2]. Actually, ΔP_{max} is consistent, within an order of magnitude, with P_P estimated roughly using the values of n_e and T_e mentioned in the Section 2. When ΔP takes its lower limit during the oscillations, z_f is in the E region and P_P causing the plasma plugging effect is lost. Therefore, P_P dominates the amplitude of the ΔP-oscillation.

On the other hand, the value of Q_D that corresponds to ΔP_{max} at its plateau (indicated by the arrow in Fig. 4), which is given by $C_{eff}\Delta P_{max}$, lies in the range of 0.12–$0.18\,Pa\,m^3\,s^{-1}$ for all gas species. The change in $C_{eff}\Delta P_{max}$ for gas species is much smaller than the changes in C_{eff} and ΔP_{max}. This requires that C_{eff} is approximately inversely proportional to P_P, because ΔP_{max} is proportional to P_P. That inverse relationship is reasonable, since C_{eff} is approximately proportional to the reciprocal of the friction force caused by collisions between ions and neutrals [11], and since the friction force is fairly proportional to P_P. Therefore, the changes in C_{eff} and ΔP_{max} for gas species can be mainly attributed to the change in P_P for the gas species.

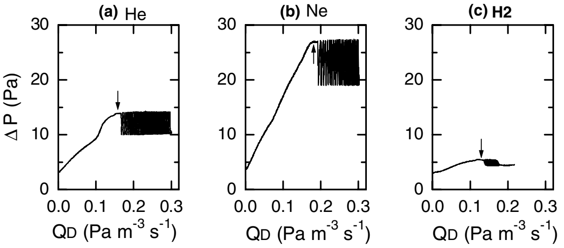

Fig. 4. Dependence of the neutral pressure difference between pressures in D and E regions on the flow rate of neutral gas injection for helium (a), neon (b), and hydrogen (c).

As can be seen in Fig. 2(iv), the reduction of the ion saturation current I_1 is most significant for hydrogen before the appearance of the oscillation. This suggests that the decay length of the plasma pressure along the magnetic field in the E region is shortest for hydrogen. The decay length, λ_z, is given by the axial and radial diffusion coefficients (D_z, D_r), and recombination and ionization frequencies (ν_R, ν_i): $\lambda_z = \{D_z/(\nu_R - \nu_i + D_r\lambda_r^2)\}^{0.5}$ [2,3], where λ_r is the characteristic radial size of the plasma. At this time, there is no sufficient data with which to discuss diffusion, so we will only mention effects of ν_R and ν_i on λ_z. Concerning ν_R three-body and radiative recombinations are not dominant in the E region until the oscillation occurs, because the spectra around 360 nm of highly excited states of He I are not observed from the E region in this period. On the other hand, the relationship for ionization of $\nu_i^H \gg \nu_i^{Ne} \gg \nu_i^{He}$ for a few electron volts in T_e is consistent with the modest reduction of P_P for neon. However, it is not consistent with the significant reduction of P_P for hydrogen; this may require additional plasma loss for hydrogen. It has been reported that molecular activated recombination (MAR) occurs before significant three-body recombination [4,12,13]. In fact, when I_1 significantly decreases during injection of hydrogen, remarkable amounts of Fulcher molecular bands around 600 nm required for the MAR are observed from the E region. Therefore, MAR is proposed to be a candidate to explain the significant loss of P_P for hydrogen.

4. Conclusion

Oscillations of the position of the detachment front, z_f, have been observed using a linear machine simulating a baffled divertor for different species of injection gas, namely, helium, neon, and hydrogen. As the flow rate of the gas injection is increased, the neutral pressure difference, ΔP, between D and E regions reaches its maximum, ΔP_{max}; then z_f and ΔP begin to oscillate. The essential properties of the oscillations, such as the z_f-dependency on plasma plugging, are common to all gas species. The amplitude and the period of the oscillations are largest for neon and smallest for hydrogen.

We showed that the period of the oscillation is determined by the effective conductance of the orifice, C_{eff}. while the amplitude of the ΔP-oscillation is dominated by ΔP_{max}. It was found that the value of $1/C_{eff}$ and ΔP_{max} are largest for neon and smallest for hydrogen. In addition, the weak dependence of $C_{eff}\Delta P_{max}$ on gas species can be interpreted by considering that $1/C_{eff}$ and ΔP_{max} are approximately proportional to the plasma pressure on the orifice, P_P. Thus, the period and amplitude can be mostly dependent on the P_P for the particular gas species. It was suggested that a modest reduction of P_P for neon can be sustained by ionization, and the significant reduction of P_P for hydrogen may be due to the MAR.

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