Charge Exchange Momentum Transfer due to Ion Beam Injection in Partially Ionized Plasmas

Atsushi OKAMOTO, Hiroyuki TAKAHASHI, Sumio KITAJIMA and Mamiko SASAO

Department of Quantum Science and Energy Engineering, Tohoku University, Sendai, Miyagi 980-8579, Japan

(Received 7 November 2011 / Accepted 16 November 2011)

Time responses of a helium plasma to helium gas puffing without and with helium beam injection in a linear plasma device are experimentally investigated. Increase in the neutral density due to gas puffing is suppressed by ion beam injection. The experimental results show that a momentum transport from the ion beam to the puffed neutral particles occurs due to the charge exchange interaction, suggesting that charge exchange momentum transport is one of the processes responsible for the spatial redistribution of neutral atoms in partially ionized plasmas.

Keywords: charge exchange interaction, momentum transfer, gas puff, ion beam, partially ionized plasma

DOI: 10.1585/pfr.6.1201153

In some cases, interactions between ions and neutral particles play important roles in weakly ionized plasmas such as the ionosphere [1], magnetically confined plasmas [2], and laboratory plasmas [3–5]. In particular, the charge exchange interaction becomes dominant in plasma dynamics [6]. In the divertor region of magnetically confined fusion devices, a high-energy ion flux is one of the external perturbations that degrades the detached plasma. Therefore, the balance of the atomic processes required for the plasma detachment might change because of the spatial redistribution of neutral atoms.

To evaluate the effect of the high-energy ion flux, we began an experimental study in a linear device [7] in which suprathermal (1–10 keV) ions were injected into a radio frequency (RF) plasma. In this paper, the time response of the neutral density in an additional gas-puffed plasma is described; a helium ion beam is found to degrades the effects of gas puffing.

The experiments were performed in an RF plasma source, the DT-ALPHA device [8] at Tohoku University. Schematic representation of this device is shown in Fig. 1. The vacuum chamber consists of an ion source [9], a differential pumping chamber, a quartz pipe coupling an antenna to a plasma, and a main chamber. The inner diameter of the aperture at the entrance to the quartz pipe is 10 mm. The plasma parameters are measured at the upstream port (0.4 m from the antenna) by using a double probe. At the downstream port (1 m from the antenna), an additional gas puffing system is installed; a single probe and emission collection optics are also installed there. The line emission intensity of the helium atom at 492.2 nm ($2^1P - 4^1D$) is measured using the collection optics to estimate the neutral density. The duration of gas puffing, as estimated from the line emission, is about 10 ms.

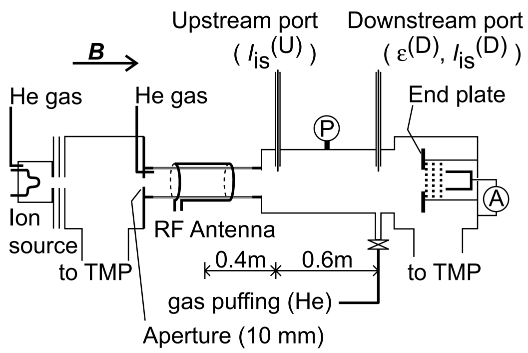

Fig. 1 Schematic representation of the DT-ALPHA device.

To exclude complex molecular processes, helium was selected as the working gas for plasma production, ion beam production, and additional gas puffing. The working pressure measured at the middle port (0.7 m from the antenna) was 0.5 Pa. The axial magnetic field intensity was about 0.1 T around the RF antenna and about 0.16 T at the downstream port. The RF power of $P_{RF} = 40$ W was used for plasma production. The typical electron temperature and density at the upstream port were $T_e = 20$ eV and $n_e = 5 \times 10^{16}$ m^{-3}, respectively. The energy of a helium ion beam in these experiments was 10 keV. The beam particle flux at the endplate, measured using an embedded Faraday cup [10], was 6×10^{16} m^{-2}s^{-1}, which is equivalent to a beam current of 0.01 A/m^2.

Helium gas was puffed in a steady-state helium plasma with and without the helium beam; time traces of a typical discharge are shown in Fig. 2 (a)-(c). As the pressure began to rise ($t \geq 0.03$ s), ion saturation currents $I_{is}^{(U)}$ and $I_{is}^{(D)}$ increased. Then, the values of $I_{is}^{(U)}$ and $I_{is}^{(D)}$ were higher than those before gas puffing. Rapid increase in the emission intensity $\varepsilon^{(D)}$ was observed at $t \simeq 0.03$ s.

author's e-mail: atsushi.okamoto@qse.tohoku.ac.jp

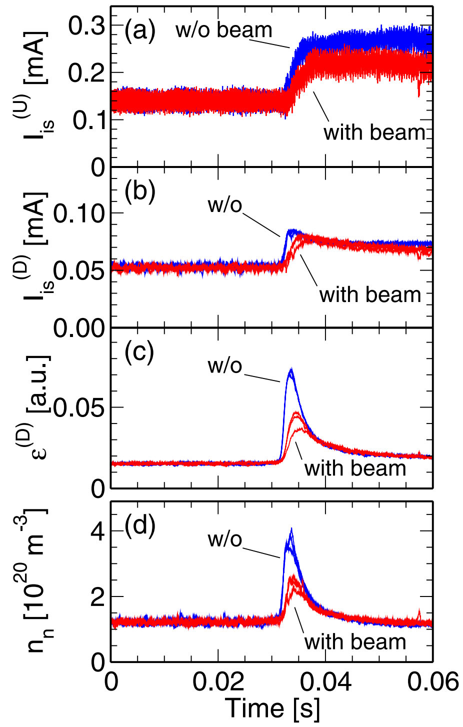

Fig. 2 Time responses of a helium plasma to helium gas puffing without and with helium beam injection. Vertical axes represent (a) ion saturation current at the upstream port $I_{is}{}^{(U)}$, (b) ion saturation current at the downstream port $I_{is}{}^{(D)}$, (c) line emission intensity at the downstream port $\varepsilon^{(D)}$, and (d) deduced neutral density $n_n \sim \varepsilon^{(D)}/I_{is}{}^{(D)}$. Three traces for each condition illustrate the reproducibility between discharges.

After the rapid increase, $\varepsilon^{(D)}$ settled down in another steady state at a higher level than that before gas puffing.

Differences appear between the time responses with and without steady-state beam injection. At the upstream port, the saturation level of $I_{is}{}^{(U)}$ decreased in the beam injection case. At the downstream port, the differences appeared in a short time-range of $t = 0.03 - 0.04$ s. The peak values of $I_{is}{}^{(U)}$, $I_{is}{}^{(D)}$, and $\varepsilon^{(D)}$ were smaller with the beam than that without it, suggesting smaller variations in electron density n_e and neutral density n_n. The time evolution of the neutral density, shown in Fig. 2 (d), was deduced from the ratio of the emission intensity and the ion saturation current, $\varepsilon^{(D)}/I_{is}{}^{(D)}$. Assuming a constant electron temperature, the ratio is an index of the neutral density because $\varepsilon^{(D)}$ and $I_{is}{}^{(D)}$ are proportional to $n_n n_e$ and n_e, respectively. The deduced n_n value increases rapidly and then recovers at $t = 0.03 - 0.04$ s. The peak density is about three times higher than the steady-state value without the beam. On the other hand, with beam injection, the density is only twice the steady-state value. Increase in the neutral density due to gas puffing is suppressed by beam injection.

To evaluate the effect of the ion beam on the neutral density, the charge exchange momentum transfer from the beam ions to the neutral atoms, $\mathrm{He}^+_{\mathrm{beam}} + \mathrm{He}^0_{\mathrm{gas}} \rightarrow \mathrm{He}^0_{\mathrm{beam}} + \mathrm{He}^+_{\mathrm{gas}}$, is estimated. Because the velocity vector of the beam is directed downward ($\boldsymbol{v}_b = v_b \boldsymbol{e}_z$), the neutral atoms obtain an effective velocity in the same direction ($\boldsymbol{v} = (v_0 + v_{\mathrm{eff}})\boldsymbol{e}_z$). The original velocity $v_0 = S_0/A \simeq 30$ m/s was estimated from the downward pumping speed $S_0 \simeq 0.1$ m^3/s and the chamber cross-section $A \simeq 3 \times 10^{-3}$ m^2. The reaction frequency for a neutral particle is $n_b \sigma_{CX} v_b = 5 \times 10^{-3}$ s^{-1}, where the beam density, the charge exchange cross-section, and the beam velocity are $n_b = 1.2 \times 10^{11}$ m^{-3}, $\sigma_{CX} = 8 \times 10^{-20}$ m^2, and $v_b = 5 \times 10^5$ m/s, respectively. When the residence time of the neutral particle $\tau_r \simeq 0.03$ s is considered, effective velocity supplied to the neutral atoms is $v_{\mathrm{eff}} = v_b{}^2 \tau_r n_b \sigma_{CX} \simeq 80$ m/s, which is of the same order as the original velocity. The neutral density is represented by $n_n = C/(v_0 + v_{\mathrm{eff}})$, where C is the constant related to the total number of injected neutral particles. Therefore, the ion beam enhances the effective pumping speed, decreasing the neutral density. Because significant differences between the cases with and without the beam were not observed in the hydrogen puffing case, momentum transport appears to be more effective between the same species (He, He^+) than between different species (H_2, He^+).

In summary, we demonstrated that the momentum of an ion beam is transferred to puffed neutral particles via the charge exchange interaction. Increase in the electron density by gas puffing is suppressed as a result from the decreasing neutral density. Momentum transport from the ion flux to the neutral atoms and the spatial redistribution of the neutral atoms due to the injected momentum are considerable processes in partially ionized plasmas.

This work was partly supported by a Grant-in-Aid for Young Scientists (B) (22740357) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

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