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Resonance radiation and high excitation of neutrals in plasma–gas interactions

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Abstract

Experimental investigation of plasma–gas interaction has been performed in LENTA linear facility in order to model processes expected to occur in the divertor of a fusion tokamak reactor. Steady-state helium plasma with density $\sim(0.2–3) \times 10^{13}$ cm^{-3} generated by beam-plasma discharge flowed into the region with high neutral pressure, interacted with neutral helium there and then reached the target plate. An intensive volume recombination and significant decrease in plasma pressure have been observed while the plasma stream interacted with gas target. Electron temperature fell below 1 eV. These processes were accompanied by an intensive emission from highly excited helium atoms and this radiation became even higher with increase in neutral pressure. Microwave emission absorption at high ($P_{\text{gas}} =$ 20 mTorr) neutral pressures in the gas target was detected. A model of plasma–gas transition layer was developed to provide physics understanding of these phenomena. Resonance radiation and stimulated radiative recombination play an important role in this model.

Keywords: Divertor plasma; Divertor simulation; Gas target divertor; Recombination

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1. Introduction

Divertor physics understanding is one of the most acute problems in the development of the next generation fusion tokamak reactor. Within the gas divertor concept, regimes of full and partial detachment have been observed in all present day divertor machines and have also been modeled experimentally in linear plasma simulators [1,2] in which divertor processes are studied with a use of intrinsic benefits in diagnostics, geometry and interpretation which linear machines possess in comparison with large fusion devices.

An experimental investigation within the gas divertor concept has been performed in LENTA linear facility (Nuclear Fusion Institute RRC, Kurchatov Institute) [3]. Steady-state plasma flowed into the region with high neutral pressure, interacted with neutral gas there and then reached the target plate. We have obtained data on properties of plasma–gas transition layer and its specific features and conditions in which plasmas detach. Physics model describing the phenomena observed was developed.

2. Experimental

Schematic of LENTA experimental device and diagnostics applied is shown in Fig. 1. Steady-state plasmas ($T_e \sim 0.5–20$ eV, $N \sim 5 \times 10^{11}–5 \times 10^{13}$ cm^{-3}) are produced in LENTA due to beam-plasma discharge in longitudinal magnetic field 1.0–2.0 kG. An intensive electron beam (diameter $d = 1$ cm) located on the axis of cylindrical vacuum chamber (diameter $D = 16$ cm) generated plasma in the discharge zone (length $L_{\text{dis}} =$ 1.5 m), thus forming initial plasma column. This plasma

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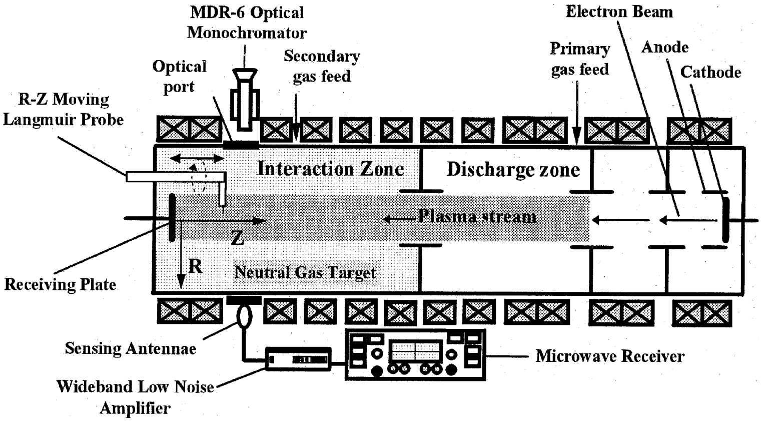

Fig. 1. Schematic of LENTA linear plasma simulator and diagnostics applied.

was free to flow from discharge zone to the gas target zone (length $L_{in} \sim 1$ m) where the receiving plate was installed as a divertor target plate imitator. Secondary neutral gas was fed to this zone thus forming gas target in front of the imitator plate. Neutral pressure in the gas target zone was varied in a range from 2 to 70 mTorr. Plasma parameters in the gas target were measured with Langmuir probe (Fig. 1) capable to move both along the axis and on a radius from $Z = 0$ and up to $Z = 65$ cm (Z is a distance from the receiving plate) along the axis and from $R = 0$ up to 9 cm on a radius. Spectroscopic measurements of plasma emission from gas target zone were performed with MDR-6 optical monochromator. Microwave measurements of radiation from gas target were carried out with microwave diagnostics shown in Fig. 1.

2.1. Plasma parameters investigations

Plasma density and electron temperature in the gas target zone have been measured with moving Langmuir probe as functions of its R and Z positions. Attention was paid to maintain constant initial parameters of incoming plasma stream.

Axial distributions of electron temperature T_e and plasma density N on neutral pressure in the gas target zone are shown in Figs. 2 and 3, respectively. These data have been taken at radial distances of 1.5 and 2 cm from the axis. With low neutral pressure $P_{gas} = 2$ mTorr in the gas target, only a weak axial variation of plasma parameters has been detected (curves 1 in Figs. 2 and 3). An additional helium feed into the gas target zone at $P_{gas} = 17$ mTorr caused an increase in plasma density away from the receiving plate at $Z = 50$ cm due to an additional ionization of dense neutral gas by plasma electrons away from the receiving plate. On the other hand, a simultaneous steep decrease in plasma density and electron temperature is clearly observed while ap-

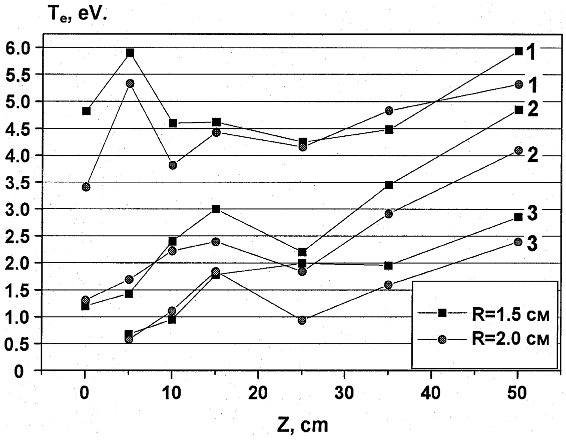

Fig. 2. Axial distributions of electron temperature at various pressures in the gas target: (1) $P_{gas} = 2$ mTorr; (2) $P_{gas} = 17$ mTorr; (3) $P_{gas} = 35$ mTorr.

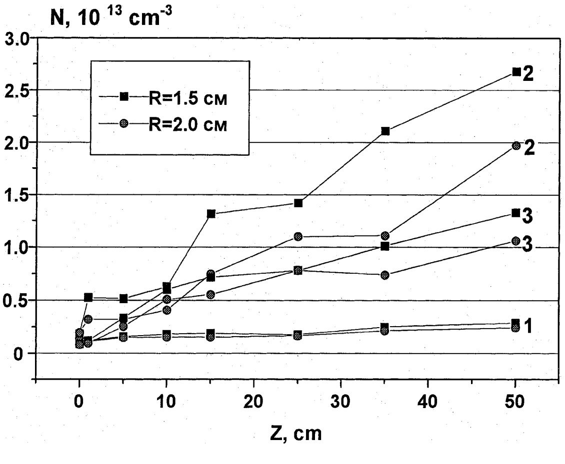

Fig. 3. Axial distributions of plasma density at various pressures in the gas target: (1) $P_{gas} = 2$ mTorr; (2) $P_{gas} = 17$ mTorr; (3) $P_{gas} = 35$ mTorr.

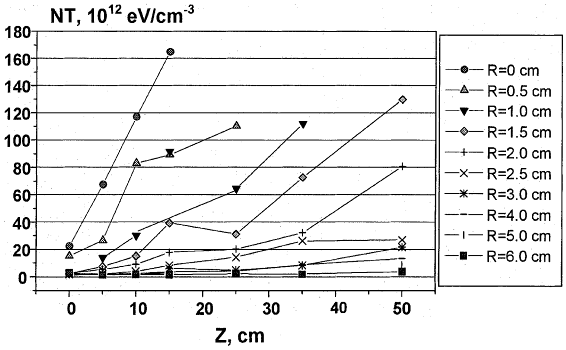

Fig. 4. Axial distributions of plasma pressure NT for various radial distances taken at neutral pressure $P_{gas} = 17$ mTorr in the gas target zone.

proaching the target plate. This may occur if volume recombination processes become important. A further decrease in electron temperature and a fall in plasma density at higher neutral pressure $P_{gas} = 35$ mTorr (curves 3 in Figs. 2 and 3) shows that recombination processes become more intensive at this pressure. The observations of plasma volume recombination at high neutral pressures become more distinctive if we take axial distributions of plasma pressure NT (Fig. 4) obtained at different radial distances for neutral helium pressure $P_{gas} = 17$ mTorr. Significant decrease in plasma pressure is observed (130-fold in maximum) while plasma was approaching the receiving plate. Plasma energy loss in volume recombination should be accompanied by the rise in radiation intensity from the plasma transition layer near the receiving plate. The next section is devoted to plasma radiation analysis.

2.2. Plasma radiation

Measurements of plasma emission from gas target zone in visual and near-ultraviolet range have been performed at $Z = 50$ cm as shown in Fig. 1. Spectral investigations have been carried out in conditions similar to those that were studied with a probe. Three typical spectra taken from the gas target zone are shown in Fig. 5. They correspond to different neutral pressures of secondary gas: (a) $P_{gas} = 5$ mTorr; (b) $P_{gas} = 20$ mTorr; and (c) $P_{gas} = 70$ mTorr, respectively. For $P_{gas} = 5$ mTorr, no peculiarities have been observed in the plasma emission (spectrum (a) in Fig. 5). Starting from $P_{gas} \sim 15$ mTorr, we observed the formation of a peculiar visible structure around plasma stream at a radial distance of $R \sim 3.0$–4.0 cm from the axis. Spectra have changed dramatically: the spectrum shown in Fig. 5(b) has been obtained at helium pressure of $P_{gas} = 20$ mTorr, where electron temperature at $R \sim 3.0$–4.0 cm according to our probe measurements was ~0.8–1.3 eV. Highly excited helium atoms with a principal quantum number n up to 17 have been detected in these conditions. The spectrum presented in Fig. 5(c) taken at helium pressure $P_{gas} = 70$ mTorr corresponds to electron temperature lower than 1 eV. Plasma radiates even more intensively at this high neutral pressure. Atoms in states with a principal quantum number n up to 20–22 have been detected in such a regime. We observed that radiation from highly excited atoms has a threshold in neutral helium pressure. Moreover, it becomes even more intensive while plasma electrons are getting colder with neutral density increase.

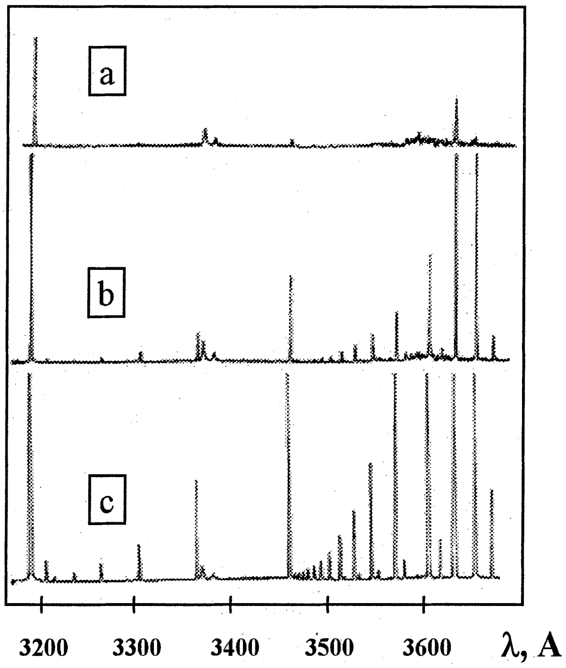

Fig. 5. Spectra of plasma radiation from gas target zone taken at $Z = 50$ cm from the receiving plate for various neutral pressures in the gas target: (a) $P_{gas} = 5$ mTorr; (b) $P_{gas} = 20$ mTorr; (c) $P_{gas} = 70$ mTorr.

The phenomena observed are interpreted below on the basis of resonance radiation occurred in the gas target which shifts the equilibrium of excited helium atoms population to high levels.

Measurements of microwave emission from the gas target have been performed in LENTA for the analysis of absorption properties of plasma–gas transition layer. Microwave diagnostic system (Fig. 1) comprised sensing antennae, wideband low noise amplifier and superheterodyne receiver. Plasma emission at frequencies from 2400 up to 3800 MHz has been measured. Four basic operating regimes have been reproduced with high ($W_{inj} = 2.55$ kW) and low ($W_{inj} = 450$ W) power injected to plasma and with high ($P_{gas} = 20$ mTorr) and low ($P_{gas} = 2$ mTorr) neutral pressures in the gas target. The

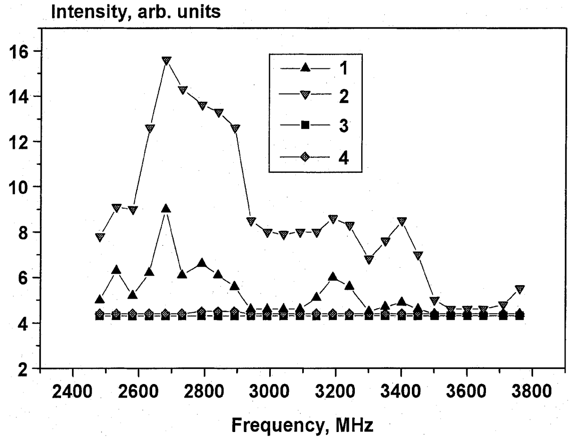

Fig. 6. Plasma microwave emission intensities at various powers injected to plasma W_{inj} and at various neutral pressures P_{gas} in the gas target: (1) $P_{gas} = 2$ mTorr; $W_{inj} = 450$ W; (2) $P_{gas} =$ 2 mTorr, $W_{inj} = 2.55$ kW; (3) $P_{gas} = 20$ mTorr, $W_{inj} = 450$ W; (4) $P_{gas} = 20$ mTorr, $W_{inj} = 2.55$ kW.

corresponding spectra are shown in Fig. 6. Microwave emission from the gas target zone has been detected in a regime with low pressure and low injected power (curve 1 in Fig. 6). This emission became more intensive with increase in power injected at the same neutral pressure in the gas target (curve 2 in Fig. 6). With secondary neutral helium feed, the situation has changed dramatically: the specific structure has been formed around plasma stream and we detected a complete absorption of 2.4–3.8 GHz emission by this structure with highly excited atoms. The emission at noise level only from the gas target was detected for both 450 W and 2.55 kW cases (curves 3 and 4 in Fig. 6).

2.3. Transition layer in plasma–gas system

The obtained data show that a great decrease in electron temperature is observed both along magnetic field and transversally as a result of plasma stream interaction with neutral gas. Highly excited atoms are generated in the region where T_e falls below 1 eV. No adequate interpretation can be found to high-rate generation of the excited atoms at the levels of excitation very close to ionization limit on the basis of usual assumptions and of coronal model. The nature of a fall in electron temperature (and probably with simultaneous drop in plasma density) that is characteristic of plasma 'detachment' phenomenon becomes comprehensive when plasma energy transformation is considered via radiation transport and plasma recombination plays a primary role in this process. Collisional-radiative models used by this time are evidently sensitive to the physics basis that determines the account of atomic processes involved [4] and their predictive capacity depends directly on it. The authors have already offered principal assumptions of a physics model for plasma–gas transition layer at steady-state condition where a system of electrons–ions–neutrals is considered with the account of resonance radiation and transport of excitation energy and electron energy [5–7]. Resonance radiation is generated far away from the receiving plate where neutral density is low and it is strongly absorbed near the plate. In this absorbing layer anomalous excitation occurs changing the neutral gas thermodynamics properties. Resonance radiation shifts equilibrium towards full ionization in the layer where the major part of neutrals would be highly excited. Intensity of radiation for resonance transitions becomes close to that of Planck radiation at these frequencies with temperature corresponding to electron temperature of the upstream plasma, i.e., at the entrance to the interaction zone. The process of stimulated radiative recombination of charged particles plays an important role in population of high atomic levels. Stimulated recombination leads to the population of these levels of very high excitation according to [8]. Frequencies of this recombination radiation are in the near-infrared and microwave intervals that are efficiently reflected from metallic walls. Therefore, the intensity of this continuous radiation is also close to that of Planck with temperature corresponding to electron temperature of the upstream plasma [6]. Ion sound barrier is formed in plasma–gas boundary that is characteristic of the phenomenon presently called 'detachment' when plasma does not disappear at the plate completely but loses its energy by radiation in the transition layer [11].

Analysis of line intensity dependence on principal quantum number of the highest level in our case indicates that there occurs an equilibrium population corresponding to Saha distribution with $T_e \sim (0.3–0.8)$ eV for transitions with $n \rightarrow 2$.

The developed model has found an experimental confirmation not only in our probe measurements and in the analysis of optical spectra but also in microwave experiment. Microwaves may be absorbed by highly excited neutral atoms. This fact may be revealed by varying neutral pressure. It is known that radiative transition frequencies between levels of Rydberg helium atoms with equal principal ($n \sim 15–20$) and different orbital quantum numbers are all in a range of 1.5–10 GHz. We have found experimentally that continuous plasma radiation generated by cyclotron instability in non-homogeneous magnetic field is absorbed at these frequencies at high pressures in the gas target. Absorption factor calculated for the case of thermodynamic equilibrium of excited levels ($n \sim 15–20$) with continuum gives the values that confirm the occurrence of specific layer between plasma and neutral gas controlled by radiation. According to [9], we evaluate the absorption efficiency of Rydberg atoms in 1.5–10 GHz frequency range by expression for radiative recombination lines [10]

$$\kappa_\nu = \frac{3}{8\pi} N_n \left(\frac{h\nu}{T_e}\right)\left(\frac{c}{\nu}\right)^2 \frac{A_n}{\gamma_n}. \qquad (1)$$

Here κ_ν is the absorption factor, ν the frequency of radiation, N_n the population of the level with principal quantum number n, $A_n \approx 5 \times 10^8 n^{-5}$ s^{-1} the probability of radiative transition, T_e the electron temperature, and c is the speed of light. According to Saha formula $N_n \approx N_e^2 n^2 (\hbar/m v_{T_e})^{3/2} \mathrm{e}^{(E_n/T_e)}$, where $\gamma_n \approx N_e n^4 (\hbar/m)^2 v_{T_e}^{-1} \Lambda$ is the electron impact width of absorbing level and v_{T_e} is the electron thermal speed. Putting characteristic values of T_e, N_e, γ_n and $n \sim 20$ into (1) and taking into account that the depth of optically radiating layer is $L \leqslant 3$ cm, we can estimate that absorption factor by highly excited atoms is sufficiently high for total absorption of electron cyclotron plasma noise $\kappa_\nu L \gg 1$.

3. Conclusion

Experimental studies of plasma–gas interactions have been performed in LENTA linear facility. Processes expected to occur in gas divertor have been modeled in these experiments. Steady-state helium plasmas with density of $(0.2\text{–}3) \times 10^{13}$ cm^{-3} interacted with neutral helium at pressures from 2 and up to 70 mTorr. Electron temperature T_e, plasma density N, plasma pressure NT have been studied at various neutral pressures in the gas target.

Neutral helium feed to the gas target zone caused electron temperature to fall to ~0.5 eV. An essential decrease in plasma pressure NT has been detected while the plasma was interacting with neutral gas. The plasma volume recombination in the gas target has been observed in these experiments. Electron temperature drop from 4–6 to 0.7–1 eV was accompanied by significant changes in optical spectra. Generation of line radiation corresponding to high ($n = 10$–22) excited levels has been observed with intensity rise for increasing pressures. Microwave radiation absorption at high neutral pressures ($P_{\text{gas}} > 20$ mTorr) have been detected in gas target zone for a 2400–3800 MHz frequency range.

The results were discussed on the basis of a new model of plasma–gas interaction. The principal features of the described physics model concern the essential role of resonance radiation in plasma–gas transition layer.

The phenomena observed and results obtained are thought to correspond to the results of divertor plasmas investigations performed in large fusion machines where detachment modes have been studied and are likely to have the similar physics origin.

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