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Journal of Nuclear Materials 266–269 (1999) 1157–1160

journal of nuclear materials

Spectroscopic observation of a helium plasma cooled by a hydrogen gas injection

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Abstract

Study of recombining plasmas resulting from a neutral gas injection has been made in a high density steady-state plasma. Recently, the inverted population between He I 1s2p^1 P and 1s3p^1 P due to the selective double electron capture process, $He^{2+} + H_2 \rightarrow He^* (1s3l) + 2H^+$, was observed in a single layer column plasma [S. Namba et al., Fusion Eng. Design 34–35 (1996) 777], when a helium plasma contacts with a hydrogen molecule. Moreover, experimental results which suggest an effect of the vibrational states of hydrogen molecules, $He^{2+} + H_2 (v') \rightarrow He^* (1s\,nl; n = 3, 4, 5) + 2H^+$, have been obtained for a double layer column plasma which was generated by a change of helium gas flow rate into the discharge region. The results on the hydrogen gas injection experiments relevant to two plasma conditions are presented. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Helium exhaust; Gas injection; Spectroscopy

1. Introduction

Recombining plasmas have received considerable attention not only in applications to X-ray lasers [1] but also in divertor and edge regions of fusion oriented plasmas. As a basic atomic process expected in the divertor region [2], we have investigated recombining helium plasmas resulting from rapid cooling by an injection of various neutral gases (H_2, D_2, He, N_2, Ne). In particular, a hydrogen molecule is considered to play an important role in recombination processes in decaying plasmas [3]. In high density helium plasmas in contact with hydrogen molecules, the following selective double electron capture process,

$$He^{2+} + H_2(v = 0) \rightarrow He^*(1s3l) + 2H^+, \qquad (1)$$

has been found to have a very large cross section ($\sim 10^{-15}$ cm^2 at 1 eV) due to an orbiting effect and accidental resonance [4]. The cross section increases as a collision velocity decrease and would follow Langevin cross section in the low energy collision [5]. The process is of interest in terms of the helium ash removal in D–T reactors, because an alpha particle is neutralized with a large cross section and then pumps out efficiently. On the other hand, the selective charge transfer has a potential of a formation of the inverted population for realizing a short wavelength laser. But, not enough quantity of the population inversion was obtained so far [6]. In the above double charge transfer process, one electron was captured into $n = 3$ state of He I, the other ground state. Although a following possible laser wavelength is 667.8 nm (transition 1s2p^{1}P–1s3d^{1}D) and much longer than soft X-ray, it is interesting as one of a means of a laser oscillation.

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PII: S0022-3115(98)00631-X

2. Experimental setup

High density, low temperature helium plasmas have been produced by TPD-II device (as shown in Fig. 1), which is operated at a discharge current of 100 A, discharge voltages of 100–160 V and a magnetic flux density of several kG. Electron density and temperature were found to be 10^{13}–10^{14} cm^{-3} and several eV respectively, as measured by Thomson scattering. The density of He^{2+} inferred was around 10^{11}–10^{12} cm^{-3} [7]. Experiments were carried out under two different discharge conditions (as shown in Fig. 2). The first with concentrated single column plasma (He gas flow rate 120 cc/min) and the second with double columns (flow rate 250 cc/min). The concentric double column plasma consists of the inner core plasma (same as the first experiment) with high electron density and the outer diluted plasma. The difference of the helium gas flow rate introduced into the plasma production region results in the two plasma states. The hydrogen gas was injected during 12 ms by a piezoelectric valve. Spectroscopic observations were made by using a 2 m vacuum ultraviolet (VUV) monochromator whose absolute intensity was calibrated by the branching ratio method.

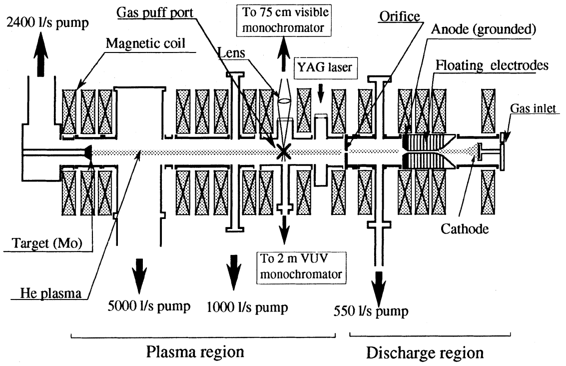
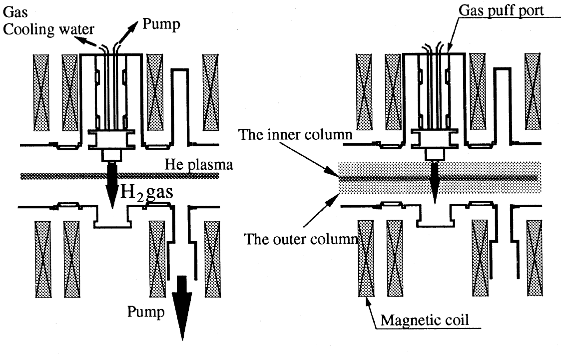


Fig. 1. Schematic diagram of the TPD-II device.



(a) He gas flow rate 120 cc/min

(b) Flow rate 250 cc/min

Fig. 2. Shapes of the plasma column near the gas puff port: (a) the single layer column plasma, (b) the double columns.

3. Experimental results

Fig. 3(a) shows the typical temporal evolution of He I singlet populations for the first experiment. The He I 1s3p^{1}P population has exhibited a sharp increase associated with the hydrogen gas injection. The inverted populations were observed between He I 1s2p^{1}P and 1s3p^{1}P. It should be noted that the intense radiative and three-body recombination was not expected to take place from 60 to 65 ms because of insufficient time to cool the electron temperature. No fast enhancements were observed in 1s4p^{1}P and 1s5p^{1}P. This fast enhancement was considered due to the double electron capture process, which became the dominant process. The later enhancements of the populations (at 75 ms) were due to the three body recombination process. The corresponding enhancement of the 1s2p^{1}P state appears also due to collisional de-excitations with electrons from the 1s3p^{1}P state. In the case of helium gas injections, the 1st peak was not observed and only later peak was observable such as hydrogen injections. Fig. 3(b) shows results of the double column discharge. There was a significant change between the results in the different

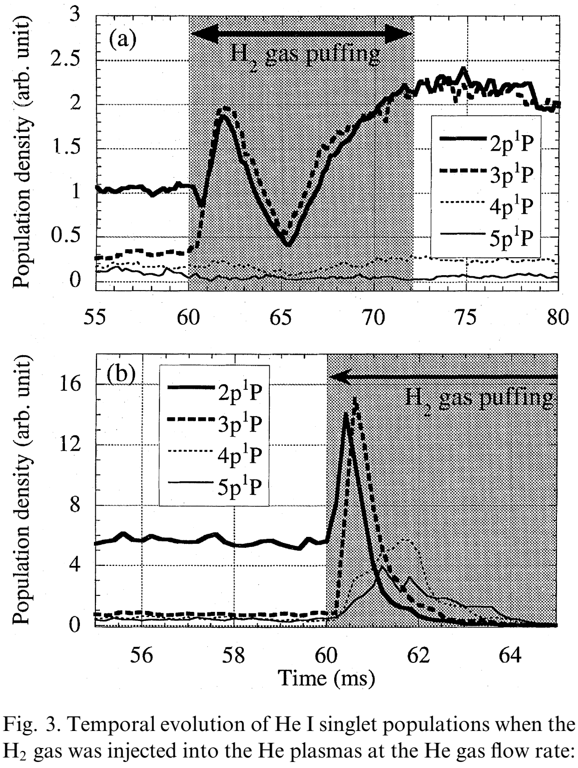


Fig. 3. Temporal evolution of He I singlet populations when the H_2 gas was injected into the He plasmas at the He gas flow rate: (a) 120 cc/min, (b) 250 cc/min.

plasma conditions. The $1s4p^1P$ and $1s5p^1P$ populations have been also enhanced and the inverted population between the levels of $1s2p^1P$, $1s3p^1P$ and the levels of $1s4p^1P$ and $1s5p^1P$ were observed.

4. Discussion

It is shown that the selective double electron capture process is one of the dominant processes at the early period of the hydrogen gas injection into a high density helium plasma. This phenomenon is consistent with calculations by Landau–Zener model [8]. Numerical calculations of He I populations based on a collisional-radiative model is also in good agreement with experimental results [9]. However, the noticeable increases of He I $1s4p^1P$ and $1s5p^1P$ populations in the latter discharge are not fully explained by the report in Ref. [6]. The most likely explanation is considered as the results of the following two step reactions. At first, the hydrogen molecule is excited to vibrational excited states by electron impacts in the outer column before reaching the inner plasma column

$$H_2(v'' = 0) + e \rightarrow H_2(v') + e. \tag{2}$$

Then, the hydrogen molecules with vibrational excited states reach into the inner plasma and interact with He^{2+} ions

$$He^{2+} + H_2(v') \rightarrow He^*(1s\,nl) + 2H^+. \tag{3}$$

In case of the $v'' = 1$ and $n = 4$ in Eq. (3), the energy difference between He^{2+} and vibrational excited hydrogen molecule is equivalent to the double ionized potential of hydrogen molecule and therefore the process of Eq. (3) can be an accidental resonant reaction such as Eq. (1) at the low collision energy. Theoretical calculation including the above vibrational state is far difficult compared with the case of ground state. The reason for the time delay between the enhanced populations of $1s2p^1P$, $1s3p^1P$ and $1s4p^1P$, $1s5p^1P$ is that some time might be required in terms of the mixture of He^{2+} and hydrogen molecule in order to produce the vibrational excited hydrogen molecule. Theoretically, the process of Eq. (3) is likely to occur due to the broadening and shift of the reaction window in the potential curve taken into account vibrational states (the term 'reaction window' means a region of a crossing distance available for a diabatic transition in the potential curve of He^{2+} and hydrogen molecule system).

5. Summary and future plan

5.1. Summary for the gas injection experiments

The hydrogen gas injection experiments for helium plasmas have been performed for the two plasma conditions. The population inversion between He I $1s2p^1P$ and $1s3p^1P$ was obtained for the single column discharge due to the double electron capture process. In case of the double column discharge, the levels of $1s3p^1P$, $1s4p^1P$ and $1s5p^1P$ were found to increase rapidly and the population inversions between $1s2p^1P$, $1s3p^1P$ and $1s4p^1P$, $1s5p^1P$ were measured resulting from the double electron capture with the vibrationaly excited hydrogen molecule. However, an accurate measurement of the number of injected hydrogen molecules is essential for the quantitative measurement of the double electron capture process. But, it is difficult to obtain the accurate number of the contacting neutral particles in our experiments. In order to cool the electron temperature more intensively, we have to inject a large quantity of hydrogen molecules leading to a collapse of the plasma in the production region.

5.2. Design and construction of a hydrogen ice pellet injector

One of the hydrogen ice pellet injection methods, which have developed in the research of refueling of

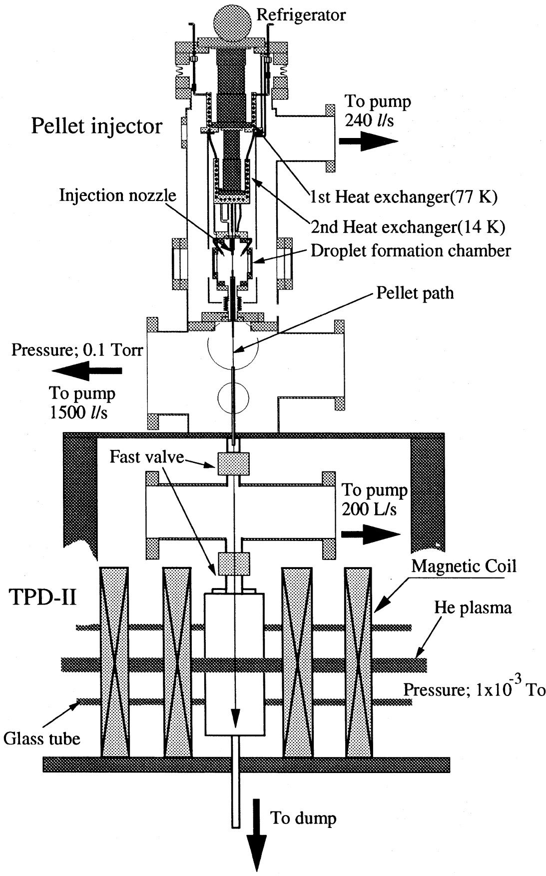


Fig. 4. The setup of the ice pellet injector for TPD-II device.

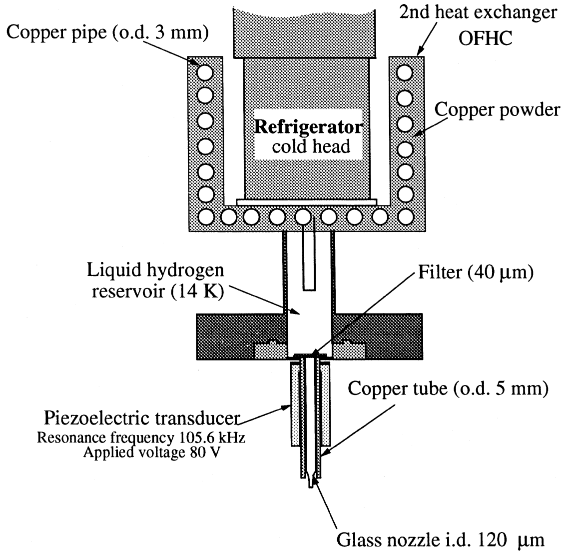


Fig. 5. Details of injection nozzle and the second heat exchanger.

fusion reactors, has a promising potential for our purpose. The adopted instrument is called 'Droplet method' [10,11]. The setup for the TPD-II is shown in Fig. 4. The principle of productions of the hydrogen ice pellet is the following. At first, the hydrogen gas is introduced into copper pipes (the outer diameter 3 mm, the inner 1 mm) of the 1st heat exchanger and precooled to below 77 K by passing through it. Next, the precooled hydrogen is liquefied in the 2nd heat exchanger which is kept close to the triple-point temperature of hydrogen. The 2nd heat exchanger consist of pure copper pipes and the high purity copper powder of diameter 100 mm and contacts to cold head. The cooling power is produced by a cryogenic refrigerator which is operated according to the Gifford–McMahon method. The liquid hydrogen is injected as a jet from glass nozzle exit. Then the jet with the acoustic perturbation by a piezoelectric transducer is broken up into uniform sized drops. Details of the 2nd heat exchanger and the jet nozzle are shown in Fig. 5. The diameter and temperature of injected droplets are around 150 mm and 6 K, respectively. Total number of hydrogen molecules are around 1.1×10^{17} molecules. Velocity of injected droplets have to be as low as possible owing to obtain long duration for the interaction with plasmas. The droplets are so accelerated by gravity that its velocity is several m/s, far lower than the kind of gas gun acceleration (up to a few km/s). The transducer with a resonance frequency 106.5 kHz is driven by an applied voltage 100 V sine wave. The production rate is to be several kHz. In order to inject an arbitrary number of droplets, two fast valves are installed between the pellet injector and the TPD-II. A large quantity of hydrogen molecules is able to be introduced by an ice pellet in the localized region at a time compared with the gas injection. The pellet injector is testing at present. We plan to report on the result for the pellet injection experiment in a separate paper.

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