Behavior of Hydrogen Fueled by Pellet Injection in the GAMMA 10 Tandem Mirror

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In the GAMMA 10 tandem mirror, the pellet injection system is installed near the mid-plane of the central cell to improve plasma parameters and to study the pellet-plasma interactions in an open system. In recent experiments, hydrogen pellets are injected with ECRH at the plug/barrier and central cells. Consequently, increases in electron densities and H_α line emission with three peaks are observed. The radial profiles of H_α line emission at the peak time have a peak in the peripheral region of the injection side. These results show that the pellet cracks into three small pieces somewhere of the injection path. In this discharge, the pellet of the third peak penetrates deeper than the pellet of first peak, although the third pellet smaller than the first pellet. This phenomenon is occurred by the decrease of the ion temperature caused by the first and second pellet.

Keywords: hydrogen pellet, penetration depth, NGS model, fueled particle, H_α line emission, tandem mirror

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1. Introduction

Sustainment of the steady state plasmas with higher densities and temperatures is one of the most important subjects to realize the fusion reactor. The development and optimization of the fueling method enable us to increase and sustain plasma density. In the present plasma experiments, there are three major fueling methods; namely, gas puff, neutral beam injection and pellet injection. Pellet injection is used as a particle source in the core region of the plasma. The importance of pellet injection is highlighted under the condition at high density and high temperature plasmas. To study the effects of the pellet injection on the target plasma, it is important to evaluate the neutral hydrogen behavior as well as plasma densities and temperatures.

In the GAMMA 10 tandem mirror, the study of particle fueling has been carried out for the purpose of producing high performance plasma discharges [1, 2]. In the central cell of GAMMA 10, the pellet injection system is installed near the mid-plane to improve plasma parameters and to study the pellet-plasma interactions in an open system [3, 4]. In recent experiments, hydrogen pellets are injected with electron cyclotron resonance heating at the plug/barrier and central cells. Then various results are obtained by these experiments; the increase of an electron density and a H_α line emission, the decrease of diamagnetism and the change of radial profiles of the plasma etc. The neutral gas shielding (NGS) model [5–8] is effective for the analysis of these results. NGS model is a simple theoretical model and enables us to evaluate the pellet ablation using the given plasma parameters.

The pellets ejected from barrel reaches the plasma through the 6 m length curved guide tube in GAMMA 10. In almost cases, the pellet cracks and slows down somewhere of the injection path. Therefore, the pellets are injected to the plasma with different size and velocity compared with the expected size and velocity. In this article, we show the experimental results of the plasma discharge with the pellet that cracks to some pieces, and discuss the behavior of fueled particles based on those results and the calculated results of NGS model.

2. Experimental Apparatus

GAMMA 10 is a 27 m long tandem mirror plasma confinement device with a thermal barrier. It consists of a 5.6 m long axisymmetric central cell, two anchor cells for suppressing magnetohydorodynamic (MHD) instabilities that are located in both ends of the central cell. Two plug/barrier cells are connected to the anchor cells for forming the plug and thermal barrier potentials. Fig. 1 shows the schematic view of the GAMMA 10 tandem mirror. In plasmas produced in the core region of the central cell, typical electron density, electron temperature and ion temperature are about 2×10^{12} cm^{-3}, 100 eV and 5 keV, respectively.

A pellet injection system has been installed in GAMMA 10 and pellets are injected near the mid plane of the central cell ($Z = -10$ cm). The schematic view of the pellet injection system is shown in Fig. 2. The installed pellet injector is a pipe-gun type pneumatic pellet injector made by the Oak Ridge National Laboratory and modified by Plasma Research Center of the University of

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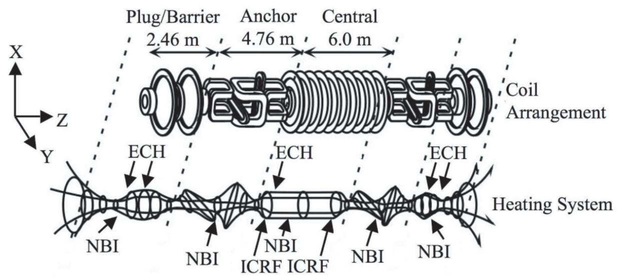


Fig. 1 The schematic view of the GAMMA 10 tandem mirror.

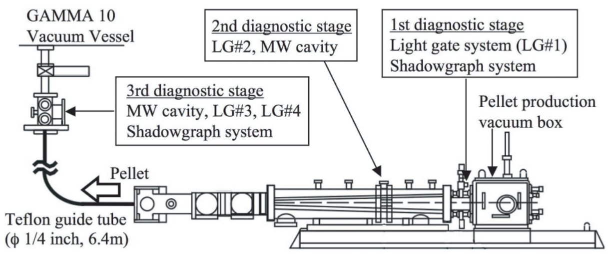


Fig. 2 The schematic view of the pellet injection system installed in GAMMA 10.

Tsukuba [9]. The eight barrels are mounted into the injector. The inner diameter of the barrel used in this experiment is 0.79 mm. The pellet is cylindrical and its aspect ratio is from 0.5 to 2. The pellet ejected from a barrel reaches the plasma through the 6 m length of Teflon tube with 1/4-inch inner diameter. This pellet injection system has three diagnostic stages. These diagnostic stages consist of the light gate system to measure the pellet velocity, the microwave cavity to evaluate the pellet mass and the shadowgraph system to observe the pellet shape as shown in Fig. 2. The first and second diagnostic stages measure pellet parameters just after an ejection. The third diagnostic stage clarifies the pellet parameters just before an injection to the plasma.

To study the effects of fueled particles, the neutral hydrogen behavior is an important subject. Then, H_α line emission detectors are installed in the central cell to clarify the behavior of neutral hydrogen density. H_α line emission detectors consist of H_α interference filters, focusing lenses, apertures, optical fibers and photomultiplier tubes. The installed position of H_α line emission detectors are $Z = -1$ cm, -71 cm and -141 cm. Near the mid-plane of the central cell, vertical ($Z = -12$ cm) and horizontal ($Z = -52$ cm) arrays [10] are mounted to measure the radial profiles of H_α line emission. Each array has 12 channel detectors and these detectors are absolutely calibrated by a standard lamp.

3. Experimental Results

The signals of light gate (LG#1) and microwave cavity and the shadowgraph of pellet obtained in the first and second diagnostic stages are shown in Fig. 3. From Fig. 3,

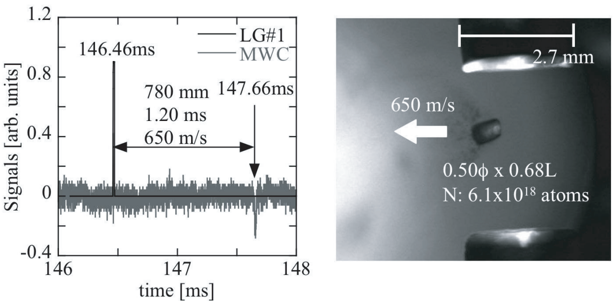


Fig. 3 The signals of light gate system (LG#1) (1st diagnostic stage) and microwave cavity (2nd diagnostic stage) (Left). The shadowgraph of the pellet obtained in 1st diagnostic stage (Right).

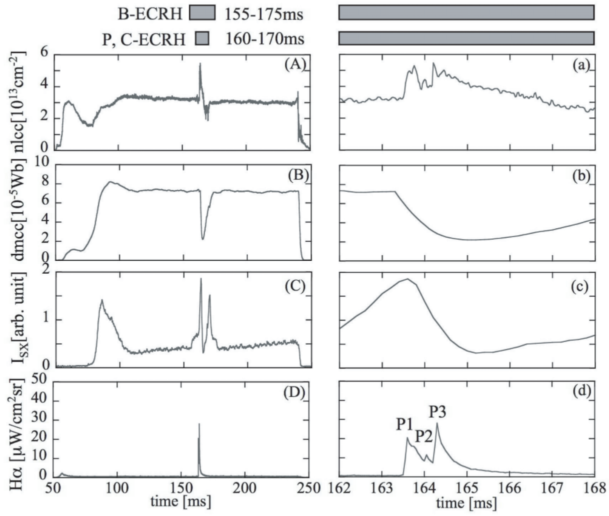


Fig. 4 Temporal behavior of line-integrated electron density (Y = 6 cm) (A), the diamagnetism (B), the intensity of soft X-ray (C), H_α brightness of the central channel of the horizontal array (D) and the close-up around the injection time of the pellet of these parameters (a ~ d).

it is found that the ejected velocity of the pellet is 650 m/s and this pellet has 6.1×10^{18} hydrogen atoms.

This pellet is injected to the plasma with the central, plug and barrier ECRH. Temporal behavior of line-integrated electron density ($Y = 6$ cm) (A), the diamagnetism (B), the intensity of soft X-ray (C), H_α brightness of the central channel of the horizontal array (D) and the close-up around the injection time of the pellet of these parameters (a ~ d) are shown in Fig. 4. The plasma of this experiment is the ICRF-heated plasma with central, plug and barrier ECRH. In Fig. 4, the electron density increases about 1.7 times. The diamagnetism and the intensity of soft X-ray decrease slowly compared with the change of the electron density and the H_α brightness. The H_α brightness increases quickly and the peak brightness is about 40 times larger than the brightness before injection. There are three peaks in the temporal behavior of the electron density and

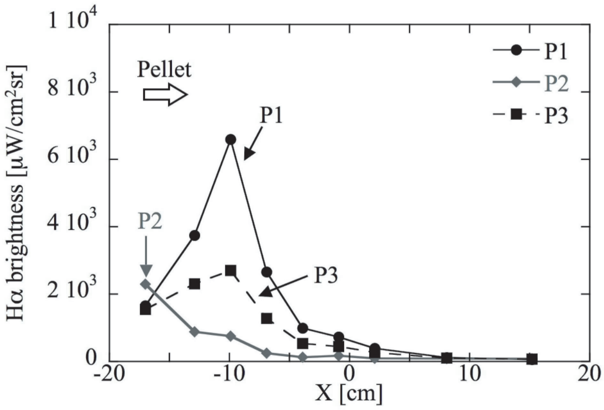
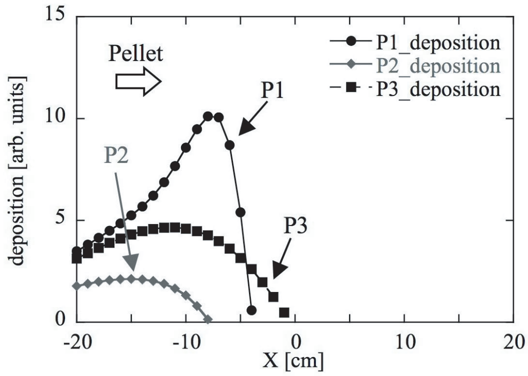


Fig. 5 The H_α brightness profiles at the each peak time measured by the vertical array.



Plasma and pellet parameters

	$n_e(0)$ [cm^{-3}]	Ti(0) [keV]	v_{pellet} [m/s]	ϕ [mm]
P1	2.15e12	4.1	610	0.44
P2	2.40e12	1.6	594	0.26
P3	2.55e12	0.76	586	0.38

Fig. 6 The deposition profiles calculated by NGS model for P1, P2 and P3, and the calculation parameters of the plasma and the pellet.

the H_α brightness. Then, the three peaks are defined pellet 1 (P1), pellet 2 (P2) and pellet 3 (P3), respectively, as shown in Fig. 4 (d). The velocities of each pellet, which are obtained from the signal of microwave cavity installed on the second diagnostic stage and the peak time of the H_α line emission, are 610 m/s, 594 m/s and 586 m/s, respectively. These results show that the pellet ejected from the pellet injector cracks into several pieces and slows down somewhere of the injection path.

Figure 5 shows the H_α brightness profiles at the each peak time measured by the vertical array of the H_α line emission detector. The H_α brightness profile is greatly changed by the pellet injection. The profile of X-direction has a peak in the peripheral region of the injection side and the peak value of these profiles reaches to about several thousands times before the pellet injection. The profiles of P1 and P3 have a peak about $X = -10$ cm. The profile shape of P1 is peaked and the peak value of P1 is large compared with that of P3. The profile of P2 has a peak near the edge of the plasma. It is thought that these differences are based on pellet size, pellet velocity and plasma parameters (density, temperature and these profiles).

4. Discussion

4.1 NGS model

NGS model is a simple theoretical model. A neutral shielding cloud around the pellet is formed by the incident energy flux from background plasma. The 1-dimension spherically symmetric hydrodynamic model of the expansion in the ablation cloud is solved in the model. The ablation rate (the recession speed of the pellet surface) is given by the scaling laws in this model. When the dominant heat source is ion, the ablation rate is written as follows [8],

$$\frac{dr_p}{dt} = 4.55 \times 10^6 \rho_s^{-1} m^{2/3} \left(\sqrt{e/\pi m}\, n_i \right)^{1/3} E_i^{0.9} r_p^{-2/3}. \tag{1}$$

Here, r_p, ρ_s, m, n_i and E_i represent pellet radius, mass density of solid hydrogen, ion mass, ion density of background plasma and incident ion energy, respectively. Therefore, the ablation profile of pellet is obtained by using this equation applied known plasma parameters.

4.2 Discussion on the experimental results and NGS model calculation

The deposition profile is calculated with simple slab model. The deposition is proportional to the number of molecular hydrogen ablated from pellet in each region. In this model, the plasma region is divided into several sections, and then the plasma parameters, electron density and ion temperature are given in each section. The ablation rate is calculated from the plasma parameters just before the pellet injection and the scaling law of NGS model. Assuming that the profile shape of the plasma is the gaussian, the electron density and ion temperature profiles are obtained by the line-integrated electron density and diamagnetism. The pellet velocity is known from the experimental results. Then the deposition is calculated by the pellet size, velocity and ablation rate given by Eq. (1). On the other hand, the profile of the pellet ablation is estimated experimentally from the profile of the H_α line emission because the profile of the H_α line emission is based on the pellet ablation profile. Therefore, the injected pellet size is evaluated by the comparison with the peak position of the H_α line emission profiles and that of the calculated result of the deposition profiles.

The deposition profiles calculated by the slab model for P1, P2 and P3 are shown in Fig. 6. The plasma and pellet parameters used for calculation are also shown in

Fig. 6. The pellet size is decided by the comparison between the peak position of the deposition profiles and that of the H_α brightness. In Fig. 6, the pellets cannot reach to positive side of the X axis (the upper side of the plasma). It is thought that the H_α emission at the positive side of the X axis is caused by the influx of atomic and molecular hydrogen ablated from pellet at the negative side of the X axis. The total number of particles included in P1, P2 and P3 is 3.8×10^{18} atoms. This is about 62 % of the number of particles included in the pellet just after the ejection. It is thought that the other particles are lost in the injection path or injected to the plasma as the small piece. Although the pellet size of P3 is smaller and the velocity of P3 is slower than those of P1, the penetration depth of P3 is larger than that of P1. This situation is occurred by the change of the plasma parameters, especially the decrease of the ion temperature, caused by the injection of P1 and P2. The ion temperature has a large effect on the pellet ablation as shown in Eq. (1). Then the ablation rate of P3 becomes small, and the penetration depth becomes long relatively. There is a possibility that this phenomenon can be applied for the pellet injection to the core region of the plasma.

5. Summary

In GAMMA 10, hydrogen pellets are injected with electron cyclotron resonance heating at the plug/barrier and central cells for the purpose of producing high performance plasma discharges. From the experimental results, the increase of density, the decreases of temperature and the increase and profile change of H_α line emission are observed. In this discharge, the pellet is injected to the plasma as the three pieces. These three pieces are analyzed based on the profile of H_α line emission and the calculated results of the deposition profile with NGS model. In this analysis, it is found that the about 30 % particles included in the pellet are lost in the injection path or injected to the plasma as the unobservable small piece. There is a possibility that the penetration depth of P3 is larger than that of P1, although the pellet size of P3 is smaller and the velocity of P3 is slower than those of P1. This phenomenon is occurred by the decrease of the ion temperature caused by the P1 and P2.

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