Dynamic Evolution of Pellet Fueling from Ablation Cloud to Reheat Mode in Heliotron J

S. Kado, G. Motojima[1,2], S. Inagaki, R. Matsutani[3], C. Feng[3], K. Ogihara[3], A. Iwata, T. Kawamukai[3], T. Shikama[4], F. Cai[3], F. Kin, S. Kobayashi, A. Matsuyama[3], Y. Nakamura[3], A. Ishizawa[3], T. Mizuuchi, S. Konoshima, S. Ohshima[5], H. Okada, T. Minami, and K. Nagasaki

Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto, 110-0011, Japan, [1]National Institute for Fusion Science, Toki, Gifu, 509-5292, Japan, [2]SOKENDAI (The Graduate University for Advanced Studies), Toki, Gifu, 509-5292, Japan, [3]Graduate School of Energy Science, Kyoto University, Gokasho, Uji, Kyoto, 110-0011, Japan, [4]Graduate School of Engineering, Kyoto University, Katsura, Kyoto, 615-8540, Japan, [5]University of California, Irvine, California 92697, U.S.A.

e-mail: kado@iae.kyoto-u.ac.jp

The effect of small pellet injection on the plasma particle fueling and subsequent confinement has been investigated in the Heliotron J. 2D imaging of the Stark broadening of H_β line reveals a round neutral cloud and an elliptic plasmoid that stretched along the magnetic field. Density profiles change from hollow to peaked after ablation, indicating a pinch effect. Impurity emissions measured using EUV spectroscopy and the AXUV detector array, exhibit a density and temperature evolutions that resemble a "reheat mode" allowing the plasma to achieve densities exceeding the ECH cut-off value.

Hydrogen pellet injection is considered an effective fueling method for fusion-relevant magnetic confinement devices. The ablation process typically progresses in three phases[1]:

1) **Ablation and Plasmoid Formation**: The solid hydrogen pellet undergoes ablation, forming a neutral cloud that subsequently ionizes into a high-density, low-temperature plasma known as the plasmoid.
2) **Plasmoid Expansion and Homogenization**: The plasmoid evolves and expands along the magnetic flux surfaces, distributing the fuel.
3) **Fuel Deposition and Plasma Profile Reconstruction**: The injected fuel integrates with the bulk plasma, modifying the density profile and completing the fueling process.

However, the interaction between the plasmoid and the bulk plasma during the progress of these phases is dynamic. Optimizing pellet fueling scenario requires a detailed understanding of both microscopic atomic processes and macroscopic transport phenomena.

Heliotron J device is a medium-sized helical device with a major radius (R) of 1.2 m, and a minor radius (a) of ~ 0.2 m, and a typical magnetic field strength (B) of 1.25 T. A small pellet injector, with a barrel diameter of 0.6 – 1.2 mm, has been developed for Heliotron J [2]. However, several challenges have emerged in analyzing the pellet fueling properties. Compared to larger machines such as LHD or W7-X, the required injection speed is significantly lower. Spectral broadening is notably narrower than that obtained using the combined interference filter, and the achievement of a state of local thermal equilibrium (LTE) in the ablation cloud is non-trivial [3]. Additionally, plasma collapse easily because the number of particles conveyed by a single pellet is much greater

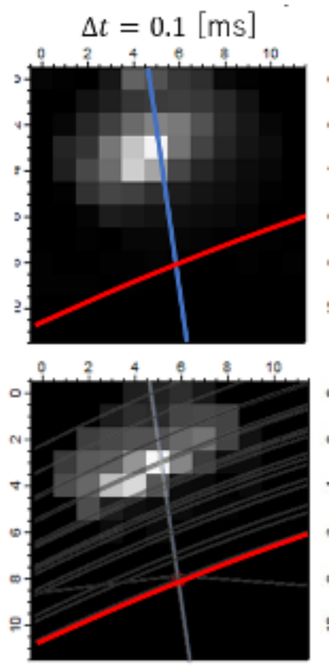

Fig. 1 2D images of the emission intensity (a) and plasmoid density (b) at the maximum emission intensity (t = 0.1 ms) of the pellet ablation cloud, observed from the upper port. The pixel resolution is 12 mm per pitch. The red line indicates the magnetic axis. [shot#82554 ECH+NBI] [4]。

(5-10 times) than that in the whole target plasma.

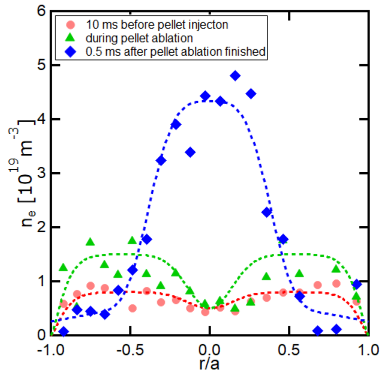

Fig. 2 Density profiles of the target plasma before pellet injection (-10 ms), during the pellet ablation (0.1 ms) and immediately after the ablation (0.5 ms from the Hα trigger ON) [shot#79541-79546 ECH+NBI] [5]。

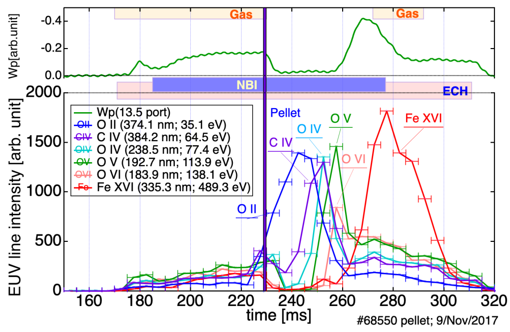

Fig. 3 Temporal evolution of the stored energy (Wp) and the EUV line spectra, indicated by the wavelength and ionization energy.

For phase 1) We developed a 2D fast visible spectrometer. The emission collected from the pellet trajectory is imaged onto a fiber optic bundle arranged in a 12 x 12 channels 2D imaging array, which is then rearranged into a 1D array along the entrance slit of the spectrometer. The reciprocal linear dispersion (RLD) is 3.50 nm/mm for the H_β line at 486.13 nm. A high-speed camera (Photron FASTCAM APX-RS) enables the frame rate of 10k fps for a rectangle region of interest (ROI) of 128 pixels in wavelength and 1024 pixels along the slit directions.

The intensity, density, and trajectory of the ablation cloud were successfully captured, providing a view of the entire ablation process, which typically last about 0.4 ms per pellet fraction[4] (Fig. 1).

For the phase 2) we have developed the event-triggered Thomson scattering system which enables the tracking of plasma profile with an arbitral interval (≥ 0.32 ms) from the ablation event using the Hα emission signal as the trigger.

Fig. 2 shows the density profile evolution for the pellet-fueled plasma. Initially, the profile exhibited a cold (T_e) hollow (n_e) shape, *presumably* suggesting a transient homogenization state[5]. Subsequently, the density profile peaked immediately after the ablation. A high-speed camera (Photron FASTCAM SA5) operating at 100k fps captured the perturbation of emission intensity from the ablation cloud. The rotational motion in the ExB drift direction around the pellet as it traveled along the magnetic field line [6] likewise represents the initial stage of the homogenization process.

The response of bulk plasma parameters, the phase 3), to the pellet ablation is characterized by a cold pulse during which highly charged impurity spectra suddenly disappear while those from lower charged ions increase. After several milliseconds, the spectra from the highly charged ions reappear, reaching levels higher than before ablation, correlating with an increase in stored energy signal(Wp). This behavior resembles the phenomenon known as "reheat" mode[7]. This trend is also obvious in the AXUV detector array signals. Following ablation, the dominant radiation power region shifts rapidly from the periphery to the core. A simple transport analysis using the n_e and T_e profiles from Thomson scattering also implies the presence of an inward pinch. The degree of the reheat appears to depend also on the heating method (ECH and/or NBI), its power, and additional gas fueling which compliments recycling fuel from the chamber wall. Understanding the mechanisms behind reheat mode and the impurity behavior will provide significant insight into high-performance plasma achievement.

[1] A. Matsuyama, *et al.*, *Plasma Phys. Control. Fusion* **54** **(**2012**)** 035007.
[2] G. Motojima, *et al.*, 2019, *Plasma. Phys. Control. Fusion.*, **61**, (2019) 075014.
[3] A. Iwata, *et al,* RSI **93**, 113537 (2022) .
[4] S. Kado, *et al.*, 2023, *Proc. 49th EPS conference, Bordeaux,* P4.040.
[5] R. Matsutani, *et al.*, 2023, *Proc. 49th EPS conference, Bordeaux,* P4.043.
[6] S. Ohshima, *et al.,* Scientific Reports, **12**, 14204(2022).
[7] S. Morita *et al.*, Proc. 14th Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research 1992, Würzburg, Vol.2, p.515 (1992).