Temporal evolution of high-density plasmas produced by advanced fuelling techniques in Heliotron J

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1. Introduction

Advanced fuelling control methods have recently been developed for the production of high density plasma and control of density profile and are utilized in many devices. In Heliotron J, such high performance plasmas have successfully been realized using a supersonic molecular beam injection (SMBI) or a short pulsed high intensity gas puff (HIGP) techniques [1,2,3].

Recently, a new far infrared (FIR) laser interferometer with 1 μs time resolution has been developed to measure such high density plasmas, and the first results were successfully obtained [4]. The temporal evolution of density profile shape obtained with FIR- and microwave- interferometers and the comparison between SMBI and the HIGP plasmas are discussed in this article.

2. Experimental setup and results

The Heliotron J device is a medium sized ($<R_0>/<a_p> = 1.2m/0.17m$, $<B_0> \leq 1.5T$) helical axis Heliotron device with $L/M = 1/4$ helical coil, where L and M are the pole number of the helical coil and helical pitch number, respectively. Figure 1 shows the top view of the Heliotron J device, and the arrangement of heating and fuelling systems and major diagnostic equipment. For density control, a conventional gas-puffing system is usually used, and HIGP is realized using the gas-puffing system shown "GAS" in Fig.1. A SMBI system is installed on 11.5 port shown "SMBI" in Fig.1 and injects SMB at 1~2 km/s.

A FIR laser interferometer and a microwave interferometer are utilized to measure line averaged density in this study, are combined to estimate time evolution of density profile shape. As shown in Fig. 2 the microwave- and FIR- interferometers are located at #8.5 port and # 14.5 port with on-axis and off-axis, vertical chords, respectively.

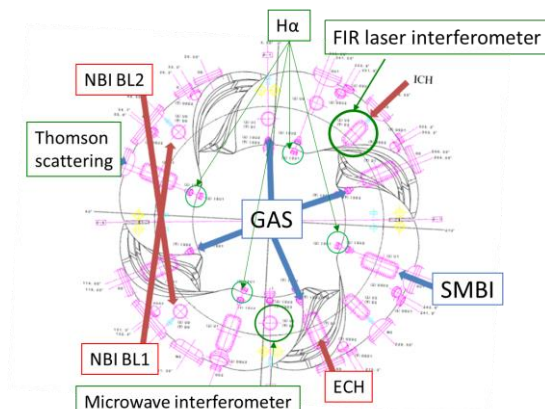In this experiment, the plasma is produced with 70 GHz ECH of 340 kW, and is

Fig. 1 Top view of Heliotron J device and the arrangement of heating and fuelling system and diagnostics.

sustained with additionally injected tangential NBI of 600 kW (NBI BL2), as shown in Fig. 3. Additional fuelling are injected at 235 ms with the time duration of 10 ms for HIGP, and at 233 ms with 1 ms short pulse for SMBI. In both cases, the maximum line averaged density are adjusted to have almost the same value with $\bar{n}_e \sim 2 \times 10^{19}$ m^{-3}.

Fig. 2. Chord of (left) FIR laser interferometer and (right) microwave interferometer

Figure 3 and 4 shows waveforms for the line averaged density measured with (a) microwave interferometer ($\bar{n}_e^{MICRO}$) and FIR interferometer ($\bar{n}_e^{FIR}$), (b) stored energy W$_p$, and (c) Hα signals in HIGP and SMBI discharges, respectively. In both cases, increase in density and decrease in W$_p$ are observed after the additional fuelling. The stored energy is kept constant at low level from ~ 245 to ~ 270 ms, and then W$_p$ starts to recover spontaneously and take a maximum value of ~ 1.8 kJ at ~ 280 ms. Several differences for the temporal responses are observed although basic features are similar. For instance, quick and sharp increases of $\bar{n}_e$ (d$\bar{n}_e$/dt ~ 0.29 × 10^{19} m^{-3} / ms) and the Hα signal are observed after the SMB injection, compared with the response of HIGP (d$\bar{n}_e$/dt ~ 0.15 × 10^{19} m^{-3} / ms). In addition, $\bar{n}_e$ and the Hα signals continue to increase for 5-7 ms after 1.8 ms short pulse of SMBI, which is different from the case of HIGP plasma where the such increase immediately stops just after the injection of HIGP. These observation should relate to the differences on fuelling process and efficiency between SMBI and HIGP, and in practice, strong toroidal asymmetry of Hα signal is observed in SMB injection in previous study [5], which is characteristics of the local, strong fuelling on the SMBI technique.

4. Time evolution of profile shape in HIGP and SMB injection.

The ratio of the line averaged density obtained with off-axis FIR- to that of on-axis microwave interferometer, $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$, is a parameter to relate to the profile shape. For example, a higher value of $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$ indicates that the contribution of edge electron density in the region of $\rho > 0.35$ is higher, which means the profile is broader. On the other hand, a lower value of the ratio means more peaked density profile. Using the ratio, temporal change of profile shape can be evaluated.

Figure 5 (a) and (b) show the time development of $\bar{n}_e^{FIR}$ and $\bar{n}_e^{MICRO}$, and the ratio, $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$, in HIGP plasma. The density
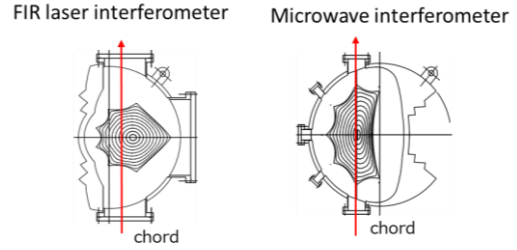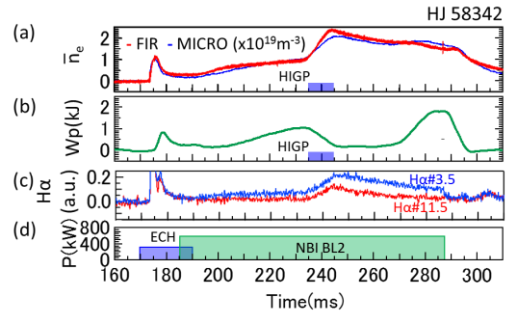

Fig. 3. Waveform of HIGP plasma experiment

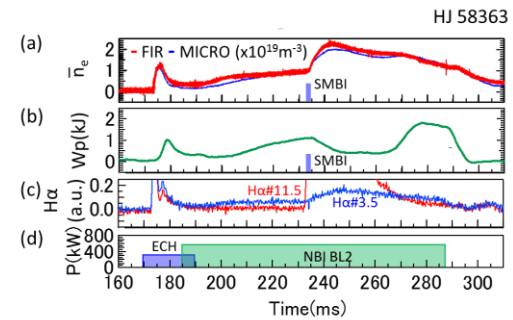
Fig. 4. Waveform of SMBI plasma experiment. Hα radiation indicates the timing of SMBI.

and temperature profile obtained with the results of Thomson scattering measurement are shown in Fig. 5 (c) [6].

A broadening of density profile is observed during HIGP injection. In Fig.5 (c), $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$ increases during HIGP injection, which suggests that the HIGP strongly fuels to outside region of $\rho > 0.35$ and modifies density profile to broader shape. Electron temperature is cooled down during the density increase phase in entire region of plasma, as shown in the temperature profile at 240 ms in Fig. 5 (c). After the termination of HIGP injection, the density profile shape start to change to be peaked moderately, and then keeps almost constant value from 250 to 270 ms.

In the recovery phase of stored energy, a peaking of density profile shape was found in the HIGP plasma, which can be seen in the decrease in $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$ ratio. The line averaged density slightly decreases but does not change so much during the recovery phase, however, electron temperature significantly rises as seen in the temperature profile at 270 and 280 ms of Fig. 5 (c). The recovery of W_p is, therefore, mainly attributed to the increase of temperature.

The result of SMBI plasma also shows similar time evolution, as shown in Fig. 6. (a-c), however, density profile broadening after SMBI is more moderate, compared to the case of HIGP plasma. The increment of $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$ is from ~ 1.0 to ~ 1.15, and is smaller than that from ~0.95 to ~1.20 in HIGP case, which indicate the profile change of SMB injected plasma is smaller than that of HIGP plasma.

The dependences of profile shape parameter $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$ on stored energy W_p are plotted in Figure 7 (a) and (b) for HIGP and SMBI plasmas. These figures clearly show that, the density profile is broaden with the decay of stored energy, and the profile is peaked with the recovery of the W_p in both cases. In addition, the variation of profile shape and stored energy are a little larger in HIGP plasma although the maximum stored energy are almost the same values (~1.8 kJ), which suggests a deeper penetration to core plasma in SMB plasma.
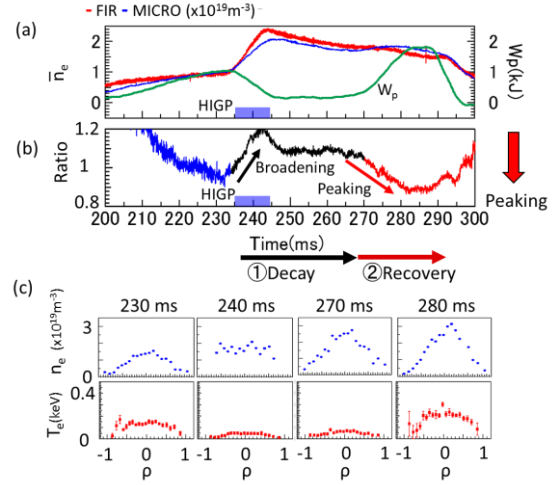

Fig. 5. (a) Time development of $\bar{n}_e^{FIR}$ and $\bar{n}_e^{MICRO}$, (b) $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$, (c) n_e and T_e profile obtained with Thomson scattering measurement.
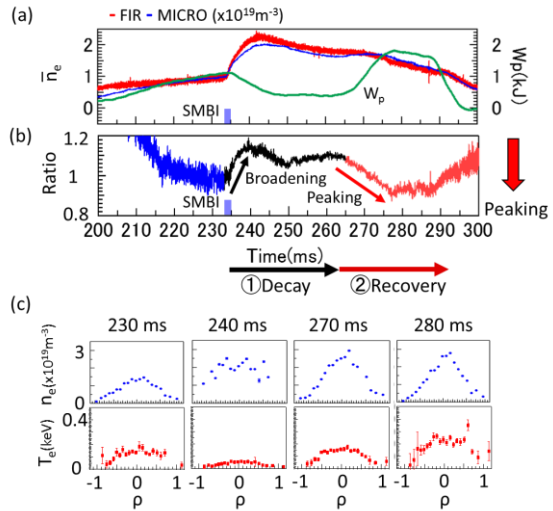

Fig. 6. (a) Time development of $\bar{n}_e^{FIR}$ and $\bar{n}_e^{MICRO}$, (b) $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$, (c) n_e and T_e profile obtained with Thomson scattering measurement.

4. Summary

The line averaged density of the high density plasma with HIGP and SMBI in Heliotron J are measured using FIR laser and microwave interferometers, and the time evolution of density profile shapes are evaluated. In both HIGP and SMBI cases, profile broadening is observed after additional fuelling with the decay of stored energy.
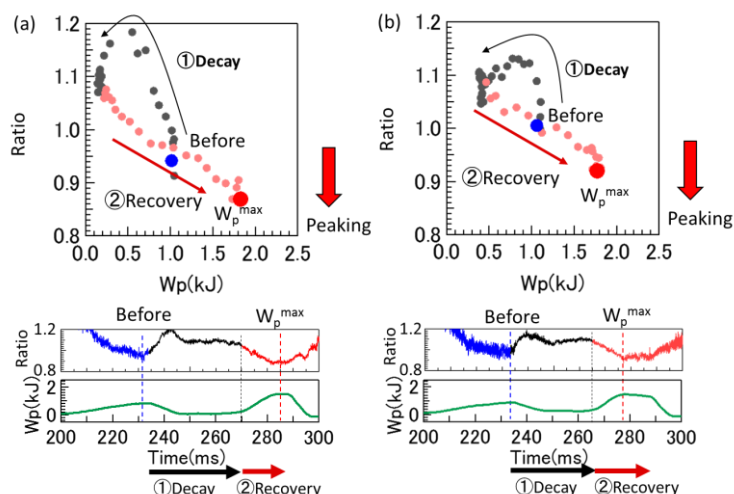
Fig. 7. The dependence of $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$ on the stored energy and time development of $\bar{n}_e^{FIR}/\bar{n}_e^{MICRO}$ and stored energy for (a) HIGP plasma, and (b) SMBI plasma

After HIGP/SMBI injection, the line averaged density is kept high value and the stored energy remains low value, continuously. After that, the density starts to become peaked profile spontaneously with the recovery of stored energy. The increase of electron temperature is the main contribution to the recovery of stored energy. The temporal response of density profile shape and its relationship with stored energy are similar, however, smaller disturbance to the plasma parameters are observed in SMBI plasma, compared to that of HIGP, which might be caused by SMB penetrating into plasma more deeply than HIGP.

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