Experimental Validation of Beam Particle Self Interaction in JT-60U by Use of N-NB

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In a toroidal system, circulating fast ions generated by neutral beam injection affect the beam stopping cross-section of the neutral beam itself. This effect is called "beam particle self-interaction (BPSI)". In a recent experiment in JT-60U with a 350 keV H^0 beam, an indication of this BPSI effect was seen for the first time. In a low density discharge at about 1×10^{19} m^{-3}, the beam shine-through decreased by about 35% within several hundred msec after beam injection. This result is consistent with a prediction by the BPSI theory.

Keywords:

BPSI, fast ions, current drive, current ramp-up, shine through, neutral beam

In a toroidal system such as a tokamak, circulating fast ions generated by neutral beam injection are predicted to affect the beam stopping cross-section σ_{eff} of the neutral beam itself through the interaction between the neutrals and the fast ions. Although the amount of fast ions is less than the amount of thermal ions, the cross-section for ionization by each fast ion is usually larger than that by each background ion, because the relative velocity between the injected neutrals and the fast ions is usually small. The contribution to the beam-stopping cross-section of this "beam-particle self-interaction (BPSI)" can be especially notable for a high-energy beam injected into a low density plasma, which results in a large beam component [1].

Figure 1 shows results of the theoretical calculation [2] on the BPSI effect in the JT-60U experiment using a negative ion-based neutral beam (N-NB) of hydrogen with an energy of 350 keV. Here, a beam power of 2–3 MW and $\overline{T}_{\mathrm{e}} = 1 - 3$ keV are assumed. The cross-section enhancement rate δ due to BPSI, δ_{BP}, is defined as

$$1 + \delta_{\mathrm{BP}} \equiv \sigma_{\mathrm{eff\,(with\,BPSI)}} / \sigma_{\mathrm{eff\,(without\,BPSI)}} \qquad (1).$$

Note that these σ_{eff} values are calculated by taking account of the effect of the multi step ionization (MSI) [3] as well as the BPSI effect. From Fig. 1, we can see that the BPSI effect will be detectable for low density plasmas.

One of the beam lines of N-NB, N-NB (U), was used for this experiment. The beam particle and main plasma component were hydrogen. The beam power was 1.5 MW (at a maximum flat-top) with an energy of 350 keV. Throughout the injection, the major plasma parameters were kept nearly constant: $I_{\mathrm{p}} = 1$ MA, $B_{\mathrm{t}} = 2.5$ T, $\langle n_{\mathrm{e}} \rangle = 0.92 \times 10^{19}$ m^{-3}, $\langle T_{\mathrm{e}} \rangle = 1.2$ keV. Since the BPSI effect becomes conspicuous after the build-up of beam components, the beam pulse should be longer than the slowing-down time of beam ions. For the above plasma parameters, the slowing-down time τ_{s} is several hundred msec (for example, $\tau_{\mathrm{s}} \sim 0.2$ sec at $n_{\mathrm{e}} = 0.9 \times 10^{19}$ m^{-3}, $T_{\mathrm{e}} = 1.2$ keV). The shine-through power is evaluated using the temperature increment of N-NB facing tiles measured by an

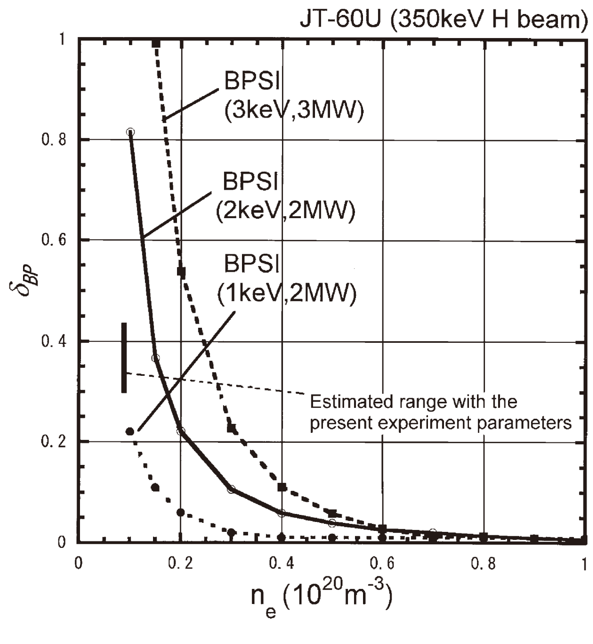

Fig. 1 Estimation of BPSI effect in JT-60U.

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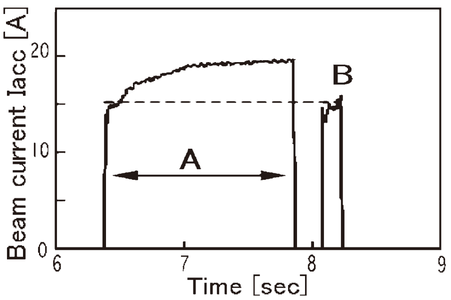

Fig. 2 Actual waveform of beam current

infra-red (IR) camera. If the BPSI effect becomes effective, a gradual reduction of the shine-through power with a time scale of τ_s should be observed.

The injection sequence of the N-NB (U) is shown in Fig. 2: After the first pulse for 1.5 sec (phase A) and a short (0.2 sec) preprogrammed interruption, the 2nd pulse was injected, but was interrupted by a breakdown after 0.12 sec injection (phase B). The available data were obtained by phase A.

In order to evaluate the shine-through power, the heat transport in the facing tile has been analyzed using the 2D numerical code ABAQUS [4]. Without the BPSI effect, the shine-through power should be in proportion to the beam power and therefore to the beam current I_{acc}. However, it is found that, the time evolution of the tile temperature in phase A is not reproduced by the calculation assuming the shine-through power in proportion to I_{acc} in Fig. 2, as shown in Fig. 3 by a fine line (indicated by 'w/o wave fit'). Therefore, we next tried to calculate the time evolution of the shine-through power so as to reproduce the time evolution of the tile temperature during the first beam pulse. Since the absolute value of the shine-through power is unknown, it is calibrated so that the calculated tile-temperature is equal to the observed one at the end of phase A.

The estimated waveform of the shine-through power is shown in Fig. 3(a) and the measured tile-temperature (dotted curve) is compared with the numerical calculation (solid curve) in Fig. 3(b).

The time evolution of tile temperature is well reproduced assuming the waveform of shine-through power shown in Fig. 3 (a), which decreases during the beam pulse in spite of the increase in injected power with I_{acc} shown in Fig. 2. The reduction of the shine-through fraction is about 35%.

This result suggests that the shine-through power was reduced within several hundred msec from the beginning of phase A. This time scale is close to the build-up (slowing-down) time of the fast ion component due to N-NB injection. According to the measurements of the electron temperature, density and radiation power, the estimated change in the effective charge of the plasma (Z_{eff}) during the phase A was less than 10%. The above 35% reduction in the shine-through fraction is not explained by such a small change in Z_{eff}.

Figure 1 also shows the δ_{BP} value estimated by the BPSI simulation using the plasma parameters used in the above experiment. Although there is some ambiguity in the estimation because of the sensitivity of δ_{BP} to the plasma profiles, the estimated range (δ_{BP} = 0.30~0.44) is consistent with the present experimental result.

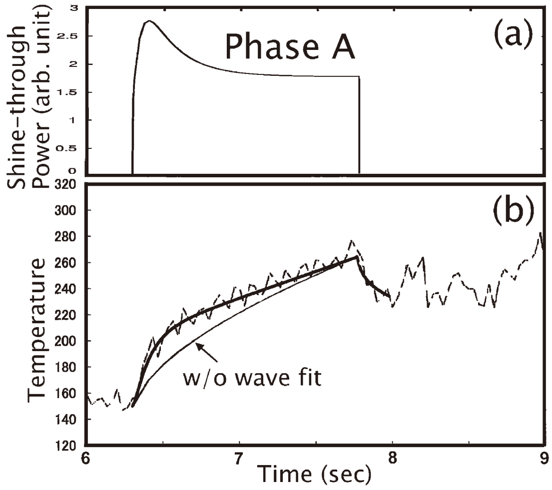

Fig. 3 (a) An estimated waveform for shine-through and (b) temperatures of the facing tiles. The measured temperature is denoted by a dotted curve while the numerical calculation is denoted by a solid curves.

In the previous experiments by JT-60U, in which the existence of the MSI was shown [5], no evidence of BPSI was reported, while the identified range of shine-through reduction by MSI was close to the range shown in Fig.1. In these experiments, however, the beam pulses were short in comparison with the slowing-down time of the beam ions. This is an essential difference from the present experiment.

Since the parameter range of the present data is restricted, further experimental evidence, for example, the density dependence of the waveform of the shine-through, will be required to confirm the existence of the BPSI effect.

In summary, it is found that the beam shine-through power decreased by about 35% within several hundred msec after the injection of N-NB into a low density plasma (~1 × 10^{19} m^{-3}) in JT-60U. This result was consistent with a prediction by the BPSI theory [1,2]. The lower density operation enabled by BPSI will increase flexibility in the design and operation of future reactors and ITER, especially in the initial start-up phase.

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