CURRENT DRIVE BY NEGATIVE-ION-BASED NEUTRAL BEAM INJECTOR IN JT-60U

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1. Introduction

The goal of negative-ion-based neutral beam injection (N-NBI), which is more efficient in producing high energy neutral beams than the conventional positive-ion-based system (P-NBI) at beam energies exceeding several hundred keV per nucleon, is heating and non-inductive current drive of high-density high-temperature plasmas in tokamak fusion reactors. For the next generation tokamaks, such as ITER, a beam energy of $\sim$ 1 MeV per nucleon is anticipated, and a number of researches and developments of N-NBI are ongoing. In this paper, the recent result of non-inductive current drive using N-NBI at JT-60U is presented.

2. Status of N-NBI at JT-60U

The N-NBI system of JT-60U[1] has a tangential beam-line co-directional to the plasma current. It has two negative ion sources located symmetrically with respect to the equatorial plane at an injection angle of 2.75°. The system is designed to deliver 10 MW of beam power at a beam energy of E_b = 500 keV for 10 seconds. The overall efficiency of the system is 40%.

The installation of the system on JT-60U completed in the spring of 1996, followed by an immediate conditioning, aging and beam injection into tokamak plasmas. The injection power increases progressively as shown in Fig. 1. Up to now 5.2 MW of deuterium beam has been injected into plasmas at 350 keV for 0.7 seconds (4.2 MW at 360 keV for hydrogen beam). The individual maximum for energy and pulse duration is 400 keV (2 MW, 0.35 s) and 1.9 seconds (300 keV, 1.2 MW).

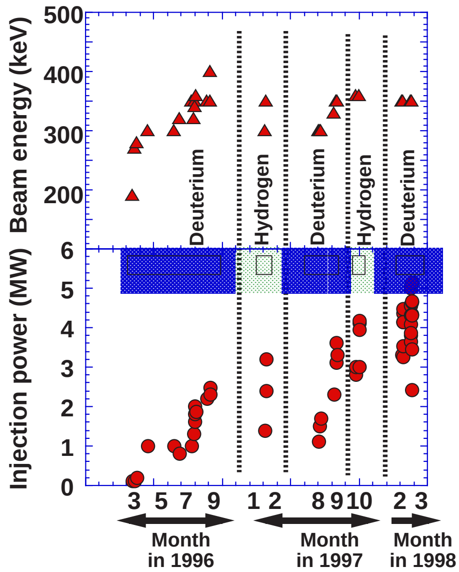

Figure 1: Progress in achieved beam energy and injection power of N-NBI at JT-60U.

3. Effective Ionization Cross-Section of N-NB

The heating and driven current profiles of N-NB depend directly on the ionization cross-section of the beam. At high beam energy and high electron density, it is theoretically predicted that multistep processes, such as excitation with subsequent ionization, become important and the beam deposition profile can be substantially modified[2]. For instance, the enhancement of ionization cross-section for E_b = 500 keV and $n_e = 10^{19}$ m^{-3} can be as large as 40-50% compared to that of singlestep processes. The optimization of beam deposition at high beam energy requires, therefore, an experimental verification of the ionization processes. However, previous experiments were limited to $E_b \leq 140$ keV per nucleon.

The effective ionization cross-section σ_s of hydrogen beam was studied in JT-60U by measuring the shine-through fraction η_{st} of N-NBI[3]. Here, η_{st} is roughly proportional to $\exp(-\int n_e \sigma_s d\ell)$. The experiments were conducted in hydrogen plasmas with Z_{eff} = 1.3–2.2, $\overline{n}_e = (1.0–4.1)\times 10^{19}$ m^{-3}, and $\sim$ 2.8 MW of hydrogen N-NBI at E_b = 350 keV. The shine-through power was measured by two sets of thermocouple arrays installed on the armor tiles.

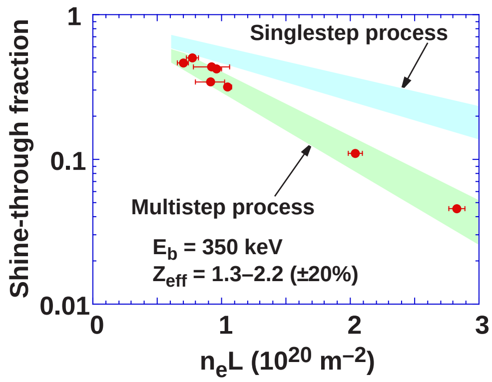

Figure 2: Shine-through fraction of N-NBI as a function of line integrated density $n_e L$.

Figure 2 shows the experimentally obtained shine-through fraction as a function of line integrated density $n_e L$. Theoretical predictions from singlestep and multistep processes are also shown, where hatched area corresponds to $\pm$20% uncertainty in Z_{eff} measurement. Clearly, rapid decrease in experimental shine-through fraction with increasing $n_e L$ agrees with multistep processes, proving the validity of the theory.

4. Non-inductive Current Drive by N-NBI

To make a reliable extrapolation of N-NB current drive to future tokamaks, it is necessary to identify non-inductive driven current profile as well as its amount. This can be done by employing the analyzing technique recently developed by Forest *et al.*[4] with motional Stark effect diagnostic (MSE)[5]. The idea is that after solving equilibrium using magnetic and MSE data, inductive portion is evaluated from the time derivative of poloidal flux ($\propto E_\parallel$) multiplied by neoclassical conductivity, then subtracted from the total to give the non-inductive current.

A typical waveform of N-NB current drive is shown in Fig. 3, where low plasma current of I_p = 0.6 MA, low density of $\overline{n}_e = 0.7\times 10^{19}$ m^{-3} was chosen and only minimum P-NBI necessary for the diagnostic was injected to clarify the pure N-NB driven current profile. The P-NBI was counterbalanced by an opposite directional beam to make the P-NB driven current negligible. By injecting 2.1 MW of N-NB at E_b = 360 keV, loop voltage dropped from 0.39 V to 0.27 V, stored energy and central electron temperature increased, however no significant change in ion temperature.

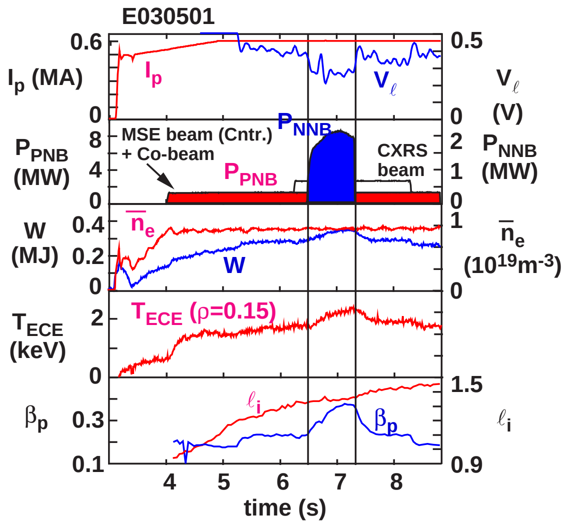

Figure 3: Waveforms of N-NB current drive.

To deduce the N-NB driven current, bootstrap current was evaluated (49 kA) with the current drive code ACCOME [6] and subtracted from the non-inductive portion.

As shown in Fig. 4, the resultant N-NB driven current profile is rather peaked at the plasma center. This is mainly due to the on-axis geometry of the N-NB beam path. A similar driven current profile is also predicted from the calculation by ACCOME. The experimental and calculated N-NB driven currents are respectively 102 kA and 79 kA. These results are consistent within the experimental error.

An attempt to drive current by the combination of N-NBI, P-NBI, and bootstrap current was also made. In a deuterium discharge with I_p = 1 MA, B_t = 3 T, $\overline{n}_e = 2.3\times10^{19}$ m^{-3}, $T_e(0)$ = 4.5 keV, 3.9 MW of N-NB at 330 keV and 16 MW of P-NB at 87 keV (tangential and perpendicular) were injected. From the MSE diagnostics, 78% of total current was identified to be driven non-inductively and 220 kA of which was driven by N-NBI. Figure 5 shows the driven current profile calculated by ACCOME for the same shot. The N-NB driven current is broader than that in Fig. 4, since the beam path was off-axis in the analyzed discharge. The calculated currents driven by N-NB, P-NB, and bootstrap current are respectively 270 kA, 125 kA, and 323 kA. The total amount of non-inductive driven fraction ∼72% is again comparable to the experimental observation. The experimentally obtained current drive efficiency of N-NBI for this shot is $\eta_{CD} = 0.42\times10^{19}$ A/W/m^2.

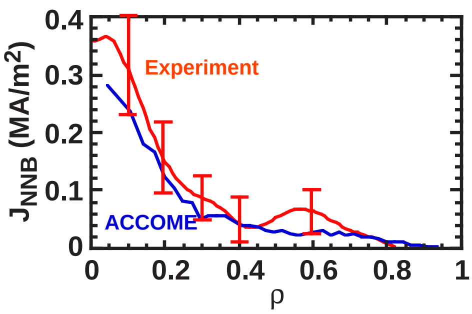

Figure 4: Measured and calculated N-NB driven current profiles.

Here, efficiency is defined by $\eta_{CD} = \overline{n}_e I_{CD} R_p / P_{CD}$ with I_{CD}, R_p, and P_{CD} being respectively driven current, plasma major radius, and current drive power. For a shot with $T_e(0)$ = 2.5 keV η_{CD} was 0.29×10^{19} A/W/m^2, so it has a tendency to increase with T_e.

When the beam velocity becomes comparable to Alfvén velocity, toroidicity-induced Alfvén eigenmodes (TAE) may be excited and deteriorate the efficiency of N-NB current drive. In JT-60U, continuous TAE modes with frequencies of 120–210 kHz were observed when hydrogen N-NB (360 keV) was injected into a low B_t (1.7 T), low magnetic shear, helium plasma. At present, however, no notable loss of fast ions is observed during N-NB injection. Further investigation on the influences of TAE and MHD instabilities are to be conducted.

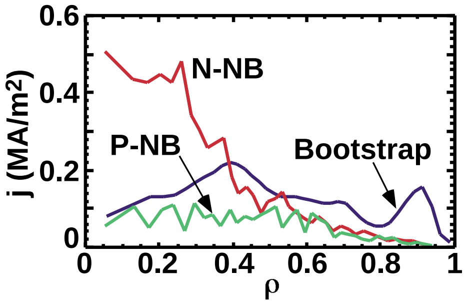

Figure 5: Current profile calculated by ACCOME for combined N-NB, P-NB, and bootstrap current drive.

5. Summary

The N-NBI system at JT-60U is making a steady progress; up to 5.2 MW of power has been injected at 350 keV. Measuring the shine-through fraction of N-NBI at 350 keV, it was experimentally verified that the ionization process of N-NB can be described by the multistep processes. The N-NB driven current profile was identified by MSE diagnostic and effective central current drive was confirmed. The current drive efficiency tends to increase with T_e. The experimental observations were consistent with theoretical prediction indicating the validity of classical picture in N-NB current drive.

Acknowledgments

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