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Observation of knock-on tail formation using neutral particle analyzer in LHD deuterium plasma

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In a thermonuclear plasma, Coulomb scattering dominates, but nuclear forces contribute to beam–bulk ion scattering. Scattering processes to which nuclear forces contribute are called nuclear elastic scattering (NES) [1]. NES has a much smaller cross section than Coulomb scattering but transfers more energy per event. One of the effects of NES is the formation of a non-Maxwellian high-energy tail (knock-on tail) in the ion velocity distribution, caused by fast ions from neutral beams (NBs) repeatedly transferring energy to bulk ions.

Our research group conducted a NES effect verification experiment[2] by injecting a 180 keV high-purity hydrogen (H) beam (<1 ppm deuterium) into the Large Helical Device (LHD) deuterium plasma. One of the results of the experiment was an order of magnitude increase in neutron emission from the $D(d,n)^3He$ reaction due to the NES caused by the H beam injection[3]. The increased $D(d,n)^3He$ reactivity indicates knock-on tail formation in the deuteron velocity distribution [3]. Meanwhile, a Compact Neutral Particle Analyzer (CNPA) has been installed on the LHD for high-energy particle diagnostics[4]. Fast deuterium derived from charge exchange reactions of fast deuterons in plasma can be detected with NPA. Therefore, by using NPA, we observe the formation of knock-on tails in the deuteron velocity distribution function from our previous LHD experiments.

Figure 1 shows a schematic of the LHD, the NBs configuration, energy, deuterium fraction, and the CNPA line of sight. The energy of neutral beams is 180 keV and the deuterium fraction is less than 1 ppm. The incidence of the NBs is tangential to the toroidal field axis, and the CNPA line of sight is perpendicular to it.

The change in the charge-exchanged deuterium count rate due to the injection of H beams into the LHD deuterium plasma was measured by CNPA. Figure 2 summarizes the data for each shot. The vertical axis represents the ratio of the deuterium count rate during periods with and without H beam injection. The horizontal axis represents the time-averaged $T_e(0)$ with beam injection. A comprehensive analysis shows the deuterium count rate ratios of 0.98 for shots at 2-4 keV and 2.37 for shots at 7-13 keV. The Rutherford differential scattering cross-section is inversely proportional to the fourth power of the relative velocity. Therefore, at lower electron temperatures, knock-on tails in the deuteron velocity distribution function are less likely to form, as energy is more easily transferred from the H beam and high-energy deuterons to electrons via Coulomb scattering. Consequently, the experimental results demonstrate that energetic component (knock-on tail) appeared at $T_e(0)$ =7-13 keV. However, the two red data points in Figure 2 (ratios 1.4 and 1.6), which have lower ratios compared to the other shots with $T_e(0)$ =7-13 keV, likely reflect insufficient knock-on tail formation due to low beam power. A detailed discussion, including numerical analysis, will be presented.

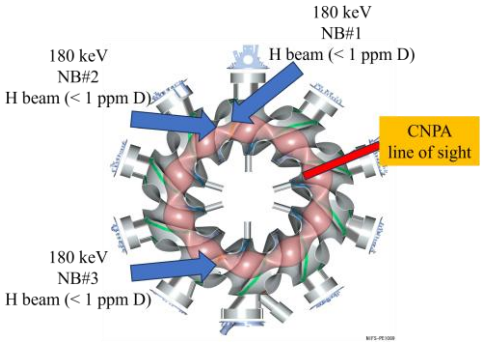

Figure 1. A schematic of the LHD, the NBs configuration, energy, deuterium fraction, and the CNPA line of sight

References
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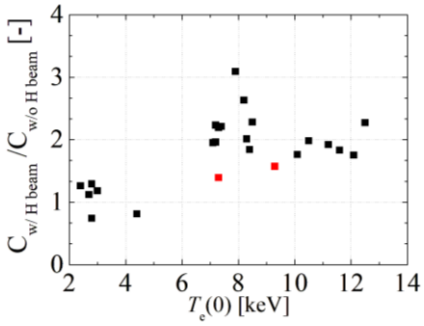

Figure 2. The ratio of deuterium count rates with and without H-beam injection, plotted against time-averaged $T_e(0)$ with beam injection for each shot.