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First Neutral Beam Heating Experiments in Versatile Experiment Spherical Torus

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Spherical Torus (ST) has been considered not only as a fusion neutron source but also as a commercial fusion reactor by noting its compactness and cost-effectiveness. However, compact ST devices may be difficult to reach high temperature with neutral beam injection (NBI) heating because of their small plasma size and weak field strength. Although high magnetic field by adopting high temperature superconducting magnet may overcome this problem as planned ST devices such as ST40, fast ion confinement still make the efficiency of neutral beam heating very low in the ST devices due to their small plasma size. Therefore, it is important to study characteristics of neutral beam heating in the ST device and find how to increase its efficiency, which will be useful to enhance fusion alpha confinement in fusion reactors.
In VEST (1), The 750 kW neutral beam injector (NBI) system was developed to deliver hydrogen neutral beam at 15keV for a pulse length of 10 ms by the Korea Atomic Energy Research Institute (KAERI) (2). As shown in Fig 1 a), the ion beam power of ~0.4MW of 14kV for a pulse length of up to 2 ms was achieved through commissioning after it is installed in VEST. On the other hand, a Secondary Electron Emission Detector (SEED) has been also developed to measure shine-through loss. Fig 1 b) shows the shine-through loss measurement results of the 12kV beam according to plasma current. Since the plasma density increases with increasing current, the shine-through losses were gradually reduced as the plasma current increased, and sufficiently lowered to below 30% when the plasma current was about 70 kA or higher. These results were consistent with the NUBEAM code (3) calculation results using the measured density profile in Fig 3 a). Therefore, shine-through loss in this range was low enough.

Figure 1: Fig. 1. a) Ion beam power of 400kW at 14kV extraction result. b) Shine through loss measurement results of 12kV beam by SEE detector.

Using these tools, the first NBI heating experiments were successfully carried out. Fig 2 a) shows the plasma parameters when NB power of 400 kW was injected for 2 ms at 304 ms. A major positive effect of the neutral beam heating in VEST was shown by increasing plasma current at the same loop voltage. And stored energy estimated from diamagnetic flux was also increased slightly. Even though electron temperature and density at R = 0.7m was not changed much, these changes can be seen as obvious evidence of heating. In order to increase the plasma current at the same loop voltage, the impedance of plasma should be reduced, it can only be achieved by increasing the electron temperature. This heating effect lasted several milliseconds, which is estimated as a fast ion confinement time. After fast ion confinement time, the plasma was cooled down with increasing inflow of impurities. It is another evidence that orbit loss is dominant in this experiment.
Figure 2 b) shows the increase in plasma current depending on the injection time of the neutral beam with a pulse width of 2 ms. The largest increase in current was when the NB is injected at 306 ms which is the time that the shine-through losses were sharply reduced. After 306 ms, the heating effect was decreased despite plasma current is increased. It is very interesting but not easily understood.

Figure 2: Fig. 2. a) VEST NBI heating experiment result. A black line (#24872) is a reference ohmic discharge shot with B_T=0.15 T. And a red line (#24882) is NB heated plasma. A red box means NB injection time (304 ms to 306 ms). b) the changes in plasma current according to the NBI injection time.

The LORBIT code (4) has been used to analyze the NB heating experiment results through the calculation of a fast ion orbit trajectory. From fig 3 a) and b), the results of previous experiments seem to be due to good confinement of fast ion by hollow current profile of early phase of discharge. As shown in Fig. 3 a), from the 304ms to 308 ms which is the early phase of discharge, the plasma density had a hollow profile. The plasma density increase with increasing current as mentioned before. Thus, Plasma current density can be also considered hollow. The fast ion orbit trajectories according to the ionized position in parabolic and the hollow current density profile case was shown in Fig. 3 b). Even though the plasma current were low, Hollow current density profile case had better fast ions confinement performance. It shows that the current density at the outboard boundary is more important than the plasma current intensity in terms of fast ion confinement.

Figure 3: Fig. 3. a) Plasma density profile measurement data by triple langmuir probe. b) Fast ion orbit trajectory of 12kV beam ion calculated by using LORBIT code. A red dot means the ionization point of the neutral beam. Same line color is the same ionization position. In #24790, I_P =116 kA, B_T=0.18 T, parabolic current density profile, In #23581, I_P =105 kA, B_T=0.15 T, hollow current density profile.

In order to increase heating efficiency even at higher currents in Fig 2 b), it is necessary to reduce orbit loss using control of the magnetic field structure, lower energy beam injection for small orbit size. In this research, a high three-atomic fractional beam heating experiment is being performed to lower the beam energy while maintaining the beam power.

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