PREDICTIVE STUDY OF NON-AXISYMMETRIC NEUTRAL BEAM ION LOSS ON THE UPGRADED KSTAR PLASMA-FACING COMPONENTS

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We simulate ion loss induced by neutral beam injection (NBI) in three-dimensional (3D) space with high fidelity on the plasma-facing components (PFCs) of the Korea Superconducting Tokamak Advanced Research (KSTAR) device. Utilizing a 3D collision detection routine [1] added to the NuBDeC code [2] and computer-aided design data reflecting the recent upgrade to a tungsten divertor, we have characterized 3D heat flux distribution and patterns over PFCs due to the NB ion loss throughout parameter scans. By elucidating the relationship between the heat flux distribution obtained from the parameter scan and beam configurations, we can strategically plan the configuration of the NBI heating system to mitigate the localization of heat flux through the use of a virtual platform [3] for integrated simulations.

First, the analysis of unfolded PFC surfaces demonstrates non-axisymmetric heat flux patterns, particularly showing band-shaped wetted areas that obliquely extend along the direction of poloidal and toroidal turns of NB ions as shown in Fig 1. This is because NB ions move both poloidally and toroidally as they drift inside the tokamak. NB ions deposited (or ionized) deeper inside the tokamak, meaning at a smaller minor radius closer to the magnetic axis, require a longer path to collide with PFC surface because they need to move further for more drift toward the wall. Then the wetted band expands diagonally over the PFC surfaces. The heat flux forms peaks due to the concentration of NB ion losses at protruding surfaces and toroidal leading edges. The change of non-axisymmetric loss pattern of this reference case will be shown and analyzed in case study elucidating parameter scan over beam and magnetic field parameters.

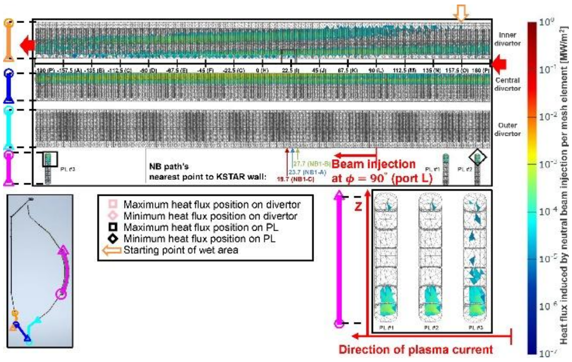

Fig 1. Heat flux colormap of the unfolded divertor and poloidal limiter (PL) surfaces from the NuBDeC simulation results of the reference setup: 100 keV NB1-C neutral beam for the equilibrium case of plasma current (I_p) 1.00 MA and poloidal beta (β_p) 1.0. The PL is zoomed-in in the bottom right panel with the z-axis and plasma current directions marked with red arrows. A white arrow with an orange boundary points to the starting point of the plasma-wetted area, which extends diagonally from the upper right to the red arrow on the left side. It continues from the red arrow on the right side spreading to the left.

Second, through a case study of NB1-C (beam source C of neutral beam 1) that results in the most loss, we analyse several changes in the heat flux patterns observed on the divertor and the poloidal limiter. Such analysis allows us to examine how variations in the parameters affect the movement of the peak heat flux position and the extent of the plasma-wetted area, if formed. It is observed that the percentage of power deposition increases with higher beam energy and larger poloidal beta values along with smaller plasma current. The results of this study are believed to help optimize design and operation of NBI heating systems.

As shown in Fig 2, the parameter scan reveals that lower I_p and higher β_p values result in increased power deposition on the divertor. Additionally, varying the beam source shows that shallower beam deposition (as with NB1-C) results in more NB ion losses compared to deeper sources like NB1-A and NB1-B. Reducing the beam energy from 100 keV to 60 keV significantly decreases both the maximum heat flux and the percentage of power deposition, forming narrower poloidal wetted areas on the divertor surface.

Movement of the magnetic separatrix's outer strike point from the outer to the central divertor significantly changes the heat flux distribution. The wetted area extends further in the direction of the strike point movement and reaches the inboard limiter. This movement also results in a wider wetted area on the PL, biased toward higher Z positions (Fig 3). Changes in the strike point position induce larger variations in the magnetic field at the plasma edge and the SOL region compared to variations caused by changes in β_p.

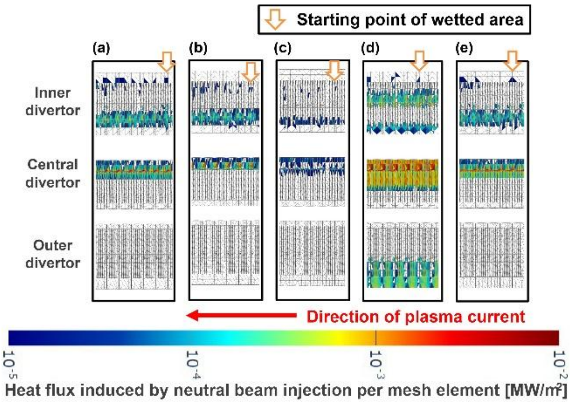

Fig 2. Enlarged planar views of the unfolded divertor comparing NuBDeC heat flux distributions due to NB ion loss: (a) reference setup, and single-parameter variations of (b) 60 keV beam energy, (c) NB1-A beam source, (d) I_p = 0.50 MA, and (e) β_p = 2.0. A white arrow with an orange boundary points to the most upstream point in the NB ion trajectories or starting point of the plasma-wetted area.

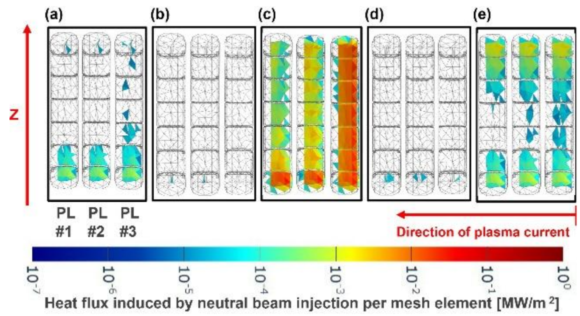

Fig 3. Enlarged planar views of the unfolded PL comparing NuBDeC heat flux distributions due to NB ion loss: (a) reference setup, and single-parameter variations of (b) NB1-A beam source, (c) I_p = 0.50 MA, (d) β_p = 2.0, and (e) outer magnetic separatrix strike point on the central divertor. Heat flux on the PL disappears when the beam source is changed from the reference case to a 60 keV NB1-C beam.

In our case study, we focus on the main parameters that control the heat flux patterns:

- The poloidal turn orbit and correspondingly the poloidal loss position are presumed to be determined by the beam deposition (i.e., ionization) position. For instance, an ion ionized near the plasma edge proximal to the HFS wall traverses a poloidal turn orbit at a larger minor radius. In this case, its trajectory collides earlier with the PFC surface after a shorter distance from its beam deposition position. In this study, we used beam sources with different tangential radii of beam injection. Notably, when the beam is injected closer to the HFS, the beam deposition also occurs closer to the HFS for the given plasma profiles. Moreover, variations in I_p and β_p lead to changes in the magnetic flux surface, which in turn causes redistribution of the plasma profile and consequently a shift in the beam deposition position.
- Shifts of the magnetic flux surfaces and the magnetic separatrix's outer strike point tend to cause NB ion losses at different positions, even with identical beam deposition distribution.
- Radial drift of NB ions causes a deviation ($\Delta \sim q v_{\parallel}$) of the center of the poloidal turn orbit [2]. $v_{\parallel}$ tends to be higher with increased beam energy. The safety factor increases due to weaker poloidal magnetic field induced by the lower I_p. Therefore, higher beam energy and lower I_p cause the particles to drift more, which results in higher heat flux on divertor.

By using a tool for quantitative analysis in a virtual environment of locally concentrated heat flux distributions based on actual geometry and experimental measurements, detailed NB ion collision information over the KSTAR PFCs can be provided. It can help analyse the thermal, chemical, and mechanical degradation, as well as atomic processes over the PFCs by providing NB-ion loss particle and energy f lux information. Ultimately, it may be possible to help optimizing H-mode operation scenarios for the KSTAR device with a tungsten divertor and support research and development of the advanced scenario for commercial fusion devices.

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