Modeling of neutral beam heating and current drive in Wendelstein 7-X

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The planning and scientific analysis of neutral beam discharges on Wendelstein 7-X (W7-X) relies heavily on simulations of neutral beam injection (NBI) and slowing down. Simulations of neutral beam injection provide the source term for calculation of energetic particle slowing down calculations. Simulations of neutral beam injection with the BEAMS3D code [1] have recently been validated with measurements in W7-X, providing a cross-code benchmark case [2]. Such simulations provide the initial condition for slowing down calculations from which values for neutral beam heating and current drive can be obtained. NBI heated discharges performed in the previous inertially cooled divertor campaign (OP1.2) [3] are being used to help validate the heating and current drive calculations [4]. These simulations are being used for both analysis of discharges conducted and informing future upgrades and experimental planning. A second beam-line is being brought online in the next campaign, along with attempts to operate at lower magnetic field. Simulations of neutral beam heating and current drive are playing a vital role in data analysis for W7-X.

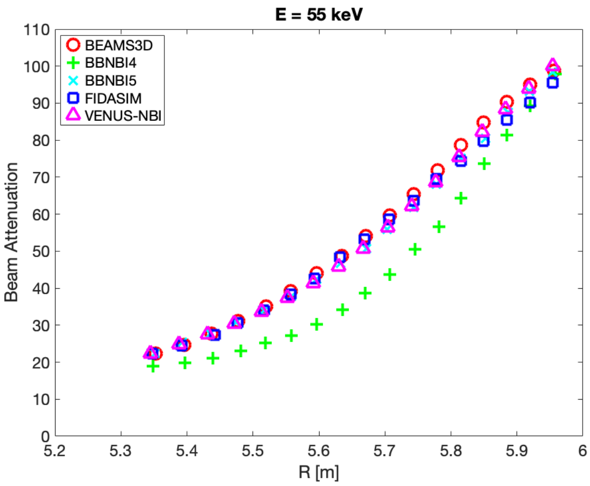

Figure 1: *Comparison of beam attenuation between a multitude of codes modeling W7-X neutral beam injection. This figure has been extended from that in reference [2] through the inclusion of the BBNBI5 code.*

Neutral beam injection simulations serve as the initial condition for NBI heating, current drive, and wall loss simulations. The W7-X NBI system is composed of two neutral beam boxes with 4 source locations each providing up to 2.5MW of neutralized NBI power [5]. In the previous campaign two source were installed in one box oriented in the direction of the magnetic field injection 55 keV Hydrogen. Measurements of neutral beam attenuation

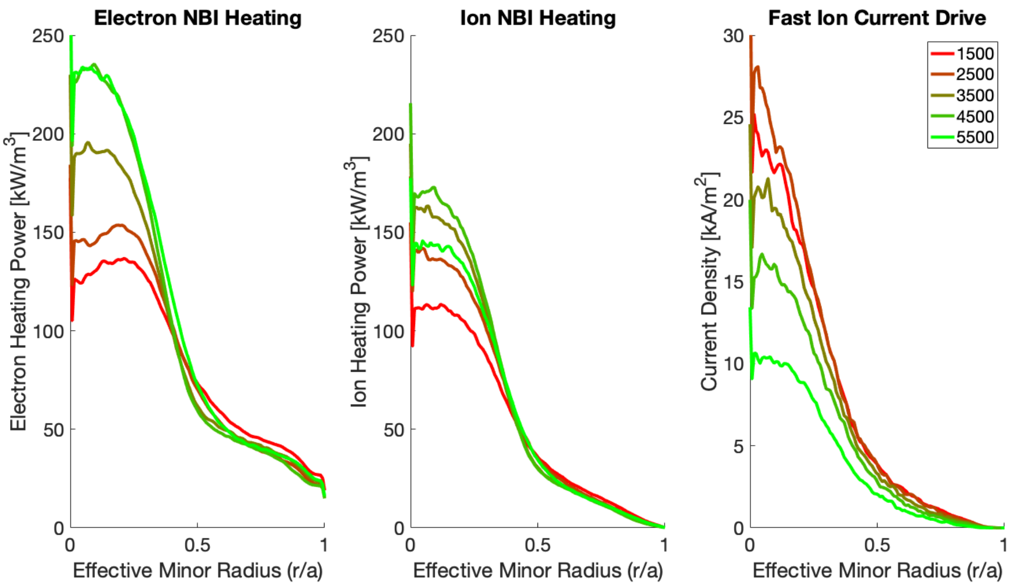

Figure 2: *Electron heating (left), ion heating (center) and fast ion current density (right) for a pure NBI discharge in W7-X (20181009.43). Legend indicates time slices in ms.*

by the beam emission spectroscopy system were used to validate neutral beam deposition models. Figure 1 depicts a cross code benchmark of neutral beam attenuation showing generally good agreement between codes. Simulations of neutral beam shine-through provide boundary conditions for ANSYS modeling of wall element. Such BEAMS3D-ANYSYS coupling is informing geometrical and material changes to the W7-X beam dumps. Validated simulations of neutral beam deposition serve as a basis for the slowing down simulations which provide information on heating and current drive.

Neutral beam heating and current drive are obtained from simulations of energetic particle slowing down through integrals over the energetic particle distribution function. The BEAMS3D code provides such simulations by evolving the trajectories of gyro-centers on a background grid. It solves the following set of equations

$$\frac{d\vec{R}}{dt} = \frac{\hat{b}}{qB} \times \left(\mu \nabla B + \frac{mv_\parallel^2}{B} (\hat{b} \cdot \nabla) \vec{B} \right) + v_\parallel \hat{b} + \frac{\vec{E} \times \vec{B}}{B^2}$$

$$\frac{dv_\parallel}{dt} = -\frac{\mu}{m} \hat{b} \cdot (\nabla B)$$

where $\hat{b} = \frac{\vec{B}}{B}$, $\mu = \frac{1}{2}\frac{mv_\perp^2}{B}$ is the magnetic moment, $\vec{E} = -\nabla\Phi$ is the electric field, and $v_\parallel = \frac{d\vec{R}}{dt} \cdot \hat{b}(\vec{R})$ is the component of velocity parallel to $\vec{B}$. Plasma quantities are stored on a cylindrical mesh where an interface to VMEC ideal magnetohydrodynamic equilibrium provides the mapping. Heating is determined by integrating the distribution function over ion and electron collisional operators. While neutral beam current drive is determined from integrals over the parallel velocity corrected for the effect of trapped electrons. Figure 2 shows the heating and fast ion current for five time slices during a discharge solely heated by NBI (20181009.43). Toward the end of the discharge we see a decrease in ion heating associated with a decreasing electron temperature. What is shown in the right most panel of figure 2 is the fast ion current which must be corrected for the effect of trapped electrons in order to represent the neutral beam current drive. Various forms for this correction term have been formulated with a low-collisionality stellarator version being recently formulated from the drift kinetic equations [6].

The large resistive diffusion time ($\sim$ 30 s), the relatively short neutral beam duration (5 s), and the lack of magnetic field pitch angle measurements in W7-X make direct measurement of NBCD difficult. What can be stated at this point is that the direction of current drive is confirmed consistent with modeling and that experiments alternating sources confirm modeling predictions of the radial and tangential natures of each source. Future work will attempt to address these shortcomings.

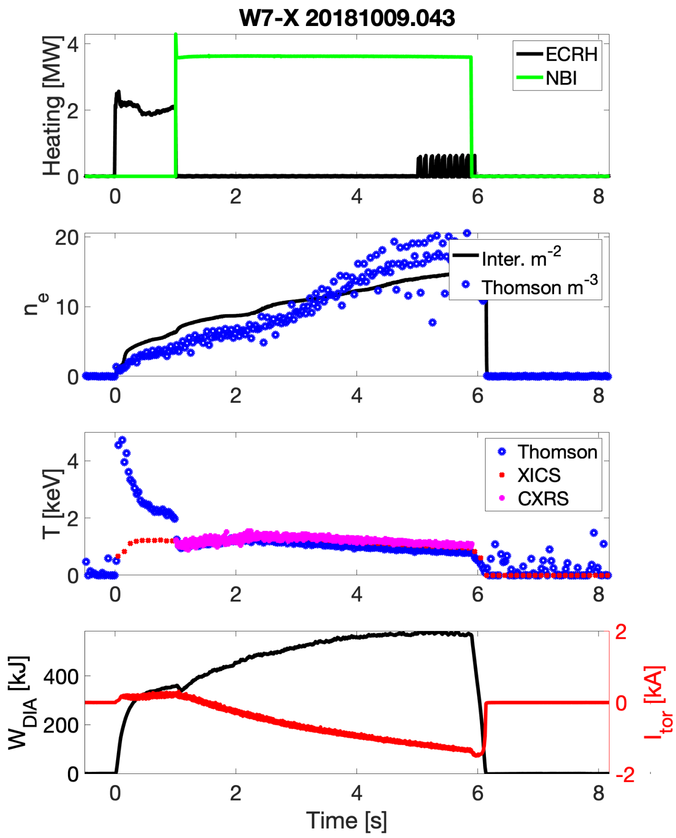

Figure 3: *Overview plot showing discharge pure NBI discharge used for modeling. Here negative toroidal current implies toroidal current in the direction of the magnetic field (consistent with modeling).*

While detailed validation of such simulations will require additional work, data from these simulations is being used to inform future planning. Full orbit simulations with ASCOT5 are being conducted to better understand wall loads and inform placement of future in-tile fast ion loss detector [7]. These simulations are leveraging BEASM3D and its interface to both VMEC and ASCOT5. As mentioned, simulations of shine through are being used to provide boundary conditions for ANSYS modeling of beam dump components. Finally, simulations at lower magnetic field and for the second neutral beam line are helping to inform planning of future experiments in W7-X. Additionally, work is underway to extend the

BEASM3D model to include fusion products along with interfaces to HINT and EFIT equilibria.

Validated models of neutral beam injection, fast ion slowing down, and energetic particle losses are key to experimental analysis and planing. Building on validated neutral beam deposition simulations, simulations of fast ion slowing down and loss are being validated. Attempts to compare experimental data to simulations highlight the need for more careful and dedicated experimental time in future campaigns. Experiments design to measure the deposited beam power will need to take into account the ~ 30 ms asymptotic time for fast ions to slow down and order 100 ms confinement times in W7-X. Measurement of neutral beam current drive will require longer NBI pulse lengths and neutral beam injection into long pulse plasmas. With validated slowing down models, work on validation of losses and wall loads can be fully explored.

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