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Predictions of Neutral Beam Deposition and Energetic Particle Losses in W7-X

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The demonstration of favorable energetic particle confinement is a key requirement for any magnetically confined fusion device to be considered for reactor development. In deuterium-tritium reactions, Helium atoms are born with 3.5 MeV energies which must slow down through collisions with the bulk plasma (thereby heating it). If these particle contact the wall before transferring the majority of their kinetic energy to the plasma, the device may have difficulty reaching a burning state. To address such particle confinement physics, the W7-X [1] device has been fitted with two neutral beam injectors. These injectors accelerate neutral hydrogen species to 55 keV which then charge exchange to become energetic ions in the plasma. Such energies provide a good mimic of the Helium particles produced in a reactor (the so-called $\rho*$ scaling). Modeling of such neutral beam systems [2] allows optimization of the W7-X magnetic structure for improved confinement of such energetic particle species [3]. In this work we examine predictions of neutral beam injection for W7-X.

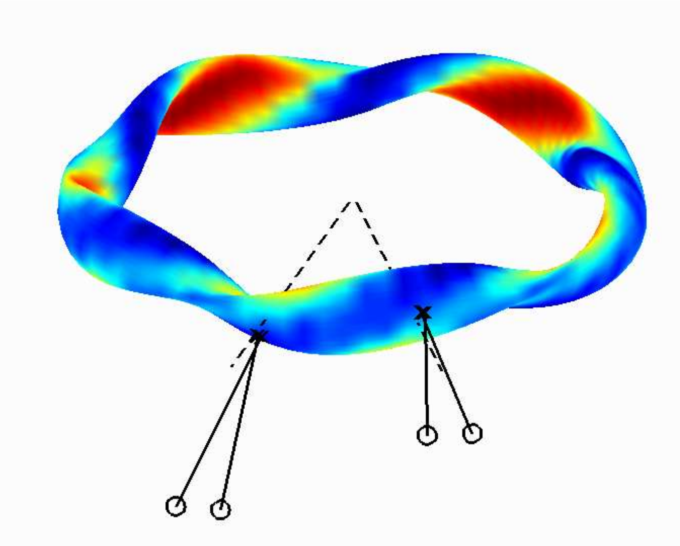

Figure 1: *Beamline geometry for the Q3, Q4, Q7 and Q8 sources. Magnitude of the magnetic field is depicted for the standard configuration.*

In order to accurately model confinement of neutral beam energetic particles a detailed model is required. The neutral beams in W7-X accelerate neutral hydrogen to 55 keV (60 keV for deuterium). These particles must then traverse the plasma, charge-exchanging, thus becoming energetic ions (or they passing through the plasma without ionization, the so-called 'shine-through'). This process is a function of the plasma densities, temperatures, stellarator magnetic equilibrium, and beam-line geometry. Once ionized the newly formed energetic ions will orbit in the magnetic field of the device. These trajectories are modified through collisions with the plasma (slowing-down and pitch angle scattering) along with magnetic fluctuations in the plasma (MHD modes, RF heating, etc.). The BEAMS3D code [2] provides us with such a tool for prediction and analysis of such a system. Interfaced to the VMEC equilibrium code [4] and using a virtual casing principle [5], BEAMS3D can follow particle trajectories from the neutral beam injector, traversing the plasma (where they may ionize), and all the way to the vessel wall.

The neutral beam system on W7-X is composed of two neutral beam injectors with four sources each (replicas of the ASDEX-Upgrade NBI-system) [6]. The port structure through which the neutral beams shine has a generally radial orientation. Each neutral beam assembly contains four sources resulting in four distinct beam-lines each. The sources are oriented such that they fire across the centerline of the beam assembly. This results in two beam lines being more radial and two more tangential. Given the three dimensional topology of the stellarator, each neutral beam assembly is situated either 30 cm above or below the mid plane of the device. For startup two sources were identified in each neutral beam assembly as being scrapped off on the port armor or possibly hitting an un-armored section of the first wall. Thus the decision was made to use only two sources in each beam line, sources Q3 (radial), Q4 (tangential), Q7 (radial), and Q8 (tangential) [7]. The sources themselves are designed to inject 55 keV H^0 (60 keV D^0) at more than 1 MW each. The 'radial' sources inject at 1.1 MW (1.8 MW D^0) and the tangential sources inject at 1.3 MW (2.0 MW D^0). Figure 1 depicts the beam line geometry against the equilibrium magnetic field of the standard configuration.

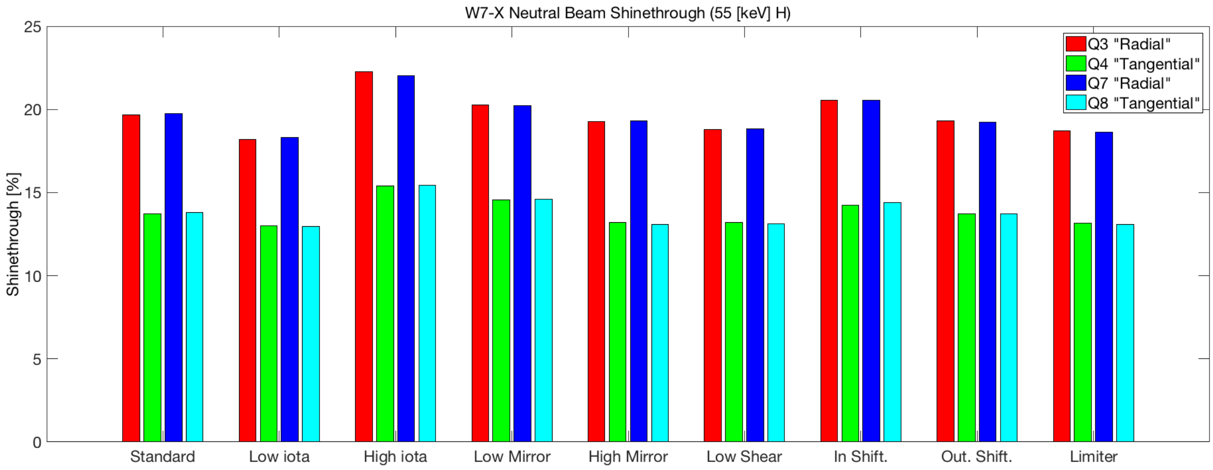

Figure 2: *Predictions of neutral beam shine-through for the 6 magnetic configurations in W7-X. The Q3 and Q4 beam lines inject in the anti-parallel direction, while Q7 and Q8 inject parallel to the magnetic field.*

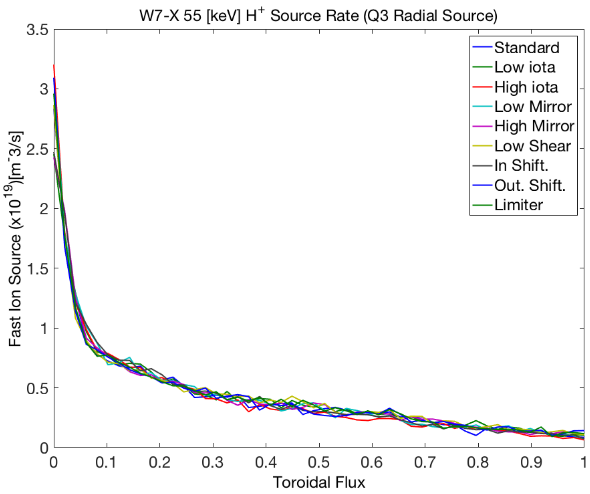

Figure 3: *Neutral beam birth profiles for the 55 keV H+ ions (Q3 Radial Source).*

Neutral beam shine-through will provide an early validation of the physical models employed in out model. At lower plasma densities not all neutral particles ionize, the un-ionized particles then pass through the plasma and contact armored tiles on the plasma vessel wall [7]. Figure 2 depicts estimates for shine through for the 6 baseline configurations of W7-X. In these simulations only the 55 keV Hydrogen component of the beams is considered. All configurations share the same density (central electron density $8 \times 10^{19}\ m^{-3}$) and temperature profiles ($T_{i0} = 3.2$ keV and $T_{e0} = 2.9$ keV). This places focus on the geometrical aspects of the configurations. Such analysis neglects the effects of magnetic configuration on confinement. All beams with ‘radial’ configurations indicate the greatest level of particle shine-through. In every configuration the ‘tangential’ beam lines indicate approximately 5% less shine-through. Although some variation exists between magnetic configurations, it is unlikely that such differences would be measurable. Comparison with experimental measure of shine-through will confirm if the ADAS cross sections are sufficient for capturing the bulk of the ionization physics (ion-impact, charge-exchange, electron-impact ionization).

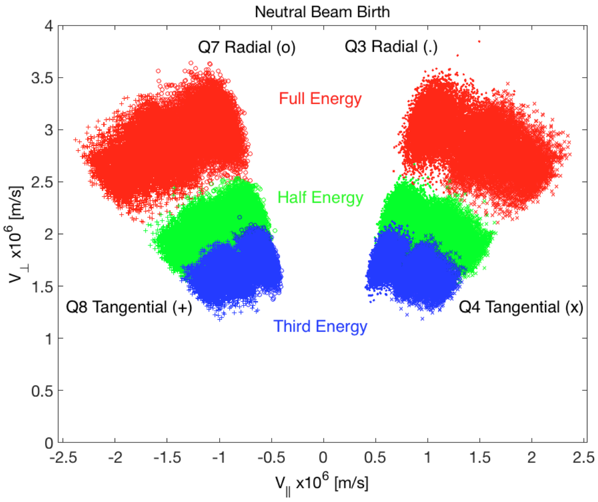

Figure 4: *Velocity space distribution of the four beam lines at differing plasma energies. Colors indicate energy while markers indicate beam lines.*

Simulations such as these allow investigation of neutral beam parameters which are difficult to directly measure. Figure 3 depicts the birth profile for the ‘radial’ Q3 source at full energy (55 keV). All configurations show similar birth profiles for the full energy component of the beam. This suggests that configuration variation should not play a large role in particle birth profiles (controlling for transport changes, similar temperature and density profiles). Examination of the full, half, and third energies indicate that the lower energy particles are ionizing at larger radii. The increased ionization rate in the core can be attributed to a smaller shine through for that component of the beam. Figure 4 depicts the pitch angles at which the particles are born. As intuition would dictate, the tangential beam lines produce particles with smaller pitch angles that those of the radial beams.

In this work the deposition of the W7-X neutral beam system has been analyzed with the BEAMS3D neutral beam code. Shine through predictions for the neutral beam system indicate a rather weak variance on equilibrium configuration. With the the tangential sources indicating a 5% increase in coupling to the plasma over the radial sources. Estimation of the birth profiles for energetic ions show little difference between configurations. A clear separation in phase space for particle births locations is also present. Here the full, half and third energies are clearly visible. There is some overlap between the radial and tangential sources, but a distinction between the populations can clearly be made. Future work will address energy deposition and current drive estimates, while a detailed wall model will allow estimation of particle loss locations.

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