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Abstract

The energetic particle slowing down model in the BEAMS3D stellarator neutral beam code is compared to analytic models and experimental data from the Wendelstein 7-X experiment (W7-X). Recently, the first neutral beam experiments were performed in W7-X, providing validation of neutral beam deposition codes (Lazerson S.A. et al 2020 Nucl. Fusion 60 076020). This work builds upon that work, and follows the gyro-center orbits of the neutral-beam-generated fast ions to the plasma boundary. Slowing down times based on measurements of diamagnetic energy changes are compared to simulation data. A discharge solely heated by neutral beam injection is used to compare neoclassical heat flux estimates to neutral beam fueling, heating, and current drive. Experimental estimates of electron heat diffusivity suggest that electron turbulence is destabilized by density peaking in the discharge. Neutral beam current drive dominates over bootstrap current, resulting in a reversal of the toroidal current, as seen experimentally. Particle losses and heat flux through the equilibrium boundary are described. The effects of the magnetic configuration and plasma density on such parameters are also assessed. Benchmarking based on analytic estimates and other energetic particle codes is presented.

Keywords: stellarator, simulation, validation, energetic particles, NBI, heating, current drive

(Some figures may appear in colour only in the online journal)

1. Introduction

Energetic particles play a significant role in magnetically confined fusion devices, and are produced via external sources in experiments and through the process of nuclear fusion in proposed energy-producing reactors. The direct measurement of energetic particle properties is difficult in these devices and, as a result, scientists rely on simulations for both prediction and interpretation of the results. In particular, the effect of such particle populations on plasma fueling, heating, current drive, and device wall loads is often sought. Such simulations must be validated against analytic estimates of such quantities and against experimental evidence. Comparisons with analytic estimates provide confidence in the numerical implementation of the underlying physical model, while comparisons

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² See Klinger et al 2019 (https://doi.org/10.1088/1741-4326/ab03a7) for the W7-X Team.

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with experimental data confirm the value of the approximations made in the physical model. A great deal of effort has been expended on such work for tokamaks, where the symmetry of the device can significantly simplify the problem. Additionally, such devices have heavily relied on neutral beam injection (NBI) for both current drive and rotation control, making energetic particle physics ubiquitous in terms of the aforementioned source terms. For stellarators, which lack two-dimensional magnetic field symmetry, less emphasis has been placed on validation of such codes. Recently, operation of the NBI system began at the Wendelstein 7-X (W7-X) stellarator [2], providing data for the validation of neutral beam deposition calculations [1]. In this work, we extend this analysis to include simulations of energetic particle confinement and their validation.

The benchmarking and validation of the BEAMS3D [3] energetic particle model is performed using a simple tokamak equilibrium and the plasmas of W7-X. A large-aspect-ratio circular-cross-section tokamak equilibrium is used to benchmark a set of energetic particle codes. This rather simple scenario allows for straightforward comparison between codes and clean verification of the accuracy of the codes against analytic estimates. Simulations of particle orbits generated by NBI in W7-X are used to validate the physical model of the BEAMS3D code. In particular, estimates of fueling, heating, and current drive are compared against experimental measurements providing validation of the bulk aspects of the fast ion distribution function. The loss pattern of particles through the equilibrium last closed flux surface is examined in this work, but validation of energetic particle wall loads is left to a future work. In the next section (section 2), the neutral beam experiments, BEAMS3D code, and benchmark problems are discussed. In section 3, BEAMS3D simulations of NBI-generated energetic particles in W7-X are presented along with comparisons to measured data, providing preliminary validation of the code. Finally, in section 4 a discussion of the results and future plans are presented.

2. Methods

The goal of this work is to compare the slowing down model of the BEAMS3D gyro-center code against experimental data obtained from W7-X. For this purpose, experimental discharges comparing plasma density and magnetic configuration are considered. A convolution of the slowing down and particle loss timescales is made using measurements of diamagnetic energy and compared to simulations. A discharge solely heated by NBI is utilized for the bulk of the profile comparison, as the use of a single heating source significantly reduces the complexity of the transport analysis. Additional discharges are used to provide predictions of NBI performance. A simple benchmark test case problem is also considered in order to compare codes and to validate the numerical models.

2.1. Neutral beam experiments in W7-X

We consider a set of six neutral-beam-heated discharges, scanning magnetic configurations, and densities in W7-X. In five of these discharges, the plasma is supported by electron cyclotron resonance heating (ECRH), while the sixth discharge is solely heated by NBI. This NBI-only discharge is used to validate predictions of heating, fueling, and current drive against measured plasma parameters. The W7-X NBI system is composed of two boxes capable of supporting four sources each. In these experiments, only two sources in one box were available. Fast ion diagnostics were limited in this campaign, making direct validation of the fast ion distribution function impossible for these discharges. Despite this, measurement of profiles and profile changes during the NBI-only discharge make it possible to validate the bulk properties of the distribution function. Such properties as fueling sources, heating sources, and current drive sources are often more valuable from a predictive standpoint than a detailed description of the energetic particle distribution function. These six discharges represent a range of operating scenarios in the W7-X device.

Table 1 provides a concise overview of the key parameters for the set of discharges considered. A set of discharges in the standard magnetic configuration allows for a comparison of discharges at low, medium, and high densities. Discharges at medium density in the high iota and high mirror configurations allow us to explore differences arising from the magnetic field. The standard and high mirror configurations both have an edge rotational transform of \( m/n = 5/5 \), while the high iota configuration has an edge transform of 5/4. The NBI-only discharge (number 20181009.43) provides a scan of plasma density at relatively constant temperatures. A discussion of density peaking for this discharge is presented in the next section. In general, discharges with ECRH heating show a rise in density and stored energy which quickly reaches an asymptote after a few hundred milliseconds and returns to previous levels after NBI ends. These discharges show no sign of density peaking and no significant temperature response. The profiles and VMEC equilibria [4] used in this work are generated by equilibrium reconstructions using the STELLOPT code [5–8], the details of which can be found in [1].

The neutral beam system on W7-X was designed to provide auxiliary heating in the device along with a source of energetic particles. In this work, we focus on discharges which took place when only two sources (S7 and S8) were installed in the NI21 beam box (injection in the toroidal magnetic field direction) [9]. The sources themselves inject neutral hydrogen at 55 keV with a neutralized power of approximately 1.7 MW each. Such particles are considered equivalent to fusion alpha particles in a larger, stronger-field reactor. Such claims are based on the gyroradius scaling

\[
\frac{r_g/a (W7-X)}{r_g/a \text{ (Helias)}} \sim 1,
\]

where \( r_g \) is the gyroradius and \( a \) the minor radius in each device. Each source is modeled using power fractions of \( P_E = 54.6\% \), \( P_{E/2} = 30.9\% \), and \( P_{E/3} = 14.5\% \). The complex nature of the superconducting magnetic coils and the port geometry result in an approximately 45° injection angle relative to the magnetic field, where S8 fires more tangentially and S7 fires more radially. Figure 1 depicts the neutral loading of the port structures and ionization distribution in real space.
This results in an approximately 7.9% loss of power to the duct for S7 and 15% for S8 (in line with previous predictions) [9].

2.2. The BEAMS3D code

The BEAMS3D code is a Monte Carlo code intended to simulate NBI and fast ion particle orbits in stellarator magnetic fields. The code evolves both neutral trajectories and fast ion particle orbits in stellarator magnetic fields. The code utilizes a database of precomputed DKES simulation results based on W7-X magnetic configurations.

In this work, the radial electric field and neoclassical flux estimates are provided by the NEOTRANSP code [11]. This code uses the reconstructed kinetic profiles and DKES simulation results to calculate the ambipolar radial electric field, particle flux, heat flux, and bootstrap current. The code utilizes a database of precomputed DKES simulation results based on W7-X magnetic configurations.

2.3. Benchmarks

A series of tests were performed using a large-aspect-ratio circular-cross-section tokamak equilibrium (A10TOK). This configuration has a major radius of 10 m, a minor radius of 1 m, an axial magnetic field of 5 T, and a total toroidal current of 636 kA. The fundamental simplicity of such a configuration allows a series of benchmarking exercises to be performed,
the background radial coordinate. Figure 3 depicts the banana orbit as calculated by BEAMS3D and ASCOT5 in both gyro-center and full-orbit modes. The orbit widening effect of the radial electric field is clearly visible, and good agreement is found between the codes. This confirms both the radial electric field implementation in BEAMS3D and the interface between ASCOT5 and BEAMS3D.

While the slowing down operators used in BEAMS3D were tested in previous works, figure 4 further confirms the implementation. In this test, 50 particles ($D^+$ ions) are initialized with a pitch angle of 95$^\circ$, $r/a = 0.25$, the same energy, and are followed in the A10TOK equilibrium for 1 ms. The equilibrium is modified through the inclusion of a constant $n_e = 1.2 \times 10^{19}$ m$^{-3}$ density, constant electron temperature $T_e = 1$ keV, and constant ion temperature $T_i = 100$ eV. Each dot in the figure represents a simulation at a fixed particle energy. The solid line depicts the theoretical estimate for the fractional electron heating. As can be seen, the simulations are a good match for the theoretical estimate. A clear transition from ion- to electron-dominated collisions is present at $E_{\text{critical}} = E_{\text{Beam}} = 19T_e$, as predicted. Since W7-X has 55 keV beams and electron temperatures between 1 and 4 keV, we can expect similar levels of electron and ion heating.

The pitch angle scattering operator can also be verified by these simulations. The range of pitch angles for each simulation can be computed from the trajectory of the 50 particles. The large initial pitch angle of the particles clearly places them in the passing regime. It can be seen from the simulation data that the range of pitch angles is relatively small for simulations above the critical energy, but it becomes large as the particle energy falls below the critical energy. For the lower energies, the parallel velocity even reverses sign, suggesting the particles have been scattered across the trapped-passing boundary. The operator itself has a random number generator in it, so direct comparison with analytic theory is difficult. However, these simulations seem to indicate that the operator is behaving correctly.

Figure 5 depicts a comparison between the ASCOT5, BEAMS3D, and VENUS-LEVIS codes for a deeply trapped particle in a W7-X equilibrium. In general, gyro-center trajectories agree surprisingly well, given that each code employs a different ordinary differential equation (ODE) solver. The agreement with VENUS-LEVIS is particularly encouraging, given that VENUS-LEVIS solves a completely different ODE and represents the magnetic field in a completely different fashion. Still, comparisons such as these can only confirm that the codes do the same thing, and cannot be used to confirm the accuracy with which they solve their set of equations. From this result alone, we can only draw the conclusion that whatever inaccuracy exists, the codes share it. It is results of the A10TOK benchmark that confirm the codes are behaving correctly.

3. Results

Simulations were performed using the BEAMS3D code and reconstructed VMEC equilibria in order to assess NBI fast ion physics in W7-X. Particle orbits, plasma fueling, plasma heat-
ing, and current drive were explored. A 5 s purely NBI-heated plasma in the high mirror configuration (20181009.43) is used to compare simulation results to experimental data and transport simulations. This provides preliminary validation of the BEAMS3D model for predictive use. The effects of magnetic configuration and plasma density are also documented in this work.

Table 2 provides an overview of the BEAMS3D deposition and slowing down results. Density clearly plays the largest role in the slowing down process. The simulation results include approximately 400 kW of power lost to the beam ducts out of the 3420 kW of neutral power from the two sources.

3.1. Orbits in W7-X

The orbits of energetic particles in stellarators (such as W7-X) can be more complex than those of tokamaks. In general, stellarators can possess passing, banana, and super-banana orbits, much like tokamaks. However, the toroidal variation in the magnetic field strength and curvature can also create more complex orbits, compared to an axisymmetric system. Stellarators can have toroidal variations in $|B|$ equal to the poloidal variation. As a trapped particle precesses toroidally, it can enter regions where it becomes locally trapped. When these regions are localized in regions of bad magnetic curvature, the particle can radially walk outwards. This is the so-called ripple loss known in tokamaks. Of course, for good curvature regions, it is also possible that the particles radially walk inward. Figure 6 depicts the standard, high iota, and high mirror magnetic fields in straight field-line coordinates (Boozer). The high mirror configuration clearly shows a smoother field structure with fewer local ripple wells. These equilibria are matched to the last closed flux surface as determined from Poincaré plots generated from the W7-X coils. They contain the toroidal field coil ripple.

In figure 7, we see the trajectory of a deeply trapped collisionless particle in the three magnetic configurations considered in this work. The particle itself is a 55 keV proton with a pitch angle $\alpha = \tan^{-1}(v_{\text{parallel}}/v_{\text{perpendicular}}) = 10^\circ$ born at the outboard mid-plane in the half-field-period region (triangular cross-section). The particle is born at $r/a = 0.5$ in the equilibrium radial coordinate. The high mirror configuration clearly shows a deeply trapped banana-orbit like behavior, while the standard and high iota configurations show a more complex orbit. The behavior of this particle in the high mirror and high iota configurations appears mirror-like, in that the particle appears to reverse course in stronger field regions. However, the motion of these particles is even more complex, as the high mirror particle is drifting radially outwards while the high iota particle is drifting radially inwards with a much larger pseudo-banana width. In the standard configuration, the orbit is mirrored across multiple field periods and deviates from what we traditionally would think of as a banana orbit. The curvature of the trajectory around $\theta \sim 1$ can be explained by changes in the local curvature.

![Figure 3. Banana orbit showing the effect of a large radial electric field that widens the orbit. The orbit without radial electric field was approximately 1 cm in width. The inset shows good agreement between guiding center codes.](image-url)
Figure 4. Fraction of power deposited to electrons as a function of the particle energy for a large-aspect-ratio tokamak ($A = 10$). The plasma is chosen to have a 1000 eV electron temperature and an electron density of $1.2 \times 10^{20}$ m$^{-3}$.

Figure 5. Comparison of a collisionless particle orbit between ASCOT5, BEAMS3D, and VENUS-LEVIS showing good agreement on the particle trajectory of a deeply trapped particle. In these plots, distance refers to path length along the gyro-center orbit.

However, we must be careful when interpreting particle orbits in non-straight field line coordinates. Figure 8 depicts the orbits of passing particles launched from the same physical position as those shown in the trapped example. While the trajectory may look strange, it is simply an artifact of the poloidal-like angle used by VMEC ($\theta$ in the plots). These particles are simply tracing out field lines along the surface from which they are launched.

3.2. Beam fueling

The process by which a beam fuels the plasma is generally complex, but can be broken down into one part which is due
to the birth of the fast ion and another part associated with the thermalization of the fast ion through slowing down processes. The injection of a high-energy neutral particle into a plasma generally results in a charge exchange process (although electron and ion impacts are also considered in our beam model). This begins a cascade of charge-exchange processes between thermal ions and electrons donated by the fast neutral particle. Eventually, a dissociation event takes place and the thermal neutral becomes a thermal ion and electron. While proper modeling of such fueling requires a code such as FIDASIM [16, 17], we can approximate this electron density source term using the BEAMS3D fast ion birth profile. As the particles slow down and thermalize, they provide a source term for the ion density. In this way, the effect of neutral beam fueling in W7-X can be assessed.

Figure 9 shows BEAMS3D modeling of the electron and ion density source terms for five time slices of the purely NBI-heated discharge (20181009.43). The reconstructed time rate of change of the density of change is plotted in these figures. The simulated electron density and ion density source terms are around a factor of two higher than the experimentally measured value. Here, the variation in the density rate term, as determined from reconstructed profiles, is depicted as a shaded region. The black line indicates the density increase as determined from reconstructed profiles, is depicted as a shaded region. The stored energy measurement may then be corrected for this density rise, leaving the fueling appears qualitatively consistent with the density rise. Additionally, we note that without profiles of $Z_{\text{effective}}$ the core ion density (and hence rate) may be underestimated. Finally, it is possible that a pinch effect proposed for spherical tokamaks plays a role as well [18]. However, confirmation of this will require more careful experimental planning in the future.

In figure 10 the dependence of ion fueling is compared for different plasma densities and magnetic configurations. The ion fueling is chosen as it is a function of both the neutral deposition, particle orbits, and slowing down operators (as opposed to the electron fueling which is not a function of the fast ion physics). The strong dependency on density can be attributed to both the neutral beam deposition and the confinement of particles. No strong variation in fueling can be seen for a variation in magnetic configuration. The lack of variation with configuration can be attributed to the fact that for the plasma parameters achieved, the radial electric field plays a strong role in the particle confinement. These discharges all had 4 MW of ECRH heating and appear to be in the electron root. These discharges all had relatively flat density profiles (characteristic of ECRH discharge in W7-X), as opposed to discharge 20181009.43 which exhibited strong density peaking during operation with NBI alone. Thus the fueling profiles appear less core peaked than those in figure 9.

3.3. Particle deceleration

In W7-X, discharges with both ECRH and NBI provide a unique opportunity to estimate the slowing down time. In these discharges the density and stored energy of the plasma indicate an asymptotic behavior when the neutral beam is injected. During this time negligible changes to ion or electron temperature are registered, presumably due to strong heat transport. Examination of the Thomson scattering measurements confirms the density rise measurement, but indicates no significant change in profile shape during this period. The stored energy measurement may then be corrected for this density rise, leaving the fast ion response. This correction is necessary as fast-ion (0–100 ms), energy (50–200 ms), and particle confinement time (~500 ms) act on different timescales. By correcting

<table>
<thead>
<tr>
<th>Shot ID</th>
<th>Mag. Conf.</th>
<th>$n_{\text{e0}}$ (m$^{-3}$)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Born</td>
</tr>
<tr>
<td>20180821.12</td>
<td>Standard</td>
<td>6.37 × 10$^{19}$</td>
<td>2300</td>
</tr>
<tr>
<td>20180821.17</td>
<td>Standard</td>
<td>2.80 × 10$^{19}$</td>
<td>1400</td>
</tr>
<tr>
<td>20180821.19</td>
<td>Standard</td>
<td>11.3 × 10$^{19}$</td>
<td>2760</td>
</tr>
<tr>
<td>20180822.12</td>
<td>High iota</td>
<td>5.82 × 10$^{19}$</td>
<td>2140</td>
</tr>
<tr>
<td>20180823.20</td>
<td>High mirror</td>
<td>7.39 × 10$^{19}$</td>
<td>2500</td>
</tr>
<tr>
<td>20181009.43</td>
<td>High mirror</td>
<td>10.5–27.8 × 10$^{19}$</td>
<td>2820</td>
</tr>
</tbody>
</table>
for density changes, an estimation of the slowing down time ($\tau_{\text{exp}}$) can be made by fitting an exponential form to the diamagnetic energy ($f(t) = A(1 - \exp(-t/\tau_{\text{exp}})) + B$). A similar analysis can be performed when the beam turns off. The time constant as determined from the turn-on and turn-off exponential fits then provide a range of values. The average of these two values is taken to be the slowing down time, the range then defines the error on the measurement.

Figure 11 depicts the slowing down times as obtained from simulations and experiment. Error bars for the experimental data were generated by comparing the slowing down times obtained both at the turn-on and turn-off of the neutral beam. As the neutral beam carries the majority of its power in the full and half energies one would expect to see two characteristic time scales in the diamagnetic energy data. This is not the case. Additionally, we can see that for similar densities a range of 20 ms in characteristic time is obtained from experiments. Thus it could be argued the true error bar for these measurements is 20 ms. The simulation results have been broken down by injection energies. At medium and low densities we find these asymptotic rise times fall within the simulated slowing down times. At higher densities the observed slowing down times appear to be larger than the simulated values. The nature of this discrepancy points to the rather large uncertainty associated with this method of approximating the fast ion slowing down time. Future work will use proposed fast ion loss diagnostics to measure such quantities in more precise terms [19]. We also note that instabilities in the ion source itself may be influencing the measured data when the beam is first fired.

3.4. Plasma heating

Heating of the plasma by fast ions is accomplished through collisions with the background plasma. These collisions reduce the velocity of the fast ions while imparting energy to the ions and electrons. In addition, collisions can deflect the trajectory of particles through pitch angle scattering. In an attempt to validate the model in the BEAMS3D code, simulated heating profiles are compared against profile measurements for the discharge with NBI heating only. In this analysis, the BEAMS3D code provides the heating source terms, the NEOTRANSP code provides the neoclassical heat fluxes, and the time rate of change terms come from the experimental profiles. The NEOTRANSP code calculates the neoclassical transport using a database of DKES simulations for a given W7-X magnetic configuration [12].

The energy transport equation can be written as follows:

$$\frac{3}{2} \frac{\partial n_k T_k}{\partial r} = \frac{1}{V'} \frac{\partial}{\partial \rho} \left( V' \langle |\nabla \rho| \rangle Q_k \right) + P_k + P_{\alpha/\beta}^{\text{coll}}, \quad (3)$$

where $n_k$ is the species density, $T_k$ is the species temperature, $V' = dV/d\rho$ is the volumetric radial derivative, $\rho$ is the radial coordinate, $Q_k$ is the species heat flux density, $P_k$ is the heating source term, $P_{\alpha/\beta}^{\text{coll}}$ is the collisional heat-transfer term, and $k = e, i$ denotes the fluid species (electron or ion). It should be noted that the heat flux can be written in terms of the diffusivity coefficient $\chi_k$

$$Q_k = \langle |\nabla \rho|^2 \rangle \chi \nu n_k \frac{\partial T_k}{\partial \rho}, \quad (4)$$

where $\langle \rangle$ denotes an average over a radial flux surface. Taking the ion and electron temperatures to be nearly equilibrated and
constant over time, the heat-transport equation reduces to
\[ 0 = -\frac{1}{V'} \frac{\partial}{\partial \rho} \left( V' \langle |\nabla \rho| \rangle Q_k \right) + P_k, \tag{5} \]
where the $\partial n_i T_k / \partial t$ term is neglected, as it amounts to only a small correction to the heat flux.

In figure 12, the various components of equation (5) are plotted for a W7-X discharge solely heated by NBI (20181009.43). For both ions and electrons, the heat fluxes cannot be explained by the neoclassical heat flux; thus, the dominant transport channel must be related to turbulence. The strongly peaked electron density and broad temperature profiles of this discharge would suggest that ion temperature-gradient-driven turbulence is suppressed while the trapped electron mode is destabilized. The temporal terms have been plotted from the reconstructed profiles to justify their neglect in equation (5). This provides some level of validation of the heating profiles produced by BEAMS3D.

An initial estimate can be made of the experimental heat diffusivities for this discharge. Figure 13 depicts the experimental heat diffusivities calculated by (5), using BEAMS3D data for $P_k$ and experimental profiles for the temperatures and densities. The turbulent heat diffusivity as calculated from the GENE gyrokinetic code is plotted against this data for a single radial datapoint [20, 21]. These simulations were performed non-linearly for a flux tube at $r/a = 0.3$. At this radial location, the gradient length scales fall in the following ranges: $a/Ln = [0.8, 2.6]$, $a/LT_e = [0.9, 1.5]$, and $a/LT_i = [0.4, 1.04]$. The discharge starts at a density gradient of $\sim 1$ and similar temperature gradients and ends at a high density gradient and low temperature gradients. We can see that for the electron channel (at this radial location), the transport is described well by the turbulence model. For the ion channel, the experimental and simulated $\chi_i$ agree early in the discharge, with increasing discrepancies toward the end of the discharge. As the temperature gradient is becoming small, this can strongly influence the calculation of $\chi_i$ from the experimental data. Additionally, the GENE simulation used finite $a/LT_e$ but a zero $a/LT_i$. Such a result shows that the BEASM3D heat flux and experimental profiles appear consistent with preliminary transport modeling. Future work will attempt to better assess the turbulent nature of NBI discharges in W7-X.

The effect of plasma density on neutral beam heating is shown in figure 14. The electron heating shows a clear increase in coupled power with electron density. The ion heating can be explained by differences in electron temperature that result in changes to the critical energy of the particles. It should also be noted that at lower densities, fewer of the neutrals couple to the plasma, so that the overall fast ion density is lower. The factor-of-two reduction in heating at low densities seems a dramatic effect, but is in line with the reduction in ionized power.

The effect of the magnetic configuration on neutral beam heating is shown in Figure 15. The ion heating in the standard
Figure 8. Trajectory (BEAMS3D) for a passing (pitch angle 80°) collisionless particle in W7-X. The particle is launched from the outboard mid-plane in the triangular cross-section. Color contours indicate local field strength, the toroidal angle $\zeta$ is defined over a field period, and the poloidal angle $\theta$ is the spectrally condensed VMEC angle.

Figure 9. Electron (left) and ion (right) thermal density source terms for a purely NBI-heated discharge in W7-X. The reconstructed density change is plotted by linearizing the density profile from 1.5 s to 5.5 s of the discharge. The shaded region depicts the range of possible values based on reconstructed profiles (experimental), while colored lines are generated from BEAMS3D data.

and high iota configurations is similar, while the high mirror shows significantly less ion heating. The difference between the high mirror and standard configurations can be attributed to both the difference in plasma profiles and the generally improved confinement of fast ions at the mid radius. The difference is more clearly seen in electron heating. We note that the high mirror has a larger mirror ratio and is expected to have enhanced neoclassical transport, compared to the high
Figure 10. Scans of plasma density in the standard configuration (left) and magnetic configuration at fixed density (right) were performed, showing the effect on ion fueling (BEAMS3D). Plasma density clearly plays the largest role governing the NBI deposition and thus the source term for the slowing down calculation. Discharges 20180821.12, 20180821.17, 20180821.19, 20180822.12, and 20180823.20 with both ECRH and NBI heating are shown.

Figure 11. Slowing down times estimated from simulation data and from experimental data. The experimental deceleration times ($\tau_{\text{exp}}$) are calculated from both the rise and fall time of the density corrected diamagnetic energy at beam turn-on and turn-off. Slowing down times for the three beam energy ($E$) components are shown for the simulation data.

From table 2, we can see that for similar plasma densities (20180821.12, 20180822.12, 20180823.20) but different magnetic configurations, the high mirror has the highest density and the highest birth power. This speaks to the strong influence that density plays on neutral beam ionization. Although, based on figure 15, one may think that the high mirror has the lowest electron heating, one must recognize that each configuration has a different specific volume which vanishes toward the core of the plasma; thus, variations in the deep core play the weakest role in the overall deposited...
Figure 12. Comparison of thermal transport terms for a discharge solely heated by NBI (20181009.43). Shaded regions indicate the variation of the discharge period. The neoclassical term is calculated using the NEOTRANSP code, the heating terms are obtained from BEAMS3D slowing down simulations, and the time derivative term is based on from experimental data.

Figure 13. Profiles of $\chi_i$ (left) and $\chi_e$ (right) calculated from the BEAMS3D heating terms and experimental profiles. Data from a GENE simulation is plotted against the experimental data; error bars attempt to capture the statistical nature of the GENE simulation.

power. Therefore, the slightly high electron heating of the high mirror at the mid radius plays a large role in the increased overall electron heating. The high iota has the smallest overall volume of the three configurations, resulting in a similar total heating to the standard configuration, despite a larger power density.

3.5. Current drive

The circulating fast ions in W7-X contribute to a toroidal current which can be calculated from the fast ion distribution function and a correction associated with trapped electrons. In general, the total neutral beam current drive (NBCD) can be written as:

$$j_{\text{NBCD}} = j_f \left[ 1 - \frac{Z_f}{Z_{\text{eff}}} (1 - G) \right],$$

where $j_f$ is the current associated with the fast ion population, $Z_f$ the charge number of the fast ions, $Z_{\text{eff}}$ is the effective charge number of the background plasma, and $G$ is the trapped electron correction to the Ohkawa current [22]. In the limit where $v_e \gg u_f$ (the electron velocity is much greater than the fast ion velocity), it has been shown that the factor $G$ is identical to the $I_{31}$ neoclassical transport coefficient [23]. In this work, the convenient choice was to calculate the $I_{31}$ coefficient using the well known Hirshman–Sigmarm moment method [24].
\[ l_{31} = \frac{x \left[ (0.754 + 2.21Z_{\text{eff}} + Z_{\text{eff}}^2) + x \left( 0.348 + 1.243Z_{\text{eff}} + Z_{\text{eff}}^2 \right) \right]}{1.414Z_{\text{eff}} + Z_{\text{eff}}^2 + x \left( 0.754 + 2.657Z_{\text{eff}} + 2Z_{\text{eff}}^2 \right) + x^2 \left( 0.348 + 1.243Z_{\text{eff}} + Z_{\text{eff}}^2 \right)} \] 

where \( x = f_{\text{trapped}}/(1 - f_{\text{trapped}}) \) is the trapped passing fraction on a given magnetic flux surface. It should be noted that this equation was developed for the banana regime (low collisionality) and that a more general form has been developed by Sauter [25]. While these methods were developed for shaped tokamaks, the theory and resulting equations can be applied to stellarators in the nested flux surface limit through a transformation to straight-field-line coordinates. The trapped particle fraction on a surface is then written

\[ f_{\text{trapped}} = 1 - \frac{3}{4} \frac{\langle B^2 \rangle}{B_{\text{max}}} \int_0^1 \frac{\lambda \, d\lambda}{\sqrt{1 - \lambda B/B_{\text{max}}}}. \]

where \( \lambda = \mu B_{\text{max}}/E \) is the normalized pitch angle parameter, \( B_{\text{max}} \) is the maximum magnetic field on the flux surface, \( B \) is the magnetic field, \( \langle \rangle \) denotes an average over the flux surface, \( E \) is the particle energy, and \( \mu \) is the particle’s magnetic moment.

In figure 16, we can see the effect of the correction on the high mirror magnetic configuration. A factor of up to two is present, owing to the large trapped-particle fraction in W7-X. In this case, we see that although the bootstrap current is small, it is directly opposite to that of the neutral beam. The discharge starts with 1 s of ECRH before NBI begins. The time trace of the total plasma current indicates a
reversal in current at the time of switchover, which is consistent with this picture. Unfortunately, given the nearly 30 s resistive time in W7-X, it was not possible to observe the asymptotic current driven by the NBI. Simulation results would suggest approximately 10 kA of neutral beam current drive, while the discharge reached only 1.2 kA of measured toroidal current over 5 s.

Variations in plasma density play a large role in current drive efficiency. Lower density discharges in the standard configuration are predicted to have higher core current densities than those at higher densities. This finding is despite the fact that at lower densities, fewer neutral beam particles are ionized in the plasma. Simulation data suggests that lower densities increase the slowing down time, allowing the particles to maintain higher velocities for a longer time. The evidence of this behavior has not been clearly discerned in the experimental data. Discharges alternating between source 7 and source 8 show a stronger current drive signature in the measured plasma current for source 8. This aligns well with these simulations, as source 8 contributes more to the fast ion current due to its more tangential orientation.

3.6. Losses

From these simulations, we can make some general statements about the flow of power to the first wall in W7-X. In this work, particles were followed to the VMEC equilibrium domain. At this location, a 3D wall was generated from the equilibrium data in the BEAMS3D code. Predictions of the first wall heat loads require full orbit models of particle orbits [26]. From table 2, we can see that the plasma density plays a larger role than magnetic configuration in the variation of power leaving the equilibrium domain. However, the total power can be misleading, as heat fluxes can locally be much larger.

Figure 17 depicts the variation in heat flux through the equilibrium boundary for the standard, high iota, and high mirror configurations. The peak heat fluxes are 101 kW m$^{-2}$, 126 kW m$^{-2}$, and 156 kW m$^{-2}$ for the standard, high iota, and high mirror configurations respectively. The sharp feature in each configuration running from $\theta = 0$ to $\theta = 1.3$, most pronounced in module 2, is associated with the bean-shaped region of high curvature and hence the divertor in W7-X. A clear up/down asymmetry can be seen in all cases, along with a toroidal asymmetry where modules 3 and 4 seem to have the highest loads. These are attributed to locally trapped particles, since the NBI system deposits particles in module 2. The high mirror configuration indicates a strong localization of particle losses in module 3.

The effect of density on the losses is less dramatic; lower-density discharges resulting in larger heat fluxes. The peak heat fluxes for the standard configuration at $3 \times 10^{19}$ m$^{-3}$, $6 \times 10^{19}$ m$^{-3}$, and $11 \times 10^{19}$ m$^{-3}$ are 134 kW m$^{-2}$, 101 kW m$^{-2}$, and 90 kW m$^{-2}$, respectively. Comparing these cases, the general pattern of losses appears consistent across the density scan. This corroborates the notion that the magnetic configuration determines the general geometric features of the loss channels, while the plasma parameters determine the flux to those channels. What can be clearly seen is that as density is increased, losses reduce, suggesting that high-density operation causes fewer device safety issues than that of low density.

Analysis of the loss patterns for the purely NBI-heated discharge suggests that as density continues to increase, the peak heat loads are reduced from 83 kW m$^{-2}$ to 67 kW m$^{-2}$. This discharge (20181009.43) differs from the ECRH heated high
Figure 17. Heat flux through the VMEC equilibrium boundary for the standard (top), high iota (center), and high mirror (bottom) magnetic configurations. In these plots, $\theta = 0$ corresponds to the outboard midplane of the device. Similar maximum levels of heat flux are present between configurations, while loss patterns vary somewhat.

mirror discharge (20180823.20) in that losses are more localized to module 3 for all densities. The pure NBI discharge had a peaked density profile with lower electron temperature. More detailed analysis is left to future works in which a full wall model can be implemented.

4. Discussion

In this work, we have presented calculations of fast ion orbits generated by NBI in W7-X. An effort has been made to utilize experimentally relevant plasma profiles and equilibria in order to compare simulations with experimental measurements. For a set of discharges with both ECRH and NBI heating, experimental estimates of the slowing down time are consistent with simulated results for those plasmas. Estimates of both electron and ion fueling were made for a discharge solely heated by the NBI system. The observed density increase appears smaller than the fueling rate calculated by simulations, suggesting a strong transport which cannot be explained by neoclassical calculations. Estimates of ion heating in such a discharge show a transport shortfall for the ions, along with an even stronger shortfall in the electron channel. The strong peaking of the density suggests that trapped electron modes are triggered, which could explain the levels of electron transport measured in the experiment. The triggering of trapped electron modes by strongly peaked density profiles and broad temperatures profiles is consistent with our current understanding of turbulence in W7-X [27]. The exact nature of such peaking is still not understood. Calculations of the neutral beam current drive and bootstrap current are found to provide a consistent picture of current drive. Quantitative measurements will require discharge evolution modeling, which is beyond the scope of this work. Finally, estimates of the fast ion losses at the equilibrium boundary suggest the mitigation of loads with increasing density. Such work provides a basis for more sophisticated full-wall modeling. While more data will clearly be collected from W7-X in the coming years, this analysis provides a preliminary validation of the BEAMS3D slowing down model for W7-X.

Building upon the results presented here, future work will be focused on wall modeling, current drive, and future NBI scenarios. As the validation of neutral beam deposition calculations served as a basis for this work, validating slowing down calculations, this work serves as a basis for validation of fast ion wall loads. In our future work, gyro-orbit and full-orbit models will be employed to validate wall loads against experimental measurements. Preliminary estimates of NBCD will be applied to full time-dependent simulations to provide validation of our current drive predictive capability. This is key to the operation of W7-X, as net toroidal current directly impacts divertor operation. Finally, the validated heating profiles presented here should allow us to provide a more accurate assessment of the interplay between NBI and ECRH heating in W7-X. It is hypothesized that careful application of ECRH heating during NBI heating could help to tailor the density profile, reducing electron-scale turbulence while preserving the ion turbulence suppression, thereby resulting in the achievement of higher plasma betas. Detailed fast ion distribution...
tomography is left to a future time when an array of fast ion diagnostics is available.

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