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First neutral beam experiments on Wendelstein 7-X

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Abstract

In the previous divertor campaign, the Wendelstein 7-X (W7-X) device injected 3.6 MW of neutral beam heating power allowing for the achievement of densities approaching $2 \times 10^{20} \text{ m}^{-3}$, and providing the first initial assessment of fast ion confinement in a drift optimized stellarator. The neutral beam injection (NBI) system on W7-X is comprised of two beam boxes with space for four radio frequency sources each. The 3.6 MW of heating reported in this work was achieved with two sources in the NI21 beam box. The effect of combined electron-cyclotron resonance heating (ECRH) and NBI was explored through a series of discharges varying both NBI and ECRH power. Discharges without ECRH saw a linear increase in the line-integrated plasma density, and strong peaking of the core density, over the

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^a See Klinger *et al* 2019 (<https://doi.org/10.1088/1741-4326/ab03a7>) for the W7-X Team.

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discharge duration. The presence of 1 MW of ECRH power was found to be sufficient to control a continuous density rise during NBI operation. Simulations of fast ion wall loads were found to be consistent with experimental infrared camera images during operation. In general, NBI discharges were free from the presence of fast ion induced Alfvénic activity, consistent with low beam betas. These experiments provide data for future scenario development and initial assessment of fast-ion confinement in W7-X, a key topic of the project.

Keywords: stellarator, fast ions, energetic particles, neutral beam, fusion

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

1. Introduction

The recent inertially cooled divertor campaign on Wendelstein 7-X (W7-X) included the commissioning and operation of the neutral beam heating system on the device (among other milestones). The system is designed to inject 60 kV deuterium neutrals into W7-X providing both plasma heating and energetic ion populations (although to date only 55 kV hydrogen has been injected). This choice of acceleration voltage was made such that these particle scale to fusion alphas in a reactor sized device (r_g/a). The energetic particles generated by this system help to assess energetic particle confinement on W7-X, one of the key project goals. Additionally, it provides direct ion heating which contributes to the project goal of assessing the performance of an optimized stellarator at plasma betas of 4%. The first of two neutral beam boxes was commissioned, with two of the four possible sources, during the experimental campaign [1]. Each beam source has an extracted power of ~ 5 MW with ~ 1.8 MW of neutralized power in hydrogen. Calorimetric measurements of the beam itself along with losses to the beam duct were found to be in-line with theoretical estimates [2]. Approximately, 1.5% and 4% of the ionized power is lost to the ports from the two sources. Experiments began with injection into plasmas sustained by electron cyclotron resonance heating (ECRH), allowing for control of target plasmas and densities. These experiments provided a wealth of information to help validate both neutral beam deposition [3] and wall loss estimates [4]. Discharges heated solely by neutral beam injection (NBI) were also demonstrated. In these discharges 5 s of NBI was achieved, along with density control by the reintroduction of a small amount of ECRH. While Alfvénic activity was present in many discharges on W7-X, such modes could not be correlated with the presence of fast ions [5]. Additionally, this NBI system provided a wealth of information in the form of spectroscopic plasma measurements [6]. Data from NBI experiments is helping to validate synthetic diagnostic, fast ion, and MHD instability codes for three dimensional systems. In the next section, the commissioning and discharge of NBI into ECRH heated plasmas is discussed. Then in section 3 the behavior of plasmas heated only by NBI are examined. Finally in section 4, we conclude with a discussion of future upgrades to the neutral beam system.

2. Injection into ECRH plasmas

NBI experiments on W7-X began with adding NBI to discharges heated by ECRH. Plasma breakdown by unassisted NBI was predicted to take longer than the allowable unmitigated heat flux onto the beam dump region of the wall [7]. This necessitated the creation of a target plasma first by ECRH such that the shine-through could be reduced to acceptable levels. As fast ion wall loads to steel components were predicted to be considerable [8] a stepwise approach to NBI duration was taken. During plasma operation no evidence of damage to said panels was detected and pulse length limits were lifted from under ~ 100 ms to 3 s in the standard magnetic configuration. Loads to immersion tube steel collars in the high iota configuration were confirmed to be consistent with modeling [9]. A post-mortem inspection of the vessel showed no signs of damage or excessive loading of the steel panels.

Figure 1 (left) shows the stereotypical evolution of a discharge with NBI injected into an ECRH plasma. In the case of combined ECRH and NBI heating, an asymptotic rise in the line integrated density is confirmed by Thomson scattering measurements showing an increase in density at all radii. Core density rises from $5 \times 10^{19} \text{ m}^{-3}$ to $7 \times 10^{19} \text{ m}^{-3}$, while the edge density rises by about $1 \times 10^{19} \text{ m}^{-3}$. The electron temperature profile shows a reduction of around 1 keV core electron temperature, most likely associated with the increased density. The core ion temperature indicates no discernible change in profiles, with charge exchange confirming ion temperature measurements made by the x-ray imaging crystal system (XICS) [10]. This suggests anomalous transport continues to play a strong role in these discharges [11]. A fast rise in stored energy on the order of 30 ms is present when the NBI is switched on. This is consistent with modeling of slowing down times for fast ions in W7-X [12]. A slower more asymptotic rise in the stored energy can be associated with the rise in density. A similar feature can be seen in discharges with an ECRH power step-up. Fast ion loss detector measurements confirm the time evolution, although discrepancies exist between measured and predicted signals amplitudes [4].

Thomson data for this discharge (figure 2) indicates a slight decrease in core temperature and increase in density at all radii when the NBI is injected. The NBI power density for

Figure 1. Stereotypical W7-X discharges showing the effect of adding NBI to and ECRH discharge (left) and a discharge purely heated by NBI (right). Thomson, XICS, and CXRS indicate core channels.

this discharge is small in the core especially when compared to the centrally deposited electron heating provided by the ECRH. As such, the rise in density coupled with essentially constant electron heating power results in a decrease in electron temperature in the core region. This is corroborated by the notion that ECRH heats in the core while NBI has a broader heat deposition, resulting in temperature outside the core staying relatively constant. The core density rise appears to be of the order of $2 \times 10^{19} \text{ m}^{-3}$ in the core while at larger radii the density rise is approximately half this value. This is consistent with the notion of a broad NBI deposition which is core peaked.

At 3 s into discharge 20180919.16 an iron (Fe) filled tracer encapsulated pellet (TESPEL) was injected into the plasma [13, 14]. This can be seen in the overview plots (figure 1) as a small bump in the diamagnetic energy and charge exchange ion temperature measurements. Figure 3 shows the time traces of C^{+5} , Fe^{+15} , and Fe^{+21} emissions as measured by the high efficiency XUV overview spectrometer [15, 16]. Values have been scaled by the line integrated density. Spectroscopic measurements show a strong rise in iron and carbon light which quickly returns to levels before TESPEL injection within 500 ms. Such behavior is consistent with ECRH discharges showing a prompt flushing of impurities from the core [17]. In a discharge without ECRH a similar experiment was performed (20181009.38, figure 3 right), however 1.2 s after

TESPEL injection the plasma collapsed. During that 1.2 s, spectroscopy indicated no decrease in carbon emission with a significant increase in the Fe^{+14} emission. A strong drop in diamagnetic energy and plasma temperatures was present shortly after TESPEL injection. The presence of ECRH appears to strongly affect impurity transport, consistent with experiments in tokamaks [18]. However, we note that this is a multi-dimensional effect as the ion and electron temperature also drop after TESPEL injection in this discharge. A detailed discussion of impurity transport, ECRH/NBI mix, and the ramifications for future alpha heated devices is beyond the scope of this work and left to the future.

In situ measurement of fast ion wall loads were limited to the divertor IR camera views. As such, it was difficult to disambiguate fast ion loads from the convective thermal loads of the plasma. Additionally, these cameras did not view the steel panels which were predicted to be critically overloaded. Post-mortem inspection of the steel panels suggested no overloading although a small material sample holder, attached to the steel panels was found to be melted. This was later found to have occurred during a discharge without NBI, presumably from an energetic electron beam. Thus no damage due to NBI was found in the device. The high iota configuration provided a unique opportunity for analysis as the fast ion loads were predicted to hit the main divertor in a region where the convective loads were not predicted to be. Figure 4 shows a comparison

Figure 2. Thomson data from discharge 20180919.16 before (0.4–1.3 s) and during NBI injection (2.0–2.8 s) showing an increase in density and slight core decrease in temperature. Vertical solid lines (red) depict the approximate location of the vacuum separatrix and the dashed line indicates the location of the vacuum magnetic axis.

Figure 3. Traces of impurity emission measured by the survey spectrometer for ECRH + NBI (left, 20180919.16) and pure NBI (right, 20181009.38) discharges with Fe TESPEL injection at 3 s. Line emissions have been scaled by the line integrated density and a vertical dashed line has been added to indicate TESPEL injection.

between simulated data and measured heat flux in the divertor region. The arrow highlights the hot spot which appears as NBI is injected into the experiment. Simulations predict an up/down asymmetry in NBI driven divertor loads which is confirmed by camera data. In this simulation deposition and slowing down of fast ions were performed with the BEAMS3D code [19] and collisionless full orbits from the equilibrium boundary to the wall were simulated with the ASCOT5 code [20].

In general, no evidence of NBI driven Alfvénic activity was present in this experimental campaign. Simulations suggest that higher beam betas would be required in W7-X to

trigger such modes [21]. Although, isolated events where the NBI source would drop out and recover did seem to correlate with the formation of a magnetic fluctuation. Furthermore, Alfvén modes did appear in ECRH discharges although the exact nature of such modes is still an active topic of research.

3. Pure NBI operation

Experiments solely heated by NBI were conducted toward the end of the campaign in the high mirror configuration (figure 1, right). Initiated by a 1 s ECRH pulse, these discharges were

Figure 4. Simulated fast ion wall loads (left) and measured heat flux in the divertor of W7-X (right). The arrow highlights the hot stop which is correlated with NBI injection. (Discharge 20180822.12, AEF21 camera).

Figure 5. Evolution of density profile for the discharge heated solely by NBI (left) and one in which 1 MW of ECRH heating is introduced at 3 s into the discharge (right). Density measurement made by Thomson scattering, mapped to rho coordinate using vacuum flux surfaces, and averaged over radial bin.

sustained solely by NBI for 5 s. Discharges into the torus of up to 700 ms showed no sign of breakdown confirming predictions that unassisted NBI startup would not be possible in W7-X. Additionally, attempts to startup at 1.7 T with combined NBI and third harmonic ECRH were not successful. Plasmas solely heated by NBI were found to exhibit a continual density rise with strong density peaking toward the end of the discharge as seen in figure 5. Reintroduction of ECRH heating was found to arrest the density rise and flatten density profiles in the core of the plasma.

While quantitative measurements of neutral beam current drive are difficult given the long resistive diffusion time in W7-X ($L/R \sim 30$ s) and NBI pulse length (5 s) some qualitative measurements were possible. The reversal of toroidal current as measured by the Rogowski coil (figure 6) is consistent with bootstrap and neutral beam modeling. Here, negative current implies current in the counterclockwise direction as viewed from above (in the direction of the toroidal magnetic field). The neutral beam is directed in the direction of the toroidal field while the bootstrap current is in the opposite direc-

Figure 6. Toroidal current evolution (left) and NBI power (right) for W7-X discharge 20181009.24 where NBI source 7 and source 8 were alternated demonstrating differences in NBI current drive. Source 7 begins to develop difficulties after 3 s into the discharge, but between 1 s and 3 s source 8 (the more toroidal source) is clearly driving more toroidal current.

tion. Figure 6 demonstrates the geometric effect of the two neutral beam source through alternation of the two sources. The NBI sources on W7-X are aligned in a pattern where the sources inject across the centerline of the port, resulting in one source depositing more tangentially (S8) and one more radially (S7). From the measured toroidal current it becomes clear that source 8 was driving more toroidal current than source 7, despite source 7 becoming unstable after 3 s into the discharge.

4. Discussion

In the first inertially cooled divertor campaign on W7-X, the first neutral beam experiments were performed using two of four sources in one of two beam boxes. These experiments demonstrated safe neutral beam operation up to the designed pulse length in hydrogen. Densities around $2 \times 10^{20} \text{ m}^{-3}$ were achieved with equilibrated electron and ion temperature. Such experiments provided a wealth of data for validation of fast ion codes and synthetic diagnostics. The neutral beam system also provided charge exchange measurements helping to corroborate ion temperature measurements made by the XICS system. The neutral beam system will be expanded in the coming experimental campaign to include two more sources in the second beam box. This upgrade will double the available power and allow for balanced beam injection. Future upgrades will include installation of an additional two sources in each beam box, a further doubling of the power. A further increase in power is envisioned when the switch to deuterium operation begins, as a result of improved neutralization efficiency.

Future work will focus on leveraging diagnostic upgrades and improved NBI parameters to explore the physics of W7-X. Increased NBI heating power along with a mix of ECRH should allow for higher ion temperatures to be achieved and to investigate the role of ECRH density pump-out. A growing set of fast ion diagnostics (an FC-FILD array [22], ion cyclotron emission [23], spectroscopic beam measurements [6], and collective Thomson scattering [24]) will allow for more detailed studies of the fast ion distribution function. This includes a program to perform fast ion phase space tomography. Attempts to prolong the NBI pulse duration, past the W7-X current redistribution time (~ 30 s), should allow for a quantitative assessment of neutral beam current drive models. The interplay between the ion cyclotron resonance heating system and NBI will also be examined once the such a system is brought into operation. The nature of Alfvénic activity and role of magnetic islands on fast ion confinement will be explored through carefully designed experiments. Finally, once W7-X begins operation with deuterium, neutron diagnostics will become available for triton burn-up studies [25].

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