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Predictive modelling of NBI wall loads in W7-X scenarios exhibiting vanishing bootstrap current

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Introduction. Demonstrating good confinement of fast ions is an important goal of W7-X. This is not only to ensure efficient heating, but also because good confinement of NBI ions in W7-X implies good confinement of α -particles in a prospective stellarator reactor, on important difference being that the α -particle distribution would be isotropic. The NBI beams in W7-X will be commissioned in the operational phase OP1.2b in 2018. One way to experimentally study the confinement of NBI ions are short NBI beam blips, which produce a well-defined fast particle population and are nearly non-perturbative to the plasma profiles. In addition, predictive modelling of NBI beams for any suggested operational scenarios is important, because it allows identifying potential beam hot-spots even before commissioning the beams. This requires simulating the NBI ionization distribution, and then following the ionized particles with an orbit-following code [1] [2].

Bootstrap current (j_b) is an intrinsic plasma current generated by pressure gradients. In tokamaks, where rotational transform (t) is achieved by means of a plasma current (j), the bootstrap current presents an easy way of achieving higher t with less inductive current drive. On the other hand, the rotational transform in the W7-X stellarator is produced purely by external coils. Any bootstrap or other current can thus modify the plasma equilibrium, and must be controlled to avoid changing the edge-t which determines the island divertor configuration. Due to this, W7-X needs to either minimize or compensate any bootstrap current in the device.

In this contribution, we simulated NBI beam blips with the BBNBI [3] and ASCOT [4] codes in low bootstrap current scenarios, previously simulated by Y. Turkin & al. [5]. Of the two types of discharge scenarios – with vanishing (less than 8 kA) bootstrap current, and with bootstrap current and compensating counter-ECCD – only the vanishing bootstrap current scenarios are addressed here.



Figure 1: Simulated NBI ionization distributions in the standard- ι scenario for three different densities: low density (a), intermediate density (b), and high density (c). The red and the blue lines show the last closed flux surface (LCFS) in the toroidal direction of the two beams, and the black line shows the LCFS for the z = 0 plane.

Fast ions in vanishing bootstrap current scenarios. All of the scenarios had a toroidal magnetic field $B_T = 2.5$ T and 5 MW of ECRH heating. Three different edge rotational transforms were considered:

- 1. Low edge- $\iota = 5/6$ (mirror term $b_{01} = 0.24$ and $j_b < 5$ kA)
- 2. Standard edge- $\iota = 5/5$ (mirror term $b_{01} = 0.11$ and $j_b < 6$ kA)
- 3. High edge-i = 5/4 (mirror term $b_{01} = 0.04$ and $j_b < 8$ kA)

For each of the scenarios, three different central density (n_0) values were analyzed:

- 1. Low density plasma with $n_0 = 0.3 \times 10^{20} \,\mathrm{m}^{-3}$
- 2. Intermediate density plasma with $n_0 = 0.75 \times 10^{20} \,\mathrm{m}^{-3}$
- 3. High density plasma with $n_0 = 1.5 \times 10^{20} \,\mathrm{m}^{-3}$

The NBI ionization distribution was generated with BBNBI using the detailed geometry and design parameters of the W7-X injectors. The simulated beams were 55 keV hydrogen beams. The beam lines in W7-X are very perpendicular to the plasma, due to geometrical constraints of the W7-X superconducting coils. Two boxes, each with one 1.78 MW and one 1.64 MW source were utilized, corresponding to the sources planned for use in OP1.2b [6].

Representative ionization distributions for the three different densities for the standard- ι scenario are shown in Figure 1. Clearly plasma density significantly alters the ionization distri-

bution. In addition, shine-through was found excessive for the low density scenarios. Due to this observation, full particle orbit analysis was only carried out for the intermediate and high density plasmas for each of the scenarios.

A total of 10^6 markers corresponding to the ionized NBI particles were simulated on the Triton cluster using ASCOT. The ions were followed until they reached a plasma facing surface, or were thermalized. In the core, only the particle guiding centers were simulated, but the full particle gyro orbits were used for wall collision checks.

The results of the simulations are shown in Table 1. Of the simulated scenarios, the low- ι high density plasma was found to be the best with regards to the NBI wall loads. The highest wall loads were observed in the low- ι intermediate density scenario, indicating that the low- ι scenario is sensitive to density variation. For all values of edge- ι , the wall loads were higher in the intermediate density scenarios. In addition, the standard- ι scenarios performed better than the corresponding high- ι scenarios. The low- ι high density scenario simulated here had a total NBI wall load comparable to the high mirror (0.5 MW) and inward shifted high mirror (0.6 MW) configurations, previously found to be good for fast ion confinement [1].

Table 1:	Summary	of ASCOT	simulation	results	for the	vanishing	bootstrap	current	scenarios:
ionized	power P_{ion} ,	absorbed p	bower P_{abs} ,	wall loa	d P _{wall} ,	and shine-	-through p	ower P_{S}	Т·

	$\iota = 5/6$		$\iota = 0$	5/5	$\iota = 5/4$	
$n_0 (10^{20} \mathrm{m}^{-3})$	0.75	1.5	0.75	1.5	0.75	1.5
$P_{\rm ion}$ (MW)	6.2	6.8	6.1	6.7	5.7	6.6
P_{abs} (MW)	4.4	5.8	4.5	5.4	3.8	4.9
P_{wall} (MW)	1.2	0.4	0.8	0.6	0.8	0.7
$P_{\text{wall}}/P_{\text{ini}}$ (%)	19.6	5.9	12.7	8.5	17.1	11.7
P _{ST} (MW)	0.7	0.07	0.8	0.1	1.2	0.2

ASCOT also allows evaluating the distribution of power on the wall. Only certain wall components are designed to tolerate high power loads. The most critical parts to monitor are the closure, vessel, ports and pumping slits [7]. Figure 2 shows the wall loads to the W7-X wall for individual wall tiles in the high-t high density scenario. The high peak power loads are due to the very small area of the wall triangles, a problem that could be alleviated by using more test particles or combining smaller triangles. In previous W7-X ASCOT simulations, the solutions converged with 10^8 markers [1].



Figure 2: Simulated NBI wall load for the high-*i* high density scenario for individual wall tiles.

Conclusions. ASCOT is now a working tool for NBI studies in W7-X. Of the current-free scenarios, the low- ι high density scenario is the best with regards to the global NBI confinement. The power loads were concentrated on the parts of the wall designed for high heat loads. It should be noted that in addition to different edge- ι , the scenarios also had different mirror terms: b_{01} was highest in the low- ι scenarios, and lowest in the high- ι scenarios. This could impact the beam ion confinement in addition to the density and edge- ι value.

As a refinement to these simulations, an increase of simulation markers from the current 1 million to 10–100 million has been concidered, to account for the complex plasma and wall structure of W7-X. Since the NBI operations at W7-X will only begin in 2018, there is still time for predictive work. In view of these simulations, NBI operation in the studied scenarios may need to be limited to short beam blips to avoid damaging the walls.

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