

Estimate of 3D power wall loads due to Neutral Beam Injection in EU DEMO ramp-up phase

P. Vincenzi^{a,*}, J. Varje^b, P. Agostinetti^a, J.F. Artaud^c, T. Bolzonella^a, T. Kurki-Suonio^b, M. Mattei^d, P. Sonato^a, M. Vallar^a

^a Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy

^b Department of Applied Physics, Aalto University, FI-00076 Aalto, Finland

^c CEA, IRFM, F-13108 Saint Paul Lez Durance, France

^d Ass. CREATE-ENEA, Seconda Università di Napoli, Naples, Italy

ABSTRACT

Heating and current drive systems such as high energy Neutral Beam Injection (NBI) are being considered for pulsed EU DEMO (“DEMO1”) pre-conceptual design. Their aim is to provide auxiliary power, not only during flat-top, but also during transient phases (i.e. plasma current ramp-up and ramp-down).

In this work, NBI fast particle power loads on DEMO1 first wall, due to shine-through and orbit losses, are calculated for the diverted plasma ramp-up phase. Numerical simulations are performed using BBNBI and ASCOT Monte Carlo codes. The simulations have been done using a complete 3D wall geometry, and implementing the latest DEMO NBI design, which foresees NBI at 800 keV particle energy. Location and power density of NBI-related power loads at different ramp-up time steps are evaluated and compared with the maximum tolerable heat flux taken from ITER case. Since NBI shine-through losses (dominant during low density phases) depend mainly on the beam energy, plasma density and volume, DEMO has a more favourable situation than ITER, enlarging NBI operational window. Using ITER criteria, DEMO NBI at full energy and power could be switched on during ramp-up at $\langle n_e \rangle \sim 1.3 \times 10^{19} \text{ m}^{-3}$. This increases the appeal of neutral beam injectors as auxiliary power systems for DEMO.

1. Introduction

The European DEMO project is in the pre-conceptual design phase and different design options are under evaluation. One of the key points deals with the choice of the auxiliary power systems, devoted to assist the plasma in its various phases of the discharge, providing mainly heating and, for advanced plasma scenarios, driving plasma current. Neutral Beam Injection (NBI) is one of the methods being considered to provide auxiliary power to the plasma.

The most advanced EU DEMO project regards the so-called DEMO1, a pulsed reactor ($\sim 2 \text{ h}$ discharge duration), which is the scenario investigated in this work. It is based on the ITER expected performances with conservative assumptions on physics and technology improvements. DEMO1 (2015's design with $R = 9.1 \text{ m}$ and $B_{T,0} = 5.7 \text{ T}$) is supposed to have a flat-top phase with a D-T plasma having a current $I_p = 19.6 \text{ MA}$, a volume-averaged electron temperature $\langle T_e \rangle \sim 13 \text{ keV}$, a volume-averaged ion temperature $\langle T_i \rangle \sim 12 \text{ keV}$, a central electron temperature $T_{e,0} \sim 27 \text{ keV}$, a central ion temperature $T_{i,0} \sim 24 \text{ keV}$, a volume-averaged electron density $\langle n_e \rangle \sim 8 \times 10^{19} \text{ m}^{-3}$, a central electron density $n_{e,0} \sim 1 \times 10^{20} \text{ m}^{-3}$ and an additional flat-top heating power $P_{\text{add,FT}} = 50 \text{ MW}$, producing 2 GW of fusion power (a complete description of the machine used in

this work can be found in [1]).

The strategy on DEMO1 ramp-up is not trivial and it is currently under discussion within the Power Plant Physics and Technology EUROfusion department. DEMO ramp-up must guarantee a robust and fast access to the target flat-top H-mode scenario, taking into account the flux swing consumption that impacts on the discharge duration. The experience from present devices is taken into account, together with the expected strategies for ITER, with the difference of having a much larger device where alpha particle heating becomes dominant approaching the flat-top. From recent studies [2], it appears clear that additional power (even more than what is needed for flat-top) is needed during the ramp-up phase to heat the plasma and access the H-mode. Additional heating power is needed also in the ramp-down phase to compensate for high radiation power losses. The plasma parameters evolving in ramp-up/down phases are strongly different from the flat-top phase, but the heating and current drive systems are optimized to work during flat-top, resulting in possible low coupling of additional power to the plasma. A clear example is the NBI system, which suffers of shine-through losses (i.e. the part of the beam not ionized in the plasma and colliding with the first wall) at low plasma density during ramp-up and ramp-down phases. In ITER, shine-through losses set a lower limit on plasma density for NBI operation at

* Corresponding author.

E-mail address: pietro.vincenzi@igi.cnr.it (P. Vincenzi).

<https://doi.org/10.1016/j.nme.2018.12.031>

Received 25 July 2018; Received in revised form 14 December 2018; Accepted 26 December 2018

2352-1791/ © 2018 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

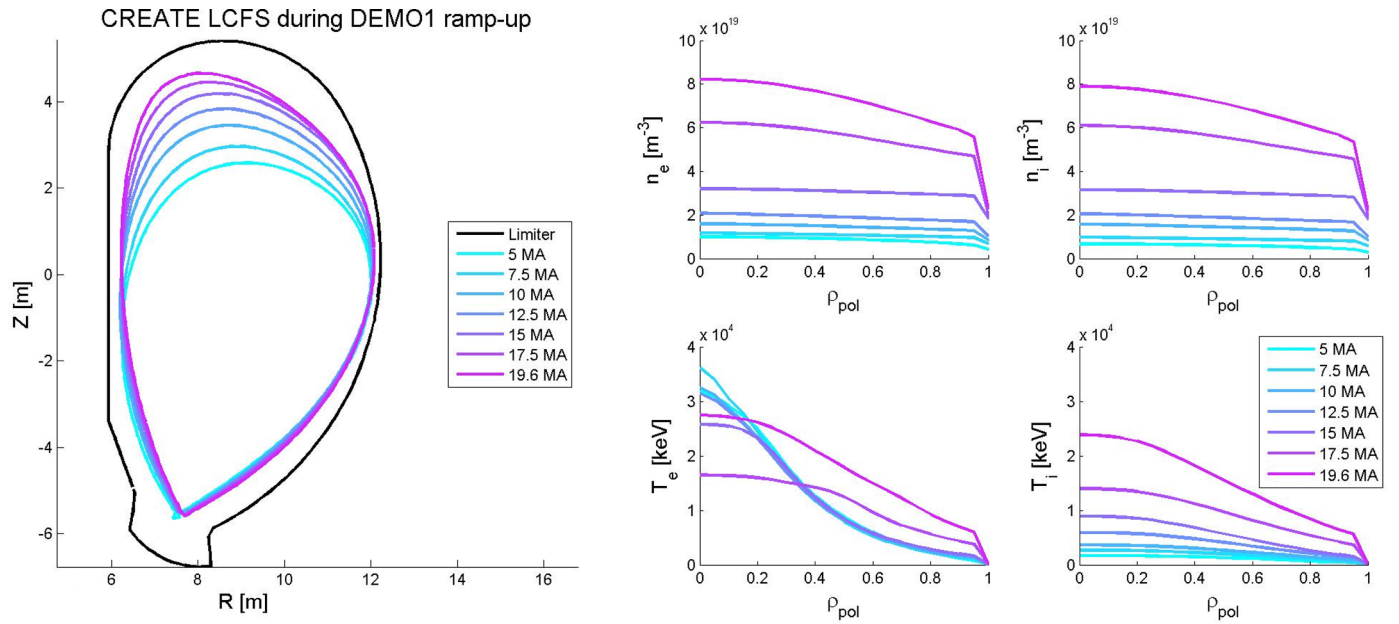


Fig. 1. Plasma boundaries (last closed flux surface - LCFS) and plasma kinetic profiles (electron/ion density and temperature) at the selected DEMO1 ramp-up snapshots.

$\langle n_e \rangle \sim 3 \times 10^{19} \text{ m}^{-3}$ [3] (calculated for H plasma and H⁰ NBI), limiting its use during the ramp-up/down phase due to low plasma density. It is therefore crucial to understand the NBI usability for DEMO low density phases and evaluate the ramp-up shine-through power losses (which is the dominant loss channel at low density). Shine-through is an immediate loss channel, present continuously during the injection, with intensity that depends on plasma density. These losses can reach values above the tolerable heat flux on the first wall. The duration of these heat fluxes depends on the speed of plasma density evolution towards the flat-top value, i.e. on the chosen scenario strategy (topic which is beyond the scope of this paper). A typical DEMO1 plasma current ramp-up (considering only the diverted plasma phase) can last about 200 s [2]. In steady-state conditions, DEMO peak heat flux limit on the first wall is assumed to be 1 MW/m^2 [4], much lower than the limit for ITER (4.7 MW/m^2 [5]). In fact, this number includes all the possible sources of heat loads (charged particles, radiation, ELMs etc. in static conditions) together with the beam power losses. A possibility is to design local first wall components that tolerate higher heat fluxes for limited duration (e.g. up to 20 MW/m^2 based on ITER divertor monoblock technology).

In this work the wall heat fluxes due to NBI power losses are calculated for the diverted plasma ramp-up phase of EU DEMO1 by numerical simulations, in a complete 3D wall geometry. NBI power losses are mainly due to shine-through process (dominant during ramp-up), fast ions born or arriving into unconfined orbits (i.e. orbit losses, estimated in this work) and charge exchange losses (fast ions that charge-exchange with background neutrals, not considered in this work, and expected to be negligible for DEMO due to low background neutral density). Fast particle dynamics is expected to happen on time scales (\sim seconds) much shorter than ramp-up duration (e.g. $\sim 200 \text{ s}$, as in [2]). Previous studies already showed that NBI power losses are negligible during plasma flat-top [6,4]. Considering the additional power requirements during ramp-up, it is important to understand the limitations on using the NBI flat-top system also with lower plasma density and to consider the respective wall thermal loads when designing the first wall. The latest design of the DEMO NBI system and the plasma ramp-up scenario used in this work are described in Section 2, while a brief description of the codes can be found in Section 3. The results are reported in Section 4 and conclusions of the work are presented in Section 5.

2. Description of the NBI system and ramp-up plasma scenario

An innovative concept for a DEMO Neutral Beam (NB) injector has been proposed by Consorzio RFX in collaboration with other European research institutes [7]. The design considers several solutions aimed at improving the system efficiency, mainly regarding a modular beam source, the compatibility with the integration of a photoneutralizer and the vacuum pumping system. These new solutions require an uncommon beam shape, “thin and tall”. This injector is designed to deliver D neutral particles at the energy of 800 keV, lower than the ITER NBI energy (1 MeV, D⁰), in order to relax some constraints on the NB system, allowing operations in a more efficient regime, and to better cope with high voltage issues. From the shine-through point of view, the reduced NBI energy is of course favourable. Also the enlarged DEMO plasma volume with respect to ITER is favourable since the NBI path in the plasma is longer and we can expect higher beam ionization. The beam shape affects the NBI “footprint” on the wall and therefore the way NBI shine-through losses are spread on the wall. In the present case, the NBI footprint is quite large since the beam focus is at the wall port. Each injector is capable of injecting 16.8 MW in the plasma, and DEMO1 reference design foresees 3 identical injectors for a total of 50.4 MW entering the plasma with a horizontal inclination of 30° at the first wall with respect to the radial direction.

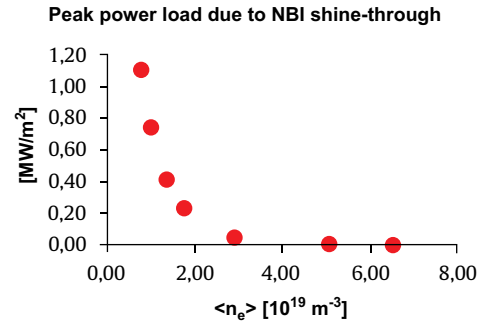
The analysis of NBI absorption during DEMO1 flat-top has been reported elsewhere [6,8] and will be also discussed in more details in a future publication.

In this work we concentrate on the DEMO1 ramp-up phase, starting from the first diverted plasma (at $I_p = 5 \text{ MA}$) up to the start of the flat-top ($I_p = 19.6 \text{ MA}$). During this phase, not only the plasma current, but also the plasma density is evolving. Low density may result in low beam ionization with localized high-energy neutral particle losses on the first wall. The optimization of the ramp-up, in order to save swing flux and to access the H-mode with the most advantageous conditions, is matter of ongoing debate and we leave this topic to other publications. In this work we took 6 snapshots (+ 1 point at the start of the flat-top), during one of the possible ramp-up plasma evolutions of [2] (in the selected case there is additional ECRH power during ramp-up as can be deduced from temperature profiles in Fig. 1). Each ramp-up point analysed is described in the simulations by: plasma current, axisymmetric magnetic equilibrium calculated with CREATE NL free boundary equilibrium

Table 1

Main parameters and NBI losses for DEMO1 ramp-up together with a plot of the peak power load due to NBI shine-through as a function of the volume-averaged electron density.

I_p [MA]	5	7,5	10	12,5	15	17,5	19,6
$\langle n_e \rangle$ [10^{19} m^{-3}]	0,78	1,01	1,36	1,78	2,92	5,11	6,54
$\langle T_e \rangle$ [keV]	5,92	5,50	5,73	5,95	6,22	8,19	12,89
Plasma volume [m^3]	1843	2012	2086	2202	2313	2384	2434
Shine-through %	28,64	19,86	10,89	5,44	0,75	0,01	0,00
Max. Shine-through [MW/m^2]	1,10	0,74	0,41	0,23	0,05	0,004	0,00
Fast ion orbit losses %	1,03	1,02	0,48	0,44	0,87	0,52	0,86



code [9] and D-T plasma kinetic profiles calculated with METIS fast tokamak simulator [10] as described in [2], using Xe as seed impurity. The plasma current, in the selected snapshots, is 5, 7.5, 10, 12.5, 15, 17.5 and 19.6 MA. The corresponding plasma boundaries and plasma kinetic profiles are shown in Fig. 1. Volume-averaged electron density and temperature together with plasma volumes are listed in Table 1. We do not refer to time in these snapshots because the relation among current, density and time depends on the adopted ramp-up scenario strategy, still on discussion for DEMO1. Since the shine-through at fixed NBI energy depends mainly on the plasma density and only weakly on other parameters (e.g. T_e and B_T) through the ionization cross section [11,12], this work remains interesting also for other ramp-up strategies (or even ramp-down) that cross similar density profiles in the same or similar machines (including similar NBI geometry).

3. Simulation tools

Stand-alone simulations of the interaction between the NB injected particles and plasma have been performed using the profiles and information described in Section 2 (i.e. the plasma kinetic profiles are “frozen” and not modified from NBI energy and particle sources in these simulations). This steady state approach for each ramp-up snapshot becomes a good approximation for long ramp-up times, as it is for DEMO (ramp-up duration of hundreds of seconds with respect to a fast ion slowing down time of seconds, see next section for values).

Two coupled Monte Carlo codes are used: BBNBI [13] calculates the beam ionization in the background plasma and the shine-through losses, taking into account the accurate 3D beamlet-by-beamlet

description of each injector (Fig. 2-left). ASCOT [14] evolves the fast particle population generated by BBNBI during the slowing down by solving kinetic equations of fast ions, and calculates fast ion trajectories, power deposition, fast ion orbit losses, driven current etc. Scrape-off layer (SOL) is taken into account in the simulation extrapolating 1D density and temperature profiles beyond the last closed flux surface. Nevertheless, the impact of the low SOL density on NBI particle losses is negligible.

A 3D wall, with a 2D axisymmetric magnetic field and plasma, has been used in order to evaluate the actual footprint of the NBI shine-through on the wall during ramp-up. The shine-through is calculated by BBNBI code using 10^6 Monte Carlo test particles to have an accurate assessment of the 3D wall NBI footprint (and to ensure a considerable number of test particles for each portion of the mesh of the 3D wall). The fast ion losses, evaluated by ASCOT, are small, mainly due to high penetration, co-injection directed NBIs (see next sections and Table 1) and, thus, ASCOT simulations were carried out with reduced marker number of 5×10^4 .

4. Estimation of NBI power losses on a 3D wall

The 3D simulations have been run for all DEMO1 ramp-up snapshots presented in Section 2.

The most critical phase regarding NBI power losses is the start of the ramp-up, due to the low density plasma, and consequent higher shine-through. In Fig. 2 (right), the heat flux on the 3D wall due to the 3 NB injectors (16.8 MW each) at $I_p = 5$ MA ($\langle n_e \rangle = 0.78 \times 10^{19} \text{ m}^{-3}$) is shown. Since the 3 NB injectors are identical, in Fig. 3 we show the NBI

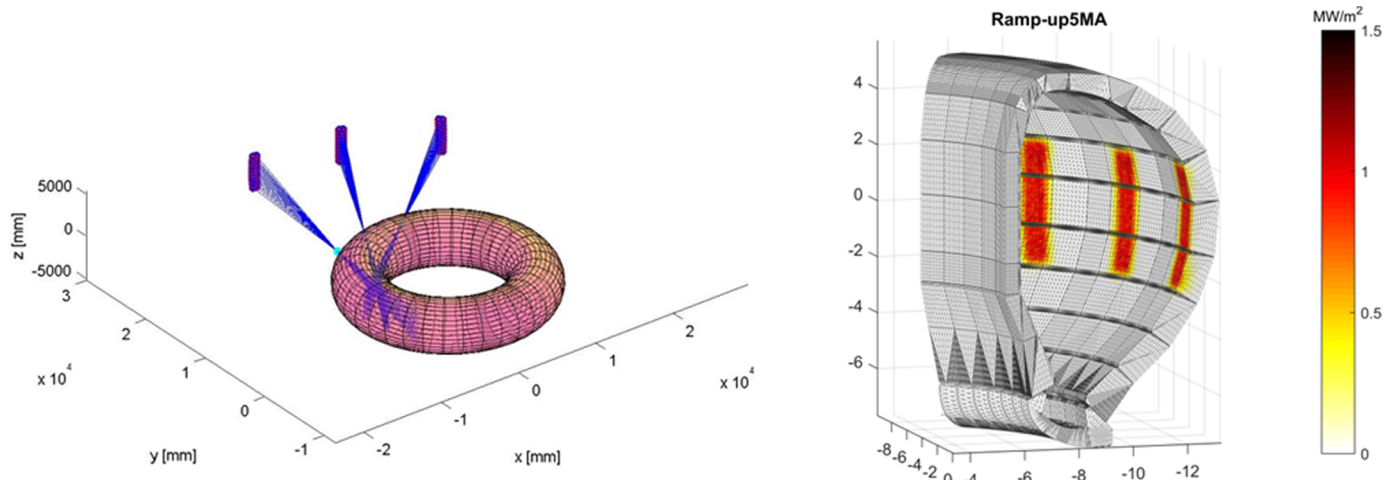


Fig. 2. DEMO NBI system implemented in the 3D simulations (left) and power load on DEMO1 first wall due to NBI shine-through losses during ramp-up at $I_p = 5$ MA (right).

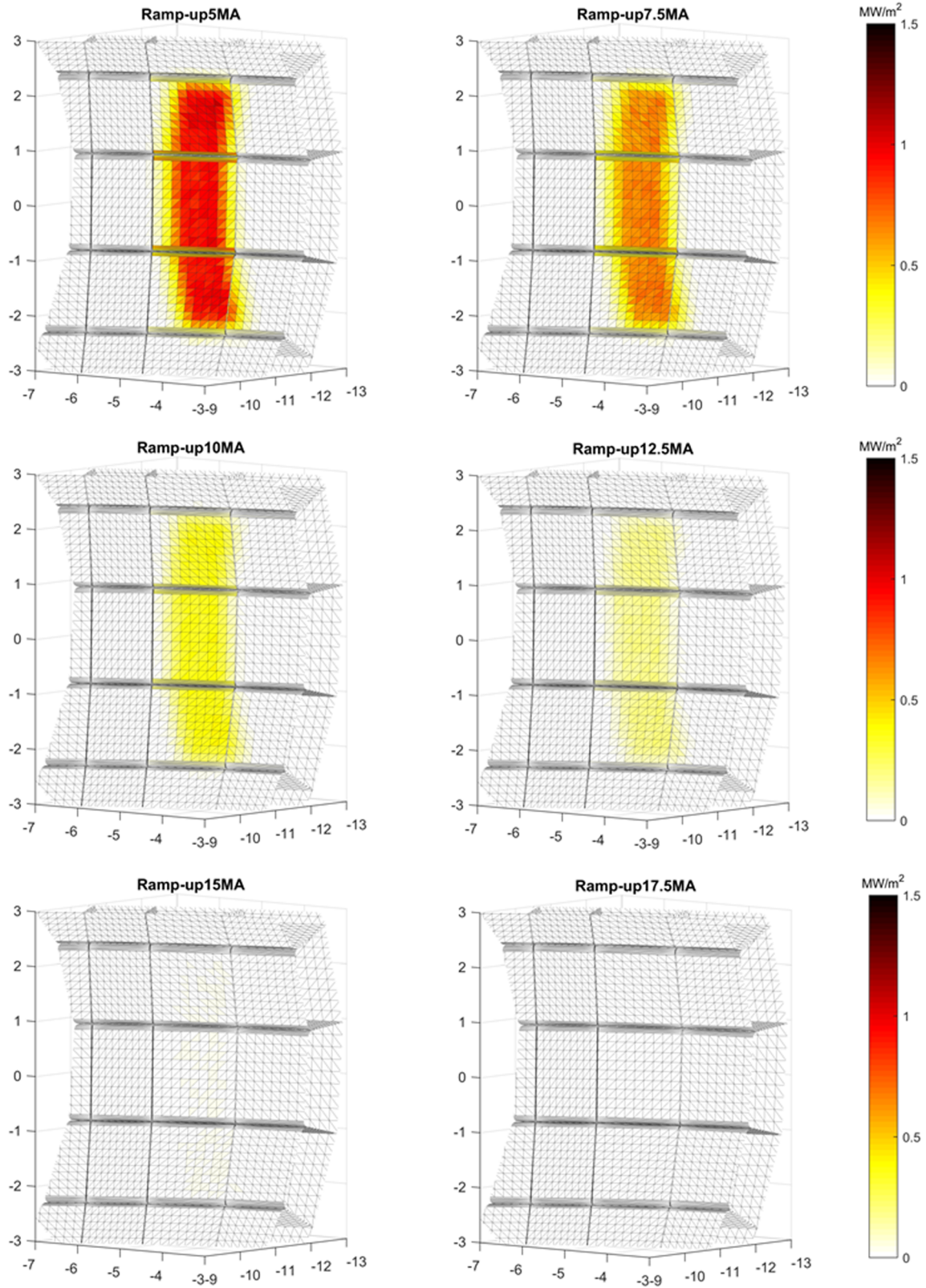


Fig. 3. Shine-through footprint and corresponding heat flux on first wall of 1 NB injector during DEMO1 ramp-up.

shine-through footprint for all the ramp-up snapshots just for one injector (here, all the 10^6 markers were assigned to a single injector to improve the resolution). The point at 19.6 MA has been excluded from this picture since the shine-through in this case is zero. A summary of the losses for each ramp-up snapshot is reported in [table 1](#).

At $I_p = 5$ MA ($\langle n_e \rangle = 0.78 \times 10^{19} \text{ m}^{-3}$), on average, each injector is found to lose about 29% of its power due to shine-through. The power lost is concentrated in a localized region of the wall at the end of the beam path (see [Fig. 2](#), right). The NBI orbit losses, which are present in addition to shine-through losses and are due to unconfined fast ion

orbits, are negligible ($\sim 1\%$ of the injected NBI power, or lower, during all the ramp-up phase); moreover, unlike the shine-through, the ion losses are broadly distributed on the wall and the divertor and, therefore, we don't discuss them in details here since their contribution to the power wall load is not significant. However, the magnetic ripple introduced by TF coils can lead to localized beam ion losses, but also in this case the peak heat flux of orbit losses is still negligible ($< 0.1 \text{ MW/m}^2$ [8]). The peak power load due to shine-through at 5 MA reaches 1.1 MW/m^2 which is slightly higher than the DEMO limit for the heat flux from all sources (1 MW/m^2). For comparison, the heat flux due to NBI fast ion losses only, during the flat-top phase, in a 2D axisymmetric magnetic background is estimated to be less than 0.1 MW/m^2 [4]. It should also be kept in mind that the wall load in the ramp-up phase is not static, but concentrated in the first phase of the ramp-up. The first-wall components receiving high peak loads could be designed with reinforced components which tolerate higher dynamic peak heat fluxes. This option is for instance under discussion for specific first wall components under significant heat load flux during the limiter phase of the ramp-up (not studied in this work) [4].

The peak heat flux decreases considerably in the later ramp-up snapshots (Fig. 3) due to the exponential decay of the shine-through losses with the (increasing) plasma density (clearly seen in the plot of Table 1). At $I_p = 15 \text{ MA}$ ($\langle n_e \rangle = 2.92 \times 10^{19} \text{ m}^{-3}$) the shine-through becomes negligible, but already at $I_p = 10 \text{ MA}$ ($\langle n_e \rangle = 1.36 \times 10^{19} \text{ m}^{-3}$) the shine-through ($\sim 11\%$) and related peak heat flux (0.41 MW/m^2) are already $\sim 1/3$ of the initial ramp-up point.

Fast ion slowing down time is longer for lower densities, and decreases from $\tau_{SD} \sim 5 \text{ s}$ at $I_p = 5 \text{ MA}$ ($\langle n_e \rangle = 0.78 \times 10^{19} \text{ m}^{-3}$) to $\tau_{SD} \sim 1 \text{ s}$ at flat-top, confirming that fast ion dynamics characteristic time is much shorter than ramp-up duration, as speculated in Section 3.

5. Discussion and conclusions

In this work we used the Monte Carlo NBI codes BBNBI and ASCOT to estimate the NBI power losses during the ramp-up phase of DEMO1. The simulations have been performed using a 3D beamlet-by-beamlet description of the NBI system and a 3D DEMO first wall, but axisymmetric plasma and 2D magnetic field. Due to the lower plasma density with respect to the flat-top phase (which the NBI system is optimized for), the shine-through losses are dominant in the first phase of the ramp-up, reaching $\sim 29\%$ of the total injected NBI power at $I_p = 5 \text{ MA}$ ($\langle n_e \rangle = 0.78 \times 10^{19} \text{ m}^{-3}$, the lowest plasma density considered in this work). The corresponding peak heat flux at $I_p = 5 \text{ MA}$ is 1.1 MW/m^2 . For comparison, the steady-state (flat-top) heat flux on DEMO first wall should not exceed 1 MW/m^2 including all the possible heat sources [4]. However, during ramp-up, the other heat sources harming the first wall in static flat-top conditions (e.g. thermal fluxes, radiation, ELMs etc.) can be expected to be lower, leaving more margins for shine-through losses. The installation of an additional armour on the first wall should be anyway carefully considered, since it would considerably increase the tolerable heat flux. The shine-through rapidly decreases with increasing plasma density in the later phases of the ramp-up until reaching flat-top density, where it becomes negligible. At $I_p = 10 \text{ MA}$

($\langle n_e \rangle = 1.36 \times 10^{19} \text{ m}^{-3}$) the shine-through is already $\sim 1/3$ of the initial point and becomes negligible at $I_p = 15 \text{ MA}$ ($\langle n_e \rangle = 2.92 \times 10^{19} \text{ m}^{-3}$). Were we to use the same criteria as in ITER ($P_{\text{NB,shine}} < 0.5 \text{ MW/m}^2$ without any additional armour on the first wall [3]), the density limit for full power NBI (800 keV) switch-on in DEMO1 would be $\langle n_e \rangle \sim 1.3 \times 10^{19} \text{ m}^{-3}$ (corresponding, in this ramp-up scenario, to about $I_p = 10 \text{ MA}$). This is to be compared to the ITER limit of $\langle n_e \rangle \sim 3 \times 10^{19} \text{ m}^{-3}$.

The operational window of DEMO NBI would be therefore enlarged to lower plasma densities, making possible its use during, at least, part of the ramp-up (and ramp-down) phase. This guarantees additional power with the same flat-top NBI system also during ramp-up, facilitating e.g. the access to H-mode. Nonetheless additional first wall armour would be beneficial and it was under discussion for ITER to increase the tolerable $P_{\text{NB,shine}}$ to $\sim 4 \text{ MW/m}^2$ [3] (for DEMO much lower values would be required). In order to extend even more the NBI operability, it is also possible to imagine a modulation of NBI power at the beginning of ramp-up to reduce peak power loads on the first wall, depending on the requirement of auxiliary power during the chosen ramp-up plasma evolution. At fixed NBI energy, heat fluxes due to shine-through will scale linearly with the applied NBI power.

The larger NBI operational window in DEMO low density phases with respect to ITER case, due to a favourable combination of NBI energy and plasma volume, increases the appeal of neutral beam injectors as DEMO auxiliary power systems.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement number 633053. This work has been supported by a EUROfusion Engineering Grant. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

- [1] R. Wenninger, et al., Nucl. Fusion 57 (2017) 016011.
- [2] P. Vincenzi, et al., Fus. Eng. Des. 123 (2017) 473–476.
- [3] A.R. Polevoi, et al., Nucl. Fusion 53 (2013) 123026.
- [4] R. Wenninger, et al., Nucl. Fusion 57 (2017) 046002.
- [5] R. Mitteau, et al., J. Nucl. Mater. 415 (2011) S969–S972.
- [6] P. Vincenzi, et al., EPS Conf. Proc. P4.146 (2017).
- [7] P. Sonato, et al., Nucl. Fusion 57 (2017) 056026.
- [8] J. Varje, et al., EPS Conf. Proc. P2.147 (2017).
- [9] R. Albanese, et al., Fusion Eng. Des. 96–97 (2015) 664–667.
- [10] J.F. Artaud, et al., Nucl. Fusion 58 (2018) 105001.
- [11] P. Vincenzi, et al., Plasma Phys. Control Fusion 58 (2016) 12008.
- [12] S. Suzuki, et al., Plasma Phys. Control Fusion 40 (1998) 2097.
- [13] O. Asunta, et al., Comput. Phys. Commun. 188 (2015) 33–46.
- [14] E. Hirvijoki, et al., Comput. Phys. Commun. 185 (2014) 1310–1321.