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

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Abstract

High energy Neutral Beam Injection (NBI) is one of the methods being considered in EU DEMO pre-conceptual design phase to provide auxiliary power to the plasma. From recent studies, it appears clear that auxiliary heating power is needed during the ramp-up (and ramp-down) phase to guarantee a robust access to H-mode (and to compensate for high radiation power losses in ramp-down). The use of NBI during ramp-up has to be carefully considered due to possible shine-through losses which can exceed the maximum heat load tolerated by the first wall (for DEMO the steady state peak heat flux limit is 1 MW/m^2). In ITER, shine-through losses pose a lower limit on density for NBI operation at $n \sim 3*10^{19}$ m^{-3}. This limits for ITER the operational window of the NBI system and can prevent its use during the ramp-up phase due to low plasma density.

In this work the heat wall loads due to NBI shine through and orbit losses are calculated for the diverted plasma ramp-up phase of EU DEMO pulsed scenario by numerical simulations performed using BBNBI and ASCOT Monte Carlo codes. The simulations have been done in a complete 3D geometry considering the latest DEMO NBI design, which foresees NBI at 800 keV energy. Location and power density of NBI-related heat loads at different time-steps of DEMO ramp-up are evaluated and compared with the maximum heat flux limit. Since NBI shine-through losses depends mainly on the beam energy, plasma density and volume, DEMO has a more favourable situation than ITER, enlarging NBI operational window. 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 configurations, inducing 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 (~2h 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 m and $B_{T,0}$=5.7 T) is supposed to have a flat-top with a D-T plasma having a current I_p=19.6 MA, an average electron temperature $<T_e>\sim13$ keV, a volume-averaged ion temperature $<T_i>\sim12$ keV, a central electron temperature $T_{e,0}\sim27$ keV, a central ion temperature $T_{i,0}\sim24$ keV, a volume-averaged electron density $<n_e>\sim8*10^{19}$ m^{-3}, a central electron density $n_{e,0}\sim1*10^{20}$ m^{-3} and an additional flat-top heating power $P_{add,FT}$=50 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 a trivial problem 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 which impacts on the discharge duration. The experience of present devices is taken into account, together with the expected strategies for ITER with the difference of having a much larger device and a dominant alpha heating when the plasma is heated approaching the target temperatures. 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 in ramp-down too to compensate for high radiation power losses. The plasma parameters in these phases are strongly different from the flat-top phase and this poses the issue of the additional power coupling to the plasma with systems optimized to work during the flat-top. 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) at low plasma density, as it is during ramp-up and ramp-down. In ITER, shine-through losses cause a lower limit on density for NBI operation at $<n_e>\sim 3*10^{19}$ m^{-3} [3] (calculated actually for H plasma and H^0 NBI), preventing its use during the ramp-up/down phase due to low plasma density. It is therefore crucial to understand the NBI usability for DEMO early plasma phases evaluating the shine-through power losses during the ramp-up phase, taking into account the tolerable heat loads on the first wall. In steady-state conditions, the 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]). This limit in fact includes all the possible sources of heat loads (charged particles, radiation, ELMs etc. in static conditions) with the NBI power losses representing only one of them. An option would be to design local first wall components which 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 (results in section 4) by numerical simulations in a complete 3D geometry (more details on the codes can be found in section 3). Previous studies [6], [4] already showed that NBI power losses are negligible during plasma flat-top. The latest NBI system design for DEMO and the plasma ramp-up scenario used in this work are described in section 2. Considering the additional power requirements during ramp-up, it is important to understand the possibility of using the NBI flat-top system also with lower plasma density and to consider the respective wall thermal loads when designing the first wall. Conclusions of the work are presented in section 5.

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

A new 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 innovative solutions aimed at improving the system efficiency, mainly regarding a new modular beam source, 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, D^0), 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. Each injector is capable of injecting 16.8 MW in the plasma, and the reference design foresees 3 identical injectors for a total of 50.4 MW entering the plasma with an inclination of 30° with respect to the radial direction.

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

In this work we concentrate on DEMO1 ramp-up phase, starting from the first diverted plasma (at I_p=5MA) up to the start of the flat-top (I_p=19.6MA). During this phase not only the plasma current is increasing, but also the plasma density. Low density may result in low beam ionization with localized losses on the first wall at the end of the beam path in the plasma (i.e. shine-through). The optimization of the ramp-up in order to save swing flux and 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 we have ECRH additional power during ramp-up as it is possible to deduce from temperature profiles in figure 1). Each ramp-up point analysed include as input: the plasma current, the 2D plasma axisymmetric magnetic equilibrium calculated with CREATE NL free boundary equilibrium code [9] and the plasma kinetic profiles calculated with METIS fast tokamak simulator [10], [11] as described in [2]. The plasma current of 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 represented in figure 1. Volume-averaged electron density and temperature together with plasma volumes are listed in table 1. 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 [12], [13], this work remains interesting also for other ramp-up strategies (or even ramp-down) which crosses similar density profiles in the same or a similar machine.

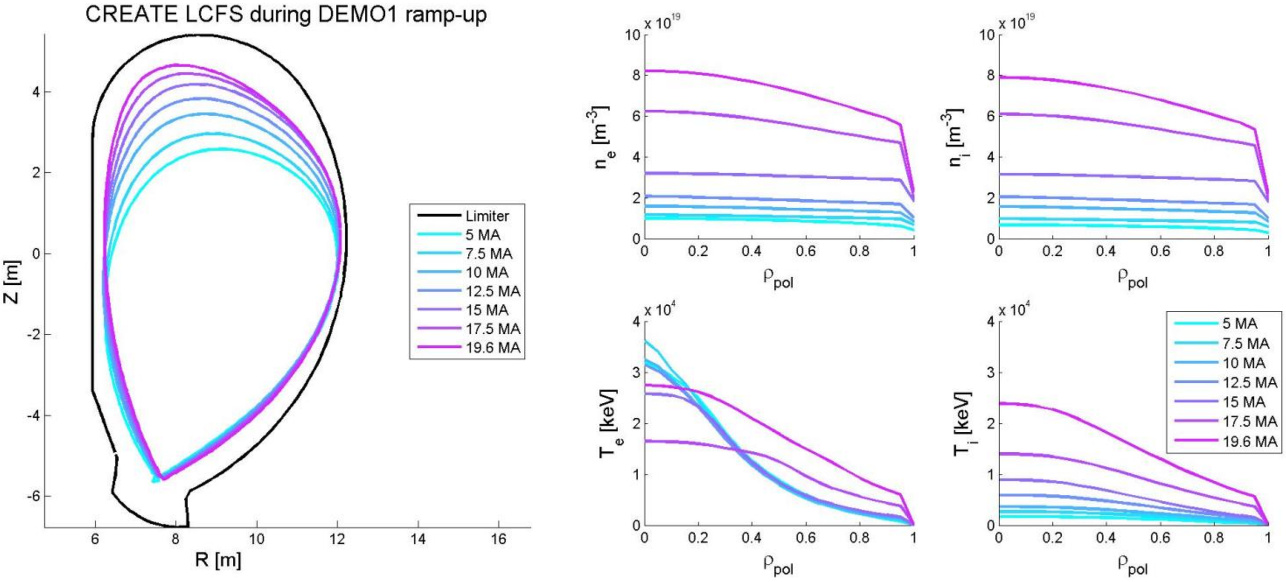

Figure 1: Plasma boundaries (LCFS) and plasma kinetic profiles (electron/ion density and temperature) at the selected DEMO1 ramp-up snapshots

3. Simulation tools

We performed stand-alone simulations of the interaction between the NB injected particles and plasma 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).

Two coupled Monte Carlo codes have been used: BBNBI [14] calculates the beam ionization in the background plasma and the shine-through, taking into account an accurate 3D beamlet-by-beamlet description of each injector (figure 2-left). ASCOT [15] evolves the fast particle population generated by BBNBI during the slowing down by solving kinetic equations of fast ions and calculates fast ion orbits, power deposition, fast ion orbit losses, driven current etc.

The simulations used a 3D wall description in order to evaluate the actual footprint of the NBI shine-through on the wall during ramp-up, which is the goal of this work.

The shine-through has been calculated with BBNBI code using 10^6 NBI 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 other information (like fast ion orbit losses) are estimated with ASCOT through reduced simulations with $5*10^4$ Monte Carlo test particles.

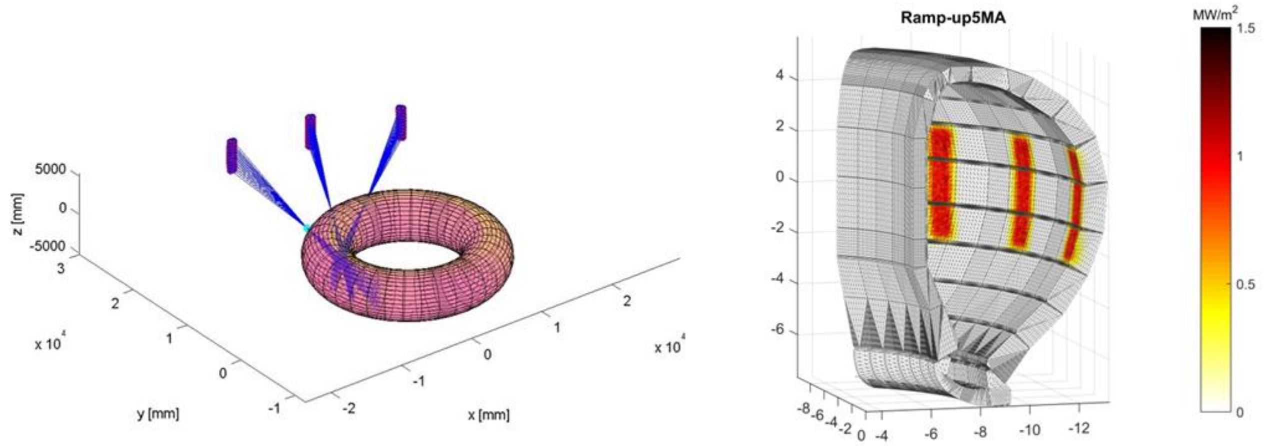

Figure 2: DEMO NBI system implemented in the 3D simulations (left) and power load on DEMO1 first wall due to NBI power losses during ramp-up at I_p=5 MA (right)

4. Estimation of NBI power losses with 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 figure 2 (right) the heat flux on the 3D wall due to the 3 NB injectors (16.8 MW each) at I_p=5 MA ($<n_e>=0.78*10^{19}$ m^{-3}) is shown. Since the 3 NB injectors are identical, we show in figure 3 the NBI shine-through footprint for all the ramp-up snapshots just for one injector (in this case, the simulation was run with only 1 injector and 10^6 Monte Carlo test particles to increase the accuracy). 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.

I_p [MA]	5	7,5	10	12,5	15	17,5	19,6
$<n_e>$ [10^{19} m^{-3}]	0,78	1,01	1,36	1,78	2,92	5,11	6,54
$<T_e>$ [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

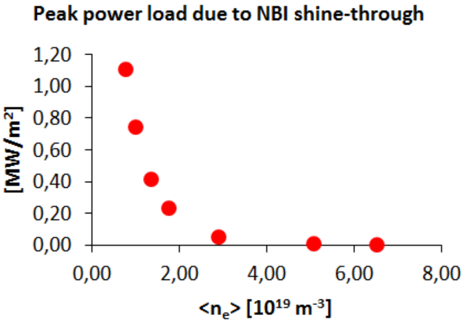
Peak power load due to NBI shine-through

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 average electron density

It is possible to see that at I_p=5 MA ($<n_e>=0.78*10^{19}$ m^{-3}), on average, each injector loses 28,64% of its power due to shine-through. The power lost is distributed on a localized region of the wall (see figure 2-right) corresponding to the intersection of the trajectory of the beam and the first wall. The NBI orbit losses, which are present in addition to shine-through losses and are due to unconfined fast ion orbits, are negligible (~1% of the injected NBI power or lower during all the ramp-up phase) and moreover they are not localized as shine-through is, therefore we don’t discuss them in details here since their contribution to the heat wall load is not significant. NBI orbit losses in fact may be localized if a perturbed 3D magnetic equilibrium is considered (e.g. due to the effect of magnetic field ripple), but also in this case the peak heat flux of orbit losses is still negligible (<0.1 MW/m^2 [8]). The power peak load due to shine-through at 5 MA reaches 1.1 MW/m^2 which is slightly higher than the static peak heat flux limit in DEMO (1 MW/m^2, but this limit includes all the possible sources of heat loads). For comparison the heat flux due to only NBI fast ion losses during the flat-top phase in a 2D axisymmetric magnetic background is estimated to be less than 0.1 MW/m^2 [4]. In fact shine-through heat load is not static, but concentrated in the first phase of the ramp-up, and it may be possible to evaluate the design of localized reinforced first wall 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 following ramp-up snapshots (figure 3) due to the exponential decay of the shine-through losses with the (increasing) plasma density (clearly seen in the plot of table 1). In particular from I_p=15 MA ($<n_e>=2.92*10^{19}$ m^{-3}) the shine-through becomes negligible, but even from I_p=10 MA ($<n_e>=1.36*10^{19}$ m^{-3}) the shine-through (10.89%) and related peak heat flux (0.41 MW/m^2) are already ~1/3 with respect to the initial ramp-up point analysed here.

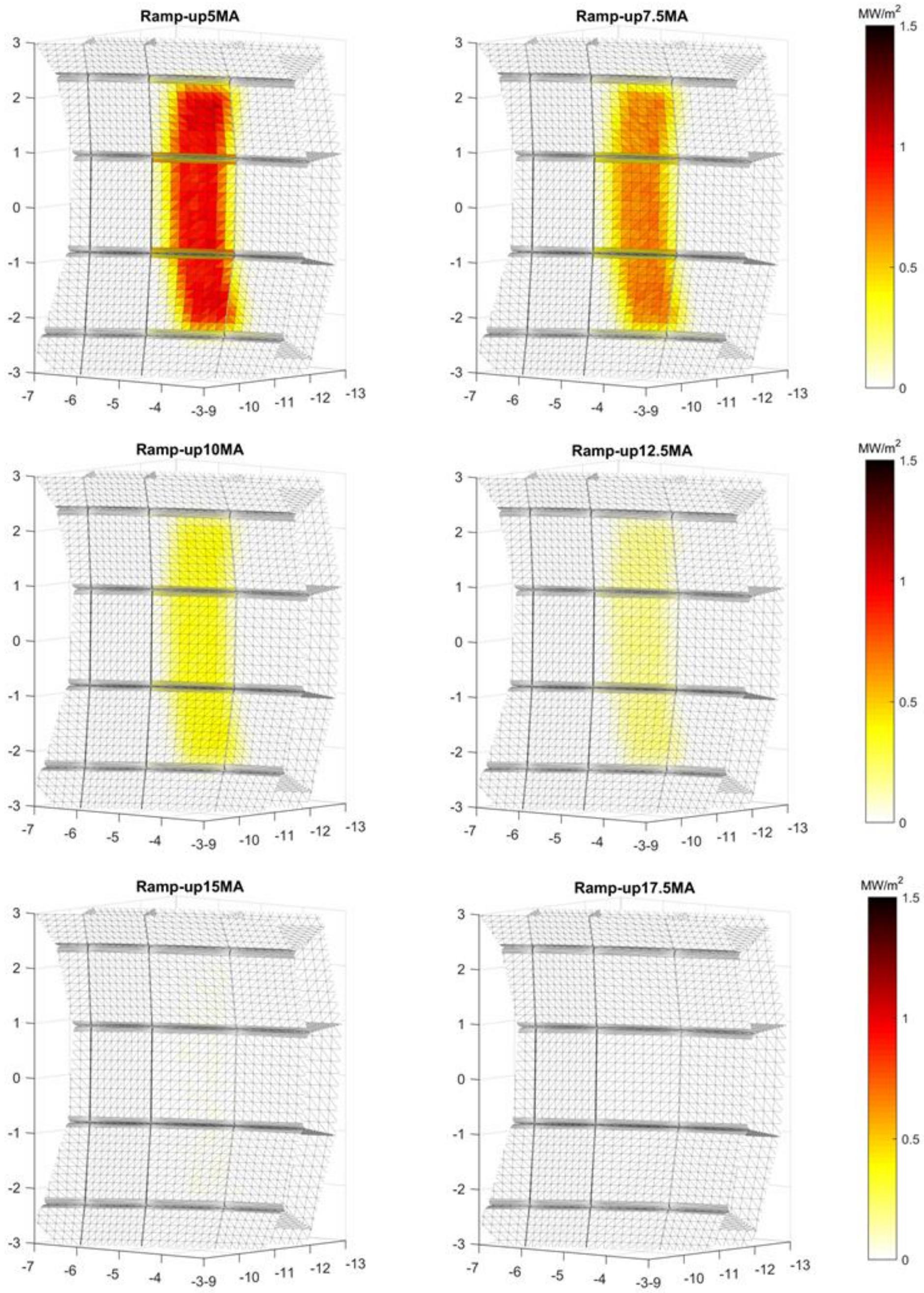

Figure 3: Shine-through footprint and consequent heat flux on first wall of 1 NB injector during DEMO1 ramp-up

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 considering a

3D beamlet-by-beamlet description of the NBI system and a 3D DEMO first wall. 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 significant in the first phase of the ramp-up, reaching ~28% of the total injected NBI power at I_p=5MA ($<n_e>=0.78*10^{19}$ m^{-3}, which is the lower density plasma here analysed). The corresponding peak heat flux at I_p=5MA reaches 1.1 MW/m^2. For comparison, the static limit for the heat flux on DEMO first wall has been estimated in 1 MW/m^2 including all the possible heat sources. However it is not excluded that an additional armour on the first wall could be installed considerably increasing the tolerable heat flux. The shine-through rapidly decreases with the increase of plasma density in the following part of the ramp-up, being already ~1/3 at I_p=10 MA ($<n_e>=1.36*10^{19}$ m^{-3}) and becoming negligible from I_p=15 MA ($<n_e>=2.92*10^{19}$ m^{-3}). If we adopt the same criteria used for ITER ($P_{NB,shine}<0.5$ MW/m^2 without any additional armour on the first wall [3]) we would have a density limit for DEMO NBI switch-on of $<n_e>\sim1.3*10^{19}$ m^{-3} (corresponding in this ramp-up scenario to about I_p=10 MA), to be compared to a limit for ITER of $<n_e>\sim3*10^{19}$ m^{-3}. This would enlarge the operational window of the NBI in DEMO also during the ramp-up (and ramp-down) phase, even without any localized reinforced first wall components, guaranteeing additional power with the same flat-top NBI system also during ramp-up, facilitating the access to H-mode. Anyway additional first wall armour was under discussion also for ITER to increase the tolerable $P_{NB,shine}$ to ~4 MW/m^2 [3].

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

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