Neutral beam ion shine-through calculations for the reduced field and current plasmas in ITER

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Introduction

ITER research plan includes Pre-fusion Power operation (PFPO) phases that plan an operation with reduced fields and currents. The aim is to demonstrate an H-mode access in H and He plasmas. This is important since the predictions of the threshold power by extrapolating empirical scaling laws are uncertain and because only limited amount of heating power will be available. Moreover, all systems, e.g. related to ELM control, have to be tested prior DT operation. In the second phase of the PFPO, a neutral beam injection (NBI) operation is foreseen. The access to H-mode favors operation in low electron density but, on the other hand, the NBI shine-through (ST) poses a lower limit to electron density. Fortunately, the NBI system can be operated with lower injection voltage to decrease the shine-through. In this work we aim at building knowledge of the NBI system operation in the PFPO in terms of the shine-through. This is done by carrying out beamlet-based NBI simulations and calculating the shine-through power load distribution at the wall structures, especially to those components made of material not designed to last high power loads.

The ST power density (STPD) maximum on the NBI facing components depends on the NBI energy, NB species, NBI focussing (beam divergence [1]), NBI direction. In ITER design the reduction of STPD can be provided by reduction of the NBI energy to 500 keV, by affecting the NBI power ($P_{\mathrm{NBI}} \propto E_{\mathrm{inj}}^{2.5}$). For the same NBI parameters the STPD is higher for the H0-NBI. The STPD depends also on plasma parameters. It decreases for lower temperatures, higher densities, sort plasma fuel (H, He, D, DT) and presence of impurities, Zeff [1, 2]. Thus, the maximal affordable STPD restricts the operational space, where the NBI heating & CD can be used stationary, which is studied in [1] in details. The reduction of the STPD can be controlled by increase of plasma density and contamination by impurities [1] . For the chosen NBI configuration and directivity the density which guarantees the stationary NBI operation is called the ST density limit (SHDL). Note that the SHDL depends on the NBI aiming and divergence, because the maximal affordable power is determined by the NBI power, which reaches unprotected components, rather than by the STPD maximum at the NBI axis [2].

Modeling tools

The main modeling tool is the BBNBI code [3] that is part of the ASCOT-suite of codes [4]. It is a beamlet-based NBI ionization tool that starts following the neutral particles from the grounded grid and utilizes a probabilistic model to evaluate whether the particle is ionized along its ballistic path. If not, the neutral particle will hit the blanket and contributes to shine-through losses. In order to evaluate the shine-through losses, we utilize realistic blanket model directly triangularized from the CAD-data, together with METIS and/or JINTRAC calculated axisymmetric plasma equilibrium and kinetic profiles. The ionization cross-sections are from Suzuki *et al.*[5]. The simulated cases are helium plasmas with hydrogen beam ions.

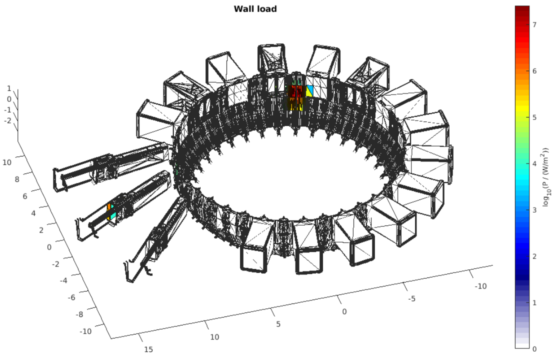

Figure 1: The simulations are carried out for the middle beam for which the shine-through losses occur on the outer blanket wall, about 120 degrees from the injector as indicated by the colors.

The beam geometry is shown in figure 1: ITER has two heating NBI injectors and all simulations in this contribution are carried out using the middle heating beam port in this figure. Since the beam is not perpendicular to the plasma, the shine-through losses are not observed in the central column but on the outer blanket wall at the opposite side of the injector with roughly 120 degree toroidal shift.

One-third field scenario with 5 MA plasma current

For this scenario the plasma profiles with 40% Greenwald fraction and corresponding equilibrium were calculated using the METIS code. The beam power was scanned keeping in mind that the power depends in the injection voltage due to beam perveancy criteria ($P_{\rm NBI} \propto E_{\rm inj}^{2.5}$). Each simulation was carried out using 100k markers. In figure 2a) we show the total injected power, total shine-through power and the peak power heat load at the first wall as a function of

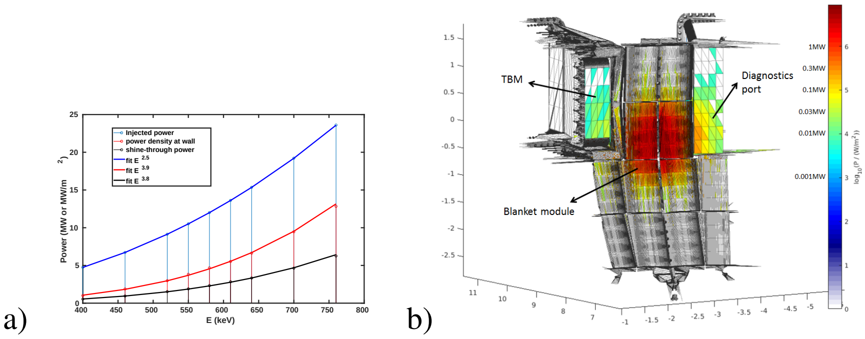

Figure 2: a) The NBI beam injected power, total shine-through loss power and peak power load density at the first wall as a function of the injection voltage and b) the shine-through power load in the first wall panels and adjacent ports.

the injection voltage, together with the power law fits. One can notice that the voltage dependency of the shine-through power and peak heat load have the same exponent (roughly 4) that is about 1.5 larger than the injected power (=2.5). This is due to higher probability for the neutrals with higher energy to penetrate though the plasma without ionization. The total shine-through fraction for nominal 580 keV/12 MW injection energy/power is 19% (2.3 MW).

While the first wall panels facing the injector are designed to endure power loads up to 4.7 MW/m^2, the total power to normal panels is restricted to below 2.0 MW/m^2 and to port plugs to below 0.3 MW/m^2. In particular, this is the case with the two ports adjacent to the re-inforced shine-through panels. As figure 2b) illustrates, to the left of the ST panels is the TBM port and its frame and to the right a diagnostic port. In particular the latter one is receiving power values of up to 0.3 MW/m^2 even in the absence of other power sources from the plasma itself.

Half-field scenario with 7.5 MA plasma current

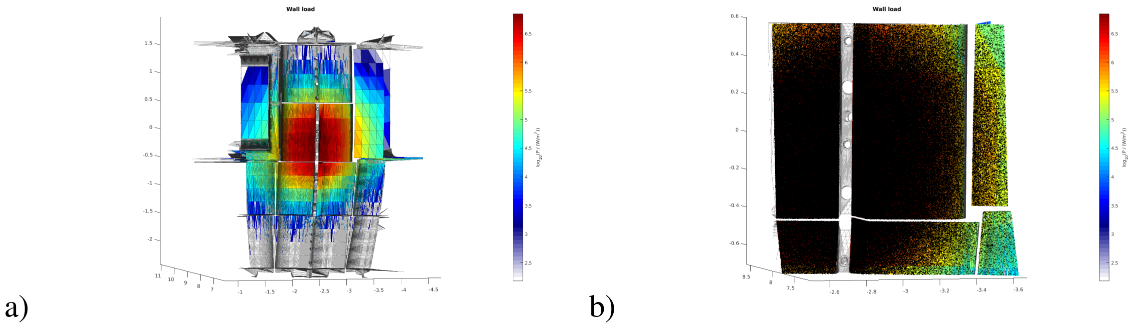

Figure 3: a) Shine-through power load in the first wall panels and adjacent ports and b) the zoom to diagnostic port with scattered markers overlaid showing that several markers contribute to a single triangle.

The density of this He plasma corresponds to 40 % Greenwald fraction and has current of 7.5 MA. The kinetic profiles and equilibrium were calculated with the JINTRAC transport code. Total number of 2M markers were used in the Monte Carlo simulations. The beam was set to inject full 16.5 MW with the injection voltage of 870 keV, as proposed in [1]. The total shine-through power fraction was observed to be 21% (3.5 MW). The resulting power load is shown in figure 3. To illustrate the good statistics, in this figure we also show a zoom to the diagnostic port side with the markers contributing to the shine-through heat load marked with black dots - several tens of markers are found on each important wall triangle.

Discussion and outlook

The electron density of $n_e = 0.4 n_G$ was selected here as a lower limit of foreseen operational window. Higher densities are possible while still being able to reach the H-mode. This would significantly ease the shine-through limit as larger fraction of the beam will be ionized. Such of an optimization regarding the density will be carried out as a future work. The local deposition of the shine-through power depends on the fine details of the blanket module, where some small adjustments have been made since our CAD model. Further work will be to repeat the simulations with an updated version of the blanket module. Importantly, there is also a horizontal gap between the blanket modules and this allows some of the shine-through particles to penetrate between the first wall, which are then neutralized on the shielding block, bringing strict limitation. As was discussed in [2], this pose the limiting constraint in terms of the ST losses, and an analysis to estimate this power load is left for future work. Furthermore, we are in the process of comparing our results qualitatively with the ones presented in [2]. Moreover, the effect of beam scrapers on the distribution of shine-through losses is been investigated and will be reported in future. The electron density of $n_e = 0.4 n_G$ was selected here as a lower limit of foreseen operational window. Higher densities are possible while still being able to reach the H-mode [1]. This would significantly ease the shine-through limit. Such of an optimization regarding the density will be carried out as a future work.

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