Beam Ion Performance and Power Loads in the ITER Pre-Fusion Power Operating Scenarios (PFPO) with Reduced Field and Current

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Abstract:

The ITER Organization is considering additional options for provision of 30 MW for initial operation in the Pre-Fusion Operation campaign (PFPO-1) which do not rely in the availability of an ICRH antenna in this phase to allow H-mode operation at 5 MA/1.8 T. Such options also open up a wider operational space for hydrogen H-mode operation at 5 MA/1.8 T in the follow-up phase of the Pre-Fusion Operation campaign (PFPO-2). It is thus necessary to evaluate the operational space and issues associated with the generation of fast particles (ICRH and NBI) used for heating such hydrogen plasmas, namely shine-through losses (NBI) and ripple losses (NBI and ICRH). Here we report fresh results from ASCOT simulations of hydrogen beams on *hydrogen* plasma, with emphasis on the shine-through and ripple losses. The contribution also includes a detailed description of the geometry of the critical wall components. The shinethrough is analyzed for hydrogen H-mode plasmas in the 1/3-field scenario (5 MA/1.8 T) and with two different kinetic profiles: at 50% of the Greenwald density with temperature profiles corresponding to about 40 MW auxiliary heating, and at 90% of Greenwald density with over 50 MW of heating. It is found that neither the beam shinethrough nor the charged-particle losses pose a threat to the receiving structures at the proposed operating parameters for the hydrogen operation at 50 % and 90 % of the Greenwald density.

1 Introduction

Due to the quite limited heating power as well as the challenges in predicting the necessary power for L-H transition in ITER, it has deemed necessary to include in the ITER research plan scenarios operating with parameters reduced compared to the so-called half-field/half-current (2.65T, 7.5 MA) scenario. The ITER Pre-fusion Power Operating (PFPO) phase is now foreseen to include one-third field operation (1.8T, 5MA), which ought to allow H-mode access even with limited heating.

Due to some delays with the ICRH antenna, PFPO-1 will rely entirely on ECRH. in PFPO-2, about 30MW of ECRH will be supplemented by 10 – 20 MW of beam power. The PFPO phases are non-nuclear and, thus, the plasma will consist of either hydrogen or helium. The beams will be operated with reduced acceleration voltages. Reduced voltages are the result of competing requirements: the empirical scaling favors low density for H-mode access[1], but low density increases shinethrough (ST) of the beams. the shinethrough can be reduced by reducing the energy of the injected particles. The technological limit for the hydrogen beam energy in the PFPO phases is 870 keV. In order to ensure that the shinethrough stays at acceptable level, this energy is further reduced according to the plasma density. In the 1/3-field scenario, the beam energy is below 600 keV when the plasma density is 50 % of the Greenwald density, while at 90 % of the Greenwald density the beams can be injected at 745 keV [2].

In ITER 15 MA baseline scenario, quite good approximation to axisymmetry is achieved by the optimized ferritic inserts: the toroidal field ripple at the separatrix is mitigated to 0.3% everywhere else except near the NBI ports (0.6%). However, reducing the field strength compromises the optimization so that, due to over-compensation, the effect can even turn into ripple enhancement. Indeed, at the low field value scenarios in the PFPO phases, the TF ripple phase is reversed and, in the 1/3-field scenario, the ripple strength at the outboard midplane separatrix can reach -1.3%. This could compromise the good confinement of beam ions. Additional perturbations are introduced by the test blanket modules (TBM), made of ferromagnetic material and installed to test tritium breeding. TBMs cause poloidally and toroidally localized perturbations to the magnetic field. Therefore, while the confinement of beam ions is predicted to be very good in the main operating phases (15 MA baseline, 12.5 MA hybrid, and 9 MA advanced scenarios [3], the operating scenarios where both the field and the plasma current are significantly reduced can introduce new uncertainties.

The goal of this contribution is to determine the distribution and magnitude of beam power loads, both from charged and neutral particles, to the ITER first wall in the 1/3-field scenario. Since recently the beam shinethrough (ST) has raised some concerns in the PFPO phase, special attention is devoted to it. The He plasma case for both the half-field and the 1/3-field scenarios has already been briefly reported in [4], so here the focus is on hydrogen plasma.

2 Beam shinethrough and ITER wall structure

The ST level depends on both the beam parameters and the plasma. In ITER design, ST can be reduced by reducing the beam energy, i.e., the acceleration voltage, thus affecting not only the penetration depth of the beams but even the beam power via the perveance relationship, $P_{\rm NBI} \propto E_{\rm inj}^{2.5}$. Also the injected species plays a role: for the same NBI parameters, hydrogen beams will have higher ST than helium. The plasma parameters affect the shinethrough via ionization efficiency. Therefore ST decreases for lower temperatures and/or higher densities, but also the plasma species (H, He, D, DT) and the presence of impurities (Zeff) affect the ST level [5, 2].

The cross-sectional profile of the beam shinethrough arriving at the receiving components depends on the NBI energy and direction, the beam species, and the beam focussing (beam divergence [5]). The *maximum* ST Power Deposition (STPD) also depends on the structure of the receiving components. The operational space, within the limits of maximal affordable STPD, that allows continuous beam heating & CD has been studied in detail by Polevoi et al. [5]. Increasing the plasma density and/or impurities were found effective in controlling STPD. For the chosen NBI configuration and directivity, the density that guarantees the stationary NBI operation is called the SHinethrough Density Limit (SHDL). It is important to keep in mind that SHDL depends on the NBI aiming and divergence, since it is the power reaching unprotected components rather than the STPD maximum at the NBI axis that sets the highest affordable power [2].

The structure of the ITER wall in the vicinity of the shinethrough has to be carefully modeled. The first wall is composed of *blanket modules*, each of which has two parts: the massive 3D structure called the *shield block*, designed to shield neutrons from fusion reactions, and the plasma-facing plate called the *first wall panel* mounted on it. The FW panels receiving ST power are re-inforced to tolerate *total* power loads of up to 4.7 MW/m^2 and, from this on, will be referred to as *ST panels.* For port plugs the constraint is stringer: the total power load from different sources should remain to below 0.3 MW/m^2. It is therefore necessary to address also the closest unprotected components around the ST panels.

The bulk of the shinethrough is received by four ST panels, two in the horizontal row 15S and two in the row 16S, toroidally located about 110° from the injectors. The power limits on these panels are very unlikely to be exceeded even with the low-density operation of PFPO. However, there are *gaps* between the ST panels that have lately drawn some attention. The relevant structures are illustrated in Fig. 1, showing that the vertical gaps are covered by the right-hand-side ST panels having slanted pieces called *facets.* These pieces are found to receive the beam shinethrough at highest angle of incidence and are thus of the same reinforced material as the rest of the ST panels. As for the horizontal gap between rows 15S and 16S, the top of shield blocks in the row 16S are equipped with a special slanted piece that prevents the ST particles the access to the stainless steel vessel wall behind the blocks. However, these slanted 'ST protectors' are not made of the same material as the ST panels and, thus, the beams ought not to be directed such that the STPD lands on them.

Naturally the significance of these gaps has been understood from early on and, consequently, the issue has already been addressed by Polevoi [5] and Singh et al., [2] using an analytical model for the beam cross section. It was found that the most severe limitation for the beams is set by the acceptable power load on the slanted 'ST protectors' on the top of the shield blocks in the two horizontal gaps between rows 15S and 16S. This limitation is about 0.3 MW/m^2, equivalent to 0.8 MW/m^2 of incident power on the first wall. However, making sure that the life time of these special shield blocks equals or exceeds the life time of ITER is considered so important that Monte Carlo test particle simulations with high statistics was seen necessary to verify that the limit of 0.8 MW/m^2 of incident power is not exceeded. This analysis also allows for checking if divergences of different beamlets would lead to excessive losses on the components neighboring the

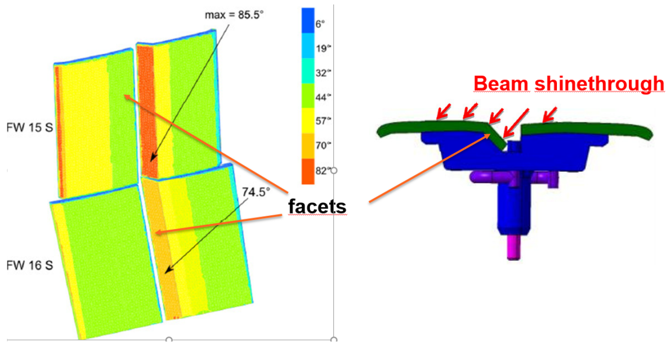


FIG. 1: The geometry of the four ST panels, colored according to the angle of incidence by the beam shinethrough (left), and the stucture of the entire blanket module (right) with shield block in blue and ST panel in green. The direction of the shinethrough neutrals is indicated by red arrows.

ST panels, i.e., the diagnostic port to the left or the TBM frames to the right of the ST panels.

3 Modelling beam particles: BBNBI and ASCOT

The main modeling tool is the BBNBI code [6] that is part of the ASCOT-suite of codes [7]. 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. The ionization cross-sections are from Suzuki *et al.*[10], and the ionization probability is evaluated using METIS [8] and/or JINTRAC [9] calculated axisymmetric plasma equilibrium and kinetic profiles. If an NBI neutral survives the plasma, it will hit one of the ST panels and contribute to ST losses.

ITER has two heating beams and one diagnostic beam as illustrated in figure 2. All simulations in this contribution are carried out for the heating beam in the middle. Since the beam is tangential, the ST losses are received by the outer wall components (rows S15 and S16) about 120 degrees away from the injector. In order to evaluate the ST distribution as accurately as possible we utilize realistic blanket model directly triangularized from the CAD-data.

3.1 530 keV beams in 50% Greenwald density hydrogen plasma

The density of the hydrogen plasma corresponds to 50% of the Greenwald density and the temperature profile is a result of about 40 MW of auxiliary heating: 30 MW of ECRH, combined with almost 10 MW of beam power. The kinetic profiles are shown in Fig. 3(a). The applied beam voltage was 530 kV to reduce ST, with 4.7 MW injected from both on- and off-axis beams. Altogether 10^5 markers, generated by BBNBI and representing the beam ions, were followed by ASCOT for the entire slowing-down time. The resulting

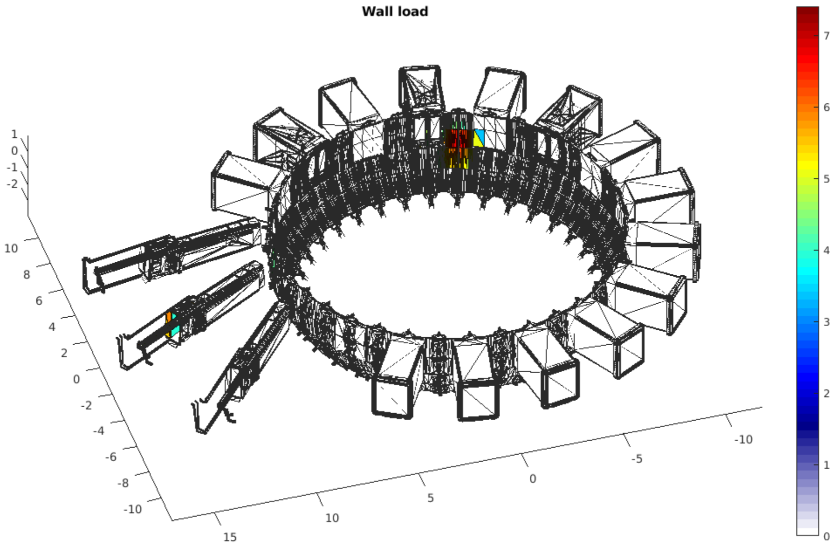


FIG. 2: ITER beam geometry. The simulations are carried out for the middle beam for which the shine-through losses occur about 120 degrees from the injector as indicated by the colored spot.

ST footprint on the panels is illustrated in Fig. 4. The highest power, in the range of 1 MW/m^2, is found to land predominantly on the ST panels in row 15S (upper) for the on-axis beam and on the row 16S panels (lower) for the off-axis one. The power is distributed fairly uniformly between the two ST plates in row 15S, while in row 16S the bulk of the power lands on the left panel and some power is even spilled to the regular panel adjacent to it. Overall, the high-power ST footprint is smaller for the on-axis beam. The load to the critical horizontal gap at around $z = -0.5$m is about 0.2 MW/m^2, well below the limit of 0.8 MW/m^2 determined by Singh *et al* [2]. The structures adjacent to ST panels in row 15S also appear to receive some of the shinethrough, in particular on the TBM frame (to the right) with the on-axis beam, but only in the range of tens of kW's. The slowing-down simulations with ASCOT verified that the beam ion confinement remains reasonable in these hydrogen plasmas: charged particle losses amounted to less than 3 % of the total beam power (270 kW).

3.2 745 keV beams in 90% Greenwald density hydrogen plasma

When the density of the hydrogen plasma was increased to 90% of the Greenwald density, also the beam voltage was upped to 735 keV, allowing the power of 11.15 MW for both on- and off-axis beams. Again, 30 MW of ECRH power was applied, and the corresponding kinetic profiles are shown in Fig. 3(b). The ST footprint from 10^5 BBNBI neutrals, illustrated in Fig. 5, is similar to the 50 $\% n_{GW}$ case, but the magnitudes are about five

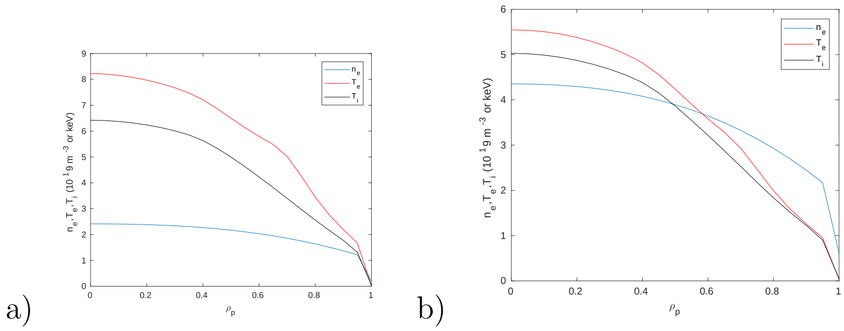


FIG. 3: The plasma profiles corresponding to the operation at 50% (a), and at 90 % (b) of the Greenwald density.

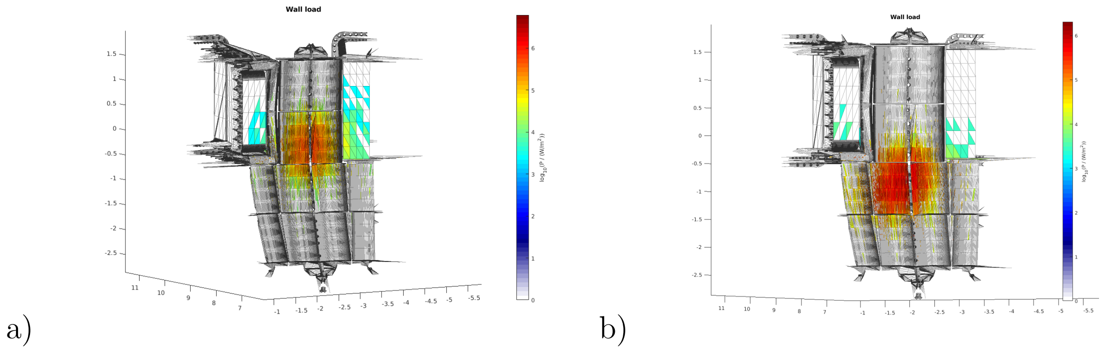
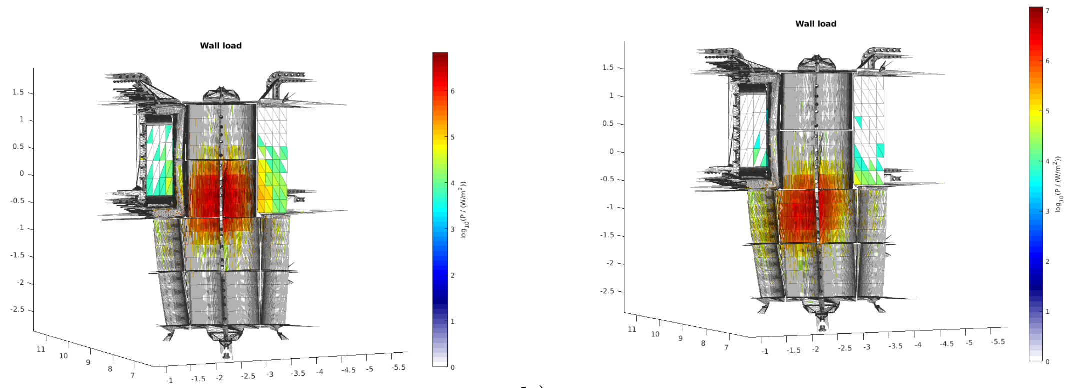


FIG. 4: The shinethrough power distribution for (a) on-axis, and (b) off-axis beams for the hydrogen plasma at 50% of the Greenwald density. The BBNBI simulation was carried out with 10^5 *markers.*

times higher. An important qualitative difference is that now the high-power spot from the on-axis beam (row 15S) is as large as from the off-axis beam. This results in higher loads on both the TBM frame and the diagnostic port, reaching up to 100 kW/m^2. However, to accurately model the peripheral ST loss distribution, it is necessary to account for the possible scraping surfaces *inside* the injector. A triangularized CAD model of the scrapers has already been used for He plasmas [4] and could be applied here as well. The power to the sensitive horizontal gap between rows 15S and 16S now approaches the 0.8 MW/m^2 limit. The slowing-down simulations with ASCOT verified that the beam ion confinement remains almost uncompromised in these hydrogen plasmas: only 65 kW of the ionized beam power of nearly 20 MW was lost.



a) b)

FIG. 5: The shinethrough power distribution for (a) on-axis, and (b) off-axis beams for the hydrogen plasma at 90% of the Greenwald density. The BBNBI simulation was carried out with 10^5 *markers.*

4 Conclusions and future work

The shinethrough of the beams in the 1/3-field scenario hydrogen plasmas was found well below the limits set by the material of the receiving panels. This was the case for both the plasma at 50 % Greenwald density (530 keV beams with $P_{NBI} = 4.7$ MW per beam) and at 90 % Greenwald density (745 keV beams with $P_{NBI} = 11.15$ MW per beam). Also the power arriving at the sensitive regions, i.e., the horizonal gap between rows 15S and 16S and the adjacent structures in row 15S, is probably acceptable. However, for 90% n_{GW} the power to TBM frame reaches 100 kW/m^2 for the on-axis beam. Therefore, if found necessary, these beams could be simulated again including the scraping surfaces inside the injector, which is likely to reduce the peripheral ST power.

The power loss from the ionized beams was found negligible for the plasma at 90 % Greenwald density and tolerable (less than 3 %) at 50 % Greenwald density.

The work will be continued with a scan of injected power/acceleration voltage and plasma density. Also the significance of the plasma-wall gap will be addressed.

5 Acknowledgements

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