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# Modeling of the ITER Heating/CD and Diagnostic Neutral Beams

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## 1. Introduction.

Neutral beam injection (NBI) is a dominant method for heating and current drive (CD) in ITER [1]. ITER diagnostics neutral beam (DNB) is the key element for the range of principal diagnostics. These motivate the efforts to make the ITER NBI modeling as accurate as possible.

The ionization process and physics governing the slowing down history of the fast ions are well understood providing the possibility for the first principle based simulations. Various tasks originated from ITER engineering, diagnostics and integrated scenario needs are focused on the different aspects of the NBI physics, providing the necessity to develop the hierarchy series of the NBI models. In the present paper we discuss the models for ITER heating/CD (HNBI) and DNB based on the full orbit following Monte Carlo (OFMC) simulations with use of the DRIFT [2] code and newly developed 1D-3D kinetic models. Recent comparison of the various NBI codes done for ITER reference scenario #4 [3] revealed in particular the importance of accurate setting the injection geometry. Special emphasis in development of the present models was done in precise description of the NBI source. It allows for all necessary details of the NB duct structure, beam focusing and divergence for the full Monte-Carlo and 3D Fokker-Plank models and keeps the most important features for the reduced 2D & 1D kinetic simulations.

Finally, the results of ITER DNB ripple loss calculations for original DNB design with strictly perpendicular injection ($R_{targ}$=0) and for rotated beam are presented. For the original design first wall heat loads, associated with ripple loss of the DNB ions, were found to be extremely high, of order 2~4MW/m$^2$. Rotation of the DNB to $R_{targ}$>1.3m reduces FW heat loads to the level of 0.1 MW/m$^2$ or smaller.

## 2. Neutral beam source.

New NBI source module includes complete interface with Beam transport with re-ionization (BTR) code [4] used for the design of the both ITER H&CD and diagnostics neutral beams. It allows taking into account all necessary details of the realistic NB injector affecting geometric properties of the beam entering the ITER plasma.

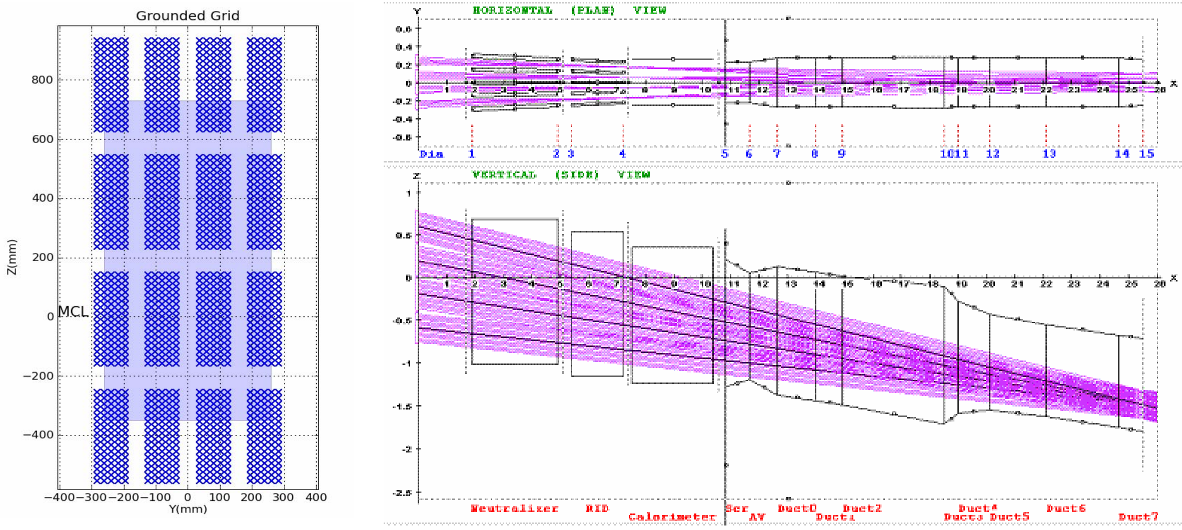


**Fig.1** ITER H&CD injector layout. Grounded grid (left) and FW opening (shadowed). Diaphragms (right).

Initial position and velocity direction of a neutral in the most complete ITER-NBI source module, incorporated in OFMC and 3D Fokker-Planck NBI models, are randomly sampled at the NB grounded grid allowing for the exact geometry of the aperture allocation, Gaussian spreading of the beams from each aperture, their focusing and losses on the diaphragms in the NB duct (Fig.1). The possible tilting of the HNBI providing on/off axis heating and CD and rotation of the DNB are taken into account in the NB source models.

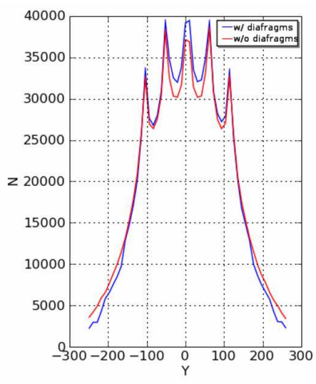


**Fig 2a** Horizontal distribution of H&CD power at the FW window.

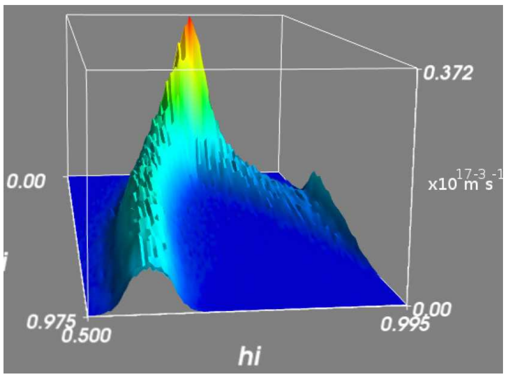


**Fig 2b** 2D distribution of the beam source S( , ) in ITER scenario #4.

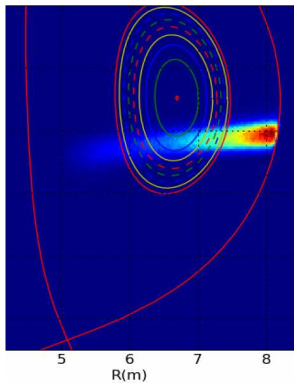


**Fig 3c** Beam ionization points in ITER scenario #4.

Horizontal distribution of the NB power at the FW opening is shown at the Fig.2a. Five picks originated due to the earlier horizontal focusing of the apertures within a group ($f_a$=7.2m) than of the central lines of the groups ($f_g$=25.48m). The ionization point of an atom in the plasma is then calculated with use of the crossection given by [5]. The distribution of the ionization points for off-axis injection in ITER scenario #4 is shown at the Fig.2c. At the ionization point the equilibrium magnetic field is then calculated to determine initial value of pitch angle $= v_{\parallel}/v$. 2D distribution of the NBI source in the plasma $S( \ , \ )$ is shown at the Fig.2b. Initial pitch angle distribution is of principal importance in calculations of the driven current and of the ripple losses.

## 3.Thermalization of the NBI ions.

Slowing down history of the NBI ions is calculated with use of the DRIFT OFMC code [2] and with newly developed 3D-1D Fokker-Plank models. In **3D** model the bounce averaged Fokker-Plank equation is solved by Monte-Carlo technique with use of the corresponding Langevin equations written in terms of the drift motion integrals: toroidal momentum (effective radial variable), magnetic moment (pitch angle at the minimum B point at the orbit), and the module of particle velocity. This full set of variables saves radial neoclassical diffusion of the fast ions in the consideration. NBI source in 3D model is exactly the same as in the full OFMC calculations. All necessary bounce averaged values at the 3D grid are precalculated with use of the modules of the DRIFT code. Post-processing of the results, i.e. calculations of the profiles of power and momentum transfer to plasma species, driven current etc. is also employs the DRIFT subroutines to allow for the finite orbit width effects. Comparison of the 3D and DRIFT simulations for ITER scenario #4 (all conditions are the same as in [3]) revealed complete agreement, but 3D model is at least 100 times faster. At the present only stationary version of 3D model is ready. Time dependent version development is in progress. Reduction to the **2D** model achieved using the zero drift orbit width approximation. Then the radial (collisional) diffusion is neglected. Also beam source

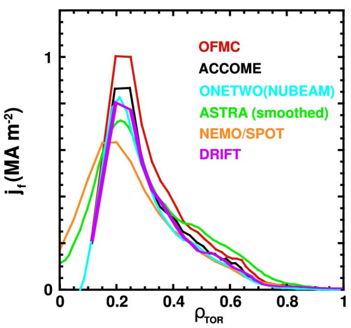


**Fig 3a** Comparison of the fast ion current profile calculated by DRIFT code with results of [3].

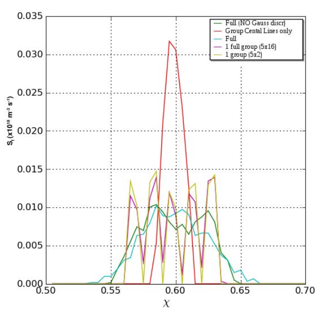

**Fig 3b** Source pitch angle distribution at the plasma entrance for the range of finite number of apertures (groups) in NB source.

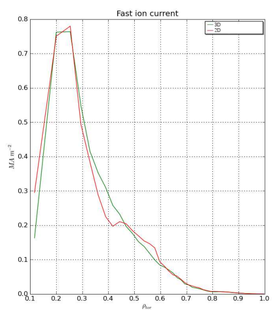


**Fig 3c** Comparison of the fast ion current profiles in 3D (green) and 2D models. For 2D the minimum (5x2) aperture number was set.

for reduced models is replaced by finite number of the beam lines (no divergence). It was found that even minimum number of beam lines (one group centered at the injection axis with 5x2 appertures (see Fig 3b)) in the beam source provides fairly good agreement in calculation results. Most visible difference is seen in calculated current profile (Fig 3c). However, even in this case the difference in total fast ion current is negligible (2.59MA in 2D vs. 2.65MA in 3D and DRIFT cases). **1D** model is based on the analytical solution of the FP equations neglecting the pitch angle scattering, i.e. it can't provide the current calculations.

## 4. Ripple loss of the ITER diagnostic beam ions.

Calculations of the ripple loss of the ITER DNB was calculated by DRIFT code. Precise injection geometry is of principal importance for these calculations. Ripple amplitudes from toroidal coils and compensating ferromagnetic inserts were taken from [6]. Results of the calculations confirmed the necessity to rotate ITER DNB to avoid trapping in the local wells.

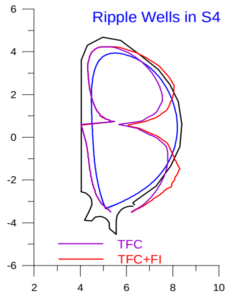


**Fig 4a** Ripple wells in ITER scenario #4.

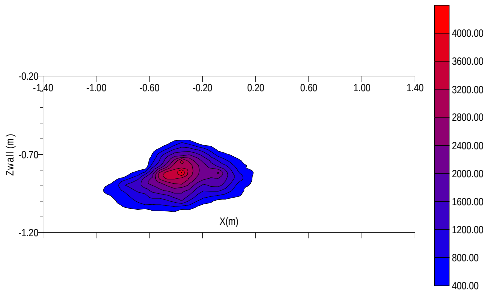


**Fig 4b** Heat loads (kW/m$^2$) due to ripple loss of the strictly perpendicular DNB.

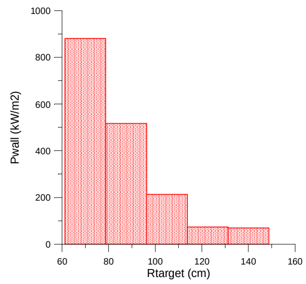


**Fig 4c** Maximum heat loads for the range of beam aiming radius

Reference perpendicular injection ($R_{targ}$=0) of the Diagnostic Neutral Beam results in extremely high (of several MW/m$^2$) localized heat loads near the beam duct associated with losses of the beam ions from the plasma periphery through the local magnetic well.

Rotation of the DNB for $R_{targ}$=141.3cm results in the essential decrease of the heat loads. In all operation regimes considered, the maximum heat load for rotated DNB was found to be smaller than 0.1MW/m$^2$. For smaller rotation with $R_{target}$<120cm heat loads associated with DNB ion ripple loss pose serious danger for the FW components.

Sensitivity study for the heat loads variation with changing the plasma density and temperature reveals that for the basic revised design FW loading remains in the tolerable limits, while for the strictly perpendicular beam rising the plasma density for 25% is accompanied by the increase of the loads up to the 5MW/m$^2$.

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