BTR code Recent Modifications for Multi-Run Operation

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Abstract. BTR code (*Beam Transmission with Re-ionization*) has been used for many years in the design and performance optimization of Neutral Beam Injection (NBI) systems based on negative or positive ion sources. BTR beam formation and transmission along the beam line is simulated by a simple and comprehensive 6D beam model, which accounts for beam losses and power deposition on the injector surfaces. Beam particles are followed in a deterministic manner in electromagnetic fields, with transforming on gas and plasma targets, including the neutralization and ionization in gas or plasma. Power flux and power deposition profiles are the main BTR output which can be calculated in any plane along the injector. For older BTR versions, each single *Run* (or beam start) supposed a direct data input through user interface tools. Besides, older BTR was not flexible enough to work with different *Tasks* (tracking options) within each Run. In order to obtain and process the results from multiple BTR Runs, a User had to spend lots of time and efforts. BTR recent *upgrades,* which come with the new version BTR-5, make possible to run multi-parametric scans of different Scenarios of NBI operation - with small manual efforts and with higher results control, given a predefined list of Scenarios input. NBI geometry has become more flexible, allowing the combination of the *Standard* NBI approach and *Free-Surfaces* input, which can be taken from CAD design. New, Multi-Run approach implemented in BTR-5 offers to set the parameters for each BTR Task within a Scenario. This allows to have optimum statistics for detailed maps resolution, and to reduce the overall time for runs and results processing. BTR-5 has been used in the design studies of the Duct Liner Module (DLM) for ITER HNB. The DLM model was created by CAD and imported to BTR-5 in text format, combined with standard NBI components Configuration. The results of the power loads throughout different operation scenarios are shown. The conclusions are made on the DLM *worst case scenario*, and on the maximum power load for each DL surface.

INTRODUCTION

Neutral Beam Injection (NBI) is one of the dominant methods of auxiliary heating used fusion devices, it is generally used for plasma heating, rotation, current drive source and operation modes control in tokamaks. NB energy is matched with the plasma target parameters (density and electron temperature), and is limited by the beam penetration depth required for effective capture and current drive. ITER like designs require NB energies ~ 500 keV/amu. The neutral beams with this energy level are derived from accelerated negative ions.

NBI operation scheme can be briefly described by the following chain: source ions (hydrogen/deuterium positive/negative) ions are extracted from plasma in a beam source (BS) and accelerated in a multi-grid, multi-aperture electrostatic accelerator, the last grid has zero potential (grounded - GG). The ion beam is next neutralized through charge exchange in a neutralization cell. If the neutralization on gas target is used, the Neutralizer typically has multi-channel structure, to minimize gas injection requirements. The neutralization efficiency on gas is limited to ~57%. The remaining charged fractions are removed from the beam in a Residual Ion Dump (RID), which can employ electrostatic or magnetic deflection, depending on the ions species and energy spectra. Due to neutralization and transmission losses, a total power injected to plasma will not exceed ~50% of the source power extracted, and the beam transmission will depend on the source beam divergence.

To resume, the main factors which determine the NBI efficiency are the source beam current density, neutralization efficiency and beam transmission. The source beam divergence and uniformity determine the transmission. The actual beam divergence is unknown so the ITER reference design [1] approaches the problem by adopting three possible core divergences 3 mrad, 5 mrad and 7 mrad accompanied by a beam halo, containing 15% of the beam particles, with a high halo divergence (30 mrad). The core divergence is a critical parameter for the beam transmission. Using the Beam Transmission & Reionization (*BTR*) code the transmission to the tokamak is shown to vary from 70% to 95% over this range of divergence. Due to the direct beam power losses on the mechanical components, and possible high heat fluxes expected on some beam-facing parts, an accurate modeling is needed to set the thermo-mechanical requirements for all NBI components. The accurate calculation of the power density deposition requires the detailed input of the source beam and NBI geometry, with careful account of electric and magnetic field. The fields deflect the charged particle tracks (e.g. source ions) along the beam line, leading to the NB additional scattering in velocity space and higher interception. Besides, secondary particles, generated due to the beam interaction with background gas, are producing additional power fluxes and power loads onto the beamline surfaces. All these effects need to be numerically studied with help of comprehensive 3D models. BTR is one of the codes, used for these studies.

At first, the paper gives a short overview of the ITER NBI, this is followed by BTR code application for the design studies. Next, BTR-5 example of the multi-parametric design study (ITER NBI Duct Liner) is shown.

NBI FOR ITER

The heating neutral beam injectors (HNBs) of ITER [2] are designed to deliver 16.7 MW of 1 MeV D^0 or 0.87 MeV H^0 to the ITER plasma for up to 3600 s. They will be the most powerful neutral beam (NB) injectors ever, delivering higher energy NBs to the plasma in a tokamak for longer than any previous systems have done.

ITER will initially be equipped with 2 heating neutral beam injectors (HNBs) that are designed to deliver 33.3 MW of either 1 MeV D^0 or 0.87 MeV H^0 to the ITER plasma for up to 3600 s. A third HNB may be installed later. The choice of 1 MeV as the D^0 beam energy is based on the need to deposit power across the plasma minor radius for an effective current drive, despite the technological problems of the required accelerated D^- current density production. When an accelerator optimized for D^- (40 A at 1 MeV) is used for with H^- beam, the optimum optics is achieved at 870 kV and 46 A. The neutralization, beam transmission and other losses in the beamline will be similar for H^- and D^-, with the power injected. H^0 beams will be used in the early, non-nuclear, phases of ITER operation. Operation in H^- is expected to be essentially the same as with D^-. The general layout of HNB beam line, taken from [3] is shown in **Figure 1**.

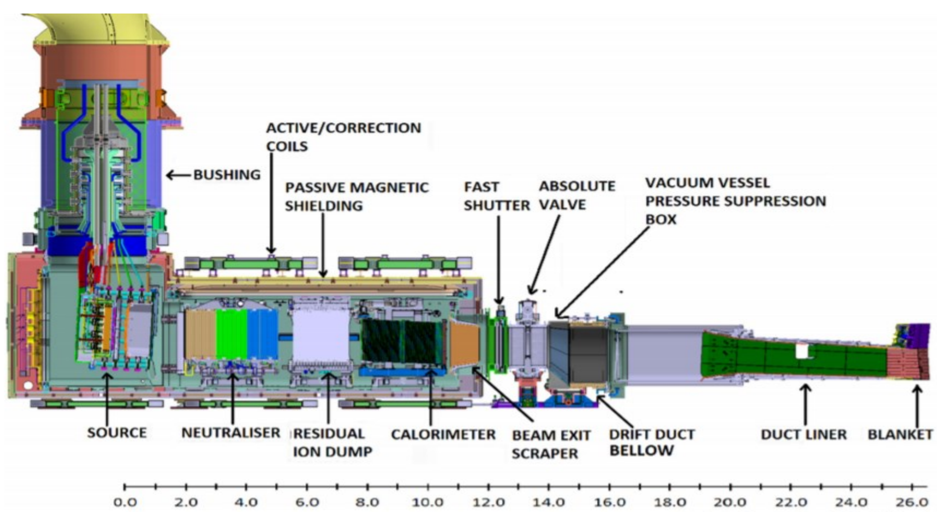

FIGURE 1. Sectional view of HNB beam line, taken from [3]

As shown in Figure 1, the NB line is a combination of the vacuum vessel housing the beam line components (BLCs), the exit scraper (ES), followed by a series of front end components (FEC) comprising a fast shutter (FS), absolute valve (AV), drift duct liner (DDL), vacuum vessel suppression system (VVPSS) box, connecting duct liner (CDL) with a liner and the duct liner (DL) made up of several modules. The end of the DL couples to the ITER vacuum vessel port. The ion beams produced and accelerated by the BS should not be deflected by the magnetic fields from the tokamak, the values of which can vary depending on the mode of operation of the machine. This is achieved by having a combination of passive magnetic shield (PMS) and a set of active correction compensation coils (ACCC). The PMS for the HNB and DNB beam lines not only provides the desired field compensation but also acts as a neutron shield.

BTR CODE FOR NEUTRAL BEAM DESIGN

BTR-code (*Beam Transmission with Reionization*) [4, 5] is a common tool for NBI engineering design and thermal analysis. It was released for public usage in 2005, and due to the original user-friendly approach, BTR is often used not only for calculations, but for NBI studies and training. All BTR models are *"light"*, i.e. fast and easy to verify. Basic BTR beam includes an accurate beamlet based 6D representation (space + velocity). The beam tracing model is *deterministic*, and the particles are tracked in a *real* physical environment. BTR models allow for high resolution of power maps, which are needed for thermal analysis of the NB-line components. BTR beam also can be traced in plasma, and to perform a detailed analysis of beam stopping, ions generation, delivering beam power footprints and shine-through power loads. BTR description of the injector and ducts geometry is a combination of 2 main approaches: *Standard* and *Free*. The former is applied to standard NBI components, such as multi-channel Neutralizer and RID, the Calorimeter (open or closed state), and simplified rectangular Duct "tubes" (~10 sections). This approach is most effective during the optimization stage of NBI design, when the source beam and NBI geometry need to be mutually fine-tuned. Free geometry approach is applied when the NB system design is already chosen and *almost frozen*, thus more detailed beamline geometry is necessary for accurate thermal loads analysis.

BTR code (**Figure 2**) traces the beamlets array (elementary current cones, emitted from BS GG) through the NB injector channels, beam ducts and finally through plasma - until the final stop at the tokamak first wall (FW) surface. The number of power maps calculated along the path is unlimited (e.g. the present NBI configurations are represented in BTR by ~300 surfaces, including virtual normal planes for beam footprints). The power deposition on each surface results from beam direct interception and secondary fluxes. The background fields and gas conditions define particles deflection and transformations. The maps can be calculated with high resolution (~1mm cell size), which can be limited only by RAM. Due to unlimited amount of particles in a model (at present 10^5-10^9) BTR provides the most detailed beam geometry and optics at plasma, within moderate running times: to run 10^5 particles takes less than 1 minute on old Windows-system (2 cores). BTR is a small Win32/64-application (2/6MB), created by means of MS Visual C++.

In older BTR versions, each single Run (i.e. beam start) required all the input data to be tuned manually for each NBI operation Scenario - with direct input interface tools. Besides, old BTR model was not too flexible for running different Tasks (i.e. tracking options) within the same Run. Therefore, in order to get and process the results of multiple BTR Runs, needed for typical design tasks, BTR User had to spend lots of time and efforts for the Input routines and code restarts. BTR-5 makes possible to run automatically *multi-parametric scans* of different Scenarios with minimal efforts - and with higher results accuracy, just using a predefined list of scenarios input. The NBI geometry input has become more flexible, combining the standard NBI approach with Free-Surfaces supply, which can be imported from CAD packages (text format). BTR-5 at present allows independent settings for each BTR Task within a Scenario (*Multi-Run* approach), for optimum statistics and detailed maps calculation. This reduces the overall time for BTR runs and results processing.

Apart from these changes, plasma model input in BTR-5 has become more user-friendly in beam-plasma stopping calculations, and the model can be easily verified with other codes.

The most important modifications in BTR-5 include:

- Plasma module optimization with beam ionization, shine-through maps
- BTR Scenarios, Multi-task settings, specific Run options

- Static maps allocation (for solid and transparent surfaces), refined resolution (up to 1000x1000)
- Scenario Input: scenario parameters, Macro-commands
- Output Folders Tree, automatic Reports (TXT, CSV), All Scenarios Summary, etc.
- Terminal screen, Log-file (safety and control)

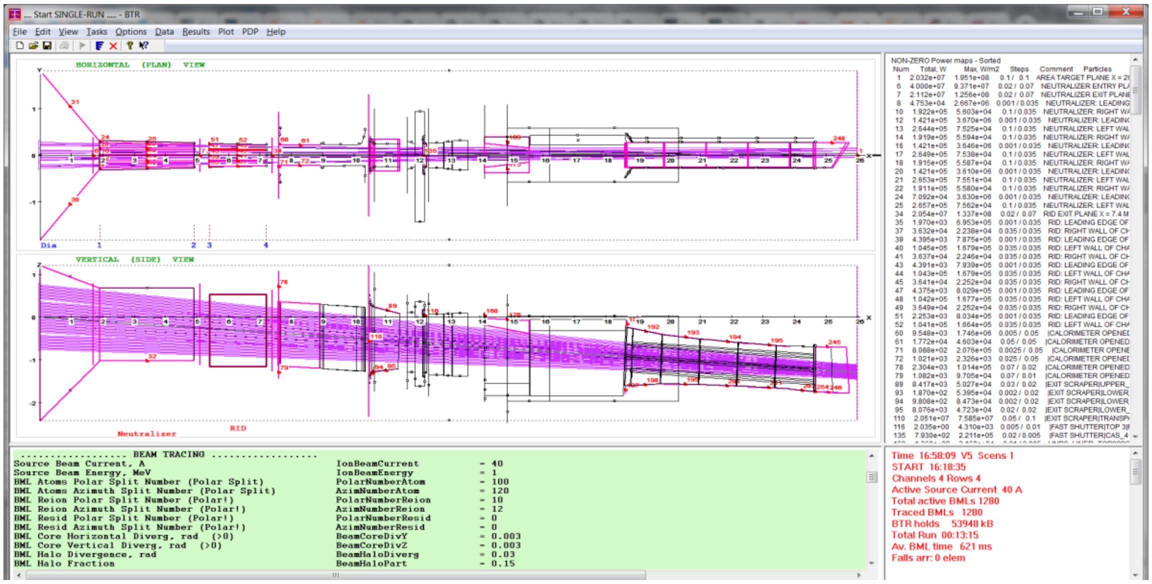

FIGURE 2. BTR Screen with ITER HNB geometry: horizontal and vertical plane views. Standard NBI geometry is combined with Free surfaces import, which begins from the Calorimeter (x = 7.6m). Beam model is Standard, i.e. defined by regular array in Config-file. The beamlets axes are shown violet. Result power maps Summary (text) is shown top-right.

PARAMETRIC STUDY OF ITER HNB DUCT LINER

New BTR-5 has been used in the design studies of the Duct Liner Module (DLM) of ITER NBI - through different NBI operation scenarios. The analysis main outcome was to define the DLM *worst case scenario*, and maximum power loads for each DL surface through all scenarios – for DL cooling system dimensioning.

BTR-5 allows to set splitting numbers for the source beamlets in optimum manner. The best splits across different tasks are found experimentally: for the directly intercepted (DI) beam particles, i.e. the source ions or the atoms, the splitting should be high enough (~100x100), while for the Re-ionized (RI) particles production, generated in the beam-gas interaction, the source beamlet splitting can be small (to ~10x10). These optimal values allow for sufficient particles statistics need for refined power maps. The independent options for each particles tracing reduces much the statistical noise of the results, raise the total model capacity and running speed.

In the simulations presented, about 9 million source particles (80x90x1280) were used for primary beam interception (DI), and only 153.000 source particles (10x12x1280) for generating the swarm of re-ionized (RI) particles by collisions of atoms with the gas. The gas profile along the beamline was provided by MCGF-code [6], the magnetic field with account of magnetic shielding was provided by ANSYS calculations done by CIEMAT. Both profiles are used as input for BTR. The neutralization efficiency of the gas target is around 56%. The simulations are made for nominal parameters of the ITER BS, i.e. 40 A Deuterium beam at 1 MeV - for the ITER fusion operation using deuterium-tritium plasma, and 46 A Hydrogen beam at 0.87 MeV - for the ITER preliminary operation in Protium or Helium.

The DLM detailed model is created by CAD and imported to BTR, combined with standard NBI components. The beamline Standard geometry input was applied with reading BTR Standard geometry Input - Config-file. It contains full geometry of Standard NBI components. The Standard geometry of Duct is removed, it was replaced by Free surfaces from CAD, specified in text files - by defining the 3D coordinates of each surface corner. Next the Free surfaces are processed by the code is the same manner as the Standard components. Yet, but the large amount of surfaces can decrease the running speed, so it is desirable to reduce it, when the design requirements allow. For the current design purposes DLM is modelled by 54 surfaces. The total set of Free surfaces obtained from CAD and added to BTR, is shown in **Figure 3**. The coordinates are given in the grounded grid coordinate system (GG CS), with the origin position at the GG center of the GG (x=0).

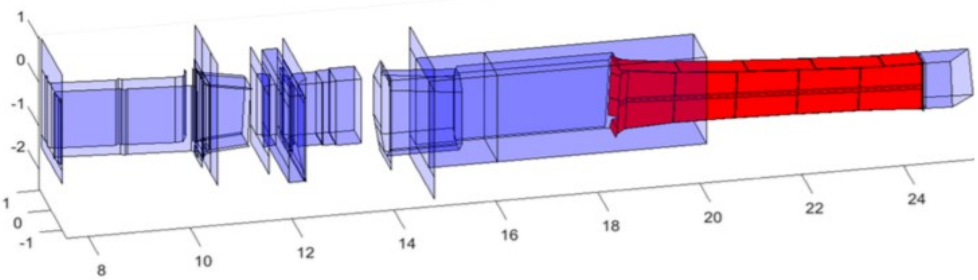

FIGURE 3. MATLAB generated view of the CAD surfaces imported by BTR as TXT-files. From the left to right: Calorimeter, Exit Scraper, Fast Shutter, Absolute Valve, Drift duct liner, connecting duct, and the duct liner DLM (red).

In **Figure 4**, a view of the DLM surfaces is shown. The surfaces are divided to groups and labelled according to their position with respect to the beam direction: top, bottom, left and right. The output surfaces in BTR are exported with a map resolution from 50x50 cells and more. Smoothing is applied – in some cases (few stray particles accepted by highly refined mesh).

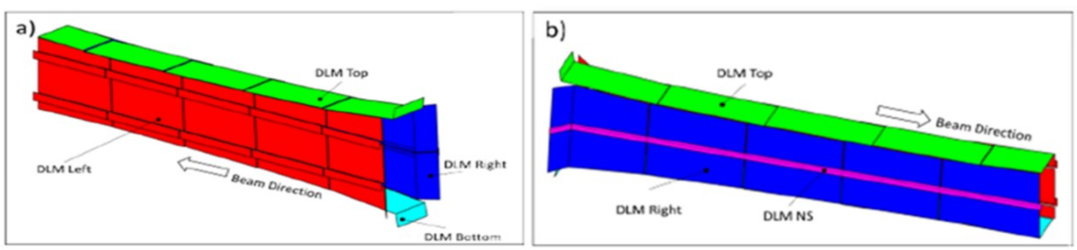

FIGURE 4. MATLAB generated view of the surfaces of the DLM: **54 surfaces**, including two surfaces mimicking the DLM opening towards the neutron shield (DLM-NS) area behind the duct liner

All the *scenarios* are specified with the following notation: “s1, n1, n2, n3, s2”, where s1 - is the particle specie: D or H (deuterium or hydrogen beam), n1 - is the beam divergence, n2 - is the beam horizontal misalignments; n3 - is the vertical tilting of the source with respect to the reference aiming of the HNB (-49.2 mrad); s2 - the magnetic field configuration of ITER which depends of the intensity of the field created by the coils and the intensity of the current flowing into the plasma: FFTC - full field third current, FFHC - full field half current, FFFC - full field full current, HFHC - half field half current.

At first, the simulations are made for *Deuterium* beam with a fixed magnetic field profile (FFFC) and different values of divergence (3 and 7, i.e. min and max of the expected operational range of ITER NBI), horizontal misalignment (+/-2 mrad) and vertical tilting (+/- 10 mrad). Then, the sensitivity of results against the magnetic field was tested. Finally BTR was run with *Hydrogen* beam.

The histograms of Total power (W) and Peak Power Density (W/m^2) for 8 scenarios of Deuterium beam are shown in **Figure 5**. The power loads on the DLM components are shown highlighting the contribution of each source power fraction, which can be either from the Directly Intercepted (DI) primary beam, or from the Re-ionized (RI) power flux due to beam atoms interaction with the residual gas.

From these results, we can deduce the following:

- Neutral atoms intercepted directly (DI) mainly load DLM Top panels in case the beam tilting up, and DLM Bottom panels - if the beam is tilted down;

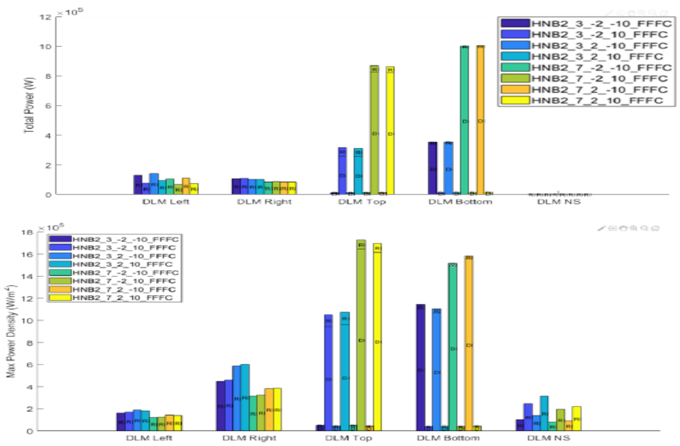

FIGURE 5. Open view the DLM surfaces showing the numbering and labelling of each surface. *Deuterium.*

- Maximum peak power density, as well as the total power loads, come from DI power;
- The re-ionized particles (RI) are deflected with accordance to the local magnetic field (especially by vertical Bz component), and their power is mainly deposited on the DLM Left and Right;
- The horizontal misalignment of beam axis has a small effect on the power distribution – this result can be explained by the beam "tails" already scrapped by all the upstream NBI components (before DLM);
- Both Total Power and Peak Power Density at Top and Bottom DLM panels are highly sensitive to the beam divergence (3 vs 7mrad)

These deductions help to reduce the set of other simulations necessary to assess the worst case conditions.

ITER Magnetic Field (MF) Effect

As the maximum power loading is due to the atoms, deflected by MF only before their Neutralization, we can expect the MF in the DL region plays a minor role in changing the power profiles. The effect expected is only the profiles peak shift along the left/right panels of the DLM. With this assumption only 4 scenarios were tested for different values of the MF. The results confirm the expectation. The power loads and total power are basically constant with respect to the MF variation. The effect of MF in shifting the power profiles is evident from a comparison of the power loading maps on the Right panels of DLM, as reported in **Figure 6**. The total power on the panels shown in the figure is also very similar: 84.4 kW, 86.3 kW and 86 kW respectively.

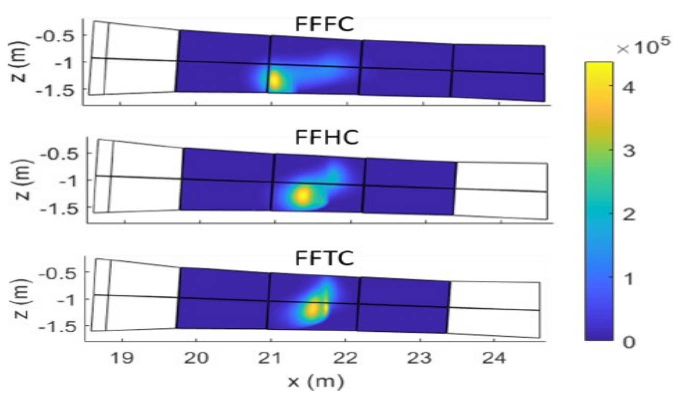

FIGURE 6. Power loads on the Right surfaces of the DLM - for three options of the magnetic field. *Deuterium.*

The same scenarios set was simulated for Hydrogen beam (0.87 MeV, 46 A), with adjusting the atomic cross sections accordingly. For this case, the conclusion on smaller effect of magnetic field was used, so only one magnetic field option was applied - FFFC. The results are very close to Deuterium, with smaller power load values.

Results Discussion

All the cases within the simulation are compared to identify the worst-case scenario, and to assess the maximum power peak on each DLM panel. The main conclusions for the **Deuterium** beam are confirmed. The highest power peaks (W/m^2) correspond to the cases where the beam is tilted vertically (±10 mrad), with the peaks localized on the top/bottom panels according to the tilting direction.

In particular, the highest peak (1.3 MW/m^2) is located at DLM Top is observed in scenario: D 7,-2,+10, FFFC. The power loads at different DLM panels in this scenario are shown in **Figure 7** and **Figure 8**. The fraction of power straying out toward the *neutron shield* across the opening of the DLM panels is relatively small (1.1 kW) and not shown. The total power deposited at all DLM panels in this case is 1.03 MW. We also note that the *worst case* with maximum power deposited at DLM panels (**1.24** MW) refers to the scenario D, 7, -2, -10, FFTC. Under this case the power peak is located at DLM bottom. This value should be used in the cooling system dimensioning.

Worst Conditions (Maximum Load) for each Surface

The multi-run version of BTR also allows to compare in straightforward manner all the results of the different scenarios tested, and to identify the highest power load at each DLM surface automatically. Maximum power in this case corresponds to different scenarios. These worst cases of power loads are summarized in **Figure 9.**

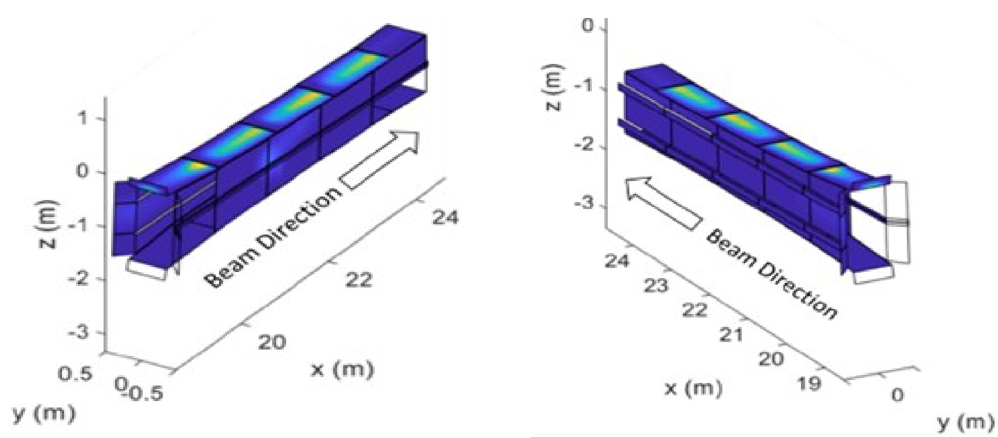

FIGURE 7. 3D views of the power load map (W/m^2) at DLM surfaces for the scenario D, 7,-2, 10, FFFC

CONCLUSIONS

BTR code new version (BTR-5, *Multi*) is more adapted for massive design calculations, and can be used more efficiently for complex thermal load studies in NB lines and beam Ducts. The recent modifications allow parameters scanning without code restarts, a flexible geometry input of NBI components, control and diagnostics of input parameters, and unlimited particles statistics and power maps resolution. All the Input/Output routines have become more automatic, facilitating the results control and verification with generated *Reports*. The new BTR version can be applied efficiently also for NBI geometry optimizations (not illustrated in this paper) – at the 1st stages of NBI Design, when all NBI components and the beam structure need to be carefully tuned.

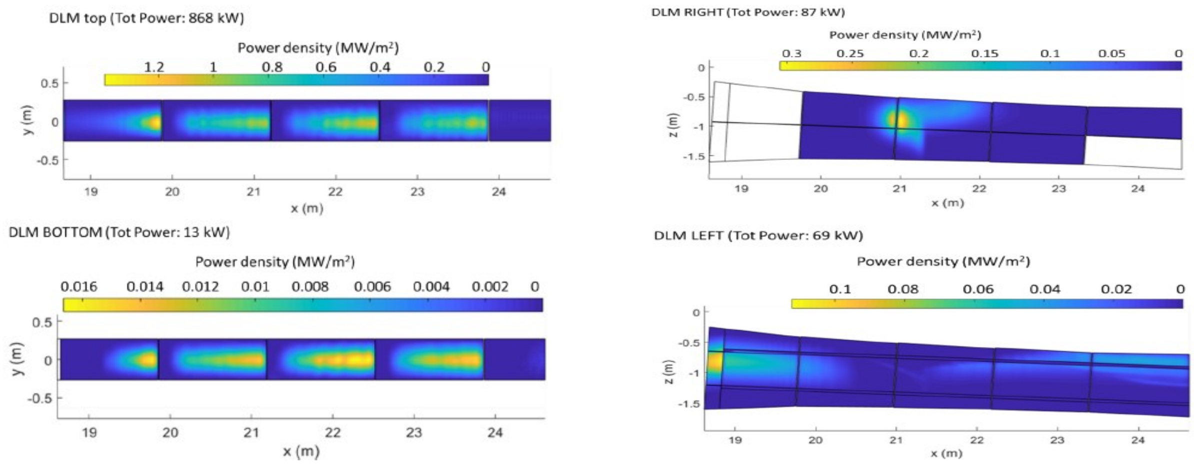

FIGURE 8. 2D views of the power loads at DLM panels for the scenario D 7,-2,+10, FFFC

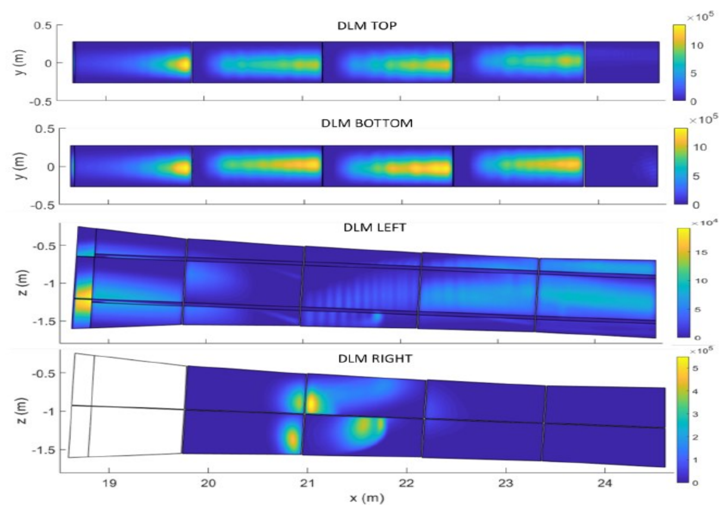

FIGURE 9. 2D views (XZ and XY planes) of the maximum power loads at each DLM panel throughout all the scenarios

Parametric study of ITER HNB Duct Liner by means of BTR-5 (Multi) allows producing the power images needed for the dimensioning of the cooling circuits and optimization of critical parts. The comparative analysis of different operational scenarios of the NBI is also helpful to highlight the operational modes that could jeopardize the critical component of the machine.

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