Development of the models of the magnetic shielding system for ITER neutral beam injectors

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Abstract. The paper is devoted to the development of the models of magnetic shielding system for the ITER neutral beam injectors. As the reactor operation is quasistationary, the magnetic field reduction system of the injectors combines a passive magnetic shield and a set of active correction coils. Due to the strict restrictions on the field inside the injectors, precision computations are required during the design stage. A special attention has been paid to possible gaps between steel panels of the passive magnetic shields due to manufacturing and assembly inaccuracies. A set of models with different levels of detail has been built for the convergence study. It was shown that the mesh needs to have tens of millions finite elements to provide the required computational accuracy.

1. Introduction
High-energy neutral beams (NB) are used in present-day tokamaks for additional heating to provide plasma burn and current drive [1]. The heating is most effective when the NBs are injected into plasma in the direction of the plasma current.

NB injection is also one of the basic techniques of measurement of local plasma parameters from the response to the injected beams.

The NBs are produced by neutralization of accelerated ions. The main components of an NB injector are a beam source (BS), a gap where the beams are extracted, formed and accelerated, a neutralizer, commonly with a gas target, and a residual ion dump (RID).

The paper describes the model and computational results for the Diagnostic Neutral Beam Injector (DNBI) of the ITER tokamak. The same approach has been used for the Heating & Current Drive Neutral Beam Injector modelling.

The residual field inside ITER DNBI during operation should be as low as 0.2 G in the Neutralizer region and 0.5 G in the Gap region to avoid deflection of the ion beams. The Magnetic Field Reduction System (MFRS) is used to reduce the stray field produced by the tokamak EM systems and plasma [2–4], which reaches 150–500 G at the injector location, to an acceptable level inside the injectors. The DNBI MFRS consists of a passive magnetic shield (PMS) and active correction and compensation coils (ACCC) to provide the strict design criteria during a plasma scenario.

2. Computational models
The tokamak is simulated as a set of poloidal field (PF) coils, the central solenoid (CS) and plasma, presented as a circular moveable current filament. The stray field of the tokamak is calculated with the KLONDIKE code [5], which implements integral volume elements and the Biot-Savart integration.
The original CATIA model is shown in Fig. 1. The KOMPOT model and the local coordinate system used in the computations is shown in Fig. 2.

The final element (FE) approximation is used to simulate the PMS, which is a bolted assembly of panels composed of three 50-mm-thick low carbon steel (S235) plates with a 25 mm air gap between them. Also, the model includes the Neutralizer case made from 35-mm-thick soft iron sheets to provide an additional shield for stray field reduction in the Neutralizer as the most magnetically crucial component. Circular holes in the PMS are simulated as rectangles with the same area. The computations were performed with the KOMPOT code [6].

Several models have been built to study the electromagnetic behaviour of DNBI MFRS. Model A is a gapless model of the PMS with the Neutralizer case which contains about $4.2 \times 10^7$ elements. In Model B, possible horizontal construction air gaps were implemented between the side/front/rear and top/bottom PMS panels to assess their impact on the residual field inside the PMS. The simulations have demonstrated an increase in field up to 17% in the Gap region due to the increased magnetic reluctance of the path for the magnetic flux through the PMS. Thus, the construction gaps should be taken into consideration in the PMS magnetic model.

The Model C (Fig. 3) has a full set of construction air gaps. It has about $5 \times 10^7$ finite elements in which the air gaps are simulated via the filling factor and equivalent magnetic permeability with a spacing of 10 mm.

A more detailed model with about $6 \times 10^7$ finite elements and 1 mm air gaps, Model D, was also built. As Model D requires high computational resources, it is used only to validate the results obtained with the Model C.

Finally, to study the EM effect of eddy currents induced in PMS in the reference scenario, Model E with $4 \times 10^6$ DOF (degrees of freedom) was built (see Fig 4).

Figure 1. CATIA model of ITER DNBI PMS. Colored lines show 1 mm construction air gaps locations.

Figure 2. KOMPOT model of ITER DNBI PMS. Coordinate system is shown.

Figure 3. Model C of DNBI MFRS.

Figure 4. Model E of DNBI MFRS.
3. Computational results

Figure 5 shows the residual field inside the PMS (along the central line of the beam aperture) simulated for the EOB (end of burn) time point of the operation scenario, when the peak stray field occurs.

With the use of Model C, a DNBI MFRS Controller has been designed under the assumption of a linear dependence between the ACCC currents and the CS, PF and plasma currents during the operation scenario. The Controller allows control of the driving currents in the ACCC using a single matrix so as to keep the residual field inside the DNBI close to the design field criteria. The Controller with the desired performance was constructed via an iterative procedure utilizing influence functions for the ACCC currents. As an example, a residual field along the center of the aperture with Controller ACCC currents is shown in Fig. 6.

4. Solution convergence

Models C and E were used to investigate convergence at different DOFs. To make Model C close to Model E, the side holes, construction air gaps, and the Neutralizer case were excluded.

The shielding efficiency of MFRS depends on its magnetic permeability. The higher the permeability, the more efficient the PMS. Local saturated zones reduce the shielding efficiency. Particularly, saturated zones in PMS (2 T, $\mu_r = 100$) are observed below the ACCC that produce high field gradients. In numerical computations, the permeability is determined through an iterative procedure utilizing influence functions. The bigger the FE size, the higher the overestimation for the permeability. The average field is found by integration of the gradients over an FE volume. In the saturated zones, the integration always gives overestimation of the permeability. The bigger the FE size, the higher the overestimation of the shielding effect of the PMS.

![Figure 5](image-url)

**Figure 5.** Residual field $B_z$ along center of aperture. EOB state. 1 – Model A, 2 – Model B, 3 – Model C, 4 – Model D. Dashed lines indicate field design criteria.
Figure 6. Residual field $B_z$ along center of aperture. Model C. EOB state, ACCC currents obtained with Controller. Dashed lines indicate field design criteria.

As seen in Fig. 7, the results differ depending on the number of DOFs. A comparison of the results demonstrates that the ACCC currents evaluated with the $4 \times 10^6$ DOF and $5 \times 10^7$ DOF models diverge significantly with underestimated ACCC currents for the first model. Further mesh refinement implies high computational cost, however, it does not guarantee desired precision. For such EM analyses, a validation is strongly recommended by comparison between calculations performed by different models and experimental data to make sure that a particular model and solution strategy provide required accuracy.

Figure 7. Residual field $B_z$ along center of aperture. 1, 3 – Model C ($5 \times 10^7$ DOF) with no Neutralizer case, side wall holes and air gaps, 2, 4 – Model E ($4 \times 10^6$ DOF); 1, 2 – zero ACCC currents, 3, 4 – energized ACCC.
5. Conclusions
To provide required accuracy, computational models (FE meshes) for DNBI MFRS should have at least tens of millions DOF for correct estimation of magnetic permeability distribution in PMS that has a drastic effect on PMS shielding efficiency.

Disclaimer
The views and opinions expressed herein do not necessary reflect those of the ITER Organization.

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