SIMULATION OF PRECISION MAGNETIC SHIELDING SYSTEM FOR BEAM INJECTORS IN TOKAMAKS

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Abstract

Beam injectors in tokamaks are utilized for plasma heating and diagnostics. Due to the relatively large distance between the injectors and plasma, the tokamak stray magnetic field inside injectors during the operation should be very low (down to the tenths of Gauss) to avoid the deflection of the ion beams. The Magnetic Field Reduction System (MFRS) should be used to reduce the stray magnetic field produced by the tokamak EM systems and plasma to an acceptable level inside the injectors. In total, the complex MFRS can consist of a passive magnetic shield and active coils to provide the strict design criteria during a plasma scenario.

To provide precise computations, detailed numerical models of MFRS should have the dimensions up to several tens of millions of degrees of freedom. Such problem could be solved only with the use of high-efficiency vector algorithms and parallel computations.

The paper is dedicated to simulation of MFRS for beam injectors in tokamaks.

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 the 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 plasma diagnostics. It allows detection of plasma particles and measurement of local plasma parameters from the plasma 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, a gap where the beams are extracted, formed and accelerated, a neutralizer, commonly with a gas target, and a residual ion dump.

The paper describes the model and computational results for the Diagnostic Neutral Beam Injector (DNBI) of ITER tokamak.

The residual field inside ITER DNBI during operation should be as low as 0.2 Gs in the Neutralizer region and 0.5 Gs in the Gap region to avoid the deflection of the ion beams. The Magnetic Field Reduction System (MFRS) should be used to reduce the stray field produced by the tokamak EM systems and plasma [2, 3, 4], reaching 150-500 Gs 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. A CATIA model of ITER DNBI PMS is shown in Fig. 1.
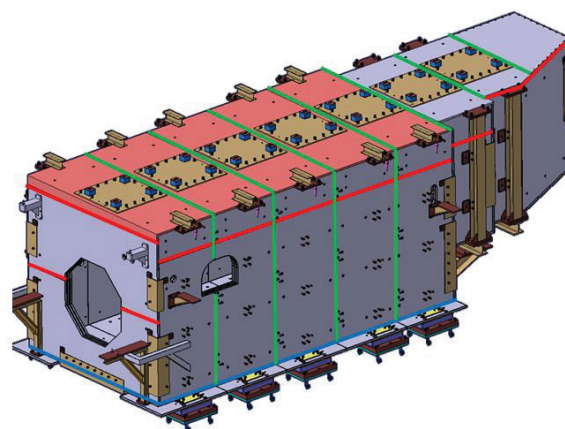

Figure 1: CATIA model of ITER DNBI PMS. Colored lines show 1 mm construction air gaps locations.

MAGNETIC MODEL

The tokamak is modeled as a set of PF coils, central solenoid (CS) and plasma, presented with a circular moveable current filament. The stray field of the tokamak is calculated with the code KLONDIKE [5] that implements integral volume elements and the Biot-Savart integration.

The FE approach is used for modeling the PMS. PMS is a bolted assembly of panels composed of three 50 mm thick low carbon steel (S235) plates with a 25 mm air gap between the plates. Also, the model includes the Neutralizer case made of 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 PMS are modeled as rectangular ones with the same area. The FE model and the computations were performed with the code KOMPOT [6].

COMPUTATIONAL RESULTS

Several models have been built for the study of DNBI MFRS. The Model A (Fig. 2) is a gapless model of PMS with the Neutralizer case which has about $4.2 \cdot 10^7$ elements. In the 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. Computations have demonstrated an increase in field up to 17% in the Gap region due to the increased magnetic reluctance of the path for magnetic flux through PMS (see Fig. 4). Thus, the construction gaps should be taken into consideration for the PMS magnetic model.
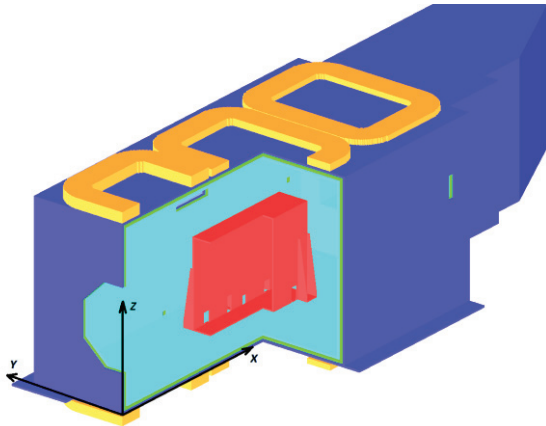

Figure 2: Cross-section of Model A and coordinate system (mesh is not shown).

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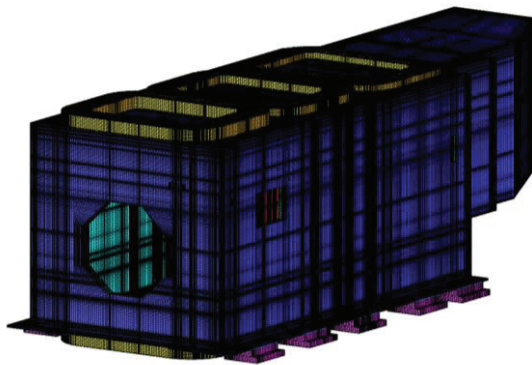

Figure 3: Model C.

Finally, a detailed model of about $6 \cdot 10^7$ finite elements, Model D, with the 1 mm air has been developed. As Model D demands high computational resources, it is used only to validate the results obtained with the Model C.

Fig. 4 shows a residual field inside the PMS (along the central line of the beam aperture) for the EOB time point of the operation scenario when the peak stray field occurs.
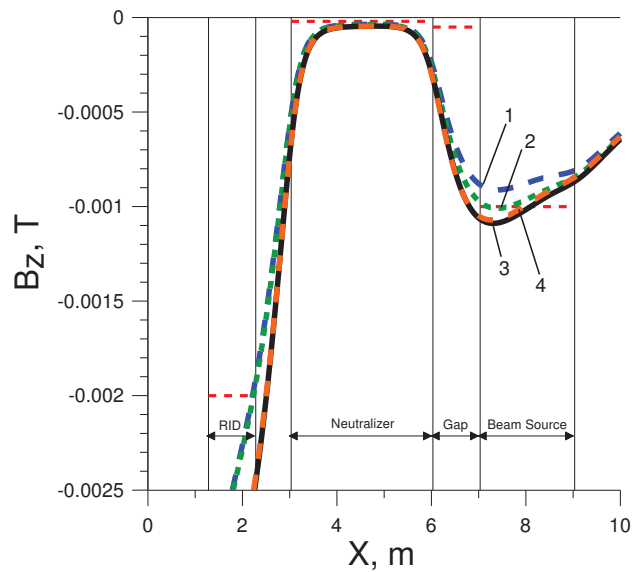

Figure 4: B_z component along center of aperture. EOB state. 1 – Model A, 2 – Model B, 3 – Model C, 4 – Model D. Dashed lines correspond to field design criteria.

With the use of Model C, a DNBI MFRS Controller has been designed supposing 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 ACC coils using a single matrix so that to keep the residual field inside the DNBI close to the design field criteria. The Controller with the desired performance was achieved 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. 5.
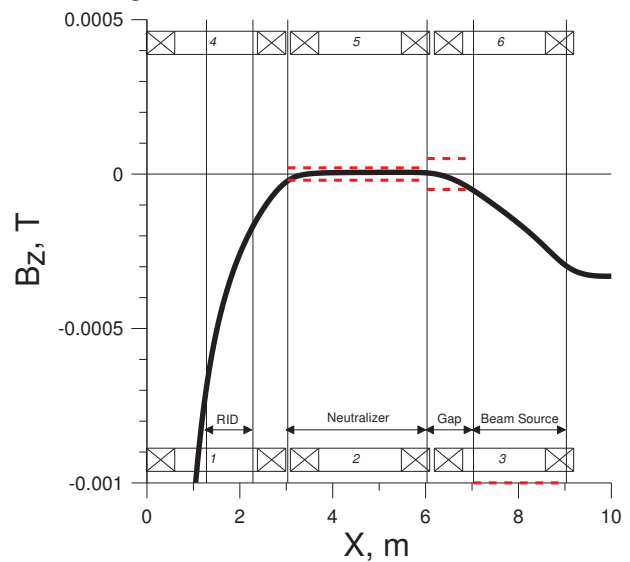

Figure 5: B_z component along center of aperture. Model C. EOB state, ACCC currents obtained with Controller. Dashed lines correspond to design field criteria.

SOLUTION CONVERGENCE

To study the EM effect of eddy current induced in PMS at the reference scenario, Model E with $4 \cdot 10^6$ DOF was developed (see Fig 6).
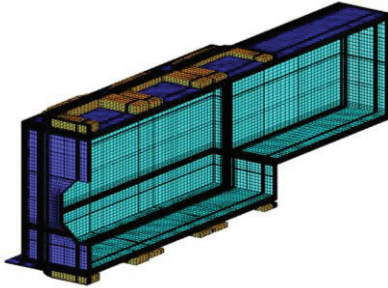

Figure 6: Model E.

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, the Neutralizer case were excluded.
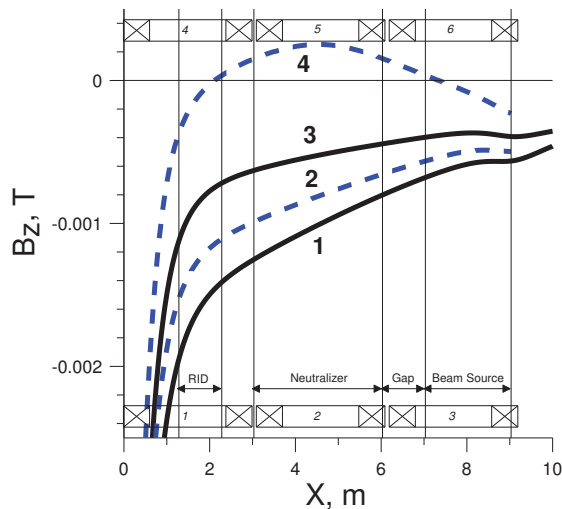

Figure 7: B_z component along center of aperture. 1, 3 – Model C with no Neutralizer case, side wall holes and air gaps, 2,4 – Model E; 1,2 – zero ACCC currents, 3,4 − energized ACCC.

As seen from Fig. 7, the results differ depending on the number of DOFs.

The shielding efficiency of MFRS depends on its magnetic permeability. The higher is permeability, the more efficient is the PMS. Local saturated zones would reduce the shielding efficiency. Particularly, saturated zones in PMS (2 T, μ_r = 100) are observed below ACC coils that produce high field gradients. In numerical computations, the permeability is determined through a field averaged within a finite element and assumed to be constant. As a result, the average field is found by means of integration of the gradients over an FE volume. In the saturated zones the integrations always gives overestimation for the permeability. The bigger is the FE size, the higher is overestimation of the shielding effect of PMS.

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

CONCLUSION

To provide required accuracy, computational models (FE meshes) for DNBI MFRS should have at least tens of millions of DOF for correct estimation of magnetic permeability distribution in the PMS that has drastic effect on PMS shielding efficiency in computations.

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