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THE MECHANICAL BEHAVIOR OF THE EIC BEAM SCREEN DURING A MAGNET QUENCH

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Abstract

As part of the Electron-Ion Collide (EIC) upgrade at Brookhaven National Laboratory (BNL), the development of new beam screens for the vacuum system is underway. The mechanical design of the beam screens received support from the European Organization for Nuclear Research (CERN), particularly in addressing the mechanical response during a magnet quench, i.e. a resistive transitions in the superconducting magnets. Maintaining an overall elastic behavior in this component is crucial for the efficient functioning of the collider. The mechanical behavior of the EIC beam screen during a quench was initially analyzed using analytical methods and subsequently validated through a Multiphysics FEM model developed for the High-Luminosity LHC (HL-LHC) beam screen. The FEM model underwent an initial verification against analytical formulations in its simpler 2D magnetic-based version. Following this, thermal and mechanical physics were fully coupled with the magnetic model in a 3D framework. Various features, including partial weld penetration, pumping holes, and guiding rings, were then taken into consideration. Additionally, the plastic behavior of the beam screen materials was also considered. The assessment included an analysis of the maximum deformation and stress experienced by the EIC beam screen during a magnet quench, resulting in an overall elastic response for the proposed design.

INTRODUCTION

The EIC beam screen, shown in Fig. 1, is a special vacuum liner positioned in the cold bore of the superconducting magnets.

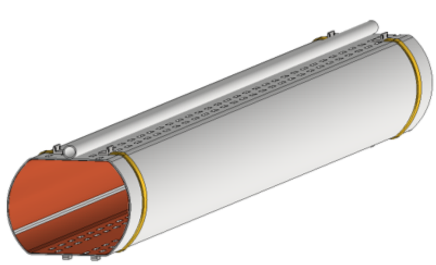

Figure 1: The EIC beam screen.

A liner is required due to the increased resistive wall heating that will be generated from the more intense EIC beams [1]. Constructed from high nitrogen, high manganese stainless steel sheets, the EIC beam screen is co-laminated with 75 m of high purity copper to lower beam impedance and minimise the power losses. The screen is perforated to pump particles effectively on the cryopumping surfaces of the cold bore as well as supplemental cryo absorber [2].

During operational phases, it is possible for a superconducting magnet to experience a quench. In such instances, significant eddy currents are generated, leading to Lorentz forces within the beam screen. It is crucial to evaluate the stress state of this component during a quench to prevent residual plastic deformation, which could compromise the accelerator performance.

To tackle this issue, the vacuum group at CERN, which had previously developed specific numerical techniques for the LHC and the HL-LHC beam screens, shared its competences with the vacuum colleagues at BNL to examine the mechanical response of the EIC beam screen during a magnet quench. This assessment involved the utilization of analytical methods as well as Finite Element Methods (FEM) models. An overview of the modelling procedure and the obtained results will be presented in this paper.

MODELLING

The dipole magnetic field decay used in the analysis is shown in Fig. 2.

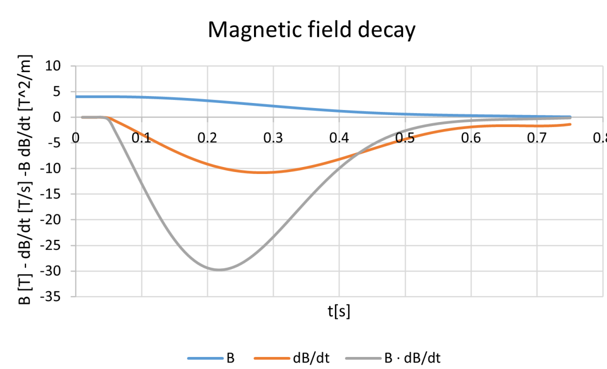

Figure 2: Magnetic field decay B seen by the EIC beam screen during a quench in blue, its time derivative $\dot{B}$ in orange and the $B\,\dot{B}$ product in grey.

A phased approach was employed to model the EIC beam screen. Initially, a simplified analytical solution was used to predict the Lorentz forces, which were then compared to a 2D FEM model. Subsequently, the coupling with temperature and deformations affecting the Lorentz forces were integrated into the model to increase the accuracy of the loads applied. Finally, features such as pumping slots and elasto-plastic material properties were accounted for in a 3D FEM model.

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Analytical

Estimating the force for a quarter of the beam screen is sufficient due to the symmetric geometry along both the horizontal and vertical axes, as illustrated in Fig. 3. This quarter is, in turn, divided in two regions, denoted as region 1 and 2, where the the forces can be calculated using the respective equations 1 and 2. Since the beam screen tube is considered very long compared to the cross section dimensions and that a vertical dipole field is applied, only longitudinal currents and therefore horizontal forces are developed.

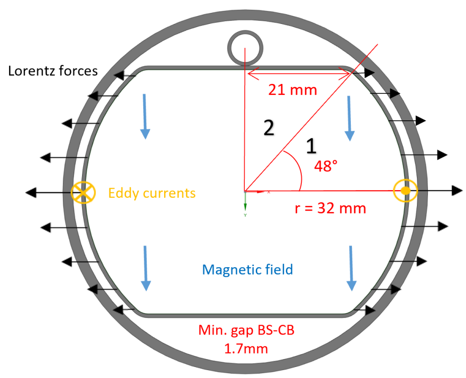

Figure 3: In regions 1 and 2, Lorentz forces are calculated using closed-form expressions. Different colors delineate the magnetic field, currents, and forces.

$$F_{x_1} = B_y \dot{B}_y t \frac{r^2}{\rho} sin(48^\circ) = 11\,\mathrm{N/mm} \quad (1)$$

$$F_{x_2} = B_y \dot{B}_y t r^2 \frac{cos(48^\circ)^2}{2\rho} = 3.2\,\mathrm{N/mm} \quad (2)$$

where $\dot{B}$ is the magnetic field, $\dot{B}$ its time derivative, r is the internal radius, t the thickness and ρ the electrical resistivity of the material.

The forces reach their maximum when the absolute value of the product $B\,\dot{B}$ is highest. As depicted in Fig. 2, this peak occurs at 0.22 s and amounts to $-30\,\mathrm{T}^2/\mathrm{m}$. The horizontal force in the two regions of the copper inner layer totals 14.2 N/mm at 5 K. The force induced in the stainless steel (st. st.) can be disregarded due to its electrical resistivity over thickness ratio being more than two orders of magnitude higher.

FEM-2D

The FEM model developed at CERN for the design of the HL-LHC beam screen was employed [3] [4]. It includes a primary magnetic module (*mf*) where the magnetic field decay is assigned using the reduced field formulation to compute eddy currents and Lorentz forces. This module is then coupled with thermal (*th*) and mechanical (*sm*) modules. The coupling between the *mf* and *th-sm* modules can be either one-way or two-way. In the one-way coupling, the magnetic output is transferred solely to the *th* and *sm* modules, resulting in lower computational time. In contrast, in the two-way coupling, the *mf* module receives back the output of the *th* and *sm* modules, specifically temperature and displacement, to refine the results. Although this approach requires longer computational time, it enhances results accuracy. Two-way couplings are implemented within a direct solver. Geometrical nonlinearities have been included (stiffness matrix updated for each time step) as well as the elastic-perfectly plastic behavior of the copper layer. The Residual Resistance-Ration (RRR) considered for copper was 100 and no magneto-resistivity effects were considered. Figure 4 illustrates the evolution of the Lorentz force when considering solely the magnetic physics of the model, compared to when it is coupled with thermal and mechanical ones. The initial observation reveals a close agreement between the FEM method and analytical formulations, with values of 14 N/mm and 14.2 N/mm respectively (a difference of 1.4%). During a magnet quench, the temperature of the beam screen increases due to heat losses caused by eddy currents. The material's temperature-dependent properties, such as electrical resistivity and heat capacity, are taken into account through a two-way coupling between the magnetic and thermal modules. This coupling leads to a reduction in forces of approximately 4 N/mm and an advance in the occurrence of peak forces by 60 ms. The two-way coupling between the *mf* and *sm* modules leads to a slight increase of forces 10.5 N/mm. During a quench, the beam screen gets compressed along the horizontal plane. This expansion leads to an increase in forces exerted on the BS as the magnetic module accounts for a deformed geometry to calculate the Lorentz forces.

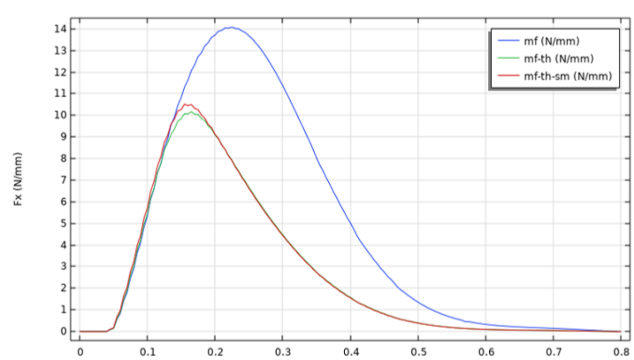

Figure 4: Comparison of the forces induced in a quarter of the beam screen without temperature coupling (blue curve, *mf*), with temperature coupling (green curve, *mf-th*) and with displacement coupling (red curve, *mf-th-sm*).

A scenario was simulated for the beam screen with a st. st. thickness of 0.8 mm, incorporating a copper layer 75 m thick. The largest displacement and stress of the beam screen are 1.66 mm and 547 MPa respectively, are illustrated in Fig. 5 and Fig. 6. The mechanical response of the beam screen is driven by the st. st. which remains elastic, indicating that the component is not permanently deformed

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after the quench. The longitudinal weld, featuring a 50% penetration, was strategically situated in a low-stress area.

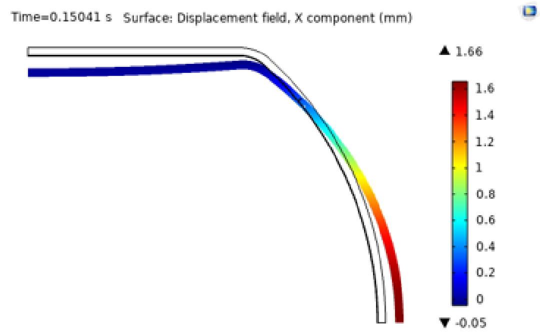

Figure 5: Maximum horizontal displacement with a 0.8 mm st.st. thickness and a longitudinal weld depth of 50%.

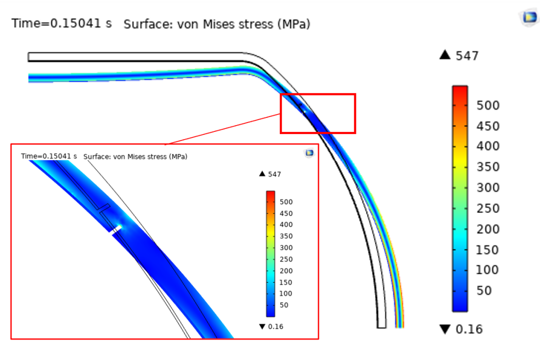

Figure 6: Maximum von Mises stress with a 0.8 mm st.st. thickness and a 50% deep longitudinal weld.

FEM-3D

The 3D model was developed to evaluate the reduction of stiffness in the beam screen resulting from the presence of pumping holes, aiming for a high degree of realism. The forces induced in the *mf* module of the 3D model without pumping holes were compared to those of a 2D model, leading to identical results. For the 3D geometry with pumping holes, to mitigate the extreme computational cost linked with meshing the thin copper layer in the *sm* module, a workaround involving the transfer of Lorentz forces was implemented. This was achieved through a one-way coupling in a separate *sm* study.

Therefore, a *mf-th* study was conducted without incorporating the copper layer but by adjusting the resistivity of st.st. so that the force distribution would be the equivalent as if the copper layer was included. The Lorentz force field obtained from the *mf-th* study was then transferred to a separate *sm* study, which included both the st.st. and copper materials. The presence of the copper layer was taken into account solely for an accurate mechanical response. The transferred force field was incrementally increased using a linear parameter ranging from 0 to 1. This allowed to accurately capture geometrical nonlinearities. The presence of pumping holes results in a reduced stiffness of the beam screen. Compared to the equivalent 2D simulation illustrated in Fig. 5 and in Fig. 6, this leads to a higher displacement and stress, amounting to 1.88 mm and to 600 MPa. Consequently, the component makes contact with the cold bore, which is positioned 1.7 mm away from the beam screen.

Another scenario was examined, considering a full penetration longitudinal weld and a stainless steel thickness of 1 mm instead of 0.8 mm. The maximum displacement and stress are depicted in Fig. 7 and in Fig. 8, respectively. With the increased thickness, the displacement is reduced to 1.18 mm, ensuring no contact with the cold bore. The stress on the most compressed part of the beam screen is 460 MPa. Stress concentrations can reach up to 1060 MPa in the pumping holes, yet they remain below the elastic limit of the stainless steel grade used for this application, i.e. 1620 MPa at 4.2 K [5].

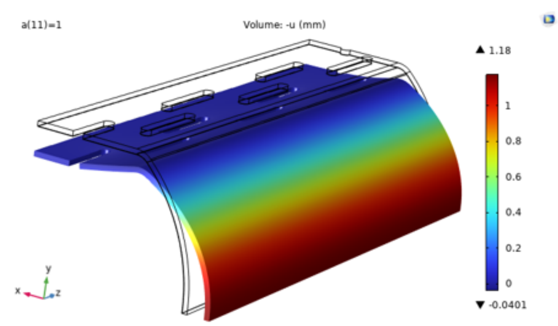

Figure 7: Maximum horizontal displacement with a 1 mm st.st. thickness and a longitudinal weld depth of 100%.

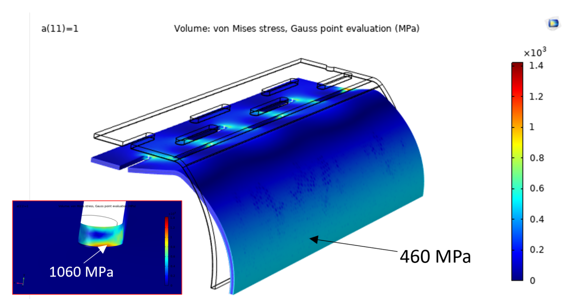

Figure 8: Maximum von Mises stress with a 1 mm st.st. thickness and a 100% deep longitudinal weld.

CONCLUSIONS

The FEM simulation approach used for the HL-LHC beam screen during a magnet quench was used also for the EIC beam screen. The 1 mm thick beam screen with a 100% penetration longitudinal weld was compared to the 0.8 mm thick version with a 50% penetration weld. Both cases exhibit elastic behavior. Stress on the lateral side decreased from 600 to 460 MPa, and around pumping holes from 1230 to 1060 MPa. Maximum deformation reduced from 1.88 mm to 1.18 mm, ensuring no contact with the cold bore (BS-CB gap = 1.7 mm).

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