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High Temperature Superconducting Coating for the Beam Screen of the Future Circular Collider

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Abstract—CERN's next generation particle accelerator, the Future Circular Collider (FCC), aims to reach center-of-mass collision energies of 100 TeV with a 91 km tunnel where charged particles are accelerated and collided. One of the key devices in circular accelerators is the beam screen, responsible for shielding the steering and focusing magnets from the synchrotron radiation generated by the orbiting particles. Due to its proximity to the particle beam, however, it is important that its coupling impedance with the beam is low to avoid the introduction of instabilities. High Temperature Superconductors (HTS) are promising materials for such an application, as they present low surface impedance even at the demanding operating conditions of the FCC, with high magnetic fields of up to 16 T, temperatures of 40-60 K and frequency of 1 GHz. This work evaluates the feasibility of a segmented HTS coating for the FCC beam screen, capable of maintaining high field quality and low surface impedance. Finite Elements Method (FEM) simulations are employed to analyze the electromagnetic and thermomechanical responses of the coated beam screen to regular operation conditions and in the event of a quench of the main dipole magnets.
Keywords—low impedance coating, FEM, HTS, field quality

INTRODUCTION

In circular particle colliders, the particle beam emits synchrotron radiation (SR) due to its circular motion. This radiation poses a threat to the safe operation of the superconducting magnets which, if impinged by it, can surpass their target temperature range. To avoid this, a stainless-steel beam screen (BS) is placed around the particle beam trajectory, absorbing the SR (see Fig. 1) [1]. However, the structure itself interacts with the beam through wake fields and image currents, which can lead to destabilization of the beam orbit. The magnitude of this effect is given by the beam coupling impedance, which depends on the surface impedance and the geometry of the structure surrounding the beam [2]. To minimize it, the beam screen is coated with a highly conductive material. While copper is the standard choice, as is the case with the Large Hadron Collider (LHC), the higher operating temperatures of the BS of the Future Circular Collider (FCC) require a better conductor even at the high magnetic fields targeted by the next generation accelerator.
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The employment of rare earth barium copper oxides (REBCO) high temperature superconductors (HTS) has been proposed to achieve this low impedance coating for the FCC BS [3]. Nevertheless, the trapped fields induced by the superconducting magnets in the HTS coating lead to a decrease in the field homogeneity in the vicinity of the beam, which itself represents another source of instabilities. To mitigate this, the coating is split into narrow segments separated by gaps revealing the copper layer below, which decrease the trapped fields and increase field quality in the vacuum chamber, while maintaining low overall surface impedance [4-6]. Beyond these requirements, it is also important to meet thermomechanical requirements both during regular operation and in the event of a magnet quench.

NUMERICAL MODEL

To evaluate the thermomechanical response to the magnetic fields induced by the superconducting magnets in the HTS-coated BS, finite elements method (FEM) analysis was employed, with Multiphysics coupling between electromagnetic, thermal, and mechanical interfaces. All simulations were performed in COMSOL Multiphysics® [7].
The shielding currents induced in the coating by the ramping dipole magnets were calculated through the H-formulation, assuming that there are no currents flowing through any medium other than the HTS [8]. To enforce this, the value of electric resistance used for vacuum and the normal conductors is 1 Ω, and the

HTS segments are electronically insulated, that is, the total current flowing through any cross-section is zero [9]. The resistivity of the HTS was defined with Anderson-Kim's power law with the critical current density J_c and transition index N dependent on temperature, as well as magnetic field intensity and angle, based on material properties of commercially available CCs [10,11]. On a different simulation interface, the image currents induced by the beam in the coating were calculated with the approximation that all materials are perfect conductors, which is the same as restricting all current flow to the very surface of all materials.
To consider the event of a magnet quench, the beam effects were disregarded, and the reduced field formulation was employed to decrease the computational effort required to deal with the quick drop in magnetic field from 16 T to zero. Nevertheless, for the same reason, all materials were considered to have current flow, and therefore their temperature dependent electric resistance values were considered.

Fig. 1: Photograph of the beam screen of the Future Circular Collider with interior copper coating. The HTS segments are attached onto the copper coating.

In both scenarios, the heat and force loads were calculated from the electric field, magnetic field and current density obtained from the aforementioned interfaces. A negative heat source with a heat transfer coefficient of 5000 W/(m2K) represents the helium cooling channels located on the top and bottom of the BS. These loads were then used as inputs to calculate the temperature and mechanical stress distributions in the BS with the aid of the solid mechanics and the heat transfer in solids interfaces.

RESULTS

As shown in Fig. 2, the results of the thermomechanical simulations show that there is no expected temperature shift for the regular operation of the HTS-coated BS, when the dipole field is increased at a rate of 0.8 T/min. The heat generated in this case never surpassed 65 mW/m, half of that which would be generated in a full copper coating. With respect to its mechanical response, although the forces are higher than in a full copper coating due to the shielding currents in the HTS, the maximum stress was of 3 MPa, well within the elastic limits of all materials involved, including the HTS coating.
The response to a main dipole magnet quench, however, are quite distinct. Firstly, the high current density induced by the plummeting magnetic field produce up to 30 kW/m, which is enough to bring the maximum temperature to 80 K within the 300 ms of quench. Nevertheless, the temperature stabilized back at 50 K a few seconds after the quench. The force loads also increase to the point of inducing stresses in the range of hundreds of megapascals, but never surpassing the yield stress of the stainless-steel, 1100 MPa, and the stress above which irreversible J_c degradation would occur in the HTS, around 700 MPa.
In terms of both mechanical and thermal behavior, the greatest contribution comes from the copper, where 81% of the heat is generated, as well as 91% of the total forces. This is corroborated by the similarities between these results and the response of a copper-coated BS to a magnet quench, as reported in previous studies [12].
To consider the event of a magnet quench, the beam effects were disregarded, and the reduced field formulation was employed to decrease the computational effort required to deal with the quick drop in magnetic field from 16 T to zero. Nevertheless, for the same reason, all materials were considered to have current flow, and therefore their temperature dependent electric resistance values were considered.

Fig. 2: Thermomechanical response of one quadrant of the FCC BS during regular operation and in the event of a magnet quench. Maximum temperatures and mechanical stresses are within the yield stress of stainless-steel and the irreversibility limit of the HTS.

CONCLUSIONS

In this work, we have employed SEM simulation interfaces with COMSOL Multiphysics® to evaluate the response of the HTS-coated FCC BS to the ramping magnetic fields of the main dipole magnets during regular operation and in the event of a magnet quench. We have considered material properties from commercially available CCs to calculate the beam- and magnet-induced currents in the coating as well as their corresponding heat and force loads. The thermomechanical results revealed tolerable temperature shifts and mechanical stresses considering the operating range of the BS and the plastic limit of its materials. Furthermore, since the dominant contributor was the copper already present in the beam screen, the results showed that the performance of the HTS coating with respect to its thermomechanical behavior was comparable to that of a full copper coating.

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Topic

Applications in large instruments such as high-field magnets, medical magnets and accelerator magnets

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