

HTS-COATED BEAM SCREEN FOR SPPC BENDING MAGNETS

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Abstract

For studying new physics beyond the Standard Model, Super proton-proton Collider (SPPC) with a circumference of 100 km and a centre mass energy of 100 TeV is proposed and under study in China. Due to the high particle energies and 16 T high magnet field, the synchrotron radiation power emitted from the proton beams reaches 48.5 W/m in the bending magnets, two orders of magnitude higher than that of LHC. A novel beam screen is anticipated to screen cold chamber walls from the massive synchrotron radiation power and transfer the heat load to cryogenic cooling fluid. For drastically reducing resistive wall impedance and saving refrigerator power, we have studied high temperature superconductor (HTS) coated beam screen operating in liquid nitrogen temperature area. Singly from the point of temperature, the feasibility of HTS-coated beam screen is demonstrated by steady-state thermal analysis. Two kinds of potential HTS material are also discussed in this paper.

INTRODUCTION

The Institute of High Energy Physics (IHEP, Beijing, China) is proposing a two-stage particle collider: CEPC-SPPC [1]. The first stage is a circular electron-positron collider (CEPC). After Completing its experiment, CEPC will be upgraded to a super proton-proton collider (SPPC), aiming at discovering the physics beyond the standard model. The high-energy, high-intensity beams of SPPC generate high heat loads in the cryogenic environment through different processes: synchrotron radiation, beam image currents, impingement of photo-electrons, loss of particles scattered by the residual gas or produced by nuclear reactions in the collisions. A beam screen is required to absorb and guide out the high heat load to protect the superconducting bending magnet, meanwhile to minimize second electron yields (SEY), wall impedance and vacuum instability. The SPPC synchrotron radiation power is about 48.5 W/m per aperture, much higher than 0.22 W/m at LHC [2]. The multifunctional LHC beam screen [3-5] is a successful one, but not suitable for heat load much more than 1 W/m. The main challenges for SPPC beam screen design are discussed in the following sections, as well as preliminary thermal analysis and HTS material choice.

SPPC BEAM SCREEN ISSUES

The synchrotron radiation is one of the major challenges of SPPC beam screen design, not only for its massive

power but also for the contribution to the dynamic vacuum pressures increase [6] and electron cloud effect, leading to poor beam lifetime. Figure 1 shows refrigeration power needed at different cold bore temperatures as a function of beam screen operating temperature. For saving refrigeration power, the optimal beam screen operating temperature is more than 100 K, much higher than LHC (5-20 K). The operating temperature is constrained by heat radiation and conduction to the cold bore. It is suggested that the residual heat leak of thermal radiation and conduction to the cold bore should be less than 1 W/m. Only when the beam screen temperature below 175 K will the heat leak be permissible to cold bore (see Fig.2). On the other hand, the resistivity of copper increasing with temperature and magnetic field [7] will make the resistive wall impedance to be intolerable and lead to beam instability, if coating copper on the inner surface of beam screen like LHC. To balance the refrigeration power and resistive wall impedance, HTS-coated beam screen operating in liquid nitrogen temperature area is proposed and studied. The beam screen structure with synchrotron absorber is shown in Fig.3. The copper coated on the outside surface is used to conduct the heat load efficiently. Pumping slots are on the top and bottom plane, and on the left side for providing enough pumping speed.

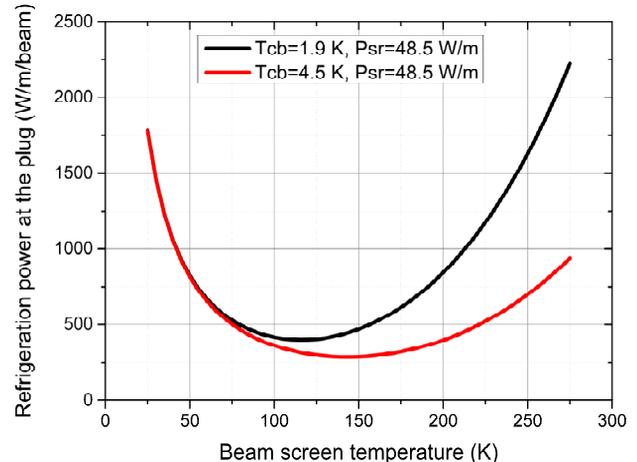


Figure 1: Refrigeration power for beam screen cooling.

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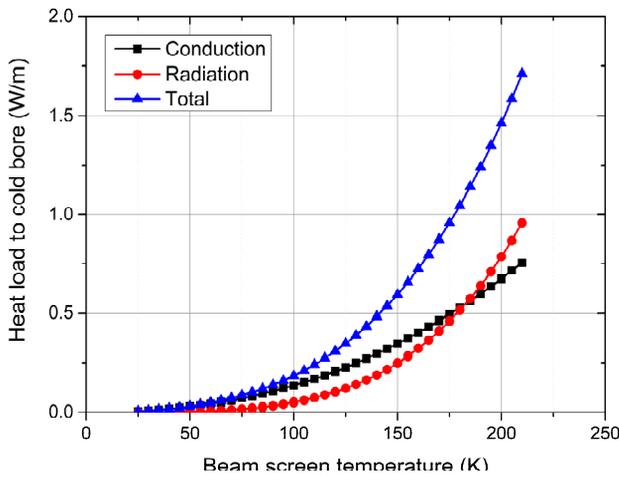


Figure 2: Residual heat leak from beam screen to cold bore.

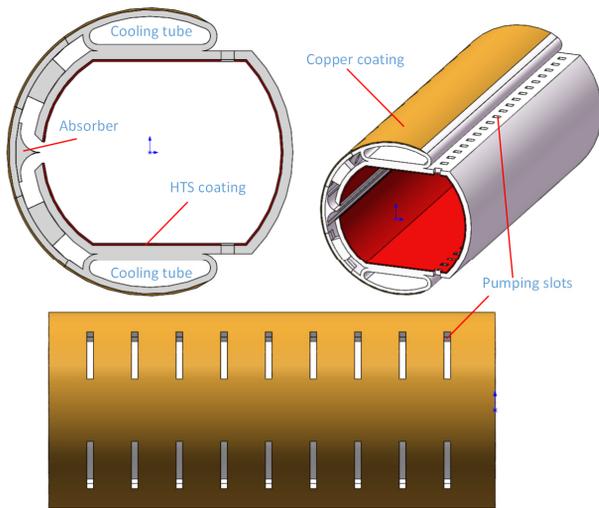


Figure 3: Beam screen structure model.

THERMAL ANALYSIS

The thermal analysis was performed using ANSYS Workbench [8]. We calculated the wall heat transfer coefficient through CFX module, and then imported the results to the Steady-State Thermal module for thermal analysis. The parameters of the cooling fluid [9] used in CFX is shown in Table 1. Liquid nitrogen and oxygen are candidates of the refrigerant. In simulation, their mass flow rates are set as 50 g/s and 45 g/s, respectively, estimated from 53 m half-cell cooling system. The results are shown in Fig.4.

Table 1: Parameters of the Cooling Fluid

Cooling fluid	Nitrogen	Oxygen
Phase	Liquid	Liquid
Pressure (bar)	1	1
Temperature (K)	65	60
Density (kg/m ³)	859.75	1282.10
Cp (J/g•K)	2.00	1.67
Viscosity (uPa•s)	280.44	649.15
Therm. Cond. (W/m•K)	0.173	0.194

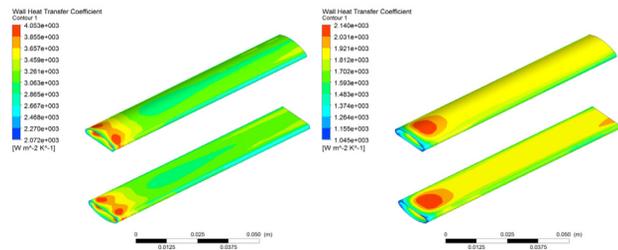


Figure 4: Wall heat transfer coefficient of nitrogen and oxygen.

In thermal analysis simulation, the thermal conductivity of copper and stainless steel at 60 K are about 600 W•m⁻¹•K⁻¹ and 8 W•m⁻¹•K⁻¹, respectively [10,11]. The HTS material is Yttrium Barium Copper Oxide (YBCO) conductor whose thermal conductivity is about 400 W•m⁻¹•K⁻¹ [12]. We have simulated the synchrotron radiation hitting the absorber and missing it, as the simulation conditions shown in Fig. 5.

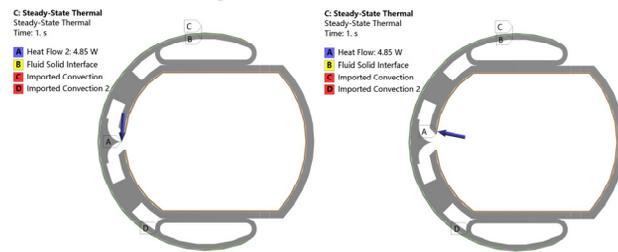


Figure 5: Thermal analysis conditions

Figure 6 illustrates the temperature distribution of the beam screen. The maximum temperature appears at the absorber tip. The maximum temperature rise of the HTS coated part is less than 3 K for both coolants when synchrotron radiation hits the absorber, and is about 9 K while missing. In both situations, within its critical temperature (90 K), YBCO conductor maintained superconductivity.

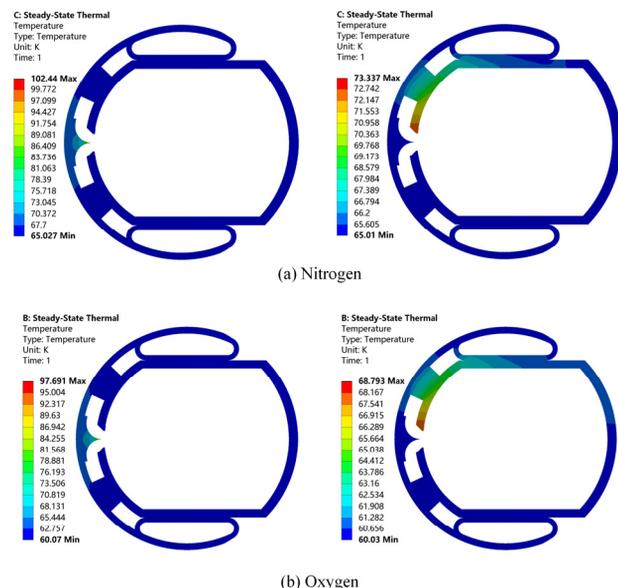


Figure 6: Temperature distribution of beam screen.

POTENTIAL HTS MATERIAL

Requirements for the HTS coating:

- The irreversible magnetic field must be higher than 16 T at beam screen operating temperature.
- The critical current density at beam screen operating temperature and 16 T must be over 4.7×10^4 A/cm² to support a current of 45 A (see Fig.7) over about 1 μm penetration depth at 3 kHz revolution frequency.

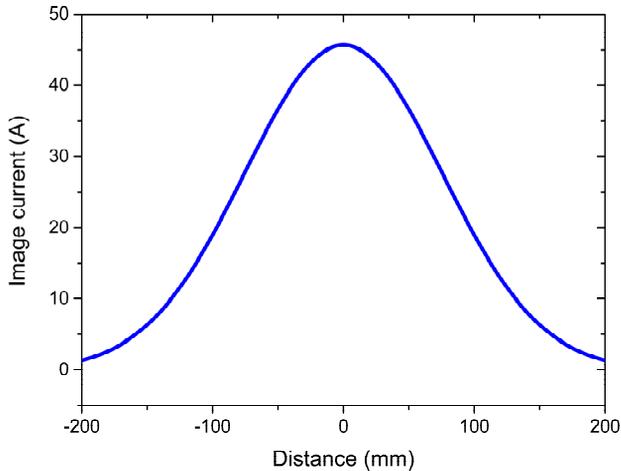


Figure 7: Image current of one beam bunch.

There are two kinds of HTS material which may satisfy the requirements in the future. One is YBCO mentioned in the thermal analysis; the other is $TlBa_2Ca_2Cu_3O_{9-\delta}$ (TI-1223). Their characteristic parameters are given in Table 2 [13]. The irreversible magnetic field (H_{irr}) is far behind the required magnetic field of 16 T. Recent researches find that $YBa_2Cu_3O_{7-x}$ thin films doped with additional rare earth (RE) = (Gd, Y) and Zr and containing strong correlated pins (splayed $BaZrO_3$ nanorods and RE_2O_3 nanoprecipitates) can reach about 15 T of H_{irr} at 70 K when H/c [14]. And the critical current density J_c of YBCO can be enhanced not only by doping with rare earth and adding higher density of nanoscale defects with strong vortex pinning properties [15-17], but also by practical ion irradiation [18,19]. These results demonstrate the immense potential of YBCO for using at high magnet field and higher temperature. However, the growth of good quality YBCO films at large scale is far from application. TI-1223 has potential to apply overdoping or gamma irradiation [20] to strongly increase J_c and H_{irr} and good properties at large scale on Ag plated substrate [21]. However, it is toxic and difficult to preparation. The HTS technology will be there one day, though it is a long way to achieve these goals. Additionally, their RF characteristics, coating techniques, contribution to SEY and radio-toxicity of some heavy elements are also need to be studied owing to the beam screen severe working conditions.

Table 2: Characteristic Parameters of YBCO and TI-1223

HTS	T_c [K]	H_{irr} (77 K) [T]	J_c (77 K, 0 T) [A/cm ²]
YBCO	90	5-7	10^5 - 10^6
TI-1223	125	6-8	10^5 - 10^6

CONCLUSION

HTS-coated beam screen is a proper solution for lowering refrigeration power and decreasing resistive wall impedance. The thermal analysis with nitrogen or oxygen cooling fluid indicated that the HTS could maintain its superconductivity even if the synchrotron hit on the HTS surface. YBCO and TI-1223 are advisable candidates. However, their properties are still far from the requirements and need to be improved.

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