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EVALUATION OF THE IMPACT OF REBCO-COATED CONDUCTORS ON THE RESISTIVE WALL IMPEDANCE OF THE FCC-hh*

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Abstract

The beam screen for the Future Circular hadron-hadron Collider (FCC-hh) has a baseline design based on a copper (Cu) coating. Calculations have indicated that the resistive wall impedance will be the major contributor to the beam impedance for the FCC-hh at both injection and collision and that Cu loss might be on the limit to ensure beam stability. To increase the safety margin, it is desirable to reduce the resistive wall impedance. In this contribution, we present an approach to reduce the beam impedance based on the reduction of the surface resistance of the beam screen coating by using High-Temperature Superconductors based on $REBaCu_3O_{7-x}$ coated conductors (REBCO-CCs). These HTS-CCs have transition temperatures around 90 K, and critical current densities which are high enough even in the presence of a strong magnetic field, being therefore, good candidates to substitute Cu in the FCC-hh beam screen, which will be operating at around 50 K and under a magnetic field of 16 T. Using measured data of the surface impedance of REBCO-CCs, the beam impedance has been estimated for an elliptical beam screen with the same vertical dimension as that of the baseline design. A REBCO-CCs contribution dependence study to determine the optimum beam screen will be shown. Resistive wall impedance studies using an ellipse are a step forward towards determining the performance of the REBCO-CCs on the FCC-hh beam screen.

INTRODUCTION

Resistive wall (RW) impedance which is the coupling impedance arising from the finite resistivity of the beam screen has been shown [1] to be a limiting factor on the performance of the FCC-hh. The baseline design of the FCC-hh beam screen [2] proposes to use co-laminated Cu. The results obtained are, however, close to the limit of what is acceptable from an operational point of view at the foreseen operating temperature of 50 K, and a higher impedance margin has been sought. For that purpose, High-Temperature Superconductors (HTS) with the chemical composition $REBaCu_3O_{7-x}$ (RE = Y, Gd, Eu) in the form of tapes, which are available commercially, have been proposed as an alternative material to reduce the RW impedance. A hybrid structure made of HTS and Cu will be required to keep the magnetic field quality within specifications [3]. Extensive studies of its surface impedance at or close to the working conditions of the FCC-hh have been performed [4–9]. Recently the data obtained has been used to calculate the RW impedance of a round pipe fully coated with REBCO-CC [9]. We present here an approach by calculating the beam impedance of a hybrid elliptical beam screen with varying contributions of REBCO-CC. The vertical axis of the elliptical beam pipe has been chosen to be identical to the dimensions of the FCC-hh beam screen, as shown in Fig. 1.

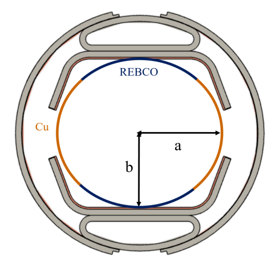

Figure 1: Schematic of the elliptical beam screen with dimensions adapted from the FCC-hh beam screen of [2].

ELLIPTICAL BEAM COUPLING IMPEDANCE THEORY

The frequency spectrum relevant for beam impedance studies in the FCC-hh ranges from about 2 kHz to 3 GHz because of its long circumference (close to 100 km) and to a bunch length of about 8 cm. This is the chosen frequency range in which we are presenting results for the resistive wall impedance. General expressions of the beam coupling impedances of an infinitely thick elliptical chamber have been explicitly calculated in [10, 11]. The calculations assumed an ultra-relativistic beam travelling inside the beam pipe of arbitrary length L, beam offset x_1 or y_1 for vertical or horizontal dipolar transverse impedance, respectively, and pipe wall's material properties defined by its surface impedance $Z_s(f, B, T)$. Calculations have assumed a temperature of 50 K, where we can consider that the thick wall approximation is valid for Cu at all frequency ranges of interest. For REBCO-CC, the London penetration depth, which is frequency independent, is about 0.2 µm; thus, smaller than the REBCO-CC thickness of about 2 µm.

Consider an elliptical pipe with u, v elliptical coordinates: curves of constant u are confocal ellipses, and curves of constant v are hyperbola. The u_0 is a particular value of u

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which corresponds to an ellipse with major and minor axis denoted by $2a$ and $2b$, respectively, with,

$$a = c\cosh u_o\ ,\ b = c\sinh u_o\ ,\ c = \sqrt{a^2 - b^2} \qquad (1)$$

where c is the focal distance of the ellipse. The transformed coordinates will be,

$$x = c\cosh u\cos v, y = c\sinh u\sin v. \qquad (2)$$

To account for a beam screen with varying surface impedance along the v coordinate, the surface impedance as a function of v has been introduced in the general expressions from [10]. The resulting RW impedance general expressions of an elliptical pipe are :

$$Z = \begin{cases} Z_z = \frac{L}{2\pi b}\int_0^{2\pi} Z_s(v)G_o(v)dv \\ Z_y = \frac{Z_o L}{\omega\pi\mu_o b^3}\int_0^{2\pi} Z_s(v)G_{1y}(v)dv \\ Z_x = \frac{Z_o L}{\omega\pi\mu_o b^3}\int_0^{2\pi} Z_s(v)G_{1x}(v)dv \end{cases} \qquad (3)$$

for longitudinal, vertical, and horizontal, respectively. In addition :

$$G_o(v) = \frac{\sinh(u_o)}{2\pi}\frac{Q_o^2(v)}{\sqrt{\sinh^2(u_o)+\sin^2(v)}}$$

$$Q_o(v) = 1 + \sum_{m=1}^{\infty}(-1)^m\frac{\cos(2mv)}{\cosh(2mu_o)}$$

$$G_{1y,x}(v) = \frac{\sinh^3(u_o)}{4\pi}\frac{Q_{1y,x}^2(v)}{\sqrt{\sinh^2(u_o)+\sin^2(v)}} \qquad (4)$$

$$Q_{1y}(v) = 2\sum_{m=0}^{\infty}(-1)^m(2m+1)\frac{\sin((2m+1)v)}{\sinh((2m+1)u_o)}$$

$$Q_{1x}(v) = 2\sum_{m=0}^{\infty}(-1)^m(2m+1)\frac{\cos((2m+1)v)}{\cosh((2m+1)u_o)}$$

To calculate the frequency dependence of the beam impedance, we have assumed a normal metal frequency dependence for Cu, $R_s = X_s \propto \sqrt{f}$, as at the operating temperature and frequency of the FCC-hh the anomalous skin effect can be neglected [12]. For the REBCO-coated conductors, we have assumed $R_s \propto f^2$ and $X_s \propto f$, for the surface resistance and surface reactance, respectively, estimated within the framework of the two-fluid model surface impedance of superconductors [13]. At 50 K and 8 GHz, we have used experimental data of $R_s = X_s = 7.8\,\mathrm{m\Omega}$ for Cu and R_s=0.23 mΩ and X_s=10 mΩ for REBCO-CC [8].

RESISTIVE WALL IMPEDANCE VS REBCO-CC CONTENT

We have used the surface impedance values and frequency dependence presented in the previous section to calculate the beam impedance as indicated in Eq. (3). REBCO-CC tapes, with increasing percentage of coverage, have been placed symmetrically at the top and bottom of the beam screen as illustrated in Fig. 1, leaving the sides of the beam screen exposed to Cu.

Figure 2 illustrates Z_z, Z_y, and Z_x as a function of frequency for different REBCO-CC contents. Additionally, for comparison a fully Cu coated beam screen, i.e. 0% (red curve), and a fully REBCO-CC coated beam screen, i.e. 100% (black curve) have been included. Solid lines correspond to the real part of the impedance, while the dashed lines correspond to the imaginary part.

In general, for the real part, one can observe how the behavior of Cu dominates the frequency dependence of the RW impedance; all lines being parallel to the Cu RW. Only for high frequencies and above 74% REBCO-CC does the vertical RW tend to that of pure REBCO-CC. For the imaginary part at low frequencies, the RW follows the same dependence of Cu, while at higher frequencies, it converges towards the imaginary RW impedance of REBCO-CC. These findings suggest that there is a crossover from a regime dominated by the frequency behavior of Cu at lower frequencies, with impedances that present the same slope as that of Cu, to a regime dominated by the behavior of the REBCO-CC at high frequencies. Extending these calculations to higher frequencies will allow to check if the behaviour observed for Z_y is reproduced for Z_x and Z_z .

RESISTIVE WALL IMPEDANCE EVALUATION AT THE OPERATING CONDITIONS OF THE FCC-hh

We have calculated the beam impedance for a beam screen with 74% of REBCO-CC at two specific frequencies: f_c = 2.1 kHz, corresponding to the couple bunch instability frequency and f_s = 0.93 GHz corresponding to the single-bunch frequency [12] and compare it with a fully coated Cu beam screen. The vertical RW impedance, Z_y, identified as the most critical one for the FCC-hh [1] contributes significantly to the coupled-bunch impedance budget at both injection and collision energies, while the single bunch instability contributes mostly at injection.

In the following we will refer to the FCC-hh's injection and collision energies by its corresponding magnetic field B of 1T and 16T at the dipole magnets, which changes the surface impedance of the pipe wall's material. For Cu, a magnetoresistance effect will be present, which however, at the operating temperature and externally applied magnetic field of the FCC-hh has been demonstrated to be negligible [4]. On the contrary, in the case of the REBCO-CC, the change in the surface impedance due to an externally applied magnetic field cannot be neglected. Table 1 summarises the values for REBCO-CC and Cu used in this study [6].

Table 2 summarizes the RW impedance ratio between a fully Cu-coated beam screen and a beam screen with 74% REBCO-CC, where inside and outside the parentheses are the results of the real and imaginary parts, respectively.

The results for the real part, indicate an overall reduction of the impedance in the three planes compared with a fully

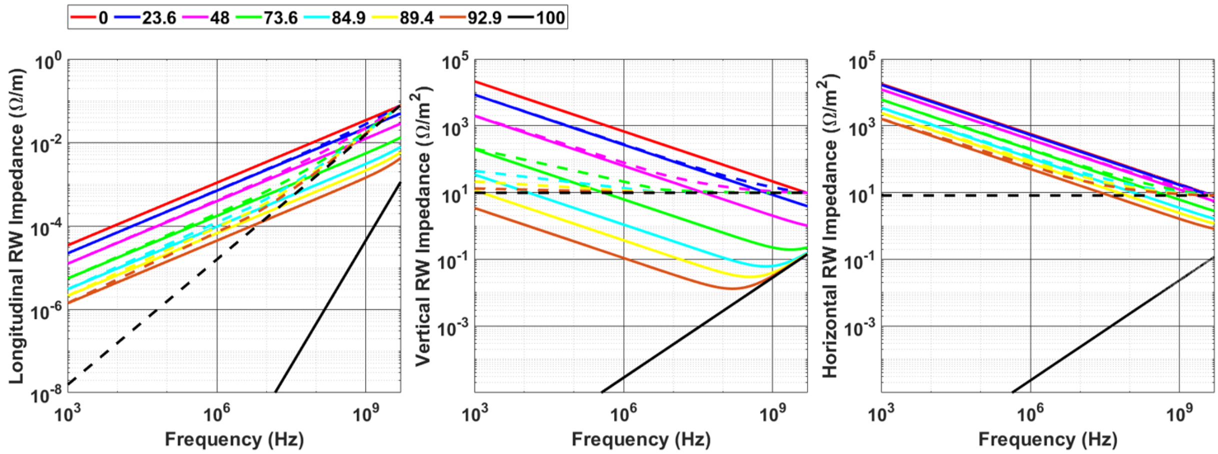

Figure 2: Calculated resistive wall impedance for various REBCO-CC contents at 50 K as a function of frequency. Solid lines indicate the real part and dashed lines indicate the imaginary part.

Table 1: Surface Impedance Measured at 50K and 8 GHz Taken from [6]

samples	$R_s(\Omega)$	$X_s(\Omega)$
FCC-hh Cu 1T	0.0078	0.0078
REBCO-CC 16 T	0.0044	0.0320
REBCO-CC 1 T	0.00034	0.0113
REBCO-CC 0 T	0.00023	0.0100

coated Cu beam screen at both injection and collision energiesand at both frequencies studied. In the case of the imaginary part, at collision and for single bunch instabilities, the impedance is larger than the one of Cu. Nonetheless, the contribution of this impedance to the total budget is small.

At the coupled-bunch frequency, the RW impedance is the same at injection and at collision. This is due to the small dependence of the surface impedance on the applied magnetic field at low frequencies. This is not true at high frequencies, therefore the large difference observed between injection and collision at the single bunch frequency [8].

We see a significant reduction, by almost two orders of magnitude, for Z_y at both single bunch and coupled-bunch frequencies at the injection energy. At collision energy, the reduction is still of two orders of magnitude at the coupled-bunch frequencies, while it is about a factor of 32 at the single bunch frequency.

For Z_z the reduction at both frequencies and energies is around a factor 6, and for Z_x, the reduction is a factor 3. We believe the smaller reduction in the horizontal beam impedance is due to the remaining 26% of Cu at the sides of the elliptical pipe. It is worth mentioning that the side walls for the FCC-hh beam screen, as shown in Fig. 1 are further away from the beam due to the introduction of the vertical slot; therefore the results on the elliptical beam pipe presented in this study should be taken as an upper limit for Z_x of the FCC-hh.

Table 2: Summary of the ratio of single bunch and coupled-bunch resistive wall impedances of FCC-hh Cu and 74% REBCO-CC for real and imaginary part inside the parenthesis at both collision and injection.

regime	**RW**	**injection, 1 T**	**collision, 16 T**
single bunch f_s	Z_z	6.2 (1.7)	5.6 (0.7)
	Z_y	91.9 (2.0)	31.9 (0.7)
	Z_x	2.9 (1.5)	2.8 (0.8)
coupled-bunch f_c	Z_z	6.3 (6.2)	6.3 (6.2)
	Z_y	109.1 (103.4)	109.1 (94.3)
	Z_x	2.9 (2.9)	2.9 (2.9)

CONCLUSION

We performed a systematic study to evaluate the reduction of RW impedance associated with varying the content of REBCO-CC on an elliptical beam screen that has the same dimensions as the FCC-hh beam pipe. The results indicate a gradual reduction of the resistive wall impedances with an increasing REBCO-CC content. The impedances, however, are limited by the contribution of Cu and follow the dependence of a fully Cu coated elliptical pipe at low frequencies. Nevertheless, with the optimum use of a 74% REBCO-CCs, we report two orders of magnitude reduction in the vertical resistive wall impedance at both injection and collision compared to the nominal FCC-hh Cu. The reduction for the longitudinal and horizontal impedances should be taken as an upper limit owing to the different geometry studied compared to that of the FCC-hh. These results confirm that a lower RW impedance can be obtained by an appropriate geometry of the hybrid beam screen that makes use of both REBCO-CC and Cu.

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