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Potential Impedance Reduction by REBCO Coated Conductors as Beam Screen Coating for the Future Circular Hadron Collider

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Abstract –The Future Circular Collider study creates a conceptual design for a post-LHC particle accelerator using 16 T superconducting dipoles to achieve collision energies of up to 100 TeV in a 90 km circumference ring. A copper-coated beam screen, similar to that used in the LHC, is planned. However, the undertaken research indicates that copper at the high working temperature of 50 K has a strong influence on the accelerator's performance, particularly at injection energy. In this work, we relate the experimentally determined properties of REBCO-coated conductors with their potential performance in the FCC-hh beam screen. Specifically, we use a round pipe approximation to demonstrate that a beam screen coated with a combination of REBCO and copper can have a much lower resistive wall impedance than one using only copper. The reduction is substantial (several orders of magnitude), and is observed in both the longitudinal and transverse wall impedance. Such a reduction has important effects on beam stability, operating costs, potential reduction in beam screen size, and lowering the stringent specifications of the 16 T magnets required for the Future Circular Hadron Collider.

Introduction. – Expanding the energy of particle colliders could provide a path to exploring uncharted areas of particle physics. One of the ongoing studies is the Future Circular Hadron-Hadron Collider (FCC-hh) feasibility study [1], which is an international collaboration hosted by CERN to design the successor of the Large Hadron Collider (LHC) [2]. The FCC-hh aims to be a 90 km circumference long accelerator with a 100 TeV centre-of-mass collision energy. Such a large collider demands a more challenging technological development effort compared to the present LHC, which has a centre-of-mass collision energy of 14 TeV in a 27 km long accelerator. Superconducting bending magnets (BMs) up to 16 T will be needed to guide the two counter-rotating proton beams in the FCC-hh. Synchrotron radiation (SR) originating at these BMs is known to be the origin of several undesirable secondary effects, such as detrimental beam effects related to vacuum instabilities and excessive heating of sensitive components at or close to the vacuum chamber where the particles circulate. In the case of the FCC-hh, the SR produced by the higher beam energy compared to the LHC significantly increases by approximately a factor of 160, reaching a linear power density of around 35.7 W/m per beam [3]. Consequently, the FCC-hh's vacuum chamber design requires a beam screen (BS) to protect the surrounding equipment from direct radiation. Numerous investigations summarised in [1] have shown that maintaining the BS between 40 and 60 K is necessary to achieve a suitable balance between the electrical cooling power needed to preserve the superconducting magnet temperature and, simultaneously, ensure vacuum stability by preventing stimulating vapour pressure instabilities.

Beam screens, usually made of metal to hold vacuum, simultaneously resemble a Faraday cage. The travelling charged particle bunches in the centre of the beam screen will be accompanied by a ring of induced image charges of the same total magnitude formed on the surface of the beam screen walls. The restriction to operate the BS at a much higher temperature than the LHC (5-20 K) raises the surface impedance (Z_S) presented by the Cu coating to the proton beams. The resistivity hinders the image currents in their flow, leading to ohmic dissipation, heating, and to the generation of wakefields that perturb the proton beam by way of the so-called resistive wall impedance (Z^{RW}).

The beam screen's contribution to the total impedance compared to the most critical machine elements for the proposed FCC-hh is summarised in the impedance budget indicated in fig.1 for the single bunch and coupled bunch (or multi bunch) impedances at injection and collision energy, respectively. As visible in this figure, the resistive wall impedance, as mentioned earlier, is the leading cause of the coupled bunch instability at injection and collision. For the single bunch instability, the resistive wall impedance plays a significant role at injection, particularly considering the need for an additional surface treatment and/or coating to mitigate the effects of the electron cloud [4]. At this point, it is important to mention that even though in the foreseen baseline design, the copper co-laminated BS ensures that the beam impedance is within the impedance budget and low enough for beam stability, a general higher stability margin by reducing the resistive wall impedance is highly desirable and advantageous from an operational point of view.

The resistive wall impedance can be reduced by either increasing the radius of the BS or by reducing the surface impedance of the material used as a beam screen coating. Expanding the beam screen's radius is frequently not an option because of the costs involved with increasing the magnet's aperture. Hence, the alternative option is to look into materials that could replace copper. One such option is using high-temperature superconductors (HTSs), which have transition temperatures above 90 K [5], and whose surface resistances are reported to be significantly lower than those of Cu in the temperature range of interest. Several recent studies [6–15] have theoretically and experimentally proven that $\mathrm{REBa_2Cu_3O_{7-x}}$ coated conductors (REBCO-CCs, RE = Y, Gd, Eu) provide a lower surface impedance than copper. The data provided in aforementioned studies has shown that REBCO-CCs can outperform Cu at the FCC-hh requirements by measuring the surface impedance of several commercially available REBCO-CCs close or at FCC-hh conditions and by extrapolating the data to FCC-hh conditions if necessary. Thus, from this point of view, they are suitable potential coating materials for the beam screen to reduce the resistive wall impedance below that attainable with copper. What is not yet clear is the impact of the experimentally determined values on the resistive wall impedance and, in turn, its impact on the accelerator performance.

The purpose of this paper is to review recent research into the surface impedance of REBCO-CCs at FCC-hh conditions and investigate its impact on the machine by comparing the differences between an entirely copper coated and entirely REBCO coated beam screen in terms of resulting resistive wall impedance for a round pipe based on the experimentally deducted values within the FCC-hh performance requirements.

REBCO-CCs Performance Requirements. – The fundamental concept for the FCC-hh is to use a hybrid BS system composed of copper and REBCO-CCs in selected locations within the FCC-hh BS to lower the total resistive wall impedance and, thus, ensure beam stability. The reason for the hybrid beam screen coating relies upon the necessity to keep the magnetic high order multipoles on the 16 T dipole magnet within specifications [1]. In the REBCO layer, the persistent currents and magnetisation might strongly impair the magnetic field quality for a complete REBCO-CC coating. However, a hybrid coating can be a possible tradeoff between field quality and resistive wall impedance reduction. This approach has been numerically verified in [12, 16].

Additionally, the REBCO-CCs will be covered by a nanometres-thin film of amorphous carbon (aC). The supplementary aC coating is anticipated to lessen the production of undesired secondary electrons (mitigate the electron cloud effect) without significantly altering the surface impedance while simultaneously protecting the REBCO

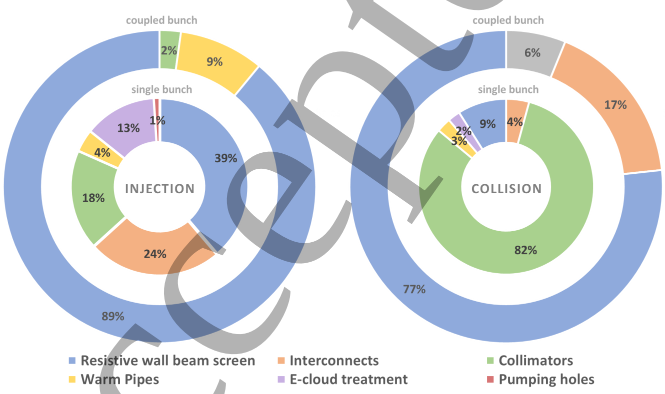


Fig. 1: Relative single bunch and coupled bunch beam impedance budget contributions at injection and collision energy for the FCC-hh with data taken from [4].

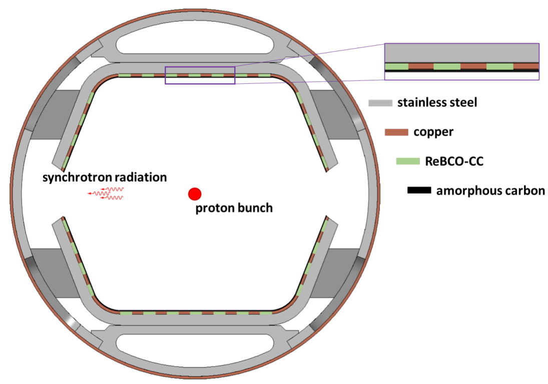


Fig. 2: Example for a hybrid beam screen with alternating REBCO (green) and Cu (orange) stripes covered with aC (black) for the baseline design beam screen. Figure adapted from [3].

layer from humidity.

Figure 2 shows a simple configuration (in this case, symmetrical with equal REBCO-CC width but generally not necessary) for a potential hybrid system within the baseline FCC-hh BS. The same figure shows that the baseline BS incorporates a dual structure into its design [3]. The outer chamber, usually called the ante-chamber, serves as a synchrotron radiation absorber and secondary electron stopper. The inner chamber is built of a 1 mm thick P506 stainless steel sheet. It has a mid-horizontal opening so the SR can pass through and be absorbed in lateral baffles explicitly designed for this purpose. A 0.3 mm thick layer of oxygen-free electronic grade copper is co-laminated onto the inner chamber to achieve low resistive wall impedance values.

In the instance of a hybrid system, the REBCO-CCs are positioned longitudinally along the beam screen length. The production of km-long REBCO-based long-length epitaxial coated conductors is already widely available and manufactured by many providers, primarily for constructing high-field magnets. The intricate layered architecture of REBCO-CCs, along with their flat geometrical shape is suitable for integration into the BS. In this arrangement, the REBCO-layer faces the beam directly without being encased by a copper stabiliser or silver protective overlayer.

The REBCO-CCs would have challenging operating conditions due to the FCC-hh beam screen's extremely demanding operational parameters. The expected average beam current in the FCC-hh is about 500 mA and will be distributed in 10400 proton bunches with a bunch length of $\sigma_{\tau,4\sigma} = 1.07$ ns [1]. At the BS location closest to the beam, this results in an induced peak current of 24 A per bunch and a peak radio-frequency azimuthal magnetic field strength of 230 A/m [15]. Given that a REBCO film is about 2 μm thick; the critical current density will have to be higher than 46 kA/cm^2 at 50 K and 16 T. In addition, a hybrid design a hybrid design is required to take into account the effect of REBCO-CCs on the multipoles of the 16T dipole field [16].

Resistive Wall Impedance Evaluation. – In this case study, we will consider the two scenarios: an entirely Cu-coated BS and an entirely REBCO-coated BS. The reason for this choice is that every hybrid coating system will have an impedance somewhere between these two coating possibilities; thus, we are providing the boundaries to the resistive wall impedance. The exact result will depend on the ratio of Cu and REBCO-CCs as well as their positioning inside the beam screen. Further, we approximate the FCC-hh beam screen as a round pipe to provide the reader with a more comprehensive knowledge of the impact and possibilities of REBCO-CCs on the resistive wall impedance reduction rather than precisely calculating the resistive wall impedance for the actual beam screen shape, regardless the precise location of REBCO. As indicated by the blue dashed circle in fig.3, for the determination of the resistive wall impedance, we assume that the BS is closed, having a radius of $b = 13.61$ mm, which is the average of the vertical and horizontal dimensions of the FCC-hh beam screen. The length of the pipe considered in the estimations is $L = 1$ m, and consequently, the results will be presented per meter length.

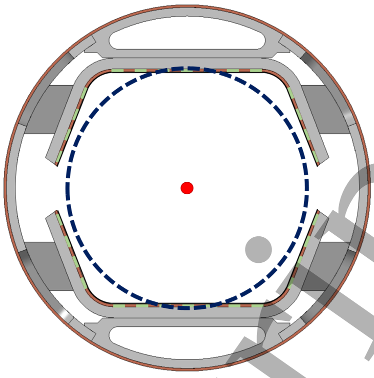


Fig. 3: Round beam screen approximation of the FCC-hh beam screen. Figure adapted from [3].

In the idealised case of a round beam screen, in the ultra-relativistic regime and medium frequency range, the resistive wall impedance can be approximated through [17]:

$$\frac{Z_{\parallel}^{\mathrm{RW}}(T,f,B)}{L} = \frac{Z_S(T,f,B)}{2\pi b} \quad \left[\frac{\Omega}{\mathrm{m}}\right], \tag{1}$$

$$\frac{Z_{\perp}^{\mathrm{RW}}(T,f,B)}{L} = \frac{cZ_S(T,f,B)}{2\pi f b^3} \quad \left[\frac{\Omega}{\mathrm{m}^2}\right]. \tag{2}$$

Here, $Z_{\parallel}^{\mathrm{RW}}$ refers to the longitudinal resistive wall impedance in the direction of the beam trajectory and $Z_{\perp}^{\mathrm{RW}}$ refers to the transverse resistive wall impedance perpendicular to the beam trajectory, L is the length, and b is the radius of the BS, Z_S is the surface impedance of the material of which the vacuum chamber is made of, which depends on temperature T, frequency f, and magnetic field B. The medium frequency range is specified as the frequency range of the beam at which the skin depth is still small enough to penetrate only the first conducting layer. For the FCC-hh, the lowest frequency important for the beam impedance is close to the revolution frequency $f_{min} \approx 2.1$ kHz at injection, while the highest frequency depends on the bunch length $f_{max} \approx 3$ GHz [9,18]. In the FCC-hh baseline, the Cu is thick enough that eqs.(1) and (2) are valid over practically the entire frequency range of interest at 50 K. For REBCO, the London penetration depth is frequency independent and varies around $\approx$ 150 nm to 350 nm, and thus, much smaller than the REBCO layer thickness. Hence, the same equations cover the frequency range of interest for the entire coating with REBCO-CCs.

The electromagnetic response of a surface is described by the above-mentioned complex surface impedance $Z_S = R_S + iX_S$, where R_S and X_S are the surface resistance

Table 1: Surface impedance for several providers determined as explained in [15] including the estimated frequency dependencies in [19]

Material	Z_S(1 T,8 GHz) [mΩ]	Z_S(16 T,1 GHz) [mΩ]
FCC-hh BS Cu	7.6 + 7.6i	2.8 + 2.8i
Fujikura	0.9 + 11.8i	0.1 + 4.5i
SuperPower	0.4 + 11.5i	0.1 + 4.0i
SuNAM	2.4 + 14.8i	0.2 + 5.8i
SuperOx APC	1.0 + 12.1i	0.6 + 8.5i
Theva	1.7 + 16.9i	0.5 + 11.0i

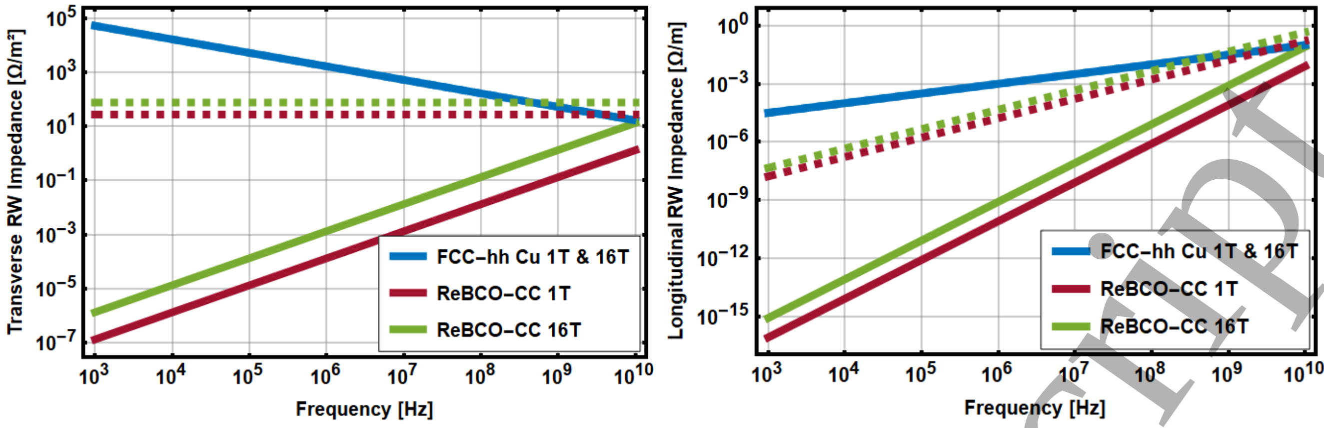
and reactance, respectively. Copper and REBCO vary widely in their surface impedance frequency dependencies. For a normal conductor such as copper, the surface impedance has a $Z_S^{\mathrm{Cu}} \propto \sqrt{f}$ dependency, for both real and imaginary part (the anomalous skin effect does not play a role at 50 K and in this frequency range). Differently, no entirely established theory exists to describe the phenomenon of high-temperature superconductivity and, consequently, as well for the surface impedance of REBCO. Nevertheless, previous research experimentally determined the surface resistance as a function of frequency for different providers by measuring at 8 GHz and 27 GHz. Previous research extracted the frequency dependence for REBCO-CCs supplied by several providers. It has been found that at 50 K, REBCO-CCs yield a frequency dependency of $R_S^{\mathrm{REBCO}} \propto f^{1.1-2}$ and $X_S^{\mathrm{REBCO}} \propto f^{0.6-1}$ [19, 20].

The surface impedance values of metals and coated conductors can be influenced when a magnetic field B is applied. At the injection energy of 3.3 TeV, a dipole magnetic field of $B = 1\,\mathrm{T}$ will be present. Then, the magnetic field will be ramped from injection to collision (1 T to 16 T) [1]. An applied magnetic field on Cu induces a magnetoresistive effect, dominant at very high purity and low temperatures, generally taken into account over Kohler's law [21]. It is important to note that in the pertinent frequency and temperature range of interest in the FCC-hh, this effect can be disregarded [18], and hence, is not taken into consideration in our investigation. Differently, an applied magnetic field of 1 T on REBCO induces vortices in the materials with normal conducting core, which interact with each other forming a vortex lattice impacting the surface impedance. In addition, the circulating proton bunches induced RF-current interacts with the vortex lattice. The RF currents' Lorentz forces cause the vortex lattice to move in a lossy periodic manner, some forms of lattice motion involve net displacement of vortices others do not [7, 14, 15].

Previous research has established that REBCO-CCs outperform Cu in surface impedance measurements up to 9 T at 50 K and 8 GHz [10, 13, 15, 19]. Measurements reported in [13, 19] are performed at 8 GHz, and hence, above the beam spectrum, and show that the depinning frequencies of all providers are $f_{dep} > 10\,\mathrm{GHz}$; thus, significantly above the FCC-hh mid-beam frequency spectrum. These results overcome the concerns raised in [9] about a low depinning frequency that would cause significant loss for frequencies above several MHz. Furthermore, previous studies to investigate the image current (or RF field) induced flux motion and flux shaking, taking into account the timing and field strength of the circulating proton bunches, demonstrated the possibility of lowering the surface resistance of the beam screen by up to two orders of magnitude by using REBCO-CCs instead of copper. In contrast, the surface reactance is of the same order of magnitude as Cu at 16 T at 50 K, 1 GHz and 230 A/m [15]. Table 1 summarises the results for REBCO-CCs and FCC-hh BS used in this study, including the extrapolation to 16 T and 1 GHz as explained in detail in [15].

The actual significance of the performed measurements in [10, 13, 15], over the frequency range relevant for the FCC-hh is visible in fig.4. The figure shows the estimated real and imaginary part of the transverse (fig.4a) and longitudinal (fig.4b) resistive wall impedance for the entire frequency range of interest at injection (1 T) and collision (16 T) in the FCC-hh BS, by substituting the measured and extrapolated Z_S-values of Cu and SuperPower given in table 1 into eqs.(1) and (2). A notable gain of several orders of magnitude is readily visible at low frequencies for both longitudinal and transverse resistive wall impedance, at which the highest instabilities for a copper beam screen are predicted [14]. As discussed in the previous section, the difference in the surface impedance frequency dependencies between Cu and REBCO-CCs is noticeable in both complex resistive wall impedance planes leading to unique impedance behaviours. This can be readily seen in fig.4b, which shows the longitudinal resistive wall impedance having the same frequency dependence as the surface impedance of the materials involved. Figure 4a, however, shows the effect of the f^{-1} term in eq.(2) resulting in a frequency dependence proportional to $f^{-0.5}$ for the real and imaginary part of $Z_\perp^{\mathrm{RW}}$ in copper, to a constant value for the imaginary part of $Z_\perp^{\mathrm{RW}}$ in REBCO, and proportional to f for its real part.

Impact on the Accelerator. – The particles circulating in the accelerator perform oscillations perpendicular to the ideal or reference orbit, referred to as horizontal and vertical betatron oscillation. The stability of these oscillations is affected significantly by transverse impedances. Even though calculating the instabilities arising due to the transverse impedance goes beyond this paper's study, the primary influence of the transverse resistive wall impedance on the accelerator shall be described briefly. As seen in fig.1, the coupled-bunch instability is primarily driven by the resistive wall impedance of the beam screen at injection. The exponential increase of the amplitude of the bunch transverse oscillation caused by the wakefield left behind by preceding bunches is determined over the temporal growth rate τ^{-1}. In order to



(a) $Z_{\perp}^{\mathrm{RW}}$ @ 50 K (b) $Z_{||}^{\mathrm{RW}}$ @ 50 K

Fig. 4: Resistive wall impedance for a thick wall round pipe approximation. The solid lines indicate the real part, while the dashed lines refer to the imaginary part of the resistive wall impedance. The real and imaginary part overlap for copper. REBCO-CC data is shown for SuperPower.

compare the growth rates between the two BS scenarios, we can use the following dependency of the growth rate with respect to the real part of the transverse resistive wall impedance $\tau^{-1} \propto \mathrm{Re}\left[Z_{\perp}^{RW}(f)\right]$ and evaluate the impedance for the single-bunch instability which can occur at the frequency $f = 0.93\,\mathrm{GHz}$ and the coupled bunch instability at $f = 2.10\,\mathrm{kHz}$ [22]. Note that generally, not only the resistive wall impedance is responsible for the instabilities growth rate. However, the ratio of the growth rates between Cu and REBCO-CCs, $\tau_{\mathrm{Cu}}^{-1}/\tau_{\mathrm{REBCO}}^{-1}$, obtained using the real part of the transverse impedance in fig.4a evaluated at the single bunch frequency and coupled bunch frequency (assuming that all parameter generally included in the calculation are the same for both cases) will provide an indication of what to expect for the two BS scenarios considered as summarised in table 2.

Table 2: Ratios of the growth rates between an entire copper coated and entire REBCO-CC coated BS.

$\tau_{\mathrm{Cu}}^{-1}/\tau_{\mathrm{REBCO}}^{-1}$	injection	collision
single bunch	450	44
coupled bunch	$13{\cdot}10^{10}$	$1{\cdot}10^{10}$

Here, the first value is estimated at injection and the second value is determined at collision. The findings suggest strong reductions in the growth rates of instabilities originating from the transverse coupled bunch instability. While in the actual FCC-hh copper beam screen scenario, the coupled bunch instability is much faster than the single-bunch instability [22], a REBCO coating could lead to the opposite effect with a faster single-bunch instability compared to the coupled bunch. Such a REBCO-CC coating of the beam screen with lower transverse impedance could allow for a reduction in the beam screen radius approaching the limitations set by the dynamic aperture, with a possible cost savings, according to [18]. Additionally, a reduced beam screen size might assist in overcoming the existing challenges in producing the high-field 16 T dipole magnets.

Besides oscillations of the entire bunch, interactions of various oscillation modes inside a single bunch exist (radial and azimuthal modes) and are responsible for placing a maximum limit on the bunch current [23]; hence, the amount of particles per bunch. The charge threshold per bunch can be defined in terms of the imaginary part of the so-called effective transverse impedance $I_b \propto 1/\mathrm{Im}[Z_{\perp}^{\mathrm{RW}}(f)]$ [8]. Note that the bunch threshold does not solely depend on the resistive wall impedance but includes the sum of all accelerator element impedances. Nevertheless, as the resistive wall impedance dominates the impedance budget, the round beam pipe analysis is sufficient for a statement of the impact on the overall accelerator. The imaginary part of the transverse impedance for REBCO-CC at injection and collision would be beneficial not only for higher beam stability but would lead as well to the possibility of operating the machine with a higher beam current compared to copper. Consequently, more particles and higher collision rates.

As the bunches move around the accelerator, they lose energy not only due to the synchrotron radiation but as well due to the power dissipated in the beam screen because of the Joule effect dissipation of the beam-induced image currents, which is expected to be much less than the synchrotron radiation power. In the worst situation, the energy emitted might overheat delicate components, which at excessive temperatures risk deformation or even destruction. Therefore, the heat load onto the beam screen shall be kept to a minimum. The power loss can be expressed in the frequency domain using the real part of the longitudinal impedance $R_{||}^{\mathrm{RW}}$ and the beam power density

$|\Lambda(f)|^2$ as [24]:

$$P_{\rm loss} \propto \int_0^\infty {\rm Re}\left[Z_\parallel^{\rm RW}(f)\right] |\Lambda(f)|^2 {\rm d}f. \qquad (3)$$

where the beam power density for a Gaussian bunch is given by [24]:

$$|\Lambda(f)|^2 \propto \exp\left[-(\sigma_{\tau,4\sigma}\pi f)^2\right]. \qquad (4)$$

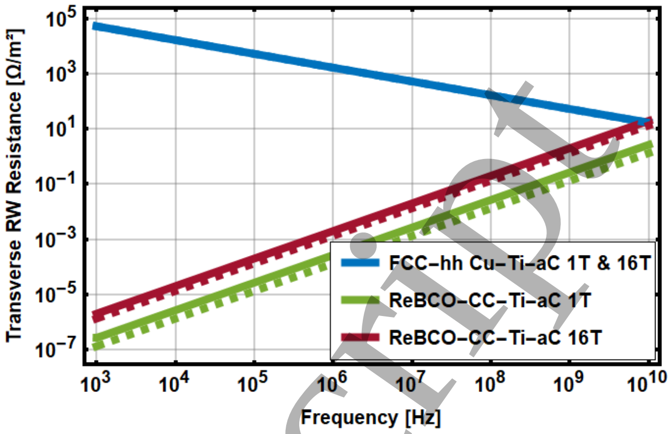
The ratios for the heat load between the copper coating and REBCO coating are:

$$\frac{P_{\rm Cu}}{P_{\rm REBCO}} = \begin{cases} 5800, & \text{at injection energy,} \\ 560, & \text{at collision energy.} \end{cases}$$

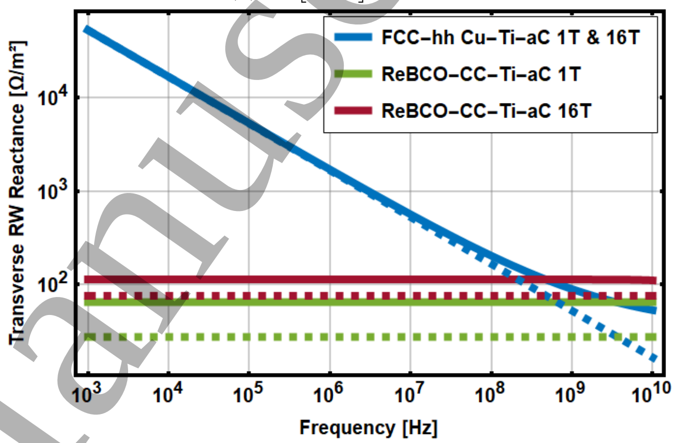
According to these data, we can infer that the usage of REBCO has a strong potential to reduce the beam induced heat load onto the beam screen walls.

For completeness, we should indicate that (a) the above discussion covered an elementary example of the resistive wall impedance for a round pipe in which the effect of the particular normal conducting ante-chamber of the FCC-hh BS is neglected, (b) we have not included in this simple approach the possibility of a residual resistance due to normal conducting inclusions in the REBCO film at low frequencies, and (c), the direction of the applied magnetic field. With respect to the direction of the magnetic field, the data used for this study resulted from measurements in which a perpendicular DC magnetic field was always applied to the REBCO-CCs surface, and therefore, resulting in the highest surface impedance [25]. The REBCO-CC placed on the inner c-shaped chamber experiences a magnetic field which is about $\Theta \approx 70°$ inclined with respect to the REBCO c-axis. Eventually, this results in an effective magnetic field which is reduced to about $B_{\rm eff} = \sqrt{\cos^2(\Theta) + \gamma^{-2}\sin^2(\Theta)}\, B \approx 0.36B$, where γ is the electronic anisotropy which ranges between 5 and 8 for REBCO [10]. Therefore, we can state that our predictions are rather conservative.

Lastly, the effect of a thin layer of sputtered amorphous carbon coating shall be discussed. The suppression of the e-cloud formation can be achieved by coating REBCO-CCs with a thin layer of amorphous carbon, provided that an underlayer of titanium is deposited between the REBCO and aC for greater adhesion. Measurements of the surface impedance in [10] have proven that REBCO does not degrade, but a slight increase in surface resistance is seen in the results. Figure 5 shows the effect of an additional Ti-aC coating inside the round beam screen approximation compared to the results without the additional coating for the real part (5a) and imaginary part (5b) of the transverse impedance. The figure shows the values for the transverse impedance as the impact of the multi-layer on the longitudinal plane is equivalent as in the transverse plane due to the linear surface impedance proportionality in both resistive wall impedance planes. The



(a) $\mathrm{Re}\left[Z_\perp^{\rm RW}\right]$ @ 50 K



(b) $\mathrm{Im}\left[Z_\perp^{\rm RW}\right]$ @ 50 K

Fig. 5: Effect of a 150 nm thick amorphous carbon coating on the resistive wall impedance. The solid lines indicate the resistive wall impedance of a REBCO with amorphous carbon coating, while the dashed lines refer to the resistive wall impedance without amorphous carbon coating. REBCO-CC data is shown for SuperPower.

titanium layer is assumed to have a thickness of 150 nm with the aC layer thickness of 100 nm. The conductivity values of Ti and aC have been determined as discussed in [26]. As can be seen, the real part of the Cu coating is unaffected by amorphous carbon, while the imaginary part changes at high frequencies starting above 1 MHz. Conversely, the effect of the Ti-aC layer on REBCO leads to a constant increase among the whole frequency spectrum of about a factor 2 in the real and imaginary part at 1 T and a factor 1.5 at 16 T. This combination of findings provides some support for the conceptual premise that even with an amorphous carbon coating of such thickness (thinner coatings can be provided) REBCO-CCs still are beneficial for the reduction of the resistive wall impedance by several orders of magnitude.

Conclusion. – In this article, we present the potential to improve the beam stability in a future circular collider by implementing REBCO coated conductors into the beam screen. It is the first time that data experimentally collected close to the FCC operating parameters is used for such a purpose. We have modelled the beam impedance by using the simple case of a round pipe being either entirely coated by copper or entirely coated by one of the best performing REBCO-CC. This way, we could draw conclusions on the true potential impact of the results on the resistive wall impedance for the accelerator:

By means of all the results, the different frequency dependencies proved through our measurements and predicted magnetic field effects on the surface impedance of REBCO-CCs and FCC-hh BS copper, employing REBCO-CCs as a beam screen coating alternative to copper promotes a significant reduction -orders of magnitude- of the resistive wall impedance in the whole beam frequency spectrum; both longitudinal and transverse.

Such a REBCO-CC coating of the beam screen with lower transverse impedance could provide a reduction in the beam screen radius approaching the restrictions set by the dynamic aperture, with potential cost savings. Additionally, a smaller beam screen size might help to solve the current challenges with manufacturing high-field 16,T dipole magnets.

Given the requirements and operating conditions in the FCC-hh, our study provides experimental evidence that REBCO-CCs are genuine potential candidates to substitute copper as the coating for the beam screen chamber of the Future Circular Hadron Collider, and in fact is the only way to obtain a surface impedance lower than that of copper in the frequency range of interest. In summary, the combination of findings together with the aforementioned drawbacks and advantages, provides support for the conceptual premise that the usage of REBCO-CCs is strongly beneficial to reduce the main impedance of the FCC-hh impedance budget.

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