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Thallium-based high-temperature superconductors for beam impedance mitigation in the Future Circular Collider

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Abstract

CERN has recently started a design study for a possible next-generation high-energy hadron–hadron collider (Future Circular Collider—FCC-hh). The FCC-hh study calls for an unprecedented center-of-mass collision energy of 100 TeV, achievable by colliding counter-rotating proton beams with an energy of 50 TeV steered in a 100 km circumference tunnel by superconducting magnets which produce a dipole field of 16 T. The beams emit synchrotron radiation at high power levels, which, to optimize cryogenic efficiency, is absorbed by a beam-facing screen, coated with copper, and held at 50 K in the current design. The surface impedance of this screen has a strong impact on beam stability, and copper at 50 K allows for a limited beam stability margin only. This motivates the exploration of whether high-temperature superconductors (HTS), the only known materials possibly having a surface impedance lower than copper under the required operating conditions, would represent a viable alternative. This paper summarizes the FCC-hh requirements and focuses on identifying the best possible HTS material for this purpose. It reviews in particular the properties of Tl-based HTS, and discusses the consequent motivation for developing a deposition process for such compounds, which should be scalable to the size of the FCC components.

Keywords: FCC, beam screen, HTS coating, thallium, Tl-1223

(Some figures may appear in colour only in the online journal)

1. Introduction and motivation for using high-temperature superconductors (HTS)

The FCC-hh study explores design options for a next-generation large hadron–hadron collider aiming for a 100 TeV center-of-mass proton–proton collision energy, which will be located in a 100 km circumference ring in proximity to the CERN site [1]. Superconducting Nb_3Sn magnets capable of generating a dipole field of 16 T at an operating temperature of 1.9 K will steer two counter-rotating proton beams, each carrying an average current of about 1 A. Each beam will emit about 28 W m^{-1} of synchrotron radiation in the arcs, the total synchrotron power of the entire accelerator amounting to approximately 4.8 MW. This power cannot reasonably be absorbed by the magnets at a temperature of 1.9 K. State-of-the-art cryoplants require about 900 W of electricity in order to extract 1 W at 1.9 K, thus resulting in more than 4 GW of electrical power. Instead, the radiation will be absorbed by a screen kept at higher temperature to improve efficiency, similarly to what is presently implemented in the Large Hadron Collider (LHC) at CERN (see figure 1).

A first optimization work has shown that a beam screen temperature of around 50 K is the best compromise for power consumption [2], while still allowing good vacuum quality.

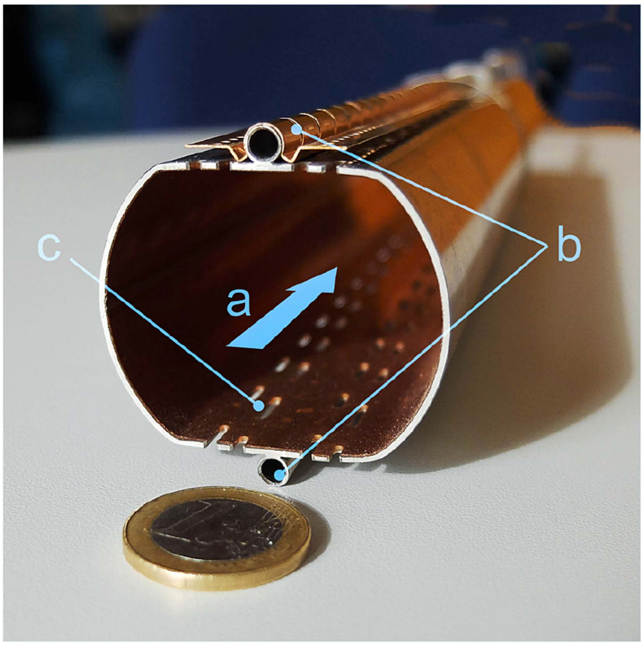

Figure 1. Photograph of the LHC beam screen. The proton beam moves along the axis indicated by the arrow (a). The tubes on top and at the bottom (b) are cooling channels for gaseous helium, and the slots (c) allow any desorbed gases to escape and to be cryopumped onto the surface of the cold bore of the surrounding magnet.

This choice has, however, strong consequences for beam stability. A charged particle beam excites electromagnetic fields in its surroundings, which generate image currents at the surface of the screen and electromagnetic fields in the wake of the particle bunches (also called 'wakefields'). While the (image) currents at the material surface induce Joule heating, the wakefields can strongly influence beam stability. Both effects are usually described in the frequency domain in terms of beam impedance [3], which is directly proportional to the surface impedance of the material facing the beam. The FCC-hh baseline design makes use of a copper coating in order to minimize impedance, as in the LHC. The surface resistance of copper at 50 K may, however, not be sufficiently low to guarantee a safe operational margin for the FCC-hh beams, in particular at injection energy. In addition, the design injection energy of 3.3 TeV might advantageously be lowered to 450 GeV, thus allowing a simplification of the FCC-hh injector chain, if beam stability could be guaranteed by the use of suitable materials.

The goal of this paper is to study the feasibility of using HTS instead of copper in order to minimize the surface impedance[6]. We first analyze the impedance requirement in the FCC, and the consequent material requirements of an HTS coating. We then focus on the specific choice of studying Tl-based HTS compounds, and review their main properties, analyzing the perspectives for this material and the motivation for developing a deposition process scalable to the size of the FCC components.

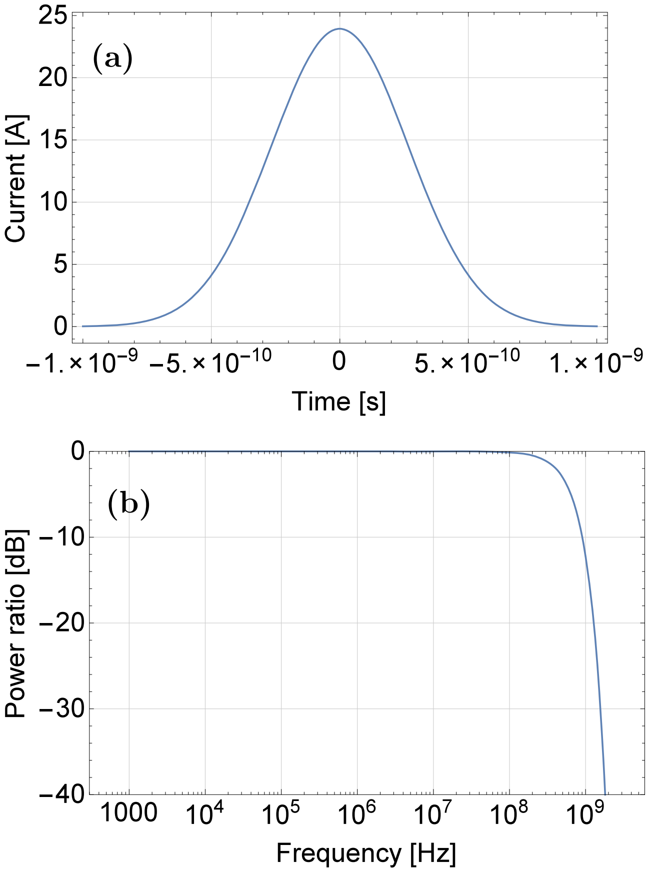

Figure 2. Instantaneous current of bunches of 10^{11} protons having a Gaussian longitudinal profile with $\sigma = 8$ cm (a), and the corresponding power spectrum, which is its Fourier transform (b).

2. Material requirements

In a cryogenic accelerator such as the FCC it is important to minimize the power dissipated in the vacuum chamber due to Joule effect dissipation of the image currents induced by the beam. The longitudinal coupling impedance is a convenient tool for evaluating the power loss. In the idealized case of a circular particle accelerator made of a cylindrical smooth vacuum chamber, it can be expressed in the simplest form as [4]

$$Z_{\mathrm{L}} = \frac{2\pi R}{2\pi b} Z_{\mathrm{s}}, \tag{1}$$

where R is the radius of the particle accelerator, b is the radius of the vacuum chamber, and Z_{s} is the surface impedance of the material of which the vacuum chamber is made, its unit being Ω. Intuitively, equation (1) is the integration of Z_{s} over the entire inner surface of the accelerator. The resistive power loss is then equal to

$$P_{\mathrm{loss}} = M I_{\mathrm{b}}^2 \,\mathrm{Re}(Z_{\mathrm{loss}}), \tag{2}$$

where M is the number of particle bunches in the accelerator, I_{b} is the bunch current, and Z_{loss} is the convolution of the longitudinal impedance Z_{L} with the beam power spectrum, whose envelope is illustrated in figure 2 for the case of Gaussian bunches. Beneath this envelope lies a discrete line spectrum whose distribution depends on the accelerator revolution

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[6] Following a suggestion by Professor Lucio Rossi, CERN.

frequency, the time interval between bunches, and the details of their motion inside the accelerator [5].

The motion of particle bunches in an accelerator follows very complex dynamics. The accelerator size, its magnet optics, and the particle energy (often determined by a highly relativistic velocity $v \approx c$) define a reference orbit and an angular frequency ω_0 for a hypothetical synchronous particle circulating along this reference orbit. In practice the particle bunches, within their motion around the accelerator, perform longitudinal oscillations along the virtual position of the synchronous particle (synchrotron oscillations). They also perform transverse oscillations with respect to the reference orbit, both in the horizontal and vertical planes (betatron oscillations). A large number of factors influence the stability of these oscillations, and the effect of wakefields which are excited by the beam is of particular importance. The wakefields act back on the particle beam, and influence both its longitudinal and transverse dynamics. Their effect is also described in terms of the beam coupling impedance [4], defined as the complex ratio of the wakefield potential and the beam current. For longitudinal oscillations this leads to a definition of Z_L identical to equation (1). Although longitudinal instabilities can also occur [3], we focus here on transverse instabilities, which are expected to be one of the performance limitations in the current FCC-hh design.

The transverse coupling impedance can be expressed as [4]

$$Z_T = \frac{2\pi R c}{\pi b^3 \omega} Z_s, \tag{3}$$

where c is the speed of light, and ω is the wakefield frequency. (We should note that Z_s itself has an intrinsic dependence on ω.) The transverse impedance Z_T is expressed in $\Omega\,\mathrm{m}^{-1}$, since its effects are proportional to the local amplitude β of the beam betatron oscillations along the path in the accelerator, which can be approximated for simplicity by the quantity β_{av}, which is an average around the ring.

The real part of the transverse impedance allows calculating the growth rate of coupled-bunch transverse instabilities, i.e. the exponential growth of the amplitude of the bunch transverse oscillation due to the wakefield created by preceding bunches. The exact formalism goes beyond the scope of this paper (see for example [6] for a detailed discussion of the LHC case). We underline here that the so-called resistive wall transverse instability has a temporal growth rate τ, which exhibits the dependence

$$\frac{1}{\tau} \propto \frac{I_b M \beta_{av}}{EL} \mathrm{Re}(Z_T^{\mathrm{eff}}), \tag{4}$$

where L is the length of the particle bunches and E is the beam energy. In practice, the effective transverse impedance Z_T^{eff} is calculated for each transverse oscillation mode (azimuthal, radial, coupled bunch), by a convolution of Z_T over the appropriate beam mode spectrum [7]. The lowest coupled bunch mode has in fact the spectrum shown in figure 2, while higher modes have higher frequencies and lower amplitudes. Single lines in the mode spectrum may dominate the behavior, in particular at low frequency because of the ω^{-1} term in equation (3). It has been estimated [8] that in the case of the FCC-hh the lowest frequency line at 2 kHz might drive a coupled bunch instability of the beam over a few tens of turns around the machine, at the injection energy of 3.3 TeV, if using a copper-plated beam screen. This is rather close to the limit of a hardware feedback and correction system.

On the other hand, high-frequency interactions of different oscillation modes within a single bunch, called transverse mode coupling instabilities, set a maximum limit to the bunch current. Provided some other resonant conditions are established, the intensity threshold can also be conveniently described in terms of Z_T^{eff} as

$$I_b \propto \frac{E}{\mathrm{Im}\,(Z_T^{\mathrm{eff}})}. \tag{5}$$

It is apparent that in all cases it is most favorable to minimize the surface impedance of the material facing the particle beam. Reducing this quantity significantly below the value of copper necessarily implies the use of an HTS of appropriate choice.

The operating conditions of HTS in the proposed FCC-hh beam screen are, however, extremely challenging. As already mentioned, the beam screen of about 30 mm diameter [9] would operate in a temperature window around 50 K, and the coatings would have to remain superconducting up to a field of 16 T. The 8 cm long bunches of $\sim 10^{11}$ protons would induce peak currents of the order of 25 A in the HTS, as illustrated in figure 2. Assuming that this current is carried by the HTS within a layer whose thickness equals the skin depth, which is of the order of 1 μm in the frequency range of interest, the critical current density J_c should be at least about $2.5 \times 10^8\,\mathrm{A\,m}^{-2}$ at 50 K and 16 T.

Based on literature reviews [10], it is safe to assume that the intrinsic surface resistance of HTS such as Y-123 or Tl-2212 is lower than that of copper at frequencies below 10 GHz. Nevertheless, a strong magnetic field such as in the FCC-hh will significantly increase the surface impedance of the HTS, thus limiting the advantages. The effect of an applied magnetic field $B_0 > B_{c1}$ on the surface impedance can be described in terms of the oscillations of the rigid fluxon lattice driven by the RF currents, which lead to a dissipation of energy by viscous motion [11]. For large applied magnetic fields B_0, i.e. of the same order as the upper critical field B_{c2}, the intrinsic surface impedance of the HTS can be neglected, and the surface impedance as a function of frequency ν is dominated by its field-dependent component [12]:

$$\begin{aligned} Z_{sf} &\equiv Z_f = Z_n \sqrt{\frac{B_0}{B_{c2}}} \quad \text{for } \nu \gg \nu_0, \\ R_{sf} &\equiv R_f = \frac{R_n}{\sqrt{2}} \sqrt{\frac{B_0}{B_{c2}}} \left(\frac{\nu}{\nu_0}\right)^{3/2}, \\ X_{sf} &\equiv X_f = R_n \sqrt{2} \sqrt{\frac{B_0}{B_{c2}}} \left(\frac{\nu}{\nu_0}\right)^{1/2} \quad \text{for } \nu \ll \nu_0. \end{aligned} \tag{6}$$

The above equations make use of the usual notation $Z_s = R_s + \mathrm{i}X_s$, where $R_n = \sqrt{\mu_0 \rho_n \pi \nu}$ is the normal-state surface resistance of the HTS. The so-called depinning frequency ν_0 is given by [12]

$$\nu_0(B_0) = \frac{\rho_{\mathrm{n}}\sqrt{B_0}J_{\mathrm{c}}(B_0)}{\sqrt{\Phi_0}B_{\mathrm{c}2}}, \tag{7}$$

where ρ_{n} is the normal-state resistivity of the HTS, $J_{\mathrm{c}}(B_0)$ is its critical current density as a function of the applied field B_0, and Φ_0 is the flux quantum. It is commonly reported in literature that the depinning frequency of HTS films is significantly above 1 GHz [10] in absence of an applied magnetic field, while the effect of strong magnetic fields on it is experimentally less documented [13, 14]. Equation (7) demonstrates, however, that the depinning frequency can in principle be calculated based solely on DC transport measurements. The surface impedance can then be evaluated using the simplified equation (6) or, for a frequency regime overlapping with the depinning frequency, using the full model described in [12].

Based on the best available literature results for Tl-1223, we can assume a normal-state resistivity $\rho_{\mathrm{n}} = 40\ \mu\Omega$ cm, and an upper critical field $B_{\mathrm{c}2}$ at 50 K of 70 T ($H\|c$, conservative estimate). In addition, we shall assume a range for the critical current density from 10^8 to 10^9 A m^{-2} in order to evaluate the surface resistance at the FCC injection field of 1.06 T, which according to equation (4) should correspond to the most unstable condition, and at the nominal field of 16 T. The depinning frequency ranges from 12 MHz up to 480 MHz, depending on applied field and critical current density, and we thus make use of the full formulas [12] to evaluate the surface resistance over the entire frequency spectrum of interest, noticing that equation (6) gives indistinguishable results for $\nu < \nu_0$. The results are shown and compared to copper in figure 3. At low frequencies, where the most unstable modes are predicted for a copper beam screen, a substantial gain of several orders of magnitude is clearly apparent. It is important to note the ν^2 and $\nu^{1/2}$ behavior of the surface resistance of HTS for frequencies below and above ν_0 respectively, compared to the $\nu^{1/2}$ behavior of copper for all frequencies. In the usual paradigm of accelerator design, the real part of the transverse impedance Z_{T} (see equation (3)) for normal conductors has a $\nu^{-1/2}$ dependence, which gives a stronger weight to low-frequency lines in the mode spectrum, as mentioned earlier. In the case of an HTS-coated beam screen the weighting will be different, thus requiring a re-evaluation of instabilities that goes beyond the scope of this paper.

The ratio of the surface resistances of Tl-1223 and Cu provides further information on the possible advantages of HTS, since it represents directly the ratio of transverse impedances (see equation (3)). This is reported in figure 4, which shows a clear advantage of several orders of magnitude of HTS at low frequencies, with a cross-over frequency above 10 MHz.

3. Choice of material

Based on the above considerations, the requirements (with a reasonable safety margin) on HTS films for the FCC beam screen determined by the currents induced by wakefields and by the behavior of the surface impedance can be summarized as follows:

- Upper critical field larger than approx. 70 T at 50 K.
- Critical current density larger than 2.5×10^8 A m^{-2} at 50 K and 16 T.

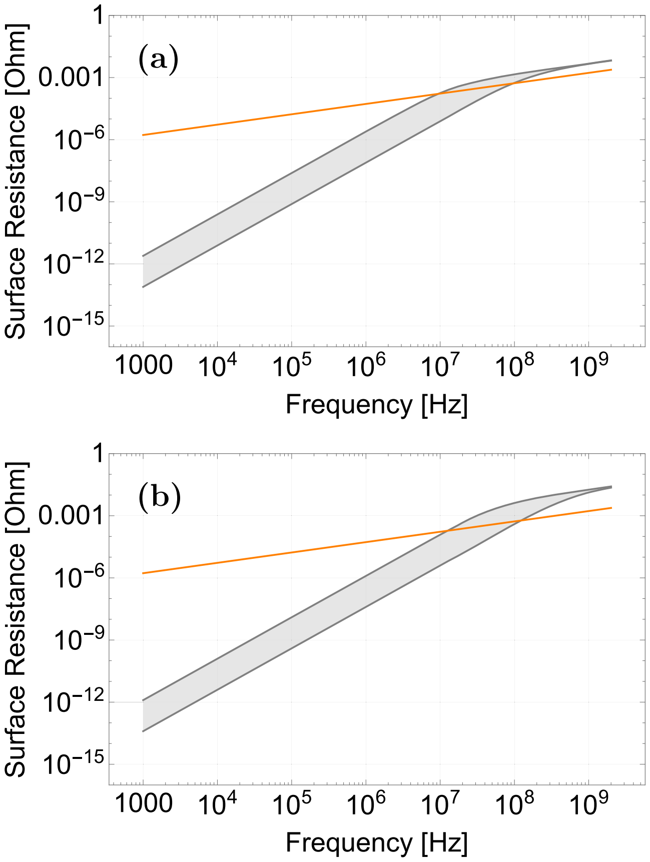

Figure 3. Predicted surface resistance at 50 K of Tl-1223 (gray band) compared to Cu (orange) at 1.06 T (a), and at 16 T (b). The band corresponds to the range of critical currents mentioned in the text.

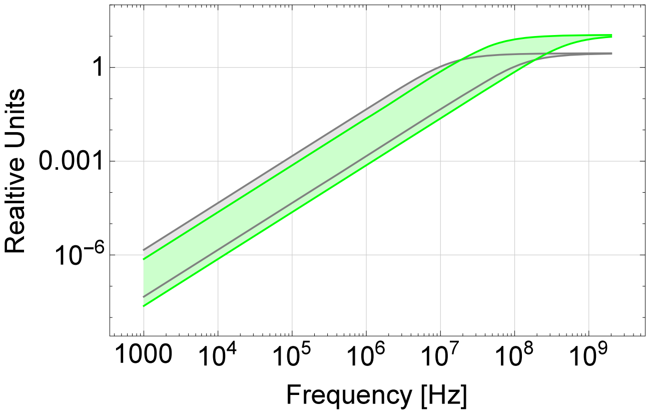

Figure 4. Ratio of expected surface resistances of Tl-1223 and Cu at 1.06 T (gray band), and at 16 T (green band). The bands correspond to the range of critical currents mentioned in the text.

Table 1. Comparison of the relevant properties of different HTS materials (typical values).

Material	T_c	B_{irr} (77 K)	γ	Substrate requirements
Y-123	~90 K	~7 T	5–7	Needs high-quality biaxial texture
Bi-2212 Bi-2223	~90 K ~110 K	<0.1 T <1 T	>20	Does not require sophisticated texture
Tl-1223	~125 K	~6 T	~8	Similar to Bi-2212

Note: since there is a large variance among the published data, the specified values are based on the experience of the authors.

A film with such properties has to be deposited with a thickness of about 1 μm on a copper substrate, or an equivalent low-resistivity metal substrate such as silver, by a technique scalable to a long tubular substrate geometry.

Unfortunately, an HTS satisfying these requirements is presently not available. The two most evolved HTS, *RE*-123 compounds such as YBCO, and Bi-based compounds, suffer from limitations which render them unsuited for coating the FCC beam screen. The *RE*-123-based conductors, which can reach the requirements on J_c and B_{c2}, have the huge disadvantage of a quasi-single crystal, two-dimensional structure in which the supercurrents have little freedom of percolation, which leads to an extreme degradation of J_c at all but very small grain misalignments. Such misalignments must be counteracted by very complex biaxial texturing processes which cannot be obtained on a tubular metallic substrate [15]. Bi-based conductors, on the other hand, only require a uniaxial texture which can easily be obtained by thermomechanical treatments of the substrate. They are, however, intrinsically limited by their huge anisotropies which make flux pinning ineffective at high temperatures, thus limiting their applicability at high fields to temperatures below ~20 K.

We have reason to believe that Tl-based HTS, in particular Tl-1223, offer an alternative to *RE*-123 and Bi-based compounds, which is suitable for coating the FCC beam screen. A comparison of the critical temperatures T_c, the irreversibility fields B_{irr}, the anisotropies γ, and the substrate requirements of the named materials is presented in table 1.

Thallium-based compounds are not a novelty—in fact they were subject to large European study projects about 20 years ago, in view of their potential application for manufacturing high-current wires and tapes [16]. These projects, mainly working with powder-based preparation techniques, showed that Tl-based superconductors suffer, as YBCO does, from weak-link problems, if an insufficient texture is imposed on the material. They achieved J_c values of the order of 10^9 A m^{-2} at 77 K in self-field, but the application of small magnetic fields (~0.1 T) reduced the critical current by about two orders of magnitude due to the presence of high-angle grain boundaries [17]. Large efforts were made to manufacture a conductor from a (partially) melted state or by growing the superconducting phase on a textured substrate. Both routes were abandoned due to technological difficulties, i.e. the temperature required for a liquid phase was above the melting point of the sheath material, and the deposition on IBAD or RABiTS templates did not produce results which could compete with Y-123. Several efforts mimicking the powder-in-tube process, which can successfully be applied to Bi-based superconductors, were carried out in the hope of realizing a suitable texture, but only modest results were obtained. In view of the toxicity of thallium, HTS research efforts based on coatings, mainly using vapor techniques, were henceforth focused on YBCO, eventually bringing about the so-called 2nd generation HTS conductors.

In our opinion it is time for a renaissance of the research on Tl-based compounds, because they may have the potential to combine the strengths of Y-123 and Bi-2212. They are crystallographically similar to the Bi-based HTS, and are known to have the tendency to establish a uniaxial texture when grown on untextured silver [18, 19]. This fact fuels our hopes that Tl-based HTS coatings can successfully be grown on a concave metal surface. They exhibit a low anisotropy, resulting in flux pinning properties akin to those of Y-123, and their high T_c values (~125 K for Tl-1223, depending on stoichiometry and doping) are certainly advantageous under operating conditions such as those of the FCC beam screen. Moreover, it is known that the Tl-compounds can be overdoped easily [20], which provides a good strategy for further increasing the inter-granular J_c [21, 22]. In the case of Tl-1223 the T_c reduction resulting from overdoping would be much less significant than it is in the Bi- and *RE*-based compounds due to the very high T_c of this material.

Since previous research efforts were unsuccessful in producing Tl-based HTS with a reasonable $J_c(B)$ dependence, we will obviously have to explore new manufacturing techniques. While in the case of Bi-2212 the local texture is achieved by growth starting from a melt, the nucleation of Tl-based HTS is also possible using almost amorphous precursors on textured or even untextured silver. Different paths are conceivable for the preparation of such precursors, which will probably involve freeze drying and/or mechanical alloying (high-energy ball milling). The freeze drying process is based on the sublimation of a solvent from a solid phase, thus avoiding the liquid phase formation. The required raw materials can easily be dissolved in a proper solvent, giving a homogeneous chemical solution. This liquid phase is then transformed to a solid phase by cryogenic freezing (using liquid nitrogen), which allows the production of nanoparticles. The solid phase is lyophilized in order to remove the solvent, and the product is reacted to produce the desired final compound.

The thus obtained highly reactive precursors can be transformed to an ink, which can be deposited on the metal substrate by various techniques [23]. An alternative route is the electrochemical deposition of the required elements directly on the substrate [24]. Both synthesis routes require a thermal treatment to produce the final HTS compound. We will start by growing thin films of Tl-1223 on (untextured) silver substrates to identify the best precursors and growth conditions for a high degree of texture by interface growth. Silver is the established choice for the substrate material, since it is chemically compatible with cuprates and allows oxygen diffusion. Other less expensive metallic substrates will also be investigated. Given the fact that a synthesis route of the Tl-compounds without the need for a controlled oxygen atmosphere or a final oxygen treatment has been demonstrated, this appears to be a realistic option [14]. Cheaper sheath materials are certainly desirable in view of cost reduction both for the production of the beam screen and for potential applications unrelated to the FCC.

Given the crystallographic similarity between Tl-1223 and Bi-2212 an additional profit may originate from this project. It is noteworthy that high-performance Bi-2212 round wires without the need for artificially imposing a strong texture on the superconductor have recently been developed [25]. Although grain boundary angles as high as 15° are common in these wires, they appear to impose no serious limitation on the macroscopic J_c, which reached a value of 2.5×10^9 A m^{-2} at 4.2 K and 20 T [26]. It is certainly worthwhile to investigate whether this is also possible with Tl-based HTS.

The most relevant quantity in view of the envisaged application is the surface impedance of the superconductor. While the theoretical predictions hereof presented in this work are certainly encouraging, we will ultimately have to test them by measuring the surface impedance of the produced samples as a function of frequency. The relatively low frequency range of interest (for this kind of measurement) puts a lower bound on required size of the sample and the cavity, thus making the measurement quite challenging. This issue is still to be addressed during the course of our undertaking, and will likely open up room for further collaborations.

4. Conclusions

In this article we presented a concept which has the potential to significantly improve the beam stability and possibly lower the required injection energy of the Future Circular Collider: beam impedance mitigation by a superconducting beam screen. Given the requirements and operating conditions, coating the inner surface of the beam screen with a HTS is the only way to obtain a surface impedance lower than that of copper in the frequency range of interest. We have to note here that using a superconducting coating raises the issue of how the supercurrents affect the dipole field which guides the beam. We assume that any perturbations stemming from the coating are sufficiently small.

Given the shortcomings of the established HTS, i.e. the high demands on substrate texture of YBCO, and the performance limiting anisotropy of BiSCCO, we believe that the thallium-based compound Tl-1223 is the best option for this task. Research on Tl-based HTS was conducted several years ago with unsatisfactory results in terms of the critical current density in applied magnetic fields, but we believe that this HTS family was abandoned prematurely. Tl-1223 has a high potential for combining good flux pinning properties (comparable to Y-123) with an undemanding nature in terms of substrate texture (similar to Bi-2212). Within a collaboration between CERN, CNR-SPIN, and TU Wien we will devote our efforts to the exploration of advanced synthesis routes for HTS based on thallium, guided by feedback from a comprehensive characterization of structural and superconducting properties. If successful, this project may be the herald of a renaissance of Tl-based HTS.

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