LOW-IMPEDANCE BEAM SCREEN DESIGN FOR FUTURE HADRON COLLIDERS*

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Abstract

In future hadron colliders with collision energies greater than the energy of the Large Hadron Collider (LHC), the beamscreen becomes an increasingly important source of beam coupling impedance. This may lead to coherent beam instabilities, especially in the transverse plane, and potentially a failure to reach the desired beam intensity. Here we discuss design choices affecting the beamscreen impedance in the proposed Future Circular Collider (FCC-hh). We consider the resistive impedance of the copper walls and their high-temperature superconductor alternative, the impedance due to the surface treatment for electron cloud suppression, and the geometric impedance of the pumping holes and the interconnects.

INTRODUCTION

The Future Circular Collider (FCC) study includes three different collider options: the hadron-hadron collider FCC-hh, the electron-positron collider FCC-ee, and the hadron-electron collider FCC-eh. Details on the design of all the proposed FCC options can be found in the conceptual design report [1]. Furthermore, the machine design of the FCC-hh is thoroughly described in the extended version of the CDR [2]. As far as the FCC-ee is concerned, the impedance issues of the vacuum chamber are discussed in [3] (in particular, impedance due to the synchrotron radiation absorbers and the NEG coating). The FCC-hh and the FCC-eh both rely on the same 100 km long hadron ring and the same beamscreen impedance design. In this paper, we focus exclusively on the FCC-hh beamscreen, with the described impedance study potentially applicable to other future hadron colliders (e.g. the proposed High Energy Large Hadron Collider - HE-LHC [4]).

In the FCC-hh, the beamscreen is the part that separates the particle beam from the magnet cold bore in the long and the short arc sections, occupying 86% of the collider circumference. The cross-section of the beamscreen is shown in Figure 1. In comparison to the LHC, in the FCC-hh the beamscreen becomes a much more significant source of impedance, overshadowing the collimators for some instabilities [2, 5]. This is due to the following necessary design choices driving the beamscreen impedance up:

- Low aperture to reduce the magnet cost
- High surface temperature (50K) to extract the heat from synchrotron radiation 200 times higher than in the LHC
- Large pumping holes for high vacuum quality
- Surface coating (or treatment) for e-cloud suppression

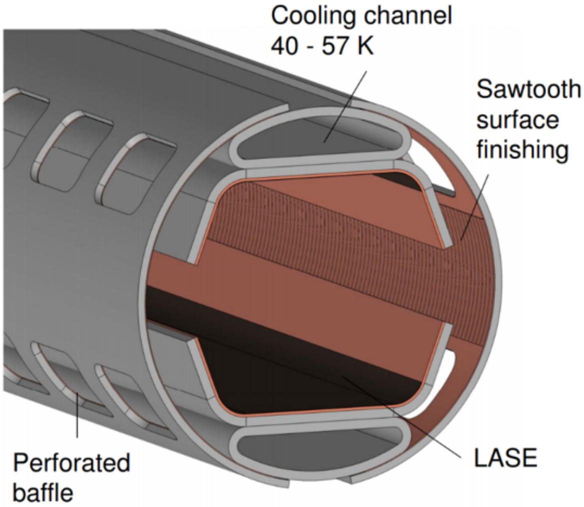

Figure 1: FCC-hh beamscreen cross-section. The copper coating is shown in brown, with the Laser Ablation Surface Engineered (LASE) part shown in black. The pumping holes are marked as the perforated baffle.

Below we summarize the studies on different sources of the impedance of the beamscreen, starting with the resistive impedance of the copper-coated walls and mentioning the alternative of the high-temperature superconductor, then the impedance e-cloud surface treatment which is studied separately, and finally the geometric impedance due to the pumping holes and the interconnects. The data presented in this paper correspond to the FCC-hh impedance database [6] which also contains the impedance information on the other elements of the collider.

RESISTIVE WALL IMPEDANCE

The walls of the beamscreen are made of stainless steel (grade P506, resistivity 6×10^{-7} Ωm), with the sides facing the beam co-laminated with a 300 μm thick layer of copper. To slow down the coupled-bunch instability, this copper layer has to be much thicker than that of the LHC beamscreen (due to the longer skin depth at the lower collider revolution frequency). The copper layer is assumed to have the Residual Resistance Ratio (RRR) of 70, similar to the LHC beamscreen (see [7], p.185). The temperature of the beamscreen walls is set to 50 K, resulting in the copper resistivity of 7.5×10^{-10} Ωm in the absence of an external magnetic field.

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The resistivity increases with the dipole magnetic field according to Kohler's rule [8], becoming 7.9×10^{-10} Ωm at injection and 1.4×10^{-9} Ωm at the top energy. The impedance of the two-layer walls is calculated with the Impedance-Wake2D code [9] for a circular pipe with a radius of 12.22 mm - the vertical aperture of the beamscreen. Then, form factors are applied to account for the non-circular cross-section: $F_x = 0.45$, $F_y = 0.83$, $F_z = 0.82$, as estimated with the wakefield solver of CST [10]. Finally, the dipolar impedances are weighted with the average β-functions in the arc FODO cell. The resulting transverse impedance in the vertical plane is shown in Figure 2 as the most critical one, with impedance in the other planes available in [6].

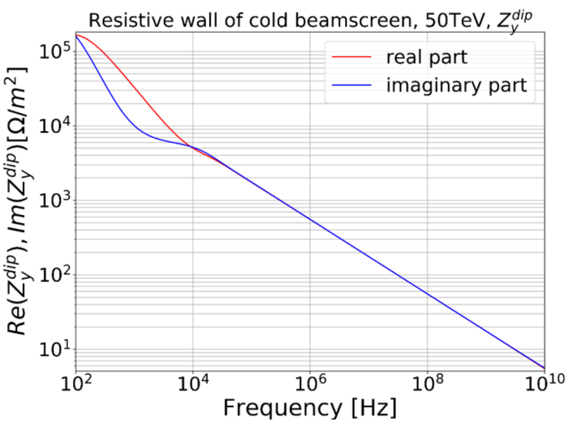

Figure 2: The *per unit length* resistive wall impedance of the beamscreen. The data shows the transverse dipolar impedance in the vertical plane at the collision energy (50 TeV).

It is also important to mention a potential problem of the current design. The copper coating is absent on some walls that do not face the beam but nevertheless affect the impedance due to the non-zero surface electromagnetic fields. In particular, at the edges of the slit a small area of uncoated stainless steel is exposed, which affects the dipolar impedance in the horizontal plane. A number of solutions to this issue exist, including re-shaping the edge or applying a thin copper coating. See [11] for more details.

While the copper coating of the walls is the baseline solution, an exciting new alternative is being investigated. The interior of the beam screen can instead be coated with a High-Temperature Superconductor (HTS) such as REBCO or Tl-1223 [12,13]. The first measurements of the surface resistance in a dielectric resonator are very promising (Fig. 3). The measured surface resistance for the REBCO tapes with artificial pinning centers is lower than the predicted value and might be even lower for further custom-tailored tapes.

SURFACE TREATMENT FOR E-CLOUD SUPPRESSION

There are two proposed solutions for the e-cloud surface treatment. The solution currently assumed in the impedance

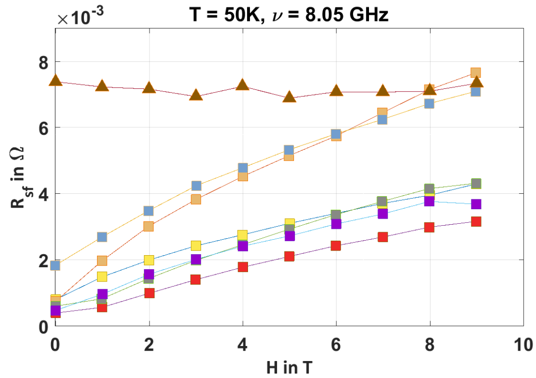

Figure 3: Measured surface resistance of REBCO Coated Conductors (squares) compared to copper (triangles) as a function of applied magnetic field. The lower four curves (red, purple, yellow, green) are measured for materials having artificial pinning centers.

model is to coat the inner surface of the beamscreen with a layer of amorphous carbon. The coating prevents an electron cloud build-up by reducing the secondary emission yield (SEY) of the surface. The thickness and the resistivity of the coating are assumed to be 200 nm, and 10^{-4} Ωm, respectively. The increase of the longitudinal impedance is proportional to the frequency, and the increase of the transverse impedance is a constant of frequency. In the frequency range of interest, the coating impedance is purely imaginary and gives a moderate (around 30%) increase in the dipolar broadband impedance of the beamscreen [2].

Alternatively, laser treatment of the beamscreen surface can be used. A laser beam causes μm-level roughning of the surface which reduces the SEY [14, 15]. A potential problem with this method is that a rough surface could lead to a significant increase in the beamscreen impedance at the frequencies of single bunch instabilities (on the order of 1 GHz) [16]. The technique is continuously evolving in order to achieve the best SEY reduction and at the same time avoid the impedance increase. Some latest results show no impedance increase at room temperature and at a frequency of 3.9 GHz [17]. Nevertheless, more measurements are needed to estimate the impedance increase in realistic conditions (the temperature of 50 K and a strong external magnetic field) [18].

PUMPING HOLES AND INTERCONNECTS

Pumping holes connect the space inside the beamscreen to the outer region from where the air is pumped out (labeled as "perforated baffle" in Figure 1). The novel design of the FCC-hh beamscreen significantly reduces the impedance of the pumping holes by shielding them away from the beam, so that the holes are only connected to the beam region through a narrow slit.

The complexity of the beamscreen geometry does not allow to apply analytical methods to estimate the impedance of the holes. In order to estimate the broadband dipolar impedance of the holes, numerical simulations were carried out accounting for traveling waves synchronous with the beam [19], and the results are shown in Figure 4. They agree with Wakefield solver of CST when the impedance is high enough to be measured with the wakefiled solver (artificially increased slit to worsen the shielding). Both the value obtained for the actual shielding and the extrapolation of the curve for the increased slit size show that all 10.5 million holes amount to less than 0.1 MΩ/m of broadband dipolar impedance in the horizontal plane. Estimation of the real part of the longitudinal impedance is on-going to prevent excessive heat loss in the cold bore.

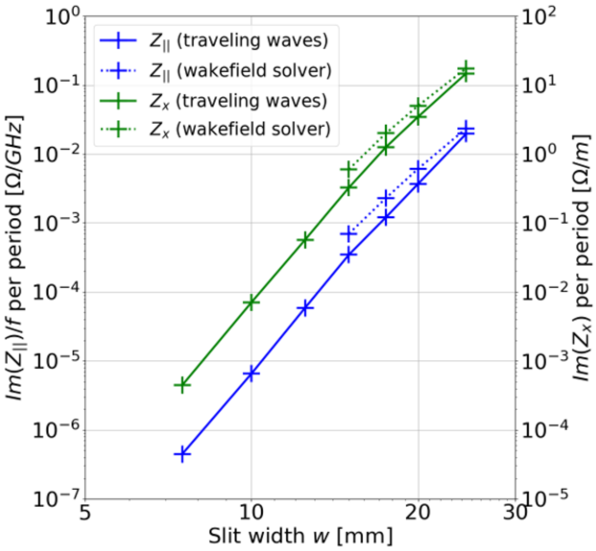

Figure 4: Imaginary part of the longitudinal (blue) and horizontal dipolar (green) impedance per one period of pumping holes as a function of the slit width. Comparison between the traveling wave method (solid lines) and the CST-wakefied solver (dashed lines).

Another source of the geometric impedance of the beamscreen is the interconnects placed between the cryo-modules. Each interconnect has tapers that transform the complex beamscreen shape to a circle on both sides such that the two sides can be connected with RF fingers. Unlike in the LHC, such transformation involves an abrupt change in the cross-section, although only behind the shielding. Additionally, the upstream taper is made of the taper-down and the taper-up parts to form a barrier that prevents the intense synchrotron radiation from hitting the RF fingers. The low-frequency broadband impedances of the tapers are simulated with the CST Wakefield solver [10]. The resulting total broadband imaginary impedances are $\mathrm{Im}\,(Z_x)^{\mathrm{inter}}_{\mathrm{total}} = 1.5\times10^6\ \Omega/m$ and $\mathrm{Im}\,(Z_y)^{\mathrm{inter}}_{\mathrm{total}} = 1.9\times10^6\ \Omega/m$ which constitutes a significant part of the allowed broadband impedance at injection [20].

CONCLUSIONS

We have summarized the most important impedance aspects in the FCC-hh beamscreen, and the design choices related to these aspects. Despite the beamscreen impedance being much more critical than in the case of the LHC, the beamscreen fits in the allowed impedance budget of the machine. With the current baseline solutions, no insurmountable problems have been identified. Nevertheless, an investigation of the non-traditional design solutions (HTS coating, LASE surface treatment) is on-going and can pave the way to an even better design in the future.

ACKNOWLEDGEMENTS

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