Potential Remedies for the High Synchrotron-Radiation-Induced Heat Load for Future Highest-Energy-Proton Circular Colliders

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We propose a new method for handling the high synchrotron radiation (SR) induced heat load of future circular hadron colliders (like FCC-hh). FCC-hh are dominated by the production of SR, which causes a significant heat load on the accelerator walls. Removal of such a heat load in the cold part of the machine, as done in the Large Hadron Collider, will require more than 100 MW of electrical power and a major cooling system. We studied a totally different approach, identifying an accelerator beam screen whose illuminated surface is able to forward reflect most of the photons impinging onto it. Such a reflecting beam screen will transport a significant part of this heat load outside the cold dipoles. Then, in room temperature sections, it could be more efficiently dissipated. Here we will analyze the proposed solution and address its full compatibility with all other aspects an accelerator beam screen must fulfill to keep under control beam instabilities as caused by electron cloud formation, impedance, dynamic vacuum issues, etc. If experimentally fully validated, a highly reflecting beam screen surface will provide a viable and solid solution to be eligible as a baseline design in FCC-hh projects to come, rendering them more cost effective and sustainable.

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The discovery of a Higgs boson at two Large Hadron Collider (LHC) experiments in 2012 has completed the standard model of particle physics, concluding almost 80 years of theoretical and experimental efforts [1,2]. The standard model is not a full theory, since there are several outstanding questions, which are left over and imply new physics. Many of them can be addressed through high-energy and/or high-intensity accelerators. With our present understanding, the energy scale of the new physics is unknown [3]. The next 20–30 years will see the full exploitation of the Large Hadron Collider and its high luminosity upgrade (HL-LHC). Those next years will also be the right time to produce a significant effort to study and plan a post LHC collider, since past experience shows that a reasonable preparatory time for such an ambitious machine cannot be less than 20–25 years. CERN has launched the Future Circular Collider (FCC) study to deliver a conceptual design report focusing on a 100 TeV center of mass (c.m.) proton-proton collider (FCC-hh), based on 16 T Nb_3Sn magnets in a new 100 km tunnel, with a peak luminosity of $5 - 20 \times 10^{34}$ $cm^{-2}\,s^{-1}$, as shown in Table 1 [4]. Other studies for similar machines are also ongoing at the Institute of High Energy Physics (IHEP) in China [5]. Power consumption of large accelerator projects at the energy frontier has become a major issue in their technical feasibility, economic affordability and social acceptance. Power savings are, therefore, essential aspects of the study of such machines from the conceptual design phase. This Letter presents the scientific bases of one of the viable solutions aiming at this specific goal.

As seen in the Table 1, FCC-hh is synchrotron radiation (SR) dominated [8], and the limit which such machines can operate is primarily due to their high power consumption. The energy budget for efficient cooling of the SR heat load plays a dominant role. This is even more relevant when the use of superconducting dipole magnets force the dipole walls to be at 1.9 K.

The power consumption required to dissipate a given heat load strongly depends on the absorbing system temperature, since cooling efficiency strongly decreases with operating temperature. For instance, dissipating 1 W

TABLE I. Baseline parameters of FCC-hh compared with LHC and HL-LHC [4,6,7] (Values for the 83 km FCC-hh in brackets).

	LHC/HL-LHC	FCC-hh
Center of mass [TeV]	14	100
Circumference [km]	26.7	100(83)
Dipole field [T]	8.33	16(20)
Injection energy [TeV]	0.45	3.3
Peak lum. [10^{34} $cm^{-2}\,s^{-1}$]	1.0/5.0	5.0
Stored beam energy [GJ]	0.392/0.694	8.4(7.0)
SR power per Ring [MW]	0.0036/0.0073	2.4 (2.9)
Arc SR HL [W/m/aperture]	0.17/0.33	28.4(44.3)
Critical photon energy [keV]	0.044	4.3(5.5)

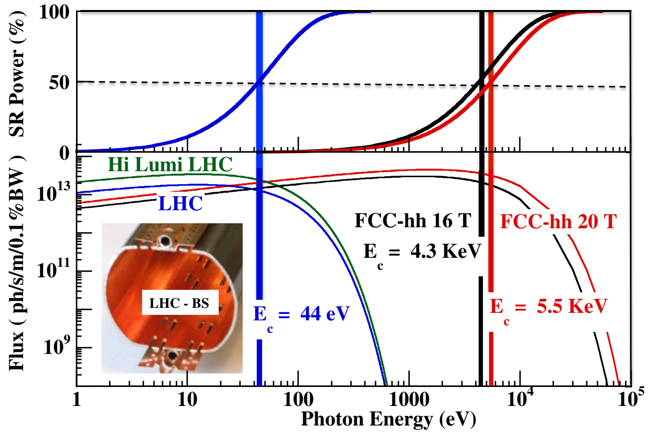

FIG. 1 (color online). Calculated SR properties and critical energies (E_c) for nominal parameters of: LHC, HL-LHC, FCC-hh with 16 and 20 T dipole magnets. Top panel: percentage of SR power carried by all photons at lower energies than a given photon energy ($h\nu$); Bottom panel: Calculated SR Flux. Inset: picture of LHC-BS.

on a 4.2 K surface may cost more than 1 kW at the plug. For the LHC case, it would be impossible to dissipate the predicted SR heat load at the cold bore held at 1.9 K, and for this and other reasons, it was necessary to build a separate cooling system acting on a so called beam screen (BS), held at temperatures between 5 and 20 K. This BS, shown in the inset of Fig. 1, intercepts and dissipates such heat load in an affordable way. The BS is a very complex technological component which has been designed with a number of different functionalities that should all be simultaneously fulfilled to allow operational conditions [9]. The strategy adopted for the LHC, which has been proven to be successful and solid, was to reduce, as much as possible, the reflectivity of such a beam screen in order to absorb the photons where they first reach the wall. For this reason, it was proposed to groove a saw tooth structure on the SR illuminated BS surface, so that SR will impinge at near-normal incidence, efficiently reducing forward reflectivity and photoelectron production from top and bottom BS surfaces [10–13]. The issues that should be simultaneously tackled and solved in order to produce a BS compliant to expectations are many [9]. Among them, the reduction of beam-induced cryogenic loads or the full control of collective effects, like electron cloud formation [10], require a complete knowledge of all BS material properties like ac conductivity and surface properties like temperature dependent adsorption or desorption, reflectivity, photoelectron yield (PY), and secondary electron yield (SEY). SEY and PY measure the number of electrons produced per incident electron or photon, respectively. Those items have been studied in great detail [10,13–16] in order to reach the extraordinary performance obtained at the LHC by the installed BS. The nature and power of the SR heat load in FCC-hh is so extreme, that a simple cost estimate to remove the foreseen 28.4 (44.3) W/m/aperture, at the cold bore temperature of 1.9 K, gives unthinkable corresponding total electrical power for the refrigerators of 4–6 GW. As for the LHC case, beam screens are, indeed, mandatory solutions to stop SR power at higher temperatures, thus, reducing the electrical power consumption. An opportunely modified LHC-type beam screen, which absorbs all the SR produced heat load in the cryogenic part of the machine, is a solid and convincing base line design for any higher energy future circular hadron collider. While optimization of the corresponding BS temperature, cooling systems, and geometry are underway, BS and thermal shield cooling remain the largest refrigeration load for the machine. Preliminary estimates seem to indicate that FCC-hh will require more than 100 MW of electrical power (which is about 20% of the total power foreseen for FCC-hh) to absorb all SR heat load where it first reaches the specially designed BS [7]. Therefore, it is assumed that FCC-hh beam current will be limited by the cryogenics cooling power available for the cold arcs [4,7]. The specific FCC-hh geometry and the SR photon energy distribution suggest a completely different approach than the one adopted at the LHC. The SR angle of incidence will depend on the actual BS radius and geometry, but can be calculated to be as small as $\Theta \sim 0.62$ mrad (0.035°). SR light will hit the BS at more than 20 m from the particle beam source, and beam parameters imply that most of the power will be concentrated in a photon fan strip of less than 2 mm in height.

Figure 1 shows the photon flux and power emitted by LHC (at nominal parameters and in its HL version) and by the corresponding FCC-hh with dipole fields of 16 and 20 T, respectively. Figure 1 also shows the different values of the critical Energy (E_c) in the studied cases. E_c, is the photon energy at which the SR power spectrum is divided into two equal parts, and depends on the mass, the energy, and the radius of curvature of the circulating particles. E_c is a very significant parameter in this context. So, in contrast to the LHC and its HL upgrade cases, where a power of 0.17 (0.33) W/m/aperture is mainly delivered by less than few hundred eV photons, for the FCC-hh case, most of the power density is brought by photons with much higher energies, in the x-ray range. In this Letter, we suggest exploiting the geometry as well as the photon spectrum typical of FCC-hh and to realize a surface coating able to forward reflect most of the x-ray photons and, with them, most of the related heat load. Once most of the heat load is forward reflected away from the cold parts, one can insert, in the machine, a series of room temperature SR absorbers where this heat load can be more easily and cheaply dissipated. Those room temperature (RT) absorbers and their actual distribution along the machine should be carefully optimized in order to minimize their perturbing effects on the lattice design. Assuming one RT SR absorber every 600 m of cold dipoles and a BS power reflectivity of about 95%, it is possible to estimate that the power required to dissipate the SR heat load will be less than 40 MW. This savings can be increased if higher reflectivity BS can be produced and/or more frequent RT absorbers can be distributed along the machine. To this goal, x-ray reflectivity (R) has been calculated for relevant material surfaces and surface finish using RAY [17] a ray tracing software developed by one of us, which is in use for beam line design study within the synchrotron radiation community. X-ray reflectivity depends on a limited number of parameters, which are photon energy and light polarization, angle of incidence, material, and surface roughness. We will analyze them in detail in the following. Figure 1 shows, in the top part, the calculated power percentage transported below a certain photon energy (hν) in the case of interest. For the FCC-hh under analysis, the SR induced heat load is mostly carried by x-ray photons, while the power carried by low energy photons is, indeed, marginal. From Fig. 1, it is clear that photons of energy lower than 500 eV bring only about 4% of the entire emitted power. This suggests that a performing beam screen should have optimized reflectivity in the x-ray photon energy range, and one can tolerate a less optimized reflectivity for the low energy photons. This brings us to the notion that preferably low Z materials must be chosen, to avoid atomic absorption edges in the x-ray energy range. The exact angle of incidence of SR light onto the BS wall, will obviously depend on the detailed structure of the lattice, dipole magnet (DM) and interconnects (IC) length, the actual BS shape, the dipole bending radius, and the angle between subsequent DMs. Here, it is not so important to exactly calculate such values but to estimate their order of magnitude. Assuming FCC-hh preliminary parameters [6] and a BS radius of 13 mm, the SR emitted at the entrance of a dipole magnet will hit the walls of a long straight section, following it, at ~20 m and with an incidence angle of 0.62 mrad (0.035°). In the case of two subsequent DMs, the incidence angle will be the one previously calculated plus the angle between two (or more) dipoles. The angle between two subsequent 15 m long DMs + IC can be estimated to be around 1.35 mrad. The angle of incidence at which the SR light will impinge on the BS wall, depending on the actual geometry and point source position, will be either 0.62, 1.97, or 3.32 mrad. The R calculations do not significantly differ in this range and will be done in the following for 0.62 mrad. As already mentioned, materials showing optimized reflectivity for x rays must have the minimum number of atomic adsorption edges in that energy interval. Figure 2 shows our calculations done on various BS surface materials at realistic angles of incidence and roughness (R_a).

The materials used to calculate the reflectivity are all potential candidates to be the final surface of the BS. Cu and TiZrV are the final coatings used in LHC, while Nb_3Sn and MgB_2 are part of a superconductor coatings family which could be used in FCC-hh to reduce detrimental impedance effects. It can be clearly observed that, even at

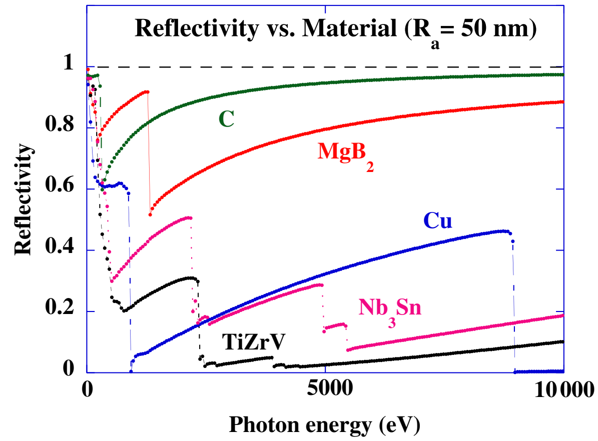

FIG. 2 (color online). Reflectivity calculation at 0.62 mrad angle of incidence and $R_a = 50$ nm for different materials in the photon energy range of interest [17].

those very grazing angles, the reflectivity is very poor in the x-ray energy range due to the presence of high Z material adsorption edges with the noticeable and extraordinary exception of carbon. Because of the absence, above its C 1s edge at around 280 eV, of deeper absorption edges, the reflectivity of C is extremely high even for the roughness used in the calculation reported in Fig. 2. The poorer reflectivity observed close to the C 1s absorption edge is in a region were photons do not carry a significant amount of SR power and can, therefore, be tolerated for the FCC-hh cases under study. Carbon, in different forms, is one of the most studied materials and has already attracted a large interest for its potential applications also in high energy particle accelerator contexts [10,15,16,18]. A very important parameter in the calculations is the surface roughness (R_a), which is the parameter that quantifies the deviations in the direction of the normal vector of a real surface from its ideal, perfectly smooth, form. This is particularly important for technical surfaces, where the surface finish is far from being perfectly flat. For the case of the LHC, all the straight sections and Cu coated beam screens have been requested to have a surface roughness $R_a < 0.2$ μm, while the measured values were in the range of $0.04 < R_a < 0.1$ μm without any extra care during the production processes. There are indications that well established industrial procedures can produce surfaces with R_a as low as 20 nm over the large scale production of interest here. If this is the case, as can be seen in Fig. 3, the coating reflectivity is extremely high and will allow a net reduction of the heat load to be absorbed within the cold part of the machine. One needs to carefully address if introducing such roughness in optical calculations as a Debye-Waller term is still a valid assumption at such extreme grazing angle of incidence or is overestimating its effect in reducing R. This issue needs a careful analysis and requires a detailed experimental verification. Preliminary experiments show that experimental validation is, indeed, achievable using

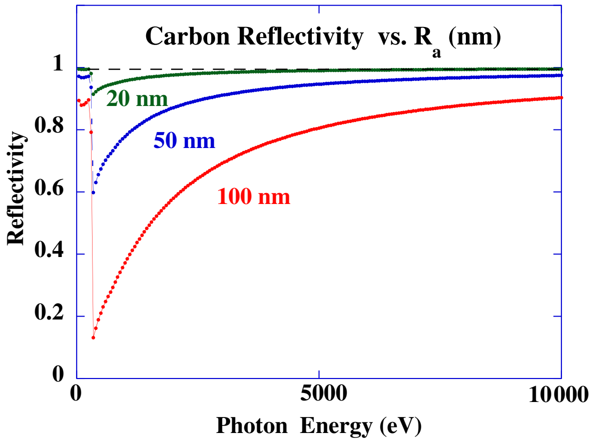

FIG. 3 (color online). Reflectivity calculation at 0.62 mrad angle of incidence for carbon versus achievable R_a in the photon energy range of interest [17].

existing techniques [10,19–21], and an *ad hoc* set up has to be realized to study the very low angle of incidence regime of interest here.

It can be extremely advantageous to be able to avoid photons hitting the top and bottom of the BS in dipoles, since this will reduce the number of photoelectrons interacting and affecting the circulating beam [10]. This reduction was achieved in LHC design by minimizing, with the saw-tooth structure, the total number of forward reflected photons [10,12,13]. Apparently, then, a high reflectivity of BS will allow the reflected beam to diverge and illuminate, nearly homogeneously, the BS, with detrimental effects on control of beam instabilities in the DM. This effect could be controlled and beaten just by a careful choice of the geometrical shape of the BS reflecting surface. Not only, as designed, will the beam screen reflect most of the SR power, but, due to its intrinsic cylindrical mirrorlike curvature, it can be used to focus the beam in such a convenient way as to confine most of the reflected photons in the orbit plane. A proof-of-principle calculation has been performed using RAY [17] and is shown in Fig. 4. This simulation assumes a monochromatic x-ray photon flux of energy Ec ($h\nu = 4.5$ keV), emitted by a source of 10×10 μm and 1 mm long, with an arbitrary horizontal photon beam divergence and a vertical one of $\sigma_c = 1/\gamma = 18.7$ μrad. The radius of the cylindrical BS is assumed to be 13 mm. The described geometry is shown in Fig. 4, where the top and side artistic views of the BS are shown together with the photon footprint at various distances from the single point source. The present calculations do not consider the angle between different DMs and will slightly change when the detailed machine geometry will be considered, but this calculation shows that one can even optimize the BS curvature to exploit its high reflectivity to confine photons (and photoelectrons) in the horizontal plane of the accelerator, reducing most of the instabilities induced by collective effects. Since reflected

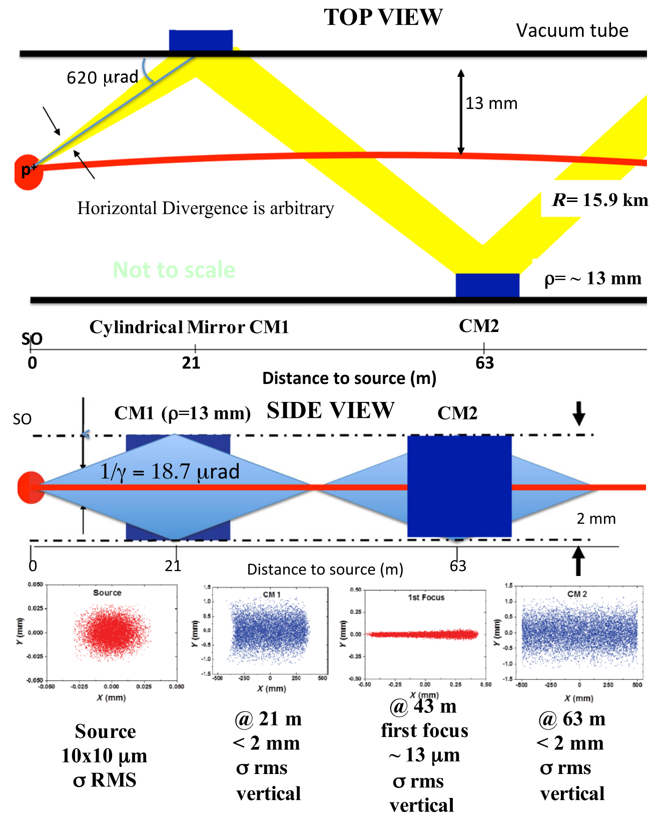

FIG. 4 (color online). Top (top panel) and side (bottom panel) view of the geometry for Ray tracing inside a cylindrical BS. The bottom panel also shows the calculated photon footprint. Distances not to scale.

photons will not induce photoemission, photoelectrons will not only be horizontally confined, but also mainly produced at photon absorbers. There, a positively biased electrode could easily remove them from the beam pipe. On the other hand, a carbon overlayer, although with extraordinarily good reflectivity performance, has a very poor conductivity, much lower than Cu, and hence, has an unacceptable high resistive wall impedance and, at first glance, it can not be used. Also, in this case, the extreme grazing angle of incidence comes as a substantial help: the required thickness to attenuate to $1/e$ the impinging photon flux at the grazing angle is, in the energy range of our interest, as thin as $\sim$3.5 nm; hence, a total thickness of $\sim$20 nm of carbon will be enough to reflect all the photons and will be thin enough to be irrelevant to the impedance budget. Resistive wall effects in FCC-hh are expected to act on 300 μm [6] so as to render a 20 nm coating irrelevant to this issue. In addition, carbon is known to have low SEY and PY [10,15,16,18] and to be a significantly stable and nonreactive coating.

In conclusion, we present, here, a sound theoretical analysis of a new paradigm to control and reduce the impact of SR induced heat load in future proton circular colliders at the energy frontier, improving their sustainability and, possibly, also their final performance. While it is clear that the proposed solution will require a complete experimental validation campaign, the preliminary results here presented seem to indicate that a novel approach to SR induced heat load dissipation in cold elements is, indeed, a viable research line which should be further addressed to the general and fundamental goal of improving efficiency of power consumption and optimizing energy management in future accelerator operation.

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