

# SYNCHROTRON RADIATION ISSUES IN THE VLHC\*

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## Abstract

Fermilab and other DOE high energy physics laboratories are studying the possibility of a Very Large Hadron Collider (VLHC) for operation in the post-LHC era. The current VLHC design [1] foresees a 2-staged approach, where the second stage (referred to as VLHC-2) has a proton energy up to 100 TeV at a peak luminosity of  $2 \cdot 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ . The protons are guided through a large 233 km circumference ring with 10 T bending magnets using Nb<sub>3</sub>Sn superconductor at 5 K. The synchrotron radiation (SR) power emitted by the beam in such a machine is  $\sim 5 \text{ W/m/beam}$  [1]. However, other VLHC scenarios (e.g. [2]) with smaller rings and higher luminosity result in SR power levels exceeding this value, reaching 10 or even 20 W/m/beam. Intercepting and removing this power in a cryogenic environment is a major challenge. In this paper a discussion of SR in the VLHC-2, and various approaches to the issue, are presented. One possibility is the use of a beam screen (BS) to intercept the synchrotron radiation power. The BS operating temperature is chosen to balance thermodynamic efficiency, cryogenic-, vacuum-, beam-stability- and magnet-aperture issues. Another approach is to intercept the radiation in discrete points between the magnets with photon-stops (PS). The PS-s, having to intercept much higher power densities, are challenging components from engineering, vacuum, and beam-stability viewpoints.

## 1 INTRODUCTION

Fig. 1 gives an overview of the level of SR power in existing and future machines. The currently proposed VLHC-2 would be the first cryogenic collider to operate in a SR dominated regime (above line in Fig. 1). This means rapid damping of the beam emittance (2.5 hrs in the VLHC-2) and efficient cleaning of the beam-tube surface via photo-induced desorption, resulting in fast conditioning of the machine (45 hrs in the VLHC-2 with a

initial conditioning beam current of 30 mA). Vacuum calculations were performed in the context of the recent VLHC study, indicating that excellent vacuum conditions can easily be achieved [3]. On the other hand the SR power has to be extracted from a cryogenic environment, which demands large compressor power (30 MW in the VLHC-2). This and other problems appearing in SR dominated hadron colliders have been pointed out before [4]. The following discusses different solutions to the SR problem, as proposed for the VLHC-2. In addition, the attempt is made to present the solutions in the general context of any future energy frontier hadron collider. The extensive work that was performed for the SSC and LHC vacuum systems will, in many cases, serve as benchmark.

## 2 A BEAM SCREEN FOR VLHC-2

The VLHC-2 beam-screen (BS) design presented here was developed along the lines of the LHC BS [5], scaled to the SR heat load and the magnet aperture of the VLHC-2 (40 mm). At the heart of the LHC vacuum system is the cooled, perforated liner, or BS, which allows to extract the beam induced heat-load at a temperature different from that of the magnet and pumps out the gas desorbed from the beam tube walls by SR and shields it from re-desorption. The gas-load is cryopumped to the cold magnet bore (CB). The liner concept is currently the best-known technical solution to the thermal and vacuum problems caused by SR in cryogenic colliders.

The cooling of the BS is the leading contributor to the cryo-budget in the VLHC-2. The required BS refrigeration power varies strongly with the BS temperature. The optimum BS temperature balances between the heat load absorbed by the BS refrigeration system and the heat load absorbed by the cold-mass. At low BS temperature, the heat load is mostly extracted by the BS, at low thermodynamic efficiency and thus at high cost. For a high BS temperature, the cost of BS cooling is reduced, but a large part of the heat load is transferred from the BS by conduction and radiation to the 5 K cold-mass, where it is extracted with low efficiency. Fig. 2 shows the calculation results for the power transferred via radiation/conduction from the BS to the CB as a function of BS temperature. The radiation power was calculated, using the emissivity for concentric steel tubes with the geometrical parameters of the VLHC-2 BS system (BS outer diameter 32.5 mm, CB inner diameter 34 mm). The conductance used in the conduction power calculations

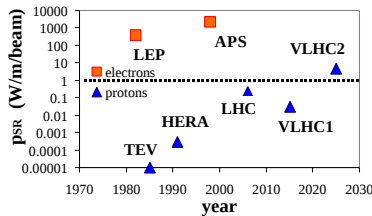


Figure 1: SR power in current and future(?) colliders.

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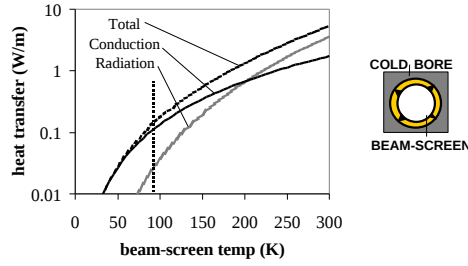


Figure 2: Heat Transfer from beam-screen to cold-bore.

was measured on LHC BS prototypes [6] with thin brass/stainless steel support rings spaced by 0.5 m. The conductive component dominates up to 200 K. Fig. 3 shows how the optimum liner temperature evolves with the SR load. The optimum BS temperature is found by minimizing the total plug power required for extraction of the SR load from the magnet and BS systems at the respective Carnot efficiency, taking into account the heat transfer from the BS to the CB (Fig. 2). The optimum BS temperature in the VLHC-2 was calculated to be 86 K [7] (line in Fig. 3), resulting in a total plug power of 15 MW per beam for the complete VLHC-2. The second curve in Fig. 3 shows the coolant cross-section area in the magnet bore required to extract the given heat load at the optimum temperature. In the LHC BS cooling system the pressurized He-gas (3 bar, 5-20 K) takes 10 mm<sup>2</sup> of cross-sectional area. As the SR increases beyond the LHC level, the optimum BS temperature rises fast, as does the required mass-flow of coolant. To compensate for the loss of density at higher coolant temperatures the pressure in the cooling system was increased to 20 bar for the VLHC-2. All solutions shown in Fig. 3 feature a reasonable pressure drop (~1 bar) and temperature difference (~20 K) between inlet and outlet over half the arc cell length (135 m). The VLHC-2 case with 5 W/m/beam requires a coolant cross-section area of 80 mm<sup>2</sup> (9 % of the area enclosed by the cold bore). Fig. 4 shows a sketch of the proposed VLHC-2 BS. It is designed for 6 W/m to include other beam-induced heat-loads such as image current heating and multipacting. Fig. 5 shows the total power cost vs. SR power for such a system, as compared to the total cost for a system operating at room temperature. The comparison indicates that the room-temperature BS is the more economical solution in the SR range beyond the VLHC-2. However, it has to be pointed out, that the room-temperature BS has a drawback: it requires a 80K thermal shield to protect the cold mass from the 3.7 W/m of thermal radiation and conduction emanating from the

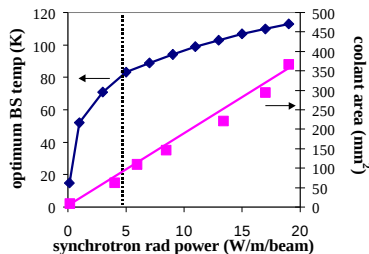


Figure 3: Opt. BS temp. and cooling channel size vs. SR.

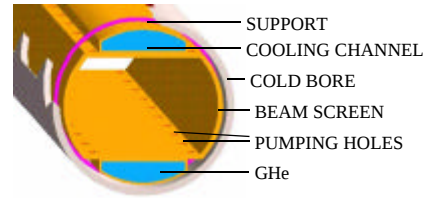


Figure 4: The proposed VLHC-2 beam-screen assembly.

room temperature BS. The shield and cooling tubes, the additional gaps for supports and the BS cooling system require more space than available in a 40 mm aperture magnet. The cost of increasing the magnet bore certainly prevails over any possible gain in cryo-operation cost up to a SR heat load exceeding the range investigated here. An additional complication related to the room-temperature BS is the interference with the cryopump function and its large resistive wall impedance. Fig. 5 shows as well that the most economical solution is the room temperature photon-stop (PS), which will be discussed in part 3.

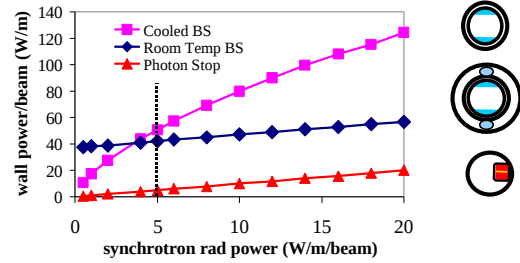


Figure 5: Wall power density vs. SR load for different solutions(cold BS, warm BS/shield and PS).

Therefore, resuming the discussion above, we propose a BS operating at ~100 K for the VLHC-2 (Fig. 4). Its design is similar to that of the LHC liner, except for the larger cooling channels and the scaling to the smaller aperture of the VLHC-2 magnets. The vertical/horizontal BS aperture is 20 / 30 mm. The required pumping hole fraction is 1.5%, which translates to a pumping speed of 60 lit/sec/m. The resistive wall impedance of a 233 km long liner at 100 K is large. The e-folding time of the resistive wall instability is of the order of 4 turns (200  $\mu$ m Cu coating). However, an analysis of beam-stability in the VLHC-2 indicates that it can be controlled with a straight forward feed-back system [8]. The image current heating in the Cu layer is of the order of 10 mW/m. The quench-forces are 2x1 ton/m for a 200  $\mu$ m thick Cu coating.

### 3 A PHOTON-STOP FOR VLHC-2

Fig. 6 shows that in the VLHC-2 it appears entirely feasible to place a room-temperature “finger”, or photon-stop (PS), between magnets, that will intercept all of the SR from the second magnet up-stream. The insert in Fig. 6 illustrates the concept, showing how the radiation emitted by the first magnet passes the first PS and hits the second PS just before it would hit the beam tube. In the

VLHC-2, with its large arc bending radius, this occurs if the magnet length is  $<14$  m. A PS system would reduce the SR related refrigeration power cost by 95% (see Fig. 5). PS-s are commonly used in SR light sources [9].

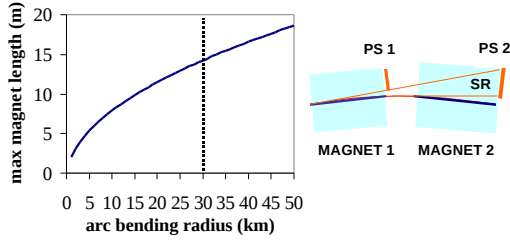


Figure 6: Maximum magnet size versus arc-radius.

Fig. 7 shows an engineering design of the PS [10]. The PS enters the BS from the side, where it is hit by the SR. At its core is a coaxial arrangement of tubes for the cooling water ending in the absorber. The outer cooling tube and the absorber are machined out of bulk GLIDCOP™. The absorber shape is a prism, 3.5 cm long, 1 cm wide and 1 cm deep. The surface required to extract the  $\sim 70$  W of SR power emitted in one  $\sim 14$  m long magnet is  $>1$  cm<sup>2</sup>. Fully deployed, the PS reaches 1 cm into the beam tube, which brings it within  $\sim 5$  mm of the beam. To reduce the reflectivity, the absorber piece is hollow, trapping the photons, entering through a  $\sim 1$  mm wide slot. During operation the nose piece attains  $\sim 360$  K, the cooling water flux is 0.2 lit/sec. Heaters, wrapped around the core, prevent freezing of the coolant when the SR stops. To adapt to imperfections of the beam orbit as well as to avoid aperture restrictions during e.g. injection, the PS-s have to be retractable.

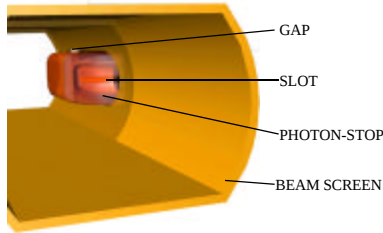


Figure 7: Sketch of the proposed VLHC-2 photon-stop.

Wake-function calculations using MAFIA® and analytical models, indicate a total longitudinal impedance  $Z_{||}/n$  for all 14500 PS around the VLHC of  $\sim 25$  m $\Omega$  and a total transverse impedance  $Z_{\perp}$  of  $\sim 8$  M $\Omega$ /m [11]. To keep the impedance small, the azimuthal extension of the absorber has to be kept minimal (here 1 cm) and the edges rounded (the impedance of step and elliptical shape differ by a factor 2). A more longitudinally extended PS (here 3.5 cm) would reduce the impedance, but is not recommended because of the increased thermal radiation from the warm PS to the cold environment. In terms of  $Z_{\perp}$  the PS are comparable to (shielded) bellows. The total VLHC-2  $Z_{\perp}$  budget, including the PS, is  $\sim 50$  M $\Omega$ /m, setting the TMCI threshold at injection to  $2 \cdot 10^{11}$ , which is safely above the VLHC-2 bunch population of  $7.5 \cdot 10^9$ .

The damping length for the TM-01 mode is 4 cm, much less than the distance between two PS, so coupling between the PS is not a concern. An issue, that deserves close attention are trapped modes. The gap in the beam-tube surrounding the absorber will act as a cavity and should thus be as small as possible. To increase the resonance frequency to well above the bunch-length frequency (bunch length at collision is  $\sim 3$  cm) the open volume behind the gap was minimized. MAFIA® calculations indicate that for a 1 cm depth of the gap-cavity,  $Z_{\perp}$  is not noticeably increased from the level indicated above and resonance can be avoided.

## 5 CONCLUSIONS

There were concerns in the past that SR could be a limitation for high energy hadron colliders. The analysis of the SR in the VLHC-2 has revealed that good solutions exist for the SR power load in the VLHC and beyond. These are - a cooled beam-screen, operating at a temperature optimized with respect to cost-issues and - a new, promising approach, consisting of a room-temperature photon-stop to extract the SR heat load at minimal cost. An R&D agenda is now being pursued to put such a device to test. For the VLHC-2 we believe that a combination of both systems is the most optimal, with the beam-screen retaining the photo-desorption pumping function and the photon-stop absorbing the SR power. In such a scheme the beam-screen cooling would operate at a lower temperature and He-flow as the photon-stop takes over the SR heat load. In addition operation of both systems at full capacity would allow the beam-current in the VLHC to be raised above nominal.

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