

SYNCHROTRON RADIATION ABSORBERS FOR HADRON COLLIDERS

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Abstract

We present the results of a design study of synchrotron radiation absorbers, or photon stops, conducted in the context of a recent study of a Very Large Hadron Collider (VLHC), [1]. Photon stops protrude into the beam tube at the end of each bending magnet to absorb the synchrotron radiation emitted by the beams. They operate at room temperature and thus with minimal cooling power. Major issues regarding photon stops, namely those related to ring-size and magnet aperture, the engineering design, photo-desorption and vacuum, electron-emission, X-ray fluorescence and beam effects will be discussed. Simulations were performed on the basis of the VLHC in its second, high-field-magnet stage design, denoted as VLHC-2 in the following. We show that photon stops are a promising solution for the synchrotron radiation problem of future hadron colliders.

1 WHY PHOTON STOPS?

Future generations of energy frontier hadron colliders will accelerate proton beams to the 20-100 TeV energy range, most likely using high field, superconducting magnets in the arcs. The beams will produce several W/m of synchrotron radiation power in the strong bending magnets. The cost of cooling this heat load rises dramatically if it is absorbed at the low operating temperatures of the superconducting magnets. The problem can be alleviated to a certain extent by absorbing the radiation in a cooled beam screen, operating at intermediate temperatures. A 100 K beam screen was proposed for the VLHC-2 to absorb 5 W/m of peak synchrotron radiation power emitted by each 100 TeV beam. In fact the synchrotron radiation cooling in this case requires 30 MW at the plug, as much as the combined power need for the beam screen (water) cooling and the cavity cryo-system of LEP-2 or as much as the complete LHC cryo-system. Fig. 1 shows how a peak synchrotron radiation power limit of 10 W/m/beam restricts the luminosity of a “typical” VLHC as a function of beam energy and machine radius. We believe that 10 W/m of radiation power is close to the limit of the cooled beam screen approach in a reasonable aperture magnet. Therefore, in the recent VLHC study, room temperature photon stops were presented as a way to reduce cooling cost by an order of magnitude and to break the radiation power constraint on luminosity [2]. Photon stops are commonly used in third generation light sources. They are new in hadron machines with cryogenic magnets.

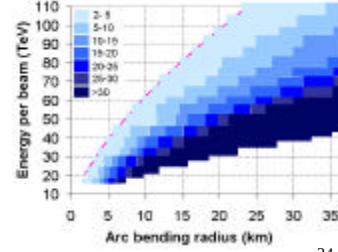


Figure 1: Max. luminosity (in units of $10^{34} \text{cm}^{-2} \text{s}^{-1}$) in a VLHC with a 10 W/m/beam peak synchrotron radiation power limit for different beam energies and machine sizes. Note that the very high luminosities for low-energy/large-tunnel configurations are not realistic because of beam stability constraints, which were not taken into account.

2 RING GEOMETRY ISSUES

The photon stops absorb the radiation emitted by the $(1-x)^{\text{th}}$ part of the 2nd magnet up-stream and the x^{th} fraction of the magnet before. The maximum possible distance between the photon stop tip and the beam occurs at $x=0$. This case, on the other hand, is the most restrictive in terms of magnet length and aperture. For $0 < x < 1$ the photon stop comes closer to the beam (and reaches the beam at $x=1$), increasing its impedance as well as the risk of accidental beam impact. The distance to the beam is typically several mm. Fig. 2 shows the calculated maximum magnet length for different magnet apertures in the $x=0$ scheme as a function of tunnel circumference. A 83% bending magnet packing factor was assumed in the arcs. Fig. 2 shows that large tunnels are better for photon stops. There are, however, ways to make medium size rings photon stop compatible, such as shifting the magnets with respect to the beam orbit to gain additional aperture or mixed regimes in which the radiation power is shared between photon stops and cooled beam screens. More on photon stop geometry issues can be found in [3].

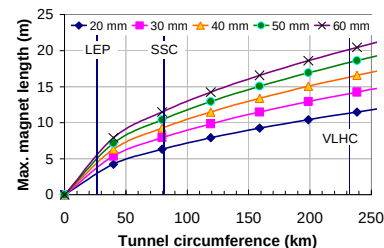


Figure 2: Maximum, photon stop compatible, magnet length versus tunnel size for different magnet bores ($x=0$).

3 ENGINEERING DESIGN

Fig. 3 shows a conceptual design of the photon stop assembly, as it could be installed into the magnet interconnect cryostat (not shown are the drive motor assembly and the cooling circuitry). The absorber enters the beam tube through a slot from the side. The photon stop insert is machined from bulk copper (or Glidcop) in one piece to avoid water to vacuum welds. Under a VLHC-2 radiation heat load of 70 W the absorber tip attains ~ 360 K at a cooling water flow of 0.2 lit/s. The absorber piece traps the radiation fan with a wedge-shaped cavity. To limit the thermal interference with the 5-100 K environment, the room temperature insert is encased in a thermal shield. The top part of the shield connects the room temperature parts to the ~ 80 K mid-section through a long bellows. At its lower portion the shield is reinforced with a second, outer shield that connects the 80 K inner shield mid-section to the 4.2 K cold bore tube at the bottom, again through a bellows (see Fig. 3). The inner shield is actively cooled to 80 K along the lower portion (with GHe from the cold-mass thermal shield). The detailed sketch of the region where the photon stop enters the beam tube in Fig. 3 shows that the photon stop assembly includes a ~ 1 m long portion of beam tube assembly. The inner, 80 K shield is welded to the (inner) beam screen, which is thus as well at 80 K. The outer shield connects to the outer beam tube which is cooled to 5 K. The dual temperature beam tube assembly serves as a cryo-pump. Model calculations, [4], indicate that the design presented here operates at less than 1 W heat load on the 5 K system and less than 4 W to the 80 K stage. At the plug, this corresponds to 6 MW for the 5 K system, 1 MW for the 80 K system and 2 MW for the water-cooling system if applied to the VLHC-2. This is to be compared to the above mentioned 30 MW plug power requirement of a 100 K beam screen system. It is hoped that the ongoing photon stop cryo-experiment, [4], will allow to further improve the design, such as to further reduce the loss, e.g. through the G10-spiders, that separate the 5 K cold bore tube from the 80 K, inner beam tube at the extremities of the cryo-pump assembly.

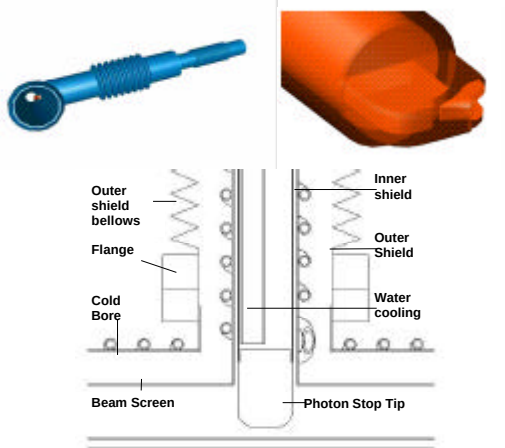


Figure 3: Conceptual design of a VLHC photon stop.

4 VACUUM

On the basis of photo-desorption data from SSC/LHC beam screen photo-desorption measurements, predictions can be made on how the beam tube vacuum evolves under the effect of synchrotron radiation induced gas desorption from the photon-stop, [5]. Fig. 4 shows the equilibrium pressure during VLHC-2 operation with a radiation flux of $1.7 \cdot 10^{17}$ ph/s/14m-magnet, as a result of photo-induced H_2 desorption from the photon stop for different CO equivalent pumping speeds. The “active” photon stop surface, that is the surface of the bounding walls of the absorbing cavity hit by the primary radiation beam is assumed to be 240 mm^2 .

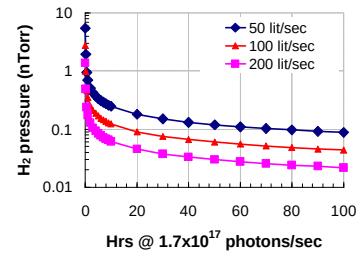


Figure 4: H_2 partial pressure in beam screen, given by photo-desorption from the photon stop due to a synchrotron radiation flux of $1.7 \cdot 10^{17}$ photons/sec for different CO equivalent pumping speeds.

By concentrating the desorption locally, photon stops do not only clean up rapidly, they could also lead to an interesting development: simulations indicate that a cryo-pump, locally restricted to the magnet interconnect region where the photon stop is, provides sufficient pumping for vacuum purposes. Fig. 5 shows the result of a numerical calculation of the axial pressure dependence assuming a 1m long, 200 lit/s cryo-pump section, [6]. The pressure bump at the photon stop location always remains below 1 nTorr. This indicates that, from a pure vacuum point of view, the elimination of the beam screen from inside the magnet becomes possible, thereby saving cost (\$ 1k/m for the current LHC beam screen assembly) as well as allowing a potential aperture reduction of ~ 10 mm in the magnets. Not included in this model is the effect of

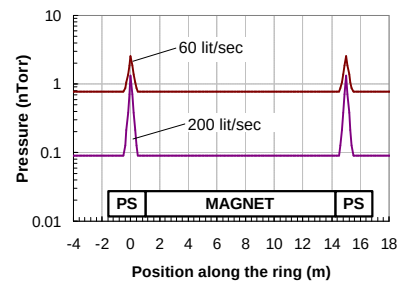


Figure 5: Calculated longitudinal pressure profile for photon stops with 1 m long cryo-pumps for different pumping speeds after starting irradiation with a flux of $1.7 \cdot 10^{17}$ photons/sec.

photons escaping the stop. The wedge-shape of the photon stop cavity together with its natural surface roughness should allow trapping of most of the entering photons. Reflection, especially at multi keV photon energy, is only occurring at grazing incidence, making it unlikely that photons will be back-scattered from the cavity. The VLHC-2 bending magnet radiation spectrum is characterized by a critical energy of 8 keV. Therefore, in first approximation, we suppose that the only process that allows photons to escape the stop is X-ray fluorescence. The fluorescence K and L lines for copper are at 8 keV and 0.9 keV, where, only the K α 1 line has a significant yield (0.44). The photon attenuation length is sufficiently small (i.e. 5.8 μ m at 10 keV), such that only the fluorescence radiation emitted toward the cavity entrance window can escape. The fluorescence flux emitted by the absorber was calculated using the energy-dependent, integrated radiation absorption coefficient, calculated from a model including the effect of “self-absorption” (that is the effect of absorption of not only the primary photons but also the absorption of the generated fluorescence radiation on its way out of the sample) [7]. Fig. 6 shows the so found fluorescence flux of Cu-K α 1 and Ag-K α 1 and Ag-L α 1 photons escaping the absorber cavity (through the 6 $\times$ 8mm² entrance window), against the background of the VLHC bending magnet synchrotron radiation spectrum. The fluorescence in silver was computed since it is a potential coating material. Incidence and emission were assumed to be vertical. The total power associated with the 10¹⁵ ph/s Cu-K α 1 fluorescence flux is 1.23 W, a few % of the total VLHC bending magnet flux per photon-stop of 70 W. This power is absorbed by the short section of 80 K beam screen and therefore not a plug power issue. A silver coating can reduce the power carried by the fluorescence photons by a factor 3. A systematic study of coatings was not performed. It has to be noted, however, that the coating thickness required is 1 mm to shield the underlying copper from the primary radiation. This sets a technological constraint on possible coatings.

The typical photo-electron emission spectrum is well known. It peaks at the work-function ($\sim$ eV) and drops fast

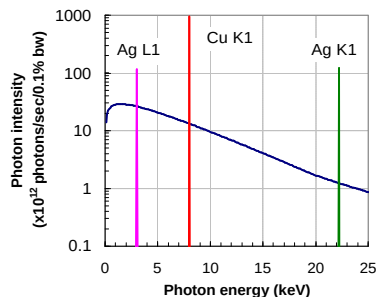


Figure 6: Calculated fluorescence flux of copper (silver) photon stop in a 14 m VLHC-2 dipole magnet radiation. The fluorescence flux peaks represent the total number of ph/sec at the respective X-edge.

toward larger kinetic energies. It is therefore believed, that electron emission from the photon stop can be mostly suppressed with a bias voltage of 100 V. This requires that the photon stop is electrically insulated.

5 BEAM EFFECTS

Wake-function calculations using MAFIA indicate a total longitudinal impedance $Z_{||}/n$ for all 14500 photon stops around a VLHC-2 of $\sim$ 25 m Ω and a total transverse impedance $Z_{\perp}$ of $\sim$ 8 M Ω /m [9]. The photon stop impedance is comparable to that of a shielded bellows. The analysis of possible beam stability issues, e.g. due to TMCI, did not raise any particular concern regarding the photon stop impedance in a VLHC-2. An issue deserving close attention, however, 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 ($<$ 5 mm) to increase the resonance frequency to well above the bunch-length frequency. Not investigated any further, at this point, were operational issues such as the effect of accidental beam impact.

6 SUMMARY

Future, post LHC hadron colliders will be limited by synchrotron radiation emitted in the cryogenic, high-field superconducting magnets. Photon stops are the most economical way to extract the synchrotron radiation heat-load and are therefore a key-technology for future hadron colliders, especially for the highest field magnet designs. We have addressed some of the important technical issues in photon stops, such as X-ray fluorescence and impedance. Possibly, another benefit from photon stops is the “localized beam screen concept”, which allows to eliminate the beam screen from within the magnets. A first photon stop prototype is in development.

7 REFERENCES

- [1] P. Limon et al., “Design Study for a Staged Very Large Hadron Collider”, Fermilab-TM-2149, 06/01.
- [2] P. Bauer et al., “Synchrotron Radiation Issues in the VLHC”, PAC 2001 Proceedings, Chicago, 06/01.
- [3] P. Bauer et al., paper T2003 / Snowmass 01 Conf. <http://www.slac.stanford.edu/econf/>.
- [4] C. Darve et al., “Concept of the first VLHC Photon Stop Cryogenic Design Experiment”, Fermilab, Technical Division Note, TD-02-017, 05/02.
- [5] P. Bauer et al., “Concept of the VLHC Photon Stop Experiment in the APS Synchrotron Radiation Beam Line”, Fermilab Tech Div. Note, TD-02-019, 05/02.
- [6] M. Pivi, “Vacuum with Localized Photon Stops in a VLHC Stage 2”, unpublished LBL Note, 06/02.
- [7] S. Eisebitt et al. “Determination of Absorption Coeff. for Concentrated Samples by Fluorescence Detection”, Phys.Rev.B, V.47/21, p. 14103, 1993.
- [8] N. Solyak et al., “A Photon Stop for VLHC-2, Impedance Calculations”, Fermilab Tech Div. Note TD-01-014, 05/01.