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A PHOTON-STOP FOR THE VLHC-2 ENGINEERING DESIGN – PART 1

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As part of Fermilab's Very Large Hadron Collider (VLHC) feasibility study, a photon-stop is being explored as a possibility to intercept the intense synchrotron radiation in the VLHC – stage 2 at room temperature. The photon-stop, if feasible, promises significant savings in cooling power compared to a solution in which the synchrotron radiation is extracted from a beam screen at cryogenic temperatures. The photon-stop is a device, which protrudes into the beam tube at the end of each bending magnet to absorb the synchrotron light emitted by the beam in the second magnet upstream from it. An engineering design for such a photon-stop, addressing mechanical, thermal and production related issues, is presented here.

1) VLHC2 PARAMETERS

A very large hadron collider (VLHC) is being proposed as a possible post LHC hadron collider. The current set of general characteristics of the second stage of this machine is listed in Table 1. Such an accelerator in its second stage, referred to as VLHC2 in the ongoing text, will produce protons at energies more than 10 times larger than the LHC.

Energy per proton E_p @ collision(TeV)	**87.5**
Gamma γ	**93284**
Peak Luminosity L ($cm^{-2}s^{-1}$)	**2×10^{34}**
Total Circumference C (km)	**233**
Bending radius ρ (km)	**29.9**
Dipole Field B @ collision (T)	**9.7**
Magnet packing factor (%)	**85.5**
Number of Bunches N_b	**37152**
Initial Nr. of Protons per Bunch $N_{p/b}$	**7.5×10^9**
Initial Beam current I_b (mA)	**57.4**
Bunch Spacing t_b (ns)	**18.8**
Revolution frequency f_0 (Hz)	**1286**
Beta* β* @ collision (m)	**0.71**
Normalized round beam emittance ε_N @ collision (RMS) µm	**$0.08\times\pi$**

Table 1: VLHC2 machine parameters (according to S. Peggs, BNL, “VLHC Accelerator Physics”, Draft Version 02.4.09, April 9, 2001.

The SR power radiated by the beam, calculated with the parameters of Table 1, is listed in Table 2 together with the other SR characteristics. A more detailed description of the calculations is given in [1],[2]. The SR power in such a VLHC2 scenario amounts to 5 W/m per beam.

SR Power per m per beam (W/m)	**4.7**
Critical energy E_{crit} (keV)	**8.03**
# of incident photons per meter Γ ($m^{-1}s^{-1}$)	**1.2×10^{16}**
Radiation damping time τ_R (hrs)	**2.5**
Incidence angle of SR (mrad)	**1.31**
RMS width of the SR strip on the beam tube (mm)	**0.5**

Table 2: Synchrotron radiation parameters in the VLHC2.

Half of the power is carried by photons with $E>E_{crit}$. Half of the photons are emitted with an energy larger than 0.08 E_{crit}. The synchrotron radiation in the VLHC2, with the operational parameters listed in Table 1, is ~50 times as much as in the LHC case. The heat load deposited by SR on the beam tube has to be removed by a refrigeration circuit. Calculations of the optimal liner temperature are reported elsewhere[3]. According to these calculations the optimal beam screen temperature is ~100 K. The total refrigeration power requirement to remove the SR heat load with a 100 K beam screen cooling system is ~25 MW at the plug. If removed at room temperature the power requirement could be reduced to 1.9 MW, which represents considerable cost savings. The use of photon-stops, operating at room temperature, could be a way of implementing such savings. Photon-stops are room-temperature devices that protrude into the beam tube at the end of each bending magnet and scrape off the synchrotron light beam emitted in the second magnet up-stream from their location. A preliminary feasibility study was recently performed[4], showing that in the VLHC it is possible to place photon-stops between the magnets as long as these magnets do not exceed 14 m, which is compatible with the maximum magnet length imposed by other requirements, such as those related to quench protection and transportation. The following describes the cooling requirements for such devices in a VLHC2 setting, followed by a proposal for its implementation and some preliminary analysis of vacuum related issues. Estimations of the cooling requirements are paramount to obtain a first estimate of the photon-stop size. The shape of the photon-stop mainly responds to stipulations regarding its impedance. A detailed discussion of the impedance related implications of the photon-stop and the results of numerical impedance calculations are reported elsewhere[5]. The high synchrotron radiation flux impinging on the photon-stop causes massive gas desorption. It is believed that this effect will allow rapid cleaning (beam-scrubbing) of the device and no vacuum related complications are expected thereafter.

2) THERMAL CALCULATIONS

Assuming that a single photon-stop intercepts the synchrotron radiation heat load emanating from one magnet, its thermal load (P_{SR}) is given by 5 W/m times the magnet-length, which equates to 70 W. The required heat exchange surface S and coolant flux dm/dt was determined from a numerical model, which equates the primary (synchrotron) heat load with the heat flux through the heat exchange surface S (assumed to be steel) and the convective heat transfer correlation for turbulent coolant (assumed to be water) flow. The equations of the model are summarized in (1)-(3), where th is the photon-stop wall thickness, d_{ct} the diameter of the cooling duct, k the thermal conductivity, c_p the specific heat, ρ the density, μ the viscosity, v the coolant flow velocity, Q the heat flux in W/m, *cond* a subscript for conductive, *conv* a subscript for convective, T_f the average temperature in the coolant, T_{fin}, T_{fout} the coolant inlet and outlet temperature, T_{ct1}, T_{ct2} the temperatures at the beam- and coolant side of the heat exchange surface.

$$Q_{cond} = \frac{S}{th}\int_{T_{ct2}}^{T_{ct1}} k(T)\,dT \qquad (1)$$

$$Q_{conv} = S\,0.023\left(r(T_f)\,v\,\frac{d_{ct}}{m(T_f)} \right)^{0.8} \left(m(T_f)\,\frac{c_p(T_f)}{k(T_f)} \right)^{0.4} \frac{k(T_f)}{d_{ct}}\left(T_{ct2} - T_f\right) \qquad (2)$$

$$P_{SR} < \frac{dm}{dt}\,c_p(T_f)\left(T_{fout} - T_{fin}\right) \qquad (3)$$

A possible graphical solution of equations 1-3 is shown in Figure 1. The complete set of parameters corresponding to this solution is listed in Table 3. Water was chosen as the refrigeration liquid. The peak heat flux is below the critical surface heat flux of water (2 MW/m^2). Other coolants, with lower freezing temperatures may be more suitable. However, the aim of the here presented calculation was to prove the feasibility of such a device from a thermal point of view. We believe that this objective was achieved.

Photon-stop Cooling System Parameters	
Synchrotron heat load per device (W)	**70**
Surface heat exchange area (cm^2)	**1**
Wall thickness heat exchanger (mm)	**1**
Heat exchanger surface temperature – beam side (K)	**360**
Heat exchanger surface temperature – coolant side (K)	**305**
Peak heat flux into coolant (MW/m^2)	**0.6**
Coolant flow rate (liters/s)	**0.2**
Coolant velocity (m/s)	**2.6**
Coolant inlet temperature (K)	**300**
Coolant outlet temperature (K)	**305**
Cooling tube inner diameter (mm)	**10**

Table 3: Possible Parameters of the photon-stop cooling system.

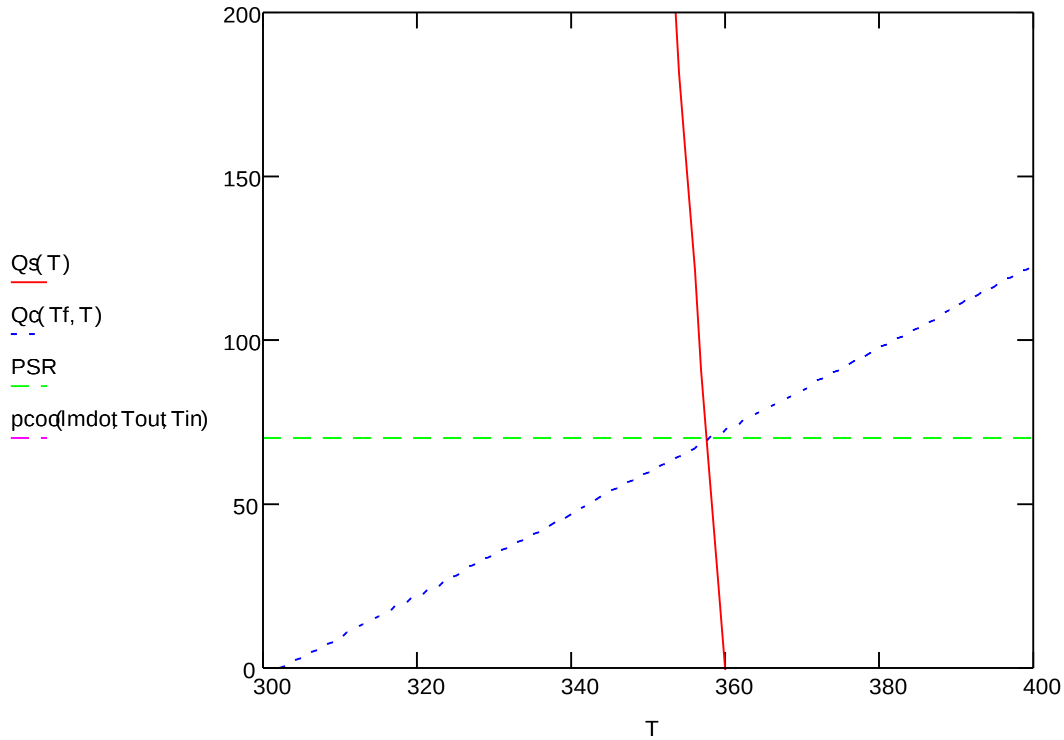

Figure 1: Graphical solutions for the equations (1-3) for the photon stop cooling: Conductive Q_{cond} heat transfer through the photon-stop wall, convective heat transfer Q_{conv} from the photon-stop wall to the coolant, total heat load P_{SR}, (in Watt) as function of photon-stop (coolant-side) wall temperature T (K).

The thermal calculations presented above suggest that such a photon-stop would have to have a heat exchange surface of ~1 cm^2 to allow the evacuation of the SR heat load. The bottleneck in the heat extraction path is the photon-stop wall, which should not be thicker than ~1 mm according to this calculation. From a thermal standpoint a high conductivity material, such as copper, together with a minimal wall thickness, are paramount. The following engineering design assumes copper as material, the wall thickness is 2 mm. The factor 2 in the wall thickness is justified by the fact that the heat conductivity of copper is much larger than that of steel, which is the material the calculation described above is based on.

3) ENGINEERING DESIGN PROPOSAL

The photon-stop, as proposed here, would be a T-shaped piece, consisting of a ~6 cm short copper tube shaped like the beam screen (but without holes) with flanges at the ends, to which a ~0.5 m long warm finger, the photon-stop, is attached perpendicularly (Figure 2). The photon-stop enters the beam screen from the side, where it is hit by the synchrotron radiation (Figure 3). The warm finger consists of an outer hull with flanges on top and bottom to fix it to the cryostat hull and the short beam screen piece with vacuum tight (Cu) seals. Into this hull the core of the photon-stop is inserted. The core piece consists of the cooling tubes with the radiation absorber at the end.
The short beam screen piece is inserted into a specially prepared gap in the beam-screen / cold-bore assembly and welded at each end. The cold-bore tube is discontinued over the ~10 cm of the photon-stop to reduce the heat influx from the 100 K beam screen/ photon-stop system (and replaced by a G10 tube). The bellows, required to allow the beam tubes contract during magnet cool-down, are placed in sections further away from the photon-stop. The beam-screen cooling tubes have to be guided out of the beam screen to bypass the bellows, usually in the form of a flexible tubes. In the case of the photon-stop we propose that the cooling tubes bypass as well the photon-stop system. Furthermore it is assumed that the photon-stop will be placed close to the magnet anchoring point. This offers the advantage of not having to cope with thermal contraction effects. Since the photon-stop, according to this design proposal, is mechanically fixed to the outer magnet cryostat hull and the beam screen, differential longitudinal motion between the beam screen and the outer cryostat would bear a risk of breakage.
Such a system could be assembled in 3 steps. During the first step the short beam screen section with the "photon-stop port" is welded in place (without the photon-stop) and inserted into the cryostat. Welding is not only better than flanging in what regards vacuum issues but it also allows to obtain a continuous path for the beam image currents from the beam screen through the photon-stop sections (and thus reduces resistive wall loss). In a second step the outer hull of the photon-stop is attached to the flange on the beam-screen, passing it through a hole in the cryostat and sliding it over the studs welded to the beam screen flange. The flanges on top and bottom are sealed and eventually the core part of the photon-stop is inserted into the outer tube. A pumping port allows to pump out the photon-stop assembly.

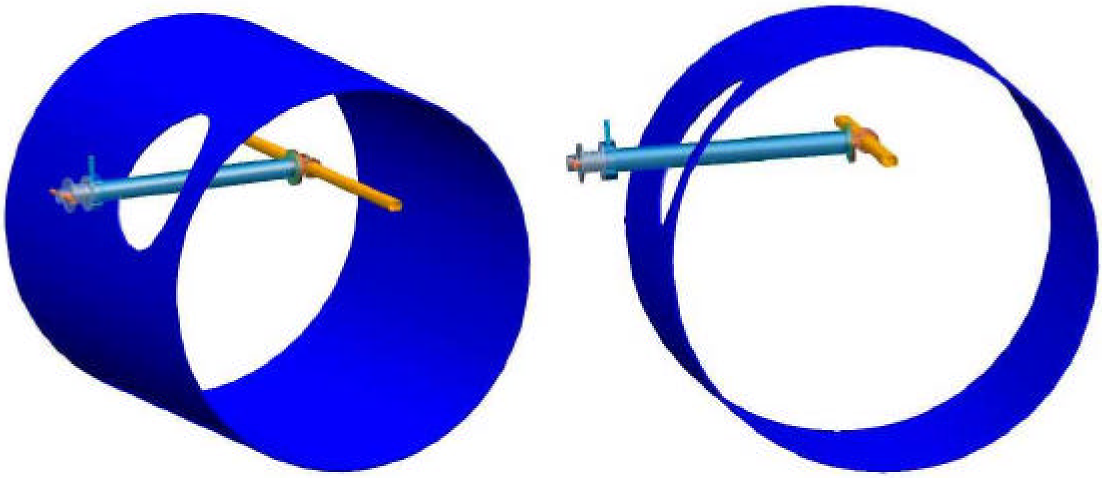

Figure 2: Photon-stop assembly – global view.

The warm finger is attached to the cryostat hull at one end and to the short beam screen piece on the other end. Its outer hull is a 5 mm thick G10 cylinder with an outer diameter of 51 mm. The G10 tube negotiates the temperature difference between room temperature on the outside and the 100 K beam screen, keeping the heat flux from the outside to the beam-screen below 50 mW. The heat flux was calculated with (4), where A is the cross-sectional area of the G10 tube $(\pi/4)(OD^2\text{-}ID^2)$, l_{G10} the length of the tube (~0.5 m), ΔT~200 K and the thermal conductivity of G10 at 200 K is k_{G10}~0.5 W/m/K.

$$\Phi \approx \Delta T \frac{Ak_{G10}}{l_{G10}} \quad (Watt) \tag{4}$$

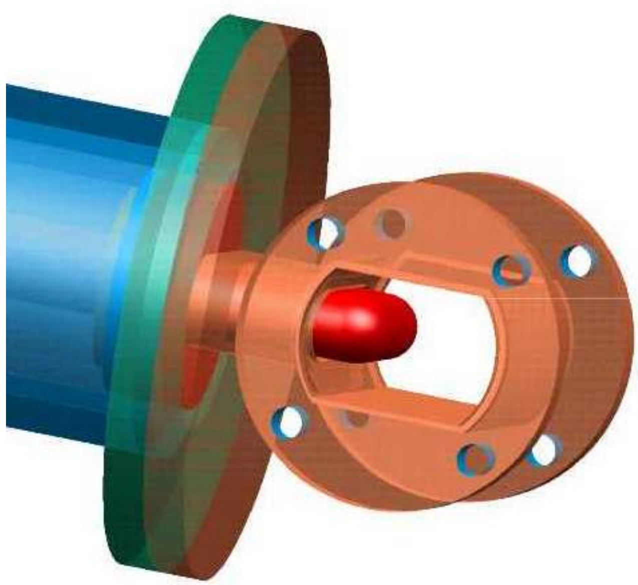

Figure 3: Photon-stop – view of the radiation absorber in the beam screen.

Not included in (4) is the thermal radiation from the cooling tubes at 300 K to the outer G10 tube. The radiation heat load between the hot, inner Cu cylinder (diameter d_{Cu}, temperature T_{Cu}, emissivity ε_{Cu}) and the concentric, outer, colder G10 cylinder(diameter d_{G10}, temperature T_{G10}, emissivity ε_{G10}) is given in (5), where l is the length of the system (0.49 m) and C_{SB} the Stefan-Boltzmann Constant ($5.67\cdot10^{-8}$ Watt/m^{2}K^4)

$$P_{rad} = l\, p_{rad} = l\, C_{SB}\left(T_{Cu}^4 - T_{G10}^4\right)\pi d_{G10} \frac{1}{\frac{1}{e_{Cu}(T_{Cu})} + \frac{d_{Cu}}{d_{G10}}\left(\frac{1}{e_{G10}(T_{G10})} - 1\right)}\ (W) \qquad (5)$$

The radiation heat load calculated with (5), ~1.5 W, is mostly absorbed by the G10 tube, raising its temperature, but with only a small effect on the overall heat influx to the beam screen part. The G10-tube is as well the envelope of the photon-stop vacuum. The flanges on top and bottom are mixed G10-copper (bottom) and G10-steel (top) flanges using an O-ring seal. A view of the bottom end of the photon-stop (Figure 4) shows that the copper adapter, welded to the beam screen on the bottom and to a flange on top, is indeed very short (~10 mm) to reduce the radiation heat load from the 300 K insert to the beam screen. Unlike in the magnet, the beam screen piece is made from bulk copper to simplify the welding procedure. For similar reasons the adapter and the lower flange are as well made from bulk copper. A bulk copper beam tube is possible, because the quench forces are negligible outside the magnets.

The cold bore tube is not continued in the photon-stop section to suppress any conductive and radiative heat transfer from the 300 K and 100 K systems to the 5 K system. On the other hand, this requires the beam screen in the photon-stop to be without holes, compromising the cryo-pumping function in this section. Vacuum related issues for the photon-stop are discussed elsewhere[6].

On the outside of the cryostat, where the photon-stop assembly is attached to the cryostat hull, ports for the cooling tubes and a 10 mm ∅ pumping port are foreseen (Figure 5). The pumping port is contained in a lower flange, the cooling tube outlets are machined into a thick upper flange. Between the two flanges a stainless steel bellow allows for the radial motion of the photon-stop. A step motor, attached to the cryostat, will induce this motion. The total travel required is ~10 mm. A system, yet not designed, that measures the position of the photon-stop with respect to the beam screen with a precision of ~ 0.1 mm will be required. It is important to note that the core of the photon-stop system, which is at 300 K along its whole length, is not supposed to touch the outer hull, except, where 2 Steel/Bronze rings provide the guiding in the G10-tube.

The inner part of the warm finger consists of a 3.5 mm thick Cu-tube (OD=35 mm) containing two copper cooling tubes (OD=12 mm wall thickness = 1 mm) with the absorber piece attached at the ends (Figure 6). Cu was chosen as material of the outer tube because of its lower emissivity (which can be further reduced by high grade polishing of the outer surface). The warm finger slides on 2 Steel/Bronze rings within the G10 outer tube. This allows the insertion and retraction of the photon-stop at minimal friction. At the same time it reduces heat conduction from the 300 K insert to the ~200 K

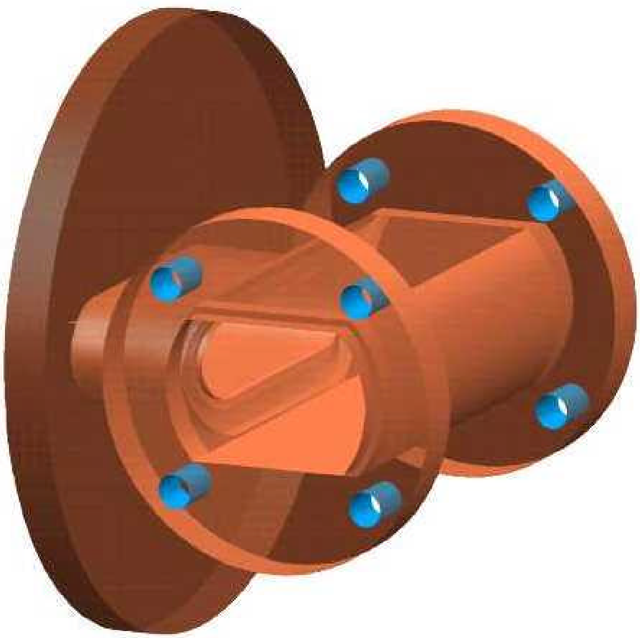

Figure 4: View of the beam-screen and flange part of the photon-stop.

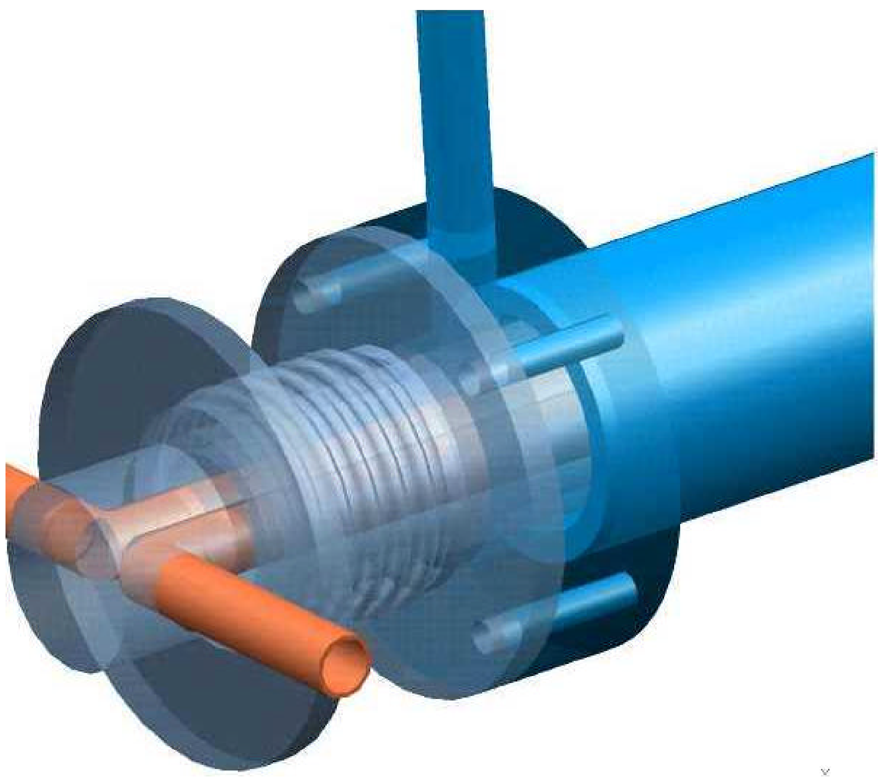

Figure 5: Top part of photon-stop assembly showing the flange with the cooling tube ports, the lower flange with the pumping port and the bellow in between to allow for the displacement.

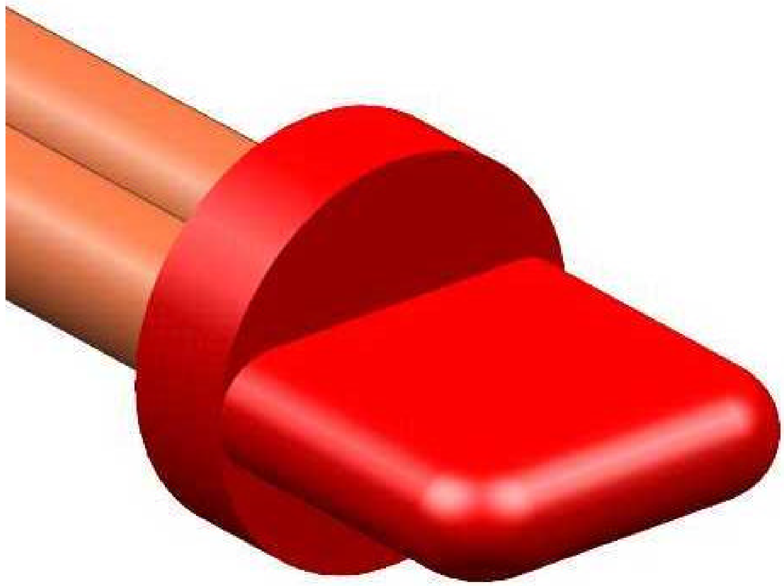

Figure 6: View of the cooling tubes and the absorber.

G10 tube. A heater is wrapped around the cooling tubes to maintain the coolant (e.g. water) in the liquid state in the absence of synchrotron radiation heating. The cooling tubes are welded into two holes in a disc that in turn is welded to the end-piece.

The end-piece (Figure 7) is a hollow cylinder, machined at one end to a special shape - the radiation absorber. The inside of the end piece is hollow to allow the cooling liquid to extract the heat deposited by the synchrotron radiation on its outer surface. The wall thickness of the absorber is ~ 1mm. The shape of the absorber was optimized to yield low impedance. The impedance calculations are documented in [5]. According to calculations presented in [4], complete radiation absorption for a given inter-connect length L_s, a beam-screen inner radius a and an arc radius ρ requires the photon-stop to reach into the beam tube by d (6).

$$d \approx \frac{a}{4} + \frac{3}{4} L_s \sqrt{\frac{a}{2r}} \qquad (m) \tag{6}$$

Hence, with a beam screen radius a=15 mm, an inter-connect length of 3 m and a bending radius ρ=29.1 km, the fully deployed photon-stop has to reach 10 mm into the beam area. This brings the tip of the photon-stop within 5 mm of the beam tube axis. The absorber piece has the shape of a prism (Figure 7) with axial / radial / azimuthal extension 35 x 10 x 10 mm and rounded edges. The edges can be rounded to almost any radius. It is made from copper to obtain a low initial photo-desorption coefficient and a high thermal conductivity. To reduce the thermal emissivity the outer surface of the end piece requires a high grade polishing.

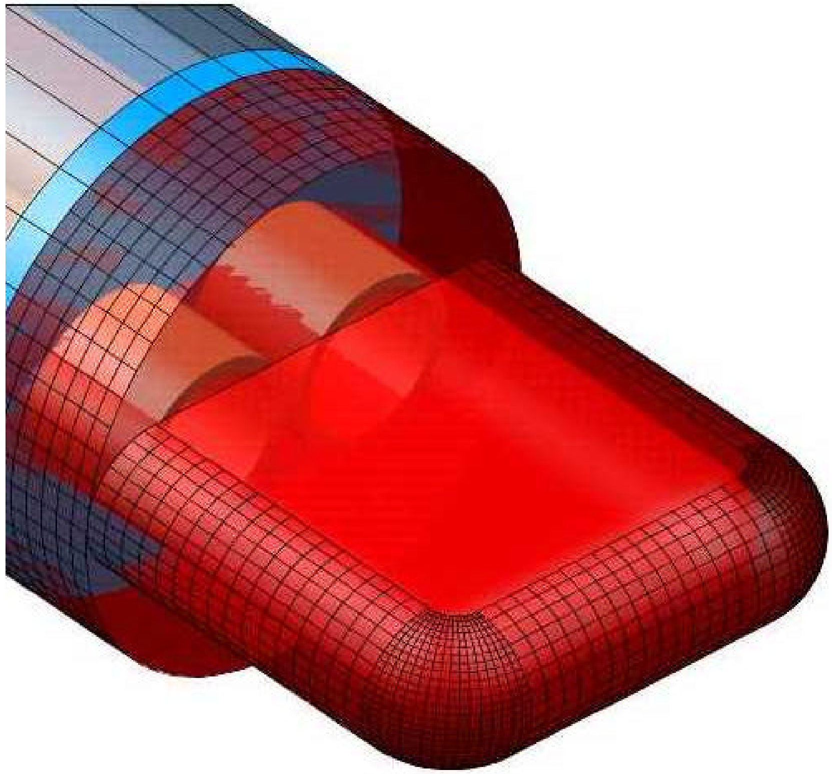

Figure 7: Close-up on absorber.

4) VACUUM ISSUES

The strong synchrotron radiation flux impinging on the photon-stop results in a fast clean-up of the photon-stop surface. However, it is necessary to pump the desorbed gas load. According to the design proposed in 3) the beam screen in the photon-stop system has no pumping holes. The desorbed gas load has to diffuse ~5 cm to each side into the beam tube to reach sections where active pumping to the cold-bore removes the gas from the beam area. During the initial beam scrubbing, however, the beam current has to be kept small to limit the beam-gas scattering at the photon-stop location (conditioning). The pumping speed during conditioning is limited by the diffusion of the gas molecules from the photon-stop to the adjacent cryo-pumps.
The high temperature of the photon-stop (~300 K) and the beam screen (~100 K) prevents re-adsorption of the desorbed gases and thus the pumping task is simplified. The high surface temperatures result as well in a higher molecular speed, accelerating the gas diffusion into the adjacent beam screen regions, where the pumping occurs. On the other hand the high temperature of the photon-stop raises the thermal desorption rate. It will be necessary to perform a high temperature heat treatment (bake-out) of the photon-stop insert before installation.
The photon-stop tubing can, providing an additional valve e.g. once every cell, can easily be converted to a pumping port for roughening down the beam tube vacuum.

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