FINITE ELEMENT ANALYSIS OF A PHOTON ABSORBER BASED ON VOLUMETRIC ABSORPTION OF THE PHOTON BEAM

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Abstract

A photon absorber is a device used to protect vacuum chambers and other hardware from synchrotron radiation by intercepting unwanted radiation, converting its energy to heat, and then removing that heat. Design of a photon absorber requires careful consideration of the high temperatures and steep thermal gradients that are possible with highly localized absorption of these photons. For next-generation machines, like the multi-bend achromat envisioned for the APS Upgrade (APS-U), a designer is likely to be simultaneously faced with more intense synchrotron radiation beams, more limited available space, and closer proximity to the particle beam than have been designed for in the past. Volumetric absorption of synchrotron radiation, which makes use of materials that are semi-transparent to x-rays, is an attractive option which gives the designer greater freedom by spreading the heat load due to the absorbed photons. Volumetric absorption may also help to reduce residual gas pressures in a vacuum system by reducing the photon-stimulated desorption that results from photons reflected by the incident absorber surface. This paper describes simulations which were performed to evaluate the benefit of utilizing volumetric absorption for a conceptual “crotch” photon absorber for the APS Upgrade (APS-U), so-called because of its location in the vacuum system where the chamber is forked to permit x-ray extraction. Results of these simulations show clear benefits of volumetric photon absorption and suggest that such an approach may help to substantially relax constraints on the size, shape, and materials used for such absorbers.

VOLUMETRIC ABSORPTION

Two crotch absorbers are planned for each APS-U storage ring sector. These are expected to intercept roughly 1-3 kW each with power densities, as would be intercepted on a normally-intercepting surface, that approach 100 watts/mm^2. Conventionally, photon absorbers are made using high opacity and high thermal conductivity materials such as copper and GlidCop™ which cause the heat load to be concentrated on the absorber surfaces. A designer typically struggles with reducing the incident angle of those surfaces and increasing the efficiency of cooling to those surfaces as much as possible to manage the thermal stresses that result. In addition, the high reflectivity of these materials to x-rays, coupled with the grazing angles, causes scattering of a considerable fraction of incident photons which can then be a significant driver of photon-stimulated gas desorption. Finally, the high water flow rates required to maintain surface temperatures at safe levels can introduce vibration that may upset critical, precisely-aligned hardware in the accelerator.

A potential solution is the use of an absorber which is semi-transparent to incident x-rays. Such an arrangement allows the heat load into the absorber to be gradually deposited in the body of the component, reducing the associated thermal stresses. In doing so, a designer can find a solution which is more compact than would otherwise be possible. Another approach is to combine an opaque absorbing body with a more transparent, but thermally conductive, material. Doing so similarly limits the resulting temperature rise of absorber materials by allowing the heat generated on the opaque body to be more effectively conducted away.

Such approaches have three distinct advantages over a conventional, surface-absorbing design:

1. The material temperatures and the thermal gradients may be reduced, reducing potentially-damaging thermal stresses, fatigue, and structural softening.
2. Reflection of photons may be reduced, thus reducing the outgassing associated with photon-stimulated desorption.
3. Heat transfer may be more efficient due to overall greater proximity of cooling to the heat load, relaxing water flow requirements.

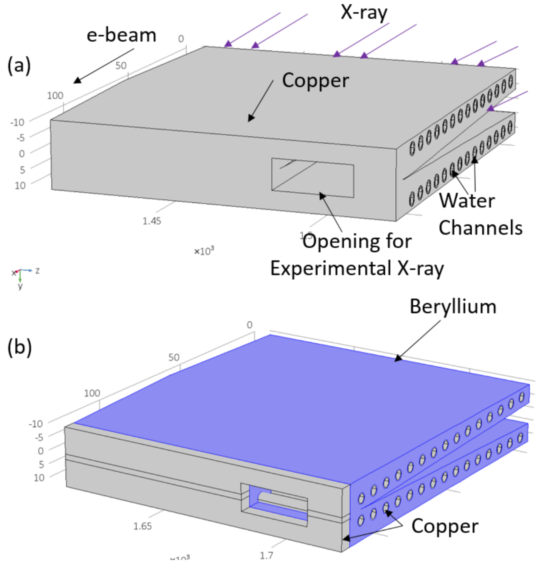

Figure 1: Conceptual APS-U crotch absorber options (a) copper body design (b) beryllium and copper design.

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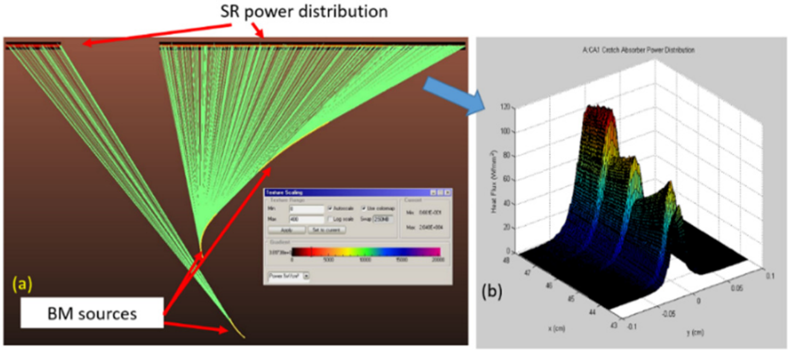

Figure 2: Power profile distribution (a) SynRad trajectories and power profile for B crotch absorber for APS-U project (b) power distribution and profile.

THEORY

The physics of the absorption of energetic photons in solids is fairly straightforward and is primarily associated with the number of electrons that can accept the required exchange of energy from the photons. The electrons that are free or easily dislocated from the orbit most readily satisfy this criterion. The electron concentration in two materials can be estimated from the atomic number. Precise tabulated data for different materials is also available over a wide range of photon energies.

The incident photon beam loses energy when interacting with material. The change in the incident beam's energy can be estimated using the following relation:

$$dI(x,y,z) = -I(y,z) \cdot n \cdot \sigma \cdot dx \; [1]$$

Where, dI(x, y, z) = the change in absorbed intensity
I(y, z) = the initial intensity, SynRad output
n = the number of atoms/cm^3
σ = a proportionality constant
dz = the incremental thickness of material from surface into the body of the absorber

Here x, and y are transverse direction while z is direction along the beam path.

The combination of the number of atoms per cubic centimetre and the proportionality constant is the linear attenuation coefficient (μ). Therefore, the equation becomes:

$$I(x,y,z) = I_0(y,z) \cdot e^{-\mu \cdot x}$$

The linear attenuation coefficient (μ) describes the fraction of a photon beam that is absorbed or scattered within the thickness of the absorber.

SIMULATION MODEL

As shown in Fig. 1 (a), the crotch absorber envisioned for the APS-U consists of two distinct features: an opening to allow synchrotron radiation passage to the experimental beamline and a central V-shape opening which captures the unwanted radiation on the absorber. Figure 2 shows the expected power distribution profile as computed with SynRad, a computer program developed at CERN [2]. The total power deposited on the crotch absorber is approximately 3 kW.

Dissipation of power in the absorber was determined using the theory described above. A thermal mechanical simulation was then performed using COMSOL Multiphysics [3]. Figure 3 shows the analysis process.

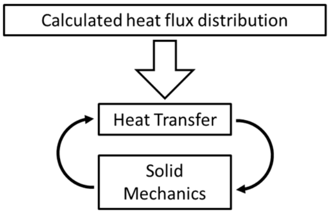

Figure 3: Flow chart of solution strategy.

For the baseline study, copper was used as the body material. The water channel is assumed to be simply machined into the body. For the volumetric absorber design beryllium was assumed for the body material and copper for lining of the water channels. In addition, a 5 mm thick copper plate was modelled on the back side of this photon absorber to capture any x-rays not absorbed by the beryllium body and copper water channels. A list of the thermal and mechanical properties assumed in the simulations are shown in Table 1.

Table 1: Assumed Material Properties for FEA

Material	**Attenuation Length @10keV**[4]	**Thermal Conductivity** [5]
Be	10,000 μm	216 W/m/K
Cu	5-30 μm	385 W/m/K

RESULTS AND DISCUSSION

Calculations of the dissipated power were as expected. The attenuation length of copper is 5- 30 microns at relevant photon energies. As a consequence, photon absorption in copper was found to occur primarily at the surface. Beryllium has a much longer attenuation length at these photon energies, roughly 10 mm, so what absorption occurs in beryllium was found to be much more distributed though the bulk of the material.

In the baseline design option, roughly 1.2 kW of power was found to be absorbed at the junction of the two halves of the V-shaped notch, while the rest was absorbed on the intercepting surface. Similarly, 1.2 kW of power was found to be absorbed in the copper back plate assumed in the volumetric absorber design.

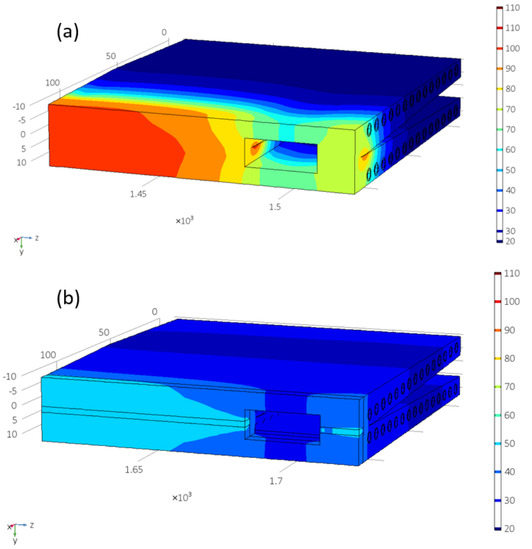

Figure 4: Temperature distribution on exterior surfaces (˚C) for (a) simple copper body design (b) beryllium and copper body design.

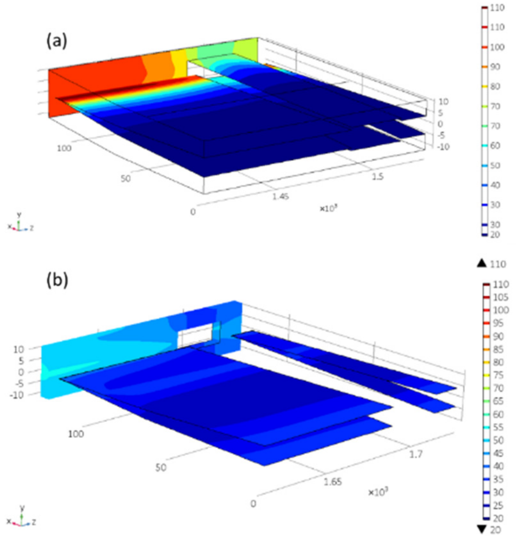

Figure 5: Temperature profile (˚C) on surface where x-rays enter the absorber for (a) simple copper body design (b) beryllium and copper body design.

The maximum temperature observed in the baseline (all-copper) design occurred at the intercepting surface where the incident photon intensity was maximum. The maximum temperature indicated was 110 ˚C. Figure 4 shows a comparison of the temperature profiles predicted for each of the cases. In the case of the volumetric absorber design, the maximum temperature occurs at the interface of the copper surface in the copper backing plate where photon intensity was maximum (see Fig. 5). The maximum temperature in case of volumetric absorber design was found to be 56 ˚C.

One sees from these results that the basic difference between the baseline design and the volumetric absorber design is the proximity of the water mass flow to the areas where heat input is the greatest. In the baseline design absorption of radiation primarily occurs at a distance of roughly 5 mm from the cooling water. In the case of the volumetric absorber design, the distance is approximately 2 mm. Structural deformation was also found to be much lower in the volumetric absorber relative to the baseline design (Fig. 6).

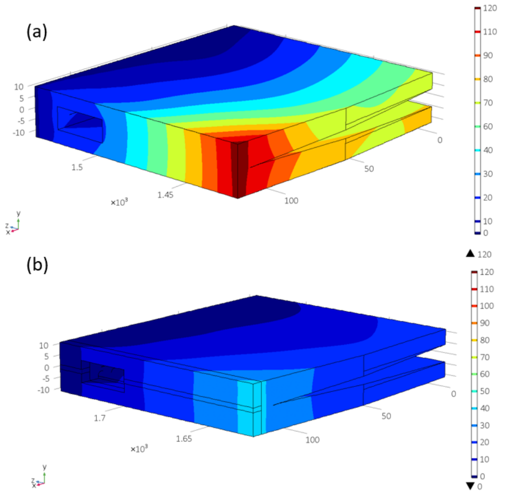

Figure 6: Deformation (µm) of (a) simple copper body design (b) beryllium and copper body design.

CONCLUSION

A simulation of a conceptual volumetric crotch absorber for the APS-U showed substantial reduction in developed material temperatures compared with a simple, all-copper baseline design. Temperature rise in the volumetric absorber was found to be 56 ˚C, which is 50 ˚C less than what was found for the baseline design. Moreover, the thermal gradient found for the volumetric absorber was much less steep, indicating substantially reduced thermal stresses. These improvements clearly suggest that employing volumetric photon absorbers can help to relax design constraints associated with the size, shape, and materials these critical components for next generation accelerators.

ACKNOWLEDGMENT

This research used resources of the Advanced Photon Source, a U.S. Department of Energy (DOE) Office of Science User Facility operated for the DOE Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357. The authors would like to thank Dr. John Noonan, Benjamin Stillwell, and Dr. Branislav Brajuskovic for valuable discussions and Jason Carter for providing SynRad-calculated radiation profiles.

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