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A Novel Calorimeter Design for Synchrotron Produced X-ray Beams

ABSTRACT

The feasibility of a novel aluminum-based calorimeter design to measure the dose rate of a synchrotron-produced x-ray beam has been assessed. The dose rate of the 65-140 keV monochromatic x-ray beams produced by the Canadian Light Source will be evaluated. The beamline produces an x-ray beam with a non-uniform field size on the order of a few mm and a peak dose rate of 0.5 - 1 Gy/s. A vacuum-based calorimeter design with an aluminum core was chosen, matching the beam profile. The choice of material and overall calorimeter design was optimized using COMSOL Multiphysics® software to perform thermal modeling while the EGSnrc radiation transport code was used to model the impact of interactions of the radiation beam with the detector components. Preliminary measurements to assess the performance of the calorimeter were conducted.

The design minimizes the effect of scatter – the conversion from the energy deposited in the detector to the energy deposited in a homogeneous aluminum phantom is within 2 % of unity. Extensive thermal modeling predicts conductive heat-losses of 2.5 %, preliminary measurements estimate an uncertainty of 0.7 % on the corrections derived thorough the thermal model and measurement reproducibility between 0.01 – 0.2 %. The uncertainty in the determination of absorbed dose to aluminum is estimated to be less than 1.5 %.

INTRODUCTION

Accurate absorbed dose measurements in synchrotron x-ray beams significantly lag those in other beam modalities. Synchrotrons produce naturally collimated and high flux x-ray photon beams with dose rates several orders of magnitude greater than conventional x-ray tubes. The potential to produce micro-meter sized pencil beams with the appropriate collimation makes them a valuable research, and ultimately a therapeutic tool. The Canadian Light Source (CLS) BMIT-ID beamline is the x-ray source of interest for this work and the aim is to accurately determine the absorbed dose rate of the 65-140 keV monochromatic x-ray beams produced by that beamline. A novel aluminum-based calorimeter has been built and its performance modelled to assess its ability to measure the dose rate of the BMIT-ID x-ray beams. Preliminary measurements indicate that the overall uncertainty in determining absorbed dose in synchrotron x-ray beams can be significantly improved from current methods.

METHODS

The beamline produces an x-ray beam with a uniform horizontal spatial distribution but a large vertical fall off, figure 1, and a dose rate estimated to be in the 1 Gy/s range. A calorimeter has been specifically designed to match these parameters:

i) Aluminum was chosen as the elemental absorber material of the calorimeter core to allow accurate dose determination and conversion to absorbed dose to water. Microbead thermistors were chosen as the temperature sensors.

ii) The core geometry was optimized to the beam geometry (40 mm x 3 mm x 0.5 mm) to reduce the impact of dose averaging, in both the axial and radial directions.

iii) A vacuum enclosure was required to minimize conductive heat losses from the core, which would have a significant impact on the dose determination for this detector geometry. Miniature Aerogel supports will be used to hold the core in the correct position within the enclosure.

The dose to the core can be determined directly from the radiation induced temperature rise using equation 1:

$$D_{core} = \frac{E_{deposited}}{m_{core}} = c_{core}.\Delta T_{core} \qquad (1)$$

COMSOL Multiphysics® software was used to thermally model the response of the calorimeter to the x-ray beam and carry out a sensitivity analysis to optimize the design (detector size, temperature sensors, mechanical components, etc). EGSnrc was used to determine the effect of radiation scatter from the detector enclosure and investigate the dose conversion procedure, figure 2. A prototype detector was constructed, figure 3, and preliminary measurements conducted to verify the feasibility of the device.

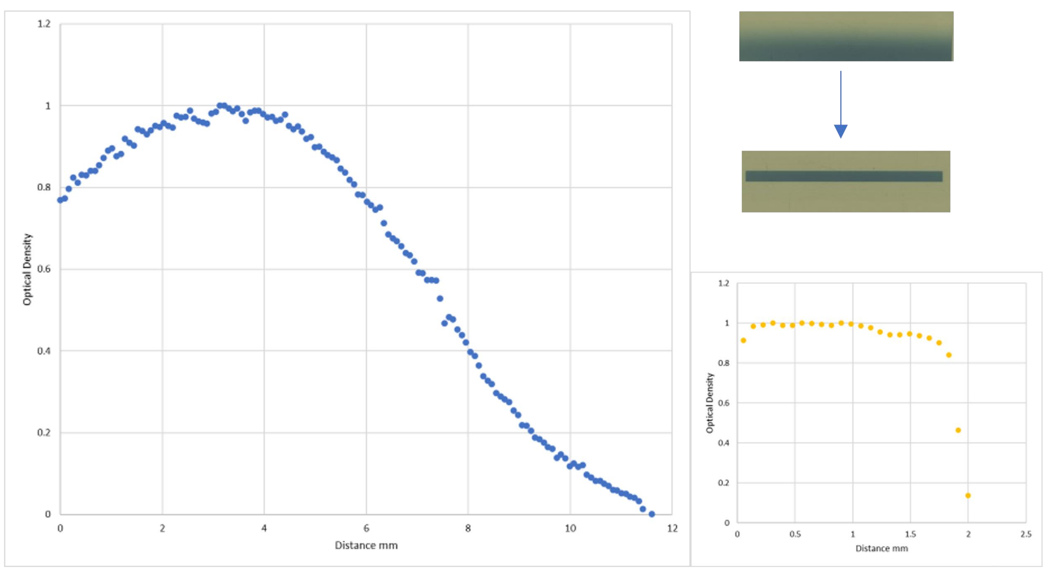

Figure 1. Left - a plot of the optical density of an EBT3 film as a function of vertical position, irradiated using the uncollimated monochromatic 140 keV beam. The insert shows a sample film before and after collimation resulting in a relatively flat beam on the order of a millimetre in the vertical direction (lower right plot).

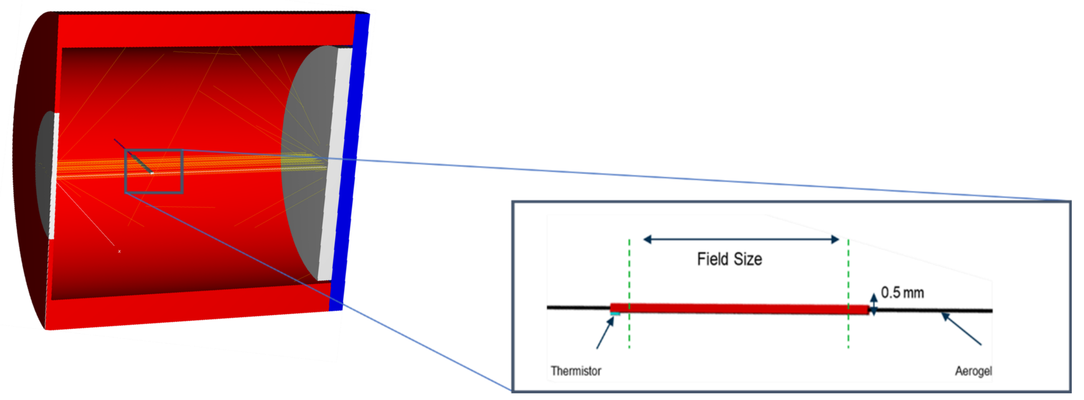

Figure 2. A cross section of the geometry used to model the calorimeter in EGSnrc for the Monte Carlo simulations. The yellow lines denote the synchrotron photons incident from left. The entire calorimeter body and core is constructed from aluminum, with different colors being used to show the design features more clearly. The cut out shows the components surrounding the calorimeter core.

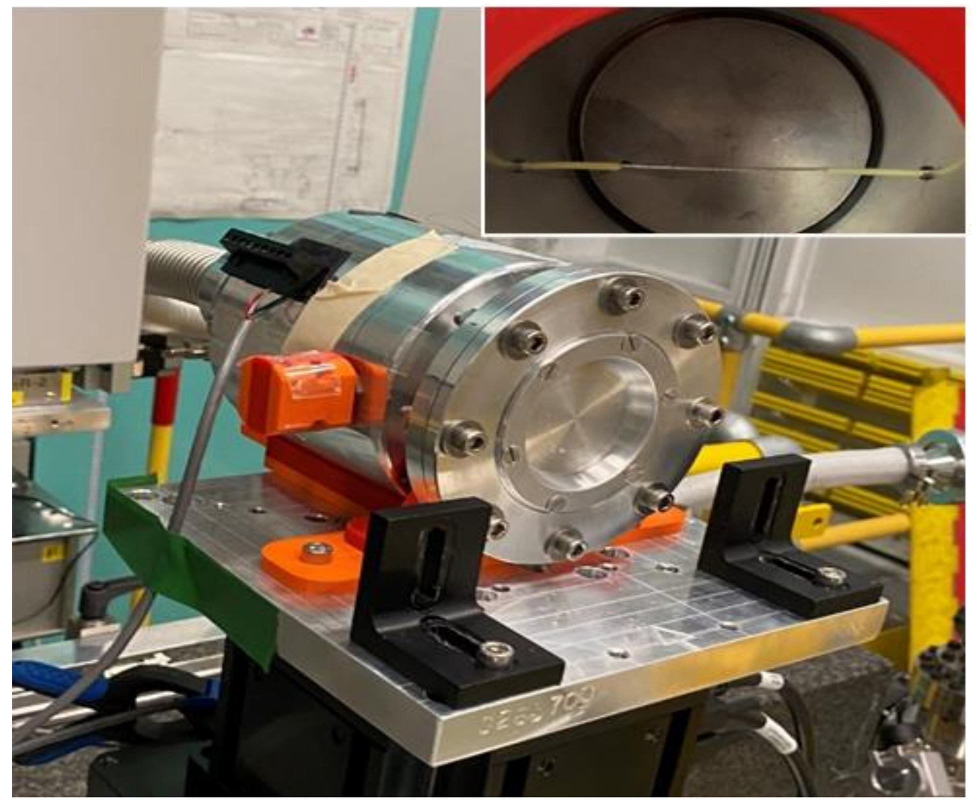

Figure 3. The calorimeter vacuum vessel is shown in position to be irradiated. The cut-out image shows the inner calorimeter core along with the aerogel supports used to minimize conductive heat losses.

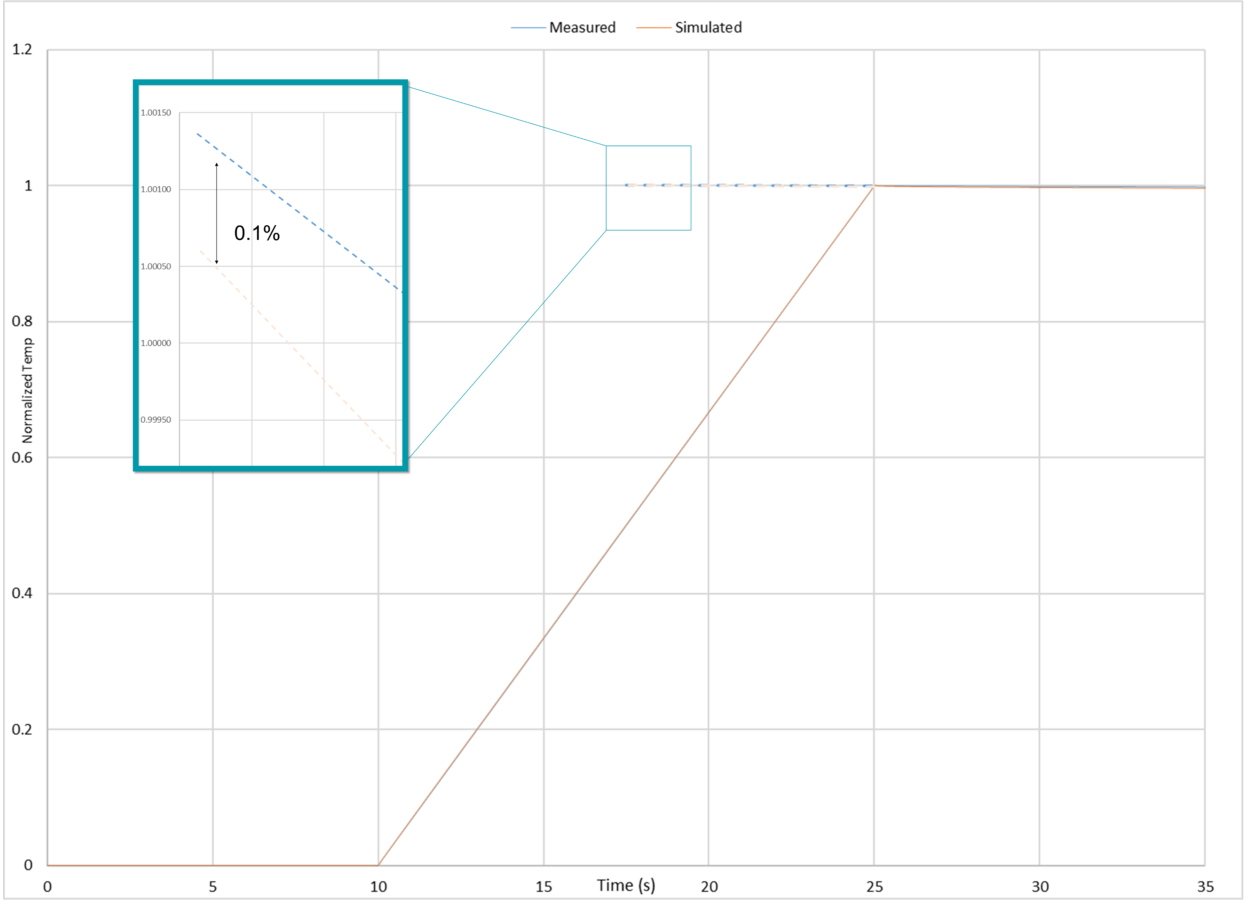

Figure 4. Normalized temperature traces for a 115 keV beam measured using the calorimeter and a temperature trace generated using a COMSOL Multiphysics® thermal simulation for the same set up. The beam is switched on for 15 seconds at the 10s mark. The extrapolated traces are shown as well as a cut-out showing the difference between the simulated and measured traces at the irradiation midpoint. For all energies, the difference between the measured and simulated extrapolations for the irradiation midpoint temperature ranged between 0.1 – 0.7 %.

RESULTS

Preliminary measurements show reproducibility at the 0.01 - 0.2 % level. Simulated and measured normalized temperature traces show agreement within 0.7 %, figure 4. An overall heat loss correction of 3 % is established for the calorimeter prototype based on the detailed thermal modeling of the experiment. The absence of any non-aluminum material in the beam path results in a 2 % scatter and attenuation correction when correcting to an aluminum mass in an aluminum phantom. Based on preliminary measurements the uncertainty on the absorbed dose to aluminum is expected to be less than 1.5 %.

CONCLUSION

This investigation serves as a proof of principle study for the use of an aluminum calorimeter to measure the radiation induced temperature rise of a millimeter sized monochromatic synchrotron beam. Modelling and preliminary measurements confirm the suitability of the overall design. The results also suggest the potential to significantly reduce the uncertainty in the absorbed dose, compared to air kerma-based approaches currently used. The next steps will involve extensive synchrotron beam measurements with the calorimeter to investigate influence quantities, characterize uncertainties and validate the theoretical conversion to absorbed dose to water.

OUR PARTNERS

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