A Novel Calorimeter Design for Synchrotron Produced X-ray Beams

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Purpose: 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 designed and its performance modelled to assess its ability to measure the dose rate of the BMIT-ID x-ray beams - thermal and radiation transport simulations have been used to optimize a final detector design. 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. The radiation-induced temperature rise in the aluminum core is related to the energy deposited by the beam through the specific heat capacity. 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.

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.

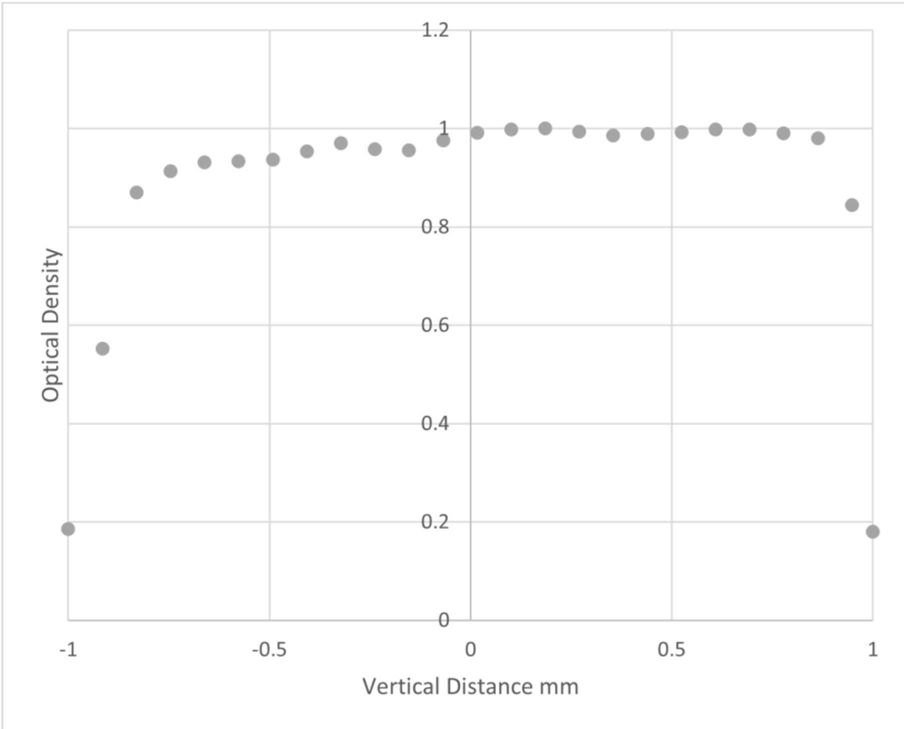

Figure 1. Normalized EBT3 optical density measurements of a 140 keV monochromatic x-ray beam profile produced by the CLS BMIT synchrotron beam line.

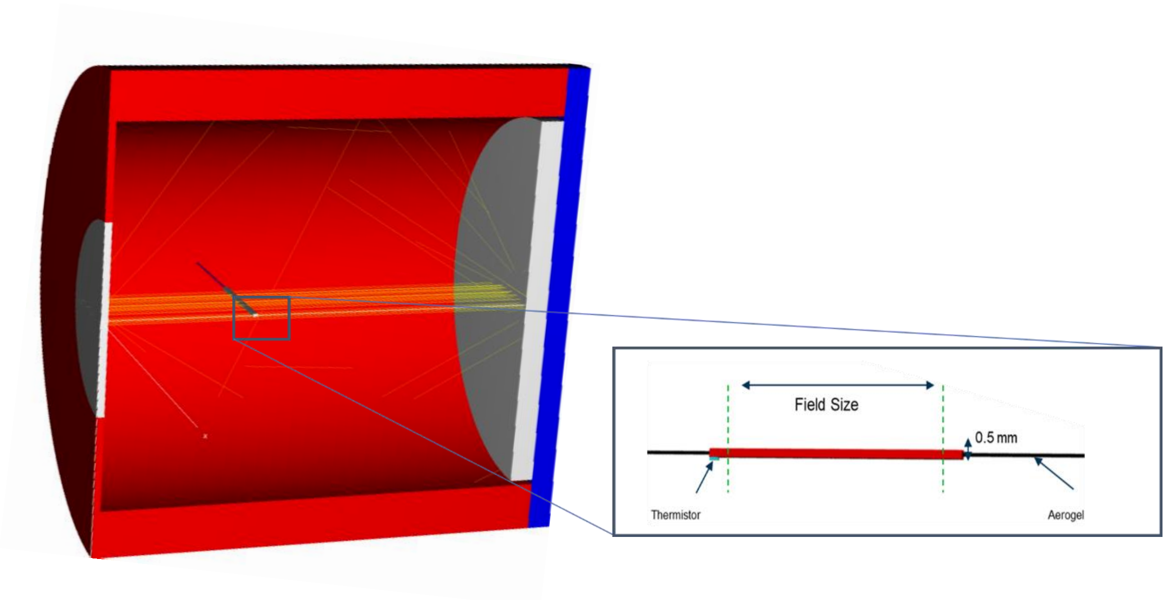

Figure 2. A cross section of the geometry used to model the calorimeter in EGSnrc for the Monte Carlo simulations. The yellow lines denote the synchrotron photons incident from left. The entire calorimeter body and core is constructed from aluminum, with different colors being used to show the design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

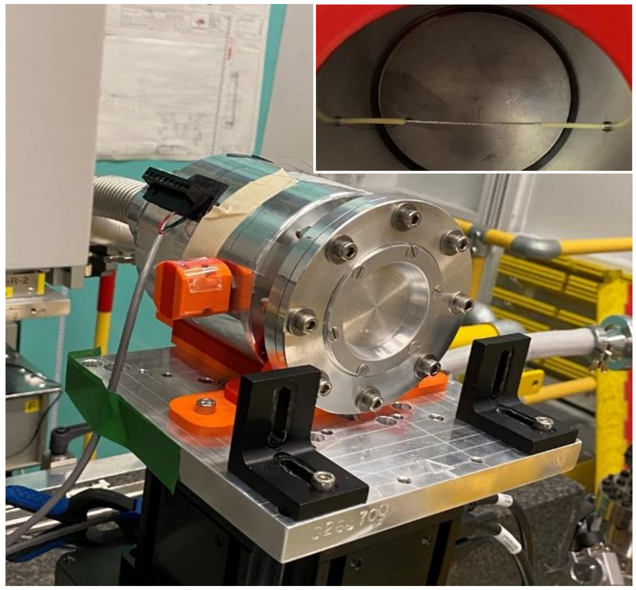

Figure 3 The calorimeter vacuum vessel is shown in position to be irradiated. The cut-out image shows the inner calorimeter core along with the aerogel supports used to minimize conductive heat losses.

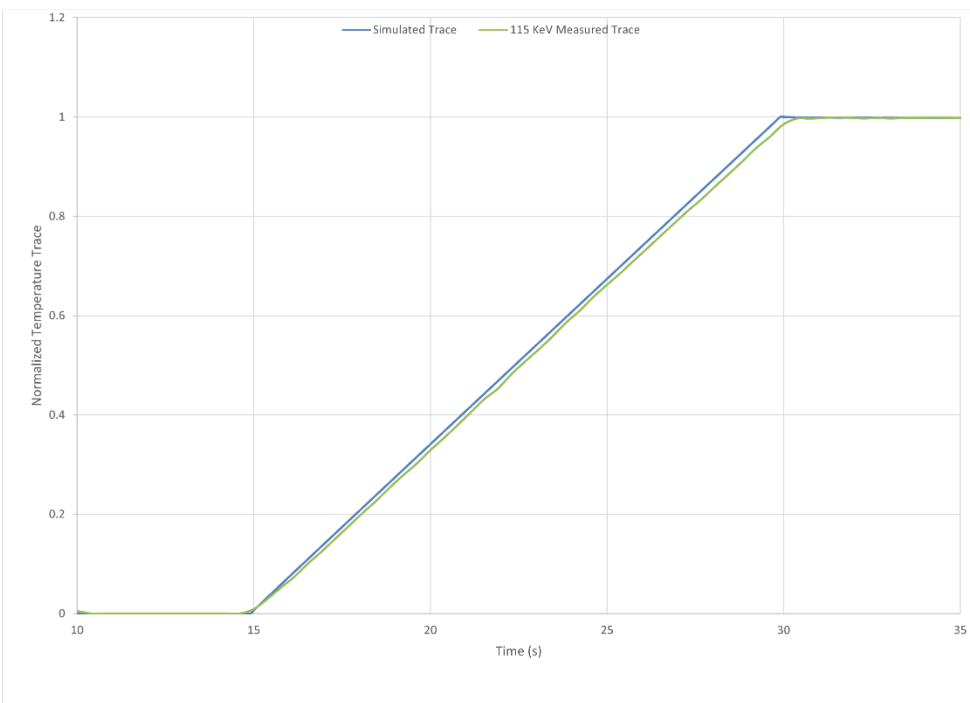

Figure 4. Normalized temperature traces for a 115 keV beam measured using the calorimeter and a temperature trace generated using a COMSOL Multiphysics® thermal simulation for the same set up. The beam is switched on for 15 seconds at the 15s mark.

Results: Preliminary measurements show reproducibility at the sub-0.5 % level. Simulated and measured normalized temperature traces show agreement within 1.2 %, 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 1-2 % scatter and attenuation correction when correcting to an aluminum mass in an aluminum phantom.

Conclusions: 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.

Relevance to CIRMS: This work forms the core of the thesis work of the first author to develop a metrology standard for synchrotron produced x-ray beams. This work relates directly to the CIRMS mission as it addresses the need for direct metrological traceability in such beams by developing a more accurate and precise, but practical, absorbed dose detector that can be operated on-site. The theme for 2022 is “Measuring what cannot be seen”; synchrotron beams have been used for imaging for many years but this work provides the absolute dose measurement necessary for developing therapeutic applications. The first author aims to become a clinical medical physicist, his research interests have centered on metrology in relation to medical physics, with publications in that field since 2013.