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Spatially and Temporally Resolved Optical Calorimetry for Proton FLASH Beams

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Read more about the development of an Optical Calorimeter…

Original Prototype [1]

Modelling Refinements [2]

Implementing Refinements [3]

Extension to 3D [4]

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INTRODUCTION

Optical Calorimetry (OC) is dosimetry technique that enables direct measurement of absorbed dose to water. Laser interferometry is used to measure radiation induced temperature changes in a water cell. Spatial and temporal dose distributions can be measured by recording the resultant interference patterns on a digital camera and reconstructing dose using a technique called Digital Holographic Interferometry (DHI).

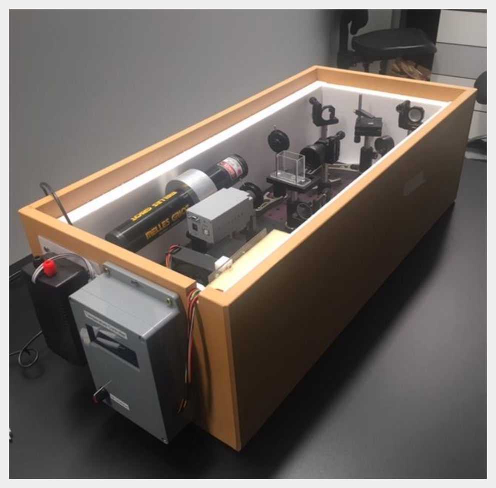
Optical Calorimetry does not rely on energy or dose-rate specific correction factors, making it particularly suited to the dosimetry of Ultra-high Dose-Rate (UHDR) beams. This work validates OC as a dosimetry method in UHDR proton beams for the first time.

METHODS AND MATERIALS

The study was conducted on the University of Washington 50 MeV UHDR research proton beam line. Delivered dose rates ranged from 80 Gy/s – 102 Gy/s. An Optical Calorimetry system was configured to measure the depth dose distribution of the proton beam, horizontally incident on a water cell. Figures 1-4 show the optical arrangement used to direct the measurement probe, an expanded (object) laser beam, through the water cell.

Irradiation of the water cell deposits heat energy, causing the phase of the object laser beam to change relative to the reference laser beam. Encoded in the fringes of the resulting interference pattern is the spatial distribution of absorbed dose within the water cell. The ability of the OC system to measure spatial distributions of absorbed dose was tested by positioning the water cell to capture the Bragg peak of the 50 MeV proton beam. The ability of the OC system to measure temporally resolved distributions was tested by continuously recording interference patterns at 60 frames-per-second following the termination of the radiation beam, to capture the diffusion of heat within the water cell.

Absorbed dose was holographically reconstructed from the recorded interference patterns, and compared to Monte Carlo simulations and ionisation chamber dosimetry.



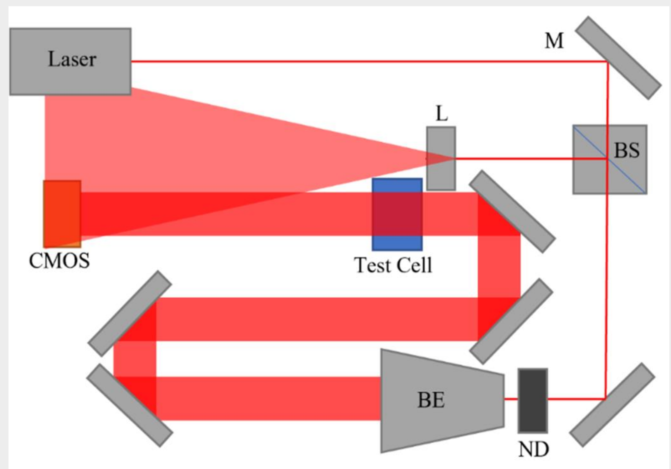
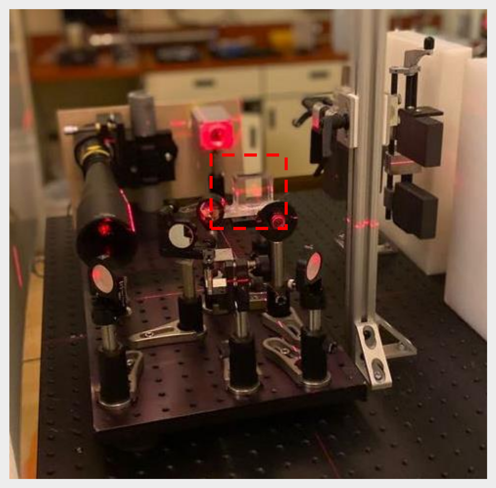


Figure 1 (Left): An example of an Optical Calorimeter used for UHDR proton dosimetry. The sensitive optical setup is contained within a temperature controlled and vibration damped housing.
Figure 2 (Right): Schematic of the optical setup used to perform DHI based dosimetry. Radiation induced refractive index changes in the water test cell influence the interference pattern recorded on the CMOS camera.



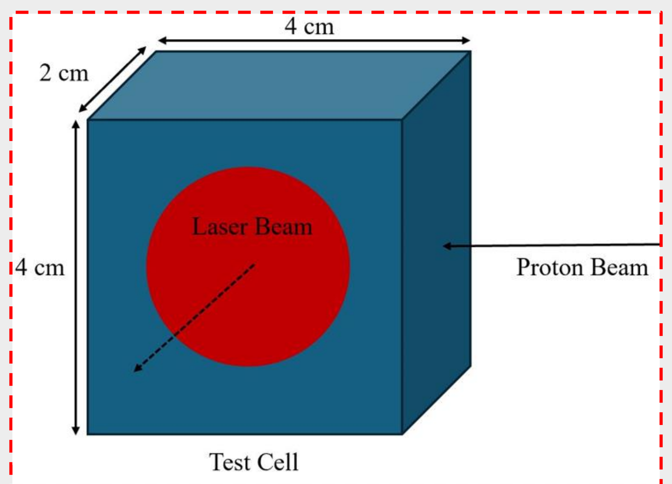


Figure 3 (Left): The Optical Calorimetry measurement setup . A laser is directed through a series of optics to probe a water cell (dashed lines), before interfering with a reference beam on a digital camera.
Figure 4 (Right): Enlarged schematic of the water cell showing direction of radiation and laser propagation.

RESULTS

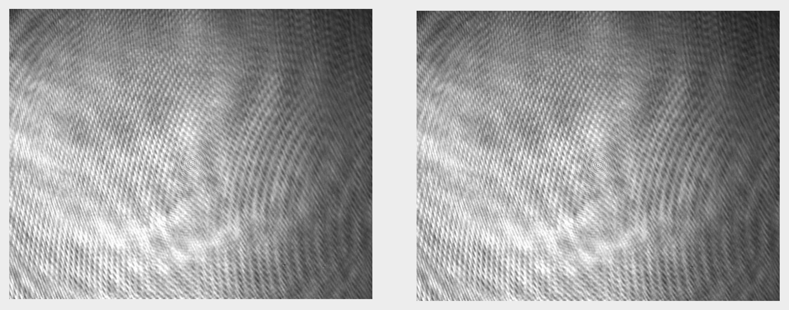


Figure 5: Interferograms measured on a UHDR beam.
Left: Reference image, captured prior to irradiation.
Right: Object image, captured during irradiation.
Encoded in these fringes is a holographic image of the radiation induced phase changes that occurred within the water cell.

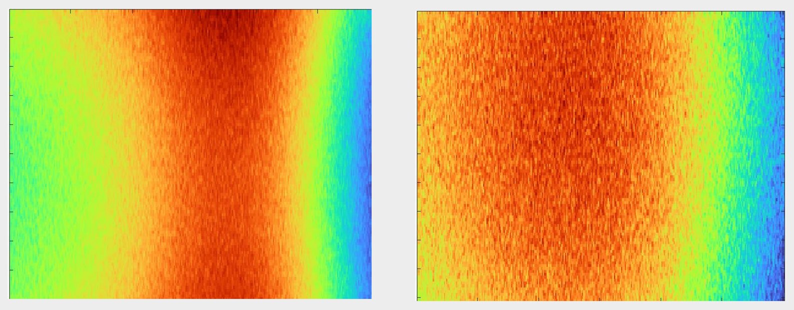


Figure 6: Holographically reconstructed images of the dose distribution within the water cell. By continuously collecting frames with the digital camera, a time evolved dose distribution can be measured. These images show the radiation induced heat energy dispersing within the water cell once the radiation beam is terminated.

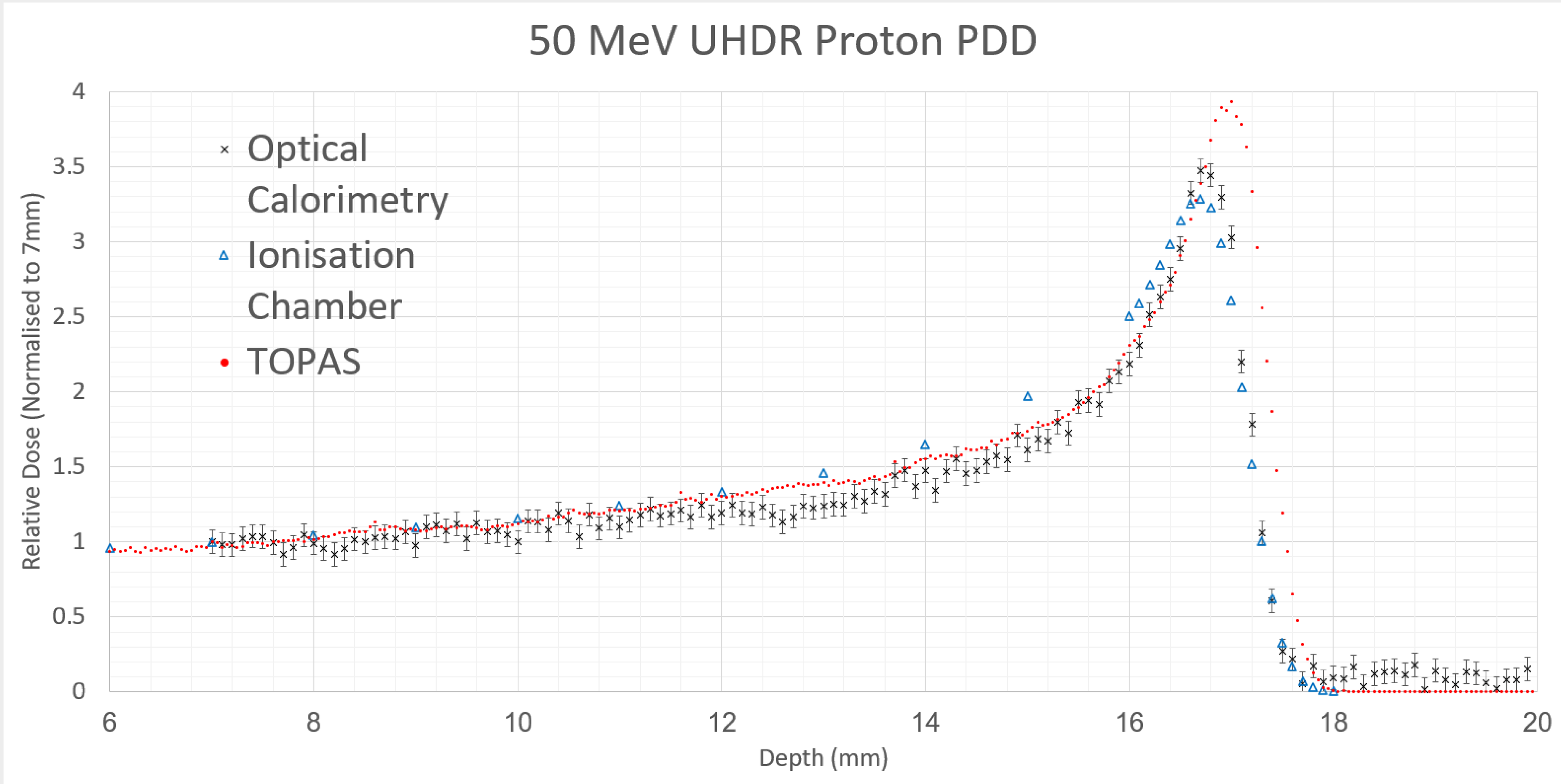


Figure 7: Comparison of PDD for a proton FLASH beam measured with an Ionisation Chamber (IC) and Optical Calorimeter (OC). Measurements are compared to Monte Carlo modelling (TOPAS). OC PDDs are constructed from a single measurement acquisition by plotting a line profile through holographically reconstructed dose distributions such as those shown in Figure 6.

DISCUSSION

These are the first measurement of a proton Bragg peak at Ultra-High Dose Rate using an Optical Calorimetry based dosimeter. The OC dosimeter measured absorbed dose to water for all points within its sensitive volume simultaneously, no scanning of a physical probe through a depth in water was required. Absorbed dose to water was calculated from radiation induced temperature changes using fundamental calorimetry equations.

OC successfully resolved the proton Bragg peak with a resolution of 50 µm. OC-derived depth-dose curves aligned closely with both Monte Carlo modelling and ionisation chamber dosimetry.

OC required no dose-rate or energy dependent correction factors to measure absorbed dose using dose rates as high as 102 Gy/s. At 102 Gy/s the IC determined entrance dose (8.8 Gy) matched OC (9.3 Gy) to within the current uncertainty (9.9%) of OC measurements.

OC successfully resolved the temporally evolving distribution of heat energy as the radiation beam was terminated and heat energy diffused within the water cell. Further work is required to characterise the OC system in temporally varying radiation fields.

For each measurement, captured interference patterns were converted to absorbed dose to water using a numerical reconstruction code in MATLAB. Reconstruction took less than one minute, and required no prior knowledge of the irradiation beam or setup, excluding the fixed arrangements of optical components within the detector.

CONCLUSIONS

An Optical Calorimetry system was used to accurately measure spatially and temporally varying dose distributions in a UHDR proton beam with high resolution.

Absolute dose determination was achieved without the need for dose-rate dependent correction factors and demonstrated a strong agreement with IC dosimetry.

Further work is required to reduce type-A measurement uncertainty and improve the practicality of performing OC dosimetry.

REFERENCES

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