Calorimetry Techniques for Absolute Dosimetry of Laser-Driven Ion Beams

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Introduction

Advancements in accelerator technology over the last years has seen systems developed capable of generating energetic ion beams at ultra-high dose rates. As such, the development of centers offering treatment based on proton acceleration has led to this modality becoming a more readily available tool in the fight against cancer. In spite of this, the huge size and cost associated with facility installation has led to more compact approaches being explored [1]. The use of intense, ultra-short laser pulses has emerged as an encouraging technique for the compact delivery of pulsed particle beams. Indeed, various experiments have already demonstrated the production of ions of several tens of MeV, lying within the range of interest for medical applications [2, 3]. Laser-driven beams display a number of unique characteristics, including ultra-short pulse durations (ps at the source, ~ ns at delivery), and dose-per-pulse up to several Gy, resulting in dose rates (up to 10^9 Gy/s) eclipsing RF accelerators by many orders of magnitude [4]. This has triggered large research initiatives investigating and demonstrating the feasibility of laser-driven beams for prospective medical applications, some of which are focusing on laser-driven ion acceleration as a potential future driver for radiation therapy [5]. Accurate dosimetry of high dose per pulse beams has proven to be technically challenging, and is further complicated for laser-driven accelerators due to the harsh experimental environment created during laser-matter interaction [4]. As such, measurements with active dosimeters become complex, requiring the development of novel approaches to replace those already established for conventional radiotherapy.

Calorimetry Techniques

Through their ability to record absolute measurements of absorbed dose (without relying on calibration in a characterized reference field), and dose-rate independence, calorimeters are perhaps the ideal detector for accurate dosimetry of laser-driven ion beams. Calorimeters, relying on measuring the radiation induced temperature rise in an absorber, are well established as primary standard level instruments for dosimetry. The National Physical Laboratory (NPL) has built a graphite calorimeter, capable of deriving the absorbed dose of proton beams from first principles. However, calorimeters had not been applied to measure the dose deposited by a beam of laser-driven ions, not least due to the distinct time-dependent and inhomogeneous dose deposition patterns. A novel approach to measure the absorbed dose of laser-driven protons using a small portable graphite calorimeter (SPGC) developed at NPL, as shown in Figure 1, was recently proposed. This device was based on a previous prototype used for several successful measurements of low energy, conventionally accelerated proton beams [6]. As divergence and absorption of the beam through the surrounding media may be significant, the thin-walled calorimeter was placed close to the entrance of the pipe to optimize the measurement of dose.

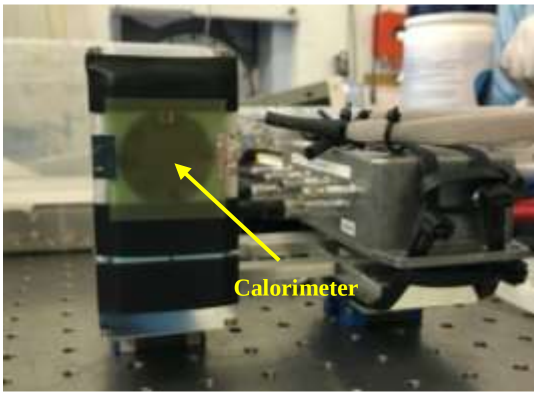

Figure 1. The SPGC assembled in a makeshift holder dedicated for the measurement using VULCAN, and electronics close by. The calorimeter indicated is composed of a sensitive core containing 4 embedded thermistors, surrounded by a graphite jacket acting to reduce heat loss to the environment. A GafChromic EBT3 radiochromic film was attached to the front surface and used to confer with the temperature derived by the calorimeter.

This represented an innovative solution to dosimetry of laser-driven beams that had never been utilized before. The experimental setup and calorimeter structure have been simulated using the Monte Carlo toolkit GEANT4 (GEometry ANd Tracking), providing useful information regarding the energy required to produce a measurable signal in the calorimeter [8].

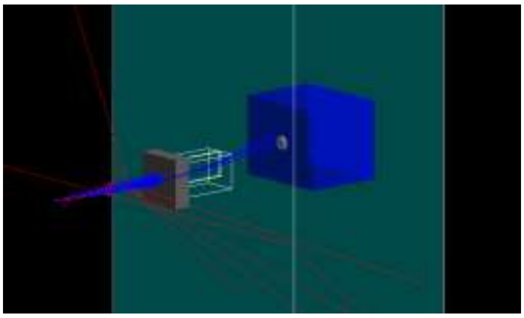

Figure 2. Graphical representation of the experimental interaction chamber and calorimeter system simulated in GEANT4.

Initial testing of this system was conducted using the VULCAN Petawatt laser of the Central Laser Facility (CLF) at the Rutherford Appleton Laboratory (RAL), using an irradiation setup for radiobiology studies [7]. Pulses of 600 J energy and ~500 fs durations were focused to intensities > 10^{20} W/cm^2 onto 15 µm Au targets, producing protons up to 45 MeV, dispersed using a 0.9 T dipole magnet. The acquisition of absorbed dose is obtained through a Wheatstone bridge used in combination with a sensing thermistor network. The instrumentation is controlled by a software developed 'in-house', with the acquired temperature data exported to output files from which it can be analyzed and finally converted to a measure of absorbed dose. Doses in the range of 1-3 Gy per pulse were produced in the energy range between 15 and 40 MeV and delivered to the sensitive area (the thermistor containing core) of the calorimeter. A very good signal-to-noise ratio, evident from the temperature rise in Figure 3, was obtained despite the harsh environment. It was an initial concern that the generation of large electromagnetic pulses (EMP) during laser-target interaction would disrupt the signal. Removing the calorimeter from the beam path allowed an ad-hoc assessment of this effect, showing no cause for concern. A limited number of shots were performed using the SPGC, with an average dose rate reaching 10^9 Gy/s. This demonstrated the proof of this principle, highlighting the feasibility of applying calorimetry techniques in a laser environment.

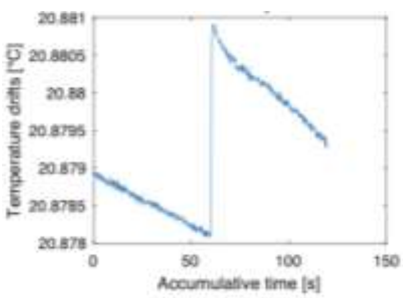

Figure 3. Measured radiation induced temperature rise of the SPGC core for a shot performed with the VULCAN laser system. This represents the first laser-driven proton beam captured by through calorimetry.

Conclusions

Delivery of highly pulsed ion beams through laser-driven acceleration has stimulated interest in its applications in a biomedical context. The harsh experimental conditions created during laser-target interaction, and extremely dose-rates of the accelerated beam, leaves many detectors for absorbed dose measurements unusable. An innovative device is presented here, showing the capability of performing dosimetry of laser-driven protons through calorimetry techniques at the high dose-rates involved. This represents the first measurement of its kind, successfully applying established methods of measuring the absorbed dose of clinical proton beams to a laser environment.

References

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