Development of a laser driven electron source for radiobiological applications

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Abstract

We report on the characterisation of a laser driven electron source for radiobiological applications. Doses in excess of 3 Gy were generated by a laser driven plasma wakefield accelerator. The electron beam duration is expected to have a duration on the order of 20 fs, indicating unprecedented dose-rates in excess of $\times 10^{13}$ Gy/s are expected. The stability of the source was characterised and its applications to radiobiological research discussed.

1 Introduction

To date, radiotheraputic techniques remain the most effective way of treating cancer worldwide [1]. This is despite the fact that it is possible to induce harmful side-effects such as secondary cancers [2]. Recent advances in radiotherapeutic techniques have focused on the precision and method of dose delivery, including treatments such as conformal radiotherapy (CRT) or intensity modulated radiotherapy (IMRT). In CRT and IMRT, the irradiation field is precisely shaped to match the size of the tumour thus reducing the dose to surrounding tissues and organs at risk [3]. However, under these conventional dose-rates, tumour cells are more radioresistant due to their naturally lower oxygen concentration [4].

Over the past decade, it has been proposed to increase the dose-rate to higher levels ($\sim$100 Gy/s). This technique, known as FLASH radiotherapy, has been shown to decrease the radiosensitivity of healthy cells while maintaining tumour control [5, 6]. This effect was initially attributed to the local depletion of oxygen, but this theory has come under recent question [7].

An alternative avenue of research has been proposed, where the dose-rate is further increased to levels in excess of $> 10^8$ Gy/s, now known as ultra-high dose-rate radiotherapy (UHDR). Here, the duration of the radiation starts to reach timescales comparable to the initial response of the cell to ionising radiation [8]. It is possible to reach these regimes with laser-driven sources, however recent work has been limited to accumulation dose over multiple pulses [9, 10, 11] or single-shot irradiations with a nanosecond-scale duration [12, 13, 14].

Recent advances in LWFA have shown that it is possible to generate relativistic electron beams (>100 MeV) with high charge (>nC). An intrinsic property of these electron beams is that they are produced with a duration of tens of femtoseconds. Notably, these high charge electron beams are capable of delivering Gy-scale doses in a single pulse with an irradiation area suitable for in-vitro and in-vivo radiobiology studies. Here, we experimentally demonstrate the capabilities of a LWFA source to provide a platform for femtosecond-scale, UHDR radiobiological research.

2 Experiment set-up

The experiment was performed using the Gemini laser at the Central Laser Facility (CLF). A simplified sketch of the set-up is shown below in figure The laser was focused using an F/40 off-axis parabola 5 mm above a 15 mm supersonic conical gas jet. 1. The normalised laser inten-

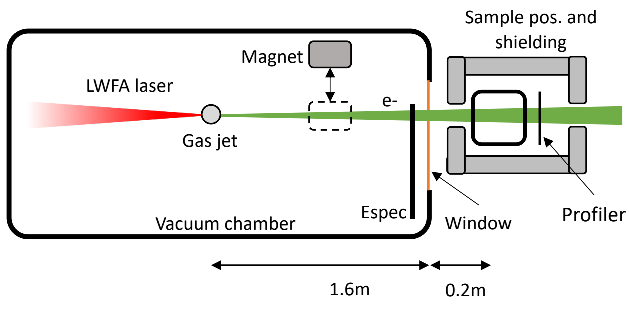

Figure 1: Simplified sketch of the experimental set-up. The 'south' laser is focused with an F/40 OAP onto the gas jet to drive the wakefield accelerator. A permanent magnet was mounted on a 30 cm stage to be moved in and out of the electron beam path for spectra measurements or irradiations respectively. Cell samples, RCFs and on-axis LANEX screen were housed in a lead box outside the vacuum chamber.

sity was measured as a_0=1.5±0.1. A mixed gas target of 2% nitrogen and 98% helium was used to induce ionisation and maximise the beam charge.

A permanent dipole was mounted on a 30 cm stage to allow electron spectra measurements or free propagation of the electron beam into the sample lead housing. A second LANEX screen was mounted inside the lead housing and dose-calibrated with EBT3 gafchromic film (RCF) [15]. This acted as an online dose and profile measurement during optimisation and characterisation. Final absolute dose measurements from the optimised electron source were measured with calibrated RCF films.

3 Main results

The electron beam was characterised with the dipole magnet for electron energies >200 MeV. A broadband energy spectrum up to a peak energy 760± 70 MeV was achieved with a charge N_e=1.9± 0.3 nC. The magnet was removed and the dosimetric properties of these beams were measured.

The duration of these electron beams can be estimated based on the radius of the plasma bubble generated (r_b). The duration of the electron beam, τ_e, can be estimated as $r_b/c = 2\sqrt{a_0}/\omega_p$, where ω_p is the plasma frequency [16]. For the parameters measured in this experiment, τ_e is estimated to be approximately 20 fs.

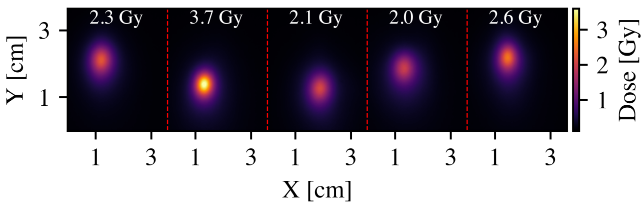

Figure 2: Dose profile and pointing stability for 5 consecutive shots after optimisation. The peak dose for each shot is printed in white. Consecutive shots are separated by a dashed red line.

The dose measured on the LANEX screen for 5 consecutive shots is shown in figure 2. It is evident that the electron beam exhibits both shot-to-shot pointing and dose fluctuations. This pointing fluctuation can be contributed to the pointing of the LWFA laser, shot-to-shot instabilities in the plasma channel and fluctuations in laser parameters [17]. The root-mean-square deviation in electron beam pointing was measured to be 3.2 mrad.

Both the dose and spatial position fluctuations limit the application of this source to radiobiological studies, which require strict dosimetry for effective measurement of biological outcomes. However, mapping of the dose to the irradiated cell area can allow for some studies to be performed, such as the induction of DNA double strand breaks on cell monolayers [18].

4 Conclusions

In conclusion, our study presents a comprehensive characterisation of a laser driven electron beam produced by the Gemini laser. Preliminary measurements indicate that doses exceeding 3 Gy can be attained within an estimated duration of approximately ∼20 fs. Notably, this electron source enables unprecedented dose rates in excess of $\times 10^{13}$Gy/s to be achieved. Importantly, the duration of the electron beam aligns with the initial cellular response to ionising radiation, allowing for a unique regime of radiobiological research to be investigated.

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