Laser-hybrid Accelerator for Radiobiological Applications (LhARA)

Conceptual Design Report

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Executive summary

Radiotherapy is central to cancer treatment. X-ray therapy is the most common modality and is performed using a source that modulates the beam intensity as it rotates around the patient. The energy deposited by X-rays falls exponentially with depth. This limits the dose that may be delivered to a tumour without exposing healthy tissue to unacceptably high radiation levels.

Proton and ion (hadron) beams overcome the fundamental limitation of X-rays because the bulk of the energy is deposited in the 'Bragg peak' that occurs as the beam comes to rest. This allows a large dose to be delivered to the tumour while sparing healthy tissue. The maximum instantaneous dose that can be delivered is limited by todays ion sources, which produce ions with kinetic energies of tens of keV. At such low energies the repulsion between the ions causes the beam to diverge rapidly and limits the capture efficiency. The limitation imposed by such 'space-charge' effects can be mitigated by using a laser-driven source to create ions with energies of up to 15 MeV and capturing them using a strong-focusing plasma lens.

The 'Laser Accelerator for Radiobiological Applications', LARA, is conceived as a novel facility dedicated to the study of radiobiology. The technologies demonstrated in LARA have the potential to be used in future hadron-therapy facilities. LARA is a hybrid accelerator system in which laser interactions drive the creation of a large flux of protons or light ions that are captured using a plasma (Gabor) lens and formed into a beam. The conceptual design of LARA permits the facility to be built in two stages. In the first stage, a programme of in-vitro experiments will be served with proton beams with energies between 10 MeV and 15 MeV. The beam will be transported and focused using a series of Gabor lenses and dipoles. In stage two, the beam will be accelerated using a fixed-field accelerator with large dynamic aperture. This will allow experiments to be carried out in vitro and in vivo with proton beam energies of $\sim$ 70 MeV. In addition, ion beams with energies up to $\sim$ 15 MeV per nucleon will be available for in-vitro an in-vivo experiments. This paper presents the conceptual design for LARA. Emphasis is placed on a detailed description of the first, in-vitro, stage of the implementation of LARA. The conceptual design of the post-accelerator required in stage two is summarised.

Lay summary

Lay summary; lead author to be defined.

1 Introduction

High-power lasers have been proposed to serve as the basis of electron, proton and ion-beams for radiotherapy and radiobiology. Such beams have the potential to overcome the space-charge limitations that restrict the instantaneous dose rate that can be achieved using conventional ion sources. Modern lasers are capable of delivering XX J in femptosecond pulses at repetition rates of $\gtrsim 10$ Hz. This makes it possible to consider a variety of time structures in which the dose is delivered. At source, a laser-driven electron beam is reproducibly well collimated and has a modest ($\sim 5\%$) energy spread. By contrast, laser-driven proton and ion sources create beams that are highly divergent, have a large energy spread, and an intensity that varies by up to 40% pulse-to-pulse. Multiple ion species, from proton to carbon, can be produced from a single laser by varying the target foil and particle-capture optics. The realisation of a practical demonstration requires that each of these issues be addressed.

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2 Motivation

Lead author: JPar, JY, KL

3 LhARA facility

3.1 Overview

Lead author: KL, JPar

3.2 Laser-driven proton and ion source

Lead author: OE, ZN

3.2.1 Technical challenges and R&D programme

3.3 Proton and ion capture

Lead author: JPo, CW

3.3.1 Technical challenges and R&D programme

3.4 Beam transport and delivery to the in-vitro end station

Lead author: JPa, WS

3.4.1 Technical challenges and R&D programme

3.5 Post-acceleration and beam delivery to in-vitro and in-vivo end stations

Lead author: JPa, WS

3.5.1 Technical challenges and R&D programme

3.6 Instrumentation

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3.6.1 Technical challenges and R&D programme

3.7 Software and computing

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3.7.1 Technical challenges and R&D programme

3.8 Staging considerations

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3.8.1 Technical challenges and R&D programme

3.9 Biological end stations

3.9.1 In-vitro end stations

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3.9.2 In-vivo end station

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3.9.3 Development of radiobiological capability

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4 Infrastructure and integration

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5 Conclusions

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A Timeline

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B Costs

Lead author: AK

C Risk analysis

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