Laser-hybrid Accelerator for Radiobiological Applications

Conceptual Design Report — Statement of Interest

The 'Laser-hybrid Accelerator for Radiobiological Applications', LhARA, is a novel hybrid accelerator in which laser interactions create a large flux of protons or light ions which are captured, formed into a beam and accelerated. The hybrid approach harnesses the unique properties of the laser-driven source: delivery of a range of ion species (p to C^{6+}) from a single source in ultra-short pulses that each deliver an enormous instantaneous dose. LhARA will be a uniquely flexible radiobiology facility serving experiments over a broad range of beam momentum and dose rate. By removing the dose-rate limitation of conventional ion-beam sources, LhARA will allow detailed investigation of FLASH (ultra-high dose-rate) radiobiology. The technologies demonstrated in LhARA may be developed for use in a new generation of similarly flexible hadron-therapy facilities.

The 'Centre for the Clinical Application of Particles' (CCAP) has recently been established at Imperial. The CCAP is ab initio a multidisciplinary collaboration between Imperial's Department of Physics, Faculty of Medicine, Academic Health Science Centre, the Imperial CRUK Cancer Centre, the Institute of Cancer Research, the John Adams Institute and the Oxford Institute for Radiation Oncology. The development of the Centre is a strategic priority for Imperial and the development of LhARA is central to the CCAP's programme.

With this Statement of Interest (SoI) we seek the resources to recruit a post-doctoral researcher for two years and a post-graduate student. Together, the two early-career researchers dedicated full time to the development of LhARA will leverage the effort of experienced personnel from the participating institutes to deliver a CDR for LhARA which will be presented in a refereed journal. During the preparation of the CDR we shall engage with stakeholders from the clinical, radiobiological, academic, and industrial communities so that when the CDR is published it will be possible to propose the staged development of the facility.

Motivation

In the UK, Europe, Asia, and the Americas, interest in proton- and ion-beam therapy is growing and a significant growth in demand is anticipated[1]. Analysis of the trends in cancer diagnosis and treatment indicates that, by 2035, 26.9 million life-years in low- and middle-income countries could be saved if the radiotherapy capacity could be scaled up[1]. There is powerful evidence that the investment required for this expansion would generate substantial economic gains as well as reduce the global cancer burden[1]. Novel techniques such as those proposed here are required if the necessary increase in capacity is to be delivered and the footprint and cost of particle-beam therapy is to be reduced.

Relative biological effectiveness (RBE) is the ratio of the dose of a reference radiation (X-rays) to the dose that must be delivered using proton or ion beams to achieve the same biological effect. RBE is known to depend on a variety of factors including energy, dose, dose-rate, tissue type, and ion species[2]. However, today a representative RBE value of 1.1 is used in proton-beam treatment-planning systems, for carbon, an RBE-weighted dose is used. This is sub-optimal and a systematic programme of radiobiology is required to underpin the development of a micro-biophysical understanding of proton- and ion-tissue interactions with precision sufficient for their biological effectiveness to be simulated and used with confidence to enhance hadron-beam therapy.

The hybrid, laser-driven approach that we propose is uniquely well suited to the radiobiology programme because it allows: a wide variety of ion species to be delivered using a single source; a very large instantaneous dose to be delivered because of the high capture-efficiency of the strong-focusing plasma (Gabor) lenses; a wide range of energy to be delivered using a single post-accelerator with large dynamic aperture based on the fixed-field accelerator (FFA) principle.

Context and opportunity

Laser-driven ions have been posited as a source for radiobiological studies for a number of years[3]. However, to date the ion energies, energy spread, and shot-to-shot variability of the flux produced has meant that such sources were not suitable to serve a radiobiology laboratory. A number of radiobiology experiments have been conducted with laser-accelerated ions, but these

have been limited in scope to single-shot illumination, either due to low laser repetition rates or the lack of a target suitable for high repetition-rate operation. Most of these experiments have been performed on facilities for which radiobiology has not been the highest priority. Until now, no attempt has been made to capture and manipulate the laser-created ion flux to produce a 'production-ready' beam. The facility proposed here will therefore be unique.

Our concept for LhARA[4] has been developed to prove the principle of the technologies required to deliver a highly-versatile hybrid, laser-driven system for clinical radiotherapy. The creation of a world-leading, proton- and ion-beam radiobiology facility using techniques that have the potential to drive a paradigm shift in the provision of particle-beam therapy is exciting and of substantial scientific and technological interest. The subsequent exploitation of the facility to deliver definitive systematic studies of the micro-biophysical impact of proton and ion beams is well aligned with the mission of research-led institutions. The proposed development of LhARA has the potential to place the UK at the forefront of the development of the next generation of accelerators for scientific and clinical application.

LhARA

We propose that LhARA be developed in two stages. In the first stage, a programme of in-vitro experiments will be served with proton beams of energy $\sim 15\,\mathrm{MeV}$. The laser-driven beam will be captured, transported and focused using a series of Gabor lenses and bending magnets. In stage two, the beam will be accelerated using an FFA with large dynamic aperture capable of accelerating a range of ion species to the required energies. This will allow experiments to be carried out in vitro and in vivo with proton-beam energies of $\lesssim 75\,\mathrm{MeV}$. In addition, ion beams (including C^{6+}) with energies up to $\sim 20\,\mathrm{MeV}$ per nucleon will be available for in-vitro and in-vivo experiments.

The initial concept for the LhARA ion source is based on a titanium-sapphire laser delivering a peak power of 15 TW in short pulses ($\sim 35\,\mathrm{fs}$) at a repetition rate of 10 Hz. The laser is focused onto a thin foil target where plasma-sheath acceleration creates a divergent beam. Initial simulations indicate that fluxes in excess of 10^9 protons-per-shot will be delivered to the in-vitro end-station at an energy of $\sim 15\,\mathrm{MeV}$. The natural divergence of the beam at source is exacerbated by the mutual repulsion of the ions. Two Gabor lenses will be used to capture and focus the highly-divergent flux and form it into a beam. The negatively-charged plasma confined within the lens provides a strong focusing effect for positive ions and efficiently manages the space-charge forces. The Gabor lens is a cost-effective solution; to produce the same focusing effect using conventional magnets would require superconducting solenoids and would result in a reduced capture efficiency as the presence of the cryostat would increase the drift length between the target and the first magnetic-focusing element.

The beam emerging from the capture system will be collimated to select the desired momentum and amplitude. A second pair of Gabor lenses will be used to vary the size and divergence of the output beam. Downstream of the second Gabor-lens-doublet beam-transport will be provided by conventional magnetic elements, including a horizontal switching dipole at which the beam is directed either to the transport line serving the in-vitro end-station or to the FFA post-accelerator. The FFA ring will be developed in close collaboration with the ISIS Department at RAL since the R&D required to deliver the proof-of-principle system that is proposed as part of the the ISIS upgrade R&D programme is closely aligned with that required to realise the LhARA FFA and will, most probably, be based on the same technology.

Beam-delivery to the in-vitro and in-vivo end-stations will include elements to allow raster scanning with variable spot-size. Beam diagnostics will ensure the proper dose and spectrum is delivered to 2D and 3D biological samples and in-vivo experiments.

Impact

The work proposed here is the essential first phase in a programme that can deliver a step-change in capability; the delivery of ions from p to C^{6+} in a single facility over a range of momentum and with instantaneous dose rates up to those required to study FLASH radiotherapy. We shall use the opportunity created by the delivery of the CDR to bring together the coalition of clinicians, researchers, facility-providers and industrialists necessary to propose and execute the staged development of LhARA, thereby proving the principle of hybrid, laser-driven acceleration and delivering a uniquely flexible facility for the systematic study of radiobiology.

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