Laser Accelerator for Radiobiological Applications (LARA)

Conceptual Design Report — Statement of Interest

Recent advances in the laser-driven acceleration of charged particles make it possible to conceive of a compact, hybrid accelerator in which laser interactions drive the creation of a large flux of protons or light ions which are captured, formed into a beam and accelerated. We propose to combine a laser-driven source with plasma-lens focusing to remove the instantaneous-flux limitation of conventional ion sources. The resulting ion beam may be exploited directly or injected into an accelerator to raise its energy to that required for the chosen application.

The 'Laser Accelerator for Radiobiological Applications', LARA, is conceived as a novel facility that harnesses the unique properties of the laser-driven source to serve a radiobiology programme with a variety of ion species over a wide range of dose rates in a single facility. LARA will prove the principle of the technologies required to exploit the novel, hybrid, laser-driven approach. The experimental programme that LARA will serve has the potential to underpin the development of the detailed, micro-biophysical understanding of proton- and ion-tissue interactions required to enhance the treatment-planning systems of the future. The technologies demonstrated in LARA may be developed for use in future hadron-therapy facilities. Therefore, LARA has the potential to drive a paradigm shift in the delivery of proton- and ion-beam radiotherapy.

With this Statement of Interest (SoI) we seek the modest resources required to deliver a Conceptual Design Report (CDR) for LARA. We seek to recruite 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 the LARA conceptual design will leverage the effort of experienced personnel from the Centre for the Clinical Application of Particles (CCAP) at Imperial and the John Adams Institute. We propose to complete the CDR over a two-year period, presenting the completed report in an appropriate refereed journal. During the preparation of the CDR we propose to 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 implementation of the facility.

Motivation

Cancer is the second most common cause of death globally. It is estimated that radiotherapy is indicated in half of all cancer patients. Today's radio-therapy facilities allow the X-ray dose to be concentrated over the tumour volume. However, the dose delivered falls exponentially with depth. Therefore, the location of primary tumours in relation to heart, lungs, oesophagus, and spine implies a fundamental limit on the photon-dose intensities that may be delivered.

Proton and ion beams lose the bulk of their energy as they come to rest in a pronounced 'Bragg peak'. Such beams overcome the fundamental limitation of X-ray therapy because, in comparison to photons, there is little (ions) or no (protons) dose deposited beyond the distal tumour edge, saving a factor of 2–3 in integrated patient dose and allowing the treatment to be conformed to the tumour volume.

Interest in proton-and ion-beam therapy is growing in the UK, in Asia, Europe, and the Americas and a significant growth in demand is anticipated. 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. There is powerful evidence that the investment required to scale-up provision would generate substantial economic gains as well as reduce the global cancer burden. Novel techniques such as those proposed 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. A representative RBE value of 1.1 is used in proton- and ion-beam treatment-planning systems. 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 with confidence. The simulations will allow enhanced treatment-planning systems to be developed that account for variations in RBE with ion species, tissue type, etc.

The Laser Accelerator for Radiobiological Applications will serve the necessary systematic programme of in-vivo and in-vitro measurements with a variety of ion species over a wide range of energy. In addition, our concept for LARA has been developed to prove the principle of the technologies required to deliver a 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 such as Imperial College London. The proposed development of the Laser Accelerator for Radiobiological Applications, therefore, has the potential to place the UK at the forefront of the development of the next generation of accelerators for scientific and clinical application.

LARA

Our concept for 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 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 a fixed-field accelerator with large dynamic aperture capable of accelerating the required range of ion species and of extraction at a range of beam 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 ^{6}+C with energies up to $\sim\sim 20\,\mathrm{MeV}$ per nucleon will be available for in-vitro and in-vivo experiments.

The initial concept for the LARA ion source is based on a titanium-sapphire laser delivering a peak power of 15 TW in short pulses (35 fs) at a repition rate of 10 Hz. The laser is focused onto a thin foil target presented in the form of a tape. Plasma-sheath acceleration creates a divergent beam containing protons and other ions. Initial simulations indicate that fluxes in excess of 10^9 protons-per-shot will be delivered at an energy of $\gtrsim 10\,\mathrm{MeV}$. The natural divergence of the beam at source is exacerbated by the mutual repulsion of the ions. Two novel, strong-focusing Gabor lenses will be used to capture and focus the highly-divergent flux and form it into a beam. Each Gabor lens will contain an electron plasma contained by crossed electric and magnetic fields. The negatively-charged plasma provides a strong focusing effect for positive ions and efficiently manages the 'space-charge effect' created by the ions mutual repulsion.

The beam emerging from the Gabor-lens capture system will be collimated to select the beam in 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 either deflected upwards to the in-vitro end-station or deflected horizontally and transported to the FFA post-accelerator.

Laser-driven plasma sources create a range of particle species. Therefore, the transport line must include elements to select a single ion species. In LARA this will be achieved by combining collimation after the Gabor-lens based capture section using electrostatic focusing with collimation in the magnetic bending sections at the switching dipole. Post acceleration will be provided by a fixed-field accelerator (FFA). The large dynamic apperture of the FFA will allow the requisite variety of ion species to be accelerated. The FFA ring will be developed in close collaboration ISIS Department at RAL since the R&D required for the FFA proposed for the ISIS upgrade is closely aligned with that required to realise the LARA FFA and will, most likely will be based on the same technology.

Beam-delivery to the in-vitro and in-vivo end-stations will include elements to allow the spot size to be varied from 1 mm to 10 mm and a scanning system to allow a raster-scan to be executed, together with beam diagnostics system to ensure the proper dose and spectrum to be delivered to the samples.