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 today's 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.

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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.

Lead author: KL, JPar

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

Laser-driven ions have been posited as a source for radiobiology studies for a number of years [refs]. Until now, however, the achievable ion energies, energy spreads, and reproducibility of such beams have meant these sources are not suitable for a full radiobiology laboratory setting. While a number of radiobiology experiments have been conducted with laser-accelerated ions, these have been limited in scope to a single shot configuration, either due to low laser repetition rates or due to a lack of target solutions for high repetition rate operation. Finally, most of these experiments have been performed on laser facilities with rapidly shifting priorities, and where the time to install dedicated and automated diagnostics and control has been impossible. To this date, a production ready ion beam source based on lasers is not available anywhere in the world. As such, the proposed facility would be a unique, state of the art system for the study of radiobiology experiments, able to exploit the numerous benefits of a laser-accelerated ion source.

Conventional ion sources are capable of producing ions of the order 10's keV with relatively modest currents (of the order 100's μA [Osmic2012]) owing to space charge effects. These are then post accelerated to the required energy, requiring large, expensive systems not often suitable to a clinical setting. A novel solution to these problems is to utilise the compact, flexible nature of a laser-driven source and couple this to a conventional beam transport line. We propose operating in a sheath acceleration regime [REFS - Clark2000, Snavely2000,

Daido2012?] for ion generation, without question the most studied and best understood scheme for laser-driven ion acceleration at present. An intense, short pulse laser is focussed onto a target, whereby the intense laser field ionises the front surface target electrons and accelerates them into the target. Should they gain sufficient energy, such electrons can traverse the target, ionising as they go, before exiting the rear and forming a strong space charge electric field; the sheath. This field in turn accelerates ions from the rear of the target. This scheme has been shown to produce ion energies greater than $40\,\mathrm{MeV/u}$ at the highest laser intensities [REF], with the peak proton energy scaling with laser intensity as, $E_p \propto I^{1/2}$; the laser intensities required to reach $< 10\,\mathrm{MeV}$ are much more modest and can be obtained with relatively laser intensities. Such laser systems can therefore be compact, relatively inexpensive, and are commerically available.

Key to the operation of this configuration is a repeatable and reproducible target solution from which to accelerate the ions of use. A number of schemes have been proposed for such studies, from high pressure gases, cryogenic hydrogen ribbons [Margarone PRX 2016, Gauthier Appl. Phs. Lett. 2017, L. Obst, Sci. Rep 2017], liquid sheets [Morrison New. Jour. Phys. 2018] and tape drives. For the proposed facility, a tape drive is proposed. Imperial College scientists have operated tape drives at target thicknesses down to $5\mu\mathrm{m}$ Al and Fe (steel) foils, and $18\mu\mathrm{m}$ plastic targets. These have the benefit of being readily and continuously replenishable, allowing high-charge (up to $100\,\mathrm{pC}$ at $8.9 \pm 1\,\mathrm{MeV}$ i.e. $> 10^9$ protons per shot), high-quality proton and ion generation at up to 10Hz or even greater. It has been demonstrated that one crucial aspect of making a tape drive as reproducible is to carefully control the tension on the tape. The tape should be stretched to properly flatten the surface, without stretching it into its plastic response. This surface flatness is important for a number of reasons. Rippling of the front surface can modify the laser absorption dramatically; uncharacterised rippling can make shot to shot reproducibility significant and unpredictable. Similarly, rear surface perturbations can modify the sheath field, resulting in spatial non-unifiormities of the proton beam or suppression of the achievable peak energies. We have designed and implemented tape drives with torsion control and monitoring to be able to maintain such a high-quality tape surface. There is considerable ongoing work at Imperial College to further optimise the design of such targets. The work centres of further optimising the reproducibility and flatness of the targets, an essential requirement for stable ion generation. Work also centres on new, thinner tapes for improved ion generation conditions and more exotic ion species, besides protons and carbon. This is an active area of R&D, and will continue with the development of the proposed facility.

The scheme for LhARA is unique when compared with previous attempts to utilise laser-driven ion sources for radiobiological applications since most experiments have been performed in single shot configuration, with high latency diagnostics. Even applications have used low repetition rates, usually due to the lack of targetry to both generate the beams and for the material under investigation. Finally, most of these experiments have been performed on either low repetition rate laser systems, or on laser facilities with rapidly shifting priorities, where the time to install dedicated and automated diagnostics and control has been impossible. The proposed system therefore offers a number of opportunities to push the frontiers in the field of laser-driven ion acceleration, in sustained high frequency ion generation, advanced targetry solutions and active, high repetition rate diagnostics. The successful development and execution of such methodologies would, without question, provide a leap forward in terms of capability for the field and open up the exciting new opportunities for applications not just in radiobiology, but also medical isotope production and materials processing. The target and diagnostic solutions which will be developed throughout the project will provide a step change in the possible laser-driven ion experiments and applications.

Similarly, the flexibility of these laser sources in terms of the continuous spectrum of ion energies available, and variable species selection provides a uniquely capable source for radiobiology studies; something traditional sources simply cannot provide. This includes systematic studies of the radiobiological effects of so called "ultra-high" dose rates; it would be expected fluxes in excess of the $\sim 100\,\mathrm{Gy}$ total irradiation dose for a tumour can be produced in a single shot. These features, along with the extremely high current beams which

can be produced result in a singular source solution which can provide unprecedented levels of flexibility for radiobiology experiments.

Important/Impact/New Horizons to the field: - Smaller footprint / lower cost? - Simple species and energy selection - Access to very high fluxes - Novel scheme not yet achieved - New radiobiology studies

Some mention of R&D process... High repetition rate operation of laser-driven sources is a relatively new, but active area of interest [REFs]. While such operating schemes pose a number of engineering challenges (consider radiation), they also offer the opportunity for enhanced acceleration output through machine learning and genetic algorithm based techniques [refs - Andreas Maier, Matt/TA2 stuff]. These have proved remarkably successful in producing enhanced particle beams, optimised for beam charge, peak energy, energy spread and divergence etc. While much of this research has so far focussed on electron beam production and x-ray yields, such methods should translate well to ion acceleration. These techniques will require appropriate R&D effort, which we envisage shall be possible using the existing laser capabilites within the laser-plasma group at Imperial College. High repetition rate ion beam diagnostics will also need to be produced to allow successful execution of the proposed facility. These will need to measure both energy composition and the spatial profile of the beams. Current methods are entirely destructive, and often low repetition rate; unsuitable for the proposed facility. To date and our knowldge, passive detectors have not been demonstrated successful, despite much effort. This is a problem that will require significant R&D effort. Insert something at the scintillator thing Ajit is meant to be building.

3.2.1 Technical challenges and R&D programme

No major R&D needed for the laser since it will be a commercial system. Target particle production and diagnostics.

3.3 Proton and ion capture

Lead author: JPo, CW

3.3.1 Technical challenges and R&D programme

Gabor lens prototype development and performance verification.

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

No major R&D needed. Effort required to do technical design of the magnet/ write tender documents.

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

FFA: Magnet design and prototyping. FFA: RF cavity performance verification.

3.6 Instrumentation

Lead author: JM

3.6.1 Dose calibration for high-intensity beams

3.6.2 Online dose monitoring

Smartphantom

3.6.3 Beam diagnostics for the low energy beam

SciWire

3.6.4 Beam diagnostics for the high energy beam

Probably conventional diagnostics.

3.6.5 Fast feedback controls and monitoring

3.6.6 Technical challenges and R&D programme

3.7 Software and computing

Lead author: WS, AK

3.7.1 Technical challenges and R&D programme

3.8 Staging considerations

Lead author: AK

The LhARA facility will be constructed in two stages. The facility will be sited in either an existing building that will be refurbished for the installation of LhARA or a new building will be constructed. The principle components of Stage 1 will include:

- the laser source and target;
- the capture, matching and energy selection beam line;
- the low energy in vitro arc; and
- the low energy in vitro end station.

The installation and commissioning of these components will be coordinated such to maximise the scientific output of LhARA and so even before Stage 1 is complete the goal will be to achieve the following scientific milestones:

- First irradiation of cells with a laser–driven ion beam

Stage 2 will then incorporate:

- the FFA;
- the extraction line from the FFA and the transfer line to the in vivo end station;
- the high energy in vitro arc;
- the high energy in vitro end station; and
- the in vivo end station.

This will allow optimising the performance of the first part of the accelerator chain whilst at the same time delivering an in vitro radiobiology programme using 15 MeV protons.

Intermediate scientific milestones

Option to construct parts of Stage 2 whilst running. • Maximise scientific output. • Shielding blocks to cordon off stage 1. • Would need detailed simulations for radiation protection. • Much of Stage 2 could be constructed with only the connection between the stage 1 beam line and the injection line for the FFA requiring beam to be off.

Upgrade options longitudinal phase space manipulation (in the capture and transfer line to in vivo) micro-beams using combs

3.8.1 Technical challenges and R&D programme

3.9 Biological end stations

3.9.1 In-vitro end stations

Lead author: JPar, JH, HTL

3.9.2 In-vivo end station

Lead author: JPar, JH, HTL

3.9.3 Development of radiobiological capability

Write about automation here?

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4 Infrastructure and integration

Lead author: JTh, GA

4.1 Facility layout

The LhARA facility will encompass two floors of roughly 42 m length and 18 m width. The ground floor will contain the laser, accelerator, in-vivo end station and required support equipment and facilities. The first floor will house the laboratory area and the two in-vitro end stations. The location of this facility is expected to be at an STFC National Laboratory or equivalent research institute. Depending on the available locations, an existing building or a new construction will be used.

The entire facility will require radiation protection in the form of concrete shielding, which will delineate the facility into three principal areas: a radiation controlled access area, a laser controlled access area and a laboratory limited access area. The radiation controlled access area will contain the laser target (not including the laser source), Stage 1 and Stage 2 of the accelerator and all end stations. The laser controlled access area will contain only the laser source. Both controlled access areas will restrict machine operation while being accessed. The laboratory limited access area will contain all laboratory facilities and will not restrict machine operation while in use. Access to the radiation controlled areas is provided through interlocked labyrinth passages for personnel access and a removable interlocked shielding wall for equipment installation. The end stations will require additional internal shielding to lower the background radiation during experimentation.

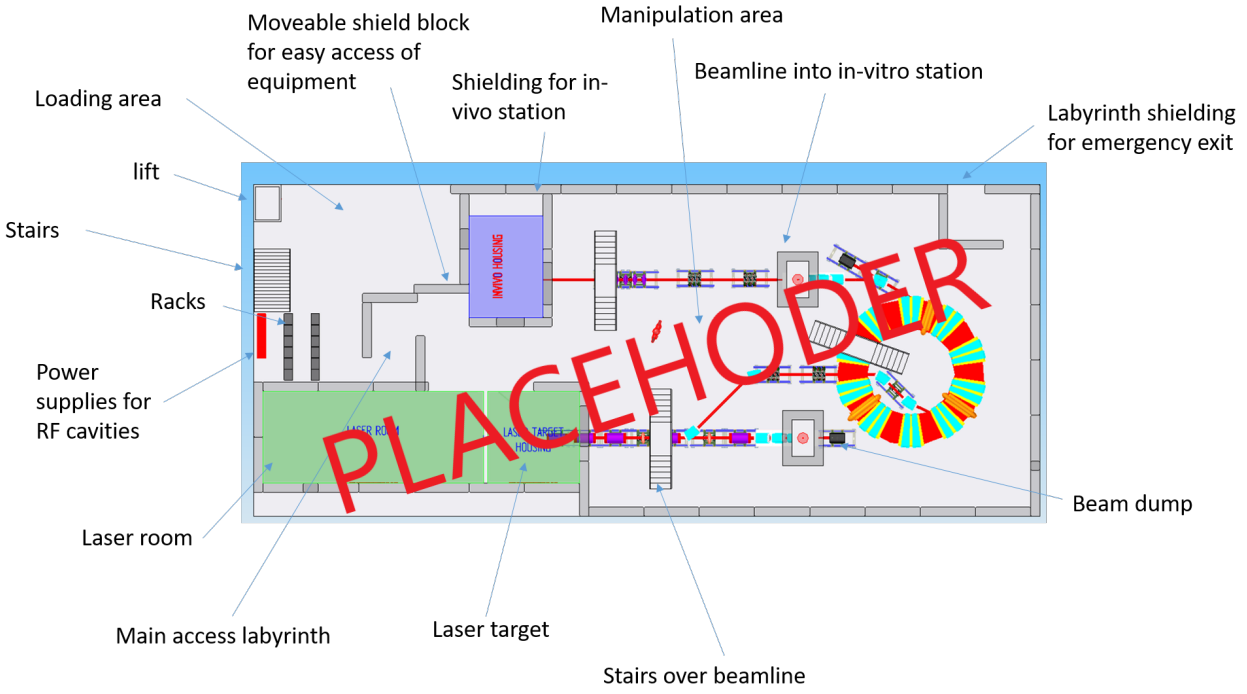

Figure 1: Top-down view of the floor layout

4.1.1 Laser rooms

The laser will occupy two rooms: a 12 m by 5 m room housing the laser system and a 5 m by 5 m room housing the laser target. There will be a shuttered pass-through between the rooms.

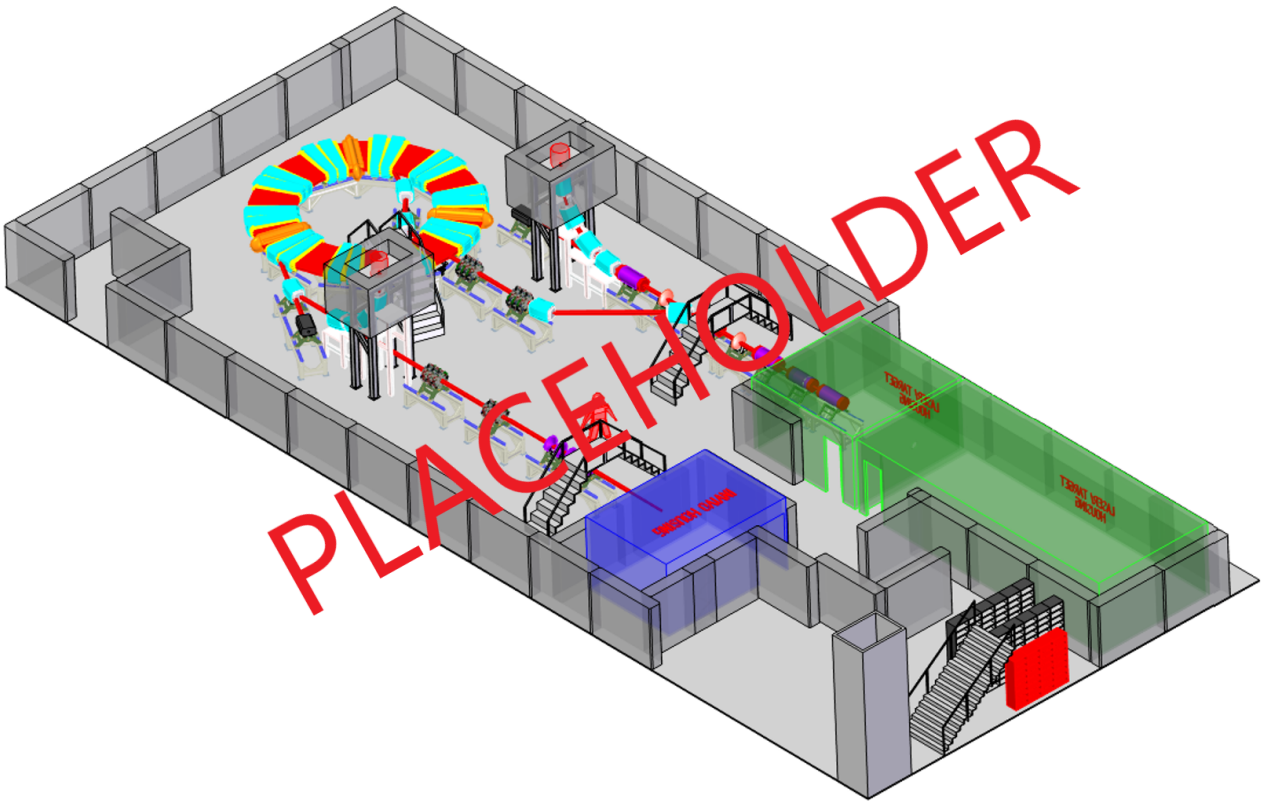

Figure 2: Isometric view of the floor layout

4.1.2 Stage 1 and Stage 2 accelerator

The accelerator area will contain both Stage 1 and Stage 2 of the accelerator and encompasses approximately 24 m by 18 m. It contains floor space for manipulation and maintenance of equipment. Bridges are provided for access to the edges of the accelerator and inside the FFA ring.

4.1.3 End stations

There will be three end stations: two in-vitro and one in-vivo. The first in-vitro station is placed at the end of Stage 1 of the accelerator and is accessed via the first floor laboratory. The second in-vitro station is placed at the extraction point of the FFA ring in Stage 2 of the accelerator and is accessed via the first floor laboratory. The in-vivo station is placed at the end of Stage 2 and is accessed via the ground floor.

4.1.4 Support equipment

Initial provisions have been made in the layout for the location of support equipment, such as power supplies and control systems. They are to be located outside of the radiation controlled access area due to the sensitivity of the electronic equipment. Space will also be made available for plant systems, such as water, electrical and air handling.

4.2 Safety

It is assumed that LhARA will be built at an STFC National Laboratory or equivalent research institute which has an established safety management system and culture in place. At STFC a comprehensive set of Safety Codes has been developed to cover the hazards associated with working in such an environment. STFC Safety Codes applicable to the construction and operation of LhARA include:

- SC6 – Risk management
- SC13 – Construction (design and management)
- SC16 – Biological safety
- SC22 – Working with lasers
- SC23 – Working with time-varying electro-magnetic fields
- SC29 – Management of ionising radiation at work
- SC34 – Electrical safety
- SC40 – Alarms, trips and interlocks (in preparation)

In practice at STFC these codes are backed-up by the knowledge, skills and experience of staff and by appointed responsible persons such as Radiation Protection Advisors, Laser Responsible Officers and Authorising Engineers. For a laser/accelerator facility such as LhARA adherence to these codes will typically involve a process of hazard identification, risk assessment and mitigation including (but not limited to) appropriate shielding, an independently verified and audited Personnel Protection System (PPS), a full commissioning plan, written operating instructions, training and signage.

Although not strictly a safety system, consideration must also be given to a Machine Protection System (MPS) to ensure equipment is protected from damage caused by exceeding normal operating parameters.

4.2.1 Laser safety

STFC operates many high power lasers and has lasers with operating parameters comparable to those for LhARA – Gemini Target Area 2 operates at just below the energy conditions (0.5 J, 5 Hz, 30 fs) and Target Area 3 above (15 J, 0.3 Hz, 30 fs). Though lower repetition rates, the safety considerations on these facilities are the same and STFC is well equipped to mitigate and control the associated hazards and risks. Any challenges associated with the higher repetition rates (such as target debris and coating) are already being investigated as part of EPAC (Extreme Photonics and Applications Centre) , a much higher energy 10 Hz laser facility.

4.2.2 Accelerator safety

The ISIS and ASTeC departments in STFC have extensive experience in the operation of a variety of accelerator facilities and test stands. The most directly comparable to LhARA is the Front End Test Stand (FETS) , which is currently undergoing commissioning at Rutherford Appleton Laboratory. The FETS operating parameters (H^- ions, 3 MeV, 60 mA, 2 ms, 50 Hz) exceed LhARA in beam power, but at lower energy. The safety considerations for FETS are therefore similar to those for LhARA, and this in combination with experience of running the much higher power ISIS Neutron and Muon Facility, gives confidence that STFC is well equipped to mitigate and control the expected hazards and risks for the LhARA accelerator structure.

4.2.3 End stations

(to be completed by J Parsons)

4.2.4 Radiation

For a facility such as LhARA radiation safety is a primary concern.

Regulation 8 of the Ionising Radiations Regulations 2017 (IRR17) requires STFC to undertake a radiation risk assessment before commencing a new work activity involving ionising radiation. A radiation risk assessment will be considered suitable and sufficient if it addresses the requirements of paragraph 70 and 71 of the IRR17 Approved Code of Practice .

Particular matters to be considered under paragraph 70 are the nature of the sources/hazard, radiation dose rates, likelihood and levels of contamination, relevant dosimetry, engineering controls and design features, planned systems of work, suitable PPE, access restriction arrangements, reasonably foreseeable accidents/incidents, consequences of failure of control measures and steps taken to prevent or limit the consequences of accidents.

For paragraph 71 consideration must be given to actions to achieve ALARP, engineering control measures, PPE requirements, dose constraint requirements, measures for pregnant women and nursing mothers, investigation levels, maintenance and testing schedules for control measures, contingency plans, training, designation of areas, access restriction, classification of works, management responsibilities and performance monitoring.

4.3 R&D plan

Risk assessments

Radiation simulations

Controls, monitors and PPS development

5 Conclusions

Lead author: KL

A Timeline

Lead author: AK

B Costs

Lead author: AK

C Risk analysis

Lead author: AK

D References