LhARA, the Laser-hybrid Accelerator for Radiobiological Applications

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Abstract

LhARA [1] the 'Laser-hybrid Accelerator for Radiobiological Applications', will be a novel, uniquely flexible, facility dedicated to the study of radiobiology. LhARA will use a high-power pulsed laser to generate a short burst of protons or light ions. These will be captured using strong-focusing electron-plasma (Gabor) lenses. Acceleration using a fixed-field accelerator will deliver proton beams with energies up to 127 MeV and ion beams, such as C6+, with energies up to 33.4 MeV/nucleon. The laser-hybrid source allows high instantaneous dose rates of up to 10^9 Gy/s to be delivered in short (10–40 ns) pulses.

The laser-hybrid approach will allow the exploration of the vast "terra incognita" of the mechanisms by which the biological response to radiation is modulated by the beam's characteristics. The technologies to be demonstrated in LhARA have the potential to allow particle-beam therapy to be delivered in completely new regimens, providing a variety of ion species in a range of spatial configurations and exploiting ultra-high dose rates[2].

This contribution describes the status of the LhARA project in the context of the Ion Therapy Research Facility.

Introduction

Cancer was responsible for over 15% of deaths worldwide in 2020 [2], yet over 25 million life-years could be saved if radiotherapy (RT) capacity can be scaled up [3]. Approximately 50% of cancer patients will receive radiotherapy as part of their treatment. The majority of this is delivered utilising conventional techniques with MV X-rays, but proton and ion beam therapy (PBT) may offer significant advantages in some cases. These therapies currently utilise dose-rates of less than 1Gy/sec delivering fractionated treatment over the course of several weeks. Recent evidence points to potential benefits of using ultra-high dose-rates (>40 Gy/sec), so-called FLASH-RT.

Lhara

LhARA, the Laser-hybrid Accelerator for Radiobiological Applications, is a proposed state-of-the-art accelerator for radiobiological research. Serving the Ion Therapy Research Facility (ITRF), LhARA aims to develop & demonstrate novel technologies for generating and transporting proton & ion beams that will enable dose delivery well into the FLASH regime. A systematic radiobiology programme is currently in development by the LhARA collaboration, which will enhance the understanding of the interactions between high energy particles with biological tissue and lay the foundations for future generations of radiotherapy.

LhARA is conceived to be developed in two stages. Stage 1 will generate high flux proton and ion beams from laser-target interactions via the Target Normal Sheath Acceleration (TNSA) mechanism. Gabor electron plasma lenses will capture & focus the beam with a number of optical configurations offering flexibility of the transverse profile dimensions. Beam transport through a vertical matching arc will deliver the beam to a low energy, *in-vitro* end station located on the first floor of the facility. Stage 2 will see a switching dipole and beamline installed after the final Gabor lenses for subsequent beam injection into an FFA ring. An extraction line will transport the beams to two further end stations, one vertical beam *in-vitro* station and the other horizontal for *in-vivo* work. A pre-conceptual design report (pre-CDR) with a full description of the LhARA baseline design can be found in [1, 4].

Laser driven ion source

Laser sources offer significant advantages over conventional sources and are key to the performance of the proposed LhARA facility. The LhARA concept requires the following beam parameters, which we are designing the source to provide:

- 10^9 protons at 12-15 MeV ± 2% at 15 msr divergence
- 10^8 carbon at 4 MeV/u ± 2% at 15 msr divergence
- Production of other ion species
- 10 Hz repetition rate
- Long term operation

The proposed TNSA mechanism, through which the LhARA beam will be generated, is the most well established technology in the field of laser solid particle acceleration. Whilst other techniques may be capable of producing higher particle energies, TNSA is the best understood and is widely thought to offer the best shot to shot stability. That said, the impact of experimental conditions on the generated beam phase space is still to be understood. The performance of LhARA's baseline design was ascertained by tracking a beam generated from laser-target interaction simulations with the PIC code Smilei [5]. This beam, however, was limited to 2D due to the demanding computational requirements for a full 3D simulation, with the third dimension generated by extrapolation [6]. We are currently performing experimental and numerical studies to inform the LhARA design. High fidelity 3D particle-in-cell simulations (using the Osiris 4.0 framework [7]) are being used to predict the target and laser parameters for optimal beam generation. These predictions will be validated by experiments at the SCAPA laser facility at the University of Strathclyde. Further issues with debris and target delivery are also being investigated at the Zhi laser at Imperial College London.

Beam Capture with Gabor Lenses

Beams typically utilise B-field focusing either with solenoids or quadrupoles. The quadrupole option offers focussing in one plane only which can cause unacceptable losses for particles with high divergence in the orthogonal plane. Solenoids produce cylindrically symmetrical focussing effects but dissipate significant power at the strengths required for the LhARA beamline. An alternative is available using E-field-based techniques which may potentially offer higher focussing strengths and shorter focal lengths at much reduced power dissipation, if the technique can be proven. A cylindrical non- neutral plasma [6] offers the ideal system whereby the focusing length, (in terms of the electron number density, plasma length, and ion energy,) is given by

$$\frac{1}{f} = \frac{e^2 n_e l}{4\epsilon_0 U}$$

Such plasmas are readily confined in cylindrical Penning-Malmberg traps see fig. 1, and theoretically offer a significant (x40) reduction in focal length for a given B-field.

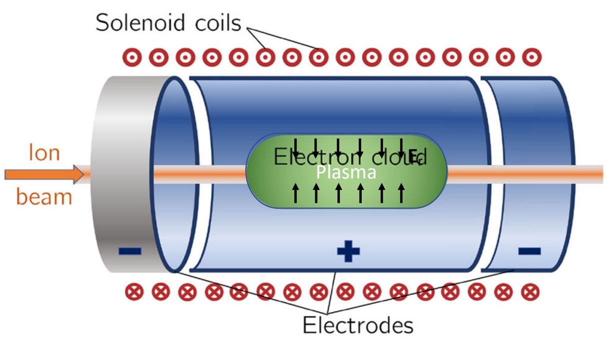

Figure 1. Penning-Malmberg trap

Ion Acoustic Imaging

Though great progress has been made recently in the stabilisation and repeatability of beams produced by TNSA, clinical application will require that the deposited dose distribution be measured in real-time. An ion-acoustic dose mapping system is under development for this purpose which exploits the ultrasound waves generated by the absorption of the ion beam energy. To evaluate the feasibility of this approach a hemispherical sensor array has been specified to evaluate the recovery of the relative spatial distribution of the absorbed dose using an iterative time-reversal algorithm. To confirm the fundamental ability of ion-acoustic imaging to recover the beam deposition profile, a three-stage simulation has been developed using Geant4 [8] and k-Wave [9]. The three stages are:

- generation of the beam-induced energy distribution
- pressure wave generation, propagation and detection,
- pressure-map reconstruction.

To compute each stage of the simulation, the active volume was split into cubic voxels with sides 0.1 mm.

End station user consultation.

The LhARA consortium includes extensive radiobiological expertise with further links to a wider range of researchers with an interest in radiobiology. In the currently funded period the collaboration envisages 4 consultation exercises, one of which has been completed and documented. To date the following key user requirements have been identified: the vertical beam lines are viewed as essential to retain. User end stations must provide atmosphere control for hypoxic investigations, and co-located areas for sample preparation are mandatory. The user stations must be served by automated handling equipment which may include robots, space for these must be included early in the engineering design.

A PhD studentship has been secured via EuPRAXIA-DN to work on the diagnostic challenges directly related to LhARA. An extensive literature review of beam diagnostic techniques for ultra-high-dose-rate beams is in progress to identify potential technologies or R&D areas. Work has also begun on adapting the gas profiler, identified as a potential diagnostic tool, which is minimally disruptive to the beam and allows monitoring of the beam intensity, profile, and energy. A successful application to the University of Liverpool Faculty Impact Scheme for £15k will allow gas-profiler measurements of protons and carbon ions during the summer of 2023 at the Dalton Cumbria Facility in Whitehaven.

Facility design and Integration

LhARA is conceived to be developed in two stages (see fig 2.) Stage 1 will deliver proton beams with energies in the range 12-15MeV +/-2% delivered via a vertical arc to an *in-vitro* end station. Stage 2 will extract the stage 1 beam before the vertical arc and post-accelerate it in an FFA before delivering the resultant 127MeV beam either via a second vertical arc to a second vertical beam end-station for high energy *in-vitro* work or to a horizontal beam *in-vivo* end station. To date, the majority of development work has been directed to Stage 1. The stage 1 beamline includes 5 Gabor lenses, to capture and focus the beam using several optical configurations to deliver a range of different beam sizes at the end station. The Gabor lenses are modelled as equivalent strength solenoids, with optimisation constraints of 1.4 T field limit which simultaneously constrains both the Gabor lens cathode voltage & magnetic field strength of contingency solenoid options.

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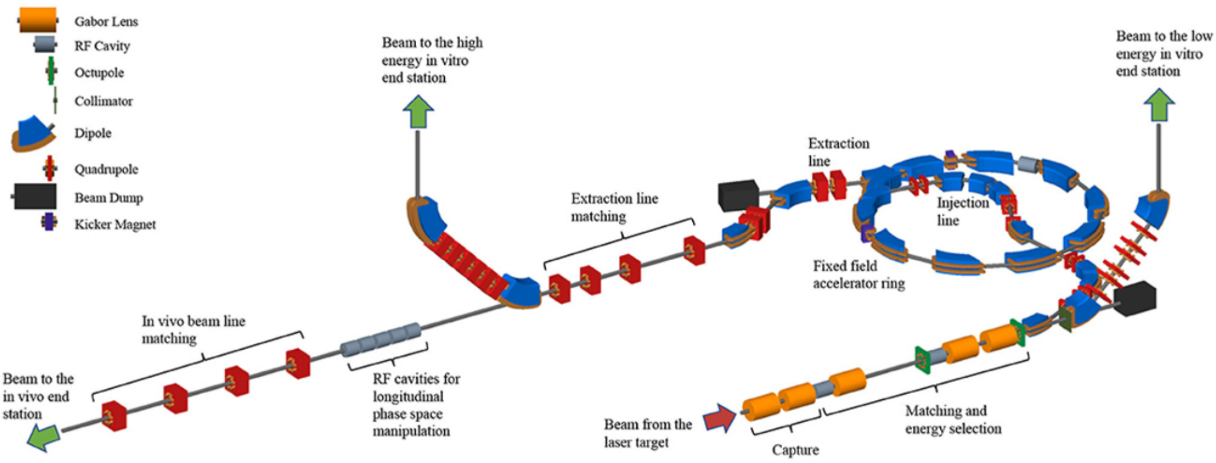

Figure 2: Illustration of proposed LhARA beamline showing FFA and 3 user end-station.

When considering particle transport modelling, we assume that the proton and electron beams generated by the laser-target interaction initially co-propagate, damping space charge effects. Modelling this scenario is non-trivial and further work is required either to validate the current assumptions or derive new conditions that better reflect reality. Hard data on particle distributions is available only for the small volume around the target which is modelled in the full 3D simulations. Propagating these distributions over the longer distances required for study of particle interactions between target and the first lens is not solved. For the studies presented here, we maintain our current strategy of down- sampling the proton beam to the 15 MeV ± 2% target energy, and assume that the beams co-propagate for 5cm after which the higher energy protons of interest have advanced beyond the lower energy electron beam.

The LhARA lattice was initially designed in Madx [10] & Beamoptics [11], neither of which consider space charge effects. Start-to-end particle transport modelling with the original beams demonstrated that space charge impacted the beam transport performance in stage 1, primarily due to further emittance growth between the nozzle and the first Gabor lens. Initial simulations in GPT showed similar performance issues, resulting in a non-ideal beam profile delivered to the end station.

To provide both the desired spot size flexibility & injection line operation, a new configuration is being investigated that includes a further two Gabor lenses. This new configuration has yet to be fully evaluated but initial indications are that it offers improved flexibility particularly in delivering smaller beam sizes to the end station and the FFA. The new configuration requires additional length in the beamline, but this can be accommodated within the building footprint as currently configured.

The LhARA building and technical infrastructure will require careful planning, design and implementation to ensure the facility delivers on its challenging scientific objectives and provides accommodation that inspires scientific research. The overall success of the facility requires an integrated approach for the high-power laser, target, capture, matching and energy selection of ions, accelerator, end stations, control rooms, building, services, as well as staff and user needs such as preparation laboratories, offices, meeting rooms and amenities. Considerable effort has been expended to optimise the laser-target/gabor lens interface, an undertaking that may have to be repeated as the particle production and capture designs evolve. The needs of all stakeholders will be solicited and taken into account from an early stage of the project to ensure that the facility design and implementation plan meets the requirements.

The site plan has been laid out on an area estimated at 72×32 m^2 , of which 57×32 m^2 is the footprint of the main building, next to which a 15×32 m^2 exterior fenced pen houses the water cooling chillers, water storage tank, water pumps and transformers. The exact capacity of these systems will be estimated when more precise details of the facility equipment are defined. The water-cooling equipment location has been chosen to be close to the heat exchangers and equipment with a high cooling load. Similarly, the transformer(s) and main electrical switchboard are located close to each other to reduce the length and cost of interconnecting cables. A 2.5 m wide access margin around the circumference of the accelerator is proposed to provide fork-lift access to equipment. allow the implementation of an overhead crane both to install and decommission the facility. Lifting solutions will also be required inside the radiation enclosures for installation, maintenance and decommissioning. For installation, maintenance and decommissioning of the vertical beam lines, permanently installed platforms next to the accelerator components are envisaged to provide a safe and efficient working environment. Sliding shield doors are used in some of the design options, but labyrinth access will also be considered during the technical design stage.

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Conclusions

LhARA, will be a novel, uniquely flexible, facility dedicated to the study of radiobiology. LhARA will use a high-power pulsed laser to generate a short burst of protons or light ions capable of delivering extremely high instantaneous dose rates of up to 10^9 Gy/s in short (10–40 ns) pulses. Particles will be captured using novel strong-focusing electron-plasma (Gabor) lenses with energy and momentum selected using well-proven, established techniques. To reach the energies required for in-vivo research acceleration using a fixed-field accelerator will deliver proton beams with energies up to 127 MeV and ion beams, such as C6+, with energies up to 33.4 MeV/nucleon. To verify the dose, a unique single shot ion-acoustic diagnostic is being developed.

References

[1] The LhARA consortium, "The Laser-hybrid Accelerator for Radiobiological Applications", Imperial College London, UK, Rep. "CCAP-TN-01", 2020; https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-01.pdf

[2] www.who.int/news-room/fact-sheets/detail/cancer

[3] Atun et al., The Lancet Oncology 16 (2015), 1153

[4] G. Aymar *et al.*, LhARA: The Laser-hybrid Accelerator for Radiobiological Applications", *Frontiers in Physics*, vol. 8, 2020. doi:10.3389/fphy.2020.567738

[5] J. Derouillat *et al.*, "Smilei : A collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation", *Computer Physics Communications*, vol. 222, pp. 351–373, 2018. doi:10.1016/j.cpc.2017.09.024

[6] H.T. Lau *et al.*, "Beam tracking simulations for stage 1 of the Laser-hybrid Accelerator for Radiobiological Applications (LhARA)", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, SP, Brazil, 2021, pp. 2939–2942. doi: 10.18429/JACoW-IPAC2021-WEPAB139

[7] R. A. Fonseca *et al.*, "OSIRIS: A three-dimensional, fully relativistic particle in cell code for modeling plasma based accelerators", *Lect. Notes Comput. Sci.*, vol. 2331, pp. 342, 2002. doi:10.1007/3-540-47789-6

[8] *CERN. 2020. User Documentation*, https://geant4.web.cern.ch/support/user_documentation

[9] *www.k-wave.org. (n.d.). k-Wave: A MATLAB toolbox for the time domain simulation of acoustic wave fields*, http://www.k- wave.org

[10] *User'sReferenceManual*, TheMad-XProgram (Methodical Accelerator Design), CERN, Geneva, Switzerland, May 2021, pp. 1-266; http://madx.web.cern.ch/madx/releases/ last-rel/madxuguide.pdf

[11] Y.Chao,"BeamOptics:Asymbolicplatformformodelingand the solution of beam optics system", CERN, Geneva, Switzerland, Rep. CERN-