

A STATUS UPDATE OF LHARA, AN ACCELERATOR-DRIVEN RADIOBIOLOGY RESEARCH INITIATIVE

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Abstract

LhARA is a multidisciplinary collaboration that aims to use laser-driven ions, in a hybrid acceleration scheme with a fixed-field alternating-gradient (FFA) accelerator, to deliver a systematic radiation biology programme and help lay the technological foundations for the transformation of proton and ion beam therapy. LhARA is in an R&D phase developing a number of accelerator technologies, and is conducting experiments through the Proof-of-Principle for LhARA and Radiobiology (PoPLaR) programme to examine the effect of laser-driven ions on biological tissue samples. Here, we present a summary of the most recent updates from the LhARA collaboration, including Gabor plasma lenses for beam capture and focusing, magnetic beam delivery schemes for variably-sized, transversely uniform beam profiles, the FFA in LhARA's second stage to reach clinically relevant ion energies, and an overview of the PoPLaR experiment.

THE LHARA/ITRF CONCEPTUAL DESIGN REPORT

LhARA is a proposed facility to deliver protons and ions to enable future ultra-high dose rate particle radiotherapy (including FLASH dose rates above 40 Gy/s and novel spatial fractionation beam delivery) through generation of ultra-short plasma-accelerated ions. This facility is part of the LhARA collaboration's efforts to contribute novel technologies to the future of cancer therapy.

In LhARA, a lower-energy 10/100 Hz source based on target-normal sheath acceleration (TNSA) that produces protons nominally at 15 MeV will be coupled to an FFA (fixed-field alternating-gradient) accelerator that retains the short bunch time structures (10s of ns) up to a maximum proton energy of 127 MeV. A primary application is as part of a UK Ion Therapy Research Facility (ITRF) to conduct radiobiological research. A recently-completed Conceptual Design Report [1] augments previous developments, and a proof-of-principle beamline (PoPLAR) has been constructed and commissioned at the University of Strathclyde's SCAPA plasma-acceleration facility, with first radiobiological irradiations underway.

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PHASE 1 DEVELOPMENT

Recently, improvements have been made to the SCAPA 350 TW laser platform that is being used as the LhARA testbed. Pre-pulses have been removed, resulting in improved proton energy and flux, giving reliable 1 Hz production of > 15 MeV protons ($> 10^9$ at 10 MeV), calibrated via radiochromic film (RCF).

Particle Tracking

The LhARA TNSA source inherently produces a broad exponential-like proton fluence spectrum with a cutoff; we have chosen to select a band somewhat below the cutoff, nominally at 15 MeV $\pm 2\%$. Selection is achieved via the strong chromatic effect of beam focusing with the Gabor lens lattice [2] and a series of round collimators; tracking of a simulated TNSA source spectrum from 1 to 27 MeV [3] through this lattice is essential to assess energy selection and beam losses. Three energy bands are simultaneously focused at the first collimator (7 m from the source, see Fig. 1) corresponding to the first three Gabor lenses. To avoid these three energy bands being further transmitted, we are considering the use of a tapered collimator since each band has a different transverse extent.

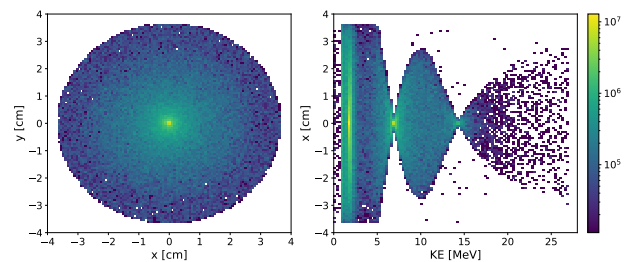


Figure 1: Beam distributions at the energy selection collimator for a 1–27 MeV TNSA spectrum of 10^9 protons. Left: transverse (X–Y) distribution. Right: X–kinetic energy phase space. Three chromatic focal bands are visible, arising from successive Gabor lenses, with symmetry reflecting the cylindrical focusing of the system.

Gabor Lens Development and Demonstration

Efficient capture of laser-driven ion beams requires focusing elements capable of handling large divergences and broad energy spreads. The Gabor lens [2] utilises the radial electric field of an electron column (confined by appropriately biased electrodes) to provide strong, axisymmetric focusing of positively charged particles; it is analogous to Penning–Malmberg (P-M) traps [4] widely used for non-neutral plasma confinement [5–7].

The focal length of the lens is $f_G = 4\epsilon_0 V_b / qn_e l$, where V_b and q are the ion kinetic energy and charge, and n_e and l are the plasma density and length; large electron densities are crucial for strong focusing, but are constrained by the Brillouin limit [8] determined by f_G . To achieve sufficient electron density, we have constructed a P-M trap with cylindrical electrodes immersed in a solenoidal magnetic field ~ 40 mT. Electrons are confined and diagnosed using a combination of electromagnetic trapping and release together with optical detection based on a phosphor screen with CCD imaging; we have observed that confined electron plasmas are subject to both radial space-charge expansion and collisional diffusion, limiting the achievable density to around 10^{13} m^{-3} . More recently we have optimized the plasma conditions [9] to yield a larger electron population and peak density that can be sustained for long periods; we believe this can be extended to the $2 \times 10^{15} \text{ m}^{-3}$ needed for LhARA Phase 1.

THE POPLAR EXPERIMENT

Beamline

In the past year we have constructed the PoPLaR beamline at the University of Strathclyde 350 TW SCAPA laser facility, as a proof of principle system for the LhARA Phase 1, and to systematically compare laser-driven radiobiology with conventional cyclotron irradiations (carried out at the Birmingham MC40 cyclotron). Over the past year, the beamline has been developed and tested. The beamline transport from a TNSA source to cell irradiation consists of up to six low-cost 150 T/m permanent-magnet quadrupoles (PMQs), manufactured by Magnet Sales, as shown in Fig. 2. Interpolation of Hall probe field-mapping measurements confirm acceptable field quality variation of ± 2 T/m across the series, with magnet centre accuracies $< 50 \mu\text{m}$ and roll errors below 0.4 deg. The present beamline utilises a doublet mounted on $x - y - z$ stages to permit good alignment; particle tracking with an in-house matrix tracking code (LHARALINEAROPTICS) was used to optimise a PMQ doublet layout to give acceptable focusing and transmission (around 10% of 10 MeV protons from the source).

RCF Stack Experiments

Transmission was verified experimentally with RCF measurements as seen in Fig. 3). A uniform beam irradiation over a 1.85 cm diameter cell dish was achieved using a $10 \mu\text{m}$ thick copper scatterer, whose position was optimised using BDSIM [10]. The resulting configuration (Fig. 4)

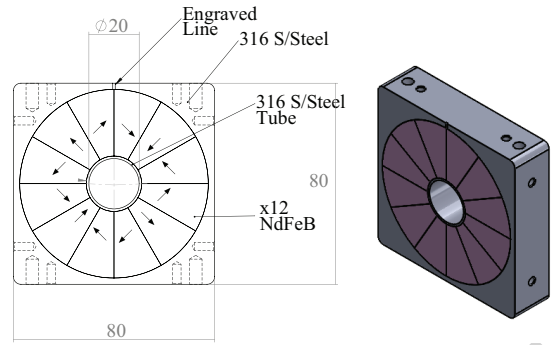


Figure 2: 150 T/m permanent-magnet quadrupoles manufactured for the PoPLAR proof-of-principle beamline.

experimentally achieves a dose with a relative standard deviation across the cell dish of 14%, measured with EBT3 RCF. The beamline employed a cell irradiation carousel to allow remote switching of cell dishes and/or RCF stacks. The average dose per shot delivered is 0.57 Gy with a shot-to-shot variation of 0.40 Gy. The variation requires that an in-beam diagnostic records delivered dose; we will likely use a sparse-scintillating fibre array placed at several locations along the beamline. We may also later employ the remaining PMQs and/or a dipole chicane to create a uniform beam without the use of a scatterer to achieve a higher dose per shot.

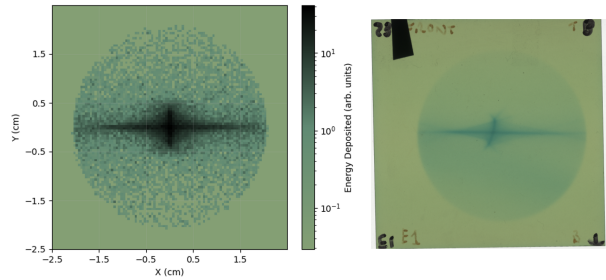


Figure 3: (Right) EBT3 RCF measured at the end of the PoPLAR beamline, which shows expected chromatic features. (Left) GEANT4 reconstruction of energy deposition in RCF, using beam tracking through a PMQ doublet mounted on $x - y - z$ stages to permit good alignment; particle tracking with an in-house matrix tracking code.

THE PHASE 2 FFA

The LhARA/ITRF Phase 2 FFA accelerator is of a 10-cell single spiral design, and takes protons/ions from the laser-driven source and accelerates them to sufficient energy for *in-vivo* studies whilst preserving the dose rate and time structure. A scaling integrated magnetic field BL (to obtain different ion species and injection/extraction energies),

$$BL(r) = BL_0 \left(\frac{r}{r_0} \right)^{k+1}, \quad (1)$$

where BL_0 is the integrated field at a reference radius r_0 , is generated by augmenting the main coil dipole field (around a

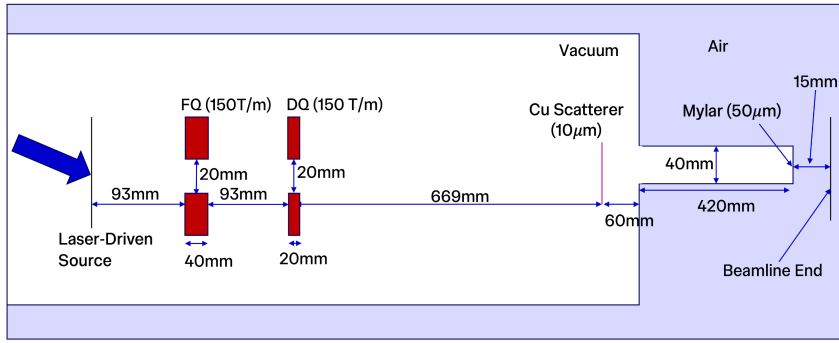


Figure 4: Schematic of PoPLaR proof-of-principle beamline, which presently is configured as a doublet (using two 150 T/m PMQs as a single F-quadrupole (FQ)) to transport protons from the laser-driven source (at left). A Cu scattering foil broadens the dose onto the cell irradiation location at the beamline end (at right). Beam transmission of 10 MeV protons is estimated to be around 10%.

flat pole profile) using 18 pole-face trim coils in 2 staggered layers, with side returns next to the main coil. Staggering the layers has been shown in an analogous prototype [11] to improve the field quality with radius. An OPERA3D model predicts a field deviation less than $\pm 0.02\%$ from the ideal scaling field, and field index within 0.5% of the desired $k = 5.23$. The FFA magnet design is shown in Fig. 5.

To confirm that a variety of injection/extraction energies can be accommodated by changing the coil excitation, two cases are calculated: 15→127 MeV and 7→57 MeV, with corresponding adjustment and optimisation of the pole-face currents. The resulting 3D field maps were used to track accelerated bunches using FIXFIELD [12], and show (Fig. 6) good control of the working point during acceleration for both cases. The corresponding dynamic aperture is sufficient, and larger than the physical aperture [1].

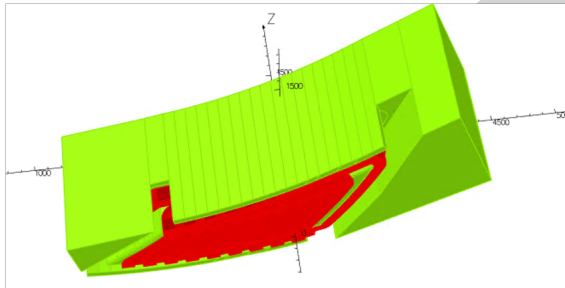


Figure 5: OPERA3D model of the LhARA C-shaped magnet, depicting just the upper half with main and (18) pole-face coils shown. Careful shaping of the field clamps confines the longitudinal field extent to constrain the magnetic field in the accelerating cavity ferrite cores [1], and yoke shaping accommodates the injection and extraction lines.

CONCLUSION

We have constructed a proof-of-principle TNSA beamline that allows flexible cell irradiations using 10 MeV incident protons to deposit their Bragg peak dose for cell irradiation at 1 Hz or more. Ongoing radiobiology studies will be reported on later.

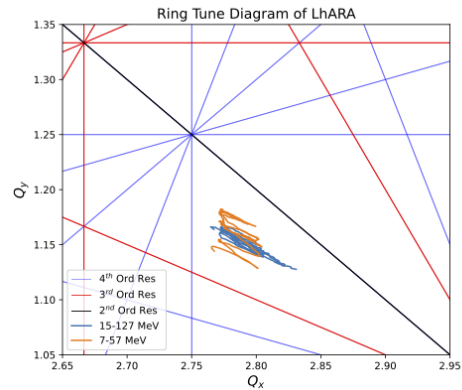


Figure 6: Working point (tune) variation in the LhARA FFA during acceleration in two representative cases: 15→127 MeV and 7→57 MeV; resonances up to fourth order are shown. The working point variation can be made similar for both cases, and can be well controlled by the use of pole-face coils in a double, staggered arrangement.

ACKNOWLEDGEMENTS

The LhARA collaboration gratefully acknowledges direct support from the UKRI Infrastructure Fund (grants ST/X005681/1, ST/Z001064/1 and associated funding) and indirect support from the Cockcroft Institute (ST/X005208/1), John Adams Institute and the STFC Accelerator Science and Technology Centre. We also acknowledge the provision of facilities and time from the Strathclyde University SCAPA facility and staff.

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