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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.

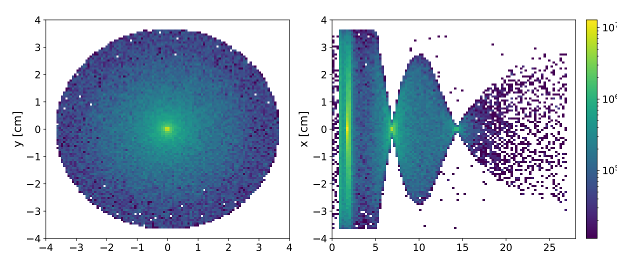

Figure 1: Beam distributions at the energy selection collimator for a 1–27 MeV TNSA spectrum of 10^9 protons. Left: transverse (X–Y) distribution. Right: X–kinetic energy phase space. Three chromatic focal bands are visible, arising from successive Gabor lenses, with symmetry reflecting the cylindrical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

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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 $f_G = 4\varepsilon_0 V_b / q n_e l$, 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 2×10^{15} 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 μm 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 μm thick copper scatterer, whose position was optimised using BDSIM [10]. The resulting configuration (Fig. 4) 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.

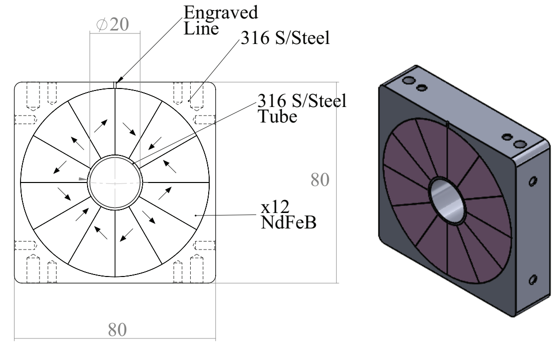

Figure 2: 150 T/m permanent-magnet quadrupoles manufactured for the PoPLAR proof-of-principle beamline.

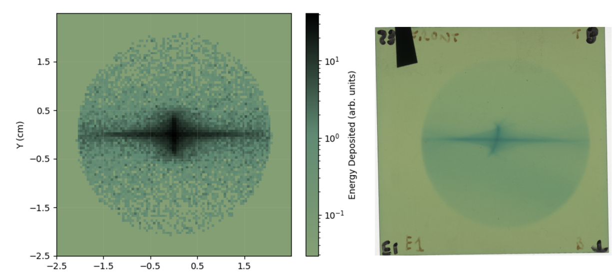

Figure 3: (Right) EBT3 RCF measured at the end of the PoPLAR beamline, which shows expected chromatic features. (Left) GEANT4 reconstruction of energy deposition in RCF, using beam tracking through a PMQ doublet mounted on $x - y - z$ stages to permit good alignment; particle tracking with an in-house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

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

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

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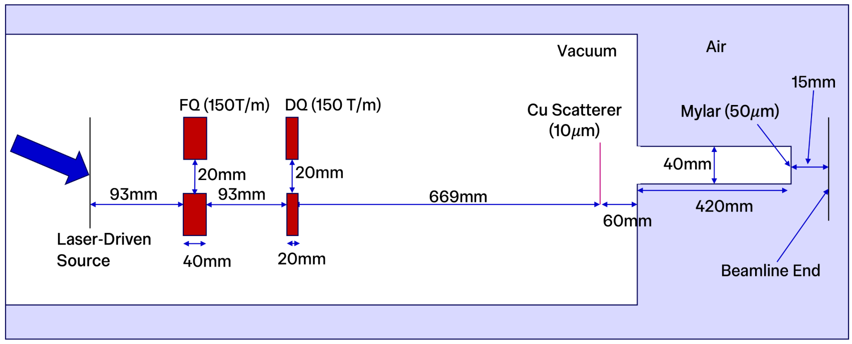

Figure 4: Schematic of PoPLaR proof-of-principle beamline, which presently is configured as a doublet (using two 150 T/m PMQs as a single F-quadrupole (FQ)) to transport protons from the laser-driven source (at left). A Cu scattering foil broadens the dose onto the cell irradiation location at the beamline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

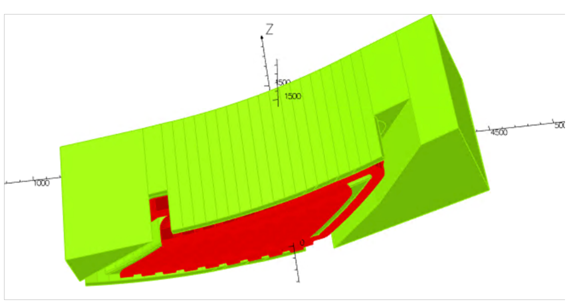

Figure 5: OPERA3D model of the LhARA C-shaped magnet, depicting just the upper half with main and (18) pole-face coils shown. Careful shaping of the field clamps confines the longitudinal field extent to constrain the magnetic field in the accelerating cavity ferrite cores [1], and yoke shaping accommodates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

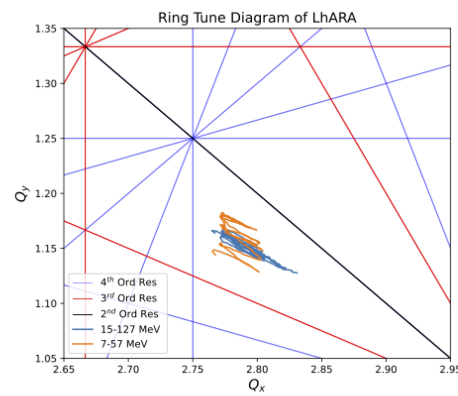

Figure 6: Working point (tune) variation in the LhARA FFA during acceleration in two representative cases: 15→127 MeV and 7→57 MeV; resonances up to fourth order are shown. The working point variation can be made similar for both cases, and can be well controlled by the use of pole-face coils in a double,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

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