Laser-hybrid Accelerator for Radiobiological Applications

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INTRODUCTION

LhARA [1] is conceived as a novel, uniquely flexible facility dedicated to the study of the biological response to ionising radiation. With the potential to deliver multiple ion species in beams with a wide range of temporal and spatial profiles at high and ultra-high dose rates. LhARA will enable the exploration of a completely new regime of particle-beam therapy. Funding from the UKRI Infrastructure Fund for a 2-year "Preliminary Activity" to deliver a CDR for the Ion Therapy Research Facility [2] served by LhARA has recently been announced.

- A high-power laser will create a large flux of protons or light ions from a foil target.
- Particles are captured and focused using electron plasma lenses.
- The fixed-field alternating-gradient accelerator (FFA) provides rapid acceleration and preserves the flexibility of the beam created at the source.

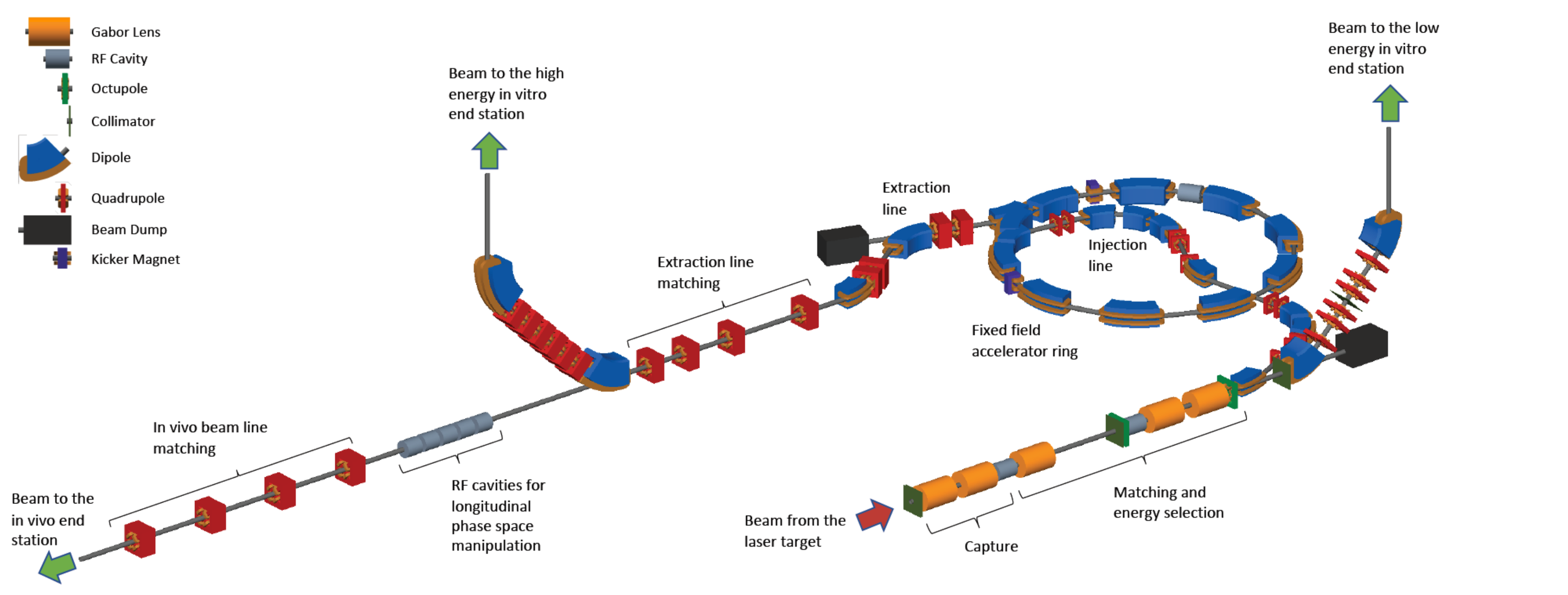

Figure 1: Schematic diagram of the LhARA beam lines. The beam from the source (red arrow) is transported either to the low-energy *in vitro* end station or the FFA injection line. The accelerated beam is directed either to the high-energy *in vitro* end station or the *in vivo* end station.

LASER SOURCE

Ions are generated via the target normal sheath acceleration (TNSA) mechanism.

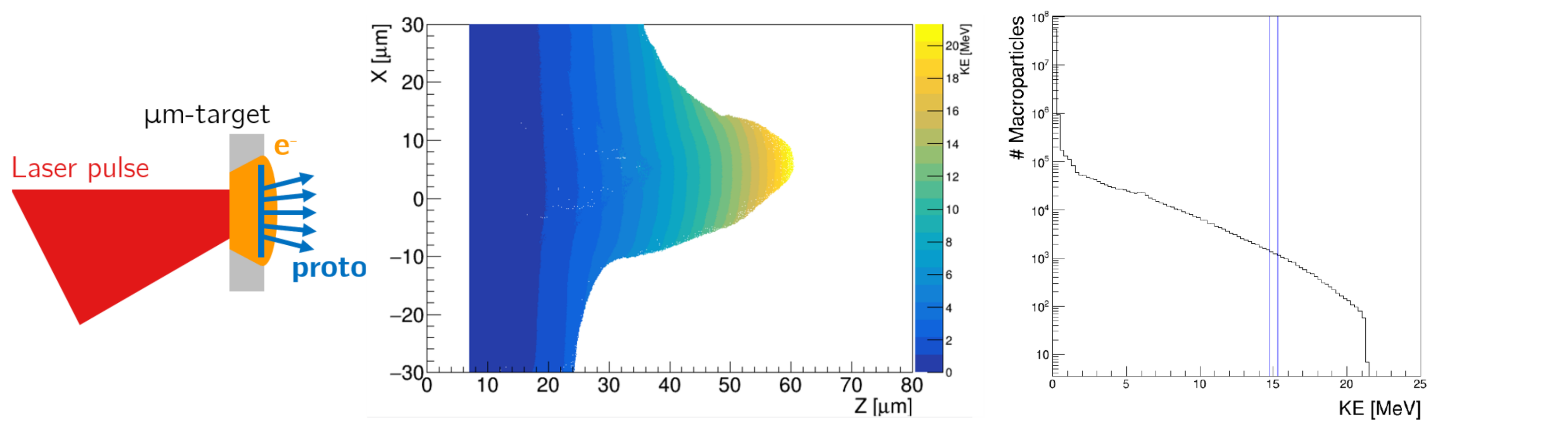

Figure 2: Schematic diagram of the laser source (left) and 2D positional spread of protons at 1 ps as simulated with Smilei [3] (middle). Kinetic energy spectrum of the protons produced in the laser-target interaction (right).

An intense laser pulse generates a sheath of electrons at the rear surface of the target. Surface-contaminant positive ions are accelerated by the strong space-charge field.

- Ion energies $>40\,\mathrm{MeV/u}$ obtained at high laser intensity.
- $100\,\mathrm{TW}$ commercial laser system with a pulse length of 25 fs and repetition rate of 10 Hz is able to deliver a high proton flux ($> \mathbf{10^9}$).
- Tape drive target is proposed to allow a reproducible proton flux with energy $\leq 15\,\mathrm{MeV}$.
- Particles captured at energies significantly above those that pertain to conventional facilities, evading the limits on the instantaneous dose rates.
- Particle production at the source simulated in 2D with particle-in-cell (PIC) code [3].

GABOR LENS

Electron cloud used for compact focussing to capture the large divergence and energy spread of the laser driven ion beam.

- Electron plasma confined within a lens with a configuration of cylindrical electrodes placed in a longitudinal magnetic field.
- Magnetic field greatly reduced compared to a solenoid of the same focal length.
- Lenses and collimator used to select particle energy.

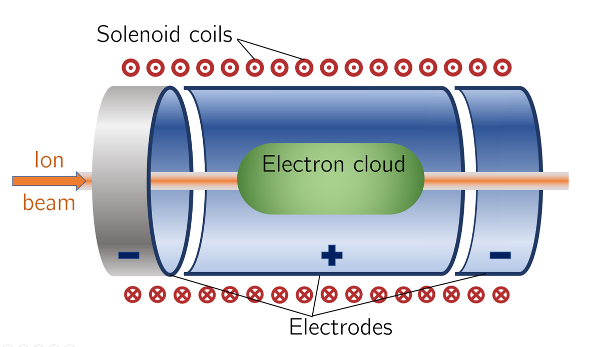

Figure 3: Schematic of a Penning-Malmberg trap proposed for use in the Gabor lens for LhARA.

- First lens prototype tested at Imperial College and Surrey Ion Beam Centre
- Recent understanding of the plasma instabilities observed with the prototype [4]
- Theoretical investigation of lens stability is underway with a PIC code [5]

FIXED-FIELD ALTERNATING-GRADIENT ACCELERATOR (FFA)

A FFA will be used to accelerate the beam in Stage 2 to energies of up to 127 MeV for protons and 33 $\mathrm{MeV/u}$ for carbon ions.

- Multiple ion capability
- Compact size and low cost
- High variable dose delivery
- Various of beam energies without the use of a degrader

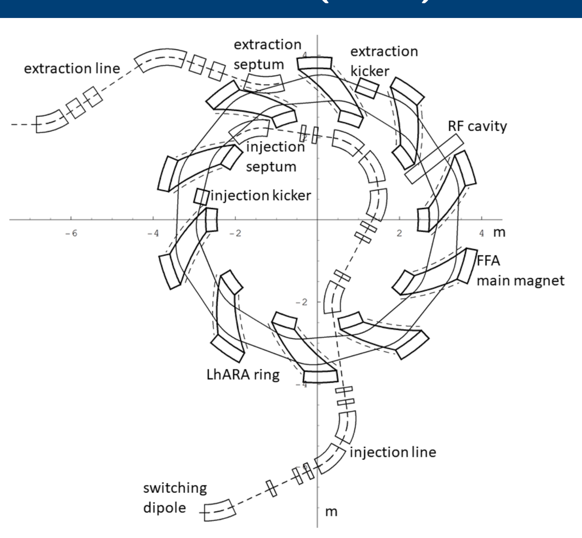

Figure 4: Layout of the FFA ring.

LhARA STAGE 1

Stage 1 of LhARA contains all the components from the laser source to the first *in vitro* vertical arc designed for studies with proton beams with energy 12 MeV–15 MeV.

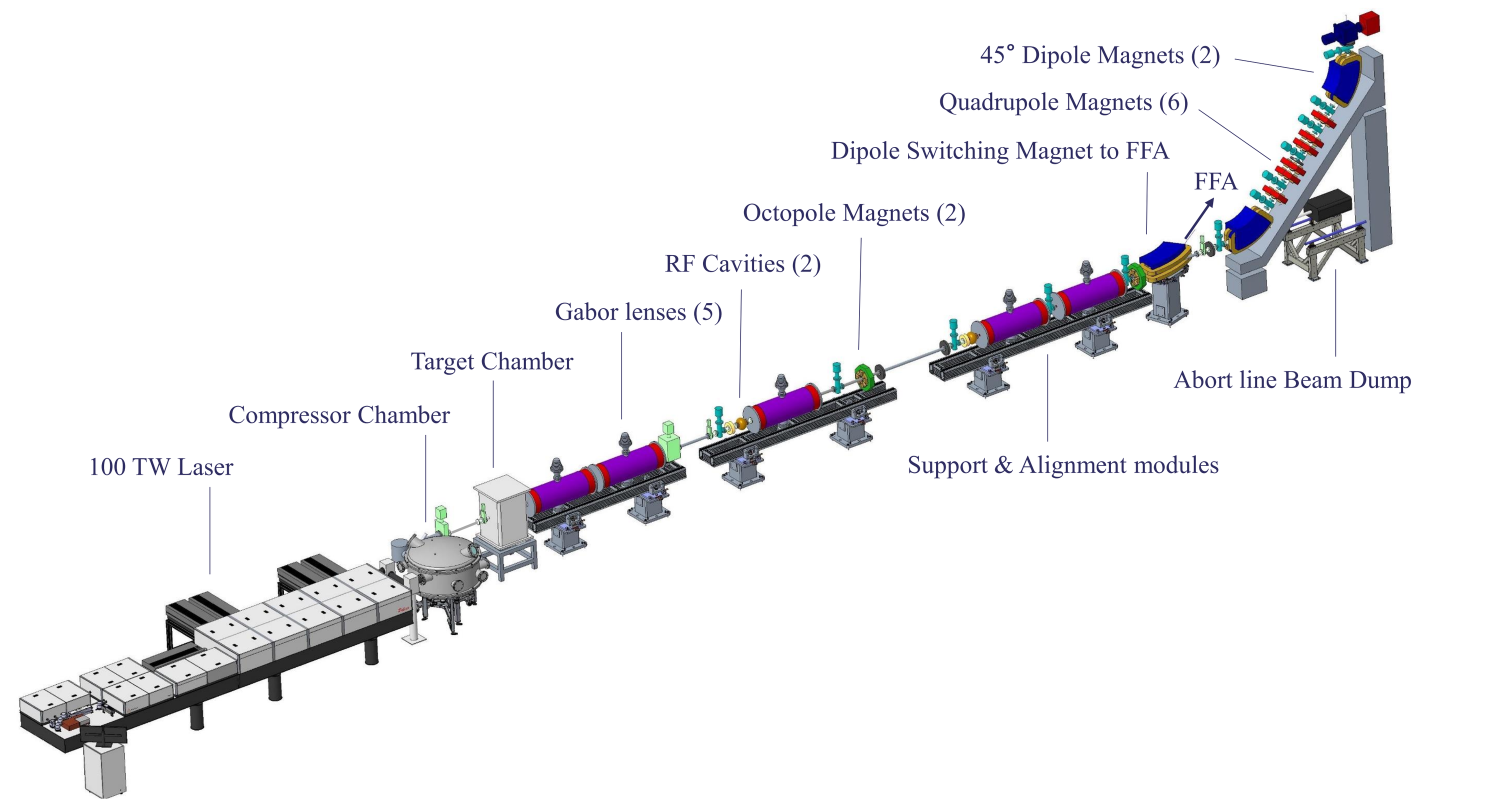

Figure 5: Schematic layout of the Stage 1 beam line. The laser is brought to a focus on the particle-production target. Capture and focusing is provided by a series of Gabor lenses. The final section of the beam line bends the beam vertical and delivers it to the low-energy *in vitro* end station.

- Preliminary end-to-end tracking of proton beam from laser target to end station.
- Planned re-optimisation of the magnet strengths for capture and transport.

LhARA STAGE 2

Stage 2 of LhARA consists of the FFA and all downstream elements that are planned to provide proton and ion beams for both *in vivo* and *in vitro* studies.

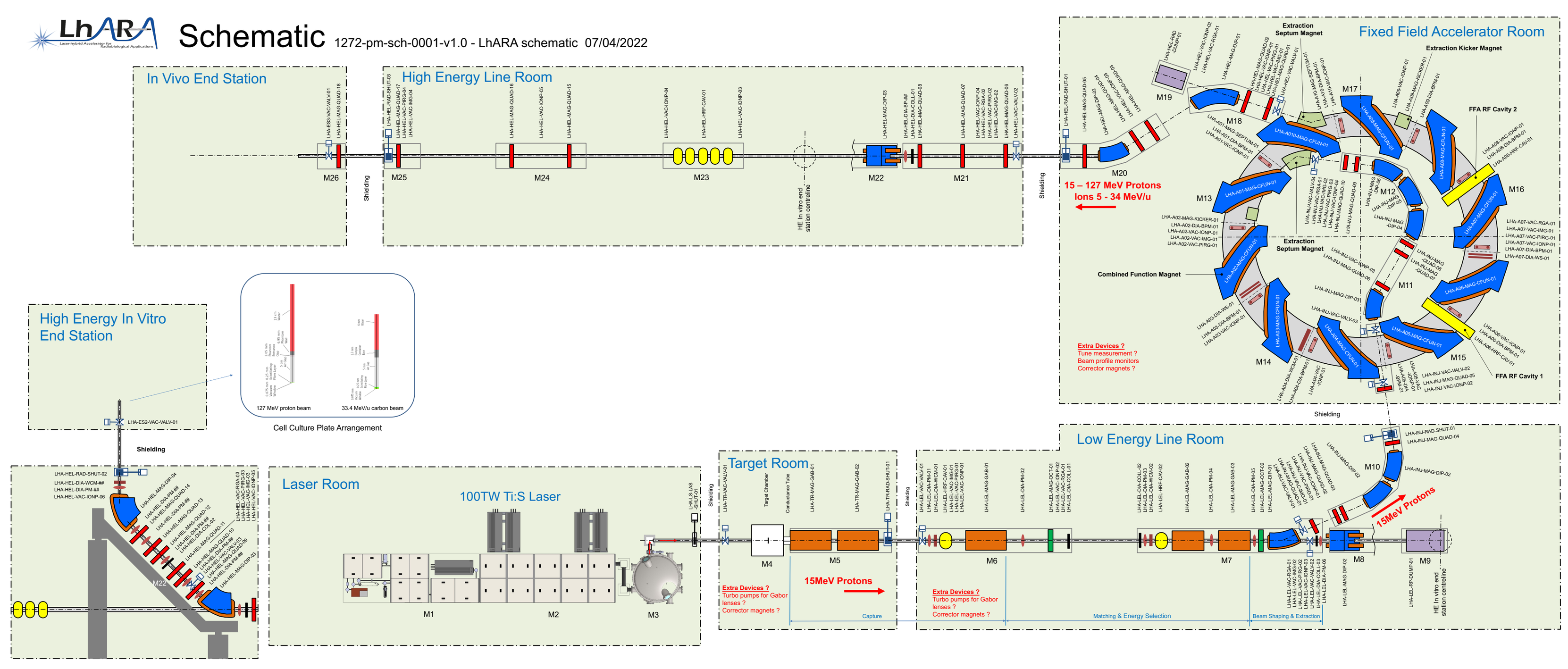

Figure 6: Schematic drawingf of LhARA Stage 2. The Stage 1 beam is injected into tge FFA which delivers proton beam energies between 40 MeV and 127 MeV to *in vitro* and *in vivo* end stations. Ion beams with energies up to 34 MeV/nucleon can also be delivered.

- Flexible optics configurations to deliver beams between 1 and 30 mm.

BIOLOGICAL END STATION

The *in vitro* end stations are envisaged for the irradiation of 2D monolayer and 3D-cell systems in culture.

- Sealed units allow for cells to be incubated prior to and during irradiation.
- Robotics will enable cell culture plates to be placed into and taken out of the beam.

The *in vivo* end stations will be used to irradiate small-animal models.

- An image guidance system will be used to enable a high level of precision and accuracy.
- The flexibility in beam sizes allows for different irradiation conditions: passive scattering, pencil-beam scanning, and micro-beam irradiation at conventional and FLASH dose rates.

BDSIM was used to evaluate the maximum dose distributions that LhARA can deliver.

- The integrated energy deposition within a fixed volume of water at the Bragg peak was recorded:

	Protons			Carbon 6+
	12 MeV	15 MeV	127 MeV	33.4 $\mathrm{MeV/u}$
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	$1.0 \times 10^9\,\mathrm{Gy/s}$	$1.8 \times 10^9\,\mathrm{Gy/s}$	$3.8 \times 10^8\,\mathrm{Gy/s}$	$9.7 \times 10^8\,\mathrm{Gy/s}$
Average dose rate	71 $\mathrm{Gy/s}$	128 $\mathrm{Gy/s}$	156 $\mathrm{Gy/s}$	730 $\mathrm{Gy/s}$

Table 1: Expected maximum dose rates LhARA can deliver for various beam energies at minimum beam size.

CONCLUSION

- LhARA aims to to demonstrate **novel technologies** and enable a **systematic programme of radiobiological studies**–both necessary for improving particle therapy.

REFERENCES

[1] G. Aymar *et al.*, "LhARA: The Laser-hybrid Accelerator for Radiobiological Applications," *Frontiers in Physics*, vol. 8, p. 432, 2020.

[2] "Ion Therapy Research Facility." https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Research/DesignStudy/Proposals/2021/2021-06-15-ITRF-1-page-Final.pdf, June 2021. Cover page submitted to support the full proposal.

[3] 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.

[4] T. Nonnenmacher *et al.*, "Anomalous beam transport through Gabor (plasma) lens prototype," *Applied Sciences*, vol. 11, no. 10, 2021.

[5] "VSim for Plasma," 2020. https://www.txcorp.com/vsim.