Laser-hybrid Accelerator for Radiobiological Applications

T.S. Dascalu (on behalf of the LhARA collaboration [1])
Department of Physics, Imperial College London

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, and at high and ultra-high dose rates, LhARA will enable the exploration of a completely new regime of particle-beam therapy.

- 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.
- Fixed-field alternating-gradient accelerator (FFA) provides rapid acceleration and preserves the flexibility of the beam as afforded by the source.

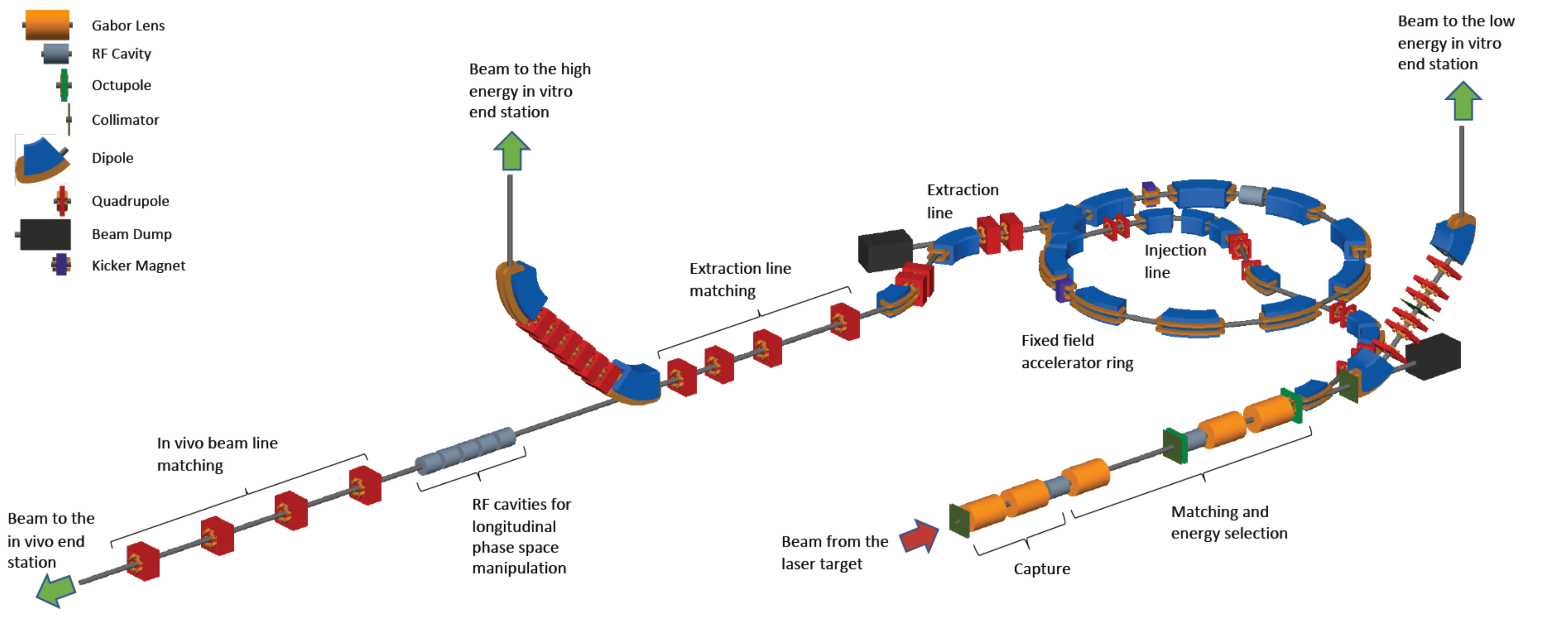

Figure 1: Schematic diagram of the LhARA beam lines. The beam from the source (red arrow) is transported either into a 90° bend to the low-energy *in vitro* end station or the FFA injection line. The FFA performs the post-acceleration where the beam is directed to either the high-energy *in vitro* or the *in vivo* end station.

LASER SOURCE

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

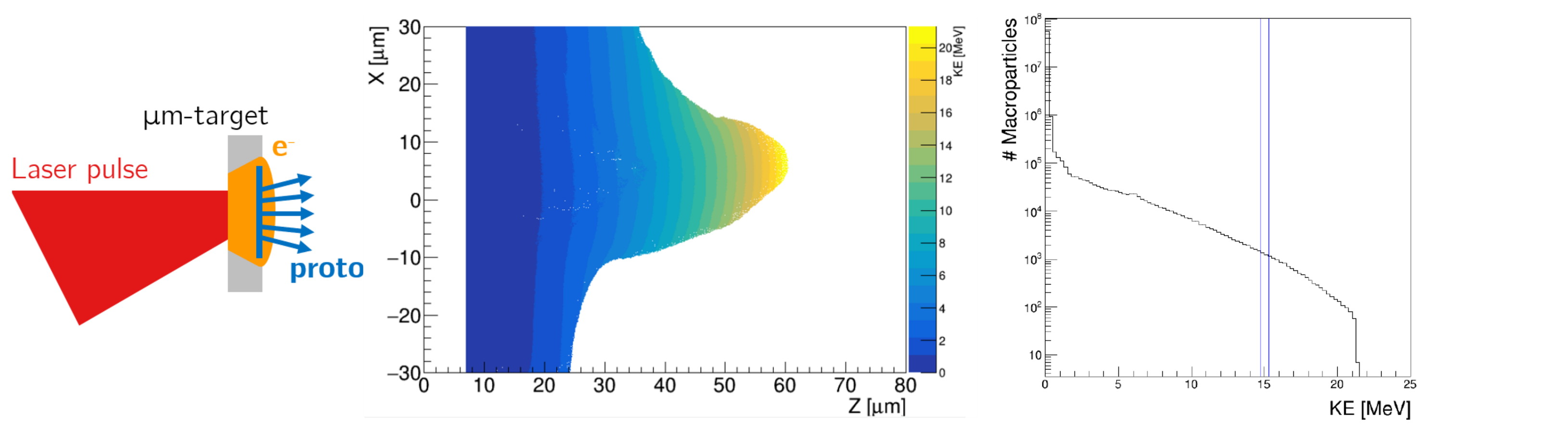

Figure 2: Schematic diagram of the laser source (left) and 2D positional spread of protons at 1 ps as simulated with Smilei [2] (middle). Kinetic energy spectrum of the protons produced in the laser-target interaction (right).

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 MeV/u obtained at high laser intensity.
- 100 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 ($> 10^9$).
- Tape drive target is proposed to allow a reproducible proton flux with energy ≤15 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 [2].
  - 3D simulation planned for comparison.

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.

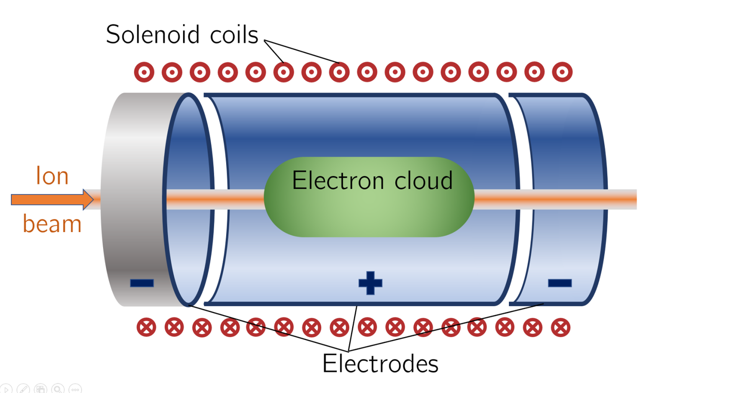

Figure 3: Schematic of a Penning-Malmberg trap proposed for use in the Gabor lens for LhARA.

- First lens prototype tested at Imperial College and Surrey Ion Beam Centre
- Recent understanding of the plasma instabilities observed with the prototype [3]
- Theoretical investigation of lens stability is underway with a PIC code [4]

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 MeV/u for carbon ions.

- Multiple ion capability
- Compact size and low cost
- High variable dose delivery
- Ability to deliver various beam energies without the use of energy degraders

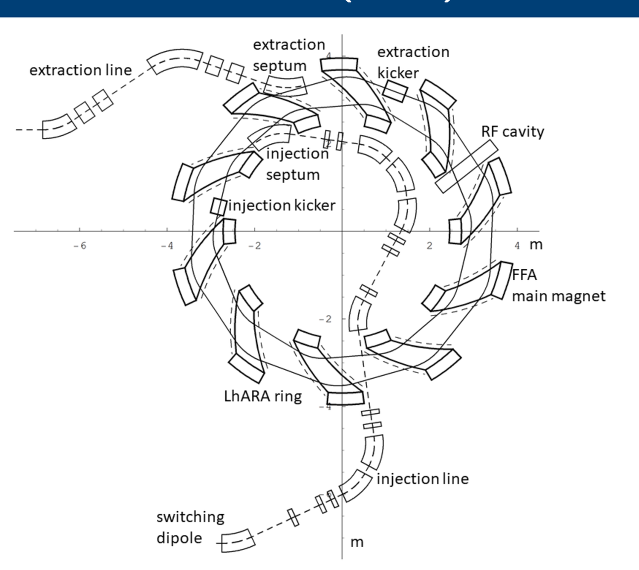

Figure 4: Layout of the FFA ring.

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 up to 15 MeV.

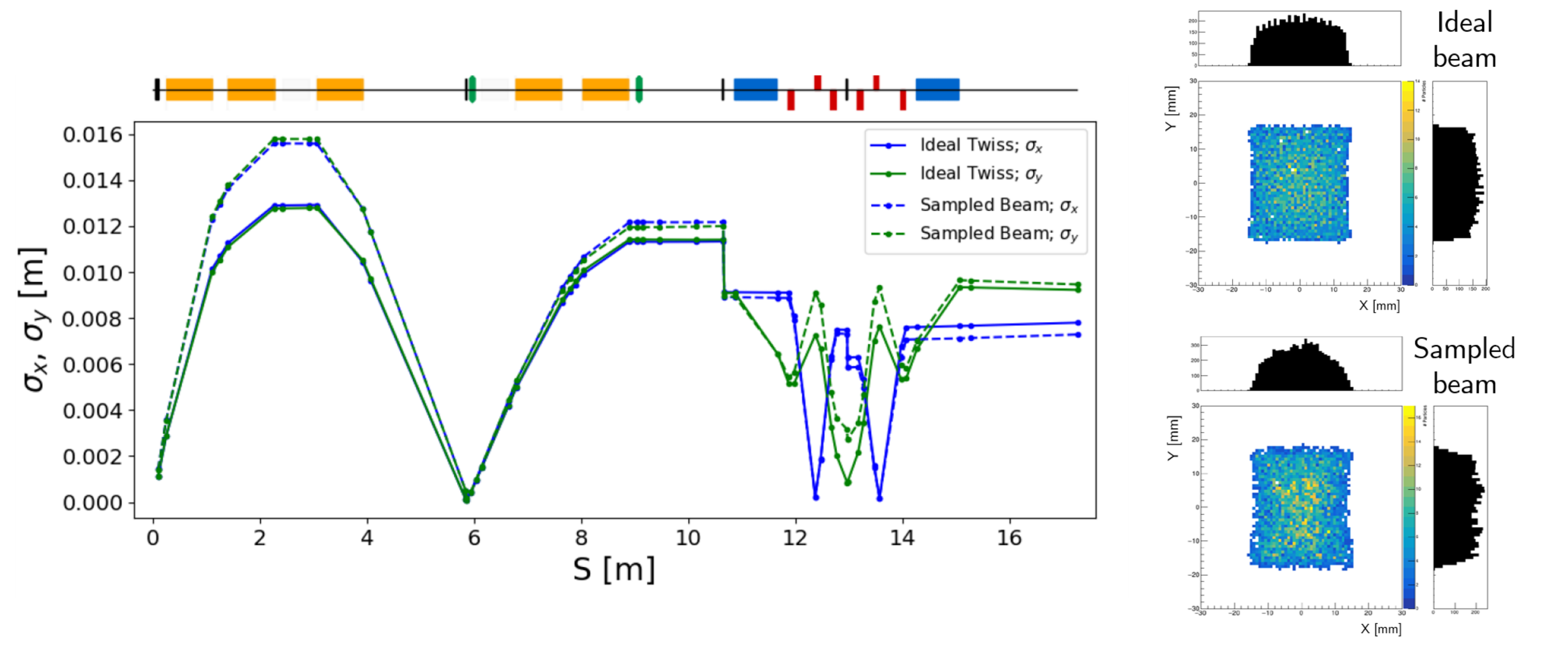

Figure 5: Left–Horizontal and vertical transverse beam sizes for the ideal beam and the beam sampled from a 2D simulation of the laser source. Right–Transverse position of protons at the end station for the ideal and the sampled beams. 10000 protons representative of the full bunch distribution were tracked in BDSIM [5].

- 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.

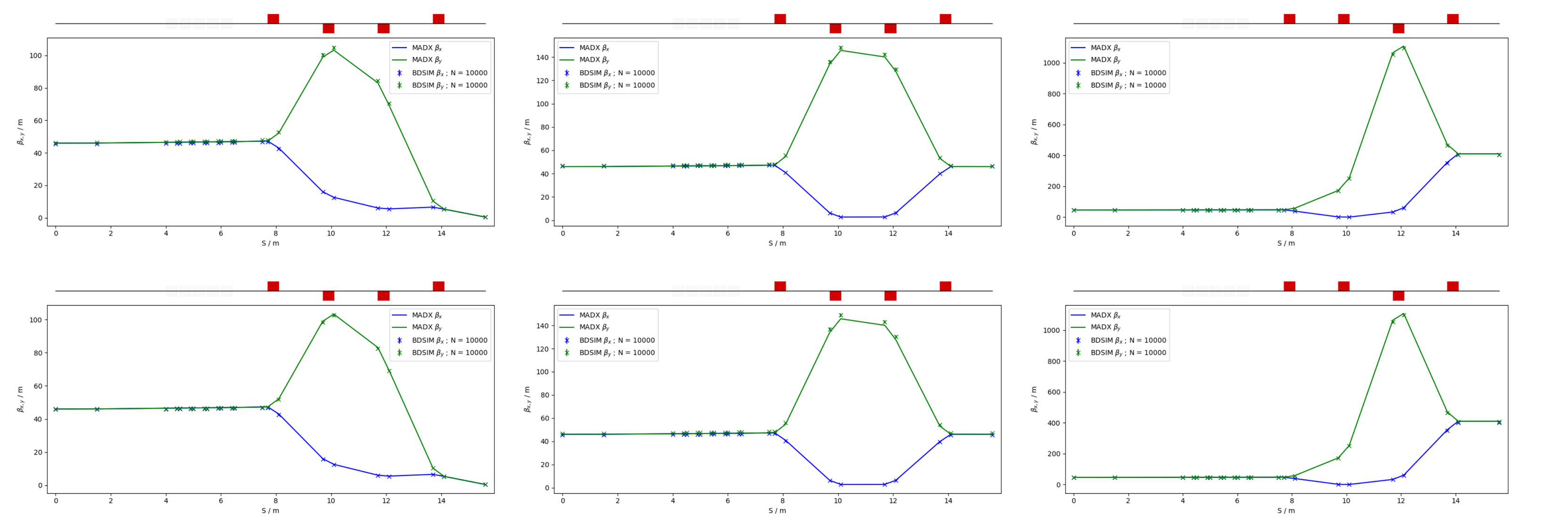

Figure 6: Simulation of the *in vivo* beam line for 40 MeV (top row) and 127 MeV (bottom row). Columns represent different quadrupole settings showing the flexibility of the beam size that can be delivered.

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

BIOLOGICAL END STATION

The *in vitro* end stations are envisioned 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 MeV/u
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	1.0×10^9 Gy/s	1.8×10^9 Gy/s	3.8×10^8 Gy/s	9.7×10^8 Gy/s
Average dose rate	71 Gy/s	128 Gy/s	156 Gy/s	730 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.
- Studies in progress for the **key risk areas**: laser-driven particle production, Gabor lenses, real time dosimetry.
- Proton beam from 2D simulation of the source is highly similar to the ideal beam.
- The focusing properties of the Gabor lens has been simulated and the plasma instability observed in a previous beam test of the lens was characterised.
- FFA model development and verification is ongoing.

REFERENCES

[1] G. Aymar *et al.*, "LhARA: The Laser-hybrid Accelerator for Radiobiological Applications," *Frontiers in Physics*, vol. 8, p. 432, 2020.
[2] 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.
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[4] "VSim for Plasma," 2020. https://www.txcorp.com/vsim.
[5] L. J. Nevay *et al.*, "BDSIM: An accelerator tracking code with particle-matter interactions," *Computer Physics Communications*, p. 107200, 2020.