PROCEEDINGS OF SCIENCE

The Laser-hybrid Accelerator for Radiobiological Applications (LhARA)

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On behalf of the LhARA collaboration.

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The 'Laser-hybrid Accelerator for Radiobiological Applications', LhARA, is conceived as a uniquely flexible international facility dedicated to the study of a completely new regime of radiobiology. The ambition of the multidisciplinary collaboration is that the technologies demonstrated in LhARA will be transformative in the delivery of ion beam therapy.

The laser-hybrid approach offers enormous potential by providing a more flexible, compact, and cost-effective high-energy particle source while evading the space-charge limitations of current sources. LhARA uses a high-power laser to generate an ultrashort burst of protons or light ions from a target. These are captured using strong-focusing electron-plasma (Gabor) lenses at energies up to 15 MeV, enabling ultra-high instantaneous dose rates of up to 10^9 Gy/s in pulses as short as 10–40 ns. Further acceleration up to 127 MeV is facilitated by a fixed-field alternating-gradient accelerator designed to accommodate the source flexibility. Measuring the extremely high flux, low energy proton and ion beams at LhARA presents significant challenges. Novel techniques such as beam-gas curtain profile monitors and ion-acoustic dose-profile monitors are being developed for use in proof-of-principle systems. The status of the LhARA project in the context of the Ion Therapy Research Facility recently funded by the UKRI will be described along with the LhARA collaboration's vision for the development of a transformative proton- and ion-beam system.

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1. Introduction

The 'Laser-hybrid Accelerator for Radiobiological Applications', LhARA, is conceived as a uniquely flexible international facility dedicated to the study of a completely new regime of radiobiology [1]. The LhARA facility, shown schematically in Figure 1, will be developed in two stages. In the first stage, the laser-driven beam, captured and transported using plasma lenses and bending magnets, will serve a programme of *in-vitro* radiobiology with proton beams of energy of up to 15 MeV. In stage two, the beam will be accelerated using a fixed-field alternating-gradient accelerator (FFA) to allow experiments to be carried out *in vitro* and *in vivo* with proton-beam energies of up to 127 MeV. Ion beams (including C^{6+}) with energies up to 33.4 MeV per nucleon will also be available.

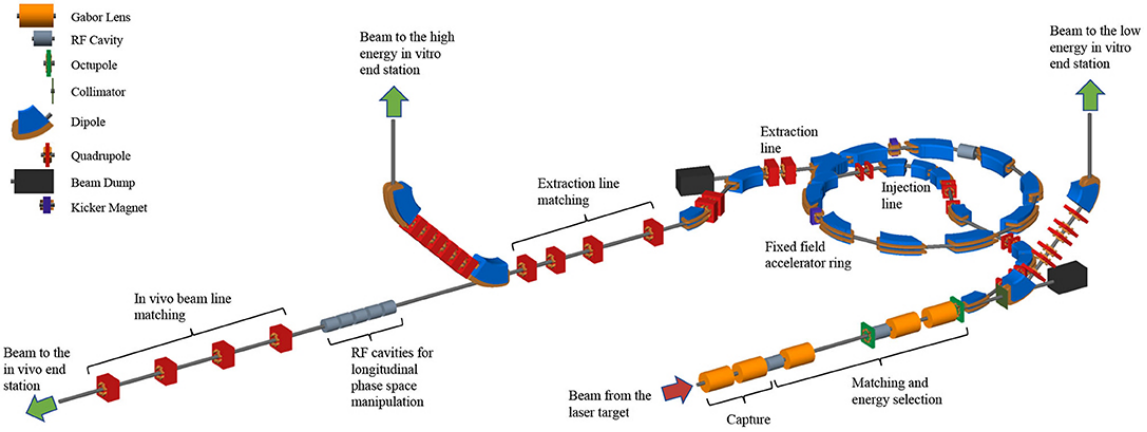

Figure 1: Schematic diagram of the LhARA beam lines. The particle flux from the laser-driven source is shown by the red arrow. The "Capture" section is followed by the "Matching and energy selection" sections, the beam is directed either into the 90° bend that takes it to the low-energy in vitro end station, toward the FFA injection line, or to the low-energy beam dump. Post-acceleration is performed using the FFA, on extraction from which the beam is directed either to the high-energy in vitro end station, the in vivo end station, or the high-energy beam dump. Gabor lenses are shown as orange cylinders, RF cavities as grey cylinders, octupole magnets as green discs, collimators as dark-green bars, dipole magnets are shown in blue, quadrupole magnets are shown in red, beam dumps (black rectangles) and kicker magnets are also shown [1].

2. The Laser-hybrid Accelerator for Radiobiological Applications

2.1 Laser source

Protons and ions are generated through the interaction of a high-power pulsed laser with a foil target. The intense electric fields generated on the front surface of the target accelerates surface electrons into the target. The electrons passing through the target ionise the material, the ionisation electrons being accelerated in turn. As the electron cloud emerges from the rear surface of the foil, an intense "sheath field" is created. Positive particles, such as protons, present on the rear surface are then accelerated by the space-charge electric field. This process is referred to as target normal sheath acceleration (TNSA) [2]. Protons with kinetic energy of several 10s of MeV have been

produced using TNSA. Large shot-to-shot variations in the flux of ions close to the end point have been observed. Therefore, the LhARA collaboration has chosen to select particles significantly below the end-point of the two-temperature ion-energy spectrum, where the flux is large.

2.2 Plasma lens

The ions created at the source will be captured and focused using electron-plasma lenses known as Gabor lenses, see figure 2. The electron plasma within a Gabor lens is confined using a cylindrical anode within a uniform solenoid in an arrangement similar to the "Penning-Malmberg trap", see Figure 2. The required magnetic field is reduced significantly compared to a solenoid of the same focal length. The Gabor lens delivers efficient capture of the large divergence and the large energy spread of the laser-driven ion beam. Once ions are captured, the energy is selected by focusing the beam into a collimator.

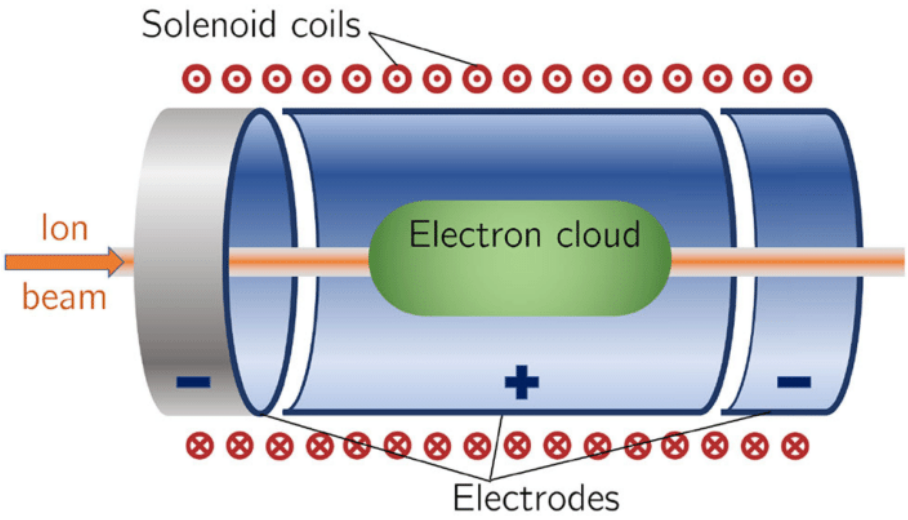

Figure 2: Schematic diagram of a Penning-Malmberg trap of the type proposed for use in the Gabor lenses to be used in LhARA. The solenoid coils, and the direction of current flow, are indicated by the red circles (the central dots indicate current emerging from the picture, crosses current entering it). The confining electrostatic potential is provided using a central cylindrical anode and two cylindrical negative end electrodes. The ion beam enters on-axis from the left and the electron cloud is indicated by the green shaded area [1].

2.3 Fixed-field alternative-gradient accelerator

After focusing and energy selection, the ions are accelerated using a fixed-field alternating-gradient accelerator (FFA). Beam energies of up to 127 MeV for protons and 33.4 MeV/u for carbon ions will be delivered. The FFA is capable of delivering a variety of ion species over a range of energy using an accelerator which is compact and can deliver high-flux beams.

2.4 End station

The *in vitro* and *in vivo* end stations must be designed to maximise the discovery potential of the LhARA facility. The two *in vitro* end-stations (high and low energy) will be served by vertical

beam lines which will be used for the irradiation of 2D mono-layer and 3D-cell systems in culture. Units capable of controlling the climate will be implemented to allow cells to be incubated within culture plates for a short time in stable conditions prior to and during irradiation. The units will be capable of holding the cells in a state of hypoxia [1].

The *in vivo* end station will be used to irradiate small-animal models. This end station is to contain a handling area for anaesthetisation and temperature-controlled holder tubes for precise positioning. To improve the alignment precision, an image guidance system (e.g. computed tomography) may be implemented.

3. Conclusion

The LhARA collaboration seeks to perform and demonstrate novel, transformative technologies that will enable a systematic programme of radiobiological studies. The further development of these novel technologies will transform clinical practice and change the gold standard for proton- and ion-beam therapy. Resources from the UKRI Infrastructure Fund have been secured to develop LhARA to serve the Ion Therapy Research Facility (ITRF). The laser-driven particle production, Gabor lenses and real-time dosimetry are currently the subject of an R&D programme aimed at reducing the technical risk. Development of the critical components of the LhARA facility (the laser-driven proton and ion source, the plasma lens, the fixed-field alternating-gradient accelerator and the end stations) is underway. The realisation of LhARA, serving the ITRF, will be a significant step towards the collaboration's goal of driving a step-change in the clinical practice of proton- and ion-beam therapy.

References

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