LASER SOURCE AND GABOR LENS FOR USE WITHIN LhARA

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Abstract

The Laser-hybrid Accelerator for Radiobiological Applications (LhARA) facility, is proposed as a highly flexible particle beam source to facilitate a programme of studies aimed at further exploring the biological response to ionising radiation and understanding the underlying radiobiological mechanisms of FLASH radiotherapy. Here we report on preliminary laser-hybrid source and non-neutral-plasma-based capture efforts undertaken as part of an initial conceptual design review. Together, these components will provide proton beams up to 15 MeV and ion beams (such as C^{6+}) up to 4 MeV/u in sub-second bursts of 10-40 ns widths.

INTRODUCTION

Responsible for over 15% of deaths worldwide in 2020, cancer is a major contributor to premature loss of life in modern society [1]. This is only expected to increase, and over 25 million life-years could be saved if radiotherapy (RT) capacity can be scaled up [2].

Currently, ~ 50% of cancer patients will receive RT as part of their treatment and the majority of this is delivered utilising conventional techniques with x-rays of MeV energies. However, in some cases, proton and ion beam therapy (PBT) may offer significant advantages. Using fractionated treatments, dose-rates of less than 1 Gy/s are typically delivered over the course of several weeks. Yet, recent evidence points to potential benefits of using ultra-high dose-rates (> 40 Gy/s), so-called FLASH-RT.

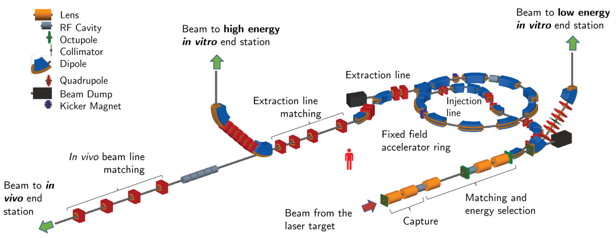

Figure 1: Computer aided design illustration of the proposed LhARA facility [4]. See text for further details.

In fig. 1, the Laser-hybrid Accelerator for Radiobiological Applications (LhARA) [3, 4] facility is illustrated, and is proposed as a highly flexible particle beam source to facilitate a programme of studies aimed at further exploring the biological response to ionising radiation and understanding the underlying radiobiological mechanisms of FLASH radiotherapy.

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LASER-HYBRID SOURCE

To achieve the high dose rates required for FLASH-RT, a commercial high power (100 TW) laser operating at a 10 Hz repetition rate will irradiate a thin dense target. Utilising the target normal sheath acceleration (TNSA) mechanism, a tightly focused laser pulse (up to intensities ~ 10^{21} W/cm^2) heats the target electrons which, in turn, generate strong, short-lived, electrostatic fields that accelerate surface ions away from the target. An illustration of the technique is shown in fig. 2.

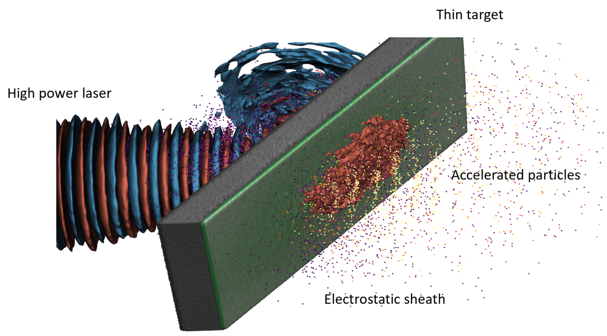

Figure 2: Illustration of 3D particle-in-cell simulation of TNSA mechanism following high-power laser impact on a thin, dense, target.

As part of the current conceptual design review (CDR), experimental and numerical studies are currently being performed to inform the design of the laser-hybrid source. High fidelity, 3D particle-in-cell (PIC), simulations are being undertaken using the Osiris 4.0 framework [5] to predict the target and laser parameters necessary for optimal proton and ion beam generation. These predictions will be validated by experiments at the Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) laser facility at the University of Strathclyde [6]. It is currently anticipated that the LhARA concept initially requires 10^9 protons at 15 MeV ±2% (and subsequently 10^8 C^{6+} ions at 4 MeV/nucleon) to be produced with a ⩽ 15 mSr divergence at a 10 Hz repetition frequency. Further, issues with debris produced by the target and delivery of the high powered laser to the target, are being investigated at the Zhi laser at Imperial College London.

PLASMA (GABOR) LENS CAPTURE

Particle accelerator-based beams typically use **B**-field focussing with 1D-based quadrupole, or 2D-based solenoid, magnets, but both have significant efficiency drawbacks within the LhARA concept. An alternative technique, based upon the internal **E**-field of a plasma, has previously been proposed by Gabor [7] which overcomes the negative magnetic-based focussing issues, and potentially offers significantly higher focussing strengths.

A cylindrical non-neutral plasma offers the ideal system whereby the focal length, f (in terms of the electron number density, n_e, plasma length, l, and ion energy, U) is given by

$$\frac{1}{f} = \frac{e^2 n_e l}{4\epsilon_0 U}. \qquad (1)$$

Such plasmas are readily confined in cylindrical Penning-Malmberg traps, and theoretically offer a significant (x40) reduction in focal length for a given **B**-field. For LhARA, it is anticipated that plasmas of $n_e \sim 10^{15}$ m^{-3}, $l \sim 0.9$ m and radius, $r_p \sim 4$ cm will be required. However, many challenges exist for obtaining plasmas of suitable size, density, and stability. Efforts elsewhere have illustrated the interaction of an ion beam with the plasma generated **E**-field [8], and the generation of a plasma comparable to that anticipated here [9].

As part of the ongoing design review, experimental and numerical studies are currently being performed to inform the LhARA facility design of the capture lenses. These studies focus upon the use of low temperature, equilibrated, non-neutral plasmas which will be confined for long-times, in contrast to the high temperature (sometimes self-sustaining) discharge plasmas of previous studies. Such low temperature plasmas with aspects similar to that required for LhARA have previously been produced (see e.g. [10, 11]). Numerical simulations will be performed with VSim [12] and WarpX [13] plasma-based PIC codes, and preliminary experiments aimed at validating the output from these PIC codes will be performed within a Swansea University-based particle trapping facility.

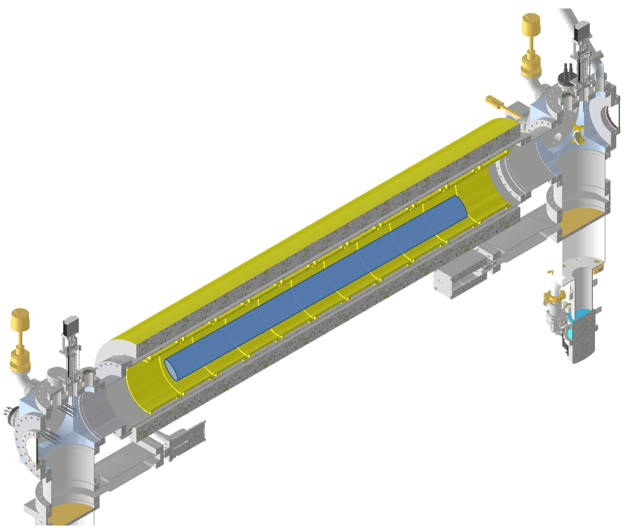

Figure 3: Cut-through computer aided design model of proposed plasma lens test bench, with illustration of a trapped plasma ■. See text for performance specifications.

The CDR will result in the specification and design of a flexible test bench, similar to that illustrated in fig. 3, expected to be capable of confining plasmas ($0.1 \leqslant l \leqslant 1.5$ m, $0.1 \leqslant r_p \leqslant 20$ cm, $n_e \leqslant 10^{14}$ m^{-3}) within 0.1 T **B**-fields, using $\leqslant 5$ kV potentials. These plasma will be a stepping-stone to achieving the final LhARA-based lenses, which are expected to operate with electrical potentials of 65 kV.

Final specifications of the plasma lens will be determined following beam tracking simulations of particles traversing the symmetry axis, S, of the proposed LhARA beamline [14]. Examples of such simulations are shown in fig. 4, for 2 different configurations of the lenses. Fig. 4a) shows the capture region parallelising the highly divergent beam (S<3 m), focussing the beam for energy selection through aperture at S~6 m, before re-parallelising at the desired size for subsequent downstream transport (S>16 m). Optimisation of the beamline elements reduces particle losses, as illustrated in fig. 4b), to ensure the highest efficiency transport of source-generated ions, and subsequent implementation of FLASH-RT.

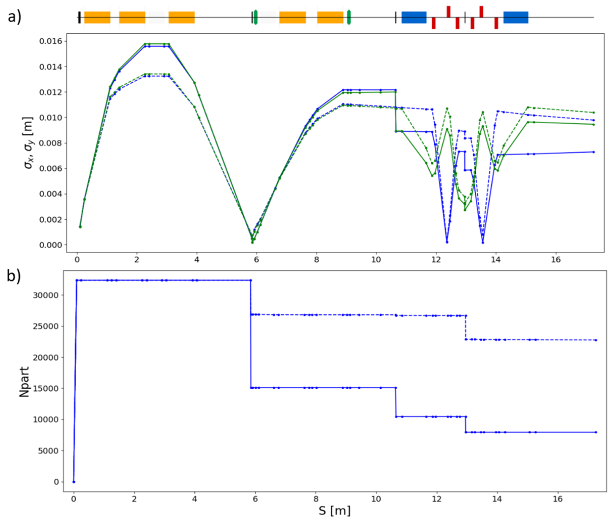

Figure 4: Simulations of an illustrative proton beam traversing the symmetry axis, S, of 2 configurations of LhARA beamline lenses. Elements of the beamline are illustrated, see fig.1 for component names (e.g. Gabor lens positions and axial length are indicated by: ■). a) x and y standard deviations of proton beam. b) The number of simulated particles traversing the LhARA beamline.

CONCLUDING REMARKS

A facility to study the radiobiological effects of FLASH-RT has been proposed, and a detailed programme for achieving the aims set out. The UKRI national funding agency is supporting the effort through the Infrastructure Fund Ion Therapy Research Facility (ITRF), with an initial 2 year CDR currently underway.

Numerical simulations and preliminary measurements form major components of the current design review, informing the target and laser source parameters, and the design of a suitable plasma lens based upon existing low-temperature, single-species (electron), non-neutral plasmas.

ACKNOWLEDGEMENTS

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