Laser source and Gabor lens for use within a Laser-hybrid Accelerator for Radiobiological Applications (LhARA)

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1. Introduction

Cancer was responsible for over 15% of deaths worldwide in 2020 [2], yet over 25 million life-years could be saved if radiotherapy (RT) capacity can be scaled up [3].

Approximately 50% of cancer patients will receive radiotherapy as part of their treatment. The majority of this is delivered utilising conventional techniques with MV X-rays, but proton and ion beam therapy (PBT) may offer significant advantages in some cases. These therapies currently utilise dose-rates of less than 1Gy/sec delivering fractionated treatment over the course of several weeks. Recent evidence points to potential benefits of using ultra-high dose-rates (>40 Gy/sec), so-called FLASH-RT.

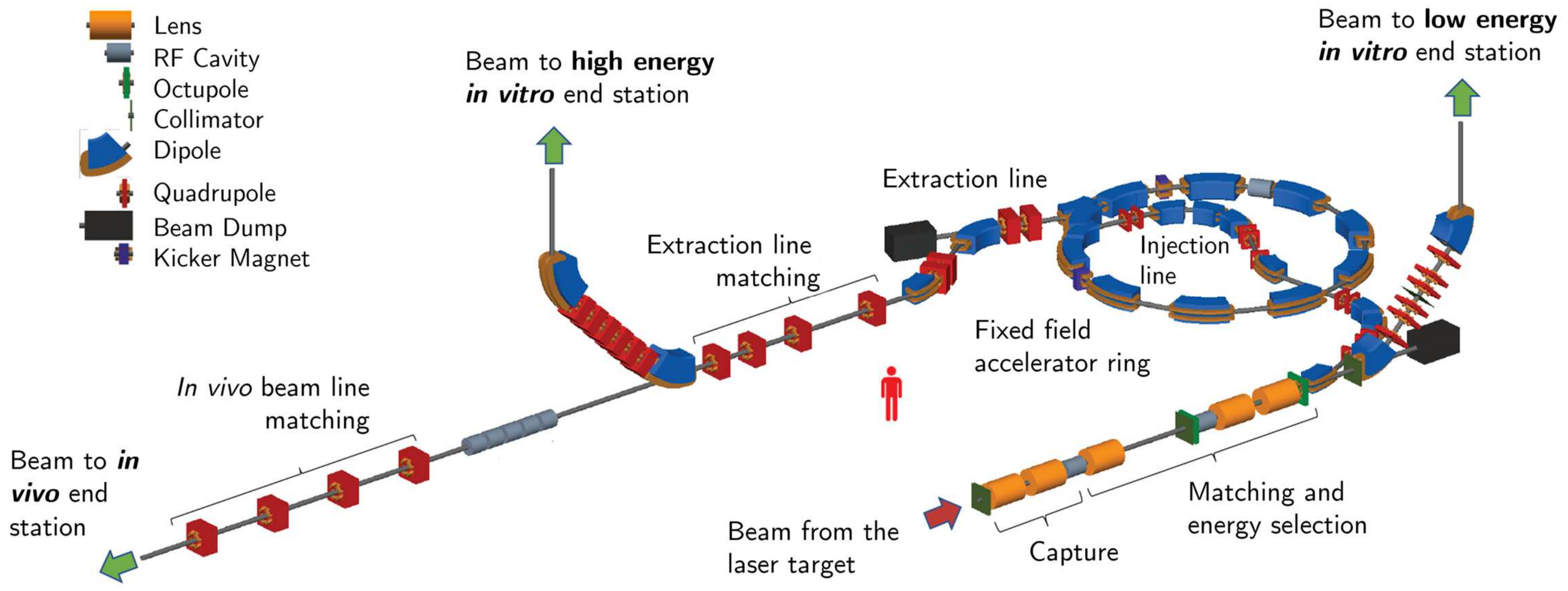

Figure 1. Illustration of proposed LhARA beamline.

2. LhARA

The Laser-hybrid Accelerator for Radiobiological Applications (LhARA) [4] facility (see fig. 1), 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 RT.

Utilising a high repetition rate laser directed at a suitable target (see section 3), a large flux of protons (or light ions, such as C^{6+}) can be produced, which will be captured and manipulated by plasma lenses (see section 4), forming a tailored ion-beams for *in-vitro*, or FFA accelerated to >120 MeV/u for *in-vitro* and *in-vivo*, studies.

Novel ion-acoustic-based detectors will provide real-time dose mapping of the ultra-high dose-rates, under a variety of temporal and spatial configurations.

3. Laser driven ion source

Laser driven ion sources deliver some significant advantages over conventional sources for the proposed high peak current LhARA beamline:

- Ultrashort (<ps) beam generation time
- Overcome space charge limitations
- Variable ion species

The LhARA source is based on the Target Normal Sheath Acceleration (TNSA) mechanism. A commercial high power laser will be used to irradiate thin dense targets, coupling laser energy (at $>10^{21}$ W/cm^2) to target electrons which in turn generate short-lived electrostatic fields which accelerate target surface ions, as seen in fig. 2.

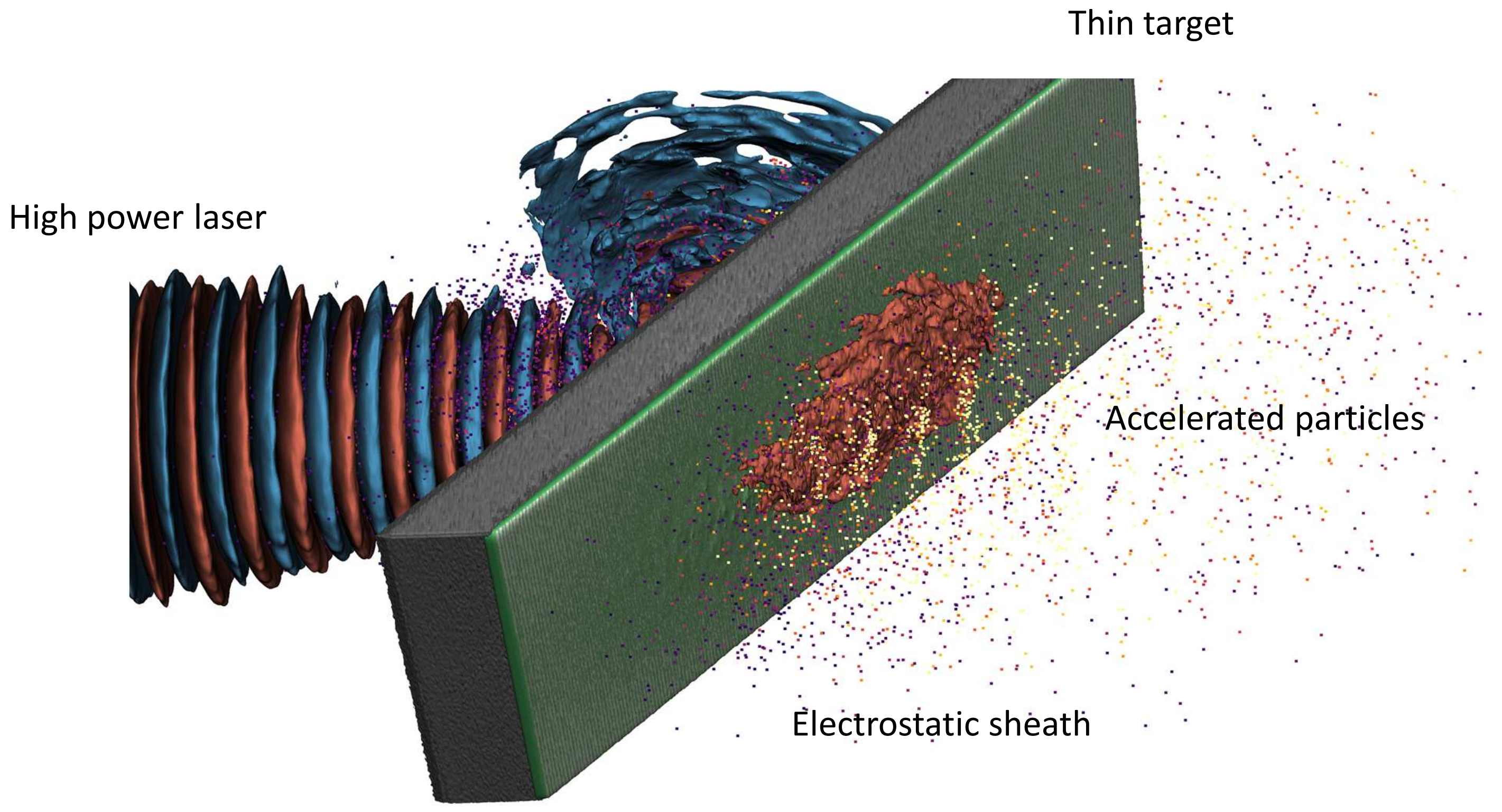

Figure 2. Illustration of 3D PIC simulation of TNSA mechanism.

We are currently performing experimental and numerical studies to inform the LhARA design. High fidelity 3D particle-in-cell simulations (using the Osiris 4.0 framework [5]) are being used to predict the target and laser parameters for optimal beam generation. These predictions will be validated by experiments at the SCAPA laser facility at the University of Strathclyde. Further issues with debris and target delivery are also being investigated at the Zhi laser at Imperial College London.

The LhARA concept requires the following beam parameters, which we are designing the source to provide:

- 10^9 protons at 15 MeV ± 10% within a 15 msr divergence
- 10^8 carbon at 4 MeV/u ± 10% within a 15 msr divergence
- Production of other ion species
- 10 Hz repetition rate
- Long term operation

4. Particle beam optics – Gabor Lens

Beams typically utilise **B**-field focusing but, owing to the potentially higher strengths, **E**-field-based techniques are of extreme interest. A cylindrical non-neutral plasma [6] offers the ideal system whereby the focusing length, f (in terms of the electron number density, n_e, plasma length, l, and ion energy, U) is given by

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

Such plasmas are readily confined in cylindrical Penning-Malmberg traps (see fig. 3 [4]), and theoretically offer a significant (x40) reduction in focal length for a given **B**-field.

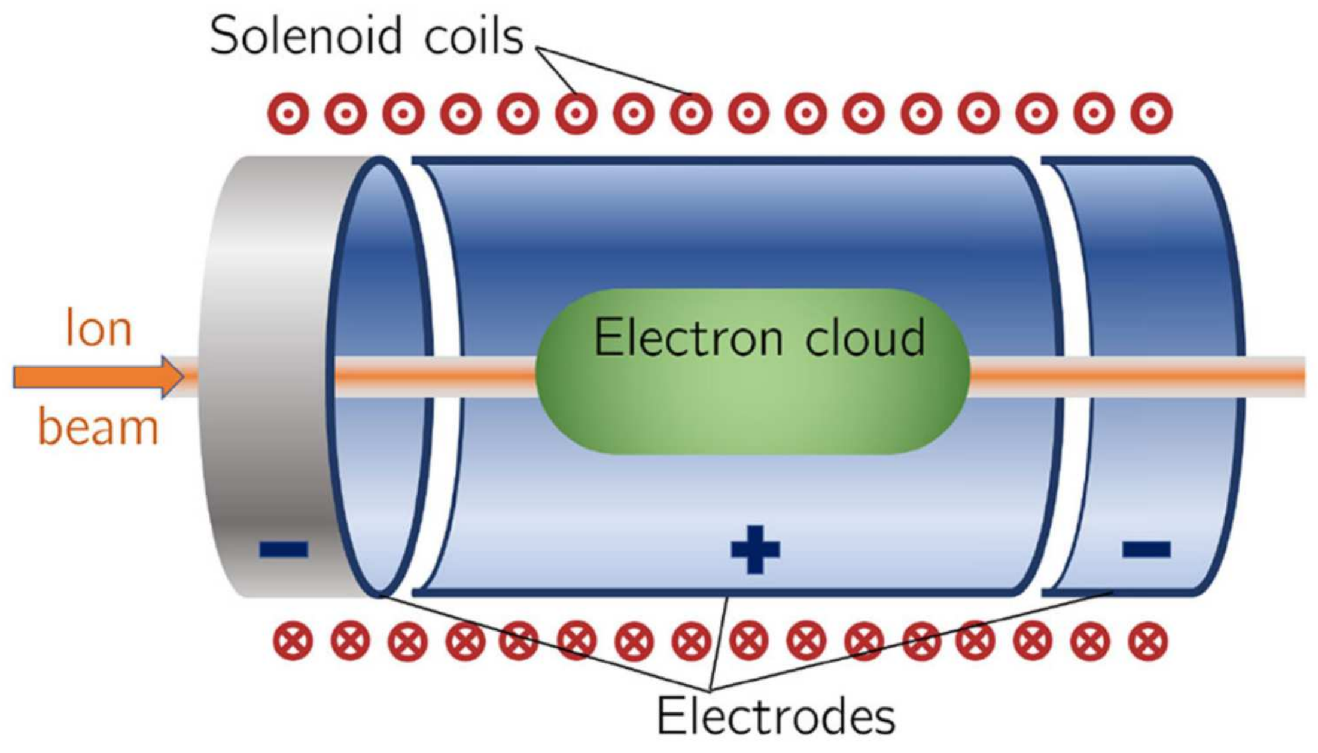

Figure 3. Illustration of plasma, or Gabor, lens concept.

The x and y standard deviation of an illustrative proton beam traversing 2 configurations of lenses within the proposed beamline (see fig. 1) is shown in fig. 4. As seen, losses occur due to energy and momentum selection apertures, which can be minimised with suitable focal length choices.

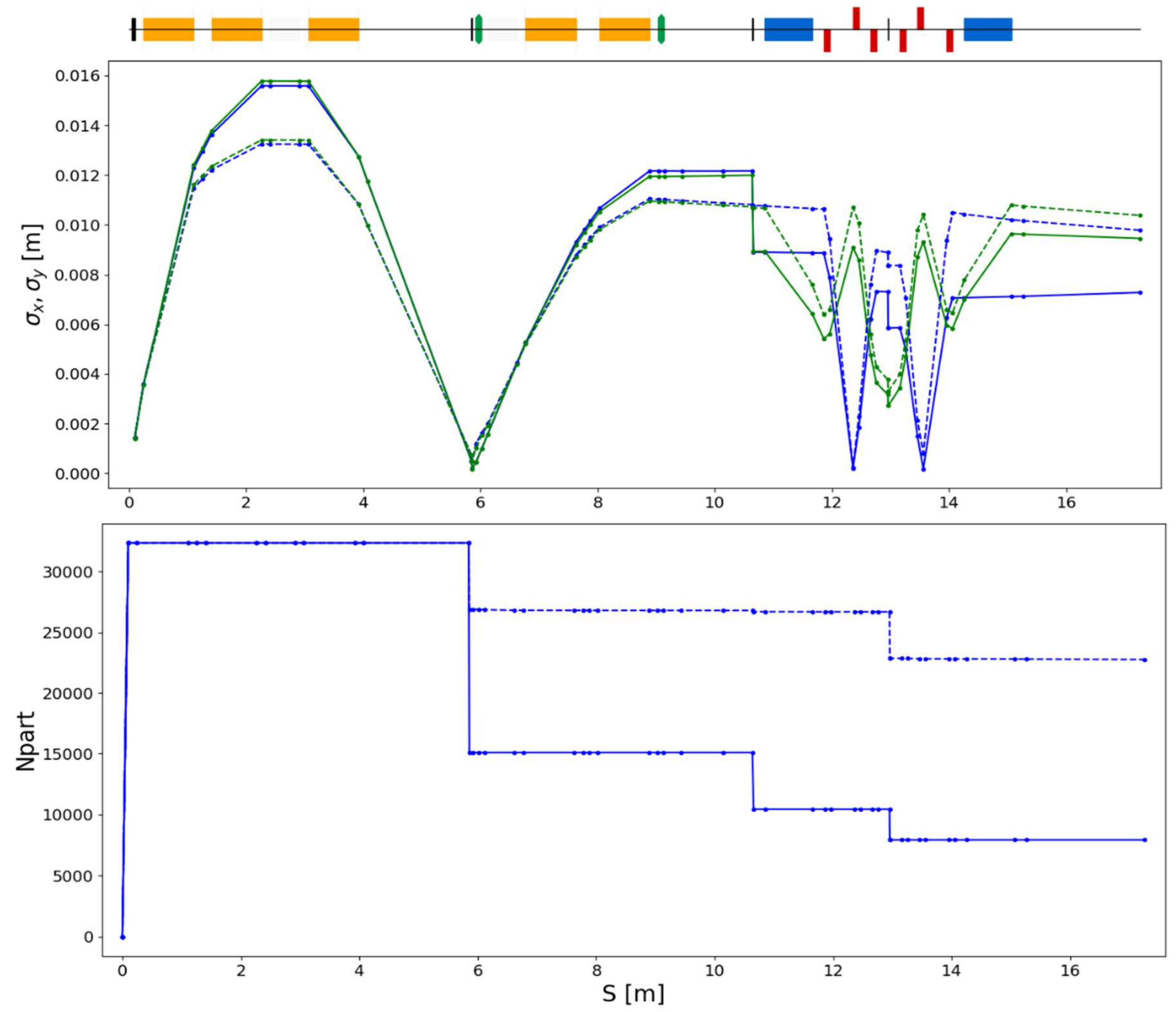

Figure 4. Particle tracking simulation. Top: Beam size. Bottom: Particle number.

5. Summary

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 its Infrastructure Fund's Ion Therapy Research Facility (ITRF), with an initial 2 year critical design review currently underway.

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

6. References

[1] www.lhara.org
[2] www.who.int/news-room/fact-sheets/detail/cancer
[3] Atun *et al.*, The Lancet Oncology **16** (2015), 1153
[4] Aymar *et al.*, Frontiers of Physics **08** (2020), 567738
[5] http://epp.tecnico.ulisboa.pt/osiris/
[6] Gabor, Nature **4055** (1947) 89
Fig's 1 & 4 modified from HT Lau PhD Thesis, Imperial College, London (2022)

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