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THE LASER-HYBRID ACCELERATOR FOR RADIOBIOLOGICAL APPLICATIONS (LHARA): AN UPDATE TOWARDS THE CONCEPTUAL DESIGN*

W. Shields†, John Adams Institute at Royal Holloway, University of London, Egham, UK

Abstract

LhARA, the Laser-hybrid Accelerator for Radiobiological Applications, is a proposed innovative facility designed to advance radiobiological research by delivering high-intensity beams of protons and ions in unprecedented ways. Designed to serve the Ion Therapy Research Facility (ITRF), LhARA will be a two-stage facility that will employ a laser driven proton and ion source Stage 1. The baseline capture energy for protons via the target normal sheath acceleration mechanism (TNSA) is 15 MeV. A series of Gabor plasma lenses will efficiently capture the beam. In Stage 1, the beam will be directed to an in-vitro end station. In the Stage 2, protons will be accelerated in an FFA ring to 127 MeV, while ions will achieve up to 33.4 MeV/nucleon. The resulting beams will be directed to either an in-vivo end station or a second in-vitro end station. The technologies demonstrated in LhARA have the potential to shape the future of hadron therapy accelerators, offering versatility in time structures and spatial configurations, with ultra-high dose rates exceeding what is believed necessary for studying the FLASH effect. Here, we present a status update of the LhARA accelerator as we approach a full conceptual design.

LHARA DESIGN STATUS

Following the pre-conceptual design of LhARA [1, 2], LhARA's current 2 year preliminary activity phase aims to generate a full conceptual design of the accelerator and facility. Three codes are used to design and evaluate the LhARA accelerator performance: MADX [3] for linear optics design & optimisation, BDSIM [4] for start-to-end Monte Carlo simulations including electrostatic focusing with Gabor lenses, and GPT [5] for modelling of space-charge forces. As the LhARA design and engineering models developed, repositioning of some Gabor lenses was required to provide space for systems such as diagnostics, collimators, and shielding. As such changes impacts the beam optics, we present here the updated LhARA accelerator design. A description of the beam modelled here can found in [6]. Gabor lenses were modelled in MADX and GPT as equivalent strength solenoids. The optics configurations shown here are not corrected for space charge effects unless otherwise indicated.

TRACKING PERFORMANCE & OPTIMISATION

To provide space for corrector magnets and diagnostics, the distance between Gabor lenses 4 & 5 and 6 & 7 has been increased. The distance between Gabor lenses 5 & 6 was also increased to provide space for a shielding wall, and a radiation shutter. Space was also reserved for a Wien filter for particle selection should LhARA be constructed in its backup solenoid configuration. To correct changes to the beam line optics, the solenoid strengths were re-optimised in MADX. Solutions were found preserving LhARA's ability to deliver a range of spot sizes (2σ) between 1 and 3 cm to the end station. The resulting horizontal beam size envelopes are shown in Fig. 1 with an additional focus at the Wien filter location. The small spot size at this position in both transverse axes may cause space charge forces to impact tracking performance. Efforts into producing smaller beams for LhARA including minibeams can be found in [7].

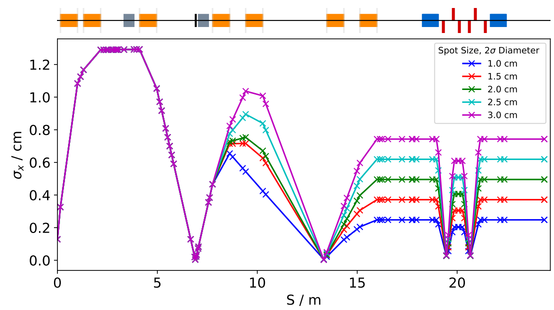

Figure 1: Horizontal beam radius for five optics configurations yielding 2σ diameter spot sizes between 1.0 & 3.0 cm. The survey above the plot shows the positions of the solenoids / Gabor lenses (orange), RF cavities (grey), dipoles (blue), and quadrupoles (red).

Figure 2 shows the beam envelope in the stage 1 optics configuration for operating the stage 2 FFA injection line. The injection line baseline assumes initial Twiss function

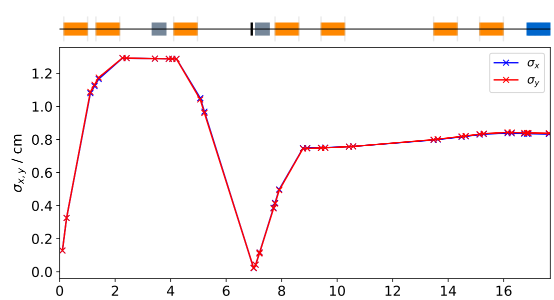

Figure 2: Stage 1 horizontal and vertical beam envelope for beam transport to the start of the stage 2 FFA injection line, optimised to mitigate effects of space charge.

* on behalf of the LhARA collaboration
† william.shields@rhul.ac.uk

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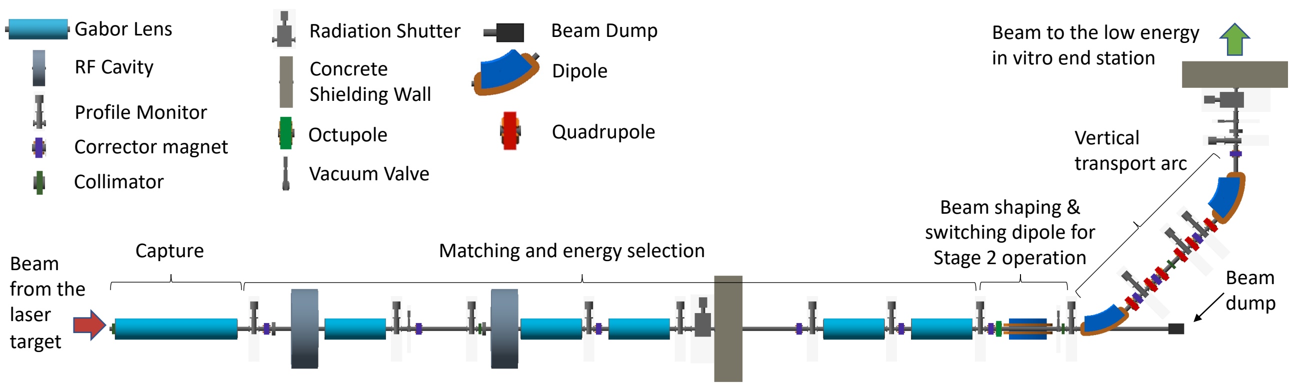

Figure 3: Schematic diagram of the LhARA stage 1 beam line including all EM beam transport components. Here, the accelerator is shown with Gabor lenses in light blue in the same locations as the solenoids in previous figures.

values of $\beta_{x,y} = 50$ m and $\alpha_{x,y} = 0$. A solution could not be found that met the injection line initial conditions when modelling the beam line in GPT with space charge forces. Space charge forces are known to increase the rms beam emittance from ~ 8.6×10^{-8} to ~ 3.5×10^{-6} mrad shortly after the laser-target interaction [6]. The original $\beta_{x,y} = 50$ m condition would therefore require an impractially large aperture in the switching dipole. Instead, a solution was found meeting the $\alpha_{x,y} = 0$ condition but with $\beta_{x,y} \approx 27$ m with the consequence that the injection line must be reoptimised with new initial conditions.

A diagram of the proposed layout of the Stage 1 of LhARA is shown in Fig. 3. The layout includes the Gabor lens and magnet positions as well as the proposed locations of collimators, beam profile monitors, corrector magnets, wall current monitors, RF cavities for longitudinal phase space manipulation, vacuum valves, radiation shutters, and shielding walls. The switching dipole for the FFA injection line is also included. The first and second Gabor lenses are shown as a single component; the close proximity of the two lenses is likely to introduce significant engineering challenges if installed seperately, therefore a single device with two field regions is being considered.

The non-optical beam line devices shown in Fig. 3 are included with basic geometry in a more detailed BDSIM model that has been assembled to allow easy synchronisation between physics particle transport models and the engineering CAD models. This BDSIM model ensures engineering concerns for provision of space for all necessary devices can be addressed, whilst also allowing rapid assessment of the beam transport performance should a device require repositioning. As the BDSIM output file stores a description of the model along with any tracking data, a Python program has been written to convert this model to a spreadsheet format from which the engineering CAD designs are derived.

STAGE 2 FFA INJECTION LINE

The solution identified in Fig. 2 requires the injection beam line be modified to transport a beam with a $\beta_{x,y}$ of ≈ 27 m at the switching dipole. The injection line was reoptimised in MADX with the $\beta_{x,y}$ and horizontal dispersion functions shown in Fig. 4 (solid lines) along with those of the baseline design (dashed lines). Only the quadrupole strengths were varied with constraints of $K_1 \leq \pm 17$ m^{-2} so as to not exceed the highest quadrupole strength in the baseline design. Despite an initial factor of ~ 2 difference in initial conditions, the modified solution meets the beam criteria at the end of the injection septum magnet with only minor changes to the quadrupole strengths. The region with high dispersion and low β_x is preserved to allow later inclusion of a collimator for momentum cleaning. This will be required to reduce the large beam energy spread produced in the laser-target interaction down to the 2% target for LhARA's end stations. Going forward, injection line modelling efforts will focus on optimising for space charge forces. It is anticipated that the 1-dimensional focusing from the quadrupoles will mean that space charge forces will have less impact on transport performance than that of the 2-dimensional focusing from Stage 1's Gabor lenses where small beam spot sizes are generated. Meeting the FFA injection conditions with space charge, however, remains a concern and its performance must be demonstrated.

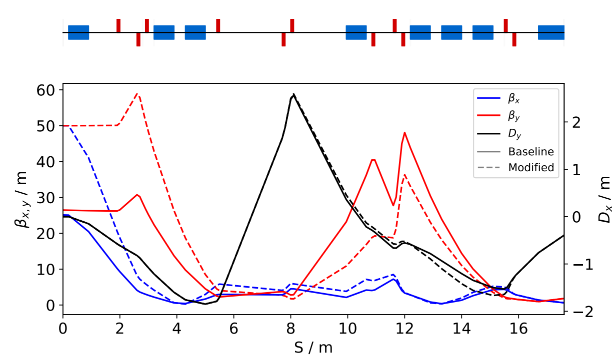

Figure 4: Horizontal and vertical Twiss β functions and horizontal dispersion for the baseline and modified designs of the LhARA stage 2 FFA injection line.

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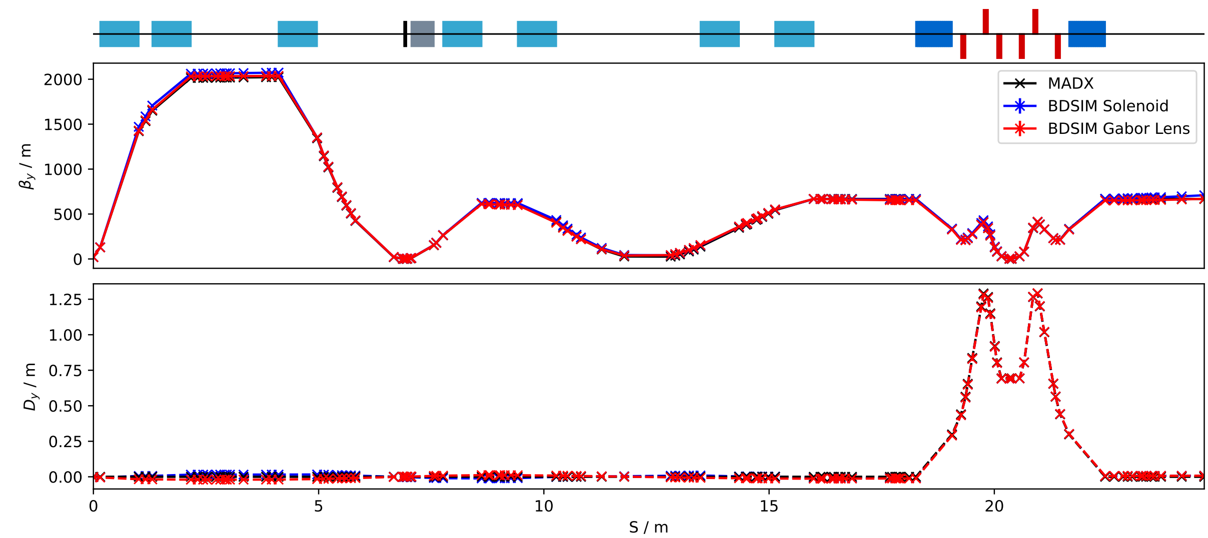

Figure 5: Vertical Twiss β (top) and dispersion functions (bottom) for LhARA stage 1 with solenoids in MADX, solenoids in BDSIM, and Gabor lenses in BDSIM. Gabor lenses are the design choice of capture devices for LhARA, solenoids are considered a contingency option. The comparison here shows both options offer viable beam transport performance.

GABOR LENS TRACKING PERFORMANCE

LhARA's baseline design uses Gabor lenses which offers solenoid-like focusing in both tranverse axes simultanously. For capturing proton beams, the solenoid field required for plasma confinement is a factor of $\approx$ 43 smaller than the equivalent field strength of a purely solenoidal device. As the maximum solenoid field in the LhARA design is 1.4 T, Gabor lenses offer a potentially attractive energy saving. Solenoids are considered as a fallback option for LhARA.

Due to software limitations, past beam transport simulations employed solenoids to model Stage 1. Recently, Gabor lenses have been added to BDSIM [8]. The Gabor lens element is constructed with a radial electric field that would arise from a confined plasma. The electric and magnetic confinement fields are not modelled. A 3.65mm anode radius is assumed for all lenses. The Stage 1 LhARA BDSIM model was run in both solenoid and Gabor lens configurations, with the vertical Twiss β and dispersion functions shown in Fig. 5 in comparison to the MADX solenoid model. Excellent agreement is observed between the models, indicating that LhARA's desired beam transport performance can be achieved with Gabor lenses and solenoids. The horizontal and vertical spatial and momentum profiles at the Stage 1 *in vitro* end station after tracking in both solenoid and Gabor lens configurations are shown in Fig. 6. Good agreement is observed between the distributions. Small differences are anticipated due to the fundamentally different focussing methods in the two configurations.

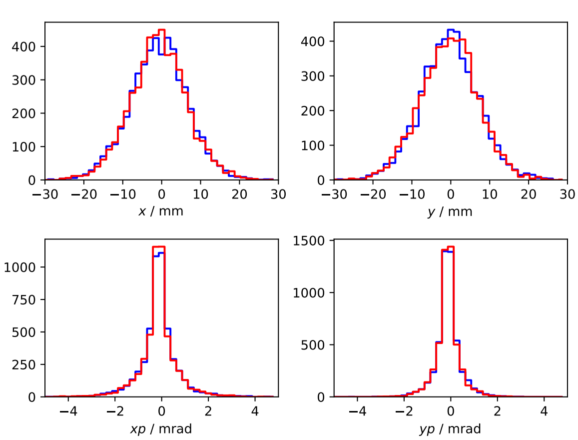

Figure 6: Horizontal and vertical spatial and momentum profiles at the stage 1 end station after tracking with solenoids (blue lines) and Gabor lenses (red lines).

CONCLUSION

Design changes to the LhARA accelerator driven by engineering considerations have modelled and shown to preserve performance specifications. Whilst the original initial conditions for LhARA's stage 2 FFA injection line could not be fully met, a solution with smaller Twiss β was found. The injection line was re-optimised and the conditions at the exit of the FFA injection septum were met. Tracking simulations with Gabor lenses and solenoids demonstrated comparable performance and confirm feasibility of Gabor lenses as devices for capture of particle ion beams.

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