PROGRESS ON THE CONCEPTUAL DESIGN OF THE LASER-HYBRID ACCELERATOR FOR RADIOBIOLOGICAL APPLICATIONS (LHARA)

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Abstract

LhARA, the Laser-hybrid Accelerator for Radiobiological Applications, is a proposed novel facility capable of delivering high intensity beams of protons and ions that will enable radiobiological research to be carried out in completely new regimes. A two-stage facility, the first stage utilizes laser-target acceleration to produce proton bunches of energies up to 15 MeV. A series of Gabor plasma lenses will efficiently capture the beam which will be delivered to an in-vitro end station. The second stage will accelerate protons in a fixed-field alternating-gradient ring up to 127 MeV, and ions up to 33.4 MeV/nucleon. The beams will subsequently be deliverable to either an in-vivo end station or a second in-vitro end station. The technologies demonstrated in LhARA have the potential to underpin the future of hadron therapy accelerators and will be capable of delivering a wide variety of time structures and spatial configurations at instantaneous dose rates up to and significantly beyond the ultra-high dose rate FLASH regime. We present here recent progress and the current status of the LhARA accelerator as we work towards a full conceptual design.

LHARA

LhARA, the Laser-hybrid Accelerator for Radiobiological Applications, is a proposed state-of-the-art accelerator for radiobiological research. Serving the Ion Therapy Research Facility (ITRF), LhARA aims to develop & demonstrate novel technologies for generating and transporting proton & ion beams that will enable dose delivery well into the FLASH regime. A systematic radiobiology programme is currently in development by the LhARA collaboration, which will enhance the understanding of the interactions between high energy particles with biological tissue, and lay the foundations for future generations of radiotherapy.

LhARA is conceived to be developed in two stages. Stage 1 will generate high flux proton and ion beams from laser-target interactions via the Target Normal Sheath Acceleration (TNSA) mechanism. Gabor electron plasma lenses will capture & focus the beam with a number of optical configurations offering flexibility of the transverse profile dimensions. Beam transport through a vertical matching arc will deliver the beam to an *in-vitro* end station. Stage 2 will see a switching dipole and beamline installed after the final Gabor lenses for subsequent beam injection into an FFA ring. An extraction line will transport the beams to two further end stations, one *in-vitro* and the other *in-vivo*. A pre-conceptual design report (pre-CDR) with a full description of the LhARA baseline design can be found in [1, 2].

Working towards a full conceptual design, recent efforts have focused on improved understanding of the generated beam, and subsequently the beam transport performance in start-to-end Monte Carlo simulations. Two codes are used; BDSIM [4], a Geant4-based program for modelling particle-matter interactions within a 3D model of the accelerator; and GPT [5], a particle transport program that can model the space charge forces that are anticipated to impact LhARA's tracking performance. Here, we show the performance of stage 1 in both the baseline configuration as well as a new experimental design configuration that potentially offers improved flexibility. A broader update on the status of LhARA can be found in [3].

SIMULATED TNSA BEAM

The proposed TNSA mechanism through which the LhARA beam will be generated is a developing technology, with the impact of experimental conditions on the generated beam phase space still to be understood. The performance of LhARA's baseline design was ascertained by tracking a beam generated from laser-target interaction simulations with the PIC code Smilei [6]. This beam, however, was limited to 2D due to the prohibitively expensive computational requirements for a full 3D simulation, with the third dimension generated by extrapolation [7]. More recent efforts within the LhARA collaboration have generated full 3D simulations with the PIC code OSIRIS [8], modelling the SCAPA facility which shares many similarities with the LhARA laser-target setup. Here, an 8 J, 800 nm laser was simulated at a normal angle of incidence upon a 2 μm thin Al^{3+} target with a 32 nm thick H^+ rear surface layer.

When considering particle transport modelling, the proton and electron beams generated by the laser-target interaction co-propagate, dampening the initial space charge effects. Modelling this scenario is non-trivial, and future investigations into this challenge are planned. For the studies presented here, we maintain our current strategy of down-sampling the proton beam to the 15 MeV $\pm$ 2% target energy, and assume that the beams co-propagate for 5cm after which the higher energy protons of interest have advanced beyond the lower energy electron beam. A 2mm radial cut is applied to the transverse profile representive of the entrance aperture of a vacuum nozzle in the laser-target chamber. The beam is tracked in GPT for a further 5cm with space charge forces modelled for an assumed total bunch charge of 10^9 protons. A second radial cut of 2.87 mm is applied representative of the nozzle exit aperture.

The beam parameters at the nozzle exit are listed in table 1. Whilst a factor ≈ 4 difference in emittance compared to

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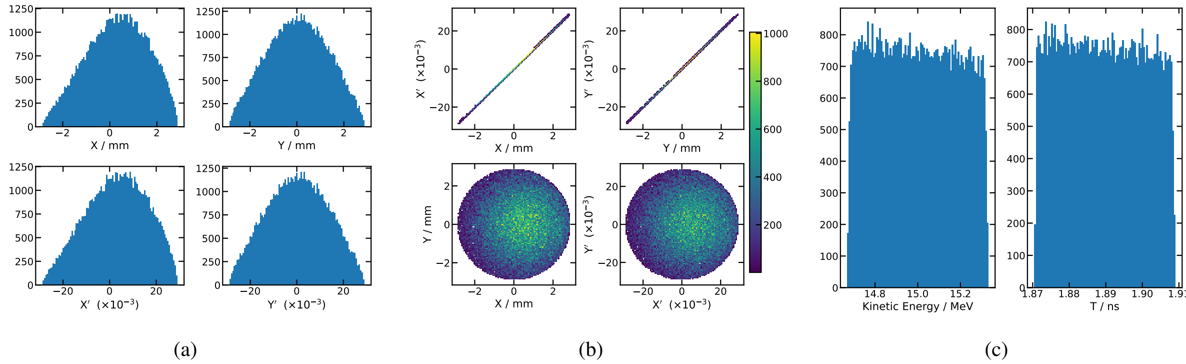

Figure 1: SCAPA beam profile 10cm downstream of the target, downsampled to 15 MeV ± 2% with transverse radial cuts representative of a vacuum nozzle aperture.

Table 1: LhARA beam parameters from TNSA simulations

Beam	**Emittance (m)**	**Beta (m)**	**Alpha**
Pre-CDR	3.26×10^{-7}	4.89	-50.22
Smilei	1.43×10^{-8}	141.34	-1418.43
SCAPA	7.98×10^{-8}	21.62	-222.23

the pre-CDR beam is observed, the SCAPA beam shows significantly better agreement than the Smilei data which is over an order of magnitude different. The origin of this discrepancy is not fully understood, however, the extrapolation of the third spatial dimension is believed to contribute to this effect. Consequently we now consider the SCAPA simulation in OSIRIS a more reliable description of the anticipated LhARA beam.

The resulting beam phase space at the nozzle exit is shown in Fig. 1. Despite a normal angle of incidence of the laser, a slight horizonal asymmetry is observed. The origin of this artefact is not understood, however beam transport performance in subsequent simulations is not adversely affected indicating good tolerance to the beam's initial direction of propagation. The beam remains highly divergent as a result of space charge forces modelled within the nozzle. The temporal and spectral profiles remain approximately uniform over the regions of interest, however further studies are planned on collimator efficiency and RF cavity simulation for longitudinal phase space manipulation.

Tracking Performance & Optimisation

The LhARA lattice was initially designed in Madx [9] & BeamOptics [10], neither of which consider space charge effects. Start-to-end particle transport modelling with the original beams demonstrated that space charge impacted the beam transport performance in stage 1, primarily due to a further emittance growth between the nozzle and the first Gabor lens [1]. Initial simulations in GPT with the SCAPA beam showed similar performance issues, resulting in a non-ideal beam profile delivered to the end station. As such, optimisation of the Gabor lens strengths was conducted using GDFSOLVE, a GPT utility program that can optimise the GPT model while considering space charge forces. The Gabor lenses are modelled as equivalent strength solenoids, with optimisation constraints of 1.4 T field limit which simultaneously constrains both the Gabor lens cathode voltage & magnetic field strength of contingency solenoid options.

Optimisation was performed to achieve 3 objectives:

- A parallel beam after the second Gabor lens, enabling a flexible length straight section for accommodating additional accelerator systems and a shielding wall.
- A spot-size focus at the collimator at $S = 6$ m for optimum energy selection efficiency.
- A parallel beam after the final Gabor lens, where beam conditions should be identical to those delivered to the end station after transport through the vertical matching arc.

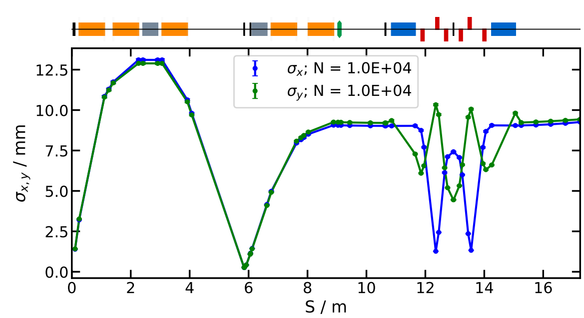

Figure 2: Transverse beam size along LhARA stage 1 with optimised Gabor lens settings to mitigate space charge induced emittance growths.

Figure 2 shows optimised optical performance of the beam transport with all 3 objectives achieved. A slight divergence remains after the vertical arc which is believed can be corrected with minor adjustments. Solutions for smaller spot sizes, however, remain challenging to achieve whilst optimising for all three objectives. This additionally impacts transport in the stage 2 FFA injection line which requires a Twiss $\beta = 50$ m after the fifth Gabor lens.

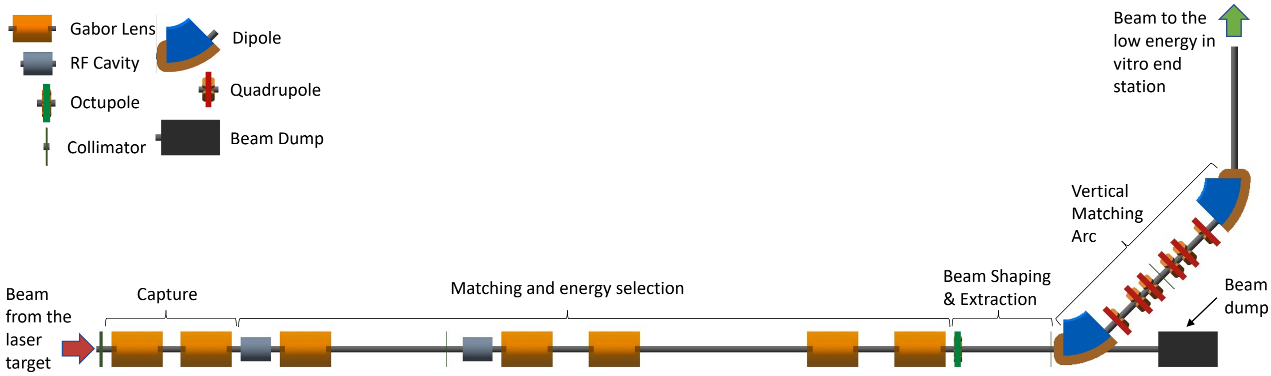

Figure 3: Schematic diagram of the seven Gabor lens configuration for stage 1 of LhARA.

7 GABOR LENS CONFIGURATION

To provide both the desired spot size flexibility & injection line operation, a new experimental configuration is being investigated that includes a further two Gabor lenses. These are installed after a new 2.5 m long drift after Gabor lens 5, in the same configuration as Gabor lenses 4 & 5 which sees an additional 20 cm drift length included. The second energy collimator after Gabor lens 3 is also replaced with an equivalent length drift space. The total length increase is 5.314 m. A schematic diagram of this stage 1 configuration is shown in Fig. 3.

To validate the design, the SCAPA beam is tracked through beam line models in Madx, BDSIM, and GPT (excluding space charge effects). The stage 1 start-to-end horizontal beam size is shown in Fig. 4. Good agreement is observed between all three models. Differences between BDSIM and GPT are attributed to GPT modelling finite strength fields at the sampled locations whereas BDSIM models hard-edged fields. When space charge effects are considered, an emittance growth is again observed, reducing the transport efficiency.

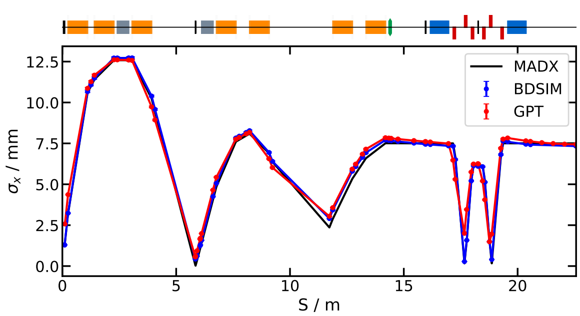

Figure 4: Nominal horizonal beam size in LhARA in MADX, BDSIM, and GPT for model validation.

Optimisation for Space Charge Mitigation

The strengths of the seven Gabor lenses were similarly optimised to mitigate the space charge induced emittance growth and achieve the previously defined objectives. Figure 5 shows the transverse beam profile along stage 1 with the optimised Gabor lens settings. Optimised solutions for smaller spot sizes have been found and remains the focus of ongoing research.

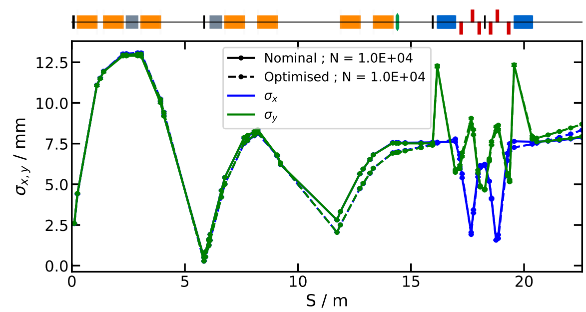

Figure 5: Horizontal beam size in the seven Gabor lens configuration of LhARA stage 1 with optimised lens strengths to mitigate space charge effects.

CONCLUSION

An improved understanding of the beam generated from a laser-target interaction has highlighted potential issues with the flexibility & stage 2 operation of the baseline design of LhARA. Whilst optimisation of the nominal optics configuration has been achieved, the requirement for smaller spot-sizes has prompted an investigation into a promising new configuration with seven Gabor lenses. Optimisation of this design has yielded an improved performance. Research remains ongoing to assess the feasibility of this new configuration, and a full comparison to the baseline design is planned.

ACKNOWLEDGEMENTS

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