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SIMULATIONS OF THE STAGE 2 FFA INJECTION LINE OF LhARA FOR EVALUATING BEAM TRANSPORT PERFORMANCE

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Abstract

A new, novel facility for radiobiological research, the Laser-hybrid Accelerator for Radiobiological Applications (LhARA), has recently been proposed. LhARA will be a two-stage facility with the first stage employing laser-target acceleration to produce intense proton bunches of energies up to 15 MeV. The second stage will accelerate the beam in an FFA ring up to 127 MeV. Optimal performance of stage 2, however, will require an emittance reduction of the stage 1 beam due to the FFA's nominal dynamical acceptance. Here, we demonstrate a new optical configuration of LhARA's stage 1 lattice that will provide this reduced emittance. The profile of the laser-target generated beam is far from an ideal Gaussian, therefore two start-to-end Monte Carlo particle tracking codes have been used to model beam transport performance from the laser-target source through to the end of the stage 2 FFA injection line. The Geant4-based Beam Delivery Simulation (BDSIM) was used to model beam losses and the collimation that is crucial to LhARA's energy selection system, and General Particle Tracer (GPT) was used to model the space-charge effects that may impact performance given the emittance reduction.

INTRODUCTION

The LhARA collaboration is a multi-disciplinary consortium [1]. LhARA, the Laser-hybrid Accelerator for Radiobiological Applications, is a proposed novel research facility that will be capable of delivering proton and ion beams in FLASH doses. It will allow researchers to develop a biophysical understanding of the interactions between protons and ions with biological tissue, and create the capability to develop new treatment modalities.

The first stage of the LhARA accelerator will see it's 15 MeV laser-target generated proton beam captured by a series of Gabor lenses that provide equivalent focusing to solenoids. The beam is subsequently delivered to an *in vitro* end station. Stage 2 of LhARA will permit the extraction of the beam after the Gabor lenses for transportion and injection into an FFA ring for acceleration and subsequent delivery to two further end stations. A full description of the LhARA accelerator including the original lattice description in MADX [2] and BeamOptics [3] can be found in [1, 4].

To ensure the injection line is capable of delivering beams matched to the FFA cell requirements, the transport performance must be assessed of both the injection line and the modified stage 1 optical configuration that produces the lower emittance beam necessary for injection. Here, we demonstrate a series of start-to-end Monte Carlo (MC) particle tracking simulations to model the beam line transport. The original beamline design in MADX is shown along with results from MADX's PTC tracking routines, the Geant4-based BDSIM [5] for demonstrating tracking, particle losses, and energy deposition, a finally GPT [6] for simulating space charge effects.

LhARA FFA INJECTION LINE

The LhARA injection beam line is 14.6 m long consisting of 10 quadrupoles, 6 dipoles, a switching dipole, and an injection septum magnet. A schematic diagram of the injection line along with the LhARA capture and energy selection sections is shown in Fig. 1. To inject the beam into the FFA, the strength of the Gabor lenses are modified from their stage 1 configurations to produce a nominal beta function value of 50 m at the start of the switching magnet.

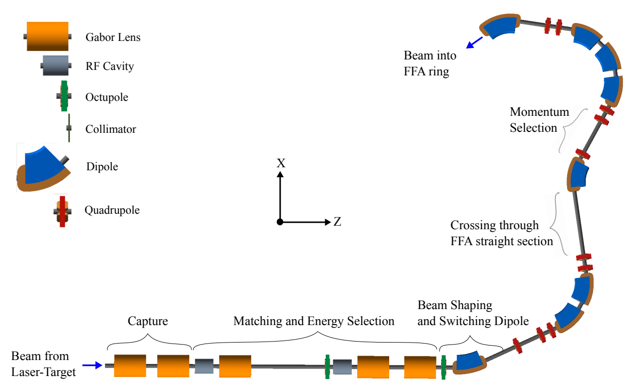

Figure 1: Schematic diagram of the LhARA stage 1 capture section, matching and energy selection section, and the stage 2 FFA injection line.

We initially assume an idealised 15 MeV Gaussian beam, the parameters of which can be found in [1, 4]. The beam produced from the laser-target interaction is expected to contain low energy contaminents that neutralise the bunch charge. The beam is therefore simulated for the first 5 cm of transport without space charge forces. After this, we anticipate the protons to have moved ahead of the contaminents, consequently the subsequent 5 cm are simulated with space charge effects. The beam consisting of 10000 particles is then prepared for further simulation in PTC, BDSIM, and GPT. The beam Twiss parameters for the MADX model are calcuated from the particle distributions at this point. As the

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MC tracking codes cannot simulate Gabor lenses, they are replaced by equivalent strength solenoids.

To verify the MC models, we first compare the horizontal and vertical Twiss beta and horizontal dispersion functions in MADX to that from PTC and BDSIM, the results of which are shown in Fig. 2. The beta and dispersion functions for both BDSIM and PTC are calcuated using BDSIM's optics analysis tool *rebdsimOptics*. To minimise particle losses in the BDSIM model, we widen the beam pipe aperture and do not simulate particle-matter interactions. Whilst BDSIM and PTC show excellent agreement with one another, they both show a discrepancy compared to the MADX optics. This inconsistency is believed to be caused by the heavily divergent beam in the capture section being on the boundary of the paraxial approximation that is assumed in MADX's matrix transport routines. Further deviations then acrue along the beam line resulting in the noticeable difference in the vertical beta function. Consequently, the final beta and dispersion functions at the injection septum to those estimated with MADX.

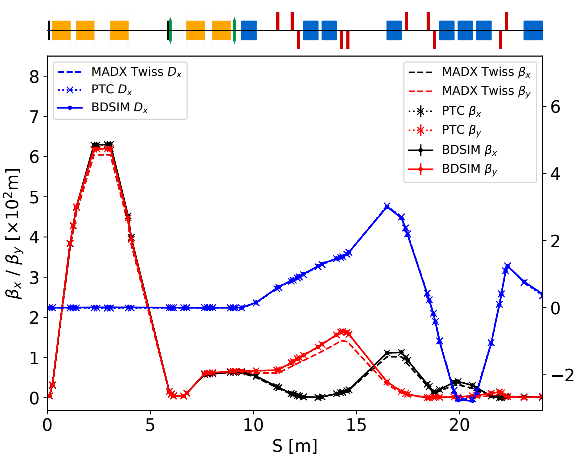

Figure 2: The beta and horizontal dispersion functions of an idealised beam from PTC and BDSIM in comparison to the nominal MADX lattice parameters.

Furthermore, when we inspect the transverse phase space at the end of the injection septum, as seen in Fig. 3, a noticable aberration is present. This aberration arises in the solenoids in the capture section and persists throughout the beam line. This behaviour was previously observed in LhARA's stage 1 transport performance simulations [1,4]. The solenoids in these simulations will eventually be replaced by full electromagnetic simulations of the Gabor lenses, at which point the aberration and transport performance will be investigated further.

SPACE CHARGE SIMULATIONS

The beam focusing in both transverse planes after the capture section is of concern due to its susceptibility to further space charge effects. We therefore simulate beam transport from the first Gabor lens to the injection septum in GPT

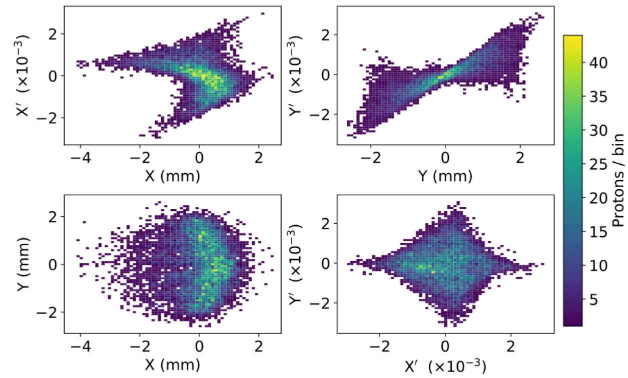

Figure 3: Transverse phase space at the exit of the FFA injection septum simulated with BDSIM.

with space charge forces. We use the *spacecharge3Dmesh* routine with the *MGCG* Poisson solver method and a fixed-sized mesh of 50, 50 and 150 mesh lines in the x, y and z directions respectively.

A comparison of the beam sizes σ_x & σ_y for BDSIM and GPT both with and without space charge effects are shown in Fig. 4. The beam sizes are shown instead of the beta functions as these are the native outputs of both BDSIM and GPT. Whilst both codes agree well when not considering space charge, a further emittance growth is observed before the first solenoid when space charge is simulated. Consequently, the divergent beam at the switching dipole entrance causes a significant deviation from the nominal performance in the injection line. Despite this disagreement, as the focusing in the injection line is limited to a single plane at a time, space charge effects are not anticipated to impact transport performance after the switching dipole. Further optimisation therefore will focus on the Gabor lens strengths to produce the correct beam parameters at the start of the injection line.

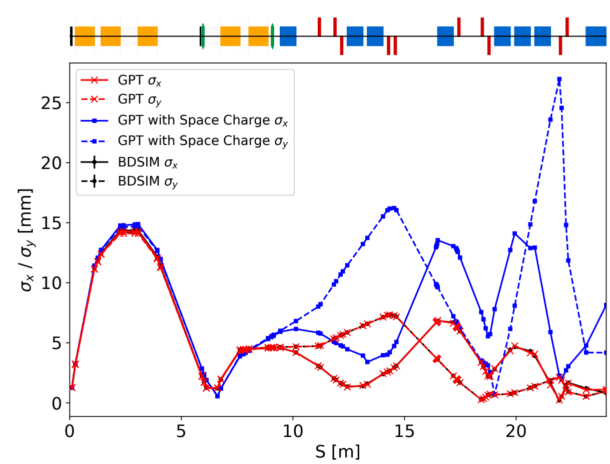

Figure 4: Horizontal and vertical beam size of an idealised beam in BDSIM and GPT both with and without space charge modelling.

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SEMI-REALISTIC BEAM

To further improve our understanding of the transport performance, the beam was updated to a semi-realistic set of particle coordinates. This beam was generated from sampled output of laser-target interaction simulation using the particle-in-cell code Smilei [7]. A description of the beam generation process can be found in [8].

Figure 5 shows the σ_x & σ_y beam sizes for BDSIM and GPT both with and without space charge effects. The effect of space charge is reduced compared to the ideal beam due to larger initial beam dimensions. The beam is less divergent at the switching dipole entrance, thus the remaining beam transport performance being broadly comparable to that of BDSIM. The final dimensions, however, do not match FFA cell requirements and further optimisation is still required.

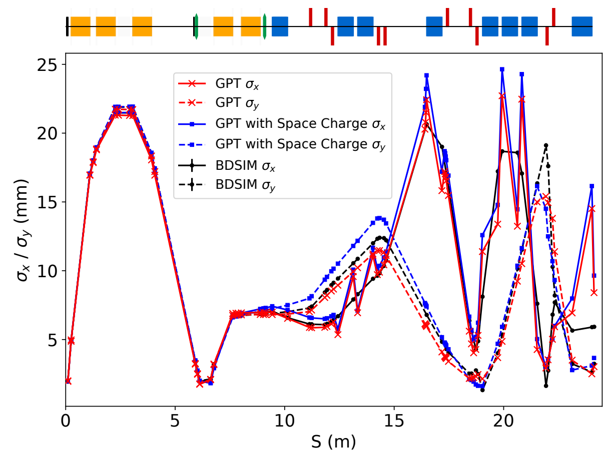

Figure 5: Horizontal and vertical beam size of a semi-realistic beam in BDSIM and GPT both with and without space charge modelling.

The GPT simulation results contains horizontal beam size jumps due to GPT's *tout* outputs capturing the bunch's longer temporal profile partially within sector-bend fields. These discontinuities are therefore considered a simulation artefact and not the beam transport performance.

Collimation and Energy Deposition

The realistic beam was also simulated in BDSIM with particle-matter interactions using Geant4's *QGSP_BIC_EMZ* physics list. The momentum selection collimator aperture radius was set to 0.5 mm, the same settings for stage 1 *in vitro* energy collimation.

Figure 6 shows that energy deposition from the primary protons and secondary emissions is mostly restricted to within +/- 2 m of the collimator. The collimator is the principle location where particles first undergo a physics process and consequently where the majority of the lost particle's energy is deposited. Due to the aforementioned aberrations and collimator settings, heavy losses are observed with < 1% of the beam reaching the FFA septum magnet. New collimator settings are therefore required for energy selection through the injection line. This will also be addressed when simulations of the Gabor lenses are available.

CONCLUSION

LhARA's FFA injection line has been modelled in Monte Carlo simulations to assess it's optical transport performance. Space charge causes an early emittance growth in an idealised beam, resulting in the beam being unmatched to FFA cell parameters. A more realistic beam showed less susceptibility to space charge effects, but the final beam parameters requires tuning of the lattice to match the FFA requirements. Optimisation of the beamline is therefore required. The combination of space charge effects in GPT and BDSIM's accurate beam loss and energy deposition capabilities are highly suited to optimisation studies going forward.

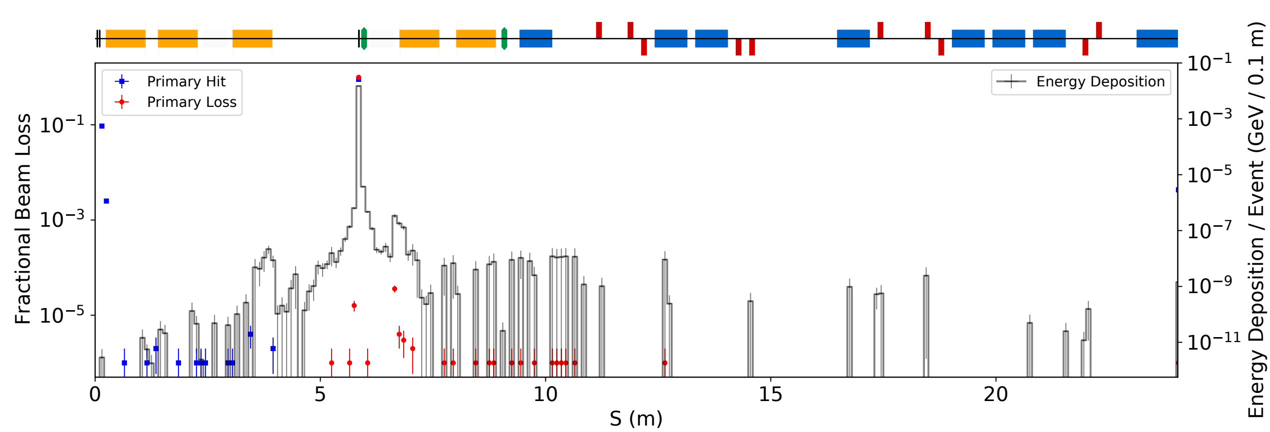

Figure 6: BDSIM loss map showing primary hits, losses and energy deposition in 10 cm bins along the length of the simulated beam line.

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