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DEVELOPMENT OF NOVEL MAGNETICALLY-FOCUSSED MINIBEAMS FOR IN VIVO AND IN VITRO END STATIONS FOR LhARA*

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on behalf of the LhARA Collaboration

Abstract

Radiotherapy is an effective, non-invasive, widely used treatment for cancerous tumours that uses x-ray photon, electron and ion beam sources. The Laser-hybrid Accelerator for Radiobiological Applications (LhARA) is a novel laser-driven accelerator system under development that aims to prove the principle of the laser-driven approach to Particle Beam Therapy (PBT). This study aims at the development of a novel system to deliver different light ion minibeams to the in vivo and in vitro end stations. The desired minibeams will be delivered by magnetically focusing and steering the incoming proton and light ion beams, without the use of collimators. Minibeams with a diameter of approximately 1 mm spot will be delivered at an energy of 15 MeV to the in vivo and in vitro end stations. An update on the status of the development of this magnetic focusing technique will be presented here.

MINIBEAM RADIATION THERAPY

Minibeam Radiation Therapy (MBRT) is a radiotherapy technique which uses very small and highly focussed beams to deliver ionising radiation into tumorous tissues [1]. Minibeams are defined as beams with diameters of between 0.3 - 1 mm [1]. These minibeams are essentially small radiation fields with a small cross-sectional area. These properties are beneficial when targeting specific regions in tissue which require precise tumour cell targeting. Ion minibeams can be used to maximise the dose of radiation delivered to the tumour whilst exhibiting sparing of the surrounding normal, healthy tissues by minimising the entrance and exit doses.

MAGNETIC BEAM FOCUSING

To create the desired minibeams, a novel technique for focusing the incoming proton and light ion beams, without collimation, is being developed. Collimation is a common method for generating minibeams however, it has limitations [2]. When a collimator is used, there is a reduction in instantaneous dose rate delivered because some of the intensity of the beam is lost when it is incident on the surface of the collimator. Collimation also produces secondary inelastic scattering when protons scatter off the collimator edge causing dose contamination [3]. Magnetically focusing a proton beam into a minibeam is possible and was demonstrated in [4]. From these results, it is evident that magnetic beam focusing will be vital in achieving LhARA's goal of maximising and maintaining the intensity of the beam from source to target in order to deliver high instantaneous dose rates of radiation to our biological targets. The updated LhARA baseline design, modelled in BDSIM [5, 6], has been shown to deliver ultra-high dose rates (UHDRs) of ~120 Gy/s with 15 MeV protons to the Stage 1 in vitro end station [7]. This baseline design has only been shown to deliver spot sizes of 1-3 cm to the end station however, delivering smaller beams by only varying the Gabor lens strengths has proven challenging. This gives further motivation to developing a magnetic beam focusing system.

LHARA BEAM FOCUSING DEVELOPMENT

Starting from this updated LhARA baseline design, displayed in Fig. 1 [8], a quadrupole magnet system is being developed to focus the incoming 15 MeV proton beam towards the minibeam regime and deliver it to the low energy in vitro end station at the end of the LhARA stage 1 beam line.

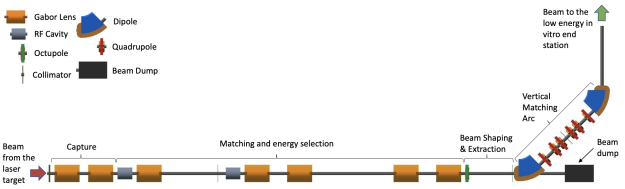

Figure 1: A schematic diagram of the seven Gabor lens configuration for the LhARA stage 1 beam line [8].

This beam focusing system will deliver a minibeam with a spot diameter of $\lesssim 1$ mm, at the end station. This system is constrained to be 2 m, in length. The BDSIM model simulates a 15 MeV proton beam and tracks 5000 particles from the laser-ion source to the low energy in vitro end station. All simulations presented here run from the end of the 20 cm long drift after the second dipole magnet in the vertical matching arc to the low energy end station. The model used to simulate the data prior to this point (from the laser-ion source to 20 cm beyond the second dipole in the vertical matching arc) was simulated for a 1 cm spot size, detailed in [6]. The beam focusing system being developed is informed by design of a system with similar requirements detailed in [1]. The beam focusing system simulated in this previous study consists of a quadrupole doublet with one focusing quadrupole magnet and a defocusing quadrupole magnet with lengths of 11.4 cm and quadrupole strengths, K, of 2.2502 m^{-2} and 2.0708 m^{-2}, respectively, for a beam energy of 150 MeV [1].

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Quadrupole Doublet Configuration

The initial configuration chosen for the LhARA beam focusing system is a quadrupole doublet positioned above the end of the 20 cm drift after the second dipole magnet in the vertical matching arc, shown in Fig. 2. The quadrupole doublet consists of a defocusing quadrupole magnet followed by a focusing quadrupole magnet with lengths of 11.4 cm and quadrupole strengths, K, of 11.695 m^{-2} and -22.712 m^{-2}, respectively. This configuration is based on the quadrupole doublet previously described in [1]. A scaled down doublet configuration was estimated for a 15 MeV beam by reducing the magnetic field strengths by a factor of 10 to give quadrupole strengths (K) of 22.5022 m^{-2} and 20.7082 m^{-2}. An optimisation, starting from this quadrupole configuration, minimised the average of the square root of the covariance matrix for x and y positional values for the 5000 simulated particles by varying the quadrupole lengths, strengths and separation between the doublet. A spot size of 0.6 mm rms was achieved, indicating that the final simulated spot size delivered to the low energy in vitro end station would be within the correct order of magnitude to produce a minibeam.

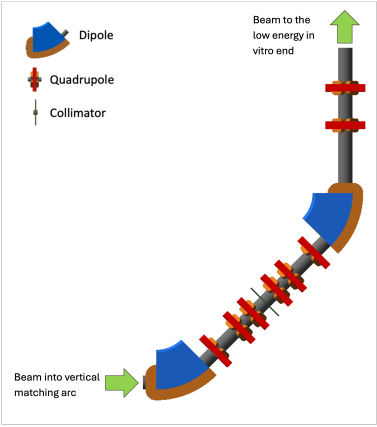

Figure 2: A schematic diagram of the vertical matching arc up to the low energy in vitro end station with the quadrupole doublet beam focusing configuration, along the vertical axis.

Phase Space

The phase space of the beam exiting the 20 cm drift after the second dipole magnet in the vertical matching arc is shown in Fig. 3. The spatial projections, in the horizontal (x-plane) and vertical (y-plane) directions, after the 20 cm drift are shown in Fig. 4. From Fig. 3 and 4, the majority of the 5000 protons simulated converge on a spot size of < 5 mm.

Figure 5 shows the beam profile at the exit of the drift to the low energy in vitro end station. The simulations have demonstrated that the quadrupole doublet system has focussed the beam in both x and y planes. The spatial projections, in the horizontal and vertical directions, after the final drift are shown in Fig. 6. From Fig. 5 and 6, the majority of the 5000 protons simulated converge on a spot size of ≈ 1 mm.

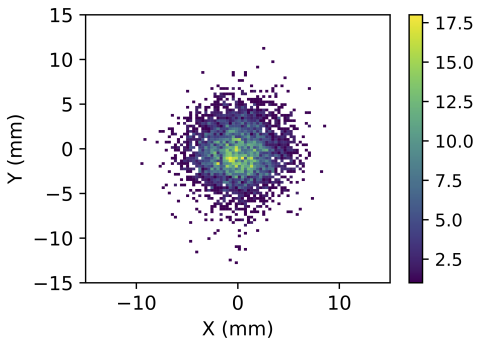

Figure 3: Beam profile in the x-y plane 20 cm downstream of the second dipole magnet in the vertical matching arc.

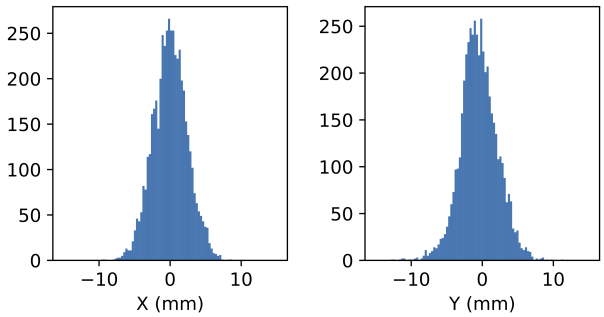

Figure 4: Horizontal and vertical spatial projections 20 cm downstream of the second dipole magnet in the vertical matching arc.

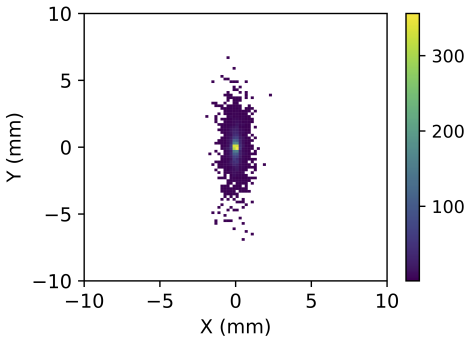

Figure 5: Beam profile in the x-y plane at end of the final drift at the low energy in vitro end station exit; after the quadrupole doublet.

This quadrupole doublet focusing system is therefore capable of producing minibeams. However, further optimisation of the quadrupole focusing system is necessary to maximise the intensity of the minibeam reaching the low energy in vitro end station with a 1 mm spot size and to investigate delivery of beams with asymmetric spot-sizes. A dipole system, similar to that presented in [1], is also under consideration to allow scanning of the minibeam spot across the sample volume.

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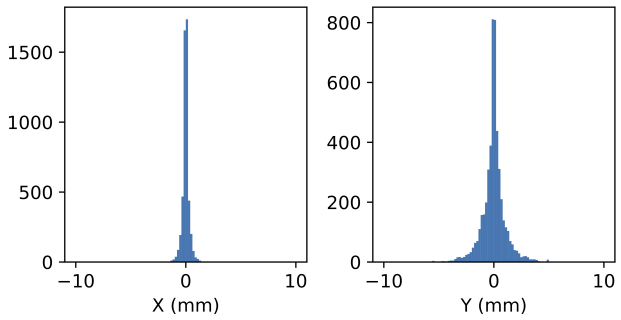

Figure 6: Horizontal and vertical spatial projections at the end of the final drift at the low energy in vitro end station exit; after the quadrupole doublet.

Twiss Beam Parameters

Figure 7 presents the beam size ($\sigma_{x,y}$) from the end of the 20 cm drift after the second dipole magnet in the vertical matching arc to the low energy in vitro end station. Physically, $\sigma_{x,y}$ is the rms beam radius. From this quadrupole doublet focusing system, $\sigma_x \approx 0.2$ mm and $\sigma_y \approx 1.2$ mm at the end station. Beam divergence in the x-z plane is minimal with this quadrupole configuration so σ_x satisfies the condition to be classed as a minibeam. However, dispersion in the y-z plane is not fully compensated and more optimisation will be necessary to reduce σ_y to satisfy the minibeam condition.

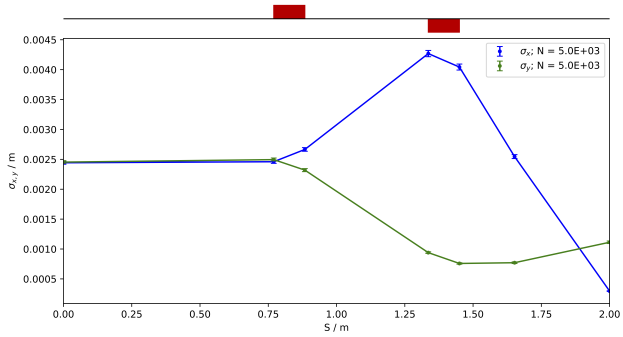

Figure 7: Horizontal and vertical beam radii from 20 cm downstream of the second dipole magnet in the vertical matching arc to the final drift at the low energy in vitro end station exit. The survey above the plot shows the positions of the two quadrupoles (red).

CONCLUSION

The quadrupole double configuration presented demonstrates that this simple focusing system is capable of producing a 1 mm spot size in the xy-plane, at the end station. This suggests that further optimisation of the system will allow for production of minibeams which satisfy the < 1 mm diameter condition in both the horizontal and vertical planes. This 1 mm minibeam will then allow for a novel spot-scanning beam system to be developed to deliver the beam to "spots" in a treatment.

In conclusion, this paper presents the progress made towards generating a minibeam for radiobiological use at the first of LhARA's three end stations. The work on the configuration for the low energy in vitro end station will inform the configurations that will be designed for the high energy in vitro and in vivo end stations in LhARA stage 2.

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