DESIGN OF LhARA - LASER HYBRID ACCELERATOR FOR RADIOBIOLOGICAL APPLICATIONS

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Abstract

Recent developments of using lasers interacting with targets for the creation of ion beams offer a possibility to provide beams for radiobiology research. This research aims to precisely study the radiobiological effectiveness of charged particles on various cultures of cells, which is essential to inform next generation hadron therapy treatment plans. The Laser hybrid Accelerator for Radiobiological Applications (LhARA) has been proposed to use a laser driven beam, which will be captured and focused using Gabor Lenses. The beam will be then energy and momentum selected to create a beam for in-vitro cells studies or sent to a post-accelerator ring to create beam for in-vivo studies. The optical design of LhARA is presented in this paper.

INTRODUCTION

Cancer is a major cause of death worldwide with a growing number of new cases each year. Its incidence rate is predicted to increase to 27.5 million new cases per year by 2040 [1]. Radiotherapy remains an important treatment option and may need to address the needs of low-income countries in the near future. The majority of the radiotherapy being delivered nowadays is based on X-rays, which, although well understood, still have some drawbacks. In particular, the dose delivery to sensitive organs in close proximity to tumours is an issue as the X-ray dose deposited decreases exponentially.

Hadrontherapy is able to address these issues by providing a very different dose distribution due to the Bragg peak, which means the dose is rapidly terminated beyond the tumour. However the radiobiological effectiveness of hadron beams remains to be fully characterised. Current treatment planning using proton beams assumes that the relative biological effectiveness (RBE) is 1.1 [2]. This is an average value, in fact RBE varies with several physical and biological parameters such as dose, dose rate, linear energy transfer and biological endpoint. A number of other studies have also shown there can be significant variation in the RBE, see [3], [4] and [5]. A detailed systematic study of the RBE for protons and especially heavier ions, under different physical conditions, with different tissue types would provide important information on RBE variation and could enable improved treatment planning protocols in hadrontherapy centres improving the prognosis for patients.

This motivates the need for a program of experiments dedicated to the study of radiobiology using a wide spectrum of ion species and beam conditions. Although such a program could, in principle, be realised in existing therapy facilities, in practice it is rather difficult as their primary goal is the delivery of treatment. In addition, there are several technical difficulties related with switching between ion types and dose profiles, when executed in conventional accelerator systems. Recent advances in using laser-driven particle beams open an interesting possibility to apply them to perform radiobiological experiments [6, 7, 8]

The Laser hybrid Accelerator for Radiobiological Applications (LhARA) was proposed within the Centre for the Clinical Application of Particles (CCAP) at Imperial College London [9] as a facility dedicated to the systematic study of radiobiology. The CCAP is composed of clinical oncologists, medical physicists, accelerator and instrumentation scientists, and radiobiologists. The goal of LhARA is to prove the principal of certain novel technologies for future therapy facilities by developing a proton and light-ion radiobiology facility for in-vitro and in-vivo studies. This paper describes the principles of the LhARA design.

RADIOBIOLOGICAL FACILITY

In Stage 1, LhARA aims to deliver proton beams to the radiobiological end station in the 12-15MeV energy range over a wide range of dose. In Stage 2, a Fixed Field Alternating gradient (FFA) ring will be used to boost the energies of proton and ion beams to serve in-vitro experiments using ion beams and in-vivo experiments using proton beams.

The laser driven ions are typically produced over a wide energy range and with a large divergence. A high intensity laser pulse is fired at a thin target at an angle of 45° which causes an ion beam to be generated from the contaminants on the back surface of the target [10]. In order to make an efficient use of such a beam a dedicated capture system with a large acceptance and an energy-selection system is needed.

Gabor Lenses for Capture and Focusing

Gabor lenses [11] are proposed to be used in LhARA to provide the very strong focusing needed with a compact footprint and a low cost. Gabor-lens focusing exploits a confined electron plasma to produce an electro-static field which can focus positively charge ions. A prototype Gabor lens, shown in Figure 1 was fabricated at Imperial College and is under test.

The focusing strength of a Gabor lens, k, can be calculated using the following equation:

$$k = \frac{2V\gamma P_F}{R^2 (\gamma+1)E} \ [m^{-2}], \tag{1}$$

where V is the cathode voltage in kV, R is the cathode radius in m, E is the proton beam kinetic energy in keV and γ is the beam relativistic factor. P_F represents an effective space-charge filling factor and is assumed to be ~0.5.
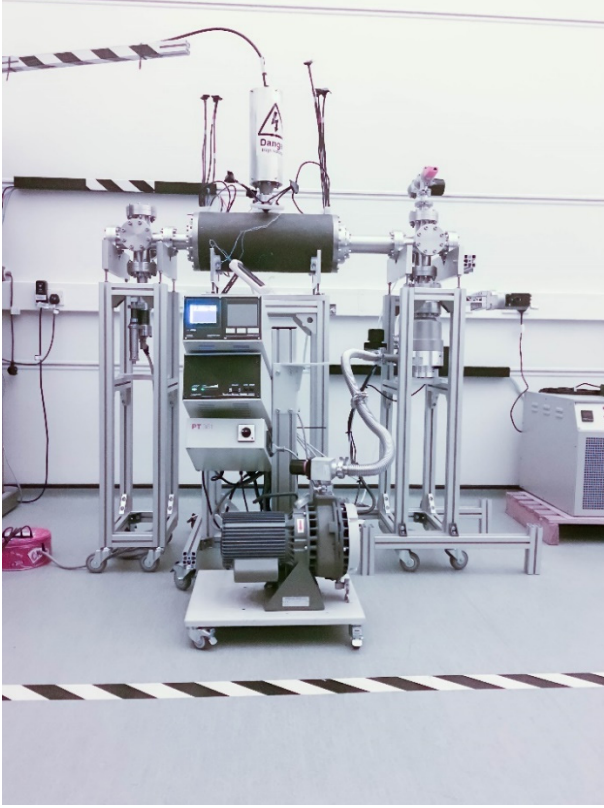

Figure 1: Gabor lens at the test stand at Imperial College.

LhARA Lattice Design

The LhARA Stage 1 lattice design consists of two Gabor lenses, which focus the beam from the laser target to provide initial capture. The beam is then focused in to a narrow collimator slit (typically 1mm in aperture) by the third Gabor lens. As this focusing is energy dependent, a strong dependence of the focus location on energy results, which enables the collimation in the subsequent drift to be an efficient energy selection system. Two more Gabor lenses are then used to provide flexible matching for the output beam size and divergence. The beam size assumed in the in-vitro end station is required to be flexibly varied in the range of 1-15 mm. Table 1 shows the principal parameters of the Gabor lenses assumed in the design of LhARA, which are carefully chosen to mitigate technical risks. The maximum achievable focusing strength of the Gabor lens with those parameters for a 15 MeV proton beam would be equivalent to 1.44 T solenoid. This would allow the use of normal-conducting solenoids in LhARA, however with a significantly higher cost.

Table 1: Parameters of Gabor Lenses Assumed in LhARA

Parameter	Value	Units
Total length	1.157	m
Effective focusing length	0.857	m
Max. Cathode voltage	65	kV
Cathode radius	0.0365	m

The beam is then bent vertically upwards by 90° arc consisting of four combined-function sector magnets into the end station, where the cells will be irradiated. Vertical delivery of the beam allows the use of conventional cell-culture plates, that provide breathable wells where the cell sample is grown on the bottom of a well filled with cell-nutrient liquid. This arrangement is preferred as it would facilitate the radiobiological experiments. The arc will also be used to perform momentum selection by collimation in the dispersive region which, in combination with preceding energy-selection, will allow particle-species selection. This is an important feature as typical target made of a plastic foil will emit both protons and carbon ions. In order to obtain a compact footprint an arc design consisting of identical magnets is foreseen. Figure 2 shows the layout of LhARA Stage 1 created using the BDSIM code [12].

Optics

The evolution of the optical functions in LhARA Stage 1, shown in Figure 3, reflects the characteristic properties of a lattice using Gabor lenses in a laser-driven accelerator. The initial beam parameters from the target result in a very large variation of betatron function over the initial capture
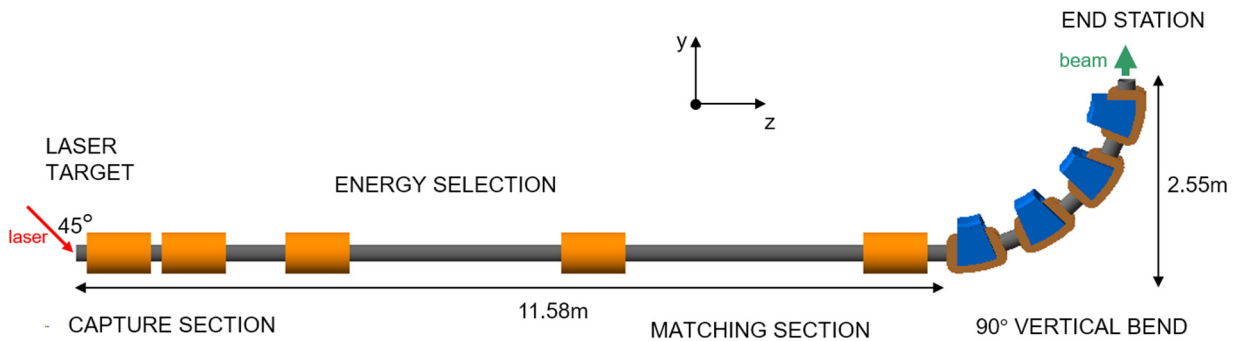

Figure 2: Layout of LhARA Stage 1 lattice. The laser target is located on the left. Four Gabor lenses (yellow boxes) are used to capture focus and transport the beam to the vertical arc, which bends the beam by 90° upwards towards the in-vitro end station.

section followed by refocusing into the energy selection system. Horizontal and vertical beta functions are also identical and start to differ only in the arc section. The choice of phase advances in the vertical arc is set to allow for dispersion suppression at the end station to remove the undesirable correlation between beam energy and position at the irradiated sample. This is realised by making the bending plane (vertical) phase advance equal to 2π and the non-bending (horizontal) phase advance equal to π. In addition, this arrangement makes the optics transparent through the arc preserving the matching performed using upstream Gabor lenses. This can be realised using tilted sector combined-function magnets, which is not shown correctly in Figure 2.
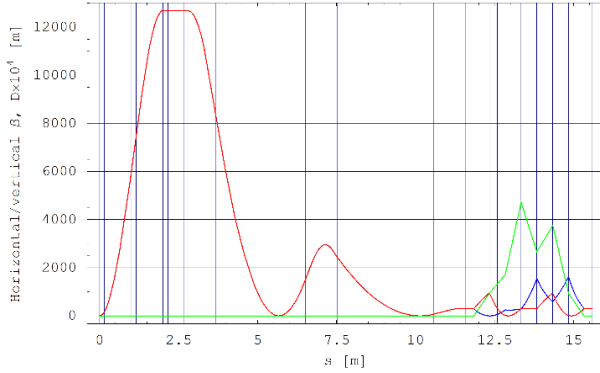

Figure 3: Vertical (red) and horizontal (blue) betatron functions, and dispersion (green, scaled by 10^4 in order to be visible on the plot) in LhARA Stage 1.

Table 2: Parameters of LhARA, Stage 1

Parameter	Value	Units
Total length	15.58	m
Length w/o arc	11.58	m
Rep. rate	10	Hz
Initial pulse duration (FWHM)	35	fs
Beam spot size at the target (FWHM)	4	um
Physical emittance (rms)	0.021	π.mm.mrad
Proton energy range	12-15	MeV
Final energy spread	$\pm2\%$	-
Mean dose rate	2	Gy/min
Final spot size (total diameter)	1-15	mm
Final bunch intensity	10^6-10^9	-

Table 2 summarises basic parameters of the LhARA Stage 1.

CONCLUSION AND FUTURE PLANS

The LhARA facility will explore novel accelerator technologies to deliver intense beams of protons and ions from helium to carbon. The optics design of the beam-line for the first stage of LhARA has been created. This stage of the facility will be used to explore beam energies in the range 12-15 MeV allowing the cells to be irradiated before and within the region of the Bragg peak. The ion beams needed for Stage 2 of the facility will also be commissioned.

Dedicated beam dynamics studies, including tracking studies with and without space charge effects, will now begin to verify the performance of the facility. In parallel, Stage 2 of the facility will be designed including an FFA-based post-accelerator.

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