GABOR LENS FOCUSING FOR MEDICAL APPLICATIONS

J. Pozimski[#], M. Aslaninejad, Imperial College, London, UK

Abstract

The widespread introduction of Hadron therapy for cancer treatment is inhibited by the large costs for the accelerator and treatment facility and the subsequent maintenance costs which reflect into the cost per treatment. In the long term future hadrons accelerated by laser beams could offer compact treatment devices with significantly reduced treatment costs, but at the moment the particle distributions produced by such accelerators do not fulfil the medical requirements by far. Nevertheless steady progress in the field should change the situation in future. Besides the reliable production of a sufficient number of ions at the required energy the formation of a particle beam suitable for treatment from the burst of ions created in the acceleration process is one of the major challenges. While conventional optical systems will be operating at the technical limits which would be contradictory to the cost argument, space charge lenses of the Gabor type might be a cost effective alternative. In this paper a beam line consisting of such lenses will be presented together with particle transport simulations.

INTRODUCTION

In Hadron therapy, to treat deep seated tumours, proton beams with energy up to 250 MeV or beams of carbon with 450 MeV/u are required. Currently, this can be achieved by conventional accelerators like cyclotrons or synchrotrons but at significant cost for accelerator and gantries for beam delivery. The widespread introduction of Hadron therapy for cancer treatment is inhibited by the large cost of the accelerator and treatment facility and the subsequent running and maintenance costs which determine the cost per treatment. On the other hand, recent experiments indicate that laser driven proton accelerators could be an alternative to replace conventional accelerators for certain applications. They have added advantages of reduced size and cost over the usual synchrotrons.

Using Ion acceleration by irradiating ultra-thin foils with high intensity laser pulses, beams of protons with energies up to 60 MeV have been observed [1]. Although not confirmed yet, it is predicted that the energy can be increased by a factor of 5-10 which make the laser accelerated ions a potential candidate for cancer treatment. In the long term laser accelerated hadrons could offer compact treatment devices with significantly reduced treatment costs. At the moment the particle distributions produced by such accelerators do not fulfil the medical requirements by far. Nevertheless, steady progress in the field might change the situation in future. However, laser accelerated ion beams have unique

#j.pozimski@ic.ac.uk

features requiring special beam handling for collection and focusing. In future, in addition to acquiring higher energies suitable for medical applications, work has to be dedicated to solve the major problems of beam collection and delivery to the patient [2-3]. Large energy spread and angular divergence, small transverse and longitudinal emittances and short duration, together with large number of protons per bunch make the capturing, focusing and the transport of laser driven protons a challenging problem [4]. Attempts have been made to investigate production of such high energy beams together with their collection and focusing. In [2], the advantage of particle collection by a high field super conducting solenoid magnet was shown and compared with the case of using a pure aperture solution. The employment of a pulse power solenoid to capture and transport the laser accelerated protons were also discussed in [3]. While conventional optical systems like solenoids or quadrupoles will be operating at today's achievable technical limits which would be contradictory to the cost and space argument, space charge lenses of the Gabor type [5] might be a cost effective alternative. A basic theory of space charge Gabor lenses (**GL**) together with a description of the simulations tools is presented in the next chapter followed by a summary of particle tracking results for beams of protons at therapy energies.

GABOR SPACE CHARGE LENSES

The properties of space charge lenses are very advantageous as they can theoretically provide a strong linear cylinder symmetric force on the beam particles. The space charge lenses investigated has been suggested and published by Gabor in 1947 [5]. For focusing ion beams the use of a magnetically confined electron cloud could reduce the required external fields by a factor of 10 or more and could simultaneously reduce emittance growth by external field errors and the influence of space charge forces [6]. The electron cloud is confined longitudinally by the potential of a central cylindrical anode surrounded by two grounded electrodes. Radial confinement is achieved by a solenoidal magnetic field. To achieve the same focal length Gabor lenses use reduced magnetic and electrostatic field strength compared with conventional lenses and can in theory produce linear transformation in phase space [6-7]. Following [6] the achievable charge density is a function of the radial enclosure condition which can be calculated using the Brillouin flow to be:

$$\rho = \frac{e\varepsilon_0}{2m}B^2 \qquad (1)$$

For the longitudinal enclosure, the ratio of the voltage on the anode and the anode radius can be expressed by:

$$V_{\text{anode}} = \frac{er_{\text{anode}}^2}{8m}B^2 \qquad (2)$$

The main design values of the three GL's in the lattice shown in Figure 2 are summarized in Table 1. Each GL was optimized to achieve optimum performance for each purpose while keeping the anode voltage constant to allow for one HV power supply. This can be achieved by adopting the magnetic field strength and anode/cathode radius according to equation 1 and 2.

Table 1: Summary of the main lens parameters (maximum values) for the three lenses used in the lattice for particle tracking simulations (values given for a nominal beam energy of 200 MeV).

Parameter	Lens 1	Lens2	Lens3
Anode radius	18 mm	29 mm	14mm
Anode voltage	630kV	630 kV	630 kV
Cathode radius	12 mm	23 mm	8 mm
Total length	400 mm	600 mm	400mm
B-field	0.307	0.172	0.405
Charge density	6.07e-2 C/m^3	1.89e-2 C/m^3	10.53e-2 C/m^3

The density distribution of the enclosed electrons have been derived, together with the potential and field distribution using a significantly improved version of the GABOR code [6]. The results of the simulations are summarized in Table 1. One detailed result of such a simulation utilizing method 4 (fully self consistent with pseudo temperature distribution) is shown in Figure 1 for the lens geometry 2.
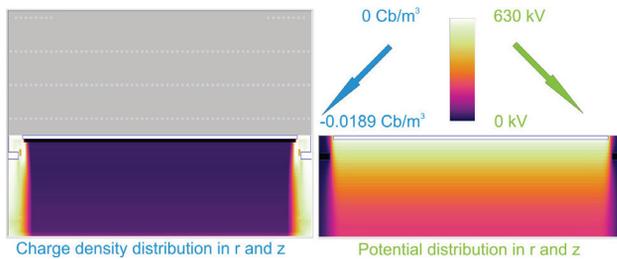

Figure 1: Results of self consistent simulation of GL2 shown in false colour representation. The left hand plot shows the configuration with coil and electrodes together with the electron charge density, the right hand plot shows the potential distribution of the lens in equilibrium.

PARTICLE TRACKING RESULTS

The lattice investigated consisted of 3 GL's and a very small aperture for beam collimation as shown in Figure 2. The first lens close to the source of ions was optimized to deliver a very strong focussing for beams of relatively small radius to increase the angular acceptance of the

setup to capture a large fraction of the produced ions. The second lens is optimized to focus the significantly larger and still divergent beam into the aperture of the collimator and the third lens will produce a mainly parallel beam immediately after collimation. Lens 2 and 3 together with the collimator are arranged in a so called telescope setup. The overall length of the setup from the ion source to the treatment room is less than 4.5 m allowing for direct placement of the setup on a gantry. An additional dipole can be installed after the third lens if required.
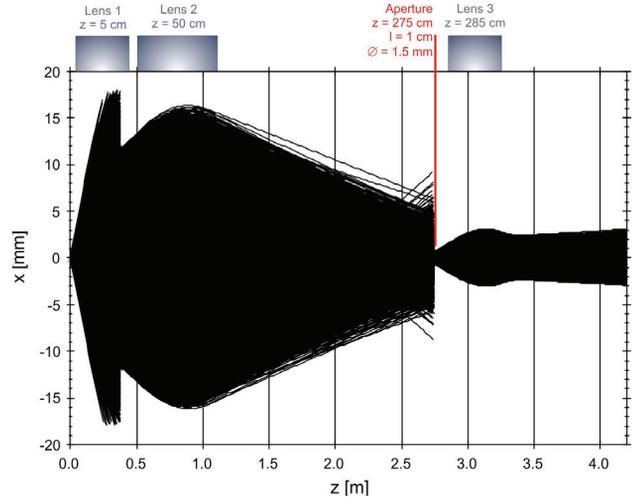

Figure 2: Setup of the beam transport lattice consisting of 3 GL's plotted together with the beam envelope.

The field maps produced by the code GABOR where imported into the General Particle Tracer code (GPT) for particle tracking. The input beam consisted of 100 000 particles with Gaussian distribution in the transversal planes, homogeneous in the z direction and Gaussian distribution in kinetic energy (see also Figure 3 & 4). The beam envelope shown in Figure 2 demonstrates the main features of the particle transport. In the first lens the divergence angle of the beam delivered by the source is strongly reduced and the particles outside the acceptance of the transport channel are collimated ($\sim z = 40$ cm). The cone angle accepted by the transport channel is ± 37 mrad with 81.3% of all particles accepted by the transport channel. The beam is then transport through lens 2 without further losses and focussed onto the collimator. Due to the variation of the focal length with particle energy the very small aperture (r=0.75 mm, length=1 cm) of the collimator in the focal spot for particles with nominal energy (200 MeV) removes a large fraction of the particles at wrong energies. The transmission of particles with nominal energy (within a 938 keV energy bin) is $\sim$ 92 %. In Figure 3 the transversal beam profiles and emittances 1 cm behind the ion production and at 4 m distance are plotted. Just behind the ion production the beam has a small spot radius of $\sim$1 mm (Gaussian distribution) and a huge divergence angle of $\sim$±75mrad of which approximately ±37mrad are accepted by the transport channel.
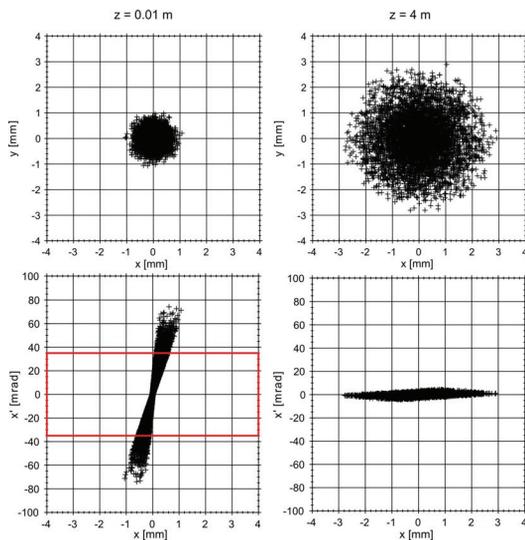
Figure 3: Initial (left) and final (right) transversal beam profile and beam emittance. The initial energy spread of the beam was ± 6.1 %. Particles within a cone of ± 37 mrad have been accepted by the beamline.
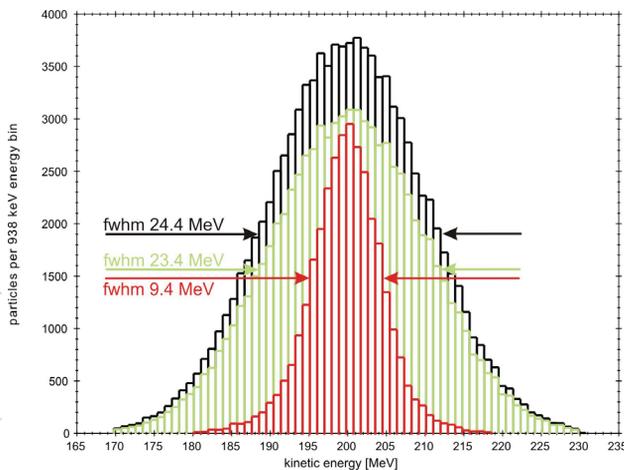

Figure 4: Histograms of the energy distribution of the particle bunch calculated for 100000 particles at different positions. At the start of the bunch the energy spectrum had a width of ±24.4 MeV (black graph). After collimation due to the geometric acceptance of the transport channel the width is reduced to ±23.4 MeV (green graph). After further collimation at the aperture the energy spread is reduced to ±9.4 MeV (red graph).

At the end of the beam transport line (4 m) the beam has increased in radial radius to ~3 mm of half of which is occupied by the core of the beam and the rest is beam halo allowing for a voxel size of ~4 mm squared to be irradiated. According to the telescope arrangement of lenses 2 and 3 the beam divergence is ~12 mrad allowing for further beam handling with conventional beam optics or for direct irradiation.

Figure 4 demonstrates the influence of the aperture in conjunction with the telescope arrangement on the energy spread. The collimation of the beam at the end of the first

lens has as expected very little influence on the beam energy distribution with the fwhm value reduced from ±24.4 MeV to ±23.4 MeV (~96% of original value). At the end of the beam line behind the aperture, the energy spread is strongly reduced to ±9.4 MeV (~ 40 % of the energy spread transmitted into lens 2). While this value is already a big step forward towards a treatment relevant value it seems still comparatively large if benchmarked against beams delivered by synchrotron solutions. Therefore future investigations will focus on further reduction of the energy spread and an increase of the acceptance angle. While the presented results for particle tracking using Gabor lenses show similar or improved properties compared with conventional beam transport systems, the required technical and financial effort, as well as the space requirements for the accelerator and the gantry, are drastically reduced. All together could lead to a significantly reduced investment and running cost of a treatment facility. Further improvements on the energy spread and the beam size to enable an even smaller voxel size for precise treatment utilizing spot scanning seems possible with moderate additional effort.

OUTLOOK

Although our main focus in this paper has been on proton therapy, Gabor lenses have even more advantages when using heavier ions like carbon. In fact for a 450 Mev/u carbon 6^+ beam a solenoid capture system with a magnetic field of about 20 Tesla compared with a 14 Tesla SC solenoid for capturing the protons would be required, while a Gabor Lens solution would still stay far below 1 T enabling the use of normal conduction magnets.

While further theoretical work will be required to improve acceptance angle and energy spread, Gabor Lenses will open a new field of compact beam formation and transport devices for medical and other uses. The delivery of suitable beam energies for cancer treatment from Laser driven accelerators still seem to be a while into the future, a first experimental study of GL focussing for Laser accelerated ions appears to be the appropriate next step in the foreseeable future.

REFERENCES

[1] B. M. Hegelich et al., Laser acceleration of quasi-monoenergetic MeV Ion beams, Nature (London) 439, 441(2006).

[2] I. Hofmann et al., Collection and focusing of laser accelerated ion beams for therapy applications, Phys. Rev. ST Accel. Beams. 14 (2011) 031304.

[3] T. Burris-Mog et al., Laser accelerated protons captured and transported by a pulse power solenoid, Phys. Rev. ST Accel. Beams. 14 (2011) 121301.

[4] C.-M. Ma et al., Development of a laser-driven proton accelerator for cancer therapy, Laser Phys. 16 639 (2006).

[5] D. Gabor, Space charge lens for the focusing of ion beams, Nature (London) 160, 89(1947).

[6] J. Pozimski and O. Meusel, Space charge lenses for particle beams, Rev. Sci. Instrum. 76 (2005) 063308.

[7] J. A. Palkovic et al., Rev. Sci. Instrum. 61(1) (1990).