

# ADVANCED GABOR LENS LATTICE FOR MEDICAL APPLICATIONS

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## 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 [8] 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

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 is presented, followed by a summary of particle tracking results for beams of protons at energies from 70-250 MeV.

## 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:

$$\rho = \frac{e\epsilon_0}{2m} B^2 \quad (1)$$

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

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

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Table 1: 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 <sup>3</sup>	1.89e-2 C/m <sup>3</sup>	10.53e-2 C/m <sup>3</sup>

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], with the results summarize in Table 1.

**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. Further beam elements as dipoles or cavities can be installed after the third lens if required. 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.

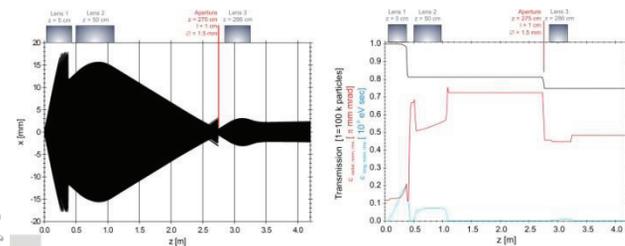


Figure 1: Setup of the beam transport lattice consisting of 3 GL's plotted together with the beam envelope for a beam of 200 MeV and zero energy spread.

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 (~ 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. In an next step an energy spread of ± 6.1 % was added to the initial particle distribution (Figure 3).

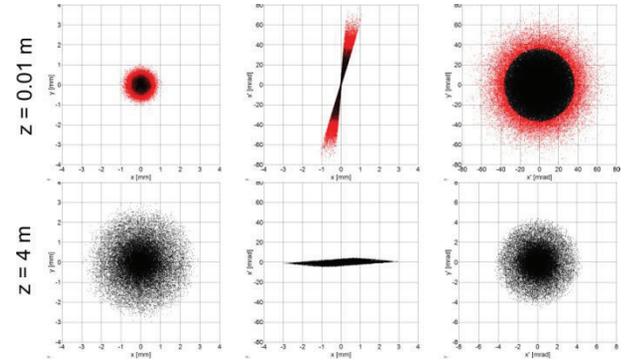


Figure 2: Plots of initial and final beam profiles and beam emittance. Particles within a cone of ± 37 mrad have been accepted by the beamline.

Due to the variation of the focal length with particle energy the very small aperture (r=0.75 mm, length=1 cm) in the focal spot for particles with nominal energy (200 MeV) a large fraction of the particles at wrong energies (see Figure 4) are removed.

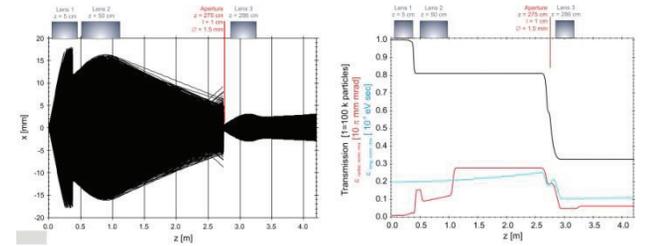


Figure 3: Lattice consisting of 3 GL's plotted together with the beam envelope for a beam of 200 MeV and an initial energy spread of ± 6.1 %.

As shown in Figure 4 (right hand side) the transmission of particles with nominal energy (within a 938 keV energy bin) is ~ 92 %. At the start of the bunch the energy spectrum had a width of ±24.4 MeV (black graph Figure 5 left). 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).

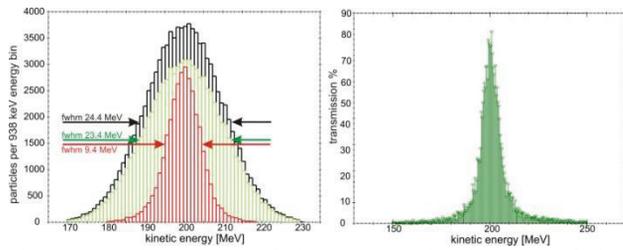


Figure 4: Histograms of the energy distribution of the particle bunch calculated for 100000 particles at different positions (left) and the spectral acceptance (right).

After collimation due to the geometric acceptance of the transport channel the width is reduced to  $\pm 23.4$  MeV (green graph). After further collimation at the aperture the energy spread is reduced to  $\pm 9.4$  MeV (red graph).

To allow for an energy variation of the output beam, as required for hadron therapy, the settings of all three lenses can be varied to allow for output beams, which share all transversal properties for different energies. The parameters required for all three lenses to achieve certain mean output energies are summarized in table 2. Due to the specific design of the lenses, the voltages are the same for all lenses, which allows for one High Voltage power supply. As the system is fundamentally electrostatic in behavior, the required change in voltage is linear to the change in energy ( $\sim$  factor 3.6) of the particles. As expected from equation 3, the magnetic field scales with the square root of the particle energy ( $\sim$  factor 1.9). Since the magnetic fields required by the lenses are relatively low, the simulations have been based on a model using air coils without iron to reduce the inductivity of the magnet. This would allow for a relatively fast scan of the energy over the full range within seconds.

Table 2: Variation of lens parameters for an energy variation between 70-250 MeV.

Energy (MeV)	B Field(T)	Lens 1	Lens 2	Lens 3	Anode Voltage (kV)
70	0.182	0.182	0.102	0.240	220.5
150	0.266	0.266	0.149	0.351	472.5
200	0.307	0.307	0.172	0.405	630
250	0.343	0.343	0.192	0.452	787.5

For the 4 particle energies presented in table 2 the beam transport has been calculated. In Fig. 5 the beam transmission through the aperture is plotted for the 4 different lens settings. The plot demonstrates the energy selection properties of the proposed setup in conjunction with an excellent transmission ( $\sim 80\%$ ) of particles with the selected energy.

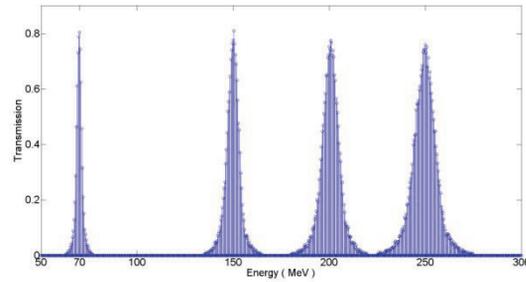


Figure 5: Spectral acceptance of the GPL lattice at therapy energies for different lens settings.

While the transmission at mean energy is practically constant over the energies considered, the width of the distribution scales proportionally with energy. This is typical for electrostatic systems.

### 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 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. 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.

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