ADVANCED GABOR LENS LATTICE FOR LASER DRIVEN HADRON THERAPY AND OTHER APPLICATIONS*

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Abstract

The application of laser accelerated ion beams in hadron therapy requires a beam optics with unique features. Due to the spectral and spatial distribution of laser accelerated protons a compact ion optical system with therapy applications, based on Gabor space charge lenses for collecting, focusing and energy filtering the laser produced proton beam, has significant advantages compared with other setups. While a passive momentum selection could improve already the usability of laser driven hadron, we show that an advanced lattice utilizing additional RF cavities not only will deliver a momentum spread smaller than conventional accelerators, but also will increases the dose delivered. Furthermore, a possible near term application in the field of radio nuclide production is presented.

INTRODUCTION

Theoretical and numerical investigations of the beam transport of laser accelerated ions using Gabor (space-charge) lenses show very encouraging results for medical applications in cancer therapy. A lattice consisting of three lenses can capture and focus a particle beam in a way compatible with the therapy requirements, at least in the transversal phase space. The energy spread of the beam has also been reduced by a factor of up to 3, which is a significant improvement compared with other proposed lattices [1, 2]. These results are very encouraging and represent a significant improvement of the energy distribution for laser generated ion beams, whilst still preserving particle numbers within a large acceptance angle of ~40-100 mrad depending on the energy selected and lattice configuration. The enormous reduction in lattice complexity together with the excellent performance, superior to any conventional lattice proposed so far, makes the proposed setup a very strong candidate for further consideration.

The very compact size of the lattice allows for mounting the whole beam acceleration and delivery system directly on the gantry, significantly reducing the complexity of the treatment system with lower treatment costs as a consequence. A further improvement by a factor of 3 to 5 in energy spread, is required before medical applications can be seriously considered. Work has already begun to extend the presented lattice by the use of bunching cavities following the third Gabor lens. Together with the improvement of the geometry of the collimation aperture, a further significant reduction of the energy spread is predicted.

Although our main focus has been on proton beams, Gabor lenses are even more advantageous than conventional systems in using heavier ions like carbon.

One of the applications considered within the reach of the available technology is the radio nuclide production, with an example shown at the end of this article.

BEAM DYNAMICS

The particle distribution of laser accelerated ions is considerably different from that of conventional accelerators. This is down to the fact that for laser accelerated ions the beam is produced in a few femtoseconds long burst and in a spot of the size of a few micrometres, covering an area several orders of magnitude smaller than the aperture of an ion source. Virtually, all particles are produced at one time in one position.

As a consequence, the beam delivered by laser acceleration is excellent in 5 of the 6 phase space dimensions – only the energy spread is a significant issue. The lattice presented in [1, 2] makes use of the relatively small transversal emittance of the beam delivered. This, together with the cylindrical symmetric focussing properties of the Gabor lens, allows the beam to be focussed to a small spot and to reduce its energy spread by collimation.

The RF cavities in the presented new advanced lattice utilize the excellent correlation between the time particles travel to reach a certain position downstream of the laser target and their energy. This way the spread in energy translates into spread of arrival time at the position where cavities are installed. The precise position, frequency, phase and amplitude of the RF cavity defines the magnitude of deceleration or acceleration for certain particle energies. Therefore, a small number of cavities is able not only to reduce significantly the energy spread of the beam, but also to increase the particle number for a desired energy. This would be impossible using passive collimation only.

While for the presented phase space manipulation using RF cavities a preselection of energies via passive aperture collimation might be helpful to improve the rejection of certain energies, this is not necessarily required in all cases.

HADRON THERAPY

The results presented here are based on the lattice (shown in Figure 1), which was developed starting from the lattice presented in [1, 2]. The following changes have been introduced:

- Size, position and shape of initial collimation aperture has been optimized.
- 4 RF cavities have been added after the third lens in the region 3-4 meters behind the target.
- An additional "clearing" aperture has been added after the cavities.
- A very simplified beam delivery system has been added (mostly for illustration purposes).

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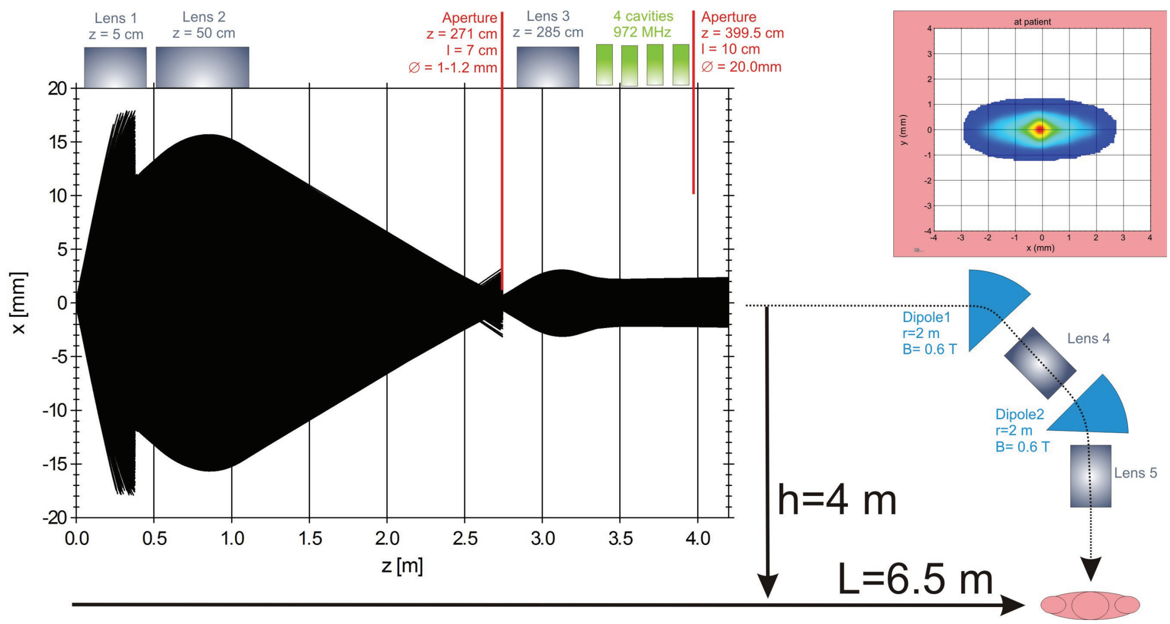

Figure 1: Advanced lattice with improved aperture geometry, 4 RF cavities at 928 MHz and simplified beam delivery system. At a length of 6.5 m and height of 4 m the lattice could be fitted to a gantry. The beam size at the patient position is shown in the upper right corner.

Table 1: Parameters for the Gabor Space Charge Lenses Shown in Figure 1

Lens	Anode radius R_A (mm)	Cathode radius R_C (mm)	Total length L (mm)	Max Electron Density (C/m^3)	Anode voltage V_A (kV)	Magnetic field B_Z (T)
1	18	12	400	-6.1*10^{-02}	630	0.31
2, 4, 5	29	23	600	-1.9*10^{-02}	630	0.17
3	14	8	400	-10.5*10^{-02}	630	0.41

Aperture Optimisation

In the lattice proposed initially [1,2] a circular aperture of r=0.75 mm and 10 mm length was used. A calculation of the penetration depth of 250 MeV protons in iron using SRIM indicates that a minimum of 70 mm is required to stop the mismatched 250 MeV protons. Investigation of the influence of aperture shape and size on transmission showed a good optimum for a design with a first section of r=0.6 mm (20 mm in z) followed by r=0.5 mm (30 mm in z) and then again r=0.6 mm (20 mm in z).

Energy Spread Reduction

Particle tracking using GPT was performed initially assuming the positons of the cavity gaps at z=3.4 m, 3.65 m and 3.9 m using an idealized cavity model in TM010 mode running at 648 MHz. The gap is assumed to be 6 cm long and the amplitude 40 MV/m. This frequency was chosen together with the gap length to allow the slowest particles to cross the gap within half of the RF period. As comparatively very little energy variation is required at 80 MeV, in subsequent simulations the frequency was chosen to be higher (972 MHz), the number of cavities increased from 3 to 4 and simultaneously the amplitude reduced to 30 MV/m. Additionally, the idealized cavity model was replaced by a field map of a more realistic cavity design based on SUPERRFISH simulations.

The development of the energy spread of a beam with a mean energy of 250 MeV is shown in Figure 2, based on the setting of the lenses as per Table 1. In the given example, compared with an aperture collimation only, the energy spread was reduced by a factor of 5 and is approximately within ±1 MeV, therefore in the range suitable for cancer therapy. Figure 1 (top right corner) shows for a very simple beam delivery system that the spot size of the beam at the position of the patient would be in the range of x=5 mm and y=2 mm (100% of particles).

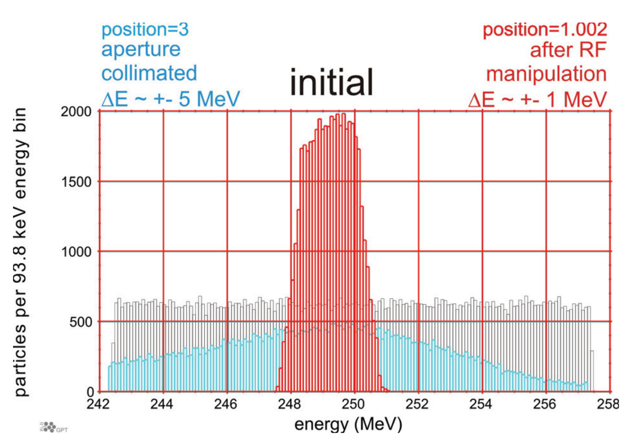

Figure 2: Development of energy spread due to aperture collimation and after manipulation with RF cavities.

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Rapid Energy Variation at 80 MeV

For a beam energy of 250 MeV the available RF power is just sufficient to reduce the energy spread to competitive values compared to conventional accelerators. At lower energy, for instance at 80 MeV (used for eye treatments), the same RF power allows for a novel, extremely fast way of energy variation that could reduce treatment times significantly. Changing the phase of the RF cavities with respect to each other and to the timing of the beam pulse will allow a variation of the beam energy in the range of ±5% with an energy spread less than 1%, as shown in Figure 3.

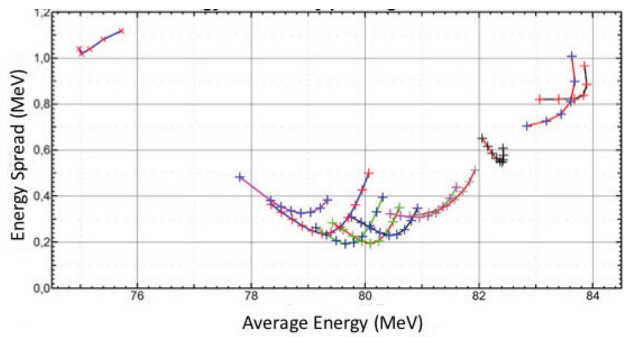

Figure 3: Energy Spread as a function of Average Energy for a variation of the phase of 4 cavities. Each line represents one case with 3 cavity phases fixed and the phase of the remaining cavity varied.

RADIONUCLIDE PRODUCTION

While the application of laser accelerated ions for cancer therapy using a lattice as shown in Figure 1 might need another 10 to 15 year to realize, a shorter term application based on available technology could be the production of radio nuclides (Tc^{99}). Available laser systems allow protons energy exceeding 25 MeV, more than sufficient for the proposed production for Tc^{99} from Mo^{99}. A lattice consisting of Gabor lenses and an aperture is only able to preserve the particle number for a selected energy (bin) while suppressing other energy particles with an FWHM of about ±0.8 MeV (~10% energy spread). Further improvement in yield can only be achieved using active manipulation of the distribution. Two possible lattices investigated for this purpose are shown in Figure 4.

In the first lattice investigated (Lattice 1, see Figure 4 upper graph) the distribution is manipulated after the aperture collimation. The cavities are based on a realistic model and have been have been simulated using SUPERFISH. The power given is the peak power with the average power to be significantly lower depending on duty factor. While the number of particles after the aperture is constant, the maximum particle number per energy bin is increased by a factor of 5 and now contains 46% of particles transmitted compared to the previous case, as shown in Figure 5(b).

In the second lattice investigated (Lattice 2, see Figure 4 lower graph) the distribution is manipulated before and after the aperture collimation. The total number of particles transmitted has increased nearly by a factor 2 compared to Lattice 1. More than 60% of the particles transmitted are now in a single energy bin of 93.8 keV width, a factor 2.5 better than in Lattice 1 and more than a factor of 10 better than aperture collimation alone. While a commercial production of Tc^{99} using this technology is mainly a question of the achievable repetition rate, the proposed lattice would be excellently suited to investigate the production yield as a function of the beam energy with very high energy resolution at a moderate investment cost.

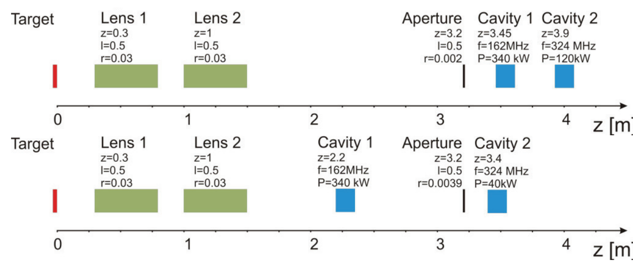

Figure 4: Lattice 1 (upper) and Lattice 2 (lower) using Gabor (space-charge) lenses and two single cavities. Both are optimised for the production of Tc^{99}.

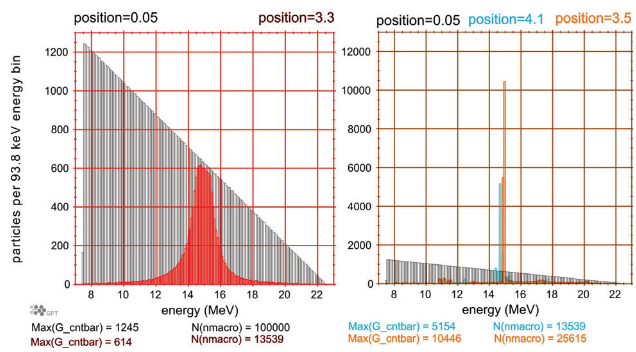

Figure 5: Left: (a) Energy spectrum of the initial beam vs. passive selection only. Right: (b) at the end of Lattice 1, (c) at the end of Lattice 2.

CONCLUSION

We have shown that using an advanced lattice consisting of Gabor lenses, collimation apertures and RF cavities the momentum spread can be reduced to very competitive levels compared to conventional accelerators. Additionally, new modalities of treatment by cavity phasing could improve significantly treatment times. Furthermore, new applications as nuclides production could benefit from an increased production rate. An experimental program has been funded at the Imperial College London with the aim of demonstrating the properties of a Gabor lens lattice at low energies (Cerberus Laser System). First results are expected for summer 2016 and discussions for a possible test of an advanced lattice at the Central Laser Facility at RAL are underway.

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