Preliminary design of a laser accelerator beam line *

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Abstract: A compact laser plasma accelerator (CLAPA) is being built at Peking University, which is based on an RPA-PSA mechanism or other acceleration mechanisms. The beam produced by this laser accelerator has the characteristics of short duration, high pulse current, large divergence angle, and wide energy spectrum. The beam cannot be produced by a normal ion source and accelerator. The space charge field in the initial is very strong. According to the beam parameters from preparatory experiments and theoretical simulations, a compact beam line is preliminarily designed. The beam line mainly consists of common transport elements to deliver proton beam with the energy of 1–50 MeV, energy spread of 0–±1% and current of 0–10^8 proton per pulse to satisfy the requirement of different experiments. The simulation result of a 15 MeV proton beam with an energy spread of ±1%, current of 400 mA, and final spot radius of 9 mm is presented in this paper.

Key words: laser plasma accelerator, beam line, common transport elements

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1 Introduction

High energy particles can be produced when a laser interacts with a plasma [1]. A laser accelerator can reach 10^{12}V/m accelerating electric field gradient, which is at least 1000 times higher than conventional accelerators [2]. In addition, a laser accelerator can accelerate ions more effectively and greatly reduce the scale and cost. It has promising prospects in compact ultra high energy ion accelerators and has many applications [3].

A compact laser accelerator (CLAPA), which is according to RPA-PSA mechanism [4–6] or other acceleration mechanisms [7], will be built at Peking University. Many research studies will be carried out by CLAPA, including: basic research in physical mechanism of laser-plasma acceleration, ultra short and intense pulse beam transport, and self-supporting ultra-thin target production. Applications include research in medicine [8], inertial confinement fusion (ICF) [9], astrophysics, etc.

At present, laser accelerators are being studied at many institutes around the world [10], but application research is still at an exploratory stage [11–19]. The reason is that the beam produced by laser accelerator has the characteristics of short duration, high pulse current, and wide energy spectrum [20]. The beam pulse duration is only tens of picoseconds and 10^8–10^{10} ions are produced in one pulse [21], so the peak current can reach the ampere scale. The initial beam spot is as small as a laser spot, which means that the beam spot radius is a few microns. There is no doubt that the space charge effect will be very strong. Although the beam contains co-moving electrons that can neutralize the space charge effect initially, these electrons will be moved out of the beam under the effect of transport elements. So, the initial collection and collimation is a very difficult and critical part of the beam line. Many kinds of elements have been tried, such as a permanent magnet quadrupole lens [12, 13], solenoid magnet [14, 15] and laser triggered micro-lens [16]. Particle selection is another critical part. Because the beam has a wide energy spectrum, the chromatic aberration of the collected beam is a serious issue. The beam must be selected with the desired energy spectra. It usually depends on a bending magnet [17] or a set of dipole magnets [18, 19].

To solve the above problems, we preliminarily design a compact beam line for CLAPA. The beam line is mainly composed of common transport elements to deliver a proton beam with an energy of 1–50 MeV, an energy spread of 0–±1% and a current of 0–10^8 protons per pulse.

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2 Beam line

In this section, we mainly talk about the beam line on request of biomedical irradiation. The beam parameters are shown in Table 1. A simulation of a higher energy beam transport, such as a 50 MeV proton beam, is shown at the end.

Table 1. The beam parameters of CLAPA.

ion	proton
energy/MeV	15
current/(proton/pulse)	1×10^{8}
initial energy spread(%)	±15
final energy spread(%)	±1
initial transverse radius/mm	0.005
initial longitudinal length/mm	1.06
final transverse radius/mm	9
final longitudinal length/mm	70

The beam line is composed of two parts: a collection part and an analysis part. In the collection part, the aperture is used to initially remove the large divergence angle protons as much as possible. Then, the beam is collected by a quadrupole-triplet lens and a quadrupole-doublet lens. In the analysis part, the beam is analyzed by a bending magnet. Finally, the beam is focused by another quadrupole-doublet lens and delivered to the experimental platform. The structure of the beam line is shown in Fig. 1.

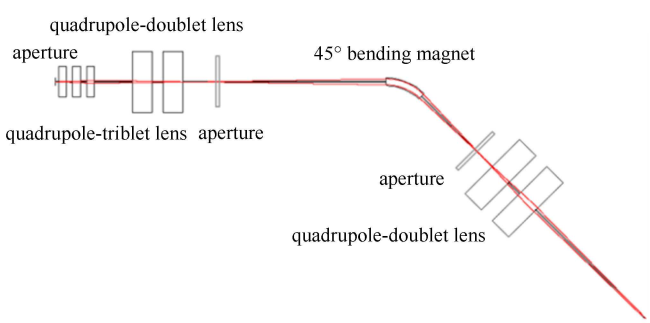

Fig. 1. The schematic diagram of beam line.

The first order simulation of the transport is carried out by the Trace-3D program and a high order simulation is carried by the Track program [22]. The simulation results are shown in Fig. 2.

In the simulation, a 400 mA current is used. The average current is only 10^{-6} mA, with a frequency of 100 Hz, because of the very short pulse width. Although the simulation result may not exactly coincide with the actual condition, we can accept the simulation result in the preliminary design. In the future, we will be able to verify the design if we find more suitable methods.

Comparing the results of the two programs, the beam envelopes are almost the same, except for the size of the final spots. This difference is caused by chromatic aberration. That is to say, the big energy spread causes the difference. There is no good way to deal with the chromatic aberration, but the energy spread can be reduced after analysis. The detail of beam line structure is presented below.

Aperture: Due to the laser acceleration mechanism and high space charge effect, the beam has a large divergence angle. According to the simulation, the divergence angle is bigger than ±150 mrad [23]. It is impossible to deliver all of the protons to the end. To avoid the influence of large divergence angle ions and reduce the space charge effect, the beam is screened by an aperture at the beginning of transport. The radius of aperture is 3 mm. The distance is 50 mm away from the laser target. The proton beam passes through the aperture with divergence angle of ±50 mrad, transverse emittance of 0.25QQ mm·mrad and current of 1×10^{8} proton/pulse.

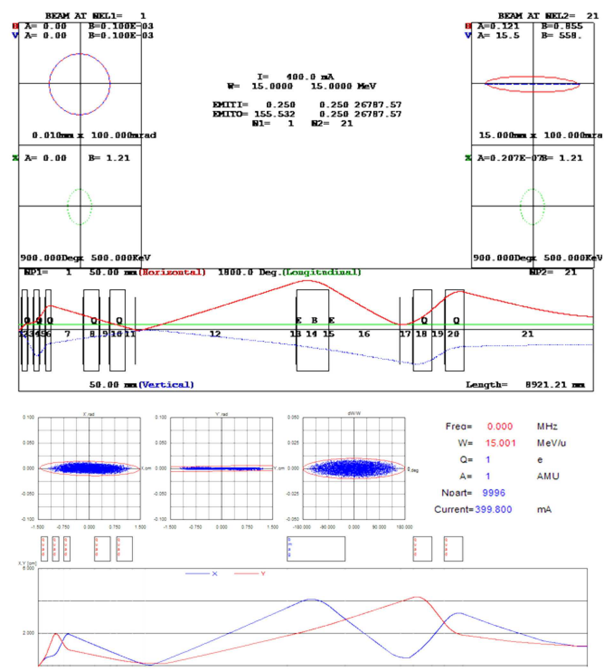

Fig. 2. (color online) The simulation results of proton beam transport. The upper part is the result of Trace-3D and the lower part is the result of Track.

Collecting lens: After passing the aperture, the beam will expand quickly in a transverse direction. It is necessary to focus the beam as early as possible to avoid unnecessary losses. A quadrupole-triplet lens is designed to focus the beam, which is adjoined to the aperture. The inner radius of lens is 20 mm, the length of the lens is 100 mm and the distance is 80 mm between each other. When the magnet fields of the lenses are 5.00, −4.71 and 2.75 kG/cm, the proton beam can be perfectly collected.

Assistant collecting lens: The collecting lens can collect protons that have an energy lower than 30 MeV. But it is difficult to collect the protons with a higher energy because of the limit of the magnet field. Consequently, a quadrupole-doublet lens is added to assist collection. The inner radius of the lens is 40 mm, the length of lens is 250 mm, and the distance is 150 mm between each other.

The collection part consists of the upper three transport elements. Because of the small radius of bunch and high peak current, the space charge field is very strong. Consequently, we decided to deliver the beam with a divergence angle of ±50 mrad to weaken the space charge effect by widening the beam envelope. That is why the collecting lens is only 50 mm away from the laser target and the structure is so compact. Otherwise, the beam envelope will become too large to deliver. The chromatic aberration is also used to screen a part of the different and large energy spread ions to weaken the space charge effect.

Bending magnet: The proton beam produced by laser accelerator has wide energy spectrum and a lot of different ions. Although the different ions may be screened partly in the collecting stage, the proton beam still contains different ions. To get a high quality proton beam, a 45° bending magnet is used to analyze the beam. The radius of the bending magnet is 650 mm. The analyzing ability of bending magnet is simulated by the Track program (Fig. 3).

Post focusing lens: A quadrupole-doublet lens is used to focus the proton beam to the end. The inner radius of lens is 50 mm, the length of the lens is 300 mm, and the distance is 20 mm between each other. When the magnet fields of lens are −0.278, 0.368 kG/cm, the radius of the beam focus is 9 mm.

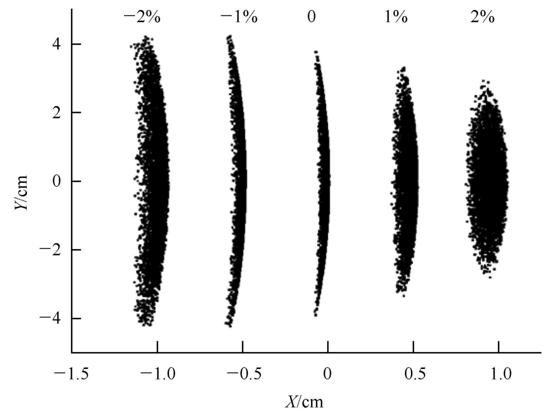

Fig. 3. The simulation of analyzing ability of bending magnet. The energy of center beam is 15 MeV. The other beams have ±1% and ±2% different energy compared with the center beam. The energy spread of every beam is ±0.000001%.

3 Efficiency of transport

From the simulation of a 15 MeV proton beam by the program of Track (Fig. 4), we can get the efficiency of transport.

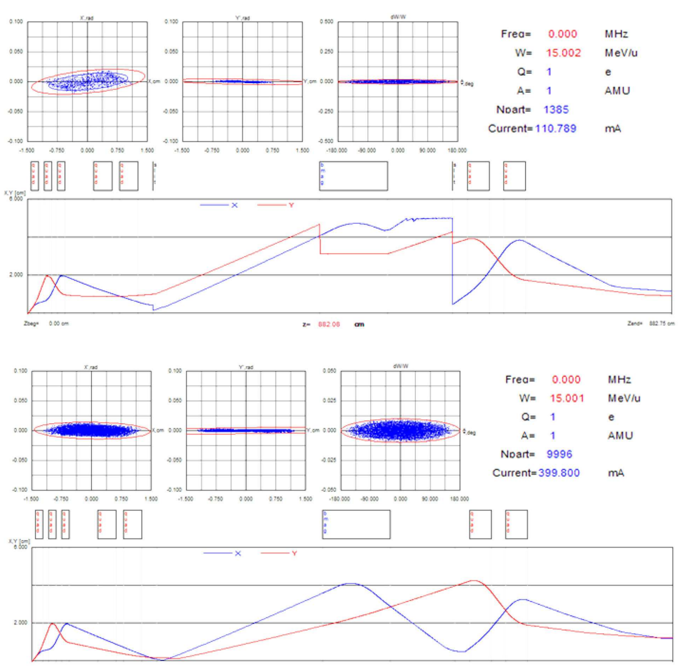

Fig. 4. (color online) The efficiency simulation of 15 MeV proton beam. The upper part is with the energy spread of ±15% and the lower part is with the energy spread of ±1%.

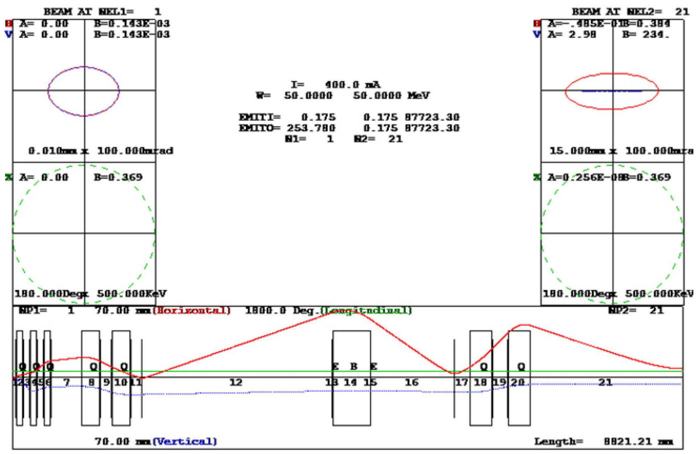

Fig. 5. (color online) The transport of 50 MeV proton beam.

Most of the protons with an energy spread of ±15% can be delivered to the bending magnet after being focused by the collecting lens. Some protons with a large energy spread impact the vacuum tube of the bending magnet in a vertical direction, the others impact the vacuum tube and analysis aperture outside of the bending magnet in a horizontal direction. Finally, we can get the proton beam within the energy spread of ±1%.

The efficiency of all protons is nearly 14%. The efficiency of needed protons, which means the protons with initial energy spread smaller than ±1%, is larger than 99%. Considering the magnet field distortion of quadrupole lens, the efficiency of needed protons is nearly 94%.

4 Transport of higher energy beam

The proton beam produced by the laser accelerator has a wide energy spectrum. In order to widen the scope of application, the transport of the higher energy proton beam is also taken into consideration. The transport of the higher energy beam is achieved just by changing the magnet fields of lenses and bending magnet. The transport of a 50 MeV proton beam with the current of 400 mA is shown in Fig. 5.

5 Summary

The beam line of CLAPA is preliminarily designed with common transport elements. From the simulations of the Trace-3D and Track programs, the beam line is able to deliver the proton beam with an energy of 1–50 MeV and an energy spread of within ±1%. In the future, the design will be improved if we are able to get more accurate beam parameters.

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