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PRELIMINARY EMITTANCE MEASUREMENT OF LASER DRIVEN PROTON BEAM EMPLOYING A QUADRUPLE TRIPLET MAGNET

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Abstract

The Compact Laser Plasma Accelerator (CLAPA) has been built recently at Peking University, which composed of a 200TW laser acceleration platform and a beam line system. Proton with energy spread of <1%, up to 10 pC charge and different energies below 10 MeV have been produced and transported to the irradiation platform. Emittance is a critical parameter for beam transportation. The preliminary emittance measurement has been performed for CLAPA's proton beams using the quadrupole scan technique (QST). In the experiment, the focal spot size of the proton beam was changed by scanning the current of a quadrupole triplet magnet. The result shows that the normalized emittance is smaller than 0.01 mm·mrad for 5 MeV laser driven protons, which is on the same level of the previously reported work [1].

INTRODUCTION

Laser driven ion acceleration has evolved rapidly interest as its high accelerating gradient of TV/m, which is three orders than conventional accelerator. Meanwhile, such ion beams shows some unique characteristics: small emittance [1, 2, 3], small initial size [1, 4] and short pulse duration. However, their exponential spectra with 100% energy spread and large divergence angle obstruct its potential application. Aiming to solve these issues, many schemes such as double layer target [5], micro-structure target, et al have been used. But, the improvement of the energy spread and the divergence angle was limited in the experiments.

In order to acquire proton beams with energy spread of 1%, a reliable proton beamline based on the laser plasma acceleration have been built at Peking University, beam line design detailed in ref [6]. This beam line is consisted of three parts: (1) a quadrupole triplet electromagnet to collect and pre-focus the proton accelerated by a ultra-intense laser pulse, (2) a dipole electromagnets to spread protons with different energy and a controllable slit for energy selection, (3) a quadrupole doublet electromagnet to refocus the selected protons with adjustable energy spread (from 1% to 4%) onto the irradiation platform. Protons of 3 to 10 MeV with 1% energy spread are been successfully transmitted.

Emittance is a critical parameter in the beam optics, which determines the envelop of the beam along the beam line. The emittance of laser driven proton have been measured by using object such as knife edges [3] or meshs[1] or using micro-structure target , showing a value between 0.004 mm·mrad to 0.23 mm·mrad. Objects were used on the beam path in the above measurements, which may induce charge up [2] that reflecting the beam. While the emittance of the beam from a flat solid target is different from that of using a micro-structure target, due to the change of the sheath field and the electron filamentation [7].The quadrupole scan technique (QST) is a common emittance measurement method for the conventional accelerators. Using the first quadruple triplet in the CLAPA beam line, the emittance of laser driven protons has been measured.

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QUADRUPOLE SCAN TECHNIQUE

Emittance Calculation

In the six-dimensional phase space {x, y, z, p_x, p_y, p_z}, the beam can be described as incompressible fluid. Ignoring the coupling force, it can be divides into three two-dimensional transverse phase spaces { x, p_x },{ y ,p_y } and{ z, p_z }, and the envelop of beamlet is described by a matrix σ(z).

$$\sigma(z)=\begin{bmatrix}\sigma_{11}(z) & \sigma_{12}(z)\\ \sigma_{21}(z) & \sigma_{22}(z)\end{bmatrix} \tag{1}$$

Where $\sigma_{11}(z)$ is the square of the root mean square (RMS) size of the beam, $\sigma_{12}(z)$ and $\sigma_{21}(z)$ are the cross correlation term and $\sigma_{22}(z)$ is the square of the beam divergence.

There are several different definitions of the beam emmitance. The boundary emittance is defined by the beam area in phase space

$$\varepsilon=\sqrt{\det(\sigma)}=\frac{\int_{ellipse}dxdx'}{\pi} \tag{2}$$

The emittance changes with the change of the beam velocity. In aacceleration system, people also use normalised emittance, which is expressed as

$$\varepsilon_n=\beta\gamma\varepsilon \tag{3}$$

Note that once leaving the sheath field for a small distance (above 1 cm), the space charge force and the nonlinear electromagnetic force on the laser driven protons can be ignored, and the beam will transport in a drift space where its normalised emittance remain unchanged.

Assuming the proton beam is transported from initial position z_0 to a position z, its σ matrix can be determined by the transformation matrix R(z) and the initial matrix $\sigma(z_0)$, written as

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$$\sigma(z) = R(z)\sigma(z_0)R^T(z) \tag{4}$$

Using the σ(z) expressed in Eq.1, Eq.4 can be written as

$$\sigma_{11}(z_0)R_{11}^{\ 2} - 2\sigma_{12}(z_0)R_{11}R_{12} + \sigma_{22}(z_0)R_{12}^{\ 2} = \sigma_{11}(z) \tag{5}$$

Note that $\sigma_{11}(z)$ can be derived form the measured beam profile in the experiments. The R(z) matrix is also known for certain beam optics, like quadruple magnets. So Eq.5 becomes an equation with three unknows $\sigma_{11}(z_0)$, $\sigma_{12}(z_0)$ and $\sigma_{22}(z_0)$. This means twiss parameter in z_0 can be solved from Eq.5 by measuring $\sigma_{11}(z)$ in three different R(z) conditions (three equations with three unknows). Using Eq.2, the normalized emmittance can then be calculated by

$$\varepsilon_n = \beta\gamma\sqrt{\det(\sigma)} = \beta\gamma\sqrt{\sigma_{11}(z_0)\sigma_{22}(z_0) - (\sigma_{12}(z_0))^2} \tag{6}$$

In the experiment, by scanning the current of the quadruple triplet electromagnet, different transformation matrix R(z) and different rms size $\sigma_{11}(z)$ of the proton are achieved. Using Gaussian fitting, the focused beam profile can be expressed as

$$L(x) = Ae^{-\frac{(x-\mu)^2}{1.96\times(\Delta x)^2}} - L_{bg}(x) \tag{7}$$

In Eq. 7, the A, μ and Δx can get from data fitting. Δx is the spot radius containing 57.6% particles. Because of the 100% energy dispersion of the laser accelerated protons, only the beam with designed energy can be focused to an optimum spot size by the triplet magnet on the detection medium; the rest of the beam are focused to a bigger size, and the more the energy deviates from the focused energy, the bigger the spot is. Together with the noisy of camera, this forms the background signal $L_{bg}(x)$ and need to be treated carefully. Then with the parsed Δx, Eq. (5) can be written as

$$\sigma_{11}(z_0)R_{11}^{\ 2} - 2\sigma_{12}(z_0)R_{11}R_{12} + \sigma_{22}(z_0)R_{12}^{\ 2} = (\Delta x)^2 \tag{8}$$

By setting the current of the quadrupole magnet at least three different values and measuring the corresponding Δx, we can get $\sigma_{11}(z_0)$, $\sigma_{12}(z_0)$, and $\sigma_{22}(z_0)$ by solving Eq. (8), as well the emittance from Eq. 6.

EXPERIMENT SETUP

The experiments were performed in the CLAPA system at Peking University. The system delivers laser pulses with a central wavelength of 800 nm and a 45 nm bandwidth, which can be compressed down to 30 fs duration at full width at half maximum (FWHM). The p-polarized laser beam was focused by an f/3.5 off-axis parabola onto Aluminium metal foil at 30^{o} incident angle with respect to the target normal direction. The pulse energy on target was 1.3 J with a focal spot of 5 μm in diameter (full width at half maximum, FWHM), containing 30% of the laser energy, corresponding to a peak intensity of 6×10^{19} W/cm^2.

Figure 1 shows the layout of the experiment. The quadrupole triplet with an entrance of 16 mm diameter was placed 15 cm away from the target. As listed in Fig. 1, Q1 and Q3 quadrupoles are for horizontal (X) direction beam focusing and Q2 is for the vertical direction (Y) beam focusing .A scintillator was positioned 2.5 meter away from the Q3 was used to detect the beam profile. A 16-bit ICCD is employed to image the scintillator to provide online analysis. The quadrupole parameter is indicated in Table 1. With this parameter, 5 MeV proton are focused on the scintillator.

Table 1: Experiment Parameter

	Current(A)	Gradient(T/m)
Q1	81.91	14.58
Q2	-248.74	-11.89
Q3	284.75	14.19

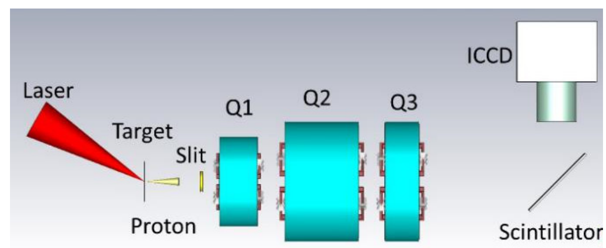

Figure 1: The layout of emittance measurement experiment.

Since changing the current of Q1 will also change the proton collection rate, which may influence the beam actual size, so a Q2 current scan is adopted in this experiment, with a scan range of +/- 2A .

EXPERIMENT RESULT

The profiles of proton beam for different Q2 current are displayed in figure 2, where from left to right, the Q2 current was changed -2A, 0 and +2A compare to the current in Table 1, which was initially set to focus 5 MeV protons on to the scintillator. The expansion of the beam profile is obvious with the increasement of the Q2 current. Please note that the detected focused beam profile has a diamond shape, which is caused by the overlap of the protons with different energies. Fig.3 is the simulated proton profile using TRACK code. The proton energy is set as 3 to 7 MeV with a gauss distribution. The simulated profiles is basically consistent with the experimental spots; the inconsistencies may be caused by the slight misalignment of the laser interaction point and the axis of the triplet magnet.

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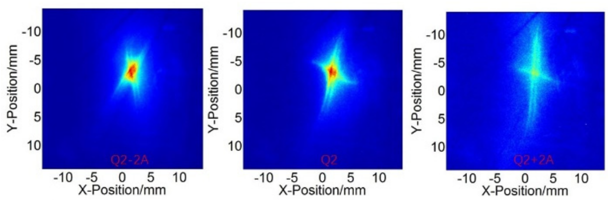

Figure 2: Quadrupole scan result, from left to right is Q2 current changed -2A, 0 and +2A compare to the initial current in Table 1 .

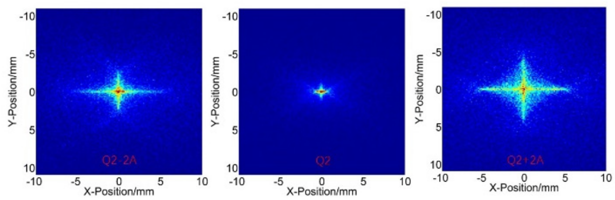

Figure 3: Simulated quadrupole scan result, from left to right is Q2 current changed -2A, 0 and +2A compare to the current in Table 1.

Using Eq. 6 to Eq. 8, the calculated RMS diameter, the emittance and the normalized emittance (assuming the observed focusing proton energy did not deviated much from 5 MeV then changing the Q2 current) are listed in Table 2. The $\varepsilon_{n,y}$ is 0.0076 mm·mrad and $\varepsilon_{n,x}$ is 0.0053 mm·mrad, which are on the same level with previous reported work [2, 3].

Table 2: Calculating Result of rms Size and Emittance

	Δ x (mm)	Emittance (mm • mrad)	Normalization Emittance (mm • mrad)
Q2-2(Y)	2.98	0.0737	0.0076
Q2(Y)	2.75		
Q2+2(Y)	3.97		
Q2-2(X)	2.13	0.0512	0.0053
Q2(X)	1.81		
Q2+2(X)	2.08		

Although preliminary QST experiment is verified to be feasible in the emittance measurement for laser driven proton beams, however, the energy spread induced error needs more careful analysis. Experiments with precise current scan for different proton energies will also be carried on in the near future.

CONCLUSION

Quadrupole scan technique has been performed using a quadrupole triplet magnet to measure the normalized emittance of laser driven proton beams at CLAPA. The value of the normalized emittance is measured on the level of 0.01 mm·mrad for 5 MeV proton.

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