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Magnetic quadrupoles lens for hot spot proton imaging in inertial confinement fusion

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ABSTRACT

Imaging of DD-produced protons from an implosion hot spot region by miniature permanent magnetic quadrupole (PMQ) lens is proposed. Corresponding object-image relation is deduced and an adjust method for this imaging system is discussed. Ideal point-to-point imaging demands a monoenergetic proton source; nevertheless, we proved that the blur of image induced by proton energy spread is a second order effect therefore controllable. A proton imaging system based on miniature PMQ lens is designed for 2.8 MeV DD-protons and the adjust method in case of proton energy shift is proposed. The spatial resolution of this system is better than 10 μm when proton yield is above 10^9 and the spectra width is within 10%.

1. Introduction

In laser-driven inertial confinement fusion (ICF), understanding and control of implosion dynamics is crucial, for achieving spherical compress of assembled fuel is a prerequisite for optimal burn and ignition [1–3]. Thus direct experimental observation of the hot spot is very important. Traditional methods, including X-ray imaging [4], neutron-emission imaging of deuterium-tritium (DT) burn [5,6], proton penumbra emission imaging [7,8], have been widely used to measure hot spots on large laser facility such as NIF [9–11]. Among these methods, neutron imaging is widely used to diagnose the hot spot region as neutrons have a high penetrability. However, for the same reason, it is also hard to record the image. The protons from the hot spot, on the other hand, are good information sources for imaging due to its high detection efficiency. Some methods such as proton penumbra emission imaging have already been proposed, but the resolution is worse than 16 μm when the yield of the protons is below 10^9 [7]. Hence improving the spatial resolution of proton imaging method is important for low proton yield implosion experiments.

In the past few years, magnetic quadrupole lens have been widely used in accelerator physics [12–15]. High resolution GeV proton radiography has been achieved with magnetic quadrupole lens, but it has not been applied in ICF so far. Recently, miniature permanent magnetic quadrupole (PMQ) have been introduced to the field of laser-plasma interaction to focus the laser-accelerated protons [16–19] and electrons [20–22]. Miniature PMQ is suitable for table-top beam lines since they have high magnet field gradient and are very small. In this paper, a specially designed magnetic quadrupole lens composed of four miniature PMQs is proposed to directly image the primary DD-produced protons from the hot spot region in ICF for the first time. The influence of proton spectra and yield on imaging spatial resolution is analyzed.

This article is organized as follows: Section 2 gives a theoretical analysis of this magnetic quadrupole lens. The object-image relationship is deduced and the adjust method is given. In Section 3, a design for the 2.8 MeV DD-produced protons is presented, and the adjust method to compensate the influence of proton energy downshift is also proposed. In Section 4, the imaging spatial resolution of our magnetic quadrupole lens is analyzed by simulation. At the end of this article, we give a conclusion.

2. Theoretical analysis

First, we would like to analysis the magnetic quadrupole lens for proton imaging theoretically and deduce the object-image relation. A typical magnetic quadrupole lens is composed of four magnetic quadrupoles, and the beamline is reflection symmetric in the form of $+A-B+B-A$ [15] as shown in Fig. 1. The magnetic field integration along the axis for magnet B must be larger than that of A to obtain a magnified image [15].

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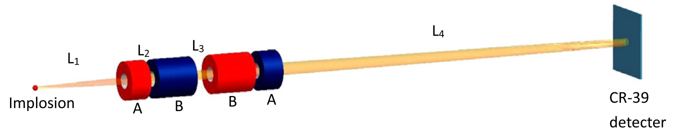

Fig. 1. Schematics of our proton imaging system. The magnet polarity flips between adjacent magnets.

This proton imaging system has 3 parts, a main magnet part and two drift tubes. The transfer matrix of the main magnet part is

$$\mathbf{M_m} = \begin{bmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & m_{33} & m_{34} \\ 0 & 0 & m_{43} & m_{44} \end{bmatrix}, \tag{1}$$

where $m_{21}=m_{43}$, $m_{11}\times m_{22}-m_{12}\times m_{21}=1$, $m_{33}\times m_{24}-m_{34}\times m_{43}=1$, and $m_{11}+m_{22}=m_{33}+m_{44}$. If the distances between the magnets are suitable, $m_{11}=m_{33}$ can be satisfied, which gives $m_{22}=m_{44}$. Since $m_{21}=m_{43}$ and $m_{12}=m_{34}$ are satisfied, that is to say, the matrix of the main magnet part is the same in x and y direction.

The transfer matrices of the two drift tubes before and after the main magnet part are

$$\mathbf{M_1} = \begin{bmatrix} 1 & L_1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

and

$$\mathbf{M_2} = \begin{bmatrix} 1 & L_4 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{3}$$

hence the total transfer matrix is

$$\mathbf{M} = \mathbf{M_2M_mM_1} = \begin{bmatrix} m_{11}+L_4m_{21} & L_1(m_{11}+L_4m_{21}) + m_{12}+L_4m_{22} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & m_{33}+L_4m_{43} & L_1(m_{33}+L_4m_{43}) + m_{34}+L_4m_{44} \\ 0 & 0 & m_{43} & m_{44} \end{bmatrix}. \tag{4}$$

As the transfer matrix of the main magnet part is the same in x and y directions, the total transfer matrix at any position of the drift tube is also the same in x and y direction, according to Eq. (4). So the imaging is symmetric in x and y directions.

The imaging condition is then

$$L_1(m_{11}+L_4m_{21}) + m_{12} + L_4m_{22} = 0, \tag{5}$$

which can also be written as

$$L_1 + L_4 + L_1L_4\frac{m_{21}}{m_{11}} + \frac{m_{12}}{m_{11}} = 0. \tag{6}$$

The object-image relation of an optical lens is

$$\frac{1}{L_1+x} + \frac{1}{L_4+x} = \frac{1}{f+x}, \tag{7}$$

where f is the vertex focal distance and x is the distance from the lens surface to the principal plane, L_1 is the distance from the object to the front lens surface and L_4 is the distance from the back surface of lens to the image. Eq. (7) can be rewritten as

$$L_1 + L_4 - \frac{L_1L_4}{f} + 2x + \frac{x^2}{f} = 0. \tag{8}$$

Compare Eq. (6) to Eq. (8), it is clear that the focal length of our PMQs is determined by the transfer matrix of the main magnet part. The magnification of this magnetic lens is $m_{11}+L_4m_{21}$, which is determined by image distance and the transfer matrix of the main magnet part. For a given magnification, the object distance is solely decided by the image distance. Since the imaging condition in Eq. (5) is a single valued function, therefore it can be satisfied by adjusting only one of the parameters (the magnet field gradient and the distance between magnets). For example, we can keep the system intact except changing L_3, the distance between two magnets at the center of the magnetic lens system as shown in Fig. 1 to match the imaging condition.

Our analysis of the point to point imaging condition above is for monochromatic proton sources, in which $x_f=M_{11}x_0$, where x_0 is the horizontal position at the object location, x_f is the horizontal position at the image location, and M_{11} is the magnification of the magnetic quadrupole lens. However, a real proton source always has a finite spectrum width. In ICF, the DD-produced protons undergo Coulomb scattering and lose energy through ionization before they enter the magnetic lens system. The resolution of the image hence will degrade and the finally horizontal position becomes

$$x_f = M_{11}x_0 + T_{116}x_0\delta + T_{126}\theta_0\delta, \tag{9}$$

where $\delta=\Delta p/p$ is the momentum deviation, T_{116} and T_{126} are the second order chromatic terms in TRANSPORT notation [23]. As the second term is very small compared to the last for our system, minimize the chromatic length T_{126}/M is an effective way to get higher spatial resolution, which means one should choose a magnification as high as possible. Or technically, minimize the distance from the object to the first magnet while maximize the field gradient of the quadrupole magnets [15]. As a result, we should adopt high field gradient miniature PMQs in our proton imaging system.

3. The miniature magnetic quadrupoles lens for DD proton

In this paper, the system is designed for protons with energy around 2.8 MeV. Since the DD-produced protons have an energy down-shift after they pass through the implosion hot spot region, we also provide a method to adjust the magnetic lens system in case the proton energy deviates from 2.8 MeV. As such experiments are carried out in vacuum target chambers, the magnetic fields of this system must be provided by permanent magnet materials such as NdFeB48.

Consider the ratio law [24] in beam line design that the dipole bend angles would be kept by reducing all physical dimensions (longitudinal and transverse) of a large system by a factor of $\xi=(B\rho)_s/(B\rho)_l$ while designing a smaller system, where $B\rho$ is the magnetic rigidity, subscript *s and l* represent small and large. Hence the size of this magnetic quadrupoles lens would be much smaller than that used in high energy proton radiography systems as the energy of DD-produced protons is much lower.

After optimization, we get the structure of the magnetic quadrupoles lens shown in Fig. 2. The PMQ segments is 1.5 cm thick and its inner and outer diameters are 1.4 cm and 4.2 cm. There are two pieces 3 mm thick shield iron before and after the PMQ segments, hence the total thickness of a PMQ is 2.1 cm. The inner of magnetic quadrupole lens are assembled from 2 segments each, so are 4.2 cm long. The outer half-strength pair are 2.1 cm long, and made of 1 segments each.