COMPACT HIGH ENERGY RADIOGRAPHY SYSTEM DESIGN BASED ON PERMANENT MAGNET QUADRUPOLE*

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Abstract

High energy electron radiography (HEER) is a promising diagnostic method for High Energy Density Physics (HEDP) or Inertial Confinement Fusion (ICF) owing to its capability of picosecond-nanometer spatial-temporal resolution, and is cost-effective in the meantime. A Compact HEER (CHEER) system based on Permanent Magnet Quadrupole (PMQ) instead of conventional electromagnetic quadrupole is proposed. Its lattice design and beam optics optimization is finished, and experiment is to be carried out on Tsinghua Thomson X-ray source (TTX) beamline after PMQs' fabrication and installation.

INTRODUCTION

Matter properties under extreme pressure and temperature conditions are the main focus of high energy density physics (HEDP). In order to figure out the fast process, diagnostic methods with high spatial and temporal resolution are in urgent demand. In addition, areal density or thickness resolution is often required when thick targets are used, such as the target in ICF. The early radiographic sources of x-rays countered the problems of energy deposition and focusing, thus limiting the dynamic range and resolution. These difficulties were overcame by the use of charged particle beams, which are first developed at LANL and excellent results with aspect to both time and space resolution have been demonstrated [1]. Lately, this promising tool was extended to the applications with high energy electron beam due to its cost effectiveness and portability [2]. Several labs using RF photocathode techniques enabled generation of high quality beams to validate the feasibility of HEER method for HEDP diagnosis [3,4]. The principle of charged particle radiography is rather clear [5]: beam passed through a thick target is transported to a magnetic imaging lens system and then form a point-to-point image on a luminescent screen. An aperture located on the back focal plane of the imaging system is employed to select beams with specified spread angle to let pass, where the position of the beam is only related to the initial spread angle after the target.

Different to the commonly used electro-magnetic quadrupoles in HEER imaging system, permanent magnet quadrupoles serve several unique advantages: much higher gradient (~ a few hundred T/m or even higher), much smaller size and more stable. With the high gradient PMQs and suitable magnifying lens design, a compact HEER(CHEER) system can be configured. In this paper, we report on the design and study of a CHEER system based on PMQ and the so-called Russian type quadruplet configuration [6].

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CHEER SYSTEM DESIGN

PMQ Design

Due to the simple axially symmetry geometry, solenoids are commonly used as an imaging lens in low electron energy region, and become much less effective when the beam energy is beyond a few MeV. The gradient of conventional electromagnetic quadrupoles is limited to tens of T/m，much lower compared to that of Halbach type PMQ made of high remanence permanent magnet material and with small aperture. In our design, 12-segment Halbach PMQ model is adopted and the CST model of the PMQ is shown in Fig 1 a). the mechanical length of the PMQ is 2cm, and the inner diameter is 1cm while the outer diameter is 5cm. The blue part is high remanence permanent magnet material whose choose is based on the gradient we need. In one example, the residual remanence is 1.2T, giving a high gradient of 287 T/m. The red part outside the permanent magnet segments is made of pure ion and used for shimming magnetic field. It is worth mentioning that a small ferromagnetic ring placed before and after the PMQ is utilized to suppress the fringe field from 2mm to 0.18mm, which turns out to be quite effective.

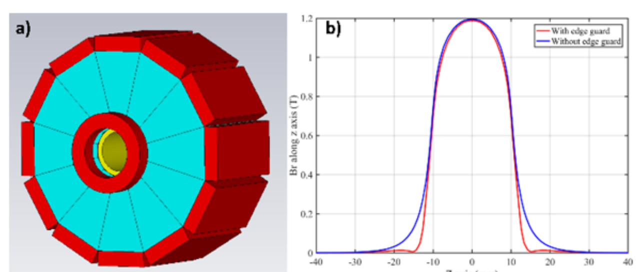

Figure 1: a) CST model of PMQ; b) fringe field with and without edge guard.

Magnifying Lens Design and Optimization

Unlike the behavior of a solenoid focusing the beam on both x and y planes, a single quadrupole focuses the beam in one plane while defocuses in the other. So at least two or more quadrupoles are needed to comprise an axially symmetric imaging lens. Furthermore, in order to obtain in both planes the same positions of the image planes and the focal planes, the same magnifications and even the same spherical aberrations, the simplest system geometry is the so-called Russian quadrupole quadruplet(RQ) [6], which can be analogous to an axisymmetric lens. In RQ

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configuration, the polarities and the strengths of the four quadrupoles are sorted as +A-B+B-A, while the length of the quads(l) and distance (s) between them are l1–s1–l2–s2–l2–s1–l1, thus making this configuration anti-symmetric.

The first order transfer matrix of the RQ can be expressed as:

$$R_x = \begin{bmatrix} a & b \\ c & d \end{bmatrix}, \quad R_y = \begin{bmatrix} d & b \\ c & a \end{bmatrix}. \tag{1}$$

The whole imaging system consists of a RQ and drift length L1 ahead and another drift length L2 after, then the total matrix is:

$$\begin{gathered} R_{x,total} = \begin{bmatrix} a+cL_2 & L_1(a+cL_2)+(b+dL_2) \\ c & d+cL_1 \end{bmatrix} \\ R_{y,total} = \begin{bmatrix} d+cL_2 & L_1(d+cL_2)+(b+aL_2) \\ c & a+cL_1 \end{bmatrix} \end{gathered}. \tag{2}$$

To form a point-to-point image, the R12 element of the total transfer matrix is to be zero. With the requirement of equal magnification factor, same position of focal and image planes on both planes taken into consideration, the requirement of a=d must be satisfied. Then, drift length L2 can be expressed as a function of matrix R and drift length L1:

$$L_2 = -\frac{b+aL_1}{d+cL_1}. \tag{3}$$

The focal length of the imaging system is f=-1/c, while the magnification factor is

$$M = a - \frac{L_2}{f} \approx -\frac{L_2}{f}. \tag{4}$$

assuming L2 is much too larger than the focal length.

Unlike the case of limited magnification factor of conventional RQ configuration using electromagnetic quadrupoles [6], the high gradient of PMQs can reduce the focal length of the lens to cm scale or even mm scale. So the magnification factor can be several tens with acceptable drift length from the lens to the image plane. The parameters of an example of such an imaging sys-tem is listed in Table I.

Table 1: RQ Parameters

Para.	Value	Para.	Value
l_1	2cm	l_2	2cm
G1	287.8T/m	G2	184.3T/m
s_1	2.52cm	s_2	12.65cm
L_1	6cm	L_2	13.86cm
M	3	$C_{c,x}$	-1m
$C_{c,y}$	-0.5m	$C_{s,x}$	4.7m
$C_{s,y}$	0.83m		

Particle Tracking

Using the imaging system discussed above, imaging process of a virtual TEM grid is simulated via A Space Charge Tracking Algorithm [7]. The energy of the electron probe is 45MeV, the total charge is 100pC, and the normalized emittance is 0.2 mm.mrad (rms). Simulation results are shown in Fig 2.

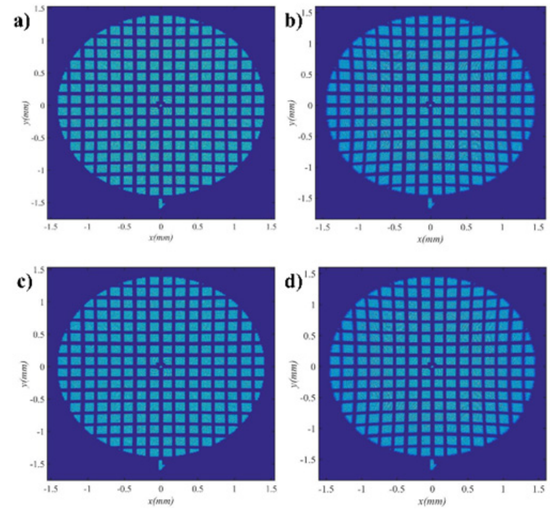

Figure 2: Simulation of virtual sample.

The upper two images are simulated without space charge and the lower with space charge. It is obvious to see that space charge is not a big concern to degrade space resolution, owing to the fact that space charge effect is greatly mitigated in high energy electron beams. In the left two images, the initial divergence angle is set to 2mrad while the right is 5mrad, where pincushion distortion due to spherical aberration can be observed. However, for an electron beam whose energy is 45MeV and emittance is 0.2um, the average divergence is estimated to be 10urad, provided that the beam size on target is 2mm. Since spherical aberration is proportional to cube of divergence, there is no need to pay much attention to it. Therefore, the chromatic blur resolution is defined by [8]

$$\Delta = C_c \theta \delta. \tag{5}$$

The rms energy spread of the electron probe is about 0.1%, then the resolution is about a few micros, which is sufficient for the case of pump-probe experiment. In our planned dynamic experiment, radiographs of reversible process will be obtained by adjusting the time delay between the electron probe and pump laser. As to irreversible process, one can use bunch train to record the process and use an RF deflecting cavity to separate different slices of bunch train [9]. The sketch of experimental setup is shown in Fig 3, where high quality electron beams generated by S-band photo-injector probe the excited state of the target hit by 800nm pump laser.

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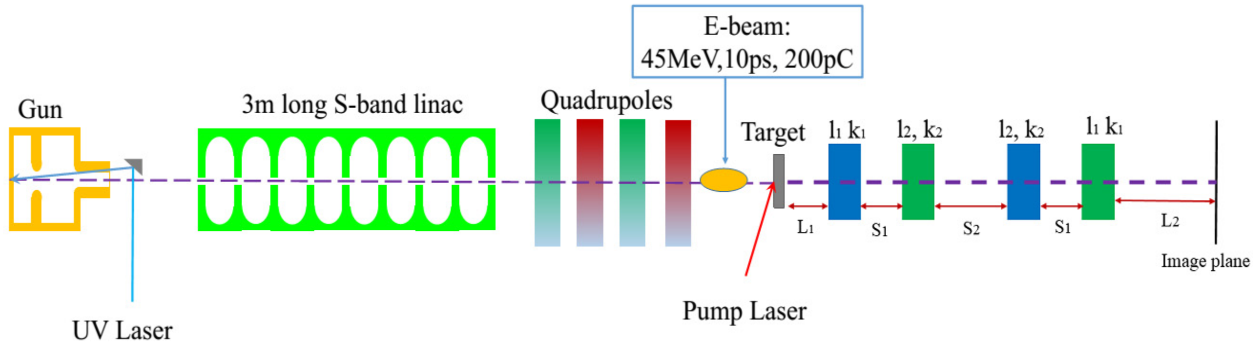

Figure 3: Sketch map of pump-probe experiment based on TTX beamline and RQ imaging system.

MULTISTAGE IMAGING

As discussed above, a single RQ can be used as a basic imaging unit. Since the resolution up to second order transfer matrix is inversely proportional to magnification factor M, it's a nature choose to design a large magnifying imaging system in order to obtain sub-micrometer even nanometer space resolution. Like the commonly used object-intermediate-project lens system in conventional TEM or Ultrafast Electron Microscope [10], multistage RQ imaging approach can be employed to reach that goal.

Once the parameter of the RQ is settled, the magnification factor of the imaging unit is determined by the drift length L_2. Another set of RQ aimed at large magnification factor is optimized to M=33.3 in less than 2.3m, as shown in Table 2.

Table 2: RQ Parameters

Para.	Value	Para.	Value
l_1	1.25cm	l_2	1.25cm
G1	200.83T/m	G2	475.36T/m
s_1	1.23cm	s_2	1.23cm
L_1	1.74cm	L_2	2.2126m
M	33.3	$C_{c,x}$	-1m
$C_{c,y}$	-0.5m	$C_{s,x}$	4.7m
$C_{s,y}$	0.83m		

If we use a same RQ as the projector lens, then the total imaging system magnifies 1000 times in less than 5m long space. With this configuration completed, it can be applied to targets with certain thickness and sub-micrometer features, such as integrated circuit chips. Combined with CT technology, three dimensional imaging of IC chips can be achieved, which is suitable for IC chips inspection.

CONCLUSIONS

High energy electron radiography has been drawn great attention as a promising diagnostic method for high energy density physics. We proposed a compact HEER system based on PMQ. Design of Halbach type PMQ have been optimized to gain high gradient and suppressed fringe field. Simulations of the whole imaging system by both high order beam dynamics code based on transfer matrix and particle tracking code were conducted, and they agreed quite well. The CHEER system is estimated to have a good spatial resolution of a few micros, and it will soon be installed on TTX beamline, then pump-probe experiment will be carried out. Moreover, multistage or 'cascaded' imaging based on RQ imaging units were proposed in order to get large magnification factor.

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