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SINGLE-SHOT CASCADED HIGH ENERGY ELECTRON RADIOGRAPHY BASED ON STRONG PERMANENT MAGNET QUADRUPOLE COMPOSED IMAGING LENS*

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Abstract

High energy electron radiography, an extension of conventional transmission electron microscopy, is suitable for imaging of thicker objects and expected to be a promising tool for diagnostics of high energy density physics (HEDP). A cascaded high energy electron radiography system using two-stage imaging lenses based on strong permanent magnet quadrupoles is designed, optimized and finally installed at Tsinghua university. Encouraging result of 1.6-µm space resolution is obtained in our primary experiments, along with the clear imaging of a spherical capsule as a substitute of the targets used in inertial confinement fusion. Successful implement of cascade high energy electron imaging system is necessary for reaching better resolving power of the imaging system, and well matching of design, simulation with experimental results paves the way to high energy electron microscopy to provide full capacities for diagnostics of HEDP with sub-µm and picosecond spatiotemporal resolutions.

INTRODUCTION

As an alternative of high energy proton radiography [1–3], a mature tool for the study of dynamic material properties under extreme pressure and temperature conditions, high energy electron radiography (HEER) is expected be a suitable diagnostic tool for high energy density matters with high spatiotemporal resolutions, and at a much lower cost [4, 5]. The working principle of HEER is similar to charged particle radiography [6]: high electrons are scattered while traversing the sample, then focused by imaging lens made of several quadrupoles and finally projected onto a screen to form a point-to-point image of the sample. Since proposed, HEER has drawn considerable interest and intensive efforts have been devoted to development of this technique [7–11]. At present, the spatial resolution of HEER is limited to a few microns, which is insufficient for diagnostic of ultrafast laser-induced processes at a time scale from femtosecond to picosecond. To push the limit of HEER to sub-µm level, a novel imaging optics is required.

On this occasion, we propose a cascaded high energy electron radiography (CHEER) system based on two stages imaging lenses, which are composed of high-gradient permanent magnet quadrupoles (PMQs). This scheme is similar to a transmission electron microscopy (TEM), where the image of first-stage will be further magnified by a second stage imaging lens, and the final magnification factor is the product of that of each stage lens. Design, simulation and successful demonstration of this CHEER system will be present in following sections.

ELECTRON OPTICS DESIGN

Unlike the electromagnetic solenoids commonly used in keV and MeV TEM, quadrupoles have to be used to focus the high energy electrons. Among different kinds of quadrupoles, PMQ is a strong, compact and cheap type, making it a popular choice in high energy particle transport and focusing [12]. Use of such a PMQ can not only make the whole imaging section compact by shortening the focal length *f*, but also help to suppress high order chromatic aberrations spherical aberrations, since the chromatic and spherical aberration coefficients is on the same order of focal length [13]. However, using of PMQs is much more complicated than solenoids, since they will focus electrons in x/y direction while defocus them in y/x direction. Therefore, three or more PMQs are required to make up a imaging lens, with equal magnification factor, same focal plane or even same chromatic and spherical aberration in both transverse planes. Possible configurations of such an imaging lens include triplet, quadruplet, quintuplets [14], sextuplets, etc. Among them, triplet and quadruplet are commonly used due to their simple form and convenience in practice.

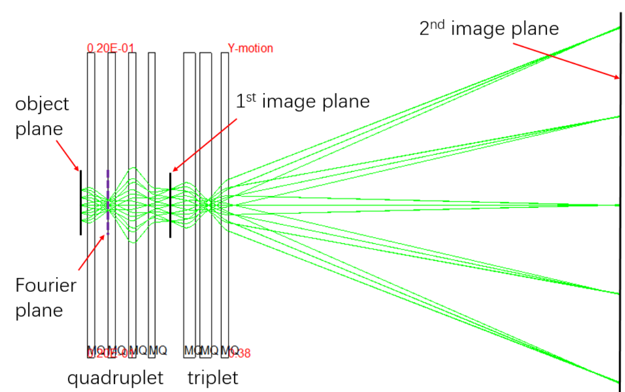

Figure 1: Electron trajectory tracking in CHEER using COSY INFINITY [15].

In our design, the CHEER system is realized by the combination of a Russian quadruplet and a triplet, acting as the first-stage and second-stage imaging lens. Each stage len is optimized to meet the requirement of point-to-point imaging, which can be conveniently expressed in matrix formulism as $R_{12} = R_{34} = 0$. The transfer matrix of the CHEER system

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after optimization (using code COSY INFINITY) is:

$$R = \begin{bmatrix} 12.26 & 0 & 0 & 0 \\ 10.7 & 0.082 & 0 & 0 \\ 0 & 0 & 11.89 & 0 \\ 0 & 0 & 13.1 & 0.084 \end{bmatrix} \quad (1)$$

Effectiveness of this electron optics is verified by observing the electron's trajectories in imaging section, as shown in Fig. 1, where a point-to-point image of the sample is formed sequentially on the first and second stage image planes.

PARTICLE TRACKING SIMULATION

In beam dynamics simulations mentioned above, the space charge effect is not taken into consideration, but in practice it can act as a defocusing lens and deteriorate the final image [13]. Additionally, overlap of fringe fields of real quadrupoles lead to unphysical field distribution and reduce effective focusing strength. Therefore, we conduct detailed particle tracking simulations, with space charge forces and measured field distribution of PMQs added in, to validate the imaging process. The electron probes used are generated from a S-band photoinjector. Parameters of the electron bunch at the sample is listed in Table. 1.

Table 1: Parameters of the Plectron Probe at Sample

Parameter	Value
Bunch charge	600 pC
Kinetic beam energy	45 MeV
rms energy spread	0.12%
rms normalized emittance	1 mm.mrad
Transverse beamsize	1-3 mm
Bunch length	10 ps

In particle tracking simulations using code ASTRA [16], a virtual 200 mesh TEM grid with 100% initial contrast is adopted as the object, and beam pattern is recorded on the 1^{st} and 2^{nd} image planes. Clear images of the object are obtained in simulations, as shown in Fig. 2, indicating the effectiveness of the designed CHEER electron optics. Here we note that space charge force induced image blurring is negligible in our simulations, since the beam energy γ is about 100 and space charge effect is dramatically suppressed, compared to the MeV or lower energy electron imaging scenario.

EXPERIMENTAL RESULTS

Next we carry out the proof-of-principle CHEER experiment on Tsinghua Thompson scattering X-ray source platform [17], which mainly consisted of a high-gradient (100 MV/m) S-band rf photocathode gun, a 3-m long travelling wave accelerating tube and some other elements for beam control and measurements. In our experiment, high energy high brightness electron beams (parameters listed in Table. 1) are generated and accelerated to 45 MeV at the

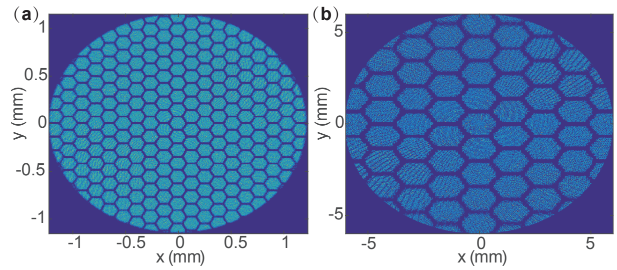

Figure 2: Simulated first stage (a) and second stage (b) images of a virtual 200 mesh TEM grid.

exit of the photo-injector, and matched into the imaging section by a conventional electromagnetic triplet. The imaging lenses, including the first-stage quadruplet and second-stage triplet, are installed in the 0.7-m long vacuum chamber. In order to improve the resolution of electron detection system, a 150 µm thin YAG screen perpendicular to beam axis is used. The fluorescence generated by electrons' hitting the screen is deflected by a 45° mirror and then collected by a lens-coupled high resolution CCD. Experimental setup is present in Fig. 3.

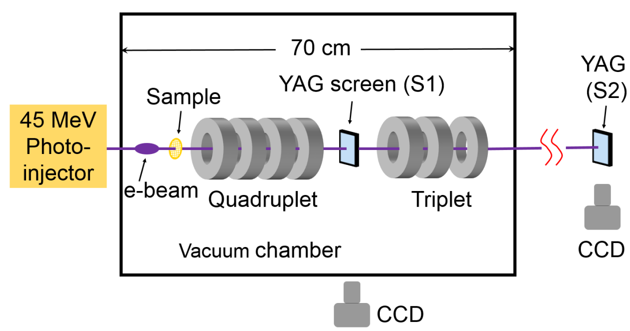

Figure 3: Schematic of the CHEER experiment.

A standard 200-mesh hexagonal TEM grid is used to evaluate the imaging process and calibrate the spatial resolution of CHEER system. Images of the sample are obtained on each stage image plane, as shown in Fig. 4. As we can see, these imaging results of each stage correspond well to simulated ones. Knowing the physical dimensions of the grid, the final magnification factors are determined to be 15.2 and 12.8 on the horizontal and vertical planes, in fair agreement with design values. By calculating the electron flux across the edge bar of the grid, the spatial resolution of this CHEER system is estimated to be 1.6 µm.

In addition, we attempt to image a ϕ 900 µm spherical capsule made of glow discharge polymer with CHEER system to evaluate its feasibilities for imaging the targets used in inertial confinement fusion (ICF). As we can see from Fig. 5, distinct radiographs of the capsule are captured by CHEER system, though the image qualities are hampered by the non-uniform beam transverse distribution. Successful imaging of the spherical capsule lay the foundation for future time-resolved imaging of the ICF target driven by heavy ions or high power lasers.

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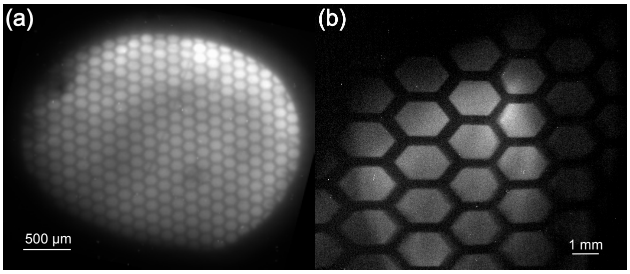

Figure 4: (a):first-stage and (b):second-stage images in experiments. Note: the yardsticks represent the dimensions on the image plane.

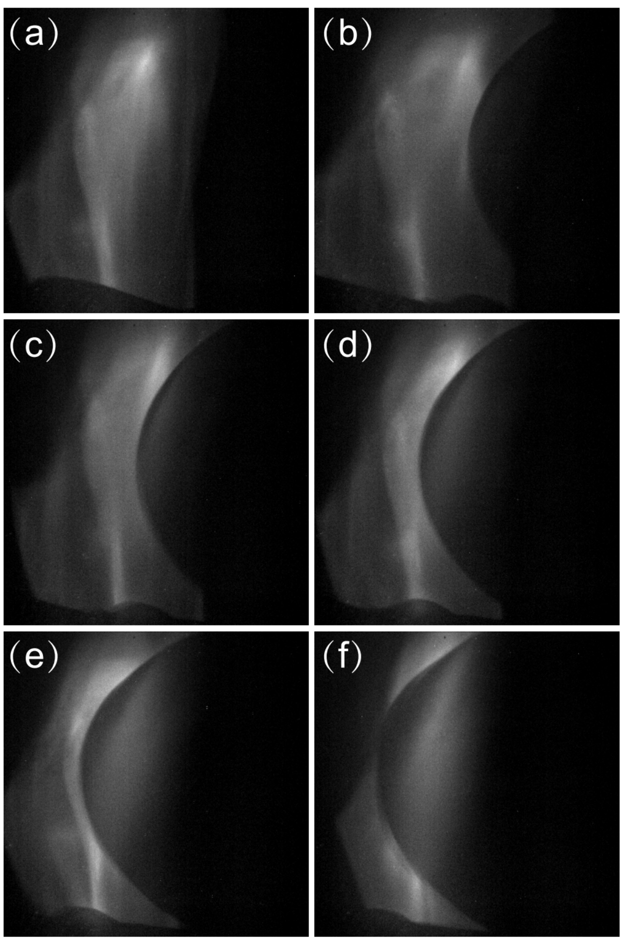

Figure 5: (a): the electron beam distribution. (b)-(f):images of the capsule as it approaches into the field-of-view from right to left.

CONCLUSION

In summary, we propose a cascaded high energy electron radiography scheme using two-stage imaging lenses based on high-gradient PMQs. Proof-of-principle experiments are demonstrated in our laboratory at Tsinghua university, in excellent matching with electron optics design and particle-tracking simulations. The encouraging results of 1.6 µm obtained in experiments should have a positive impact on the diagnosis of high energy density matters. One could further improve the resolution to sub-µm by improve the magnification factor of the imaging system, but the physics and technology remain the same as present in this paper.

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