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RUSSIAN QUADRUPLET BASED ELECTRON OPTICS FOR ULTRAFAST ELECTRON MICROSCOPY*

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Abstract

With the development of Mega-electron-Volt ultrafast electron diffraction technology, electron microscopy based on photocathode radio-frequency (RF) electron guns has become a promising tool for high spatiotemporal resolution and shows obvious advantages of suppressing the space charge effect. Ultrafast electron microscopy is being developed at HUST. Russian Quadruplet (RQ) based electron optics is selected to achieve simultaneous focusing and equal magnification in both vertical and horizontal directions. The RQ exit beam position must be highly dependent on the entrance beam position and independent of the entrance beam divergence to achieve a point-to-point image, which defines the first-order transfer matrix parameters. COSY Infinity code is implemented for optics design. The simplified hard-edge model, the fringe field effects, and high-order lens aberrations are discussed and further optimized for the electron beam optics design.

INTRODUCTION

An Ultrafast Electron Microscopy (UEM) based on MeV relativistic electrons from a photocathode radio-frequency (RF) electron gun provides a new solution to the difficulty of single-shot imaging, which is limited by the space charge effect [1, 2]. This technique is expected to be a powerful tool to probe irreversible ultrafast dynamics, hoping to achieve direct imaging with high spatiotemporal resolution in real space [3, 4].

A MeV UEM platform is being developed at Huazhong University of Science and Technology (HUST MeV UEM). The schematic diagram is shown in Fig. 1. After the electron beam interacts with the sample, the magnetic lens system is designed to manipulate the beam to achieve point-to-point imaging between the object and the image plane, which can eliminate the image blur caused by the electron beam divergence.

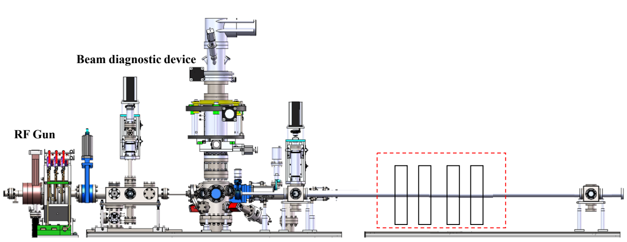

Figure 1: Layout of HUST MeV UEM.

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Instead of the commonly used solenoids, quadrupole magnets are preferred as imaging lenses for MeV UEM because of their more effective focusing ability [5-7]. The magnetic imaging lens system based on the Russian Quadruplet (RQ) [8] configuration has been designed at HUST. The electron optics design is optimized to minimize the high-order aberrations effects. The actual magnetic field model and fringe field effects on imaging are also presented in this paper.

ELECTRON BEAM OPTICS DESIGN

As the focusing effect of a single quadrupole on electrons is opposite in the horizontal and vertical directions, multiple quadruplets are needed to achieve simultaneous focusing and magnification. Russian quadruplet with a highly antisymmetric structure is a good choice to provide the same magnifications and focal planes in the x and y planes. The configuration of the system is shown in Fig. 2.

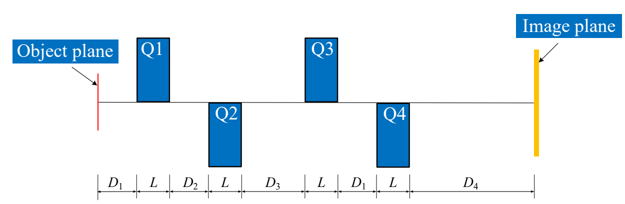

Figure 2: Layout of the magnetic imaging lens system.

Point-to-point imaging

When the horizontal and vertical plane coupling is neglected, the transfer matrix for electrons passing through the magnetic lens system can be expressed as [9]

$$\begin{pmatrix} x \\ x' \\ y \\ x' \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 \\ R_{21} & R_{22} & 0 & 0 \\ 0 & 0 & R_{33} & R_{34} \\ 0 & 0 & R_{43} & R_{44} \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ y_0 \\ y_0' \end{pmatrix} + \begin{pmatrix} T_{116} & T_{126} & 0 & 0 \\ T_{216} & T_{226} & 0 & 0 \\ 0 & 0 & T_{336} & T_{346} \\ 0 & 0 & T_{436} & T_{446} \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ y_0 \\ y_0' \end{pmatrix} * \delta . \quad (1)$$

In first-order beam optics, achieving high-quality point-to-point imaging requires the RQ exit beam position must be highly independent of the entrance beam divergence. Additionally, the magnification factor should be the same in both transverse directions. These requirements can be expressed in the transfer matrix elements as R_{12}=R_{34}=0 and R_{11}= R_{33}=M, where M represents the magnification factor.

For MeV UEM, the spatial resolution is mainly limited by high-order chromatic and spherical aberration when the first-order point-to-point imaging is satisfied [10]. Extending the transfer matrix to the third order from Eq. (1), the resolution determined by the aberrations can be derived as

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$$\Delta x = \frac{T_{126}\varphi\delta}{M} + \frac{U_{1222}\varphi^3}{M} = C_{c,x}\varphi\delta + C_{s,x}\varphi^3 . \quad (2)$$

Where φ is the average scattering angles, δ is the relative energy spread. $C_{c,x}$ is the chromatic aberration coefficient and $C_{s,x}$ is the spherical aberration coefficient, which are both respectively related to the second-order and third-order transfer matrix element.

Optics design result

COSY Infinity code is implemented for the optics design and optimization. The detailed specifications of the Russian Quadruplet system are listed in Table 1. The whole transfer matrix between the object and image plane is

$$R = \begin{pmatrix} 4.0 & -0.189\times10^{-6} & 0 & 0 \\ 4.587 & 0.2500 & 0 & 0 \\ 0 & 0 & 4.0 & -0.376\times10^{-6} \\ 0 & 0 & 4.587 & 0.2500 \end{pmatrix} . \quad (3)$$

Table 1: Specifications of the Russian Quadruplet system

Name	Length	Gradient	Position
Q1	0.1 m	1.250 T/m	0.3 m
Q2	0.1 m	-0.769 T/m	0.55 m
Q3	0.1 m	0.769 T/m	0.85 m
Q4	0.1 m	-1.250 T/m	1.1 m

Here, the terms R_{12} and R_{34} are optimized to a relatively small level, and the magnification factor R_{11} and R_{33} are equal to 4, proving the achievement of point-to-point imaging with the same magnification in both transverse directions.

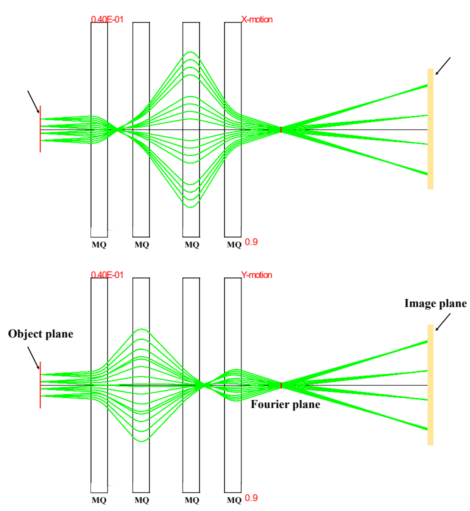

Figure 3: Electron trajectories tracking in COSY Infinity.

Figure 3 shows the tracking trajectories of electron beams with various initial divergences and positions in the magnetics lens system. Electrons with the same position at the object plane will converge at the same position at the image plane, and their trajectories in the horizontal and vertical directions outside the magnetic lens system are completely consistent. This confirms the effectiveness of the optics design for magnetic imaging lens system.

High-order lens aberrations

The optimization of chromatic and spherical aberration is crucial for achieving high-resolution imaging in optics design. High-order beam optics can be further studied using the COSY INFINITY code. We investigate the optimization results of various imaging system schemes with fixed magnification but different magnet lengths. The relationship curves between imaging system parameters vs. the total length and the main aberration coefficients vs. the focus length are shown in Fig. 4.

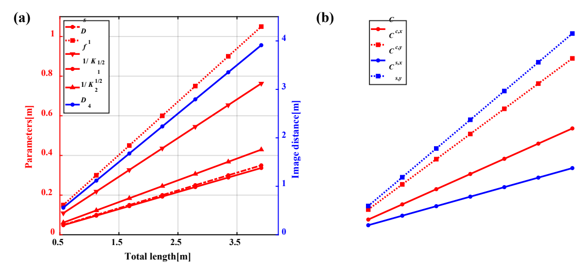

Figure 4: The variation of the (a) parameters vs. total length of the imaging system; and (b) main aberration coefficients vs. focus length, where the magnification is fixed.

The lengths of the magnet and drift in the imaging system, and even the focus length, are inversely proportional to the square root of the magnet focusing strength, which verifies that the magnetic imaging lens system follows the object-image relationship similar to the geometric optics theory [11].

As the quadrupole gradient increases, the focal length diminishes, and high-order lens aberrations also decrease proportionally. This suggests that boosting the quadrupole gradient is a feasible way to make the imaging system compact and suppress high-order lens aberrations, thereby improving spatial resolution.

IMAGING PROCESS SIMULATION

We simulate the imaging process of a virtual sample to roughly estimate the imaging performance of the system. The electron beam has an energy of 3 MeV with a rms size of 0.02 mm. The beam divergence is 1.8 mrad, and the energy spread is 1.0E-05. The simulation result at the image plane is presented in Fig. 5, which proves the ability of the RQ system to achieve point-to-point imaging.

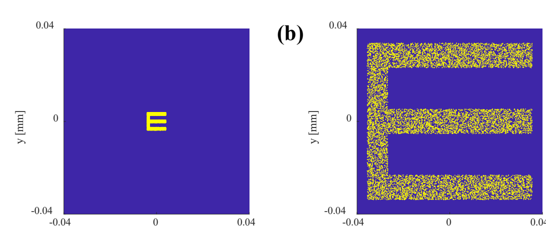

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Figure 5: (a) beam distribution after the virtual sample; (b) final image of the sample.

Impact of energy spread

Electrons with different energies passing through the magnetic lens converge at different locations on the axis, resulting in blurred images. The imaging results of electron beams with different energy spread are shown in Fig. 6. Chromatic aberration has a non-negligible effect on the electron transverse position when the energy spread reaches the order of E-04, causing significant image blurring and a noticeable decrease in spatial resolution.

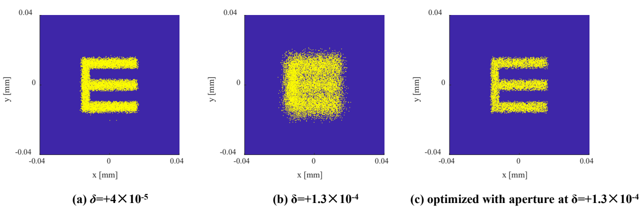

Figure 6: Simulated electron beam images at different beam energy spread and after optimized.

Figure 6(c) shows the multi-shot integral imaging result of the electron beam after passing through an aperture located in the Fourier plane. The aperture blocks electrons with initial large divergences from participating in imaging, resulting in the restoration of the original blurry pattern. The method effectively mitigates the impact of high-order aberrations and partially compensates for the worsening resolution caused by excessive energy spread.

Fringe Field Effects

The two-dimensional and three-dimensional model of the quadrupole prototype is designed and optimized by the software OPERA. The 3D simulation model in OPERA is presented in Fig. 7. The transverse pole shape shimming and pole-end chamfer are utilized to improve the magnetic field quality in the good field region.

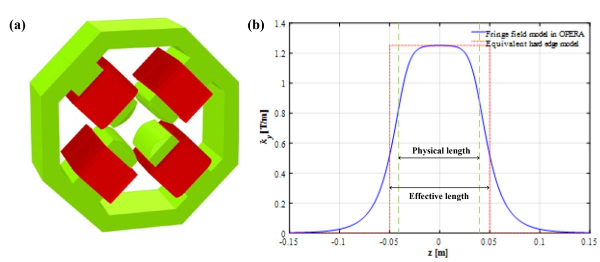

Figure 7: (a) Simulation model of the quadrupole magnet in OPERA; (b) fringe field distribution along the radius of 10 mm.

For a real quadrupole, the magnetic field at the boundary always diminishes smoothly to zero. The Enge model is used to fit the fringe field shown in Fig. 7, and the optics design results based on the simplified hard-edge model are verified under the actual magnetic field. The beam envelope under the fringe field model is shown in Fig. 8(a), revealing that the point-to-point imaging designed based on the initial optics design scheme is destroyed. The fringe field effects on imaging cannot be ignored when designing a compact MeV UEM, and therefore it is necessary to optimize the beamline scheme.

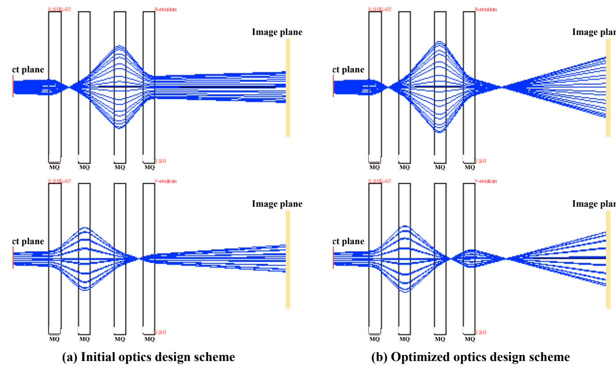

Figure 8: The beam envelope under the fringe field model.

The gradient of quadrupoles is optimized without changing the existing system layout, where the beam envelope is shown in Fig. 8(b). The optimized gradient and transverse size are slightly increased. It shows that the simplified hard-edge model significantly underestimates the imaging aberrations, and the contribution of the fringe field effects to spherical aberration is apparent, as shown in Table 2. This suggests that fringe field effects can exacerbate blurring to some extent. Thus the harmonic components of the quadrupole lens should be minimized to reduce the imaging aberration.

Table 2: Main aberrations of the imaging system

Parameters	$C_{c,x}$	$C_{c,y}$	$C_{s,x}$	$C_{s,y}$
Hard-edge	-6.97	11.55	45.84	138.42
Fringe field	-7.88	-12.74	326.86	927.56
Variation	+13.15%	+10.32%	+6.13	+5.70

CONCLUSION

This paper presents the electron optics design of a magnetic lens imaging system based on the Russian quadruplet for HUST MeV UEM. High-order chromatic and spherical aberrations are studied, and optimization methods for suppressing the lens aberrations are discussed. The effectiveness of the optics design is validated by simulating the imaging process with a virtual sample, and the impact of chromatic aberration caused by beam energy spread on imaging is analyzed. A comparison of the imaging differences between the fringe field model and the simplified hard-edge model shows that the fringe field effects significantly contribute to spherical aberration. To further improve the spatial resolution, a multistage lens system can be thoroughly explored for larger magnification, referring to the design approach outlined in this paper.

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