ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPMP016

DESIGN OF THE CONDENSER SYSTEM AND IMAGING SYSTEM FOR A UEM*

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Abstract

The ultrafast electron microscope provides a useful tool for exploring fine structure and observing dynamic process at nanometre and picosecond scale, which has been extensively applied in chemistry and biological field. After emitting from the electron gun, electron beams are focused on the stage sample by the condenser system and then be projected by the imaging system on the screen. In the present study, a two-lens condenser system is simulated by Parmela and a three-lens imaging system is designed using thin-lens approximation. Besides, the shape factor of metallic spheres which have different radius for perturbation method is measured, which is conductive to measuring the Z/Q parameter and the electric field along the axis of the C-band 3 MeV photocathode gun for the UEM.

INTRODUCTION

The electron microscope is a useful tool for observing and studying materials and cells in very small scale with wide application in many laboratories. The ultrafast electron microscope (UEM), which differs from a traditional electron microscope, employs ultrafast electron beams with higher energy from hundreds of keV to several MeV level as a probe to discover molecule structure. Besides, the ultrafast electron beams with short pulse of picosecond level, could also be used to observe the dynamic process of live biological material and chemical phase changing with high temporal resolution. [1,2]

A UEM consists of several parts, including an electron photocathode gun, a condenser system, a sample stage, an imaging system and other assistant systems. The condenser-lens system is designed to focus electron beams on the sample stage into a small spot, to ensure that sufficient electrons could be able to pass through the sample and finally be projected to a magnified picture with enough brightness on the screen. It usually consists of two lenses including C1 and C2. The C1 lens is a strong lens with small focal length, which could offer strong force on electron beams to decrease its radius. The C2 lens is a weak lens compared with the C1 lens, of which magnification factor is around 1.

The imaging-lens system produces magnetic field to affect electron beams and project the beams on the screen to include an objective lens, an intermediate lens and a projector lens. The objective lens is a strong magnetic lens which is also the most important lens in the system. It needs to be designed cautiously for decreasing the aberration. The intermediate lens is a weak lens relatively to provide changeable magnification factor and the projector lens is a strong lens with few mm focal length to minimize the aberration. [3,4]

In the current work, the two magnetic lenses of the condenser system are designed and the electron dynamic processes are simulated. Using the thin-lens approximation, the magnetic field of the three lenses in the imaging system is calculated. Some parameters including focal length and magnification factor are calculated and the properties of the magnetic lenses are discussed. Besides, we fabricated a C-band standard aluminium pillbox to measure the shape factor for metallic spheres of different radius, which would be used in the experiment for measuring the electric field along z-axis and the value of Z/Q parameter inside the C-band electron gun designed for this UEM.

CONDENSER SYSTEM DESIGN

The design of the two-lens condenser system shown in Figure 1 is divided into two parts. First, the magnetic field of C1 lens and C2 lens is designed and the dynamic process has been simulated. Besides, the effect of the condenser aperture is discussed, which could control the radius on the sample stage with the changeable current in the C2 lens. Then, the full dynamic process of the electron beams from emitting from the electron gun to arriving at the sample stage has been simulated in Parmela. The electron beams are accelerated to 3 MeV by the C-band photocathode gun and then are focused by the condenser system during the dynamic process. The parameters of electron beams at the sample stage has been listed after simulation.

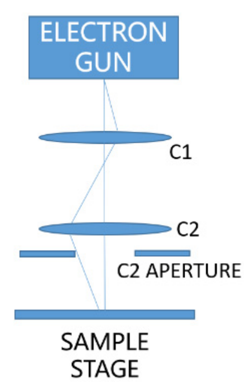

Figure 1: The condenser system for the UEM.

Design of the C1 and C2 Lenses

The C1 lens is a strong magnetic lens with focal length of several millimetres of which magnetic field strength could be quite high, while the C2 lens is a weak magnetic lens with focal length of several centimetres compared to

* Supported by National High-tech R&D Program (No.na8211009b).
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ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPMP016

the C1 lens. The magnetic field along z-axis of condenser system is presented in Figure 2 and the Figure 3 presents the change of rms radius of electron beams during the dynamic process. The focal length and magnification factor of the two lenses are shown in Table 1. The demagnification of the full condenser system is 0.0165, which could decrease the rms radius of electron beams to 16.7 μm on the sample stage.

Table 1: Parameters of the C1 lens and C2 lens

Focal length of C1 lens	2.23mm
Magnification of C1 lens	0.0146
Focal length of C2 lens	3.8425cm
Magnification of C2 lens	1.1409
Magnification of full system	0.0165
Rms diameter of electron beams on sample stage	16.7μm

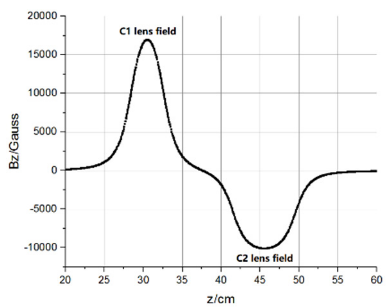

Figure 2: Magnetic field along z-axis of C1 and C2.

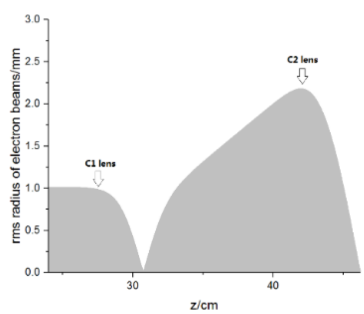

Figure 3: Focus process of electron beams.

Simulation of the Full Dynamic Process

The dynamic process of electron beams from the electron gun to arriving at the sample stage is simulated after the condenser system has been designed. After emitting from the photocathode, electron beams are accelerated by the 1.6-cell gun to 3 MeV. Then the condenser system focuses electron beams into a small spot on the sample stage. Several dynamic parameters of electron beams at the spot on the sample stage are presented in the Table 2.

Table 2: Dynamic Parameters at the Sample Stage

rms diameter on x	**0.016mm**
rms diameter on y	0.016mm
Beam quantity	0.1pC
Beam energy	`3.04MeV

The cross section of the electron beam at the sample stage is shown in the Figure 4, from which could be found that electron beams are focused into a small spot with radius of less than 1 μm.

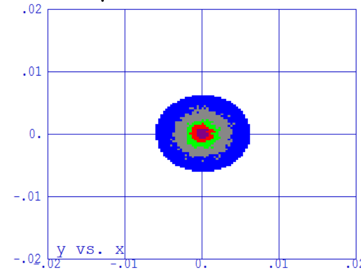

Figure 4: The cross section of the electron beam.

IMAGING SYSTEM DESIGN

The imaging system presented in Figure 5 consists of an objective lens, an intermediate lens and a projector lens. The magnetic field of the three lenses are calculated by thin-lens approximation.

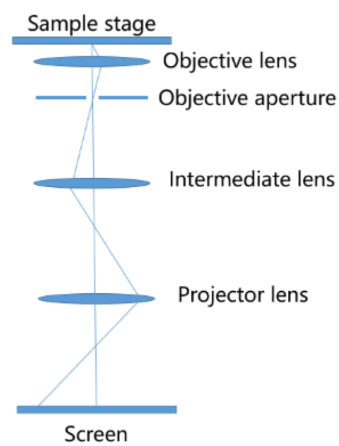

Figure 5: The imaging system for the UEM.

Design of the Lenses

The magnetic lenses provide focusing force for electron beams which is similar to optical lenses in conventional optic microscope. The principles for convex lens imaging and thin-lens approximation could be used while the magnetic field concentrates into a short length. The Glaser model is adopted to estimate the magnetic field and the focal length could be calculated by the equation below.

$$\frac{1}{f} = \frac{e}{8mV}\int_{-\infty}^{\infty} B_z^{\,2} dz = \frac{\pi e}{16mV} aB_0^{\,2}$$

The magnetic field and focal length of three lenses is calculated and listed in Table 3.

Table 3: Main Parameters of the Three Lenses

Lens	Maximum magnetic field/T	Focal length/cm
Objective lens	1.995	0.3
Intermediate lens	0.527	5
Projector lens	1.667	0.5

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MEASUREMENT OF SHAPE FACTOR

A 3MeV C-band photocathode electron gun with a coaxial coupler for the UEM has been designed and is now being fabricated. In order to measure the electric field along the axis of the gun and get the value of Z/Q parameter, the perturbation method is adopted in the experiment. A metallic sphere is used as the probe to perturb the field inside a high-Q resonant cavity and cause the working frequency shift, which could be measured and calculated the value of the electric field along the axis by using the equation:

$$\left[\left(\omega_0^2-\omega^2\right)/\,\omega_0^2\right]=4\pi r_0^3 E_0^2$$

A standard aluminium pillbox is simulated and fabricated in the experiment for measuring the shape factor of metallic spheres with different radius. Z/Q is an important parameter which is only related to the shape of a cavity. After measuring the shape factor the value of Z/Q could be calculated in any nonstandard cavity while using the same perturbator to measure the frequency shift. [5]

$$\frac{Z_s}{Q}=\frac{2}{\pi\varepsilon_0 L f^2}\cdot\frac{1}{F\Delta v}\left(\int_0^L\sqrt{-\Delta f\left(z\right)}dz\right)^2$$

Experiment of Measuring Shape Factor

We used metallic spheres (the material is stainless steel) of radius from 0.6mm to 0.9mm as the probe in the experiment. A threading hole of which diameter is 2.5mm is punched through the metallic sphere for moving along the z-axis of the pillbox. High energy laser is used as the punching method due to the small radius and this part of work was done in USTC centre for micro- and nanoscale research and fabrication.

Since the hole diameter on spheres is fixed, the deformation brought by punching hole on spheres with different radius is different. When using the equation of sphere, an error will emerge compared to the result of a standard sphere probe. However, a metallic sphere with bigger radius might disturb the original electric field in the cavity and correct result could not be got while using it. Thus, the sphere with suitable radius will be chosen by combining the result of experiment and the result of calculating the shape factor.

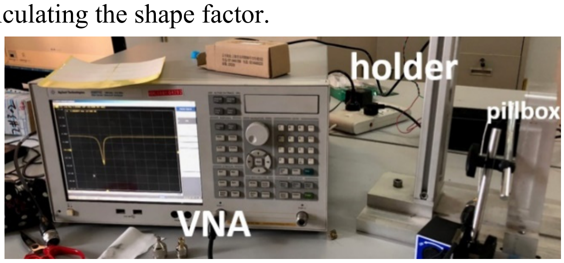

Figure 6: The experiment platform.

An experimental platform presented in Figure 6 has been built, which includes a computer, an electric motor, a holder, a vector network analyser (VNA). The frequency shift measured is shown in Figure 7 and the shape factor calculated is listed in Table 4. The 0.8 mm and 0.7 mm spheres are chosen to be the perturbation probe in next experiment measuring electric field considering both the deformation brought by the punching hole and the enough perturbation in the experiment.

Table 4: Shape Factor of Different Radius

Diameter of metallic sphere/mm	Shape factor F
0.9	3.233E-06
0.8	3.071E-06
0.7	3.029E-06
0.6	2.824E-06

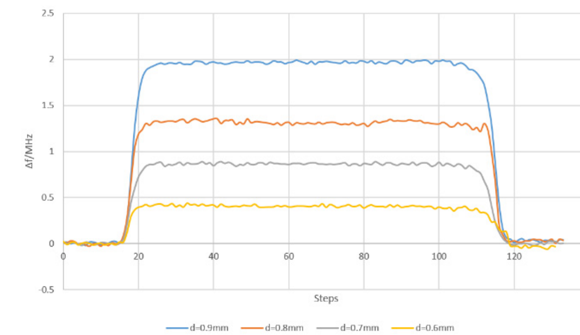

Figure 7: Frequency shift perturbation along the z-axis

CONCLUSION

In this paper, the condenser system for UEM is finely designed and the dynamic process of the electron moving through the system has been done. Several parameters of the electron beams are presented and the electron beams finally are focused into a spot which rms radius is 16.7 µm. Then the imaging system has been calculated using the thin-lens approximation. After the condenser system is finished, the magnetic lenses of the imaging system would be designed and the dynamic process of the electron beams passing through the system would be simulated. Besides, the space and temporal resolution would be calculated and the aberration of the system would be considered. The shape factor of metallic spheres is measured and then the electric field and the Z/Q parameter of the C-band photocathode gun would be measured after finishing fabrication and the results would be compared to the results of simulation.

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