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BEAM PARAMETER OPTIMIZATION FOR UEM FACILITY WITH PHOTO-EMISSION S-BAND RF GUN

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Abstract

Ultrafast Electron Microscopy (UEM) can provide snapshot images of a dynamic process in samples with an ultrafast time resolution, which is shorter than picosecond. The Future Accelerator R&D Team at KAERI has been preparing a UEM facility with a photo-emission S-band (= 2856 MHz) RF gun by collaborating with GIST and KRISS. To achieve a higher spatial resolution as well as a higher time resolution, the transverse beam emittance, beam divergence, and energy spread should be smaller, and the bunch length should be shorter. Beam dynamics simulations with ASTRA code are used to optimize those beam parameters in the RF gun. In this paper, we describe ASTRA optimizations of the S-band RF gun to achieve high spatial-temporal resolutions for the UEM facility.

INTRODUCTION

In the field of science and technology, there have been numerous efforts to observe fine structures of materials. Although we can understand some dynamics in biology, chemistry, and solid state with the Transmission Electron Microscopy (TEM), the direct observation of dynamical processes at atomic level is difficult. However, that was realized when UEM was first developed in 1990s [1, 2]. Since ultrashort energetic electron beams with an ultrasmall spot size can be generated by shooting an ultrashort laser pulse on a cathode, the photo-emission RF gun is widely used to generate a high quality electron beam source for the UEM. While propagating from the cathode to the sample, electrons in a single bunch are spreading in space and time due to space charge forces. Therefore, magnetic focusing lenses such as solenoids are used to compensate transverse space charge force at upstream and downstream of a sample, and the velocity bunching technology is used to compress bunch length against the longitudinal space charge force. In the sample, the incoming electron waves interact with atoms of the sample, and diffracted and scattered off. The electrons come out from the sample go into the fluorescent screen and finally an image of the atomic structures is formed by a CCD camera. Figure 1 shows the schematic components for UEM. From a technical standpoint, the UEM can be divided into three sections. The first section is the laser-driven photo-emission RF gun, in which the electron beam is generated and accelerated. For an atomic movie, the atomic spacing of sub-nanometer and ultrafast change within sub-picosecond should be resolved. Therefore, the bunch length should be ultrashort and the beam size should be small [3]. A laser-driven photo-emission RF gun can be an appropriate tool to make the bunch length ultrashort and beam energy high in fighting the space charge forces. The second section is the beamline downstram of the RF gun, where high quality electron beams with proper parameters are sent to the sample for high spatial-temporal resolutions. To compensate the transverse space charge force, which induces electron beam size growth, solenoid magnets are included in the beamline. The third section is the CCD camera system by which structural images of the sample are formed. While passing through the sample, electron waves with a wavelength $\lambda = h/p$, where h is the planck constant and p is the electron beam moment, interact with and are scattered off by atomic structures in the sample, and go into the fluorescent screen. Then an image of the atomic structures is formed by the CCD camera system, and we can see dynamical fine details of the sample through the monitor screen.

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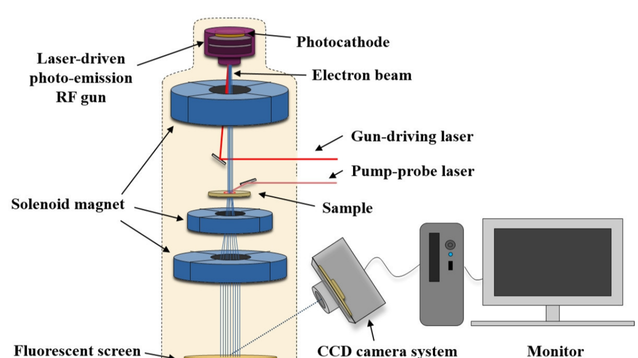

Figure 1: Schematic components for UEM.

LIMITATION IN RESOLUTION OF UEM

The electrons just come out of the cathode in vacuum state easily spread out due to the Coulomb repulsive force between electrons, space charge force, which is dominant in the UEM

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facility which requires the ultrashort and compact beam at a low beam energy. And this is the main cause of increasing beam emittance at gun, deteriorating the spatial-temporal resolutions as well. The transverse and longitudinal space charge forces are described as below.

Space Charge Force

If N electrons with the charge of q are Gaussian distribution, the transverse space charge force on the radial position r could be expressed as

$$F(r) = \frac{Nq^2}{2\pi\epsilon_0 l\gamma^2}\frac{1-\exp(-\frac{r^2}{2\sigma^2})}{r}. \quad (1)$$

Here, γ denotes Lorentz force, σ is an rms beam size, ϵ_0 is the permittivity of free space, and l is a bunch length in the stationary lab frame. The longitudinal space charge force for a parabolic density distribution is given by

$$F_{\parallel} = \frac{3}{\pi}g\frac{Nq^2}{\epsilon_0 l^3\gamma^2}z, \quad (2)$$

$$g \equiv 1 + 2\ln\frac{b}{a}, \quad (3)$$

where a is the radius of an electron beam in the lab frame and b is the radius of a conducting chamber in which the bunch is moving [4,5]. According to those formulas, the space charge forces become large for a shorter bunch length, a smaller spotsize, and a higher charge at a lower beam energy, which are required beam parameters for high spatial-temporal resolutions. Therefore, deep optimization processes along the gun and beamline should be performed to obtain those high quality beam parameters against the space charge forces.

DESIGN CONCEPT

The capability of an electron microscope is normally determined by image resolution. The requirements of spatial-temporal resolutions for an atomic movie are summarized as follows [5,6].

- Considering the dynamic characteristics of atoms such as spatial-temporal domains of atomic bond and breaking, the electron bunch length should be sub-picosecond and the transverse beam emittance should be sub-micrometer.
- For those ultrashort and ultrasmall electron beams, the beam energy should be high enough to reduce the space charge forces. The appropriate range of the beam energy is about 1 MeV ~ 5 MeV.
- Different kinetic energies among electrons make differences in velocity between electrons. This can result in chromatic aberration which depends on the energy spread. To reduce the chromatic aberration in the UEM, the energy spread ($\Delta E/E$) should be 10^{-4} or less.
- If the CCD camera has 1000 × 1000 pixels, 10^6 or more electrons are required in a single bunch. Then, the electron bunch charge is about 1 pC or more.

Table 1: Required Beam Parameters for UEM

Parameter	Value	Unit
average kinetic energy	≤ 5	MeV
single bunch charge	≥ 1	pC
rms bunch length σ_z	≤ 100	fs
normalized transverse emittance ϵ_n	≤ 100	nm
rms beam size σ_x and σ_y	≤ 200	μm
rms divergence $\sigma_{x'}$ and $\sigma_{y'}$	≤ 25	μrad
rms relative energy spread $\Delta E/E$	$\leq 10^{-4}$	·
total length from cathode to sample	≤ 1.0	m

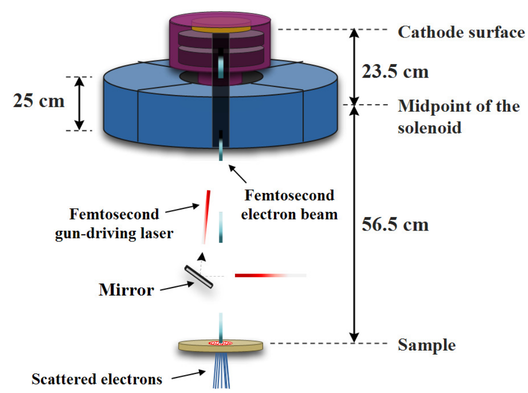

Figure 2: Optimized layout of UEM beamline.

OPTIMIZED BEAM PARAMETERS

Recently, Mr. Pikad Buaphad of KAERI designed the structure of a laser-driven photo-emission S-band RF gun operating at the π-mode with 1.6 cells with CST simulations. Since it can accelerate the electron beam quickly up to a few MeV, the space charge force can effectively be reduced though the beam is ultrashort and compact. To supply sufficient beam parameters as summarized in Table 1, ASTRA beam dynamics simulations were performed [7]. Figure 2 gives the optimized layout of UEM components including the newly designed RF gun, a solenoid, and the sample. Considering the fact that the characteristics such as a pulse length and spot size between the gun driving laser and the emitted electron beam on the cathode are almost identical, a sub-picosecond laser pulse length and a sub-millimeter laser spot size were used for the optimization. The electron bunch charge had been fixed to 1 pC which is the minimum required charge for the UEM imaging. However, the electron beam with those characteristics still had strong space charge forces. Therefore, a high gun gradient with a proper phase was selected to make the beam energy high, which could reduce the space charge forces in the gun region. After the RF gun, one solenoid was used to compensate the transverse beam emittance against the the transverse space charge force. The strength and position of the solenoid were chosen to obtain the required beam size and divergence at the sample. Since the optimized beam energy is higher than 3 MeV in this optimization, β is close to 1. Therefore, the velocity

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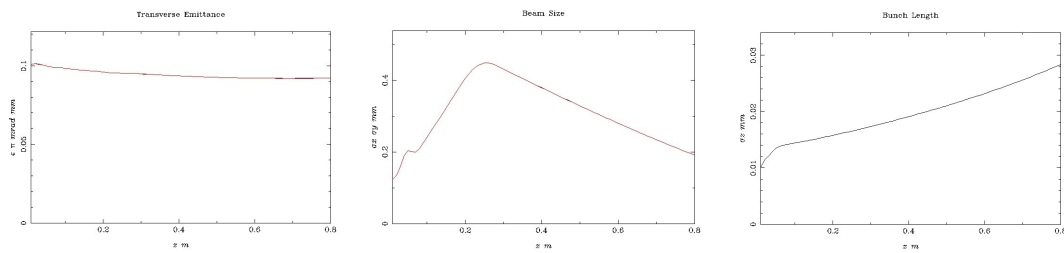

Figure 3: Optimized beam parameters along the beam line; normalized transverse emittance, rms beam size, and rms bunch length.

bunching is not effective. In this condition, the bunch length at the sample is longer as the drift space is longer. Taking this into account, we optimized the total length from the photo-cathode down to the sample to be 0.8 m. The final optimized parameters of RF gun components are summarized in Table 2. The normalized transverse emittance, rms beam size, and rms bunch length along those optimized beamline are shown in Fig. 3. At the sample, the finally optimized normalized transverse rms emittance and longitudinal rms bunch length are 92 nm and 95 fs, respectively as shown in Fig. 4 and summarized in Table 3.

Table 2: Optimized Parameters of Machine Components

Parameter	**Value**	**Unit**
laser rms spot size	120	μm
laser pulse length	10	fs
electron bunch charge	1	pC
laser longitudinal profile	Gaussian	·
laser transverse profile	radial uniform	·
rms thermal emittance	87	nm
strength of solenoid	0.27	T

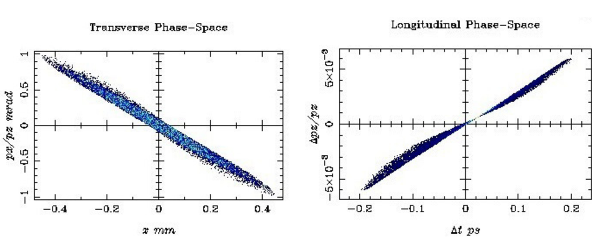

Figure 4: Transverse and longitudinal beam phase spaces at the sample.

SUMMARY

For a UEM facility, we have optimized beam parameters with a laser-driven photo-emission S-band RF gun. To obtain a direct atomic movie at high spatial-temporal resolutions, we have been performing beam dynamics simulations under various conditions with ASTRA code. To control the transverse beam size and to compensate the transverse emittance, a solenoid magnet is inserted at 23.5 cm downstream from the cathode. The optimized beam parameters so far are summarized in Table 3. To improve the beam parameters such as beam divergence, bunch length, and energy spread further, new optimizations with the flat-top longitudinal laser profile and a lower beam energy (3 MeV) for the effective velocity bunching are on going now.

Table 3: Optimized ASTRA Results

Parameter	**Value**	**Unit**
average kinetic energy	4.47	MeV
rms bunch length σ_z	95	fs
normalized transverse emittance ϵ_n	92	nm
rms beam size σ_x and σ_y	191	μm
rms divergence $\sigma_{x'}$ and $\sigma_{y'}$	413	μrad
rms relative energy spread $\Delta E/E$	2.71×10^{-3}	·
total length from cathode to sample	0.8	m

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