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OPTIMIZATION OF BEAM PARAMETERS FOR UEM WITH PHOTO-EMISSION S-BAND RF GUN AND ALPHA MAGNET

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Abstract

Ultrafast Electron Microscopy (UEM) is a powerful tool to observe ultrafast dynamical processes in sample materials at the atomic level. By collaborating with KRISS and GIST, the future accelerator R&D team at KAERI has been developing a UEM facility based on a photo-emission S-band (= 2856 MHz) RF gun. Recently, we have added an alpha magnet in the beamline layout of the UEM to improve beam qualities such as emittance, divergence, energy spread, and bunch length. To achieve high spatial and time resolutions, we have been optimizing those beam parameters and other machine parameters by performing numerous ASTRA and ELEGANT code simulations. In this paper, we describe our ASTRA and ELEGANT code optimizations to obtain high-quality beam parameters for the UEM facility with a photo-emission S-band RF gun and an alpha magnet.

INTRODUCTION

UEM is a powerful tool to visualize atomic or molecular dynamic processes at sample materials [1]. To visualize the atomic bond breaking or making, the spatial and temporal resolutions of sub-angstrom and femtoseconds are required. The spatial and temporal resolutions strongly depend on the electron beam parameters. To achieve the higher spatial and temporal resolutions, the beam parameters such as the transverse beam emittance, beam size, and divergence should be smaller, and the bunch length should be shorter while keeping a higher bunch charge [2]. However, the higher bunch charge makes the space charge force stronger, which can deteriorate the beam quality. Therefore, it is important to optimize those beam parameters by performing beam dynamics simulations under various conditions. Recently, Osaka University has developed a MeV UEM with a photoemission S-band RF gun. By obtaining a bunch length of about 100 fs (rms), they have achieved the temporal resolution of about 170 fs (rms) better than conventional UEMs with a DC gun [3]. The future accelerator R&D team at KAERI has also been studying to develop a MeV UEM to obtain the bunch length shorter than 100 fs (rms). To do so, we have recently added an alpha-magnet to compress the bunch length further. In this paper, we describe our design concepts and beam dynamics simulation results of the MeV UEM with a photoemission S-band RF gun and an alpha-magnet.

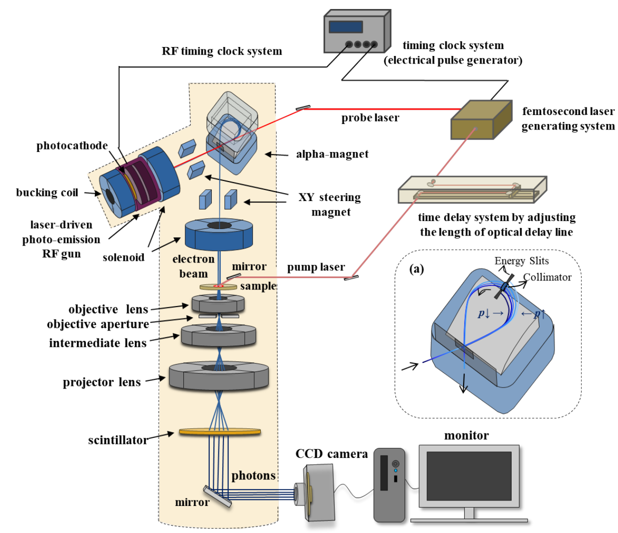

Figure 1: A schematic of the UEM with an alpha-magnet.

REQUIRED BEAM PARAMETERS

Generally, a conventional UEM consists of an electron gun, a beam transport system, a laser system, a sample, and an imaging system. Among them, beam qualities are mainly determined by the electron gun and beam transport system. To determine the beamline component and its lattice, the requirements of the beam parameters, summarized in Table 1, have been investigated as follows.

- The atomic bond breaking and making occur at femtoseconds time domain. Therefore, a femtosecond long bunch length is required for a high temporal resolution at the atomic level.
- If electron beam is accelerated up to 3 MeV, the electron speed is close to that of light, and de Broglie wavelength of electron beam becomes shorter than 0.01 angstrom. For a high spatial resolution, a small transverse beam emittance of 100 nm is chosen [4].
- Considering the number of pixel sensors (1000×1000) of the imaging system, at least 10^6 electrons are required to obtain bright images. Therefore, a single bunch charge should be much higher than 0.16 pC at the sample.

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- To avoid the chromatic aberration, the relative rms energy spread should be near 1×10^{-4}.

Table 1: Required Beam Parameters for UEM

Parameter	Value	Unit
average kinetic energy	≤ 3	MeV
single bunch charge	$\gg 0.16$	pC
rms bunch length σ_z	≤ 100	fs
rms norm. transverse emittance ε_n	≤ 100	nm
rms beam size σ_x and σ_y	≤ 30	μm
rms divergence $\sigma_{x'}$ and $\sigma_{y'}$	≤ 1	mrad
rms relative energy spread $\Delta E/E$	$\leq 10^{-4}$	·
total length from cathode to sample	≤ 1.5	m

DESIGN CONCEPT

The UEM layout includes a photoemission S-band (= 2856 MHz) RF gun designed by Mr. Pikad Buaphad at KAERI. This RF gun can quickly increase a beam energy up to over 3 MeV, which can reduce the space charge force effectively [5]. Downstream the RF gun, the gun solenoid is located as close to the exit of the RF gun. That solenoid is used to compensate emittance growth due to the transverse space charge force. Although we can use the velocity bunching technique to compress the bunch length, it requires a negative energy chirp where the beam energy of the tail part is higher than that of the head part. However, with the S-band RF frequency and femtosecond bunch length, the change in acceleration energy is too small to use the compression technique. Therefore, we recently added an alpha-magnet as a bunch compressor for the electron beam with a positive chirp. An alpha-magnet is an electromagnet designed as a half of a quadrupole magnet. This can effectively compress the electron bunch with a positive energy chirp where the beam energy of the head part is higher than that of the tail part. The beam dynamics in the magnet follows the magnet rigidity rule, which is given by

$$p = qB\rho. \tag{1}$$

Here, p is the momentum of an electron, q is the charge of an electron, B is a magnetic field, and ρ is a radius along a design orbit. According to this formula, the bunch length is compressed by moving the head and tail parts of the electron bunch toward the center part along the beam path of the alpha-magnet as shown in Fig. 1(a). Moreover, the beam quality such as energy spread, beam size, and transverse beam emittance can be improved by removing the non-localized part of the electron beam if we insert energy slits and collimators into the alpha-magnet.

BEAM PARAMETER OPTIMIZATION

To perform beam dynamics simulations for the optimization, we have used ASTRA and ELEGANT codes [6, 7]. The machine parameters of the RF gun and main solenoid have been optimized with ASTRA simulations, and those of alpha-magnet have been optimized with ELEGANT simulations as summarized in Table 2. Generally, the beam brightness is given by

$$B_p = (\beta\gamma)^2 \frac{Q}{\varepsilon_n^2 \sigma_z}. \tag{2}$$

Here, $\beta = v/c$, where v is the speed of electron beam, c is the speed of light, γ is the Lorentz factor corresponding to the normalized relativistic energy, Q is the bunch charge, ε_n is the rms normalized transverse beam emittance, and σ_z is the rms bunch length. According to this formula, we need higher bunch charge for a higher beam brightness, but the energy slits and collimators in the alpha-magnet may inevitably reduce the bunch length during the collimation. Although the bunch charge is reduced, the beam brightness can be improved by reducing the normalized transverse beam emittance. A low normalized transverse beam emittance can be obtained with a smaller laser spot, which can improve the thermal emittance [8]. We chose a small laser spot size of 50 μm.

Table 2: Optimized Machine Parameters

Parameter	Value	Unit
rms laser spot size	50	μm
FWHM laser pulse length	30	fs
electron bunch charge	1	pC
laser longitudinal profile	flat-top	·
laser transverse profile	radial uniform	·
rms thermal emittance	36	nm
solenoid center location	0.16	m
maximum solenoid field value	0.267	T
alpha-magnet entrance location	0.6	m
gradient in the alpha-magnet	31	T/m

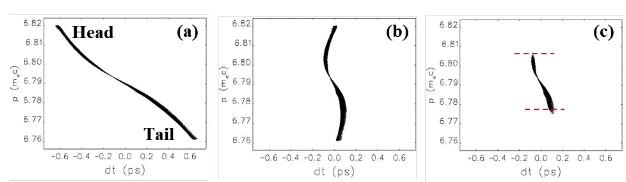

Figure 2: Longitudinal phase spaces; (a) σ_z = 317 fs (rms) at the entrance of the alpha-magnet; (b) σ_z = 56 fs (rms) at the exit of the alpha-magnet without energy slits; (c) σ_z = 47 fs (rms) at the exit of the alpha-magnet with energy slits.

RESULTS AND FUTURE PLANS

We have optimized the beam parameters at the exit of the alpha-magnet with energy slits as summarized in Table 3. The design goal for the rms bunch length has been achieved with the magnet as shown in Fig. 2. However, the design goal for the transverse phase spaces have not been achieved yet, and the horizontal and vertical phase spaces are different

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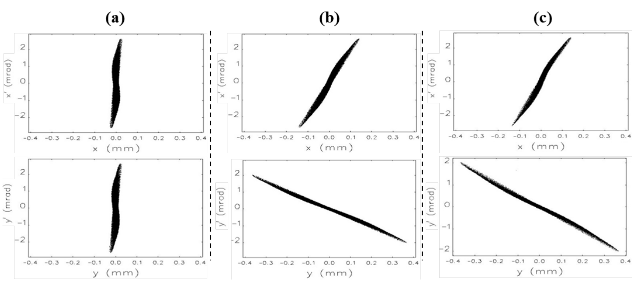

Figure 3: Transverse phase spaces; (a) ε_{nx} = 50 nm, ε_{ny} = 50 nm at the entrance of the alpha-magnetat; (b) ε_{nx} = 50 nm, ε_{ny} = 50 nm at the exit of the alpha-magnet without energy slits; (c) ε_{nx} = 55 nm, ε_{ny} = 59 nm at the exit of the alpha-magnet with energy slits.

Table 3: Optimized Beam Parameters

Parameter	Value	Unit
average kinetic energy	3	MeV
single bunch charge	0.54	pC
rms bunch length σ_z	47	fs
rms normalized transverse emittance ε_{nx} and ε_{ny}	55, 59	nm
rms beam size σ_x and σ_y	45, 150	μm
rms divergence $\sigma_{x'}$ and $\sigma_{y'}$	0.99, 0.76	mrad
rms relative energy spread $\Delta E/E$	8.9×10^{-4}	·
total path length of the beam from cathode to sample	0.7	m

from each other at the exit of the magnet as shown in Fig. 3. To meet the design goal for the transverse beam property, the optimization for the collimation and transverse beam emittance compensation are ongoing now. To improve the beam quality further, we are planning to design another layout with a single-cell RF cavity instead of the alpha-magnet. We expect to be able to apply the velocity bunching for the bunch compression by flipping the chirp without degrading the transverse beam property with the design concept for that layout as shown in Fig. 4. [9].

SUMMARY

In this study, we have identified the possibility of the bunch compression and energy collimation by using an alpha-magnet with energy slits. To optimize the space-charge-dominated electron beams through the UEM with alpha-magnet, we have performed the beam dynamics simulations with ASTRA and ELEGANT codes. Now, the optimization for the collimation and transverse beam emittance compensation are ongoing. To improve the beam quality

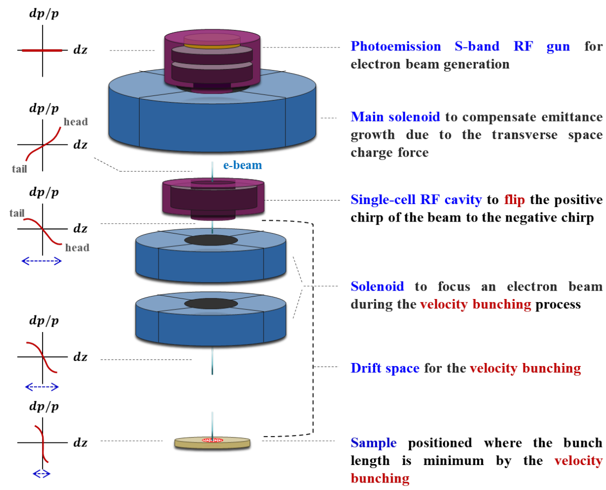

Figure 4: The design concept of bunch compression with a single-cell RF cavity.

further, we are planning to design another layout with a single-cell RF cavity that can change the energy chirp. After comparing the optimization results for different UEM layouts, we will determine our final UEM layout.

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