Optimization of Beam Parameters for UEM with Photoemission S-band RF Gun and Alpha Magnet

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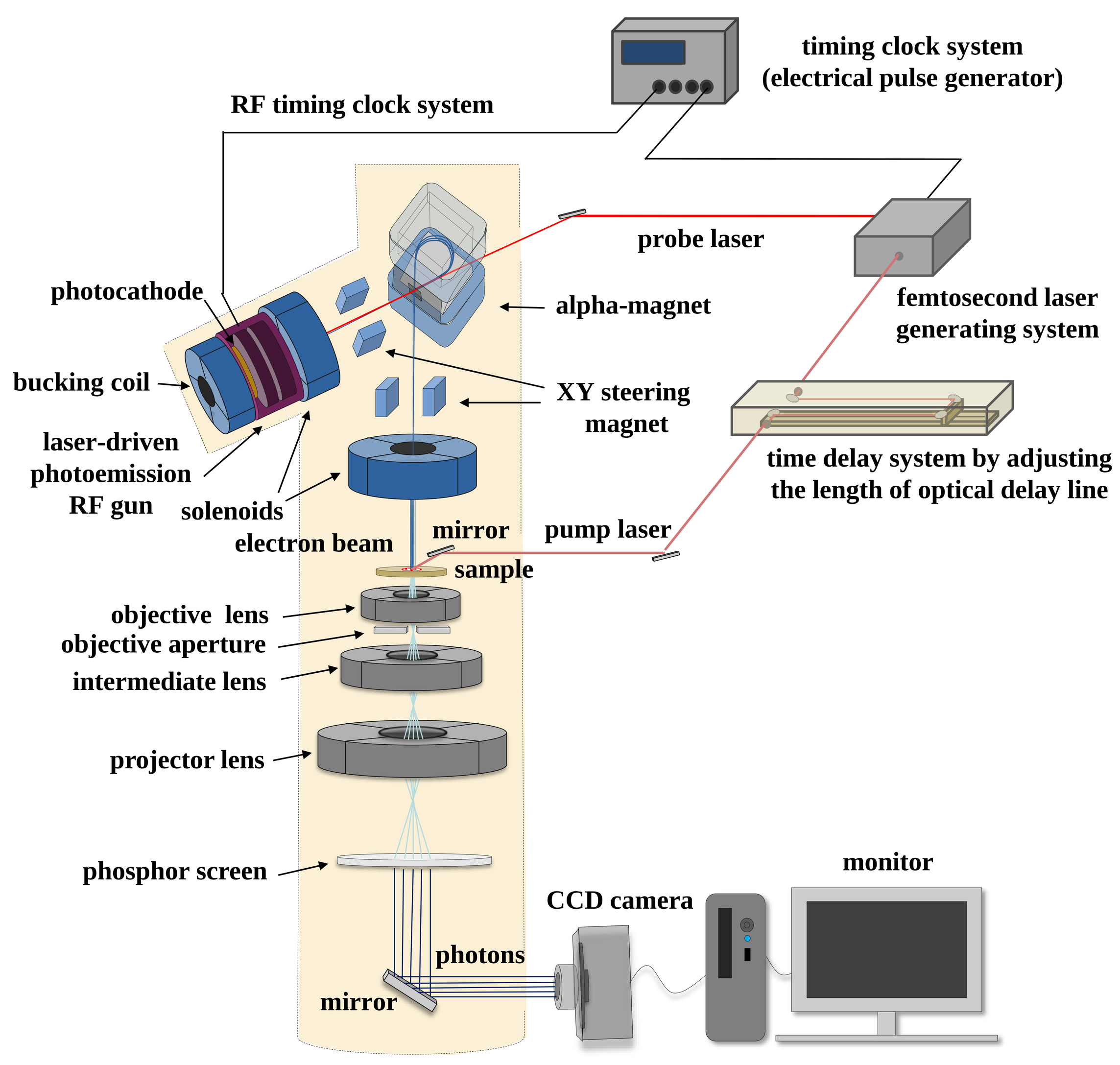
Abstract

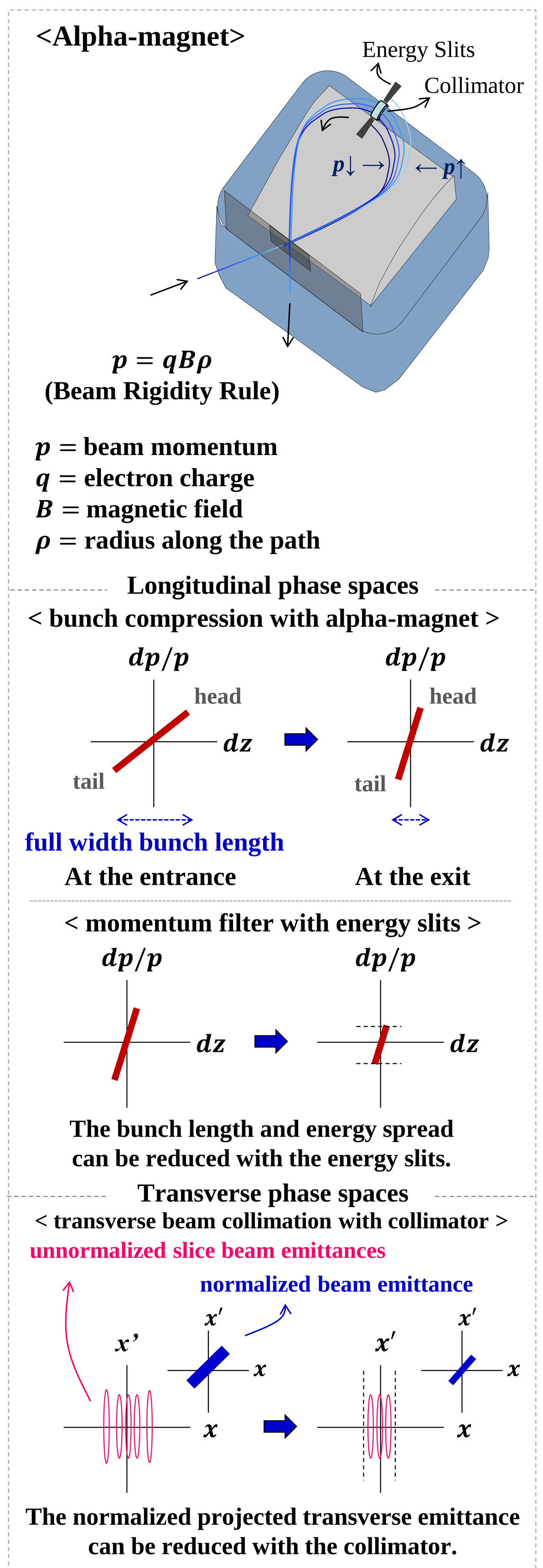
Ultrafast Electron Microscopy (UEM) is a powerful tool to observe ultrafast dynamical processes in sample materials at the atomic level. By collaborating with KRISS and GIST, the future accelerator R&D team at KAERI has been developing a UEM facility based on a photoemission S-band (=2856 MHz) RF gun. 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 photoemission S-band RF gun and an alpha-magnet.

Introduction

UEM is a powerful tool to visualize atomic or molecular dynamic processes at sample materials. 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 transverse beam emittance, beam size, and divergence should be smaller, and the bunch length should be shorter while keeping the high bunch charge. 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, they have achieved better spatial and temporal resolutions than conventional UEMs with a DC gun. 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. In this paper, we describe design concepts and beam dynamics simulation results of the MeV UEM with a photoemission S-band RF gun and an alpha-magnet.

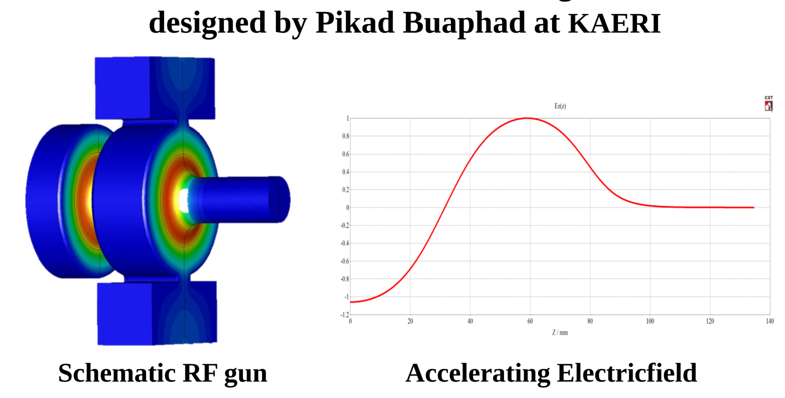
Design Concept





The UEM layout includes a photo-emission 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. 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 forces. 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 have recently added an alpha-magnet as a bunch compressor for the electron beam with a positive chirp.

Photoemission S-band RF gun designed by Pikad Buaphad at KAERI



Schematic RF gun　　Accelerating Electricfield

RF properties	Value	Unit
frequency at π-mode	2856	MHz
$\Delta f = f_\pi - f_0$	15.54	MHz
length of LINAC	0.14	m
unloaded quality factor, Q_0	13837	·
external quality factor, Q_{ext}	12125	·
loaded quality factor, Q_L	6462	·
shunt impedance, R_{sh}	21.3	MΩ/m
external coupling coefficient	1.14	·
filling time of structure	0.72	µs
peak electric field	120	MV/m
RF input power for 5 MeV	10.2	MW

Design Goal

Beam Parameters	Value	Unit
average kinetic energy	3	MeV
single bunch charge	$\gg 0.16$	pC
bunch length (rms)	≤ 100	fs
transverse normalized emittance (rms)	≤ 100	nm
transverse beam size (rms)	≤ 10	μm
transverse divergence (rms)	≤ 1	mrad
relative energy spread (rms)	$\leq 1 \times 10^{-4}$	-
total linac length	$\leq$ 1.5	m

- 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.
- 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 (= 10^6 electrons) at the sample.
- To avoid chromatic aberrations, the relative rms energy spread should be near 1×10^{-4}.

Optimization of Beam Parameters

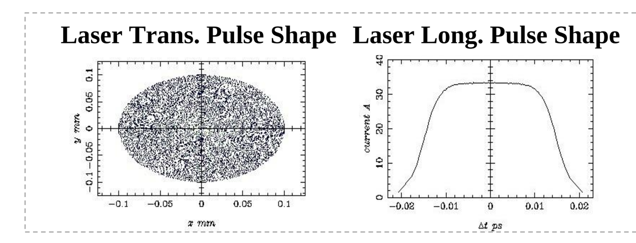
To perform the beam dynamics simulation for the UEM with the alpha-magnet, we have used the ASTRA and ELEGANT codes together.

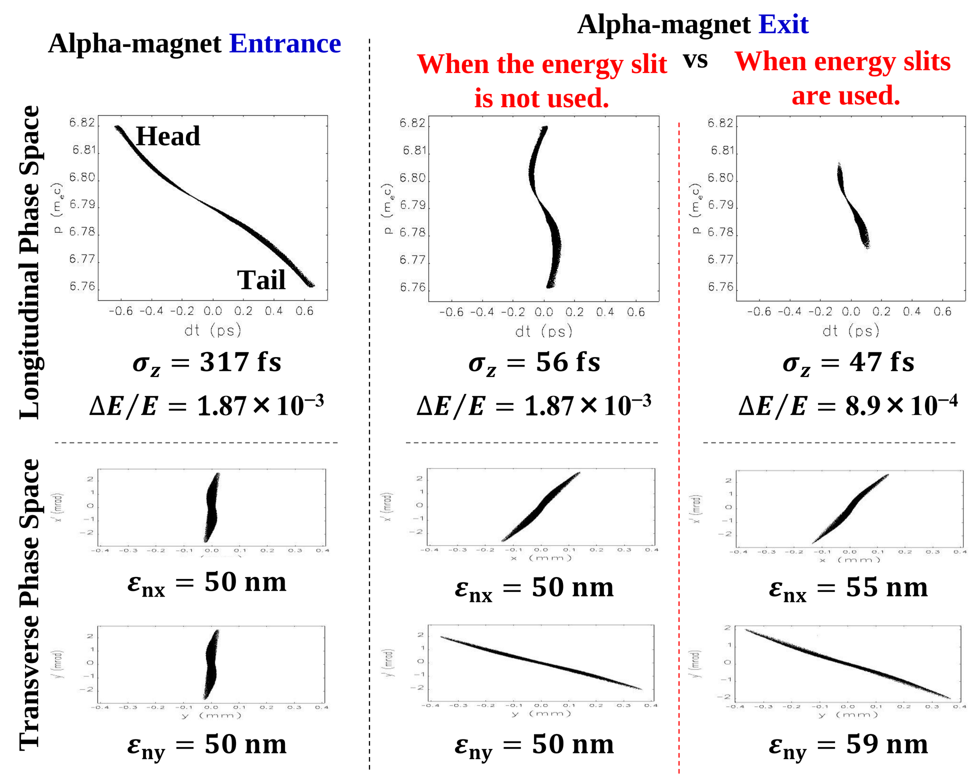
Beam Brightness: $B_p = (\beta\gamma)^2 \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}\sigma_z}$

Here, $\beta = v/c$, where v is the speed of electron beam, and c is the speed of light. γ is the Lorentz factor corresponding to the normalized relativistic energy, Q is the bunch charge, ε_{nx} and ε_{ny} are the rms normalized horizontal and vertical beam emittances respectively, and σ_z is the rms bunch length.

The energy slits and collimators cut off the non-localized part of the electron beam. Then, total bunch charge can be reduced inevitably. The beam brightness can be improved by reducing the normalized transverse beam emittance though the bunch charge is reduced. Generally, the smaller laser spot size can make the longitudinal space charge force stronger due to the 3D space charge effect. A low transverse beam emittance can be obtained because the thermal emittance can be improved with a smaller laser spot. We chose a small laser spot size of 50 μm.

Machine Component	Value	Unit
average kinetic energy	3	MeV
single bunch charge	1	pC
laser spot size (rms)	50	μm
rms thermal emittance	36	nm
laser transverse profile	radial uniform	·
laser pulse length (rms)	30	fs
laser longitudinal profile	flat-top	·
solenoid center position	0.16	m
maximum solenoid field value	0.267	T





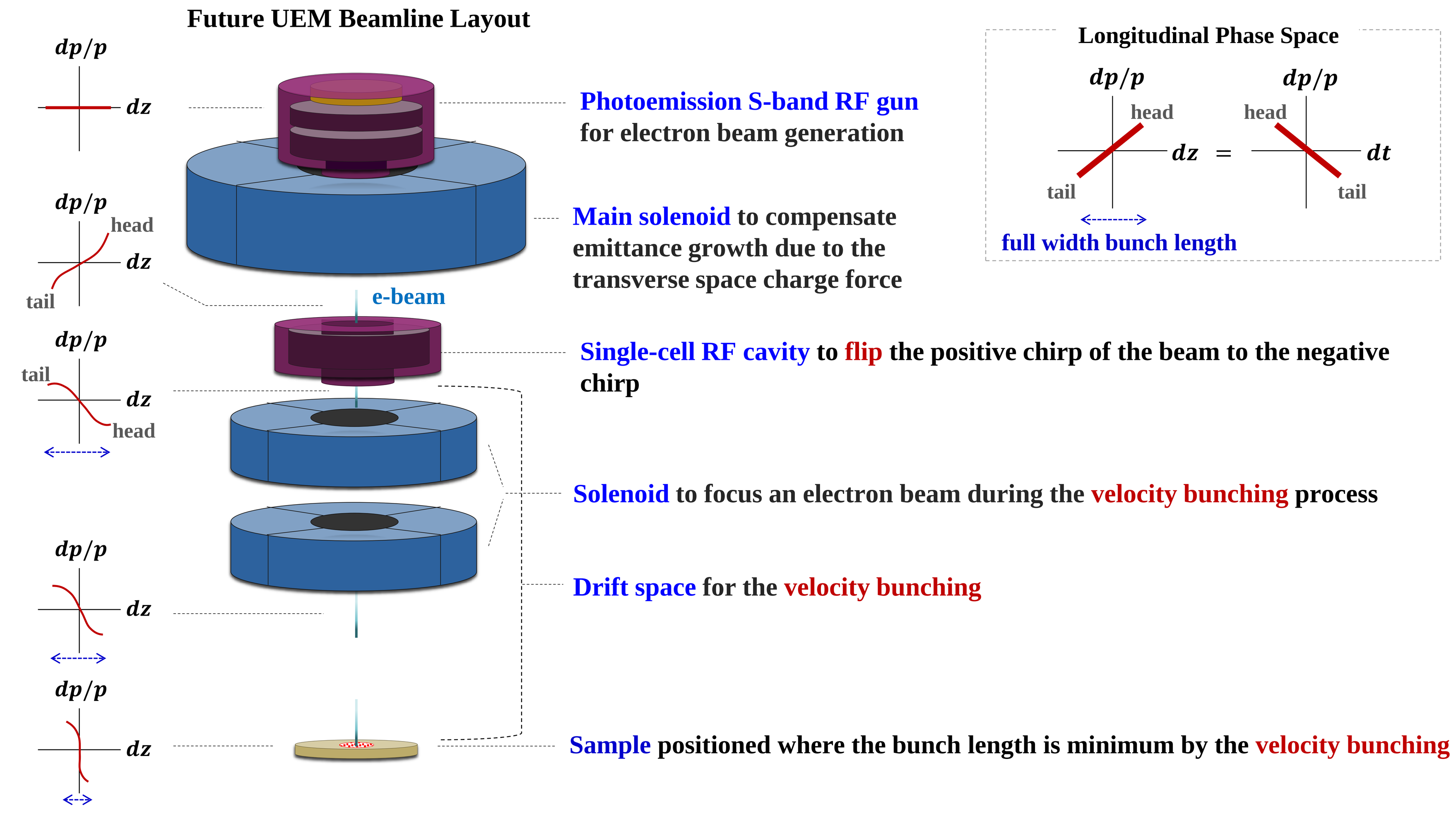
Beam Parameters at the Exit of the Alpha-magnet with the Energy Slits	Value	Unit
average kinetic energy	3	MeV
single bunch charge	0.54	pC
rms bunch length (σ_z)	47	fs
transverse normalized emittance (rms, ε_{nx}, ε_{ny})	X:55 / Y:59	nm
transverse beam size (rms)	X:45 / Y:150	μm
transverse divergence (rms)	X:0.99 / Y:0.76	mrad
energy spread ($\Delta E/E$) (rms)	0.89×10^{-3}	-
alpha-magnet entrance position	0.6	m
gradient in the alpha-magnet	31	T/m
distance from the photocathode to the alpha magnet exit	~ 0.7	m

We have optimized the beam parameters at the exit of the alpha-magnet with energy slits as above. The alpha-magnet was optimized to have the minimum bunch length at the exit of the magnet. When we compare the present simulation result with the design goal, the transverse beam parameters are not satisfied yet. Now, the optimization for the collimation and transverse beam emittance compensation are ongoing to meet the design goal.

Future Plan

We are planning to design another layout with a single-cell RF cavity instead of the alpha-magnet to compress the bunch length. With the single-cell cavity, we can apply the velocity bunching for the bunch compression by flipping the chirp without degrading the transverse beam property so much.

Future UEM Beamline Layout



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 the alpha-magnet, we have performed the beam dynamics simulations with ASTRA and ELEGANT codes. Now, the optimization for the collimation and the compensation of transverse beam emittance are ongoing. To improve the beam quality 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.