BEAM SIMULATIONS OF HIGH BRIGHTNESS PHOTOCATHODE DC GUN AND INJECTOR FOR HIGH REPETITION FEL LIGHT SOURCE

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Abstract

As a next generation FEL light source based on linac, high repetition rate operation to increase average FEL power has been proposed, e.g. LCLS-II project. The injector, which generates high brightness and high average current beam, is one of key components. A photocathode DC gun and superconducting RF cavities, which are developed for ERL light source, can be employed for the high repetition rate injector. For high repetition rate operation of FEL light source, injector simulations were carried out based on ERL injector with demonstrated hardware performance by the cERL beam operation in KEK. The optimization results show that the gun voltage of 500 kV is helpful to achieve low emittance. In addition, to estimate optimum gun voltage and cavity acceleration gradient for the FEL operation, two optimizations with different injector layouts were carried out. The results show that the both different layouts have potential to achieve target emittance for FEL operation. Under the realistic operation condition, the transverse normalized rms emittance of 0.8 mm mrad with the rms bunch length of 3 ps, the bunch charge of 325 pC, and the beam energy of 10 MeV is obtained from the optimizations.

INTRODUCTION

To increase average FEL power, high repetition rate operation of FEL light source based on linac is important for the next generation FELs, e.g. LCLS-II project [1]. In order to achieve the high repetition rate operation, the injector, which generates high brightness and high average current beam, is one of key components. The target emittances of high repetition rate FEL are 0.45 mm mrad and 0.7 mm mrad with the bunch charges of 100 pC and 300 pC, respectively [2]. A photocathode DC gun and superconducting RF cavities, which are developed for ERL light source, can be employed for the high repetition rate injector. The performance of ERL injector has been demonstrated at Cornell University, and 90 % transverse normalized emittance has been reached to 0.51 mm mrad with 77 pC/bunch [3]. In KEK, a high repetition rate and high brightness injector, whose repetition rate is 1.3 GHz, is being operated for compact ERL (cERL), which is a test ERL accelerator [4, 5]. In the beam operation, the hardware performance has been demonstrated. In the cERL operation, although the design gun voltage and the injector acceleration gradient are 500 kV and 15 MV/m, respectively, to keep stable beam operation we reduced them and demonstrated the beam operation with 390 kV and 7 MV/m. Based on the demonstrated performance of the cERL injector, particle tracking simulations and optimizations of it with several hundred pC/bunch for the FEL injector were carried out. In addition, to estimate optimum gun voltage and acceleration gradient of cavity for FEL operation, we carried out two optimizations with different injector layouts.

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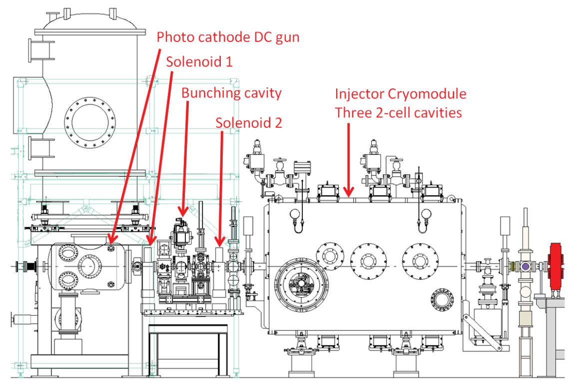

Figure 1: Layout of cERL injector.

Table 1: Center Positions of Injector Elements from Cathode Surface

Element	Original cERL (m)	New layout (m)
SL0	-	0.294
SL1	0.445	0.494
BC	0.809	0.752
SL2	1.218	0.909
SC1	2.221	1.519
SC2	2.781	2.079
SC3	3.341	2.639
SC4	-	4.519
SC5	-	5.079
SC6	-	5.639

PERFORMANCE OF CERL INJECTOR

The cERL injector consists of a photocathode DC gun, two solenoids, a bunching cavity, and three 2-cell superconducting cavities inside an injector cryomodule. Figure 1 shows the layout of the cERL injector. In this paper, SL, BC, SC denote that the solenoid magnet, the bunching cavity, and the 2-cell superconducting cavity, respectively. The element positions of the cERL injector are shown in Table 1. For ERL operation, the target maximum bunch charge is 77 pC, which corresponds to 100 mA average current. The cERL injector layout was optimized for 77 pC operation.

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Photocathode DC Gun

The photocathode DC gun, which was employed for the cERL, was developed by JAEA. The first design of the electrode with the gap of 100 mm is shown in Fig. 2. Before the installation of it to the cERL in KEK, high voltage processing was carried out at JAEA, and generating a 500 keV electron beam with currents up to 1.8 mA was demonstrated [6]. To achieve 500 kV, the design of the electrode was modified, and the gap was expanded to 160 mm to avoid discharge problem [7]. The expanded electrode shape is shown in Fig. 3. Due to the modification, the electric field on the cathode surface with the voltage of 500 kV was reduced from 6.7 MV/m to 5.8 MV/m as shown in Fig. 4. The lowest normalized emittance from a photocathode DC gun depends on the surface electric field on the cathode [3,8]. It is estimated to be

$$\epsilon_n \propto \sqrt{q \cdot \frac{k_B T}{E_{\text{cath}}}}, \quad (1)$$

where q is bunch charge, $k_B T$ is effective transverse energy of photoelectrons, and E_{cath} is electric field on the cathode surface. The relation shows that the electric field on the cathode is important to reduce the emittance. Therefore, the emittance for longer gap layout becomes worse compared with shorter gap layout, even if the gun voltage is same. To generate high brightness electron beam, the surface electric field on the cathode is one of important parameters.

On autumn 2012, the photocathode DC gun was transfered from JAEA to ERL development hall in KEK, and connected to the cERL injector beamline. However, in high voltage processing at KEK, a trouble about a ceramic insulator was found. To avoid serious damage of the ceramic insulator, we decided that to decrease the gun voltage from 500 kV to 390 kV in the beam operation.

In order to reduce the emittance growth caused by space charge effect, not only the gun voltage but also the surface electric field on the cathode are important as shown in Eq. (1). However, the relation of them is not so simple. In order to estimate the effects, we carried out beam simulations with different gaps and different gun voltages. Especially, to estimate the optimum gun voltage and the surface electric field on the cathode for FEL injector, the beam simulations with the bunch charges of 100 pC and 300 pC were carried out.

Injector Cavity

In the injector cryomodule, there are three 2-cell superconducting cavity. The RF frequency is 1.3 GHz. The design maximum acceleration gradient E_{acc} was 15 MV/m, and it was enough to accelerate the beam to 10 MeV. Before the beam operation, high voltage processing of the injector cavity was carried out. In the processing, the acceleration gradient of 8 MV/m was demonstrated in CW operation. Based on the results, we decided that the operation E_{acc} was 7 MV/m, and the injector beam energy was 5 MeV.

From April 2013, we started the beam operation of the injector, and demonstrated stable beam operation with the gun voltage of 390 kV and the acceleration gradient of 7 MV/m [4]. However, to reduce emittance growth caused by space charge effect, higher beam energy at the exit of the injector is required. To increase the beam energy keeping the demonstrated E_{acc} of 8 MV/m, we proposed a new injector layout with two injector cryomodules. The simulations for the new layout, which contains six 2-cell cavities, were carried with the bunch charge of 325 pC.

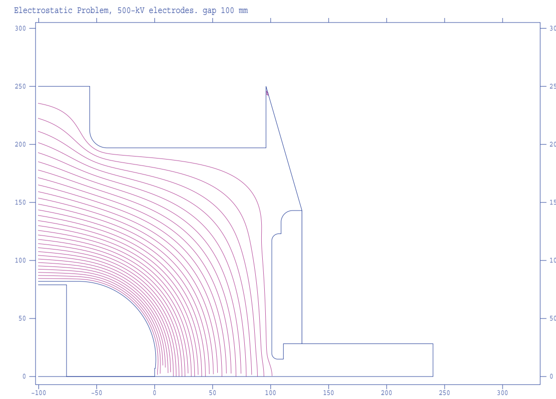

Figure 2: Electrode of a photocathode DC gun with gap of 100 mm. The horizontal and vertical axes are longitudinal and radial directions, respectively.

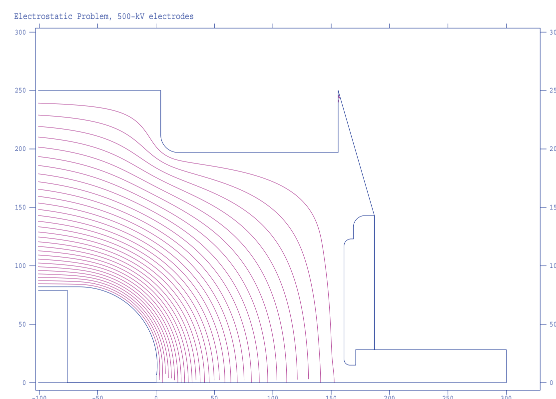

Figure 3: Electrode of a photocathode DC gun with gap of 160 mm.

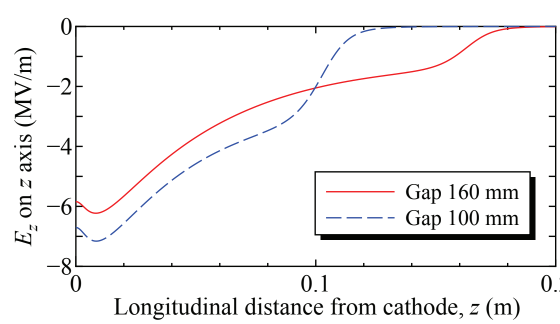

Figure 4: Longitudinal electric field of photocathode DC guns with different gaps.

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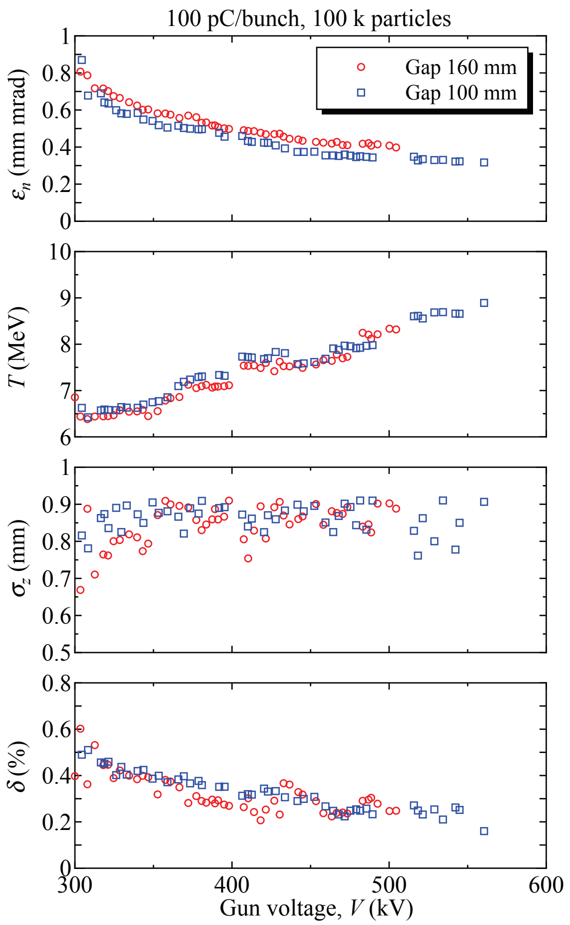

Figure 5: Optimization results with bunch charge of 100 pC for original injector layout.

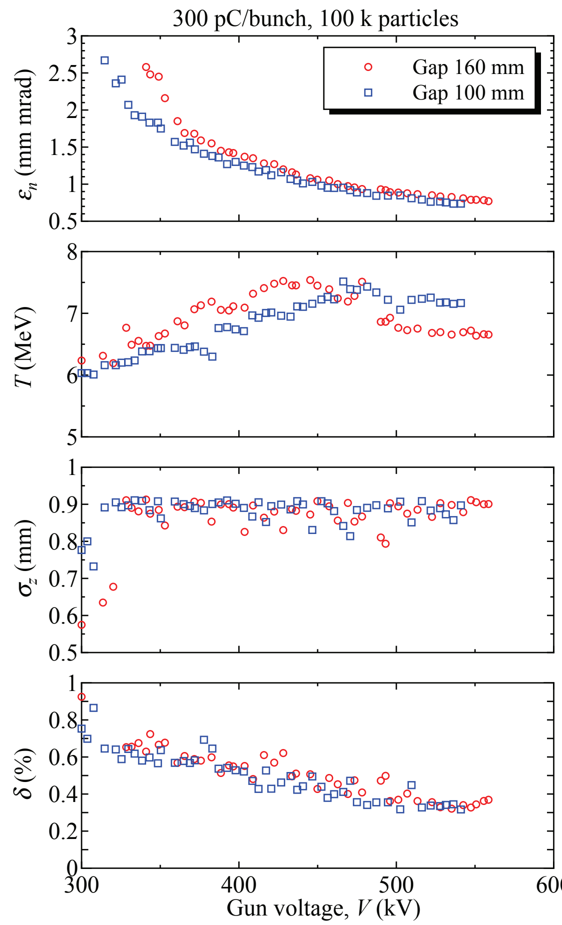

Figure 6: Optimization results with bunch charge of 300 pC for original injector layout.

INJECTOR OPTIMIZATION FOR HIGH BUNCH CHARGE OPERATION

In the simulations, we used General Particle Tracer with 3D mesh space charge routine [9]. As an initial parameter, $k_B T$ of 90 meV was assumed in the simulation. Initial emittance just after a cathode is calculated to be $\epsilon_{nx} = \sigma_x (k_B T/mc^2)^{1/2}$, where σ_x is rms laser spot size. As an initial laser distribution, beer-can shape was assumed. For the transverse direction, the particle distribution is radial uniform distribution described by laser diameter. The longitudinal distribution is flat-top distribution described by laser pulse length. To reproduce the measured beam dynamics of the cERL injector, the model of the photocathode gun was modified [10].

Effect of Gun Voltage for Original Layout

In order to estimate optimum gun voltage and gap of electrode, optimizations of injector parameters were carried out using Multi Objective Genetic Algorithm [11]. The original layout of the cERL injector as shown in Table 1 was used, and the element positions were fixed. The beam parameters were calculated at 6 m from the cathode surface, and we treated space after the exit of SC3 as pure drift space without any magnet. In the optimization, gun voltage and projected normalized rms emittance were minimized. Free parameters are laser diameter, laser pulse length, gun voltage, two solenoid magnetic fields, buncher voltage and phase, and acceleration gradients and phases of SC1, SC2 and SC3. The maximum E_{acc} is 15 MV/m. The definition of cavity phase is the difference from the on-crest acceleration phase. The rms bunch length was limited to be less than 0.9 mm, which corresponds to 3 ps. The bunch charges are 100 pC and 300 pC. The number of macro-particles are 100,000 particles. In the optimizations, two different gaps of gun electrode, 100 mm and 160 mm, were used to estimate the effect of the surface electric field of the cathode.

For the bunch charge of 100 pC, the optimized results are shown in Fig. 5. The projected normalized emittance is 0.4 mm mrad for the gun voltage of 500 kV. The results shows that the cERL injector with E_{acc} of 15 MV/m can achieve the target emittance of 0.45 mm mrad for FEL operation. As shown in Fig. 5, the gap of 100 mm gives lower emittance comparing with the gap of 160 mm. However, the effect of the gap on the emittance is less than 0.1 mm mrad.

For the bunch charge of 300 pC, the optimized results are shown in Fig. 6. For the gun voltage of 500 kV, the projected

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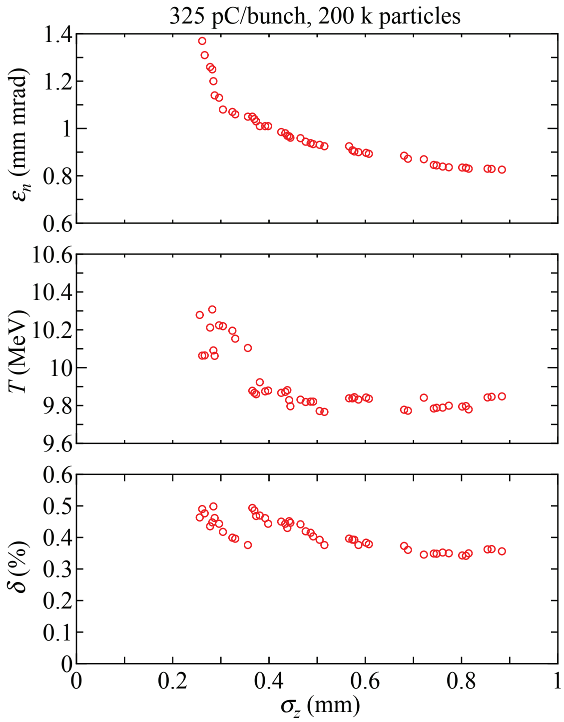

Figure 7: Optimization results with bunch charge of 325 pC for new layout with two injector cryomodules.

normalized emittance is 0.8 mm mrad. Compared with the results for 100 pC, the difference of emittance caused by the gap is smaller. The minimum emittance of 0.8 mm mrad is close to the target emittance of 0.7 mm mrad for FEL operation. The results show that higher gun voltage is better to achieve the target emittance.

Effect of Cavity Acceleration Field for New Layout

In order to estimate the effect of E_{acc}, we optimized a new layout of injector beam line with maximum E_{acc} of 8 MV/m, which is demonstrated value. The new layout contains two cryomodules, and total number of 2-cell cavities is six. In order to compensate emittance growth caused by space charge effect, we added a solenoid magnet, SL0, between the gun and the 1st solenoid, SL1. The beam parameters were calculated at 8 m from the cathode surface. In the optimization, projected normalized rms emittance and rms bunch length were minimized. Free parameters are laser diameter, laser pulse length, three solenoid magnetic fields, buncher voltage and phase, and acceleration gradients and phases of SC1, SC2 and SC3. The maximum E_{acc} is 8 MV/m. The gun voltage and the gap of electrode are fixed to be 500 kV and 160 mm, respectively. The bunch charge is 325 pC. The number of macro-particles are 200,000 particles.

The optimized results are shown in Fig. 7. For the bunch length of 0.9 mm, the projected normalized emittance is 0.8 mm mrad. The optimized injector parameters and element positions are shown in Table 2 and Table 1, respectively. The results show that the new layout with two cryomodules and the maximum E_{acc} of 8 MV/m can also achieve

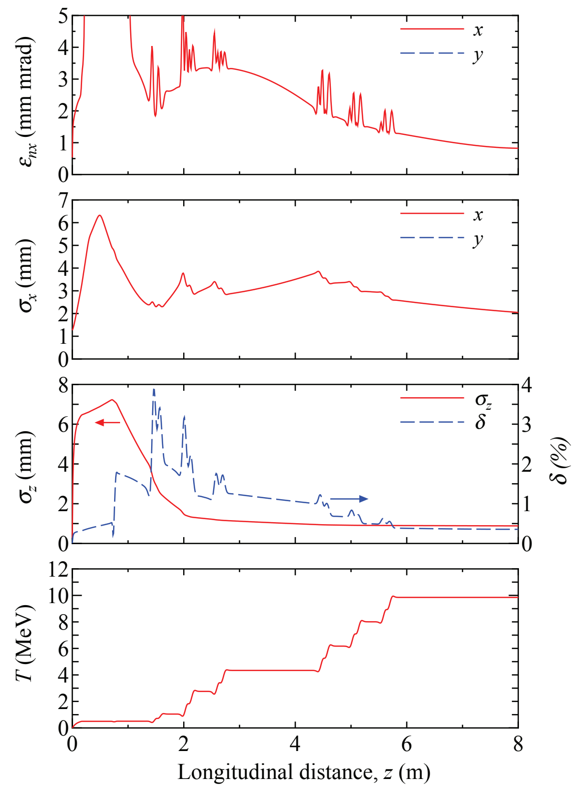

Figure 8: Time evolutions of beam parameters with optimized parameter for new injector layout. The bunch charge is 325 pC.

0.8 mm mrad. This value is close to the target emittance of 0.7 mm mrad.

The time evolutions of the beam parameters with the optimized parameters in Table 2 are shown in Fig 8. The emittance reduced to be 0.8 mm mrad at 8 m from the cathode surface. The rms beam size is 2 mm after the injector cryomodules. It is slightly lager to connect the beam envelope to downstream the injector. In the next step, to reduce the beam size and the envelope matching is required.

The both optimizations for the original and new injector layouts show that an ERL injector, which consists of a photocathode DC gun and superconducting cavities, has potential to achieve the low emittance beam, which is required for FEL operation.

SUMMARY

For high repetition rate operation of FEL light source based on linac, injector simulations were carried out based on ERL injector, which consists of a photocathode DC gun and superconducting RF cavities. The performance of the injector components were already demonstrated on the cERL beam operation in KEK. Based on the demonstrated hardware performance, we optimized the injector parameters to achieve the requirement for high repetition rate FEL, and investigated the effects of gun voltage and acceleration gradient of injector cavity using the original injector layout and

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Table 2: Optimized Parameters for New Injector Layout with 325 pC

Parameter	Value
Laser diameter	5.06 mm
Laser pulse length (FWHM)	73.4 ps
Gun voltage	500 kV
Magnetic field of SL0	0.0356 T
Magnetic field of SL1	0.0299 T
Magnetic field of SL2	0.0109 T
Buncher voltage	115 kV
E_{acc} of SC1	2.98 MV/m
E_{acc} of SC2	7.98 MV/m
E_{acc} of SC3	7.97 MV/m
E_{acc} of SC4-6	8.00 MV/m
Buncher phase	-89.0 degree
Phase of SC1	-25.8 degree
Phase of SC2	-14.4 degree
Phase of SC3	-29.7 degree
Phases of SC4-6	0 degree

new layout with two injector cryomodules. The optimization results show that the gun voltage of 500 kV is helpful to achieve low emittance, and the both original and new layouts have potential to achieve target emittance for FEL operation.

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