OPTICS DESIGN OF THE COMPACT ERL INJECTOR FOR 60 pC BUNCH CHARGE OPERATION

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Abstract

EUV-FEL light source based on ERL has been designed at KEK for EUV lithography light source. The advantage of ERL is to accelerate high average current beam due to CW operation, and it is possible to drive high average power FEL. To generate the target EUV-FEL power, which is 10 kW, the bunch charge of 60 pC, the beam energy of 10.5 MeV and the bunch length of 1 ps are required at the end of the EUV-FEL injector. In order to demonstrate the target beam performance for the EUV-FEL accelerator, a high charge beam test was carried out at the cERL in KEK. We designed a new optics of the cERL injector prior to the high charge beam operation. To calculate beam dynamics more accurately, accelerator models corrected according to the condition of the actual cERL injector is used for the optics design. From results of the optics design that minimized the emittance and bunch length using the corrected accelerator models, the emittance and bunch length at the end of injector are 0.8 mm-mrad and 3.4 ps. Furthermore, based on the design optics, we carried out high bunch charge beam operation.

INTRODUCTION

Free-electron laser (FEL) light sources that generate light having a wavelength in the extreme ultraviolet (EUV) range are expected as next generation lithography light sources. Since the EUV-FEL is a single-pass FEL, a high peak current beam is required to obtain the enough FEL gain. The energy recovery linac (ERL) can accelerate the high peak and high average current beam due to CW operation. EUV-FEL light source based on ERL has been designed at KEK [1]. The required injection beam performance for the ERL-based EUV-FEL light source is the bunch charge of 60 pC, the beam energy of 10.5 MeV, and the bunch length of 1.0 ps. Target values of the normalized emittance and energy spread at the exit of the EUV-FEL injector are 0.6 mm-mrad and 0.2%. Since the bunch length, emittance and energy spread are conflicting relationships in the low energy region due to space charge effect, the optics of the EUV-FEL injector was designed by the multiobjective optimization method (MOGA; multiobjective genetic algorithm) to minimize them.

In order to demonstrate the target beam performance for the EUV-FEL, the high charge beam test was carried out at the compact ERL (cERL) in March 2017. Here, the cERL is a compact ERL test facility in KEK. The schematic view of cERL injector is shown in Fig. 1. The injector has a photocathode DC gun, two solenoids, a normal conducting

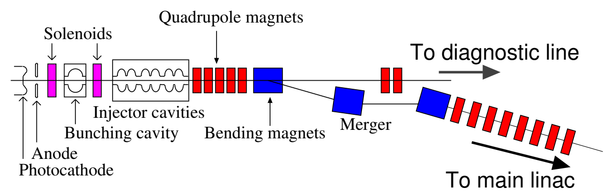

Figure 1: Schematic view of cERL injector. The injector consists of a photocathode DC gun, two solenoids, a normal conducting buncher cavity, three 2-cell superconducting cavities. The beam is injected into the main linac and recirculation loop through the merger. The injector beam can be transported to the beam diagnostic line to measure the beam performance.

buncher cavity and three 2-cell superconducting cavities. The maximum beam energy of the cERL injector is limited to 6 MeV. For the high charge beam operation, we designed a new optics of the cERL injector. First, accelerator models used for the optics design were corrected according to the actual cERL injector condition in order to calculate beam dynamics more accurately. After the model correction, using the corrected models, a new optics was designed by MOGA in order to minimize both emittance and bunch length. This paper presents results of model corrections and optics design of the cERL injector for high charge beam operation.

MODEL CORRECTIONS

In order to make the optics design more accurately, accelerator models used for the particle tracking were corrected to reproduce the measurement results. First, we measured the gun focusing force, the temporal structure of the photocathode excitation laser, and the voltages of injector cavities. After the measurements, the accelerator models were corrected based on the measurement results.

Gun Focusing Force

A photocathode DC electron gun, whose gap between the cathode and anode is 160 mm, is used in the cERL injector. The focusing (divergence) force acts on the beam according to the electrode shape of the electron gun. The cathode electrode has a margin to connect the cathode pack. When the cathode pack is reloaded, the recess between the cathode electrode and the cathode pack surface, which affects the electric field around the cathode, may change due to manufacturing accuracy of individual cathode pack. The distorted electric field also affects the gun focusing effect around the cathode surface, and the effect is expanded in the

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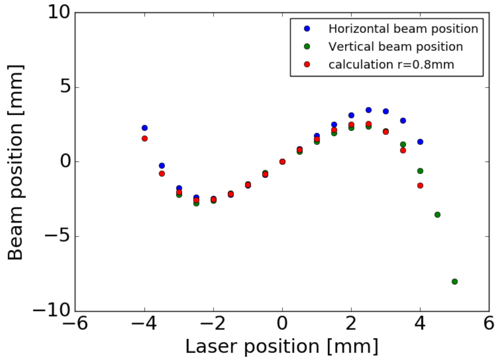

Figure 2: Results of gun focusing force measurements and model correction. The horizontal axis is the deviation on the laser position on the cathode surface from the cathode center.

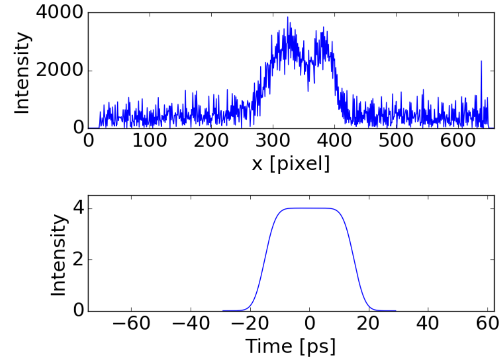

Figure 3: Measured temporal structure projected by the first injector cavity to horizontal direction (top) and the corrected laser model (bottom). The measured FWHM is 148 pixel. Since the calibration coefficient is 2.14/10.3 [ps/pixel], the FWHM of temporal structure corresponds to 30.8 ps. The temporal structure of the corrected laser model is flat-top with FWHM length of 31 ps.

downstream beam line. In order to correct the recess of the gun model, we measured the gun focusing force.

The measurement method of the gun focusing force is explained in [2]. The beam position on a screen, which is located at 1.02 m from the cathode surface, was measured, when the laser irradiation position on the cathode was changed. The beam position on the screen is affected by the electric field around the cathode surface. The measured result is shown in Fig. 2. The laser irradiation position was shifted little by little in the horizontal or vertical directions from the cathode center. When the recess of the gun model was corrected to 0.8 mm, the measurement result was reproduced by particle tracking simulation by GPT (General Particle Tracer) [3]. Therefore, the electron gun model with the recess corrected to 0.8 mm is used for optics design. The difference of the measured focusing forces between horizontal and vertical directions becomes large, when the deviation of the laser irradiation position from the cathode center is larger than 1 mm, as shown Fig. 2. This suggests that the cathode pack may be tilted. However, around the cathode center, the asymmetry between the horizontal and vertical directions is small, and the model and measurements are in good agreement. Therefore, we irradiated the excitation laser on the center of the cathode in this beam operation.

Temporal Structure of the Laser

In the photocathode electron gun, the initial temporal structure of the generated bunch is equal to the temporal structure of the excitation laser. Therefore, it is very important to measure the temporal structure of the laser. For low bunch charge operation, we used a temporal structure of 3 ps RMS Gaussian distribution. In this beam operation, the temporal structure of the laser is extended by the pulse stacking in order to decrease the charge density and space charge effect. In order to extend the laser length, we used eight stacked Gaussian pulses to generate flat-top temporal distribution. Furthermore, the bunch length is an important parameter to calculate space charge effect and minimize the bunch length. Before the high bunch charge operation, we measured the temporal structure of the initial bunch for low bunch charge, and fed back the result to the laser model for the particle tracking simulation.

To measure the temporal distribution of the bunch, we used the first 2-cell injector cavity as the deflector cavity [4]. A beam having a transverse position offset with respect to the center axis of the cavity is kicked transversely by the radial electric field of the cavity. Since the amplitude of the radial electric field depends on the acceleration phase, which corresponds to the time delay inside the bunch, the temporal structure of the bunch is projected to the transverse direction.

In order to calculate the bunch length from the measured transverse beam size, we measured a calibration coefficient. To measure the coefficient, we measured the response of the beam position on the screen by changing the phase of the injector cavity using a single Gaussian pulse. The measured calibration coefficient is 10.3 pixel per degree of phase. Since the cavity frequency is 1.3 GHz, the calibration coefficient is 2.14/10.3 [ps/pixel].

The measured projected temporal structure for the horizontal direction is shown in Fig. 3. The FWHM of the measured horizontal beam size is 148 pixel, and this corresponds to 30.8 ps. We also projected the temporal structure for the vertical direction. The measured temporal structure is 31.4 ps FWHM. From these measurements, the average FWHM of the temporal structure is 31 ps. Therefore, we make a flat-top laser model with temporal structure 31 ps FWHM, as shown Fig. 3, and use it for the design optics.

Voltages of Cavities

In order to accurately determine the voltage of each cavity, the cavity was turned on one by one from the upstream, and the beam energy accelerated in each cavity was mea-

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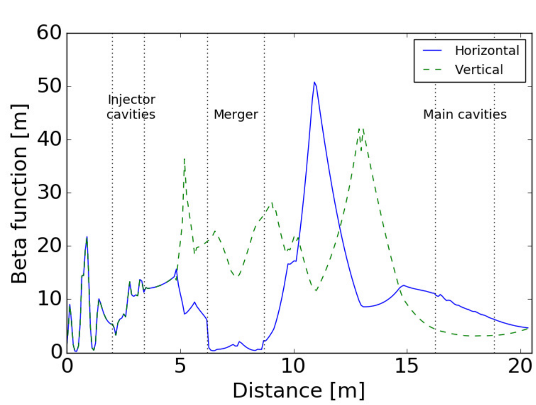

Figure 4: The designed beta functions.

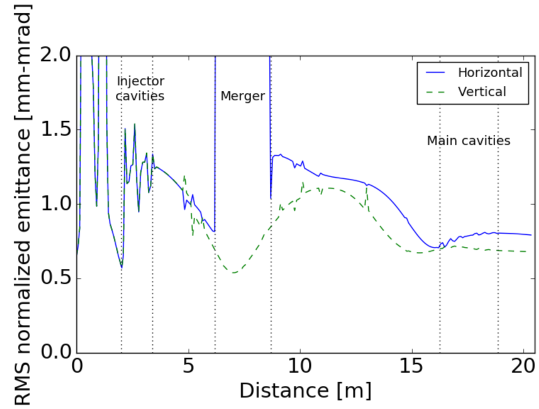

Figure 6: The designed RMS normalized emittances.

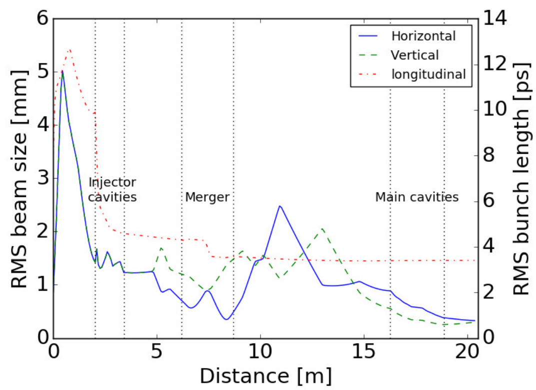

Figure 5: The designed RMS beam sizes and bunch length.

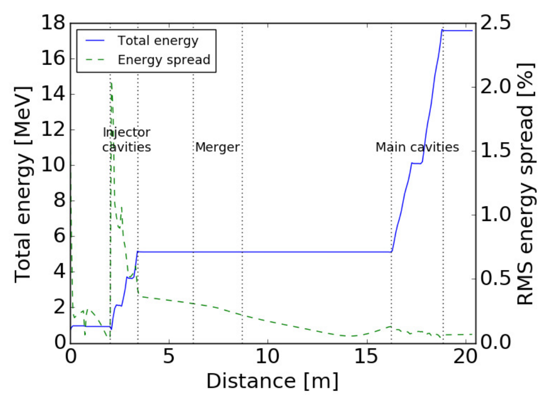

Figure 7: The designed Total energy and RMS energy spread.

sured using first bending magnet in the merger. The beam energy after passing through each cavity is 2.11, 3.64 and 5.12 MeV. Hence, the acceleration gradient of each cavity in the model is corrected to be 6.22, 6.8 and 6.5 MV/m from the upstream.

OPTICS DESIGN

Based on the above corrected accelerator models, we designed new optics of the cERL injector for high bunch charge operation. To minimize the emittance and bunch length, MOGA was used for the optics design. Before the beam operation, we designed the optics for 60 pC. However, the maximum bunch charge was limited to 40 pC due to the limitation of the maximum laser power. Therefore, we redesigned the optics for the bunch charge of 40 pC.

Figure 4-7 shows the time evolution of the beam parameters during transport from the gun to the exit of the main linac. At the exit of the linac, the optimized RMS normalized horizontal and vertical emittances are 0.8 mm-mrad and 0.7 mm-mrad, respectively. The optimized RMS bunch length is 3.4 ps. RMS horizontal and vertical beam size is 0.3 mm, and RMS energy spread is 0.07%. The optical functions are $\beta_x = 4.6$ m, $\beta_y = 4.5$ m, $\alpha_x = 0.29$, $\alpha_y = -0.75$, which are in the ranges where it is possible to match with the optics of the recirculation loop taking energy recovery into account. Based on the design optics, we carried out the high charge beam operation with the bunch charge of 40 pC [5].

SUMMARY

The gun model, the temporal structure of the excitation laser and the voltages of injector cavities were corrected from the actual beam response to make the optics design more accurately. Using the corrected models, we optimized the optics of the cERL injector to minimize the emittance and bunch length for the 40 pC bunch charge operation. The optimized emittance and bunch length at the exit of main linac are 0.8 mm-mrad and 3.4 ps (RMS). Furthermore, the beam test was carried out with this optics and the beam parameters were measured. Details are described in [5].

ACKNOWLEDGEMENTS

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