# 60 pC BUNCH CHARGE OPERATION OF THE COMPACT ERL AT KEK

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*Abstract*

The compact ERL (cERL) at KEK was operated in March 2017 to demonstrate generation, acceleration and transportation of the target bunch charge of 60 pC without energy recovery. However, the maximum bunch charge was limited to 40 pC due to the limitation of the excitation laser power. For the bunch charge of 40 pC, the bunch length and the normalized emittance were measured in the injector diagnostic line. The results of the bunch length measurement gave good agreement with the values that had been obtained by model simulation. The measured normalized rms emittances for 40 pC were 0.9 to 2.4 $\pi$mm·mrad, and they were lager than the design value of 0.6 $\pi$mm·mrad. To achieve the design emittance, we have studied the source of the emittance growth for the bunch charge of 40 pC.

## INTRODUCTION

The compact ERL (cERL) is a test energy recovery linac to demonstrate low emittance, short bunch length and high average current beam operation [1]. The cERL consists of a photocathode DC gun, a superconducting injector, a main superconducting linac, and a recirculation loop. Figure 1 shows the layout of the cERL. The tentative target of the cERL is the average current of 10 mA with the normalize emittance of 1 $\pi$mm·mrad. So far, we achieved 0.9 mA CW energy recovery operation with the repetition rate of 1.3 GHz and the bunch charge of 0.7 pC [2]. In addition, a good prospect is now seen for CW 10 mA operation, because we have achieved very low beam loss in 0.9 mA CW operation with the repetition rate of 162.5 MHz and the bunch charge of 5.5 pC, which corresponds to the bunch charge for the 10 mA CW operation with the repetition rate of 1.3 GHz [2]. As the next topic of the beam experiment for the cERL, we planned to increase the bunch charge toward the development of CW-FEL accelerator based on a superconducting linac, since it requires higher bunch charge and higher peak current. For example, EUV-FEL accelerator based on ERL for future lithography light source requires the bunch charge of 60 pC [3], and CW-XFEL accelerator like the LCLS-II requires the bunch charge of 300 pC. As the first step of the high bunch charge operation in the cERL, we planned beam operation to demonstrate generation, acceleration and transportation of the bunch charge of 60 pC without energy recovery in March 2017. In this paper, we report the progress of the cERL high bunch charge operation.

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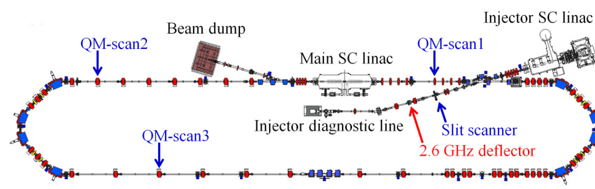


Figure 1: Layout of compact ERL. In the injector diagnostic line, there are horizontal and vertical slit-scanners and a 2.6 GHz deflecting cavity.

## PREPARATION OF 60 pC OPERATION

### *Operation Plan*

The high bunch charge operation was planed from 13 March to 31 March 2017. Since the operation period was limited to three weeks, we gave priority to generation of high bunch charge beam, in which the maximum target charge was 60 pC, and beam transportation without emittance degradation. In order to decrease the emittance growth caused by space charge effect, we increased the injector total energy from 2.9 MeV for energy recovery operation to 5.1 MeV. For this injector energy, we can not recirculate the beam due to the limitation of the ratio between the injection and the recirculation energies in the merger chicane. In this operation, we transported the high bunch charge beam to the injector diagnostic line or the long straight section in the recirculation loop as shown in Fig. 1, and measured the emittance and the bunch length. In the beam operation, we carried out the following beam tuning and measurements. For low bunch charge beam with the laser temporal shape of 3 ps rms Gaussian distribution, in which the charge was less than 100 fC, we carried out acceleration phase tuning, orbit tuning, and the correction of accelerator model for numerical simulation [4]. After the correction of accelerator model [5], we redesigned the beam optics for high bunch charge beam based on the measurement results. For high bunch charge beam, in which the laser temporal shape was a flat-top distribution with 31 ps FWHM generated by eight stacked Gaussian pulsed, we carried out optics tuning including space charge effect, the measurements of emittance and bunch length, bunch compression study in the recirculation arc, and beam halo study.

### *Preparation of Operation*

As the preparation of the beam operation, we carried out the high voltage operation of the DC photocathode gun, and the high gradient processing for the injector and main linac SC cavities. In the high voltage operation of the gun, we achieved stable 500 kV operation without a GaAs photocathode. However, we observed field emission from the gun voltage of 470 kV, when we inserted the GaAs cathode. Therefore, we decided to operate the gun with the voltage of 450 kV to avoid the field emission. From the results of the high gradient processing for the injector cavities, we decided the maximum accelerating gradients for the first, second and third 2-cell injector cavities to 6.5, 7.3 and 6.8 MV/m, respectively. Based on these results, we re-optimized the design optics [5].

## RESULTS

### *Generation of Higher Bunch Charge*

The quantum efficiency (QE) of the GaAs cathode, was measured every day before the beam operation. The measured QE was 3 %, and the degradation of it was very small in this period. In order to test the maximum bunch charge, we used two different temporal distributions of the excitation laser, a single Gaussian distribution with 3 ps rms and a flat-top distribution with 31 ps FWHM generated by eight stacked Gaussian distributions [5]. For high bunch charge operation, we used the flat-top distribution to decrease charge density. The generated bunch charge from the GaAs photocathode was measured by a Faraday cup, which was located at 1.37 m from the cathode. The measured results are shown in Fig. 2. For the distribution of 3 ps rms, we achieved the generation of 60 pC bunch charge. However, the maximum bunch charge was limited to 40 pC for the flat-top distribution. To extend the laser pulse width, we used birefringent crystals, and it decreased the laser power on the cathode. The stacked laser power was about 1/3 of the original power. Therefore, we decided to decrease the maximum bunch charger from 60 pC to 40 pC in this period, and re-optimized the design optics [5].

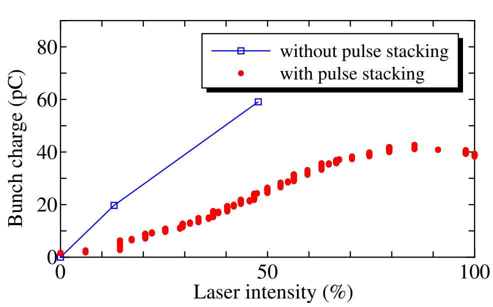


Figure 2: Generated bunch charge from GaAs photocathode with and without pulse stacking of excitation laser. The bunch charge measured at a Faraday cup, which is located at 1.37 m from the cathode. The intensity of the excitation laser is controlled by a filter.

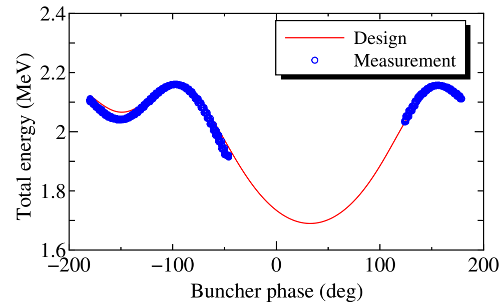


Figure 3: Designed and measured responses of accelerated beam energy to buncher phase. In the measurement, the beam was accelerated by the buncher cavity and the first injector cavity. The phase of the first injector cavity was fixed to maximum acceleration phase. The beam energy was measured by the first bending magnet in merger section.

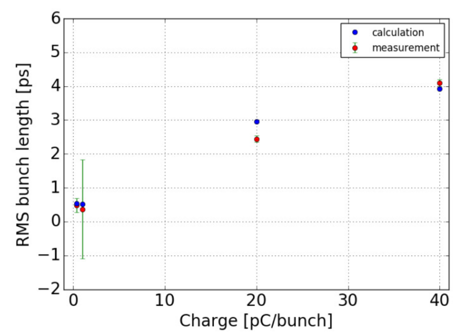


Figure 4: Designed and measured bunch length. The bunch length was measured by a 2.6 GHz deflecting cavity, which is located in injector diagnostic line.

### *Bunch Length Measurement*

In the previous cERL operation, the agreement of the longitudinal dynamics between measurement and model was not so good, because the previous phase tuning procedure for the buncher and the injector cavities was not the same as a procedure for optics design simulation. In order to improve the longitudinal beam dynamics, we improved the procedure to be consistent with the optics design simulation. Figure 3 shows the designed and measured responses of accelerated beam energy to the buncher phase after the improved phase tuning. As shown in Fig. 3, the measured response is almost the same as the designed response. Figure 4 shows the designed and measured bunch length, which is measured in the injector diagnostic line. As shown in Fig. 4, the results of the bunch length measurement gave good agreement with the values that had been obtained by model simulation. Therefore, the longitudinal dynamics was improved by the improved phase tuning procedure.

### *Emittance Measurement*

After optics tuning for the bunch charge of 40 pC, we measured normalized rms emittances by a slit-scanner in the injector diagnostic line and quadrupole scan method in the recirculation loop. Using the slit-scanner, we measured emit-




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tances in two different transport conditions, measurement 1 and measurement 2. In the measurement 1, the vertical beam size was focused at the slit-scanner as shown in Fig. 5. In the measurement 2, the horizontal beam size was focused at the slit-scanner. Figure 6 shows the designed and the measured normalized rms emittance. For the bunch charge of 40 pC, the measured emittances are 0.9 to 2.4 $\pi$mm·mrad, and they are not achieved to the design emittance. After the measurement of the beam performance in the injector diagnostic line, we transported the high bunch charge beam to the main linac and the recirculation loop. In the recirculation loop, we measured the emittances at QM-scan1, QM-scan2 and QM-scan3 as shown in Fig. 1. At QM-scan1, the horizontal and vertical emittances are 2.0 and 2.4 $\pi$mm·mrad. At QM-scan2, the horizontal and vertical emittances are 9.2 and 3.2 $\pi$mm·mrad. At QM-scan3, the horizontal and vertical emittances are 9.7 and 4.2 $\pi$mm·mrad. In the recirculation loop, we observed the emittance growth after the merger and the main linac.

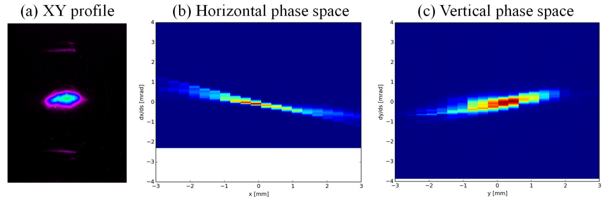


Figure 5: Transverse beam profile and horizontal and vertical phase space distributions at slit-scanners in injector diagnostic line with the bunch charge of 40 pC.

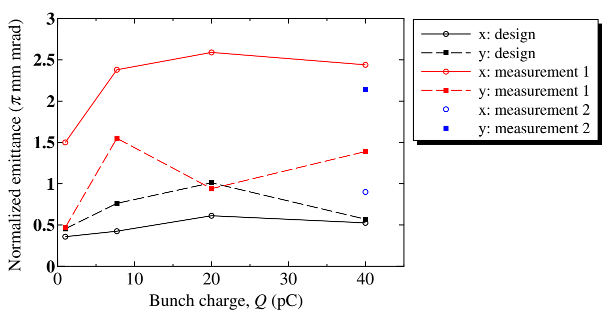


Figure 6: Designed and measured normalized rms emittances at slit-scanner in injector diagnostic line.

## DISCUSSION

To achieve the design emittance, we are studying the source of the emittance growth for the bunch charge of 40 pC. As the first step of this study, we measured the transverse beam dynamics in the low energy region from the gun to the exit of the injector. Although the transverse profile has the cylindrical symmetry in the model simulation, in this region, we observed the asymmetric transverse profile as shown in Fig. 7. In order to find the source of the asymmetry, we carried out single kick response measurements in the low energy region. Figure 8 shows the single kick responses

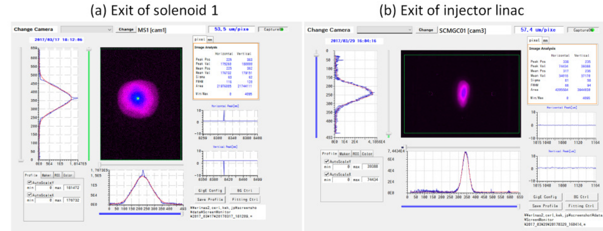


Figure 7: Measured transverse beam profiles at (a) the exit of solenoid 1 and (b) the exit of injector linac with the bunch charge of 40 pC.

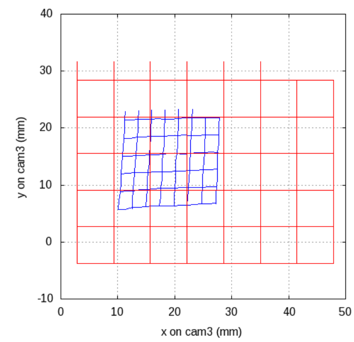


Figure 8: Single kick responses from the entrance to the exit of injector SC linac. The beam is kicked by horizontal and vertical steering magnets, which are located at the entrance of injector SC linac. The red lines show the responses, when all the injector cavities are turned off. The blue lines show the response, when the first injector cavity is turned on, and it is affected by the focusing force caused by the first cavity.

about the first injector 2-cell cavity. As shown in Fig. 8, we obtained asymmetric focusing force for the horizontal and vertical directions. The input and HOM coupler may cause the effect. Based on the measurement results, we are correcting the model of the injector cavity.

## SUMMARY

In March 2017, we carried out the high bunch charge operation of the cERL, and achieved generation, acceleration and transportation of 40 pC bunch charge beam. For the bunch charge of 40 pC, the bunch length and the emittance were measured. Using the improved phase tuning procedure, we improved the longitudinal dynamics. However, for the transverse beam dynamics, we observed the disagreement between the measurement and the model. To achieve the design emittance, we are studying the source of the emittance growth in the low energy region.

## ACKNOWLEDGMENT

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