CONSTRUCTION AND COMMISSIONING OF COMPACT-ERL INJECTOR AT KEK

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Abstract

The Compact Energy-Recovery Linac (cERL) is under construction at KEK in order to demonstrate the technologies that are needed for the future 3-GeV ERL project. In April 2013, the 5-MeV injector of the cERL was completed and commissioned. During April to June in 2013, we tuned up the injector and evaluated its beam performance. From July to November in 2013, we are constructing the entire cERL including its return loop.

INTRODUCTION

In KEK, we aim to construct a 3-GeV energy recovery linac (ERL) [1,2] that will be used as a super-brilliant and ultra-short-pulse synchrotron light source as well as a driver for an X-ray free-electron-laser oscillator (XFEL-O). This project was recently named the PEARL (Photon Factory Advanced Research Laboratory). To demonstrate the production, acceleration, and recirculation of low-emittance and high-current beams that are need to the 3-GeV ERL, we are constructing the Compact ERL at KEK.

A planned layout of the cERL is shown in Fig. 1. The cERL consists of a 5-MeV injector, a main linac, and a return loop. Low-emittance electron beams are produced in a 500-kV photocathode DC gun, and they are boosted to a beam energy of about 5 MeV in a superconducting (SC) injector cryomodule. The beams are merged to the superconducting main linac where the beams are accelerated to a kinetic energy of 35 MeV, and they are transported through the return loop. The beams are then decelerated through the main linac, and are dumped. The beams from the injector can also be transported to an injector dump through an injector-diagnostic beamline. This allows us to evaluate the various beam properties of the injector. Design parameters of the cERL are given in Table 1.

The cERL injector was completed in April 2013. From 22 April to 28 June in 2013, we commissioned the injector and measured beam properties such as the beam emittance, the bunch length, the momentum spread, and the momentum jitter. During July to November in 2013, we are constructing the return loop [3].

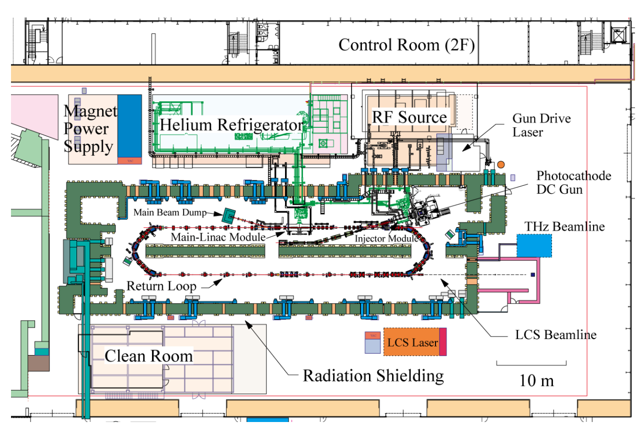

Figure 1: Planned layout of the cERL.

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Table 1: Design Parameters of the cERL

Beam kinetic energy (injector) (return loop)	5 MeV 35 MeV
Beam current (initial goal) (future goal)	10 mA 100 mA
Normalized beam emittance	< 1 mm·mrad
Repetition frequency of bunches	1.3 GHz (CW)

CONSTRUCTION OF THE INJECTOR

From March to September in 2012, we constructed a radiation-shielding room which consists of reinforced concrete blocks in the ERL development building of KEK. The shielding room covers an area of about 60 m × 20 m. The thicknesses of side walls and a roof are 1.5 m and 1 m, respectively. After its construction, we installed air conditioners, a ventilator, electric lights, and a drainer system for the cERL.

The first 500-kV photocathode DC gun [4,5] was developed at JAEA. In October 2012, we successfully demonstrated [4] the beam production at high voltages up to 500 kV at JAEA. Then, the gun was disassembled and was transported to KEK. From October 2012 to March 2013, we reassembled the gun, and carried out high-voltage tests on the gun assembly. During the test, we found a slight problem in two of the ten pieces of ceramic insulators of the gun. For this reason, we chose a modest voltage of 390 kV as an applied voltage to the cathode during the injector commissioning. Figure 2 shows an injector section of the cERL including the 500-kV photocathode DC gun.

Figure 2: The injector of the cERL at KEK. The 500 kV photocathode DC electron gun and a superconducting cryomodule for the injector are shown.

Following the first gun, the second 500-kV photocathode DC gun is under development at KEK [6]. In this gun, several measures to achieve extremely-high vacuum have been employed. At present (September 2013), we could apply high voltage of 500 kV to the gun assembly.

To excite the photocathode (Gallium Arsenide) of the gun, a drive laser system [7] was developed. The laser system consists of a 1.3-GHz Nd:YVO_4 oscillator, both pre- and main-amplifiers using Yb photonic-crystal fibers (at a wavelength of 1064 nm), a second-harmonic generator (wavelength: 532 nm), a gating system, and a pulse shaping system.

A cryomodule for the injector, which houses three two-cell cavities, was assembled from April to June 2012. The injector module was installed in the cERL in June 2012, as shown in Fig. 2. We carried out cool-down test, low-power measurements, and high-power test during September 2012 to April 2013. During the high-power test [8], we could operate the injector cavities up to an accelerating gradient of 15 MV/m in pulsed operations (duty factor of 10%). We could also demonstrate stable operations of the injector cavities at an accelerating gradient of 8 MV/m in CW operation. We found that heating up of HOM couplers limited the maximum gradient in CW operations. Although an advanced design [9] was employed for these HOM couplers which are suitable for CW operations, the cooling of the HOM couplers was still insufficient because these HOM couplers were placed out of the helium jackets. In a future design, we will reinforce the cooling of the HOM couplers.

In a short (1.12 m) section between the gun and the injector module, we installed a laser-input chamber, a 1.3-GHz buncher cavity, and a screen chamber. To keep the lifetime of the photocathode, extremely-high vacuum is required in this section. We pre-assembled this section in a clean room, and installed it in a local clean hut. After the bake out, we achieved ultrahigh vacuum of about 2×10^{-9} Pa in the laser input chamber.

In order to evaluate the beam properties from the injector, we constructed an injector diagnostic beamline [10], as shown in Fig. 3.

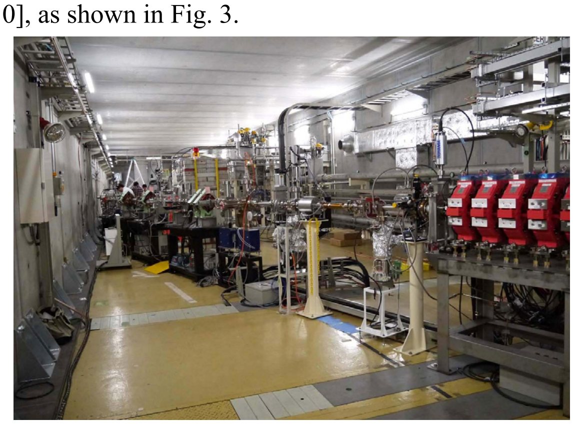

Figure 3: The injector diagnostic beamline.

An rf system [11] for the injector consists of rf sources, a digital low-level rf system, and an rf distribution system. For the rf sources of the injector, we employed a 20-kW IOT, a 25-kW klystron, and a 300-kW klystron, to drive the buncher cavity and three SC cavities of the injector. Using the digital low-level system, we could precisely stabilize the amplitudes and the phases of cavity voltages. We have so far achieved amplitude and phase stabilities within 0.1% (rms) and 0.1 degrees (rms), respectively.

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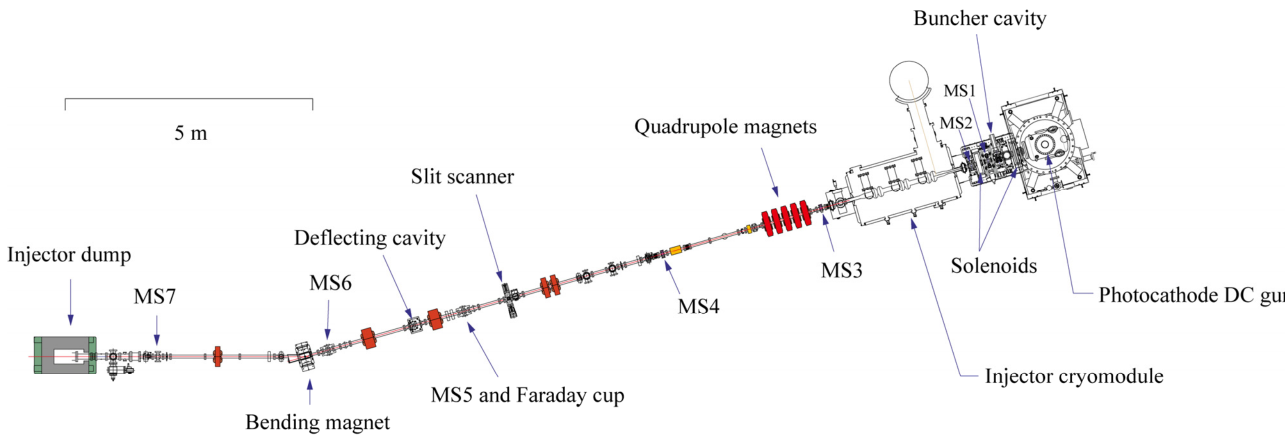

Figure 4: Plane layout of the cERL injector and its diagnostic beamline. The symbols "MS" indicate screen monitors.

A cryogenic system for the cERL consists of a TCF200 liquid-helium refrigerator, a 3000-liter Dewar, two 2K cold boxes, and a pumping system. The system has a cooling capacity of about 600 W at a temperature of 4.5 K, and that of about 80 W at 2 K using eight sets of evacuating pumps for helium gases.

Each component of the cERL is controlled through the Experimental Physics and Industrial Control System (EPICS). For safety management, we also constructed a personnel protection system (PPS) and a machine mode system (MMS).

A cryomodule for the main linac, which houses two 9-cell cavities, was assembled from August to October 2012, and it was installed in the cERL. We cooled it down to 2 K in November 2012, and carried out cryogenic test, low-power test, and high-power test in December 2012. In the cool down test, we confirmed that the components such as input couplers, frequency tuners, and HOM absorbers, worked well as expected. In the high-power test, we achieved accelerating voltages of 16 MV (accelerating gradient of 15.4 MV/m) in both cavities [12]. Unfortunately, field emissions started at an accelerating voltage of about 8 MV in both cavities. We are preparing to use this cryomodule to the main linac of the cERL. In future, we will continue R&D effort on the module assembly technique to reduce the field emissions.

COMMISSIONING OF THE INJECTOR

Setup of Injector Beamline

Figure 4 shows a plane layout of the injector beamline which was used for the commissioning during April to June, 2013. Electron beams were produced at the photocathode DC gun with a cathode voltage of 390 kV. The beams passed through the buncher cavity which produced energy chirp needed to compress the electron bunches. The beams were transported to the injector cavities while being focused by two solenoid magnets. The beams were then accelerated by the three injector cavities up to kinetic energies of about 5-6 MeV. The beams were then transported to the injector dump through the diagnostic beamline.

The positions and profiles of the beams were observed using seven screen monitors (indicated by MS1 to MS7 in Fig. 4). We employed Ce:YAG scintillator having a thickness of 0.1 mm for these screen monitors. The screens were placed at an angle of 45 degrees to the beam direction while the scintillation lights were observed at a right angle to the beam. To measure the beam emittances [10], we installed a slit scanner, having both horizontal and vertical slits, in the diagnostic beamline. We also installed a 2.6-GHz transverse deflecting cavity for bunch-length measurement [10]. The beam current was monitored using a faraday cup at the location of the screen monitor "MS5" as well as using the injector dump as a faraday cup. The beam current was also measured at a power supply of the DC gun by subtracting offset currents due to divide resistors of the insulators.

Initial Commissioning

To observe the beams using screen monitors at low average currents, we produced macropulse beams from the gun by gating the drive-laser pulses. Typical parameters of the macropulse operation are given in Table 2. Under the macropulse operations of the beams, the gun high-voltage and the injector cavities were operated in DC or CW modes.

On 22 April in 2013, we started commissioning of the injector. First, we adjusted the position of the laser spot to the center of the cathode, and positioned the beams to the centers of two solenoids. Then, we adjusted the phase of each injector cavity to that of on-crest acceleration; the buncher cavity was tentatively turned off. While adjusting the phases, the beam momentum was monitored by using a steering magnet and a screen monitor. In the first five days, we could accelerate the beams up to the kinetic energy of about 5.6 MeV, and could transport the beams to the injector dump. Typical machine parameters during the initial commissioning are shown in Table 3 (see columns labeled by "At low charges").

By elongating the length of macropulses to 1.6 ms, we demonstrated the (temporary) maximum average beam current of 300 nA at a beam energy of 5.6 MeV. We confirmed that the radiation levels were background ones at the outside the shielding room at the maximum current.

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After the initial commissioning, we adjusted the parameters of the injector step by step. At the same time, we measured the beam properties such as the beam emittances at very-low bunch charges of 10-20 fC/bunch. Then, we increased the bunch charges up to 7.7 pC/bunch, and measured the beam properties at these charges.

Table 2: Typical parameters of the beam pulses during the commissioning

Parameter	Value
Repetition frequency of bunches	1.3 GHz
Charge/bunch	0.01 - 7.7 pC
Temporal length of macropulses	1 μs (typically)
Repetition frequency of macropulses	5 Hz (typically)
Rise/fall times of macropulses	10 ns
Number of bunches/macropulse	1300
Average beam current	65 pA - 50 nA

Table 3: Typical parameters of the cERL injector during the commissioning operations

Parameter	At low charges	At modest charge
Charge/bunch	~ 10 fC	7.7 pC
Gun DC voltage	390 kV	390 kV
Laser spot diameter	1.2 mm	1.2 mm
Laser pulse length	3.3 ps rms (Gaussian)	15.7 ps FWHM (semi-flat)
Magnetic fields of solenoids No. 1, 2	(0.0248, 0.0103) T	(0.0286, 0.0172) T
Voltage and phase of buncher cavity	0 kV or (40 kV, -90 deg.)	(50 kV, -90 deg.)
E_{acc} of three injector cavities	(6.2, 6.7, 6.2) MV/m	(6.2, 6.7, 6.2) MV/m
Phases of injector cavities	0 degree (on crest)	0 degree (on crest)
Beam kinetic energy	5.6 MeV (typ.)	5.6 MeV (typ.)

Emittance of Beams from the Gun

We measured the emittances of 390-keV beams from the gun at low bunch charges of 10-20 fC/bunch under the macropulse operation (shown in Table 2). A setup for the measurement is shown in Fig. 5. While changing the fields of solenoids, we measured the beam sizes using screen monitors. An example of the wait scan is shown in Fig. 6, where the solenoid "SL2" shown in Fig. 5 was scanned while the beam sizes were measured using the screen monitor "MS3" in Fig. 4; the injector cavities were turned off and detuned. From three sets of such measurements, we estimated the normalized beam emittance of $\varepsilon_n \approx 0.070$ mm·mrad at the exit of the gun.

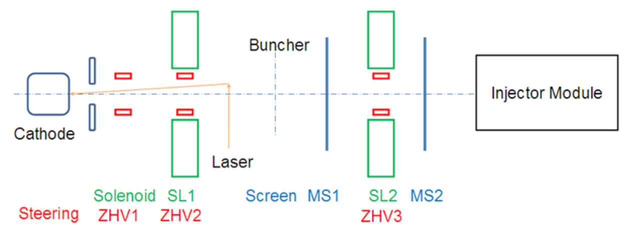

Figure 5: Setup of the emittance measurement of the beam from the photocathode DC gun.

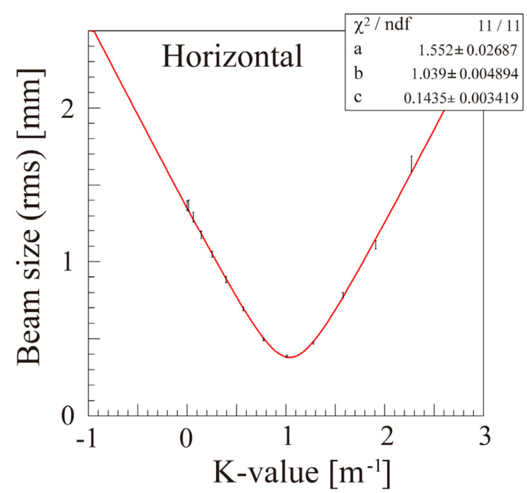

Figure 6: An example of the waist scan. Measured horizontal beam sizes at "MS3" are shown as a function of the focusing strength of the solenoid "SL2".

Emittance of Accelerated Beams at Low Charges

We measured the emittances of accelerated beams using a slit-scan method under the macropulse operation. The method of the measurement is schematically shown in Fig. 7. We scanned the position of a beam slit having a width of 100 μm; the slit was cut in a tungsten plate having a thickness of 1 mm. At each position of the slit, we measured the beam profile with a screen monitor. From these data, we deduced a distribution of particles in phase space. Both horizontal and vertical slits were installed in the silt scanner, and these slits were apart from the screen monitor "MS6", where the beam profile was measured, by 3.79 m and 3.94 m, respectively.

An example of the emittance measurement is shown in Fig. 8. In this example, the bunch charge was approximately 20 fC; a short (3 ps rms) laser pulse was used; the buncher cavity was turned off. The kinetic energy of the beam was approximately 5.6 MeV. From the measurement, we estimated the normalized emittance to be $\varepsilon_n \approx 0.17$ mm·mrad (at 20 fC/bunch). At a higher charge of 0.77 pC/bunch, we obtained a normalized emittance of $\varepsilon_n \approx 0.3$ mm·mrad.

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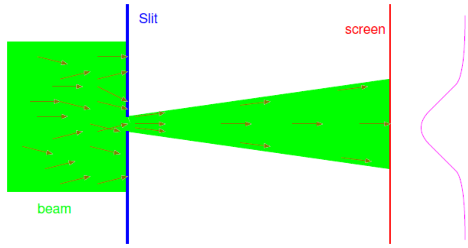

Figure 7: Schematic drawing of the slit-scan method.

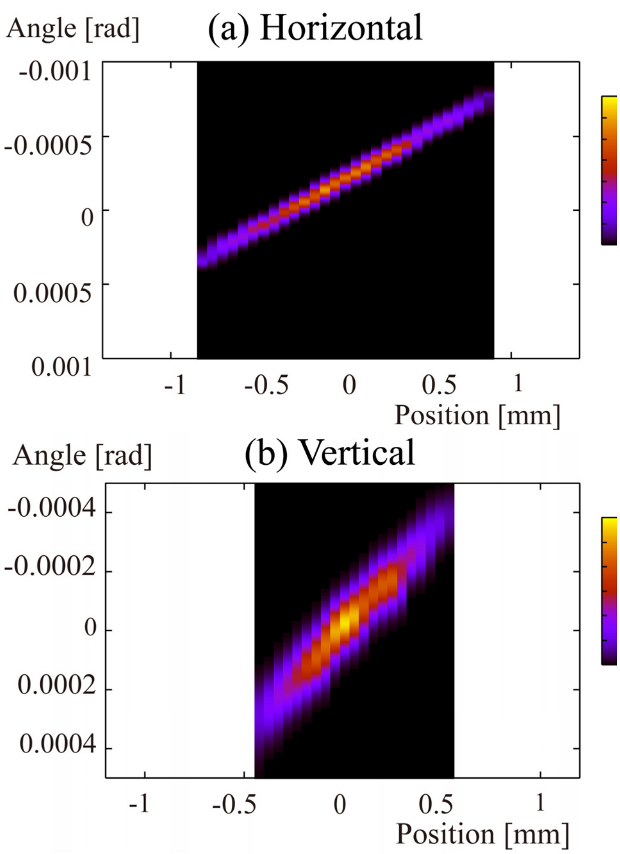

Figure 8: Example of the emittance measurement at a bunch charge of about 20 fC. The figures (a) and (b) indicate the measured distributions of particles in the horizontal and the vertical phase spaces, respectively.

Beam Emittance at Higher Charges

At higher bunch charges, we needed to optimize the machine parameters so that the space charge effects could be compensated. We expect that the space charge effect in the low-energy section can be mitigated by using longer laser pulses. For this reason, we prepared two laser pulses: (1) Gaussian shape having an rms length of 3 ps, and (2) semi-flat shape having an FWHM length of approximately 15.7 ps. Typical rf voltages (for particle of *v/c*=1) of the buncher cavity were set to 40-50 kV in both cases. Typical parameters of operation at a bunch charge of 7.7 pC are given in Table 3.

At higher charges, we observed that the beam profiles were not axially symmetric after the acceleration, as shown in Fig. 9. We measured the beam emittances using the slit-scan method at bunch charges of up to 7.7 pC. The measurements were carried out using both short and long laser pulses. The results of the emittance measurements are shown in Fig. 10. Typical normalized emittances at 7.7 pC/bunch were 0.90 mm·mrad in horizontal, and 0.49 mm·mrad in vertical, respectively, after the acceleration (~ 5.6 MeV) using the long (15.7 ps) laser pulse. Note that due to limited time, the above measurements were carried out before sufficient optimization of the injector. Contrary to our expectation, the beam emittance did not improve much by elongating the laser pulses under the present parameters.

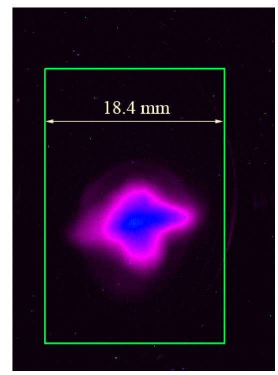

Figure 9: An example of the beam profile at a bunch charge of 7.7 pC, which was observed at a screen monitor “MS6” (after acceleration to about 5.6 MeV).

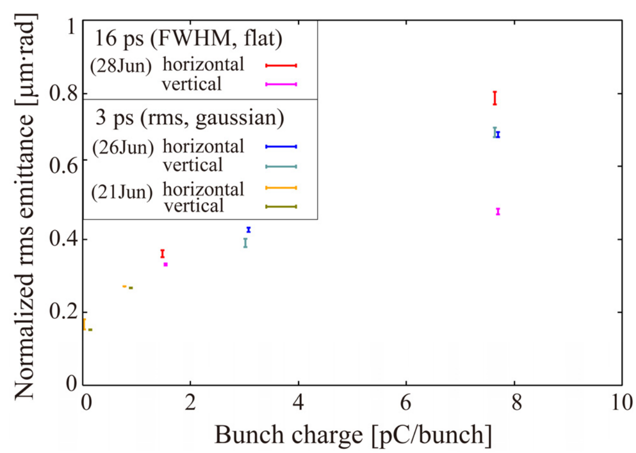

Figure 10: Measured beam emittances (at the kinetic energy of about 5.6 MeV) as a function of the bunch charge. Results with the short (3 ps rms) and the long (16 ps semi-flat) laser pulses are shown.

Bunch Length and Momentum Spread

To measure the bunch length, we applied transverse (vertical) kicks to the bunches using the 2.6-GHz deflecting cavity (in Fig. 4). The longitudinal distribution of particles was then projected to the vertical plane at a downstream screen monitor “MS6”. To improve the resolution of the measurement, we adjusted the beam optics between the deflecting cavity and the screen monitor so that small beam sizes were obtained at the

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monitor while the deflections due to rf kicks became large. We estimated typical time resolution of the measurement to be 0.7 ps.

Figure 11 shows the measured bunch lengths as a function of the bunch charge; the measurements were carried out using both short and long laser pulses. The bunch length elongated as the bunch charge. Note that the optimization of the machine parameters was insufficient at high charges. At present, we did not understand the reason why the bunch length did not change much by changing the laser pulse lengths.

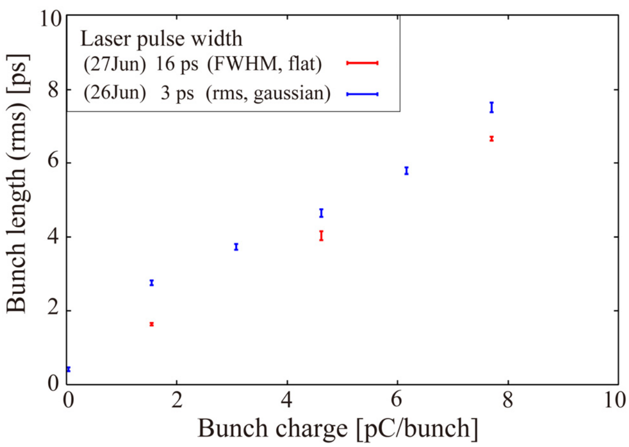

Figure 11: Measured bunch lengths as a function of the bunch charge. Results with the short (3 ps rms) and the long (16 ps semi-flat) laser pulses are shown.

The momentum spread of the accelerated beams was measured using a screen monitor "MS7" where the dispersion function was approximately 0.825 m. Figure 12 shows the measured momentum spreads as a function of the bunch charge. The momentum spread increased as the bunch charge. At a bunch charge of 7.7 pC, we obtained a typical rms momentum spread of 1.5×10^{-3}.

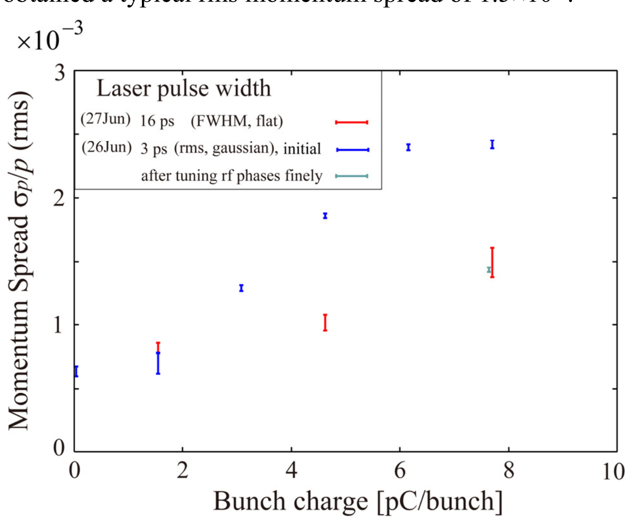

Figure 12: Measured momentum spreads as a function of the bunch charge. Results with the short (3 ps rms) and the long (16 ps semi-flat) laser pulses are shown.

CONCLUSION

The 5-MeV injector of the cERL was completed and commissioned. We measured beam properties such as the beam emittance, the bunch length, and the momentum spread, at bunch charges of up to 7.7 pC. At very low charges of 10-20 fC/bunch, we obtained a typical normalized emittance of 0.07 mm·mrad at the exit of the gun (voltage: 390 kV), and that of 0.17 mm·mrad after acceleration to about 5.6 MeV. We are on the way to optimize the parameters at higher charges, and at present, we have obtained typical normalized emittances of 0.49 - 0.90 mm·mrad at 7.7 pC/bunch.

During April to June 2013, we carried out the beam operation of the injector for about 202 hours. During this period, we demonstrated stable operations of the injector including the photocathode DC gun (at a cathode voltage of 390 kV) and the injector SC cavities (at an accelerating gradient of approximately 7 MV/m). From July 2013, we are constructing the return loop of the cERL. From these R&D results, we are approaching to obtain the technology needed to construct the PEARL project.

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REFERENCES

[1] KEK Roadmap, May 23, 2013 http://www.kek.jp/ja/About/OrganizationOverview/Assessment/Roadmap/roadmap2013-E.pdf
[2] "Energy Recovery Linac Conceptual Design Report", KEK Report 2012-4, KEK, October, 2013 http://ccdb5fs.kek.jp/tiff/2012/1224/1224004.pdf
[3] M. Shimada, talk at the ERL-2013, WG205.
[4] N. Nishimori, R. Nagai, S. Matsuba, R. Hajima, M. Yamamoto, T. Miyajima, Y. Honda, H. Iijima, M. Kuriki, M. Kuwahara, "Generation of a 500-keV electron beam from a high voltage photoemission gun," Appl. Phys. Lett. 102 (2013) 234103.
[5] N. Nishimori, talk at the ERL-2013, WG109.
[6] M. Yamamoto et al., in these proceedings, WG108.
[7] Y. Honda et al., "Photo Cathode Laser System for Compact-ERL Injector," to be published in the Proceedings of the 10th Meeting of Particle Accelerator Society of Japan, August 2013 [in Japanese].
[8] E. Kako et al., "High Power Tests of Injector Cryomodule for Compact-ERL," IPAC2013, Shanghai, May 2013, WEPWO013, p. 2340.
[9] K. Watanabe, S. Noguchi, E. Kako, K. Umemori, T. Shishido, "Development of the superconducting rf 2-cell cavity for cERL injector at KEK," Nucl. Instrum. Methods Phys. Res. A 714 (2013) 67.
[10] Y. Honda, "Beam Performance Measurement at Compact-ERL Injector", poster presentation at ERL-2013, PS03.
[11] T. Miura et al., in these proceedings, WG306.
[12] K. Umemori et al., "Construction of Main Linac Cryomodule for Compact ERL Project," IPAC2013, Shanghai, May 2013, WEPWO016, p. 2349.

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