RECENT DEVELOPMENTS AND OPERATIONAL STATUS OF THE COMPACT ERL AT KEK

T. Obina†, M. Adachi, S. Adachi, T. Akagi, M. Akemoto, D. Arakawa, S. Araki, S. Asaoka, M. Egi, K. Enami, K. Endo, S. Fukuda, T. Furuya, K. Haga, K. Hara, K. Harada, T. Honda, Y. Honda, H. Honma, T. Honma, K. Hosoyama, K. Hozumi, A. Ishii, X. Jin, E. Kako, Y. Kamiya, H. Katagiri, H. Kawata, Y. Kobayashi, Y. Kojima, Y. Kondou, T. Konomi, A. Kosuge, T. Kume, T. Matsumoto, H. Matsumura, H. Matsushita, S. Michizono, T. Miura, T. Miyajima, H. Miyauchi, S. Nagahashi, H. Nakai, H. Nakajima, N. Nakamura, K. Nakanishi, K. Nakao, K. Nigorikawa, T. Nogami, S. Noguchi, S. Nozawa, T. Ozaki, F. Qiu, H. Sagehashi, H. Sakai, S. Sakanaka, S. Sasaki, K. Satoh, Y. Seimiya, T. Shidara, M. Shimada, K. Shinoe, T. Shioya, T. Shishido, M. Tadano, T. Tahara, T. Takahashi, R. Takai, H. Takaki, T. Takenaka, O. Tanaka, Y. Tanimoto, N. Terunuma, M. Tobiyama, K. Tsuchiya, T. Uchiyama, A. Ueda, K. Umemori, J. Urakawa, K. Watanabe, M. Yamamoto, N. Yamamoto, Y. Yamamoto, Y. Yano, M. Yoshida, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
R. Hajima, M. Mori, R. Nagai, N. Nishimori, M. Sawamura, T. Shizuma, National Institutes for Quantum and Radiological Science and Technology (QST), Tokai, Naka, Ibaraki 319-1195, Japan
M. Kuriki, Hiroshima University, Higashihiroshima, Hiroshima 739-8530, Japan

Abstract

The Compact Energy Recovery Linac (cERL) at KEK is a test accelerator to develop critical components of future light sources. After beam studies on beam dynamics and survey for beam losses, we have achieved circulating 1-mA CW beam with total beam losses better than 0.1%. In parallel to the increase in beam current, various research and developments have been carried out: beam tuning for low emittance, short pulse generation below 1 ps, improvement of DC gun voltage, etc. A laser Compton scattering (LCS) system for high-flux X-rays has been successfully commissioned and has benefitted from the increase in the beam current.

INTRODUCTION

Energy Recovery Linacs (ERL) or high-repetition-rate FEL linacs (CW-FEL) are one of the candidates for future X-ray light sources in KEK. Key components for both accelerators are high performance (small transverse emittances, short bunch length, low energy spread, large current) electron gun and superconducting (SC) linacs. The cERL has been constructed and operated for research and developments (R&D) of the future light sources [1, 2]. A Laser Compton scattering (LCS) experiment for X-ray imaging and proof-of-principle of a non-destructive assay of nuclear materials has been carried out [3], by taking advantages of its compact size and high beam current of the cERL. Also, by utilizing short bunch-length with high repetition rate feature, the cERL has a possibility to be used as a high-power THz radiation source.

Typical operational parameters of the cERL are tabulated in Table 1. Note that these values are neither a design goal nor nominal values, and cannot be achieved simultaneously.

Table 1: Typical Operational Parameters of cERL

		Value	Unit
Total energy		19.9	MeV
Injector energy		2.9 - 6.0	MeV
Electron gun energy		390 - 450	keV
Maximum current		1.0	mA
Beam repetition	(standard)	1300	MHz
	(LCS)	162.5	MHz
Bunch length	(standard)	1 - 3	ps
	(compressed)	0.15	ps
Total path length	(gun-dump)	120	m

After the first beam commissioning in December 2013, a legal beam-current limit has been increased step-by-step like 1 μA, 10 μA, and 100 μA as shown in the left figure of Fig.1. In autumn 2015 we applied for 1 mA operation and received a permission of machine tuning for higher beam current on 19/Jan/2016. Then, we carried out the beam tuning from 15/February until the inspection on 8/Mar. Strategy for higher beam current is described in the next section and in refs. [4, 5]. We present major achievement and lessons learned from the operation.

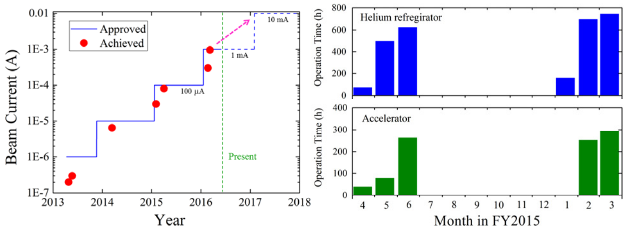

Figure 1: Approved and achieved beam currents after the initial commissioning (left) and operational statistics in the fiscal year 2015 (right).

---

† takashi.obina@kek.jp

Figure 1 (right) shows the statistics of beam operation time. In Japanese fiscal year (FY) 2015, we have operated the cERL accelerator for about 12 weeks. The operation time of the helium refrigerator was five weeks longer than the accelerator operation time for cool down and conditioning of superconducting cavities.

HIGH AVERAGE CURRENT OPERATION

The bunch charge was selected to be 0.77 pC/bunch with the beam repetition of 1300 MHz to achieve high beam current of 1 mA. We had been operated the cERL with 0.5 pC/bunch with 162.5 MHz rep-rate (80 μA on average) for the LCS experiments; hence, it was straightforward for us to increase the beam repetition eightfold higher. The approach is better to keep the same space charge effects in low-energy areas before the main linac.

From the experience of LCS beam tuning and CW operation, we noticed the beam orbit was drifting as beam operational time proceeds. Also, after the long CW operation, transverse beam profile at the entrance of an injector linac shows distinct asymmetry. We identified the origin of the asymmetry and orbit drifts; they were coming from charge-ups of laser mirrors inside the vacuum chamber. We replaced the dielectric mirror with the metallic one during the summer shutdown. Another issue during the 100-μA CW operation is a discharge of ceramics components in the vacuum. After we had introduced a copper cover to hide ceramics before the main dump, we installed cover to protect a ceramics of a Faraday cup from the field emission of the injector linac.

Fast and reliable machine protection systems are indispensable for high-current operation. The number of beam-loss detectors is doubled along the beam path, and they are connected to a fast interlock system to stop laser pulse within 10 μs. To avoid any damages of the beam dump, we installed a new screen monitor to check a beam profile on the dump and installed a rastering system which keeps the beam position on the beam dump time-varying.

It is essential to match the measured beam optics to the ideal optics which is derived from simulations. We have introduced five locations to measure and match the beam optics with the same method described in ref. [6]. We have also established many standard tuning procedures to improve reproducibility of the beam parameters.

We have developed beam loss monitors used for both pulsed and CW beams and utilized five collimators to suppress beam losses. Details of beam tuning are reported in ref. [4]. The measurement, simulation, and mitigation of beam halo are presented in ref. [7].

The government authority inspected the CW operation of the cERL on 8/Mar and approved for 1-mA operation. Figure 2 shows a beam current history of the first attempt above 900 μA. Laser shutter was sometimes closed to set an appropriate threshold of the beam loss monitors. The red line denotes a difference between an input and a reflected power of the main linac (ML). A change in this value can be used to estimate the efficiency of energy recovery [8]. The change due to the current change from 0 μA to 900 μA was less than 10 W despite the 4-W measurement errors, which corresponds to 99.94% ± 0.03% energy recovery. It shows a good agreement with the beam loss of 0.01%, which is evaluated from the radiation measurements [5].

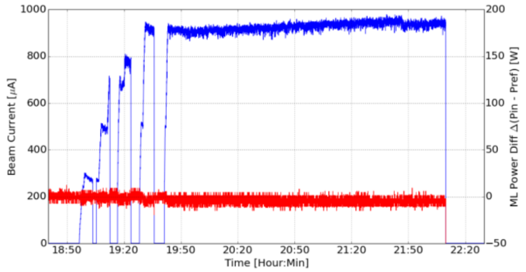

Figure 2: Beam current at the main dump (blue, left axis) and difference between input and reflected power of the ML (red, right axis) while the first attempt above 900 μA.

HIGH BUNCH CHARGE OPERATION

The next target current of the cERL will be 10 mA. Same way as the previous beam tuning for 1 mA, we have operated the machine with a peak charge of 7.7 pC/bunch with a beam rep-rate of 162.5 MHz. Eight laser pulses are stacked to reduce the peak current, and the bunch is compressed in the injector linac. Machine tunings such as optics correction, optics tuning and loss measurements were executed in the burst (macro-pulse) mode. Duration of the macro-pulse was set to 500 ns to avoid transient beam loading of the injector cavity.

To keep the axial symmetry in the injector, we precisely adjusted the orbit in the injector solenoid. The beam orbit in the injector linac was adjusted to its center by using HOM pickups of the cavities. This approach is suitable for low emittance; however, it becomes relatively difficult to cut the bunch-tail from the gun. Further improvement both in cathode and optics is anticipated [4].

EMITTANCE MEASUREMENT

Low emittance is a key feature of the linac-based light source. The final target of the emittance is 0.1 mm·mrad with 7.7 pC/bunch (6-MeV injector linac and 30-MeV main linac) in the cERL. The normalized emittance of the recirculation loop was measured by a Q-scan method.

Table 2: Tentative Emittance Measurement

Bunch Charge	**Normalized Emittance (h/v) [mm·mrad]**
0.02 pC	0.14 / 0.14
0.5 pC	0.27 / 0.17
7.7 pC	1.5 / 1.1 (tentative)

Table 2 lists a tentative result of emittance measurement with 2.9 MeV injector energy and 19.9 MeV after main linac. At a bunch charge of 7.7 pC, we obtained the normalized emittances of 1.5 mm·mrad in horizontal and 1.1

mm·mrad in vertical. These values were obtained during the limited operational time. We plan to perform more tuning and analysis in the next operation.

BUNCH COMPRESSION

High-intensity THz radiation is one of the competitive features of the cERL [9, 10]. Bunch length is compressed in the 1st arc section and decompressed in the 2nd arc section with the combination of off-crest acceleration in the main linac and non-zero longitudinal dispersion (R_{56}). In the summer of 2015, four sextupole magnets were installed to correct second-order energy dependent path length (T_{566}) [11].

Bunch length monitor is essential for compression tuning. A coherent transition radiation (CTR) monitor with Al target was installed in the middle of a south straight section. Extracted THz radiation is analyzed by a Michelson interferometer. Various kinds of detector have been tested and evaluated: Schottky diode detector (90 GHz, 140 GHz, 220 GHz), liquid-helium cooled Si bolometer, QOD (Quasi-Optical Schottky Diode detector), etc.

Figure 3 shows the preliminary result of bunch compression. The left figure shows an interferogram and the right shows estimated power in the frequency domain. We observed frequency components near 1 THz region and estimated bunch length about 150 fs. Further experiments are required for quantitative discussion of bunch length.

CTR measurements are destructive and therefore can be used only under burst beam operation. During the CW operation, we observed THz radiation from a bending magnet with a pyroelectric sensor with a chopper.

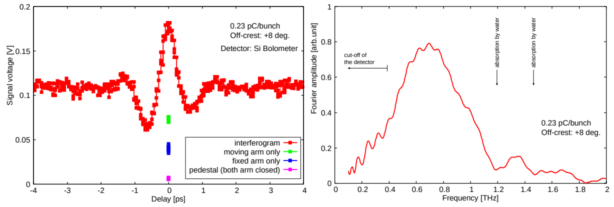

Figure 3: Interferogram (left) and its Fourier spectrum (right) of THz radiation produced by the CTR target.

LASER COMPTON SCATTERING

A quasi-monochromatic LCS photon source has been developed in the end region of the south straight section. In Apr/2015, we observed a 6.9-keV X-ray on the detector in the experimental hutch which corresponds to the source flux of 4×10^7 ph/s with a 58-μA electron beam current [12, 13]. In Mar/2016, intensity of the X-ray has been increased six times higher than the experiment in April. The beam current was 900 μA in the experiment. We expect to achieve more than ten times higher X-ray flux by optimizing both the beam and laser parameters in the next operation.

Small beam size (~30 μm) at the interaction point (IP) requires special care both for optics and beam dynamics. For now, beam losses after LCS section are 3-5 times greater than that of high beam current with 1.3 GHz repetition rate beam. The amount of the loss is already acceptable for the future 10-mA operation, though we plan to continue the beam tuning for smaller beam losses.

DEVELOPMENTS

Cathode Lifetime

A bulk p-type GaAs cathode has been used in the cERL. We used two cathodes from January to Mar/2016. Total extracted charge was 14.2 Coulomb for cathode #1, and 25.6 Coulomb for #2. On the last day of each period, the quantum efficiency of the first and second cathode was about 1.4% and 2.4%, respectively. These values are high enough for 1-mA and coming 10-mA operation.

Preliminary results show about 1,000 hours of a dark lifetime. We plan to evaluate the charge lifetime after the extraction of more charges next year. The vacuum pressure of the gun is about 1 - 2×10^{-9} Pa even in the CW operation. There seem no critical issues on vacuum design of the electron gun. Details are reported in ref. [14].

Electron Gun

The gun voltage for daily operation has been limited to 390 kV while 500 keV was previously achieved at JAEA [15]. For lower emittance beams, we installed two new segmented ceramics to improve the breakdown voltage. In the last two days operation in Mar/2016, we successfully extracted a 450 keV electron beam from the gun and accomplished the energy-recovery operation to the main dump. The tentative emittance measurement shows smaller emittance than that of the 390 keV beam.

Injector SC Cavity

On 10/June/2015, we experienced degradation in the injector SC cavity performance; highest accelerating gradient had to decrease from 7 MV/m to 5 MV/m to avoid field emission. After pulsed-power aging of the SC cavities, accelerating gradient has successfully recovered near its original value. Details are reported in ref. [16].

SUMMARY AND FUTURE PLAN

Based on the scientific and experimental knowledge in the past cERL operation, we have carried out the improvements of components to realize high-current and low-emittance beam operation. We achieved 1-mA beam operation after the approval of beam operation. Results of high bunch charge operation indicate a green signal to the 10-mA operation. Bunch compression experiment shows the CTR components up to 1-THz region, and a corresponding bunch length of 150 fs.

Operational schedule of cERL in FY2016 is still unclear because financial supports from KEK headquarter have not been decided yet. Furthermore, short-term priority for the next light source project in KEK is now moving from linac-based light source to the high-performance ring accelerator. We believe it is quite important to keep the R&D activities at the cERL, to realize EUV light source [17] or CW-FEL light source in KEK.

REFERENCES

[1] N. Nakamura *et al.*, "Present Status of the Compact ERL at KEK”, in *Proc. IPAC’14*, Dresden, Germany, paper MOPRO110, pp. 353-355

[2] S. Sakanaka *et al.*, "Recent Progress and Operational Status of the Compact ERL at KEK", in *Proc. IPAC’15*, Richmond, VA, USA, paper TUBC1, pp. 1359-1362

[3] R. Hajima *et al.*, "Laser Compton Sources Based on Energy-Recovery Linacs", presented at ERL2015, Stony Brook, NY, USA, paper WEIBLH1050

[4] S. Sakanaka *et al.*, "Measurement and Control of Beam Losses Under High Average-Current Operation of the Compact ERL at KEK", presented at IPAC’16, Busan, Korea, May 2016, paper TUPOW038, this conference

[5] H. Matsumura *et al.*, "Beam Loss Estimation by Measurement of Secondarily Produced Photons under High Average-current Operations of Compact ERL in KEK", presented at IPAC’16, Busan, Korea, May 2016, paper WEPOR020, this conference

[6] T. Miyajima *et al.*, "Status of Higher Bunch Charge Operation in Compact ERL", in *Proc. IPAC’15*, Richmond, VA, USA, paper TUPWA067, pp. 1583-1586.

[7] O. Tanaka *et al.*, "Simulation Study of the Beam Halo Formation for Beam Loss Estimation and Mitigation of the Compact ERL at KEK", presented at IPAC’16, Busan, Korea, May 2016, paper TUPOW039, this conference

[8] H.Sakai *et al.*, "Measurement of the Cavity Performances of Compact ERL Main Linac Cryomodule During Beam Operation", in *Proc. SRF'15*, Whistler, BC, Canada, paper TUPB021, pp. 592-596

[9] N. Nakamura *et al.*, "Simulation Study on Bunch Compression and Decompression for the Compact ERL", in *Proc. IPAC’15*, Richmond, VA, USA, paper TUPWA069, pp. 1591-1593

[10] M. Shimada *et al.*, "Bunch Compression at the Recirculation Loop of the Compact ERL", presented at IPAC’16, Busan, Korea, May 2016, paper WEPOY010, this conference

[11] A. Ueda *et al.*, "Design and Fabrication of the Compact-ERL Magnets", presented at IPAC’16, Busan, Korea, May 2016, paper TUPMB005, this conference

[12] R. Nagai *et al.*, "Demonstration of High-flux Photon Generation from an ERL-based Laser Compton Photon Source", in *Proc. IPAC’15*, Richmond, VA, USA, paper TUPJE002, pp. 1607-1609

[13] A. Kosuge *et al.,* "Development of a High Average Power Laser for High Brightness X-ray Source and Imaging at cERL", in *Proc. IPAC’15*, Richmond, VA, USA, paper TUPWA066, pp. 1579-1582,

[14] N. Nishimori *et al.*, "DC Photoemission Gun Upgrade at the Compact ERL", presented at IPAC’16, Busan, Korea, May 2016, paper THPOW008, this conference

[15] N. Nishimori *et al.*, Phys. Rev. STAB 17, 053401 (2014).

[16] E. Kako *et al.*, "Long Term Cavity Performance in Compact-ERL Injector Cryomodule", presented at IPAC’16, Busan, Korea, May 2016, paper WEPMB013, this conference

[17] N. Nakamura *et al.*, "Design Work of the ERL-FEL as the High Intense EUV Light Source", in *Proc. ERL2015*, Stony Brook, NY, USA, paper MOPCTH010, pp. 4-9