THE FIRST BEAM RECIRCULATION AND BEAM TUNING IN THE COMPACT ERL AT KEK

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Abstract

To demonstrate overall technologies for the energy-recovery-linac(ERL)-based light source, we constructed the Compact ERL (cERL) during 2009-2013. In March, 2014, we succeeded in recirculating the CW beams of 6.5 μA in the cERL; the beams were successfully transported from the gun to the beam dump under energy recovery operation in the main linac. We report our experience on commissioning the cERL, as well as the results of initial measurements of beam properties.

INTRODUCTION

Superconducting(SC)-linac-based light sources [1,2], which can produce ultra-brilliant photon beams in CW operation, are attracting worldwide attention. In Japan, we have been conducting R&D efforts towards the energy-recovery-linac(ERL)-based light source [3] since 2006. To demonstrate overall technologies for the ERL, we constructed the Compact ERL (cERL) [4] at KEK during 2009-2013. Basic configuration and the principal parameters of the cERL are shown in Fig. 1 and Table 1.

In the cERL, high-brightness CW electron beams are produced using a 500-kV photocathode DC gun. The beams are accelerated to a nominal energy of 5 MeV in a SC injector module, and merged into the main linac (ML) where the beams are accelerated to a nominal energy of 35 MeV. The beams are then transported through a recirculation loop, decelerated in the main linac, and dumped. A major challenge in the cERL is the production and transportation of low-emittance and high-current beams which are required for the ERL light source.

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The injector of the cERL was constructed in Japanese fiscal year 2012, and it was completed in April, 2013. Commissioning of the injector [5] was conducted from April to June in 2013 with a total beam-operation time of 202 hours. During this period, we successfully produced low-emittance beams from a GaAs photocathode, and accelerated them to a typical total energy of 6.1 MeV.

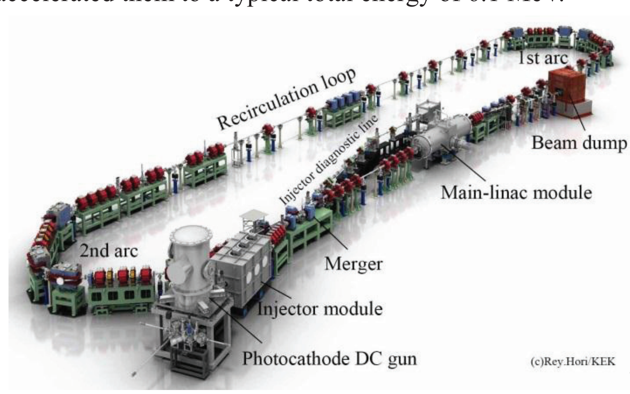

Figure 1: Illustration of the Compact ERL.

Table 1: The principal parameters of the cERL

Nominal beam energy E	35 MeV
Nominal injector energy E_{inj}	5 MeV
Beam current I_0 (initial goal)	10 mA
Normalized emittance ε_n	< 1 mm·mrad
RF frequency	1.3 GHz

From July to November in 2013, we constructed the recirculation loop including magnets, girders, vacuum

ISBN 978-3-95450-142-7

chambers, and beam monitors. A cryomodule for the main linac, having two nine-cell SC cavities, was installed in FY2012. During its high-power test [6], the two cavities could produce accelerating voltages of 13.5-14 MV for more than 1 hour. However, field emissions emerged at an accelerating voltage of about 8 MV. We then decided to start commissioning the cERL at a total energy of 20 MeV with accelerating voltages of 8.3-8.5 MV/cavity (8.0-8.2 MV/m) in ML cavities. During the construction, the path length was adjusted to be optimum one at 20 MeV.

TUNING OF BEAM RECIRCULATION

After cool-down process and high-power conditioning of SC cavities, we started commissioning the cERL on December 16, 2013. A layout of the cERL is shown in Fig. 2. Thirty fluorescent screens are used to measure both positions and profiles of beams at low average currents. Forty-five stripline BPMs are used to measure beam positions non-invasively. Beam currents are measured at the beam dump and at the gun power supply by subtracting offset currents, as well as can be measured using three movable Faraday cups (FCs) along the beamline.

During machine tuning, we produced low-intensity macropulse beams from the photocathode DC gun with a cathode voltage of 390 kV. Typical parameters of beam pulses were: macropulse width of 1.2 μs, bunch charges of about 20 fC/bunch, repetition of macropulses of 5 Hz, repetition of bunches of 1.3 GHz, and an average beam current of 160 pA.

First, we set up injector beams. Rf phases in three injector cavities were adjusted to on-crest acceleration while a buncher cavity was turned off; beams were steered at the centers of two solenoids and of the first injector cavity. Total energy of the injector beams was adjusted to be 2.9 MeV (initially, 3.4 MeV). Next, we steered beams through a three-dipole merger and ML cavities. RF phases in ML cavities were then adjusted to on-crest acceleration which gave a total beam energy of 19.9 MeV.

We transported beams through the first arc, the south straight section, and the second arc; beams were steered at approximately the centers of major quadrupoles while changing each quadrupole strength and monitoring the beam positions downstream. The recirculated beams passed further through an injection chicane where a dipole kick due to a merger dipole is canceled by the other two dipoles. We set the momentum ratio of recirculated beam to injected beam to be 7 to 1 (initially 6 to 1); the momentum ratio should be larger than 6 to 1 due to finite aperture in the injection chicane.

In the main-linac section between the injection chicane and the dump chicane, both injected and recirculated bunches pass while they are separated longitudinally by approximately a half rf wavelength. Since non-invasive measurement was needed, we measured the beam positions using four BPMs. The signals were detected at 1.3 GHz, and signals from two beams were separated utilizing the timing difference between them by a beam-recirculation time of 300 ns. We steered beams in this section using corrector magnets which located upstream the injection chicane since the use of correctors in the main-linac section affected both two beams. This procedure required delicate tuning in beam recirculation.

The recirculated beams decelerated when they passed through the ML cavities. We adjusted an rf phase of deceleration by changing the path length of the recirculation loop. Figure 3 shows an example. The path length was changed by an orbit bump in the second arc section (Fig. 3, right); the corresponding momenta of decelerated beams were measured at a screen (No. 31) in the dump line. The path length was adjusted so that the momenta took a minimum. The path length can be changed by ±10 mm in each arc, and by ±5 mm in a path-length control chicane; the former method was mainly used because the latter chicane produced some hysteresis in the beam orbit. We found that an initial path length was very close (within a few mm) to the optimum one.

Following these tuning process, we observed the first beam signal at the beam dump on Feb. 6, 2014. As reported in [4], problems during the initial stage of commissioning were mostly due to unwanted magnetic fields.

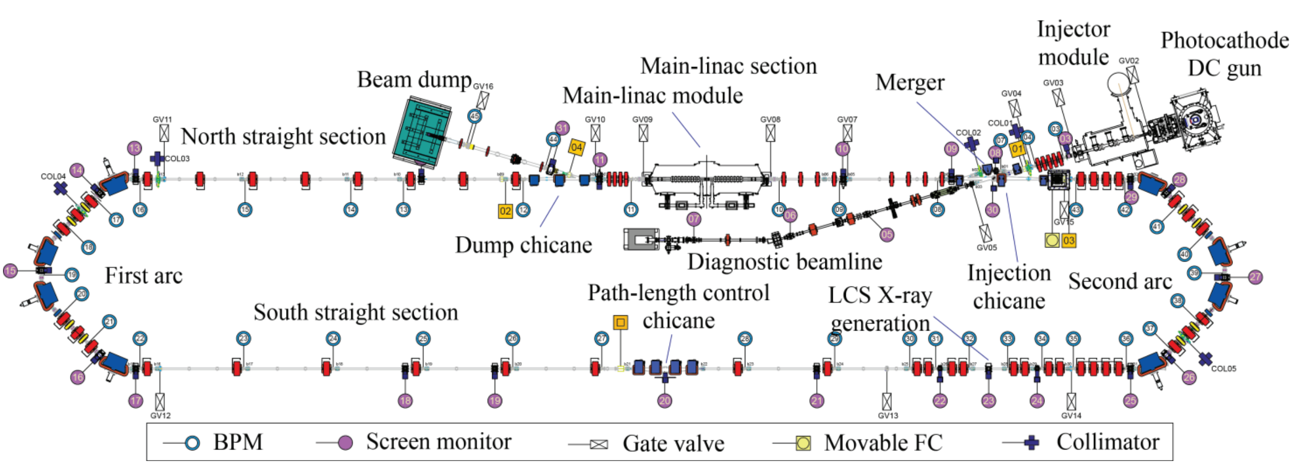

Figure 2: Layout of the Compact ERL. Blue and red symbols denote dipole and quadrupole magnets, respectively.

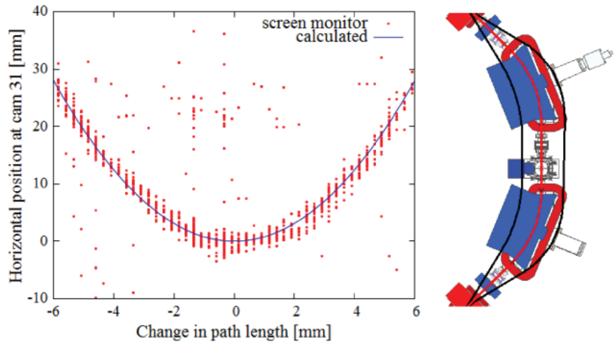

Figure 3: Tuning of decelerating phase. (Left) horizontal beam positions at the dump line as a function of the path length. (Right) path length control in the second arc.

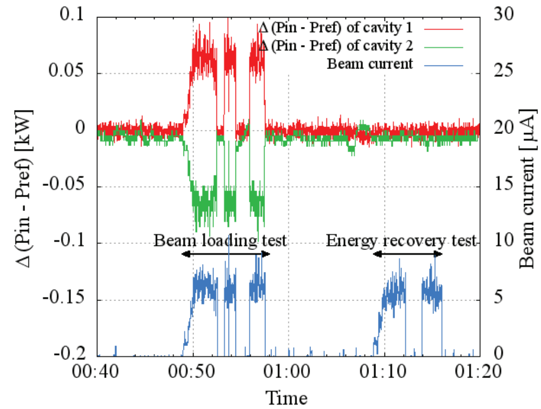

Figure 4: Demonstration of energy recovery in the ML cavities. Differences in the input and reflected rf powers are shown for the ML cavity 1 (red) and 2 (green), respectively. The beam current is indicated by blue lines.

BEAM MEASUREMENTS AND TUNING

Optics Measurements and Corrections

We corrected beam optics before the first arc and at the other three locations. We measured the response of beam sizes at a screen while changing the strength of an upstream quadrupole. The measured response was compared to that from design optics, and we corrected the strengths of four upstream quadrupoles so that the measured response became close to design one. Due to these corrections, beam losses in the recirculation loop became small.

We also measured responses of beam positions due to single kick at each corrector. These measurements were useful for finding unwanted magnetic fields along the beamline. The dispersion function was also measured using screen monitors by changing rf voltages of ML cavities, and it was partly corrected.

CW Operation and Energy Recovery

After several tuning to reduce beam losses, we tried to recirculate CW beams. The use of a buncher cavity with an rf voltage of 30 kV helped to reduce the beam losses. In March, 2014, an average beam current of 6.5 μA was successfully transported to the beam dump with small beam losses under CW operation. The radiation levels outside the accelerator room were almost background ones. Beam current is currently limited to 10 μA due to our present application to the authority, and we plan staged increase in beam currents.

Figure 4 shows a demonstration of energy recovery in the ML cavities under CW operation. First, we conducted a non-ERL operation by reversing an rf phase in the downstream (ML2) cavity; a 2.9-MeV beam was accelerated and decelerated in ML1 and ML2 cavities, respectively, and was transported directly to the dump. Under this operation, both positive and negative beam loadings were observed in the ML1 and ML2 cavities, respectively. Under the usual ERL operation, on the other hand, we observed little beam loading in these cavities.

Emittance Measurement

Beam emittances were measured using quadrupole-scan method; we varied the field strength of a single quadrupole located upstream a screen and measured beam sizes. Measurements at four locations showed that the normalized emittances could be preserved well through the main linac and the first arc at low bunch charges. For example, horizontal and vertical normalized emittances were both 0.14 mm·mrad just after the first arc at a bunch charge of 14 fC/bunch (macropulse beam).

High Charge Operation

We tried to recirculate macropulse beams at higher charges of up to 7.7 pC/bunch for a week. We needed considerable tuning such as longer laser pulses, stronger focusing in solenoids, and optics matching in the loop. We could transport about 90% of injected beams to the beam dump within a week. Due to limited time, the normalized emittances were modest; roughly 2.9 mm·mrad (@2.9 MeV) in the injector, and 5.8 mm·mrad (@19.9 MeV) after the first arc. We will conduct further tuning hereafter.

CONCLUSION

The Compact ERL was commissioned at a beam energy of 19.9 MeV. A CW beam of 6.5 μA was transported from the photocathode DC gun to the beam dump under energy recovery operation with small beam losses. Fine optics tuning and beam measurements are underway.

ISBN 978-3-95450-142-7

REFERENCES

[1] N. Nakamura, “Review of ERL Projects at KEK and Around the World”, IPAC’12, New Orleans, May 2012, p. 1040 (2012).
[2] J. Galayda, “The Linac Coherent Light Source-II Project”, IPAC’14, Dresden, Germany, p. 935 (2014).
[3] “Energy Recovery Linac Conceptual Design Report”, KEK Report 2012-4, KEK, October, 2012; http://ccdb5fs.kek.jp/tiff/2012/1224/1224004.pdf
[4] N. Nakamura et al., “Present Status of the Compact ERL at KEK”, IPAC’14, Dresden, Germany, p. 353 (2014).
[5] S. Sakanaka et al., “Construction and Commissioning of the Compact-ERL Injector at KEK”, ERL2013, Novosibirsk, p.16 (2013).
[6] K. Umemori et al., “Construction of Main Linac Cryomodule for Compact ERL Project”, IPAC’13, Shanghai, China, p. 2349 (2013).

ISBN 978-3-95450-142-7