RECENT PROGRESS AND OPERATIONAL STATUS OF THE COMPACT ERL AT KEK

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Abstract

The Compact Energy Recovery Linac (cERL) is a superconducting test accelerator aimed at establishing technologies for the ERL-based future light source. After its construction during 2009 to 2013, the first CW beams of 20 MeV were successfully transported through the recirculation loop in February 2014. In the autumn of 2014, we installed a laser Compton scattering (LCS) system which can provide high-flux X-ray to a beamline. We report our progress in the cERL including recent advances in beam tuning, an increase in the beam current, and successful commissioning of the LCS system.

INTRODUCTION

Superconducting (SC) linacs can provide both low-emittance and high average-current electron beams that are very useful for producing ultra-brilliant X-rays [1] or for driving X-ray free-electron lasers in continuous wave (CW) operation [2]. In Japan, we have been conducting R&D effort for the ERL-based synchrotron light source [3]. To demonstrate critical technologies for the ERL-based light source, we constructed the Compact ERL (cERL). The principal parameters of cERL are given in Table 1.

Figure 1 shows the statistics of beam operation time (that is, the time while the beam was on) during FY2013-2014. The first CW beams of 20 MeV were successfully transported through the recirculation loop in February 2014 [4,5]. After the commissioning, various accelerator studies have been carried out. They include an establishment of start-up tuning, correction of beam optical functions, study on beam losses [6], and measurements of beam emittances in a recirculation loop. Some of the results of these studies are reported in the next section.

Table 1: Principal Parameters of the cERL

	Design	In operation
Beam energy	35 MeV	20 MeV
Injector energy	5 MeV	2.9 - 6 MeV
Normalized emittance	0.1 µm·rad@7.7 pC 1 µm·rad@77 pC	under study
Beam current	10 mA	80 µA

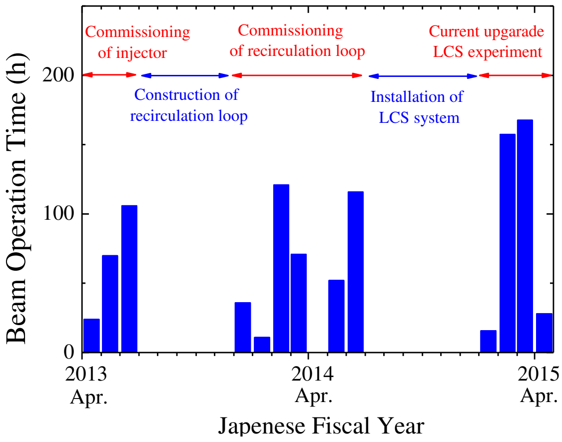

Figure 1: Statistics of beam operation time per month.

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* On leave

In the summer of 2014, we applied for a change of the maximum beam current (from 10 μA to 100 μA) to the authorities, and got approval in September. We then conducted high current operations in 2015.

From September to December in 2014, we installed an LCS system which aims at demonstrating technology for the future high-flux gamma-ray source [7,8] as well as aiming at developing advanced X-ray imaging technology by compact accelerators [9,10]. The LCS system consists of an optical cavity resonator, a 1064-nm drive laser, an X-ray beamline, and an experimental hut. During February to April in 2015, we have established an operation for the LCS experiment. Accelerator issues related to the LCS experiment are reported in Sec. 4. The commissioning result of the LCS system is primarily reported in [8,10].

BEAM TUNING

Effects of Ambient and Remanent Fields

Due to low total energy of 20 MeV, beams are very sensitive to ambient or remanent magnetic fields. For example, leakage fields from cold-cathode gauges (CCGs) affected beams, and they were shielded. We also found that an excitation current of the KEKB bending-magnets produced magnetic fields of about 20 mG at the cERL, which largely deflected beams. We then managed to avoid beam tuning when the excitation current changed.

We also found that remanent fields of quadrupoles caused gradient errors (ΔK/K) of an order of 10-20% due to low operating fields. In addition, gradient errors due to hysteresis were accumulated through daily tuning. We are studying effective standardizing procedure in exciting quadrupoles to improve their reproducibility.

Procedure of Start-Up Tuning

Every running day, we start-up the cERL in the morning, tune the beam, carry out accelerator studies or experiments until 11 p.m., and shut down. Through these operations, we have almost established tuning procedure.

Using burst beams (macropulse length: 1 μs, repetition: 5 Hz), we steer the beam at the centers of major quadrupoles or of solenoids. This is done by modulating the strength of each quadrupole or solenoid, measuring the beam position at a downstream screen, and correcting the beam position at each quadrupole or solenoid. Rf phases in injector cavities or in main-linac (ML) cavities are finely adjusted so that the beam momentum takes a maximum; we usually use on-crest acceleration. We optionally position the beam at the center of each cavity; this is done by changing an rf phase of each cavity and monitoring the change in the beam position, that is, utilizing the focusing force due to rf fields.

After the beam is accelerated in the main linac, we steer the beam through the first arc, the south straight section, and the second arc (see Fig. 2). After the second arc, we adjust both position and angle of the beam using steering coils at the location indicated by (a) in Fig. 2 so that the beam passes through the ML cavities while decelerating, and is extracted to the dump line; in the second beam passage, we do no change any steering magnets between the injection and the dump chicanes where both low- and high-energy beams pass.

Since beam profiles in the dump line are very sensitive to gradient errors, we adjust them by tuning the quadrupoles finely in a location (a) in Fig. 2. We sometimes adjust quadrupoles in a location (b) in Fig. 2 for the same purpose, however, this affects the first passage of the beam and needs some iteration. Next, we adjust finely the path-length so that the beam momentum takes a minimum at the dump line.

To speed-up tuning process, we have developed several tuning “knobs”. With a path-length knob, we can change the path length by exciting four steering magnets or coils in each arc section. Another example is an R_{56}-control knob by which several quadrupoles in each arc section are changed by a determined ratio.

Once the beam is transported to the beam dump, we check if there is no significant beam loss along the beamline using beam-loss monitors [11]. If beam losses are small, we can switch to CW beams for high-current operations.

Optics Matching and Beam Emittance

Because of large gradient errors due to remanent fields etc., the optical functions in the cERL should be corrected so that they become close to design ones. We measured the optical functions at some locations along the cERL using quadrupole-scan method, and corrected them. The method of optics matching is reported in [12].

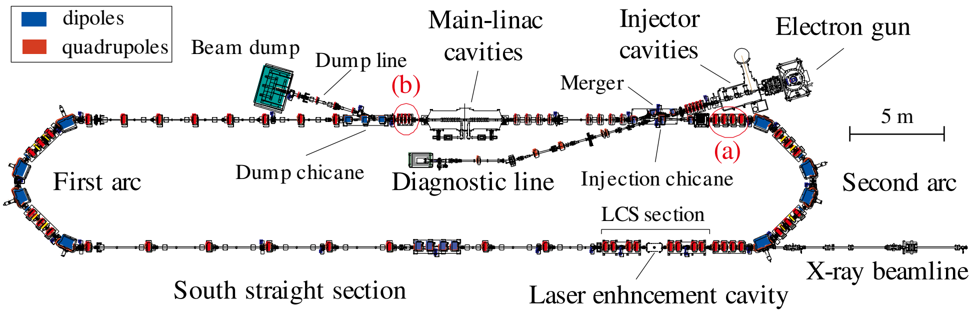

Figure 2: Layout of the Compact ERL after the laser Compton scattering (LCS) system was installed.

During February to March in 2015, we concentrated to obtain low-emittance beams in the LCS section, which is important for the LCS experiment. After several tuning, we obtained normalized emittances of $\varepsilon_{\mathrm{nx}}$ = 0.41 μm·rad (horizontal) and $\varepsilon_{\mathrm{ny}}$ = 0.3 μm·rad (vertical) at a bunch charge of 0.5 pC [12].

HIGH-CURRENT OPERATION

Small beam losses are essential in high current operations. To this end, we carefully carried out beam tuning and optics matching. To control beam losses, we used beam collimators. There are five collimators, and each of them has four movable copper rods which are cooled by water. A collimator (No. 2) at a merger section (E = 2.9 MeV, η_{x} = 0.23 m) was found to be very effective to eliminate beam tails or halos with modest increase in radiation. The right (low-energy side) and upper rods were typically inserted to the distances of 2.0 mm and 3.4 mm from the beam, respectively. To avoid any troubles due to large beam losses, we used a fast interlock system for stopping the gun laser when large signals were detected at beam loss monitors [11].

In April 2015, we succeeded in transporting the maximum beam current of 80 μA to the beam dump. Operational parameters were: beam energies of 19.9 MeV at the loop and 2.9 MeV at the merger, a bunch repetition rate of 162.5 MHz, a bunch charge of 0.5 pC, and beam optics for the LCS experiment. Beam losses in the recirculation loop were controlled well using the beam collimator No. 2.

LASER COMPTON SCATTERING

In an operation for the LCS experiment, electron beams are focused to a very small size (typically, 30 μm rms) at an interaction point (IP) where the electron bunches collide with laser pulses. Beam losses in the LCS section should be minimized to avoid undesirable background radiation to detectors. Therefore, there is some compromise between small beam size and small beam losses nearby the IP. Figure 3 shows an example of low-β optics in the LCS section. In this design, beam sizes at the IP are expected to be σ_{x}^{*} = 21 μm (horizontal) and σ_{y}^{*} = 33 μm (vertical) using measured normalized emittances of $\varepsilon_{\mathrm{nx}}$ = 0.47 μm·rad and $\varepsilon_{\mathrm{ny}}$ = 0.39 μm·rad at a bunch charge of 0.5 pC.

We have established the following tuning procedure of the beam optics in the LCS section. First, we set up designed K-values of quadrupoles, actually having some errors. After the optics matching before the LCS section, we scanned K-value of a quadrupole QMLC04 in Fig. 3, and measured beam sizes using a screen monitor at the IP. While looking at the response curves, we adjusted the K-value of QMLC03 so that both horizontal and vertical beam sizes (σ_{x}, σ_{y}) had waists at the same K-value of QMLC04; the K-value of QMLC04 was determined so that both σ_{x} and σ_{y} took minima. After the tuning, we obtained, for example, beam sizes of $\sigma_{\mathrm{x}}^{*}\approx$13 μm and $\sigma_{\mathrm{y}}^{*}\approx$25 μm at the IP, which was estimated from the Q-scan measurement.

Using the “LCS optics” mentioned above, we succeeded in transporting the beam to the dump with small beam losses. In the LCS experiment, we chose a bunch repetition frequency of 162.5 MHz that was matched to the frequency of laser pulses. An waist size of the laser was approximately 30 μm in rms at the IP. After we adjusted both positions and phase of laser pulses, we succeeded in colliding the electron bunches with laser pulses. As a result, we observed 6.9-keV X-ray signal [8,10] with a detector at the end of the beamline. Finally, we conducted the LCS experiment at a bunch charge of 0.5 pC in CW operation (average current: 80 μA). Typical count rate of X-ray was 1200 counts/s in the detector (diameter: 4.66 mm, distance from the source: ~ 16.6 m) at a beam current of 58 μA. The success of sustained collision between the beam and laser demonstrated high quality and high stability of cERL beams.

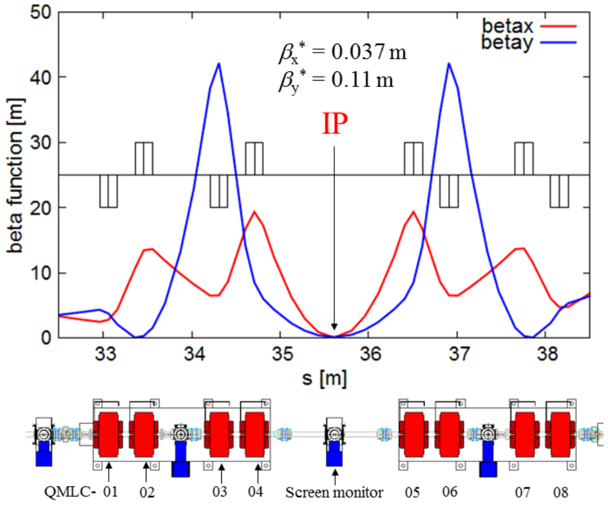

Figure 3: Design of low-β optics in the LCS section.

CONCLUSION

Various accelerator studies are in progress in the Compact ERL. We have achieved the maximum beam current of 80 μA in CW operation. The successful beam-laser collisions demonstrated both high-quality and high-stability of cERL beams. Hereafter, we will study lower-emittance operation at high bunch charges, higher beam currents, bunch compression, and higher X-ray flux in the LCS experiment.

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