MEASUREMENT AND CONTROL OF BEAM LOSSES UNDER HIGH AVERAGE-CURRENT OPERATION OF THE COMPACT ERL AT KEK

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Abstract

The compact ERL (cERL) [1, 2] at KEK is a superconducting accelerator aimed at demonstrating ERL technologies for the future light source. In cERL, low-emittance and high-average-current electron beams of up to 10 mA will be recirculated in future. Toward this goal, we studied high-average-current operations where the beam losses should be controlled to very-small fractions. We have so far succeeded in recirculating beams of up to 0.9 mA with very-small beam losses. We report our accelerator tuning method for high-average-current operation, and present measured radiation data showing very-small beam losses.

INTRODUCTION

In cERL, production and transportation of low-emittance (< 1 mm·mrad) and high-average-current (≥ 10 mA) electron beams are primarily important. In high-intensity linacs such as cERL, reduction of beam loss is essential in order to reduce the risk of radiation hazard as well as to avoid damages in accelerator components.

Till June of 2015, electron beam having an average current of 80 μA was successfully transported to the beam dump in cERL. Due to careful accelerator tuning and the use of beam collimators, beam losses along a recirculation loop were reduced to small amounts. At this time, we conducted radiation measurements with several methods, and estimated amounts of beam losses [3]. Based on these data, we installed some additional radiation shields, and applied an increase in our authorized beam current, that is, from 100 μA to 1 mA. This application was approved by the government in January, 2016.

Until March of 2016, we established high average-current operations of cERL up to a maximum beam current of 1 mA. Typical operational parameters are given in Table 1. We can choose one of two repetition rates of bunches, 1.3 GHz or 162.5 MHz, by selecting one of the laser oscillators of a photocathode DC gun. First, we tuned the machine at a higher bunch-repetition rate (1.3 GHz) with lower bunch charge (0.7 pC/bunch). After this operation has been established, we conducted operations at lower repetition rate (162.5 MHz) and higher bunch charge (5.5 pC/bunch). Under this operation, controlling space-charge effect in an injector section is important.

Table 1: Typical Operational Parameters of cERL

Beam energy	19.9 MeV
Injection energy	2.9 MeV
Bunch repetition rate (usual)	1.3 GHz
(for laser-Compton scattering)	162.5 MHz
Maximum average beam current	1 mA

ACCELERATOR TUNING FOR HIGH-AVERAGE-CURRENT OPERATION

Before high-average-current (or continuous wave; CW) operation of cERL, we tune the machine under burst mode. Under this mode, we produce low-average-current macropulse beams having macropulse length of 0.5 – 1 μs and macropulse-repetition rate of 5 Hz. Both the bunch charge and the bunch-repetition rate (1.3 GHz or 162.5 MHz) are kept the same as those under the target CW operation in order to keep the same space-charge effect in the injector. Then, we conduct accelerator tuning using such monitors as fluorescence screens, beam position monitors, and beam-loss monitors. Important issues for beam-loss reduction are: 1) careful optics tuning, 2) beam-halo collimation, and 3) suitable amplitude of rastering at a dump line.

Tuning of Beam Optics

In the injector, we adjusted the beam orbit so that the beam profile was kept cylindrically symmetric as much as possible. We found that strongly-excited corrector dipoles between the gun and the injector-cavities produced some non-linear fields. Then, we weakened these correctors while the beam was off-center at two solenoids.

In front of the main-linac (ML) cavities, we carefully matched the beam optics of injected beam to the design optics of the recirculation loop. As a result, beam profiles in the recirculation loop became more similar to those of design. In addition, we corrected the beam optics at some locations of the loop. The method of optics matching is presented in [4].

We found that the beam of cERL has some spatial halos around a core of the beam. Mechanism of halo formation is under study [5]. One of the possible mechanisms is a transformation of beam tails, which are produced at a photocathode, into spatial halos. To reduce the beam losses along the recirculation loop, the beam halos, or tails, should be eliminated well. We found that when the beam enters the injector cavities with a slight angle about the central axis of the injector, we can enhance the elimination of beam halos or tails. This is probably because the beam tail is kicked transversely by rf fields, which yields transverse offset at collimators. This method is usually

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used in our high-average-current operation. In order to achieve extremely-small beam emittance, it is desirable to disuse this offset angle by such means as reducing the beam tails at the photocathode gun.

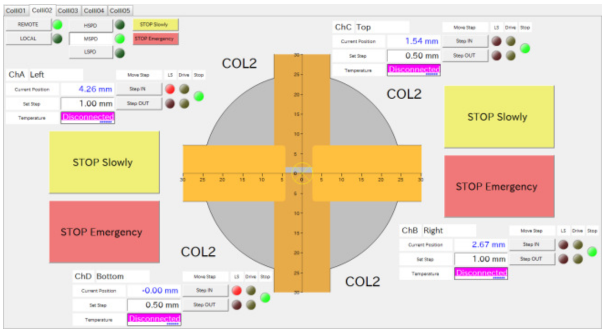
Beam Collimation

Five beam collimators, shown in Table 2 and in Figs. 4 and 5, are installed. Two of them, COL1 and 2, are especially useful because we can eliminate beam halos at a low-energy (2.9 MeV) section. Each collimator has four movable plungers (water-cooled copper, diameter: 14 mm), as shown in Fig. 1. These collimators are shielded by lead plates or blocks.

We adjust the position (defined by a distance of a plunger-head from the center of beam duct) of each plunger so that we eliminate beam halos effectively while avoiding loss of beam core. An example of the adjustment is shown in Fig. 2. In this example, we transported a burst beam having a peak current of approximately 300 μA at a bunch repetition rate of 1.3 GHz. While looking at beam-loss monitors in the recirculation loop, we inserted the plungers of a collimator “COL2”. Corresponding to the insertion of plungers, we observed reductions in beam losses in the recirculation loop. When we inserted a right plunger too much at 16:47, on the other hand, we observed a decrease in the beam current at the dump. This indicated a loss of beam core, which should be avoided. The loss of beam core can also be detected by a loss monitor nearby the collimator. We finally set COL2 as shown in Fig. 1, and then, adjusted another COL1 similarly. Under a succeeding high-average-current operation, we confirmed that the beam losses were very small along the recirculation loop.

Table 2: Beam Collimators

Name	Location	Dispersion η_x
COL1	Exit of injector	0
COL2	Merger	0.23 m
COL3	North straight section	0
COL4	First arc	-1.28 m
COL5	Second arc	-1.28 m



ChA Left
Current Position 4.26 mm
Set Step 1.00 mm
Temperature Disconnected

ChC Top
Current Position 1.54 mm
Set Step 0.50 mm
Temperature Disconnected

ChB Right
Current Position 2.67 mm
Set Step 1.00 mm
Temperature Disconnected

ChD Bottom
Current Position -0.00 mm
Set Step 0.50 mm
Temperature Disconnected

Figure 1: Schematic of a beam collimator, COL2.

Due to small bunch charges of up to 7.7 pC (with a beam current of 10 mA at 1.3 GHz), we expect that transverse wakes induced in the collimators do not bring much growths in projected emittances. However, this issue should be confirmed by experiment or by calculation in future.

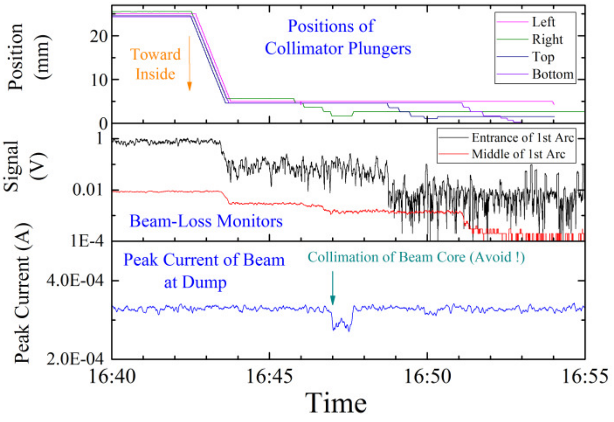


Figure 2: Typical process of collimator adjustment; (upper) positions of plungers of a collimator COL2; (middle) signals of two beam loss-monitors in log scale; (lower) peak current of beam at the dump.

Adjustment of Rastering Amplitude

To reduce the power density at the beam dump, we raster the beam in the dump line. Large amplitude of rastering caused some increase in the beam loss in the dump line. We determined the amplitude by a compromise between the power density and the beam loss. Current parameters are full amplitude of approximately 10 mm in both horizontal and vertical directions at a frequency of 9.9 Hz.

RADIATION MEASUREMENTS

During a high-average-current operation, shown in Fig. 3, we measured radiation levels on the top of the radiation shield. The upper shield is made of reinforced concrete of 1-m thick, and the radiation level on the top reflects a distribution of beam losses. A result of the measurement is shown in Fig. 4. Bunch repetition rate and bunch charge were 162.5 MHz and 5.5 pC, respectively. Three collimators, COL1, 2, and 4, were used during this operation.

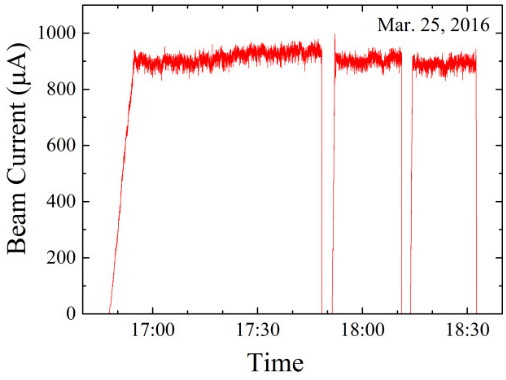


Figure 3: Beam current during a high-average-current operation. Bunch repetition rate: 162.5 MHz.

The measured radiation level in Fig. 4 was satisfactorily low. Some radiation levels were detected in: area (a) where darkcurrent from main-linac cavities produced radiation, and area (b) where a collimator (COL4) eliminated some of beam halos at high energy. An estimated beam-loss ratio at COL4 was 0.009% [3], which was deduced from the measured radiation level of 3.8 μSv/h above COL4. Although beam halos were also eliminated at collimators COL1 and COL2, they did not contribute to measured radiation levels due to low beam energy.

In the radiation-shield room of cERL, twelve radiation monitors, MAR-782 from Hitachi Ltd., are installed and used as calibrated loss monitors. Figure 5 shows the measured radiation levels using these monitors under the same operation in Fig. 4. These data, together with data from the other loss monitors, indicate the following major beam-loss locations: (a) at COL1 and COL2 where beam halos were eliminated at low energy, (b) COL4 where beam halos were eliminated at high energy, (c) the last part and an exit section of the second arc, and (d) an exit of the main linac and the dump line. These locations (a) – (d) are indicated in Fig. 5. Nearby the main-linac, darkcurrent from the main-linac cavities also contributed to the radiation, as indicated by blue numbers in Fig. 5.

CONCLUSION

By careful accelerator tuning and beam collimation, we have achieved very-small beam losses under high-average-current operation of cERL. The beam current achieved was 0.9 mA at a bunch charge of 5.5 pC. The beam current is presently limited by authorization. It is technically possible to increase the beam current to 10 mA by changing the bunch repetition rate to 1.3 GHz and by increasing the bunch charge by a factor of 1.4.

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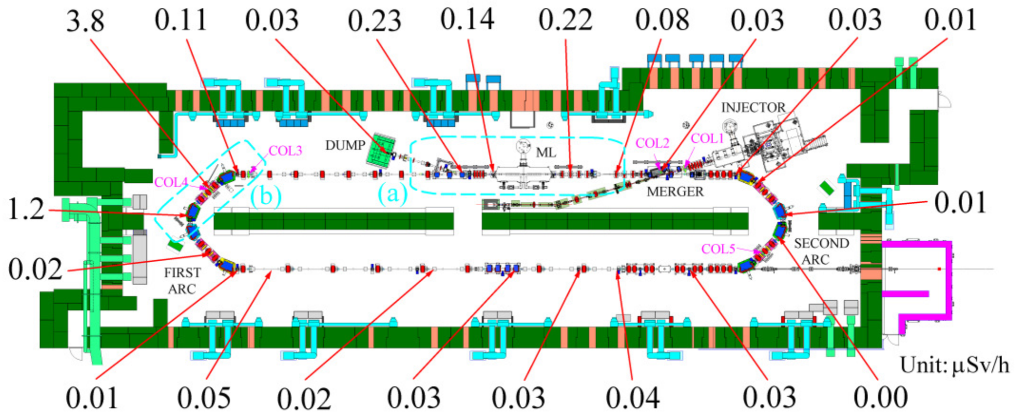

Figure 4: Measured radiation levels (in unit of μSv/h; after background subtraction) on the top of radiation shield. An NaI scintillation survey meter (TCS-171B from Hitachi Ltd.) was used. Average beam current: approximately 900 μA, repetition rate of bunches: 162.5 MHz.

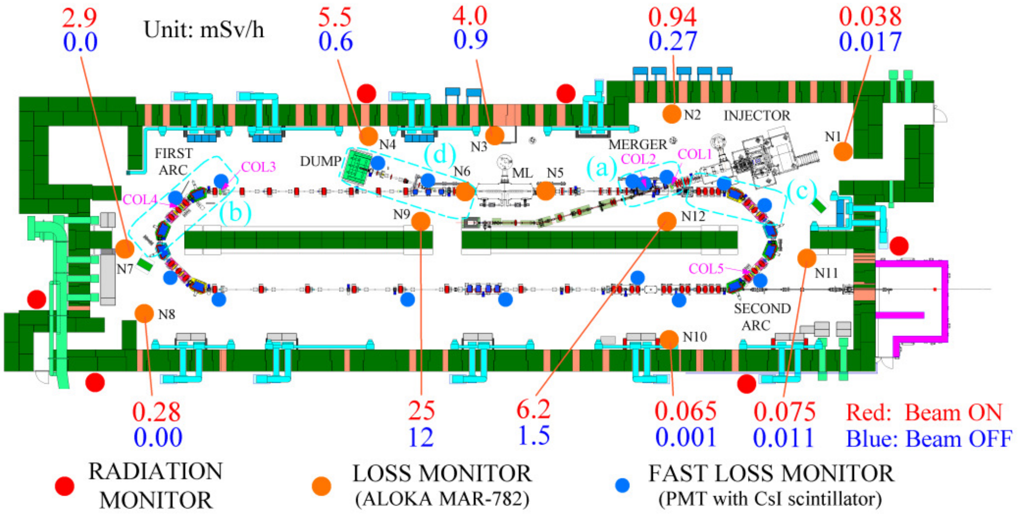

Figure 5: Measured radiation levels (unit: mSv/h) inside the radiation shield. Numbers in red and blue colors indicate those with beam (beam current: 900 μA) and without beam (but with darkcurrent from SC cavities), respectively.

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