BEAM HALO OBSERVATION AND EXAMINATION FOR BEAM LOSS REDUCTION AT THE KEK COMPACT ERL

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Abstract

Since the KEK Compact ERL (cERL) was constructed and successfully commissioned, the beam loss studies are performing systematically to prevent the radiation damage of the accelerator elements, and to keep the irradiation outside the machine at the safety level. It is known from the beam tuning experience that the most likely cause of the beam halo in cERL is longitudinal bunch tail originated at the photocathode transferred into the transverse plane. We guess it occurs due to rf field kicks. And the reason of these kicks is believed to be the complex effect of injector cavities misalignment and steering coils influence on the beam trajectory inside the cavity. Such mechanisms launch a transverse offset at collimators. Thus, the collimation system cuts the beam halo well, resulting to the beam loss reduction in the recirculating loop. To sum up the goal of the beam halo measurements and simulations reported here is to check and to confirm the tail transformation hypothesis of beam halo formation and beam loss issues in cERL.

INTRODUCTION

The development of the KEK Compact Energy Recovery Linac (cERL) goes according to the plan. Recently, several achievements, such as beam current increase up to 1 mA, beam loss reduction to a few nA, successful commissioning of laser Compton scattering (LCS) system, were reported [1 – 2]. To make these improvements possible, a great deal of work has been done. First, the beam loss mitigation was allowed not only by the careful accelerator adjustment, but due to the effective use of the collimation system, due to the proper radiation measurements with several methods [3 – 5], and due to the dump line amplitude rastering [6]. Then, the beam optics tuning and orbit correction were carried out in order to suppress the emittance increase due to the space charge effect, and to achieve a high current operation of 1 mA [7 – 9]. Typical parameters of cERL are summarized in Table 1.

At present time the storage ring-type light source is chosen as the first stage of the future light source plan at KEK. KEK-LS (KEK Light Source) is scheduled as a low-emittance electron storage ring of energy 3 GeV [10 – 12]. Nevertheless, the second stage of the plan is linac-type light source establishment. Thus, large-size ERL is going to be used as CW-XFEL (high-repetition-rate FEL linac) or EUV-FEL (FEL for Extreme Ultraviolet lithography) [13 – 14]. That is why the R&D of ERL technologies in KEK is still very urgent task. Also with proper improvement cERL can find its applications as high-power THz light source or as the high-flux LCS facility [15 – 16].

Table 1: Typical Parameters of cERL

Parameters	Design	In operation
Beam Energy	35 MeV	19.9 MeV
Injector energy	5 MeV	2.9 – 6.0 MeV
Gun high voltage	500 kV	390 – 450 kV
Maximum current	10 mA	1 mA
Bunch length	1 – 3 ps	1 – 3 ps (usual) 0.15 ps (compressed)
Repetition rate	1.3 GHz	1.3 GHz (usual) 162.5 MHz (for LCS)

R&D of the current machine include lower emittance (< 1 mm mrad) establishment at higher bunch charges (7.7 pC), and beam current increase up to 10 mA [1]. Recent studies demonstrate a technical possibility to do it. The current increase scheme includes the following steps:

1. Beam repetition rate increase.
2. Accelerator adjustment (optics tuning, orbit corrections (especially in the injector line), radiation surveys, beam loss estimation).
3. Beam halo collimation (to reduce the beam losses along the beam line).

The last step becomes very important when the average current is increased. Several mechanisms such as space charge, intrabeam scattering, and many others [17] come into effect, resulting in the beam halos or tails and, consequently, in the beam losses. Our beam tuning and beam loss reduction experience allows us to conclude that the most likely cause of the beam halo in cERL is longitudinal bunch tail transferred into the transverse plane due to "design-related" reasons. Namely, it could be rf field kicks, which produce a transverse offset at collimators. We believe the reason of these kicks to be the complex effect of injector cavities misalignment and steering coils influence on the beam trajectory inside the cavity. The transverse offset allows the collimation system work well for the beam loss reduction purpose [1, 3, and 18]. Longitudinal bunch tails issues, originating at the photocathode are discussed in [19]. Studies of other beam halo and beam loss reasons (Coulomb scattering, dark current etc.) are given in [20]. These reasons are out of the scope of this paper, because they become serious in high-energy ERLs.

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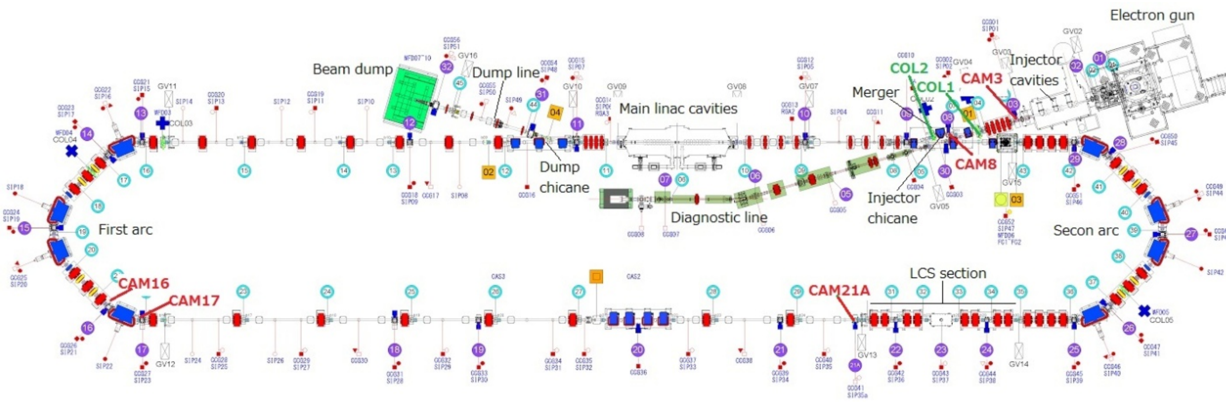

Figure 1: Layout of cERL with measurement equipment.

Therefore, the goal of the beam halo measurements and simulations reported here is to check and to confirm the tail transformation hypothesis of beam halo formation and beam loss issues in cERL.

BEAM HALO MEASUREMENT

A series of beam halo measurements were performed from Feb. to Apr., 2016 to approve the tail transformation mechanism above. We used several CCD cameras, collimators in the merger section, and beam loss monitors to observe the beam loss level changes during the measurement (see Fig1). The choice of the observation locations was made based on the radiation survey results. Thus, CAM8 placed in the merger section, where the dispersion impacts to the halo formation. CAM 16 of the 1st arc is also located in the dispersive section. Therefore, some particles with an energy spread could be observed. South straight section, were we chose CAM17 and CAM21A, is known for its beam losses. CAM17 picks up the beam profiles in the place with big betatron oscillations. Location of CAM21A (before the LCS system) coincides with the loss point. COL1, 2 helpful to reduce the beam loss in the recirculating loop, are in the merger section.

Table 2: Halo Measurement Settings

Settings	Burst	Long pulse
Macro pulse duration	1 μs	1.5 ms
Macro pulse frequency	5 Hz	0.6 Hz
Integration time	10 μs	2 ms
Bunch charge	0.2-0.3 pC	2.6 fC
Average current	1.5 nA	3 nA
Peak current	300 μA	15 nA
Repetition rate	1.3 GHz	1.3 GHz
Beam energy	2.9 - 20 MeV	20 MeV

The measurement was performed in three steps. The measurement settings are listed in the Table 2. First, we adjust the trigger delay so that only one macro pulse 1 μs (1.5 ms) could be captured during one camera shutter pulse 10 μs (2 ms). Set the camera gain to maximum (22 dB). Then the sets of beam halo profiles are collected automatically with macro pulse frequency 5 Hz (0.6 Hz). And last step is collimators insertion. After that, steps 1 – 2 should be repeated. The beam loss in the recirculating loop is monitored by the loss monitors during all the measurement.

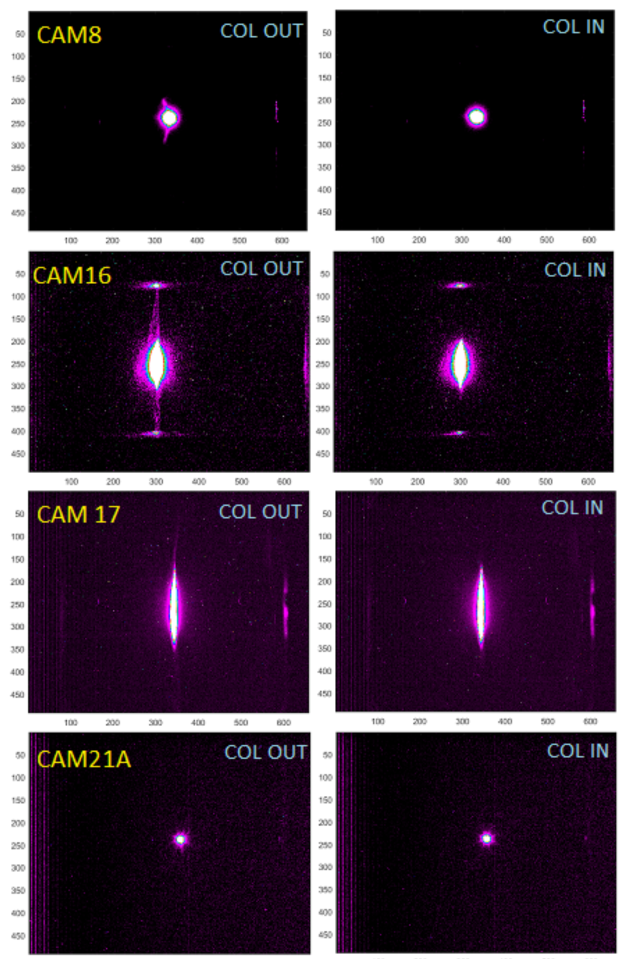

Figure 2: Observed vertical beam halos. CAM8: 3/2, burst mode, gain 22, integration time 10 μs, CAM16 – 17: 3/9, long pulse mode, gain 22, integration time 2 ms, CAM21A: 3/14, burst mode, gain 22, integration time 10 μs.

After the proper data processing, vertical halos at all camera locations can be observed clearly (see Fig. 2). On the contrary, there weren't any vertical halos at the profiles, captured when collimators were in. Note, that the light spots on the top and the bottom of the CAM16 profiles as well as on the left and on the right at CAM8, 17, and 21A profiles are YAG screen light reflected in the CCD camera's chamber walls (not diffraction at the camera's aperture). Therefore, from these beam halo profiles one can conclude:

1. Vertical beam halo can be truncated using collimation system effectively.
2. The nature of vertical beam halo isn't CCD blooming caused by the CCD pixels saturation (otherwise the halo should be seen regardless of collimators are in or out).

More urgent finding is that the beam loss reduction in the recirculating loop and the vertical halo truncation by the collimation system were simultaneous. We believe it is a good confirmation of the effectiveness of the beam tuning together with the collimation system.

BEAM HALO SIMULATION

The main goal of the simulations below is to check one more time the tail transformation hypothesis of beam halo formation and beam loss issues in cERL. First, the injector lattice was modified to fit current operational conditions. Thus, the K values of the quadrupole magnets and the fields of the steering coils were adjusted properly. Then, we also added the injector cavity offset to complete the rf field kicks simulation. Layout of cERL injector is shown at Fig. 3.

For the start-to-end particle tracking an initial distribution (uniform in transverse plane and Gaussian with 100 ps tail in longitudinal plane) was generated at the cathode (see Fig. 4). The initial simulation parameters are summarized in Table 3. The probability density of longitudinal distribution is obtained from the GaAs bulk photocathode measurement [21 – 22]. Such type of cathode is utilized at cERL. Tracking up to the exit of the main cavity (see Fig. 1) was performed with GPT (General Particle Tracer [23]) routine. We found the space charge effect negligible for the bunch charge 0.2 – 0.3 pC. Then the distribution obtained was tracked through the recirculating loop matrix (from the main cavity exit to the dump) via ELEGANT tracking code [24]. Thus, we evaluated beam halo distribution at all camera's locations. The results are shown at Fig. 5.

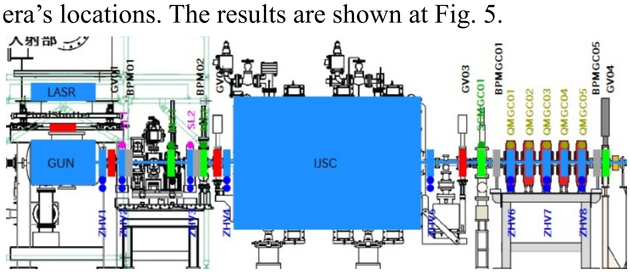

Figure 3: Layout cERL of injector line.

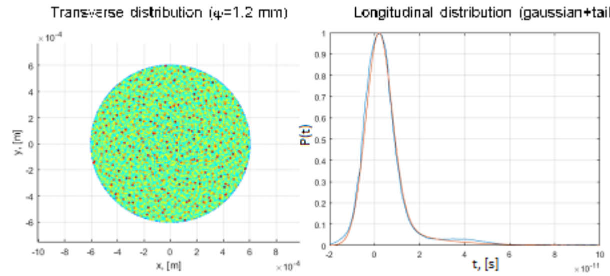

Figure 4: Input distribution simulated at the cathode.

Table 3: Simulation Input Parameters

Number of particles	10^4
Beam energy	2.9 – 20 MeV
Total charge	0.3 pC / bunch
RF frequency	1.3 GHz
Laser spot diameter	1.2 mm
Bunch length	3 ps

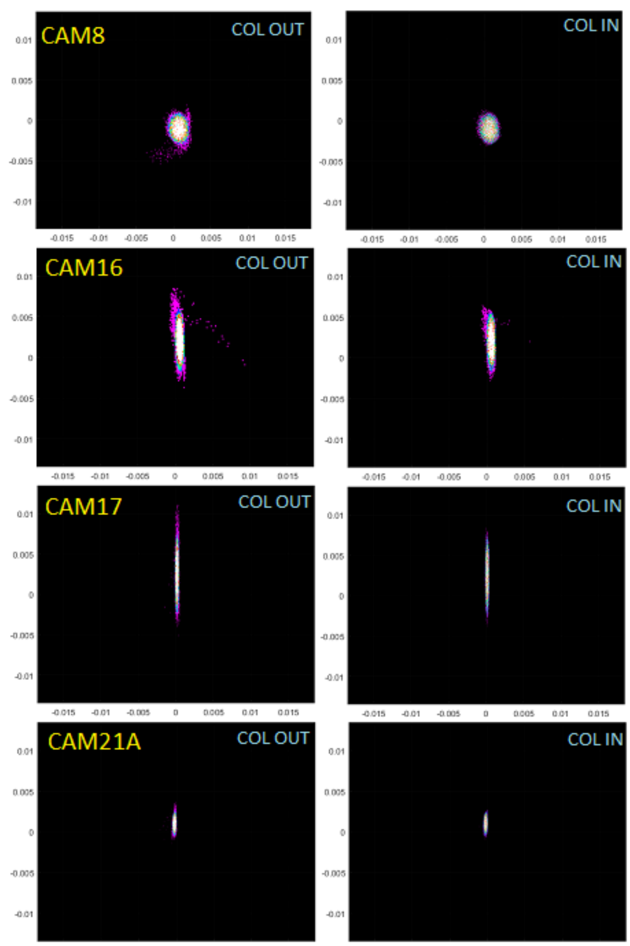

Figure 5: Simulated beam halo profiles.

DISCUSSION

The above simulation yielded beam profiles with vertical halos. Still, there is no perfect match between measured data and simulated data. Nevertheless, one can say that the beam halo dynamics is quite similar, while the simulation has a possibility to treat this halo formation mechanism more accurately. So, from the simulation we learned that the lower part of the halo at CAM8 is very likely caused by longitudinal bunch tail transferred into transverse plane. As for the upper part of this halo, it seems to be due to the injector cavities rf field kicks. The statement above is opposite for CAM16, 17, and 21A. Thus, the upper part is due to the tail and lower part due to the rf field kicks. These kicks were simulated as a complex effect of injector cavities misalignment and steering coils influence. To determine how much each of these factors effects alone, additional calculations are required.

To summarize, the qualitative description of the beam halo formation mechanisms was given here. To provide some quantitative description of the effect, we picked the beam core-halo ratio estimations from the measured and from the simulated profiles into the Table 4. The order of the values is the same that once again confirms the correctness of our hypothesis.

Table 4: Core-halo Ratio Estimation

Place of observation	Measurement		Simulation	
	Core,%	Halo,%	Core,%	Halo,%
CAM8	99.45	0.55	99.07	0.93
CAM16	99.37	0.63	99.43	0.57
CAM17	99.64	0.36	99.50	0.50
CAM21A	99.48	0.52	99.48	0.52
Average	99.49	0.51	99.37	0.63

CONCLUSION

The next step of cERL R&D is low-emittance and high bunch charge operation, while the average beam current is increased. Thus, the study of the beam halo formation mechanisms is indispensible for overall beam loss reduction. As we learned from the beam tuning experience, the most likely cause of the beam halo in cERL is longitudinal bunch tail originated at photocathode transferred into the transverse plane. Our guess, that it occurs due to rf field kicks, find the experimental and computational evidences. Therefore we succeed in beam loss mitigation utilizing the collimation system. However, a further beam loss elimination with achieving extremely low emittance is inextricably linked to the reduction of the longitudinal bunch tail originating in the photocathode. One more possible but still unexplored halo reason is an influence of the input coupler of injector cavity. Due attention should be paid to space charge effect when the bunch charge will be increased. We should also make efforts to solve these problems.

ACKNOWLEDGEMENT

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REFERENCES

[1] S. Sakanaka *et al.*, "Measurement and control of beam losses under high average-current operation of the compact ERL at KEK", in Proceedings of IPAC'16, TUPOW038.

[2] T. Obina *et al.*, "Recent developments and operational status of the compact ERL at KEK", in Proceedings of IPAC'16, TUPOW036.

[3] S. Sakanaka *et al.*, "Operations with 1-mA beam current at the compact ERL", this conference, WEOM15.

[4] H. Matsumura, "Beam loss estimation from the ceiling dose" (in Japanese), KEK, cERL Beam Dynamics Work Group Meeting, April (2016).

[5] H. Matsumura *et al.*, "Beam loss estimation by measurement of secondary produced photons under high average-current operations of compact ERL in KEK", in Proceedings of IPAC'16, WEPOR020.

[6] K. Harada *et al.*, "Rastering system with interlock for the beam dump of cERL", this conference, MOP079.

[7] M. Shimada *et al.*, "Beam optics for bunch compression at the compact ERL", this conference, TUP062.

[8] M. Shimada *et al.*, "Emittance and optics measurements at the compact ERL commissioning", this conference, TUP063.

[9] T. Miyajima *et al.*, "Orbit correction and optics tuning in cERL commissioning", this conference, TUP063.

[10] KEK-LS Conceptual Design report (in Japanese), https://www2.kek.jp/imss/notice/assets/2016/06/08/KEKLS_CDR_Accelerator_160608.pdf .

[11] K. Harada *et al.*, "The HMBA Lattice Optimization for the New 3 GeV Light Source", in Proceedings of IPAC'16, THPMB012.

[12] K. Harada *et al.*, "Design of the 3GeV light source of HMBA type lattice with short straight section", this conference, WEOM16.

[13] R. Hajima *et al.*, "Simulations of XFELO for the KEK ERL", in Proceedings of PASJ2012, WEPD30.

[14] N. Nakamura *et al.*, "Simulation Study of An High-Power ERL-Based EUV-FEL Light Source", this conference, TUP074.

[15] Y. Honda *et al.*, "Design of THz Source utilizing an Resonant CDR System at cERL", this conference, MOP076.

[16] T. Akagi *et al.*, "Development of laser-Compton scattering X-ray source at cERL", this conference, MOP057.

[17] A. V. Fedotov, "Beam halo formation in high-intensity beams", Nucl. Instrum. Methods Phys. Res. A557 (2006).

[18] O. Tanaka *et al.*, "Simulation study of the beam halo formation for beam loss estimation and mitigation at KEK compact ERL", in Proceedings of IPAC'16, TUPOW039.

[19] O. Tanaka *et al.*, "Beam Halo Propagation and Mitigation for Beam Loss Study at KEK Compact ERL", in Proceedings of PASJ2015, THP020.

[20] O. Tanaka *et al.*, "Beam loss studies for the KEK compact ERL", in Proceedings of PASJ2014, SAP018.

[21] S. Matsuba *et al.*, "Initial Emittance and Temporal Response Measurement for GaAs Based Photocathodes", in Proceedings of IPAC'12, MOPPP035.

[22] M. Yamamoto, private communications.

[23] GPT - A simulation tool for the design of accelerators and beam lines, http://www.pulsar.nl/gp.

[24] M. Borland, "ELEGANT: A Flexible SDDS-Compliant Code for Accelerator Simulation", Advanced Photon Source LS-287, September (2000).