SIMULATION STUDY OF THE BEAM HALO FORMATION FOR BEAM LOSS ESTIMATION AND MITIGATION AT KEK COMPACT ERL

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Abstract

At KEK Compact ERL (cERL) we are aiming to produce high-current and low-emittance electron beams (up to 10mA) without significant beam loss. We believe that beam halo makes a significant impact into the beam loss. Therefore, we are performing beam loss simulations to meet the results of the beam loss measurements [1], [3]. In particular, a simulation of the bunch tail originated from the electron gun was performed to understand the mechanisms of the beam halo formation. Since some measured beam profiles demonstrated unexpected halo particles, several factors such as misalignment of beam line elements and kicks from the steering coils were added into the simulation. Simulation study results are compared with the related beam loss and halo measurements here.

INTRODUCTION

The last operation of KEK cERL was performed from January to April, 2016. As it was planed, the beam current was successfully increased up to 1 mA in February. Apart from the beam current increase, we had several priority goals in the operation. They are: electron gun system improvements, high bunch charge operation, beam loss elimination, further development of LCS (Laser Compton Scattering) system, and bunch compression studies for THz radiation [2 - 4].

Since the machine was properly tuned before to start the high current operation, we had an essential beam loss decrease comparing with the last year operation. The level of the beam loss was a few nA [3], while the beam collimation system applied successfully. Otherwise, transverse beam halo was observed during beam measurements. We guess that understanding the beam halo formation mechanisms is the key factor for further beam loss mitigation, which is indispensible for the following current increase.

There are several processes causing the beam halo, and as the result yielding the beam losses. Scattering from residual gas, Touschek scattering, dark current from the gun and from accelerator cavities was discussed in [5]. The study of low energy bunch tail, originated from the electron gun was done in [6]. In order to explain the observed beam halos and to mitigate the beam loss, we added two more halo formation mechanisms in the simulation study. They are: injector cavity cells misalignment and kicks from the steering coils. The results of beam halo measurement and beam halo simulation are presented below.

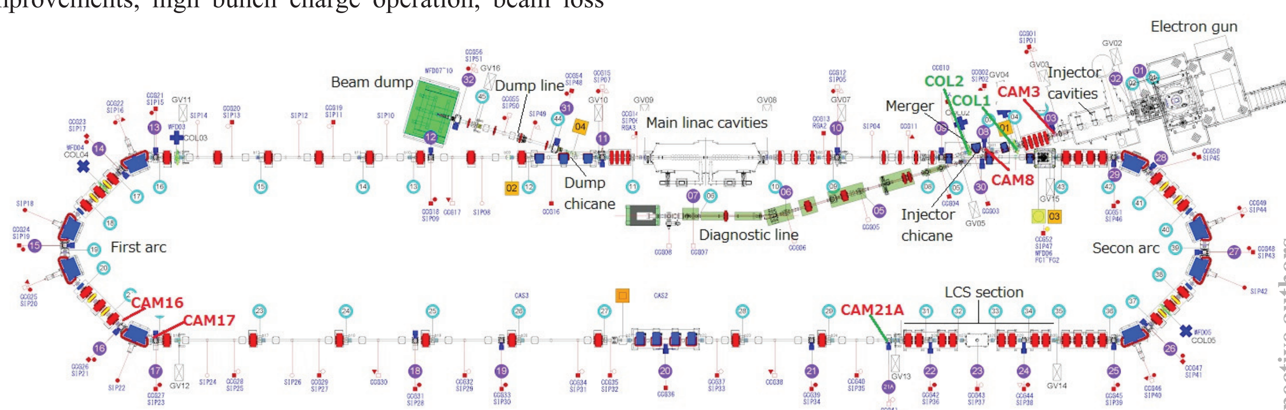

Figure 1: Layout of cERL.

BEAM HALO MEASUREMENT

We perform a series of beam halo measurements during this year cERL commissioning [2] (from Jan. to Apr., 2016).

To understand the beam halo formation mechanisms several CCD cameras at different locations of the beam line were chosen (see Fig1). CAM3 in the injector line allows to check whatever we have a bunch tail form the electron gun or not. CAM8 in the merger section and CAM16 in the 1st arc help to observe the energy spread of the particles. CAM17 (south straight section) picks up the beam profiles in the place with big betatron oscillations. CAM21A placed ib. before Laser Compton Scattering (LCS) system. The beam measurement settings are summarized in the Table 1.

The measurement was done accordingly the following workflow:

1. Insert a screen.

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2. Check whatever the 1 μs (1-10 ms[1]) beam is visible while setting the integration time of the camera to 10 μs (1-10 ms[1]), which is the least value. Adjust the trigger delay if needed. It allows capture only one macro pulse during one camera shutter pulse. We set the gain to maximum to see the beam halo better.
3. Capture the beam halo profiles during 10 s automatically with 5 Hz (0.1 Hz[1]) macro pulse frequency. Thus, the data obtained contain 50 profiles (1 profile[1]).
4. Insert the collimators (see Fig. 1) to check the effectiveness of the collimation system against the beam halo. It also allows to estimate the beam loss rate using loss monitors.
5. Perform the screen capture described in 3 above once again.

Table 1: Beam Measurement Settings

Burst mode (1 μs width)	
Macro pulse duration	1 μs
Macro pulse frequency	5 Hz
Integration time	10 μs
Bunch charge	0.2-0.3 pC / bunch
Average current	1.5 nA
Peak current	300 μA
Repetition rate	1.3 GHz
Beam energy	2.9 - 20 MeV
Long pulse mode (1.5 ms width)	
Macro pulse duration	1.5 ms
Macro pulse frequency	0.6 Hz
Integration time	2 ms
Bunch charge	6 nC / pulse
Average current	3 nA
Peak current	15 nA
Repetition rate	1.3 GHz
Beam energy	20 MeV

To obtain for the total beam halo image, all the profiles of one capture were summarized. The sharp saturated peak of the beam core is cut on the acceptable level to recognize the beam halo easily. Vertical beam halos were observed at CAM8, CAM16, CAM17 and CAM21A (see Fig. 2). The usage of collimators was found to be efficient enough to get rid of these halos and to decrease the beam loss significantly.

BEAM HALO SIMULATION

Vertical beam halos were observed almost along whole the recirculating loop (from the merger section (CAM8) up to the 2nd arc entrance (CAM21A) see Fig. 1) during the measurement. We assume the main reasons of these halos to be: misalignment of the injector cavity cells; kicks from the steering coils.

The non-linearity of the positions of the three injector cavities was evaluated by using the HOM coupler signals

[1] For long pulse mode.

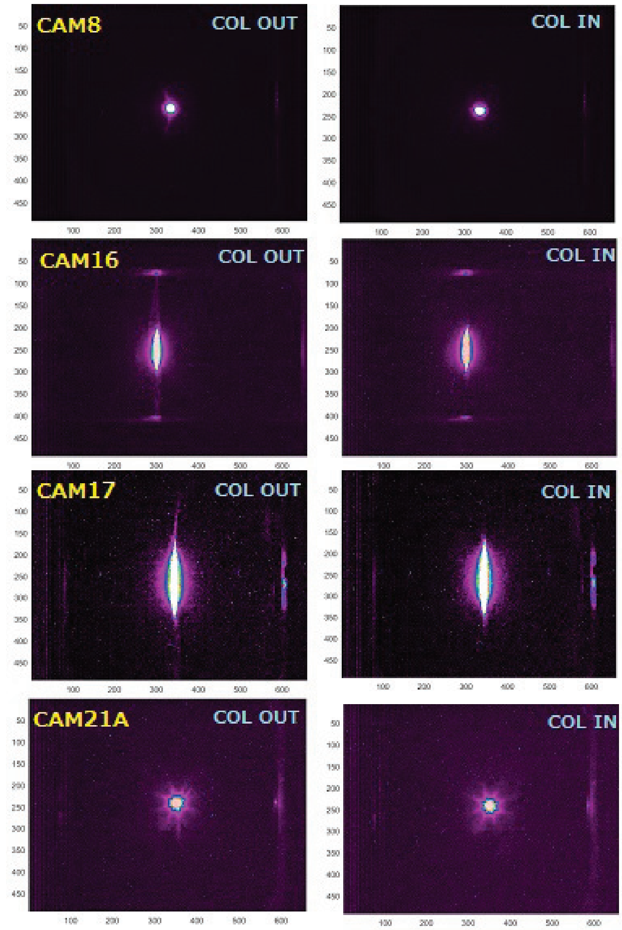

Figure 2: Observed beam halos. CAM8: 2/23, burst mode, gain 22, integration time 10 μs, CAM16-21A: 3/9, long pulse mode, gain 22, integration time 10 μs.

[7]. Thus, it was found that cell#2 has the 2.6 mm offset in x direction of the cavity transverse plane. One more aspect of the successful operation was the beam collimation. To make use of COL2 (see Fig. 1) effective, we have had to steer the beam in vertical direction by steering coil ZHV4 (see Fig. 3). Therefore, the low energy longitudinal bunch tail was pulled up, producing the vertical halo. Then this halo was collimated by the COL2, and essential beam loss decrease was observed. Steering coils#1–8, bunch tail 100 ps, as well as injector cavity cell#2 2.6 mm offset are included into the beam halo simulation.

cERL steering coils are two pairs of rectangular shaped coils putted in parallel in the transverse plane of the beam. The layout of coils is shown at Fig. 3. As far as there is no static magnetic element of this particular shape included in GPT (General Particle Tracer [8] used for injector simulations), we calculated the integrated magnetic field of the pair of rectangular coils separately with MATLAB routine [9]. Coil parameters listed in Table 2.

The initial distribution (uniform in transverse plane and Gaussian with 80 ps tail in longitudinal) was generated and tracked through the injector lattice with GPT, creating the output distribution at the exit of the main cavity (see Fig. 1). SC (Space Charge) effect is negligible. The input beam parameters are listed in Table 3.

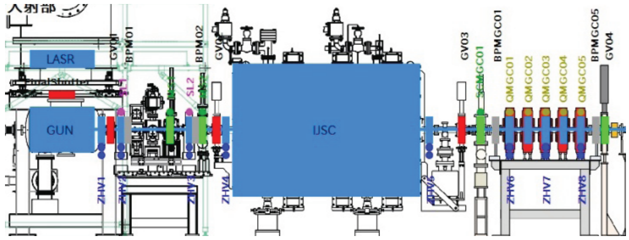

Figure 3: Layout of injector line steering coils.

Table 2: Steering Coils Parameters

Stee ring	Cur- rent [A]	ItoBL [T*m/A]	Len. [mm]	Gap [mm]	Wid. [mm]
ZV1	-0.90	3.2e-5	59	133	95.5
ZV2	-0.18	6.1e-5	59	132	66
ZV3	0.00	6.1e-5	59	132	66
ZV4	-3.18	3.6e-5	59	133	95.5
ZV5	0.25	7.5e-5	79	143	95.5
ZV6	1.70	1.7e-4	100	60	140
ZV7	0.00	1.7e-4	100	60	140
ZV8	-0.58	1.7e-4	100	60	140

Table 3: Simulation Input Parameters

Number of particles	10^6
Beam energy	2.9 – 20 MeV
Total charge	0.5 pC / bunch
RF frequency	1.3 GHz
Laser spot diameter	1.2 mm
Bunch length	3 ps

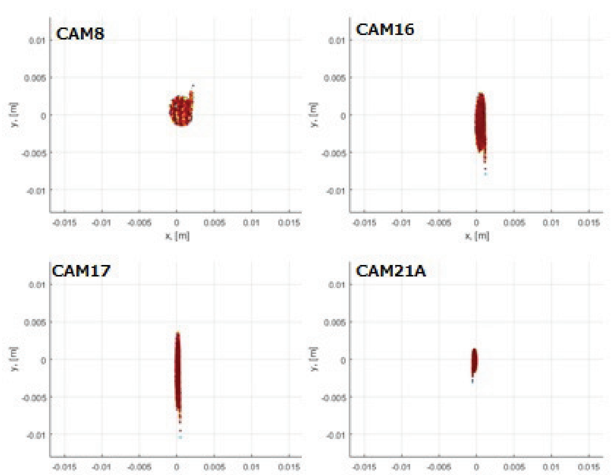

Figure 4: Simulated beam halo profiles.

Then obtained beam - halo distribution was tracked through the recirculating loop (from the main cavity exit to the dump) using tracking code ELEGANT [10]. The effects of steering coils and misalignment yield the beam halos in the vertical direction, as shown on the Fig. 4. It is interesting to note, that passing the beam through the center of the misaligned cavity cells, as described above, makes the beam halo appearance negligible. That was well observed during the beam measurement.

A longitudinal bunch tail (80 ps) originating in the electron gun added into the simulation along with injector cavity cells misalignment and steering coils. The presence of such tail yields a horizontal halo from the low energy side of the beam profile in the dispersive sections of the beam line (CAM8, CAM16, see Fig.1) along with the vertical halo mentioned above.

Our simulation outputs also the beam loss distribution along the beam line. The lost current is estimated simultaneously. The formula for the total beam current calculation is the following:

$$J = Q_{tot} \cdot f = 650\,\mu A^{1}\,, \qquad (1)$$

where Q_{tot} is the charge per bunch, f is the repetition frequency rate, and N_{tot} is the number of electrons per bunch. Simulated beam loss rates without and with collimators insertion as well as its ratio to the total beam current (in percents) are summarized in the Table 4. It should be noted that collimators insertion, in accordance with the measurement setup, decreases the simulated loss rates essentially. Beam loss rates obtained from the simulation results are in a good accordance with those calculated from the radiation survey measurements [3]. At the same time the beam loss distribution along the beam line essentially differs from the measured one. This is a point to be improved.

Table 4: Beam Loss Rates Comparison

Place	Simulated, COL out [nA, %]	Simulated, COL in [nA, %]	Calculated[2] COL out [nA, %]
LCS section	0, 0	0, 0	2, 0.0006
2nd arc	1.3, 0.0002	0, 0	0, 0
Dump chicane	1.95, 0.0003	0.65, 0.0001	0, 0
Dump line	7.8, 0.0012	1.95, 0.0003	0, 0

CONCLUSION

On performing beam halo and beam loss simulations, we found that still simulated effects cannot perfectly meet the results of the beam halo and beam loss measurements. Nevertheless, a simulation of the injector cavity cells misalignment together with including steering coils into the injector lattice demonstrated the presence of the vertical halos in the beam profiles. Also there are some unaccounted factors. It could be kicks from input / HOM couplers. Therefore, the following simulation study should properly take such factors into account.

ACKNOWLEDGEMENT

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[1] Calculated for Table 3 parameters.
[2] For the total beam current 300 µA, see reference [11].

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