KEK のコンパクト ERL でのビームコリメータと 60 pC 電子ビームに対するウェーク場評価

A WAKE FIELDS EVALUATION FOR BEAM COLLIMATORS AND THE 60 pC ELECTRON BEAM AT THE COMPACT ERL AT KEK

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Abstract

When the high intensity particle beam passes through locations with narrow apertures such a collimator's rods, it leads to the creation of the unwanted wakefields. At the Compact ERL at KEK we have five beam collimators (one in the injector line, one in the merger section, and three in the recirculation loop), which are used for the beam halo reduction and for the beam loss localization. Those collimators consist of four cylindrical rods of 7 mm radius made of copper. They could be independently inserted from the top, bottom, left and right sides of the beam chamber. The transverse wake field may affect the beam emittance and the longitudinal wake field can cause the energy loss and the energy spread. In the present study we investigated the collimator's impact to the beam. We evaluated the collimator's wake fields through the CST simulations. The estimated transverse kicks, longitudinal wakes, and expected energy losses are demonstrated here.

1. INTRODUCTION

The Compact ERL (cERL) at KEK [1] has five collimators (one in the injector section, one in the merger section and three in the recirculation loop, see Fig. 1) to remove the beam halo and to localize the beam loss. An operation at 10 mA average beam current and 1.3 GHz repetition rate is planned in the near future. The collimator's wakefields are expected to play an important role, even when the bunch charge is increased up to 60 pC. Current beam parameters of the cERL are summarized in the Table 1.

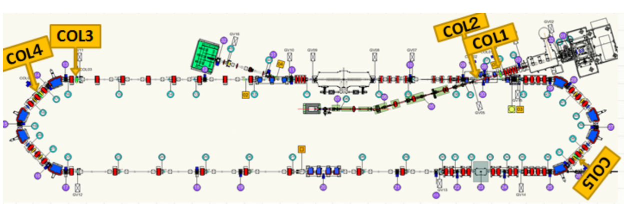

Figure 1: A layout of the cERL and its collimators.

All cERL collimators consist of four cylindrical rods of 7 mm radius made of copper. They could be independently inserted from the top, bottom, left and right sides of the beam chamber. Collimators COL1 – 3 were designed for the straight sections, therefore they have a round chamber 50 mm radius made of stainless still. Its schematic is given at Fig. 2.a. Note that the energy at collimators COL 1 – 2 is 4 MeV (see Table 1), while the energy at rest of them is 17.6 MeV. Collimators COL4 – 5 are dedicated to the arc section, thus their chambers are elliptical 70 x 40 mm diameter.

Table 1: cERL Electron Beam Parameters

Parameter	Design	In operation
Beam energy [MeV]:		
Injector	4	4.05
Recirculation loop	17.6	17.5
Bunch charge [pC]	60	60
Repetition rate [GHz]	1.3	1.3
Bunch length (rms) [ps]	2	4.5
Energy spread [%]	<0.1	0.12
Normalized emittance (rms) in injector [μm·rad]:		
Horizontal	< 3	2.88±0.09,
Vertical	< 3	1.99±0.20

Materials used are the same. The detailed scheme can be found at Fig. 2.b.

In the present study, first, we have estimated transverse kicks imposed by the collimator's rods. This calculation is needed to account for the beam blow up (emittance growth) associated with collimator's wake. Then, longitudinal wakes were summarized to obtain the expected energy losses of the beam passing through the collimator and its energy spread. Finally, we have compared those results with results of the measurements using cERL beam. Present study is helpful towards the IR-FEL upgrade of cERL [2 – 3].

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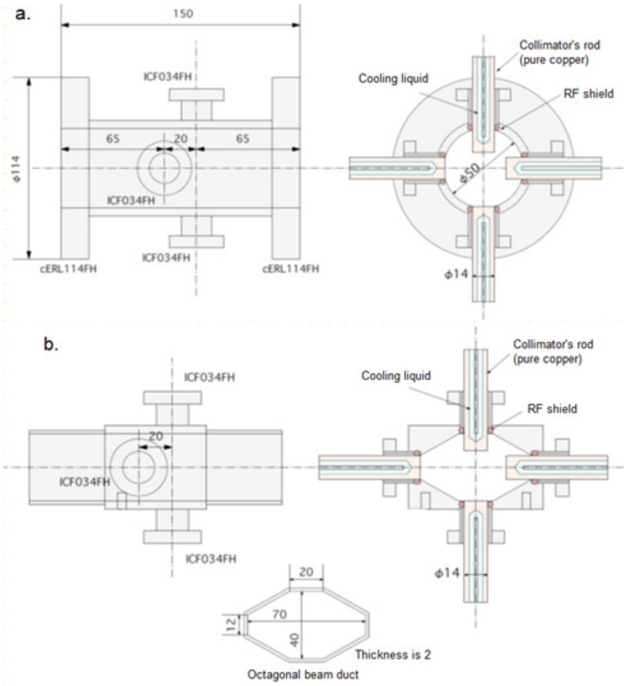

Figure 2: A schematic of the collimators with chambers made of stainless steel and rods made of copper: a. Collimators COL 1 – 3 for the straight sections; b. Collimators COL 4 – 5 for the arc sections.

2. INFLUENCE OF THE COLLIMATOR WAKE

2.1 Transverse wake and emittance growth

Let us consider first transverse wakefields created by the vertical rods of the collimator. The summary of simulation results together with analytical calculations is demonstrated at Fig. 3. We have estimated the emittance blow-up for the 60 pC electron bunch at cERL using analytical expression [4]:

$$\frac{\Delta\varepsilon_y}{\varepsilon_{y0}} = \sqrt{1+\frac{\beta_y\sigma_\omega^2}{\varepsilon_{y0}}} - 1, \tag{1}$$

where the value $\Delta\varepsilon_y$ is the *transverse emittance growth* with respect to the initial emittance ε_{y0}. The rms of the centroid kicks caused by the longitudinally varying field σ_ω could be found as follows [5]:

$$\sigma_\omega = \frac{Q}{E/e} k_\perp^{rms} y_0. \tag{2}$$

In Eq. (2) the value E is the beam energy at the location of collimator (see Table 1). The value $Q = 60\,pC$ is the bunch charge. The value y_0 is the beam centroid offset, and lastly, the value $k_\perp^{rms}$ is the rms kick factor, estimated for the bunch head-tail difference in the kick. For Gaussian bunch $k_\perp^{rms} = k_\perp/\sqrt{3}$.

Expected values of the emittance blow-up due to the collimator half gap 1.5 mm are summarized in Table 2.

Since for 60pC per bunch and burst mode of the operation the emittance growth effect is expected to be small, let us treat longitudinal wake.

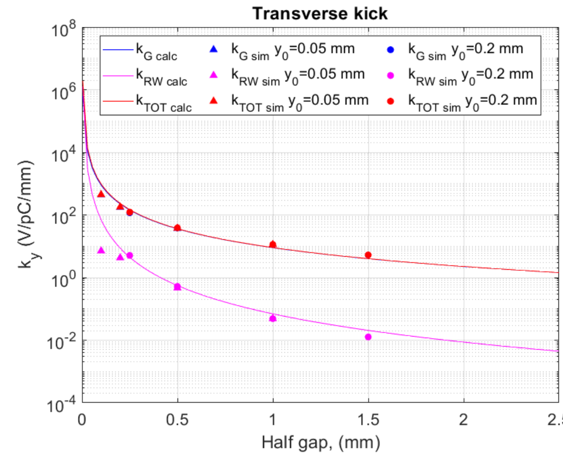

Figure 3: A summary of the transverse wake kick factors of the collimators.

Table 2: Expected Values of the Emittance Blow-Up for the Collimator Half Gap 1.5 mm

Collimator	ε_{y0} [μm×rad]	β_y [m]	$\Delta\varepsilon_y/\varepsilon_{y0}$ [%]
COL1 $E = 4\,MeV$	1.15	27.47	1.05
COL2 $E = 4\,MeV$	1.25	19.23	0.84
COL3 $E = 17.6\,MeV$	0.954	34.76	3.82
COL4 $E = 17.6\,MeV$	0.954	6.99	1.61
COL5 $E = 17.6\,MeV$	0.954	6.99	1.61

2.2 Longitudinal wake and energy spread

Now, let us consider a problem of longitudinal wake fields excited by collimators. The values of the wake-loss factor were evaluated numerically through the CST simulation for half-gap values in the range from 0.1 to 1.5 mm. For the analytical description, the following equation was considered [6]:

$$k_\parallel = \frac{Z_0 c}{2\pi^{3/2}\sigma_z} \ln\left(\frac{b}{a}\right). \tag{3}$$

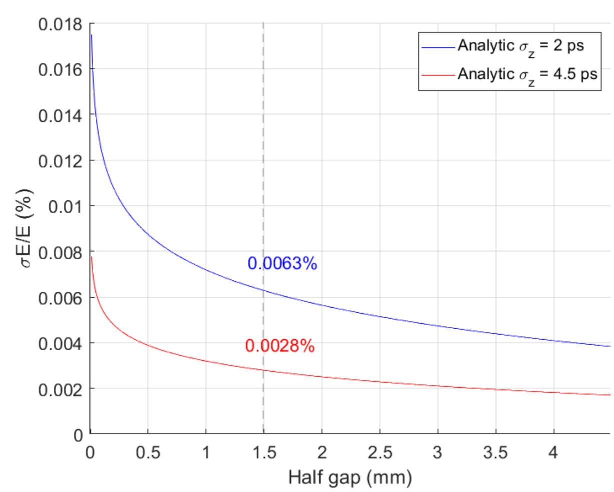

Figure 4: A wake-induced energy spread for different values of the collimator half gap and bunch lengths 2 ps (blue line) and 4.5 ps (red line).

In Eq. (3) the value $Z_0 = 120\pi$ is the impedance of the free space, $c = 3 \cdot 10^8\ m/s$ is the speed of light, σ_z is the bunch length, $b = 25\ mm$ is the vacuum duct's half aperture, and a is the collimator's half gap.

The wake-induced energy spread for Gaussian bunch due to one collimator for the 60 pC bunch is the following:

$$\frac{\sigma_E}{E} = \frac{0.4 \times 60[pC] \times k_{\parallel}[V/pC]}{17.6[MeV]}. \quad (4)$$

The factor 0.4 appears since the rms energy spread of a Gaussian bunch is given by $k_{\parallel}^{rms} = k_{\parallel}\sqrt{2/\sqrt{3}-1} \approx 0.4k_{\parallel}$.

The dependence of the energy spread on the collimator's half gap for the designed (2 ps) and current (4.5 ps) bunch length is demonstrated at Fig. 4. Now, when all impacts are summarized, let us demonstrate measurement results and they comparison with theoretical predictions.

3. BEAM-BASED MEASUREMENTS

3.1 Energy spread measurement

For the measurement of the energy spread caused by the collimator's longitudinal wake, we used COL3 located before first arc entrance, CAM13 located between COL3 and the entrance and CAM15 located just in the middle of the arc (see Fig. 1). CAM13 needed to monitor the the beam spot, which was successively cut by collimator's rods. The measurement itself was done by CAM15. To do so, first, we have restored the history of the quadrupole magnets to have the best beam spot at the COL3 location. Then we have degaussed all quadrupoles of the first arc between CAM13 and CAM15 to make the dispersion maximized. We have measured the dispersion to be 2.41 m. The default energy spread was $\sigma_E/E_{default} = \sigma_z/\eta = 0.117\%$. It is a ratio of the rms beam size to the dispersion. However, in the following we care only the change of the energy spread, not its default value.

Next step was to insert the collimator COL3. We used two horizontal rods, because the beam spot at the collimator location is known for its vertical beam halo. Therefore, we have avoided an influence of the halo on our energy spread measurement. We have performed the measurement for the half gap values 2 mm, 1.5 mm, 2 mm, 2.5 mm, 4 mm, COL out correspondingly. Related rms beam sizes and beam profile peak positions were recorded at CAM15. The raw data of the beam profile was fitted automatically by the python routine at the control room. Then we have processed it manually using Gaussian fitting routine and weight analysis. An example of the measurement data processing could be found at Fig. 5. Here the upper image is a CAM15 beam spot, the blue curve at the bottom plot is the raw data, the red line is its Gaussian fitting, and the magenta mark denotes the peak position with respect to the data weight.

Weight analysis [7] gives the following expression for the profile peak position:

$$x_c = \frac{1}{N}\sum_{i=1}^{659} x_i N_i, \quad where \quad N = \sum_{i=1}^{659} N_i. \quad (5)$$

Here N is the number of data points, and x_i is the value of the i-th data point. The rms beam size is given by:

$$\sigma_x = \sqrt{\frac{1}{N}\sum_{i=1}^{659} N_i (x_i - x_c)^2}. \quad (6)$$

Results of the processing of all six measurements are demonstrated at Fig.6. The rms beam size is not changed significantly within the error bar except in the case of the 1.5 mm half gap. This is consistent with the impedance evaluation. Apparently the beam core was found to be damaged when the collimator's half gap become 1.5 mm.

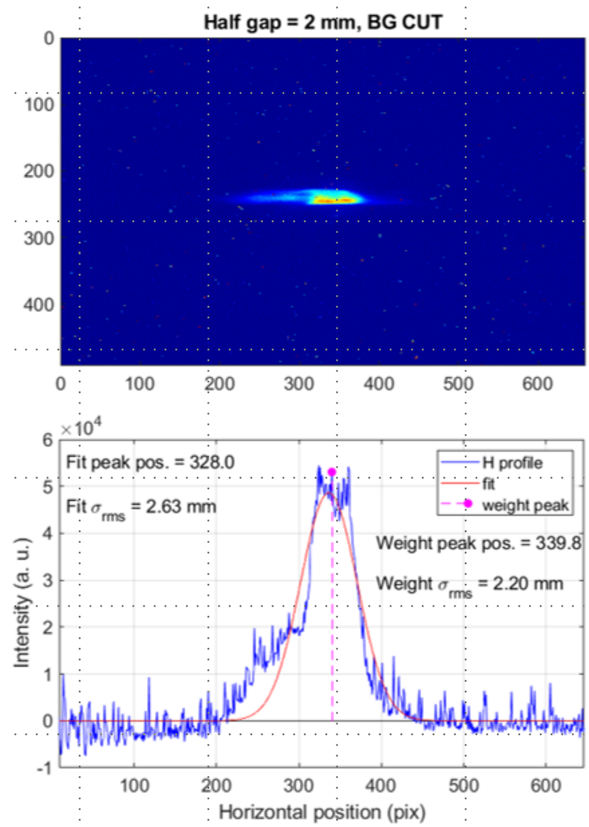

Figure 5: An energy spread measurement data at CAM15: beam spot (top), raw data and its fitting (bottom).

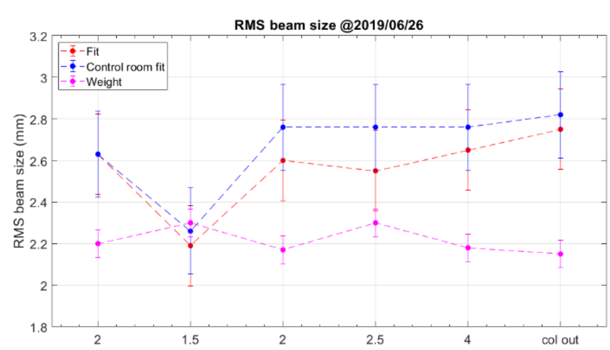

Figure 6: A horizontal beam size at CAM15 with respect to the horizontal collimation.

3.2 Influence of the beam halo

The location of the collimator COL3 (before the arc entrance, Fig. 1) is known for the considerable vertical beam halo [8]. The correspondent beam spot at CAM13 is shown at Fig.7. Thus, by inserting vertical rods of the collimator COL3, one can study the beam halo influence on the energy spread and consequently manage the beam quality by removing the halo by the collimator.

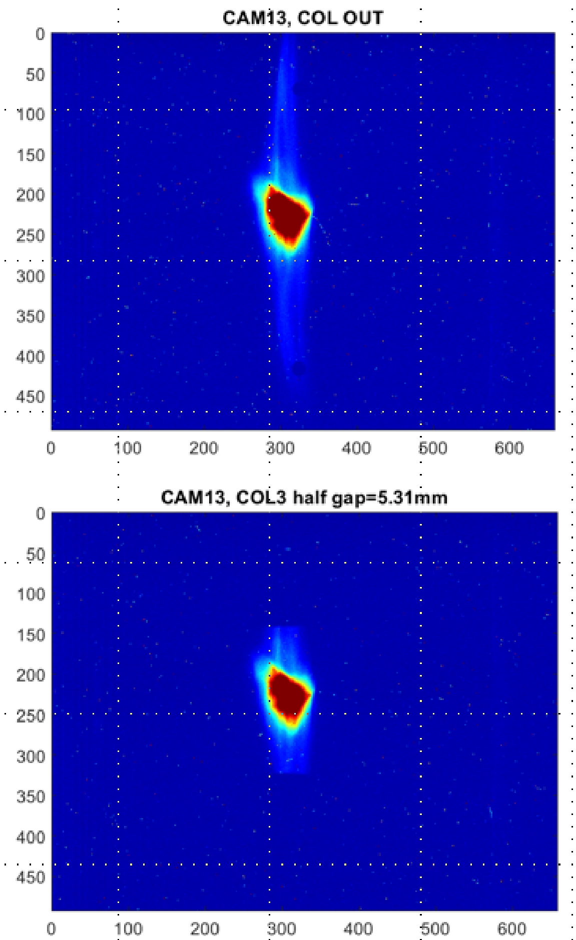

Figure 7: A beam spot at CAM13: without (top), and with (bottom) the collimation.

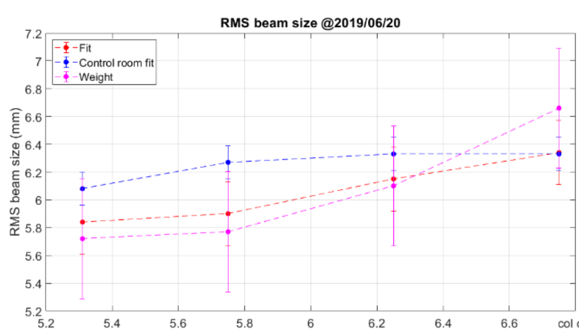

Figure 8: A horizontal beam size at CAM15 with respect to the vertical collimation.

To study this effect, we performed the same measurements as was described in the previous section. Although the vertical collimation was allowed. A series of four measurements was done. The collimator's half gap was set to 5.31 mm, 5.75 mm, 6.25 mm, and COL3 out correspondingly. Then the proper data processing gave results, presented at Fig. 8. One can see the horizontal beam size is slightly decreased with the cutting away the vertical beam halo. This means that the beam halo increases the energy spread.

4. CONCLUSION AND OUTLOOK

We have performed a study of the collimator's wake influence on the 60 pC electron beam at cERL. It should be taken into account for an intense short bunch, when a considerable beam collimation is required. We have estimated the expected emittance growth due to collimator's wakefield under current operational conditions at cERL. It is a few percent or less.

Collimators are also generating the wakefield effect that brings an additional energy spread. At cERL we find it to be 0.0028 % at 17.5 MeV. Easy to account for the energy loss per bunch at one collimator. It is $\Delta E = k_{\parallel} Q^2$=168.7nJ for the 60 pC bunch. This value is acceptable since the machine is operated in burst mode currently. The CW operation (1.3 GHz, 80 mA, 2 ps) with 219.3 W power loss might require an additional machine protection.

Experimentally we have found, that for current beam parameters (bunch charge is 60 pC (burst mode), bunch length is 4.5 ps, energy spread is ~0.12%, beam energy is 17.5 MeV (injector energy is 4.05 MeV) even if one put the half gap of the collimator up to 2 mm, the emittance and energy spread are not affected so much. Thus we approved the beam collimation at cERL.

Considering future cERL upgrade to the IR-FEL, a possibility of consequent degradation of the FEL performance should be taken into account. Correspondent power loss was obtained as 13.7 W (81.25 MHz, 5 mA, 2 ps). In this paper, we have shown numerical, analytical and measurement results on the collimator's wakefields that will be important for the next step operation.

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