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THE EFFECT OF WAKE FIELDS ON THE FEL PERFORMANCE*

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Abstract

When a beam travels near collimator jaws, it gets an energy loss and a transverse kick due to the back reaction of the beam field diffracted on the collimator's jaws. The effect becomes very important for an intense short bunch when a tight collimation of the background beam halo is required. In the Linac Coherent Light Source (LCLS) at SLAC a collimation system is used to protect the undulators from radiation due to particles in the beam halo. The collimators in the LCLS must remove the halo particles before they affect and eventually degrade the very precise fields of the permanent magnet undulators [1]. The wake field effect from the collimators not only brings an additional energy jitter and change of the trajectory of the beam, but also rotates the beam on the phase plane that consequently leads to a degradation of the performance of the Free Electron Laser (FEL) at LCLS. In this paper, we describe a model of the wake field radiation in the SLAC linac collimators. We also present results of experimental measurements, which clearly confirm our model.

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Abstract

When a beam travels near collimator jaws, it gets an energy loss and a transverse kick due to the back reaction of the beam field diffracted on the collimator's jaws. The effect becomes very important for an intense short bunch when a tight collimation of the background beam halo is required. In the Linac Coherent Light Source (LCLS) at SLAC a collimation system is used to protect the undulators from radiation due to particles in the beam halo. The collimators in the LCLS must remove the halo particles before they affect and eventually degrade the very precise fields of the permanent magnet undulators [1]. The wake field effect from the collimators not only brings an additional energy jitter and change of the trajectory of the beam, but also rotates the beam on the phase plane that consequently leads to a degradation of the performance of the Free Electron Laser (FEL) at LCLS. In this paper, we describe a model of the wake field radiation in the SLAC linac collimators. We also present results of experimental measurements, which clearly confirm our model.

INTRODUCTION

The effect of collimators with small apertures on the transverse beam dynamics was observed during the operation of the Stanford Linear Collider (SLC) [2]. The problem of wake fields excited by collimators becomes more important for linac operation and x-ray production at LCLS. The backward reaction of the wake field from the collimators on the beam brings an additional energy jitter and a change of the trajectory of the beam. It leads also to a degradation of the FEL performance at the LCLS. This is because of the special character of the wake fields: the response reaction depends on the longitudinal position of the particles in the bunch. The "head" of the bunch is not deflected at all, but the "tail" gets the maximum deflection force. This kind of kick leads to the bunch being geometrically tilted. Because the "tail" of the bunch may oscillate in the lattice, the orientation of the bunch in space will oscillate too. Effectively the transverse projected emittance is increased and the FEL performance is degraded.

SLAC LINAC COLLIMATOR

Nine adjustable beam collimators are used in the LCLS operation, mainly accomplished in two main sections: at end of the SLAC linac and in the region from the linac to the undulators (LTU). Each collimator is composed of horizontal and vertical pairs of rectangular collimator jaws. The geometry of a collimator assembly is very complicated because each jaw is independently and remotely adjustable and can completely shadow the beam path. A collimator is essentially a kind of assembly of RF cavities coupled to the beam. Bellows with a chamber form two quarter-wave coaxial cavities. There are several trapped RF modes inside the collimator volume. In a multi-bunch operation, some energy is deposited in this region. One jaw can be in a position that is too close to the beam path while the other jaw is moved out. The jaws have a titanium alloy body with a slightly curved face (10-m radius) and a titanium-nitride jaw surface for improved conductivity and survivability against beam hits [3]. Currently the gap between jaws is kept approximately ±1.6 mm in all collimators. However, the spontaneous beam halo requires smaller gaps.

A TRANVERSE KICK FROM A COLLIMATOR JAW

Based on the analytical estimates [4] we assume that the kick from a collimator jaw is inversely proportional to the distance to this jaw. We estimate a kick for a particle with longitudinal position s in a bunch as

$$g(s) = \frac{Z_0}{4\pi} I_b \frac{s}{\delta}, \qquad (1)$$

where δ is a transverse distance from the bunch to the collimator jaw, I_b is the bunch current, and Z_0 is impedance of free space. The average bunch kick will be

$$g_{av} = \frac{1}{8\pi\varepsilon_0} \frac{Q}{\delta}. \qquad (2)$$

Opposite to the energy loss, which is proportional to the bunch current, the average kick is determined by a bunch charge Q and the proximity of the beam to the edge of the collimator jaw. The nonlinear behaviour of the kick leads immediately to emittance growth if a bunch travels very close to a collimator jaw edge. However, even a linear kick may increase the effective or projected emittance because a bunch "head" and a bunch "tail" will get different kicks. A "head" will receive nothing, but a "tail" will get a maximum kick.

A DIPOLE KICK FROM A COLLIMATOR WITH TWO JAWS

If we know a kick from one jaw, we can calculate a kick from a collimator with two jaws. Each jaw attracts the beam and the total kick must be the sum of the two kicks

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$$g_{av} = \frac{Q}{8\pi\varepsilon_0}\left(\frac{1}{\delta_1} - \frac{1}{\delta_2}\right), \tag{3}$$

where δ_1 and δ_2 denote displacements from the two jaws.

If a bunch has a small offset Δx relative to a symmetry plane between the two jaws, then we get a dipole kick

$$g_{av} \approx \frac{Z_0 c Q}{4\pi} \frac{\Delta x}{a^2} \qquad \Delta x << a\,. \tag{4}$$

Here we assume that the distance between the two jaws is *2a*. The average kick is proportional to the displacement of a bunch from a symmetry plane and inversely proportional to the square of the distance between the jaws, contrary to the theoretical model in reference [2]. The latter model predicts a kick inversely proportional to the bunch length and the distance between jaws. This model did not get agreement with experimental results.

MEASUREMENTS AND DATA ANALYSIS

The SLAC collimators are installed mainly at the end of the linac and in the LTU beam line. The beam line regions containing the collimators are detailed in [1]. We use upstream and downstream beam position monitors (BPMs) to determine the incoming and outgoing trajectories of the beam. The measurement of the beam positions at the locations of these BPMs allow us to measure the kick angle created by the transverse wake fields. The BPMs also provide information about the bunch charge. Controlling the bunch charge, we may determine position of a jaw when it touches the beam. The initial beam trajectory corresponds to a normal LCLS operation when the beam is centered in the collimators by using feedback kicks. We record BPMs dataset for each position of a collimator jaw (20 machine pulses). For each measurement only one jaw is moved in the direction to the collimator center, while the other jaw is taken far away from the beam. Each time the jaw position is changed in a step of 0.05 mm or less. Measurements of the beam kick due to the collimator wake fields were made with the beam energy of 11.5 GeV and the bunch charge of 150 pC.

For every position of a jaw we averaged all dataset (20 machine pulses) removing any failed pulse or BPM malfunction. We also calculated a ratio of a bunch charge before and after the measuring collimator using the BPM data. This ratio is shown in Fig. 1 for the vertical collimator with a vertical jaw moving down. The red circles correspond to the measured values. As the collimator jaw touches the beam, the ratio is decreased. When a bunch charge loss reaches 50%, the collimator jaw edge is in the center of the bunch. We have to note that the measured position of the beam may not be exactly in the center of the collimator. Assuming that the transverse distribution of the bunch charge has a Gaussian shape, we approximate the measured data by the Error function and determine the displacement of a bunch relative to a collimator jaw and the bunch size. The black solid line in Fig. 1 shows this approximation. We found that the displacement is 106 micron for this collimator and the vertical bunch size is equal to 65 micron. Measurement with a horizontal collimator showed that the horizontal beam size is the same as the vertical of 65 micron.

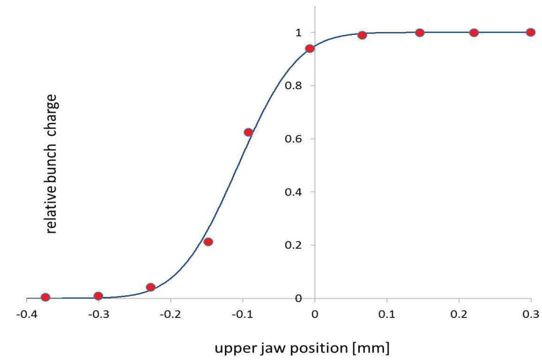

Figure 1: Ratio of a bunch charge after and before a collimator as a function of the collimator jaw position, where the upper jaw is moving down. Red circles: measurement, black solid line: analytical approximation.

For the transverse kick analysis we chose only those positions of a jaw where the bunch charge due to a collimator is not changed much. The first goal was to determine the direction of a kick induced by the wake fields. To resolve it, we measured a beam trajectory along the linac, LTU and undulator regions, where a jaw position was close to the beam, and compared it to a reference trajectory where a jaw was moved far away from the beam. Figure 2 shows the difference of the horizontal projections of these trajectories downstream of the measured horizontal collimator corresponding to the left jaw moving towards the beam. One can see that the beam receives a negative kick.

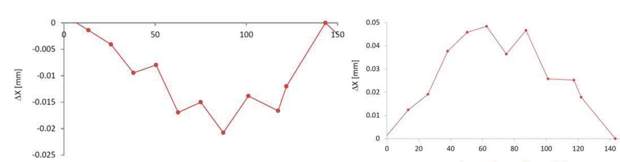

Figure 2: Difference of the horizontal projections of the measured and reference beam trajectories downstream of a horizontal collimator when the left or right jaw moved towards the beam.

When the right jaw of the same collimator was moved towards the beam, it resulted in a positive kick, as can be seen in Fig. 3 showing the difference of the horizontal projections of the measured and reference trajectories. Here the orbit effect due to the right jaw is larger since it was moved closer to the beam as compared to the left jaw. In both cases the beam gets a kick in the direction of

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the closest jaw. In some sense, one can say that a jaw "attracts" the beam. The same effect was observed with the vertical collimators. This is a good experimental check of our theory.

The collimator kick leads to beam oscillations downstream of the collimator. Figure 3 shows the beam trajectory in the case where the bottom jaw of a vertical collimator is moved closer to the beam. The solid line is the vertical projection of the beam trajectory and the dotted line shows the horizontal projection.

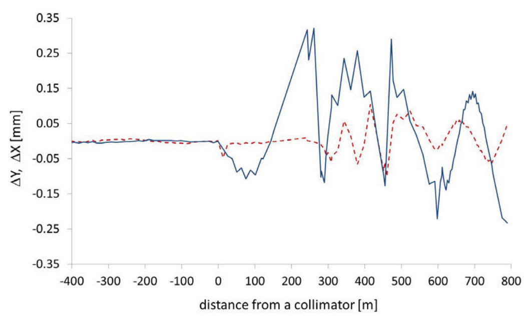

Figure 3: The vertical (solid line) and horizontal (dotted line) projections of the beam trajectory, where the bottom jaw of a vertical collimator is moved close to the beam.

In Fig. 3 we can see vertical oscillations in the undulator region (the last 100 meters), caused by the wake field effect from the vertical collimator. It is interesting to note that this is also accompanied by a horizontal oscillation indicating some unexplained coupling in this region.

To check the dependence of the average kick upon the collimator jaw position we analyse the BPM data at the place where the bunch gets the maximum displacement. As one can see in Fig. 2, this region is approximately 60-80 m downstream of the collimator. The measurement results for different collimators are presented below. Figure 4 shows a beam position and a relative bunch charge after a collimator as a function of a bottom jaw position. One can see that the beam starts to get a kick before it touches the collimator jaw. These measurement results were compared with the formula (2), which predicts a kick to be inversely proportional to the distance between the beam and the collimator jaw. Based on this prediction, we calculated the averaged beam displacement using the linac lattice parameters.

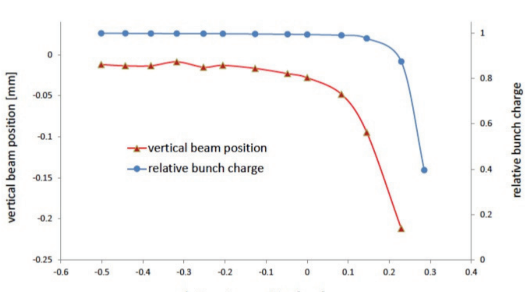

Figure 4: A vertical beam position (the line with triangles) and a relative bunch charge (line with circles) versus position of the collimator bottom jaw.

To make an accurate comparison, we approximate the measured data by our analytical prediction, optimising the possible mistakes in measuring of a jaw edge position and a position of a BPM. The results are shown in Fig. 5 for four jaws of a horizontal and a vertical collimator. In the measurement, each jaw was moved towards the beam keeping the other jaws far away from the beam. In these plots the horizontal axis is an inverse position of a jaw which makes the displacement a straight line. One can see a good agreement with our prediction for all the jaws. However, we found that the calculated approximate position of a collimator jaw is about 100 microns closer to the beam as compared to a jaw position measured at the point where a loss of 50% of the bunch charge occurs. This discrepancy can be explained by the fact that the beam, as we discussed before, has a non-zero transverse size. The latter can be included in the formula (2). The error of the BPM position was found to be inside a 5-10 micron range.

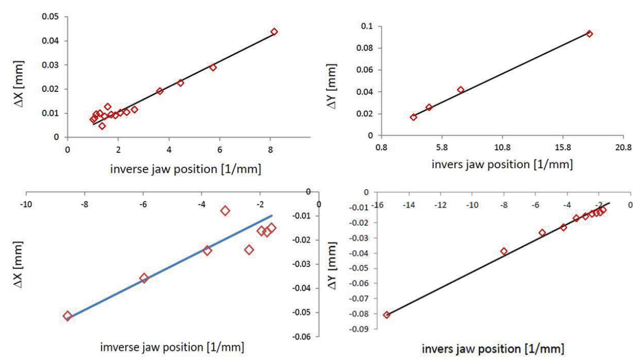

Figure 5: Comparison of the measured beam displacement after a collimator (red diamonds) with the theoretical prediction (black solid line) for four jaws of the horizontal and vertical collimators.

The special character of the wake fields is that the response reaction depends on the longitudinal particle position in the bunch. The "head" of the bunch is not deflected at all, but the "tail" receives the maximum deflection force. Since the transverse kick leads to the oscillations in the focusing system, the particles at different positions in the bunch will oscillate with different betatron phases. This makes the bunch geometrically tilted. This tilt angle will also perform oscillation in the lattice. In practice, the feedback system makes the head of the bunch oscillate too as it acts against the averaged kick. For this reason the feedback system cannot completely compensate the kick from a collimator.

In the beam phase space, the bunch tilt is rotating along the focusing system. Consequently, the transverse emittance may be increased. We can make an estimate of this additional emittance using a formula for the emittance and values of the β–functions, and assuming that the transverse beam size is twice the value of the beam displacement. We found that at some locations in the linac or LTU the effective (or projected) emittance can be comparable with the real beam emittance and reaching more than 1 mm-mrad. To verify this estimate,

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we did an emittance measurement using the LCLS diagnostic in the LTU region [5]. The measurement was done downstream of the collimator using 4 wire scanners with a 45° phase advance between them. The results are shown in Fig. 6 for three different positions of the collimator jaw. The left plots show the measured beam sizes in the vertical plane, and the right plots the respective normalized phase space ellipses. The dashed lines indicate the projection angle for each measurement. The projected emittance increases when a collimator jaw approaches the beam. One can also see the tilt of the bunch, which is rotating on the phase plane relative to its center.

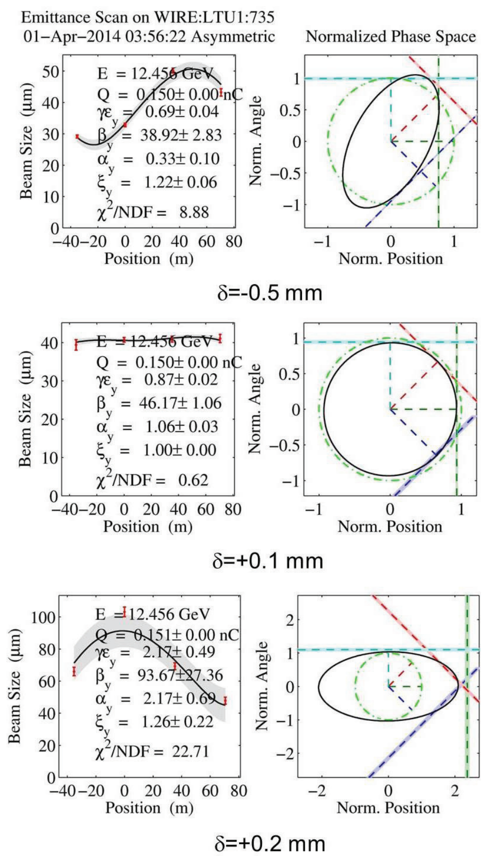

Figure 6: Emittance measurements for different positions of the collimator jaw: -0.5, +0.1, +0.2 mm.

The tilt of the bunch performs oscillations in the focusing system of the FEL. This indicates that different particles of a bunch oscillate with different betatron phases, which may disturb the coherent radiation in the FEL undulators. In this way the efficiency of the FEL performance may be reduced. We found confirmation of this prediction in the measurements. Usually the pulse energy of the X-ray beam describes the efficiency of the FEL. At LCLS this parameter is measured in a different way. Specifically, a gas detector is used to measure the FEL efficiency when a collimator jaw is moved towards the beam. The result of the measurement is shown at Fig. 7, where the relative bunch charge and the projected emittance are also shown. One can see a strong correlation between the growth of the projected emittance and the reduction of pulse energy. When a beam is close to a collimator jaw, a small change of the jaw position leads to a dramatic change in the X-ray production. We found that in this case the pulse energy exponentially depends upon the particle loss. The pulse energy decreases by 50% when only 3% of the beam particles are absorbed by a collimator jaw.

We also see the rotation of the bunch on the energy-coordinate phase plane using a new X-band transverse deflector at LCLS [6]. This deflector gives a linear kick along the bunch in the horizontal direction; hence, particles along the bunch obtain different horizontal positions.

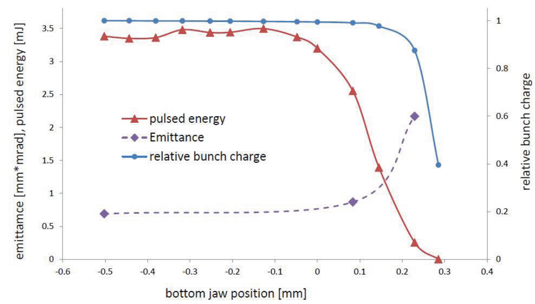

Figure 7: The FEL pulse energy (triangles), the beam emittance (diamonds) and the relative bunch charge (circles) versus the collimator jaw position.

As the bunch travels to the screen after the vertical bending magnet, particles with different energies obtain different vertical positions. In the measurement we change the position of a jaw in a vertical collimator and then take images from the screen. A typical image of a bunch, which produces an X-ray pulse energy of 3 mJ, is shown on the left plot of Fig. 8. As the collimator jaw comes closer to the beam (center and right plots in Fig. 8) the particles get transverse kicks opposite to the kick from the deflector. The energy spread also decreases as the X-ray production in the undulators is reduced. However, the horizontal size of the beam is also increasing. The latter could be explained by the existence of the vertical-horizontal coupling in the LTU as we mentioned before.

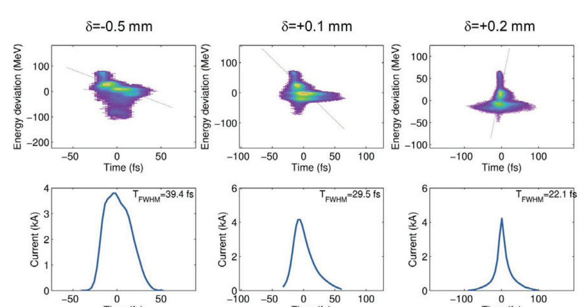

Figure 8: Bunch images on the phase plane for different positions of the collimator jaw.

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