MEASUREMENT OF THE EFFECT OF COLLIMATOR GENERATED WAKEFIELDS ON THE BEAMS IN THE SLC [*]

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I. INTRODUCTION

Collimators with adjustable jaws are used in the SLC linac, arcs, and final focus to eliminate the tails of the beams that produce backgrounds in the SLD detectors. However, if the beams are not centered within the jaws of the collimators, transverse wakefields are generated which act to increase the beam emittances. The sensitivity to the beam offset is largest in the vertical collimators in the linac where the small beam sizes ($< 100\ \mu$m) require that the gap between the jaws be reduced to about a millimeter for effective background reduction.

To study the wakefield effect of the collimators, measurements of the induced mean angular kick were made as function of the beam offset in one of the SLC collimators. We are interested in both the linear (dipole) behavior near the axis of the collimator and the non-linear behavior near the jaws of the collimator. In this paper we present the results together with a comparison to theoretical predictions. Besides helping us to quantify the effect of the collimators in the SLC these results are also useful in understanding their effect in future linear colliders, in which collimators will also be important components. (For a related paper, see Ref. [1].)

II. THEORY

Consider a vertical (y) collimator that has a pair of rectangular, metallic jaws separated by a distance $2a$ and that is set in a cylindrical tube of radius b, with $b \gg a$. Let the distance between the leading and trailing edges L be large compared to a, but not large compared to the local beta function β_y. Now consider an ultra-relativistic electron beam moving parallel and close to the axis of the beam tube (in the z direction) at vertical offset y_0. Let the beam have a longitudinal charge distribution that is gaussian, and a transverse dimension that is small compared to a (for a sketch of the layout, see Fig. 1). As the beam passes the collimator it will, due to the wakefields, experience a kick in y with an amplitude that varies along the bunch (*i.e.* that depends on longitudinal position within the bunch, s), and which therefore results in a growth in projected emittance.

The wakefield of the collimator is due to the discontinuities at the leading and trailing edge of the jaws, and to the resistance of the metallic material. At present there is no good way of finding the wakefield due to both of these effects taken together. However, when the jaws are far apart the kick is due mostly to the jaw discontinuity and is approximately the same as that of a perfectly conducting collimator, and when they are close together it is due mostly to the wall resistance and can be approximated by the usual resistive wall wake. Let us call these two types of wakefields, respectively, the geometric wake and the resistive wall wake of the collimator. In the intermediate regime one might, as an approximation, add the two contributions together. (Such an approach has been applied to studying the effect of the NLC collimators; see Ref. [2].)

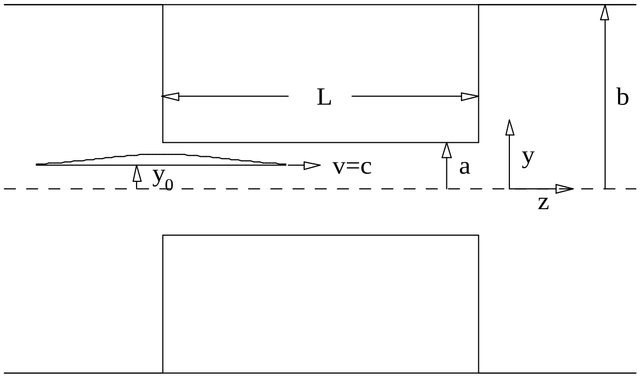

Figure 1. A sketch of the beam and collimator.

Let us consider first the effect of the geometric wake. For a gaussian beam, with rms length $\sigma_z\ versim > a$ (which is satisfied in our experiment described below), passing near the axis of a rectangular, deep ($b\ versim > 5a$), perfectly conducting collimator the kick $\Delta y'(s)$ can be approximated by[3]

$$\Delta y'(s) \approx \left(\frac{\pi}{2}\right)^{\frac{3}{2}} \frac{r_e N}{\sigma_z \gamma} e^{-s^2/2\sigma_z^2} \left(\frac{y_0}{a}\right) \qquad y_0/a \ll 1\,, \quad (1)$$

with r_e the electron radius ($= 2.8 \times 10^{-15}$ m), N the bunch population, and γ the beam energy parameter. In Eq. 1 we have multiplied the result for a round collimator by $\pi^2/8$. (Note that in a gently tapered collimator, such as will likely be used in future linear colliders a somewhat modified formula is appropriate.[4]) Note that the average value of the gaussian factor, when weighted by the gaussian charge distribution, is 0.71.

In the resistive wall wake regime we use the kick near the axis between two resistive plates of length L and conductivity σ (ignoring the end conditions):[5]

$$\Delta y'(s) = \frac{\pi r_e N L}{4a^2\gamma} \left(\frac{c}{\sigma\sigma_z}\right)^{\frac{1}{2}} f(s/\sigma_z) \left(\frac{y_0}{a}\right) \qquad y_0/a \ll 1 \quad (2)$$

with

$$f(x) = \frac{1}{\sqrt{2\pi}} \int_0^\infty \frac{e^{-(y-x)^2/2}}{\sqrt{y}}\, dy \quad . \quad (3)$$

(In a round collimator the result is $8/\pi^2$ smaller.) It is due to the extra factor of $1/a^2$ in Eq. 2 that for large a the geometric wake component dominates, while for small a the resistive

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wall wake component dominates. Note that the average value of $f(s/\sigma_z)$, when weighted by the gaussian charge distribution, is 0.78.

When the beam passes not near the axis of the collimator, but rather near one of its jaws, the above formulas do not hold. In the case of the geometric wakefield the general solution is not known, though simulations suggest that the kick will diverge $\sim 1/(a-y_0)$ as y_0 approaches a.[6] In the resistive wall case the solution is to replace the factor y_0/a in Eq. 2 by the factor[7]

$$\frac{1}{\pi}\left(\frac{\pi y_0/a + \sin \pi y_0/a}{1+\cos \pi y_0/a}\right) \quad , \tag{4}$$

which diverges as $1/(a-y_0)^2$ as y_0 approaches a. The asymptotic formula is:

$$\Delta y'(s) = \frac{r_e N L}{2\pi(a-y_0)^2\gamma}\left(\frac{c}{\sigma\sigma_z}\right)^{\frac{1}{2}} f(s/\sigma_z), \quad y_0 \longrightarrow a. \tag{5}$$

We expect that, even for large a, as the beam moves close to one jaw the resistive wall wake will eventually dominate.

III. MEASUREMENTS

A collimator two-thirds of the way down the SLC linac, in Sector 18, was used for the measurements. It is a y collimator of the type indicated in Fig. 1, with length $L = 7.9$ cm, positioned in a beam tube of radius $b = 3.5$ cm. Unlike in the figure the jaw surfaces are not perfectly flat; they are rounded slightly, with a maximum excursion in the center of 40 μm. The collimator body is made of titanium, and on the jaw surfaces a 25 μm layer of gold has been deposited. The collimator jaws can be moved independently in the vertical direction.

For the measurements the beam was first steered as well as possible over the first 20 sectors of the SLC linac with the collimator jaws open, using wakefield bumps to try to tune out any transverse beam tails that had been generated in earlier parts of the linac. Unfortunately, on the day of the measurement we were only partially successful in this; after tune-up tails could still be seen on downstream video screens. After tune-up the collimator jaws were set to a fixed separation and then scanned across the beam position. At each position, on each pulse, 8 upstream and 8 downstream beam position monitors (BPM's) were read, and the average wakefield kick of the collimator $\langle \Delta y' \rangle$ was obtained by fitting to a betatron oscillation. In this manner we could separate out incoming pulse-to-pulse jitter and obtain an accuracy of about 1/3 μrad. At each measurement the beam intensity was measured using downstream BPM's, and any data points with more than 10% beam loss were discarded. The beam position half way between the 10% loss points was taken to be the the center of the collimator, and the results were shifted to give $\langle \Delta y' \rangle = 0$ at this position.

For our measurements the bunch population is nominally $N = 3.5 \times 10^{10}$, the rms bunch length $\sigma_z = 1.3$ mm (though the bunch distribution is not gaussian; probably more like a flattened and truncated gaussian), the energy $E = 33$ GeV; the beam is roughly round, with the x and y rms bunch sizes $\sigma_x = \sigma_y = 80$ μm, and the rms y divergence $\sigma_{y'} = 1.35\,\mu$r. The conductivity at room temperature of gold is $4.4 \times 10^{17}\ s^{-1}$, that of titanium $0.21 \times 10^{17}\ s^{-1}$.

IV. RESULTS

Our first measurement was to check on the linear dependence of the kick on bunch population, to see that we really have a wakefield effect. We plot in Fig. 2 the measured kick of the beam, but scaled inversely as N, as function of offset between collimator jaws, for $N = 1 \times 10^{10}$ and $N = 3.5 \times 10^{10}$. Here, $a = 1$ mm. Repeated measurements confirm the result shown here. We notice two things from Fig. 2: First, the curves are not perfectly anti-symmetric, contrary to what we expect from the symmetry of the problem. This can be due to the beam having a $y-z$ tilt or tail due to wakefields in the upstream portion of the linac and/or due to y dispersion in the linac. Or it can be due to some asymmetry in the collimator geometry. Secondly, the two curves in Fig. 2 agree quite well, confirming that we are measuring a wakefield effect. The differences that we see can be due to: (i) a lower current beam will be shorter in the damping ring and therefore of a slightly different length in the linac, and (ii) any $y-z$ tilt or tails the beam has obtained in the upstream part of the linac can be very different for beams with such different bunch populations.

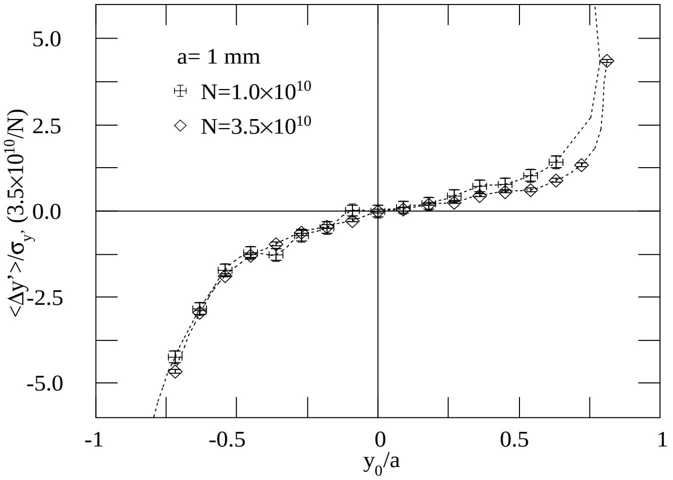

Figure 2. Kick of the beam, but scaled inversely as N, *vs.* y_0/a, for $N/10^{10} = 1$ and 3.5; $a = 1$ mm.

Next the dependence of the wakefield kick on the collimator half-aperture a was measured. In Fig. 3 we plot the kick as function of vertical offset for half apertures $a = 0.5$ mm, 1.0 mm, and 1.5 mm keeping the bunch population at $N = 3.5 \times 10^{10}$. In this data we again note the lack of symmetry mentioned above. Note that when plotting the kick as function of y_0/a if we are in the geometric wakefield regime then the curves will fall on the same straight line near the origin (see Eq. 1). And, in fact, the two curves for the larger jaw openings do roughly coalesce to one straight line over a region, though not a symmetric one, near the origin. Substituting for the parameters in Eq. 1 we find that the slope of this line should be 1.2 (the straight line in Fig. 3), which agrees fairly well with the data points.

The curve in Fig. 3 that represents the measurements using the smallest jaw opening ($a = 0.5$ mm) has a slope near the origin that is more than twice that of the other two curves. Substituting into the resistive wall wake equation, Eq. 2, taking for conductivity that of gold, we obtain, for this aperture, a contribution to the slope of 0.15, which is not significant when compared to the geometric wake contribution. However, if in fact the gold layer were damaged, for example by the beam hitting it, and if the real conductivity were more like that of the underlying titanium, then the resistive wall contribution to the slope becomes 0.7, which is comparable to the geometric wakefield contribution. Although the real slope of this curve near the origin is somewhat larger than the sum of these two contributions, the results do suggest that when reaching the smallest aperture we are in a domain where the resistive wall wakefield is becoming significant, even at small offsets.

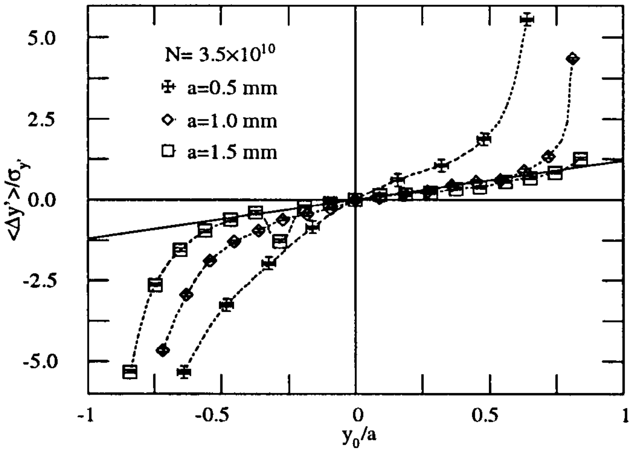

Figure 3. Kick of the beam *vs.* y_0/a for $a = 0.5$ mm, 1.0 mm, and 1.5 mm; $N = 3.5 \times 10^{10}$.

We plot in Fig. 4 the same data of Fig. 3, but now as a function of distance from the lower collimator jaw. Asymptotically we expect all data points to fall on the same curve, one that varies as $1/(a-y_0)^2$. We see that all data points roughly do follow this power law, the two larger aperture data sets on one curve and the smallest aperture data set roughly on a curve a factor of two less in amplitude, possibly due to a partial cancellation of the force by the other collimator jaw. On the same plot we show the resistive wall asymptotic contribution, Eq. 5, using the conductivity of titanium, 5.5 times this curve, and 11 times it. Even if we were to suppose that the geometric wake contribution (which we don't precisely know) were as large as the resistive wall wake contribution the calculated results would still be much lower in amplitude than the measured data. Due to the asymmetry of the data there seems to be less information about the asymptotic behavior near the upper jaw. The kick again seems to be consistent with a -2 power of distance, but this time with an amplitude of 3.5 times the resistive wall asymptote for titanium. We need to redo this measurement with good beam quality to resolve this.

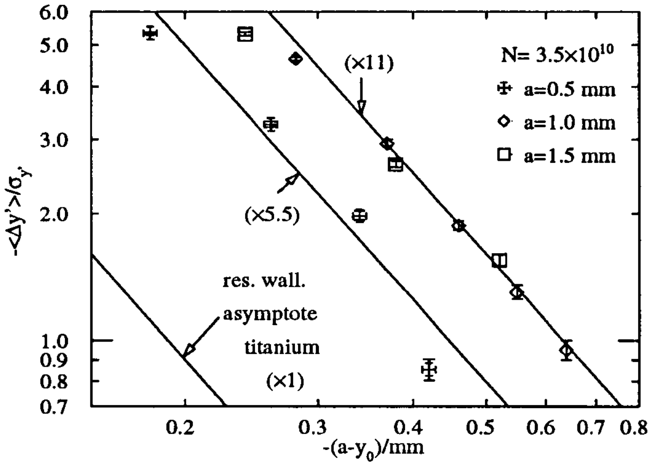

Figure 4. The same data as in Fig. 3, but plotted as distance from the lower collimator jaw. Also plotted are the resistive wall asymptotic formula for titanium, the formula times 5.5, and it times 11.

V. CONCLUSIONS

We have performed preliminary measurements of the average wakefield kick of SLC collimators as function of beam offset within the jaws. We have demonstrated that the kick depends linearly on current, as it should for a wakefield effect. For larger jaw apertures we have demonstrated that near the center of the jaws there is a linear regime of kick dependence on offset, the slope of which agrees with the analytical result for the geometric wakefield of collimators. For a smaller jaw aperture the slope in the linear regime is larger than can be accounted for by the geometric wakefield, which suggests that, for this case, the resistive wall wake has become important. However, this is consistent with calculations only if the 25 μm gold layer on the surface of the collimator jaws has been damaged. We also find that the kick when the beam is near the metallic surface is consistent with an inverse square dependence on distance; the amplitude, however, is much larger than we can account for with our theory. Finally, we should also point out that all our results have some unexpected asymmetry, which may be due to poor beam quality during the measurement or some asymmetry in the collimator geometry.

In the near future we will investigate the surface of the collimator, to see if it is indeed damaged. These measurements were preliminary and should be repeated.

References

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