DIRECT MEASUREMENT OF GEOMETRIC WAKEFIELDS FROM TAPERED RECTANGULAR COLLIMATORS*

P. Tenenbaum, K. Bane, R.K. Jobe, D. McCormick, C.K. Ng, T.O. Raubenheimer, M. Ross,
G. Stupakov, D. Walz, SLAC, Stanford, CA, USA

Abstract

Direct measurement of the short-range wakefield due to a series of tapered collimators is presented. The wakefields were measured by inserting a fixed aperture in the path of the electron beam at the 1.19 GeV point of the SLAC linac. As the vertical position of the collimator is varied, the vertical deflection of the beam is measured on 29 downstream beam position monitors. A series of apertures with different geometries were studied to permit confirmation of the scaling laws and magnitude of deflection predicted by theory. Description of the apparatus and collimator aperture specifications, predicted centroid deflections, and measured deflections are discussed.

1 INTRODUCTION

One of the limitations of present and future high-performance accelerators is the effect of short-range wakefields on the beam. The beam quality in the Stanford Linear Collider (SLC) was sensitive to the positioning of the adjustable collimators at the end of the linac [1], and the post-linac collimation systems for the Next Linear Collider (NLC) or the TeV Linear Accelerator (TESLA) will be even more sensitive [2]. The Linac Coherent Light Source (LCLS) may be limited in its performance by the resistivity and surface finish of its undulator vacuum chamber [3]. Accurate predictions of the short-range wakefield will be crucial to these facilities.

Direct measurements of short-range wakefields have often been difficult to perform, since they are usually performed on existing facilities which are not designed with such experiments in mind [4]. Analytic calculations are also limited, since the short-range effects are dominated by the high-frequency impedance which is difficult to calculate accurately [5]. To address these shortcomings, we designed, constructed and installed a dedicated apparatus for measurement of short-range wakefields, and used this apparatus to measure the wakefield deflections of a series of tapered collimators.

2 APPARATUS

The design of the wakefield apparatus has been described in detail elsewhere [6]. Here we merely summarize its critical features.

The main body of the apparatus is a rectangular vacuum chamber approximately 1500 mm long, 650 mm wide, 300 mm tall. The vacuum chamber contains an aluminum insertion which is 280 mm wide, 75 mm tall, and slightly shorter than the vacuum chamber in length. The insertion contains 5 channels which run its full length: one cylindrical channel 38 mm diameter and 4 square channels 38 mm in height and width. Each of the square chambers contains a collimator or other aperture for which the wakefields are to be measured; the circular chamber is a smooth right-circular cylinder. The insertion can be translated horizontally relative to the vacuum chamber by means of a remote-controlled stepper motor attached to a ball screw.

The apparatus is mounted on a remote-controlled magnet mover originally built for the Final Focus Test Beam (FFTB), which can move over a range of ± 1.5 mm in the vertical with a precision better than 0.001 mm [7]. It is installed in the SLAC linac at the point where electrons and positrons are extracted from the damping rings with energies of 1.19 GeV. During measurements of wakefields, one of the 4 square channels is positioned on the beam path. The wakefield is measured by raising and lowering the vacuum chamber (and thus the collimator or other aperture) via the magnet mover, and measuring the resulting deflection on the downstream beam position monitors (BPMs). The measurement technique is based on the procedure used to measure long-range wakefields at the Accelerator Structure Setup (ASSET) facility, which is a few meters downstream in the linac, except that only one beam is needed [8]. By moving the collimator and not the beam, the measurement is simplified since it is not necessary to subtract the betatron oscillation introduced when moving the beam.

3 COLLIMATOR APERTURES

The first series of collimators was designed to test the geometric wakefield of a tapered collimator. In order to minimize resistive effects, the collimators were constructed from elemental copper. Each collimator consists of a taper from the full aperture to the minimum aperture, a radiused “flat-top” of minimum length (millimeters), and a taper back to the full aperture of the channel.

Three of the collimators provide apertures which are rectangular, i.e., the collimators taper in the vertical but preserve the full 38 mm (1.5”) horizontal width at all z locations. The analytical model predicts a deflection of the centroid given by [9]:

$$\Delta y' = y_0 \frac{\sqrt{\pi}}{2} \frac{N r_e}{\gamma} \frac{h(r_0 - r_1)(r_0^2 - r_1^2)}{\sigma_z L_T r_0^2 r_1^2}, \qquad (1)$$

where y_0 is the relative vertical offset between the collimator and the beam, N is the bunch population, r_0 and r_1 are

---

* Work supported by U.S. Department of Energy, Contract DE-AC03-76SF00515

the maximum and minimum half-apertures of the collimator respectively, h is the half-width (in x) of the collimator, σ_z is the RMS bunch length, L_T is the taper length (in z), γ is the beam relativistic factor, and r_e is the classical electron radius. Note that the deflection, in the analytic model, depends linearly upon the width of the jaws h, implying that infinitely-wide collimators produce an infinite kick.

One of the collimators provides a square aperture, in which both horizontal and vertical dimensions are ramped in a pyramidal fashion. The analytic prediction of deflection in this case is assumed to be close to that of a cylindrically-symmetric tapered collimator [10]:

$$\Delta y' = y_0 \frac{1}{\pi} \frac{N r_e}{\gamma} \frac{(r_0 - r_1)^2}{\sigma_z L_T r_0 r_1}, \tag{2}$$

where the variables are as defined in Eqn. 1. Table 1 shows the geometric parameters of each collimator.

4 MEASUREMENTS

During the June and July 2000 several measurements were made of the near-center dipole wakefield deflections of each test collimator. All of the measurements were made at the nominal energy of 1.19 GeV; the bunch length was the nominal one for PEP-II injection, specfically 0.65 ± 0.05 mm RMS length [11]. Most measurements were performed at a bunch charge between 2.0×10^{10} and 2.2×10^{10}, although some were performed at charges between 1.2×10^{10} and 1.3×10^{10} in order to verify the scaling with bunch charge. All measurements were made with electrons. Estimates of the near-center component of the wakefield, for which the deflection is expected to be a linear function of the beam-to-collimator offset, were obtained by fitting a straight line to the measured deflection as a function of collimator vertical position. To minimize the contribution of the nonlinear (near-wall) wakefields only data taken between -1 mm and +1 mm were used for these fits.

Figure 1 shows the measured deflection when the round, regular aperture is engaged and moved vertically by ±1 millimeter. As expected, the deflection is zero to the limits of our precision.

Figure 2 shows the deflection when the Slot 3 collimator is engaged and its vertical position is scanned. The deflection is linear in position as expected, and the sign of the slope is correct for wakefield deflections; however, the amplitude is substantially smaller than expected (-5.9 ± 0.4 μradian/mm measured, 26 μradian/mm expected; see Table 1).

Table 1 compares the predicted deflections with the measured values, for 1.19 GeV electron bunches with 2×10^{10} particles and 0.65 mm RMS bunch lengths; the units of this kick are microradians per mm. In each case, the measured deflection is the weighted average of multiple measurements taken over the course of several weeks; the χ^2 and number of degrees of freedom in the weighted average are also tabulated. Results of measurements at lower charge are omitted, since in all cases these measurements showed that the scaling of the kick with bunch charge is within experimental errors of being linear, as expected. Table 1 also shows the results of simulations of the transverse wakefield of the collimators performed with the program MAFIA[12]. The simulations used the same beam conditions as the experiments except for bunch length, which was set to 1 mm in the simulations. Due to limited computational resources, the square collimator was not simulated.

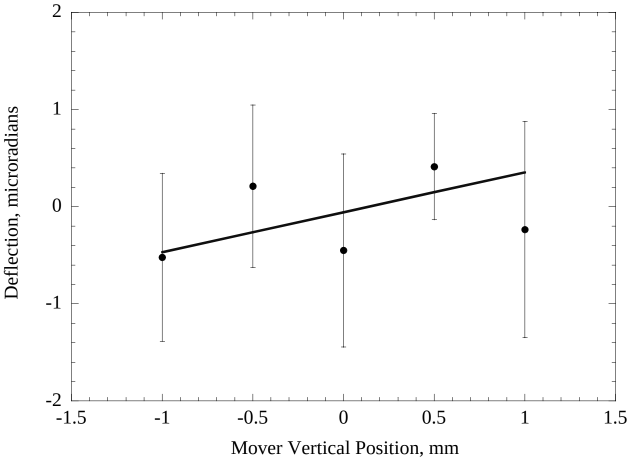

Figure 1: Beam deflection versus apparatus vertical position for collimator-free aperture.

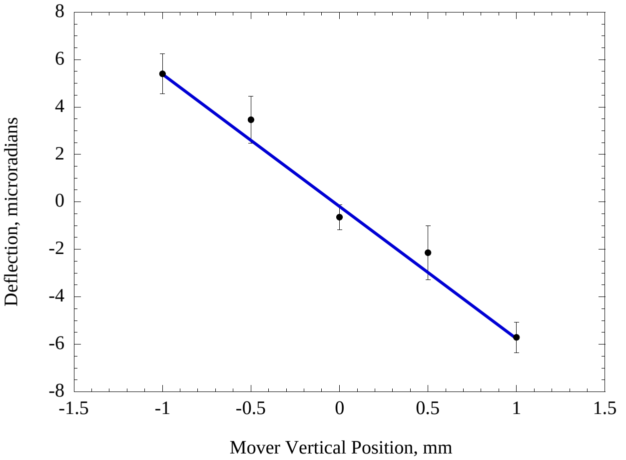

Figure 2: Beam deflection versus apparatus vertical position with tapered flat collimator engaged in beam path.

5 DISCUSSION

The range of measured wakefield deflections is much smaller than expected from the theory: we expected that the strongest deflections would be about 17 times greater than the weakest, while our actual range is less than a factor of 4. While the collimator with the largest gap has the smallest wakefield, as expected, the collimator with a small gap and a long taper has a larger kick than the one with a small gap and a short taper, which is counter-intuitive. Of the greatest interest is the fact that the collimator with a short taper and a small gap has a kick which is smaller by a factor

Table 1: Collimator geometrical parameters and measured ($\Delta y'_{\mathrm{M}}$), theoretical ($\Delta y'_T$), and simulated ($\Delta y'_S$) kicks for collimators. Units are mm for L_T and r_1, μradians/mm for deflections. Errors on theoretical deflections are due to 50 μm uncertainty in the bunch RMS length.

Slot	1	2	3	4
Type	Rect	Square	Rect	Rect
r_1	1.9	1.9	1.9	3.8
L_T	51	51	102	51
$\Delta y'_{\mathrm{S}}$	3.1	–	2.3	1.0
$\Delta y'_{\mathrm{T}}$	54 ± 4	3.2 ± 0.3	26 ± 2	12 ± 1
$\Delta y'_{\mathrm{M}}$	3.7 ± 0.2	7.0 ± 0.3	5.2 ± 0.3	1.9 ± 0.2
χ^2	3.6	1.0	1.9	1.1
ν	5	3	2	2

of 15 than expected. While MAFIA simulations agree with experiments as far as order-of-magnitude is concerned, the simulations do not predict the increase in wakefield for the longer taper.

One possible explanation for the counter-intuitive results on taper length is that collimators 1 and 3 may have been inadvertantly exchanged during installation, which would be impossible to verify at this time without disassembling the aluminum insertion. Another possible explanation concerns a limitation on the validity of Eqn. 1, specifically that the aspect ratio of the gap, h/r_1, must be smaller than the aspect ratio of the taper, $(r_0 - r_1)/L_T$. When this inequality is not satisfied, there is not enough time for *transverse* image currents to flow between the top and bottom jaws (required to keep the ratio of top and bottom *longitudinal* image currents correct as the gap height decreases), and the reduced transverse currents lead to a reduced wakefield. This would argue that collimators which more severly violate the above limit have smaller kicks than collimators which slightly violate it, thus that the wakefield does not saturate at the limits of applicability of Equation 1, but rather turns over and becomes smaller. Resolving which of these two possibilities is correct is of substantial importance to future accelerator designers.

6 CONCLUSIONS AND FUTURE DIRECTIONS

We have constructed an apparatus for the direct measurement of collimator wakefields and installed it at the 1.19 GeV point in the SLAC linac. We have performed an initial set of measurements on the geometric wakefields of tapered collimators. These measurements give reproducible results over a period of several weeks, and obey the expected linear scaling with bunch intensity.

The measurements of the near-center geometric wakefields of several tapered collimators give results which are at odds with the analytical model, but which are in somewhat better agreement with MAFIA simulations. One possible theoretical model for the unexpectedly-small deflections has been proposed. This model would also explain the paradoxical phenomenon of short tapered collimators generating smaller deflections than long tapered collimators.

We plan to perform a much larger set of measurements using the present set of collimators. In particular, we plan to measure the effect of bunch length variation with each aperture, and also the near-wall wakefield, which is expected to be nonlinear with beam offset.

We have started preparations for measurements of additional apertures. At this time, the TESLA group at DESY is fabricating a second aluminum insertion and a set of test apertures made of graphite. Graphite would be the preferred material for optically thin spoilers because of its high strength, heat capacity, and melting point. However, graphite has poor vacuum properties (which can be addressed through additional pumping) as well as extremely high resistivity (which is thought to be unacceptable for wakefields). Thus the test of graphite is of great interest to designers of linear colliders in general. In addition, we are presently constructing collimators made of titanium, which has a resistivity some 30 times larger than that of copper, in order to test resistive-wall wakefield effects. We will also construct a copper tapered collimator of sufficient length to satisfy the validity conditions of Eqn. 1, which will provide further insight into the geometrical wakefield. Other experiments might involve tests of surface finish, and ultimately tests with prototype linear collider collimator apertures and LCLS vacuum chambers.

7 ACKNOWLEDGEMENTS

The wakefield experiment could not have been performed without the efforts of SLAC's technical experts, in particular B. Brugnoletti, K. Dudley, and M. Ortega. We would also like to thank D. Burke and T. Markiewicz, our "venture capitalists."

8 REFERENCES

[1] P. Raimondi *et al*, Proceedings *EPAC-98*, 245 (1998).

[2] NLC Design Group, *Zeroth-Order Design Report for the Next Linear Collider*, SLAC-Report-474, 555-641 (1996).

[3] LCLS Design Study Group, *Linac Coherent Light Source Design Study Report*, 1-6 (1998).

[4] F.-J. Decker *et al*, Proceedings *LINAC-96* (1996).

[5] A. Chao, *Physics of Collective Beam Instabilities in High-Energy Accelerators*, chap. 2 (1993).

[6] P. Tenenbaum *et al*, Proceedings *PAC-99*, 3453 (1999).

[7] G.B. Bowden *et al*, NIM **A368** 579 (1996).

[8] C. Adolphsen *et al*, PRL **74** 2475 (1995).

[9] G. Stupakov, SLAC-PUB-7167 (1996).

[10] K. Yokoya, CERN-SL/90-88 (AP) (1990).

[11] F.-J. Decker, these proceedings.

[12] M. Bartsch *et al*, proceedings EPAC-90.