DIRECT MEASUREMENT OF GEOMETRIC WAKEFIELDS FROM TAPERED RECTANGULAR COLLIMATORS*

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Abstract

We present a direct measurement of the short-range wakefield of a series of tapered collimators. 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 extremely sensitive to the positioning of the adjustable collimators at the end of the linac [1], and the post-linac collimation systems for higher energy linear colliders such as 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]. We merely summarize its critical features here.

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], and 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 normal operation the insertion is positioned to engage the round aperture in the path of the beam, which permits high-quality beams to be transmitted without losses. During measurements of wakefields, one of the 4 square channels is engaged 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). Only the 29 BPMs in Sector 2 of the linac are used; this permits measurements when the beam is stopped at a diagnostic dump at the end of sector 2 as well as when beams are permitted to enter the PEP transport lines. The measurement technique is based on the technique used to measure long-range wakefields at the Accelerator Structure Setup (ASSET) facility 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 off the betatron oscillation introduced to move the beam towards the collimator.

3 COLLIMATOR APERTURES

The first series of collimators is designed to test the geometric wakefield of a tapered collimator. In order to minimize resistive and surface-finish effects, the collimators were constructed from elemental copper via wire electric-discharge machining; each collimator consists of a ramp from the full aperture to the minimum aperture, a radiused “flat-top” of minimum length (millimeters), and a ramp 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

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

preserve the full 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 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]:

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

where variables are defined as in Equation 1.

Table 1 shows the geometric parameters of each collimator and the predicted deflection (in μradians per mm collimator offset) for a 1.19 GeV beam of RMS length 1 mm with 2×10^{10} electrons.

Table 1: Specifications for tapered collimators. “S” indicates a square geometry, “R” indicates rectangular, with a horizontal width at the vertical minimum of 38 mm. In all cases r_0 is 19 mm, all dimensions in the table are mm.

Slot	1	2	3	4
Type	R	S	R	R
r_1	1.9	1.9	1.9	3.8
L_T	51	51	102	51
$\Delta y'$	35	2.1	17	7.5

4 MEASUREMENTS

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, 17 μradian/mm expected; see Table 1). Figure 3 shows the measured deflection for the square collimator in Slot 2; in this case, the deflection is approximately 4 times larger than predicted.

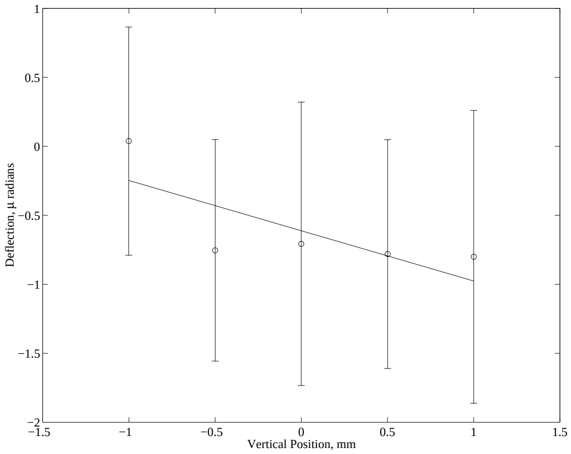

Figure 1: Beam deflection versus apparatus vertical position for collimator-free aperture

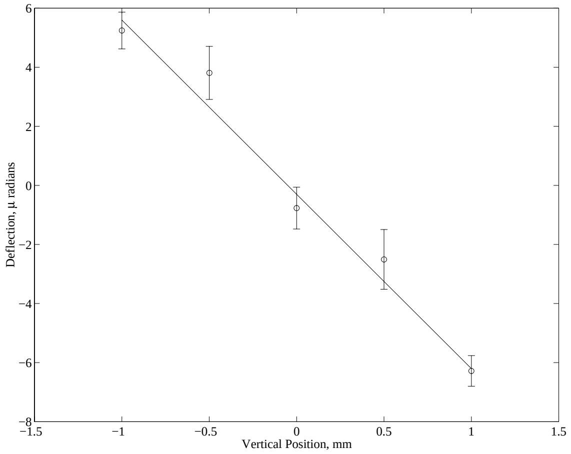

Figure 2: Beam deflection versus apparatus vertical position with tapered flat collimator engaged in beam path

Table 2 compares the predicted deflections with the measured values, for 1.19 GeV electron bunches with 2×10^{10} particles and 1 mm RMS bunch lengths; the units of this “in-phase” kick are microradians per mm. In addition, Table 2 shows the measured “out-phase” kick: this is the slope of a linear fit to the impact parameter as a function of collimator position, with units μm per mm. The out-phase kick is expected to be zero; a non-zero value could indicate that the wakefield deflection occurs over a longitudinal region which is large compared to the vertical betatron function at the collimator ($\beta_y \approx 3$ m), or that the model of the optics used to fit the incoming and outgoing beam position and angle at the collimator location is in error. The out-phase kicks are comparable to the measurement error, but the in-phase and out-phase kicks do not appear to be simply proportional. Thus a modelling error seems unlikely, but at this time we cannot determine whether the wakefield interaction is extended or pointlike. Also, we emphasize that results listed in Table 2 are preliminary.

The target resolution of the experiment was to measure

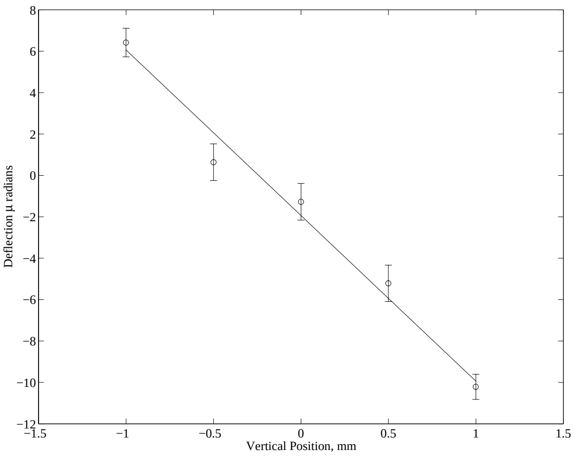

Figure 3: Beam deflection versus apparatus vertical position with tapered square collimator engaged in beam path

Table 2: Measured in-plane ($\Delta y'_{\mathrm{M}}$) and out-phase (Δy_{M}) kicks for collimators; units are μradians/mm and μm per mm, respectively. Expected out-phase kicks are zero in all cases. Expected in-phase kicks ($\Delta y'_{T}$) also shown.

Slot	1	2	3	4
$\Delta y'_{\mathrm{T}}$	35	2.1	17	7.5
$\Delta y'_{\mathrm{M}}$	3.5 ± 0.5	8.0 ± 0.4	5.9 ± 0.4	3.2 ± 0.6
Δy_{M}	1.1 ± 0.7	1.3 ± 1.0	1.8 ± 1.1	0.5 ± 1.2

the in-plane kick to ± 1 μradian/mm; the achieved resolution of 0.3 to 0.5 μradian per mm is substantially better, and was achieved without excessive averaging (10-20 pulses per mover position are averaged).

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 3. This may indicate that the linear dependence in Equation 1 is only valid up to a cut-off distance which is small compared to the full width of the beam pipe. This would indicate that analytic estimates of wakefield deflections from flat collimators are too large, which will simplify design of high-performance future accelerators.

On the other hand, the wakefields do not appear to depend in a simple fashion upon the geometries of the collimators. The collimator expected to have the smallest deflection has the largest; the collimator with a long taper has a larger wakefield than that with a short taper, when the opposite was expected; most unexpectedly, the wakefield from a pair of collimators with identical tapers but different minimum apertures are nearly identical, when the theory predicts a factor of 4 difference in their deflections.

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. Our initial measured results disagree substantially with analytic models of the wakefield, and do not lend themselves easily to simple scaling laws.

Due to time constraints, our measurements are only preliminary and should not be regarded as a resolution of the ambiguities in the theory of transverese wakefields. We plan to perform a much larger set of measurements of the present set of collimators: in particular we plan to measure the effect of bunch length and bunch charge variation in each aperture, and also the near-wall wakefield, which is expected to be nonlinear in the 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, but graphite has poor vacuum properties (which can be addressed through additional pumping) and extremely high resistivity (which is thought to be unacceptable for wakefields); thus the test of graphite is of great interest to linear colliders generally. Other experiments might involve more agressive apertures for geometric wakefield study, tests of the effect of resistance using materials such as titanium, tests of surface finish, and ultimately tests with prototype linear collider collimator apertures and LCLS vacuum chambers.

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."

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