DIRECT MEASUREMENT OF THE RESISTIVE WAKEFIELD IN TAPERED COLLIMATORS*

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Abstract

The transverse wakefield component arising from surface resistivity is expected to play a major role in the beam dynamics of future linear colliders. We report on a series of experiments in which the resistive wakefield was measured in a series of tapered collimators, using the Collimator Wakefield beam test facility at SLAC. In order to separate the contributions of geometric and resistive wakefields, two sets of collimators with identical geometries but different resistivities were measured. The results are in agreement with the theoretical prediction for the high-resistivity (titanium) collimators, but in the case of low-resistivity (copper) collimators the resistive deflections appear to be substantially larger than predicted.

INTRODUCTION

In contemporary high-performance accelerators, collimators are commonly used to remove large-amplitude particles from the beam and to protect downstream components from bunches which are following an unsafe trajectory; it is anticipated that future accelerators will continue to require mechanical collimators for these purposes. The transverse wakefields from collimators placed close to the beam can degrade the high beam quality required by advanced single-pass accelerators such as free electron lasers and linear colliders.

The SLAC linac includes a test chamber which permits direct beam-based measurements of the transverse wakefield generated by various collimators [1]. This chamber has previously been used to measure the geometric wakefield of longitudinally-tapered collimators [2], as well as the wakefield from tapered graphite collimators [3]. We now report on a series of measurements of several collimators with identical geometric wakefields and varying resistive-wall wakes.

APPARATUS AND MEASUREMENT TECHNIQUE

The apparatus and measurement technique are described fully in [1]. The test chamber is a large (5' long x 2' wide x 1' tall) rectangular vacuum chamber which can hold up to 4 test collimators at one time. During measurements one of the collimators is positioned in the path of the beam by a remote-controlled translation stage. The wakefield from the selected collimator is measured by varying the vertical position of the apparatus and measuring the resulting vertical deflection of the beam on downstream beam position monitors (BPMs). Figure 1 shows a schematic cross-sectional cutaway of the apparatus. The apparatus is positioned immediately downstream of the extraction point of the SLAC damping rings, which permits the use of bunches with high charge ($N = 2 \times 10^{10}$), low emittance ($\gamma\epsilon_y = 2 \times 10^{-6}$ m.rad), and short length ($\sigma_z = 0.5$ mm) in the measurement.

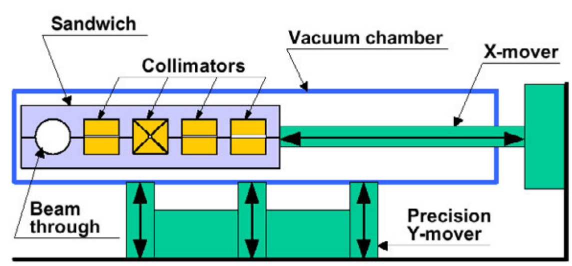

Figure 1: Cutaway schematic of collimator wakefield beam test apparatus.

THEORY OF RESISTIVE WAKEFIELDS

The theory of wakefields due to resistive vacuum chambers has been developed by Piwinski [4] and amplified by Bane [5]. For a chamber of length L, half-gap r and conductivity σ, an electron beam with RMS bunch length σ_z passing off-axis but near the center of the chamber will experience a mean wake kick given by:

$$\kappa = F_G \frac{\sqrt{2}}{\pi} \frac{r_e m_e c^2}{e^2} \frac{L}{r^3} \sqrt{\frac{1}{Z_0 \sigma \sigma_z}}, \tag{1}$$

where κ is the kick factor (typically reported in V/pC/mm) and F_G is a geometric form factor equal to 1 for a round vacuum chamber and equal to $\pi^2/8$ for a flat vacuum chamber.

In the case of a collimator which tapers from half-gap r_0 to half-gap r_1 and then tapers back to r_0, in the case where $r_0 \gg r_1$, we can rewrite Equation 1:

$$\kappa = F_G \frac{\sqrt{2}}{\pi} \frac{r_e m_e c^2}{e^2} \frac{1}{r_1^2 \tan\alpha} \sqrt{\frac{1}{Z_0 \sigma \sigma_z}}, \tag{2}$$

where α is the taper angle of the collimator.

COLLIMATOR APERTURES

A total of four collimators were used in the present set of measurements. All four collimators were 38 mm in width

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with a full gap in the vertical of 3.8 mm. In order to limit the geometric wakefield contribution, all four collimators included a 335 mrad taper from the maximum full-gap of 38 mm to the minimum full-gap of 3.8 mm, and an identical taper from minimum to maximum full-gap on the downstream end. All of the collimator inserts were carefully machined to minimize any possible impedance from surface roughness.

The colimator in Slot 1 was constructed of oxygen free electronic grade copper and consisted of a taper from maximum to minimum gap followed by a reverse taper. The collimator in Slot 2 was geometrically identical to the collimator in Slot 1, but constructed from elemental titanium. The conductivity of copper is $5.98 \times 10^7 \Omega^{-1}\mathrm{m}^{-1}$, while the conductivity of titanium is $2.38 \times 10^6 \Omega^{-1}\mathrm{m}^{-1}$. The latter is conveniently smaller than the former by a factor of 25.1; the wakefield theory therefore indicates that a titanium collimator should generate a resistive wakefield which is just over 5 times as large as an identical copper collimator.

The collimators in Slots 3 and 4 are similar to the units in Slots 1 and 2, but each includes a 1 meter flat section at the minimum full gap of 3.8 mm. The long regular section was expected to enhance the resistive wakefield contribution while keeping the geometric contribution equal to that of the Slots 1 and 2 collimators.

The analytic theory of the geometric wakefield for tapered collimators [6] estimates that the geometric kick factor of all 4 collimators should be 2.5 V/pC/mm. Measurements of a collimator with identical taper angles reported in [2] indicate that the actual geometric kick factor is closer to 1.4 V/pC/mm (see the “meas” row of Table 2 in [2], Slot 3). Table 1 reviews the kick factors expected in the 4 collimators.

Table 1: Expected kick factors, in V/pC/mm, for the 4 collimators studied in this experiment. Geometric kick factors are from measurements reported in Table 2 of [2] (“Meas” values), resistive kick factors are from the theory in [4].

#	κ_{geom}	κ_{Ω}	κ_{total}
1	1.4	≈ 0.001	1.4
2	1.4	≈ 0.006	1.4
3	1.4	0.9	2.3
4	1.4	4.4	5.8

MEASUREMENTS AND ANALYSIS

In a typical measurement, a collimator’s vertical position is stepped from -1.4 mm to +1.4 mm in 15 steps of 0.2 mm. At each step all BPMs are read out for 50 pulses, resulting in a total data set per collimator measurement of 750 pulses. In order to eliminate the contribution of BPM offsets and the nominal orbit of the beam in the SLAC linac, 100 pulses are measured when the vertical translation stage is at its center (zero) position, and these pulses are averaged to obtain a “reference orbit” which is subtracted from all BPM data obtained during a collimator position scan.

After subtraction of the reference orbit, the beam trajectories upstream and downstream of the collimator are reconstructed using appropriate BPMs, and the reconstructed orbits are used to determine a deflection angle at the collimator position. The reconstruction of the upstream and downstream orbits are also used to flag noisy BPMs or pulses which are for some reason ill-behaved. In the present configuration of the SLAC linac the quality of the orbit fit begins to deteriorate approximately 50 meters downstream of the collimator wakefield test chamber, so in general only the first 16 BPMs downstream of the chamber are used for reconstruction of the outgoing orbit.

Figure 2 shows the kick angle in microradians as a function of collimator position in millimeters for a typical scan of the Slot 1 and Slot 4 collimators. In both cases the deflection enters the nonlinear (near-wall) regime, and therefore it is necessary to fit a cubic rather than a linear equation to the data. After initially performing a weighted cubic fit to the data, the polynomial parameters are rearranged to yield a solution of the form:

$$y' = A_3(y - y_0)^3 + B_1(y - y_0) + B_0, \qquad (3)$$

where B_1 is linearly proportional to the kick factor. Note that in this formulation the offset between the center of the collimator and the center of the vertical scan range, y_0, is derived from the asymmetry of the curve.

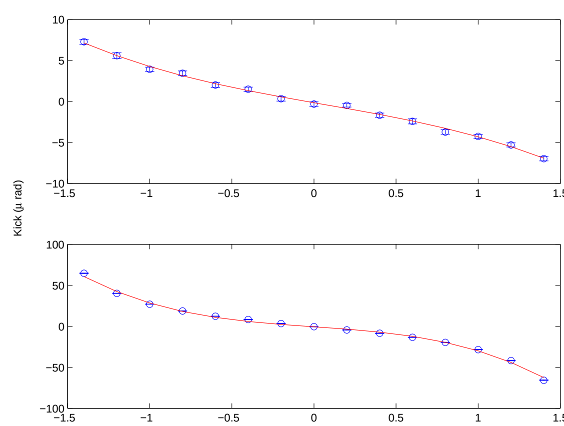

Figure 2: Kick angle vs collimator position. Top: Slot 1 (short Cu). Bottom: Slot 4 (long Ti).

RESULTS

Table 2 shows the expected and measured kick factors for each collimator for an RMS bunch length of 0.5 mm. All measurements were performed with a bunch charge of 2×10^{10} (3,200 pC). A small set of additional measurements were performed on Slot 1 and Slot 4 collimators with a charge of approximately 1,600 pC to verify charge scaling. In both cases the kick factors at the two charge values were within errors of one another, but in the case of Slot

1 the variation was rather large (0.6 to 2.2 V/pC/mm) and therefore not very informative.

Table 2: Expected and measured kick factors, in V/pC/mm, for the 4 collimators measured in this experiment.

#	$\sigma_z = 0.5$ mm		$\sigma_z = 1.0$ mm	
	$\kappa_{\rm expect}$	$\kappa_{\rm meas}$	$\kappa_{\rm expect}$	$\kappa_{\rm meas}$
1	1.4	1.43 ± 0.05	1.1	
2	1.4	1.52 ± 0.03	1.1	
3	2.3	3.87 ± 0.13	1.7	3.06 ± 0.27
4	5.8	6.00 ± 0.17	4.2	4.35 ± 0.38

As expected, the kick factors for the short Cu and short Ti collimators are within errors of one another, and agree with previous measurements of an identical collimator[1] [2]. The kick factor measured for the highly resistive long Ti collimator in Slot 4 also agrees with the expected value, obtained by simply adding the measured geometric kick of the Slot 1/2 collimator with the theoretical resistive kick of the long flat section. In the case of Slot 3 the measured kick is quite a bit larger. If we assume that the geometric contribution is again 1.4 V/pC/mm, the implied resistive kick of the long flat section is larger than expected by a factor of 2.8.

In the case of the long collimators a small number of measurements were made with an undercompressed bunch with $\sigma_z \approx 1$ mm, with the expectation that the geometric kick would reduce to 1.1 V/pC/mm (based on [2]) and that the resistive kick would be reduced by 30%, since this kick is proportional to $1/\sqrt{\sigma_z}$. In the case of the long Ti collimator in Slot 4 the measured wake agrees with the predicted value, while the long Cu collimator is larger than expected. The implied resistive kick in this case is approximately 3.2 times as large as predicted by the theory, which is within errors of the factor of 2.8 found for the shorter bunch.

An earlier measurement of collimator wakefields found that the resistive wakefield from graphite collimators agreed with the theoretical predictions [3]. A measurement carried out in the SLAC linac and the Final Focus Test Beam [7] implied that the resistive wakefield from a set of vanadium-coated collimators was larger than theory predicted by about a factor of 2, although the experimental conditions did not permit the resistive and geometric wakes to be independently investigated. It is suggestive, though not definitive, that copper has both the highest conductivity and the largest experimental discrepancy in its measured resistive wakefield; vanadium, which has a smaller discrepancy, also has a lower conductivity; and titanium and graphite, which have no apparent discrepancy, have conductivities even lower than that of vanadium.

[1] Note that in the interval between the original geometric wakefield measurements and the present it was determined that the RMS bunch lengths at that time were approximately 0.5 and 1.0 mm, not 0.65 and 1.2 mm

CONCLUSIONS

We have performed a set of beam measurements to estimate the resistive wakefields of tapered collimators constructed from elemental copper and titanium. In the case of extremely short collimators we found that, as expected, the resistive contribution is much smaller than the geometric and in this regime the wake kick does not depend on the collimator material. For longer collimators we found a resistive wake kick which agrees with theoretical expectations for highly-resistive titanium, but which is larger by about a factor of 3 for highly-conductive copper. In both cases the resistive wake kick scaled as expected with the bunch length.

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