

# Collimator Wakefield Experiment - Next Stage

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## Abstract

This note describes the current status of the collimator wakefields study experiment at SLAC linac. The results of the first series of measurements are compared to analytical predictions based on recent developments in the wakefield theory, and to numerical simulations using MAFIA code. We discuss the priorities for further research aimed at developing reliable tools for optimizing the linear collider collimation system design, and present our proposal for the next series of measurements.

## 1 Introduction

In the linear collider design, a system of collimators is used to remove large amplitude particles from the beam and to protect detectors and beam line components from bunches that follow unsafe trajectories. In order to achieve sufficient background reduction, the collimators have to be positioned very close to the beam, thus presenting a large impedance, which can significantly degrade the beam quality. Wakefields generated in collimators act back on the beam and cause jitter amplification and emittance dilution. Bunches that deviate from the nominal trajectory can travel very close to collimator jaws and therefore experience particularly strong deflection by wakefields, thus representing a machine protection issue.

Wakefields generated by the beam in a collimator can be reduced by introducing longitudinal taper and therefore making the change in the vacuum chamber cross section gradual. However, the high frequency impedance of a large tapered collimator is very difficult to either simulate numerically or calculate analytically. As a result, there is currently no reliable technique available for predicting the magnitude of collimator wakefields with the precision desirable for optimizing the linear collider design. In part, the development of analytical and numerical methods for collimator impedance calculation was hampered by the lack of accurate experimental data. Most previous attempts to measure collimator wakefields were undertaken using existing hardware and beam instrumentation that were not designed specifically for that purpose. As a result, it was very difficult to determine the

beam deflection due to the collimator wakefield with sufficient accuracy, and to distinguish between geometric (due to changes in the vacuum chamber cross section), resistive (due to finite conductivity of the collimator material), and surface roughness components of the impedance.

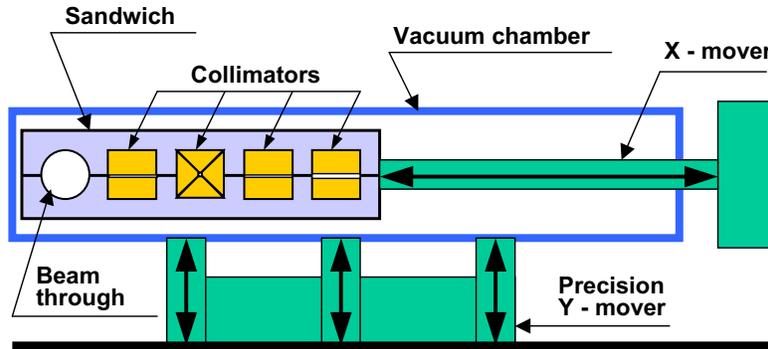


Fig. 1 Collimator wakefields measurement apparatus.

To address the shortage of experimental data, we have designed, constructed, installed, and commissioned a dedicated collimator test chamber [1] at the 1.19 GeV point in the SLAC linac. The chamber (figure 1) can hold up to 4 test collimators at a time. During measurements, one of the collimators is positioned in the beam path by a remotely controlled translation stage. The wakefield kick factor is then determined by varying the collimator’s vertical position and measuring the resulting angular deflection of the beam on downstream beam position monitors. Results of a typical scan are shown in figure 2.

Three sets of test collimators have been constructed. The first set (figure 3) is designed to study geometric wakefields while minimizing resistive and surface roughness components. To achieve this,

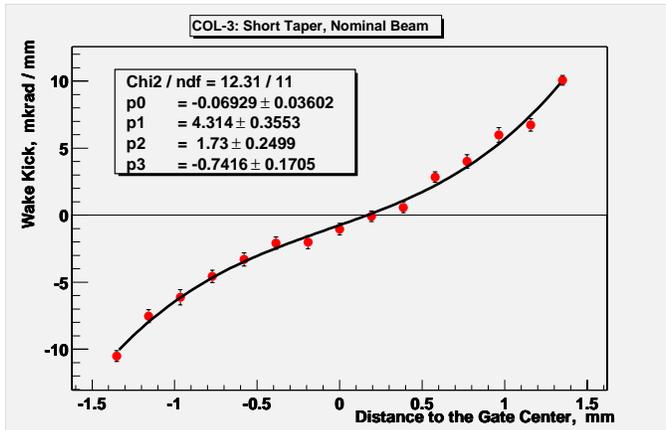


Fig. 2 Typical scan - angular deflection of the beam is measured as a function of the offset between the beam axis and the collimator axis.

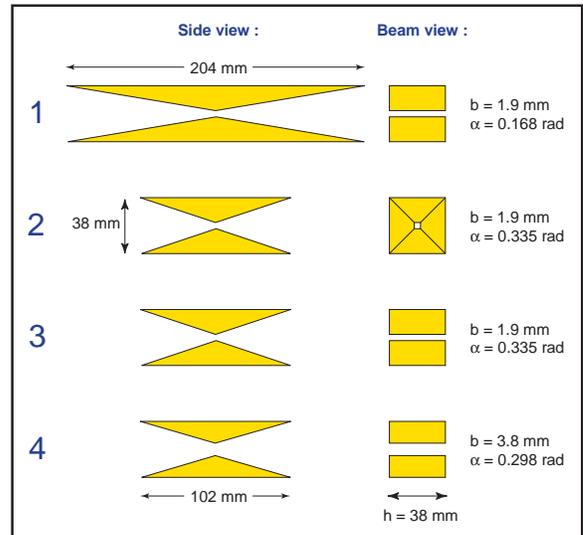


Fig. 3 First set of test collimators.

the collimators are made of copper with high quality surface finish. Three of the four apertures in this set have rectangular geometry (collimation only in vertical direction) with vertical tapers. The fourth aperture has a square opening with tapers in both X and Y.

The second and the third collimator sets are designed to study resistive wakefields and contain long flat sections of constant cross section between tapers. The second set (figure 4) was built at DESY and was intended to study properties of graphite collimators. The third set (figure 5) contains both copper

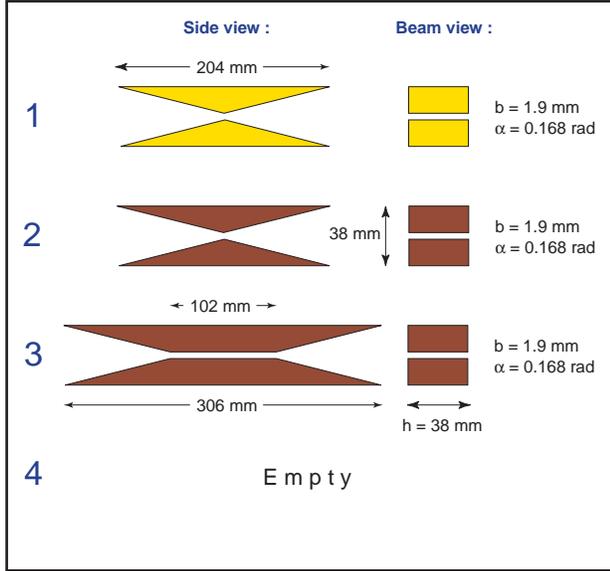


Fig. 4 Second set of test collimators. The collimator in slot 1 is made of copper, the other two are made of graphite.

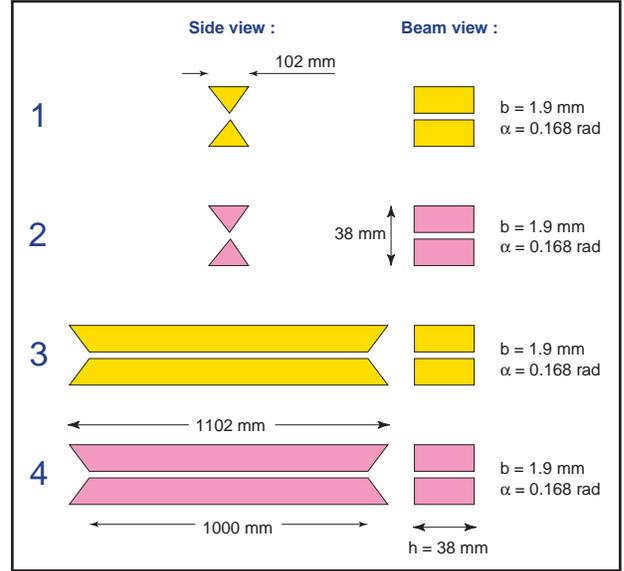


Fig. 5 Third set of test collimators. The collimators in slots 1 and 2 are made of copper, the other two are made of elemental titanium.

and titanium apertures with and without flat sections in order to facilitate distinguishing between contributions from geometric and resistive wakes. Measurements with the first two collimator sets have been finished, and the results have been reported [2, 3]. The third set is currently being installed in the test chamber, and we intend to take data in Fall 2002.

Since the effects of geometric wakefields in rectangular collimators appear to be the primary concern for the linear collider design, the next stage of the experiment will focus on them. In the remainder of this note, we will briefly discuss the results obtained with the first collimator set, summarize the current state of the theory and numerical simulations, and propose the next series of measurements.

## 2 Theory review: geometric wakefields of rectangular collimators

The part of the short range transverse wakefield that is linear with respect to the displacement between the collimator axis and the beam axis is usually characterized by the kick factor  $K$  defined so that  $KNr_e y_0 / \gamma$  gives the angular displacement of a Gaussian bunch, where  $N$  is the number of particles in the bunch,  $r_e$  is the classical electron radius, and  $y_0$  is the beam offset from the collimator axis.

Analytical models of geometric wakefields in rectangular collimators currently exist only for the three distinct regions in the collimator parameter space [4]. If  $\alpha$  is the taper angle tangent,  $b$  is the half-gate,  $\sigma_z$  is the bunch length, and  $h$  is the width of the collimator, then the three regimes for which the kick factors can be calculated are classified as follows:

Purely inductive regime (small taper angles) :

$$\frac{\alpha h^2}{\sigma_z b} \ll 1 \quad (1)$$

$$K = \frac{\sqrt{\pi}}{2} \frac{\alpha h}{\sigma_z b^2} \quad (2)$$

Intermediate regime :

$$\frac{\alpha h^2}{\sigma_z b} \geq \pi^2, \frac{\alpha b}{\sigma_z} \ll 1 \quad (3)$$

$$K = \frac{8}{3} \sqrt{\frac{\alpha}{\sigma_z b^3}} \quad (4)$$

Diffraction regime (steep tapers) :

$$\frac{\alpha b}{\sigma_z} \gg 1 \quad (5)$$

$$K = \frac{1}{b^2} \quad (6)$$

The following "quick and dirty" recipe was suggested [5] for approximate calculation of wake kick factors of rectangular collimators with arbitrary taper parameters:

$$K = \begin{cases} \sqrt{\alpha b / \sigma_z} < 3.0b/h & : 8\alpha h / \sigma_z b^2 \\ 3.0b/h < \sqrt{\alpha b / \sigma_z} < 0.38 & : 24\sqrt{\alpha / \sigma_z b^3} \\ 0.38 < \sqrt{\alpha b / \sigma_z} & : 9/b^2 \end{cases} \quad (7)$$

Numerical constants are chosen to express the kick factors in customary units of V/pC/mm if the gate size and the bunch length are expressed in millimeters. This formula extrapolates expressions (2), (4), (6) into the transition regions between the regimes described above in a way that ensures monotonic behavior with respect to the taper angle. One should not expect good accuracy from (7) when it is applied in transition regions.

### 3 Data review. Next stage of the experiment.

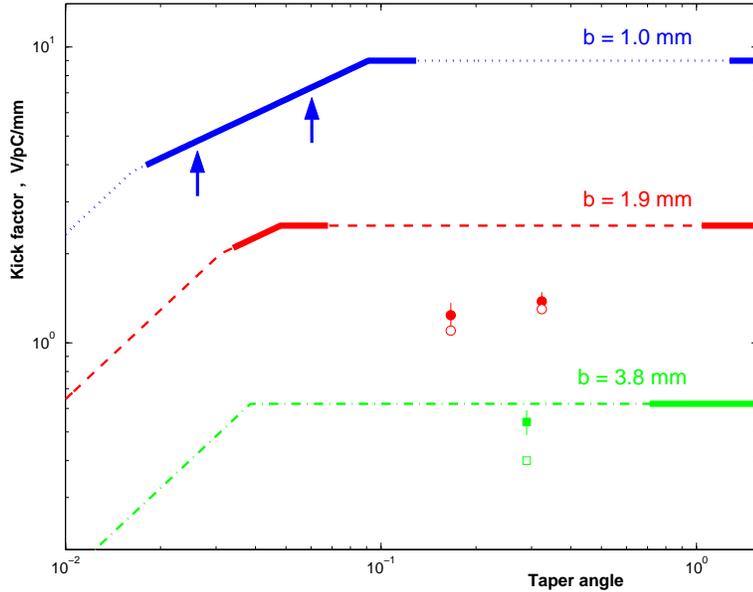


Fig. 6 Rectangular collimators: comparison between data, theory, and simulations. Geometric wake kick factors versus taper angle at 0.65 mm bunch length. The curves represent analytical behavior described by equation (7), with solid bold lines showing approximate applicability regions of the intermediate (at lower taper angles) and the diffraction (at higher taper angles) regimes. Also shown are the results of measurements with the first set of test collimators (filled markers) and the results of simulation with MAFIA code (open markers). Green square markers and red round markers correspond to 3.8 mm and 1.9 mm half-gate sizes, respectively. Blue line shows analytical prediction for the 1 mm half-gate collimators, with arrows marking taper angle values proposed for the next series of measurements.

Figure 6 shows a comparison between analytical calculations, simulations using MAFIA [6] code, and measured wakefield kick factors for the three rectangular apertures included in the first tested collimator set. Solid lines show approximate applicability regions of the intermediate regime and the diffraction regime models. In the transition regions between the regimes, analytical behavior is approximated using equation (7).

It should be noted that the parameters of all three tested collimators fall outside the applicability regions of theoretical models. Therefore, the wake kicks produced by these collimators should not be expected to be accurately described by the theory. Such choice of parameters for the first series of measurements is explained (besides our desire to have sufficiently wide gates and large kick factors for commissioning the facility) by the fact that applicability criteria (1), (3), (5) were not known at

the time these collimators were designed, and the purely inductive regime model was expected to be applicable. Observed discrepancy between measurements and theoretical predictions encouraged further development of the theory, creation of the intermediate regime model, and formulation of the applicability criteria for the three regimes.

The fact that, despite being in the transition region, the wakefield kick factors of the three tested apertures fall within a factor of 2 from the predictions based on the expression (7) clearly demonstrates its usefulness. However, better accuracy is desirable for optimizing the linear collider design, and the fact that the measured kicks are smaller than those predicted by the intermediate regime formula for smaller taper angles (see figure 6) requires further investigation. Good agreement between data and MAFIA simulations is also encouraging, but accurate numerical modeling of wakefields produced by shorter bunches required by the NLC remains highly problematic, which makes it mandatory to further pursue experimental and analytical studies.

In the current NLC baseline design, most critical collimators parameters fall within the applicability regions of the diffraction and intermediate regimes, and in the transition region between them. While we have substantial freedom in choosing the taper angle for each of the collimators, Z-space

availability and other engineering constraints make it impractical to use shallow tapers with angles lower than those described by the intermediate regime model (at least in a simple constant angle design - more on this in the next section). And since adjustable gates are necessary in many cases, rectangular geometry is required. The next logical step in the experimental program would therefore be to check the theory for rectangular collimators in the diffraction and the intermediate regimes. To accomplish this in the next series of measurements, we propose to build three test apertures with taper parameters shown by arrows on figure 6. All three have smaller gate sizes (half gate  $b = 1mm$ ) than previously tested collimators, which moves them closer in the parameter space to the collimators required by the linear collider design, and makes the wakefield kick factors bigger, facilitating measurements at low taper angles. The first two of the proposed apertures have taper angles of 0.025 (the smallest angle we can test, the collimator would use the entire available length of the vacuum chamber) and 0.060 radians respectively, and are inside the intermediate regime applicability region. The third aperture has no taper (taper angle  $\pi/2$ ) and should be accurately described by the diffraction regime model. The remaining slot in the test chamber will be used to study the 2-step taper design described in the next chapter.

## 4 2-step tapers

In any linear collider design, engineering constraints as well as cost considerations set a limit on maximum length along the beam axis available to the collimation system. The choice of collimators parameters is usually a compromise between the desire to use low angle tapers in order to reduce wakefields and the necessity to stay within available Z-space.

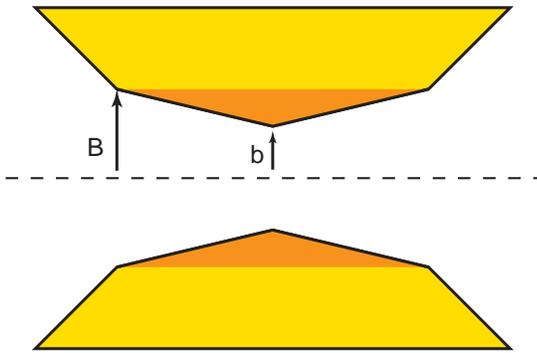


Fig. 7 2-step collimator. In the first approximation, the total wakefield kick factor can be calculated as as sum of kicks that would be produced by two separate constant taper angle collimators: one with shallow taper and gate  $b$  (orange), and one with steep taper and gate  $B$  (yellow).

The basic idea behind the 2-step taper design is to minimize the wakefield effect on the beam for a given collimator length by using steeper taper further away from the beam and lower taper angle closer to the narrowest part of the collimator where the beam is most sensitive to its surroundings. While calculating the impedance for an arbitrary shaped taper can be very difficult or impossible, analytical models used to derive the expressions of section 2 suggest that the wake kick for a 2-step collimator shown on figure 7 can, in the first approximation, be calculated using these formulas as a sum of kicks of its steep-taper portion with the gate equal to the distance between the collimator jaws at the boundary between the two tapers, and its shallow-taper portion.

For the first test of this idea, we propose to use the geometry shown in figure 8. The collimator consists of a no-taper section (taper angle  $\pi/2$ ), which should be accurately described by the diffraction regime model, and the low angle taper section. The "effective half-gate"  $B$  was chosen to minimize the overall wake kick for the given collimator length, as illustrated in figure 9. The collimator length and gate were chosen to match those of one of the

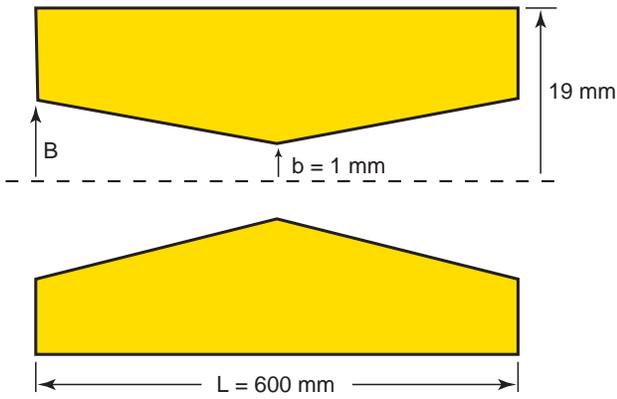


Fig. 8 2-step taper geometry proposed for the first test.

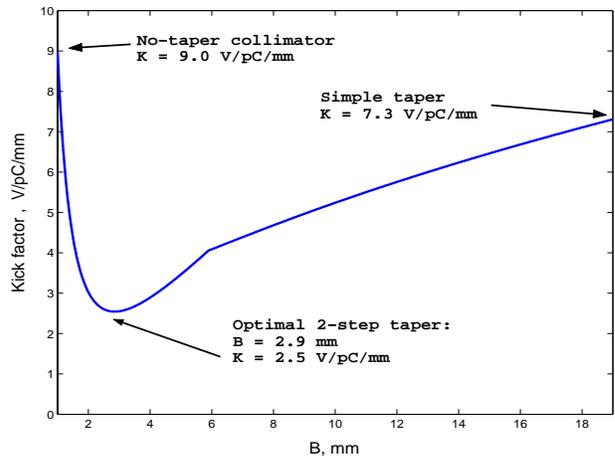


Fig. 9 Wake kick factor of the two-step collimator shown in figure 8 as a function of the "effective half-gate"  $B$  of the steep-tapered part of the collimator.

other test apertures. This should give us a direct way to observe the size of the advantage provided by the 2-step design over a simple constant angle taper geometry.

## 5 Summary and Plans

The collimator wakefield test facility at SLAC linac has been commissioned successfully and used for measuring wakefield kick factors of the first two sets of test collimators with an accuracy in the 0.1 – 0.2 V/pC/mm range. Availability of high quality experimental data prompted further advances in the theory. As a result, our level of understanding of short range transverse wakefields and their

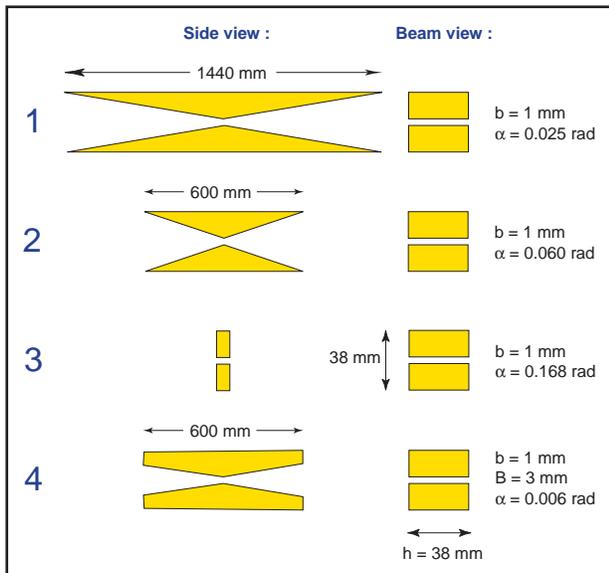


Fig. 10 Proposed fourth set of test collimators.

Collimator	Geometric kick	Resistive kick	Total kick
1	4.7	0.2	4.9
2	7.3	0.1	7.4
3	9.0	small	9.0
4	2.5	0.6	3.1

Fig. 11 Predicted wakefield kick factors for the proposed set of test collimators, in the units of V/pC/mm.

impact on beam dynamics has been significantly improved. However, further research is required to achieve the accuracy and reliability of collimator wakefield prediction necessary for optimizing the linear collider collimation system.

In the next series of measurements, we propose to check two critical pieces of the theory relevant to the NLC design: the intermediate and the diffraction regime models. We would also like to perform a first test of the 2-step taper design idea. Schematics of the proposed test aperture set is shown in figure 10. Table 11 lists the wakefield kick factors predicted by the theory for these collimators. For long shallow tapers, contributions from resistive wakefields have to be accounted for. These have been calculated approximately using the Piwinski model [7].

The goals and aperture geometries for subsequent tests will depend on the outcome of the measurements with the currently proposed collimator set - particularly on whether the validity of the intermediate regime analytical model is confirmed, and whether 2-step design shows marked advantages over a simple constant angle taper. The facility can also be used for studying wakefield effects in non-collimator structures designed for the NLC.

## 6 References

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