# MEASUREMENT OF RESISTIVITY DOMINATED COLLIMATOR WAKEFIELD KICKS AT THE SLC

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*Abstract*

Collimation of the multi-MW beams in present linear collider designs is a critical issue. Graphite as a possible collimator material exhibits good mechanical properties but a rather poor electrical conductivity. The resulting resistive wakefields can potentially deteriorate the beam quality. The knowledge of strength and scalings of such wakefields is essential for the design of the collimation systems in linear colliders.

We present measurements of the self induced wakefield kick that a charged particle beam experiences when it passes through a narrow gap of two graphite collimator jaws. The measurements where performed with the highly damped SLC beam at an energy of 1.19 GeV. The results are compared to theoretical predictions and to measurements with copper collimators of the same shape.

## 1 INTRODUCTION AND PRINCIPLE OF THE EXPERIMENT

In order to collimate the small beams in linear colliders at a few transverse RMS widths, collimator material must be positioned very close to the beam. The electromagnetic field of the beam is altered due to interaction with the shape and surface resistivity of the collimator jaws and acts back on the beam. Especially the transverse wakefields can lead to a significant emittance dilution.

The goal of the experiment was to measure the wakefield kicks for a collimator material with poor conductivity. For this purpose two pairs of graphite collimator jaws were tested. Graphite would be a potentially good material from the mechanical point of view, but it exhibits a poor conductivity. But even if graphite is not acceptable for a proposed collimation scheme, our measurements will provide the basis for a profound prediction of the resistive wall wakefields for other materials. In addition a pair of copper collimators with the same shape was installed to allow for direct separation of resistive and geometric effects. The measurements were performed in sector 2 of the SLC linac and were basically beam deflection measurements. The highly damped positron beam coming from one of the SLC damping rings was used. The natural shape of the damped beam is flat and the beam deflection was measured in the vertical plane. Basic beam parameters are given in table 1.

| $E$ | $N_p$ | $\sigma_x$ | $\sigma_y$ | $\sigma_z$ |
|---|---|---|---|---|
| 1.19 GeV | $2\,10^{10}$ | 200 $\mu$m | 50 $\mu$m | 650 $\mu$m |

Table 1: Beam parameters at the collimator insertion.

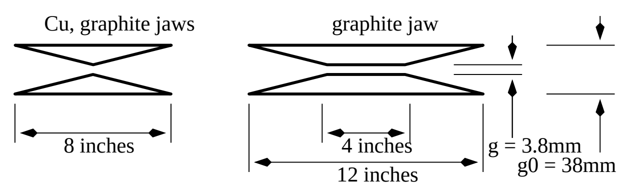


Figure 1: Two kinds of collimator shapes were used with the indicated dimensions and gap widths. The left shape was installed in slots 1 and 2, copper and graphite respectively, and the right shape made from graphite in slot 3.

The apparatus we use for the measurements [1] contains five slots, numbered 0-4, for the installation of different collimator inserts. The individual slots can be brought remotely into the beam path. The zeroth slot has a round shape and was empty to allow for undisturbed beam passage. The cassette with the five slots can be adjusted precisely with micromovers in the vertical plane. When the beam passes a pair of collimator jaws off-center it receives a deflection towards the closer wall due to the self induced wakefields. The lowest order component of the field is a dipole wake and consequently the strength of the kick increases linearly with small beam offsets from the gap center. We measure the average kick per unit beam offset by varying the gap position with the micromovers and measuring the kick the beam receives. The beam deflection is determined by analyzing the oscillation amplitude of the downstream difference orbit with a number of beam position monitors. To reduce the statistical error the measurement is repeated for each gap position 25 times. The deflection angle is measured for a number of gap positions and the linear part of the kick versus offset dependence is determined from the data.

During the measurements the apparatus contained three different pairs of collimator jaws - one pair of short copper jaws (slot 1) and one pair of short graphite jaws with the same shape (slot 2), and a pair of graphite jaws with a longer flat region (slot 3). The dimensions of the two shapes are shown in Fig. 1.

The conductivity of graphite is about three orders of magnitude lower than the one of copper. For the copper collimator one expects negligible effects from the resistive wall wake, and consequently its wakefield is practically determined by the geometric part. The idea of the experiment is to determine the resistive part by direct comparison of the copper and the graphite results. Some parameters of

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| | density [g/cm$^3$] | conductivity [$\Omega^{-1}\text{m}^{-1}$] | skin-depth at 500 GHz [$\mu$m] |
|---|---|---|---|
| Copper | $8.9$ | $5.9 \cdot 10^7$ | $0.1$ |
| Graphite | $1.95$ | $5.5 \cdot 10^4$ | $3.0$ |

Table 2: Selected parameters for copper and graphite.

graphite and copper are listed in table 2. The skin-depth is indicated for a frequency corresponding to the rms bunch length.

## 2 RESULTS AND COMPARISON WITH THEORY

As the direct result of the measurement we obtain the deflection angle of the beam as a function of the relative vertical beam position with respect to the collimator gap center. A statistical error is determined for each deflection angle. The data is fitted with a model function that contains a linear and a cubic term. The linear coefficient is the result of the measurement and can be compared with theoretical predictions. Three examples for raw data and fit-functions are shown in figures 2 and 3.

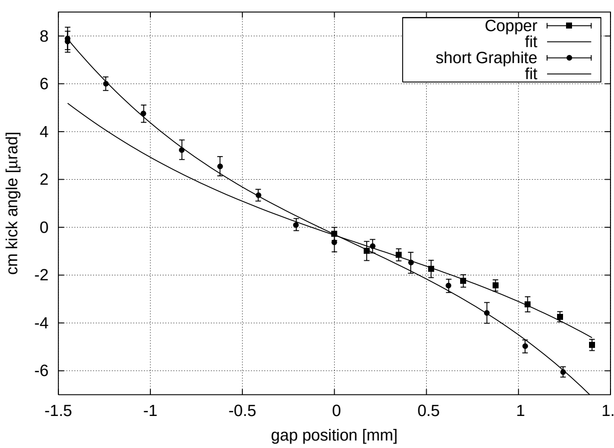


Figure 2: Beam deflection as a function of gap position for the short graphite collimator and the copper collimator.

Collimator wakefield effects can be separated into resistive and geometric parts. In the experiment we determine the average deflection angle of the bunch which we assume Gaussianly distributed for the computation of the expected values. For the prediction of the geometric kick we apply the theory by G. Stupakov [2]. With the particular combination of taper angle, bunch length and gap width of the experiment the best approach is the diffraction regime, where the beam field beyond a distance to the beam of $|y| > g/2$ is cut off and transferred into waveguide modes. However, since this is a simplification and neglects the effects of the tapers completely we expect to overestimate the kick. For the average deflection angle of the dipole mode one obtains:

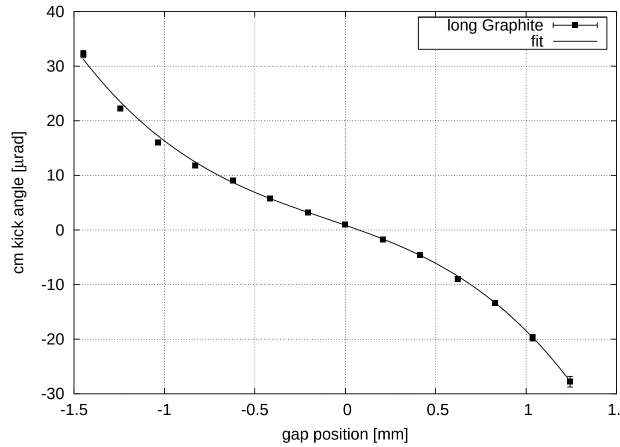


Figure 3: Beam deflection as a function of gap position for the long graphite collimator.

$$< \Delta y' >= \frac{4 N_p r_e}{\gamma g^2} y_0 \qquad (1)$$

Here $N_p$ is the number of particles in the bunch, $r_e = 2.82 \cdot 10^{-15}$ m the classical electron radius, $\gamma$ the relativistic factor, $g$ the gap width and $y_0$ the beam offset.

For the resistive kick the theory developed by A. Piwinski [3], to determine the effects of vacuum chambers on the beam, can be applied. It delivers for the bunch kick angle:

$$\begin{aligned} \langle \Delta y' \rangle &= \frac{\Gamma(1/4)}{\sqrt{2}} \frac{N_p r_e}{\gamma g^2} \frac{l_{\text{coll}}}{\sqrt{\sigma_z \sigma Z_0}} \frac{\sin\left(\frac{2\pi y_0}{g}\right) + \frac{2\pi y_0}{g}}{1 + \cos\left(\frac{2\pi y_0}{g}\right)} \\ &\approx \pi \sqrt{2}\, \Gamma(1/4) \frac{N_p r_e}{\gamma g^2} \frac{l_{\text{coll}}}{\sqrt{\sigma_z \sigma Z_0}} \cdots \\ &\quad \cdot \left( \frac{y_0}{g} - \frac{2\pi^2}{3} \left(\frac{y_0}{g}\right)^3 \right) + O\left( \left(\frac{y_0}{g}\right)^5 \right) \qquad (2) \end{aligned}$$

$\sigma$ is the material conductivity, $\sigma_z$ the rms bunch length, $Z_0 = 377\,\Omega$ the vacuum impedance and $l_{\text{coll}}$ the collimator length. $\Gamma(1/4) \approx 3.63$ is the Gamma-function. The contribution of the tapered region can be estimated by averaging (2) longitudinally with varying gap width:

$$\begin{aligned} \langle \Delta y' \rangle_{\text{tap}} &= \sqrt{2}\, \Gamma(1/4) \frac{N r_e}{\gamma (g_0 - g)} \frac{l_{\text{tap}}}{\sqrt{\sigma_z \sigma Z_0}} \cdots \qquad (3) \\ &\quad \cdot \left( \frac{1}{g} \tan\left(\frac{\pi y_0}{g}\right) - \frac{1}{g_0} \tan\left(\frac{\pi y_0}{g_0}\right) \right) \\ &\approx \sqrt{2}\, \pi\, \Gamma(1/4) \frac{N r_e}{\gamma} \frac{l_{\text{tap}}}{\sqrt{\sigma_z \sigma Z_0}} \frac{y_0 (g + g_0)}{g_0^2 g^2} \end{aligned}$$

$l_{\text{tap}}$ is the length of one taper but the formula takes both tapers, upstream and downstream, into account. $g_0 > g$ is the gap width at the end of the taper. The above approximations are valid for $g,\ g_0 \gg y_0$ and were used to compute predictions for the expected wakefield kicks. The bunch kick angles per unit offset are converted to the classical wakefield units [V/pC/mm] by multiplying with $E/N_p e^2$ where $E$ is the beam energy. The predicted results are shown in table 3, where we distinguish geometric and resistive parts, and the contributions by the taper and the flat region.

The results of the measurement are shown in table 4. The inferred resistive kick is indicated separately. It was determined by subtracting the kick of the copper jaws from the kicks generated by the graphite jaws.

| slot | resistive part | | | geom. part | sum |
|---|---|---|---|---|---|
| | taper | flat | total | | |
| 1 | 0.001 | 0 | 0.001 | 6.7 | 6.7 |
| 2 | 0.67 | 0 | 0.67 | 6.7 | 7.4 |
| 3 | 0.67 | 6.1 | 6.8 | 6.7 | 13.5 |

Table 3: Predicted geometric and resistive kick angles per beam offset. The numbers are given in [$\mu$rad/mm].

| slot | measured total | inferred resistive |
|---|---|---|
| 1 | 2.6±0.3 | (0) |
| 2 | 3.9±0.3 | 1.3±0.6 |
| 3 | 10.8±0.4 | 8.2±0.7 |

Table 4: Measured kick angles and inferred resistive part obtained by subtracting the kick of the copper jaws. The numbers are given in [$\mu$rad/mm].

## 3 DISCUSSION

It was possible to determine the wakefield kicks for graphite collimator jaws with a relatively good accuracy using beam deflection measurements. Especially the kicks of the long graphite jaws are strong and provide an excellent signal to noise ratio. We find for a pair of graphite collimators with a gap width of $3.8$ mm, a flat length of 4 inches and a taper angle of $10^\circ$ a resistive dipole wakefield of $3 \pm 0.3$V/pC/mm.

While the geometric kick tends to be overestimated by the simple diffraction theory we find better agreement for the resistive part. A direct comparison was possible since we also measured a copper collimator with the same shape that should cause negligible resistive effects.

The transverse emittance growth for a beam passing a pair of collimator jaws can be computed via $\Delta\varepsilon = \beta\theta_{\rm rms}^2$, with $\beta$ the optical beta-function at the collimator and $\theta_{\rm rms}^2 = \left\langle \Delta y'^2 \right\rangle - \left\langle \Delta y' \right\rangle^2$. For the resistive part of the wake one finds approximately $\theta_{\rm rms} = 0.4 \cdot \langle \Delta y' \rangle$. If one inserts for example the parameters of the TESLA collimation system it turns out that the emittance growth from a graphite collimator with 0.5 radiation length flat region is not acceptable. The problem could be solved either by coating the graphite, or by choosing another material like titanium, which on the other hand is not as shock resistant as graphite.

Nevertheless, the data obtained from the measurements supports the theory and allows a reliable prediction of the wakefields for other materials.

## 4 REFERENCES


[1] P. Tenenbaum *et al.*, Transverse Wakefields from Tapered Collimators: Measurements and Analysis, PAC-01, Chicago (2001)

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