SLAC–PUB–7261
Aug 1996

Design and Wakefield Performance of the New SLC Collimators*

F.-J. Decker, K. Bane, P. Emma, E. Hoyt, C. Ng, G. Stupakov,
J. Turner, T. Usher, S. Virostek, D. Walz

Stanford Linear Accelerator Center, Stanford CA 94309, USA

Abstract

The very small transverse beam sizes of the flat SLC bunches are 100-170 mm in the horizontal and 30-50 mm in the vertical near the end of the SLAC linac. Unexpectedly large transverse wakefield kicks were observed from the collimators in this region during 1995. Upon inspection, it was found that the 20 mm gold plating had melted and formed a line of spherules along the beam path. To refurbish the collimators, an improved design was required. The challenging task was to find a surface material with better conductivity than the titanium core to reduce resistive wakefields. The material must also be able to sustain the mechanical stress and heating from beam losses without damage. Vanadium was first chosen for ease of coating, but later TiN was used because it is more chemically inert. Recent beam tests measured expected values for geometric wakefield kicks, but the resistive wall wakefield kicks were four times larger than calculated.

Contributed to XVIII International Linac Conference (LINAC96)
Geneva, Switzerland
26-30 Aug 1996

* Work supported by Department of Energy contract DE–AC03–76SF00515.

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1 Introduction

To suppress background in the detector, collimators are used at the end of the SLC linac. The surface of these collimators were inspected in 1995 and the gold coating on the titanium jaws was found to be severely damaged. A dark 1 mm wide stripe along the beam path was visible, which consisted of gold flakes and spherules of ≈250 μm diameter (Fig. 1). They were responsible for a 25–50 times larger than expected wakefield kick [1]. A new durable surface material for the coating was necessary with high conductivity to reduce resistive wakefields.

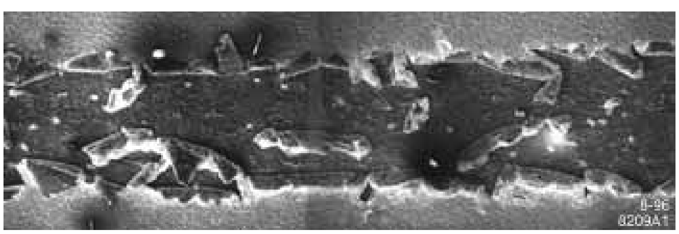

Fig. 1: Damaged collimator surface (stripe width ≈1 mm). The beam enters at the left, creating gold flakes and spherules.

2 Coating Material for Collimators

The core material for the collimator jaws is a titanium alloy Ti-6Al-4V, which best survives beam impact. The coating material requires a higher conductivity (Tab. 1, [2]).

Material	Z	X_o/ρ cm	T_{melt} °C	R μΩ-cm	E 10^{-6} psi	α 10^6 °C^{-1}	Eα psi °C^{-1}	Eα/σ_{UT} 10^3 °C^{-1}	k W/cm °C
Ti#	16.3	3.77	1650	175	16.5	11	182	1.3	0.07
Cu	29	1.45	1083	1.67	17	16.6	282	8.8	3.9
Al	13	9.03	659	2.83	10	25	250	19.2	2.39
Cr	24	1.7	1860	12.8	36	6.2	223	18.6	0.92
V	23	2.05	1735	24.8	18.2	8.3	150	2.2	0.31
Mn	25	1.6	1244	28	23	22.8	524	7.3	
Ni	28	1.35	1728	7.0	30	13.3	400	8.7	0.84
Ti	22	3.35	1680	42	15.5	8.7	135	1.5	0.17
Au	79	0.35	1063	2.44	11.3	14.3	161	10.8	2.95
TiN	14.8	3.87	2930	22	36	8.3	300		0.29
TiC	14.3	3.84	3140	60	8.0	7.4			0.21

Tab. 1: Potential conductive surface coatings for titanium collimators. Ti# stands for Ti-6Al-4V.

2.1 Background Issues

The surface material chosen initially was gold to give the particles scattered out of the core material additional *dE/dx* loss. This was a compromise between the desire to reduce background to the detector as well as resistive wakefields contributions and the known hazards of higher single bunch temperature spikes and resulting thermal shock waves. Since the linac collimators are 1.5 km from the interaction point and additional downstream clean up collimation exists, the high *Z* surface requirement has now been eliminated.

2.2 Survivability

With respect to survivability of the surface coating, no material is an obvious choice. But since the resistivity of Ti-6Al-4V is about 70 times larger than gold (the resistive wakefield kick would be √70 times larger), a material with less sensitivity (up to 10 times of gold) was needed. Nickel, vanadium, and TiN fall into that range.

Nickel is somewhat ferromagnetic at the high frequencies of the short bunch, it is difficult to coat and its figure of merit ($E\alpha/\sigma_{UT}$) is marginal, but it has the best resistivity (7 μΩ-cm). Vanadium has a larger resistivity but sputters more easily onto Ti. Some collimator jaws were coated with vanadium, which is fine for dry air or vacuum. Unfortunately, it chemically reacts with water and presents handling problems. The final choice was TiN, a golden looking coating (e.g. on drill bits) with a resistivity of 22 μΩ-cm. Not all of the material properties are understood (blank in Tab. 1), but a test with an electron arc welding torch showed good survivability for TiN. The hard coating might allow the phonon shock wave to penetrate to the Ti, while at a gold-Ti boundary it would be reflected [3].

* Work supported by DOE, contract DE-AC03-76SF00515.

3 Collimator Wakefields

The close proximity of the jaws to the beam (0.8-1.2 mm gap) will lead to wakefields. The following discusses different types due to their origin: geometric, resistive, and “granularity” wakefields with their linear and quadratic effects.

3.1 Geometric wakefield

The peak dipole component of the geometric wakefield for a round collimator (flat: $\pi^2/8$ larger) is [4]

$$\Delta y' = 4\frac{r_e N}{\sqrt{2\pi}\,\gamma\,\sigma_z}\left(\frac{y}{a}\right)$$

which is 2 μrad for $N = 5\cdot10^{10}$ particles, a bunch length σ_z = 1.25 mm, energy factor γ = 90000, classical electron radius r_e, and a beam offset y equal to the pipe radius a. This has to be compared to a beam size σ_y = 50 μm, and an angular divergence $\sigma_y{'}$ = 1.0 μrad for an emittance $\gamma\varepsilon_y$ = $0.45\cdot10^{-5}$ m-rad and a betatron function value β = 50 m. These beam parameters are assumed throughout the paper. The effect of the kick is illustrated in Fig. 2.

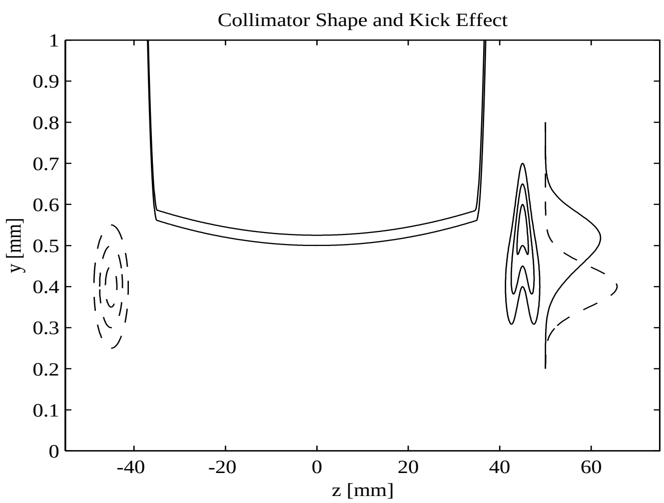

Fig. 2: Tapered collimator and a resultant wakefield kick of $3\cdot\sigma_y$. The contour lines and projections of the incoming (dashed), and outgoing beam (solid) are shown.

By rounding the edges (r = 9 mm) the geometric wakefield component of the tapered collimator (R = 10 m) is reduced by a factor of 2. This then gives an expected maximum dipole kick for our flat jaws of $\Delta y'$= 1.3 μrad. A $3\sigma_y{'}$ kick gives an emittance growth of about 30% and $5\sigma_y{'}$ about 60%.

The higher order component of the geometric wakefield was calculated with MAFIA [4] and the result divided by 2 for the rounded edges. This simulation agrees well with a round collimator scaling estimate for y'

$$\sum_{m=1}^{\infty}\frac{1}{m}r_1^m r_2^{m-1} = \frac{-\ln(1-r^2)}{r}$$

when r_1=r_2=r=y/a (see Fig. 3 dashed curve).

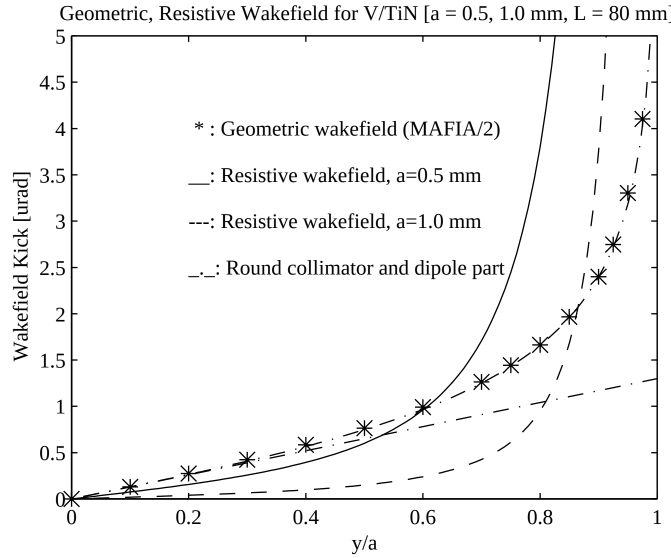

Fig. 3: Geometric and resistive wakefield estimates.

The quadrupole wakefield near the axis of a round collimator is zero (for a round beam), but for a flat collimator it is about 1/3 of the dipole kick [5]:

$$\Delta y'_2 = 1/3\ \Delta y'\ y_2/a$$

where y_2 is the offset of a second (test) particle within the centered bunch. For a half-gap of a = 0.5 mm and a $\Delta y'$ = 1.3 μrad this results in a differential quadrupole kick over the bunch with a maximum which is about 20% of a typical magnetic quadrupole strength at the end of the linac. This effect is somewhat reduced since the x and y collimator jaws are close together and have usually similar gaps ($5\sigma_x$ = 800 μm, $10\sigma_y$ = 500 μm), and therefore cancel each other.

3.2 Resistive wakefield

The resistive dipole wakefield kick due to parallel resistive plates of length L is [6]

$$\Delta y' = \frac{\pi r_e N L}{4a^2\gamma}\left(\frac{c}{\sigma\sigma_z}\right)^{1/2} f(s/\sigma_z)\left(\frac{y}{a}\right)$$

with a maximum kick of 0.95 μrad (a = 0.5 mm, f = 1, and a conductivity $\sigma = 4.1\cdot10^{17}\ \mathrm{s}^{-1}$ for TiN.

To get the higher order components, the term y/a has to be replaced by the following (with r = y/a):

$$\frac{1}{\pi}\left(\frac{\pi r+\sin\pi r}{1+\cos\pi r}\right).$$

3.3"Granularity" wakefield

The wakefield due to the spherules was roughly estimated to be [7]:

$$\Delta y' = \frac{r_e N L}{4\sqrt{\pi} a^2 \gamma \sigma_z} g\left(\frac{y}{a}\right)$$

where 25% of the surface is covered with spherules and g is the granularity (or corn size). Comparison to the resistive wakefield yields:

$$g = \pi^{3/2} \sqrt{\frac{c\sigma_z}{\sigma}}.$$

For g = 250 μm the resultant kick is about 50 times the resistivity kick from gold. This explained the large wakefields of the damaged parts.

4 Experimental Results

The collimators were set to a specific gap size *2a*, and moved across the beam. The beam position monitor signals up- and down-stream were recorded to measure the kick, the beam loss and the incoming offset (Fig. 4).

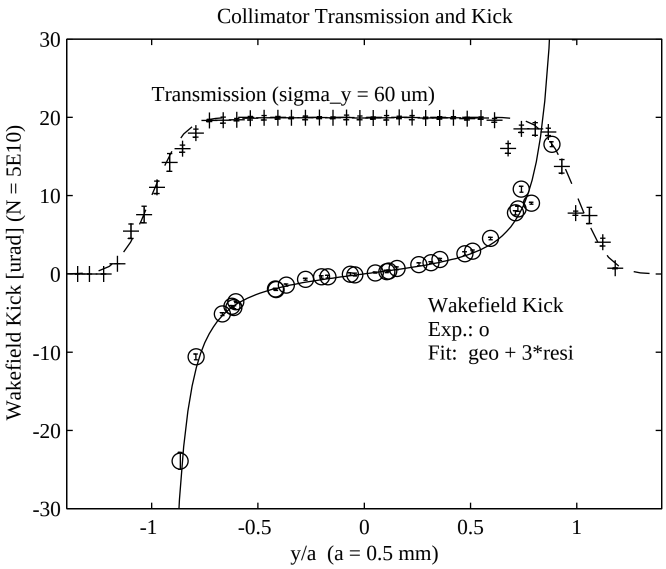

Fig. 4: Beam transmission (+) and measured kicks (o). The solid curve shows the expected behavior including 3 times the expected resistive kick.

Scanning with different collimator gap sizes allows distinction between the geometric and resistive wakefields. At wide gaps the geometric wake dominates, while at small gaps the resistive wakefield is bigger. By plotting the linear slope at $|y/a|<<1$ versus $1/a$ (a = half gap size) the geometric part should be independent of a, while the resistive part should grow quadratically (see Fig. 5).

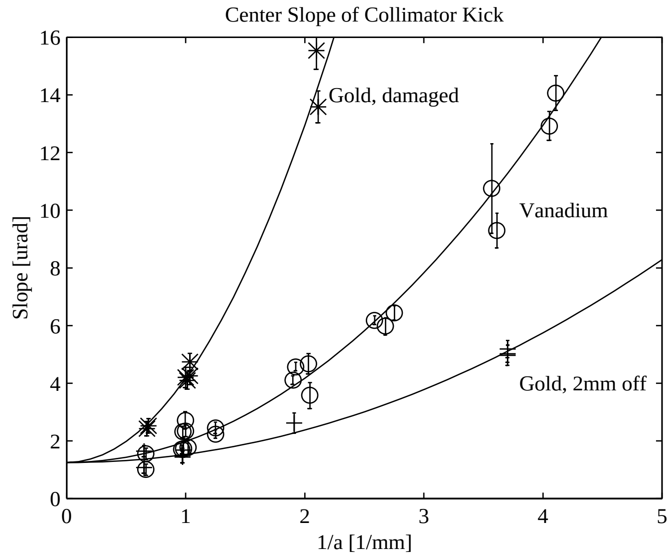

Fig. 5: Slope of the linear part of the wakefield kick versus $1/a$. The fit (solid) shows a kick about a factor of 4 higher than expected for the resistive wakefield.

The expected and measured kicks for a = 0.5 mm are summarized in Tab. 2. The average kick over the beam from the form factor f is 0.71 (geometric) and 0.78 (resistive). The 40% bigger kick for the geometric part might be due to the uncertainty of the rounded edges. But the factor of 4 difference in the resistive part is so far unexplained.

	Expected	Measured	Factor
Geometric	0.92	1.29±0.10	1.4
Au	0.26	1.12±0.06	4.3
V	0.74	2.88±0.10	3.9
Au, damaged	- - -	11.6±0.4	- -

Tab. 2: Collimator wakefield kicks in μrad.

5 Summary

The new collimators with TiN (and V) coatings have survived beam impacts. The wakefield kicks were reduced by a factor of four. The measured resistive wall wakefield kick is a factor of 3-4 larger than expected.

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