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Collimator Wakefield Calculations for ILC-TRC Report

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1 Introduction

One of the beam dynamics effects which must be evaluated for the International Linear Collider Technical Review Committee (ILC-TRC) is the influence of wakefields from the collimators in the post-linac collimation section of each design. In this Note, we summarize the relevant formalism for *near-center* wakefields (ie, wakefield effects when the beam offset from the center of the collimator aperture is small compared to the aperture), and apply it to the designs as they are presently understood.

2 Review of Formalism

The lowest-order effect of a collimator is to kick a beam which passes off-axis through the aperture. for near-center beams, the magnitude of the kick is linearly proportional to the distance of the beam from the center of the aperture:

$$\Delta y' = \mathcal{K} y. \tag{1}$$

In the assumption that the RMS incoming beam jitter is a fixed fraction of the beam size (a popular model for jitter in linear colliders), we can replace y with $m\sigma_y$, and similarly we can normalize the outgoing RMS kick angle to the beam divergence, $\Delta y' \rightarrow n\sigma_{y'}$. Thus, Equation 1 becomes:

$$\frac{n}{m} = \mathcal{K}\frac{\sigma_y}{\sigma'_y}. \tag{2}$$

Equation 2 shows that the lowest-level effect of the collimator is to amplify the overall incoming jitter. This can be more clearly seen if we define an amplification factor, $\mathcal{A}_\beta$, as follows:

$$\mathcal{A}_\beta \equiv \mathcal{K}\frac{\sigma_y}{\sigma'_y}. \tag{3}$$

From Equation 3, if there are p sigmas of incoming jitter in both betatron phases, then the effect of the collimators is to increase the jitter to $p\sqrt{1+\mathcal{A}_\beta^2}$ sigmas of jitter. Finally, note that if the collimator is near a betatron waist, we can subtly recast Equation 3:

$$\mathcal{A}_\beta = \mathcal{K}\beta. \tag{4}$$

In the case of a collimator which is placed at a point where $\eta \neq 0$, some transverse jitter is generated which is proportional to the energy jitter. Following the form of the preceding,

$$n\sigma_{y'} = \mathcal{K}\eta\delta. \tag{5}$$

For the purposes of the TRC, we have chosen as a figure of merit the number of sigmas of angle jitter which are generated by 1% variation in the beam centroid energy, thus:

$$\begin{aligned} \mathcal{A}_\delta &\equiv 0.01\mathcal{K}\frac{\eta}{\sigma_{y'}}, \text{ or} \\ \mathcal{A}_\delta &\equiv 0.01\mathcal{A}_\beta\frac{\eta}{\sqrt{\beta}}\frac{\sqrt{\gamma}}{\sqrt{\gamma\epsilon}}. \end{aligned} \tag{6}$$

With the foregoing firmly established, all that is required is a means for calculating the $\mathcal{K}$ factors which are associated with a collimator.

2.1 Geometric Wakefields

Geometric wakefields are those that arise from a change in the vacuum chamber geometry. The geometric wake of a collimator can be reduced by adding a longitudinal taper to the collimator, which minimizes the abruptness of the vacuum chamber transition. An excellent reference on this topic is available [1], and we follow the approach of that document. In the foregoing, we assume that the collimator aperture is much smaller than the aperture of the nearby vacuum system.

It should be noted that the experimental verification of the theory of geometric wakefields due to tapered collimators is not yet at the level where it would be acceptable to the linear collider endeavor. Measurements agree well in the case of a circular collimator, but measured kicks are smaller than predicted by a factor of approximately 2 for rectangular collimators. Also, the theory requires a number of simplifications (especially as regards the overall electrical continuity of the vacuum system), and may not be strictly applicable in the case of a real, engineered and buildable collimation system.

2.1.1 Circular Collimator

For a collimator with approximately equal x and y gaps, the formalism for circular collimators can be used. In this case, there are two regimes: the *diffraction* regime, for large taper angles (sudden transitions), and the *inductive* regime, for small taper angles (smooth transitions). Consider a beam with RMS length σ_z, passing through a round collimator with half-gap r and taper angle α. The kick factor $\mathcal{K}$ is given by:

$$\begin{aligned} \mathcal{K} &= \frac{Nr_e}{\gamma}\frac{2}{r^2}, \ \frac{\alpha r}{\sigma_z} > 2\sqrt{\pi}, \\ \mathcal{K} &= \frac{Nr_e}{\gamma}\frac{\alpha}{\sqrt{\pi}\sigma_z r}, \ \frac{\alpha r}{\sigma_z} < 2\sqrt{\pi}, \end{aligned} \tag{7}$$

where N is the bunch population, γ is the relativistic factor, and r_e is the classical electron radius of 2.8×10^{-15} meters.

2.1.2 Rectangular Collimator

A rectangular collimator is one in which the horizontal gap is much larger than the vertical gap, or vice versa. This is the usual form for adjustable-gap collimators. In addition to diffraction and inductive regimes, rectangular collimators have an intermediate regime. If we define h to be the half-width of the collimator (ie, the half-size of the aperture in the "bigger" direction), we find:

$$= \frac{Nr_e}{\gamma}\frac{1}{r^2}, \ \sqrt{\alpha r/\sigma_z} > 0.37, \tag{8}$$

$$
\begin{aligned}
\mathcal{K} &= 2.7\frac{Nr_e}{\gamma}\frac{\sqrt{\alpha}}{\sqrt{\sigma_z r^3}},\ 0.37 > \sqrt{\alpha r/\sigma_z} > 3.1\frac{r}{h}, \\
&= \frac{\sqrt{\pi}}{2}\frac{Nr_e}{\gamma}\frac{\alpha h}{\sigma_z r^2},\ \sqrt{\alpha r/\sigma_z} < 3.1\frac{r}{h}.
\end{aligned}
$$

2.2 Resistive Wakefields

The resistive wakefield, as the name implies, is due to the finite resistivity of the vacuum chamber. Thus, even a perfectly regular chamber, with no transitions, will have some transverse wakefield kick. The treatment here follows that of Piwinski [2]. As with the geometric wakefield, the usual caveats apply as regards the experimental verification of the theory.

The general form for the transverse resistive wake of an untapered vacuum chamber of length L and transverse half aperture r is:

$$
\mathcal{K} = F_{\mathrm{G}}\frac{\Gamma(0.25)}{\sqrt{2\pi^3}}\frac{Nr_e L}{\gamma r^3}\sqrt{\frac{c}{\sigma_z \sigma}}, \tag{9}
$$

where σ is the surface conductivity in inconvenient Gaussian units (equal to the convenient MKS conductivity multiplied by 9×10^9), and F_{G} is a geometric form factor equal to 1 for a right circular cylinder and equal to $\pi^2/8$ for a rectangular vacuum chamber. In the case of a tapered collimator, and once again assuming that the half-gap of the collimator is small compared to the half-aperture of the nearby regular vacuum chamber, we find a kick factor due to the resistivity of the taper:

$$
\mathcal{K} = F_{\mathrm{G}}\frac{\Gamma(0.25)}{\sqrt{2\pi^3}}\frac{Nr_e}{\gamma\alpha r^2}\sqrt{\frac{c}{\sigma_z \sigma}}. \tag{10}
$$

The resistive wakefield of a collimator with a taper and a flat section is expected to be the sum of the two contributions.

3 Description of Post-Linac Collimation Systems

The post-linac collimation systems are described in detail in [3, 4]. We summarize here the parameters of each system which are relevant to collimator wakefields. In all cases we assume that the surface conductivity is that of copper: $\sigma \equiv 5.39 \times 10^{17}$.

For the purposes of this Note, all spoilers which collimate in both horizontal and vertical have been treated as a pair of spoilers: a horizontal spoiler with a large vertical width, and a vertical spoiler with a large horizontal width. A similar approach has been taken in the case of absorbers with an aspect ratio far from unity (ie, they are treated as a horizontal absorber with a large vertical width coupled with a vertical absorber with a large horizontal width), since the theory is ambiguous on the kick due to a rectangular aperture in which the "gap" is larger than the "width". Absorbers with aspect ratio close to unity are treated as circular.

3.1 TESLA Collimators

Like most other post-linac collimation systems, the TESLA design includes two general types of collimators: absorbers, which are many radiation lengths thick and do the main "stopping" of halo particles; and spoilers, which are less than 1 radiation length and serve to minimize the beam energy density on an absorber in the event of a mis-steered beam. The spoilers are assumed to be made of carbon, with a 0.4 m flat section and a taper (20 mrad taper angle assumed); the carbon spoiler must be coated with copper to lower its resistivity. The absorbers are assumed to be made of titanium and copper, with a 0.5 m flat section and 20 mrad taper. Collimators are either "round" if their x:y gap ratio is near unity, or else "flat". Table 1 summarizes the post-linac collimators.

Table 1: TESLA post-linac collimator parameters. Longitudinal position, horizontal and vertical phase advance are all with respect to interaction point.

s, m	Name	ν_x	ν_y	β_x	β_y	η_x	r_x, mm	r_y, mm	Geometry
1095	spo_m2	6.25	3.25	1059	326	-0.113	1.500	0.670	rect
1050	abs_m2	6.15	3.24	25	230	-0.017	0.500	0.650	circ
989	XYSPOI1	5.38	3.14	817	754	0.000	1.500	0.500	rect
951	XYABSO1	4.98	3.13	9	154	0.000	0.350	0.320	circ
889	XYSPOI2	4.50	3.02	805	894	0.000	1.500	0.500	rect
852	XYABSO2	4.11	3.00	9	183	0.000	0.300	0.320	circ
789	XYSPOI3	3.63	2.89	825	903	0.000	1.500	0.500	rect
752	XYABSO3	3.24	2.86	10	179	0.000	0.300	0.320	circ
690	XYSPOI4	2.75	2.75	822	757	0.000	1.500	0.400	rect
661	XYABSO4	2.75	2.75	250	1045	0.000	1.570	0.770	rect
576	SPOIX1	2.25	2.25	1127	220	0.034	2.000	0.550	rect
557	ABSOX1	2.24	2.24	203	471	0.017	2.000	0.810	rect
497	ABSOX1A	1.75	1.75	722	295	0.029	2.920	0.630	rect
484	SPOIX2	1.75	1.75	1172	214	0.036	2.000	0.550	rect
467	ABSOX2	1.75	1.75	200	465	0.012	1.540	0.810	rect
392	SPOIY1	1.25	1.25	53	4691	-0.013	1.630	1.310	rect
375	ABSOY1	1.20	1.25	132	825	-0.036	4.200	2.200	rect
392	SPOIY2	0.74	0.75	52	4681	-0.017	1.630	1.310	rect

3.2 NLC Collimators

The collimators in the NLC are similar to those in TESLA. One significant difference is that the spoilers are made of copper, not carbon, and thus the flat portion of each spoiler is approximately 1 cm long, rather than 40 cm as in TESLA. The NLC absorbers are only 0.45 m long, rather than 0.5 cm, for no particularly good reason. Also, unlike TESLA, the NLC betatron collimation is not performed at equal amplitudes – the IP-phase is only slightly collimated, while the FD phase is relatively tight. The NLC includes the capability to use "tail-folding" octupoles to reduce the area of the beam halo in the final doublet phase; in this configuration, the collimator gaps are set to a larger value. For the purposes of this study, we consider only the "octupole off" case. Table 2 summarizes the NLC collimator parameters.

3.3 CLIC Collimators

The CLIC collimation system is based on an earlier NLC design, and its collimators shall be assumed to be similar (copper spoilers with 1 cm flat section and 20 mrad taper, etc.). The CLIC collimator parameters, based on the April 2002 deck, are in table 3.

Table 2: NLC post-linac collimator parameters. Longitudinal position, horizontal and vertical phase advance are all with respect to interaction point.

s, m	Name	ν_x	ν_y	β_x	β_y	η_x	r_x, mm	r_y, mm	Geometry
1434	SP1	3.50	3.01	36	7	0.000	0.300	0.350	rect
1358	SP2	3.25	3.25	103	524	0.000	0.300	0.200	rect
1282	SP3	3.00	2.51	36	7	0.000	0.300	0.200	rect
1282	AB3	3.00	2.51	36	7	0.000	1.000	1.000	circ
1358	SP4	2.75	2.25	103	524	0.000	0.300	0.200	rect
1358	AB4	2.75	2.25	103	524	0.000	1.000	1.000	circ
1145	SP5	2.64	2.01	60	5	0.000	0.420	0.300	rect
1145	AB5	2.64	2.01	60	5	0.000	1.400	1.000	circ
936	SPE	2.25	1.75	227	10059	0.213	3.200	3.200	rect
771	ABEa	1.93	1.75	245	329	0.007	1.000	1.000	circ
769	ABEb	1.93	1.74	240	284	0.006	1.000	1.000	circ
544	AB10	1.25	1.25	13277	149855	0.000	4.400	4.400	circ
523	AB9	1.25	1.25	38124	55296	0.000	6.500	3.000	rect
449	AB7	1.23	1.25	37	82	-0.026	3.900	1.000	rect

Table 3: CLIC post-linac collimator parameters. Longitudinal position, horizontal and vertical phase advance are all with respect to interaction point.

s, m	Name	ν_x	ν_y	β_x	β_y	η_x	r_x, mm	r_y, mm	Geometry
3241	ENGYSP1	4.77	7.15	1125	56710	-0.259	1.300	25.000	rect
3109	ENGYAB1	4.75	7.15	2570	31509	-0.400	2.000	25.000	rect
1826	ENGYSP2	3.77	6.15	1125	56710	0.259	1.300	25.000	rect
1695	ENGYAB2	3.76	6.15	2570	31509	0.400	2.000	25.000	rect
1071	YSP1	3.11	5.21	114	484	0.000	10.000	0.173	rect
1055	XSP1	3.10	5.20	270	101	0.000	0.344	1.000	rect
978	XAB1	2.88	4.47	270	81	0.000	1.000	1.000	circ
960	YAB1	2.87	4.46	114	482	0.000	1.000	1.000	circ
958	YSP2	2.86	4.46	114	482	0.000	10.000	0.173	rect
943	XSP2	2.85	4.45	270	101	0.000	0.344	1.000	rect
865	XAB2	2.63	3.72	270	81	0.000	1.000	1.000	circ
848	YAB2	2.61	3.71	114	484	0.000	1.000	1.000	circ
846	YSP3	2.60	3.71	114	484	0.000	10.000	0.173	rect
830	XSP3	2.60	3.70	270	101	0.000	0.344	1.000	rect
753	XAB3	2.38	2.97	270	81	0.000	1.000	1.000	circ
735	YAB3	2.36	2.96	114	482	0.000	1.000	1.000	circ
733	YSP4	2.36	2.96	114	482	0.000	10.000	0.173	rect
717	XSP4	2.35	2.95	270	101	0.000	0.344	1.000	rect
640	XAB4	2.13	2.22	270	81	0.000	1.000	1.000	circ
621	YAB4	2.11	2.21	114	482	0.000	1.000	1.000	circ

4 Wakefield Effects of Collimators

The wakefield jitter amplification parameters, $\mathcal{A}_\beta$ and $\mathcal{A}_\delta$, have been calculated for each collimator in TESLA, NLC, and CLIC, and their values are shown in Tables 4, 5, and 6, below. The betatron amplification factor is shown, as are the contributions from geometric wakefield, the resistivity of the taper, and the resistivity of the flat section.

Table 4: Wakefield jitter amplification factors for TESLA collimators.

s, m	Name	Plane	$\mathcal{A}_\beta$				$\mathcal{A}_\delta$
			geometric	Ω taper	Ω flat	Total	
1095	spo_m2	X	0.0318	0.0021	0.0111	0.0450	0.3458
1095	spo_m2	Y	0.0474	0.0032	0.0384	0.0890	0.0000
1050	abs_m2	X	0.0002	0.0004	0.0072	0.0078	0.0583
1050	abs_m2	Y	0.0015	0.0020	0.0301	0.0335	0.0000
989	XYSPOI1	X	0.0246	0.0016	0.0086	0.0347	0.0000
989	XYSPOI1	Y	0.1702	0.0134	0.2137	0.3972	0.0000
951	XYABSO1	X	0.0001	0.0003	0.0075	0.0079	0.0000
951	XYABSO1	Y	0.0021	0.0054	0.1687	0.1761	0.0000
889	XYSPOI2	X	0.0242	0.0016	0.0084	0.0342	0.0000
889	XYSPOI2	Y	0.2018	0.0158	0.2533	0.4710	0.0000
852	XYABSO2	X	0.0001	0.0004	0.0120	0.0125	0.0000
852	XYABSO2	Y	0.0025	0.0064	0.2004	0.2093	0.0000
789	XYSPOI3	X	0.0248	0.0016	0.0087	0.0351	0.0000
789	XYSPOI3	Y	0.2038	0.0160	0.2559	0.4757	0.0000
752	XYABSO3	X	0.0001	0.0004	0.0133	0.0138	0.0000
752	XYABSO3	Y	0.0024	0.0063	0.1961	0.2047	0.0000
690	XYSPOI4	X	0.0247	0.0016	0.0086	0.0350	0.0000
690	XYSPOI4	Y	0.2388	0.0209	0.4190	0.6787	0.0000
661	XYABSO4	X	0.0069	0.0004	0.0029	0.0102	0.0000
661	XYABSO4	Y	0.1192	0.0078	0.1014	0.2284	0.0000
576	SPOIX1	X	0.0191	0.0012	0.0050	0.0253	0.0567
576	SPOIX1	Y	0.0430	0.0032	0.0468	0.0931	0.0000
557	ABSOX1	X	0.0034	0.0002	0.0011	0.0048	0.0126
557	ABSOX1	Y	0.0485	0.0032	0.0392	0.0910	0.0000
497	ABSOX1A	X	0.0097	0.0004	0.0013	0.0114	0.0271
497	ABSOX1A	Y	0.0471	0.0033	0.0522	0.1026	0.0000
484	SPOIX2	X	0.0198	0.0013	0.0052	0.0263	0.0612
484	SPOIX2	Y	0.0419	0.0031	0.0456	0.0906	0.0000
467	ABSOX2	X	0.0057	0.0004	0.0024	0.0085	0.0160
467	ABSOX2	Y	0.0479	0.0031	0.0387	0.0898	0.0000
392	SPOIY1	X	0.0013	0.0001	0.0004	0.0019	0.0074
392	SPOIY1	Y	0.1849	0.0121	0.0739	0.2709	0.0000
375	ABSOY1	X	0.0009	0.0000	0.0001	0.0010	0.0067
375	ABSOY1	Y	0.0195	0.0008	0.0034	0.0237	0.0000
392	SPOIY2	X	0.0013	0.0001	0.0004	0.0018	0.0096
392	SPOIY2	Y	0.1845	0.0121	0.0738	0.2703	0.0000

Table 5: Wakefield jitter amplification factors for NLC collimators.

s, m	Name	Plane	$\mathcal{A}_\beta$				$\mathcal{A}_\delta$
			geometric	Ω taper	Ω flat	Total	
1434	SP1	X	0.0108	0.0011	0.0007	0.0127	0.0000
1434	SP1	Y	0.0017	0.0002	0.0001	0.0019	0.0000
1358	SP2	X	0.0310	0.0031	0.0021	0.0362	0.0000
1358	SP2	Y	0.2895	0.0359	0.0359	0.3614	0.0000
1282	SP3	X	0.0108	0.0011	0.0007	0.0127	0.0000
1282	SP3	Y	0.0039	0.0005	0.0005	0.0048	0.0000
1282	AB3	X	0.0002	0.0001	0.0007	0.0010	0.0000
1282	AB3	Y	0.0000	0.0000	0.0001	0.0002	0.0000
1358	SP4	X	0.0310	0.0031	0.0021	0.0362	0.0000
1358	SP4	Y	0.2895	0.0359	0.0359	0.3614	0.0000
1358	AB4	X	0.0005	0.0002	0.0021	0.0027	0.0000
1358	AB4	Y	0.0023	0.0012	0.0105	0.0140	0.0000
1145	SP5	X	0.0109	0.0009	0.0004	0.0123	0.0000
1145	SP5	Y	0.0015	0.0002	0.0001	0.0018	0.0000
1145	AB5	X	0.0002	0.0001	0.0004	0.0007	0.0000
1145	AB5	Y	0.0000	0.0000	0.0001	0.0001	0.0000
936	SPE	X	0.0010	0.0001	0.0000	0.0010	0.0530
936	SPE	Y	0.0422	0.0027	0.0002	0.0450	0.0000
771	ABEa	X	0.0011	0.0005	0.0049	0.0065	0.0108
771	ABEa	Y	0.0014	0.0007	0.0066	0.0088	0.0000
769	ABEb	X	0.0011	0.0005	0.0048	0.0064	0.0091
769	ABEb	Y	0.0013	0.0006	0.0057	0.0076	0.0000
544	AB10	X	0.0133	0.0015	0.0031	0.0179	0.0000
544	AB10	Y	0.1500	0.0172	0.0352	0.2024	0.0000
523	AB9	X	0.0387	0.0025	0.0034	0.0446	0.0000
523	AB9	Y	0.2637	0.0168	0.0505	0.3311	0.0000
449	AB7	X	0.0001	0.0000	0.0000	0.0001	0.0020
449	AB7	Y	0.0035	0.0002	0.0020	0.0058	0.0000

4.1 Combination of Jitter Amplification Factors

The fundamental limitation on the allowed amplification of beam jitter is the requirement that the beams meet one another at the IP. If we assume that the number of sigmas of beam jitter is equal in all betatron phases at the entrance to the BDS, then the betatron jitter amplification factors add linearly, but only the components that are 90 degrees out of phase with the IP:

$$\mathcal{A}_{\beta,\text{total}} = \sum_i \mathcal{A}_{\beta,i} |\sin(2\pi\nu_i)|. \tag{11}$$

A similar combination rule applies to the $\mathcal{A}_\delta$ values. In this case, the signed value of the phase advance to the IP, rather than the absolute value, is used. This is because careful manipulation of the sign of the dispersion and the betatron phase advance can be used to cause $\mathcal{A}_\delta$ components to

Table 6: Wakefield jitter amplification factors for CLIC collimators.

s, m	Name	Plane	$\mathcal{A}_\beta$				$\mathcal{A}_\delta$
			geometric	Ω taper	Ω flat	Total	
3241	ENGYSP1	X	0.0152	0.0017	0.0003	0.0172	0.6581
3109	ENGYAB1	X	0.0147	0.0017	0.0075	0.0239	0.9315
1826	ENGYSP2	X	0.0152	0.0017	0.0003	0.0172	0.6581
1695	ENGYAB2	X	0.0147	0.0017	0.0075	0.0239	0.9315
1071	YSP1	Y	0.3143	0.0419	0.0485	0.4047	0.0000
1055	XSP1	X	0.0522	0.0059	0.0034	0.0616	0.0000
978	XAB1	X	0.0020	0.0006	0.0051	0.0077	0.0000
978	XAB1	Y	0.0006	0.0002	0.0015	0.0023	0.0000
960	YAB1	X	0.0008	0.0002	0.0022	0.0032	0.0000
960	YAB1	Y	0.0036	0.0010	0.0091	0.0137	0.0000
958	YSP2	Y	0.3130	0.0418	0.0483	0.4030	0.0000
943	XSP2	X	0.0522	0.0059	0.0034	0.0616	0.0000
865	XAB2	X	0.0020	0.0006	0.0051	0.0077	0.0000
865	XAB2	Y	0.0006	0.0002	0.0015	0.0023	0.0000
848	YAB2	X	0.0008	0.0002	0.0022	0.0032	0.0000
848	YAB2	Y	0.0036	0.0010	0.0092	0.0137	0.0000
846	YSP3	Y	0.3143	0.0419	0.0485	0.4047	0.0000
830	XSP3	X	0.0522	0.0059	0.0034	0.0616	0.0000
753	XAB3	X	0.0020	0.0006	0.0051	0.0077	0.0000
753	XAB3	Y	0.0006	0.0002	0.0015	0.0023	0.0000
735	YAB3	X	0.0008	0.0002	0.0022	0.0032	0.0000
735	YAB3	Y	0.0036	0.0010	0.0091	0.0137	0.0000
733	YSP4	Y	0.3130	0.0418	0.0483	0.4030	0.0000
717	XSP4	X	0.0522	0.0059	0.0034	0.0616	0.0000
640	XAB4	X	0.0020	0.0006	0.0051	0.0077	0.0000
640	XAB4	Y	0.0006	0.0002	0.0015	0.0023	0.0000
621	YAB4	X	0.0008	0.0002	0.0022	0.0032	0.0000
621	YAB4	Y	0.0036	0.0010	0.0091	0.0137	0.0000

cancel one another out:

$$\mathcal{A}_{\delta,\text{total}} = \sum_i \mathcal{A}_{\delta,i} \sin(2\pi\nu_i). \quad (12)$$

Table 7 shows the collimator wakefield effects projected to the IP as described above, and subdivided into spoiler and absorber components in the energy collimation region, betatron collimation region, and final focus of each BDS.

Table 7: Jitter-amplification figures of merit for collimators in the final doublet betatron phase.

Parameter	TESLA			NLC			CLIC		
	$\mathcal{A}_x$	$\mathcal{A}_y$	$\mathcal{A}_\delta$	$\mathcal{A}_x$	$\mathcal{A}_y$	$\mathcal{A}_\delta$	$\mathcal{A}_x$	$\mathcal{A}_y$	$\mathcal{A}_\delta$
δ Spoilers	0.0450	0.0890	0.3458	0.0010	0.0450	0.0530	0.0345	0.0	0.0
δ Absorbers	0.0063	0.0335	0.0582	0.0055	0.0163	0.0199	0.0477	0.	0.
β Spoilers	0.0845	1.3630	0	0.0819	0.7232	0	0.1721	0.9844	0
β Absorbers	0.0329	0.5145	0	0.0033	0.0140	0	0.0307	0.0388	0
FF Spoilers	0.0553	0.7248	0.0023	0	0	0	0	0	0
FF Absorbers	0.0255	0.3069	0.0372	0.0627	0.5392	0.0020	0	0	0
Total	0.2496	3.0318	0.4435	0.1543	1.3378	0.0748	0.2846	1.0231	0.

As discussed previously, the $\mathcal{A}_\delta$ values for CLIC are essentially zero because the betatron phase advance through the CLIC energy collimation system is chosen to cause the values to cancel overall. Note, however, that the preceding calculation assumed that the collimator wakefield is a perturbation to the beam jitter through the collimators themselves, and that the jitter at each collimator is therefore dominated by the incoming beam jitter. For TESLA and NLC, in the vertical plane, this is not the case: the beam jitter is in fact dominated by the collimator wakefields. This means that the situation is likely to be somewhat different from what has been heretofore described, since the FD phase collimators will impart a significant kick to the beam, which will result in a changed beam position in the downstream IP phase collimators, which will in turn lead to a kick which changes the beam position at the later FD-phase collimators. No careful analysis of the system behavior for these parameters has been performed, since it is believed that a combined $\mathcal{A}_\beta$ value which exceeds 1 is unacceptable in any case.

4.2 Reducing the Vertical Plane Values of $\mathcal{A}_\beta$

Given that the values of $\mathcal{A}_\beta$ in Table 7 are considered unacceptable, what means of mitigation are available to the BDS designer? One approach that does not seem likely to work is to alter the optics of the BDS while maintaining the same number of sigmas for the collimation depth. Inspection of Equations 4 and 8 shows that, in the diffraction or induction regimes, the kick factor is inversely proportional to the square of the collimation depth in sigmas, and even in the intermediate regime the kick is only proportional to the fourth root of β_y. One obvious approach, therefore, is to relax the collimation depth requirements. This in turn may require an increase in the aperture radius of the vertex detector, or other geometry changes in the IR. Alternately, one might choose to use "tail-folding" octupoles, which are present in the NLC (but not used in this study). Such octupoles would permit the spoiler apertures to be relaxed by about a factor of 3, yielding about an order of magnitude reduction in jitter amplification. A third optical alternative is to relax β_y^*: since the "keep-out" region required by the detector is fixed, increasing β_y^* would allow the collimation to proceed at a larger number of beam sigmas. Unfortunately, the trade-off here is that the luminosity is reduced as well.

Another approach is to reduce the taper angle. Tables 4, 5, and 6 show that the geometric kick is much larger than the resistive kick, and therefore that there is "room to maneuver" in this parameter. Unfortunately, the selected value of the taper angle in this exercise is 20 mrad, or approximately 1 degree. It may not be feasible to construct collimators which are tapered at shallower angles than this.

Another approach is to eliminate collimators that prove to be superfluous from the point of view of beam halo attenuation. For example, TESLA contains several spoilers in the final focus which might be candidates for elimination; out of the 3 FF absorbers in the NLC, the jitter amplification is almost entirely due to a single one. In addition, all of the designs use multiple spoilers per phase in the dedicated collimation section, when only one spoiler per phase is, in principle, required to protect against incoming oscillations. Whether the remaining spoilers are required to protect against oscillations introduced in the collimation system itself (from magnet motions or collimator wakefields) is another matter entirely; if this proves not to be the case, some number of spoilers in each collimation system may be subject to removal.

Finally, it is noted that the TESLA spoilers include an extremely long flat region of 0.4 m, which is required to present 0.5 radiation lengths of graphite in the path of the beam halo. If a material with a smaller radiation length, such as titanium alloy, is chosen then the flat can be nearly eliminated. This will substantially reduce the resistive-wall wakefield of the spoilers, although the suitability of titanium spoilers from a machine protection standpoint in the context of TESLA would need to be evaluated.

4.3 Energy Scaling

Both the geometric and the resistive-wall wakefield kicks scale inversely with beam energy. If we assume that the necessary collimator gaps for halo attenuation do not scale with the beam energy, then the jitter amplification will be some 6 times worse at the Z-pole than it is at 500 GeV CM.

The energy term $\mathcal{A}_\delta$ only scales with the inverse square root of beam energy, and so this term will probably remain acceptable at all energies.

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