LCLS-II Technical Note

Wakefield Effects of Collimators in LCLS-II

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Introduction

- In LCLS-II collimators are used to clean up beam halo and to protect the machine. They can be found at the end of the gun, at the end of L0, L1, L2, L3, and upstream of the undulator
- The longitudinal wakefields induce an energy variation along the bunch. If the beam enters a collimator off axis, the beam will be kicked by an amount that varies along the bunch. For a non-round geometry (as is usual) there will also be a defocusing effect that varies along the bunch
- In this talk I will estimate the resistive wall (rw) and geometric wake effects due to the LCLS-II collimators

I thank G. Stupakov for working with me over the years on short-bunch wakes, and J. Welch in helping me understand the LCLS-II collimator arrangement

Picture of collimator

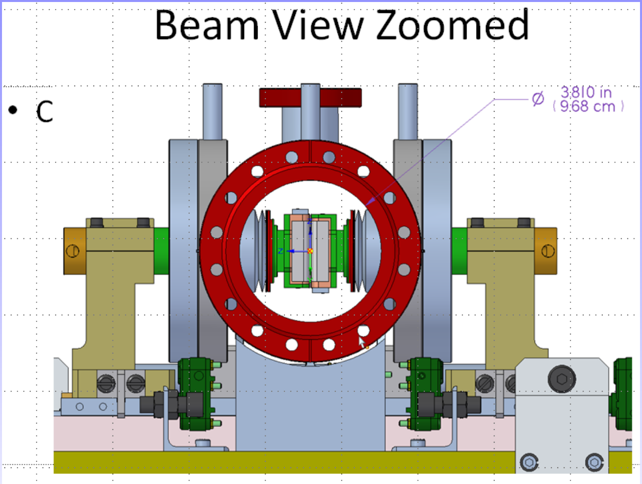

Figure: Beam view of the beam pipe and a horizontal collimator. The beam moves into the figure. Thanks to J. Welch

Model of collimator

- Total wake is sum of geometric plus resistive wall components
- Because $\sigma_z \ll a$ (a is half aperture) geometric component is well approximated by optical model

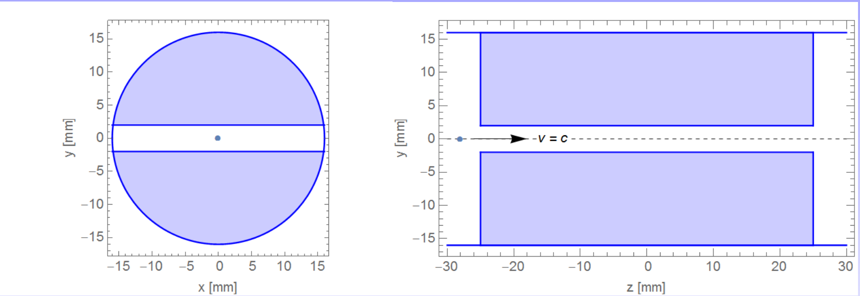

Figure: Model of a y collimator used for optical model; beam view (left) and longitudinal view (right). The collimator of length L fills the round beam pipe, except in the aperture. Shown is a collimator of half-aperture $a = 2$ mm and beam pipe radius $b = 16$ mm

Optical model of geometric wakes

See G. Stupakov et al, PRST-AB 10, 054401 (2007); K. Bane et al, PRST-AB 10, 074401 (2007)

• Applicable for objects that stick into the beam pipe. Bunch needs to be short compared to aperture. Longitudinal impedance is resistive (Z_l is constant and $V_{ind} \propto I(s)$), and transverse impedance is capacitive ($Z_l \propto 1/\omega$ and $V_{ind} \propto \int^s I(s')ds'$)

• $L \gg z_{cu} = a^2/2\sigma_z \Rightarrow$ is a "collimator" and not an "iris"

• In round pipe of radius b: for round (flat) collimator of radius (half-aperture) a

$$Z_l = \frac{Z_0}{\pi} \ln \frac{b}{a} \qquad \left(\frac{Z_0}{\pi} \ln \frac{\pi b}{4a}\right)$$

• Note: for the effects of two collimators in succession just to add, they need to be far enough apart ($\sim$ meters in L3)

Resistive wall wake

- Collimators will be made of Al, Ti, Cu, or W. Ti collimators have longest radiation lengths and total length $L = 50$ cm. For Ti, $\sigma_c = 2.38 \times 10^6\ \Omega^{-1}\mathrm{m}^{-1}$ and ac effects are small

- In round pipe of radius a the point charge, longitudinal dc wake

$$W(s) = \frac{Z_0 c}{\pi a^2}\left(\frac{1}{3}e^{-s/s_0}\cos\frac{\sqrt{3}s}{s_0} - \frac{\sqrt{2}}{\pi}\int_0^\infty dx\frac{x^2 e^{-sx^2/s_0}}{x^6+8}\right)$$

with $s_0 = (2a^2/Z_0\sigma_c)^{1/3}$. For Ti with $a = 2$ mm, $s_0 = 21\ \mu$m

- In flat chamber with half aperture a

$$Z(k) = \frac{Z_0}{2\pi a}\int_0^\infty dq\,\mathrm{sech}\,q\left(\frac{\cosh q}{\zeta_{rw}(k)} - \frac{ika}{q}\sinh q\right)^{-1}$$

with $\zeta_{rw}(k) = (1-i)\sqrt{k/2Z_0\sigma_c}$. Obtain $Z(k)$ numerically. then perform IFT to get wake

- Long-range wake ($\sigma_z \gg s_0$) is the same in flat and round geometry

Resistive wall wake cont'd

- The dc point charge wakes in flat and round geometry are universal functions of s/s_0

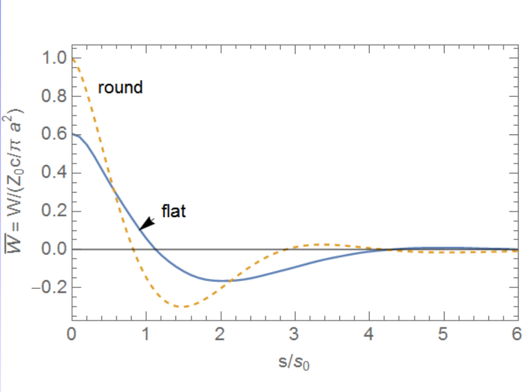

Figure: Point charge rw wake in flat (blue) and round (orange, dashed) geometry. The parameter a is half-aperture (radius) in the flat (round) case

Induced voltage

- For a bunch with current $I(s)$ the voltage induced is given by

$$V_{ind}(s) = -\frac{1}{c}\int_0^\infty W(s')I(s-s')\,ds'$$

- In LCLS-II, after the second bunch compressor, the bunch shape is approximately uniform with peak current $I = 1$ kA. For a uniform current distribution

$$V_{ind}(s) = -\frac{I}{c}\int_0^s W(s')\,ds'$$

- The average induced voltage is the loss factor $\kappa = \langle V_{ind}\rangle$; average effect $\langle \delta_w \rangle = eQ\kappa/E$ (for geometric) or $eQ\kappa L/E$ (for rw)

Loss factor

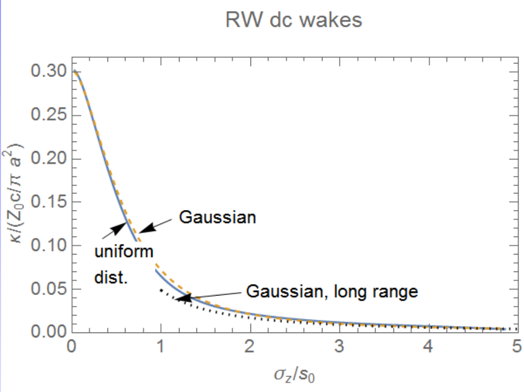

Figure: Loss factor for rw wake in flat geometry assuming a uniform (blue) or Gaussian (red, dashed) distribution. The black dots give the Gaussian, long range result

Longitudinal effect example

- There are two components: geometric (optical model) and rw:

$$V_{ind} = -\frac{Z_0 I}{\pi} \ln \frac{\pi b}{4a} \quad \text{and} \quad V_{ind} = -\frac{Z_0 I L s_0}{\pi a^2} \int_0^{\ell/s_0} \bar{W}(x)\, dx$$

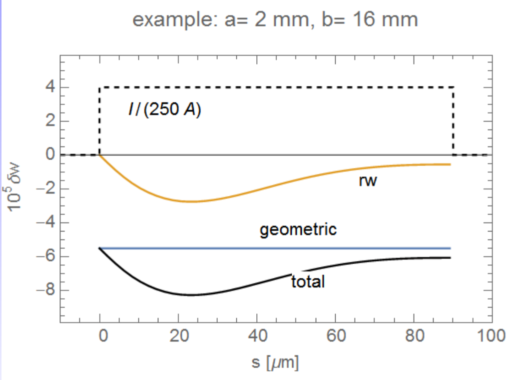

Figure: Induced energy variation, $\delta w = eV_{ind}/E$, for flat collimator with $a = 2$ mm in beam pipe radius $b = 16$ mm; we assume Ti with $L = 50$ cm; $E = 4$ GeV. Current I is also shown, with head to the left.

Echo test

- To demonstrate that summing rw and optical model wakes makes sense, we've run Echo (I. Zagorodnov's time domain wakefield solver with rw) for a round collimator in a round pipe

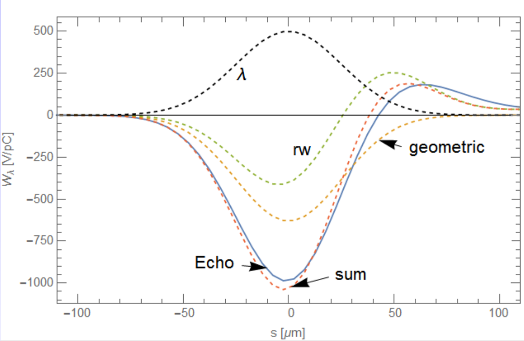

Figure: Echo bunch wake for a round, test collimator, with $\sigma_c = 2.38 \times 10^6\ \Omega^{-1}\mathrm{m}^{-1}$ (Ti), $a = 2$ mm, $b = 6$ mm, $L = 50$ cm, for a Gaussian bunch with $\sigma_z = 25\ \mu\mathrm{m}$ (blue). The dashed colored curves give the analytical rw and geometric contributions, and their sum. The bunch shape $\lambda(s)$, with head to the left, is also given (black dashes)

	z	E	β_x	α_x	β_y	α_y	δ_{spec}	a_x/σ_x	a_y/σ_y	$a/(\eta\sigma_\delta)$	a_x	a_y	P	
	[m]	[GeV]	[m]		[m]		[+/- %]				[mm]	[mm]	[W]	
LCLS2scH														
'CEHTR'	17	0.1	10.047	0.069	9.228	-0.637	1	24	16	30.0	5.5		1000	Al, Ti, Cu, W
'CYC01'	40	0.1	7.771	0.79	14.088	-1.394		24	16			4.3	1000	Al, Ti, Cu, W
'CXC01'	44	0.1	14.088	-1.394	7.771	0.79		24	16		6.5		1000	Al, Ti, Cu, W
'CYC02'	48	0.1	7.771	0.79	14.088	-1.394		24	16			4.3	1000	Al, Ti, Cu, W
'CXC02'	52	0.1	14.088	-1.394	7.771	0.79		24	16		6.5		1000	Al, Ti, Cu, W
'CYC03'	56	0.1	7.771	0.79	14.088	-1.394		24	16	0.0		4.3	1000	Al, Ti, Cu, W
'CXC03'	60	0.1	14.088	-1.394	7.771	0.79		24	16		6.5		1000	Al,Ti, W
'CEBC1'	121	0.25	10.483	2.233	58.246	-1.196	9	27	18	4.4	24.8		1000	Al,Ti, W
'CYC11'	141	0.25	7.542	0.574	14.552	-0.995		27	18			3.1	1000	Al,Ti, W
'CXC11'	145	0.25	14.09	-1.395	7.771	0.79		27	18		4.5		1000	Al,Ti, W
'CYC12'	149	0.25	7.772	0.79	14.089	-1.395		27	18	0.0		3.0	1000	Al,Ti, W
'CXC12'	153	0.25	14.089	-1.394	7.772	0.79		27	18		4.5		1000	Al,Ti, W
'CYC13'	157	0.25	7.771	0.79	14.089	-1.395		27	18			3.0	1000	Al,Ti, W
'CXC13'	161	0.25	14.087	-1.394	7.771	0.79		27	18		4.5		1000	Al,Ti, W
'CEBC2'	340	1.6	60.445	4.814	71.9	-3.149	6	29	19	8.0	26.6		1000	Al,Ti, W
'CYC21'	382	1.6	11.239	0.749	21.893	-1.429		29	24	0.0		2.0	1000	Al,Ti, W
'CXC21'	388	1.6	21.893	-1.429	11.239	0.749		29	24		2.4		1000	Al, Ti, Cu, W
'CYC22'	394	1.6	11.239	0.749	21.894	-1.429		29	24			2.0	1000	Al, Ti, Cu, W
'CXC22'	400	1.6	21.894	-1.429	11.239	0.749		29	24		2.4		1000	Al, Ti, Cu, W
'CYC23'	406	1.6	11.239	0.749	21.894	-1.429		29	24			2.0	1000	Al, Ti, Cu, W
'CXC23'	412	1.6	21.894	-1.429	11.239	0.749		29	24		2.4		1000	Al, Ti, Cu, W
'CEDOG'	940	4	27.13	-2.187	7.079	0.713	3.5	31	26	10.4	8.3		1000	Al, Ti, Cu, W
'CYBP20'	1934	4	181.29	-0.692	388.83	1.474		31	26	0.0		5.8	1000	Al, Ti, Cu, W
'CXBP21'	2035	4	388.83	1.474	181.29	-0.692		31	26		7.0		1000	Al, Ti, Cu, W
'CYBP24'	2340	4	181.29	-0.692	388.83	1.474		31	26	0.0		5.8	1000	Al, Ti, Cu, W
'CXBP25'	2442	4	385.46	2.05	182.84	-0.963		31	26	0.0	7.0		1000	Al, Ti, Cu, W
'CXQ6'	3151	4	35.356	-1.141	77.399	3.366		31	26	0.0	2.1		1000	Al, Ti, Cu, W
'CEDL1'	3235	4	4.651	-0.182	20.809	1.43	3.5	34	26	10.4	4.2		1000	Al, Ti, Cu, W
'CYBX32'	3248	4	29.989	-2.379	73.265	-3.119		34	26			2.5	1000	Al, Ti, Cu, W
'CXQT22'	3291	4	74.369	16.332	76.415	-13.196		34	26	0.0	3.3		1000	Al, Ti, Cu, W
'CEDL3'	3309	4	4.504	0.026	21.784	-1.496	2	34	26	5.2	2.3		1000	Al, Ti, Cu, W
'CYBX36'	3318	4	21.749	-1.958	60.339	-2.823		34	26			2.3	1000	Al, Ti, Cu, W
LCLS2scS														
'CXBP30'	2945	4	24.057	-0.554	127.47	1.007		36	23		2.0		1000	Al, Ti, Cu, W
'CXBP34'	3172	4	122.72	6.535	46.098	-1.166		36	23		4.6		1000	Al, Ti, Cu, W
'CYBDL'	3191	4	4.347	-0.918	72.997	13.088		36	23			2.2	1000	Al, Ti, Cu, W
'CEDL14'	3245	4	8.128	-0.535	40.272	2.317	3.5	36	29	10.4	6.0		1000	Al, Ti, Cu, W
'CYDL16'	3271	4	8.464	-0.582	38.9	2.27		36	29			2.0	1000	Al, Ti, Cu, W
'CEDL18'	3296	4	8.128	-0.535	40.272	2.317	3.5	36	29	10.4	6.0		1000	Al, Ti, Cu, W

Collimators for LCLS-II.

Apertures

- There are (17, 13) collimators in (x, y) through the hard x-ray line; after BC2, there are (10, 7)

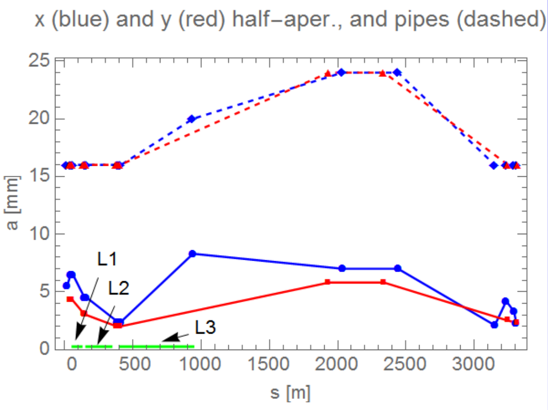

Figure: The half-apertures, a, of x (blue) and y (red) collimators (except the BC collimators; symbols connected by solid lines). The beam pipe radius is indicated by dashes. The locations of L1, L2, L3, are indicated in green; the undulator begins at $s = 3500$ m. Note: $\sigma_z = (1., 0.27, 0.025)$ mm in (L1, L2, L3). Note: 2 BC collimators are not included

Apertures Cont'd

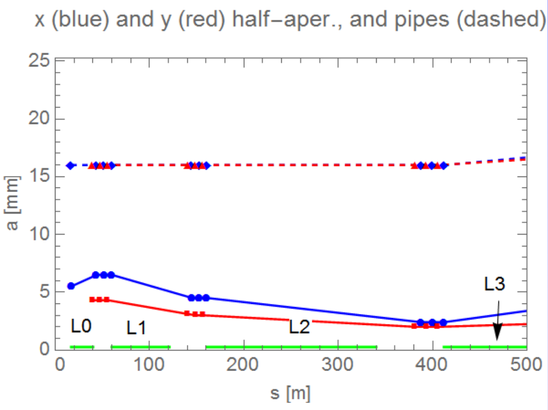

Figure: Zooming in on the beginning: The half-apertures, *a*, of *x* (blue) and *y* (red) collimators (except the BC collimators; symbols connected by solid lines). The beam pipe radius is indicated by dashes. The locations of L0, L1, L2, and beginning of L3, are indicated in green.

Total Longitudinal Effect by Region, Averaged over Bunch

Table: Beam and machine properties downstream of the different linacs in LCLS-II, giving region name, energy, rms bunch length, number of x and y collimators, average longitudinal wake effect of all collimators in x and y ("g" geometric, "rw" resistive wall) in given region. Note that bunch distribution is assumed to be Gaussian in L0, L1, L2, and uniform in L3. Here $Q = 300$ pC, at end $E = 4$ GeV. Collimators are assumed to be Ti, of length 50 cm.

Region	E [GeV]	σ_z [μm]	n_x (n_y)	$\langle\delta_w\rangle_g[10^{-5}]$	$\langle\delta_w\rangle_{rw}[10^{-5}]$
L0	0.10	1000.	4 (3)	8.5 (9.8)	0.25 (0.27)
L1	0.25	1000.	3 (3)	13.9 (14.6)	0.75 (1.11)
L2	1.6	270.	3 (3)	37.8 (29.3)	7.8 (9.3)
L3+	4.0	25.	7 (4)	25.6 (17.0)	5.9 (3.8)

Longitudinal effect: due to geometric wakes

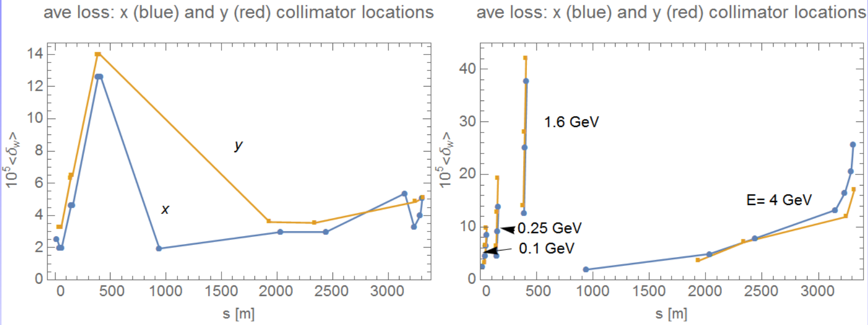

Figure: (Left) For flat geometry, the average wake loss in bunch at collimator positions (plotting symbols). Blue (red) symbols show effect at x (y) collimators. (Right) The accumulated average loss at all collimator positions. The accumulation is over regions of constant energy.

Dispersion Effect

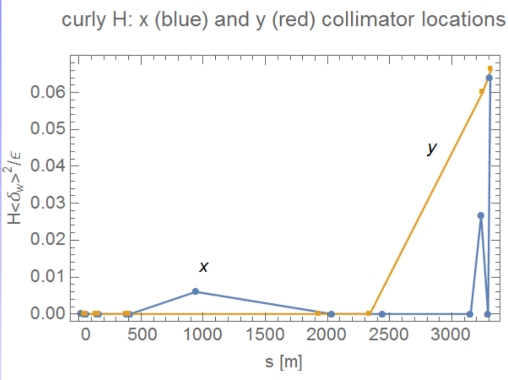

Figure: For flat geometry, the local transverse size, plotting $\mathcal{H}\delta_w^2/\epsilon$, at collimator positions (plotting symbols). Blue (red) symbols show effect at x (y) collimators.

Transverse wakes

• For a short bunch (say in L3) the longitudinal wake reaches near its max strength, and the transverse wake, which starts as $W_x(0) = 0$, is expected to be relatively weak. [See e.g. transverse wake of undulator beam pipe of LCLS-II, K. Bane and G. Stupakov, LCLS-II-TN-15-02, Jan 2015]

• In round geometry, near axis, the dipole wake dominates. In non-round geometry, near the axis, there is also a quad wake. The total impedance for a flat, vertical collimator:

$$\tilde{Z}_y = y_0 Z_{yd} + y Z_{yq} \ , \qquad \qquad \tilde{Z}_x = (x_0 - x) Z_{yq} \ ,$$

with y_0 (y) the vertical offset of exciting (test) particle; same for wakes. For $y = y_0$, $\tilde{Z}_y = y Z_y$

• Dipole wake misaligns beam slices as one moves to tail of bunch, quad wake adds (here vertical) defocusing that increases as one moves to tail

Transverse example

- Again there is both a geometric and rw component. Here consider only the geometric component
- For optical model ($\sigma_z \ll a$) for (sufficiently long) vertical collimator: $kZ_y = \pi Z_0/(8a^2)$, and $Z_{yq} = Z_{yd}/2 = Z_y/3$
- Wake $W_y \sim \int \lambda(s)\, ds$, independent of σ_z (if $\sigma_z \ll a$)!

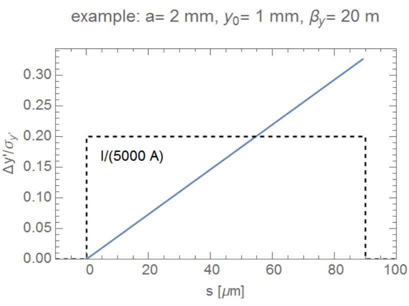

Figure: Kick [at tail $\Delta y'/\sigma_y' = e(kZ_y)cQy_0/(E\sigma_y')$] for flat collimator with $a = 2$ mm, $y_0 = 1$ mm, $\beta_y = 20$ m, $E = 4$ GeV, $I = 1$ kA, $\epsilon_{yn} = 1$ µm. Current I has head to the left. Quad wake focal length at

Transverse effect due to geometric wakes

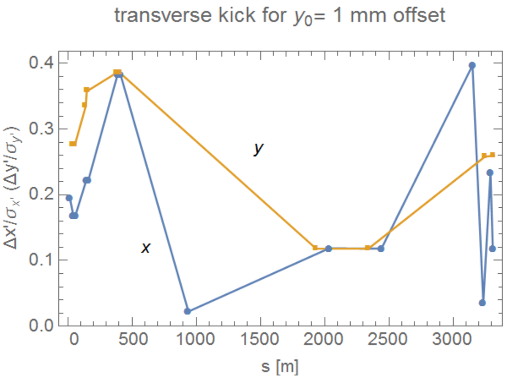

Figure: For optical model, kick at tail of 300 pC bunch when beam is offset by 1 mm in flat collimator (plotting symbols). Note $\epsilon_{yn} = 1$ µm. Blue (red) symbols show effect at x (y) collimators.

Discussion

- Optical model valid for $\sigma_z \ll a$; may not be valid near beginning of machine; can consider other models
- If a pair of collimators are too close together, there may be interference effects that I should look at
- Will do transverse rw effect, too. Depends on aperture as a^{-4} for $\sigma_z \lesssim s_0$
- Have been working with J. Welch on the first collimator design considerations
- It would be good to do eperiments. Marie experiments two years ago suggest that the measured wake effects might be larger than obtained by calculations