A Metallic Pipe with Small Corrugations Used as a Dechirper

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Outline

- Motivation
- Analytical wake formulas
- Numerical comparisons
- Commissioning measurements at the LCLS

Note: the theoretical work presented here was originally performed together with G. Stupakov, I. Zagorodnov, and/or E. Gjonaj

- References:

K. Bane and G. Stupakov, "Corrugated Pipe as a Beam Dechirper," Nucl Inst Meth A 690 (2012) 106

K. Bane, G. Stupakov, "Dechirper Wakefields for Short Bunches," Nucl Inst Meth A 820 (2016) 156

K. Bane, G. Stupakov, I. Zagorodnov, "Analytical formulas for short bunch wakes in a flat dechirper," Phys Rev Accel Beams 19 (2016) no. 8, 084401

K. Bane, G. Stupakov, I. Zagorodnov, "Wakefields of a Beam near a Single Plate in a Flat Dechirper," SLAC-PUB-16881, Nov 2016

Why a Dechirper?

- After the last bunch compressor in a linac-based, X-ray FEL, the beam is typically left with an energy–longitudinal position correlation (an energy "chirp"), with the bunch tail at higher energy than the head

- A typical value might be $h = 40$ MeV/mm. To cancel this chirp, one can run off-crest in downstream RF cavities. Running the beam on the zero crossing of the wave, we would need length $L = h/(G_{rf}k_{rf})$ of extra RF. Or with peak RF gradient $G_{rf} = 20$ MeV/m, $k_{rf} = 27$/m (for $f = 1.3$ GHz), we would need $L = 74$ m of extra active RF

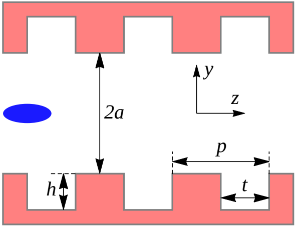
- Can we use the wakefields induced in a few meters of structure to passively accomplish the same result?

- We would like a low frequency wake (compared to the bunch; capacitive) with strong amplitude

- A passive RF cavity does not work well, since many high frequency modes are also excited by a short bunch

Corrugated Pipe in Round Geometry

A short bunch generates a strong synchronous mode in a pipe with rough surfaces (A. Novokhatski & A. Mosnier, 1997; K. Bane & A. Novokhatski, 1999)



Consider a short bunch exciting mode in corrugated pipe, with $p \lesssim h \ll a$; for simplicity let $p = 2g$:

- Wave number $k \equiv \left(\frac{2\pi f}{c}\right) = \frac{2}{\sqrt{ah}}$
- Wave number far above cut off,

low compared to inverse size of corrugation

- Amplitude of mode,

$$W(0^+) \approx \frac{Z_0 c}{\pi a^2} \qquad \text{(where } Z_0 = 377\ \Omega\text{)}$$

- Dielectric-lined, metallic pipe has an equivalent effect

Corrugated Pipe as Dechirper

- In theory, for any cavity-like structure, point charge wake can be written $w(s) = 2\sum_n \varkappa_n \cos k_n s \;\; (s > 0)$

Also, in a periodic structure $w(0^+) \equiv w_0 = 2\sum_n \varkappa_n$ only depends on the shape of the beam pipe; in a round structure, $w_0 = Z_0 c/(\pi a^2) \Rightarrow$ max. wake in structure with aperture a

- Attractiveness of using structure with small corrugations as a dechirper is that the wake is almost all in the first, relatively low frequency mode: $w(s) \approx w_0 \cos k_1 s \;\; (s > 0)$

- Bunch wake by convolution: $W_\lambda(s) = -\int_0^\infty w(s')\lambda(s - s')\, ds'$

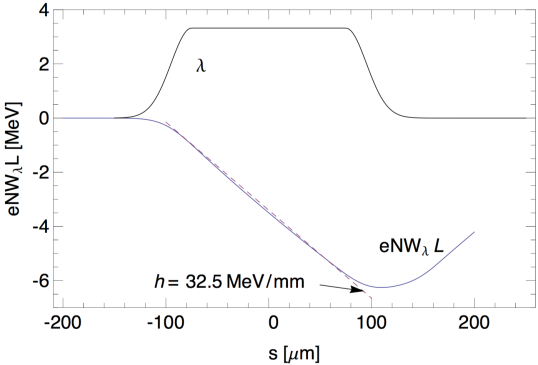
- Normally want to compensate tail of beam at higher energy than head, or want dechirper that is capacitive $\Rightarrow k\sigma_z$ small

If $k\sigma_z \ll 1 \Rightarrow W_\lambda(s) \approx -2\varkappa \int_{-\infty}^{s} \lambda(x)\, dx$

- If bunch distribution is uniform of length ℓ $(= 2\sqrt{3}\sigma_z)$, then over bunch
$W_\lambda(s) = -2\varkappa \sin[k(s + \ell/2)]/k\ell \approx -2\varkappa s/\ell$

Numerical Example–NGLS

- We performed a time-domain wake calculation using I. Zagorodnov's ECHO program; found good agreement with analytical model



Dechirper for NGLS: wake of model of NGLS bunch distribution (blue). The dashed, red line gives the linear chirp approximation. The bunch shape λ, with the head to the left, is given in black

Transverse Wakes

• If beam moves off-axis, dipole wake induced, $w_y(s) \sim 1/a^4 \Rightarrow$ limits how small an aperture can be chosen. For uniform bunch distribution, bunch dipole wake $W_{\lambda y}(s) \sim s^2$

• For flexibility, choose flat geometry. (Longitudinal wake will be $\pi^2/16 \approx 0.6$ weaker for same full aperture.) With driving and test particles at (x_0, y_0) and (x, y) near axis, you excite dipole and quad wakes (quad wakes even with beam centered on axis):

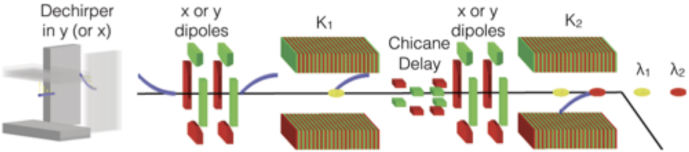
$$w_y = y_0 w_{yd}(s) + y w_{yq}(s) \ , \qquad w_x = (x_0 - x) w_{yq}(s) \ ;$$

$w_q(s)$ will result in focusing/defocusing varying from head to tail of bunch $\Rightarrow$ projected emittance growth

To mitigate this, build dechirper in two parts, one oriented horizontally, the other vertically

Transverse Wakes Cont'd

• Neither LCLS at SLAC, nor the upgrade LCLS-II, need a dechirper for chirp control. However, the ability to give a strong differential transverse kick to the beam, by passing it near one jaw, has drawn much interest and is, in fact, in use for generating *e.g.* two colors of x-rays for pump-probe experiments.



Sketch of two color generation using the dechirper (C. Emma)

• The transverse kick $\sim s^2$. An example calculation yields a 3 MV differential over a 30 μm length. For an X-band (11.4 GHz) transverse cavity, that is equivalent to 420 MV peak voltage

SLAC/RadiaBeam Dechirper

Table: RadiaBeam/LCLS Dechirper parameters. The dechirper comprises a vertical and a horizontal unit, each of which consists of two flat, corrugated plates.

Parameter name	Value	Units
Period, p	0.50	mm
Longitudinal gap, t	0.25	mm
Depth, h	0.50	mm
Nominal half aperture, a	0.70	mm
Plate width, w	12.7	mm
Plate length, L	2	m

Analytical Calculation of Wakes of Dechirper

- Analytical formulas for the wakes are desirable for *e.g.* parameter studies, simulations of novel lasing schemes using dechirper, etc.

- There are time domain, finite difference programs that can find the wakes in a flat dechirper, *e.g.* ECHO, NOVO...

- We have used a surface impedance approach in field matching to find the generalized wakes between two (horizontally orientated) dechirper plates

$$Z_l(k) = \frac{2\zeta}{c}\int_{-\infty}^{\infty} dq\, q\, \mathrm{csch}^3(2qa) f(q, y, y_0) e^{-iq(x-x_0)} \ , \qquad (1)$$

with $k = \omega/c$, the surface impedance is $\zeta(k)$, the full gap is $2a$, the drive beam is at (x_0, y_0), the test beam at (x, y), f is an analytical function; surface impedance approach: at boundary let $\tilde{E}_z(k) = \zeta(k)\tilde{H}_x(k)$, an approach that is valid when h/a small

- We can numerically perform the integral, and inverse Fourier transform, to find the generalized wakes [for usual wakes and impedances, $x \approx x_0$, $y \approx y_0$]

Analytical Calculations Cont'd

- To obtain the result for a beam passing by a *single* plate at distance b, take the two-plate result, let $y \longrightarrow a - b$, then let $a \longrightarrow \infty$

- The high frequency impedance of a periodic structure $Z(k) \sim i/k$, and the transverse impedance, $Z_y(k) \sim i/k^2$. Thus the longitudinal wake at the origin, and the slope of the transverse wake at the origin, can be obtained from the high frequency impedances as ("zeroth order approximation"):

$$w_0 = -ic \lim_{k\to\infty} kZ_l(k) \ , \qquad w'_{y0} = -ic \lim_{k\to\infty} k^2 Z_y(k)$$

From result of field matching we find *e.g.* for a beam offset at y from the axis between two plates separated by $2a$; or for a beam offset by b from a single plate

$$w_0 = \frac{\pi^2}{16}\left(\frac{Z_0 c}{\pi a^2}\right)\sec^2\left(\frac{\pi y}{2a}\right) \ ; \quad w'_{y0} = \frac{Z_0 c}{4\pi b^3}$$

Analytical First Order Approximation

- For better accuracy we need to go to the next, "first order approximation"

- For a periodic accelerating structure, the high frequency impedance can be written in the form (Gluckstern; Yokoya, Bane)

$$Z_l(k) \approx i\frac{w_0}{kc}\left[1-\frac{(1+i)}{\sqrt{2ks_0}}\right]\ , \qquad (2)$$

and this corresponds to a short-range wake approximation

$$w_l(s) \approx w_0 e^{-\sqrt{s/s_0}} \qquad (s>0) \qquad (3)$$

- For the dechirper, we take as (high frequency) surface impedance $\zeta(k)=(2it/\pi k)^{1/2}/(\alpha p)$; then we expand our field matching solution of $Z(k)$ [Eq. 1] to second order in $1/k$; comparing with Eq. 2, we can pick out w_0 and s_0; the wake is given by Eq. 3

Analytical Approximation Cont'd

- Similarly for the short-range transverse wakes, with analytic w'_{0y}, s_{0y}:

$$w_y(s) = 2w'_{0y}s_{0y}\left[1 - \left(1 + \sqrt{s/s_{0y}}\right)e^{-\sqrt{s/s_{0y}}}\right]$$

- Have analytical solutions of short-range wakes, for single and double plates, for longitudinal, dipole, and quad components

- At LCLS we measured *e.g.* the average (over the bunch) kick angle, given by $\langle y'_w \rangle = eQL\varkappa_y/E$, with Q the charge of the bunch, L the length of the dechirper plates, E the bunch energy; For a bunch with a uniform distribution of length ℓ, the kick factor is

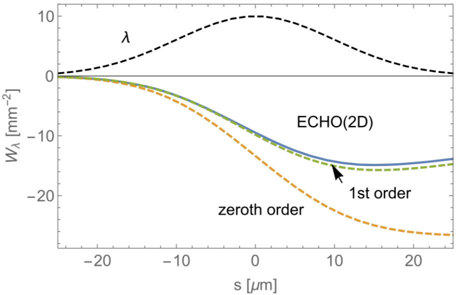
$$\varkappa_y = \frac{1}{\ell}\int_0^\ell w_y(s)\left(1 - \frac{s}{\ell}\right)ds = w'_{0y}s_{0y}f_y\left(\frac{\ell}{s_{0y}}\right) ,$$

with

$$f_y(x) = 1 - \frac{12}{x} + \frac{120}{x^2} - 8e^{-\sqrt{x}}\left(\frac{1}{x^{1/2}} + \frac{6}{x} + \frac{15}{x^{3/2}} + \frac{15}{x^2}\right) .$$

Example Numerical Comparison

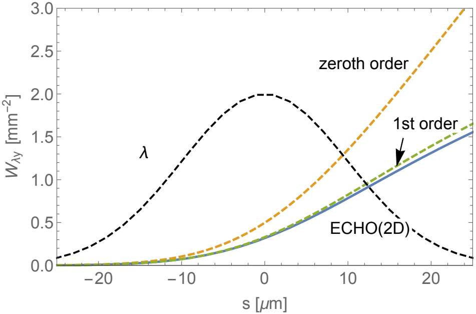
- Longitudinal bunch wake of Gaussian beam offset by y from axis of a two-plate dechirper of gap $2a$



Example calculation for LCLS dechirper: $a = 0.7$ mm, $y = 0.5$ mm. The above analytical result is given by green dashes, numerical ECHO(2D) results by the blue curve. The Gaussian bunch shape ($\sigma_z = 10$ μm), with head to the left, is given in black dashes

Example Numerical Comparison Cont'd

- Dipole bunch wake of Gaussian beam offset by y from axis of a two-plate dechirper of gap $2a$



Example calculation for LCLS dechirper: $a = 0.7$ mm, $y = 0.5$ mm. The above analytical result is given by green dashes, numerical ECHO(2D) results by the blue curve. The Gaussian bunch shape ($\sigma_z = 10$ μm), with head to the left, is given in black dashes