RadiaBeam/SLAC Dechirper

Dechirper Design and Experimental Results


Sept. 22nd, 2017
Overview

- Review of the corrugated structure (CS) dechirper
- Design challenges on hard X-ray FEL linac scale
- LCLS installation, commissioning and results
- Novel applications beyond chirp control
Description of the short-range wakefield of a beam between periodically grooved metal rails

K. Bane, G. Stupakov, I. Zagorodonov

0\textsuperscript{th} Wakefield for rectangular geometry, PRST-AB, 6, 024401 (2003).
0\textsuperscript{th} Corrugated pipe as a beam dechirper, NIMA, 690, 106 (2012)
0\textsuperscript{th} Transverse wake for flat geometry, PRST-AB, 18, 010702 (2015)
1\textsuperscript{st} Analytical formulas, PRST-AB, 19, 084401 (2016)
Theory of CS Wakes

3 periods of long CS

Point response wakefield \([E_{\text{loss}}(z)]\) from dominant longitudinal mode (perturbative approach):

\[
W_{\parallel}(z) = \frac{\pi^2 Z_0 c}{16 \pi a^2} FH(z) e^{-\frac{kz}{2Q}} \cos(kz)
\]

\[
k = \sqrt{2p/ght}
\]

Assuming \(p = 2t < h, g\) and rectangular current \(I(z)\) with bunch length \(\Delta z \ll 2\pi/k\)

\[
E_{\text{loss}}(z) = \int_{0}^{z} W_{\parallel}(z)I(z' - z)dz'
\approx \frac{\pi Z_0 c Q L}{4 g^2 \Delta z} z
\]
CS Dechirper Demonstrations

Prior demos: ~10 cm-long devices with 10 MeV, 100 pC beams (keV slice energy spreads), few mm gap
- LBNL/Pohang/SLAC
- BNL/RadiaBeam
- Shanghai collaboration

M. Harrison et al., Proc. of NAPAC 2013

Feichao Fu, et al., PRL 114, 114801 (2015)
Hard X-ray FEL beam requirements:

- High GeV energy, kA peak current
- Preserve low E spread / emittance

FEL bandwidth control requires $E_{\text{loss,Dech}} > E_{\text{slice}} \sim E_{\text{beam}} \rho_{\text{FEL}} (1 \text{ MeV})$

$$\langle E_{\text{loss}} \rangle = \frac{\pi Z_0 c Q L}{8 g^2}$$

Can’t go much smaller than ~mm!

Have to go longer…

…Much longer. A few meters long with sub-mm, in-vacuum positioning.
The RadiaBeam / SLAC Dechirper System

Mechanical, vacuum, and instrumenting by RadiaBeam (Phase II SBIR) in partnership with SLAC under a Cooperative Research And Development Agreement
Prototype LCLS Dechirper Design Parameters

- 2 x 2 m modules
  - One horiz., one vertical
  - Quadrupole wake cancellation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fin period</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Fin depth</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Nominal gap</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>Min. gap</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Peak-to-peak flatness</td>
<td>50 um</td>
</tr>
<tr>
<td>Motion Repeatability</td>
<td>25 um</td>
</tr>
</tbody>
</table>

Z. Zhang, PRST-AB, 18, 010702 (2015)
Prototype LCLS Dechirper Parameters

After dechirper

Simulations by Z. Zhang

$g = \infty$

$g = 2.0\text{mm}$

$g = 1.4\text{mm}$

$g = 1.0\text{mm}$

$W(0^+) = 60\text{ MV/nC/m}$

Z. Zhang, PRST-AB, 18, 010702 (2015)
Dechirper on SLAC Coordinate Measuring Machine

Global jaw flatness < 50 µm after rail shimming
50 µm backlash on carriage motion
Vertical Dechirper Module - Actuation

(A. Cedillos)
Vertical Dechirper Module – Insertion/Retraction

- Carrier linear speed 2.5 mm/s
- Gear reducer
- Large safety factor for motor

(A. Cedillos)
Vertical Dechirper Module – Trim Actuation

- Carrier tip trim adjustment range
  - +/- 1mm
- Gear reducer
- Large safety factor for motor

Approximate pivot points
Additional controls

New position/angle orbit feedback through Dechirper modules (R. Iverson, L. Piccoli)

EPICS-level motion control of Dechirper US/DS gaps and/or rail ends
- 8 motors
- 8 independent position encoders (Z. Oven, A. Babbitt)

New beam loss fiber – losses at beginning & end
E-beam parameters: 6.6 GeV, 150pC, gap = 1.1mm (A. Fisher)
Diagnostic layout

- BPMs (beam-based alignment)
- Transverse profile monitor & wire scanners
- X-band deflector, spectro. bend, & screen ($t$-$E$ space)
- Hard/soft X-ray spectrometers (X-ray BW)
Beam-based alignment procedure

- Off-axis beam also experiences a dipole wake
- Gap at each end well calibrated from metrology, end-to-end angle to beam less well known

- BBA: Scan single dechirper across beam with strong taper and orbit feedbacks off, measure change in orbit downstream, repeat 4x
New Dechirper GUI
1. manage all procedural setup
2. run all 4 scans
3. do all (cubic or analytical) fits to find/set offsets

(J. Zemella, M. Guetg)
Single X-band deflector measurement:
@ 4.4 GeV / 180 pC / 1 kA
Measurements @ 4.4 GeV / 180 pC / 1 kA

Average loss

\[ \Delta E = \frac{\pi Z_0 c Q L}{8 g^2} \]

For very small gap, becomes “over dechirped,” \( E \) spread grows

Projected \( E \) spread

\( E \) loss

Chirp
Measurements @ 4.4 GeV / 180 pC / 1 kA

Translates directly to measured X-ray spectra

From SXR spectrometer @ 870 eV
Adding Chirped Hard X-ray Bandwidth

Just as effective at high energy:
Observe red shift / BW increase on hard X-ray spectrometer

Can increase BW for over-compressed bunch (where desirable)
Steep Slope < 1.4 mm Full Gap

Early days: FEL degrades for gap < 1.4 mm

Correlation Plot 12-Nov-2015 16:50:17

Pulse energy vs. Gap

X-ray pulse reconstruction with XTCAV shows tail stops lasing
Steep Slope < 1.4 mm Full Gap

Seen on tail slice energy spread (no lasing). Repeatedly moving dechirper in/out to same location eliminates this growth. With FEL, also restores full intensity.

On-axis, $E$ spread should be < 100 keV on tail
Transverse wakes

**Dipole: time-correlated transverse kick**

- Dechirper
- Dechirper axis
- Electron bunch

**Quad: time-correlated focusing**

- Electron bunch slices

(A. Lutman)
Average dipole wake studies: Single jaw position scans

\[ w_x(s) = \left( \frac{Z_0 c}{4\pi} \right) A s_{0x} \left[ 1 - \left( 1 + \sqrt{\frac{s}{s_{0x}}} \right) e^{-\sqrt{\frac{s}{s_{0x}}}} \right] \]

\[ A_d = \frac{\pi^3}{4a^3} \sec^2 \left( \frac{\pi x}{2a} \right) \tan \left( \frac{\pi x}{2a} \right), \quad s_{0r} = \frac{a^2 t}{2\pi \alpha^2 (t/p)p^2} \]

\[ s_{0xd} = 4s_{0r} \left[ \frac{3}{2} + \frac{\pi x}{a} \csc \left( \frac{\pi x}{a} \right) - \frac{\pi x}{2a} \cot \left( \frac{\pi x}{a} \right) \right]^{-2} \]

6.6 GeV, 150 pC, 2 mm full gap*

13 GeV, 180 pC, 3.1 mm full gap**

* Theoretical gap reduced 11%

** Theoretical gap reduced 6%
Average dipole wake studies: Two jaws, scan gap center

\[
w_x(s) = \left( \frac{Z_0c}{4\pi} \right) A_{s0x} \left[ 1 - \left( 1 + \sqrt{s/s_{0x}} \right) e^{-\sqrt{s/s_{0x}}} \right]
\]

\[A_s = \frac{2}{b^3}, \quad s_{0xs} = \frac{8b^2t}{9\pi\alpha^2p^2}\]

13 GeV, 180 pC, 3.5 kA
Passive streaker

Strong effect, once incidentally equivalent to XTCAV…
Passive streaker

- Proposals from A. Novokhatski, S. Bettoni, P. Craievich, A. Lutman
- PSI Demo [S. Bettoni, PRAB 19, (2016)]
- First SLAC demo [A. Novokhatski, IPAC 2016, MOPOW046 (2016)]

PSI measurements

SLAC measurements

Requires algorithmic reconstruction but, self-synchronized/highly stable (vs. TDS)

< 1 fs resolution feasible
Fresh-slice X-ray free-electron lasers

- Tail of bunch undergoes betatron oscillations, head slice lases
- Only one temporal slice lases

(A. Lutman)
Slice and pulse duration control

Both X and Y dechiper used

Recorded BPM orbits

1.8 keV photons

XTCAV images: electron bunch after lasing in undulator

Bunch head
Two-color, variable delay X-ray pulses

Fresh-slice multicolour X-ray free-electron lasers


Fresh slice features:
+ Easy to setup and stable
+ Fully saturated short pulses
+ Delay controlled by chicane
+ Color controlled by undulator K’s
+ Scan through zero delay if tail lases first
+ Independent pointing in each section
+ Polarization control with Delta
+ And so much more! (Ref C. Emma’s talk TUB3CO03)

<table>
<thead>
<tr>
<th></th>
<th>Tail Pulse</th>
<th>Head Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [µJ]</td>
<td>248 ± 83</td>
<td>484 ± 91</td>
</tr>
<tr>
<td>Duration</td>
<td>~ 5 fs</td>
<td>~ 17 fs</td>
</tr>
<tr>
<td>Wavelength</td>
<td>715 eV</td>
<td>699 eV</td>
</tr>
<tr>
<td>Undulators</td>
<td>U1-U8, K~3.455</td>
<td>U26-U33, K~3.505</td>
</tr>
</tbody>
</table>

(A. Lutman)
Outlook

- A pair of crossed, 2 m, all-metal, variable-gap CS dechirpers have been built and designed for X-ray FEL applications
- Chirp control for correlated BW tuning of the LCLS has been demonstrated with excellent agreement to theory
- Lessons learned for improving motion repeatability
- Additional applications for the controlled dipole wakefield to sub-fs passive streaking and advanced, fresh-slice lasing techniques
- Not directly interceptive, application to future high-rate, high-power X-ray FEL linacs remains to be explored
Acknowledgements

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Grazie!