Demonstration of Energy-Chirp Control in Relativistic Electron Bunches at LCLS Using a Corrugated Structure

Karl Bane, 7 April 2017, 加速器物理セミナー, KEK
Introduction

• At the end of acceleration in an X-ray FEL, the beam may be left with an longitudinal position/energy correlation. The metallic beam pipe with small corrugations—a “dechirper”—was proposed as a passive device to “dechirp” the beam

• The RadiaBeam/LCLS dechirper was installed in the LCLS, to give added flexibility to operations. Device commissioning was performed over the period Oct 2015—Feb 2016

• I will present (i) basic wakefield measurements—energy loss, induced chirp, transverse kick, …—, compare to calculations, and (ii) measurements of their effect on the lasing process

• These are the first measurements of a dechirper at high energies (multi-GeV), short bunch lengths (10’s of µm’s), and in a functioning FEL
Outline

• Description of RadiaBeam/LCLS dechirper
• Basic wakefield measurements—average energy loss, induced chirp, transverse kick
• Dechirper/FEL interaction
• Conclusions

Will not discuss transverse kick for bunch length measurements—A. Novokhatkski et al

Selected references on wake theory of corrugated dechirpers:
K. Bane and G. Stupakov, Nucl Inst Meth A 690, 106 (2012)
K. Bane, G. Stupakov, Nucl Inst Meth A 820, 156 (2016)
### Contributors to Dechirper Commissioning Success (effort led by R. Iverson)

<table>
<thead>
<tr>
<th>FEL Physics</th>
<th>Radiabeam Systems</th>
<th>METS</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. Maxwell</td>
<td>M. Ruelas</td>
<td>A. Cedillos</td>
<td>A. Babbitt</td>
</tr>
<tr>
<td>P. Krejcik</td>
<td>M. Harrison</td>
<td>M.A. Carrasco</td>
<td>Z. Oven</td>
</tr>
<tr>
<td>M. Guetg</td>
<td>J. McNevin</td>
<td>G. Gassner</td>
<td>M. Petree</td>
</tr>
<tr>
<td>J. Zemella</td>
<td>D. Martin</td>
<td>E. Reese</td>
<td>J. Bong</td>
</tr>
<tr>
<td>Z. Huang</td>
<td>A. Murokh</td>
<td>K. Caban</td>
<td>M. D'Ewart</td>
</tr>
<tr>
<td>K. Bane</td>
<td>P. Frigola</td>
<td>S. Jansson</td>
<td>S. Hoobler</td>
</tr>
<tr>
<td>G. Stupakov</td>
<td></td>
<td>T. Montagne</td>
<td>S. Alverson</td>
</tr>
<tr>
<td>P. Emma</td>
<td></td>
<td>J. Garcia</td>
<td>L. Piccoli</td>
</tr>
<tr>
<td>J. Frisch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. Loos</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Lutman</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Fisher</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Novokhatiski</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R. Iverson</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We especially thank RadiaBeam for building the dechirper and collaborating on the commissioning.
Linac Coherent Light Source (LCLS)

Electron Energy : 14.3 GeV
Light Wavelength : 0.15 nm
Peak Brilliance : $2.0 \times 10^{33}$
Light Flashes : 120 per sec.
Facility Length : 3 km
Undulators : 1
Experiment Stations : 1

SINCE 2009

--LCLS-II: $10^9$ upgrade; install superconducting RF, run at 1 MHz repetition
RadiaBeam/LCLS Dechirper Installed in the LCLS

25 um precision over 2 m  
(P. Krejcik)
Vertical Dechirper Module - Actuation
Vertical Dechirper Module - Actuation

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

- Carrier position repeatability 25um
- Carrier linear speed 2.5 mm/s
- Gear reducer
- Large safety factor for motor

*Will have a manual method to retract the jaws along with E-stop.

(A. Cedillos)
Vertical Dechirper Module – Trim Actuation

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

Approximate pivot points

LTU Stand

(A. Cedillos)
Dechirper at LCLS

Note: on dump screen $x$ is proportional to time and $y$ to energy

Simulation by Z. Zhang

(R. Iverson)
The dechirper unit consists of 2 m of a vertical dechirper followed by 2 m of a horizontal one.

This configuration was chosen to partially cancel the unavoidable quad wake mismatch at the tail of the bunch.

$h, p$ not $<< a =>$ not in perturbation regime. Wakes have a droop, and dechirp in a uniform bunch is not quite as strong, not completely linear.

Note: a dechirper based on dielectric-lined, metallic plates will behave similarly.

Three periods of the vertical dechirper.
Single X-band deflector measurement:
@ 4.4 GeV / 180 pC / 1 kA

Data from dump screen

Clear, ~linear additional chirp observed
Using both dechirpers (L = 4 m)

Obtained from data from dump screen (T. Maxwell)
for uniform bunch, average loss \( \Delta E = \frac{\pi Z_0 C Q L}{8 g^2} \)

As gap becomes smaller here \( E_{\text{FWHM}} \) increases again

Projected \( E \) spread

(T. Maxwell)
Average $E_{\text{loss}}$ vs. Bunch Offset

$E_{\text{loss}} \sim \frac{QL}{g^2} \sec^2 \frac{\pi y}{g}$

$g = 2a = 2.2 \text{ mm}$

$I = 1 \text{ kA}$

$Q = 190 \text{ pC}$

$E = 4.425 \text{ GeV}$

Single dechiper

$L = 2 \text{ m}$

Measured using BPMs in dispersive region, averaged over many shots; dashes show analytical function

To obtain this agreement, a slight adjustment, $g \rightarrow 2.1 \text{ mm}$, was made
Transverse Kick vs Bunch Offset from Axis

For uniform bunch:

- near axis
  \[ \langle V_y \rangle \sim Z_0 \frac{I^2 L \ell y}{g^4} \]

- away from axis
  \[ \langle V_y \rangle \sim Z_0 \frac{I^2 L}{g^3} \sec^2 \frac{\pi y}{g} \tan \frac{\pi y}{g} \]

- \( I \) - current
- \( g \) - gap
- \( \ell \) - bunch length
- \( L \) - structure length
- \( y \) - bunch offset

Deflection angle as function of center position in one dechirper module. The gap of the simulations was reduced from \( g = 2.0 \text{ mm} \) to \( 1.8 \text{ mm} \) to fit the experimental data.
For the beam passing by a single dechirper plate: the average wake energy loss $<U_w>$ (left) and transverse kick $<y'_w>$ (right) vs. beam offset from plate, $b$, as measured (plotting symbols) and according to theory (red curve). For the fit, the measured points were shifted in $b$ by $-126 \, \mu m$ and $-135 \, \mu m$, respectively

- Absolute values of $<U_w>$, $<y'_w>$, $b$ not known; constant offsets were fit for

The agreement is very good for both plots

(A. Novokhatski, M. Guetg)
Translates directly to measured X-ray spectra

From SXR spectrometer @ 870 eV

Near nominal setting ($g = 1.4$ mm) does not degrade FEL performance  
(T. Maxwell)
Adding Chirped Hard X-ray Bandwidth

Just as effective at high energy:

Observe center downshift / BW increase on FEE HXRS

Can increase chirp for over-compressed bunch—desirable for some experiments

(T. Maxwell)
Dechirper as a fast passive kicker: experimental uses

1) Fresh slice SASE for control of pulse duration

2) Two-color fresh slice SASE with polarization control

3) Fresh bunch self-seeding with high intensity short seeded pulses

(C. Emma)
Larger kick was given by closing more the gap (instead of changing the structure offset), evidently the beam was travelling slightly off-axis from the structure.

Trajectory feedbacks keep the center of mass of the electron beam on the straight trajectory.

Larger kicks yield a shorter lasing slice.

(A. Lutman)
Fresh-slice double-pulses:
Two color scheme, with color separation and tail lasing first

<table>
<thead>
<tr>
<th>Dechirper Configuration</th>
<th>Gap</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>3.5 mm</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Horizontal</td>
<td>OUT</td>
<td>/</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Undulator Configuration</th>
<th>Status</th>
<th>K value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-8</td>
<td>IN</td>
<td>K~3.455, Strong Saturation taper from Und #6</td>
</tr>
<tr>
<td>10-25</td>
<td>OUT</td>
<td>/</td>
</tr>
<tr>
<td>26-33</td>
<td>IN</td>
<td>K~3.505 Variable Taper (Regular/Reverse)</td>
</tr>
</tbody>
</table>

![Graph showing Y Orbit vs Undulator BPMs](image)

(A. Lutman)
Fresh-slice double-pulses: Two color scheme, with color separation and tail lasing first

FEL Statistics: 746 +/- 125 µJ

Regular Taper Delta in circular polarization

first color: ~250 µJ
second color: ~ 500 µJ
first color: ~8 fs
second color: ~15 fs

Head Lasing  Single-Shot orbit

Tail Lasing
Conclusions

• Large-scale dechirper system has been realized for high-energy (GeV) short bunch (10s of um) bandwidth control at the LCLS. It is a precision instrument fully integrated into the LCLS. The vanes are straight and settings are reproducible to 25 um over 2 m.

• Wake measurements—energy loss, chirp, transverse kick—agree well with theory; also for single plate.

• The fast kicker capability of the dechirper is being applied for two-color and self-seeding applications; delivering improved two-color radiation to users.

• An improved dechirper unit (horizontal part only) is being designed and built by RadiaBeam for use in LCLS-II for use as fast kicker (not needed as dechirper). With 1 MHz bunch rate cooling is needed. The Joule heating has been studied, and the cooling requirements are not severe (~200 W/m at max).
Some of the Contributors