Attosecond Diagnostics of Muti-GeV Electron Beams Using W-Band Deflectors

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Measurement of 4...14 GeV LCLS bunch

Outline

• MeV scale X-band deflectors at SLAC
• 100 GHz Accelerating structures
• W-band deflectors
  – Kick with external rf source
  – Kick with bunch short range wake-field
Motivation

- Performance of the LCLS and LCLS-II is determined by the properties of the extremely short electron bunch. Multi-GeV electron bunches in LCLS are less than 100 fs long. Optimization of beam properties and understanding of free-electron laser operation requires electron beam diagnostics with time resolution of less than 10 fs. These were achieved with the X-band RF deflector.

- We propose the next generation of this time-resolved beam diagnostic with improvements in resolution by an order of magnitude, possibly resolving to a few hundred attoseconds at 15 GeV. We expect that, as with the current X-band deflector, it will allow smooth commissioning, operation and further improvement of LCLS-II performance.

- This 8-fold increase of the timing resolution could, in principal, be achieved by scaling the existing X-band system, which would be ~16 meter long and powered by 8 SLAC 50 MW XL-4 X-band klystrons. We see this as an impractical solution and instead propose to increase the operating frequency of the deflector from 11 GHz to 90 GHz. Two 1-meter long deflectors might be located about 10 meters after the FEL undulator for diagnostics for the electron bunch and the FEL x-ray pulse, but providing 8-times better temporal resolution down to about 0.5 fs, and less.
RF deflector resolution
– the higher frequency the better

\[ \sigma_z \gtrsim \frac{\lambda}{\pi e V_0} \frac{m_0 c^2}{\sin \Delta \psi} \sqrt{\frac{\gamma \varepsilon_n}{\beta_d}} \]

- \( \lambda \) - rf wavelength
- \( V_0 \) - peak deflecting voltage a crest phase
- \( \varepsilon_n \) - normalized emittance of the beam
- \( \beta_d \) - beta function at the deflector
- \( \Delta \psi \) - betatron phase advance from deflector to screen
- \( \gamma \) - relativistic factor of the beam
# SLAC X-band deflectors

**LCLS** — Linac Coherent Light Source — X-ray Free Electron Laser, uses 14 GeV SLAC Linac

**FACET** — Facility for Advanced Accelerator Experimental Tests, use 20 GeV SLAC Linac

**NLCTA** — Next-Linear-Collider Test Accelerator — X-band linac with S-band photo gun, 120 MeV

**XTA** — X-Band Test Area, compact X-band linac with X-band photo gun, 75 MeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LCLS</th>
<th>FACET</th>
<th>NLCTA</th>
<th>XTA</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Energy</strong></td>
<td>4,000-14,000</td>
<td>20,000</td>
<td>120</td>
<td>75</td>
<td>MeV</td>
</tr>
<tr>
<td><strong>Beam emittance</strong></td>
<td>0.5</td>
<td>40</td>
<td>2</td>
<td>0.55</td>
<td>um</td>
</tr>
<tr>
<td><strong>Structure length (with beam pipes)</strong></td>
<td>2*1.185</td>
<td>1.185</td>
<td>0.432</td>
<td>0.293</td>
<td>m</td>
</tr>
<tr>
<td><strong>Number of regular cells (including joining ring)</strong></td>
<td>2*113</td>
<td>113</td>
<td>27</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td><strong>Input power</strong></td>
<td>17.5+17.5</td>
<td>35</td>
<td>20</td>
<td>2</td>
<td>MW</td>
</tr>
<tr>
<td><strong>On-crest deflecting voltage</strong></td>
<td>45</td>
<td>30</td>
<td>6</td>
<td>0.9</td>
<td>MeV</td>
</tr>
<tr>
<td><strong>Resolution achieved</strong></td>
<td>1-4</td>
<td>70</td>
<td>30</td>
<td>30</td>
<td>rms fs</td>
</tr>
<tr>
<td><strong>Distance deflector-screen</strong></td>
<td>32</td>
<td>14.75</td>
<td>3</td>
<td>2.5</td>
<td>m</td>
</tr>
<tr>
<td><strong>Beta functions at RF deflector</strong></td>
<td>120@14 GeV</td>
<td>150</td>
<td>5</td>
<td>11</td>
<td>m</td>
</tr>
<tr>
<td><strong>Beta functions at the screen</strong></td>
<td>22@14 GeV</td>
<td>0.41</td>
<td>8</td>
<td>2</td>
<td>m</td>
</tr>
<tr>
<td><strong>Quadrupole focusing after deflectors</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Dipoles after deflectors</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
X-band RF deflector system installed at the LCLS undulator beamline

directional couplers

2nd deflector

output waveguide

input waveguide

1st deflector

P. Krejcik et al., SLAC
**XTCAV: x-ray beams temporal diagnostics**

- XTCAV streaks horizontally;
- Dipole bends vertically.

**XTCAV for x-ray temporal diagnostics:**
- High resolution, ~ few fs;
- Applicable in all FEL wavelength;
- Wide range, ~ 1 fs to ~100s fs;
- Beam profiles, single shot;
- No interruption with operation;
- Both e-beam and x-ray profiles.

Project started in 2011, and took about two years to complete, total cost ~$5M, and now routine diagnostics

SLAC X-band deflectors

• As for now, LCLS 2-m X-band deflector has unprecedented performance. Planned upgrade with rf pulse compressor will improve the resolution more.
• It is instrumental in advancing physics of FELS, see for example:


A. Marinelli et al., *High-intensity double-pulse X-ray free-electron laser*, Nature Communications 6, 6369, March 2015

...
Toward W-band deflectors: 100 GHz traveling wave accelerating structures

Questions:
• Can we build practical ~100 MV/m W-band structures?
• At what field gradients and pulse length W-band structures could operate without faults?
Goals of the E204 experiment

• Determine statistical properties of rf breakdown in metal structures vs. structure geometry, accelerating gradient and pulse length at 100 GHz frequencies

• Material test: find difference of performance between copper and stainless steel.

Method:
We use open traveling wave structures excited by the few nC 20 GeV FACET beam.
100 GHz copper and stainless steel traveling wave accelerating structures, as received from vendor

Manufacturing: EDM Department Inc.
Geometry of one quarter of one period of metallic THz structure for FACET experiment, rounded geometry version 6 February 2013

V.A. Dolgashev, 13 March 2012
First experiment: alignment camera view

- **Phosphor screen for beam alignment**
- **Mark for structure axis alignment**
- **Right forward rf horn**
- **Rf out**

**Dimensions:**
- 0.3...0.9 mm
- ~30 mm
- 30 mm
- ~25 mm
FACET experiment with *copper structure* in vacuum chamber

- vertical moving stage
- right forward rf horn
- phosphor screen for beam alignment
- 30...32.5 mm
- upper half of accelerating structure
- transparent for RF vacuum window
100 GHz Traveling Wave Accelerating Structure

• RF output coupler matched at gap=0.3 mm and with more than 80% power transmission at other apertures
Matched coupler

0.1 mm
0.55 mm
0.726 mm

R0.1 mm

D0.6 mm
0.6 mm
0.2 mm

regular cell

2xR0.2 mm
R0.3 mm

V.A. Dolgashev, 6 February 2013
Output coupler of traveling wave accelerating structure, aperture $2a = 0.3$ mm, synchronous frequency 136 GHz, fields normalized to 10 MW of input power, coupler reflection R=0.09
Power coupler of the 100 GHz structure

- Output waveguide
- Coupler cell
- First regular cell
- Electron beam
- Coupler iris
- RF output

Dimensions: 1.7 mm
Schematic layout of 100 GHz TW structure test

List of remote controls and diagnostics:
1. Video camera
2. RF beam shutter
3. X-Y stage motor
4. Structure beam-gap motor
5. Scope signals: crystal and pyro-detector

V.A. Dolgashev, SLAC, 31 March 2014
100 GHz signals

Pyro signal vs. horizontal structure position for different gaps

Peak pyro signal (@3.2mm horizontal position) vs. Vertical structure position
Surface electric fields with $E_{\text{max}} = 0.64 \text{ GV/m}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap (2a)</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Synchronous frequency</td>
<td>140.29 GHz</td>
</tr>
<tr>
<td>Phase-per-cell</td>
<td>133.46 deg</td>
</tr>
<tr>
<td>RF Power @ 3.2 nC</td>
<td>0.3 MW</td>
</tr>
<tr>
<td><strong>Acc. Gradient @ 3.2 nC</strong></td>
<td><strong>0.3 GV/m</strong></td>
</tr>
<tr>
<td>$E_{\text{max}}$ @ 3.2 nC</td>
<td>0.64 GV/m</td>
</tr>
<tr>
<td>$H_{\text{max}}$ @ 3.2 nC</td>
<td>1.3 MA/m</td>
</tr>
<tr>
<td>$v_g/c$</td>
<td>0.22%</td>
</tr>
<tr>
<td>Att. Length</td>
<td>1.56 mm</td>
</tr>
<tr>
<td><strong>Att. Length/$v_g$</strong></td>
<td><strong>2.3 ns</strong></td>
</tr>
<tr>
<td>$L/v_g$ (20 cells)</td>
<td>24 ns</td>
</tr>
</tbody>
</table>

Surface magnetic fields with $H_{\text{max}} = 1.3 \text{ MA/m}$

Fields in copper traveling wave structure at 140 GHz, excited by 3.2 nC bunch
Current status

• At FACET, we have tested tree 100 GHz traveling wave metal accelerating structures: two copper and one stainless steel.
• From SEM inspection, we estimate following “no damage” pulse parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Traveling Wave, Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc. Gradient</td>
<td>0.3 GV/m</td>
</tr>
<tr>
<td>$E_{\text{max}}$</td>
<td>0.64 GV/m</td>
</tr>
<tr>
<td>Pulse length</td>
<td>~2.3 ns</td>
</tr>
</tbody>
</table>

With these experiments we are developing understanding, tools, techniques, diagnostics, etc. which we can use for W-band deflector
W-band deflectors powered by rf source

http://www.calcreek.com/hardware.html:

Calabazas Creek Research, Inc., in association with the University of Maryland, developed a **10 MW** gyroklystron at **91.392 GHz** for W-Band accelerator research. The device is designed to produce **1 microsecond pulses at 120 Hz** with an efficiency of approximately 40% and a gain of 55 dB. A magnetron injection gun produces a high-quality, 55 A beam at 500 kV that interacts with a six cavity, frequency doubling microwave circuit. A super conducting magnet produces a 28 kG magnetic field in the gun region with a separate coil for controlling the field in the gun region.
Scaling of X-band deflector to W-band

<table>
<thead>
<tr>
<th></th>
<th>X-band</th>
<th>W-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>aperture diameter</td>
<td>10 mm</td>
<td>1.25 mm</td>
</tr>
<tr>
<td>Kick@1MW</td>
<td>7.07 MV/m</td>
<td>56.5 MV/m</td>
</tr>
<tr>
<td>Q0</td>
<td>6296</td>
<td>2226</td>
</tr>
<tr>
<td>Epeak @1MW</td>
<td>21.7 MV/m</td>
<td>172 MV/m</td>
</tr>
<tr>
<td>Hpeak@1MW</td>
<td>76 kA/m</td>
<td>610 kA/m</td>
</tr>
<tr>
<td>Att. Length</td>
<td>84 cm</td>
<td>3.7 cm</td>
</tr>
<tr>
<td>Group velocity/c</td>
<td>3.2%</td>
<td>3.2%</td>
</tr>
</tbody>
</table>

11.424 GHz
Hpeak: 76 kA/m
Epeak: 21.7 MV/m
Cell of X-band deflector, fields normalized to 1 MW of transmitted power

91.329 GHz
Hpeak: 610 kA/m
Epeak: 172 MV/m
Cell of W-band deflector, fields normalized to 1 MW of transmitted power

Table: Comparison of X-band and W-band deflector parameters.
Open W-band accelerator as deflector

W-band accelerator, aperture 1.5 mm, fields normalized to 1 MW of transmitted power

- Nominal aperture: 1.5 mm
- Reduced aperture: 1.3 mm
- Kick@1MW: 7.8 MV/m, 11.1 MV/m
- Q0: 2480, 2285
- Epeak@1MW: 91 MV/m, 99 MV/m
- Hpeak@1MW: 163 kA/m, 200 kA/m
- Att. Length: 25 cm, 16 cm
- Group velocity/c: 19.4%, 13.4%

W-band accelerator, aperture 1.3 mm, fields normalized to 1 MW of transmitted power

- Hpeak: 163 kA/m
- Epeak: 91 MV/m
- Hpeak: 200 kA/m
- Epeak: 99 MV/m
Deflection in open accelerating structure: moving beam off axis

![Graph showing deflection and acceleration vs. off-axis position.](image)
Open W-band deflectors

<table>
<thead>
<tr>
<th></th>
<th>Nominal aperture</th>
<th>Reduced aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>aperture diameter</td>
<td>1.5 mm</td>
<td>1.84 mm</td>
</tr>
<tr>
<td>Kick@1MW</td>
<td>10.83 MV/m</td>
<td>31 MV/m</td>
</tr>
<tr>
<td>Q0</td>
<td>2520</td>
<td>2230</td>
</tr>
<tr>
<td>Epeak @1MW</td>
<td>97 MV/m</td>
<td>180 MV/m</td>
</tr>
<tr>
<td>Hpeak@1MW</td>
<td>250 kA/m</td>
<td>400 kA/m</td>
</tr>
<tr>
<td>Att. Length</td>
<td>10 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>Group velocity/c</td>
<td>7.7 %</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

W-band deflector, aperture 1.5 mm, fields normalized to 1 MW of transmitted power

W-band deflector, aperture 1.84 mm, fields normalized to 1 MW of transmitted power
Example of open 12 GHz traveling wave accelerating structure, CLIC-G-OPEN
Example of open traveling wave 12 GHz accelerating structure, CLIC-G-OPEN

Half structure and full-structure assembly
Example of open traveling wave 12 GHz accelerating structure, CLIC-G-OPEN

1 mm gap

View from beam pipe
Now compare scaled X-band deflector and open W-band deflectors, field normalized to 1 MW of power flow.
Summary for rf source powered deflector

• One module, or 1-m long deflector powered by 10 MW will produce total kick of about 23 MV (for deflector with 1.84 mm aperture), other structures have total kick between 11 and 14 MV/m.

• We will need two modules to get 46 MV deflection for ~500 attosecond resolution at 14 GeV and ~120 attosecond at 4 GeV.
Wakefield-powered deflector

Electron beam shifted off-axis

100 GHz traveling wave accelerating structure
Short range wakefields in 100 GHz accelerating structure, gap 0.3 mm, bunch length 50 μm

Longitudinal wake, offset 0 mm

Loss factor

Longitudinal wake, offset 0.75 mm

Transverse wake, offset 0 mm

Kick factor

Transverse wake, offset 0.75 mm
Short range transverse wakefield, 100 GHz accelerating structure, gap 0.3 mm

110 MV/nC/m@91GHz

Offset 0.8 mm, bunch length 50 µm

160 MV/nC/m@91GHz

Offset 0.76 mm, bunch length 25 µm
100 GHz accelerating structure, gap 0.9 mm, FACET shift 4 April 2015

±0.75 mm shift = ~1 MeV kick of 20 GeV beam

Projection at 97th pixel row
Asymmetric geometry, gap 0.3 mm

Half geometry, no cavities on bottom

155 MV/nC/m@91GHz

On-axis bunch, bunch length 50 µm
Summary for wakefield driven deflector

• With practical structures we should be able to produce chirp of transvers kick needed for few hundred attosecond timing resolution of ~200 pC bunch.
• We can clearly see the kick on 20 GeV FACET beam.
• Absolute calibration would be difficult.
• Head of the bunch is not kicked, so we need to understand how useful the diagnostics with this limitation.