Measurements of the X-ray/pump laser pulse timing

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Motivation

• LCLS promises to capture the molecular action of a chemical reaction “frame by frame” using the pump-probe technique.

• In due time, ALL LCLS instruments will be performing pump-probe experiments.

• This requires either controlling the time delay to a value that is a fraction of the LCLS pulse duration (80 fs but a 2 fs operating mode already demonstrated) or measuring the timing on a shot-by-shot basis and processing the data accordingly.

• The e-beam jitter is 50 fs rms so a diagnostic must used to improve this value.

• The diagnostic must be non-destructive, robust, relatively insensitive to FEL fluctuations and operate over the full LCLS wavelength range.
Current Capabilities

- FEL-Pump laser timing measured indirectly with e-beam phase cavity and RF distribution system

- All of the sources of jitter and drift will limit the temporal resolution to \(~80\) fs rms (180 fs FWHM)
  - 50 fs e-beam to RF
  - 50 fs laser to RF
  - 30 fs RF distribution
  - 20 fs e-beam cavity resolution
Idea

We propose to directly measure relative time jitter of X-ray and pump laser pulse near the sample using a cavity excited by X-ray-initiated photoelectrons with about 10 femtosecond resolution.

The device can be located just before the sample to non-invasively monitor the relative timing jitter of X-ray and pump laser pulse.
Timing cavity (version 20100226)

- rf probe
- target
- X-ray pulse
- electron bunch
- Solid Model: Robert Reed, SLAC

14 mm
Photoelectric Effect

- Generate core (k-shell) electrons
  - Cross-section
    \[ \frac{d\sigma}{d\Omega} = r_0^2 Z^5 \alpha^4 2^{5/2} \left( \frac{m_ec^2}{h\nu} \right)^{7/2} \sin^2 \theta \cos^2 \phi \]
    Z dependent
  - Kinetics
    - Very mono-energetic for hard x-rays
      \[ E_{\text{max}}^k = h\nu - \phi \approx h\nu \]
    - Limited to certain depth given by electron mean free path
    - Prompt ~ fs time scale

FEL pulses

polarization

electron escape depth
(10-100 nm)

Prompt electron bunch

Target (Al/Si$_3$N$_4$)

h$_\nu$
Total primary e- yield

- Energy dependent
- $Z$ dependent
  - Sufficient to ring RF cavity
Electrical design, 9.64 GHz version

\[ \frac{(\bar{U}(\beta_i))^2}{\text{EstHFSS}} \]

\[ \frac{V}{\text{pC}} \]

\[ \frac{V}{\text{pC}} \]

\[ \frac{E\beta(\beta_i)}{kV} \]

\[ \frac{V}{(200\text{pC})^2} \cdot 2 \cdot \pi \cdot \frac{f\text{HFSS}}{Q\text{HFSS}} \cdot 0.32222 = 0.3548515 \text{W} \]

\[ f\text{HFSS} = 9.64 \times 10^9 \frac{1}{\text{s}} \]

\[ 10^{10} \cdot q_e = 1.6021765 \times 10^{-9} \text{C} \]

\[ \left( \frac{f\text{HFSS}}{Q\text{HFSS}} \right)^{-1} = 228.2157676 \times 10^{-9} \]
Timing cavity assembly

Solid Model: Robert Reed, SLAC
Timing detector circuit

1 deg@9.5GHz=290fs, 90um
0.1deg@9.5GHz= 29fs, 9um
Status

- We making drawings of timing cavity
- Reference cavity is (almost) done
- We ordering targets
- We plan to start two-cavity commissioning this summer

Commissioning:
- Characterize amplitude and phase jitter of rf signals including their coupling
- Study coupling of position jitter and phase jitter
- …
High gradient streak camera for X-ray – laser pulse timing
A Circularly Polarized Beam Deflector for Direct Measurement of Ultra Short Electron Bunches

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Abstract. Described herein is an accurate means of directly measuring the longitudinal phase space of ultra short electron bunches typically produced by advanced design short wavelength accelerators and photoinjectors. A circularly polarized RF beam deflector provides a highly amplified image display having electron bunch phase and energy distributions projected in orthogonally separated azimuthal and radial directions, respectively. Combining such a microwave deflector with an emittance limited focused beam offers a simple on-line diagnostic that avoids the complexity, sensitivity and a priori assumptions associated with electro-optic frequency domain methods, and also avoids RF kicker bunch length measurement ambiguities caused by longitudinal mixing of the particle energy and phase distributions. Accurate self calibration, and the avoidance of pulse jitter by directly coupling the deflector power from the linac RF source, are additional attractive features of this technique. Design parameters and phase orbit characteristics are presented for an on-line diagnostic system having a 1/4% momentum resolution, a 56 femtosecond time resolution and a 16 femtosecond sampling gate, for evaluating the short bunch longitudinal phase space performance of the 17 GHz linac at the MIT Plasma Science and Fusion Center.

FIGURE 1. Diagnostic system for the direct measurement of ultra short bunches showing the circularly polarized RF deflector with the azimuthal scan phase shifter (A) and the set quadrature phase shifter (B).

17GHz ELECTRON BUNCHING IN HIGH GAIN RELATIVISTIC KLYSTRONS AND RESEARCH ACCELERATORS

Work supported by the US Department of Energy SBIR Program

17GHz Circularly Polarized Scan
Charge Transmitted Through a Precision Matrix: Ø150μm on a 240μm (90°) Lattice

160fs
Standing Wave Deflector for ~10 fs diagnostics of MeV beams
Waveguide coupler for 6 cell SW
11.424 GHz deflector
Periodic cell of Pi standing wave deflector, 0.25 MW/cell, deflecting gradient 26 MV/m

Maximum surface magnetic fields 410 kA/m, Pulse heating 23 deg. C for 100 ns pulse.

Maximum surface electric fields 105 MV/m.

\[ a = 6 \text{ mm} \]
\[ t = 2 \text{ mm, round iris} \]
\[ Q=7,792 \]
Waveguide coupler for 6 cell SW X-band deflector, 1.5 MW of input power, deflection 2 MeV

Maximum surface magnetic fields $\sim$420 kA/m,

Maximum surface electric fields $\sim$105 MV/m.

Pulse heating 24 deg. C for 100 ns pulse.
### Parameters of 6 cell X-band SW deflector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>Beam pipe diameter</td>
<td>10 mm</td>
</tr>
<tr>
<td>One cell length</td>
<td>13.121 mm</td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td>$\pi$</td>
</tr>
<tr>
<td>One cell kick</td>
<td>0.34 MeV/\sqrt{0.25 \text{ MW}}</td>
</tr>
<tr>
<td>Structure kick (6 cells)</td>
<td>2 MeV/\sqrt{1.5 \text{ MW}}</td>
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<tr>
<td>Unloaded Q</td>
<td>7800</td>
</tr>
<tr>
<td>Loaded Q</td>
<td>3800</td>
</tr>
<tr>
<td>Maximum Electric field</td>
<td>105 MV/m / \sqrt{1.5 \text{ MW}}</td>
</tr>
<tr>
<td>Maximum Magnetic field</td>
<td>420 (kA/m) / \sqrt{1.5 \text{ MW}}</td>
</tr>
<tr>
<td>Structure length (with beam pipes)</td>
<td>12 cm</td>
</tr>
<tr>
<td>Near mode separation</td>
<td>13.6 MHz</td>
</tr>
</tbody>
</table>
Basic parameters

$q_e = 1.602 \text{ C } 10^{-19}$

$m_e = 9.109 \text{ kg } 10^{-31}$

$\lambda := \frac{c}{11.424 \text{GHz}} \quad \varepsilon_n := 1 \mu \text{m}$

$\beta_d := 5 \text{m} \quad E_n := 10 \cdot q_e \cdot \text{MV}$

$V_t := 2 \text{MV}$

$\delta t := \frac{\lambda}{2 \cdot \pi \cdot c \cdot V_t \cdot q_e} \cdot \sqrt{\frac{\varepsilon_n \cdot E_n \cdot (m_e \cdot c^2)}{\beta_d}}$

$\delta t = 7.042 \text{ fs}$
High gradient streak camera

Photocathode, 200 MV/m, 11GHz, ~2...6MW
120 MV/m, 3 GHz, ~10 MW

Vertical deflector (optional),
8MV@3GHz, ~10MW
2MV@11GHz,~1.5MW

Electrons from X-ray pulse

Electrons from X-ray pulse

Boosters, ~1...10 MV
3GHz, ~5MW
11GHz,~1MW

Vertical deflector,
8MV@3GHz, ~10MW
2MV@11GHz,~1.5MW

0.1deg@3GHz=93fs
0.1deg@11GHz=25fs