Laser techniques in accelerator R&D and application

Yuelin Li, APS
Outline

• **Techniques from the laser world**
  
  Frequency-resolved optical gating-FROG
  Electro-optical sampling of electric field

• **Application of laser technique at APS**
  
  Off-line EO technique testing
  Measuring bunch profile with EO technique at the APS/other thoughts
  Temporal characteristics of a SASE FEL
The FROG technique

= Frequency-Resolved Optical Gating

For the second harmonic FROG

\[ E_{\text{sig}}(t, \tau) \propto E(t)E(t - \tau). \]

And the measured signal on the spectrometer is

\[ I_{\text{FROG}}(\omega, \tau) \propto \left| \int_{-\infty}^{\infty} E_{\text{sig}}(t, \tau) \exp(-i\omega t) dt \right|^2. \]
**Single-shot EO Sampling technique 1**

**Time resolution:** \( \Delta t \approx [\tau T]^{1/2} \)

\( \tau \): Bandwidth-limited pulse duration of the probe

\( T \): pulse duration of the probe after chirping

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Single-shot EO Sampling technique 2

Particle beam

P1 P1

EO Crystal

Temporal resolution no longer limited by probe bandwidth!
EO Sampling: Crystal response

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Off-line test of EO technique

Key features

• Use laser-generated THz radiation as an electron beam phantom, in a lab setting
• Employ the Frequency-Resolved Optical Gating (FROG) for single-shot fs resolution

Goal

• A system with fs resolution for electron bunch profile measurement
Possible application for APS SR

EO as a standard longitudinal bunch profile monitor for the APS

1. Single shot capability
2. High dynamic range
3. High temporal resolution

We propose to use EO technique 1, due to the long APS electron bunch
Possible application for APS SR

Example 1: demonstration of temporal resolution and sensitivity

E beam: 40-ps bunch with 5 nC
        2% modulation @ period of 3 ps
Laser:  2% bandwidth @ 800 nm,
        stretched to 60 ps rms
Crystal: 0.5 mm ZnTe

A 0.01% noise is added to simulate the noise level of a 16-bit detector.
Possible application for APS SR

Example 2: demonstration measuring subtle duration change

E bunch: 40 ps (black) and 40.4 ps (red).
Laser: Similar to last A random noise
Crystal: 0.5 mm ZnTe
of 1e-4 level is added to simulate a realistic situation for a 16-bit camera.
Other thoughts on EO application

Synchronizing a laser and a electron bunch

Critical for LCLS and other short-pulse X-ray facilities where pump-probe experiments involving an optical pump laser, time resolution determined by jitter, and pump/probe pulse duration. Currently, a laser can be locked to the RF with 100 fs jitter

Jitter-free setup with a EO pulse slicer!

- Sync a laser to for high duty factor machine
- Manipulate to and use as the pump directly

Electron beam

EO Crystal

P1

P1
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  **Temporal characteristics of a SASE FEL**
Low-energy undulator test line FEL

Milton et al., Science 292, 2037 (2001)

Saturated: 6 Hz, 0.5 ps, 50 mJ @ 265-530 nm
Goal: 30 Hz, 0.5 ps, 0.5 mJ, < 50 nm

Milton et al., Science 292, 2037 (2001)
# SASE FEL FROG measurement

## Table 1: Experimental Parameters

<table>
<thead>
<tr>
<th>Experiment</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current</td>
<td>850 A</td>
<td>530 A</td>
</tr>
<tr>
<td>Effective bunch length ($\sigma_z$)</td>
<td>0.5 ps</td>
<td>0.13 ps</td>
</tr>
<tr>
<td>Energy chirp ($\sigma_\phi/\sigma_z$)</td>
<td>28 m$^{-1}$</td>
<td>65 m$^{-1}$</td>
</tr>
<tr>
<td>rms normalized emittance</td>
<td>9 $\pi \mu$m</td>
<td>6 $\pi \mu$m</td>
</tr>
<tr>
<td>Undulator period ($\lambda_0$)</td>
<td>3.3 cm</td>
<td></td>
</tr>
<tr>
<td>Undulator length (each)</td>
<td>2.4 m</td>
<td></td>
</tr>
<tr>
<td>Undulator parameter (K)</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Beam energy ($\gamma mc^2$)</td>
<td>217 MeV</td>
<td></td>
</tr>
<tr>
<td>Nominal wavelength ($\lambda$)</td>
<td>530 $\mu$m</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>6 Hz</td>
<td></td>
</tr>
<tr>
<td>Gain length ($L_G$)</td>
<td>0.68 m</td>
<td>0.87 m</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between W (J) and z (m)](image)
SASE FEL FROG measurement

(a) A065

(b) A771

(c) A454

\[ \lambda \text{ (nm)} \]

\[ \tau \text{ (fs)} \]

\[ \tau \text{ (fs)} \]

\[ t \text{ (fs)} \]

\[ \lambda \text{ (nm)} \]
SASE FEL phase measurement: chirp

Ginger simulation

Simple simulation
SASE FEL phase measurement: chirp

The FEL output is

\[ E(t, z) = E_o(z) \sum_{j=i}^{N_t} \exp \left[ i \omega_0 \left[ 1 + c \frac{\sigma_\delta}{\sigma_z} (t - t_0) \right] (t - t_j) - \frac{(t - t_j - z / v_g)^2}{4\sigma_t^2} \left( 1 - \frac{i}{\sqrt{3}} \right) \right] \]

- **Beam chirp**
- **Intrinsic chirp**

The total chirp in the pulse is

\[ \frac{2}{4\sigma_t^2 \sqrt{3}} + \omega_0 c \frac{2\sigma_\delta}{\sigma_z}, \]

Taking into account the propagation:

\[ \phi'' = \frac{d^2 \phi}{dt^2} = 2 \frac{\Omega \Theta + \Phi''_m}{\Omega^2 + \Phi''_m^2}, \]

where

\[ \Theta = \frac{1}{\sqrt{3}} + 4\sigma_t^2 \omega_0 c \frac{\sigma_\delta}{\sigma_z}, \]

\[ \Omega = 4\sigma_t^2 + \Phi''_m. \]

- \( \omega_0 \): resonant frequency
- \( \sigma_\delta \): coherence length, \( \sigma_i = \frac{1}{2\omega_0} \sqrt{\frac{z}{\rho \lambda_{\text{u}}}} \propto n_{\text{e}}^{-1/4} \)
- \( \Phi''_m \): group velocity dispersion in optics
- \( \sigma_\delta / \sigma_z \): electron beam energy chirp

Midwest Accelerator Physics Meeting, Sept. 30-Oct. 1, 2003
Temporal structure

|\phi''| (mrad fs$^{-2}$)

Set A

Set B

\sigma_t (fs)
Temporal structure

\[ \phi'' = \frac{d^2 \phi}{dt^2} = 2 \frac{\Omega \Theta + \Phi''_m}{\Omega^2 + \Phi''_m}, \]

What are the following distribution
1. Spike width
2. Spike separation
3. Phase within and between the spikes
4. etc
FEL Temporal structure: analysis

The field of the SASE FEL

\[
E(t, z) = E_0(z) \sum_{j=i}^{N_e} \exp \left[ i \omega_0 [1 + c \frac{\sigma_\delta}{\sigma_z} (t - t_0)](t - t_j) - \frac{(t - t_j - z/v_g)^2}{4\sigma_t^2} (1 - \frac{i}{\sqrt{3}}) \right].
\]

Which can be rewritten as

\[
I(t) = |E(t)|^2 = R(t)(\cos \phi(t) + \sin \phi(t)),
\]

where \(R\) and \(\phi\) are independent random variables following the distribution

\[
d\phi \frac{RdR}{2\pi \psi_0} e^{-\frac{R^2}{2\psi_0}}.
\]
FEL Temporal structure: analysis

Furthermore, $n$ random variables $U_1, U_2, \ldots, U_n$ are said to be jointly Gaussian if their joint characteristic function is of the form

$$M_U(\omega) = \exp\{j\bar{u}'\omega - \frac{1}{2}\omega'C\omega\}$$  \hspace{1cm} (2.7-4)

where

$$\bar{u} = \begin{bmatrix} \bar{u}_1 \\ \bar{u}_2 \\ \vdots \\ \bar{u}_n \end{bmatrix}, \quad \omega = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_n \end{bmatrix}$$  \hspace{1cm} (2.7-5)

and $C$ is an $n \times n$ covariance matrix, with element $\sigma_{ik}^2$ in the $i$th row and $k$th column defined by

$$\sigma_{ik}^2 = E[(u_i - \bar{u}_i)(u_k - \bar{u}_k)].$$  \hspace{1cm} (2.7-6)

The corresponding $n$th-order probability density function can be shown to be

$$p_U(u) = \frac{1}{(2\pi)^{n/2}|C|^{1/2}} \exp\left\{-\frac{1}{2}(u - \bar{u})'C^{-1}(u - \bar{u})\right\}$$  \hspace{1cm} (2.7-7)

where $|C|$ and $C^{-1}$ are the determinant and matrix inverse of $C$, respectively, and $\bar{u}$ is a column matrix of the $u$ values.

FEL temporal structure

After lengthy calculation, one can obtain the distribution function ….. (by Sam Krinsky)

\[ \Phi(R, R', R'', \phi, \phi', \phi'') \]

Spike width \( \xi = \Delta \tau / <\Delta \tau> \) distribution

\[
\frac{dP(\xi)}{d\xi} = \frac{a \eta}{(a \xi)^5} \int_0^\infty \frac{d\nu}{[3 - 2/(a \xi)^2 + (1/(a \xi)^2 + \nu^2)^2]^{5/2}}.
\]

Phase \( \nu = \phi / \sigma_\omega \) distribution at spike maxima (+) and minima (-)

\[
\frac{dp_{\pm}(\nu)}{d\nu} = \frac{\chi}{\sqrt{3 + \nu^4 \left[ \sqrt{3 + \nu^4} \pm (\nu^2 - 1) \right]^2}}.
\]

The constants are \( a = 0.8685, \eta = 9.510, \chi = 0.7925. \)
FEL temporal structure

SASE FEL basic characteristics

SASE FEL is basically a chaotic light source with multiple temporal coherence modes with an elongated coherence length with high intensities. It provides an unprecedented opportunity for thorough survey of such light sources.

We show that the chirp in an electron bunch can be directly mapped into the SASE output. It is also shown that by properly controlling the electron beam properties, one might obtain transform-limited SASE FEL pulses.
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