Laser based ultrashort electron bunch measurement

A. Halavanau, C. K. Huang, P. Niknejadi and D. Yang

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Motivation and outline

Measuring of ultrashort bunches

- Typical electron bunch duration in synchrotron is in order of ps
- FELs require fs bunches to achieve high gain regime
- Time resolution of the streak camera is limited
- Few optical techniques to study ultrashort bunches were proposed

Methods

- Optical replica
- Optical streaking
- Deflecting cavity with optical streaking (optical oscilloscope)
Optical replica method

Schematics

Phase space transformation and measurement

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Laser based ultrashort electron bunch measurement
Operation of the modulator

Electrons moving at a constant speed have net $\Delta \epsilon = 0$ when interacting with a laser in a free space.

Modulator + chicane ($R_{56} = L\theta_B^2$)

$$f_0(P) = \frac{1}{\sqrt{2\pi<(\Delta \epsilon)^2>}} \exp(-\frac{P^2}{2<(\Delta \epsilon)^2>}) \quad \rightarrow \quad f_1(P, \psi) = $$

$$f_0(P - P_0 \sin \psi) \quad \rightarrow \quad f_2(P, \psi) = f_0(P - P_0 \sin(\psi - P \frac{d\psi}{dP}))$$

(very small density modulation in the undulator)

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Laser based ultrashort electron bunch measurement
Operation of the modulator

Current profile

Then 1-D beam density yields \( b_n = e^{-1/2B^2n^2}J_n(-ABn) \), where \( b_n \) is the bunching factor at \( n-th \) harmonic, \( A, B \) some constants.

Optical pulse measurement

By properly adjusting the chicane’s \( R_{56} \) and modulation wavelength, one can achieve higher harmonics in the beam density modulation.

E. Hemsing, et. al., Rev. Mod. Phys. 86, 897

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Laser based ultrashort electron bunch measurement

E.L. Saldin, E. Shneidmiller, M. Yurkov, DESY 04-126
Laser pulse is relatively short, comparable with the bunch length
- Operating on the slope of the laser pulse
- Single shot measurement

Y. Ding, et. al., Proc. of FEL2011, WEPB22
Laser operating at fundamental Gaussian mode

Energy exchange inside the undulator

Laser E-field:
\[
\vec{E}(z, t) = \vec{e}_x \frac{E_0}{\sqrt{1+z^2/z_R^2}} \cos(kz - \omega t + \phi(r, z))e^{-r^2/\omega^2(z)-s^2/4\sigma_s^2},
\]

Where:
\[
k = \frac{2\pi}{\lambda}, \quad z_R = \frac{k\omega_0^2}{2}, \quad \omega^2(z) = \omega_0^2(1 + z^2/z_R^2), \quad r^2 = x^2 + y^2
\]

Normalized transverse velocity:
\[
\vec{v}_x = \vec{e}_x \frac{Kc}{\gamma} \cos(ku z)
\]

Resulting energy modulation:
\[
\frac{d\gamma}{dt} = \frac{e}{mc^2} \vec{E} \cdot \vec{v} = \frac{e}{mc} E_x \beta_x \rightarrow
\]

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Laser operating at fundamental Gaussian mode

Energy modulation

\[ mc^2 \frac{d\gamma}{dt} = A(z, \gamma) \cos(kz - \omega t + \phi(r, z)) \cos(k_u z) e^{-r^2/\omega^2(z) - s^2/4\sigma_s^2}, \]

where \( A(z, \gamma) = \frac{cKE_0}{\gamma} \frac{1}{\sqrt{1+z^2/z_R^2}} \)

Normalize \( \bar{z} = z/N\lambda_u \), replace \( t = z/c \), define \( \Delta \gamma = \gamma - \gamma_r \):

\[ \Delta \gamma_L(r, s) = A_0 \cos(ks) e^{-r^2/\omega^2(z) - s^2/4\sigma_s^2} \]
Deflecting (sweeping) cavity

Higher order modes of the laser result in more “degrees of freedom”

Schematics

- Can be very compact
- Subfemtosecond temporal resolution (450 to 600 attosecond demonstrated)
- Works well for the wide range of beam energy
Longitudinal profile diagnostic

High power few-cycle $TEM_{10}$ laser in Hermite-Gaussian mode

Energy exchange inside the undulator

E-field: $E_x(x, z, t) \approx \frac{2\sqrt{2}E_0x}{w_R(1+z^2/z^2_R)} \sin [k(z - ct) + \phi]$ (near axis)

Normalized transverse velocity: $\beta_x = -\frac{K}{\gamma} \sin(2\pi z/\lambda_u)$

Resulting energy modulation:

$$\frac{d\gamma}{dt} = \frac{e}{m_0c} E_x \beta_x \quad \rightarrow \quad \frac{\Delta\gamma}{\gamma} = Akx_0 \cos(k s_0)$$

Deflection method

Transverse coordinates

\[ x_f = x_i + L(x'_i + A \sin(ks_0)) \]
\[ y_f = y_i + L(y'_i + A_{rf} k_{rf} s_0) \]
Beam parameters

For a round beam: \( \frac{A_{rf} k_r f L \sigma_s}{\sigma_x} >> 1 \) and \( \frac{A L}{\sqrt{2} \sigma_D} >> 1 \)

**TABLE II.** Beam and laser parameters used in the NLCTA simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>( E )</td>
<td>120 MeV</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>( \epsilon_n )</td>
<td>1 mm mrad</td>
</tr>
<tr>
<td>Energy spread</td>
<td>( \sigma_y )</td>
<td>( 1 \times 10^{-4} )</td>
</tr>
<tr>
<td>Undulator peak field</td>
<td>( B_0 )</td>
<td>1.075 T</td>
</tr>
<tr>
<td>Undulator period</td>
<td>( \lambda_u )</td>
<td>6 cm</td>
</tr>
<tr>
<td>Undulator length</td>
<td>( L_u )</td>
<td>18 cm</td>
</tr>
<tr>
<td>Undulator parameter</td>
<td>( K )</td>
<td>6.0</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>( \lambda )</td>
<td>10.6 ( \mu )m</td>
</tr>
<tr>
<td>Laser power</td>
<td>( P_L )</td>
<td>500 GW</td>
</tr>
<tr>
<td>Laser waist</td>
<td>( w_R )</td>
<td>1 mm</td>
</tr>
</tbody>
</table>
Deflection method (NLCTA simulations)

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Conclusions

• Optical replica method has been demonstrated in a proof-of-principle experiment. However, complex features of current profile, such as microbunching, may result in inaccurate result (FEL08 THBAU04, DESY)

• Optical streaking is simpler, but requires the electron bunch to have small slice energy spread and good synchronization with a laser to operate at the intensity slope (proposed for SLAC)

• Optical oscilloscope method can provide better resolution than traditional deflecting cavity measurement but requires costly laser (recent experiment at ATF@BNL)