Laser based ultrashort electron bunch measurement

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Motivation and outline

Measuring of ultrashort bunches

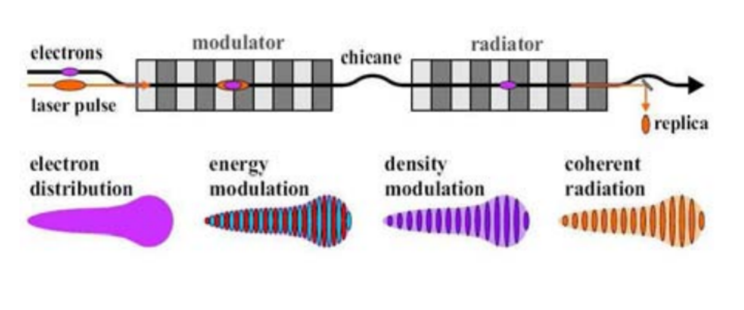
- Typical electron bunch duration in synchrotron is in order of ps
- FELs require fs bunches to achieve high gain regime
- Time resolution of the streak camera is limited
- Few optical techniques to study ultrashort bunches were proposed

Methods

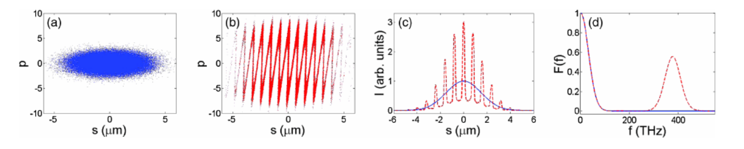
- Optical replica
- Optical streaking
- Deflecting cavity with optical streaking (optical oscilloscope)

Optical replica method

Schematics

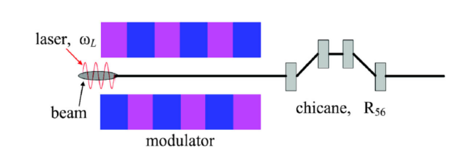


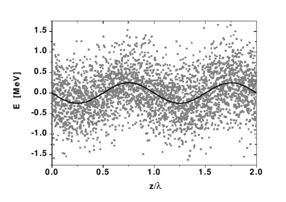
Phase space transformation and measurement



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

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

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

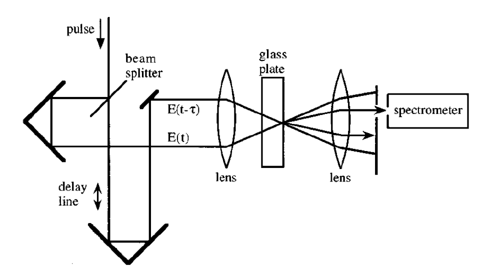
(very small density modulation in the undulator)

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.

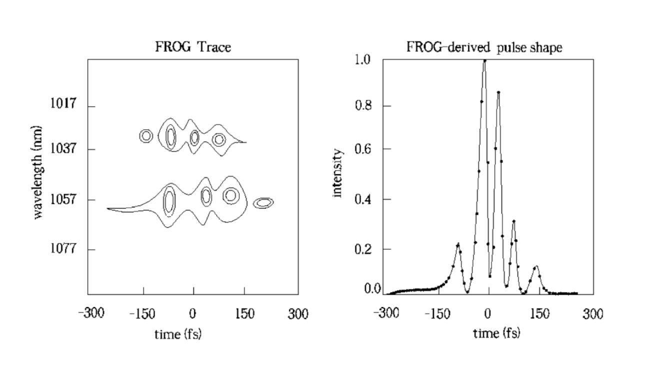
Optical pulse measurement



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

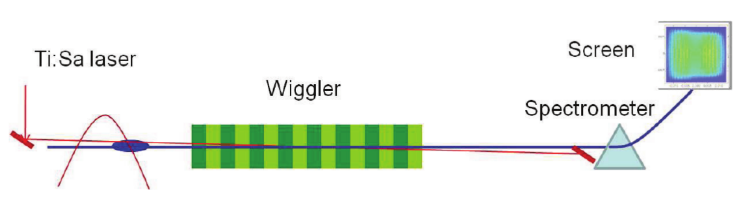
FROG



E.L. Saldin, E. Shneidmiller, M. Yurkov, DESY 04-126

Optical streaking

Schematics



- 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:

$$k = 2\pi/\lambda,\ z_R = k\omega_0^2/2,\ \omega^2(z) = \omega_0^2(1 + z^2/z_R^2),\ r^2 = x^2 + y^2$$

Normalized transverse velocity: $\vec{v}_x = \vec{e}_x \frac{Kc}{\gamma} \cos(k_u z)$

Resulting energy modulation:

$$\frac{d\gamma}{dt} = \frac{e}{mc^2} \vec{E} \cdot \vec{v} = \frac{e}{mc} E_x \beta_x \qquad \rightarrow$$

Y. Ding, et. al., Proc. of FEL2011, WEPB22
E. Hemsing, et. al., Rev. Mod. Phys. 86, 897

Laser operating at fundamental Gaussian mode

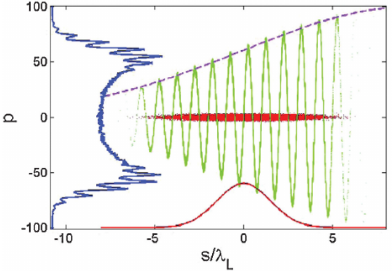
Energy modulation

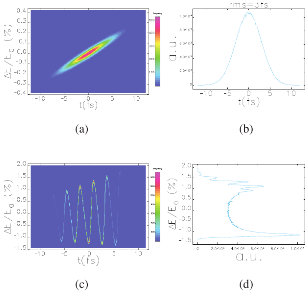
$$mc^2 \frac{d\gamma}{dt} = A(z, \gamma) \cos(kz - \omega t + \phi(r, z)) \cos(k_u z) e^{-r^2/\omega^2(z) - s^2/4\sigma_s^2},$$

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 $\Delta\gamma = \gamma - \gamma_r$:

$$\Delta\gamma_L(r, s) = A_0 \cos(ks) e^{-r^2/\omega^2(z) - s^2/4\sigma_s^2}$$

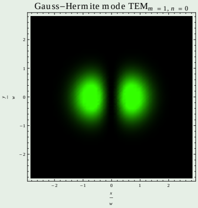


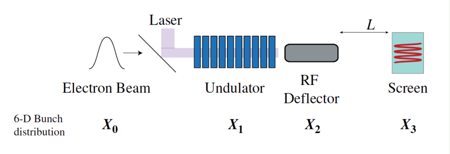


Deflecting (sweeping) cavity

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: $E_x(x,z,t) \approx \frac{2\sqrt{2}E_0 x}{w_R(1+z^2/z_R^2)} \sin\left[k(z-ct)+\phi\right]$ (near axis)

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

Resulting energy modulation:

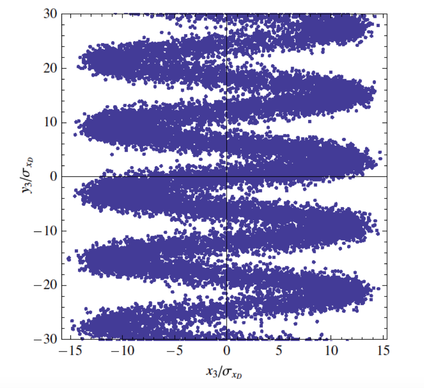
$$\frac{d\gamma}{dt} = \frac{e}{m_0 c} E_x \beta_x \qquad \rightarrow \qquad \frac{\Delta\gamma}{\gamma} = A k x_0 \cos(k s_0)$$

G. Andonian, E. Hemsing, et. al. PRSTAB 2014, 072802, 2011

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

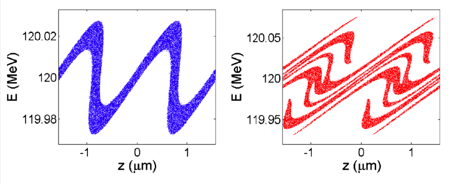
Constraints

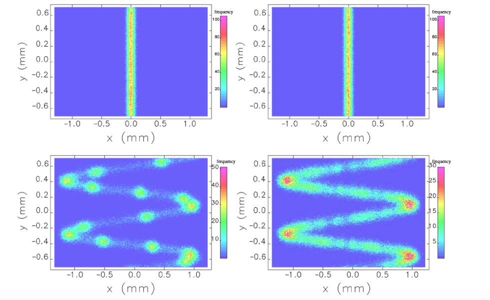
For a round beam: $\frac{A_{rf} k_r f L \sigma_s}{\sigma_x} >> 1$ and $\frac{AL}{\sqrt{2}\sigma_D} >> 1$

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

Beam energy	E	120 MeV
Normalized emittance	ϵ_n	1 mm mrad
Energy spread	σ_γ	1×10^{-4}
Undulator peak field	B_0	1.075 T
Undulator period	λ_u	6 cm
Undulator length	L_u	18 cm
Undulator parameter	K	6.0
Laser wavelength	λ	10.6 μm
Laser power	P_L	500 GW
Laser waist	w_R	1 mm

Deflection method (NLCTA simulations)





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

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)