Longitudinal diagnostic scheme with sub-femtosecond resolution for high-brightness electron beams

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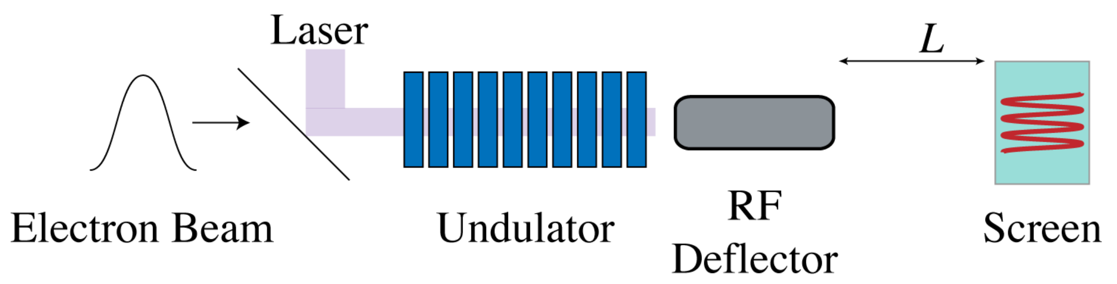
Motivation

- Bunch length/profile measurements
  - Compression techniques to generate sub-ps pulses with high current
  - Characterization of Sub-ps pulses
  - Machine performance optimization
  - Benchmark theoretical and computational models
  - Understand beam variations in emittance, current
- Bunch length measurement techniques currently limited to ~10 fs
  - Coherent radiation interferometry
  - Electro-Optical sampling
  - RF Deflector
  - Optical Replica Synthesizer
- Femtosecond resolution required for investigation ultra short pulses
  - Microbunching instability of COTR
  - Single-spike SASE FEL beam
  - Properties of attosecond x-ray production
  - *Temporal properties of echo-enabled FELs

Schematic Description



- Laser (TEM_{10} mode)/e-beam interaction in planar undulator
  - Angular modulation of beam
  - Dependent on longitudinal bunch coordinate
- RF deflector provides vertical streak to observe modulation for long bunches
- Angular modulation observable on distant screen (x’ -> x)
  - Resolvable with standard optics
- Scheme provides enhanced resolution over RF deflector alone.

General 1-D Treatment

Electron/laser interaction in undulator

Zholents and Zolotorev, NJP 10, 025005 (2008)

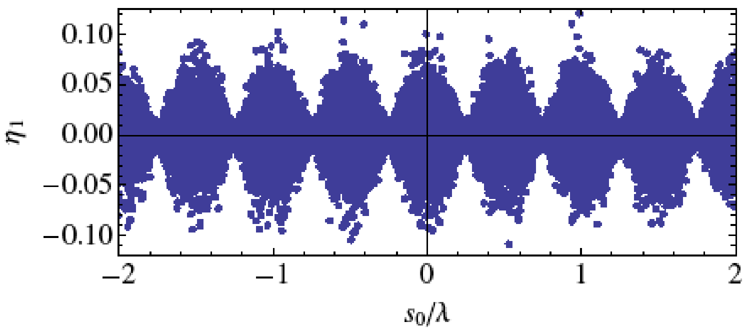
-Attosecond pulse lengths in a SASE FEL by selective lasing of electrons due to angular modulations.

TEM$_{10}$ mode ("dipole") $$E_x(x,z,t) \simeq \frac{2\sqrt{2}\, E_0\, x}{w_0\left(1+\frac{z^2}{z_0^2}\right)} \sin(k(z-ct)+\phi)$$

Motion in undulator $$\beta_x = -\frac{K}{\gamma} \sin\left(\frac{2\pi\, z}{\lambda_u}\right)$$

Energy exchange $$\frac{d\gamma}{dt} = \frac{e}{m_0 c} E_x \cdot \beta_x$$

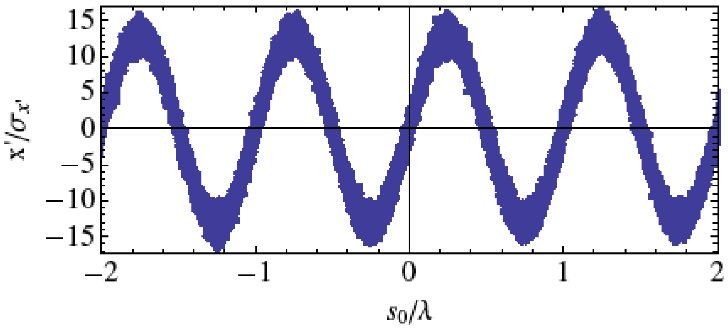
Energy modulation $$\frac{\Delta\, \gamma}{\gamma} = \eta_1 - \eta_0 = A\, k x_0 \cos(k\, s_0)$$



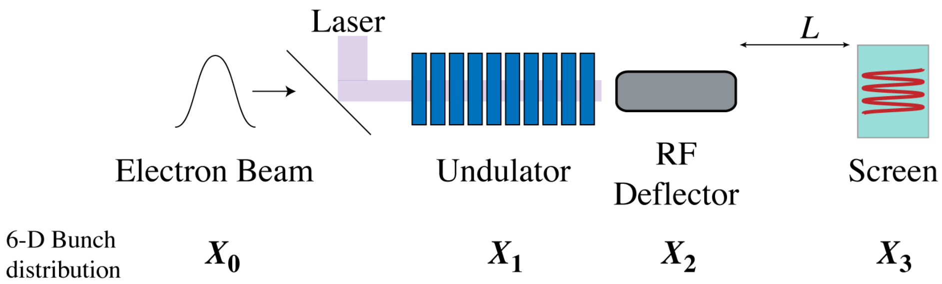
Panofsky-Wenzel Theorem $$\frac{\partial}{\partial x}\left(\frac{\Delta\gamma}{\gamma}\right) = \frac{\partial}{\partial s} \Delta x'$$

Angular modulation $$\Delta x' = A \sin(k s_0 + \phi)$$

$$A = \frac{2K}{\gamma^2}\sqrt{\frac{P_L}{P_0}}\,[JJ]\, f(L_u, z_0, \nu)$$



Quasi 1-D Analytical Treatment



Transformation at deflector

$$y'_2 = y'_1 + A_{RF}k_{RF}s_1; \qquad A_{RF} = \frac{eV_{def}}{\gamma mc^2}$$

$$\eta_2 = \eta_1 + A_{RF}k_{RF}\, y_1$$

After drift

$$x_3 = x_2 + Lx'_2 = x_0 + L(x'_0 + A\sin ks_0) \quad ;$$

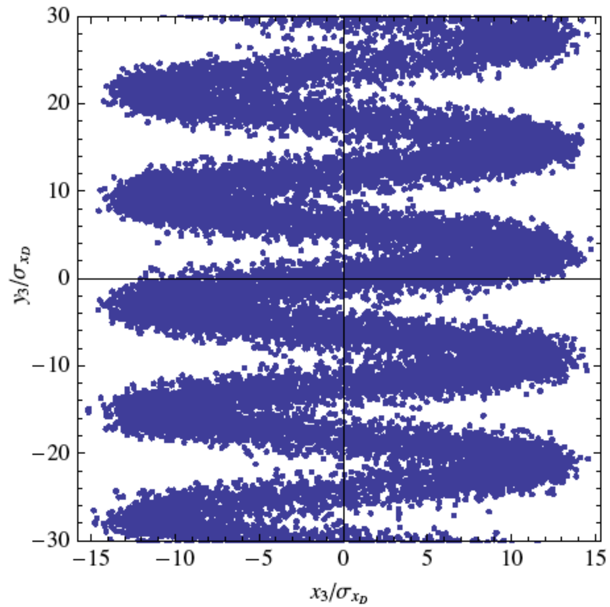
$$x'_3 = x'_0 + A\sin ks_0 \quad ;$$

$$y_3 = y_2 + Ly'_2 = y_0 + L(y_0 + A_{RF}k_{RF}\, ks_0) \quad ;$$

$$y'_3 = y_0{}' + A_{RF}k_{RF}\, ks_0 \quad ;$$

$$s_3 = s_2 + \frac{L\eta_2}{\gamma^2} = s_0 + \frac{L}{\gamma^2}(\eta_0 + Akx_0\cos ks_0 + A_{RF}k_{RF}y_0) \quad ;$$

$$\eta_3 = \eta_0 + Akx_0\cos ks_0 + A_{RF}k_{RF}y_0.$$



Initial Beam Distribution

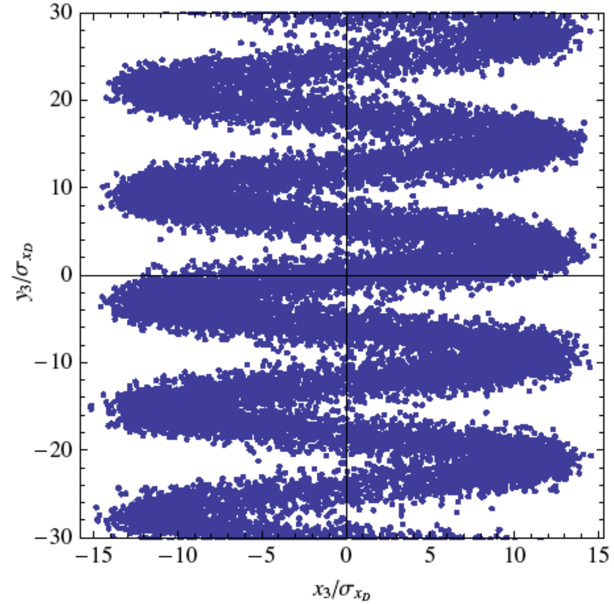
$$f_0 = \frac{1}{(2\pi)^3\sigma_x^2\sigma_{x'}^2\sigma_z\sigma_\gamma}\mathrm{Exp}\left[-\frac{x_0^2+y_0^2}{2\sigma_x^2} - \frac{x'^2_0+y'^2_0}{2\sigma_{x'}^2} - \frac{s_0^2}{2\sigma_z^2} - \frac{\eta_0^2}{2\sigma_\gamma^2}\right]$$

Beam Distribution at screen

$$f_0(x_3,y_3,s_0) = \frac{1}{(2\pi)^{3/2}\sigma_{x_D}^2\sigma_z}\mathrm{Exp}\left[-\frac{(x_3 - AL\sin ks_0)^2}{2\sigma_{x_D}^2} - \frac{(y_3 - A_{RF}k_{RF}Ls_0)^2}{2\sigma_{x_D}^2} - \frac{s_0^2}{2\sigma_z^2}\right]$$

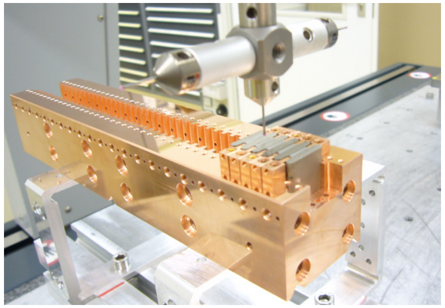
Bunch length diagnostic

- Resolution set by magnitude of imprinted angular modulation
  - Constraint: must be larger than intrinsic beam divergence
- Practical diagnostic resolution set by angular modulation by each component in scheme
  - RF deflector
  - Optical modulator (undulator)
  - Ability to resolve screen
- Constraints
  - Angular modulation must be larger than intrinsic beam divergence
  - Imposed beam deflections must be larger than "unperturbed" beam size at screen
  - May require collimators (loss of charge)
- Resolution enhancement
  - Dynamic range enhancement



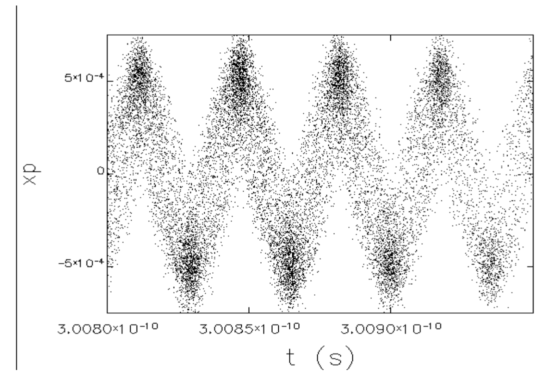
Example: UCLA Neptune

- Neptune injector facility
  - Experience in laser – e-beam interactions (IFEL, harmonic microbunching)
  - High-brightness injector
    - E = 13 MeV
    - ε_n=1mm-mrad
    - Q=500pC
  - TW-class CO2 laser
    - λ=10.6um, P_L = 300 MW (for simulation)
- Undulator
  - PrFeB (cryo cooled to 30K)
  - 9mm period, K=1.7, g=2mm
- Deflector (simulation)
  - V_d=6MV, λ_{Rf}=2.6cm
- Angular modulation ~7 mrad
  - Resolution ~ 0.3 fs (simulation)

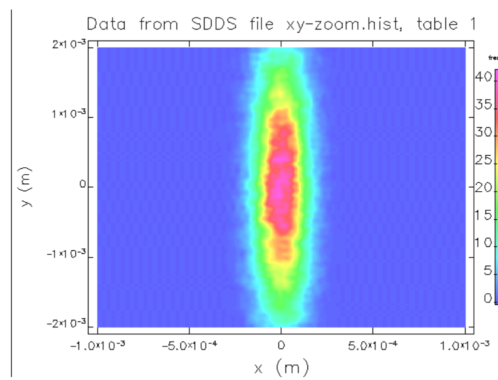


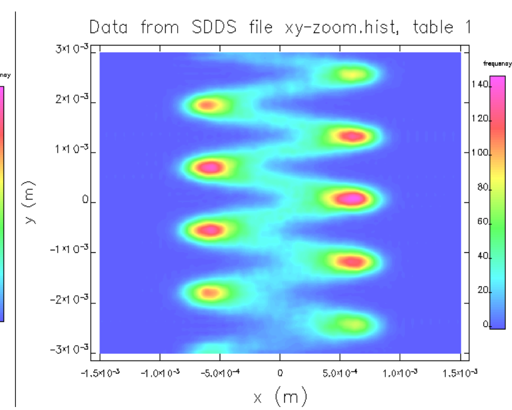
F. O'Shea, PRSTAB 13, 070702 (2010)

Simulations performed with Elegant



Angular modulation after undulator (sim)





Simulated Transverse distribution on screen (L=1m) with:

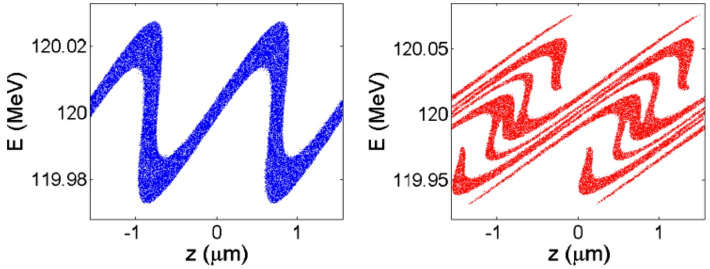
-only deflector on (left)

-deflector and optical modulator on (right)

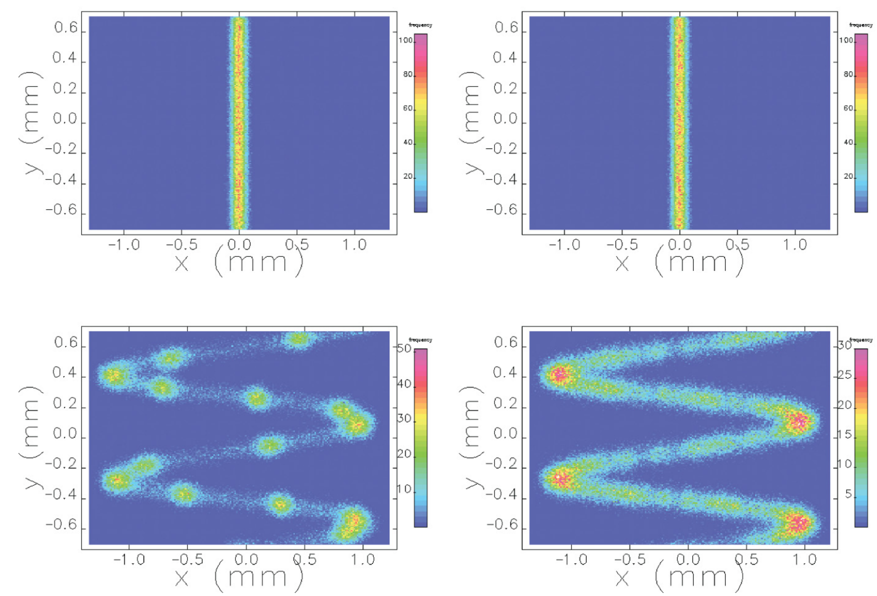
Echo-enabled FEL at SLAC NLCTA

- Experiment conducted at NLCTA (D.Xiang, et al., SLAC)
    - E-beam modulation provided by ~800nm laser and first undulator
    - Sent through chicane with large R56
        - Fine longitudinal structure imposed
    - E-beam modulated by ~1600nm laser in second undulator
    - Density modulation at short wavelength in second chicane
- Diagnostic
    - Coherent radiation at harmonics of seed lasers
    - Not trivial to determine if the radiation is from interplay of two lasers or individual laser
    - Time-domain measurement provides straightforward evidence of EEHG
- Parameters (simulation)
    - E = 120MeV, ε_n= 1mm-mrad
    - V_d = 8MV, λ_{RF} = 2.6 cm
    - K = 6.0, N_U=3, λ_U=6 cm
    - λ=10.6um, P_L=500GW
    - Resolution ~ .6fs

Simulations performed with Elegant



Phase Space after last chicane for ~1600nm laser only (left) and for interplay of two lasers (right)

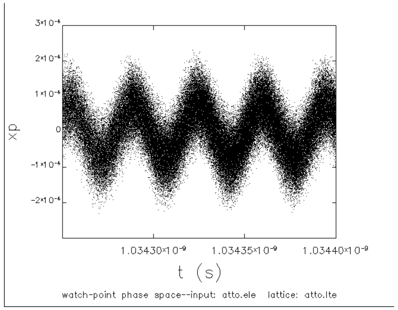


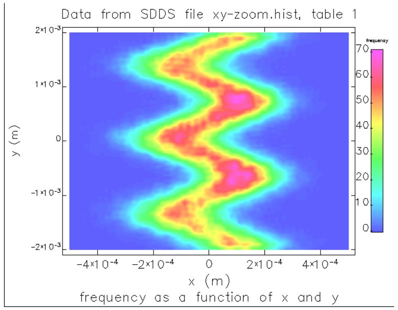
Transverse distribution at screen. TOP: Only deflector turned on. BOTTOM: Deflector and laser modulation on.

POP at BNL ATF

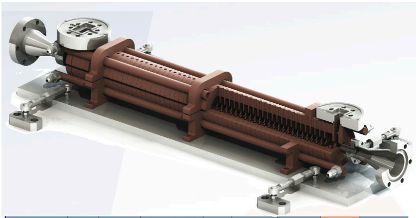
- High brightness user facility
  - CO_2 laser e-beam interactions
- Parameters (simulation)
  - E= 44 MeV, Q= 500pC, ε_n = 1mm-mrad
  - λ_u=3cm, N= 10, B_0= 1.0T, K = 3.0
  - λ = 10.6 um, P_L = 300MW
  - V_d = 10MV, L_d = 46cm
- X-band deflector
  - Built by RadiaBeam for BNL ATF
  - Optimized for ~100MeV beams
  - Freq. = 11.424 GHz
  - <10 fs temporal resolution
  - Install in 2012
- TEM_{10} laser mode
  - Previous experience from Inverse Cerenkov Acceleration experiment
    - W. Kimura, PRL 74,546 (1994)
    - Required radial polarization
  - Purity of mode
  - Splitting TEM_{00} mode and introduce π phase delay
  - Upgrade to TW
- Undulator
  - Design

Simulations performed with Elegant





Angular modulation (left) and beam distribution at screen (right)



$\sqrt{Z}=E_0/P^{1/2}$ [kV/mW$^{1/2}$]	α [1/m]	v_g/c	$E_{max}/P^{1/2}$ [kV/mW$^{1/2}$]	L_{TOT} [m]	E_{max} [MV/m]	τ_F [ns]	N_c	P_{out}/P_{in}
8.48	0.66	0.0267	20.57	0.46	92	57	53	0.55

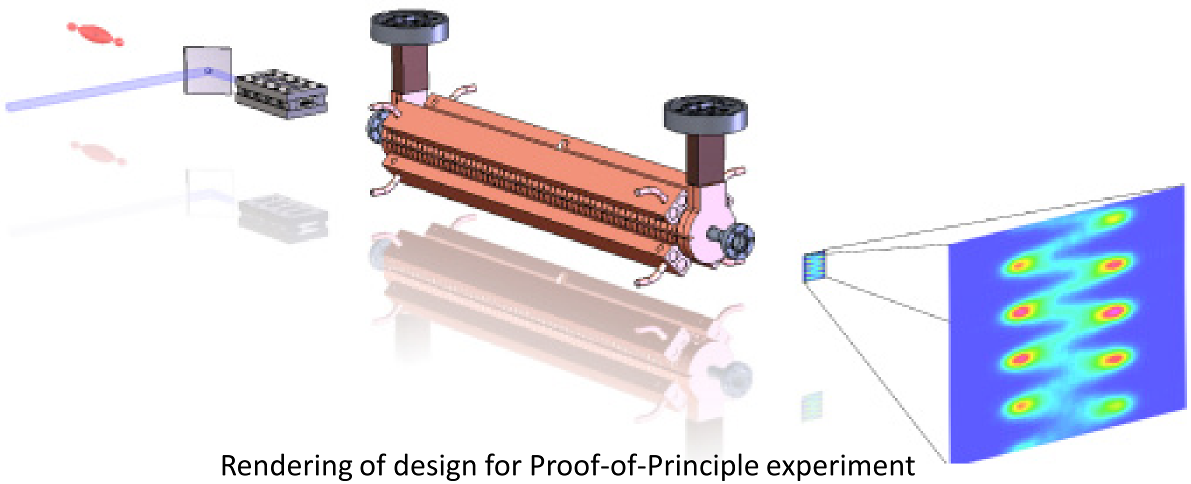
Rendering of XTD for ~10fs temporal resolution at BNL ATF (L. Faillace)

TEM_{10}–like mode simulated (left) and imaged (right) at BNL ATF

Challenges

- Nonlinear resolution
  - Resolution at turning points is “smeared”
  - Try to move beam away from “low-resolution” part of curve to linear (“high-resolution”)
  - Shift laser phase by $\pi/2$
  - Multi-shot statistics
- Diagnostic is better for lower energy beam in current scheme
  - Modulation scaling ~ $1/\gamma^2$
- Diagnostic favors long wavelength, high power laser
  - Scaling ~ $P_L^{1/2}$
  - BNL ATF, UCLA Neptune
  - Fundamental laser mode suppression
    - Leakage could cause regenerative amplification and smear desired effect
- Demanding beam properties
  - Emittance, spot size
  - Requires beam collimators which may reduce total detectable signal at screen

Summary



Rendering of design for Proof-of-Principle experiment

- Bunch length resolution on sub-fs is plausible with existing technologies
  - Enhanced resolution over deflector alone
- Alternative schemes to address open questions
  - Helical undulator
  - Undulator with harmonics
  - “Micro”-undulator
- Next step: Proof of principle experiment at BNL ATF
  - Beam diagnostics, X-band infrastructure, CO_2 laser experience