Generation and characterization of ultrashort electron-beams for X-ray free-electron lasers

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Introduction

The successful operation of the Linac Coherent Light Source (LCLS) , with its capability of generating x-ray pulses from a few femtoseconds (fs) up to a few hundred fs, opens up vast opportunities for studying atoms and molecules on an unprecedented time scale. Generation of even shorter x-ray pulses in fs to sub-fs regime is a challenging topic requiring theoretical and experimental breakthroughs to develop new concepts. At the same time, tremendous challenges remain in the mesurement and control of these ultrashort pulses with femtosecond precision, for both electron-beam (e-beam) and x-ray pulses. The objective of this project is to investigate new methods for generation and characterization of ultra-short e-beams and x-ray pulses.

Progress since 04/2010

We did diverse investigations in the first year to explore new methods for the measurement of the femtosecond e-beams and x-ray pulses. At the same time, generation of single-spike x-ray pulses at 20 pC has been studied based on computer simulations.

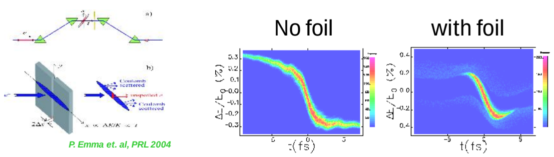
- Generation:
  - low-charge optimization
  - slotted-foil experimental studies
- Characterization:
  - longitudinal mapping: theoretical and experiments at LCLS.
  - X-band transverse deflector: theoretical, hardware and engineering has just started from 07/2011. To be ready at LCLS beamline in two years.
  - streaking and deflecting at optical frequencies:
  - frequency domain methods: statistical analysis from spectral correlation function.

Generation of ultrashort:

Start-to-end simulations have been carried out for the short pulse optimization studies [1].

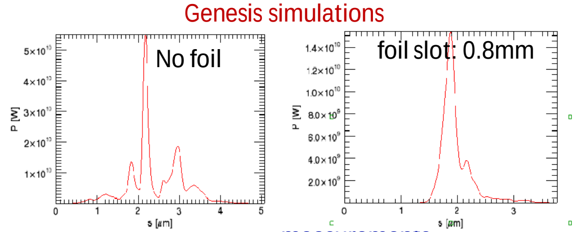
In the soft x-ray regime, simulations verified that single spike x-ray pulses can be achieved by combining low charge operation with the slotted-foil at the over-compression mode. In addition, because of the big chirp at the over-compression mode, it is also possible to use the undulator taper to select the core part of the electron bunch for lasing and hence get a shorter x-ray pulse.

At hard x-ray regime, by tuning the linac-1 rf phase and operating at full compression in BC2, sub-fs x-ray pulses can also be achieved, without using the slotted-foil.

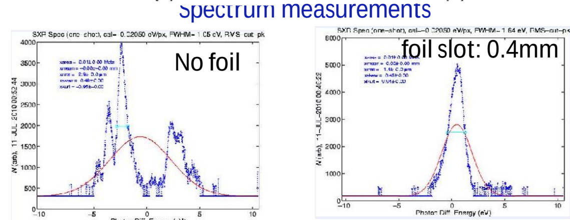


Soft x-ray 1.5nm, over-compression, 20 pC

Genesis simulations



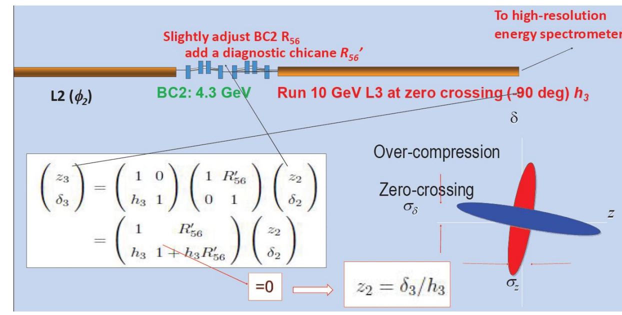
Spectrum measurements



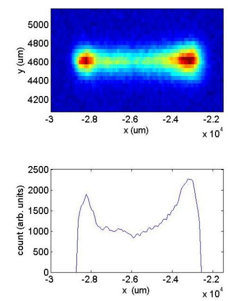
A two-bunch self-seeding scheme for generation of fully-coherent short x-ray pulses, with a pulse length as short as 10 fs at a few GW level, also has been studied [2].

Characterization of ultrashort I

A single-shot method for e-beam measurement based on longitudinal mapping using SLAC A-line high resolution spectrometer [3]:

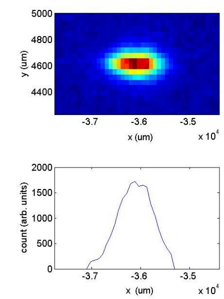


40 pC, under-compression



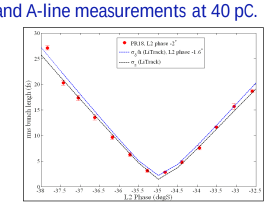
$\sigma_x = 1908\ \mu m \rightarrow \sigma_z = 2.47\ \mu m$

10 pC, full-compression

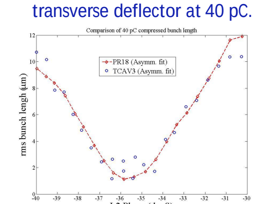


$\sigma_x = 327\ \mu m \rightarrow \sigma_z = 0.27\ \mu m$ after subtracting 250 μm → resolution ~1 fs (rms)

Comparison between simulations and A-line measurements at 40 pC.



Benchmark with the S-band transverse deflector at 40 pC.



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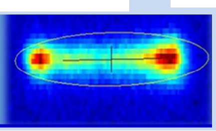

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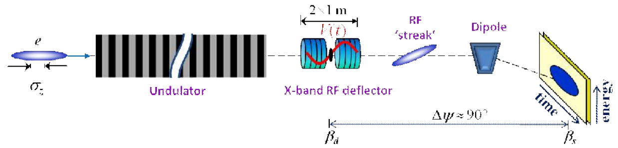
DOE Early-Career Program (starting from 04/2010)

U.S. DEPARTMENT OF ENERGY | Office of Science

Characterization of ultrashort II

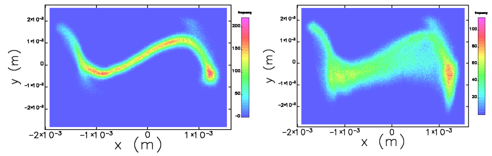
Femtosecond X-ray Pulse Temporal Characterization in Free-Electron Lasers using a transverse deflector [5].

We propose a novel method to characterize the temporal duration and shape of femtosecond x-ray pulses in a free-electron laser (FEL) by measuring the time-resolved electron-beam energy loss and energy spread induced by the FEL process, with a transverse radio-frequency deflector located after the undulator.

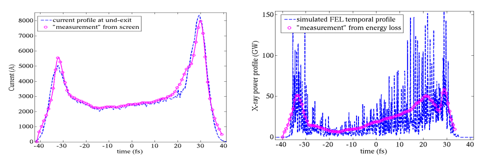


Simulated "measurements" on the screen

FEL-off FEL-on



Reconstructed e-beam profile Reconstructed x-ray profile



Advantages of this method:

- High resolution, ~ few fs;
- Single-short, any wavelength;
- Wide range, ~ 1 fs to ~100s fs;
- No interruption with operation;
- Both e-beam and x-ray profiles.

Parameter	Symbol	Value	Unit
RF frequency	f	11.424	GHz
Deflecting structure length	L	2×1	m
RF input power	P	40	MW
Deflecting voltage (on crest)	V_0	48	MV
Soft X-ray (e-beam 4.3 GeV)			
Temporal resolution (rms)	$\sigma_{t,r}$	~1	fs
Energy resolution (rms)	$\sigma_{E,r}$	56	keV
Hard X-ray (e-beam 14 GeV)			
Temporal resolution (rms)	$\sigma_{t,r}$	~2	fs
Energy resolution (rms)	$\sigma_{E,r}$	100	keV

✓ This deflector proposal has been categorized into the "must-do" list during the LCLS Scientific Advisory Committee review in this spring;

✓ We get supports from LCLS on the hardware and engineering;

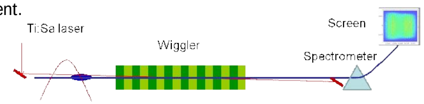
✓ Early-career program supports physicists' time;

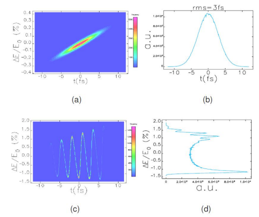
✓ Has started from this July. To be ready in two years.

Characterization of ultrashort III

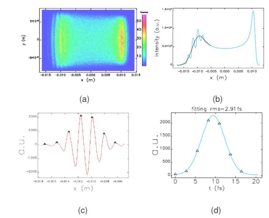
Optical streaking with a Ti:Sa laser [6].

We propose a new method based on the measurement of the electron beam energy modulation induced from laser-electron interaction in a short wiggler. A typical optical streaking method requires the laser wavelength much longer than the electron bunch length. In this method a laser with its wavelength shorter than the electron bunch length has been adopted, while the slope on the laser intensity envelope is used to distinguish the different periods. The bunch length is calibrated with the laser wavelength. With this technique it is possible to reconstruct the bunch longitudinal profile from a single shot measurement.





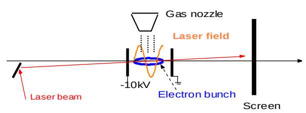
The initial electron longitudinal phase space (a) and current profile (b) before the wiggler. After laser-electron interaction, the electron longitudinal phase space (c) and energy profile (d).



The transverse image on the screen (a) and its horizontal projection (b). After removing the background by fitting a black curve in (b), the residual is shown in (c). The peak points are replotted in (d) using laser wavelength to calibrate the horizontal axis.

Optical deflecting on the ionized low-energy electrons [7].

We propose a novel approach to measure the short electron bunch profile at micrometer level. Low energy electrons generated during beam-gas ionization are simultaneously modulated by the transverse electric field of a circularly-polarized laser, and then they are collected at a down-stream screen where the angular modulation is converted to a circular shape there. The longitudinal bunch profile is simply represented by the angular distribution of the electrons on the screen. We only need to know the laser wavelength for calibration and there is no phase synchronization problem.



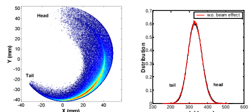


Image on the screen and its angular distribution with both beam field and laser field. The laser power is 1.2*GW* with a waist of 30*mm*.

Table 1: Main simulation parameters

Description	Value
Bunch charge	20pC
rms Bunch length	1μm
rms Beam size	5μm
Gas species	Helium
Vacuum pressure	1.0×10^{-5}Torr
Ionization length	10mm
Distance from gas box to the screen	200mm
Laser FWHM	500fs
Laser wavelength	10μm
Power of the laser	1~5GW
DC voltage	10kV

Future plans

- We will converge and focus on the X-band transverse deflector program to develop a reliable diagnostic tool for ultrashort e-beam and x-ray pulse temporal measurements in the coming two years;
- With the new diagnostic tool, we plan to study low-charge optimization based on both simulations and experiments, and further explore new schemes for ultrashort generation;
- Continue on study of the optical streaking and deflecting methods and frequency domain methods, such as the statistical analysis and wide-band spectrometer from coherent radiation.

Publication list

[1] L. Wang et al., to present at IPAC11.

[2] Y. Ding, Z. Huang, R. D. Ruth, Phys. Rev. ST Accel. Beams 13, 060703 (2010).

[3] Z. Huang, K. Bane, Y. Ding, P. Emma, Phys. Rev. ST Accel. Beams 13, 092801 (2010).

[4] Z. Huang *et al*., PAC11: THP183.

[5] Y. Ding *et al*., "Femtosecond x-ray pulse temporal characterization in free-electron lasers using a transverse deflector" (submitted to PRSTAB).

[6] L. Wang *et al*., to present at IPAC11: TUPC171.

[7] Y. Ding *et al*., to present at FEL11: WEPB22;

[8] A. Lutman *et al*., "Femtosecond x-ray pulse duration measurement from spectral correlation function". (submitted to PRSTAB).

[9] D. Xiang and Y. Ding, Phys. Rev. ST Accel. Beams 13, 094001 (2010).

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