Generating *sub-fs* hard x-ray pulses with Optimized Nonlinear Bunch Compression

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Outline

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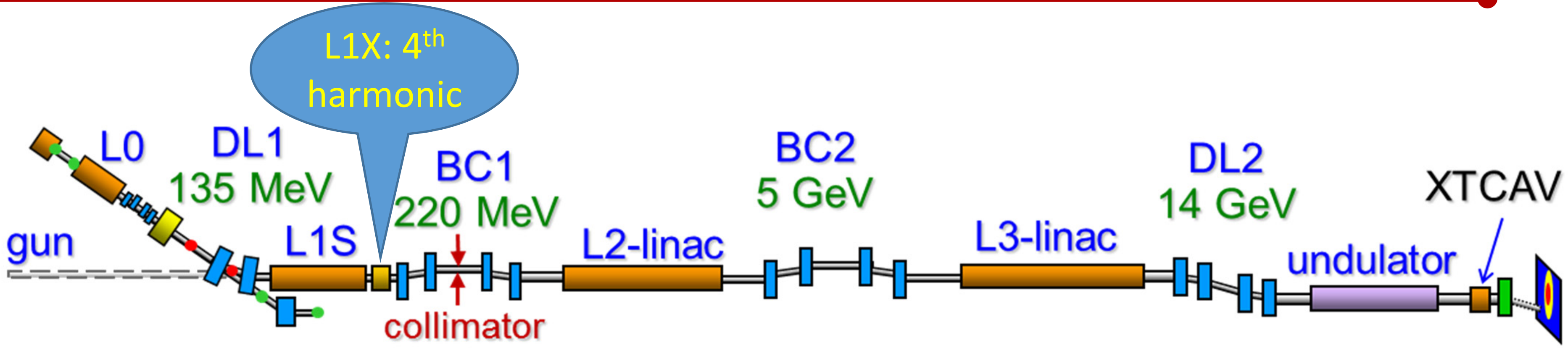
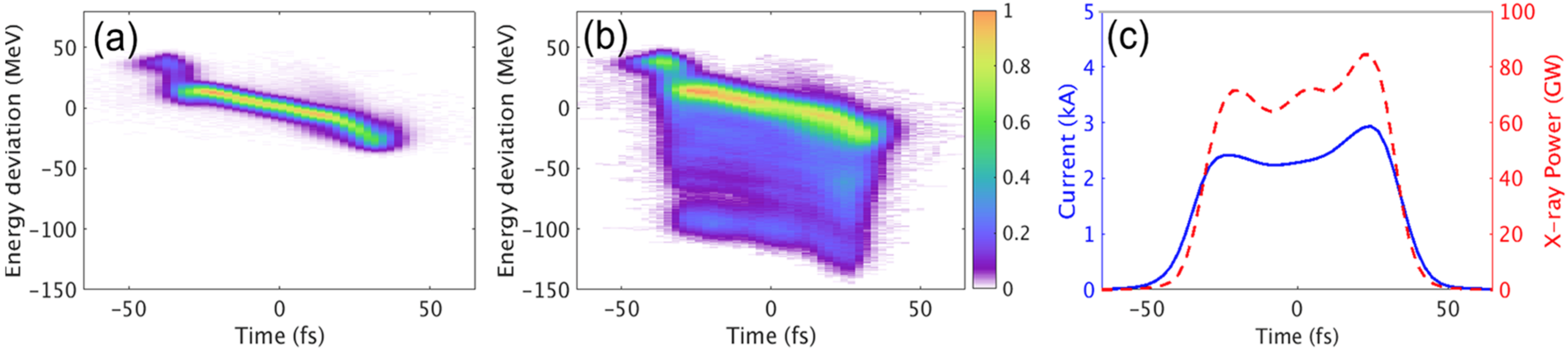
Introduction

- Growing interests in few-fs or even sub-fs x-ray pulses in FEL user community.
- However, the typical X-ray FEL pulses are at the order of few tens fs.
- Many schemes have been proposed to shorten the x-ray pulses in FEL: laser-based time slicing, slotted foil, bunch tilt, lower charge etc.
- But experimental demonstration at the sub-fs regime in X-ray FELs has not been realized before.
- We report an experimental study for generating sub-fs pulses using a simple scheme based on existing hardware at the LCLS.

LCLS at nominal operation



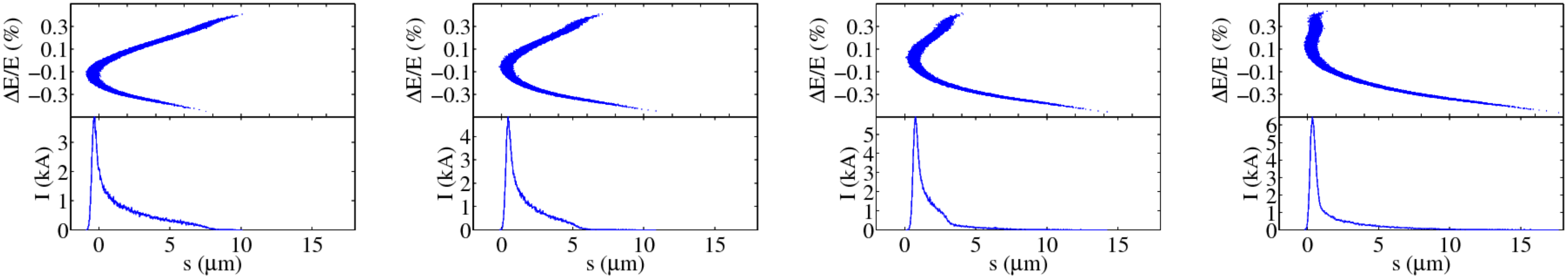
In regular operation, the 4th order harmonic cavity L1X, a **linearizer,** plays an important role for **linearizing** the longitudinal phase space.



Ding et al., PRAB 19, 100703 (2016)

The idea with nonlinear compression

Lower L1X amplitude + adjust ϕ to produce stable single current horn.



Li-Track (1D) results, head on LHS

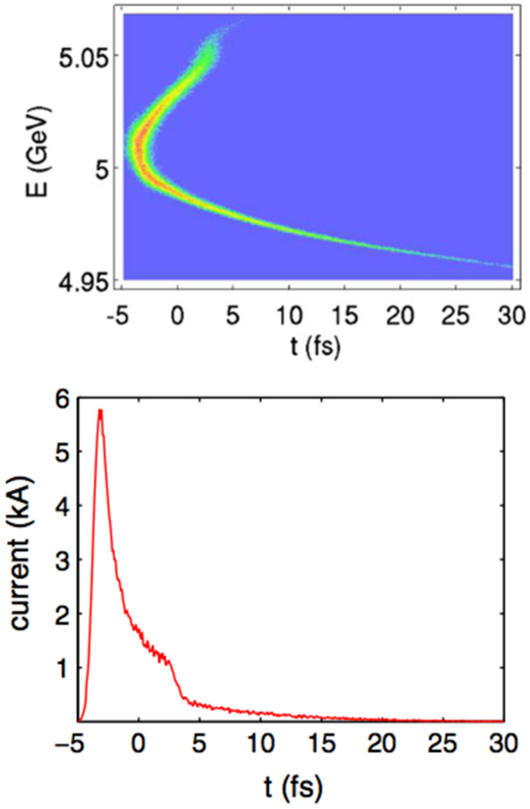
(a) L2 @ −34.3° (b) L2 @ −34.6° (c) L2 @ −34.9° (d) L2 @ −35.2°

L1X reduced from nominal 20 MV to 15 MV. After BC2 a leading current spike is formed. 20pC.

“Banana” shaped electron distribution, similar to that achieved in the early operation stage of FLASH before adding a linearizer (Dohlus et al., NIM A530, 217 (2004)).

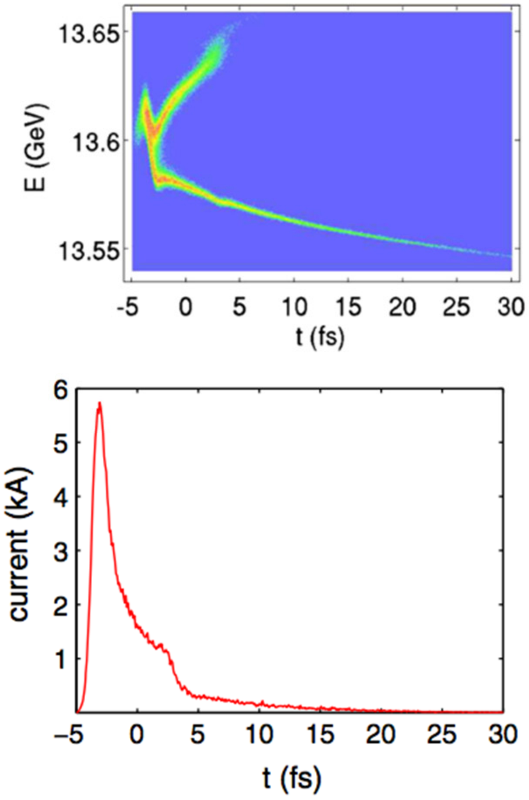
Without harmonic cavity, you can achieve a similar “banana” shape. But here with L1X at reduced amplitude we can further control the spike current by changing the curvature of the nonlinear longitudinal phase space.

Impact of longitudinal space charge (LSC)



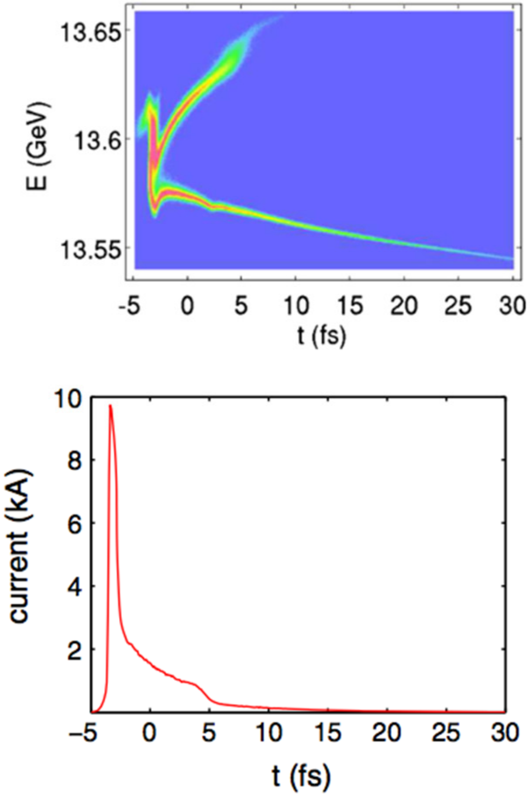
(a) BC2END

The phase space has a “banana” shape



(b) L3END

Time-energy chirp mainly due to LSC in the horn



(c) UNDBEG

Positive R56 in DL2 further rotates the phase space, leading to a significant increase of peak current

Elegant simulation results

Chirp and reverse tapering

- LSC inside the undulator continues to make a time-energy chirp, even stronger due to wiggling motion.
- Fortunately a reverse taper can be used to compensate this chirp.
- The tapering helps maintain the core part beam lasing, and at the same time suppress lasing elsewhere. This further shortens the x-ray pulse.

Reverse taper to compensate LSC-induced time-energy chirp inside the horn

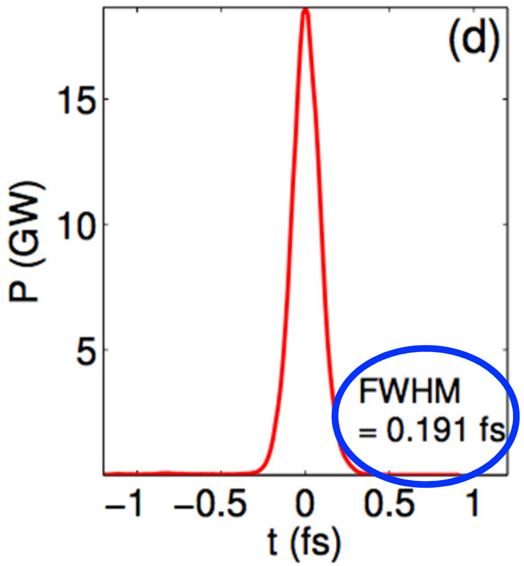
$$\frac{d\ln K}{dz} = -\frac{\lambda_s}{\lambda_u}\frac{2+K^2}{K^2}\cdot\frac{1}{c}\frac{d\ln\gamma}{dt}$$

reverse taper ~-1% over 112 m at LCLS

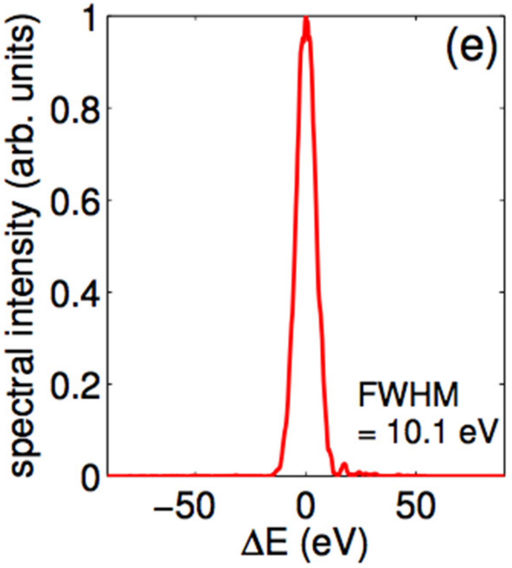
Ref.: E. L. Saldin et al., PRST-AB 9, 050702 (2006)
W. M. Fawley, NIMA 593, 111 (2008)

FEL simulation result (one typical shot)

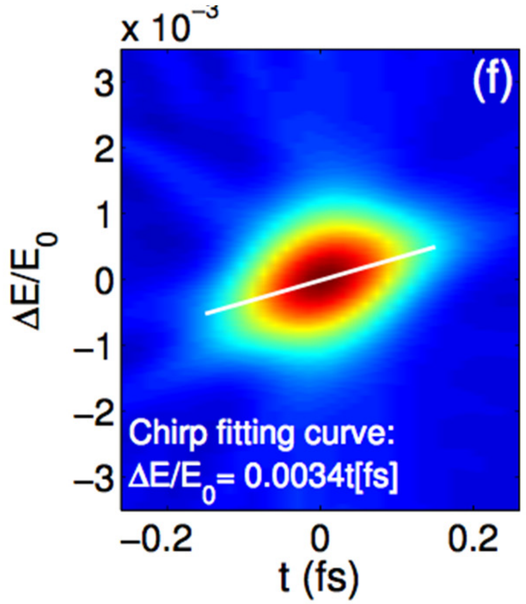
Using 20 pC, 11.5 GeV beam at the LCLS, we show one example of the FEL simulation at 5.6 keV.



power profile



power spectrum



Wigner transformation of FEL field

Linear frequency chirp observed

Experiment at the LCLS

- Start from a regular operating mode with linear compression (bunch charge 20 pC, L1X voltage set at 19-20 MV, phase at -160 degree).
- Reduce L1X rf amplitude together with L1S adjustment for maintaining the energy and current after BC1 (L1X about 12 – 15 MV).
- Scan the L2 phase to find the minimum bunch length using BC2 bunch length monitor (BLM).
- Further optimize the L1X amplitude and phase according to the measured electron profile and FEL spectra.

Available diagnostics:

➢ bunch length monitor (BLM): relative measurement, fast.

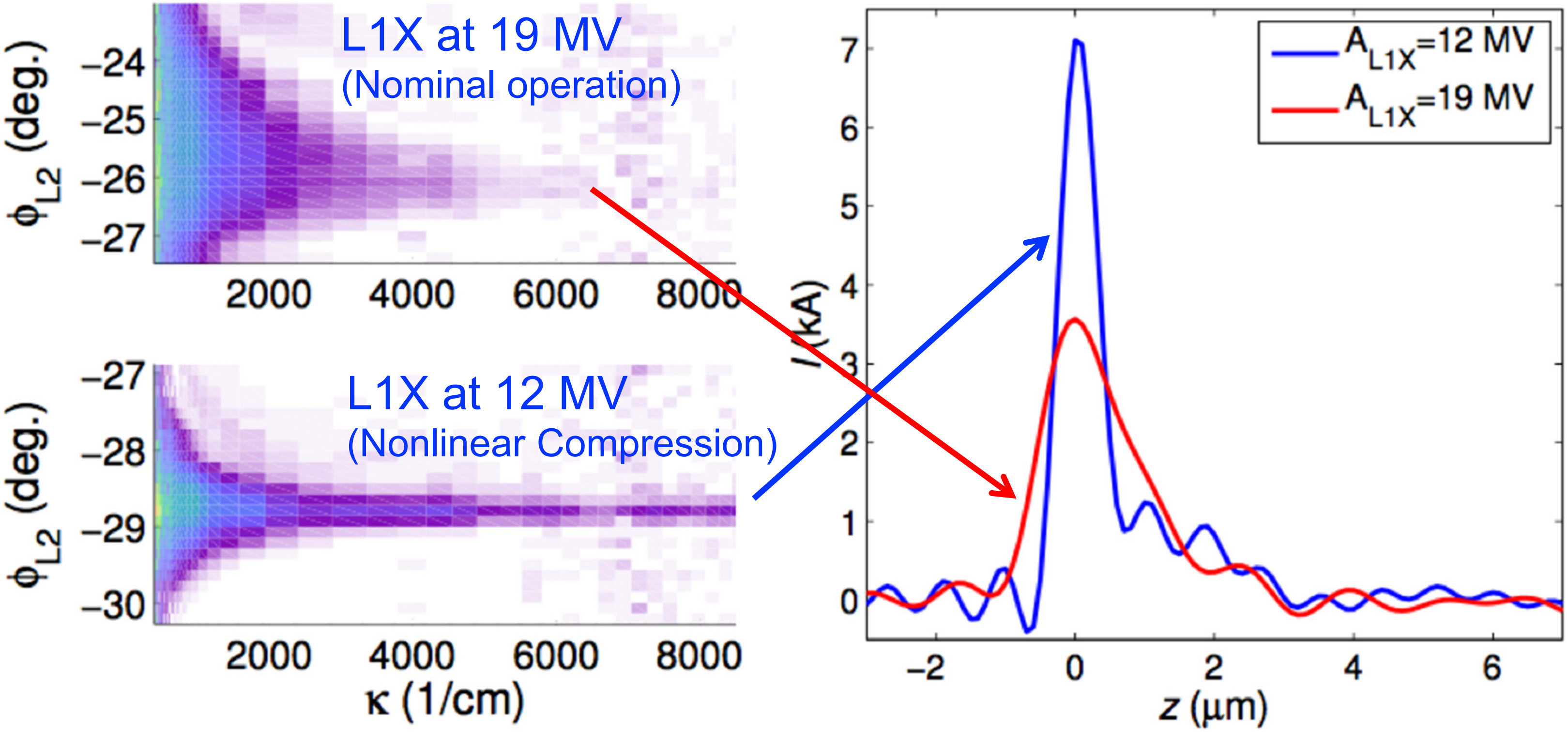
➢ XTCAV: out of resolution at this mode.

➢ Prism spectrometer: single shot, interruptive.

➢ X-ray spectrometer: good resolution, single shot.

Measurement with prism spectrometer

MIR prism spectrometer diagnostic: (i) Scan L2 phase, measure each single shot spectrum of the CTR light produced by an e-bunch; (ii) retrieve e-current profile from the measured spectra by Kramers-Kronig phase reconstruction method.



Measured spectra vs L2 phase with MIR prism spectrometer

Reconstructed current profile at maximum bandwidth

Prism spectrometer: T. Maxwell et al., PRL 111, 184801 (2013)

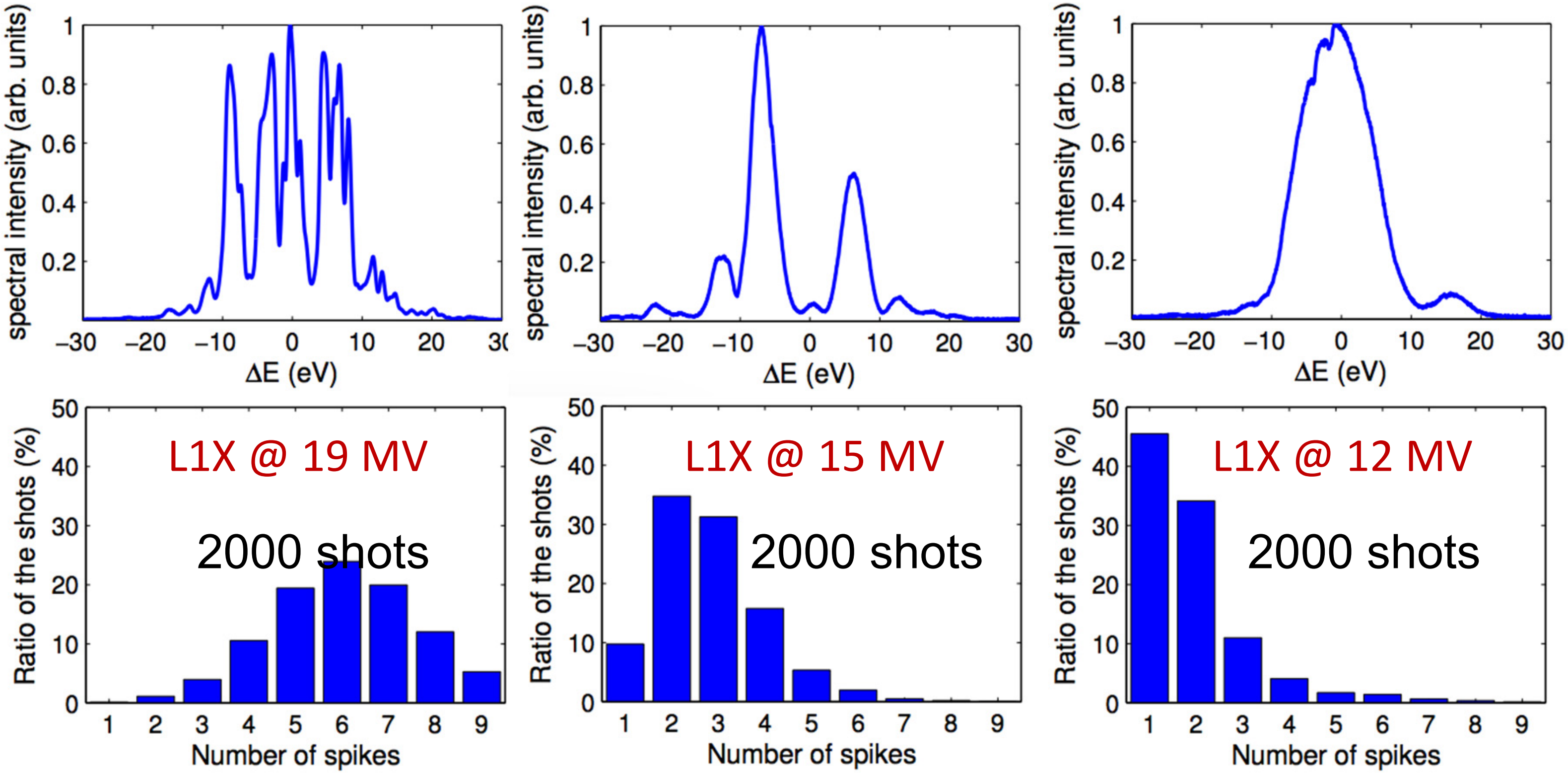
Measured FEL spectrum evolution @ 9 keV

Regular linear compression mode

Optimized nonlinear compression mode

Spectrum (example)

Number of spikes histogram)



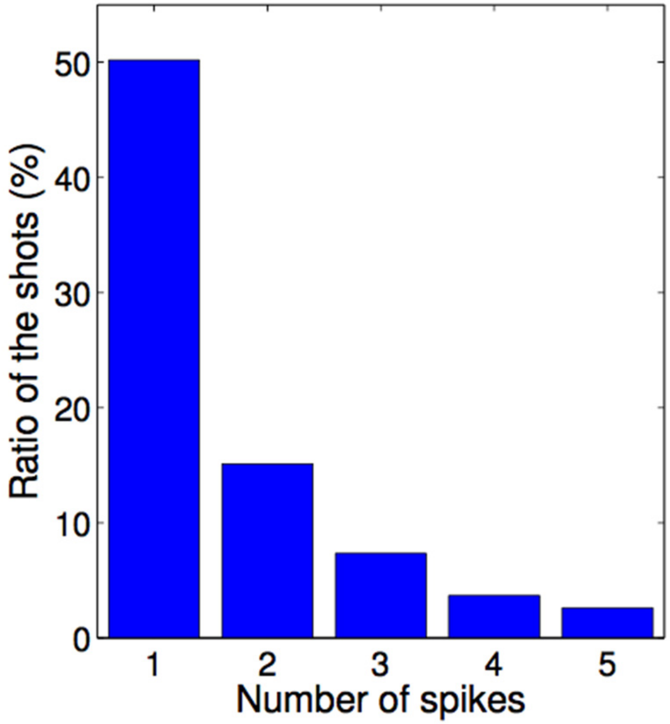
A constant reverse tapering at -1% for all the reduced amplitudes of 10-15 MV.

Single spike shots @12MV: average pulse energy $7 \pm 4\ \mu$J,

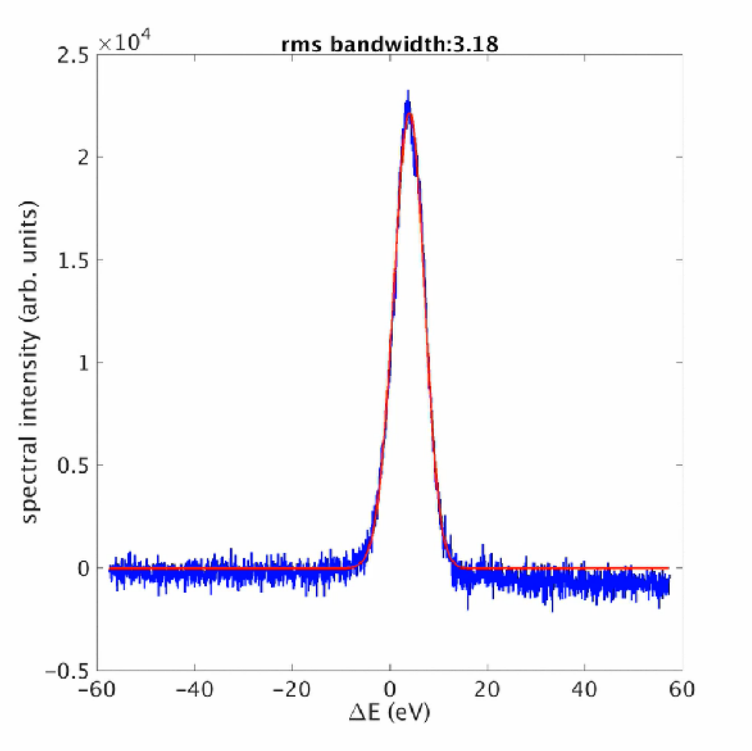
FWHM bandwidth 14.4 ± 4.7eV.

Electron energy @ 14 GeV

FEL spectra @ 5.6 keV



Number of spectral spikes
(Histogram, 8400 shots)



Examples of the sorted single-spike
x-ray spectra

A reverse tapering at -1%, L1X amplitudes of 13 MV.
Single spike shots: average pulse energy $10 \pm 7\ \mu$J,
FWHM bandwidth 11.3 ± 4.2eV.

Electron energy @ 11.5 GeV

Estimate the FEL pulse duration?

An accurate measurement of the frequency chirp is unavailable in the experiments. However, we can evaluate the upper limit for a linearly chirped Gaussian pulse at a given spectral width (assuming in a Fourier transform limited regime).

$$\tau_p = \frac{2\sqrt{2}\ln 2/\pi}{\sqrt{\Delta f_p^2 + \sqrt{\Delta f_p^4 - (4\ln 2\,\alpha f_0/\pi)^2}}}$$

Δf_p: *bandwidth*;
α: *chirp*;
f_0: *frequency*.

$$\tau_{p,max} = 2\sqrt{2}\ln 2/(\pi\Delta f_p) \quad \text{when } \alpha = \pi\Delta f_p^2/(4\ln 2\, f_0)$$

Maximum achievable frequency chirp at a given spectral width.

	FWHM bandwidth	Upper limit of FWHM pulse duration
5.6 keV	11.3 ± 4.2 eV	228 ± 85 as
9 keV	14.4 ± 4.7 eV	179 ± 58 as

Conclusion

- We have demonstrated a simple way for generating single-spike hard x-ray FEL pulses at the LCLS with optimized nonlinear compression and chirp-taper technique.
- We measured single-spike pulses with estimated FWHM pulse duration at the 200-as level at 5.6 keV and 9 keV; we expect to have a similar performance in a range of 4-10 keV.
- This kind of experiment can be carried out at any other x-ray FEL facilities without additional hardware.
- Note a recent study at LCLS with an upgraded slotted foil also measured single-spike hard x-ray pulses (A. Marinelli et al., to be published in APL)

Thanks!