Generating *fs* to *sub-fs* x-rays with a modulated chirped beam in a self-seeded FEL

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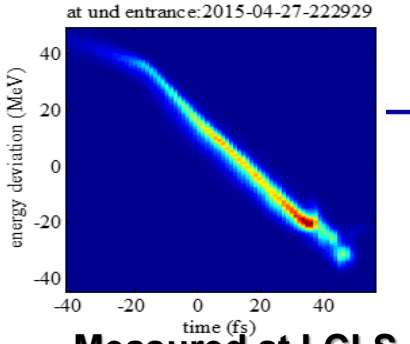
Outline

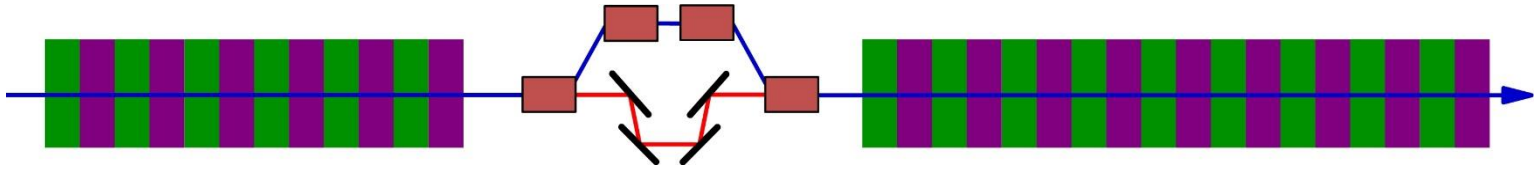
1. Concept / Scheme
2. Electron beam modulation
3. FEL simulation (**5 μm** and 2 **μ**m modulation laser)
4. Summary

Self-seeding with a chirped bunch

- Short pulse from a chirped beam with self-seeding setup [1]



Measured at LCLS

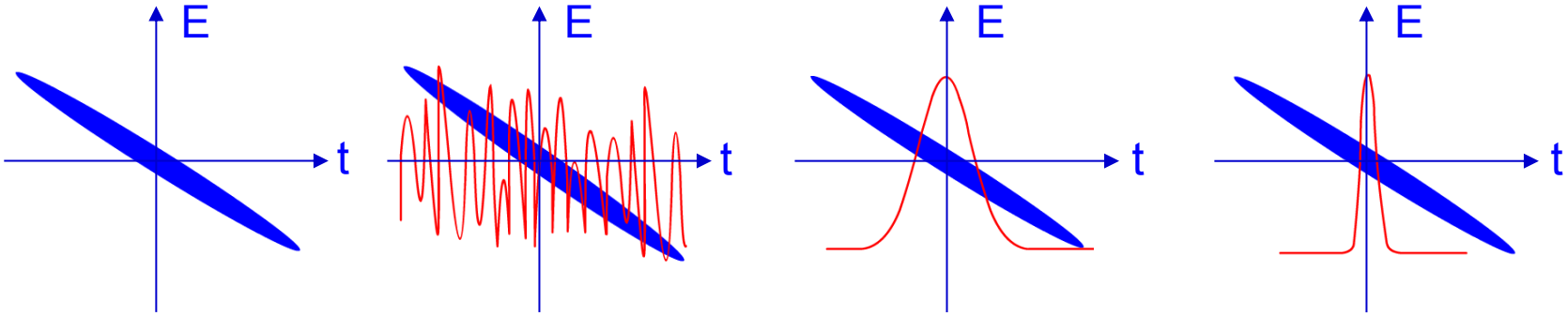


SASE Undulator
1st-stage FEL

SXRSS

Amplifier Undulator
2nd-stage FEL

after SASE undulator | after chicane/mono | 2nd-stage FEL output



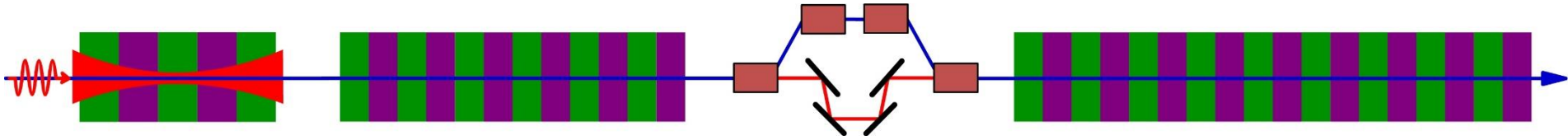
[1] Schroeder et al., NIM A 2002.
[2] Krinsky and Huang, PRSTAB 2003.

(C. Emma et al., Poster WEP075)

- The final x-ray pulse duration is [2]: $\sigma_t = \sigma_\omega / u$
- For a typical chirped bunch at LCLS, 1% over 30fs, the final pulse could be about 6 fs.

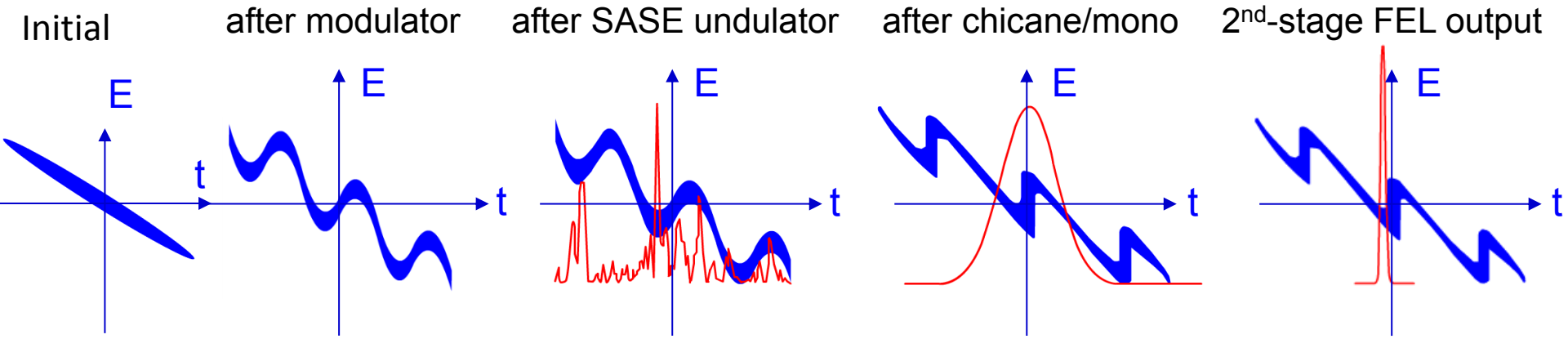
How to make it even shorter? A new scheme

e-beam modulation + Soft x-ray self-seeding configuration



Modulator **SASE Undulator** **SXRSS** **Amplifier Undulator**

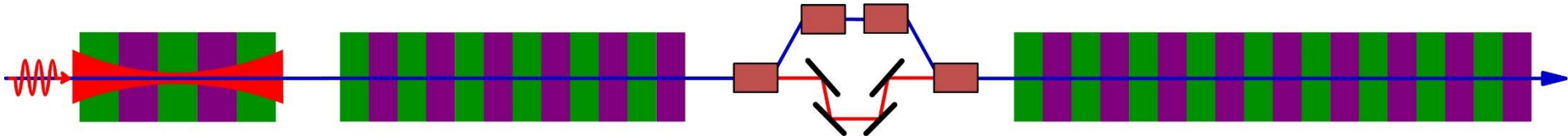
1st-stage FEL **2nd-stage FEL**



① A modulated time-energy chirped e-beam to generate SASE signals;
② Narrow bandwidth seed pulse after monochromator and electron bunch with ESASE-like current spikes after chicane (micro bunching eliminated);
③ The seed overlaps with the chirped bunch to generate short FEL pulse;
④ The final FEL pulse is mainly dominated by the current spike width.

How to make it even shorter? A new scheme

e-beam modulation + Soft x-ray self-seeding configuration



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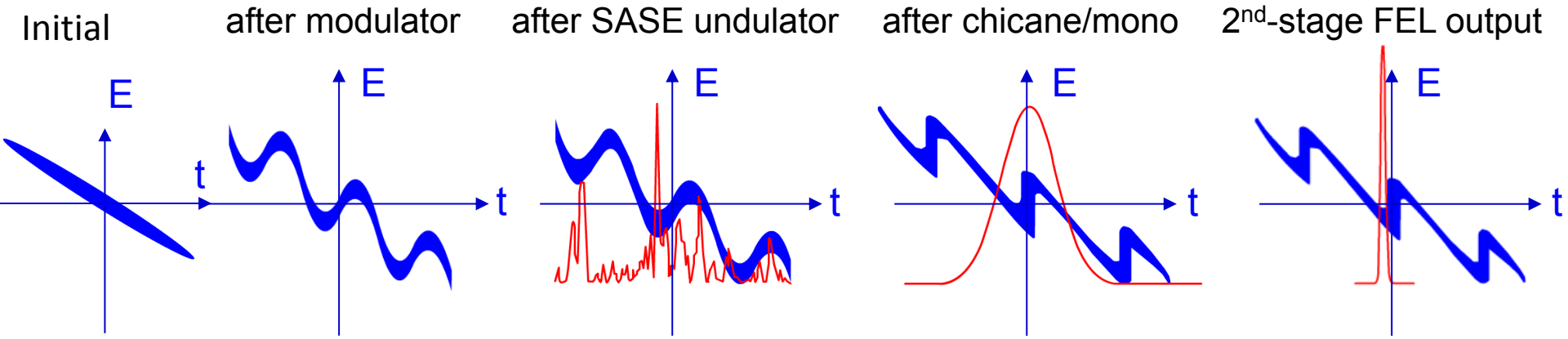
1st-stage FEL **2nd-stage FEL**

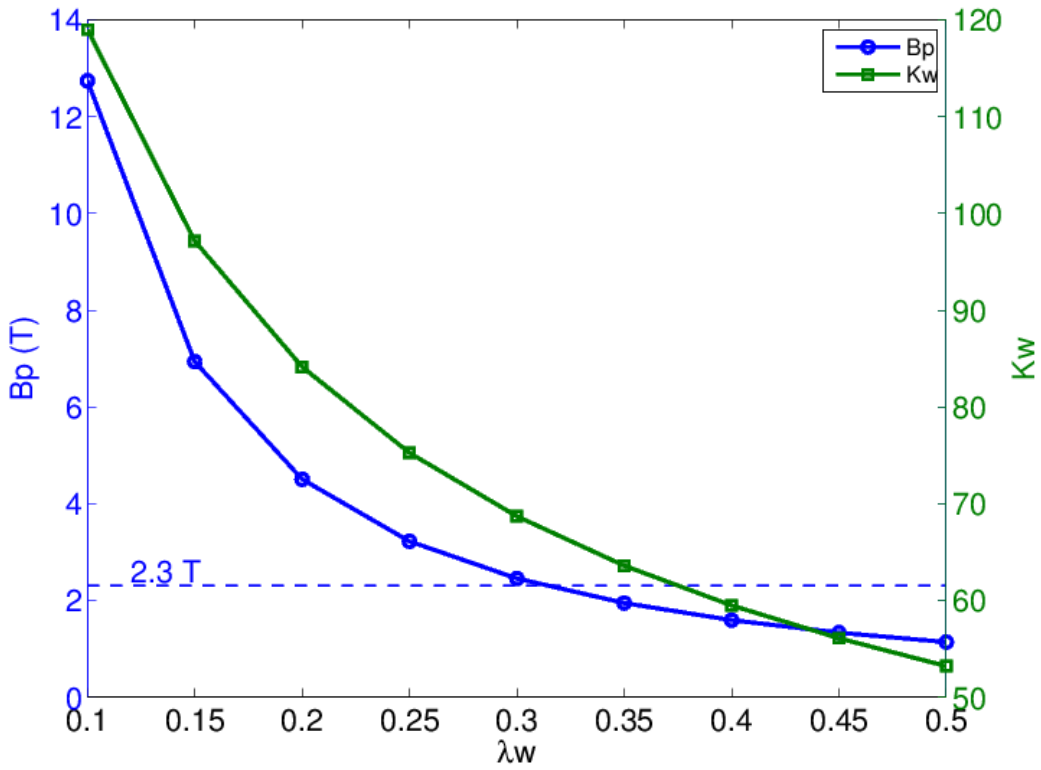


- The modulation does not rely on single-cycle laser;
- Stable wavelength from seeding mode;
- Sub-femtosecond x-ray pulses can be generated.

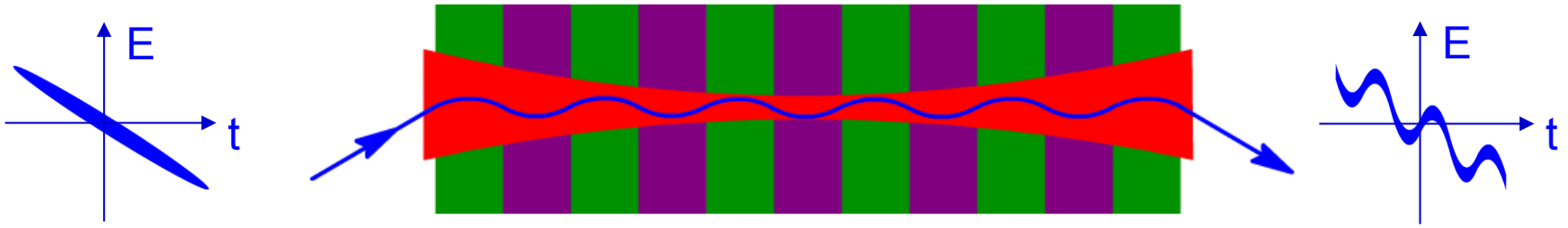
Electron beam modulation

Modulation parameters

- E-beam energy: 4.3 GeV
- Modulation laser wavelength: **5 μm**
- Wiggler period: $\lambda_w = 0.35$ m
- Wiggler strength: $K_w = 63.6$
- Modulation depth: $\Delta E = 25.6$ MeV (peak to peak)

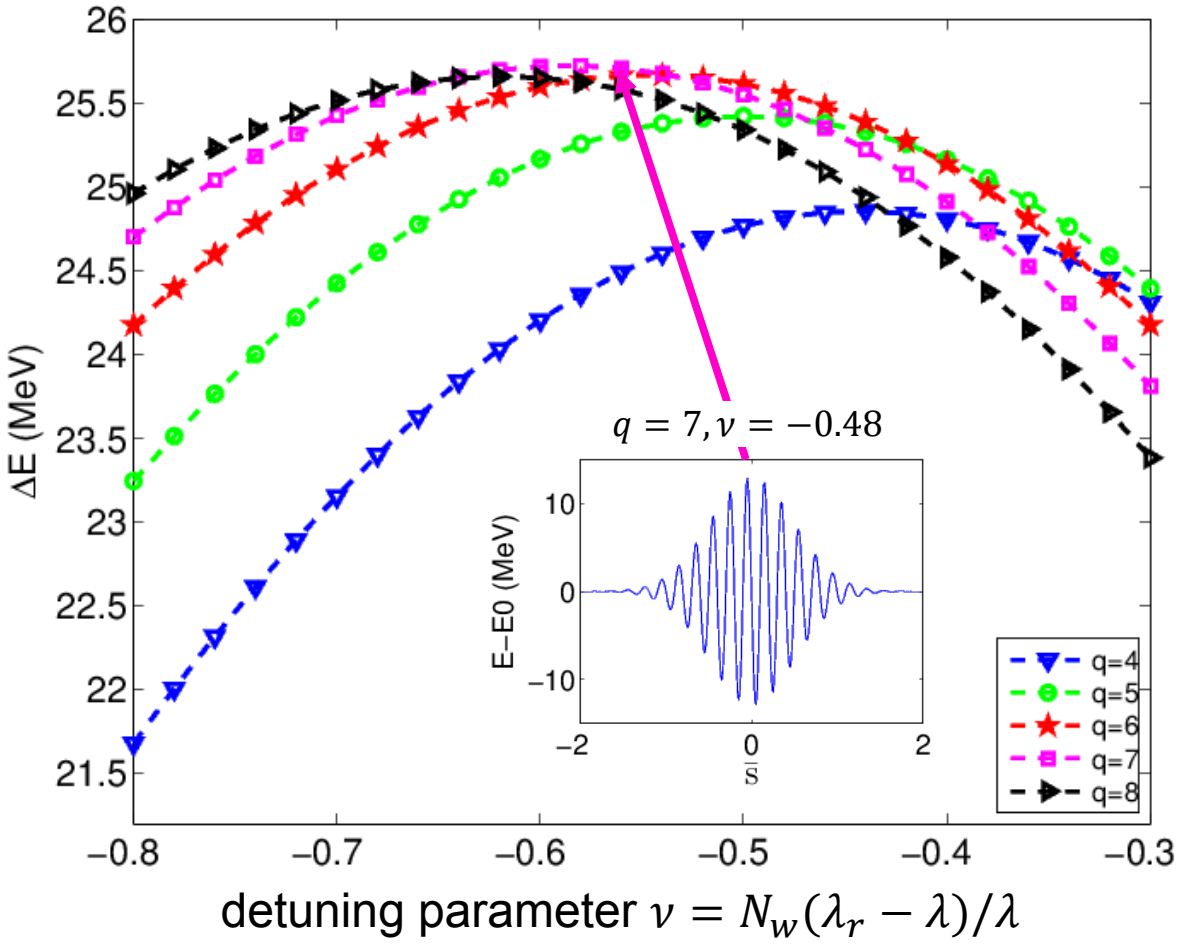


$$L_w = q\, Z_r$$



Electron beam modulation

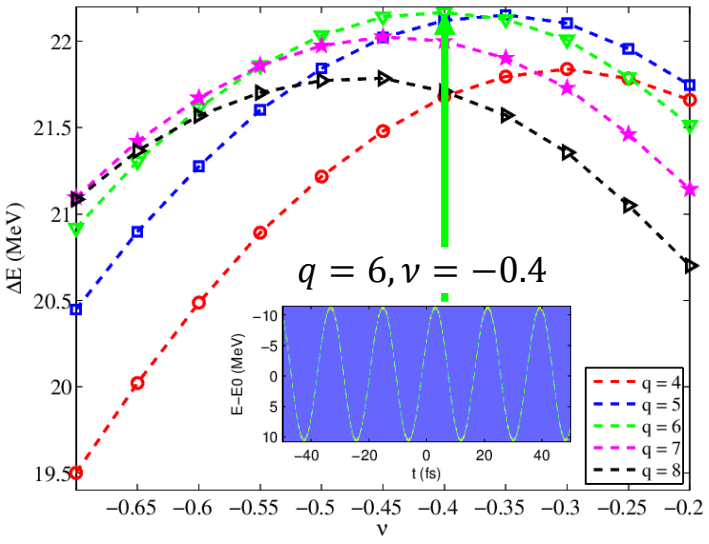
- Modulation analysis [3]



Laser parameters
- pulse energy: $A = 2$ mJ
- pulse duration: $\tau = 60$ fs (fwhm)
- rayleigh range: $Z_R = L_w/q$

Wiggler parameters
- period: $\lambda_w = 0.35$ m
- period number: $N_w = 5$
- strength: $K_w = 63.6$

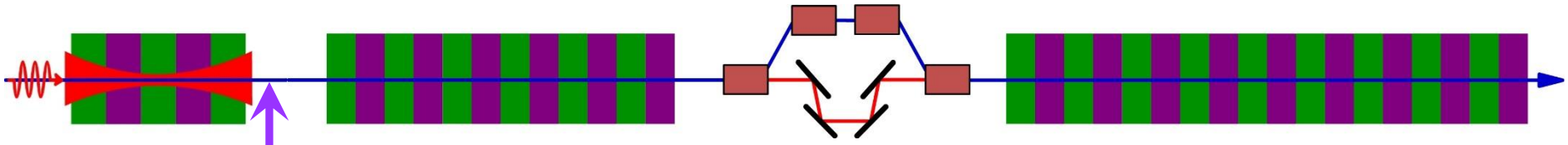
Elegant tracking results



Close to theory.

[3] A.A. Zholents and G. Penn, PRST-AB 8, 050704 (2005).

FEL simulation (1.5 nm)



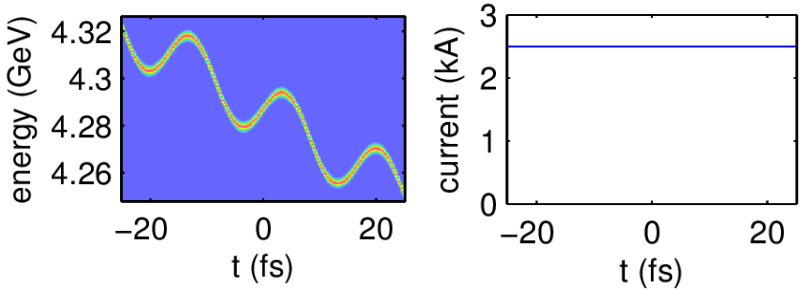
Modulator | **SASE Undulator** | **SXRSS** | **Amplifier Undulator**

period: λ_w = 3 cm
length: L_w = 19.8 m
strength: K_w = 3.5

Chiance:
R_{56} = -0.4 mm
Mono resolving power:
R = 5000

period: λ_w = 3 cm
length: L_w = 15 m
strength: K_w = 3.5
reverse taper ~ -2e-3
(from 6 m to 15 m)

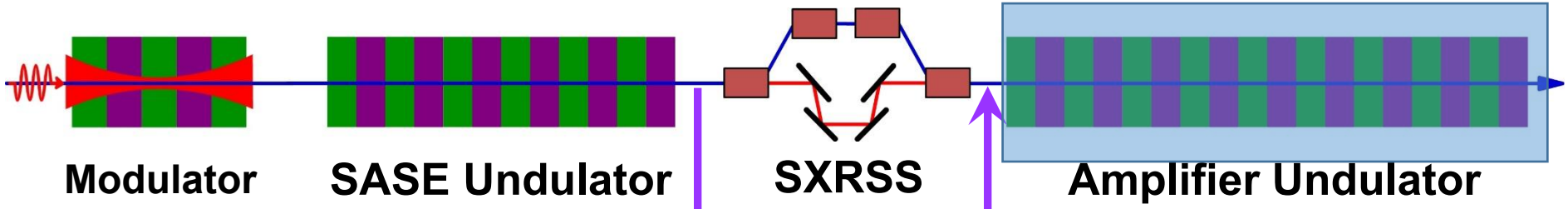
initial e-beam for FEL simulation



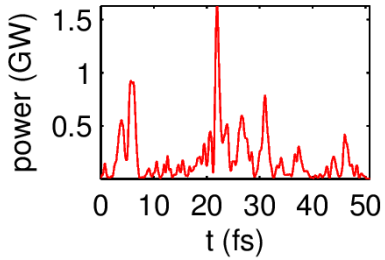
long. phase space

- energy: E = 4.3 GeV
- energy chirp: $\Delta E/E/\Delta t = -3.33 \times 10^{11}$/s
- modulation amplitude: 25.6 MeV
  (peak to peak, modulation wavelength @ 5 μm)
- bunch length: 50 fs
- bunch charge: 125 pC
- norm. emittance: 0.5 μm

FEL simulation – 1st stage

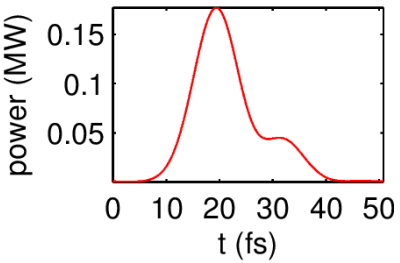


Power Profile

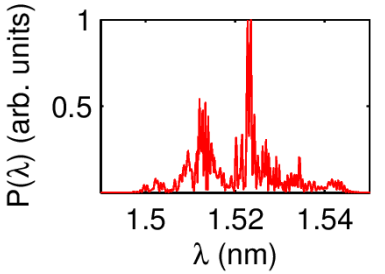


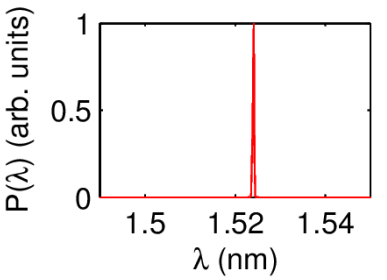
mono

R = 5000

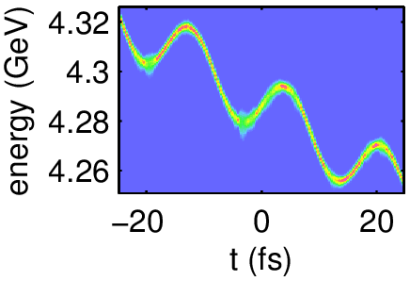


Power Spectrum



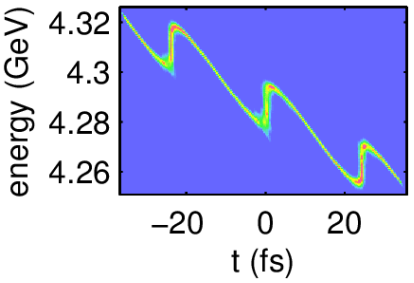


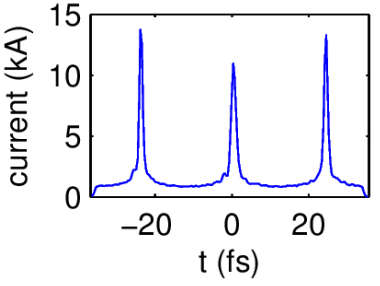
E-Beam
Long. Phase Space



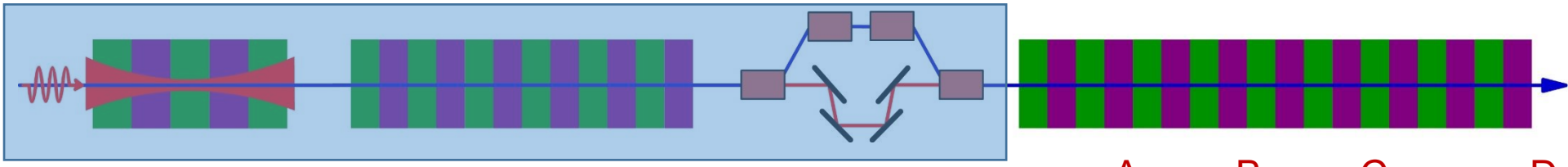
chicane

R_{56}= -0.4 mm

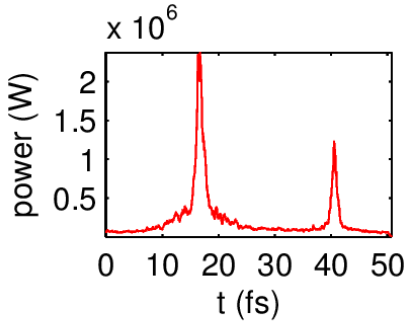


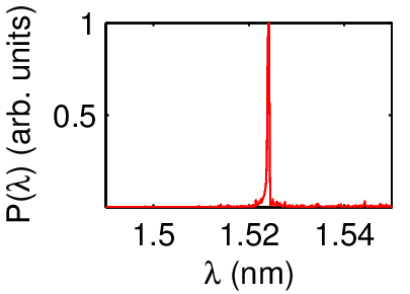


FEL simulation – 2nd stage

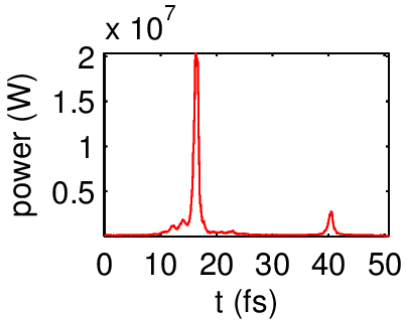


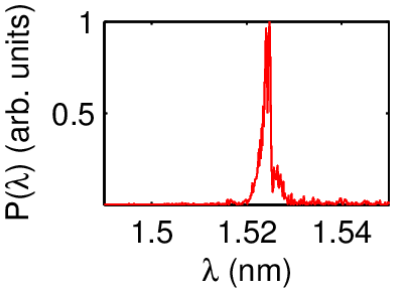
A: 3 m



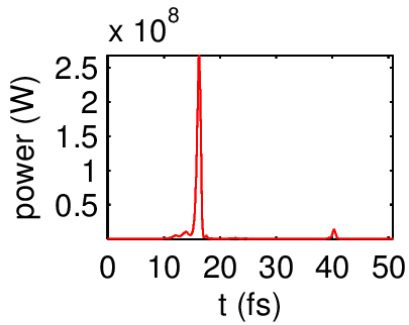


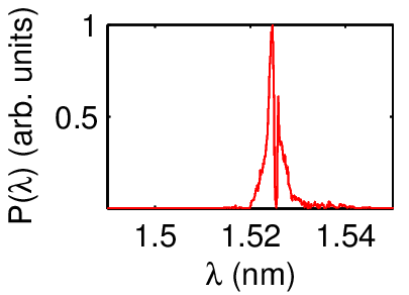
B: 6 m



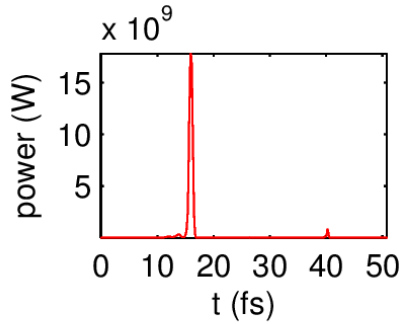


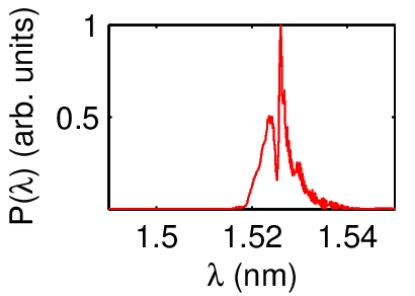
C: 9 m





D: 15 m

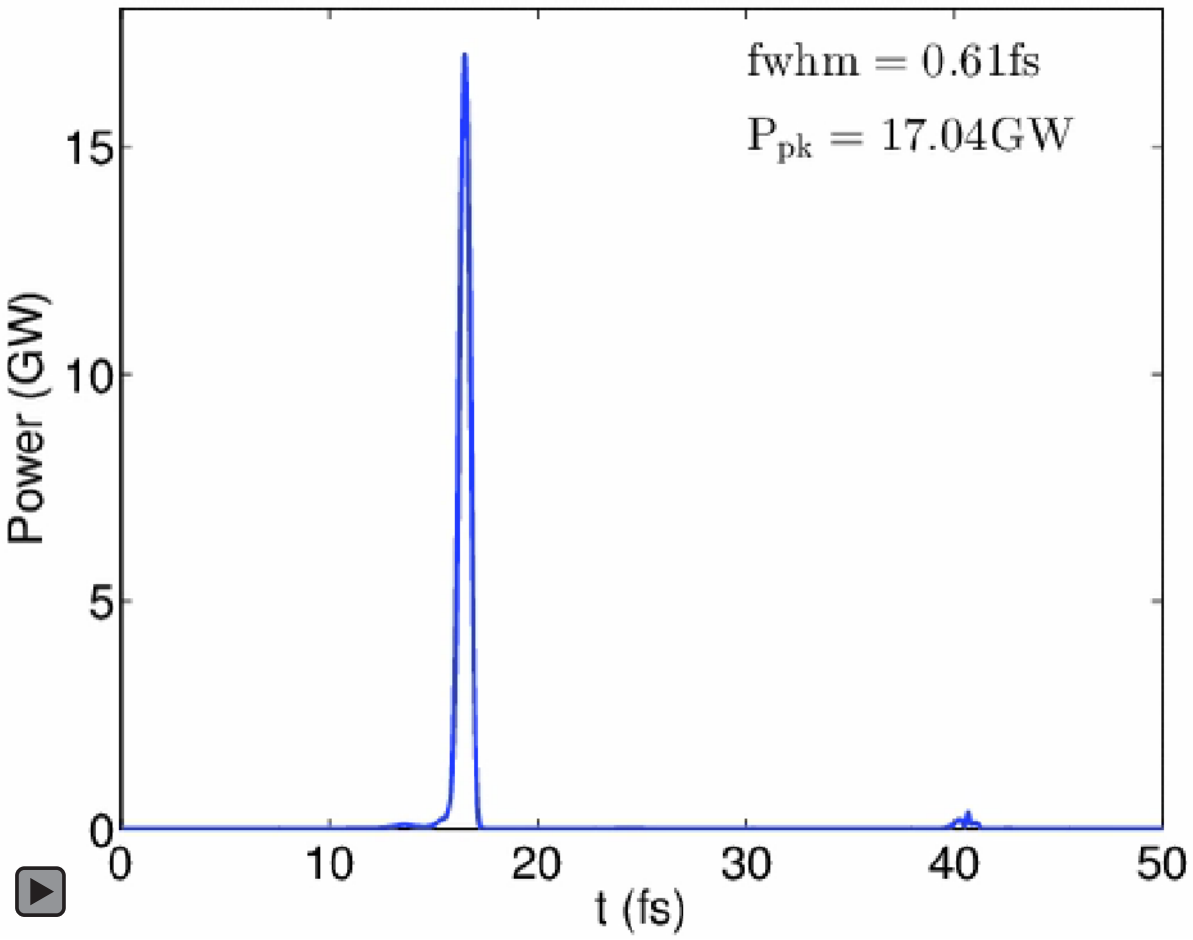




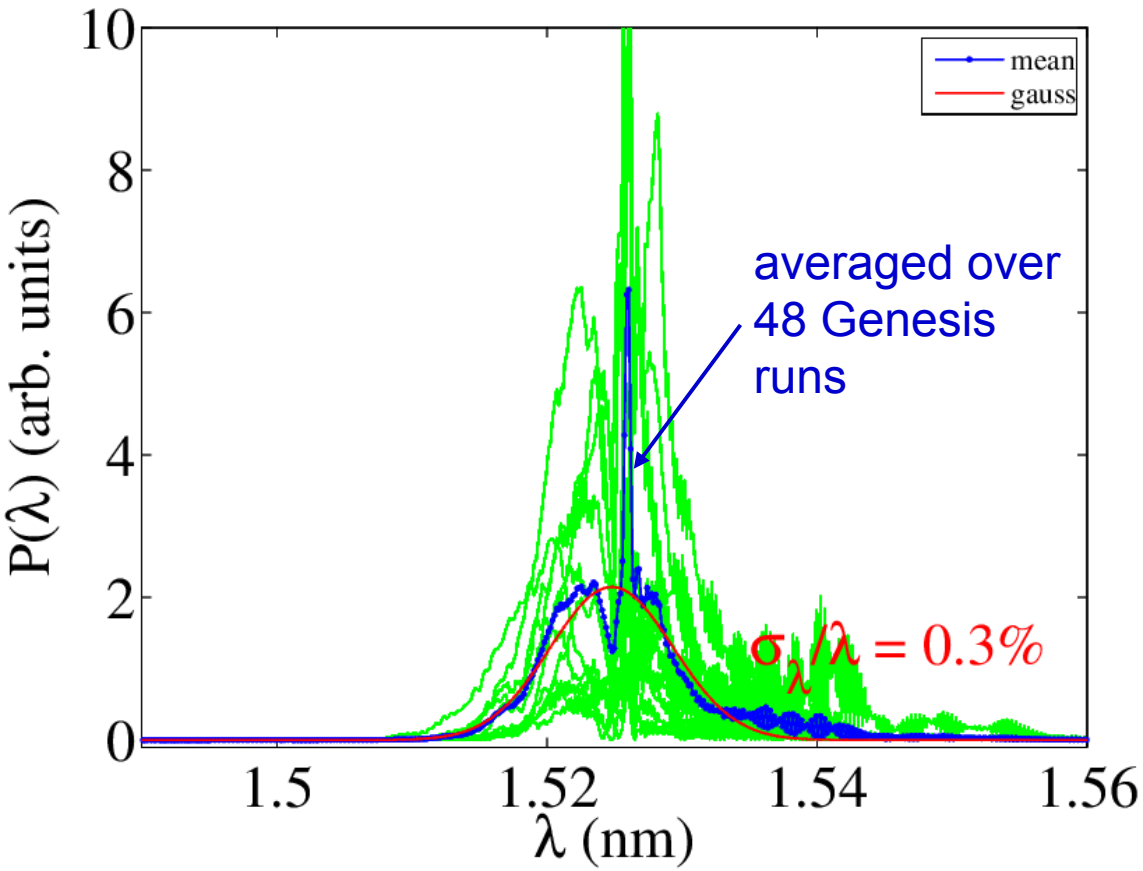
FEL simulation – Output power profiles

Independent Genesis runs

FWHM: 0.56 ± 0.09 fs; Peak power: 12.8 ± 9.7 GW



FEL simulation – Output power spectra



$\Delta t_{fwhm} = 0.56$ fs

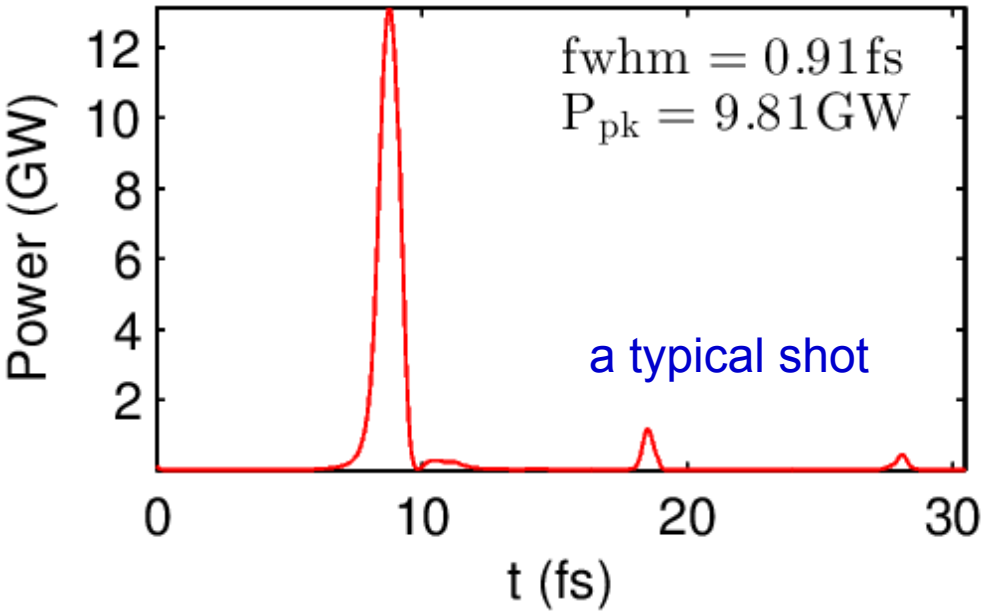
$\sigma_\lambda = 0.0045$ nm $\rightarrow \Delta\lambda_{fwhm} \sim 0.01$ nm

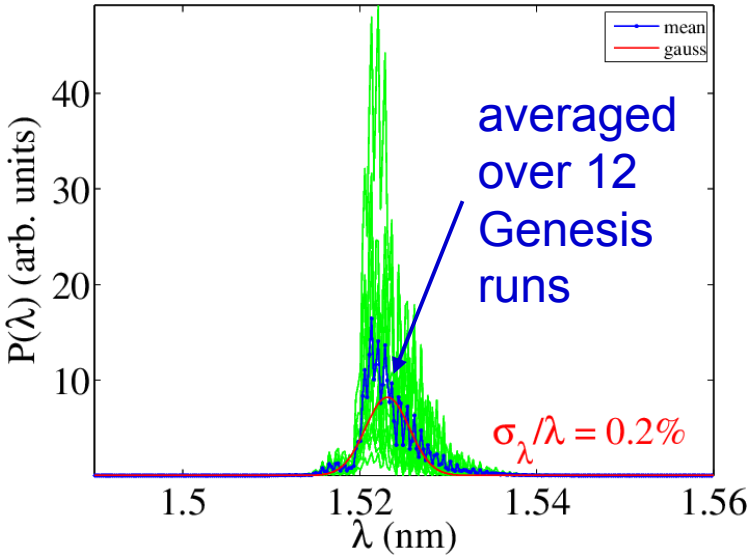
(~1.8 times Fourier transform limit for Gaussian distribution)

FEL simulation – Modulation with **2 μm** laser

Independent Genesis runs

FWHM: 0.9 ± 0.1 fs, Peak power: 6.7 ± 4.7 GW





Compared to 5-um case:

- x-ray pulse is longer (broader e-beam current spike after chicane).
- Peak power is lower (lower e-beam peak current).

Summary

- A scheme is proposed to generate femtosecond to sub-femtosecond soft x-ray pulses in a self-seeded FEL.
- Simulations have been carried out based upon the soft x-ray self-seeding FEL at LCLS.
- Using a time-energy chirped electron beam, modulated by an optical laser at 5 μm, our simulations show that soft x-ray pulses with a fwhm of 0.56 fs and a peak power of 12.8 GW can be expected.
- Further improvement with a cascaded delay shifting to other current spikes is ongoing.


FEL 2015
23rd – 28th August, 2015
Daejeon Convention Center, DAEJEON, KOREA
37th International
Free Electron Laser Conference

Thanks!