Sub-femtosecond Single-Spike X-Ray Pulse from Electron Bunches with Very Low Charge at LCLS

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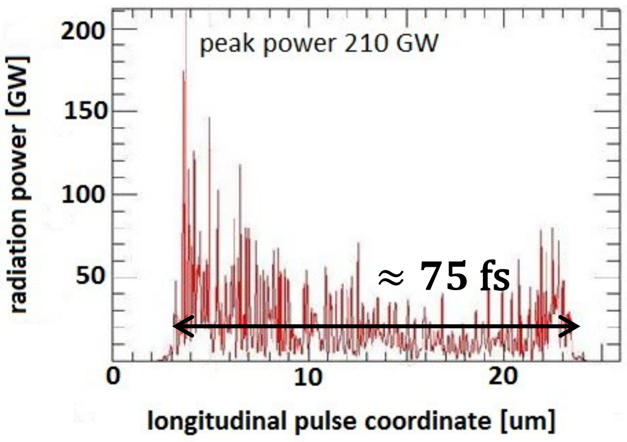
Outline

1. **Motivation**
2. **LCLS**
3. **Start-to-End Simulations**
4. **Measurements**
5. **Conclusion & Outlook**

Typical LCLS power profile for 250 pC, 13.6 GeV (λ_{FEL}=1.5 Å)



- typical power profile contains many modes
- high power, ultra-short, fully coherent x-ray pulses
- atomic length (Å) and time scale (fs)
- ultra-short pulse requires ultra-short bunch

Development of ultra-short pulse, single coherent spike for SASE X-ray FEL *S. Reiche et al.* in NIM A 593 (2008) p.45
Generation of ultra-short, high brightness electron beams for single-spike SASE FEL operation *J.B. Rosenzweig et al.* in NIM A 593 (2008) p.39

1. Motivation

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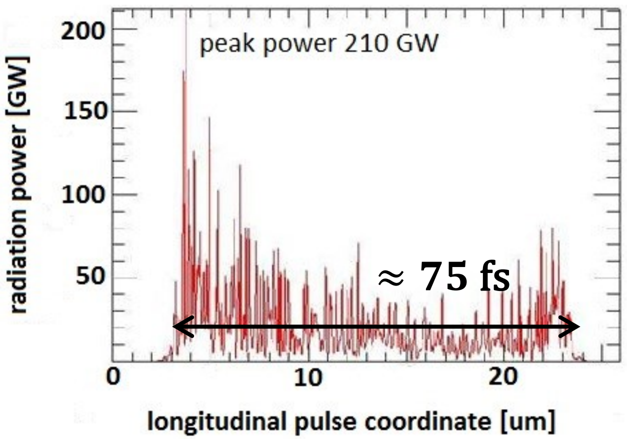

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How short must the electron bunch be for single-spike production?

requirement $\sigma_z \leq 2 \cdot L_{coop} \sim 50 \text{ nm}$

- ➢ short laser pulse length
- ➢ reduce the bunch charge
- ➢ operate near full compression

Development of ultra-short pulse, single coherent spike for SASE X-ray FEL *S. Reiche et al.* in NIM A 593 (2008) p.45
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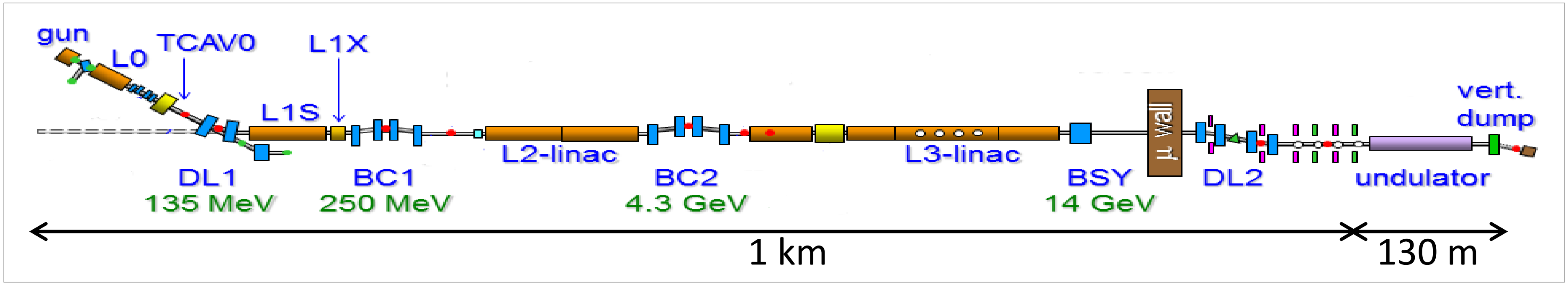
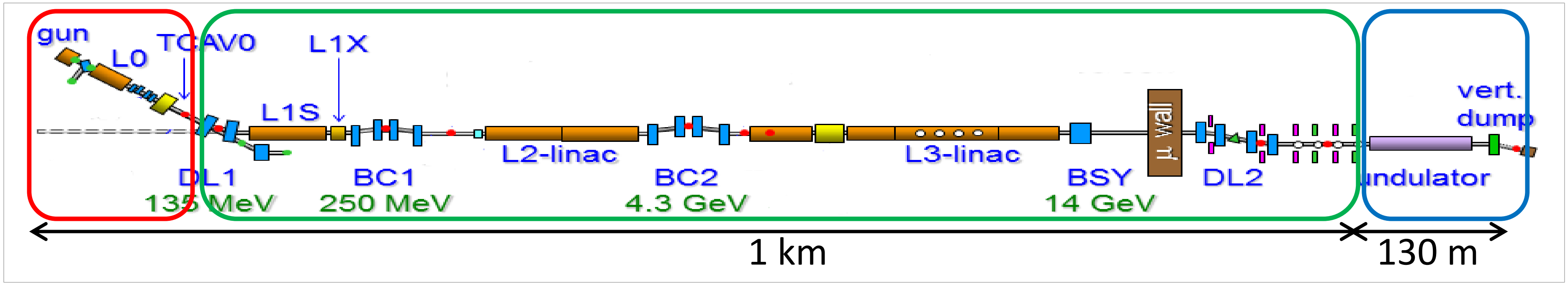
Schematic Layout of LCLS: Short Bunch Production



- photocathode rf gun (120 Hz)
- normal conducting, American S-Band (2.856 GHz) cavities
- two bunch compressors with fixed R_{56}
- 130 m long undulator section
- near (50 m downstream) and far (400 m downstream) experimental hall

Schematic Layout of LCLS: Start-to-End Simulations



ASTRA	RF gun phase, iris diameter, solenoid field → emittance optimization L0-B phase adjustment to produce symmetric phase space distribution
ELEGANT	optimization of the L1 and L2 linac RF phase to adjust the compression
GENESIS 1.3	simulation of the radiation process including LSC

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    1. Hard X-Ray [electron energy 13.6 GeV, wavelength 1.5 Å]
    2. Soft X-Ray
    3. RF Phase Jitter
5. **Measurements**
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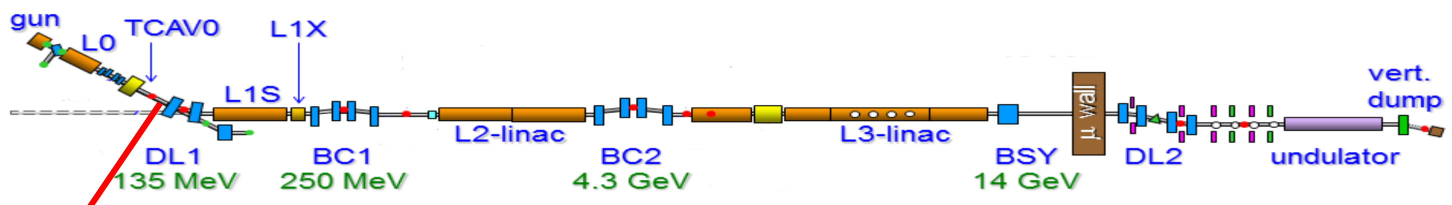
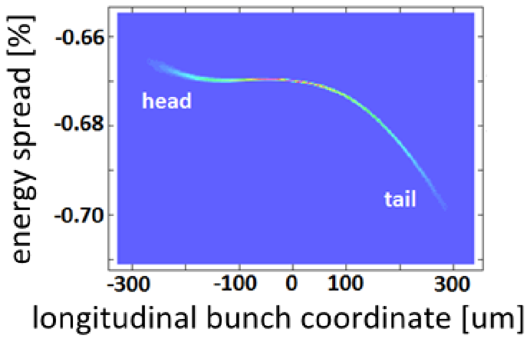
The Injector & Main Linac Simulations for 10 pC

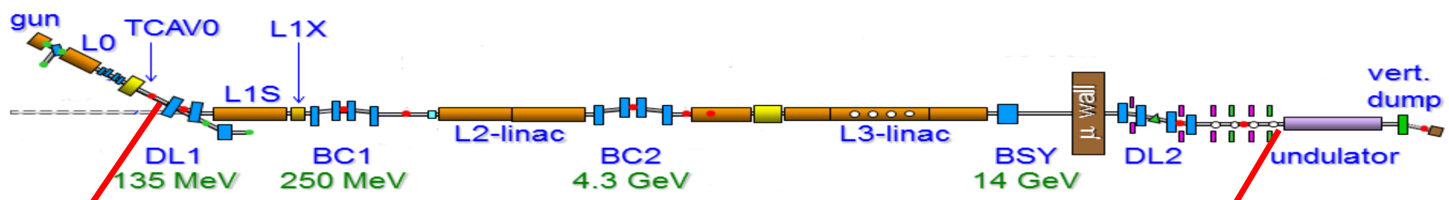


ASTRA Simulation Results

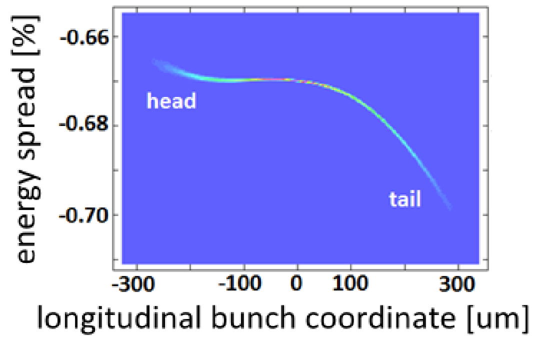


laser pulse length FWHM [ps]	1.0
longitudinal distribution	Gaussian
RF gun phase	–10.0°
iris diameter [mm]	0.5
normalized transverse emittance ϵ_n [µm]	0.17
rms bunch length σ_z [µm]	154.0
energy spread $\Delta E/E_0$ [%]	0.08

The Injector & Main Linac Simulations for 10 pC



ASTRA Simulation Results



laser pulse length FWHM [ps]	1.0
longitudinal distribution	Gaussian
RF gun phase	$-10.0°$
iris diameter [mm]	0.5
normalized transverse emittance ϵ_n [μm]	0.17
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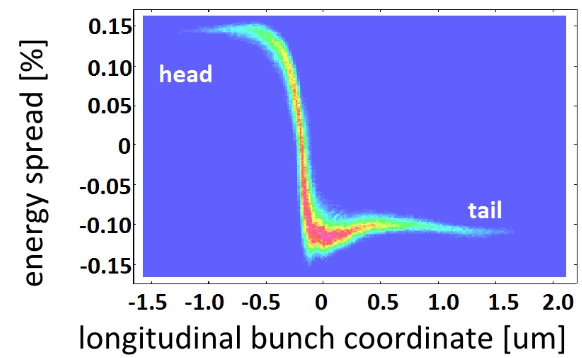
energy spread $\Delta E/E_0$ [%]	0.08

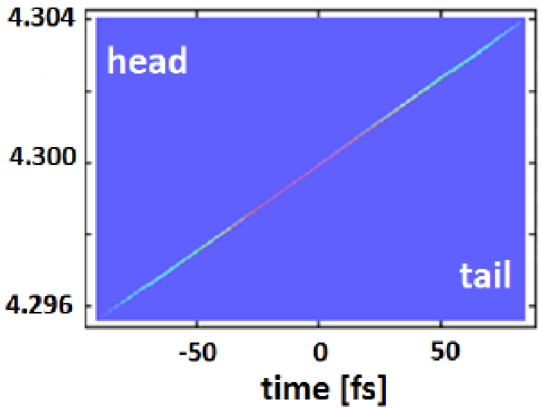
ELEGANT Simulation Results



L1 RF phase	$-17.0°$
L2 RF phase	$-34.5°$
normalized emittance $\epsilon_{n,x}$ / $\epsilon_{n,y}$ [μm]	0.37 / 0.17
rms bunch length σ_z [nm]	≈ 74.6
peak current I_p [kA]	8.5
energy spread $\Delta E/E_0$ [%]	0.4

Collective Effects in Bunch Compressors for 1 pC

Before BC2



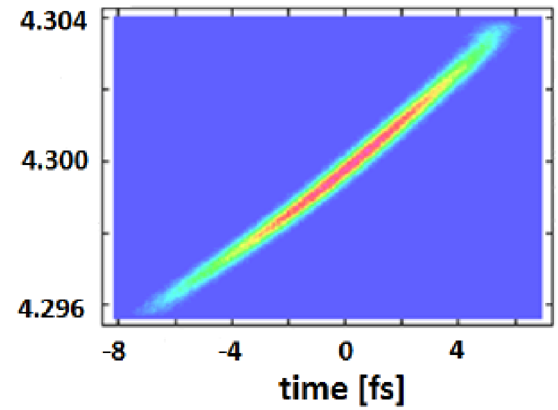
rms bunch length

$$\sigma_z = 11.9\mu\text{m} \xrightarrow{13} \sigma_z = 0.89\mu\text{m}$$

slice energy spread

$$\sigma_E = 5\text{keV} \xrightarrow{44} \sigma_E = 220\text{keV}$$

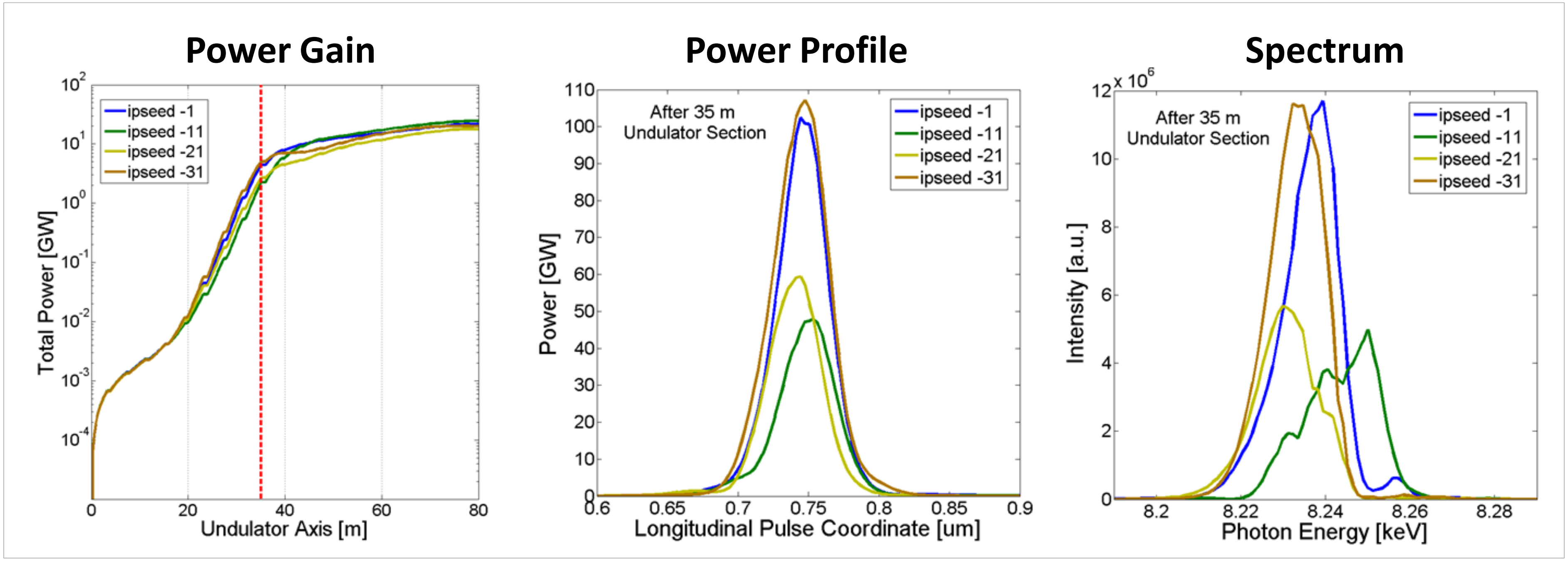
After BC2



- Incoherent Synchrotron Radiation (ISR) effect $\sigma_{\delta_{ISR}} \approx \frac{1}{L_B}\sqrt{(4.13\cdot 10^{-13})E^7\left|\theta_B{}^3\right|} \rightarrow {}^{12.5\text{keV}}/_{\text{BM}}$
- ISR effect is amplified by the compression $\sigma_{BM} = C_{BM}\cdot\sqrt{\sigma_i{}^2 + \sigma_{\delta_{ISR}}{}^2} \Rightarrow \sim 252\text{keV}, \quad \approx 50$
- CSR effect is very small $\sigma_{\delta_{CSR}} \approx 0.22 * \frac{N\, r_e\, L_B}{\gamma\, R^{2/3}\, \sigma_z{}^{4/3}} \rightarrow 20\text{keV in BM4}$

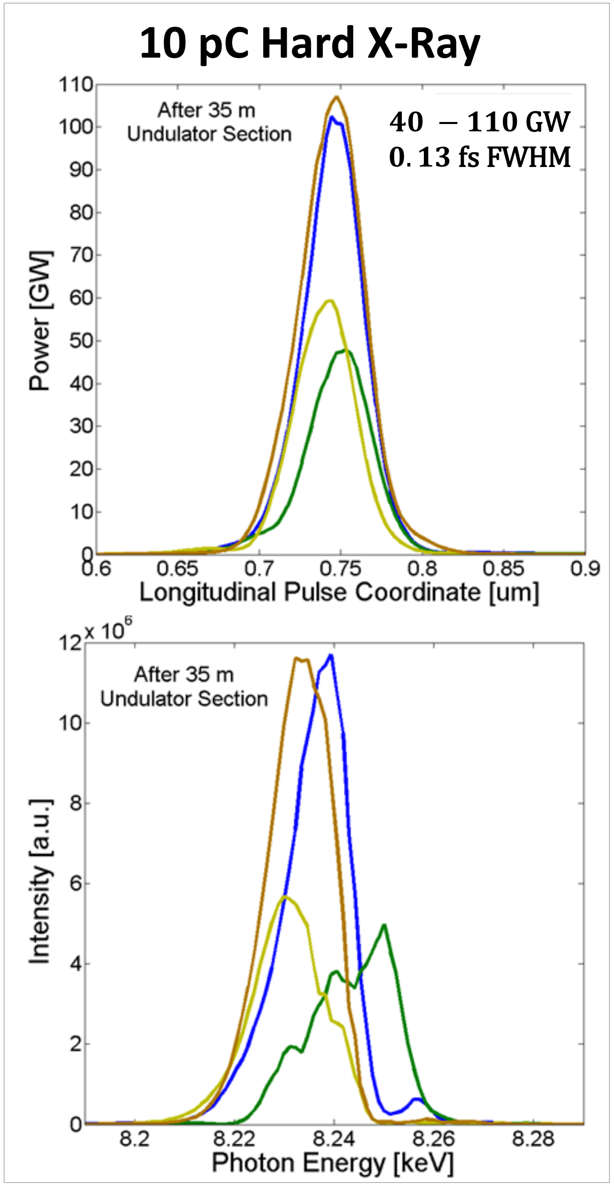
➢ **For 1pC, 3 pC, 5 pC, 10 pC and 20 pC Hard and Soft X-Rays**

GENESIS 1.3 Simulation Results for 10 pC including Longitudinal Space Charge (LSC)



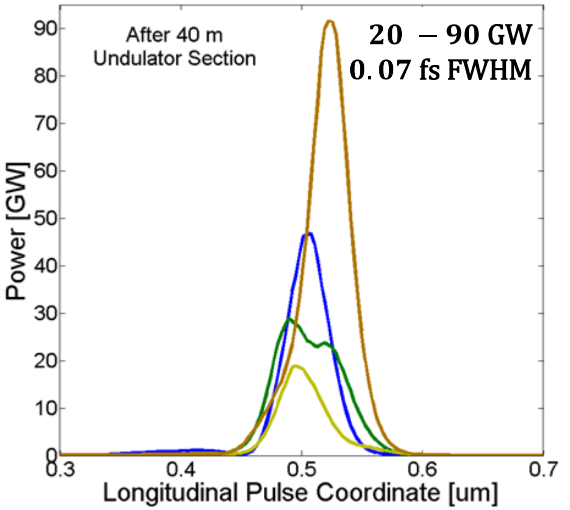
- single-spike power profile
- peak power 40 – 110 GW
- duration of 0.13 fs FWHM
- spectrum with 1-3 modes

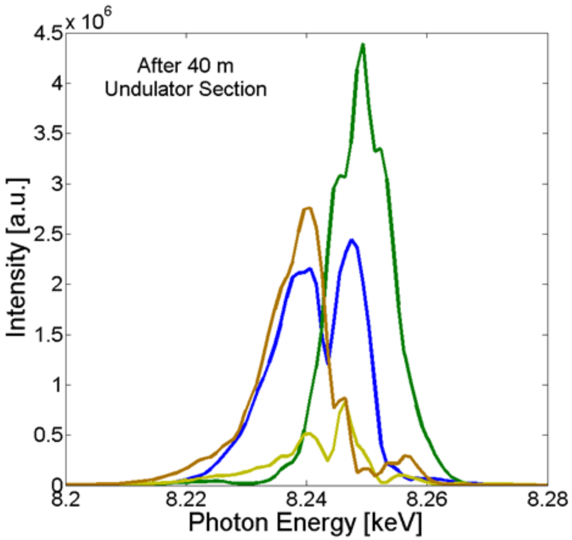
Summary of the Hard X-Ray Simulation Results



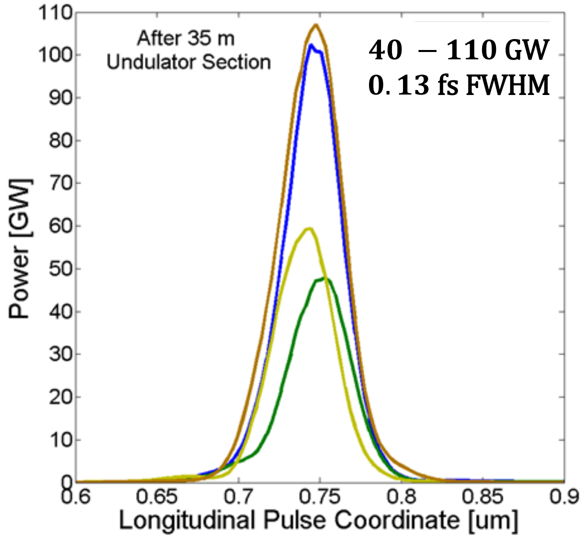
Summary of the Hard X-Ray Simulation Results

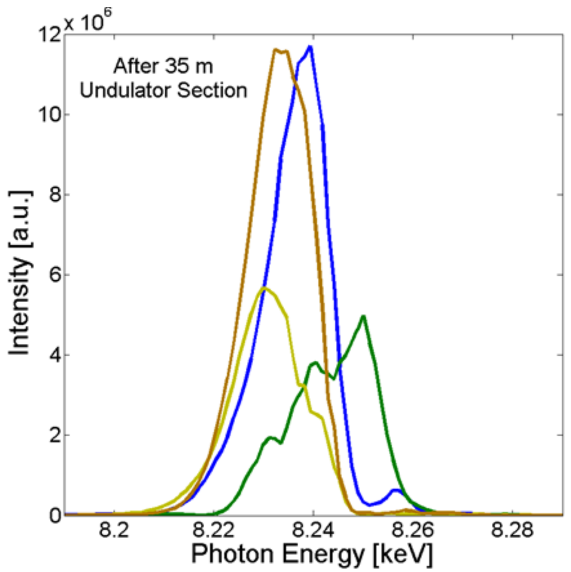
5 pC Hard X-Ray



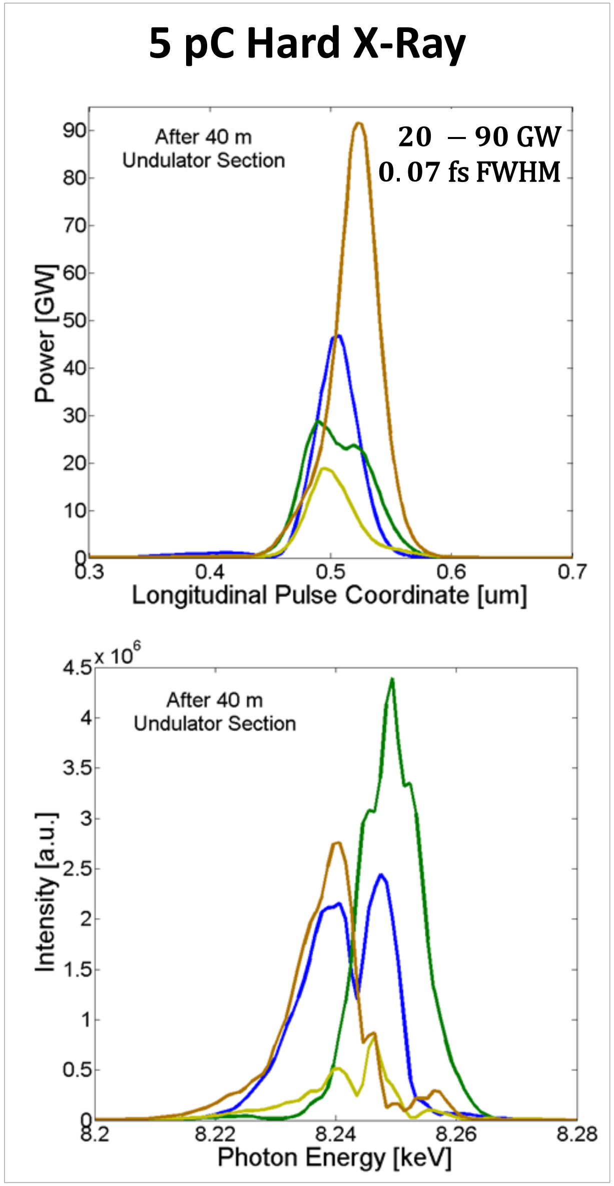


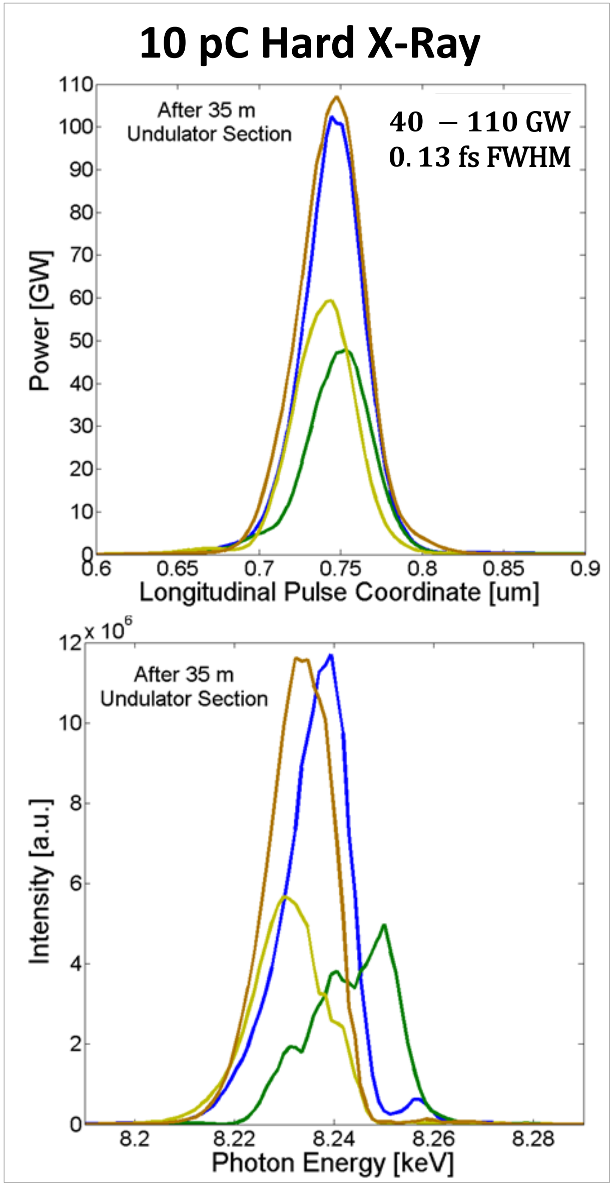
10 pC Hard X-Ray

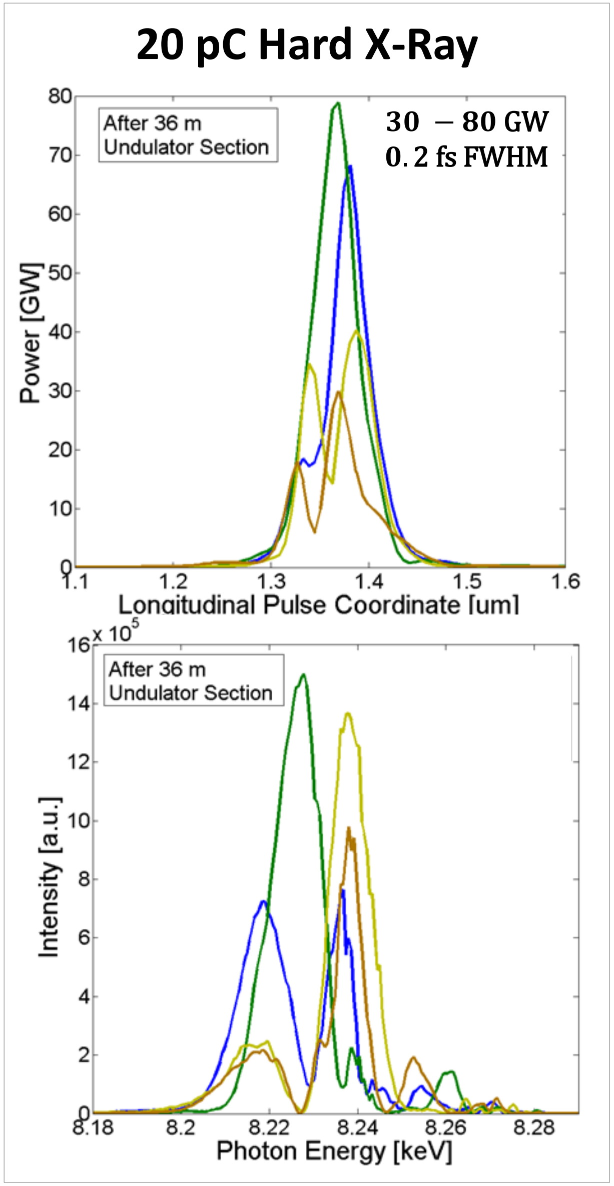




Summary of the Hard X-Ray Simulation Results







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1. **Motivation**
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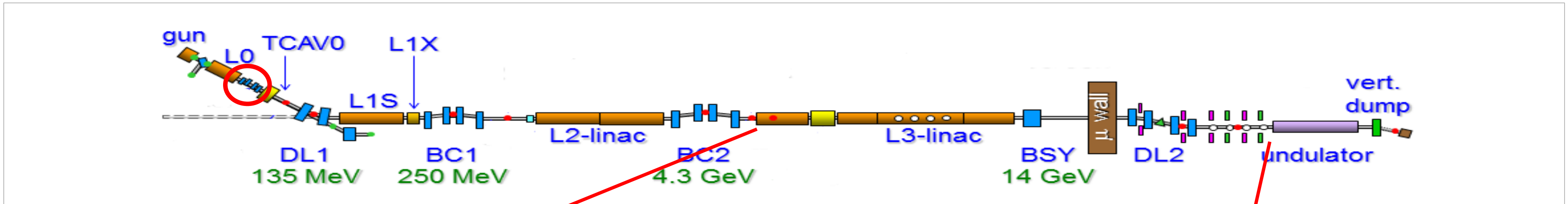
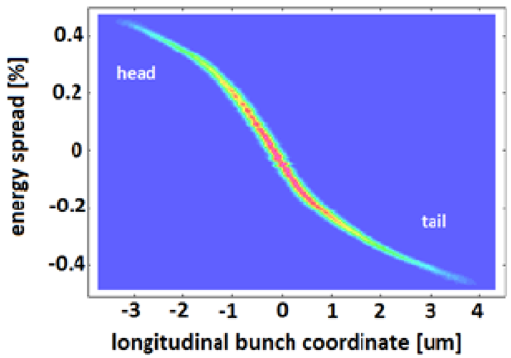
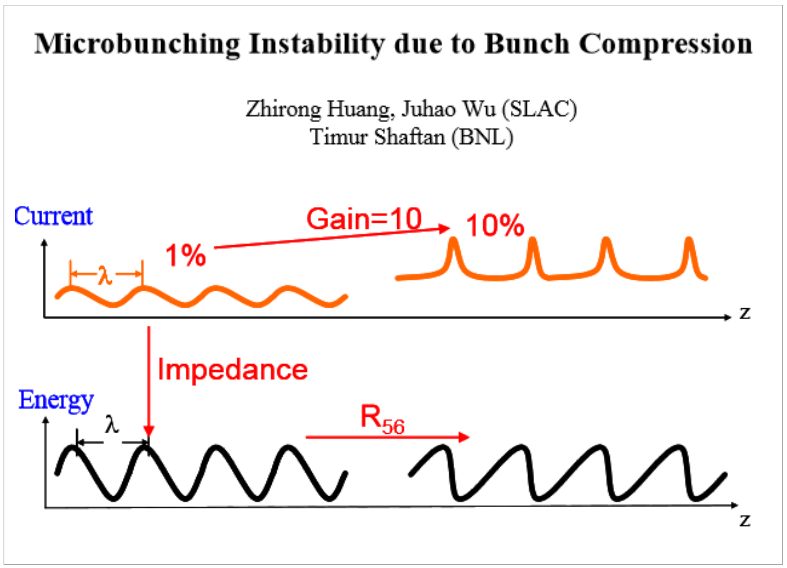
4. **Start-to-End Simulations**
    1. Hard X-Ray
    2. Soft X-Ray [electron energy 4.3 GeV, wavelength 1.5 nm]
    3. RF Phase Jitter
5. **Measurements**
6. **Conclusion**
7. **Outlook**

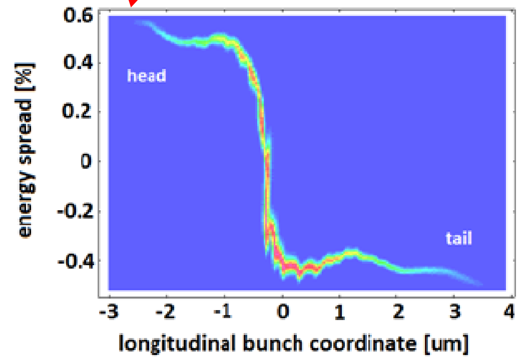
3. Start-to-End Simulations

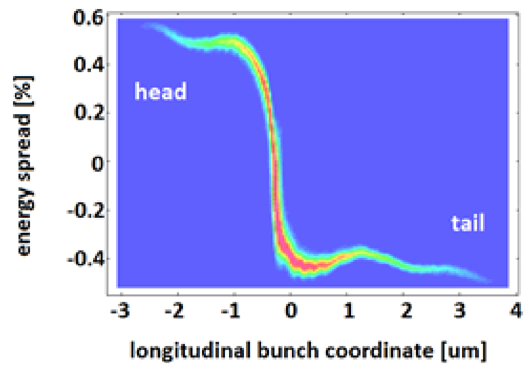
Soft X-Ray Single-Spike Pulses: The Micro-Bunching Instability





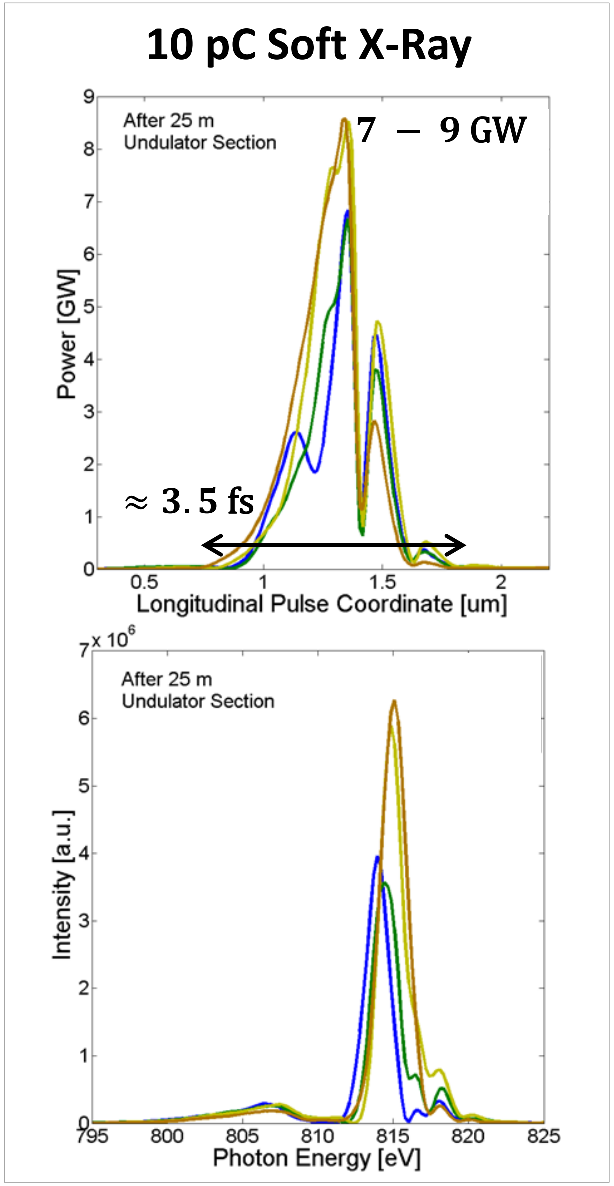






LASER HEATER

Summary of the Soft X-Ray Simulation Results



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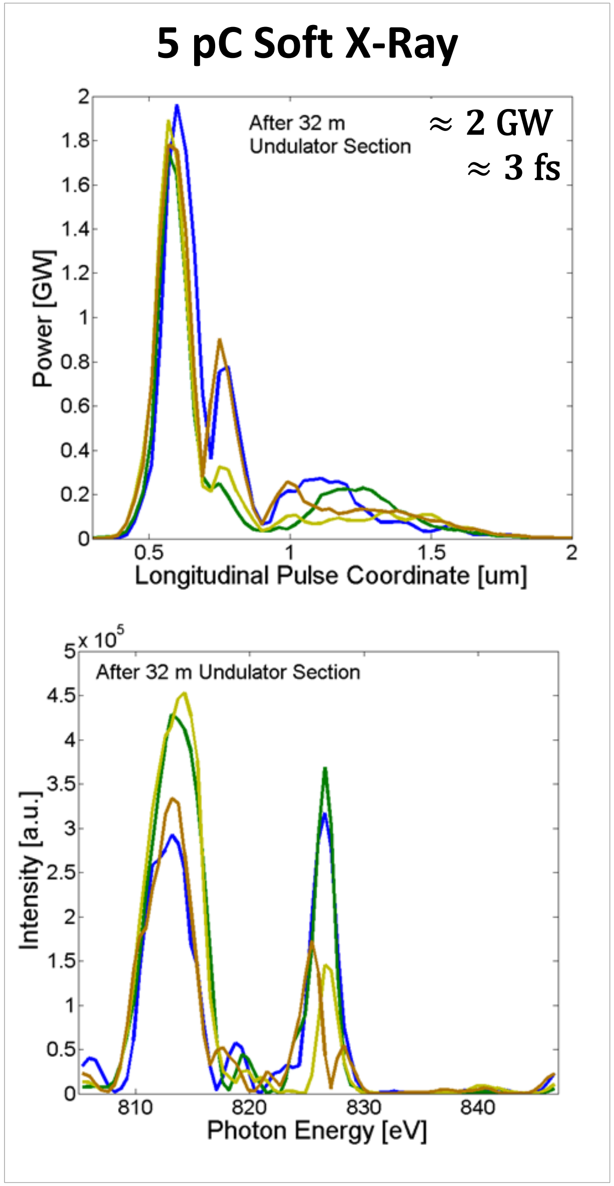
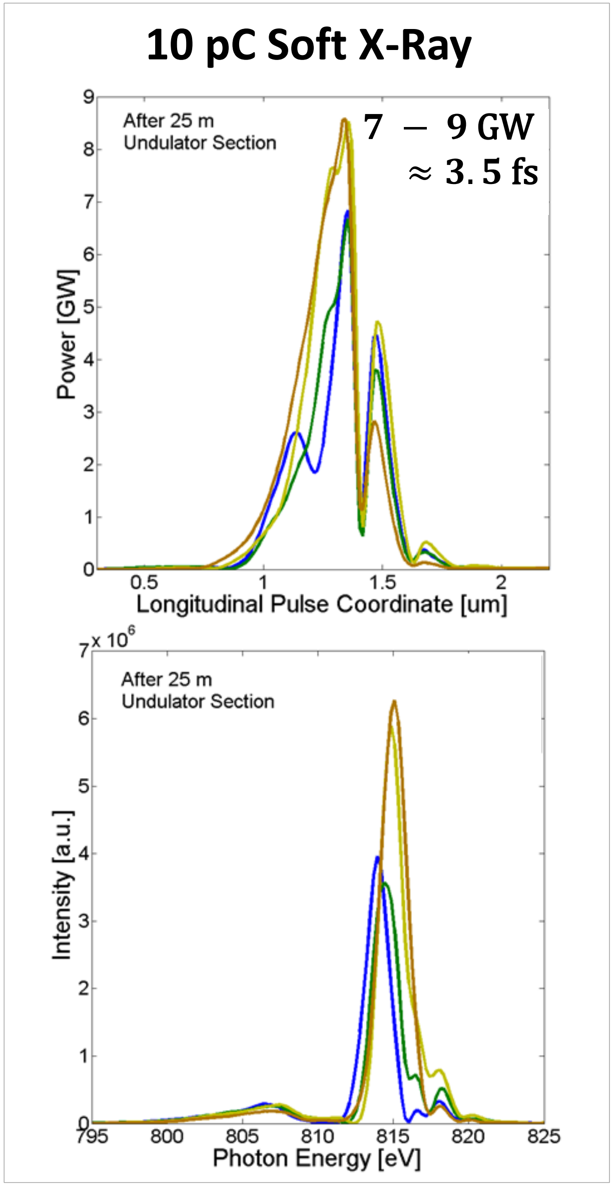
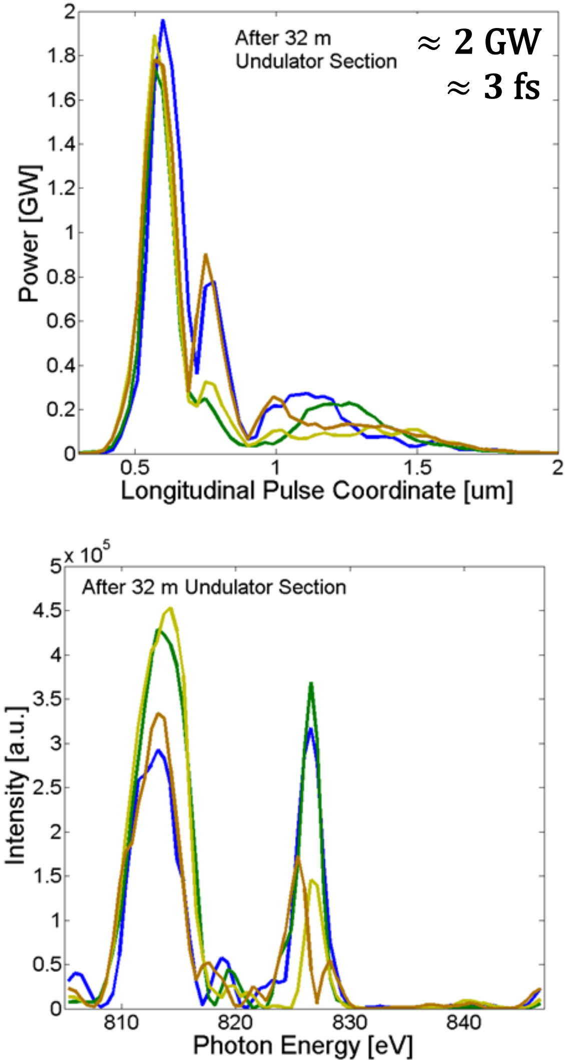
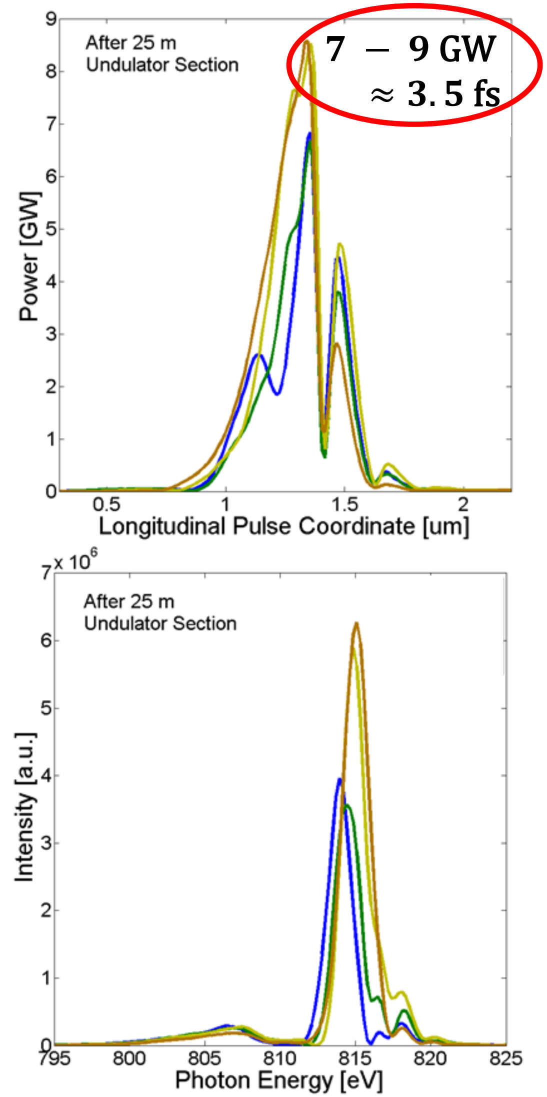




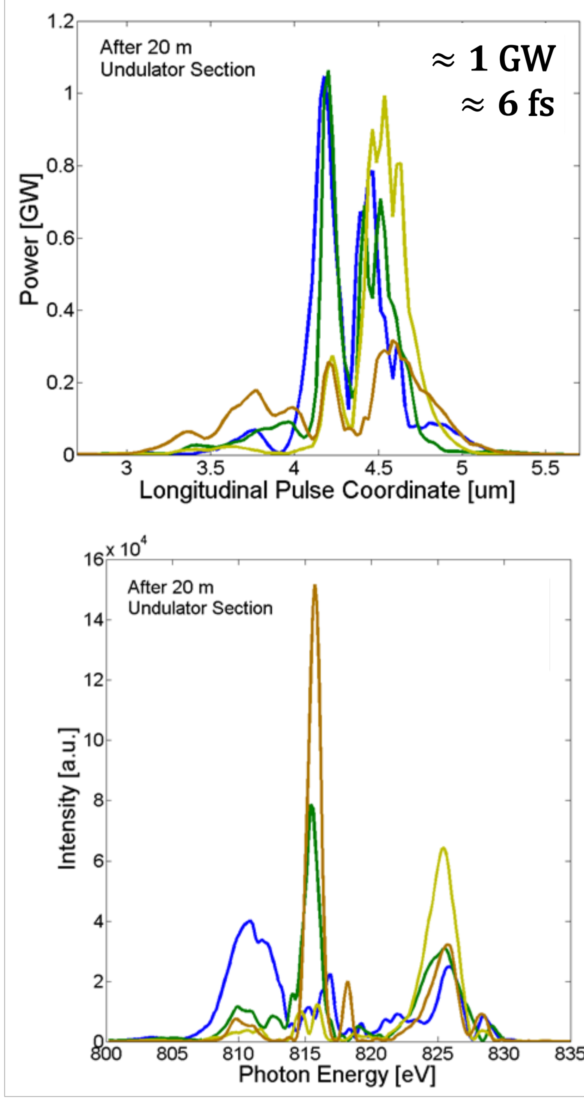
5 pC Soft X-Ray



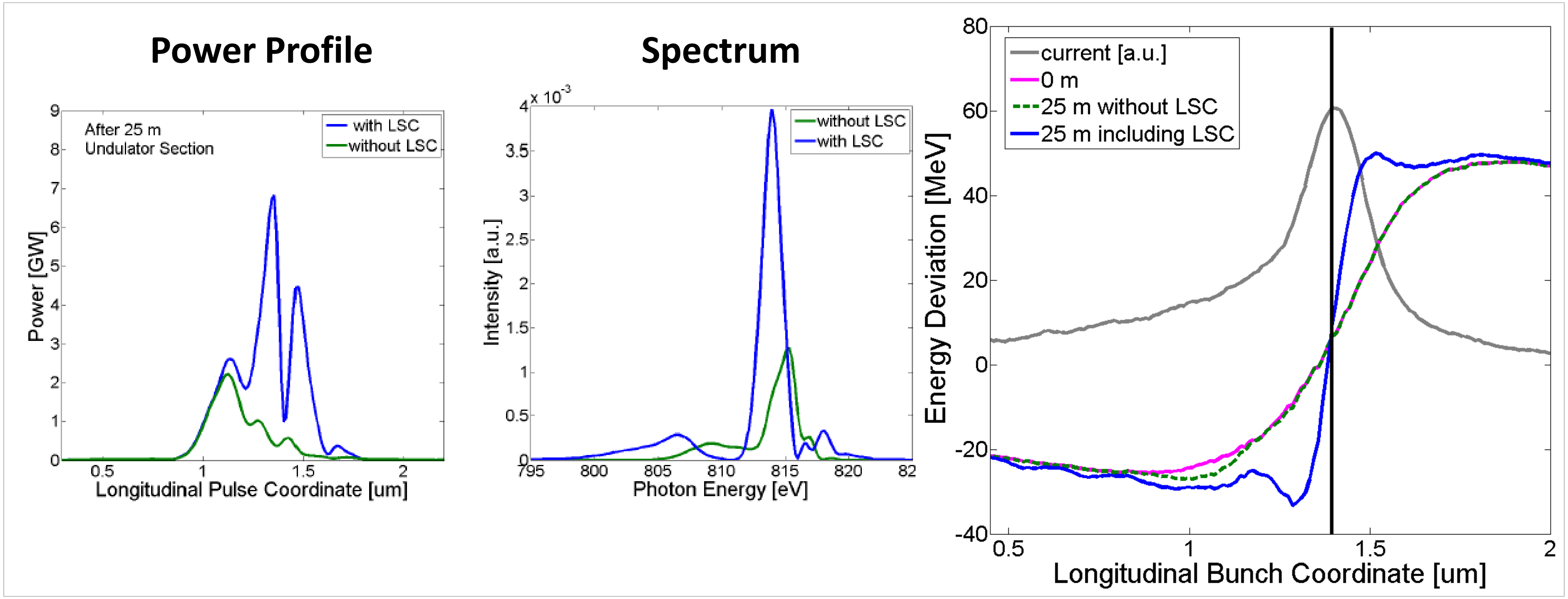
10 pC Soft X-Ray



20 pC Soft X-Ray



Comparison of GENESIS 1.3 results for 10 pC with & without LSC



- peak power increases by a factor of 3.5 for simulations **including** LSC
- equal number of modes
- ➢ “Self-Tapering” depends on bunch shape, peak current & LSC forces
- ➢ requires further studies

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The Simulation Results

Parameters	Hard X-Ray Optimization			Soft X-Ray Optimization		
Electron Energy [GeV]	13.6			4.3		
Wavelength λ_l [Å]	1.5			15		
Charge Q [pC]	5	10	20	5	10	20
Peak Power [GW]	20 - 90	40 - 110	30 -80	≈ 2	7 - 9	≈ 1
No. of spikes in temporal dist.	1	1	1-2	≥ 3	3 - 4	> 6
No. of spikes in spectral dist.	2-3	1-3	> 3	> 4	3 - 4	> 5

- Hard X-Ray Single-Spike Radiation Pulses are possible at LCLS.
- Soft X-Ray Single-Spike Radiation Pulses were not achieved with this approach.
  - tapered undulator
  - slotted foil

SLAC-PUB-14596

OPTIMIZATION FOR SINGLE-SPIKE X-RAY FELS AT LCLS WITH A LOW CHARGE BEAM*

L. Wang[#], Y. Ding and Z. Huang, SLAC, CA 94025, U.S.A.

The Influence of RF Phase Jitter on the Peak Current

Charge	Iris Diameter [mm]	Current Fluctuation for L1 Phase Jitter $\pm 0.1°$	Current Fluctuation for L2 Phase Jitter $\pm 0.1°$
1 pC	0.4	-	$\leq 16\,\%$
5 pC	1.0	$\leq 20\,\%$	$\leq 22\,\%$
	0.4	$\leq 23\,\%$	$\leq 30\%$
10 pC	1.5	$\leq 13\,\%$	$\leq 63\,\%$
	0.5	$\leq 41\,\%$	$\leq 65\,\%$
20 pC	0.7	$\leq 69\,\%$	$\leq 102\,\%$

the current fluctuation

- larger for linac L2 phase jitter
- increases with higher bunch charge
- increases smaller iris diameter

➢ depends on the charge density (space charge forces)

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The Influence of RF Phase Jitter on the Peak Current

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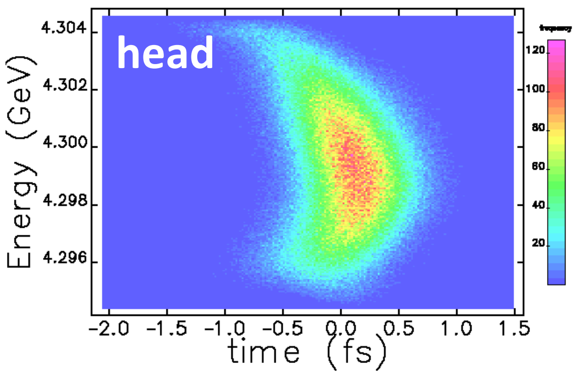
	0.5	$\lesssim 41\,\%$	$\lesssim 65\,\%$
20 pC	0.7	$\lesssim 69\,\%$	$\lesssim 102\,\%$

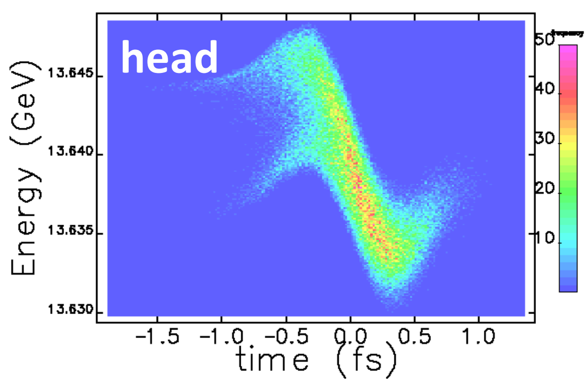
$\mp 0.05^\circ$

ELEGANT Simulation Results with a Bunch Charge of 1 pC

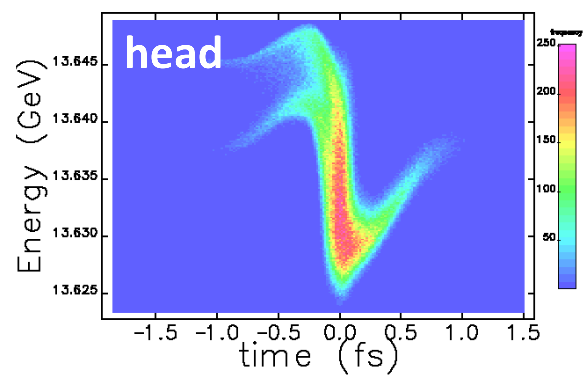
bunch compressor BC2 end



linac L3 end



undulator entrance



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    1. 20 pC Measurements
    2. 10 pC Measurements and Comparison with Simulations
6. **Conclusion**
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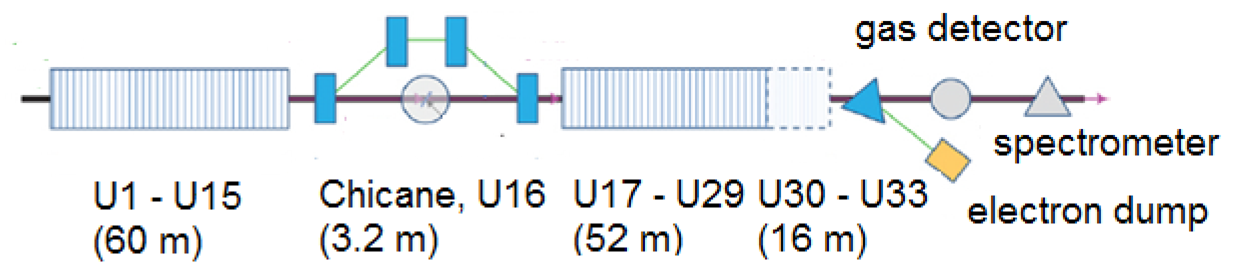
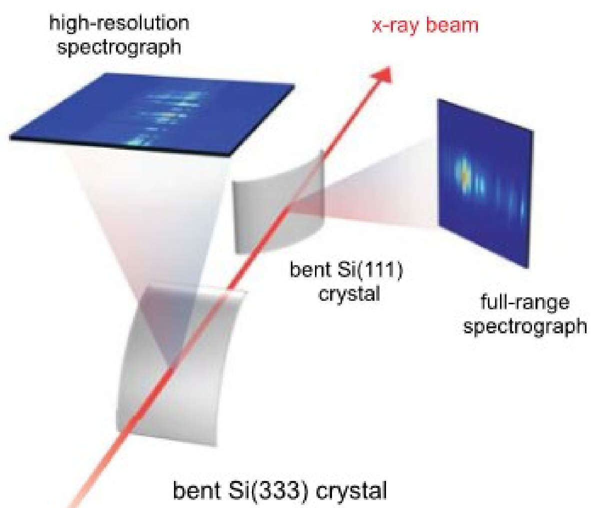
Measurement of the SASE Radiation Spectra



A single-shot transmissive spectrometer for hard x-ray free electron lasers

Diling Zhu, Marco Cammarata, Jan M. Feldkamp, David M. Fritz, Jerome B. Hastings, Sooheyong Lee, Henrik T. Lemke, Aymeric Robert, James L. Turner, and Yiping Feng
Linac Coherent Light Source, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA

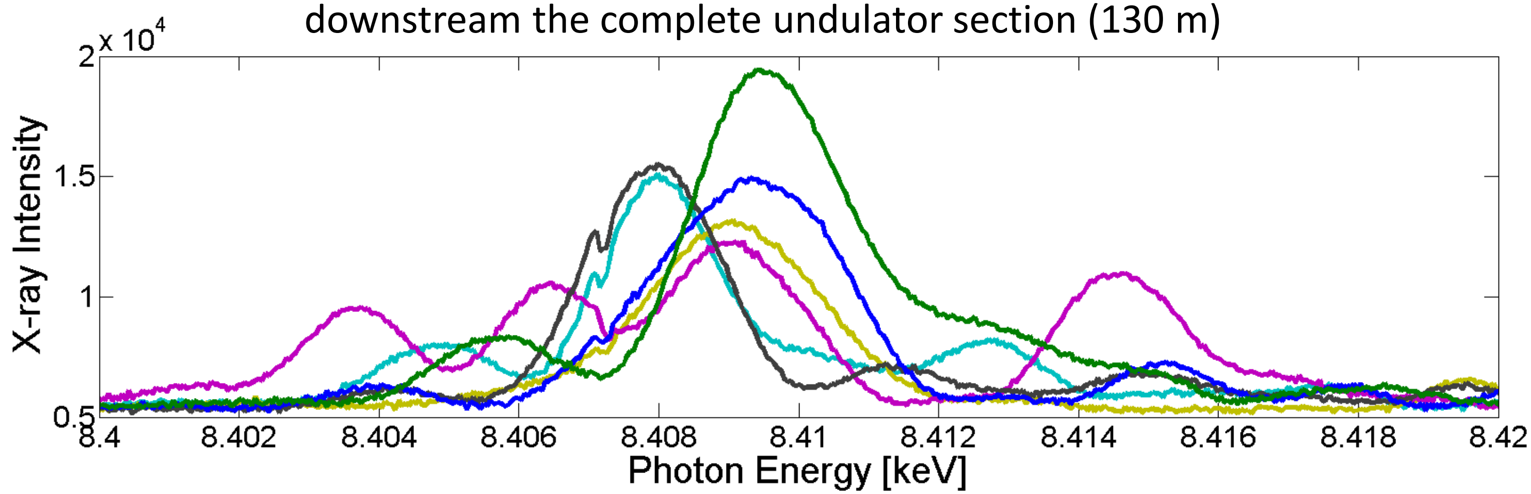


at LCLS until now only bent Si(333) crystal

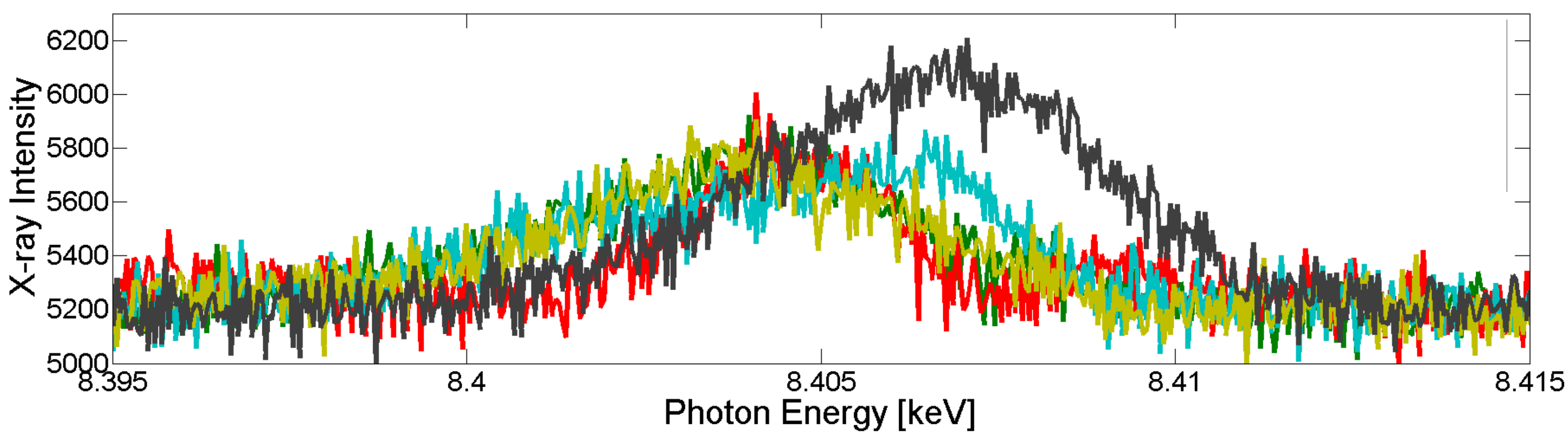
- spectral range of ~ 20 eV
- resolution of ~ 0.13 eV
- transmits $> 83\%$ at 8.3 keV

20 pC Single-Shot SASE Spectra Measurements for 13.6 GeV (1.5 Å)

downstream the complete undulator section (130 m)

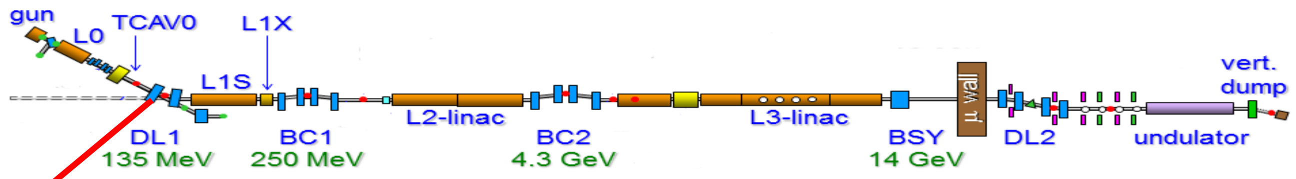


downstream 80 m of undulator section



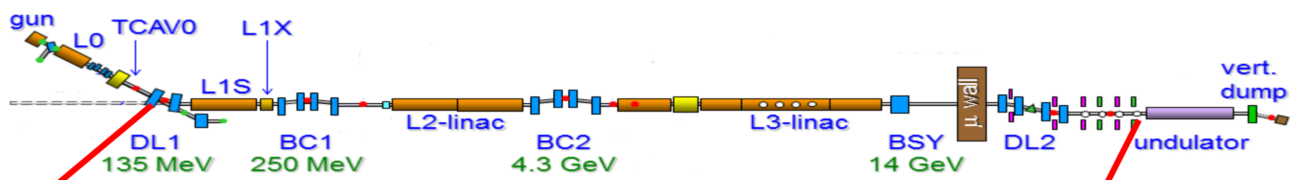
Outline

Setup and Measurements



Parameter	Simulation	Measurement
Transverse Emittance $\epsilon_{n,x}/\epsilon_{n,y}$ [μm]	0.17	0.22 / 0.23 ± 0.01
Bunch Size σ_x/ σ_y [μm]	59.2 / 55.5	-
Bunch Length σ_z [μm]	187.5	219.4 ± 9.4
Energy Spread ΔE [keV]	10.0	-

Setup and Measurements



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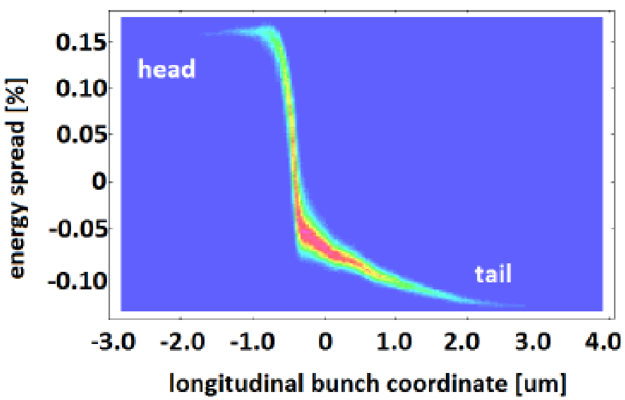
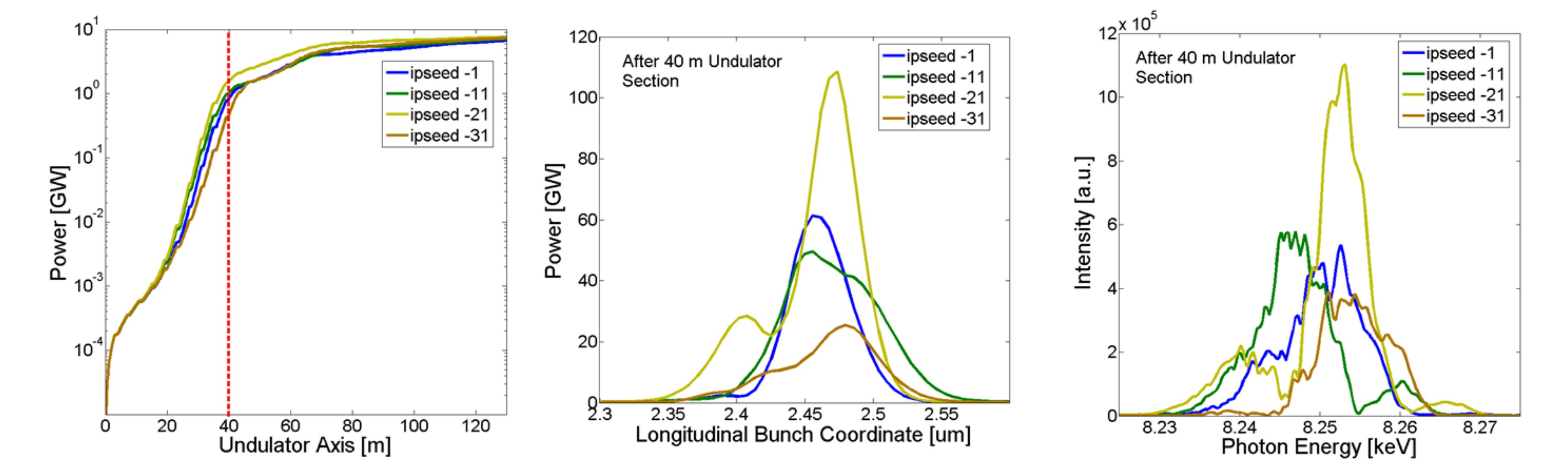


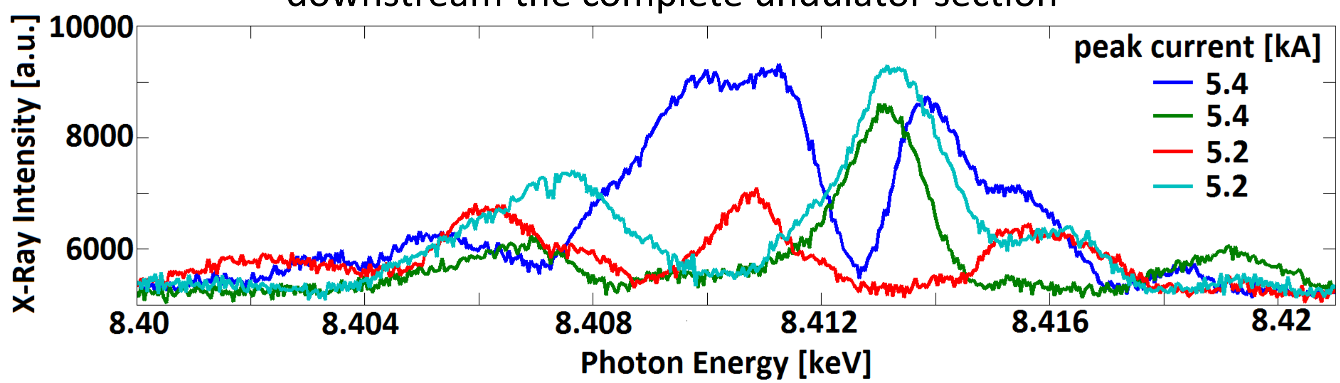
Beam Parameters at Undulator Entrance	Simulations	Measurements
normalized emittance $\epsilon_{n,x}$ / $\epsilon_{n,y}$	0.30 μm / 0.17 μm	-
rms beam size σ_x / σ_y	23.9 μm / 11.5 μm	-
rms bunch length σ_z	≈ 124 nm	≈ 285 nm ± 51 nm
peak current I_p	5.2 kA	5.3 kA ± 1.0 kA
energy deviation ΔE	4 MeV	-

GENESIS 1.3 Simulation Results including LSC

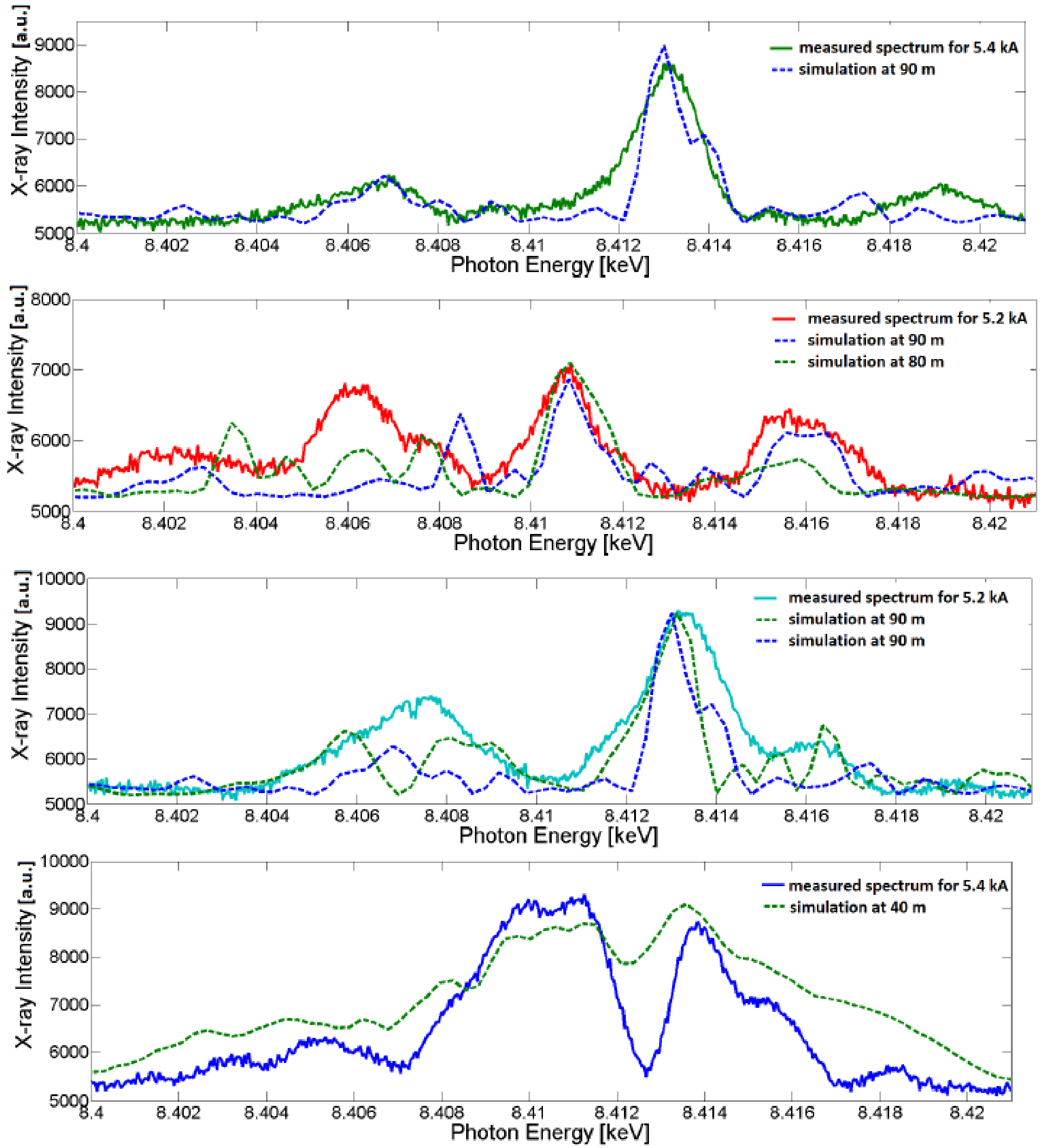


10 pC Single-Shot SASE Spectra Measurements

downstream the complete undulator section



4.2 10 pC Measurements



Hard X-Ray single-spike pulses are possible at LCLS.

Simulations

- hard X-Ray single-spike radiation pulses are possible
- 10 pC, 100 GW, 0.13 fs
- soft X-Ray more difficult
- 10 pC soft X-Ray case shows „self-tapering“
  - ➢ requires further studies
- RF phase jitter tolerance 0.05°
- strong ISR effects in bunch compressors

Measurements

- measurements agree with simulations

➢ more sensitive diagnostic required

➢ XTCAV bunch length measurements

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