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Early Career Research Program

FEL 2017: TUB04

Recent On-Line Taper Optimization on LCLS

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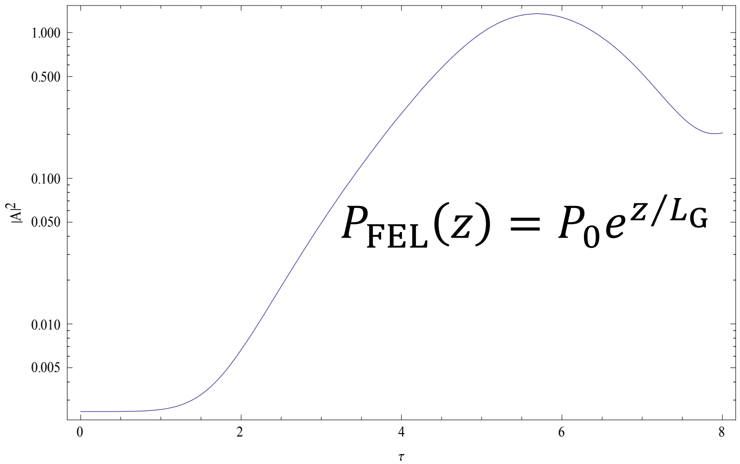
SLAC NATIONAL ACCELERATOR LABORATORY

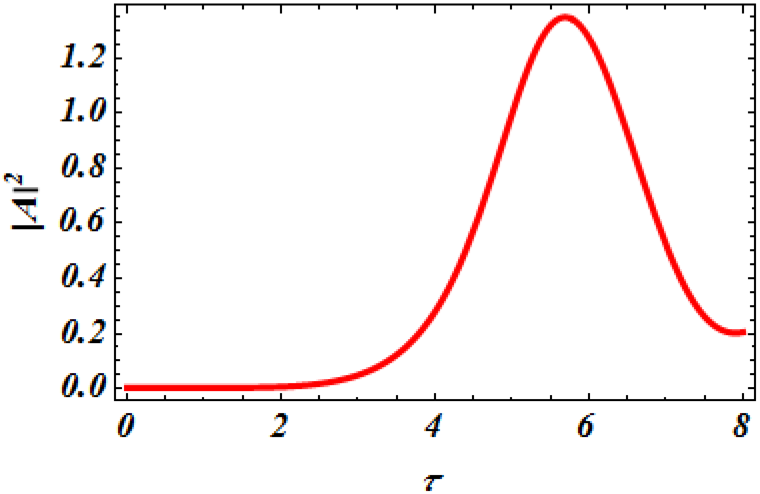
OUTLINE

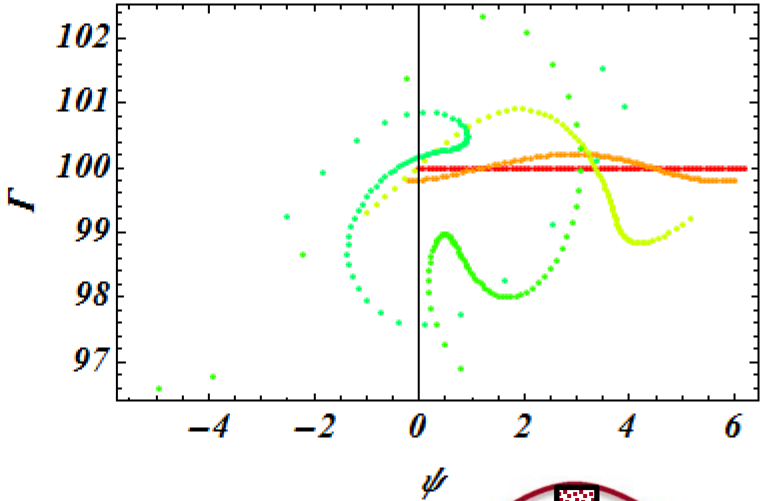
- The work reported here is within my Early Career Research Program goals: to produce high peak power FEL
  - Approach: Self-seeded Tapered FEL
- FEL physics:
  - High-gain exponential growth region: dispersion relation→ growth rate
  - Low-gain post-saturation tapered region: Hamiltonian dynamics

OUTLINE

- Exponential growth
  - Power Gain
  - Phase Space Rotation







ANALYTICAL ESTIMATE

- Post-saturation coherent emission
  - Look at the scaling

$$P_{coh} = \frac{Z_0 K^2 [JJ]^2}{8\sqrt{2}4\pi\sigma_x^2\gamma^2}\left(\int_0^{L_w} I_{pk}(z) b_1(z) dz\right)^2$$

  - Constant peak current, constant bunching factor:

$$P_{coh}(z) = \frac{Z_0 K^2 [JJ]^2 I_{pk}^2 b_1^2 z^2}{32\sqrt{2}\pi\sigma_x^2\gamma^2}$$

ANALYTICAL ESTIMATE

- Energy conservation, electron energy evolution

$$\frac{d\gamma_r}{dz} = -\mathcal{A}\frac{K^2 z}{\gamma_r^2}$$

where

$$\mathcal{A} = \frac{e[JJ]^2 Z_0 I_{pk} b_1}{2^{11/4} mc^2 \pi w_0 \sigma_x} \sin(\psi_r)$$

- Resonant condition gives the taper profile

$$K(z) \approx K_0 \left(1 - \frac{\mathcal{A}\mathcal{B}^2 \gamma_{r0}}{2K_0^2} z^2\right)$$

where $\mathcal{B} = (4\lambda_r)/\lambda_w$

PHASE SPACE—LCLS-II TYPE SYSTEM

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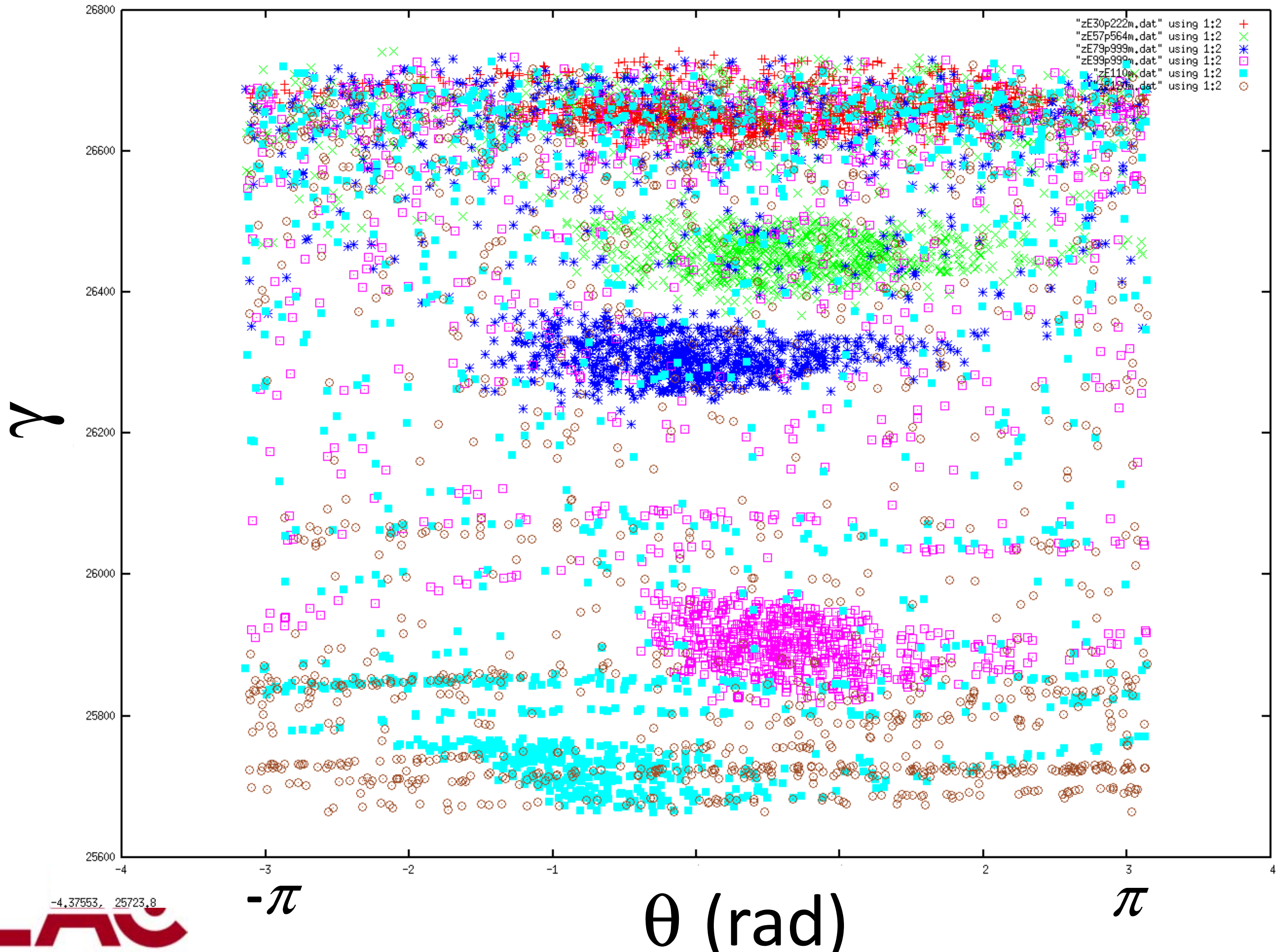
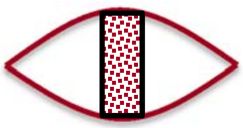
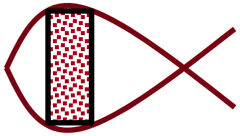
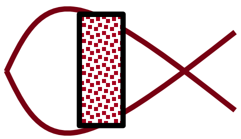
- At locations: 30, 60, 80, 100, 110, and 120 m









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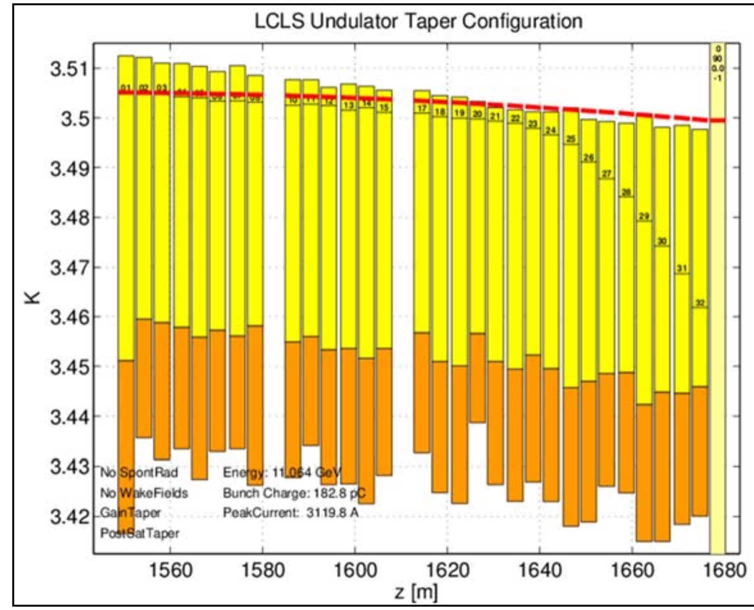
OPTIMIZATION

- Taper profile
  - Continuous function
    - Add high order terms

$$K(z) = K_0[1 - b_2(z - z_0)^2/{L_w}^2 - b_4(z - z_0)^4/{L_w}^4]$$

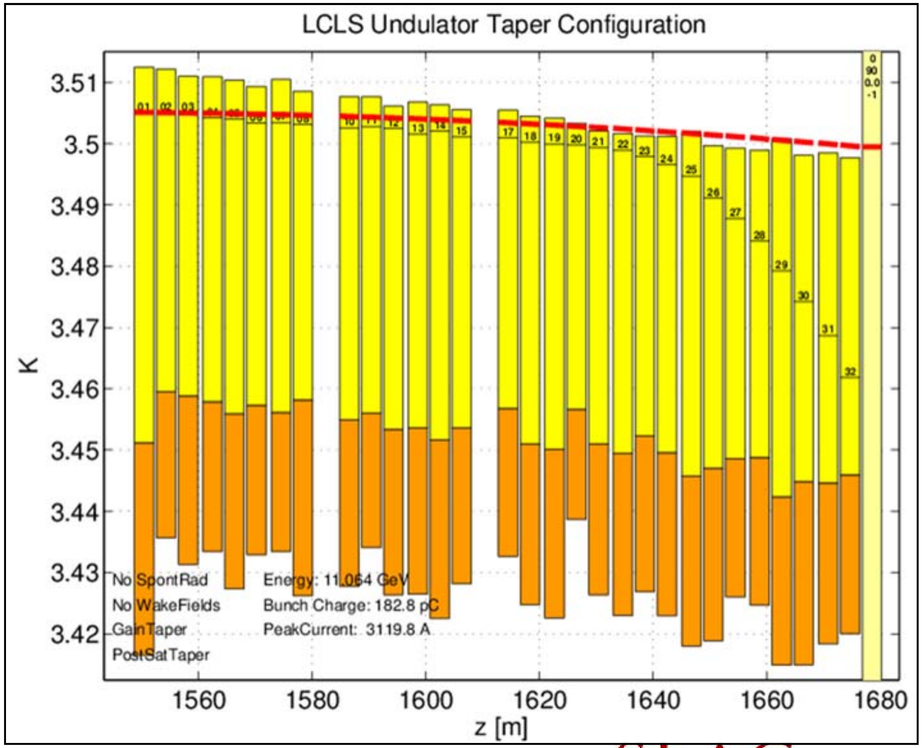
  - Discretized
    - Piecewise for 17^{th} – 32^{nd} undulator



- Optimizer
  - Robust Conjugate Direction Search (RCDS); — ***Huang, Corbett, Safranek, Wu*, NIMA, 2013**
  - Multi-Object Generic Algorithm (MOGA); — ***Wu et al.*, NIMA, 2017**
  - Particle Swarm Optimization (PSO); — ***Fang, Wu, et al.*, FEL Proc., 2015**
  - Extreme Seeking (ES); — ***Scheinker, Huang, Wu*, IEEE, 2017**
  - Simulated Annealing (SA); — ***Gupta, Fang, Wu, et al.*, IPAC Proc., 2015**
  - Reinforcement Learning (RL); — ***Wu, Hu, Fang, et al.*, 2017**
  - Markov Chain Monte Carlo (MCMC). — ***Wu, Setiawan, et al.*, 2017**

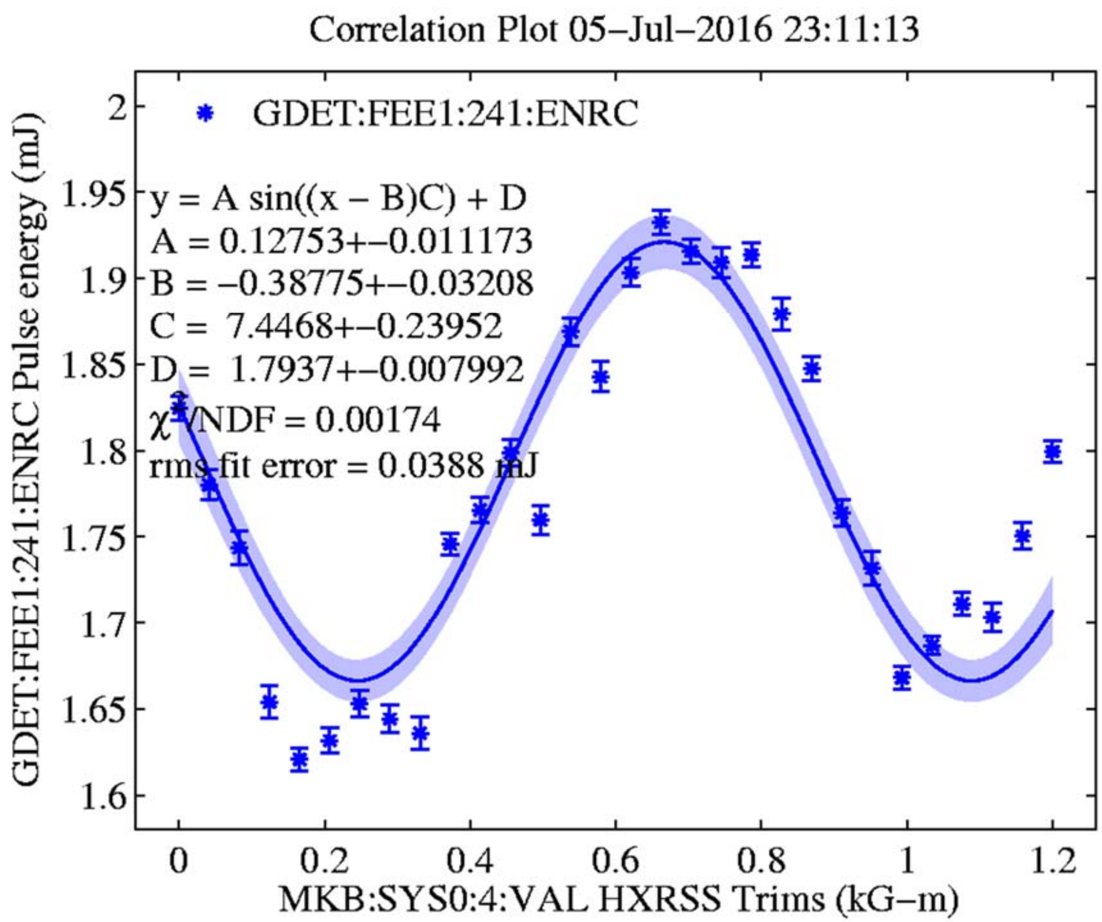
UNDULATOR

- Three Sections
  - 1 (,4) – 8: $K_j = K_{1(,4)}[1 - b_1(j - 1(,4))]$ for $j \in [1(,4)\ 8]$: SASE from 1st undulator, and seeding from 4th undulator
  - 10 – 15: $K_j = (K_8 + \Delta K_{10})[1 - b_1(j - 10)]$ for $j \in [10\ 15]$
  - 17 – 32: $K_j = (K_{15} + \Delta K_{17})[1 - b_1(j - 17) - b_2(j - j_2)^2 - b_4(j - j_4)^4]$ for $j \in [17\ 32]$
- Parameters
  - b_1: linear taper for Spontaneous Emission & Wakefield; ΔK_{10} and ΔK_{17}: detuning, phase matching; j_2 and j_4: starting point for quadratic and quartic taper



EXPERIMENT

- Seeding phase matching
- Orbit
- Overall residual chirp (XTCAV)
- Seeding
  - Use line with wider bandwidth to find the signal, and then switch to line with narrower bandwidth
  - Yaw, pitch

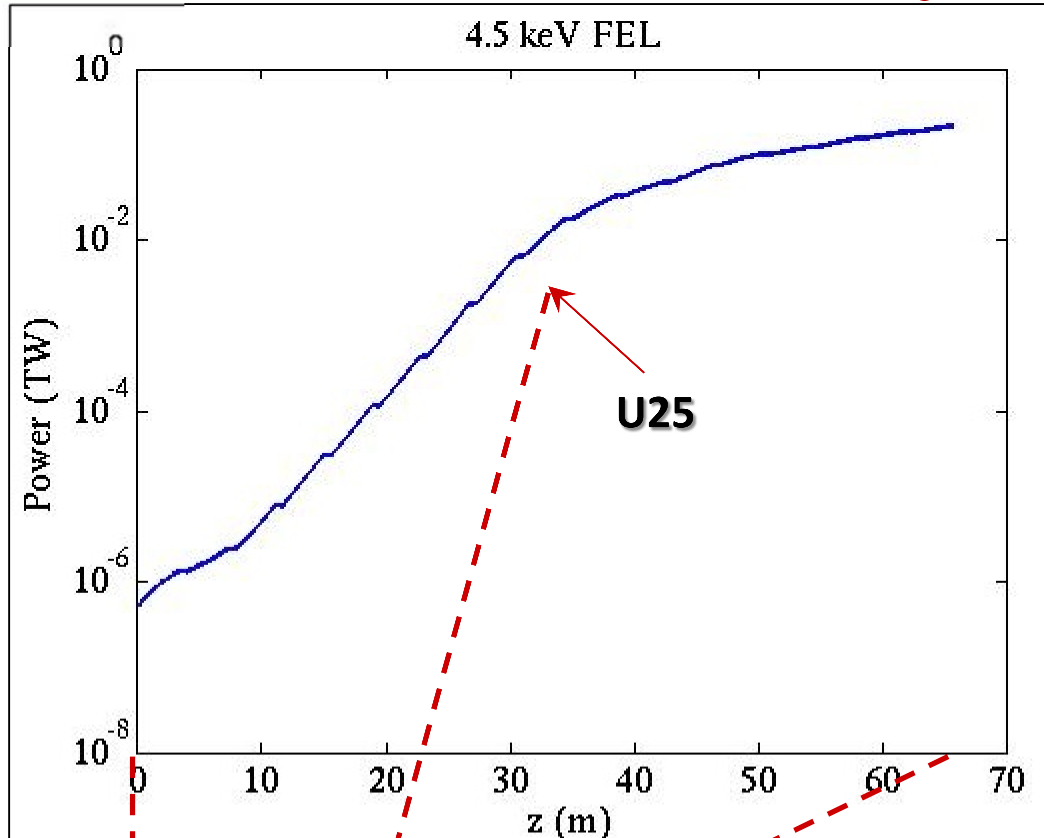


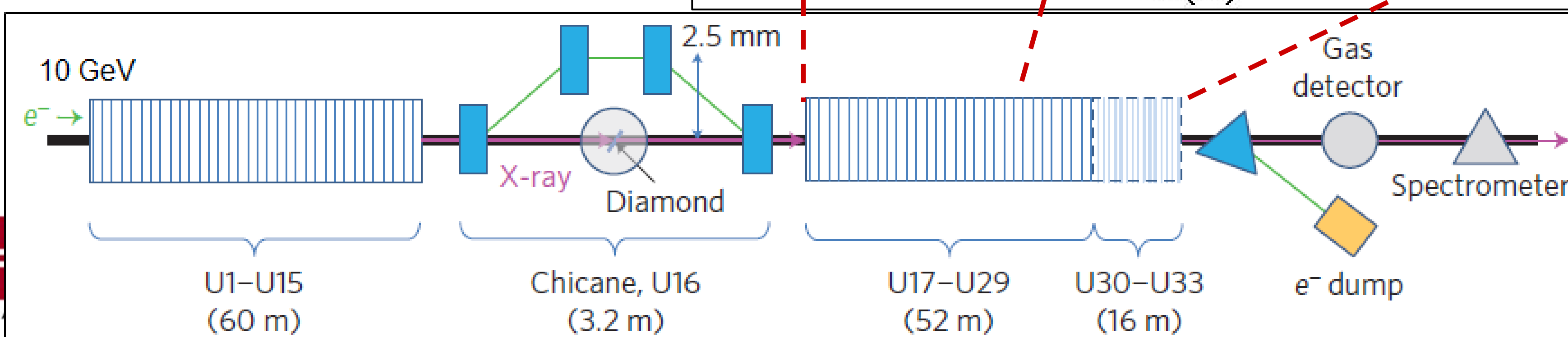
Over 100 GW SS @ 4.5 keV

- Motivation:
  - To demonstrate high-power feasibility at LCLS and LCLS-II.
- Method:
  - 4.5 keV Hard X-ray Self-seeding (HXRSS).
  - Maximizing LCLS taper of 0.8 %.

OVER 100 GW SS @ 4.5 KEV

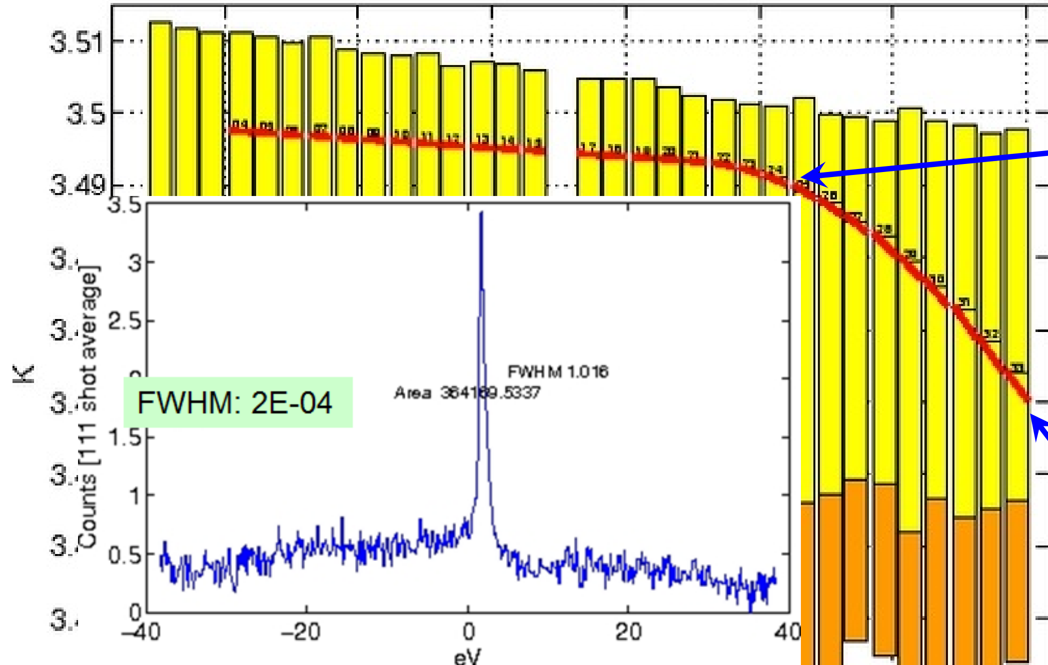
- LCLS has total of 33 undulator section; Self-seeding put the monochromator at U16; U17 – U33 for amplification
- Use [-1,1,1] to configure self-seeding at **4.5** keV
- 150 pC, 3 kA, U4-U15→ SASE FEL, seed FEL > 1 mJ

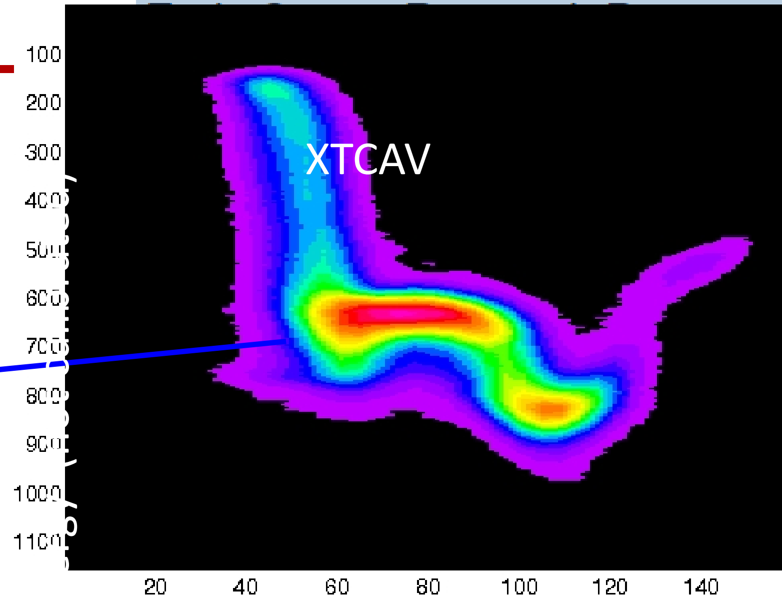


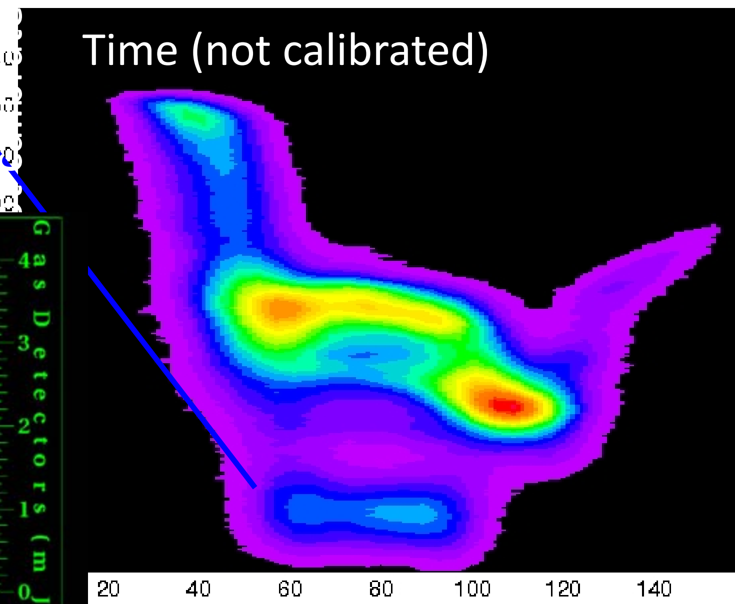


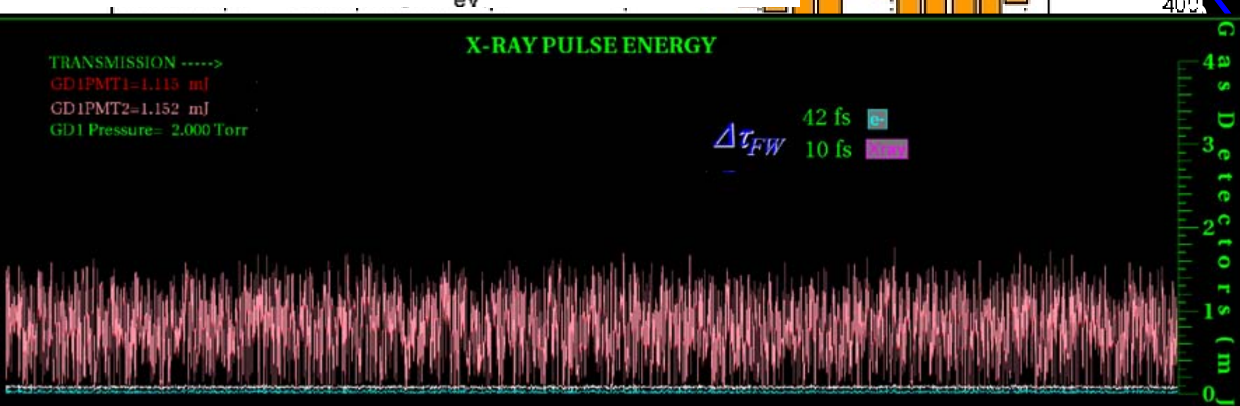
OVER 100 GW SS @ 4.5 KEV

- 4.5 keV FEL > 1 mJ in 10 fs → > 100 GW
- FWHM Bandwidth: ~ 1 eV → 2E-04









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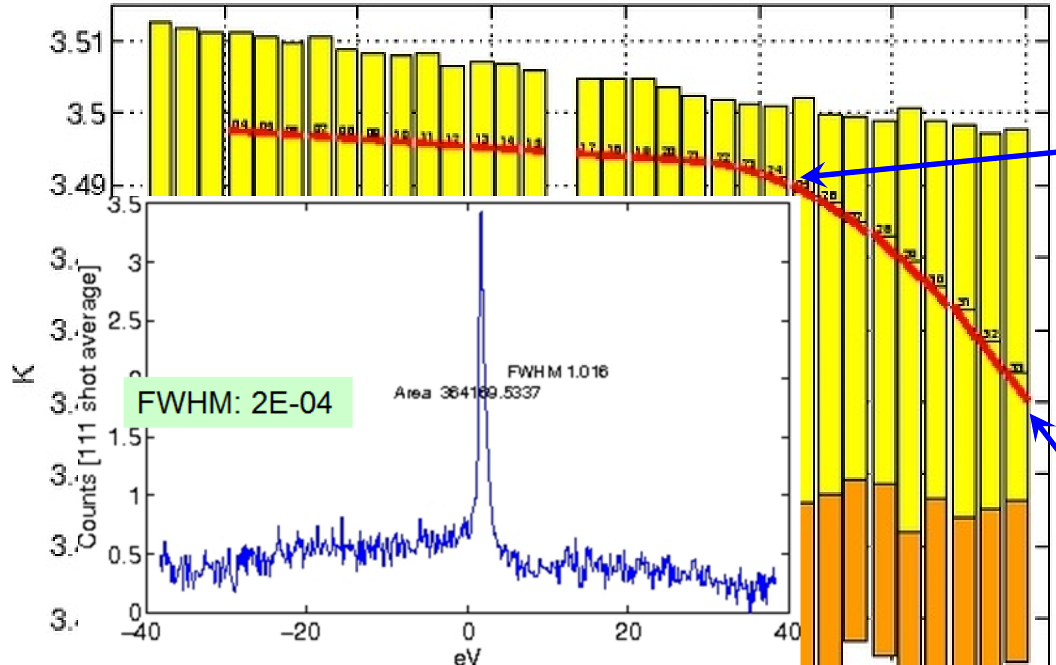
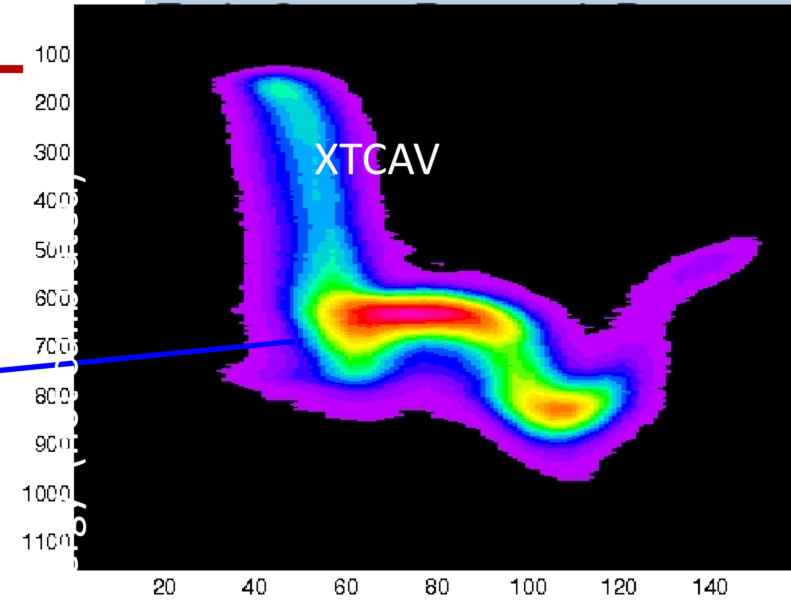
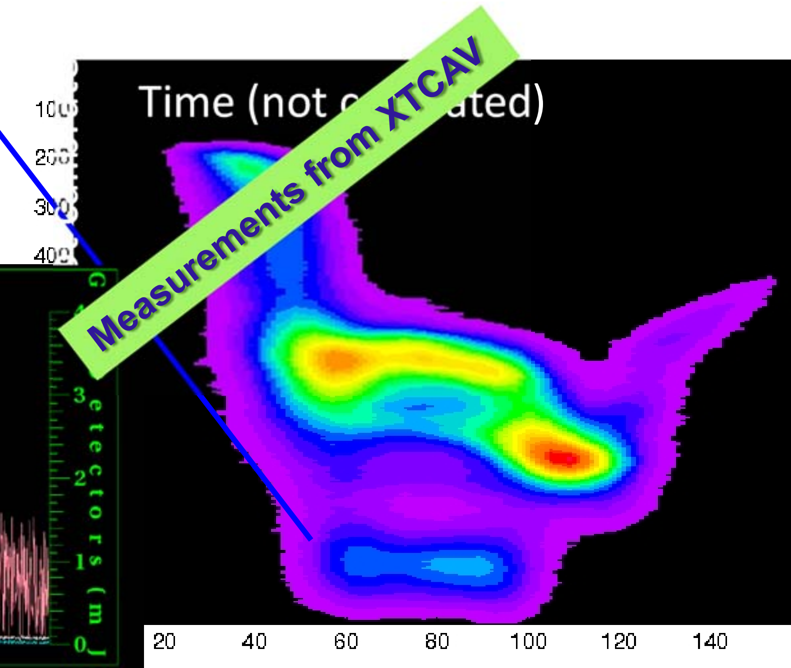
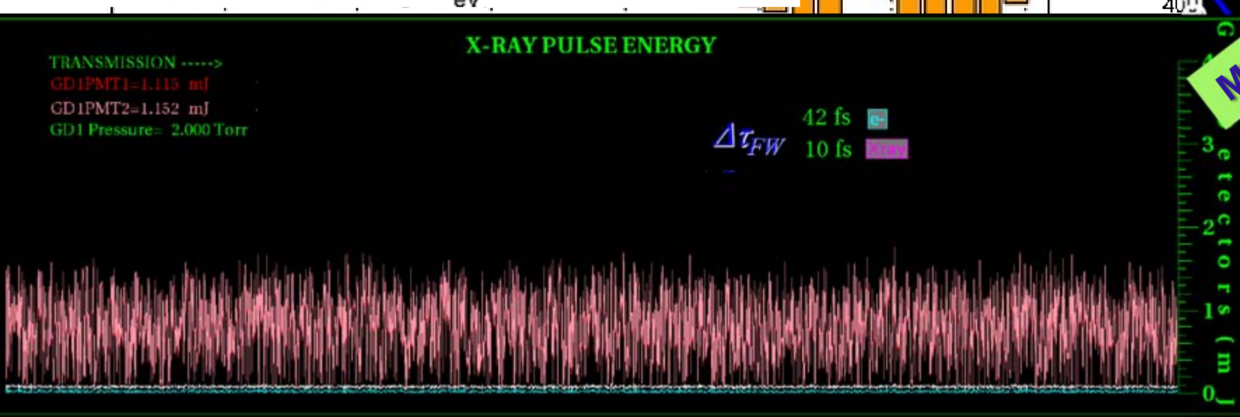
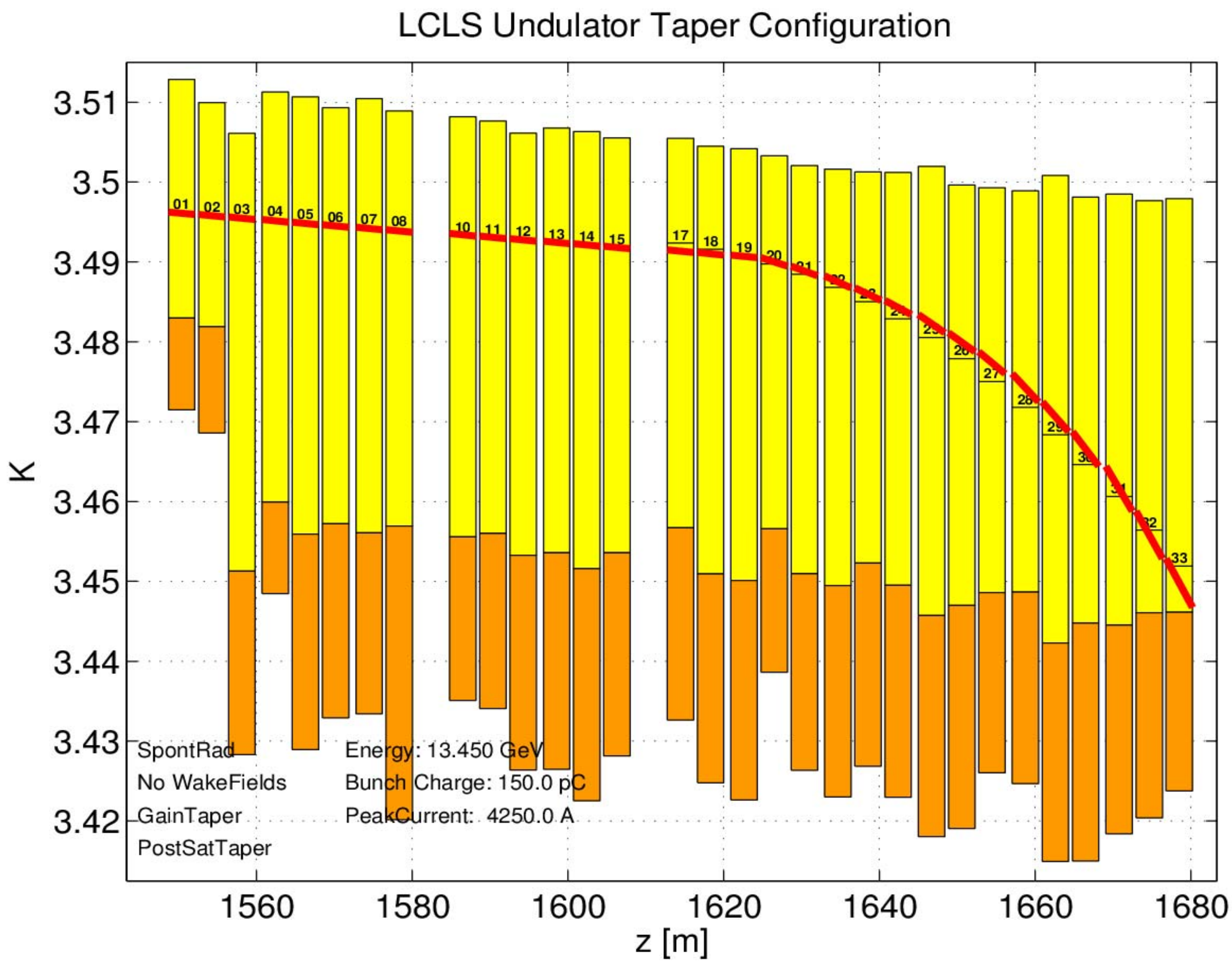






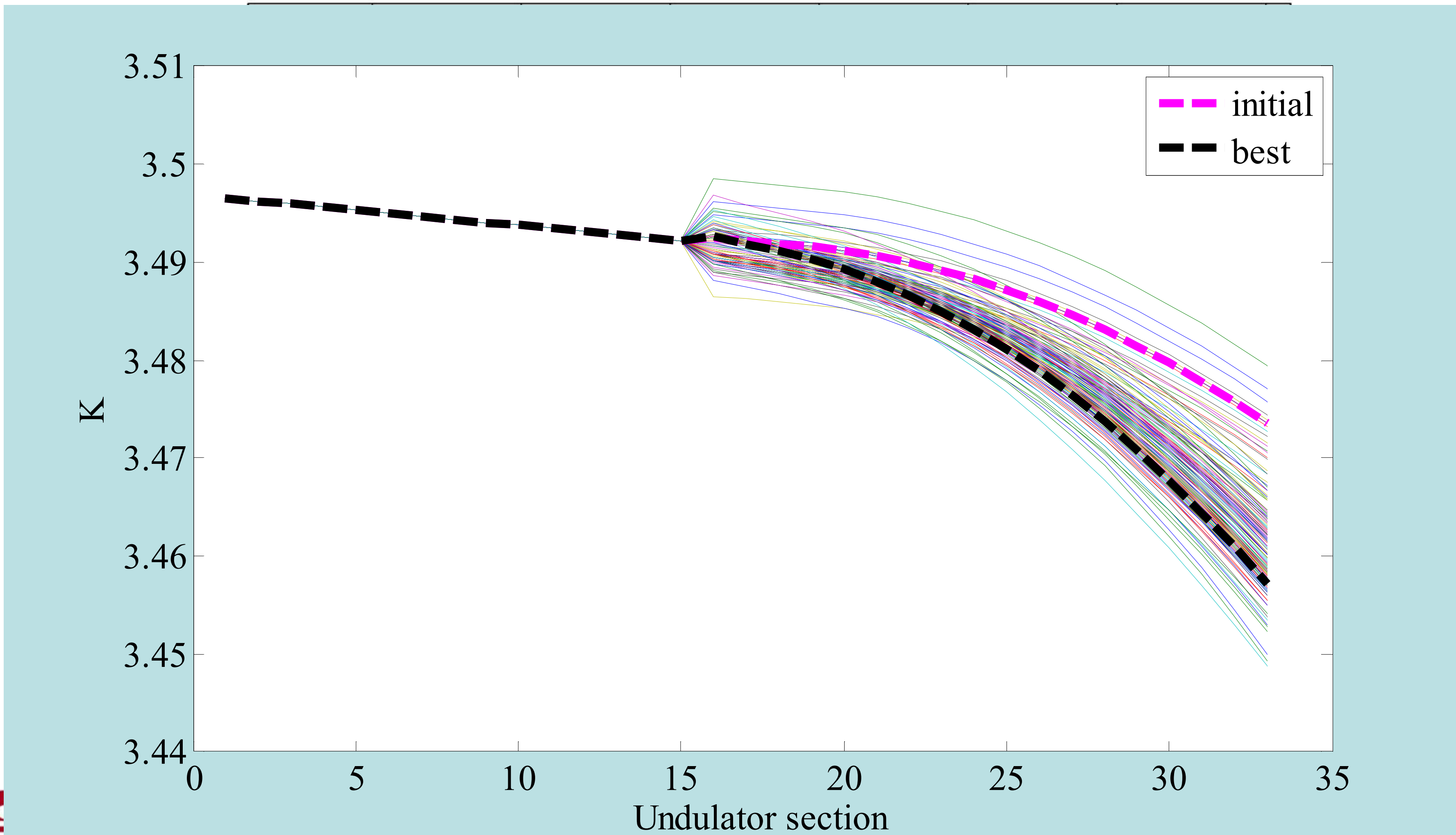


DETUNING? PHASE SHIFT?



DETUNING? PHASE SHIFT?

LCLS Undulator Taper Configuration



First demonstration of taper optimal phase

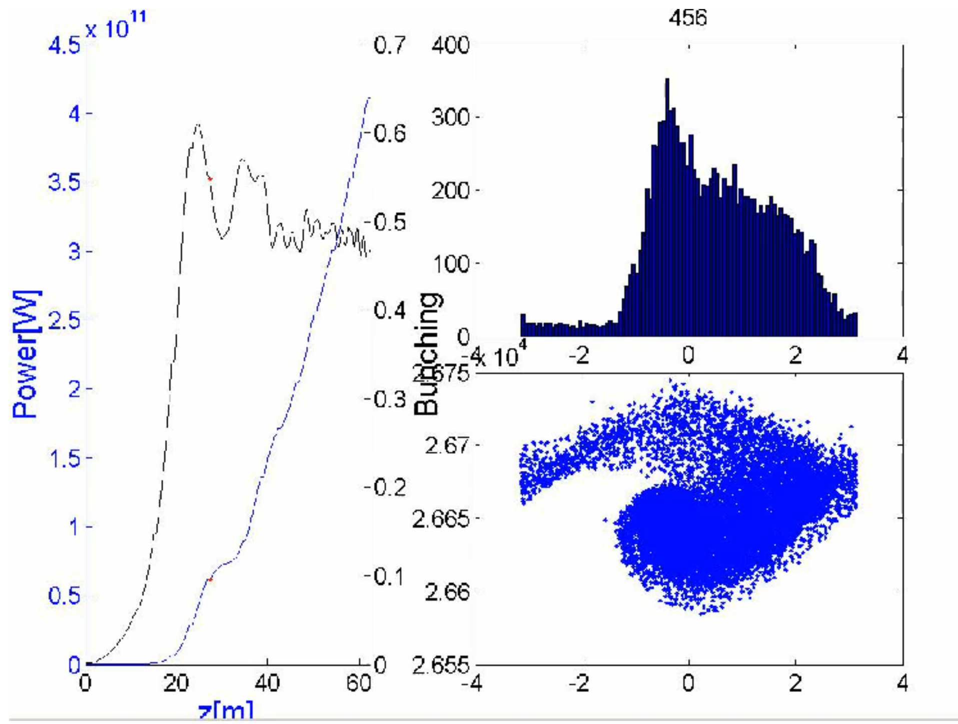
- Motivation:
  - To demonstrate experimentally the optimum phase for tapering.
  - Important to have a dedicated phase shifter around exponential saturation point for future FELs.
- Method:
  - Use Soft X-ray Self-seeding (SXRSS) for ~700 eV.
  - Use HXRSS chicane to vary phase shift versus gain.

OPTIMAL NON-ZERO TAPER PHASE

- In transition region between linear regime and post saturation regime, bunching factor oscillates, and FEL power increases slowly.

Bunching drops from 0.6 to 0.5
→ power $(0.6)^2$ to $(0.5)^2$

Deviate from 0



OPTIMAL NON-ZERO TAPER PHASE

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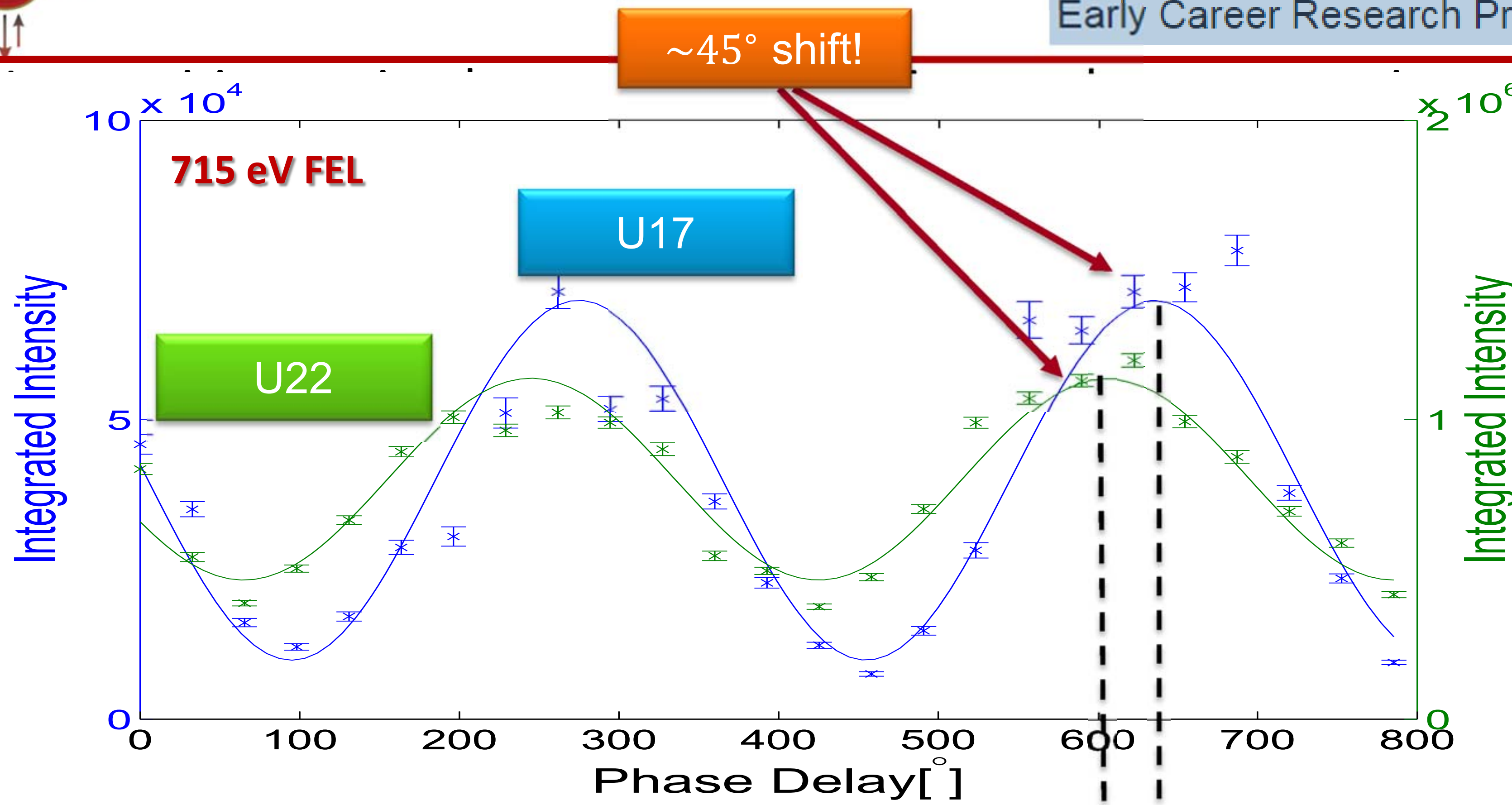
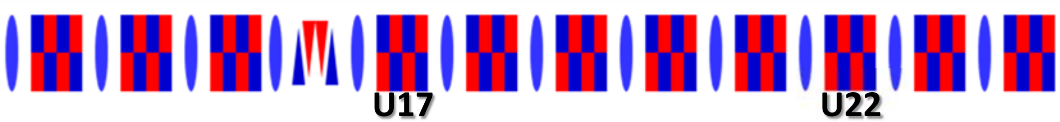
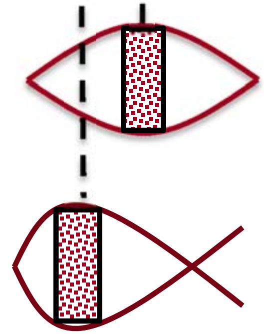


We see the peak is shifted ~45°.





LCLS experiment

***Wu, Hu, Setiawan, Huang, Raubenheimer, Jiao, Yu, Mandlekar, Spampinati, Fang, Chu, Qiang,* NIMA, 2017**

Machine learning taper optimization

- **Motivation:**
  - Develop on-line optimization package for taper optimization.
  - Make full use of the development in computer science: machine learning and artificial neural network.
- **Method:**
  - Use Machine Learning in LCLS to optimize taper during operation.
  - 5.5 keV HXRSS.

MACHINE LEARNING

- Discretized
  - Piecewise
  - Reinforcement learning
    - A set of environment states **S**;
    - A set of actions: **A**;
    - Rules of transitioning between states;
    - Rules that determine the *scalar immediate reward* of a transition; and
    - Rules that describe what the agent observes.
    - Rules are often stochastic.

MACHINE LEARNING

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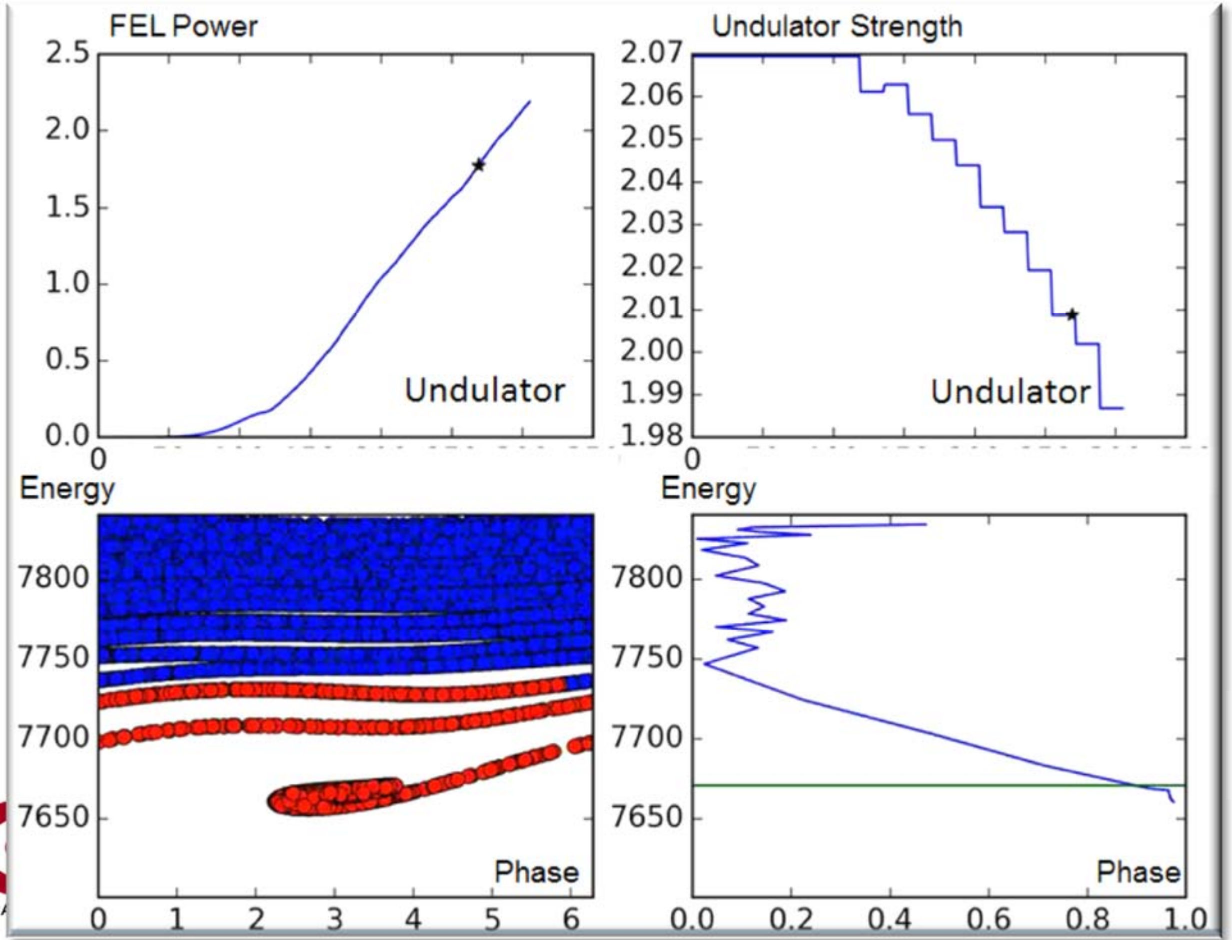
- Machine Learning (Reinforcement Learning) is adopted for LCLS tapered FEL optimization
  - ➢ A discretized taper solution: due to electron's nonlinear dynamics in the FEL bucket.
- On-line optimization: XTCAV image: Clustering → characterize state information
- Benefited from collaboration with CS@Stanford: Clustering and Reinforcement Learning

Spectrometer and Gas detector: reward

Undulator: actions



XTCAV phase space & clustering : states information

XTCAV projection & clustering: states information

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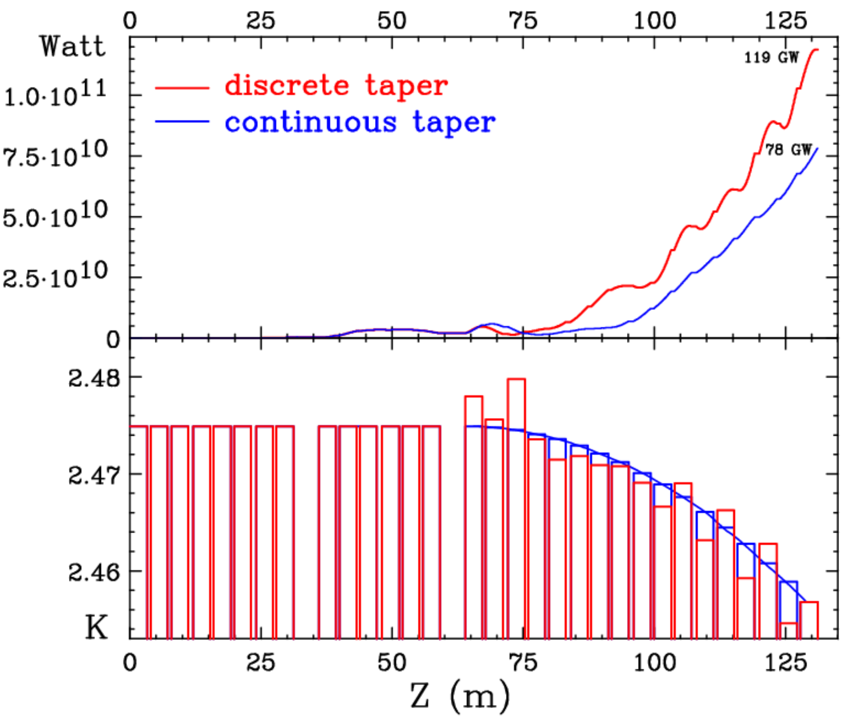
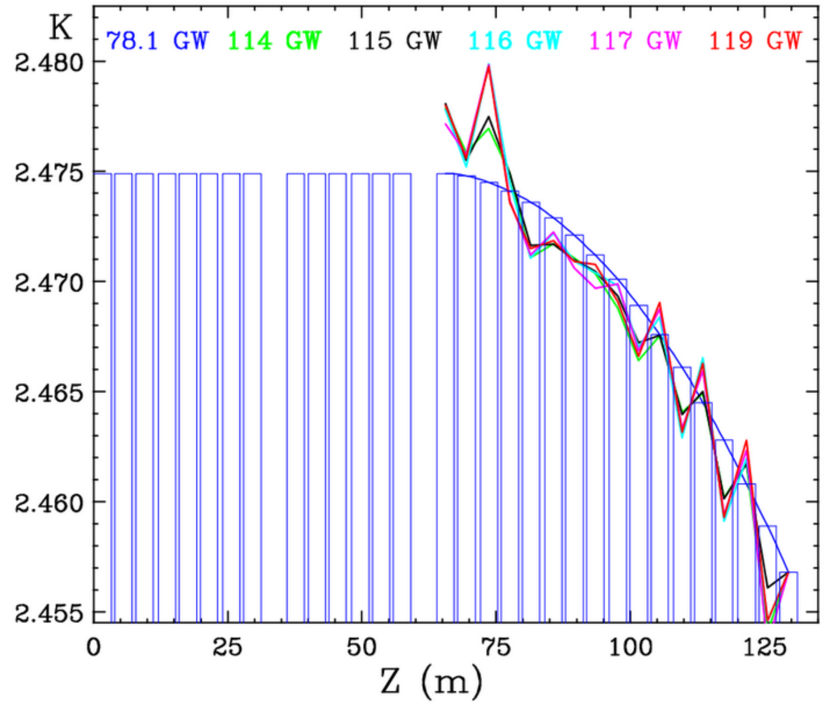
On-line optimization, Machine learning

- Learned from Start-to-end simulation data: **Zig zag** > 50% increase over **continuous** profile
- Taper optimizer:

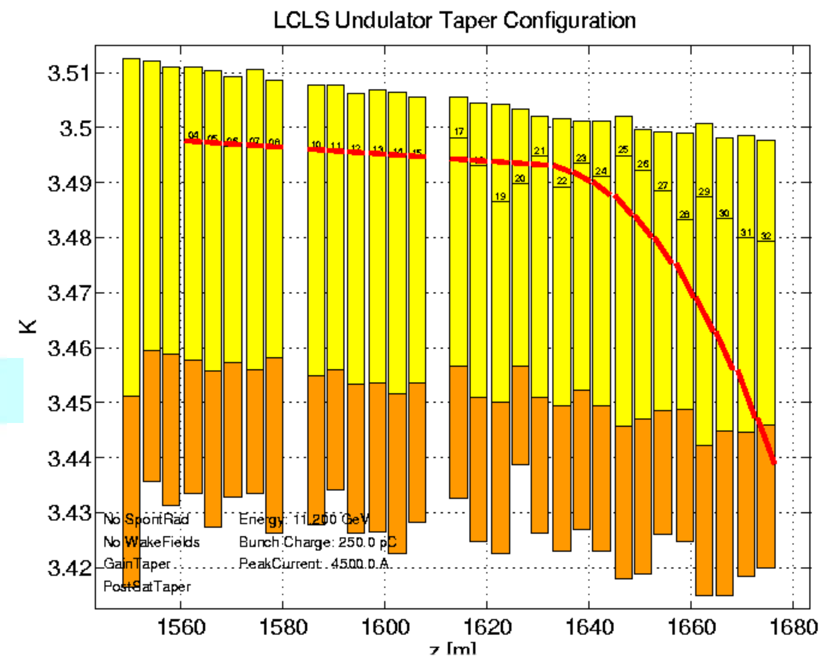


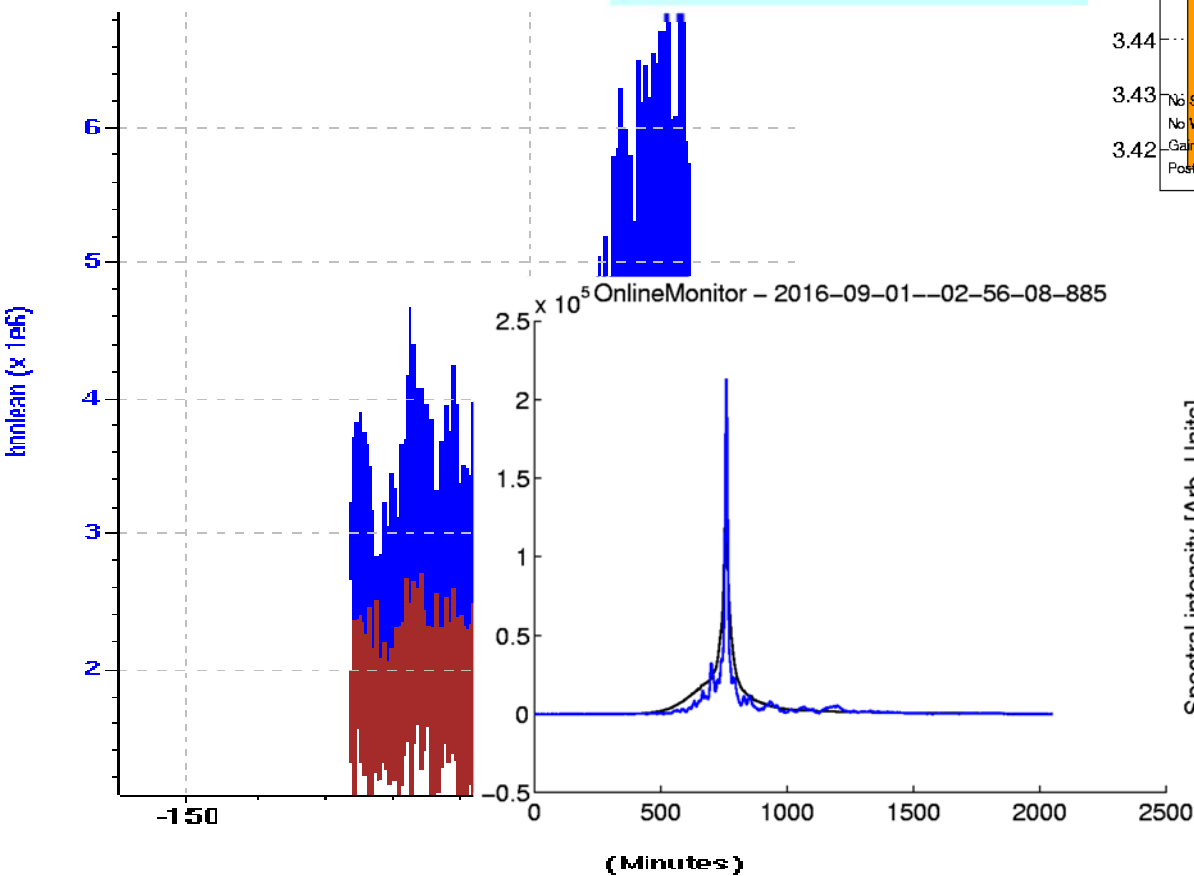


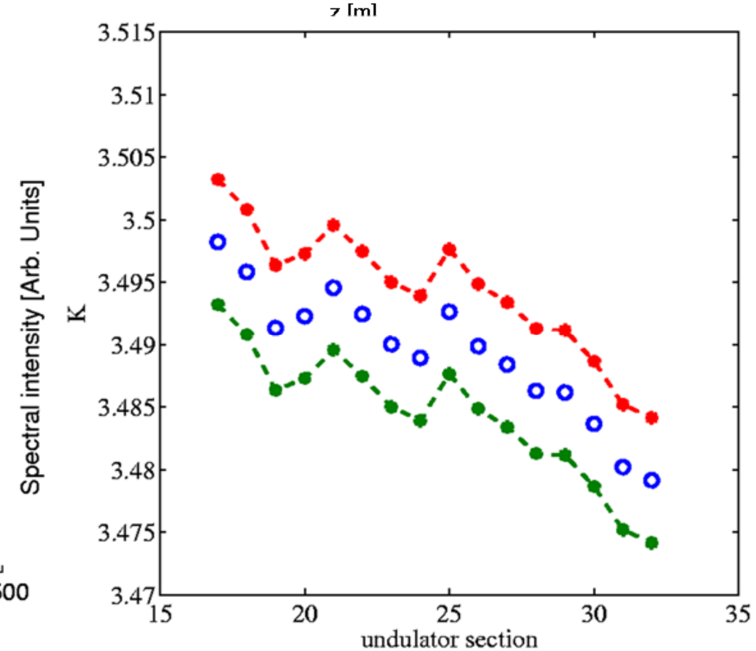
On-line optimization, Machine learning

- 5.5 KeV Self-seeding FEL
  - More than doubled peak energy
  - Zig-zag taper profile: ~ 1 mJ in 10 fs

Paper in preparation, 2017







DISCUSSION

- Extensive theoretical and numerical studies:
  - Taper model; transverse focusing
  - Transverse distribution; sideband instability
  - Coherence; mode decomposition
- Simulation optimization:
  - Physics-oriented scan-type optimization
  - Multi-Objective Genetic Algorithm (MOGA)
- On-line optimization
  - Local optimizer and global optimizer
  - Machine learning

ACKNOWLEDGEMENT

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- Thanks for your attention
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