X-ray Spectra and Peak Power Control with iSASE

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IPAC13

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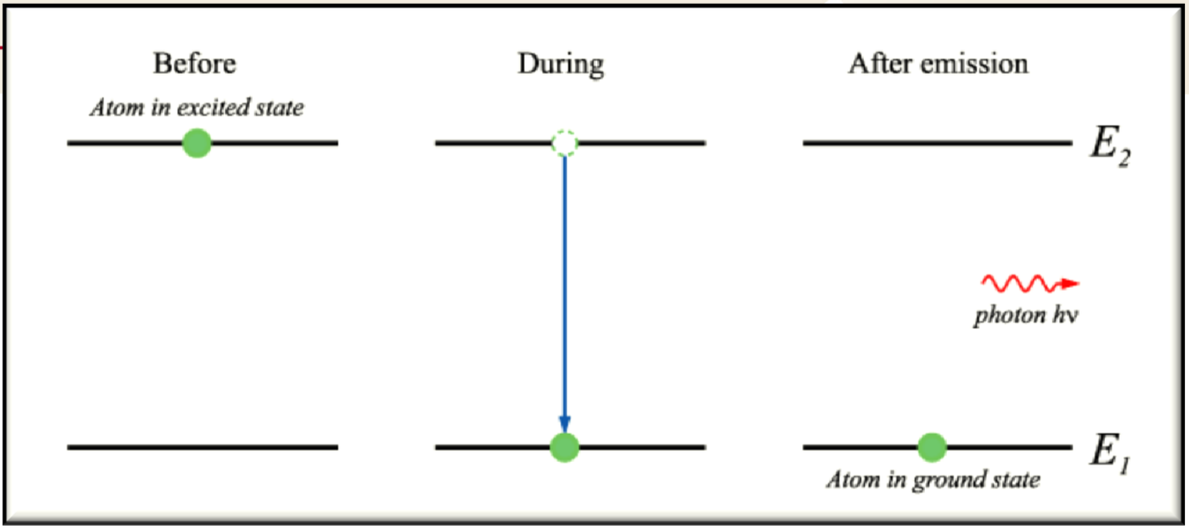
OUTLINE

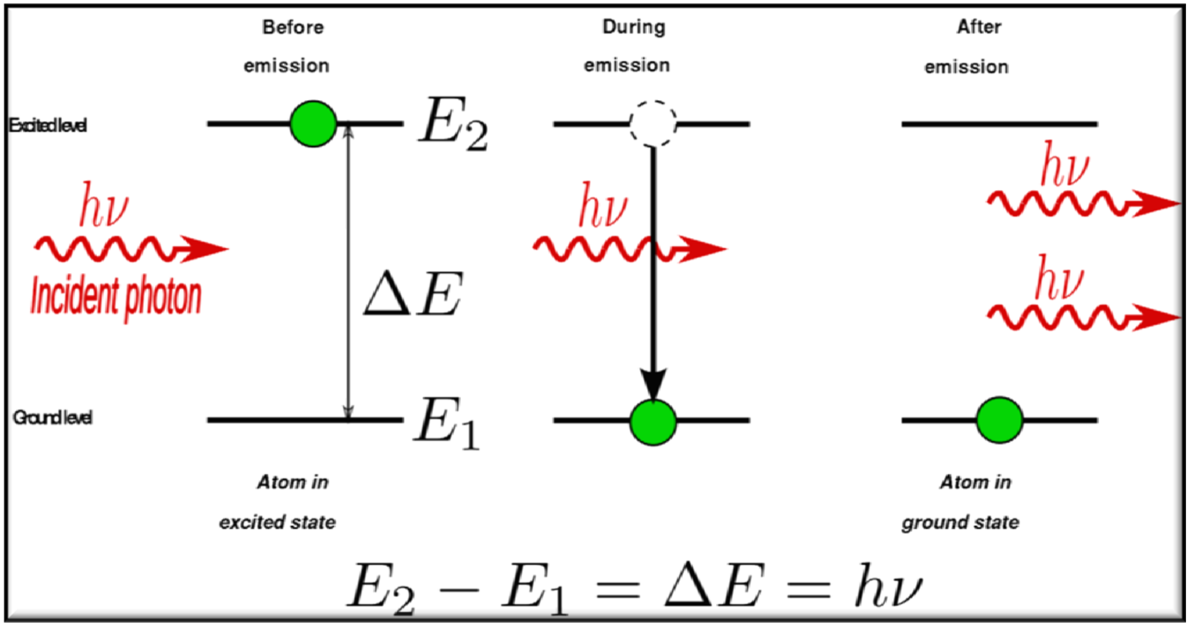
- Review SASE FEL
  - Short longitudinal coherent length leads to spiky temporal and spectral profiles
- Review schemes of improving longitudinal coherence
  - External seeding
  - Mode coupling and mode lock
- What is an iSASE
  - One-dimensional theory
  - Three-dimensional GENESIS simulation
  - First experiment on LCLS
  - pSASE
- Tapered seeded TW FEL for LCLS-II or even LCLS

EMISSION: SPONTANEOUS AND STIMULATED

- Spontaneous:



- Stimulated:



- What does this imply?

The signal has to meet the emitter

SASE FEL: POOR LONGITUDINAL COHERENCE

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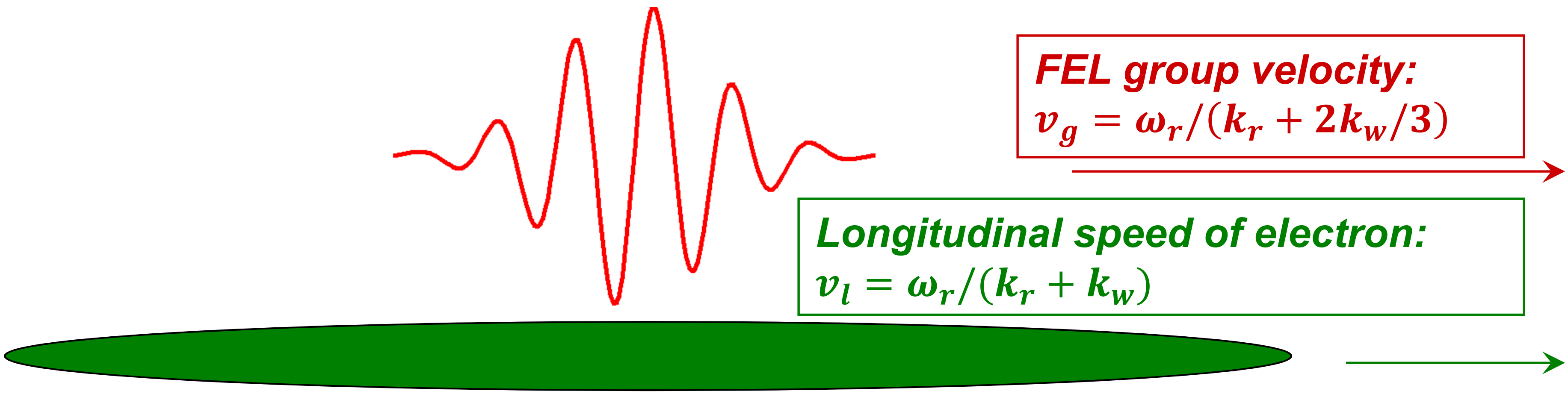
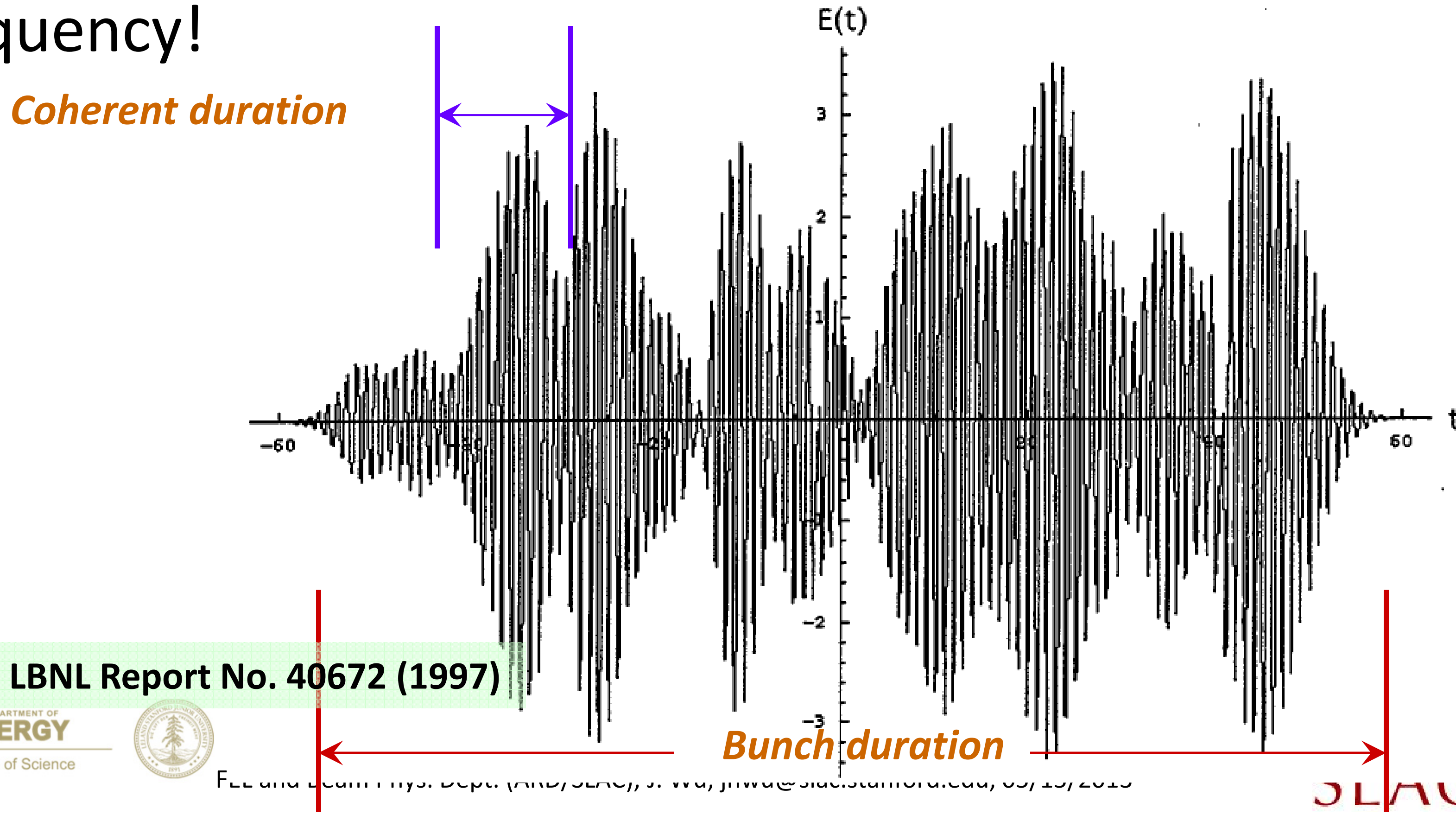
- Longitudinal / temporal enhancement: photon slips (advances) over electron bunch, the electrons being **swept** by the same photon wavepacket (which is also growing due to bunching) will radiate coherently due to the resonant condition ⇒ coherence length ⇒ **coherent** spike



- However, the emitter is too fast! almost the same speed as the signal → **short** coherent spike → limiting the “stimulation” within short spike → 0.5 fs for LCLS, while LCLS FEL pulse duration is about 50 fs for normal operation

SASE FEL: POOR LONGITUDINAL COHERENCE

- Each spike was started randomly from shot noise. Coherent Spike duration is normally short than the electron bunch duration. Spiky both in time and frequency!



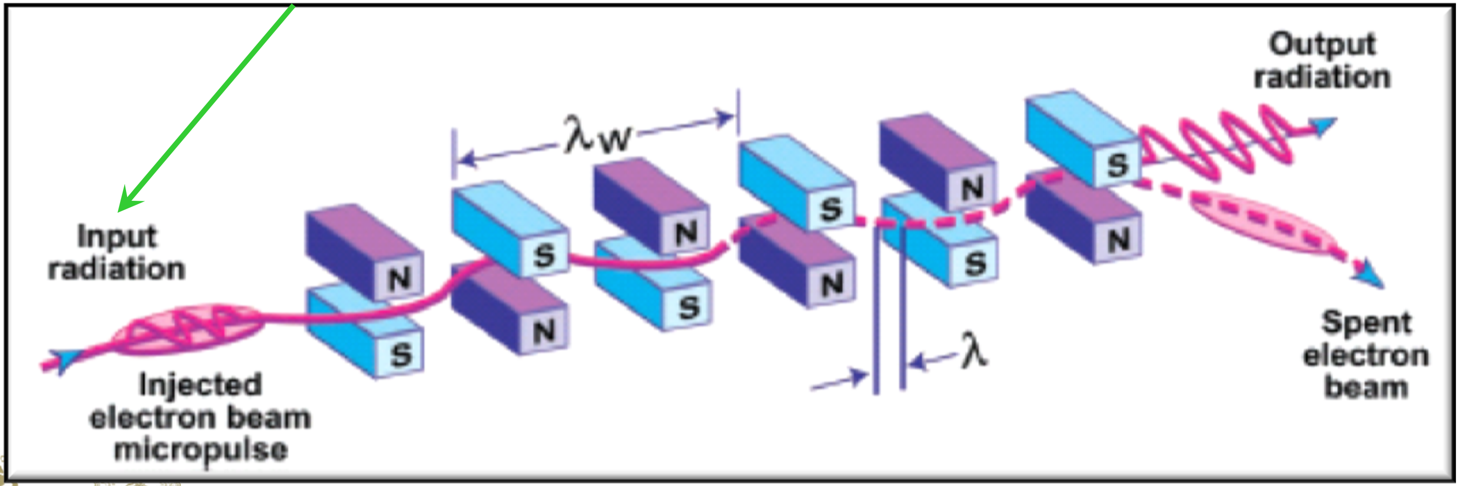
K.J. Kim, LBNL Report No. 40672 (1997)

FREE ELECTRON LASER

- Undulator radiation + feed back (on the electron distribution →instability)→ Free electron laser

- Start from undulator radiation / shot noise → Self-Amplified Spontaneous Emission (SASE) → exponential growth → mechanism for LCLS, SACLA, ...

- Start from a coherent seed → Seeded/Self-seeding FEL



SASE FEL: IMPROVE THE LONGITUDINAL COHERENCE

- Approaches: quoting A. Gover, FEL'06, p. 1, FEL prize lecture:
  - Seeding: "*If sufficient coherent seed radiation input power is attainable it makes the output power of the FEL amplifier coherent as well. But other aspects of the seed radiation injection approach, as* ***tunability*** *and operating wavelengths range still need to be addressed*".
  - Phase locking the spikes: "*The* ***current prebunching approach*** *may provide more options of frequency* ***tunability*** *and short wavelengths availability.*"

***A. Gover and E. Dyunin*, FEL'06, p. 1 (2006): FEL prize lecture**

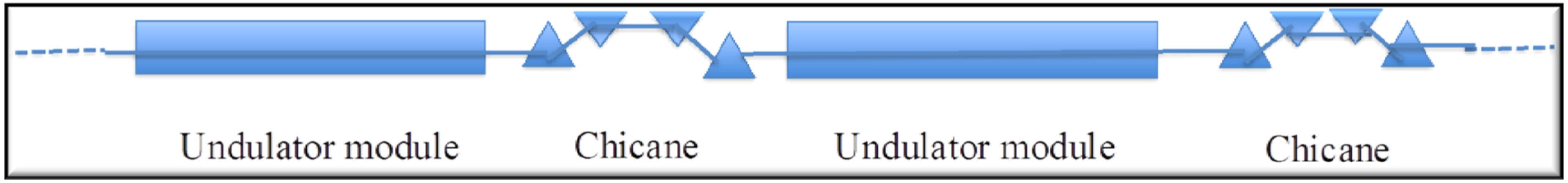
SASE FEL: IMPROVE THE LONGITUDINAL COHERENCE

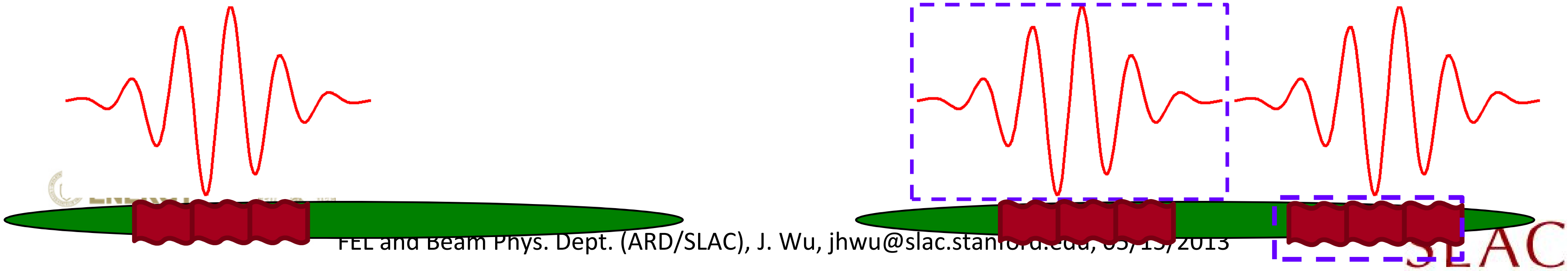
- Approaches: quoting A. Gover, FEL'06, p. 1, FEL prize lecture: *"A **third** scheme that should be considered for phase locking and increasing the coherence of the radiation in a SASE FEL consists of imposing **periodic perturbation** on the wiggler (e.g. periodic dispersive sections)"*.
  - *"The filtering effect of the periodic structure may be viewed as the analogue of linewidth narrowing of radiation emitted in a Fabri-Perot resonator."*

***A. Gover and E. Dyunin*, FEL'06, p. 1 (2006): FEL prize lecture**
***Y.-C. Huang*, private communications**

ISASE

- Do we really need **periodicity**?
- Effectively slow down the emitter (electrons) → signal can **meet** the emitter → extend the coherent length
- Speed up the longitudinal slippage → amplitude and phase **mixing** → improve longitudinal coherence
- Use phase shifter:





SLIPPAGE

- Phase Shifter:
  - Periodic Constant delay: $L_{coh} = (N+1)\ L_{coop}$
  - Geometric delay: $L_{coh} = 2^N L_{coop}$
  - Considering energy spread: $1,2,4,\ldots,2^{N-1},2^N, 2^{N-1},\ldots,4,2,1$
  - Combination of periodic and geometric: 1,2,1,4,1,8,1,16,1,32,…
  - Other combination:

***Thompson, McNeil*, PRL, 2008**
***Thompson, Dunning, McNeil*, IPAC10, p2257, 2010 with some randomization**

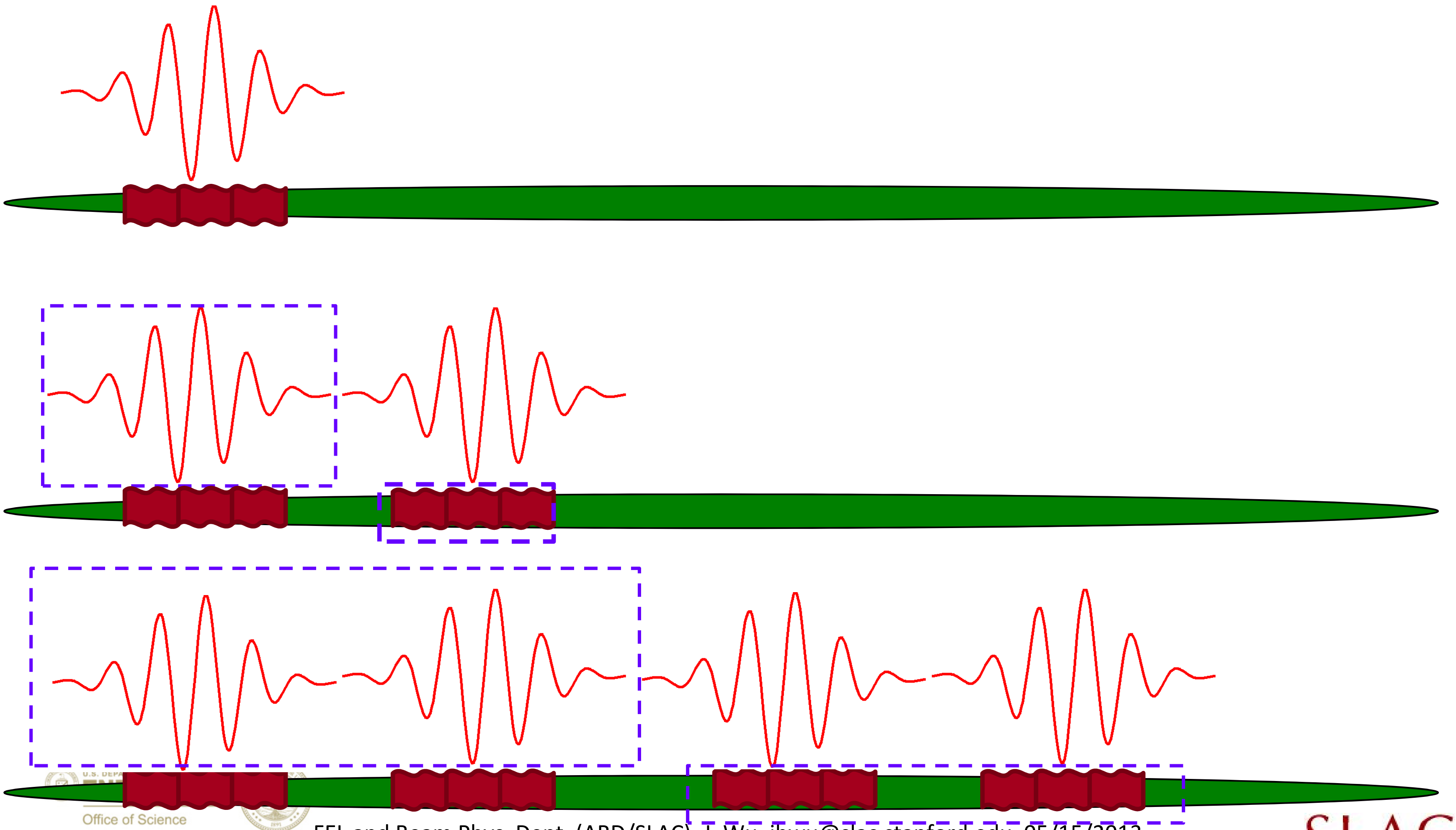
***Wu, Merinelli, Pelligrini*, FEL12, 2012**

***McNeil, Thompson, Dunning*, PRL, 2013**

- ***The Bottom Line***: total slippage comparable to the electron bunch duration
  - Periodic delay cleans up the outskirts frequency component
  - Geometric delay shrinks the central part of the frequency
- We call this improved SASE (***iSASE***)

ISASE

- Geometric



1-D THEORY

- Maxwell-Vlasov coupled equations

bunching

$$\left(\frac{\partial}{\partial z} - 2ik_u\eta\nu\right) F(\nu,\eta;z) = \kappa_1 A(\nu;z)\frac{\partial}{\partial \eta}V(\eta), \quad (1)$$

light

$$\left(\frac{\partial}{\partial z} - i\Delta\nu k_u\right) A(\nu;z) = \kappa_2 \int F(\nu,\eta;z)d\eta, \quad (2)$$

- Phase shifter

$$A(\nu;z+D) = A(\nu;z)e^{i\Delta\nu k_u D}, \quad (17)$$

$$F(\nu,\eta;z+D) = F(\nu,\eta;z)e^{i\Delta\theta}. \quad (18)$$

***Kim, Xie, Pellegrini*, NIMA**
***Kim*, NIMA**
***Vinokurov*, NIMA**
***Ding, Huang*, PRSTAB**

1-D THEORY

- SASE: first stage
  - Initial conditions:

$$E_{1\nu}(0) = 0, \qquad \int F_{1\nu}(0) d\eta = \frac{1}{N_\lambda} \sum_{j=1}^{N_e} e^{i\nu\omega_1 t_j(0)}, \qquad (29)$$

$$S(\nu) = \frac{1}{\sqrt{2\pi}\sigma_\nu} \exp\left[-\frac{(\nu-1)^2}{2\sigma_\nu^2}\right],$$

- iSASE: second stage
  - Short undulator: coherent emission, startup, transient, interference

$$E_{2\nu}(z) = E_{1\nu}(L_1)\left[e^{-i\psi}\left(1-\mathcal{B}e^{i\Delta\theta}\right)+\mathcal{B}e^{i\Delta\theta}\right]$$

$$\psi = \Delta\nu k_u z$$

$$\mathcal{B} \equiv \frac{2\rho}{\Delta\nu\mu_0^2}\left(1-\mu_0 e^{i\alpha}\rho k_u z\right)$$

1-D THEORY

- iSASE: second stage
  - Long undulator: exponential growth, high gain, interference

$$E_{2\nu}(z) \approx \frac{e^{-i2\rho\mu_0 k_u z} E_{1\nu}(L_1)}{(\mu_0 - \mu_o)(\mu_0 - \mu_d)} \left(\mu_0^2 - \frac{2e^{i\Delta\theta}}{\mu_0} \right)$$

$$\mu_0 = e^{i2\pi/3} + \frac{\Delta\nu}{6\rho} - \frac{1}{9} e^{i\pi/3} \left(\frac{\Delta\nu}{2\rho} \right)^2$$

$$\mu_o = 1 + \frac{\Delta\nu}{6\rho} + \frac{\Delta\nu^2}{36\rho^2},$$

$$\mu_d = -e^{i\pi/3} + \frac{\Delta\nu}{6\rho} + \frac{1}{9} e^{i2\pi/3} \left(\frac{\Delta\nu}{2\rho} \right)^2$$

1-D THEORY

- Spectrum **narrowing**: neglecting the optical-klystron type power enhancement,

$$R(\nu) = \frac{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2} e^{-i\rho k_r \nu R_{56}\xi} e^{ik_r\nu R_{56}/2}}{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu-\xi)^2}} \qquad (22)$$

For a cold beam, we have

$$|R(\nu)|^2 = \frac{5 + 4\cos\left(k_r R_{56}\nu/2\right)}{9}, \qquad (23)$$

Frequency filter

1-D THEORY

- SASE

$$S(\nu) = \frac{1}{\sqrt{2\pi}\sigma_\nu} \exp\left[-\frac{(\nu-1)^2}{2\sigma_\nu^2}\right],$$

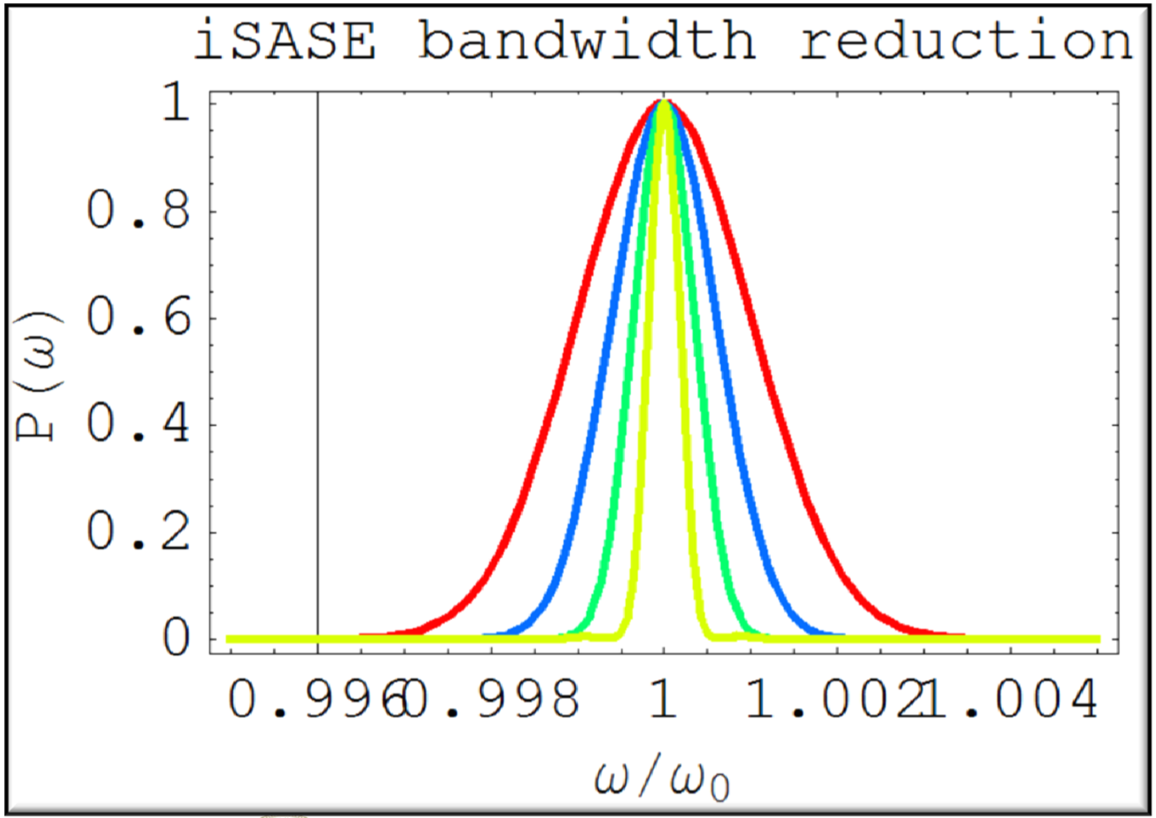
- iSASE: 2nd-stage

$$|R(\nu)|^2 S(\nu)$$

- Temporal:

$$E_2(t) = \int \frac{\omega_1 d\nu}{\sqrt{2\pi}} E_{2\nu}(L_2) e^{i\Delta\nu[(k_1+k_u)L_2-\omega_1 t]}.$$

- iSASE: multi-stage → step-by-step multiple the $|R(\nu)|^2$

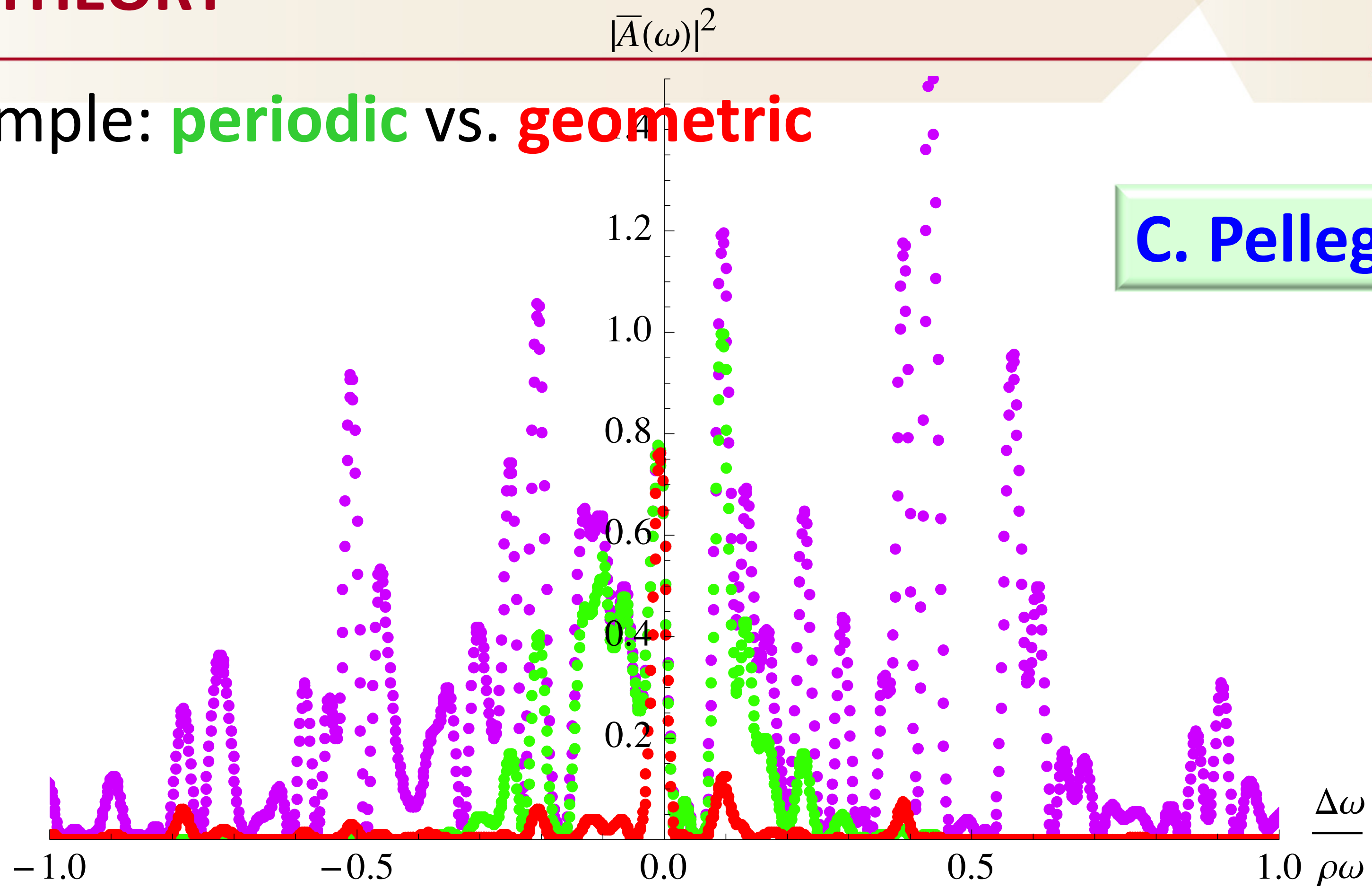


Red: SASE
Blue: 2,2,2,2,2
Green: 4,4,4,4,4
Yellow:1,2,4,8,16
-- in units of cooperation length

1-D THEORY

- Example: periodic vs. geometric

C. Pellegrini



Spectra comparison for three cases: δ =0 (in units of **coherence length**), SASE, **purple**, line width about 1 (in units of ρ); δ =3, 3, 3, 3, 3, 3, 3, iSASE, **green**, line width about 0.2; δ=1, 2, 4, 8, 16, 32, 64, iSASE, **red**, line width about 0.02.

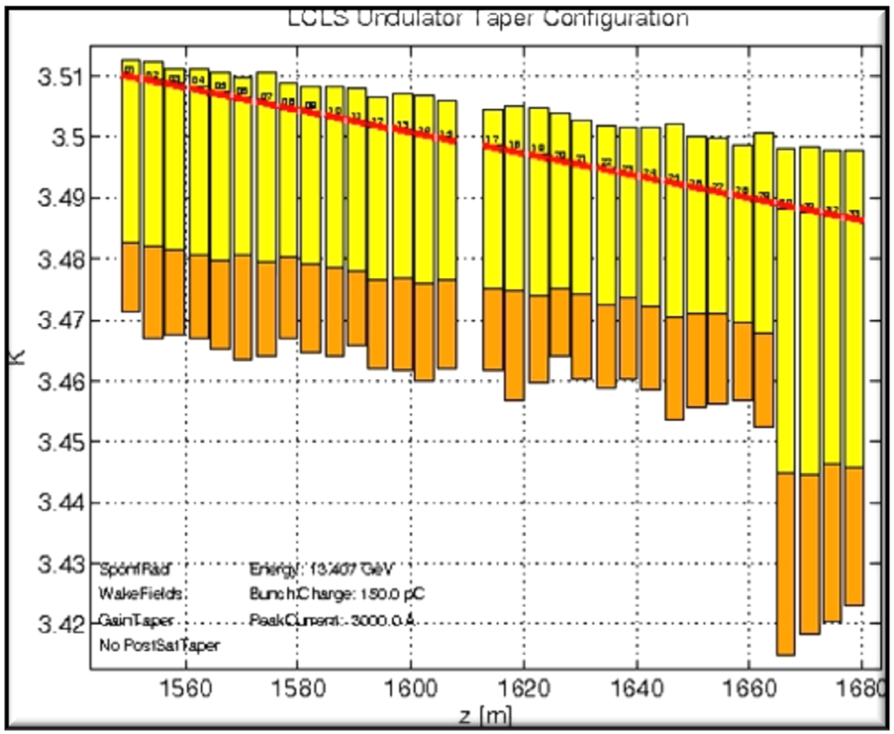
LCLS: PROOF-OF-PRINCIPLE EXPERIMENT

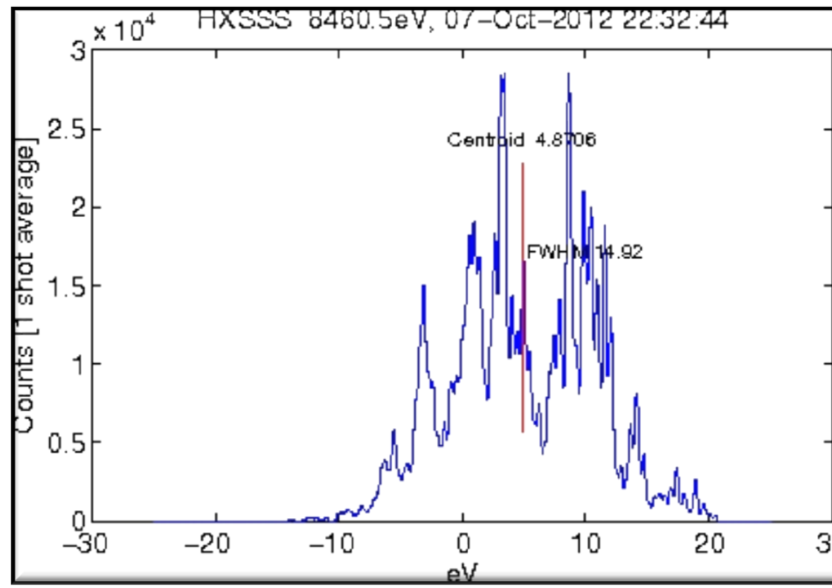
- Machine layout:
  - First 5 undulator sections on-resonant to establish the FEL wavelength
  - From 6th on, even number: 6, 8, …, 30, and 32 largely detuned (can either be **random** or form a separate spectrum line → **two color**)
  - From 6th on, odd number: 7, 9, …, 31, and 33 on resonant

- Perform proof-of-principle experiment on LCLS for an improved SASE (iSASE)
  - Electron bunch: 150 pC, compressed to ~ 3 kA
  - 8.45 keV FEE HXSSS
  - 13.825 GeV electron energy

SASE: 10/07/2012 SHIFT

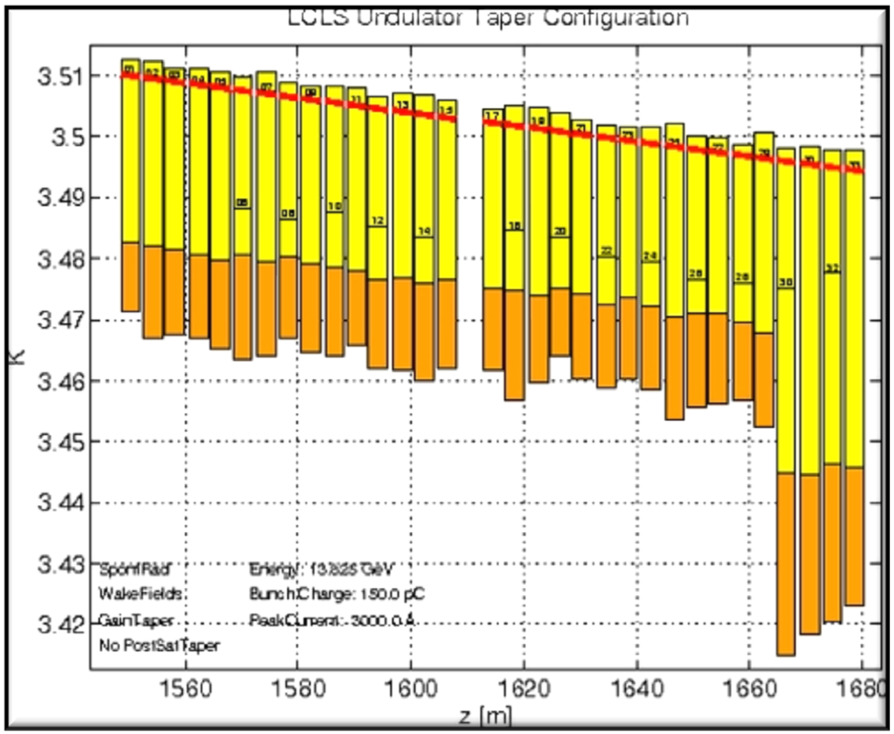
- No-post saturation taper: 1.21 mJ
  - Taper profile on left: optimized for the gain taper (-31 MeV), and spectrum on right (FWHM 15 eV, **limited** by the FEE HXSSS)

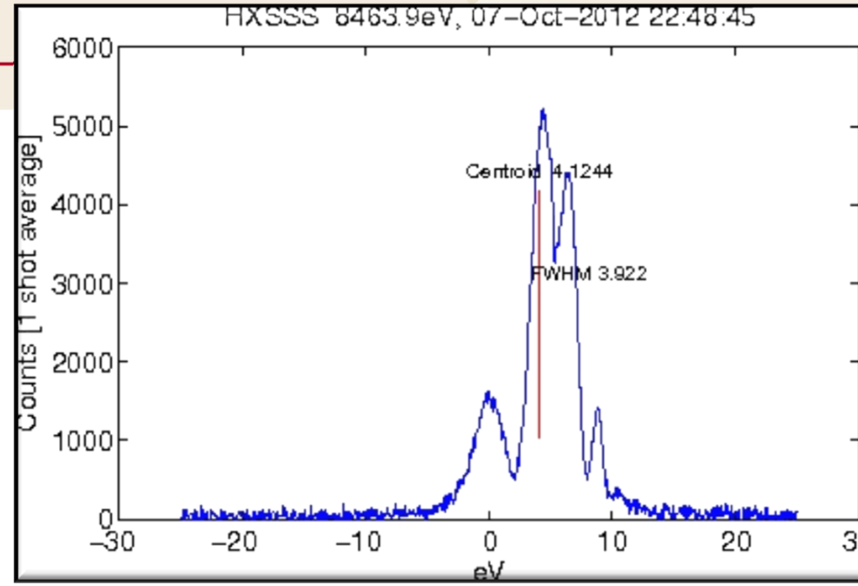


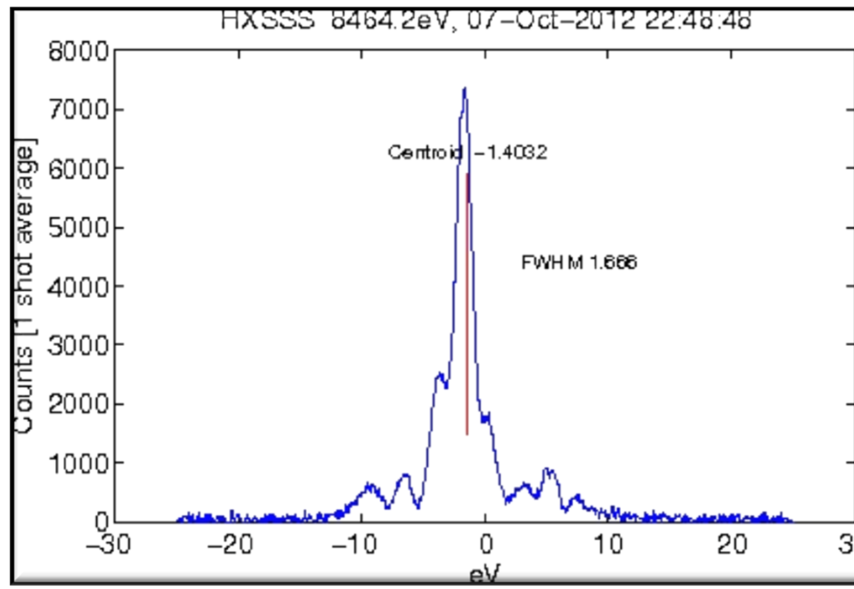


ISASE: NARROW BANDWIDTH

- iSASE: 0.4 mJ
  - Taper profile on left, and spectrum on right (**1.5** – **4** eV)

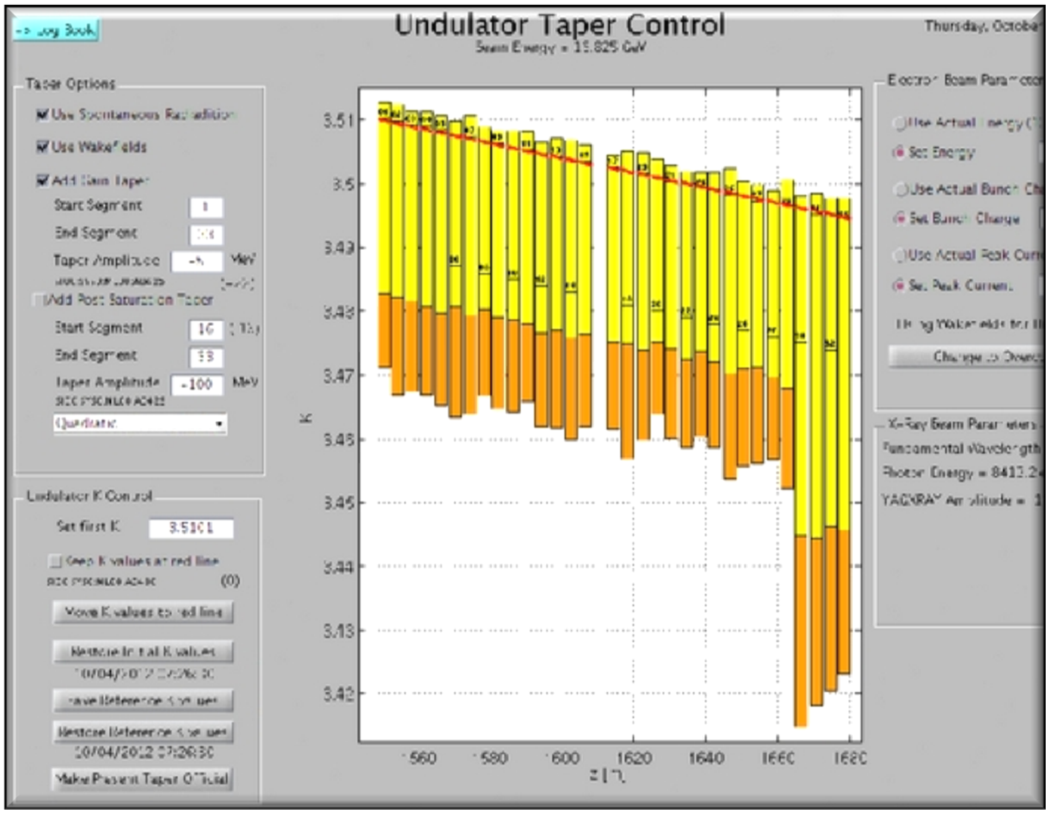


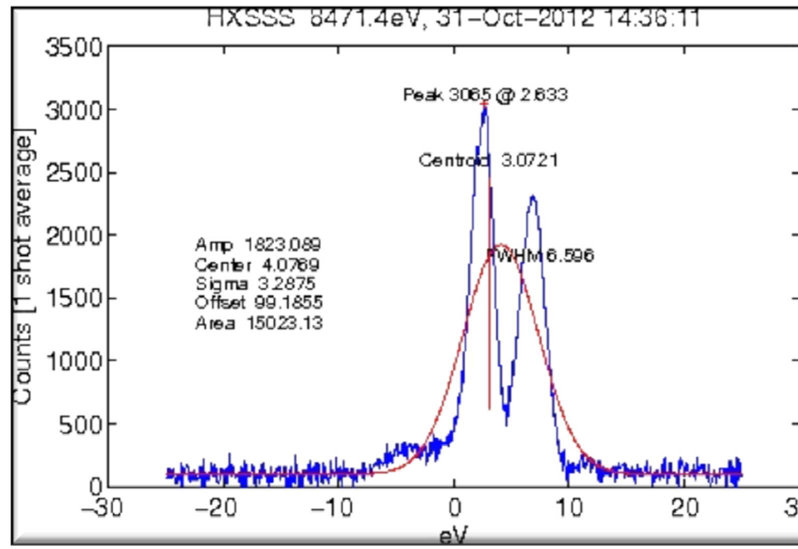




ISASE: TWO-COLOR

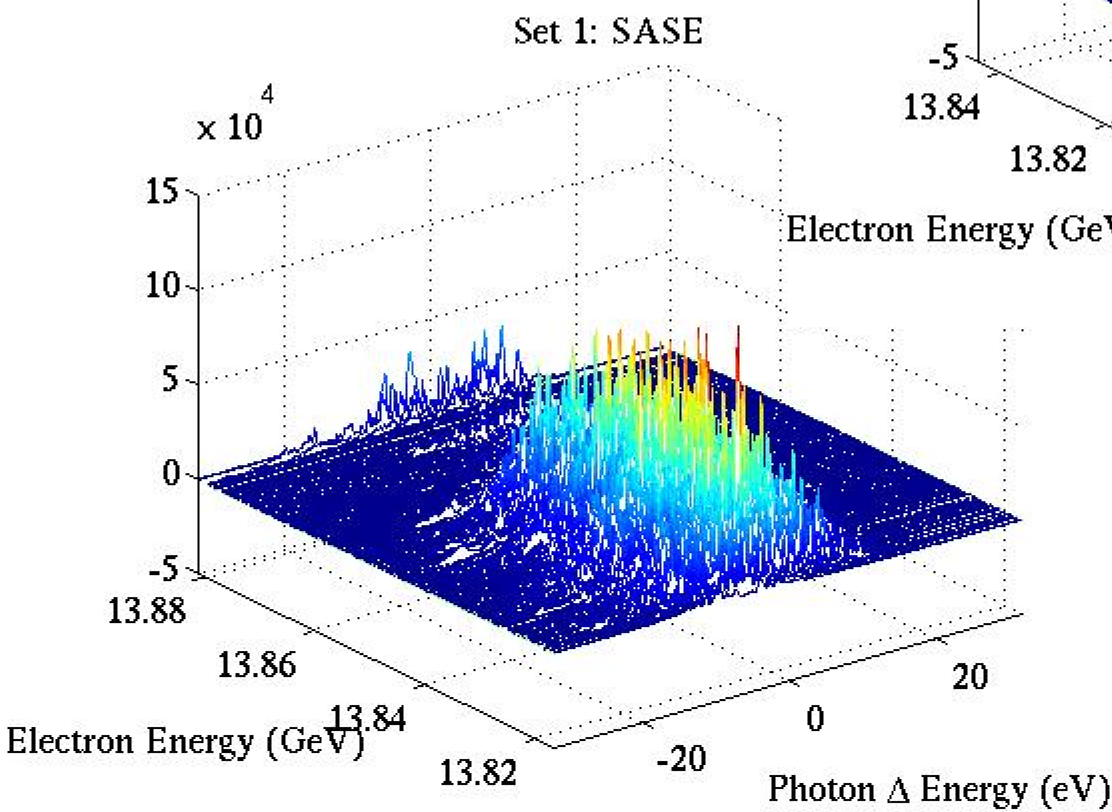
- iSASE: about 0.4 mJ
  - Taper profile on left, and spectrum on right

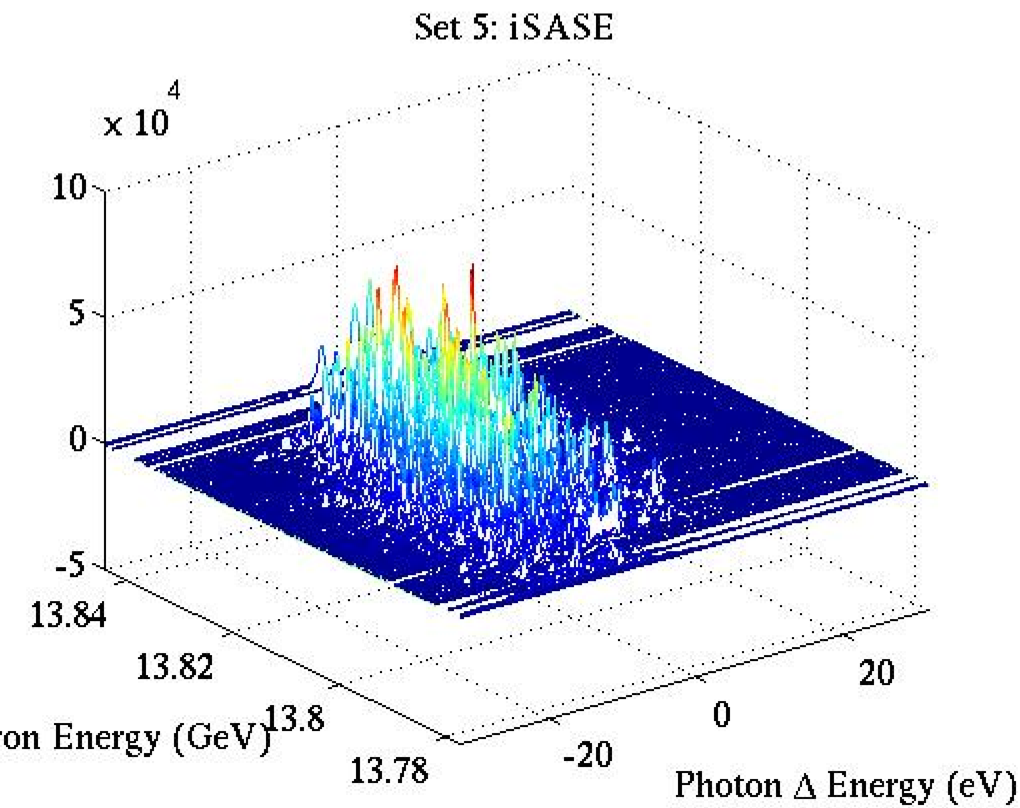


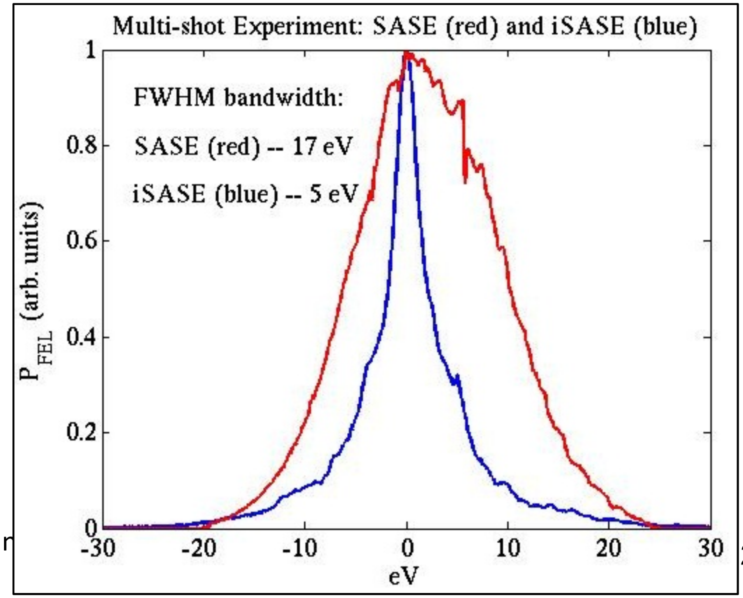


SASE VS ISASE

- Spectrum
  - Similar peak height
  - Integrated power

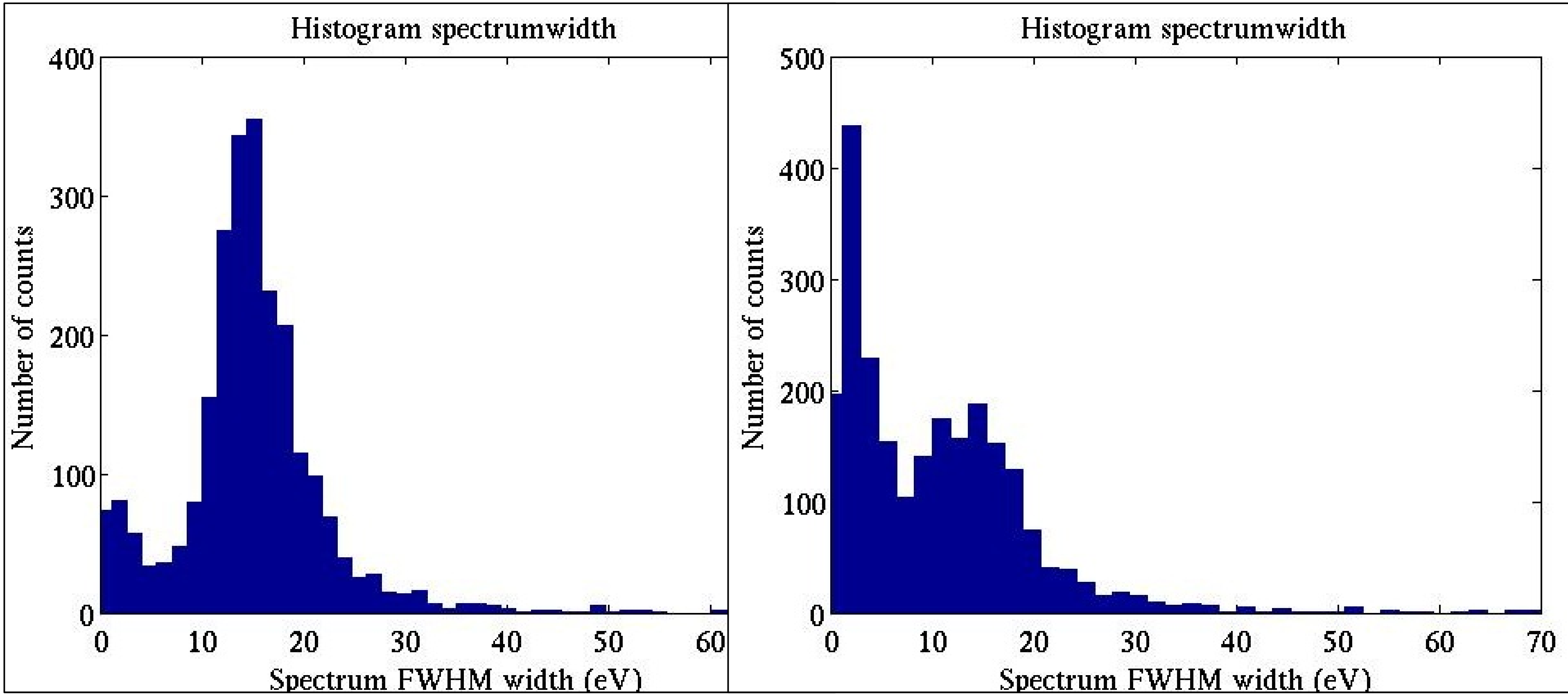






SASE VS ISASE

- FEL power vs spectrum width



Purified SASE

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 010703 (2013)

Purified self-amplified spontaneous emission free-electron lasers with slippage-boosted filtering

Dao Xiang, Yuantao Ding, and Zhirong Huang
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA

Haixiao Deng
Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai, 201800, China

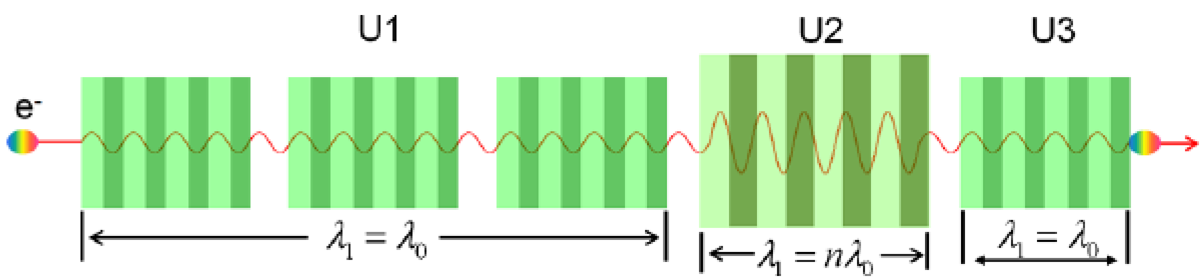


FIG. 2. Schematic layout of a pSASE FEL.

TW FEL: TAPER MODEL AND OPTIMIZATION

- LCLS-II base line has phase shifters, so schemes to improve longitudinal coherence of SASE
- Variable gap undulator → Tapered FEL to reach TW

SCALING

- An FEL is characterized by the FEL parameter, ρ, giving:
  - the exponential growth, $P = P_0 \exp(z/L_G)$, where $L_G \sim \lambda_U / 4\pi\rho$
  - The FEL saturation power $P_{sat} \sim \rho \, P_{beam}$
- For the LCLS-II electron beam: $I_{pk} \sim 4\ kA$, $E \sim 14\ GeV$, $P_{beam} \sim 56\ TW$, FEL: $\rho \sim 5 \times 10^{-4}$, $P_{sat.} \sim 30\ GW << 1\ TW$
  - Overall, the peak power at saturation is in the range of **10 to 50 GW** for X-ray FELs at saturation.
  - The number of coherent photons scales almost linearly with the pulse duration, and is ~$\mathbf{10^{12}}$ at 100 fs, $\mathbf{10^{11}}$ at 10 fs.

BEYOND SATURATION

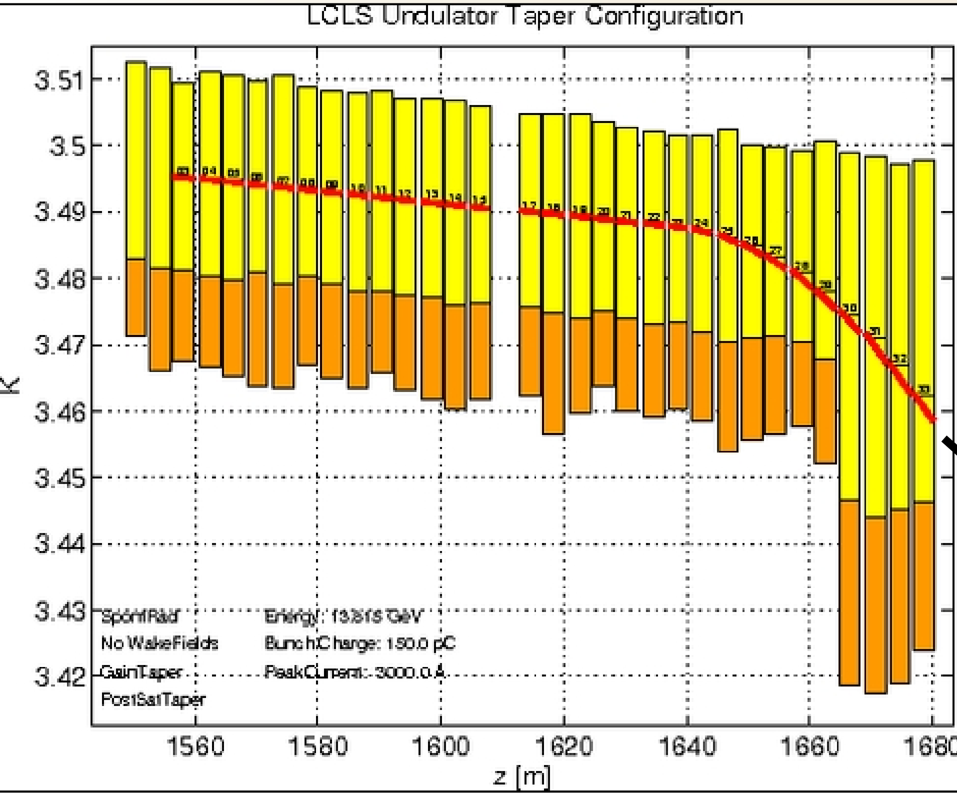
- What happens when the FEL saturation is achieved
  - Centroid energy loss and energy spread reaches ρ.
  - Exponential growth is no longer possible, but how about coherent emission? Electron microbunching is fully developed
- As long as the microbunching can be preserved, coherent emission will further increase the FEL power
  - Maintain resonance condition → tapering the undulator
  - Coherent emission into a single FEL mode – more efficient with self-seeding scheme
  - Trapping the electrons

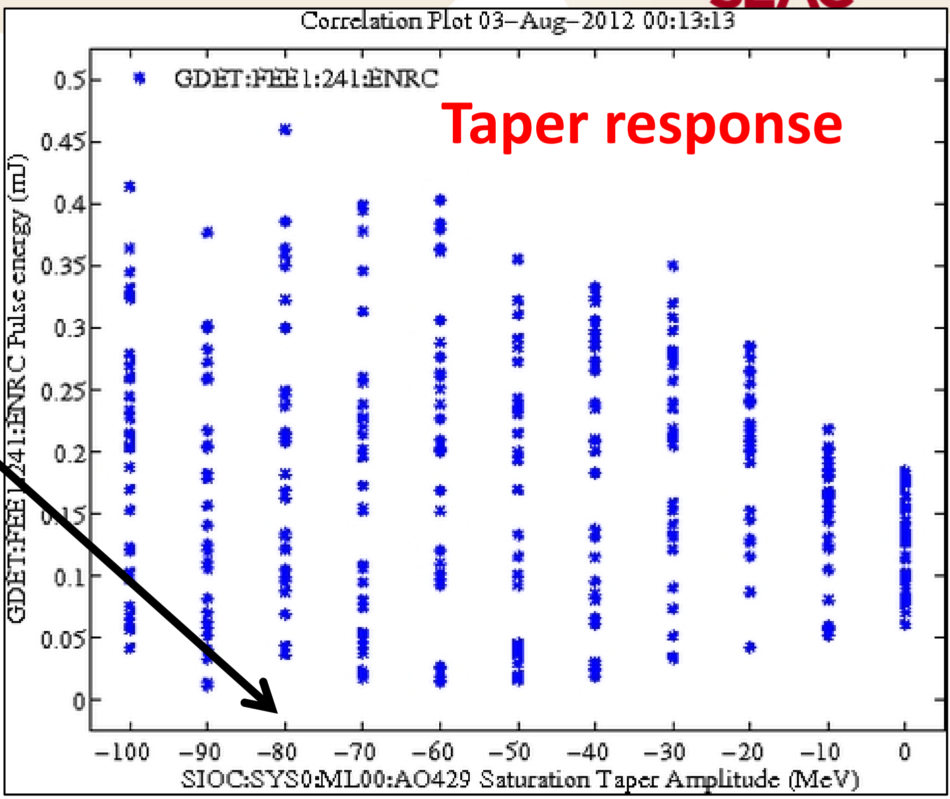
TAPERING

- Near the saturation point, start changing the undulator period and magnetic field along the undulator length to adjust to the energy of a reference electron

$$\lambda = \frac{\lambda_U(z)[1 + K(z)^2]}{2\gamma_R(z)^2}$$

UNDULATOR TAPER AT 5.5 KEV

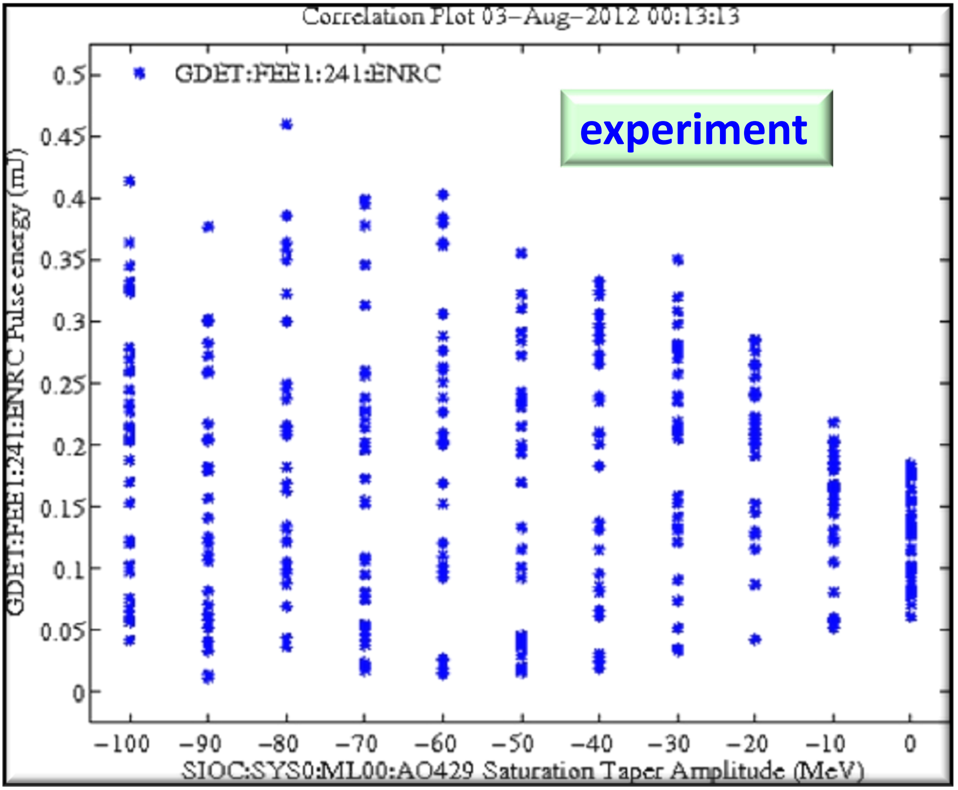


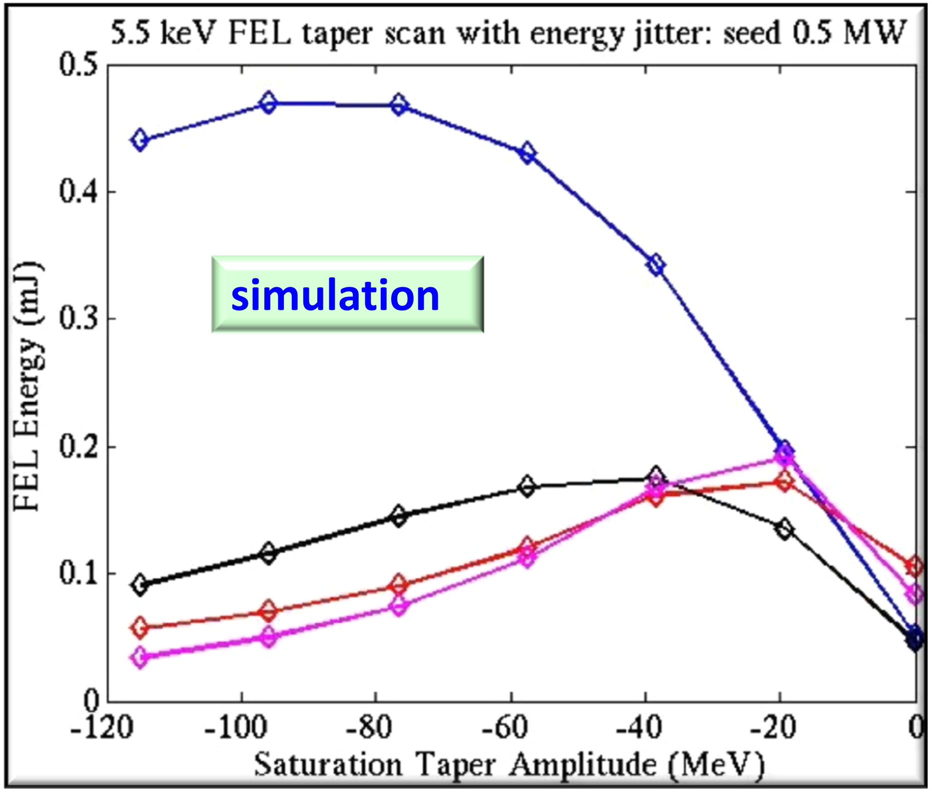


- Maximum FEL intensity (>400 uJ) responses well to strong undulator taper
- 40 pC bunch length < 10 fs, maximum peak power > 40 GW

EXPERIMENT VS SIMULATION: ENERGY JITTER, TAPER SCAN

- Taper scan for 5.5 keV





- Simulation for energy jitter: **blue** (on-energy), **black** (+0.1 %), **red** (-0.1 %), **magenta** (-0.2 %)

COMPARISON BETWEEN SASE, ISASE, AND SEEDED FEL

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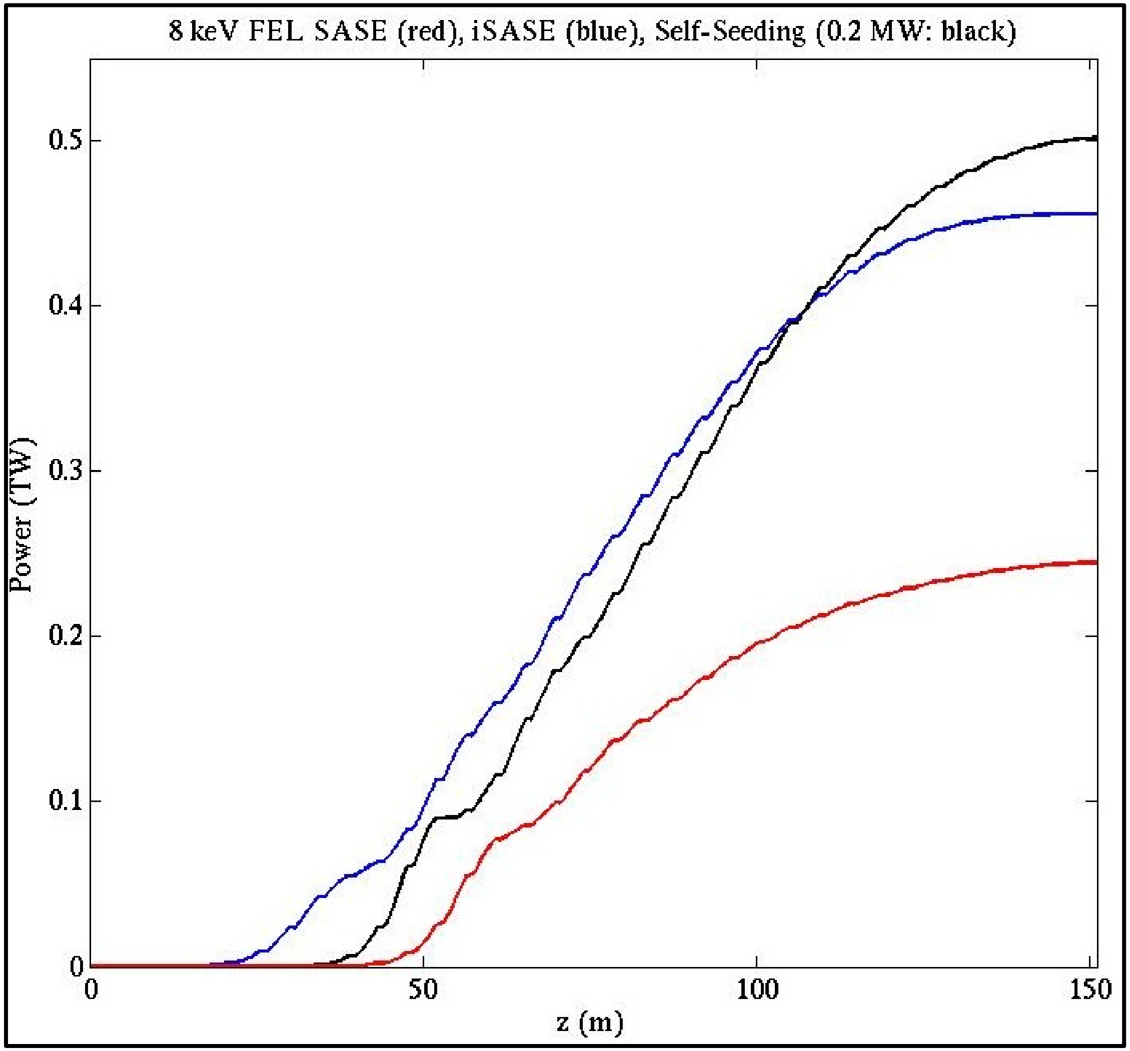
- Work with LCLS-II type system
  - Electron beam parameters -- *Energy: 13.5 GeV; Emittance: 0.3 μm-rad; slice energy spread: 1.3 MeV; peak current: 4 kA; β-function: 15 m*
  - Photon beam parameters – *Energy: 8 keV;*
  - Undulator – *period: 3.2 cm; magnetic length: 3.4 m; break distance: 1 m*
- iSASE scheme
  - Break introduces 5 optical periods
  - For each magnetic segment, the slippage between the photon beam and the electron beam is 106 optical periods, and we regard this as the coherent length
  - For iSASE, we introduce
    - Additional 400 optical periods in the breaks; or
    - Additional 400, 800, 1600, 3200 optical periods in the breaks
- As comparison, a **self-seeding** FEL with input seed power of 0.2 MW

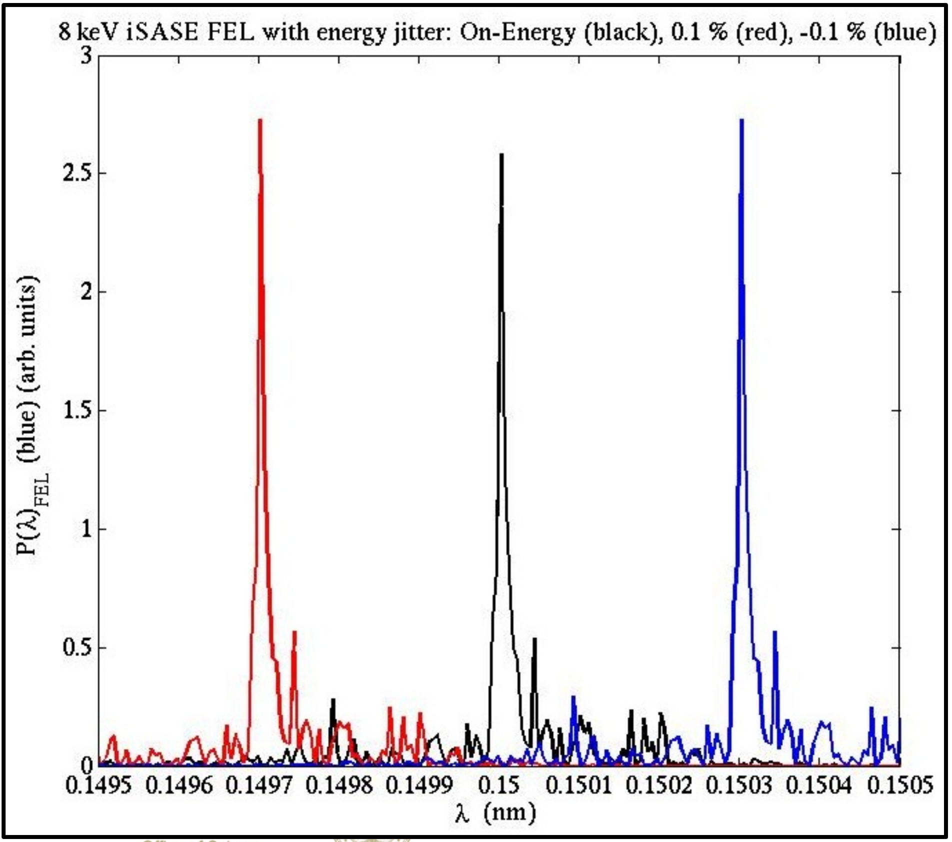
COMPARISON BETWEEN SASE, ISASE, AND SEEDED FEL

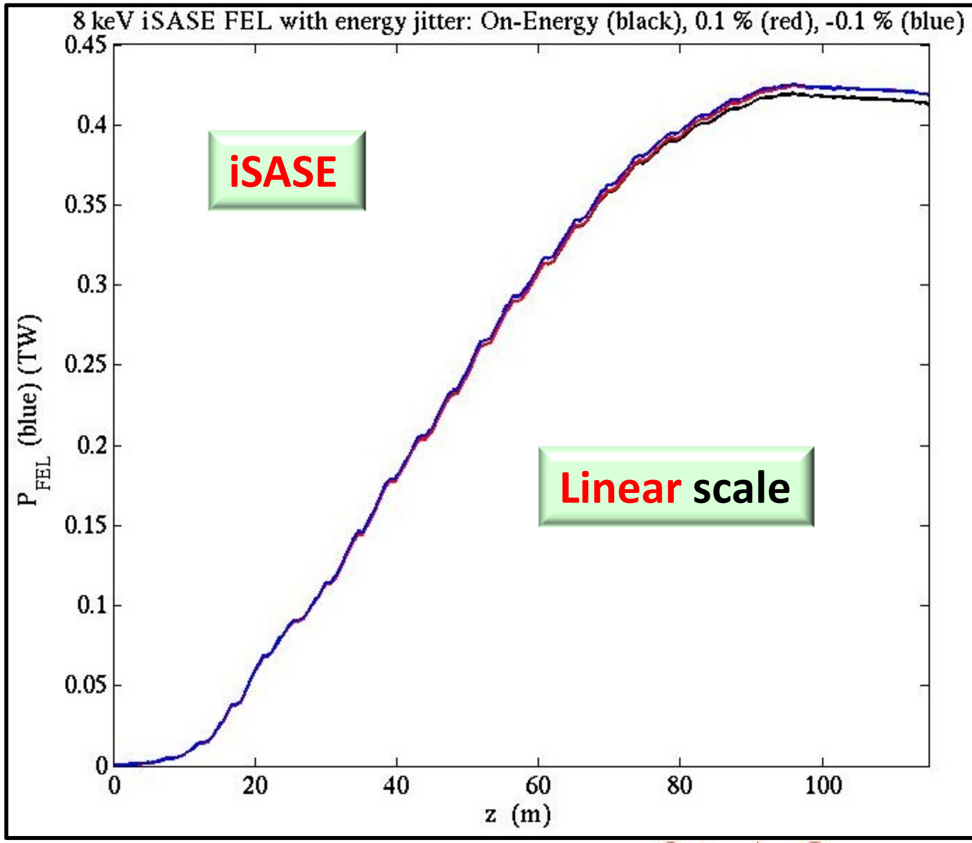
- FEL power gain curves:
  - Effective startup power of iSASE is about 0.2 MW
  - For 1 MW Self-seeding → reach TW
  - Improve startup power



COMPARISON BETWEEN SASE, ISASE, AND SEEDED FEL

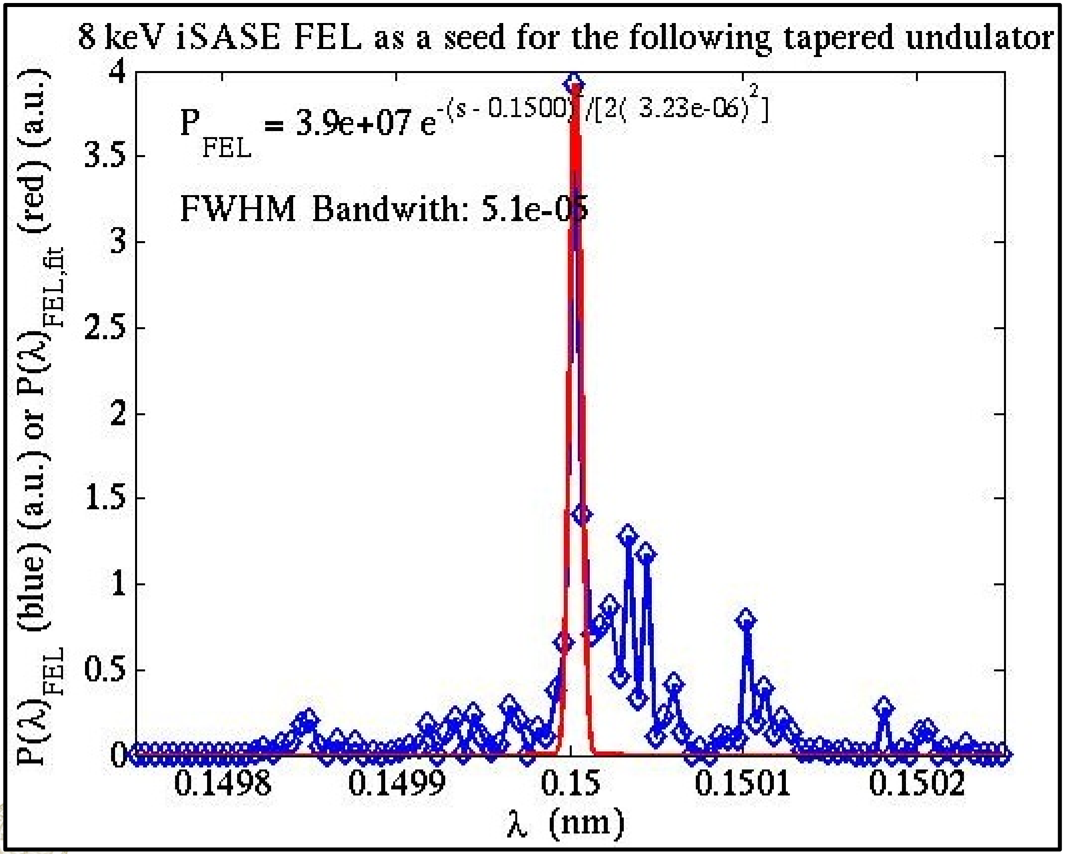
- iSASE: Energy jitter of ± 0.1 %
  - **Shift** in central frequency following the electron centroid energy
  - Yet, spectral width and power level is essentially **NO** change





COMPARISON BETWEEN SASE, ISASE, AND SEEDED FEL

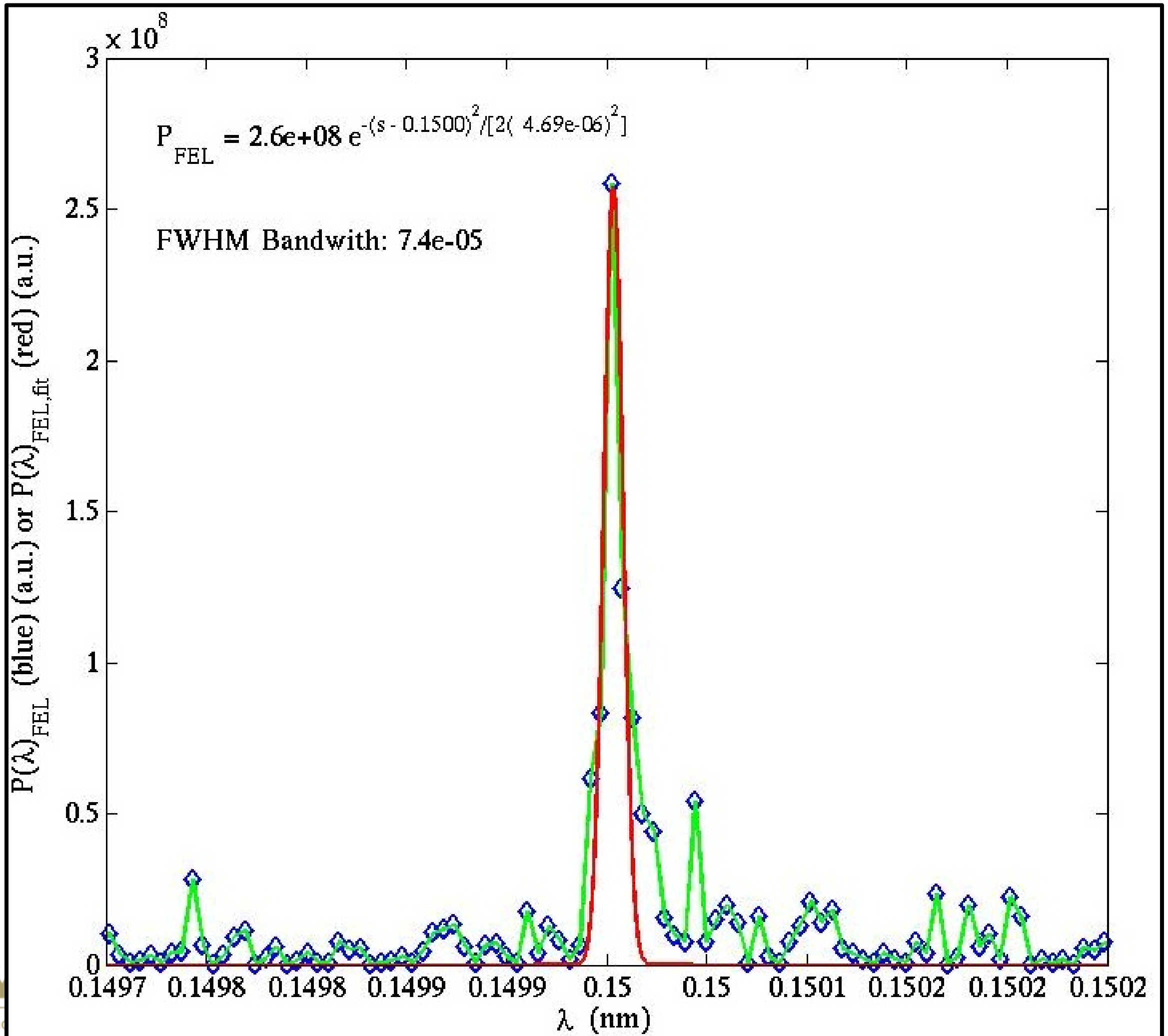
- iSASE prepared seed: narrow bandwith → close to **transform limited**



FWHM: 5.1E-05

COMPARISON BETWEEN SASE, ISASE, AND SEEDED FEL

- iSASE: narrow bandwith → close to **transform limited**



FWHM: 7.4E-05

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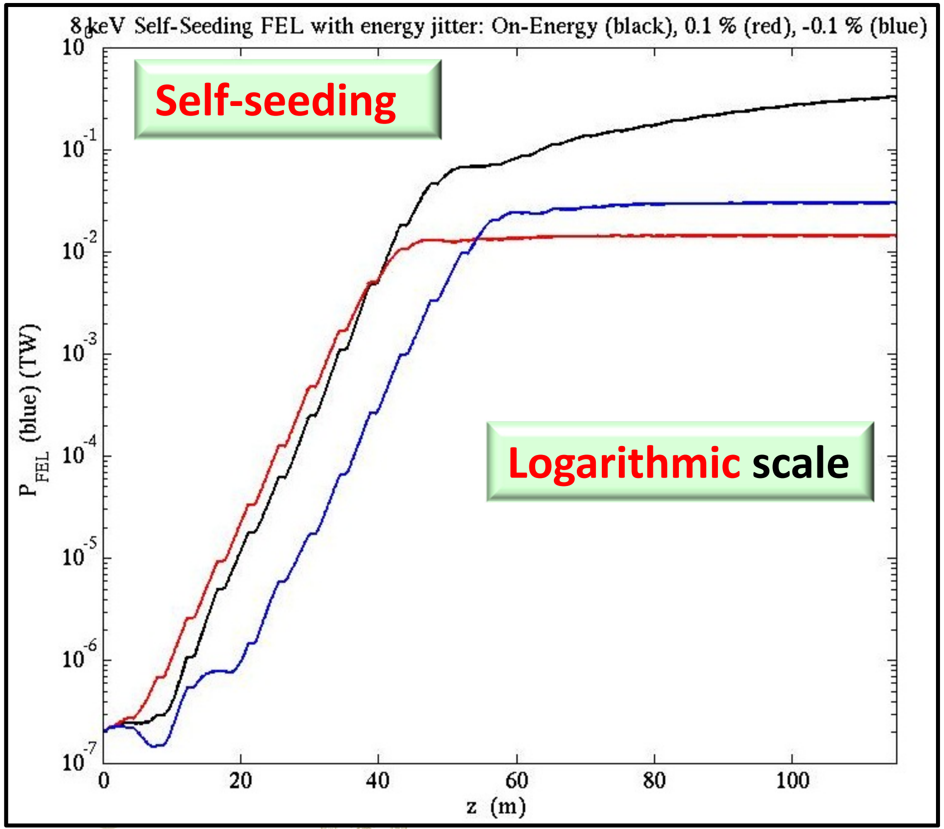
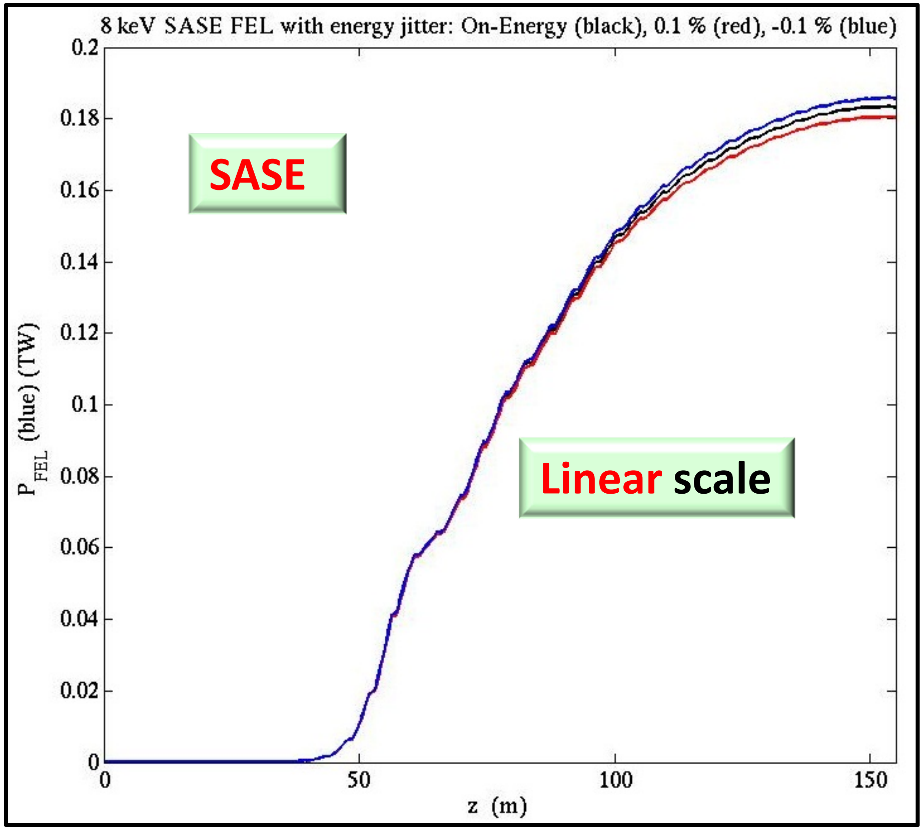
COMPARISON BETWEEN SASE, ISASE, AND SEEDED FEL

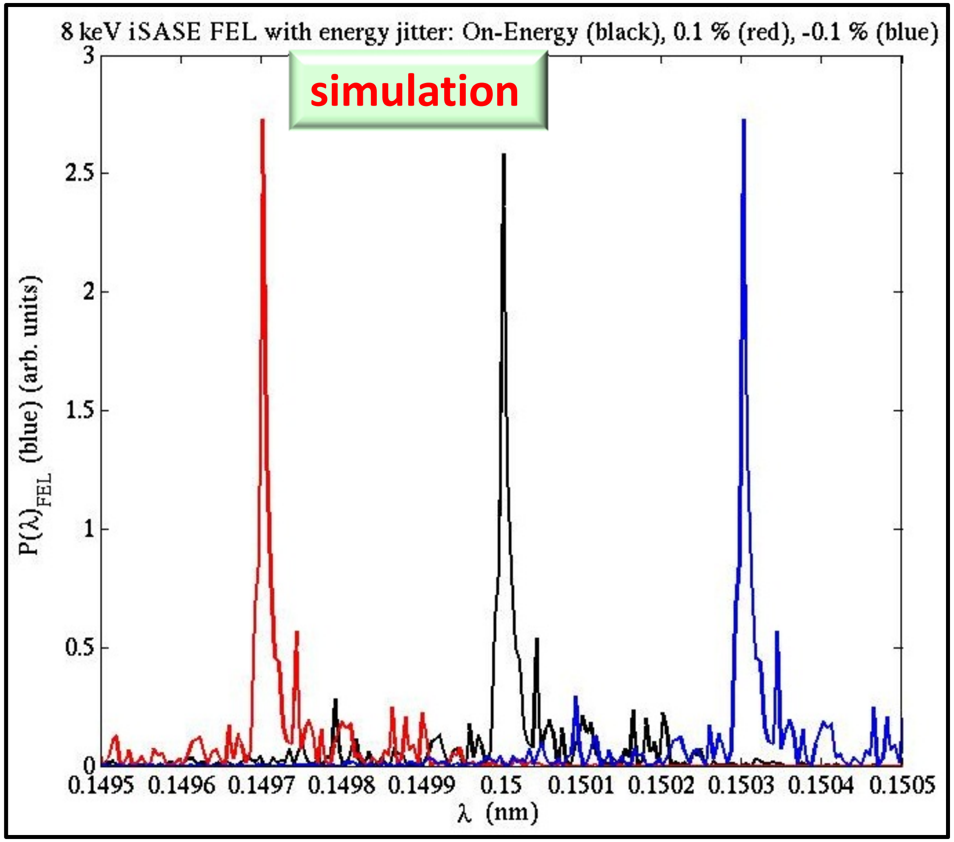
- Self-seeding: Energy jitter of ± 0.1 % → **100 %** fluctuation
- SASE: Energy jitter of ± 0.1 % → **Stable**





A TUNABLE NARROW BANDWIDTH FEL

- iSASE: Energy change of ± 0.1 %
  - FEL central frequency change ± 0.2 % following the electron centroid energy
  - Yet, spectral width and power level is essentially **NO** change



DISCUSSION

- Improved SASE (iSASE) to control the FEL spectrum
- Coherent seed either from iSASE or Self-seeding can respond to the taper well and lead to TW FEL
- Work supported by US DoE, Office of Science, under contract DE-AC02-76SF00515
- Thanks to *A. Marinelli (UCLA), H.-D. Nuhn, F.-J. Decker, Y. Feng, H. Loos, D. Ratner, D. Zhang, D. Zhu, Y. Cai, A.W. Chao, Y. Ding, X. Huang, Z. Huang, C.-C. Kao, A. Lutman, J.B. Murphy (DOE), T.O. Raubenheimer, G.V. Stupakov, et al.*