Terawatts Hard X-ray FELs for LCLS-II

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SLAC

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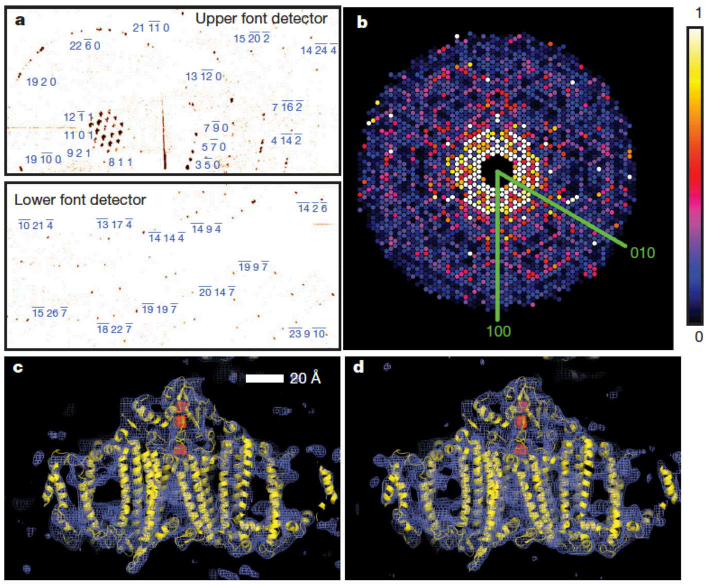
OUTLINE

- Why a Terawatt FEL @ LCLS-II
- Power and energy scaling for saturated and tapered FELs
- Results of tapered FEL simulations
- Conclusions

Present status

- LCLS is the brightest source of coherent X-rays. Its peak power and brightness are ten orders of magnitude over any other source: 10^{12} coherent photons/pulse at 1.5 Å in 70 to 100 fs, and 10^{11} at <10 fs. [P. Emma et al., Nature Photonics, 176, August 1, 2010; Y. Ding et al., Part. Acc. Conf., 300, 2009; Y. Ding et al.,Phys. Rev. Lett. 102, 254801, 2009.]
- LCLS is being used to explore many new area of science. One is imaging on femtosecond time scale of large macromolecule, a virus, cell or protein, in general non-periodic structures, using the photon coherence to measure a single shot diffraction pattern before the sample explodes. This unique capability has been successfully demonstrated, obtaining images of proteins in nano-crystals [H. N. Chapman et al., Nature, 470, 73 (2011)], and of a virus [M. M. Seibert et al., Nature, 470, 78 (2011)].

Femtosecond X-ray protein nanochrystallography
H. N. Chapman et al., Nature 470, 73 (2011).



E_{photon}=1.8 keV
$N_{photons}$~10^{12}/pulse
T_{pulse}~70fs

a) Diffraction intensity with single 70 fs pulse; resolution 8.5 Å
b) pattern of the [001] zone obtained from merging data from >15,000 nano-crystal;
c) electron density of photosystem I from LCLS data and
d) from synchrotron data with a resolution of 8.5 Å.

Nanochrystallography and more ….

The nano-crystal imaging experiment used 70 fs long pulses of about 10^{12} photons of 1.8 keV. Diffraction peaks from these data were identified and combined into a set of 3D structure factors. Reducing the pulse duration to 10 fs or less and simultaneously increasing the number of photons to about 10^{13} will allow single shot measurements of smaller nano-crystals, down to single molecules. Increasing the photon energy improves the resolution. **The interest of reaching this goal has led us to study the feasibility of a 1 TW, 10 fs X-ray FEL at 1.5 A, using the LCLS electron beam parameters. The results are reported here.**

Two examples of other applications of TW FELs: splitting the X-ray pulse for 3D imaging with multiple orthogonal beams; non-linear electrodynamics, like multi-photon creation of electron-positron pairs.

Saturated and tapered FELs

Existing hard X-ray FELs, like LCLS, operate in SASE mode, starting from longitudinal density noise in the electron beam and reaching saturation [R. Bonifacio, C. Pellegrini, and L.M. Narducci, Opt. Com-mun., 50, 373 (1984); J.B. Murphy and C. Pellegrini, J. Opt. Soc. Am. B, Vol. 2, 259 (1985)].

Kroll, Rosenbluth and Morton [N.M. Kroll, P.L. Morton, and M.N. Rosenbluth, IEEE J. Quantum Electronics, QE-17, 1436 (1981)] proposed to increase the energy transfer from the electron to the photon beam beyond saturation by adjusting the undulator magnetic field to compensate for the electron energy losses, a "tapered" undulator.

We use a tapered undulator in combination with self-seeding to reach the 1 TW level.

SCALING

An FEL is characterized by the FEL parameter, ρ, giving:

1. the exponential growth, $P=P_0 \, exp(z/L_G)$, where $L_G \sim \lambda_U/4\pi\rho$
2. The FEL saturation power $P_{sat}=\rho P_{beam}$

The FEL parameter is given by

$$\rho = \left(\frac{K}{4} \frac{\Omega_p}{\omega_U} \right)^{2/3}, \; \Omega_p = \left(\frac{4\pi r_e c^2}{\gamma^3} n_e \right)^{1/2}, \; \omega_U = \frac{2\pi c}{\lambda_U}$$

For the LCLS electron beam: $I_{pk} \sim 3\ kA$, $E \sim 14\ GeV$, $P_{beam} \sim 40\ TW$, FEL: $\rho \sim 5x10^{-4}$, $P_{sat.} \sim 20\ GW << 1\ TW$

Scaling

For X-ray FELs the FEL parameter ρ is typically $\sim 10^{-4}$-10^{-3}.

Ω_P, the beam plasma frequency, scales as $1/\gamma$. The product $K\lambda_U$ increases with γ for a fixed wavelength, so the value of the FEL parameter is weakly dependent on the beam energy, but the peak power increases with beam energy.

a. Overall, the peak power at saturation is in the range of 10 to 50 GW for X-ray FELs at saturation.

b. The number of coherent photons scales almost linearly with the pulse duration, and is $\sim 10^{12}$ at 100 fs, 10^{11} at 10fs.

BEYOND SATURATION

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- 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

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Tapering

Change undulator period and/or magnetic field to compensate the electron energy loss to the radiation field while satisfying the resonance condition.

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

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

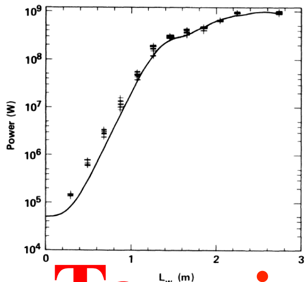
The electron energy loss depends on the amplitude, A, and phase of the radiation field

$$\frac{d\gamma_R}{dz} = \frac{eA(z)}{mc}\frac{K(z)}{\gamma_R(z)}\sin\Psi_R$$

The rate of energy change and the undulator tapering are adjusted for maximum energy transfer from the electrons to the radiation.

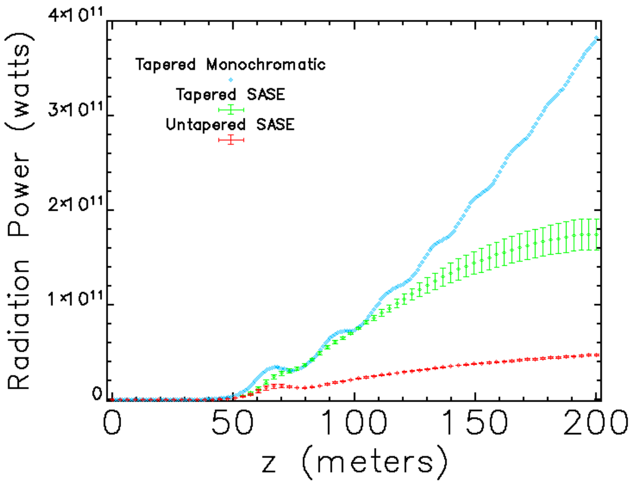
First demonstration of tapering at 34 GHz*

* T.J. Orzechowski et al. Phys. Rev. Lett. 57, 2172-2175 (1986)



Experiment was done at LLNL with a seeded, 1 cm wavelength FEL and a tapered undulator.

Tapering of LCLS Fawley et al., Nucl. Instr. And Meth. A 483, 537-541 (2002)



CLS tapering at 0.15 nm,1nC, 3.4kA. aturation power at 70 m ~20 GW. A 00m, un-tapered undulator doubles the ower. Tapering for SASE gives 200GW. monochromatic, seeded, FEL brings the ower to 380 GW, corresponding to 4 mJ 10 fs ($2x10^{12}$ photons at 10 keV). The undulator K changes by ~1.5%.

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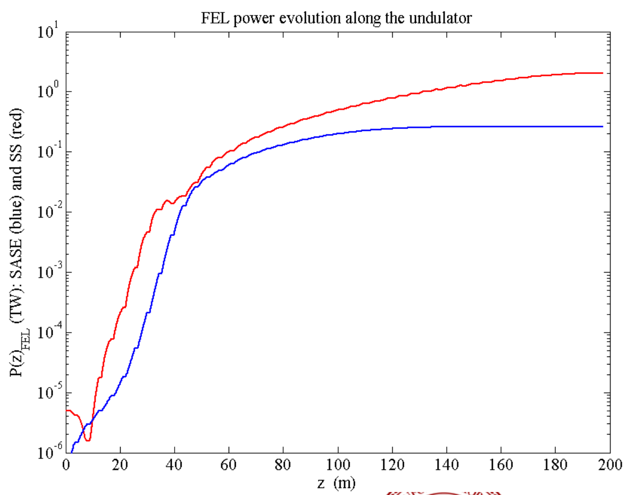
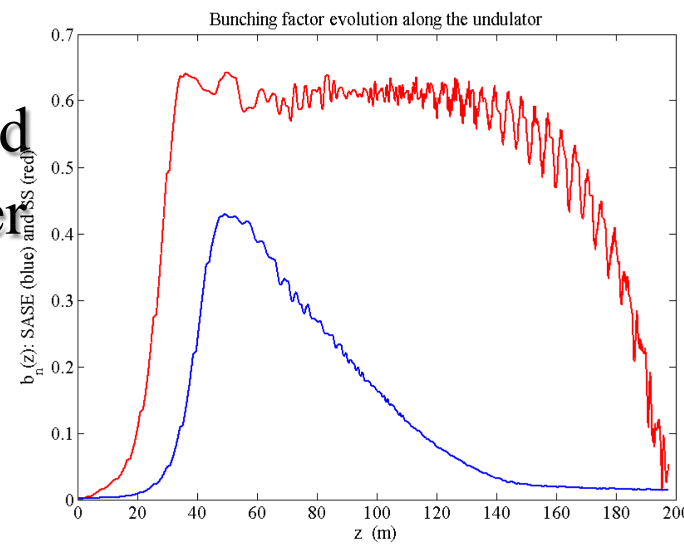
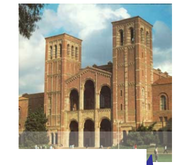
TAPERING FOR LCLS II

- We study a TW FEL for LCLS-II starting with a SASE amplifier, followed by a "self-seeding" crystal monochromator, and finishing with a long tapered undulator.
- Results show that **TW-level** output power at 8 keV is **feasible**, with a total undulator length below 200 m for a **40 pC** bunch charge, normalized transverse emittance **0.3-mm-mrad**, peak current **4 kA**, electron energy **13.6 GeV**.



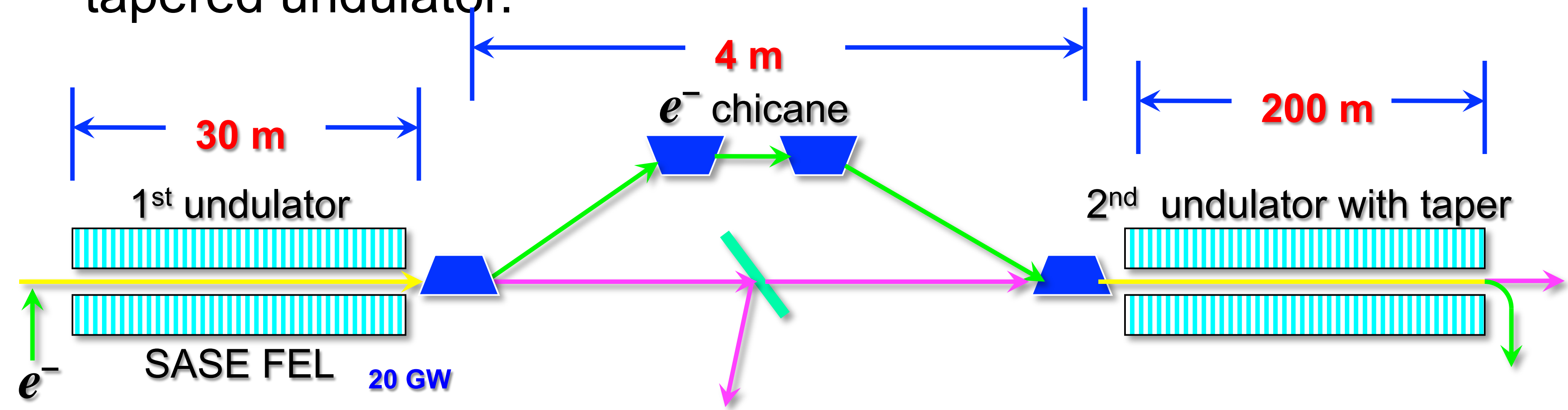
SASE vs Self-seeded
Self-seeding is better

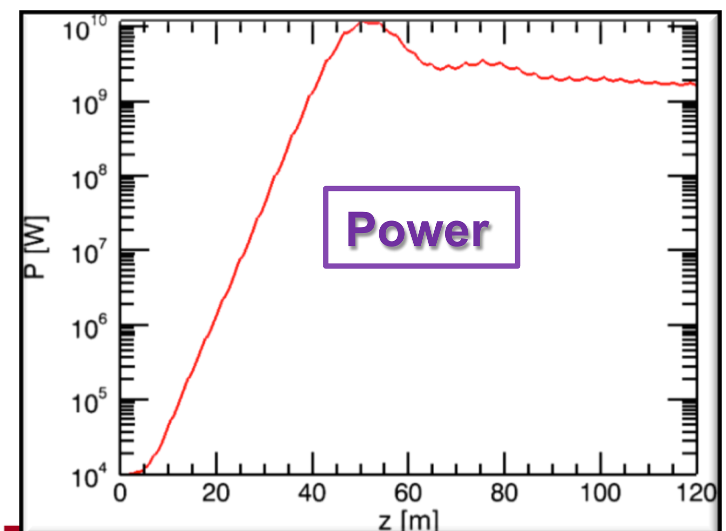


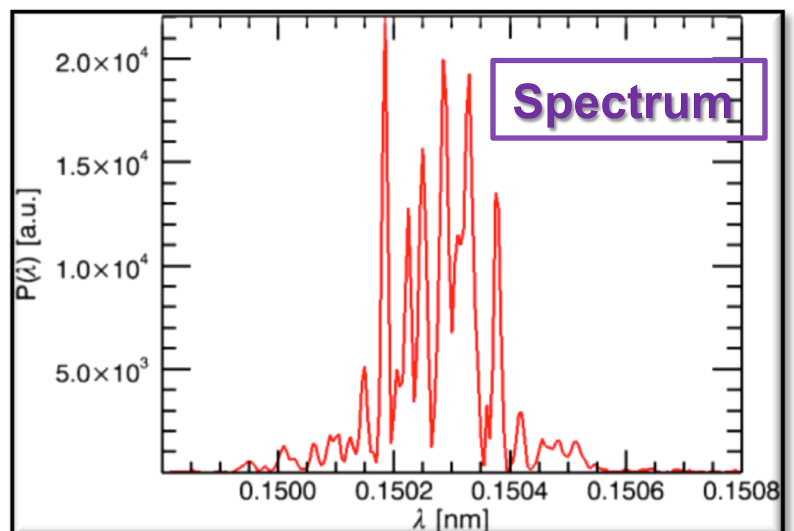


SELF-SEEDED FELS

- Start with a SASE FEL, followed by a monochromator and a tapered undulator.

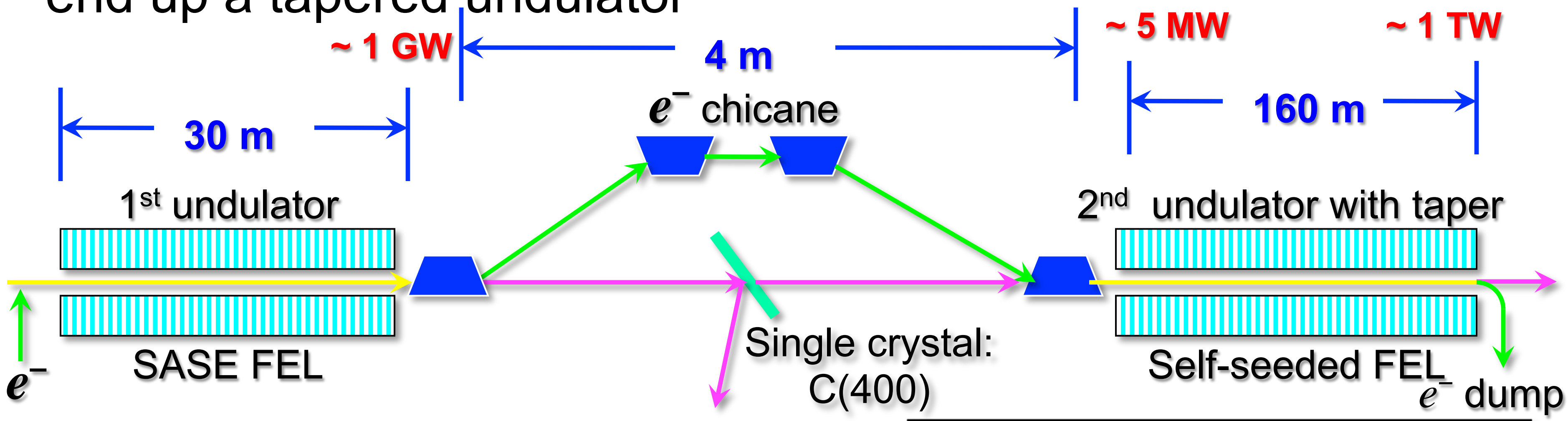


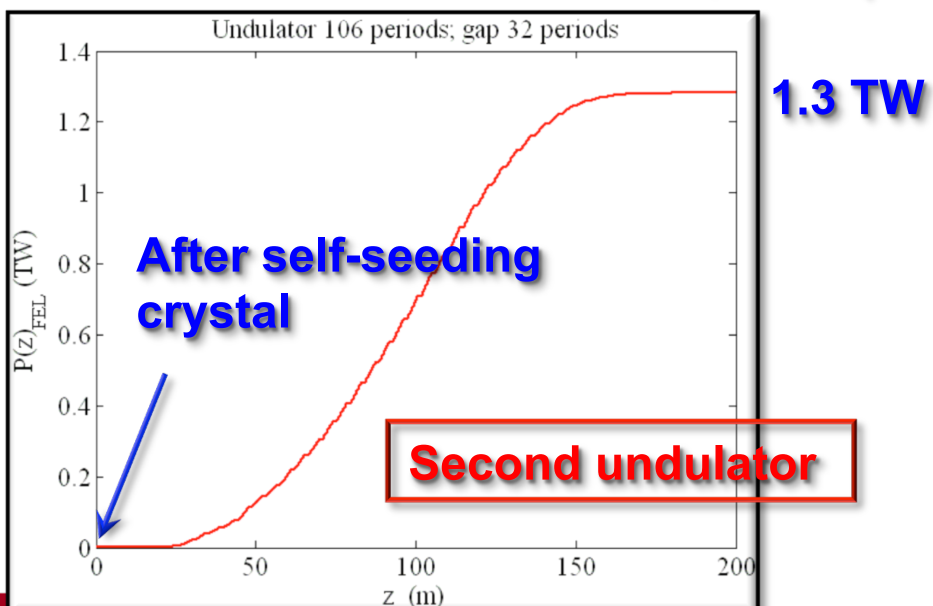


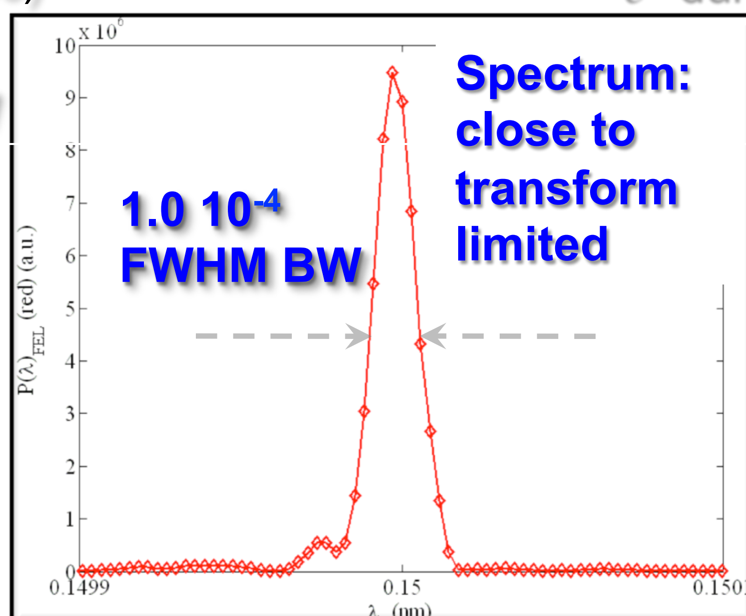


SELF-SEEDED FEL

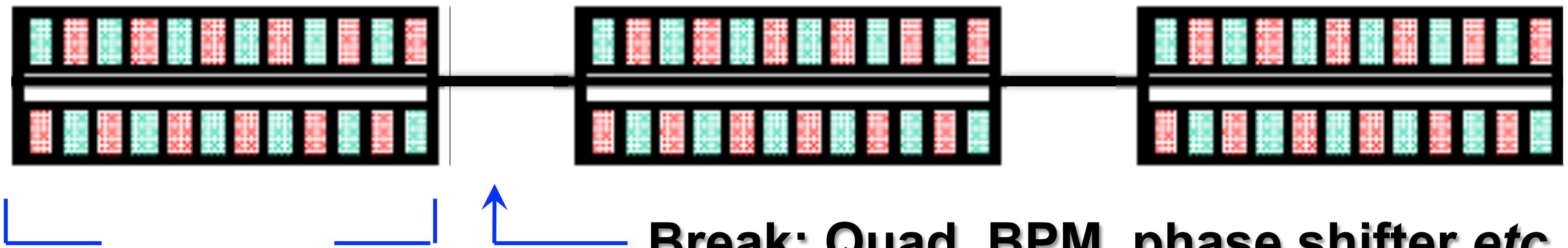
- Start with a SASE FEL, followed by a self-seeding scheme, and end up a tapered undulator







LCLSII BASELINE UNDULATOR STRUCTURE



Undulator period λ_u = 3.2 cm,
Undulator length per section L_u= 3.4 m,
Number of the undulator periods NWIG = L_u/λ_u = 106,
Break length per section L_b = 1 m
Break length in unit of undulator periods NBREAK = L_b/λ_u = 32.
Filling factor = NWIG/(NWIG + NBREAK) = 77%.

TAPERING PHYSICS AND MODEL

- Resonant condition

$$\boxed{\lambda_r = \lambda_u \frac{1 + A_w^2(z)}{2\gamma^2(z)}}$$

Undulator parameter A_w is function of z, after z_0, to maintain the resonant condition.

- Increase of the optical radiation field $a_s(z)$ follows KMR paper

$$\boxed{\frac{a_s(z)}{a_s(z_0)}\sin(\Psi_r) = -C\frac{dA_w(z)}{dz}}$$

Ψ_r is the synchronous phase of the ponderomotive bucket. Approximately constant.

C is positive constant coefficient

- With the tapering model

$$\boxed{A_w(z) = A_w(z_0)\times(1 - a\times(z - z_0)^b)}$$

The order *b* is not necessarily an integer.

- The increase of the optical radiation field follows

$$\boxed{\frac{a_s(z)}{a_s(z_0)}\sin(\Psi_r) = C\times a\times n\times(z - z_0)^{b-1}}$$

It requires $b > 1$ for a increasing electric field.

TAPERING PHYSICS AND MODEL

- Three variables in the tapering model

- **taper ratio *r*,** closely related to the **relative energy loss of the particles** trapped into the ponderomotive bucket, and therefore **the gain of the optical radiation power**.

$$\boxed{r = 1 - \frac{A_w(z_f)}{A_w(z_0)} = a \times (z - z_0)^b}$$

- **taper start point z_0**, empirically it is best to start taper **before radiation power reaching saturation, $z_0 < L_{sat}$**, so as to avoid saturation region, in which the radiation exchange energy with electrons with zero net gain.

- **Taper profile order *b***, related to the **optical radiation electric field increase slope**.

$$\boxed{\frac{a_s(z)}{a_s(z_0)} \sin(\Psi_r) = C \times a \times n \times (z - z_0)^{b-1}}$$

There is an optimal order b_0 to make the $a_s(z)$ increase as rapidly as possible, while not leading to a significant detrapping.

OPTIMAL BETA FUNCTION (TRANSVERSE, SECONDARY)

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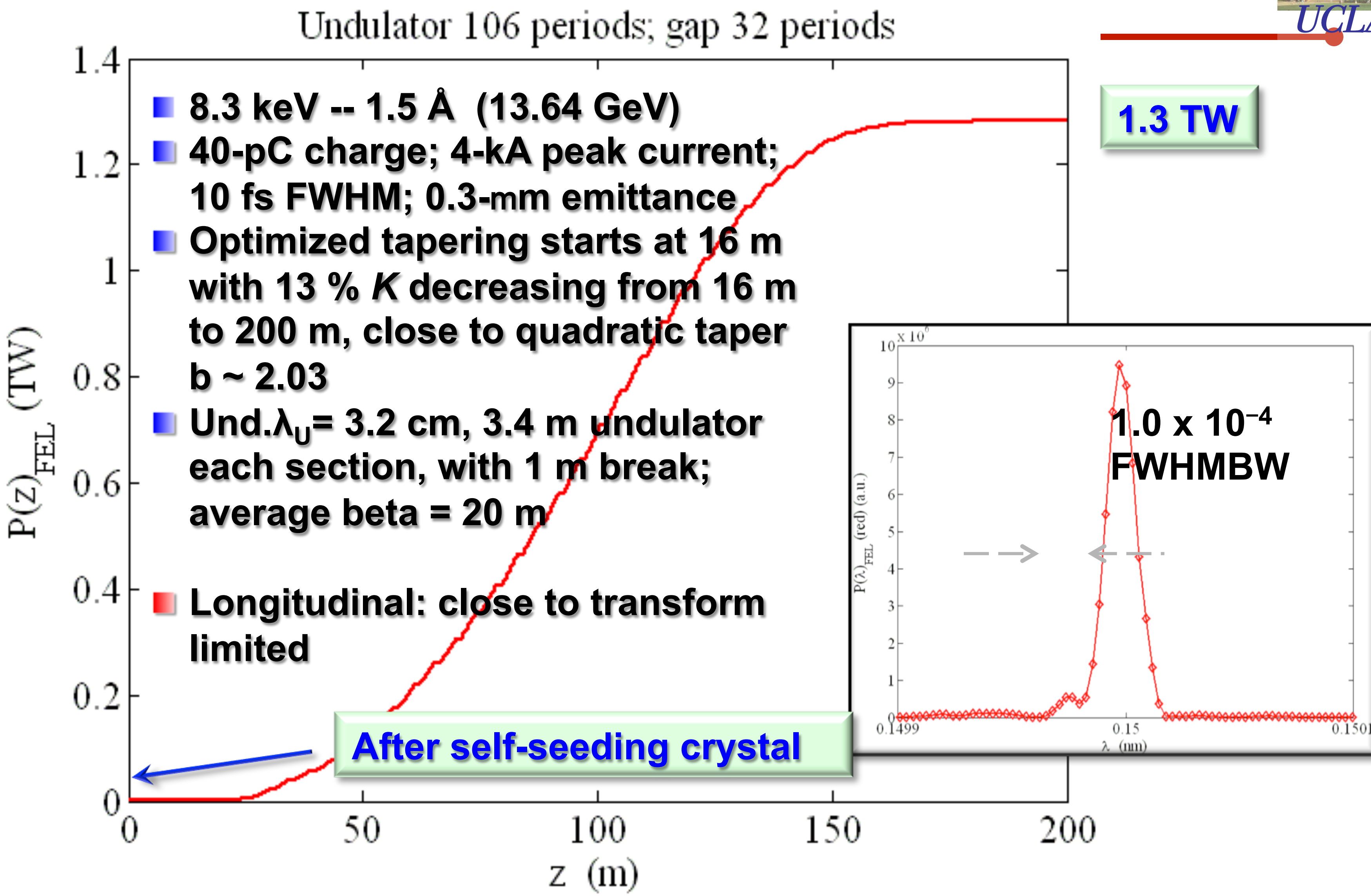
- For the tapered undulator**, before L_{sat}**, the exponential region, strong focusing, low beta function helps produce higher power (M. Xie's formula).
- **After L_{sat}**, the **radiation rms size increases** along the tapered undulator due to **less effectiveness of the optical guiding**. The requirement is **different**.
- We empirically found that a variation in beta function instead of a constant beta function will help produce higher power. In most cases, optimal beta function will help extract up to 15% more energy even with optimal tapering parameters.
- The beta function is varied by linearly changing the quad gradient

$$\boxed{K(z) = K(z_1) \times (1 - c \times (z - z_1))}$$

The coefficient *c* can be positive or negative value.

TW FEL @ LCLS-II NOMINAL CASE



- 8.3 keV -- 1.5 Å (13.64 GeV)
- 40-pC charge; 4-kA peak current; 10 fs FWHM; 0.3-mm emittance
- Optimized tapering starts at 16 m with 13 % *K* decreasing from 16 m to 200 m, close to quadratic taper b ~ 2.03
- Und.λ_U= 3.2 cm, 3.4 m undulator each section, with 1 m break; average beta = 20 m
- Longitudinal: close to transform limited

TW FEL @ LCLS-II NOMINAL CASE

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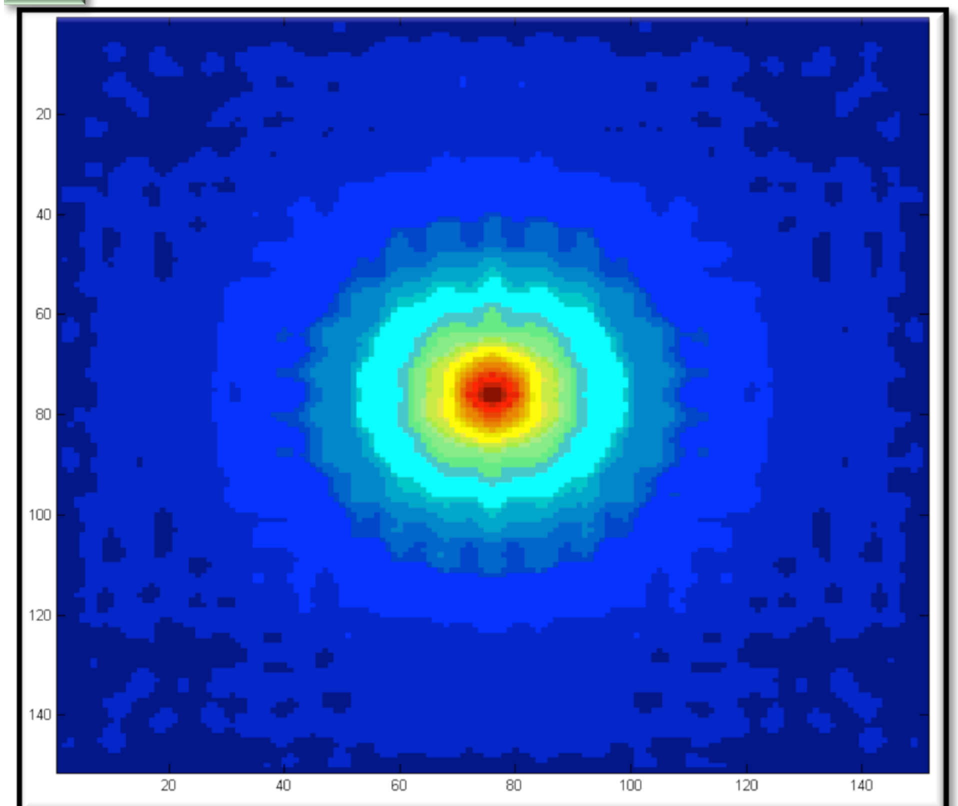
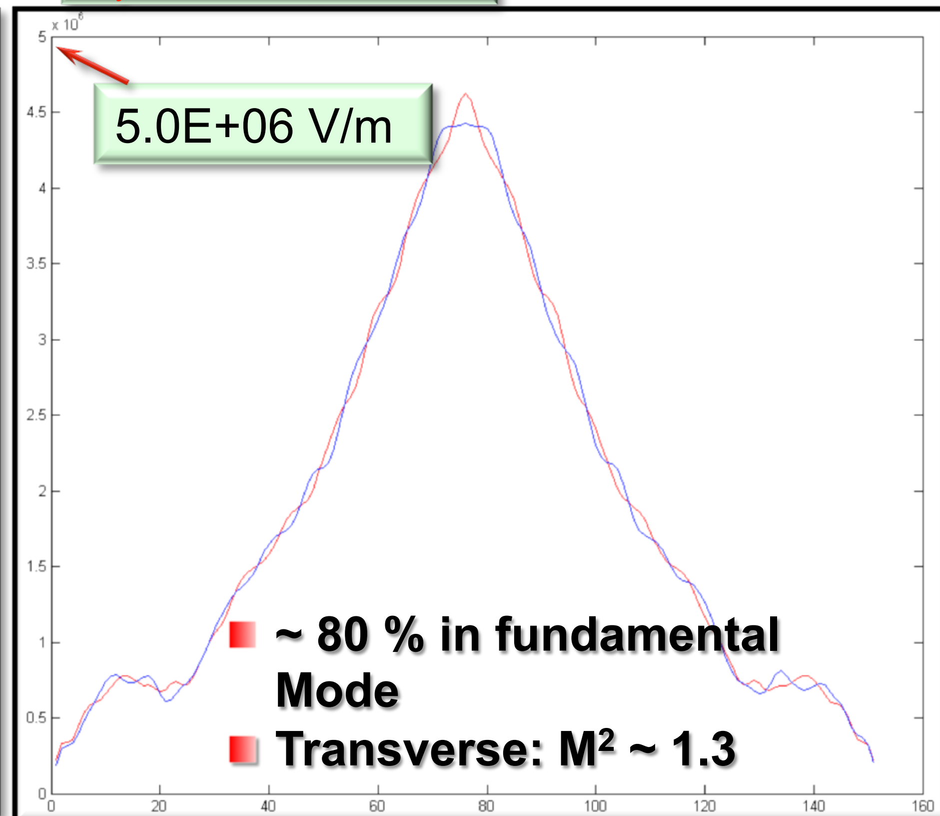
- 1.5 Å FEL at end of undulator (160 m)

y



x

E_y (red); E_x (blue)



y (red); x (blue)

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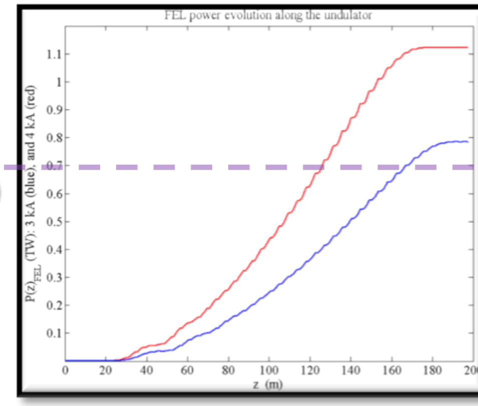
Scaling: current and emittance

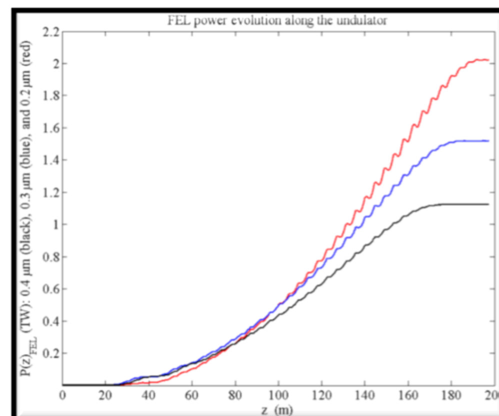
- Taper region: coherent emission, power proportional to the square of the peak current

  - 0.4-mm emittance
  - peak current: **4-kA (red)** vs **3 kA (blue)**



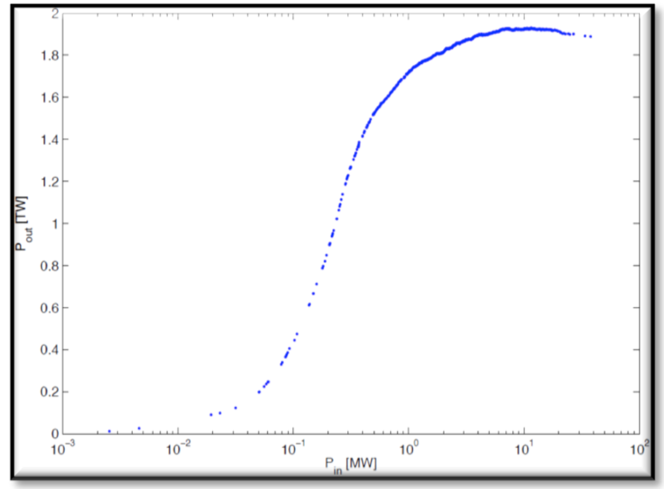
Emittance is not so stringent (current 4 kA)

- emittance: 0.2, 0.3, 0.4 -mm
- peak current: 4-kA

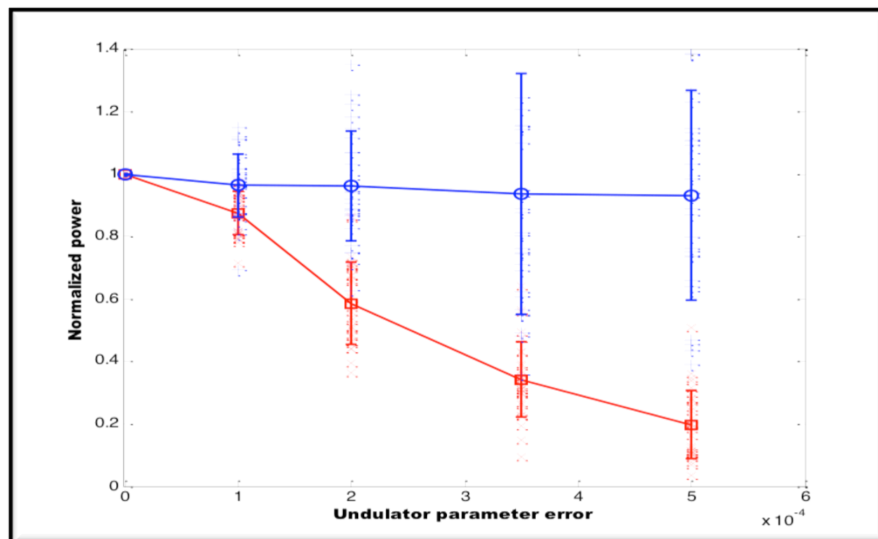


Scaling: Input power and undulator errors

The seed power should be larger than a few MW

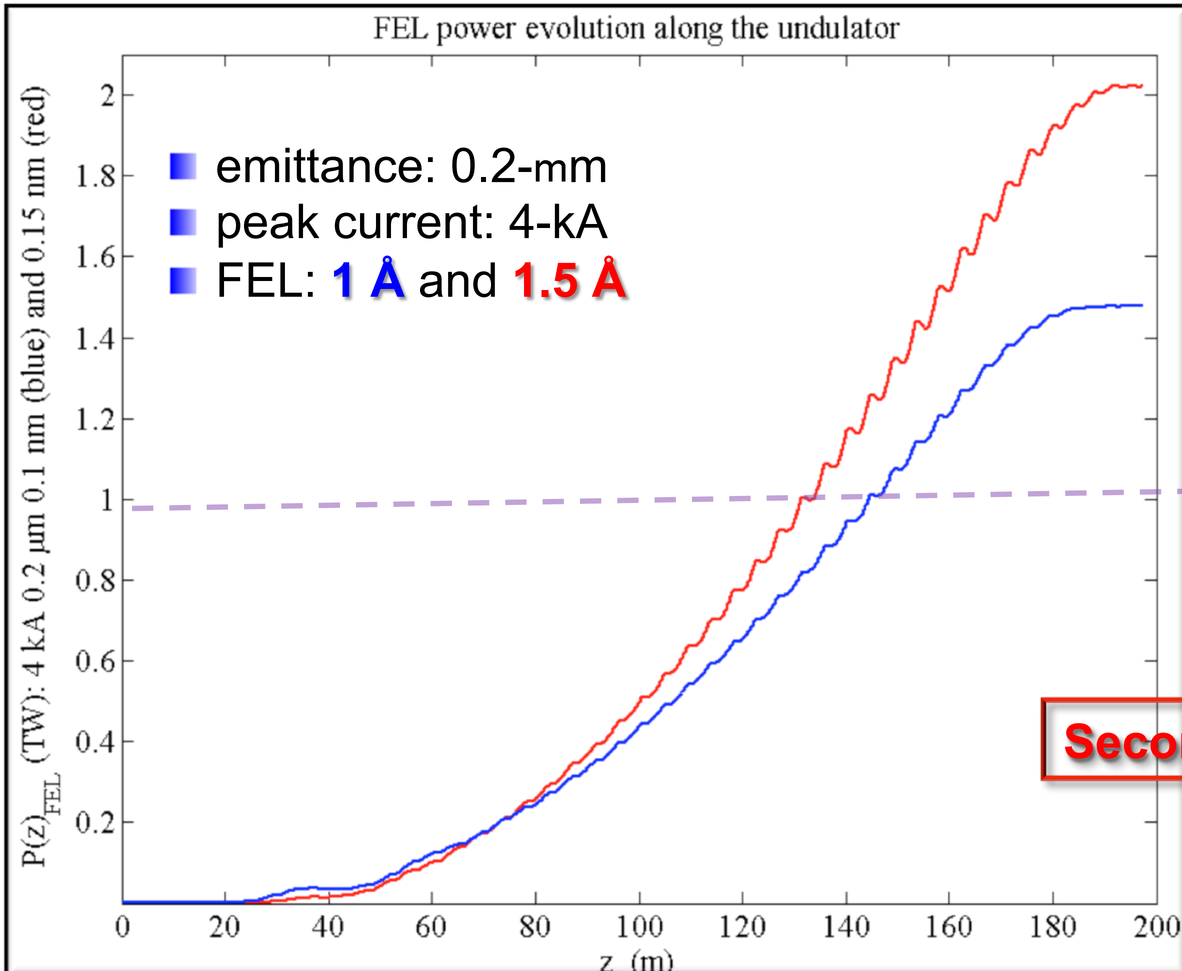


The maximum power of the tapered undulator is more sensitive to the undulator parameter errors than saturation power. The tolerance is about 10^{-4}, within the state of the art.



SCALING: EXTEND TO HIGHER ENERGY PHOTON

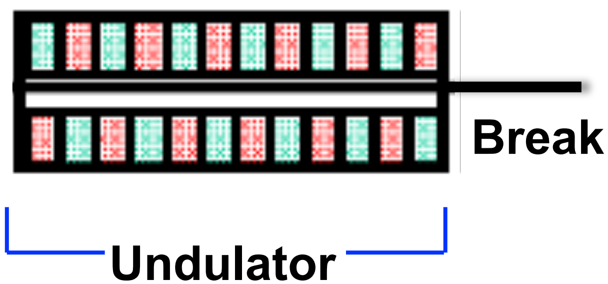
- For 4 kA, emittance 0.2 mm-mrad; good for 1 Å



Second undulator

COMPARE WITH THE UNDULATOR WITH ZERO BREAKS

- **Breaks cause bunching factor reduction, and therefore the power decrease.**



When passing through one break L_b, there is a difference between the path length of the electron and the photon,

$$\Delta L = L_{photon} - L_{electron} \approx \frac{L_b}{2\gamma^2}$$

Match the phase of the resonant particle and radiation field,

$$\Delta L \approx \frac{L_b}{2\gamma^2} = n\lambda_r$$

A particle with nonzero energy deviation relative to the reference particle, has an additional path length difference,

$$\Delta L(\delta = 0) - \Delta L(\delta \neq 0)$$

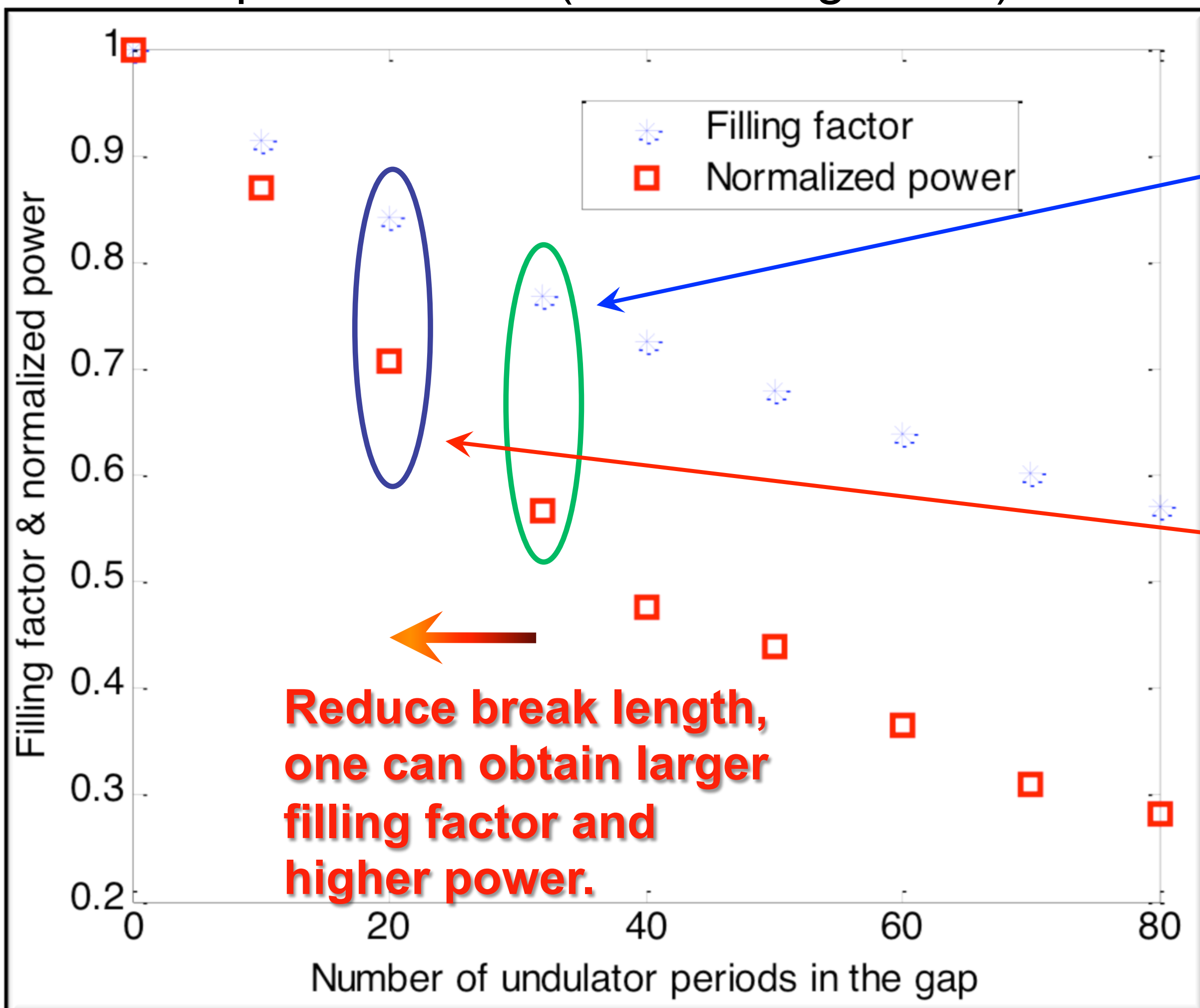
$$\approx \frac{L_b}{\gamma^2}\delta = 2n\lambda_r\delta$$

For LCLSII baseline, n = 5, d **is up to several percent at the end of the undulator**, the path length due to energy deviation is about one period, causing phase mixing and bunching factor reduction.

For zero breaks, L_b = 0, there is no additional path length difference due to the nonzero energy deviation.

POWER VS. FILLING FACTOR (CHANGE NBREAK)

Based on Genesis **time-independent** simulation.
Normalized power = P / P(100% filling factor).

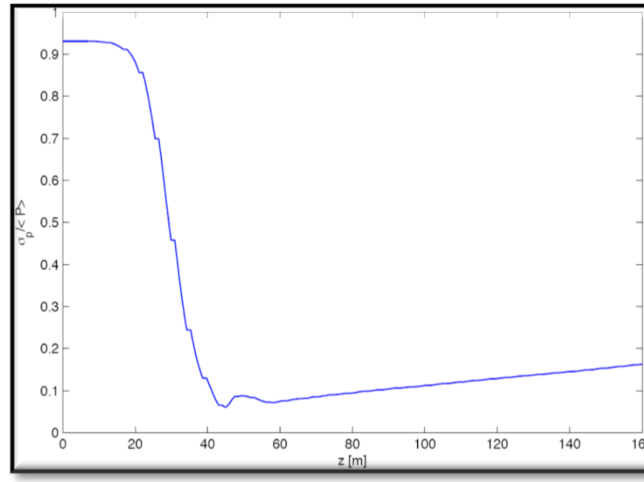


LCLSII baseline,
NWIG = 106,
NBREAK = 32,
Filling factor 77%
P = 2.77 TW
P_{norm} = 0.57

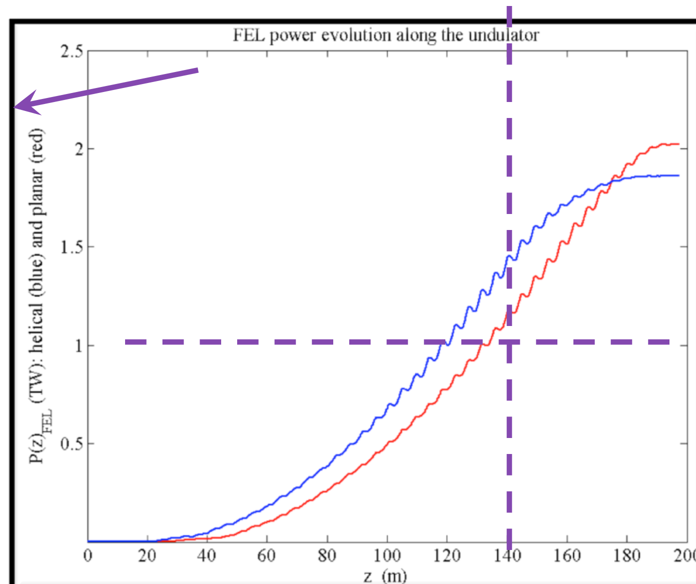
LCLSII baseline,
NWIG = 106,
NBREAK = 20,
Filling factor 84%
P = 3.45 TW
P_{norm} = 0.71
Increase ~ 25%.

Statistics and helical undulator

Statistical fluctuations increase but not dramatically



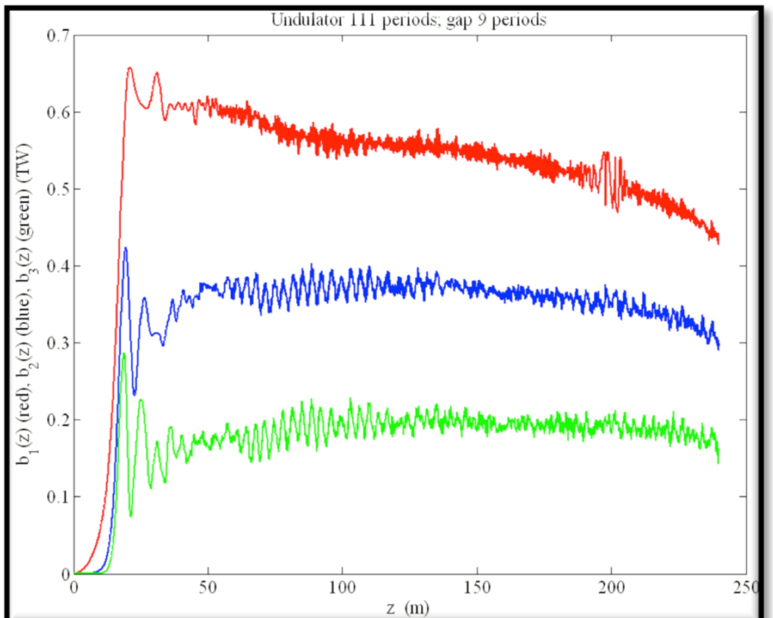
Helical undulator enhances performance 30% in power, 15m in length.
Study is ongoing.

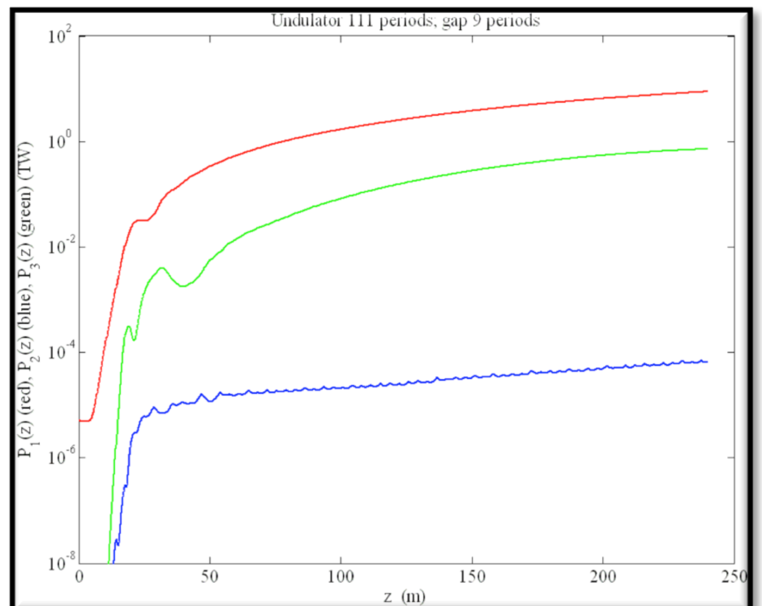


HARMONICS IN A TW FEL: BUNCHING AND POWER

- Since the bunching remains high in the long tapered undulator, harmonics can be large. We have evaluated the harmonics for an LCLS-II type undulator and electron bunch.

Fundamental (red);
Second harm. (blue);
Third harm. (green)





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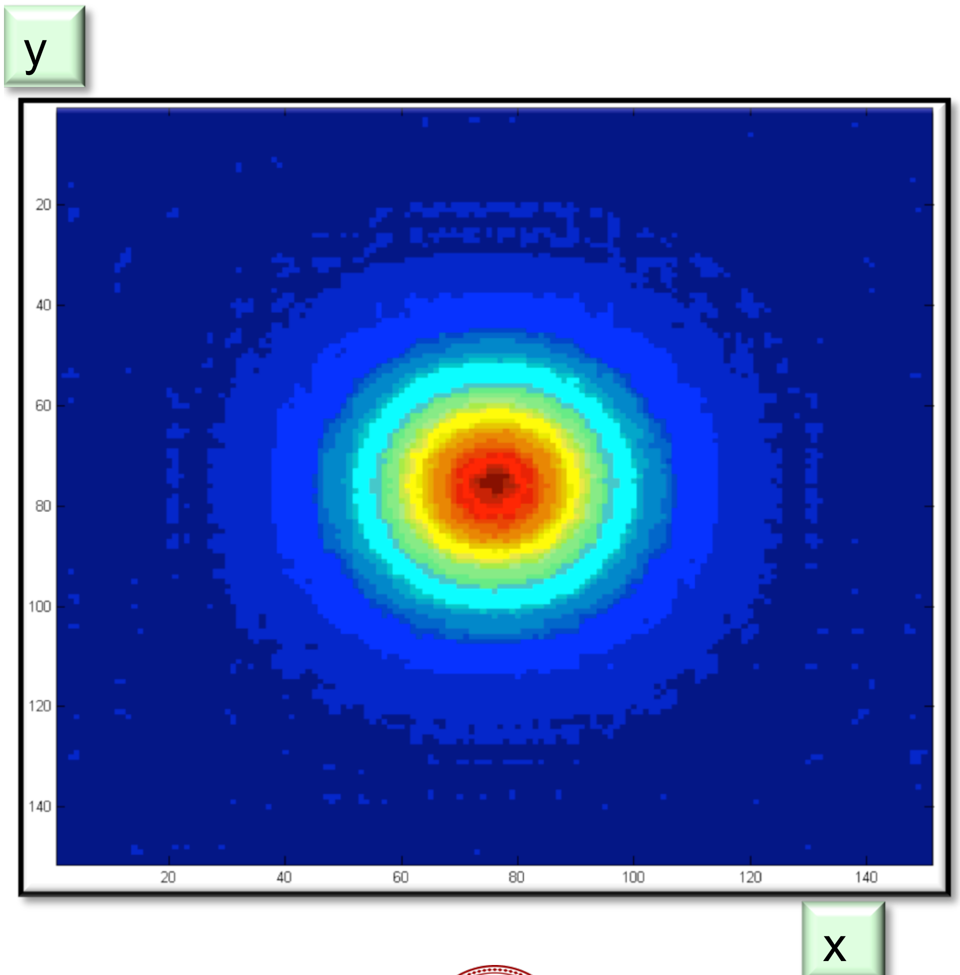
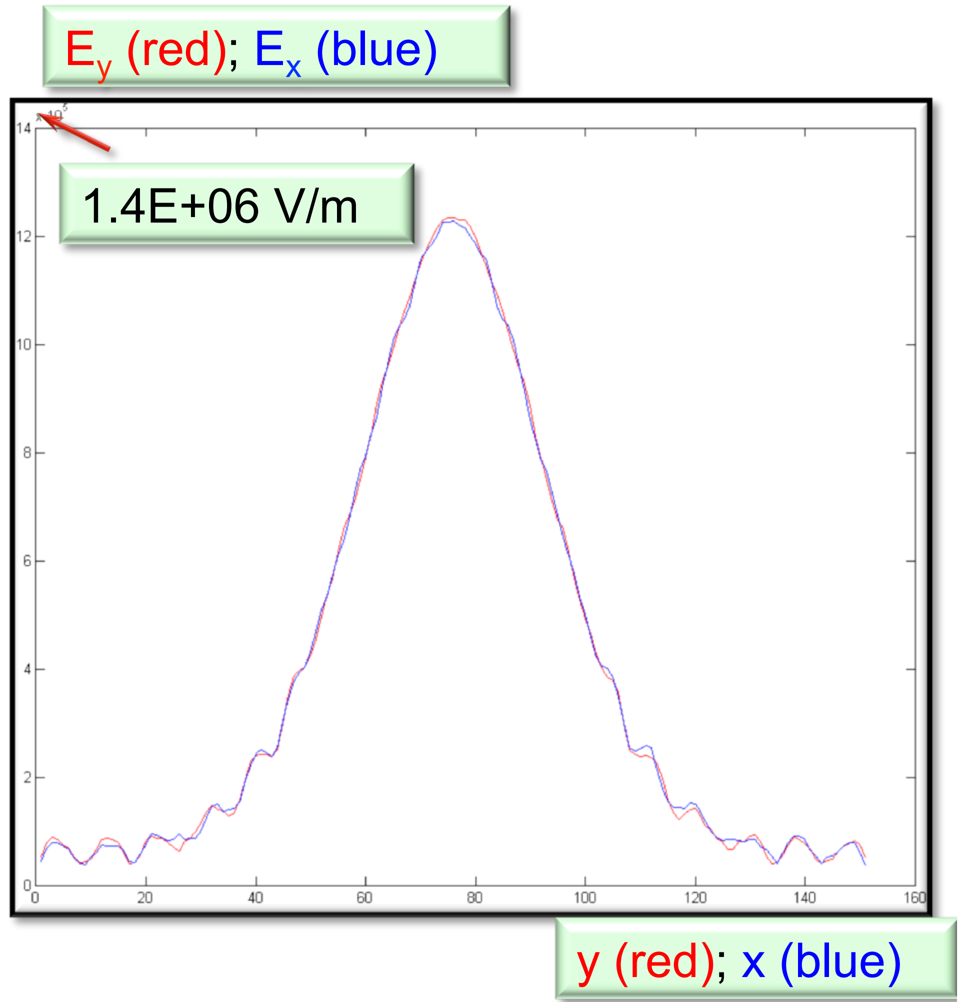
HARMONICS IN A TW FEL: FIELD PROFILE

- 3rd harmonic at undulator end





Conclusions

- ✓ A 1.5 Å TW FEL is feasible
- ✓ High power, hundreds GW at 3rd harmonic, allowing to reach higher energy photon.
- ✓ This light source would open new science capabilities for coherent diffraction imaging and nonlinear science.