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TOWARD TW-LEVEL LCLS RADIATION PULSES

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LAYOUT

- Why a Terawatts FEL @ LCLS-II
- Power and energy scaling for saturated and tapered FELs
- Simulation results for a TW FEL @ LCLS-II
- Conclusions

PRESENT STATUS

- LCLS -- the brightest source of coherent X-rays.
    - peak power and brightness: ten orders of magnitude over other sources: 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* ***4****, 641 (2010);* ***Y. Ding*** *et al., Part. Acc. Conf., 300, 2009;* ***Y. Ding*** *et al., Phys. Rev. Lett.* ***102****, 254801 (2009)*.]
- LCLS: explore many new area of science.
    - Imaging on femtosecond time scale of large macromolecule, in general non-periodic structures, using the photon coherence to measure a single shot diffraction pattern before the sample explodes.
        - **nano-crystals** [***H.N. Chapman*** *et al., Nature* ***470****, 73 (2011)*],
        - **virus** [***M.M. Seibert*** *et al., Nature* ***470****, 78 (2011)*].

A wish-list for an ideal X-ray FEL (for macromolecular imaging)

- The key metric is photon power. **Ideally ~10 TW**
  - This gives about 10^{20} W/cm^2 (with 1 micron focus, assuming beamline and focusing efficiency)
  - Only the first 10 to 30 fs of the pulse usefully contributes
- Wavelength range: **4 keV to 14 keV** (to cover elemental edges from S to Se)
  - Also: 300-500 eV for water-window imaging of cells, viruses
  - Up to 30 keV for time-resolved imaging of nanoparticles
- Repetition rate: As high as possible
  - Need to match detector capabilities. **1 kHz repetition** could be feasible
- Bandwidth: As high as possible
  - **1 to 10% bandwidth** would allow structure determination with about 1% of the required pulses. i.e. structure determined in <1000 shots

Courtesy of **H. Chapman**

SCIENCE DRIVE

- The **scientific interest** of reaching this goal and some other applications have led us to conduct an in depth study of the feasibility of a **TWs, 10 fs X-ray FEL at 1.5 Å**, using the LCLS electron beam parameters. The results of this study are reported here.

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,* ***2****, 259 (1985)*].
- Kroll, Morton, and Rosenbluth [***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

A SASE FEL is characterized by the FEL parameter, ρ

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 $P_{sat} \sim \rho\ P_{beam}$

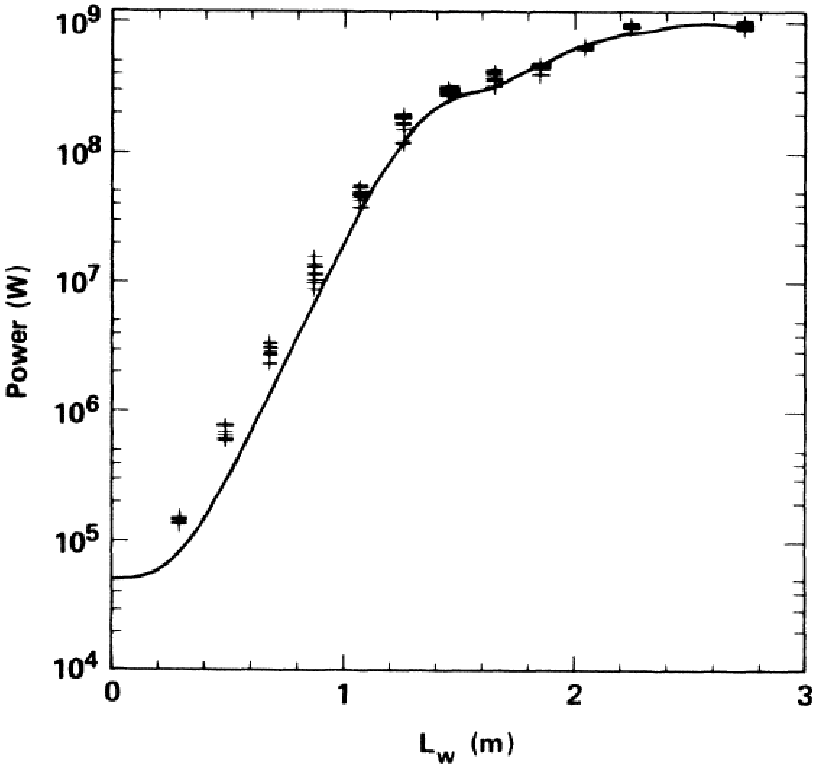
For the LCLS-II electron beam: $I_{pk} \sim 4\ k\ A$, $E \sim 14\ GeV$, $P_{beam} \sim 56\ TW$, FEL: $\rho \sim 5 \times 10^{-4}$, $P_{sat.} \sim 30\ GW << 1\ TW$

- 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 seeding scheme -- self-seeding
  - Trapping the electrons

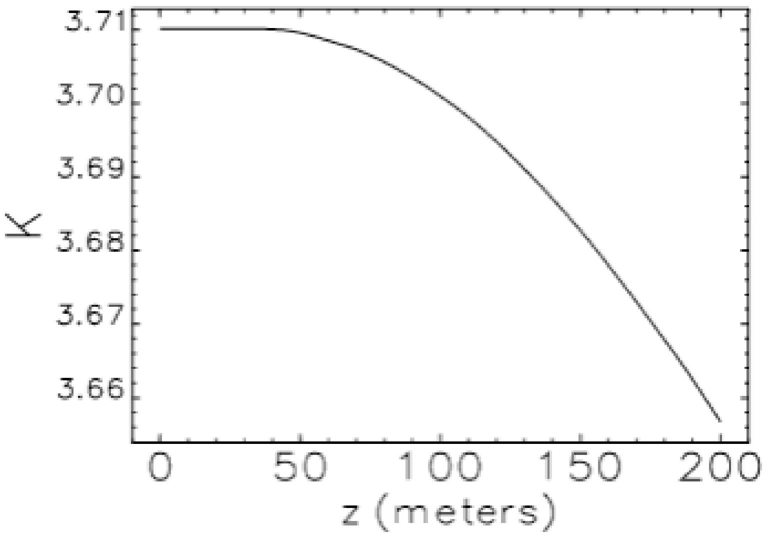
FIRST DEMONSTRATION OF TAPERING AT 30 GHZ*

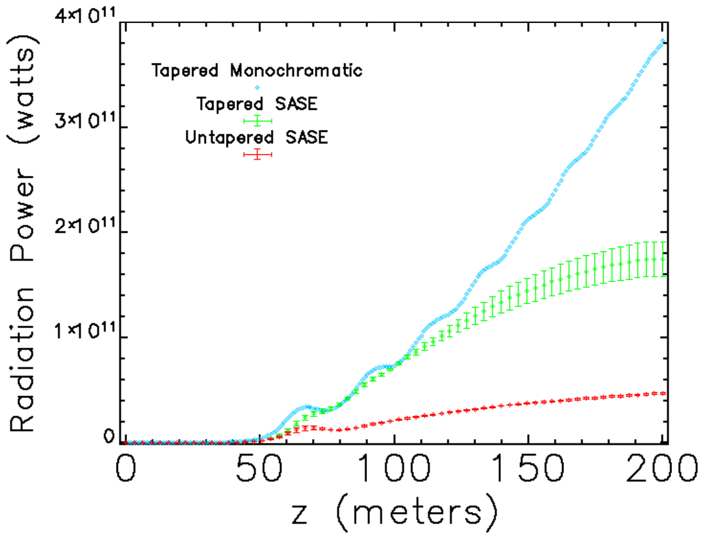


The experiment was done at LLNL with a seeded, 10 cm wavelength FEL and a tapered undulator.

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

EXAMPLE OF TAPERING: LCLS





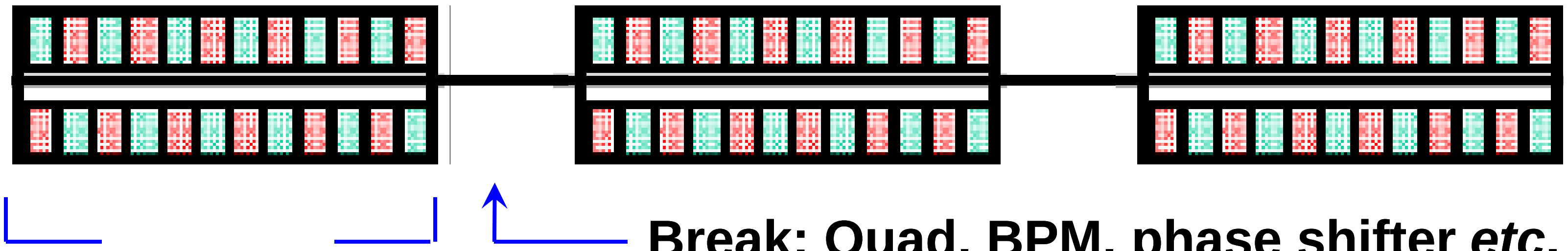
Effect of tapering **LCLS** at 1.5 Å,1 nC, 3.4 kA. The saturation power at 70 m ~20 GW. A 200 m, un-tapered undulator doubles the power. Tapering for SASE FEL generates about 200 GW. A monochromatic, seeded, FEL brings the power to 380 GW, corresponding to 4 mJ in 10 fs (**2×10^{12}** photons at **8** keV). The undulator *K* changes by ~1.5 %.

W.M. Fawley, Z. Huang, K.-J. Kim, and N.A. Vinokurov *,*
Nucl. Instr. And Meth. A ***483****, 537 (2002)*

OVERVIEW

- To overcome the random nature of a **SASE FEL**, which will set a limit to the final tapered FEL power, we study **seeded FEL**
- Producing such pulses from the proposed LCLS-II, employing a configuration beginning with a SASE amplifier, followed by a "self-seeding" crystal monochromator, and finishing with a long tapered undulator.
- Results suggest that **TW-level** output power at 8 keV is **feasible**, with a total undulator length below 200 m including interruption.
  - We use a **40 pC** electron bunch charge, normalized transverse emittance of **0.3-mm-mrad**, peak current of **4 kA**, and electron energy about **14 GeV**.

LCLS-II BASELINE UNDULATOR STRUCTURE



Undulator section

Break: Quad, BPM, phase shifter *etc*.

Undulator period $\lambda_u = 3.2$ cm,

Undulator length per section $L_u = 3.4$ m,

Number of the undulator periods NWIG = $L_u / \lambda_u = 106$,

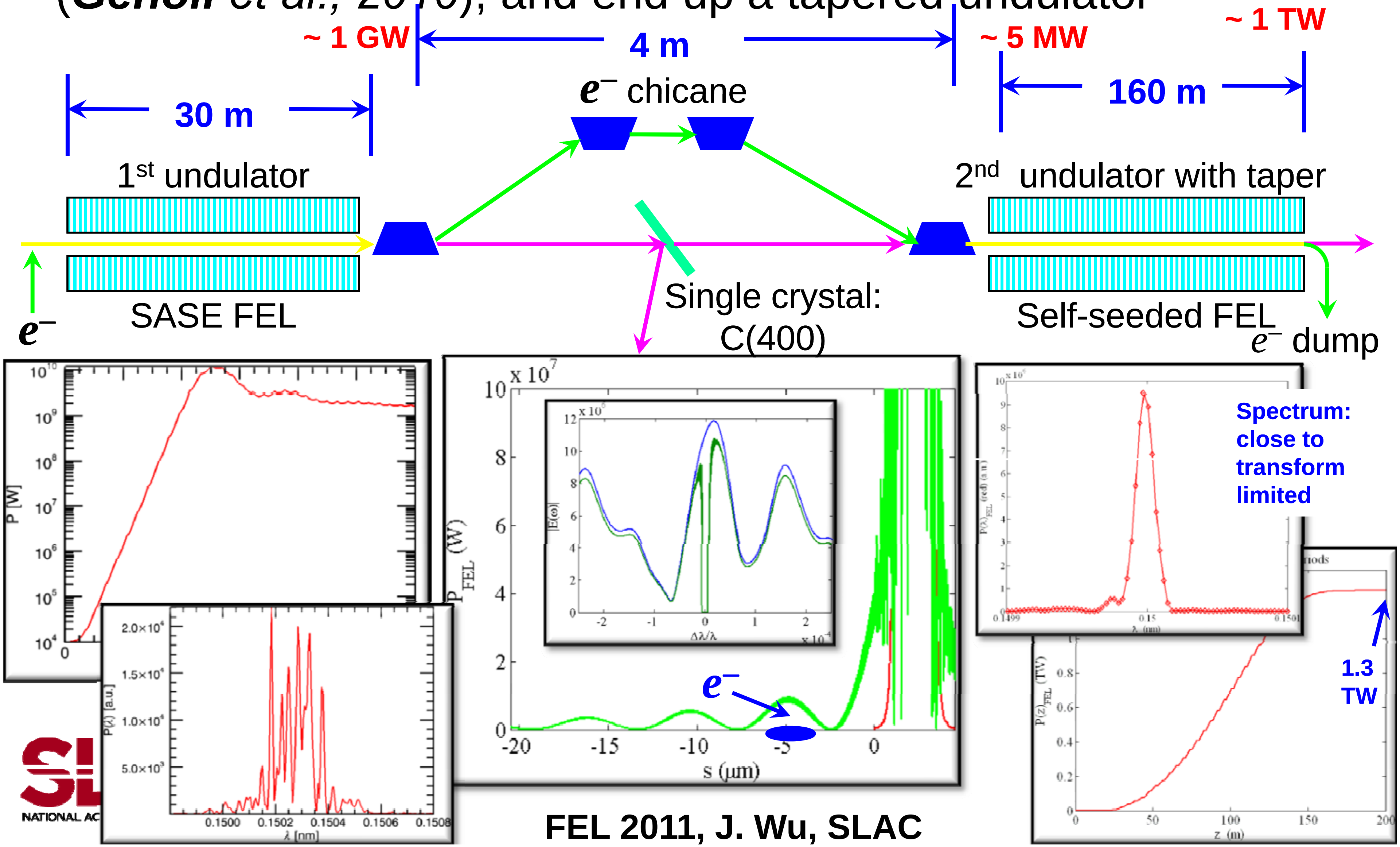
Break length per section $L_b = 1$ m

Break length in unit of undulator periods NBREAK = $L_b / \lambda_u = 32$.

Filling factor = NWIG/(NWIG + NBREAK) = 77%.

SCHEME: WITHIN 200 M TOTAL LENGTH

- Start with a SASE FEL, followed by a self-seeding scheme (***Genoli** et al., 2010*), and end up a tapered undulator



Spectrum: close to transform limited

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TAPERING PHYSICS AND MODEL (LONGITUDINAL PLANE)

- 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 (LONGITUDINAL PLANE)

- 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.

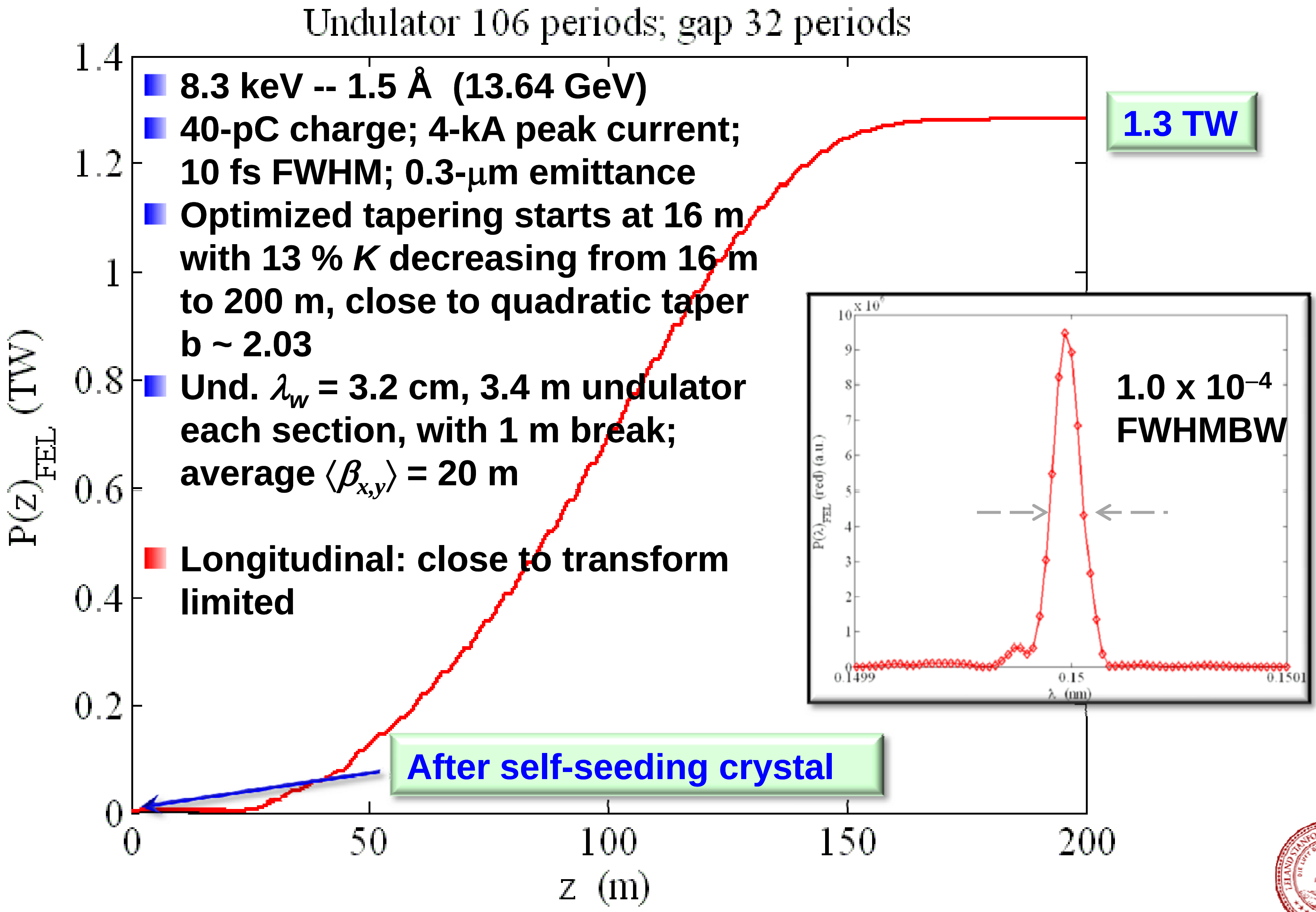
OPTIMAL BETA FUNCTION (TRANSVERSE, SECONDARY)

- 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-μm 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_w = 3.2 cm, 3.4 m undulator each section, with 1 m break; average $\langle \beta_{x,y} \rangle$ = 20 m

- Longitudinal: close to transform limited

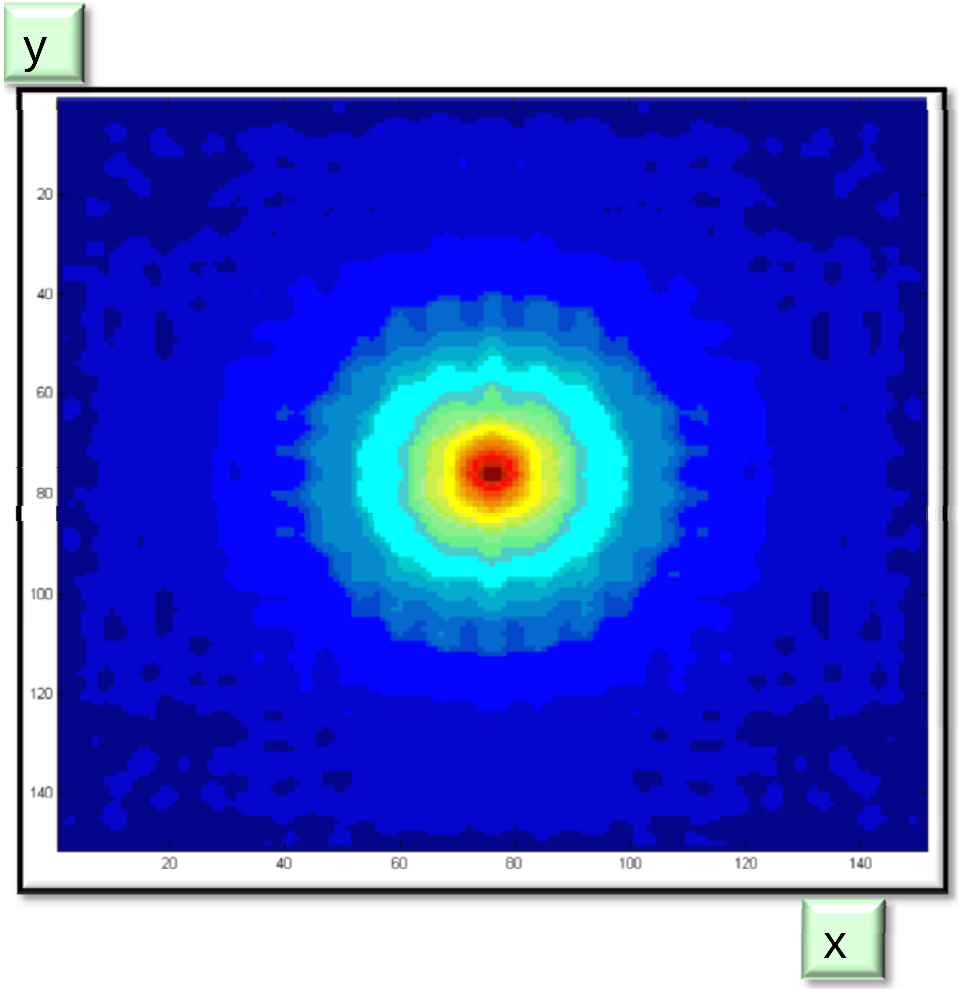
1.3 TW

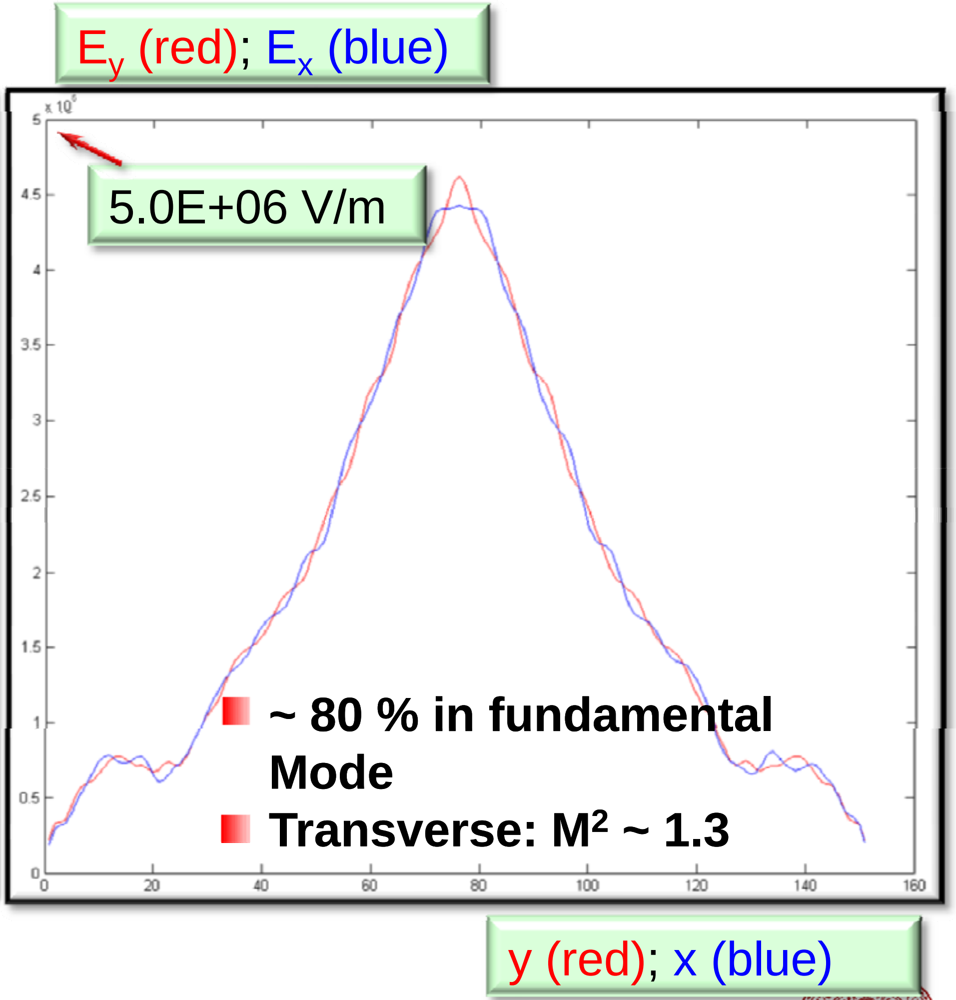
After self-seeding crystal

1.0 x 10^{-4} FWHMBW

TW FEL @ LCLS-II NOMINAL CASE

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

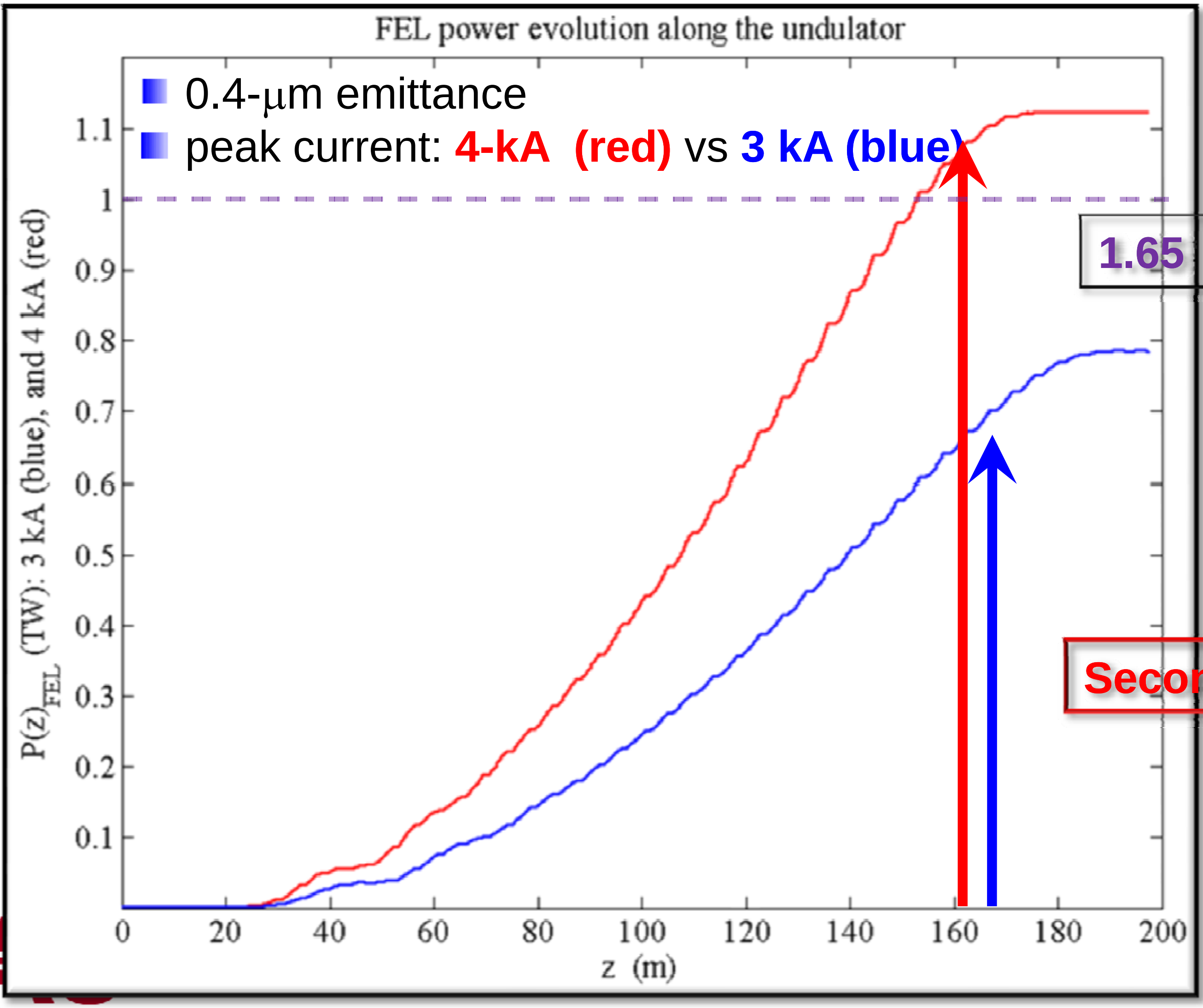




- ~ 80 % in fundamental Mode
- Transverse: M^2 ~ 1.3

SCALING: HIGH PEAK CURRENT

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



1.65 vs $(4/3)^2$ ~1.77

Second undulator

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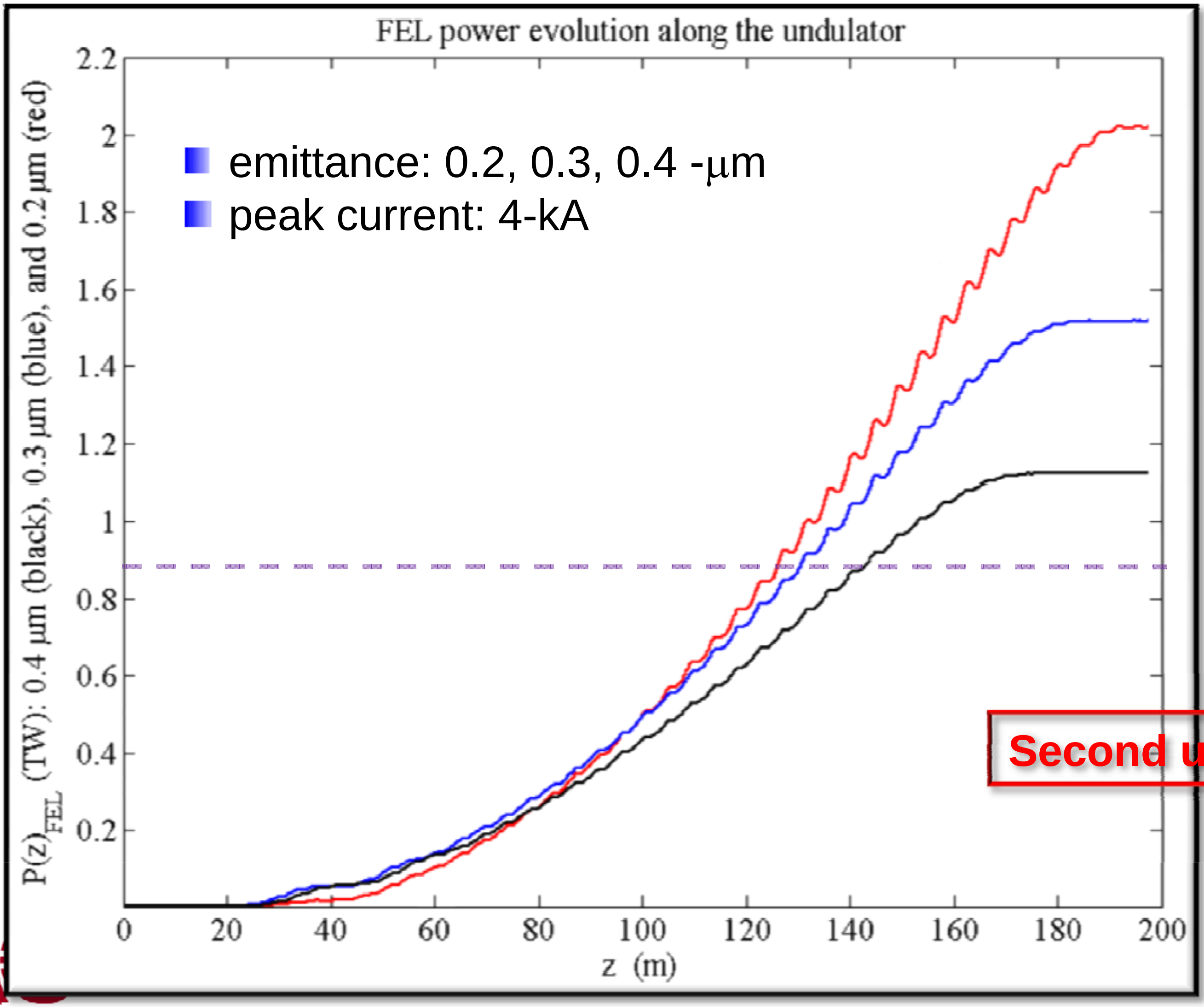
SCALING: EMITTANCE

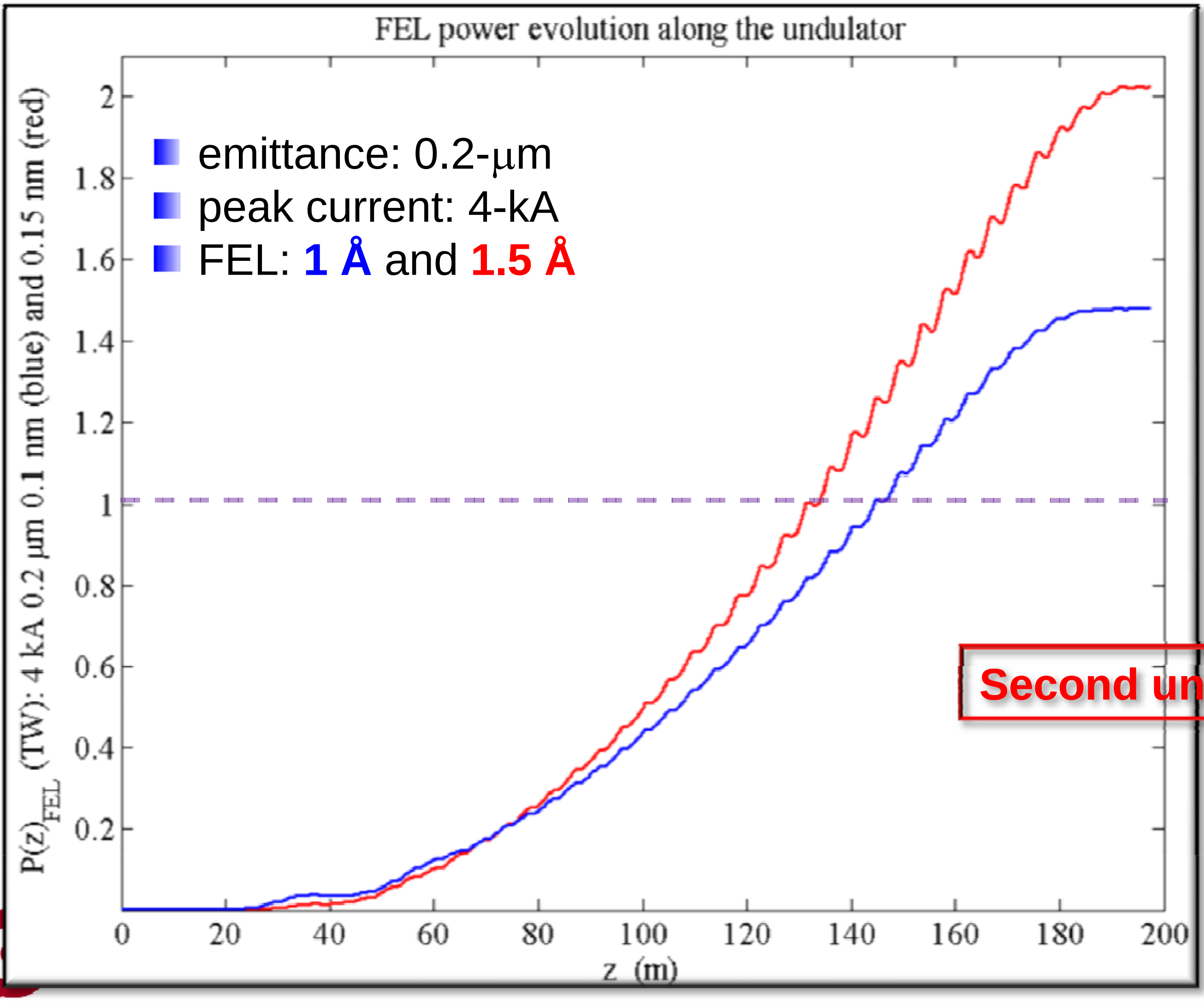
- For 4 kA case, emittance is not so stringent between 0.2 – 0.4 mm-mrad



Second undulator

SCALING: EXTEND TO HIGHER ENERGY PHOTON

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

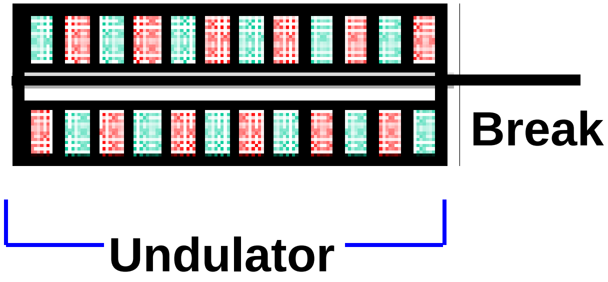


- emittance: 0.2-µm
- peak current: 4-kA
- FEL: **1 Å** and **1.5 Å**

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,

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

To matching the phase of the resonant particle and radiation field,

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

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

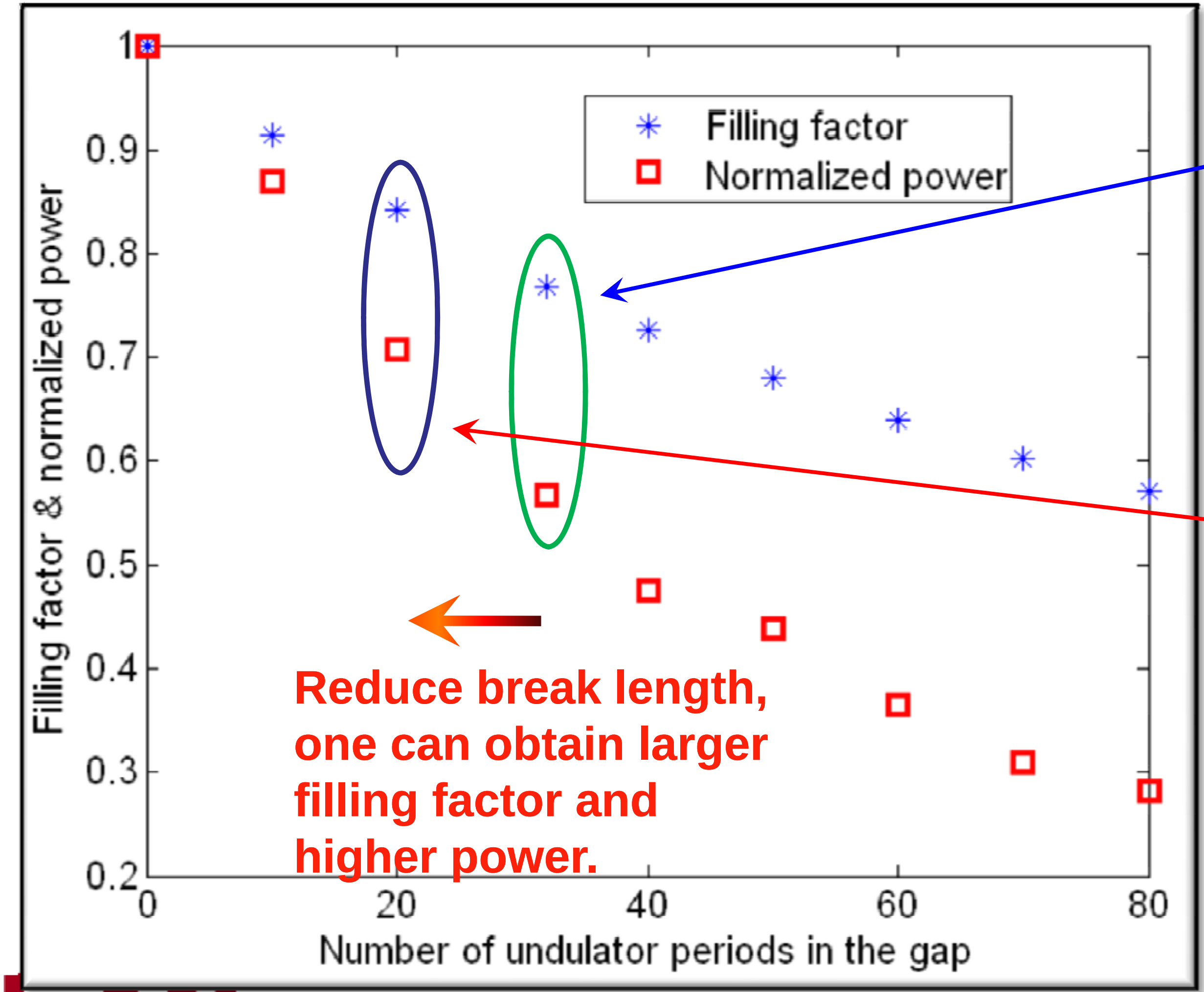
$$\boxed{\begin{aligned}&\Delta L(\delta = 0) - \Delta L(\delta \neq 0)\\ &\approx \frac{L_b}{\gamma^2}\delta = 2n\lambda_r\delta\end{aligned}}$$

For LCLSII baseline, $n = 5$, δ **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).



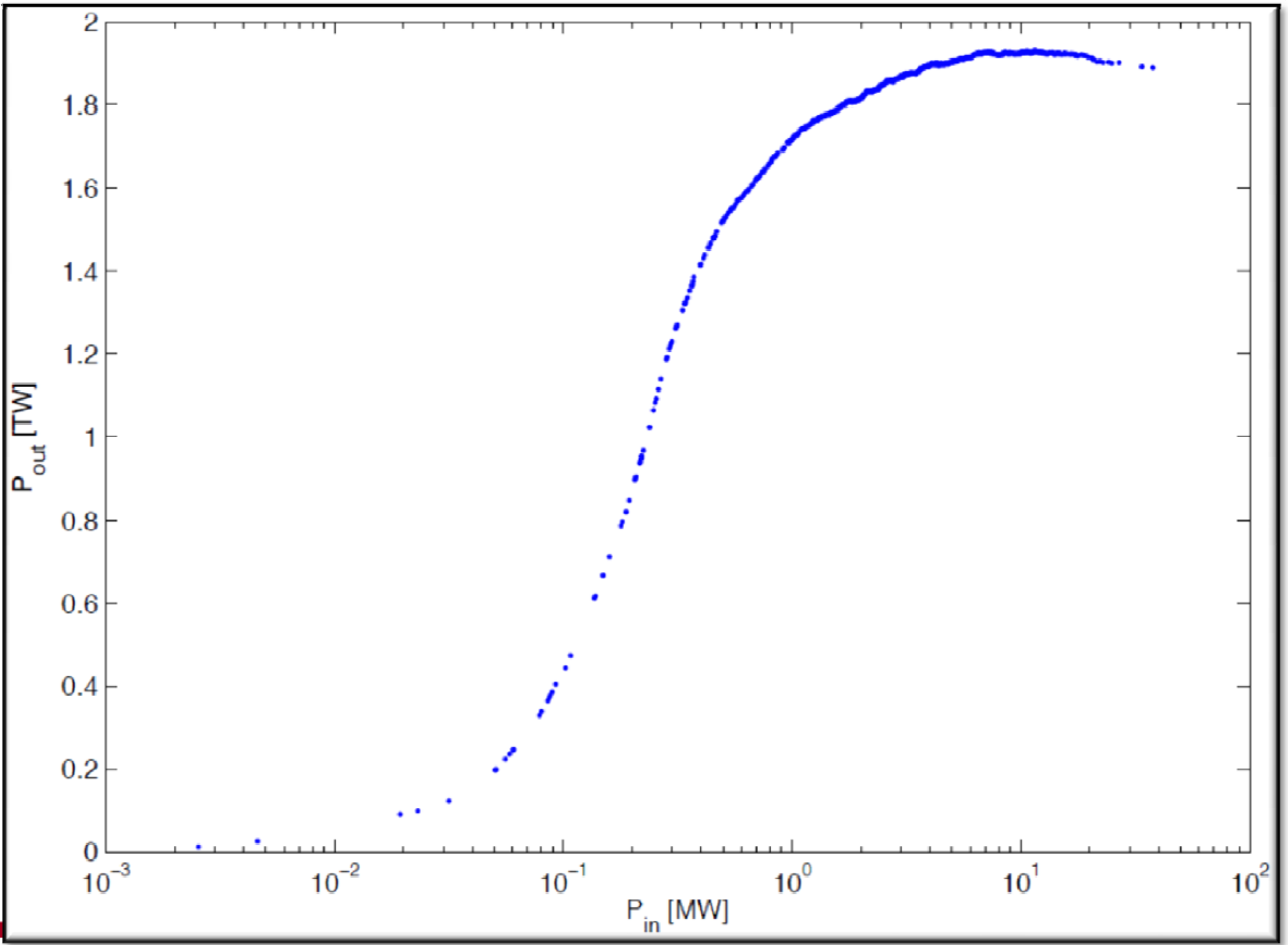
Reduce break length, one can obtain larger filling factor and higher power.

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%.

SENSITIVITY TO INPUT SEED POWER

The seed power should be larger than a few MWs



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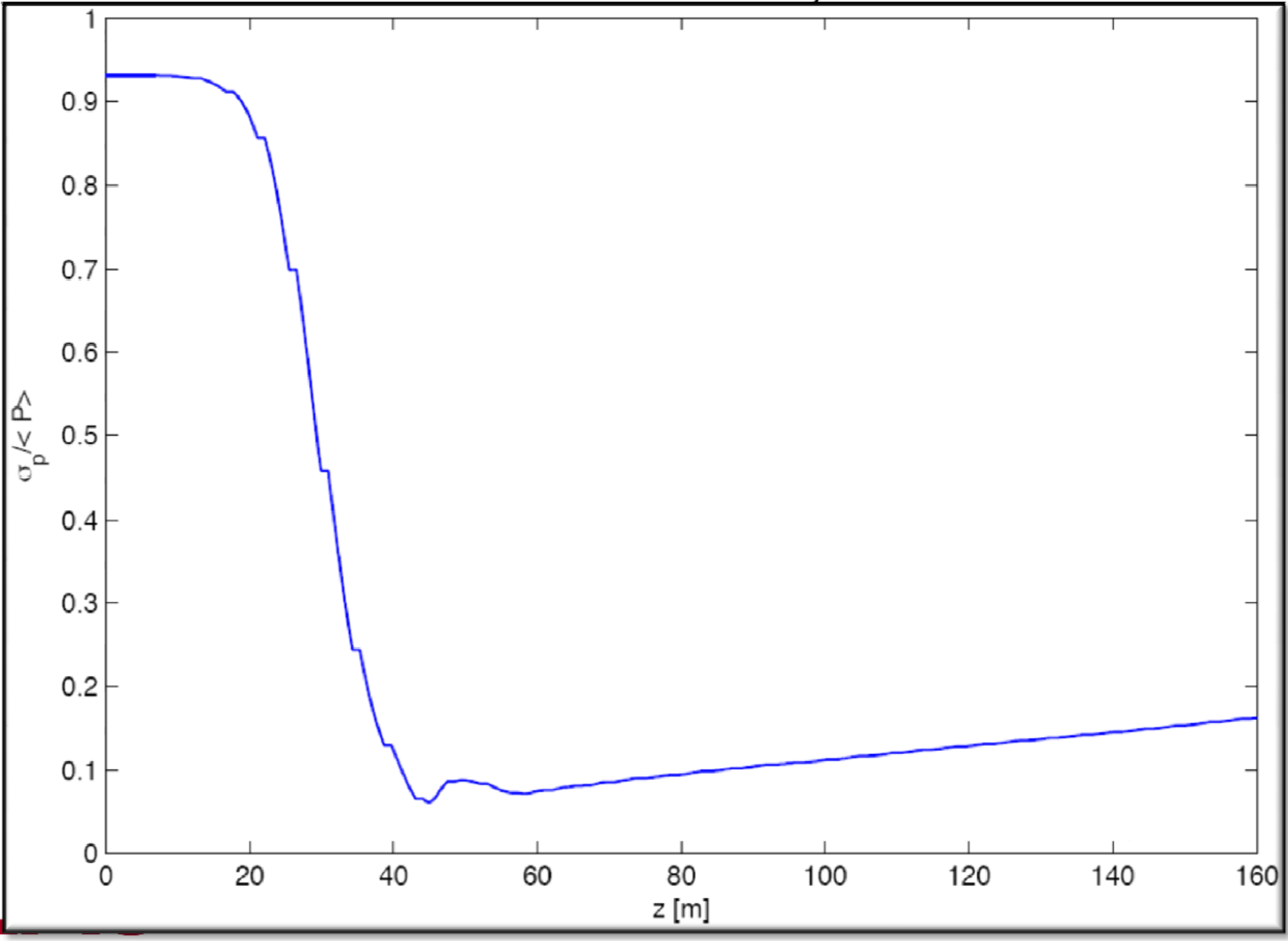
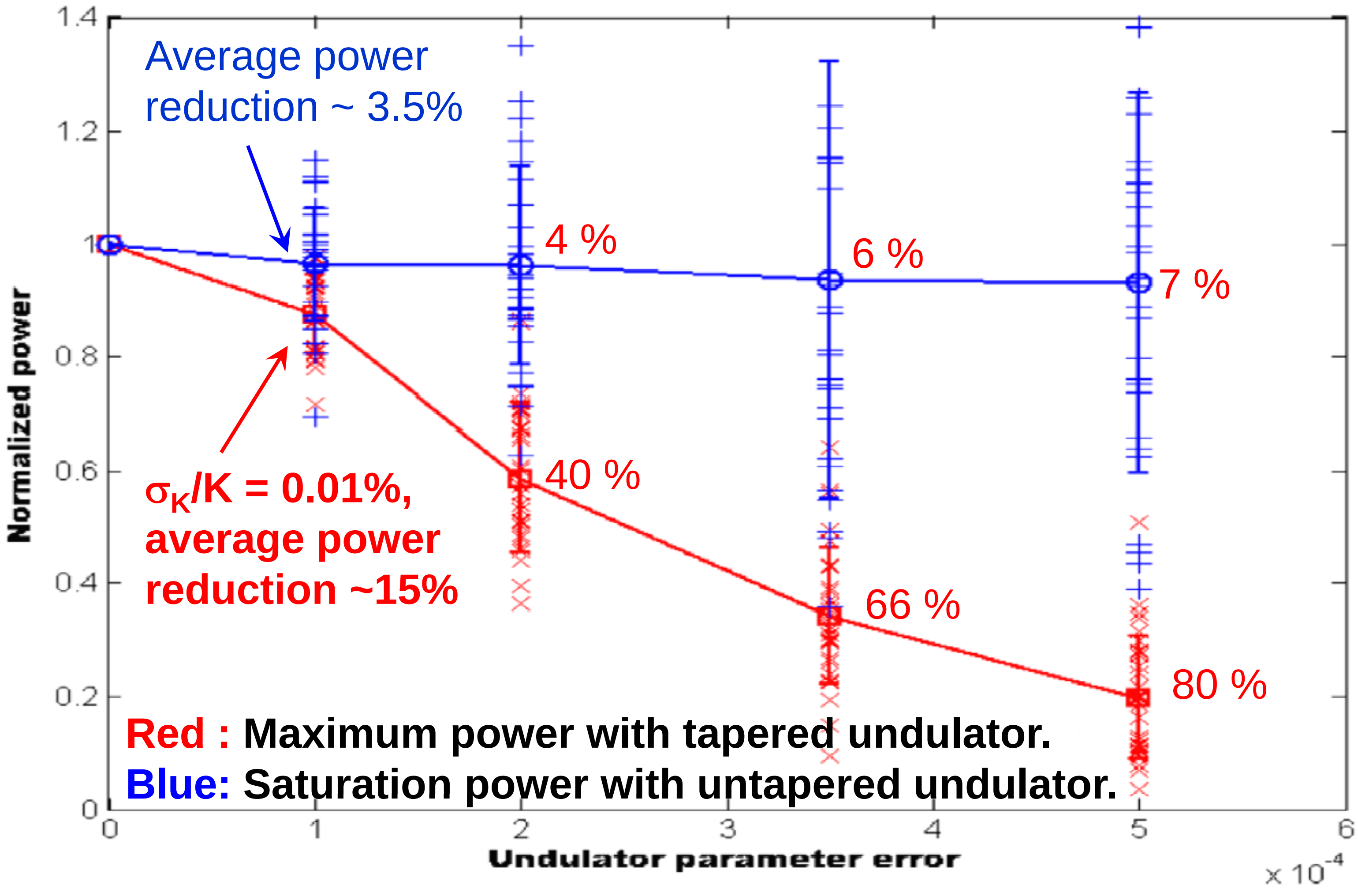
STATISTICS OF A TW FEL POWER

The statistical fluctuation increases, but not dramatically



SENSITIVITY TO UNDULATOR PARAMETER ERROR

The maximum power of the tapered undulator is more sensitive to the undulator parameter errors than saturation power.



Average power reduction ~ 3.5%

$\sigma_K/K = 0.01\%$, average power reduction ~15%

Red : Maximum power with tapered undulator.

Blue: Saturation power with untapered undulator.

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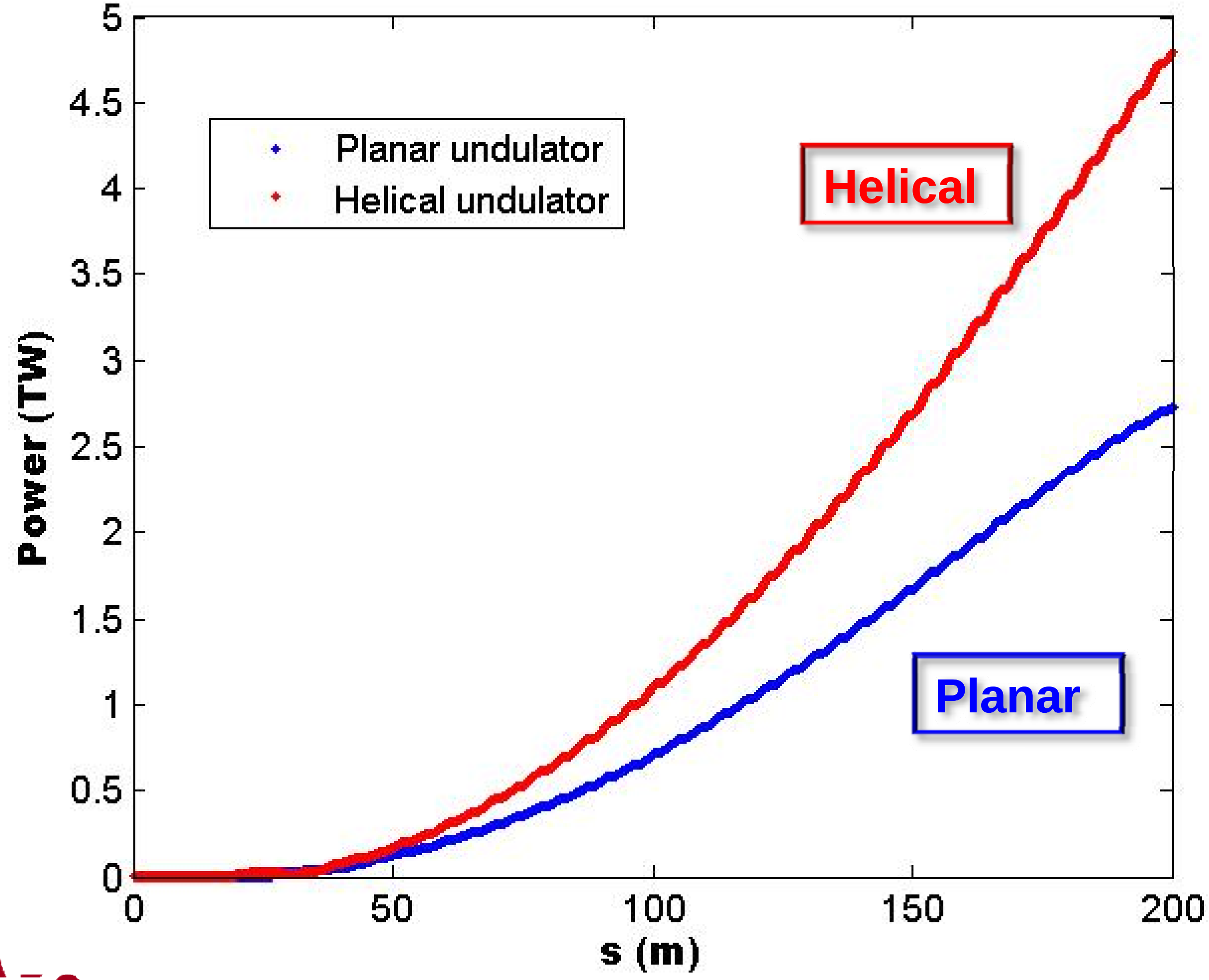
HELICAL UNDULATOR ENHANCE PERFORMANCE

- Shorten the system, higher FEL power, more than JJ^2



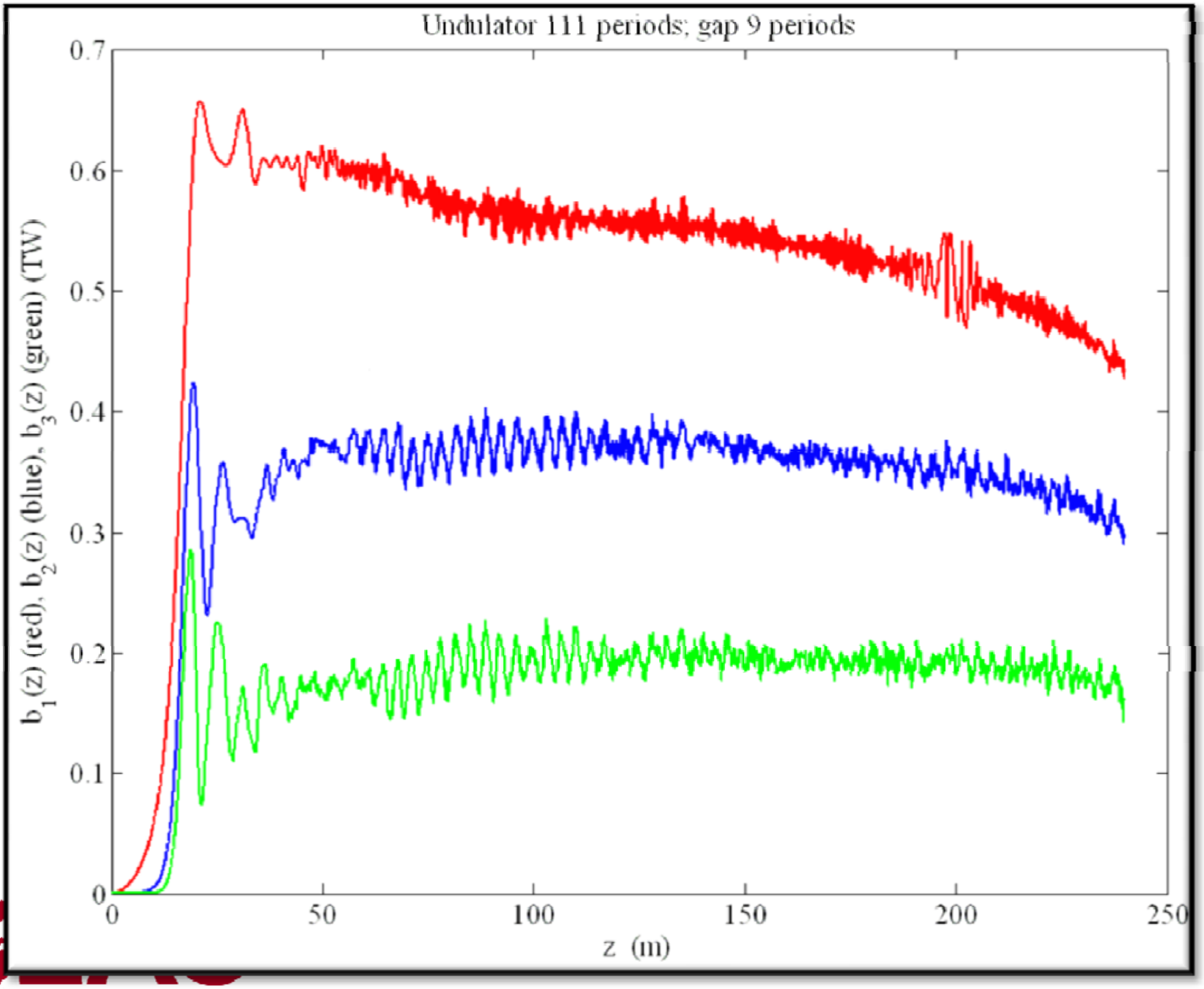
Second undulator

HIGHER ENERGY PHOTON: HARMONICS IN A TW FEL

- Since the bunching is well established all along the long tapered undulator, harmonics can be substantial as well.
  - LCLS-II type undulator and electron bunch
  - In the following, we are showing a time-independent simulation

HARMONICS IN A TW FEL: BUNCHING

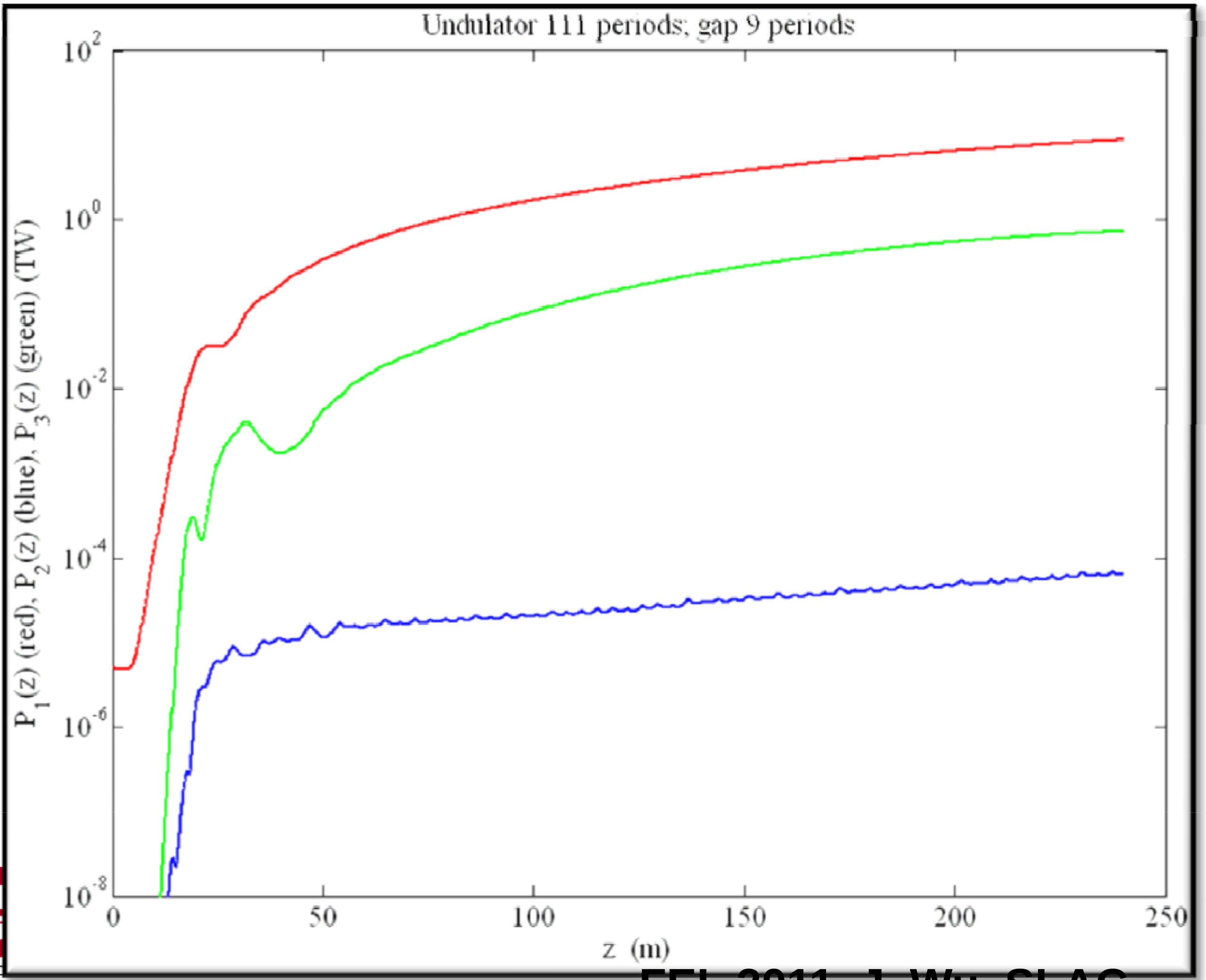
- The harmonic bunching is quite high as well → After-burner type radiator for low energy machine



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

HARMONICS IN A TW FEL: POWER

- The **3rd harmonic (25 keV)** power is quite high as well → approaching **10 % (~ TW)**; the **5th (> 40 keV)** power is quite high as well → approaching **0.3 % (> 30 GW)**

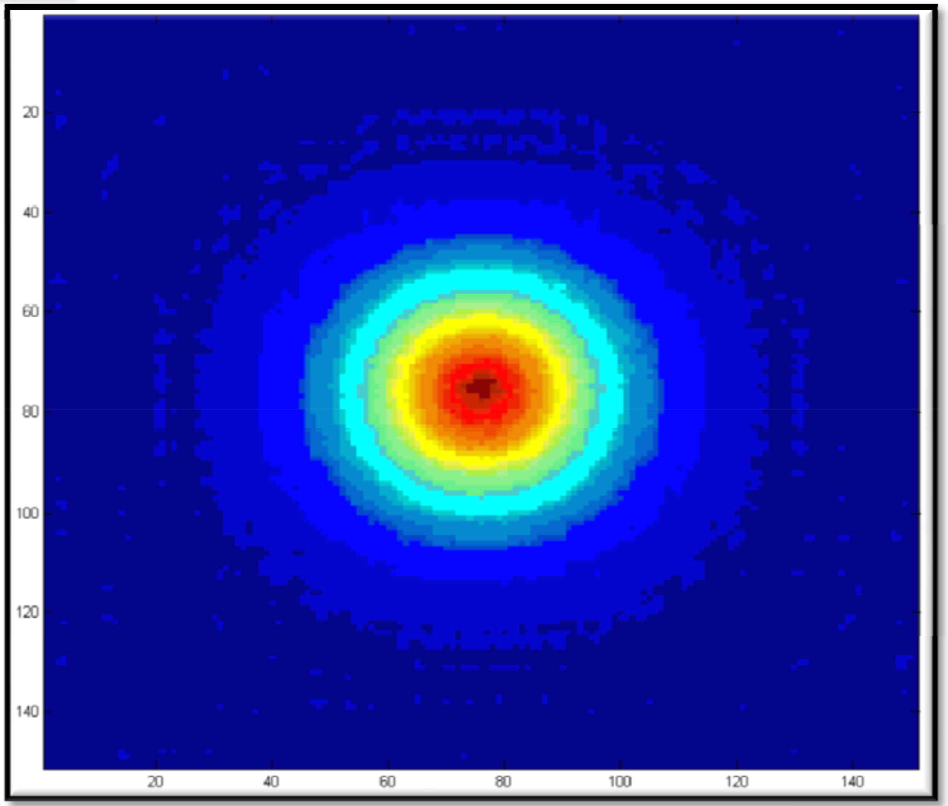


Fundamental (red);
Second harm. (blue);
Third harm. (green)

HARMONICS IN A TW FEL: FIELD PROFILE

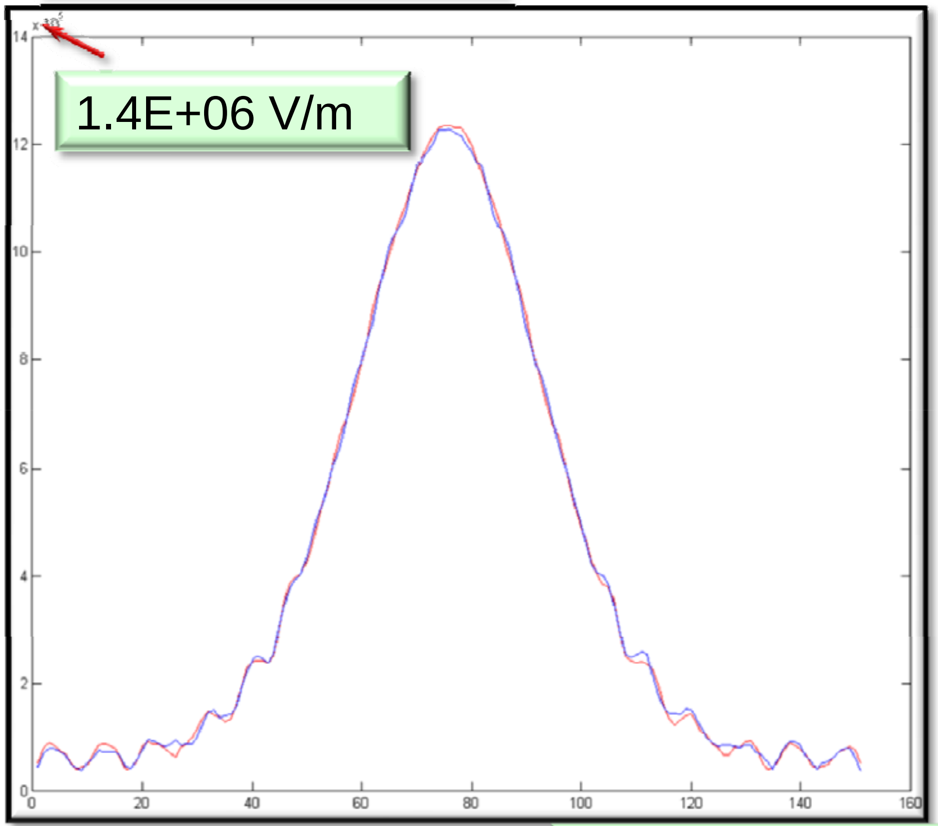
- 3^{rd} harmonic at end of undulator

y



x

E_y (red); E_x (blue)



1.4E+06 V/m

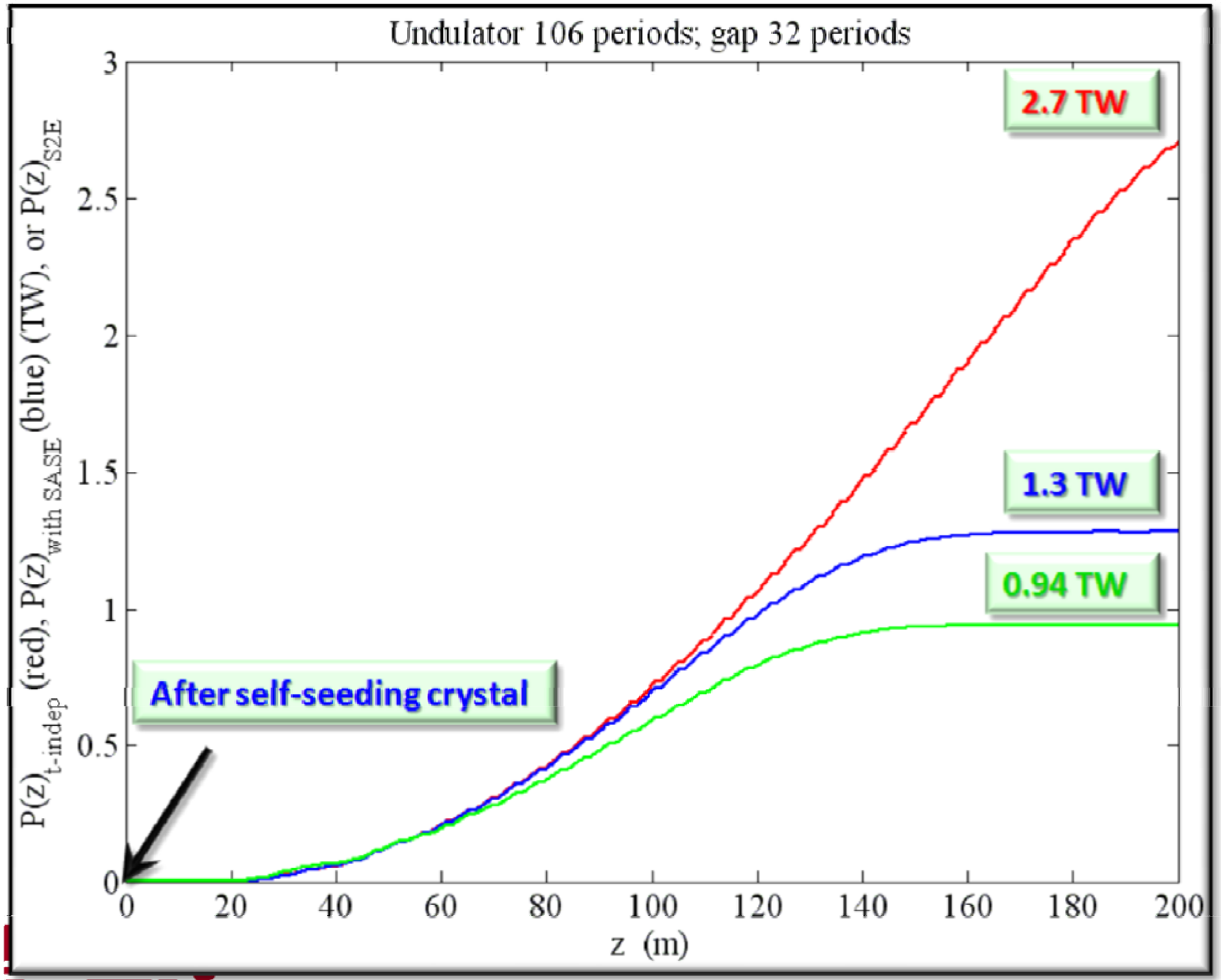
y (red); x (blue)

SIDE-BAND INSTABILITY, TAPERED FEL SATURATION

- Even though the strong seed well dominates over the shot noise in the electron bunch, the long (160 m) undulator can still amplify the shot noise and excite side-band instability [***Z. Huang and K.-J. Kim***, *Nucl. Instrum. Methods* ***A 483***, *504 (2002)*].
  - the SASE component in the electron bunch and the residual enhanced SASE components in a self-seeding scheme can then couple and excite such a side-band instability, which together with other effects leads to the saturation as seen around 160 m

SATURATION OF TAPERED FEL

- Steady state (red), time-dependent with “natural” SASE (blue), and “enhanced” noise in start-to-end (green)


Undulator 106 periods; gap 32 periods

2.7 TW

1.3 TW

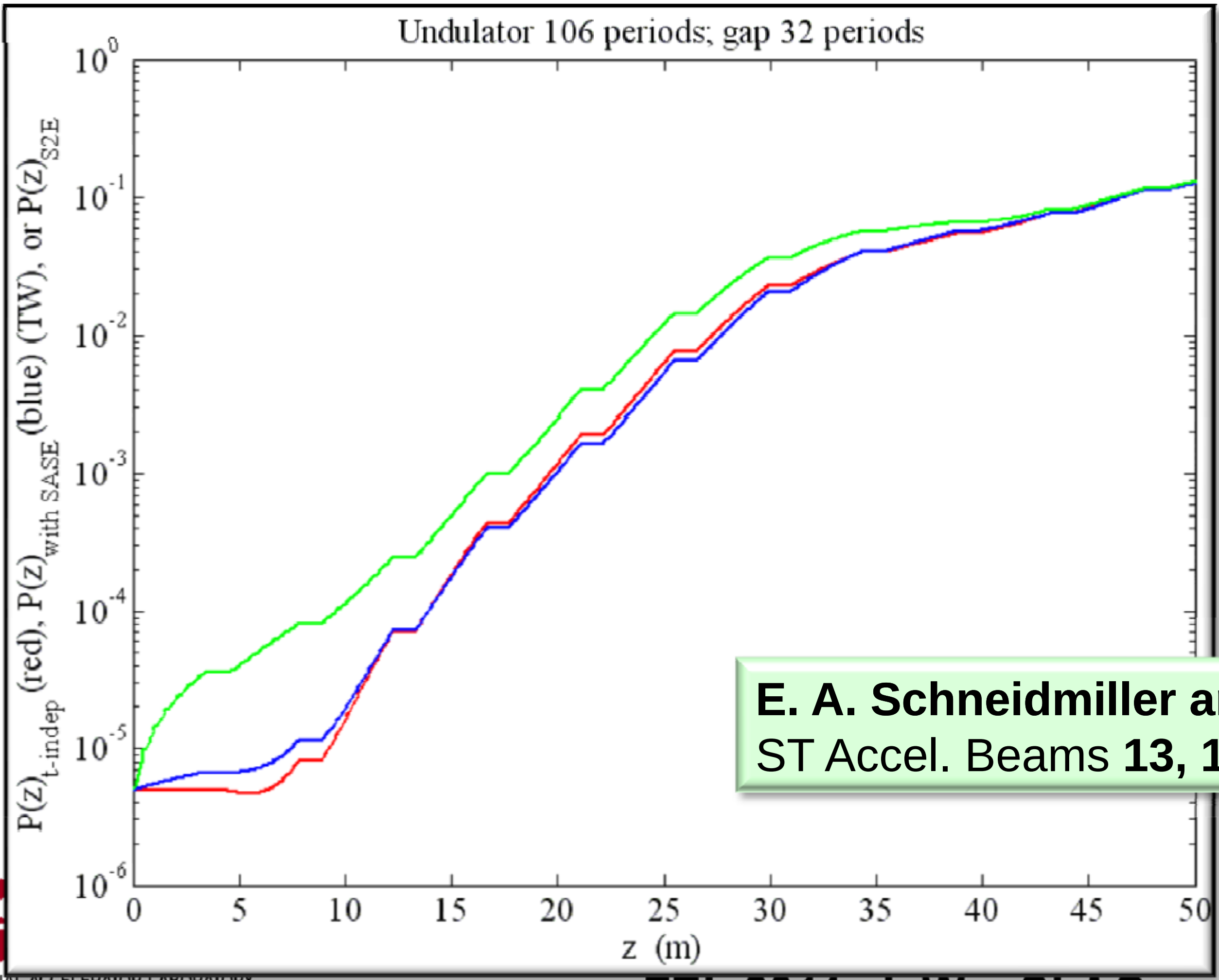
0.94 TW

After self-seeding crystal

Steady state (red);
With SASE (blue);
S-2-E (green)

STARTUP REGION

- After self-seeding chicane, the density bunch factor: **0.1** → **0.008**, but also residual energy modulation → enhanced noise

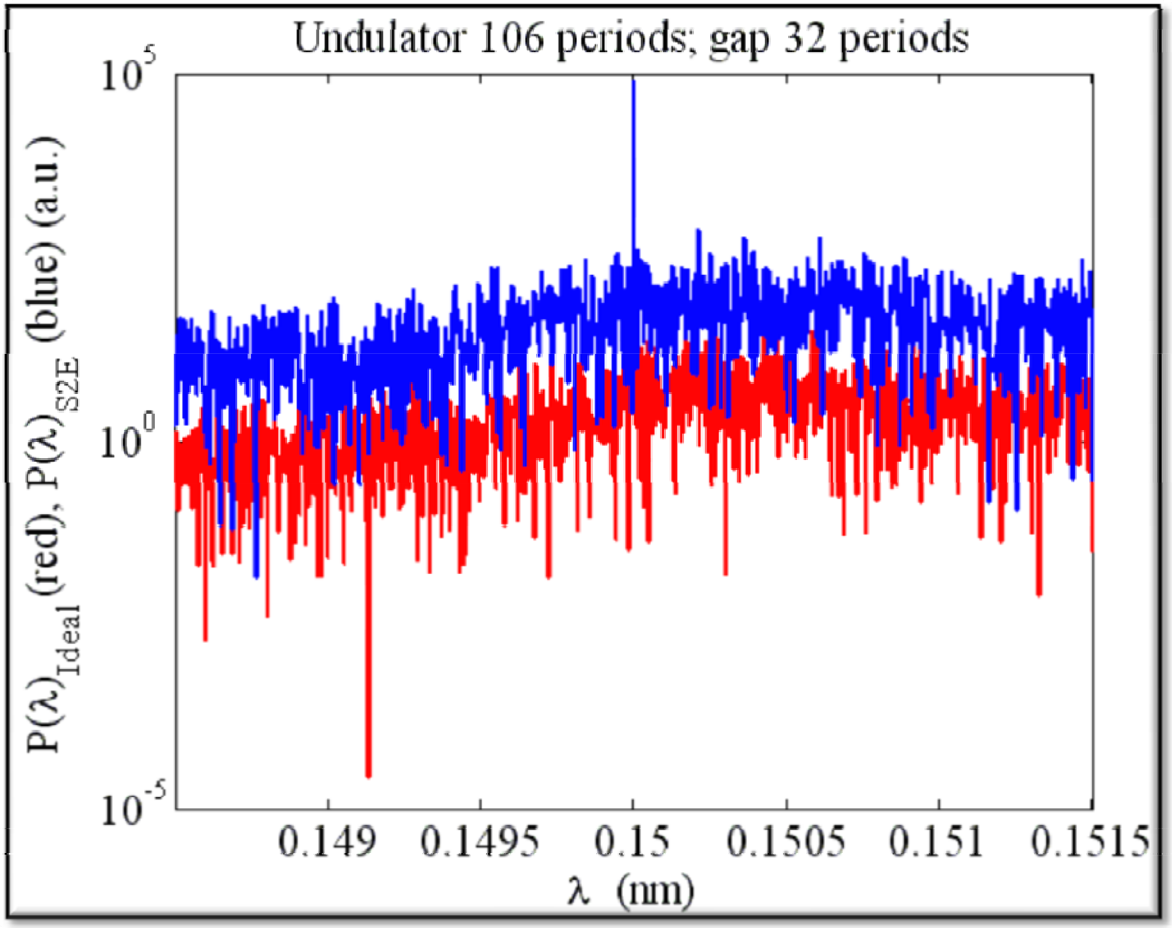


Steady state (red);
With SASE (blue);
S-2-E (green)

E. A. Schneidmiller and M. V. Yurkov, PR ST Accel. Beams **13, 110701 (2010).**

NOISE EXCITE SIDE-BAND INSTABILITY

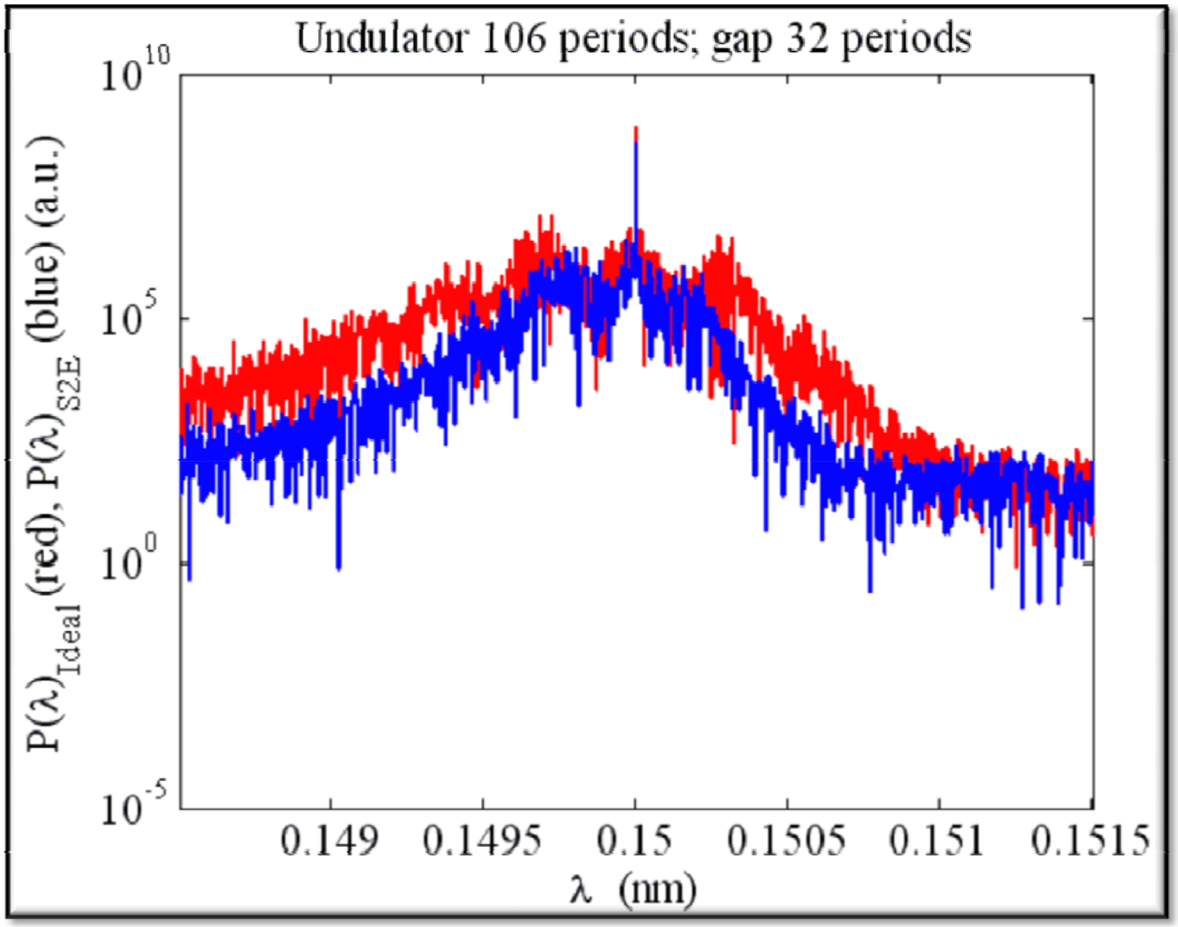
- Spectrum evolution @ 5 m



With SASE(red);
S-2-E(blue);

NOISE EXCITE SIDE-BAND INSTABILITY

- Spectrum evolution @ 160 m



With SASE(red);
S-2-E(blue);

CONCLUSIONS

- ✓ A 1.5 Å TW FEL is feasible
- ✓ High power, hundreds GW at 3rd harmonic, tens GW at 5th harmonic, allowing to reach higher energy photon.
- ✓ This novel light source would open new science capabilities for coherent diffraction imaging and nonlinear science.
- ? Towards 10 TW: helical undulator, high peak current, short interruption, fresh bunch…

ACKNOWLEDGEMENT

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Thanks the committee for providing the chance to report these results

Thanks to all the LCLS team members. In particular, thanks to E. Allaria (FERMI/Elettra), Y. Cai, A.W. Chao, H.N. Chapman (DESY), Y. Ding, P. Emma, G. Geloni (European XFEL), G.E. Penn (LBL), M. Rowen, E.V. Saldin (DESY), J. Welch *et al.* for many stimulated discussion and helpful assistance