fel 06 BERLIN

Optical Klystron Enhancement to SASE FELs

Y. Ding, P. Emma, Z. Huang (SLAC)

V. Kumar (ANL&RRCAT)

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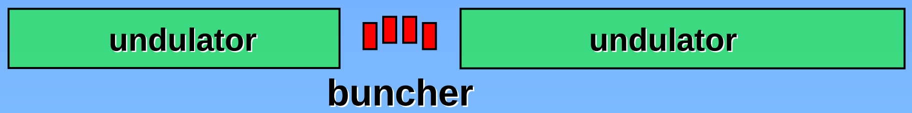
Introduction

Optical Klystron (OK) proposed by Vinokurov and Skrinsky, successfully applied in many FEL oscillators



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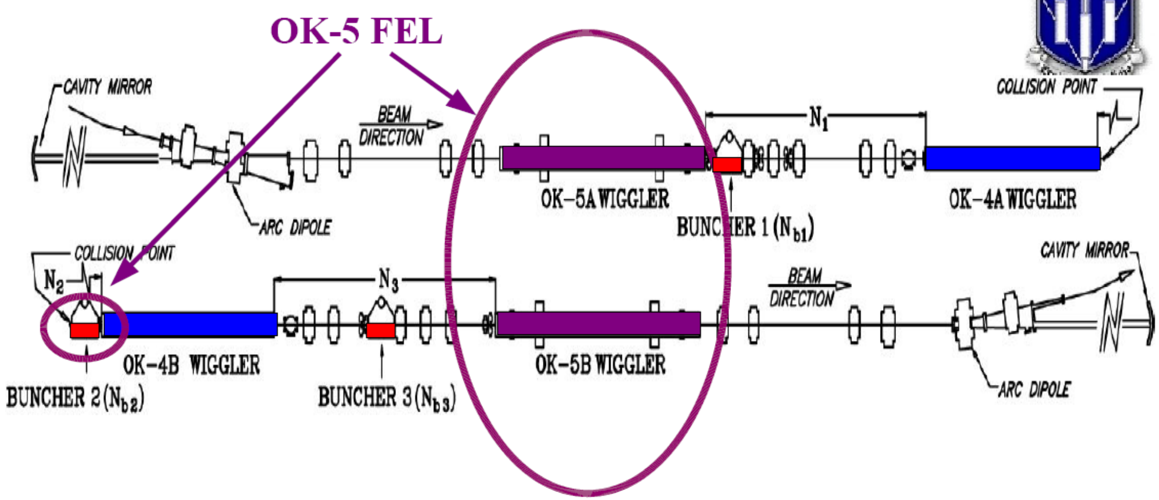
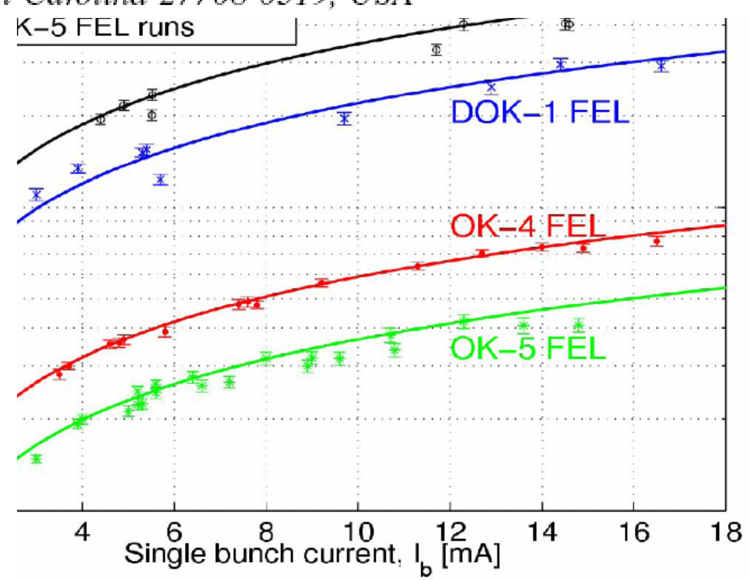
High-Gain Lasing and Polarization Switch with a Distributed Optical-Klystron Free-Electron Laser

Y. K. Wu,[1,*] N. A. Vinokurov,[2] S. Mikhailov,[1] J. Li,[1] and V. Popov[1]

[1]*Department of Physics, Duke University, Durham, North Carolina 27708-0319, USA*

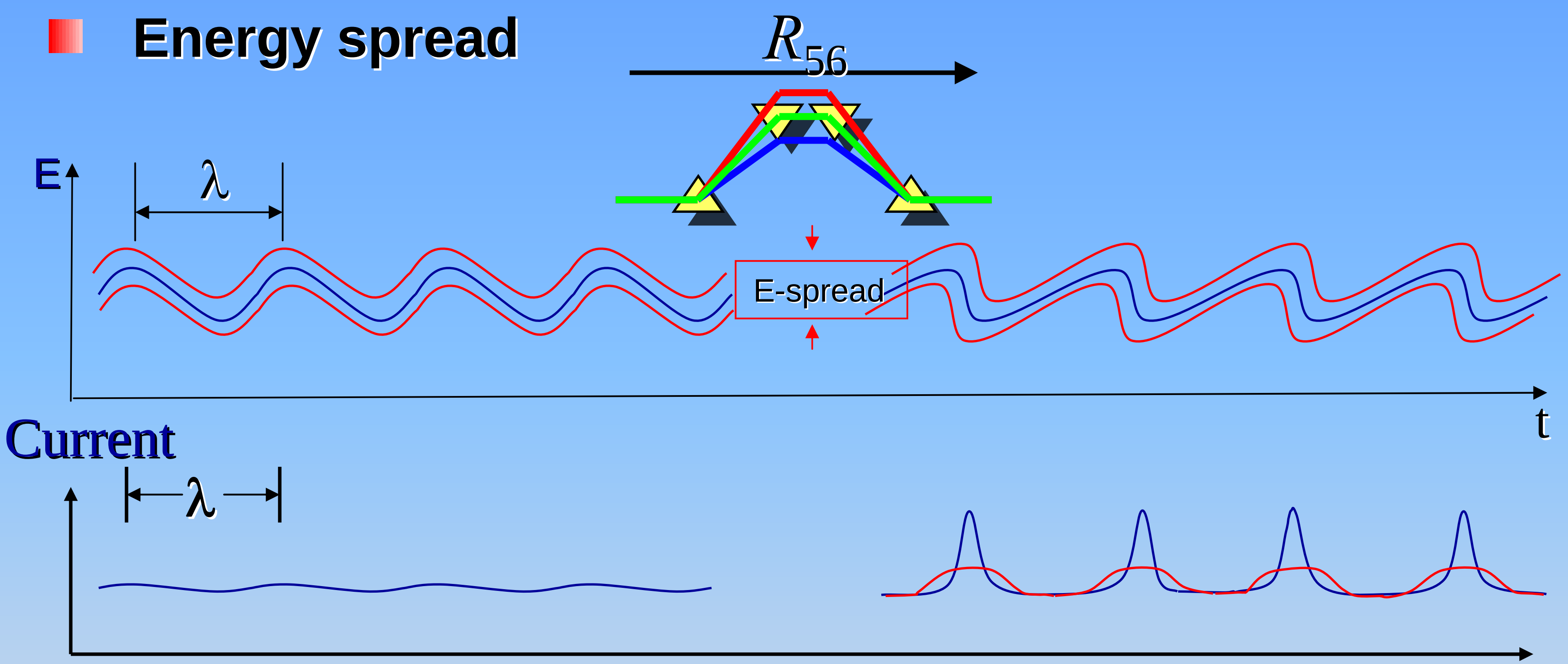
OK-5 FEL and DOK-1 FEL Layout



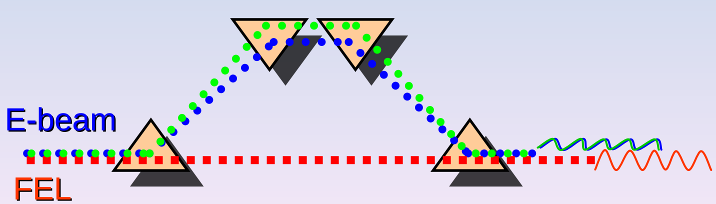


High-gain OK issues

Energy spread



Phase matching



$$\Delta\theta \approx \underbrace{-\frac{kR_{56}}{2}}_{\text{phase shift}} + \underbrace{kR_{56}\delta}_{\text{bunching}}$$

$$\delta = \frac{\Delta\gamma}{\gamma},\ k = \frac{2\pi}{\lambda}$$

High-gain OK studies

- 1-D steady-state theory

  R. Bonifacio et al., PRA 1992.
  N. Vinokurov, NIMA 1996.
  K.-J. Kim, NIMA 1998.
  …

  → $\sigma_\delta << \rho$

- Neil & Freund (NIMA, 2001), 3D seeded simulation for LCLS at 1.5 Å

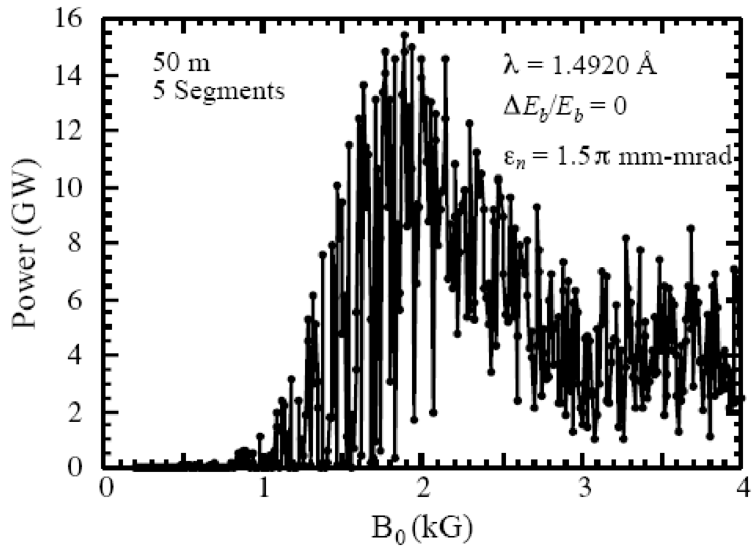


Fig. 3. Variation of the performance with B_0.

→ X-ray OK is extremely sensitive to chicane B field at 1×10^{-4} level (0.2 Gauss for every OK)

Same sensitive to energy jitters

- We find that SASE OK is not sensitive to phase matching

  Y. Ding et al., PRST-AB 9, 070702, 2006

SASE OK theory

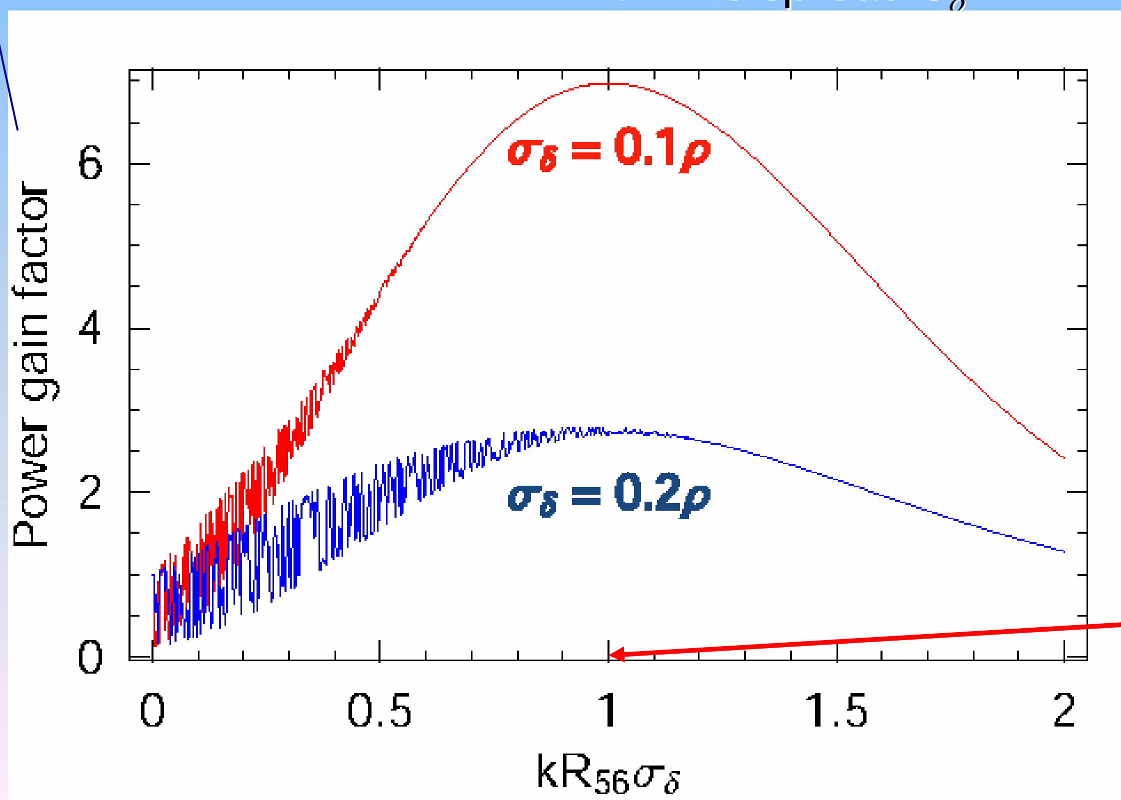
We generalize Kim's 1-D OK theory to SASE

$$G = \int d\nu \frac{e^{-\frac{\nu^2}{2\sigma_\nu{}^2}}}{\sqrt{2\pi\sigma_\nu}} \frac{1}{9} \left| 1 - \int d\xi \frac{dF(\xi)/d\xi}{(\mu-\xi)^2} e^{-i\rho k R_{56}\xi\nu} e^{ik\nu R_{56}/2} \right|^2$$

bandwidth $\sigma_\nu = \rho$

F is energy distribution with rms spread σ_δ

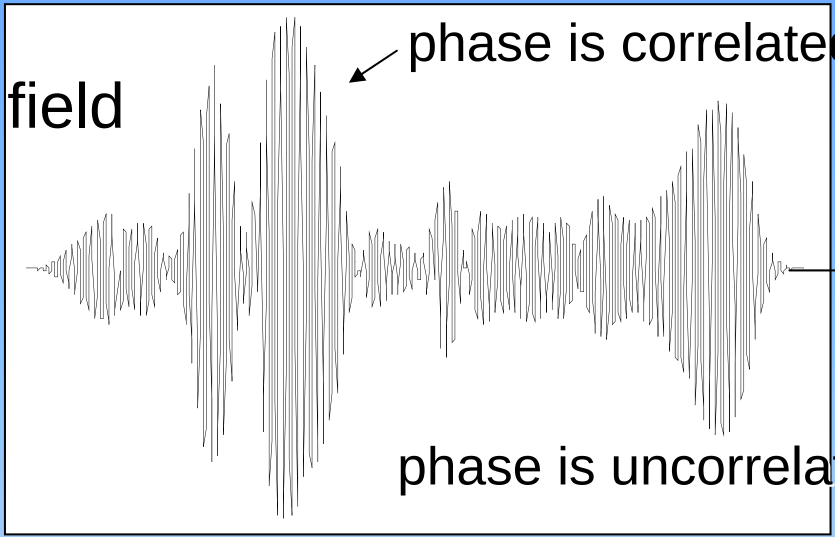
Phase term



Note $kR_{56}\sigma_\delta \sim 1$ is optimal gain

Phase matching

------Overall phase shift unimportant in SASE



- Optimal OK R_{56} is when $kR_{56}\sigma_\delta \sim 1$

- Chicane delays e-beam by

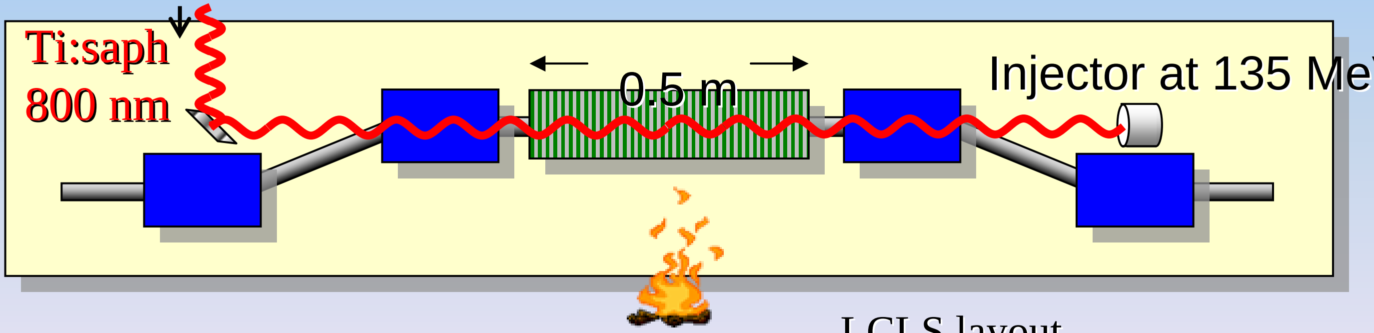
$$\frac{R_{56}}{2} \sim \frac{\lambda}{4\pi\sigma_\delta} \gg \frac{\lambda}{4\pi\rho} \text{ when } \sigma_\delta \ll \rho$$

- No need for phase matching after shifting a few spikes

Slice Energy spread

- Simulations and TTF experiments show slice energy spread from rf guns at 3 or 4 keV level
- 3 keV (rms), accelerated to 14 GeV, & compressed × 32

  ➔ $\sigma_\delta \sim 1\times10^{-5} << \text{LCLS } \rho \sim 5\times 10^{-4}$
- Microbunching instability due to compression amplifies unwanted modulations ➔ increase σ_δ beyond 1×10^{-4}
- To suppress instability, a laser heater in LCLS will increase E-spread to 40 keV and control σ_δ at undulator to 1×10^{-4}



LCLS layout

- For OK enhancement, run laser heater at 20 keV and control σ_δ at undulator to 5×10^{-5}

Energy spread in undulator

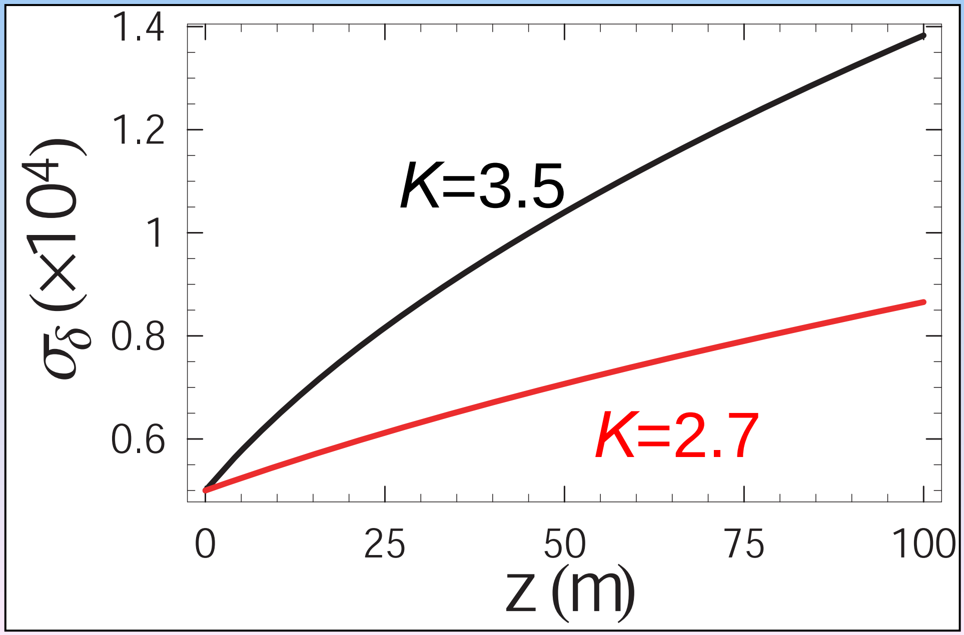
- Energy spread increase due to quantum diffusion of spontaneous radiation (Saldin et al. NIMA 1996)

$$d<\Delta\gamma^2> = \frac{14}{15}\frac{\lambda_c}{2\pi} r_e \gamma^4 k_u^3 K^2 F(K) L_u$$

$$F(K) = 0.6K \quad (LCLS)$$

at λ = 1.5Å

- Lower K and γ reduce E-spread diffusion



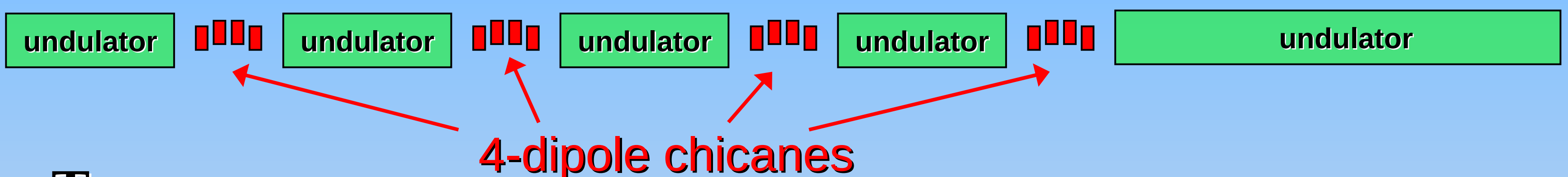
- Small increase of saturation length (a few %) from K=3.5 to K=2.7

OK enhancement to LCLS

In all our GENESIS simulations,

❖ spontaneous energy spread diffusion is included;

❖ Insert OKs in the undulator long breaks (~1m space) every three undulator sections (about 12 m)



Two cases:

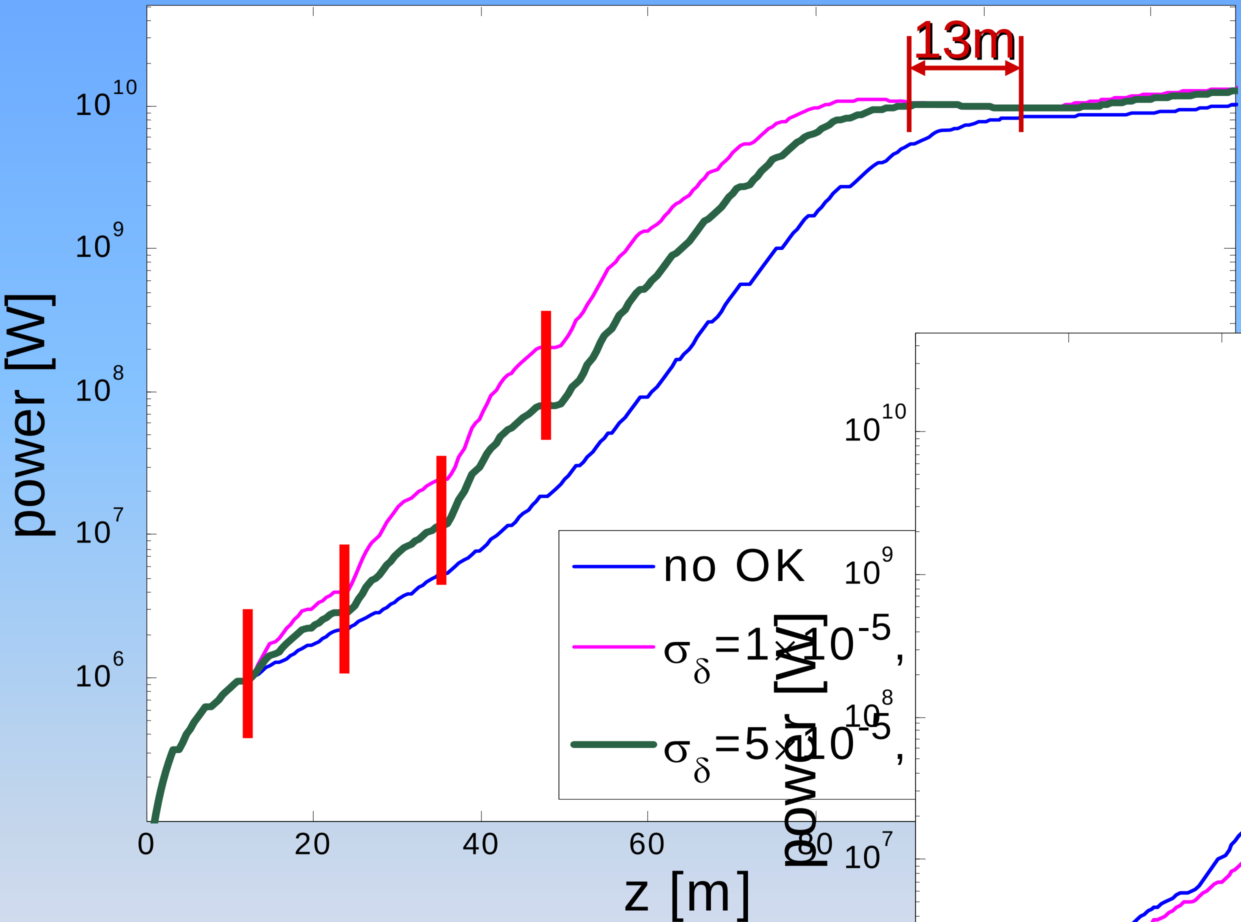
λ=1.5 Å, K=3.5, E=13.6 GeV (nominal design)

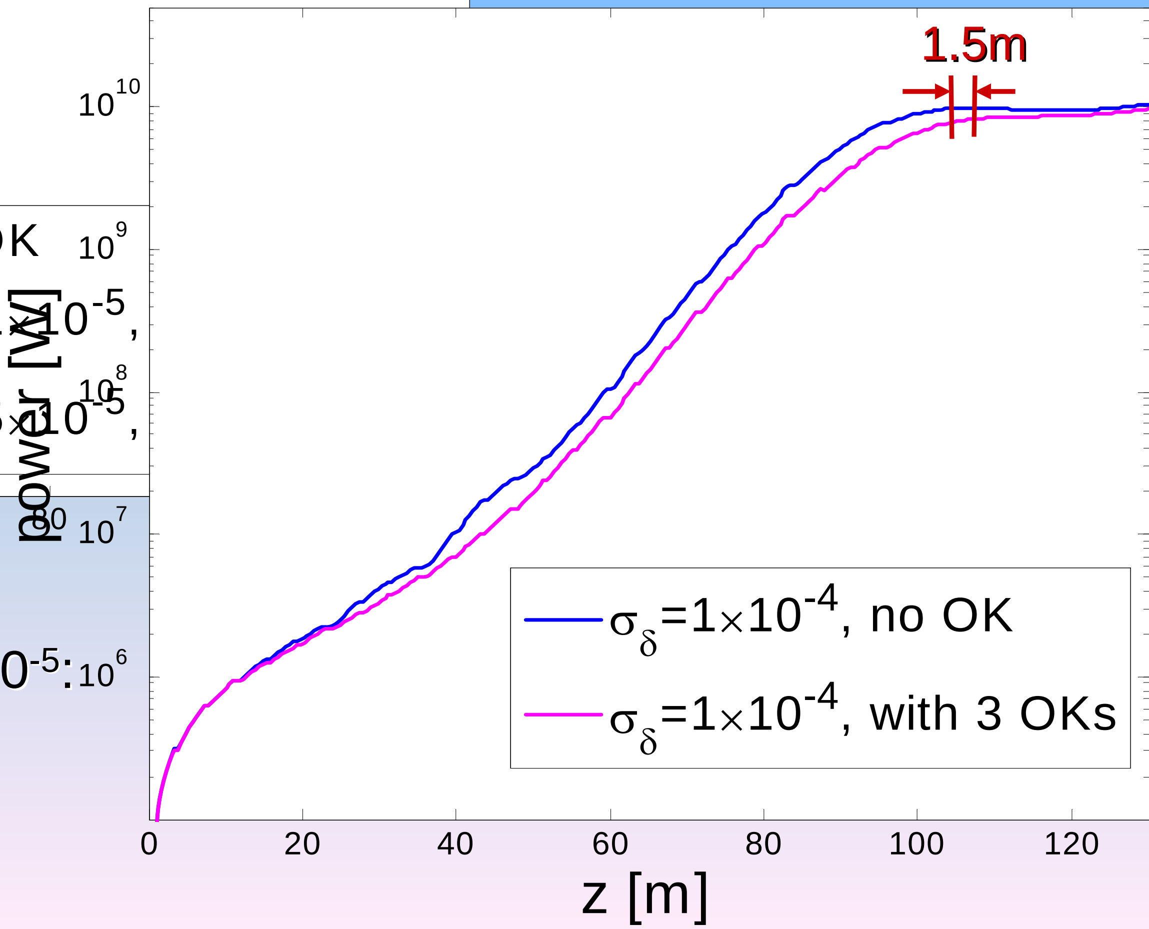
λ=1.0 Å, K=2.7, E=13.5 GeV

Undulator entrance relative energy spread (σ_δ)

1×10^{-5}	Smallest possible
5×10^{-5}	Needed for OK
1×10^{-4}	Baseline SASE

LCLS at λ=1.5 Å, K=3.5, E=13.6 GeV





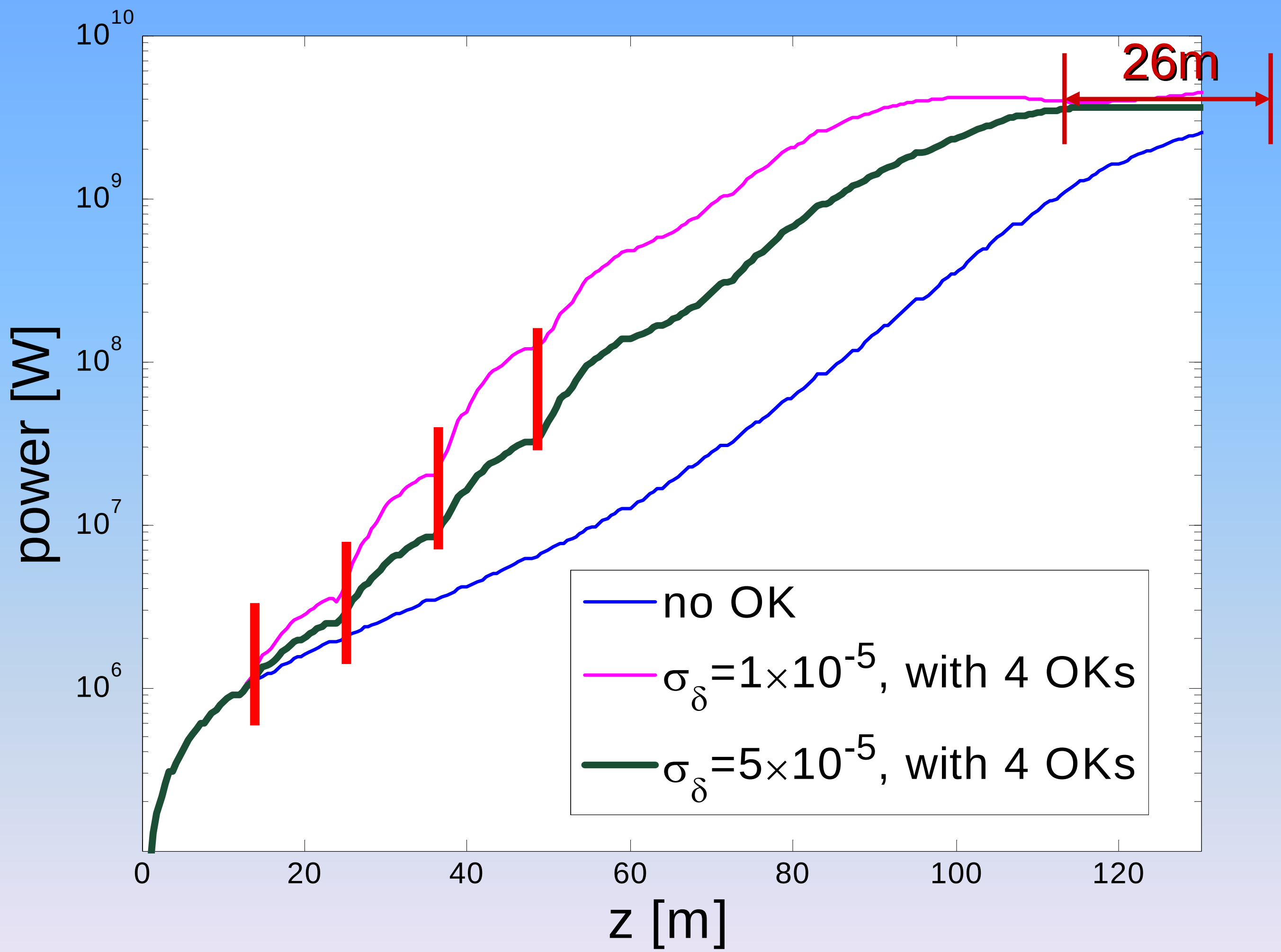
Chicane parameters at $\sigma_\delta=5\times10^{-5}$:

R_{56}~0.25μm, B~0.75T

L_B=6cm, $L_{chicane}$=51cm

LCLS λ=1.0 Å, K=2.7, E=13.5 GeV

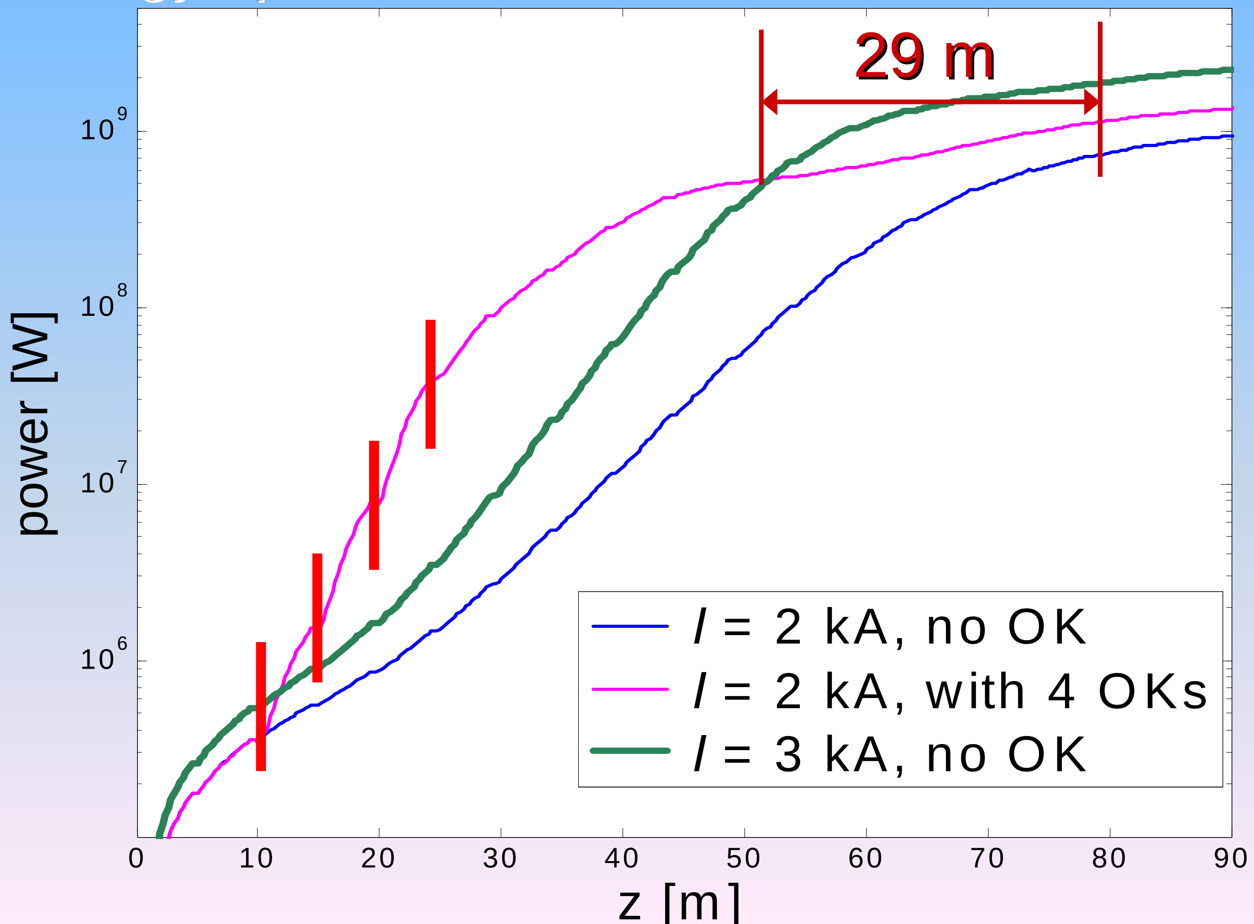
- Open up undulator gap from 6 mm to ~8 mm, *K* drops to 2.7



- Output power not sensitive to ±20% R_{56} variation

A compact x-ray FEL

- SCSS-type undulator, λ_u=1.5 cm, K =1.3, need only E = 5 GeV for λ =1.5 Å
- Assume 100 keV local energy spread after compressing the bunch to 2 kA is allowed by instability, ε_n = 1μm
- Small energy spread diffusion in undulator



Summary

- In contrast to a seeded FEL, SASE OK gain is not sensitive to phase mismatch due to chicane field errors / energy jitters

- Slice energy spread is a crucial parameter for OK gain,

E-spread diffusion in undulator depends strongly on *E* and *K*

- With a controllable energy spread by laser heater, 4 OKs significantly enhance LCLS gain and lead to earlier saturation

- These OKs may help LCLS reaches 1.0 Å with a smaller *K*

- May be useful to boost a compact x-ray FEL based on a modest beam energy and a short-period undulator