



FLS 2006

37th ICFA Advanced Beam Dynamics Workshop on Future Light Sources

Optical Klystron Enhancement to SASE FELs

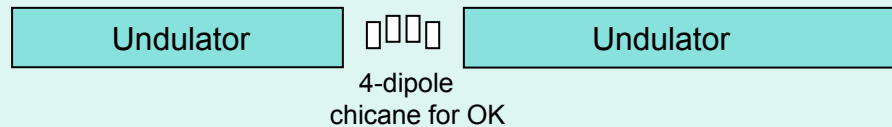
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FEL working group

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Introduction

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



- OK in high gain FELs

➔ 1-D single frequency theory

R. Bonifacio et al., PRA 1992.

N. Vinokurov, NIMA 1996.

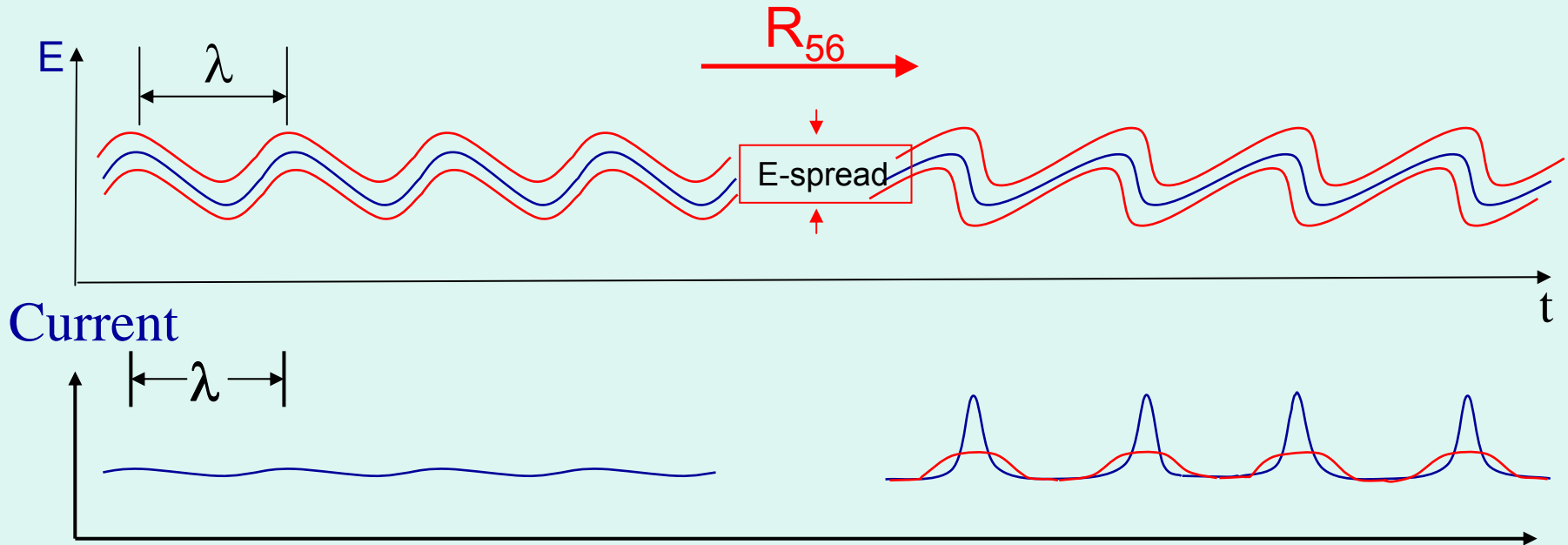
K.-J. Kim, NIMA 1998.

...

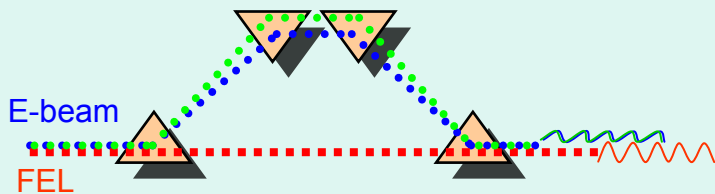
➔ More recently, G. Neil and H. Freund, NIMA 2001
(3-D seeded simulations for LCLS parameters)

High gain OK issues

- Energy spread



- Phase matching



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

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

Phase matching issue

Neil and Freund (NIMA475, 381, 2001)

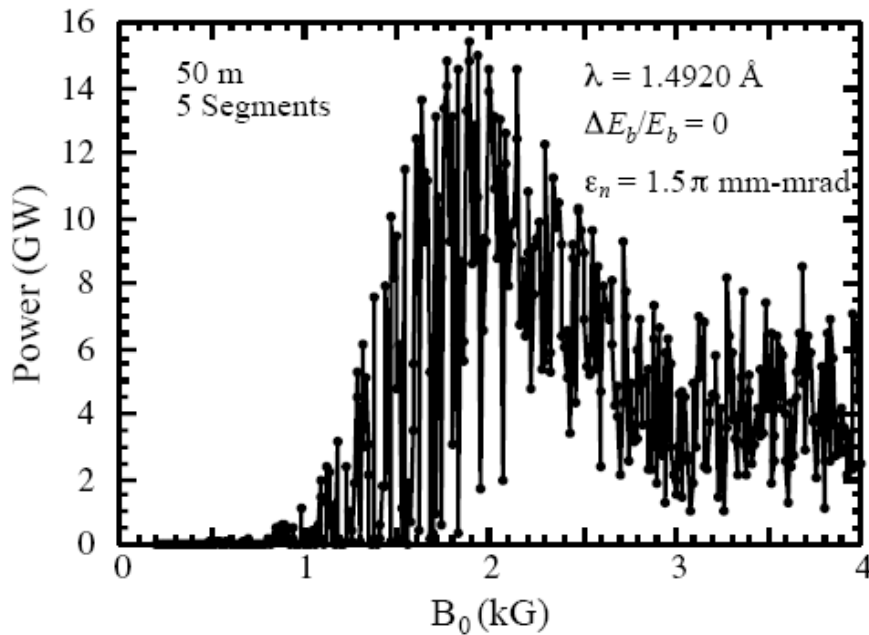


Fig. 3. Variation of the performance with B_0 .

Seeded (single wavelength) simulation shows OK is extremely sensitive to B field variation → control B field at 1×10^{-4} level (0.2 Gauss for each OK!)

Same sensitive to energy jitters

Fortunately, this is not necessary for SASE which supports many amplified wavelengths (some interferes constructively, some interferes destructively, the power averaged over all wavelengths is hence much less sensitive to phase matching of a particular wavelength)

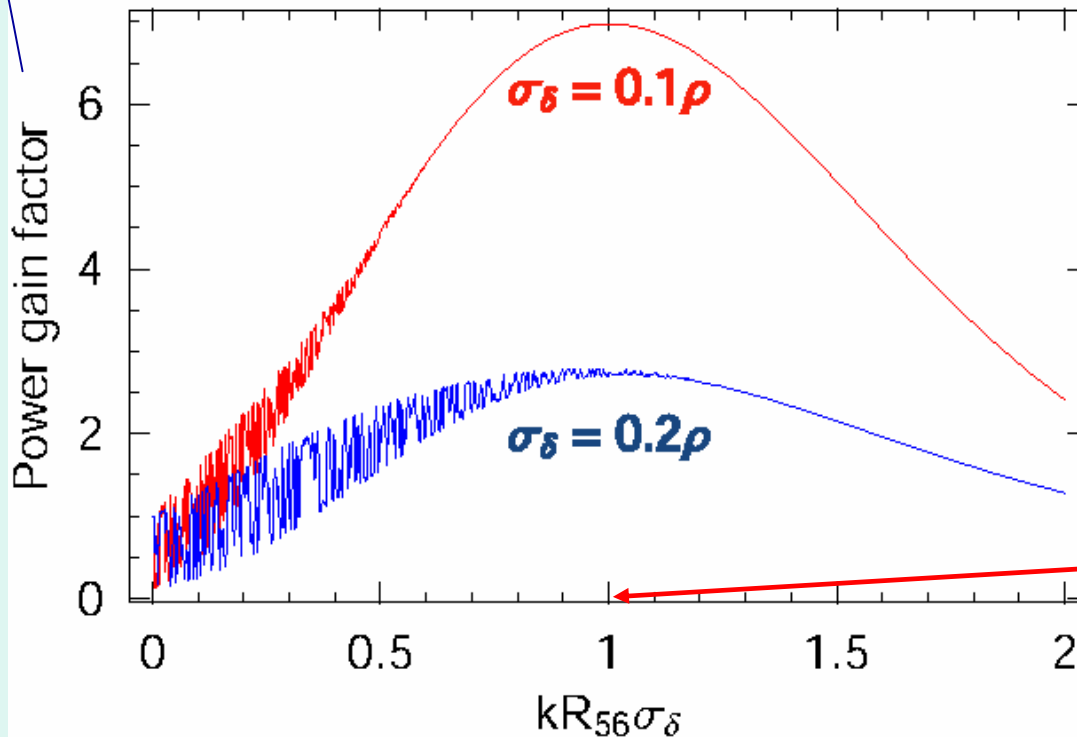
SASE OK theory

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

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

$\sigma_v = \rho$ is FEL parameter
 F is energy distribution with rms spread σ_δ

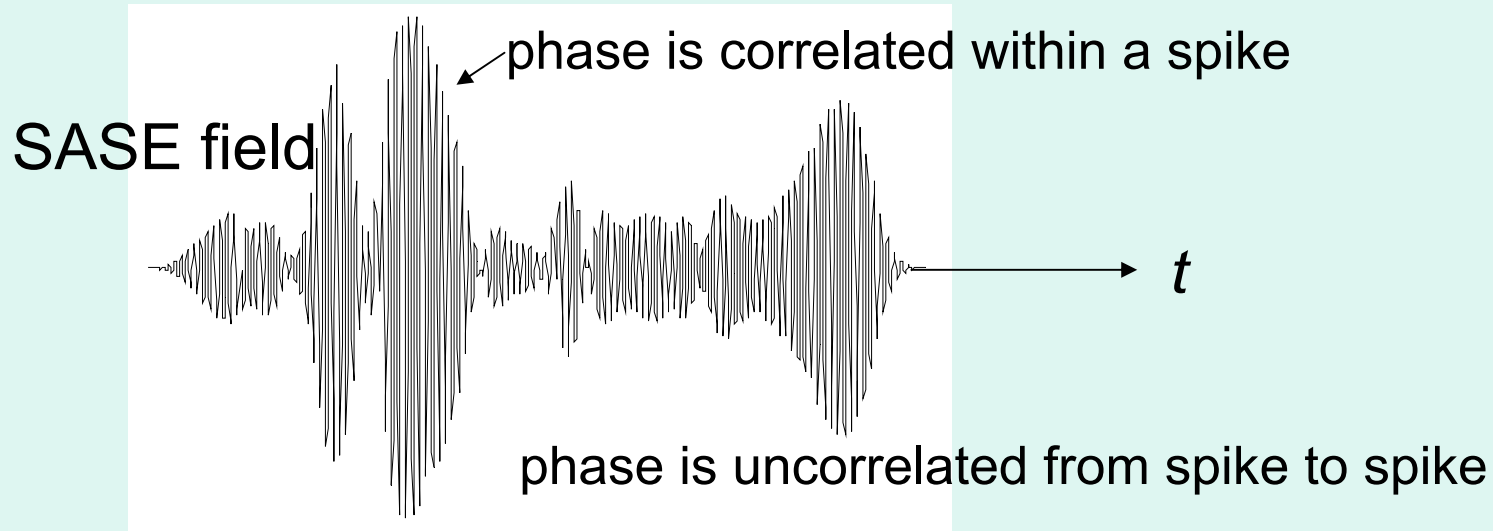
Phase term



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

Phase matching (cont.)

-----Overall phase shift unimportant for SASE



➤ Required OK R_{56} is $kR_{56}\sigma_\delta \sim 1$

$$R_{56} \sim \frac{\lambda}{2\pi\sigma_\delta} \sim 0.5 \mu\text{m} \text{ for } \sigma_\delta = 5 \times 10^{-5}$$

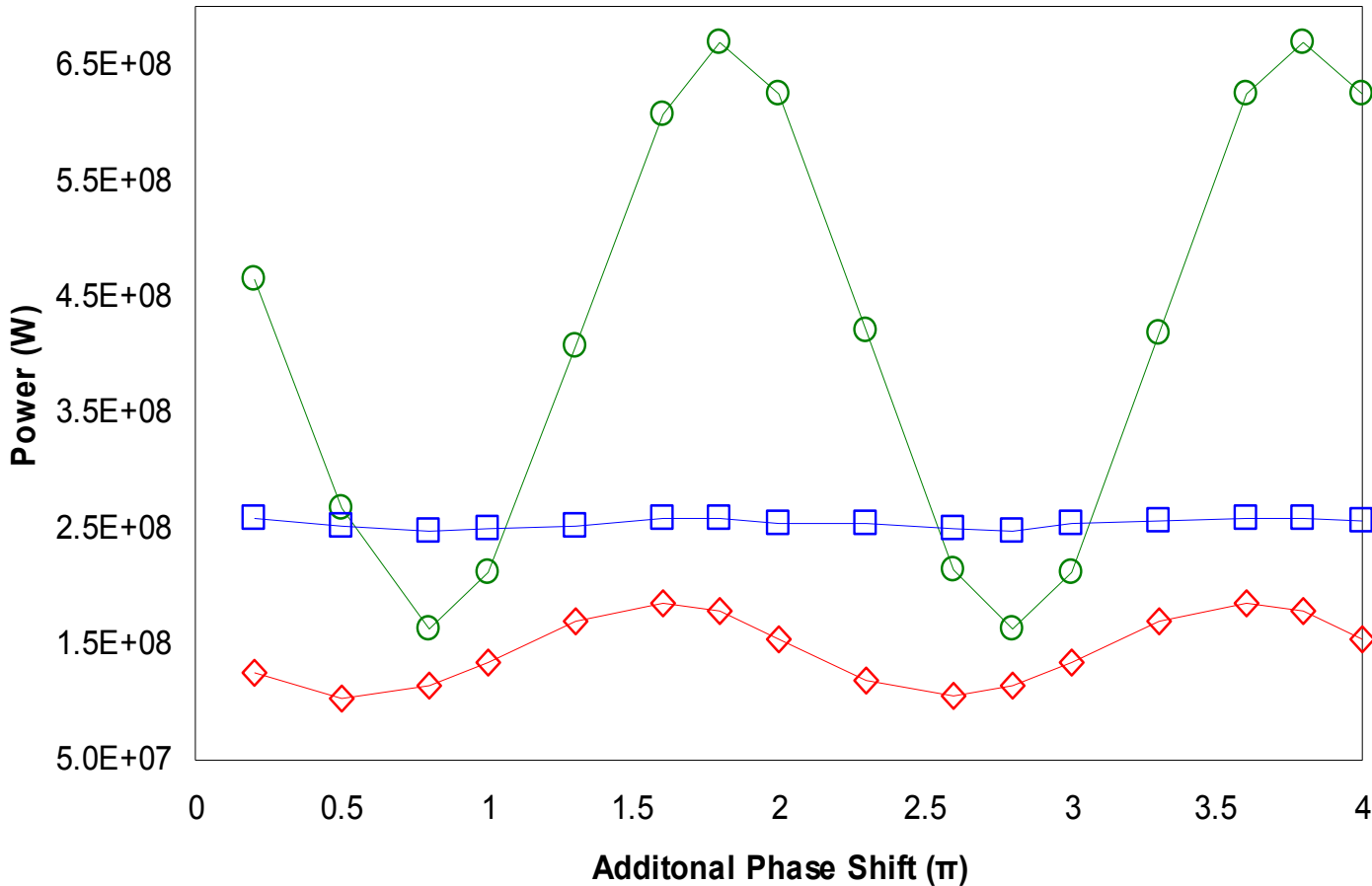
➤ Chicane delays e-beam by $R_{56}/2 = 0.25 \mu\text{m} \gg$

$$\text{SASE phase correlation length} \sim \frac{\lambda}{4\pi\rho} \sim 0.03 \mu\text{m}$$

➤ No place for phase matching

Phase matching simulations

3-D GENESIS Simulations of LCLS 1.5 Å OK2



R56=0.3 um seeded

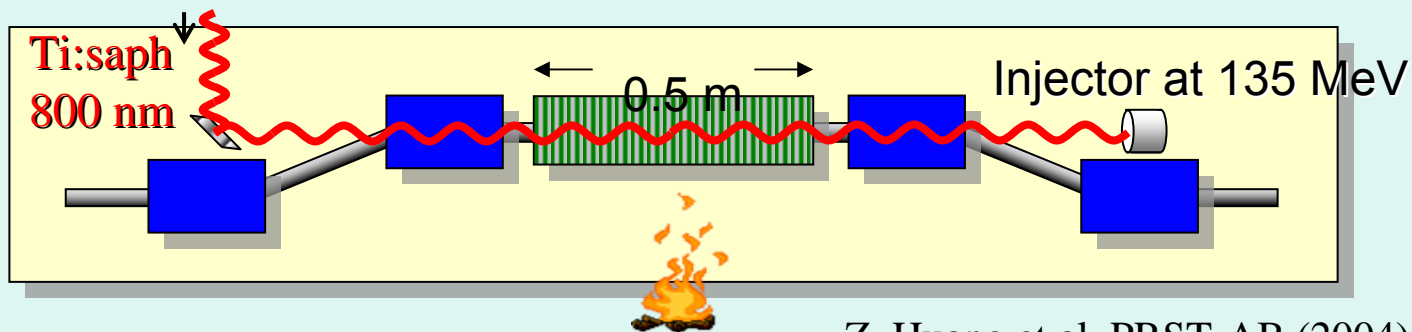
R56=0.3 um SASE

R56=0.1 um SASE

This confirms the 1-D SASE prediction

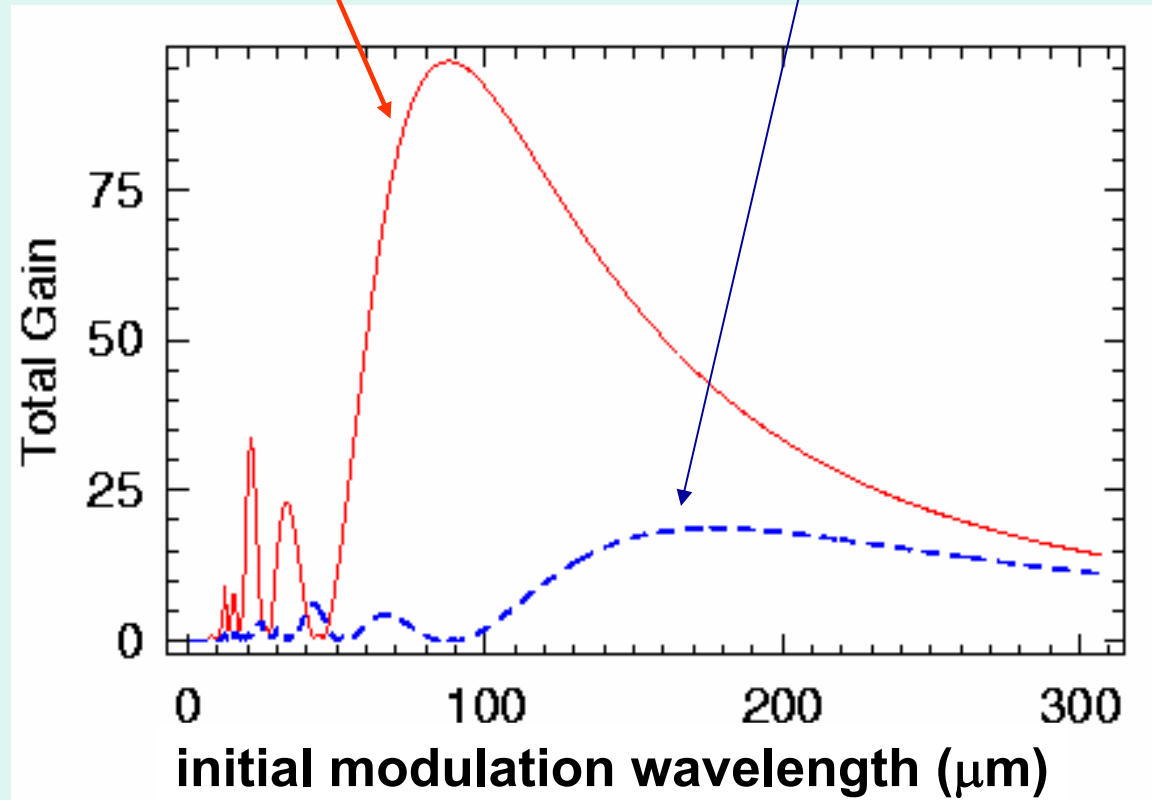
Energy spread issue

- Experiments (TTF) and simulations show intrinsic rms energy spread from rf gun ~ 3 or 4 keV
- 3 keV (rms), accelerated to 14 GeV, & compressed $\times 32$
 $\Rightarrow 3 \times 10^{-6} \times 32 / 14 < 1 \times 10^{-5}$ relative energy spread
 $\ll \rho \sim 5 \times 10^{-4}$ (LCLS FEL parameter)
- But microbunching instability due to bunch compressors amplify unwanted current modulations (similar to OK gain), increase E-spread beyond 1×10^{-4}
- To suppress the instability, a laser heater is designed in LCLS to increase intrinsic E-spread to control E-spread at undulator



- Nominal 1 nC, 3.4 kA, laser heater at rms energy spread 40 keV, undulator entrance E-spread $\sigma_\delta=1\times 10^{-4}$
- Reduce the heater-induced energy spread to 20 keV, undulator entrance $\sigma_\delta=5\times 10^{-5}$

Microbunching gain



- Tolerable microbunching gain depends on drive laser
- A low charge LCLS configuration (P. Emma et al, PAC05) has smaller instability gain

Energy spread in undulator

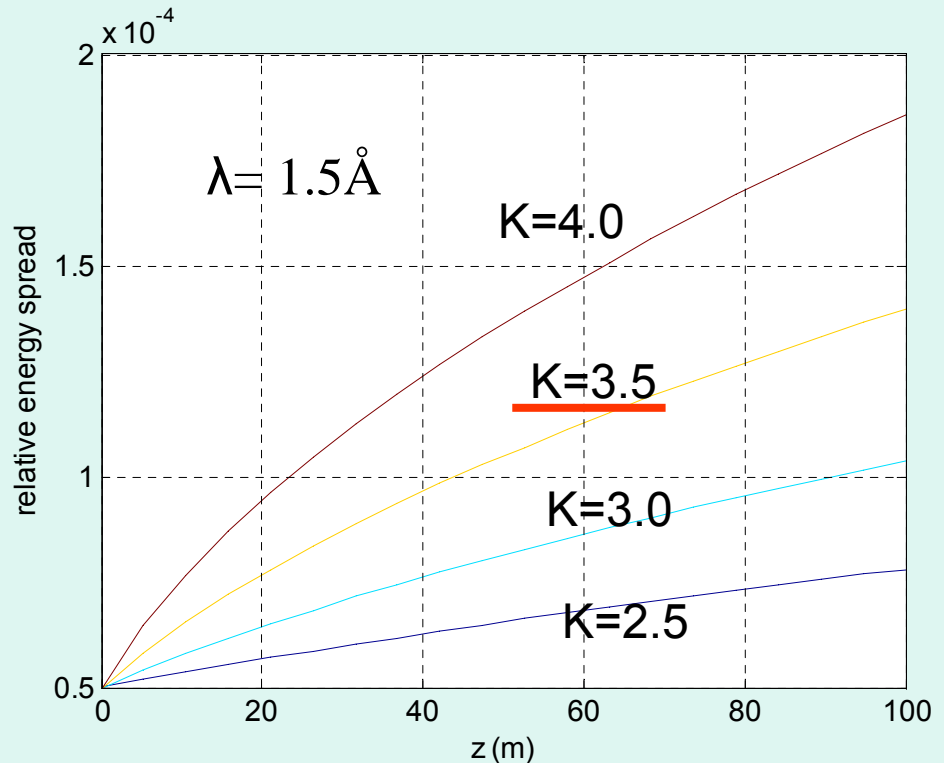
- Energy spread increase due to quantum diffusion of spontaneous radiation

$$d \langle \Delta \gamma^2 \rangle = \frac{1}{15} \frac{4}{2\pi} \frac{\lambda_c}{r_e} \gamma^4 k_u^3 K^2 F(K) L_u$$

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

(Saldin et al. NIMA 1996)

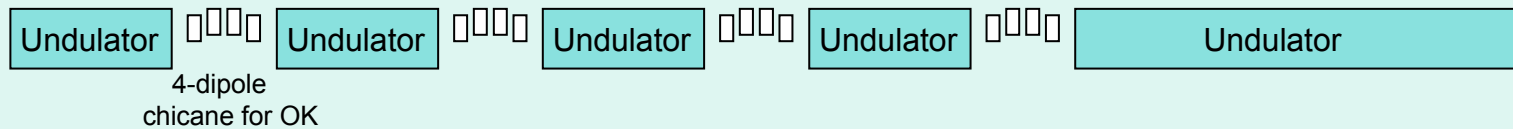
- Lower K and γ helps a lot
- Small increase of gain length (a few %) from K=3.5 to K=2.7



LCLS simulations

In all our GENESIS simulations,

- ❖ spontaneous energy spread diffusion is included;
- ❖ Insert OKs in the undulator long breaks ($\sim 1\text{m}$ space) every three undulator sections (about 12 m)



Several cases:

1.5\AA , $K=3.5$, $E=13.64\text{GeV}$

1.5\AA , $K=2.7$, $E=11.01\text{GeV}$

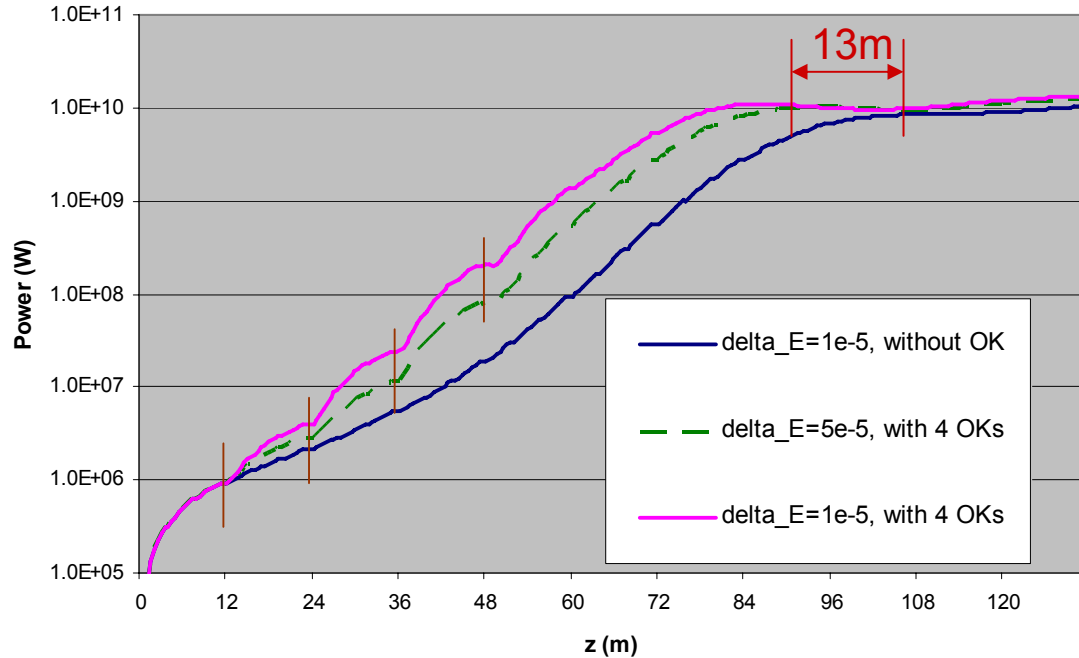
1.0\AA , $K=2.7$, $E=13.49\text{GeV}$

Undulator entrance relative energy spread (δE)

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

$\lambda=1.5 \text{ \AA}$, $K=3.5$, $E=13.6 \text{ GeV}$

1.5Angstrom, K=3.5, E=13.64GeV, SASE Power



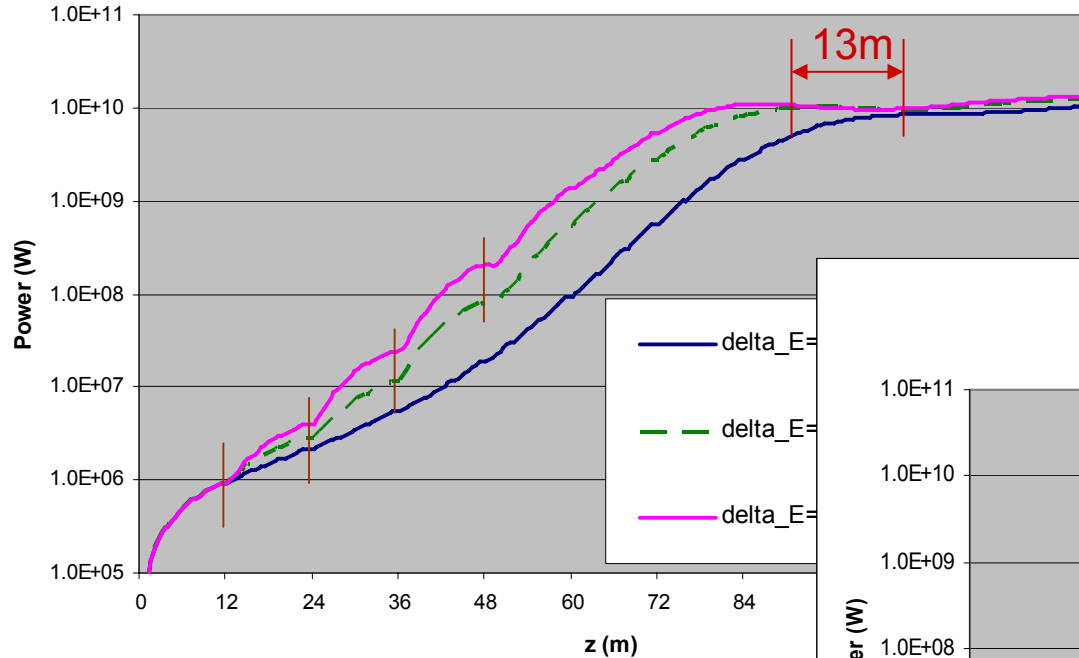
Parameters of the chicane for $\delta E=5 \times 10^{-5}$:

$R_{56} \sim 0.25 \mu\text{T}$, $B \sim 0.75 \text{T}$

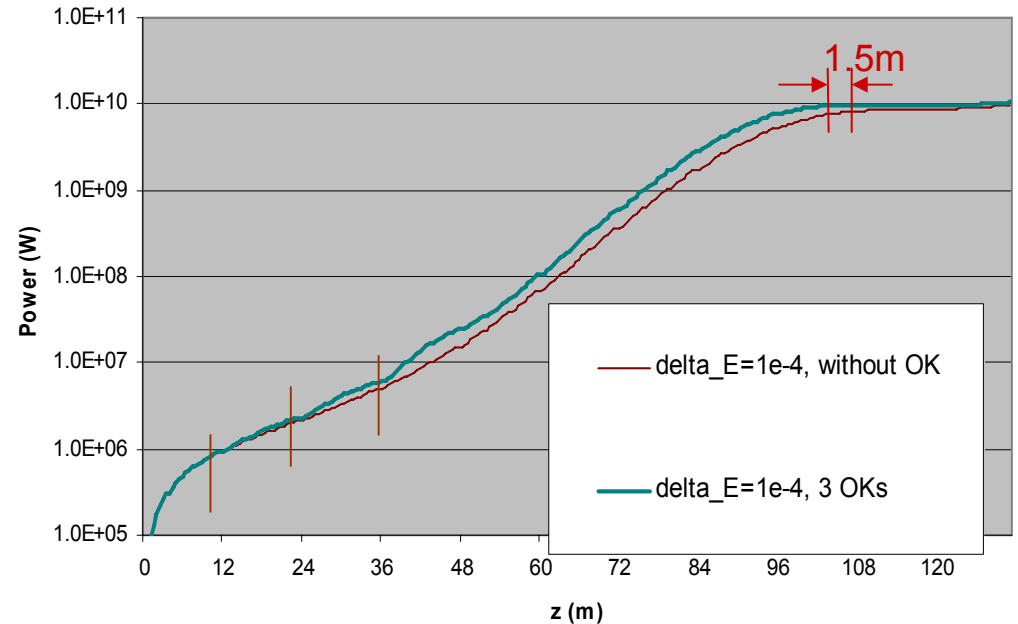
$L_B = 6 \text{cm}$, $L_{\text{chicane}} = 51 \text{cm}$

$\lambda=1.5 \text{ \AA}$, $K=3.5$, $E=13.6 \text{ GeV}$

1.5Angstrom, K=3.5, E=13.64GeV, SASE Power



1.5Angstrom, K=3.5, E=13.64GeV, SASE Power

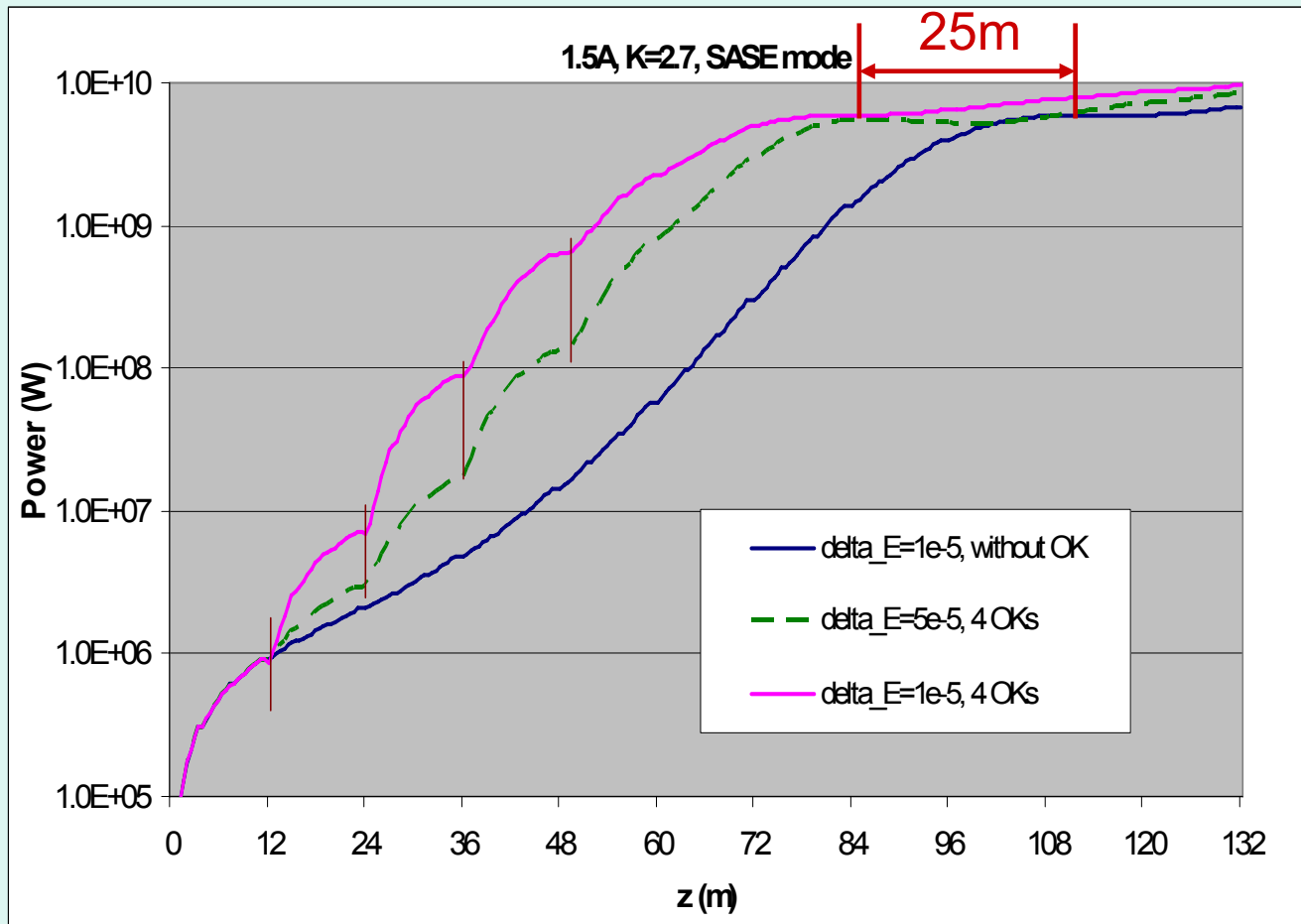


Parameters of the chicane for delta

$R_{56} \sim 0.25 \mu\text{m}$, $B \sim 0.75 \text{ T}$

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

$\lambda=1.5 \text{ \AA}$, $K=2.7$, $E=11 \text{ GeV}$

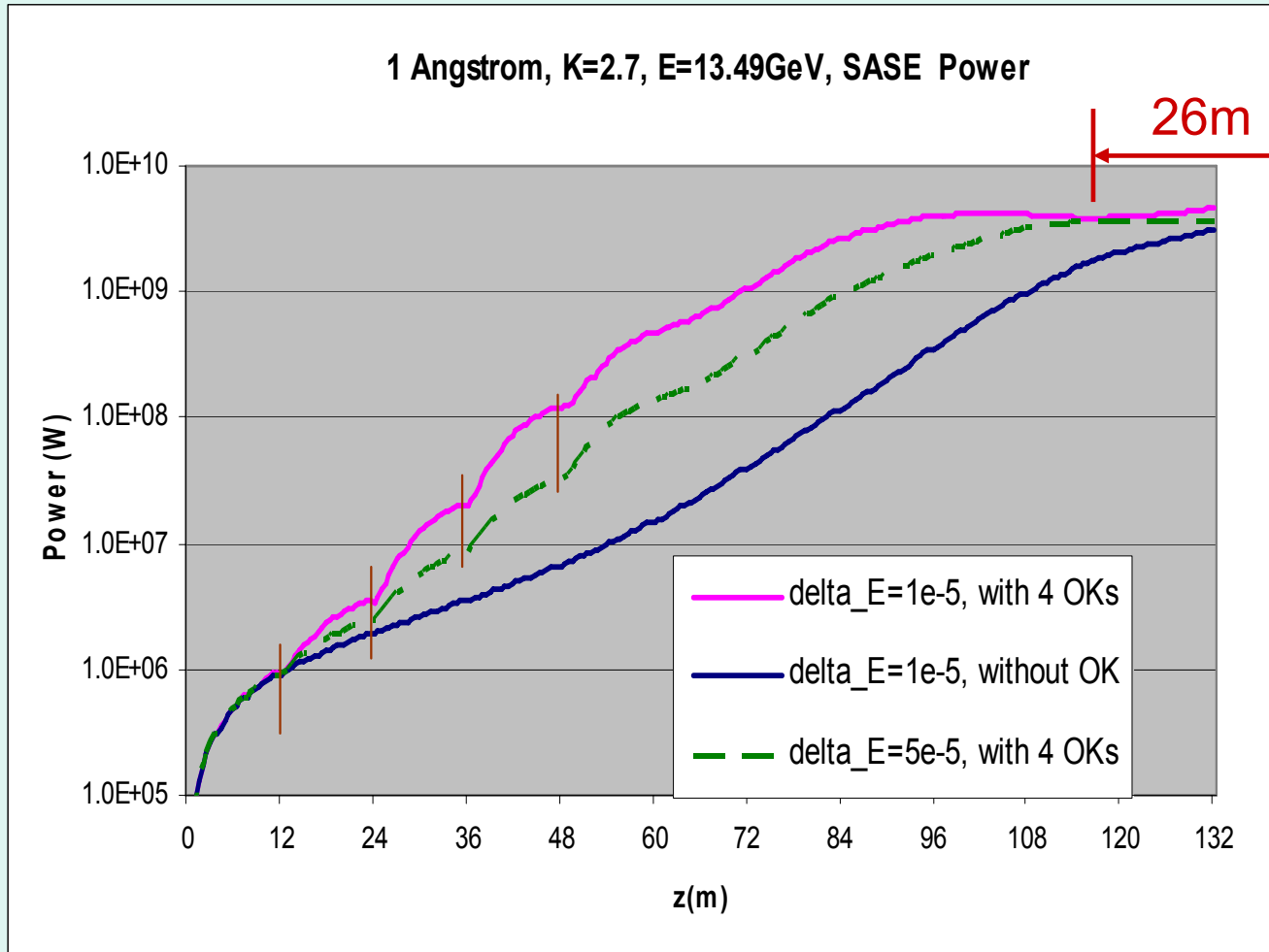


Parameters of the chicane for $\delta_E=5 \times 10^{-5}$:

$R_{56} \sim 0.30 \mu\text{m}$, $B \sim 0.65 \text{ T}$

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

$\lambda=1.0 \text{ \AA}$, $K=2.7$, $E=13.5 \text{ GeV}$



Parameters of the chicane for $\delta E=5 \times 10^{-5}$:

$R_{56} \sim 0.23 \mu\text{m}$, $B \sim 0.70 \text{ T}$

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

Summary

- In contrast to a seeded FEL, SASE optical klystron gain is not sensitive to phase mismatch between radiation and e-beam
- Slice energy spread is a crucial parameter for OK gain, spontaneous E-spread diffusion in undulator important
- With half of the baseline LCLS slice energy spread (controllable by laser heater), 4 OKs significantly enhance LCLS gain and lead to earlier saturation
- Possibility of extending LCLS to 1.0 Å by opening up the undulator gap (from 6 mm to ~8 mm)
- May also be applicable to other SASE sources with a modest beam energy and a short-period undulator

Energy spread issue

--Why small energy spread is crucial for OK?

- Optimal OK, $kR_{56}\sigma_\delta \sim 1$ $R_{56OK} \sim \frac{1}{k\sigma_\delta} = \frac{\lambda}{2\pi\sigma_\delta}$
- For undulator, an equivalent R_{56} per λ_u period is

$$R_{56UN} \sim 2\lambda$$

- To get effective bunching enhancement, R_{56OK} must be much bigger than R_{56UN} in a gain length $N_G\lambda_u$

e.g. $R_{56OK} \gg R_{56UN} \cdot N_G \longrightarrow \sigma_\delta \ll \frac{1}{4\pi N_G} = \rho$

- OK power gain factor $G \sim \frac{\rho^2}{\sigma_\delta^2}$