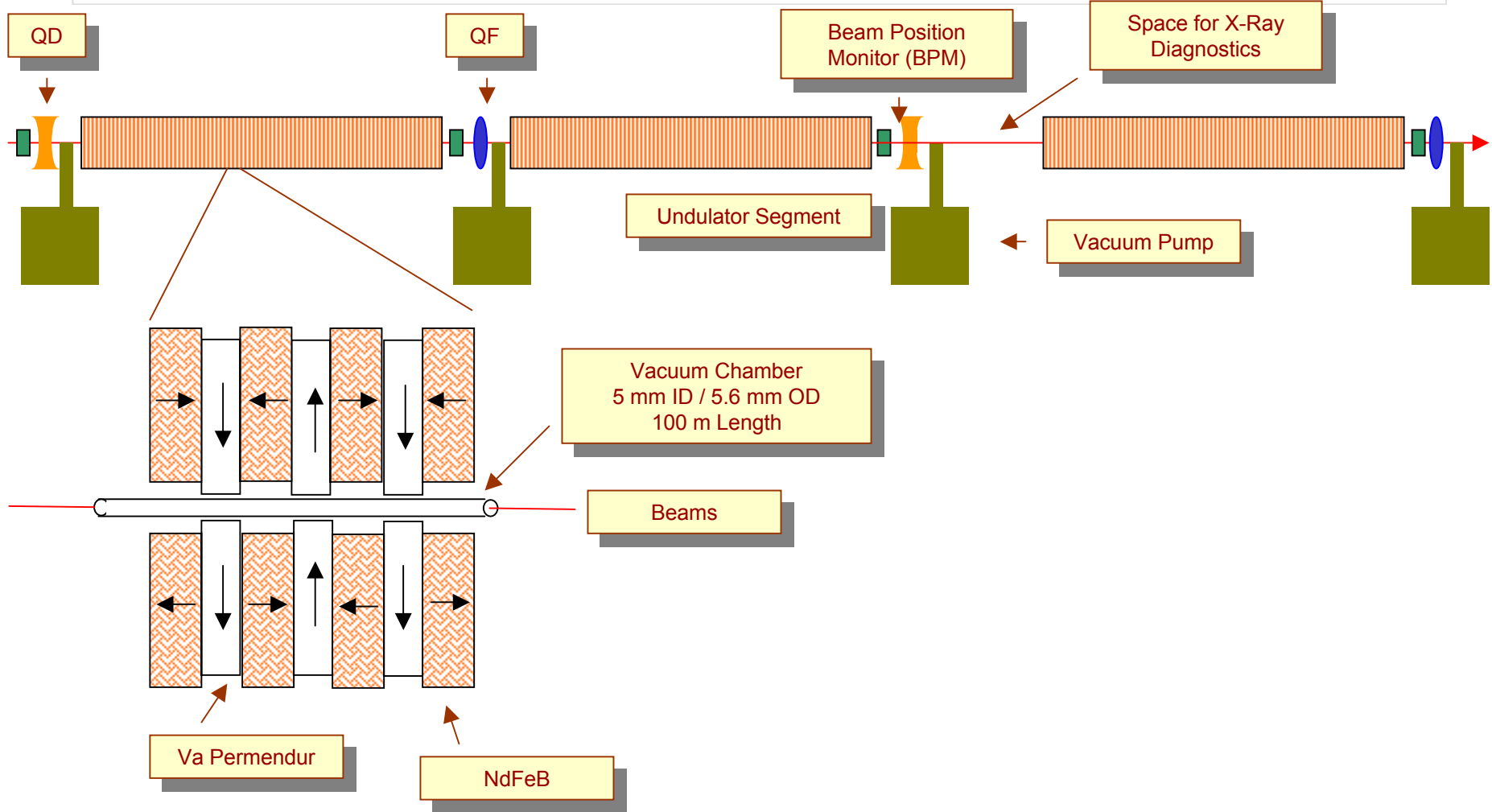


Undulator Chamber Wakefields

Heinz-Dieter Nuhn, SLAC / SSRL
December 10, 2001

- Undulator Chamber Wakefield Description
- Effects on FEL Performance
- Consequences for the LCLS

LCLS Undulator



Undulator Chamber Wakefield Sources

- ***Geometric Wakefields***
- ***Surface Roughness Wakefields***
- ***Resistive Wall Wakefields***

Geometric Undulator Chamber Wakefields

Calculations for Short Bunches Based on Diffraction Wakefield Model

$$\langle W_z^{diff} \rangle \approx \frac{\Gamma(1/4)}{4\pi^{5/2}} \frac{Z_0 c M}{a L} \sqrt{\frac{g}{\sigma_z}}, \quad \sigma_z / a \ll 1 \quad (W_z^{diff})_{rms} \approx (0.40) \langle W_z^{diff} \rangle$$

$$\langle W_x^{diff} \rangle \approx (0.463) \frac{Z_0 c M}{\pi^3 a^3 L} \sqrt{g \sigma_z}, \quad \sigma_z / a \ll 1$$

W_z	Average Wakefield Green's Function [V/C/m]
L	Total Undulator Length
Z_0	Vacuum Impedance
a	Pipe Radius
σ	Conductivity of Vacuum Chamber Material ($5.9 \times 10^7 \Omega^{-1}\text{m}^{-1}$ for Copper)
M	Number of Gaps / BPMs / Pump Slots

Geometric Undulator Chamber Wakefields

Flange Gaps

Gap Length : $g = 0.25 \text{ mm}$

Number of Flange Gaps : $M = 144$

$$\langle \delta \rangle = \frac{e^2 NL \langle W_z^{diff} \rangle}{E} = 0.008\%$$

$$\sigma_\delta = \frac{e^2 NL (W_z^{diff})_{rms}}{E} = 0.003\%$$

$$\Delta \varepsilon_n = 0.008\% \quad \text{for } 100 \mu\text{m oscillation}$$

RF Cavity BPMs

Gap Length : $g = 5 \text{ mm}$

Number of Flange Gaps : $M = 72$

$$\langle \delta \rangle = \frac{e^2 NL \langle W_z^{diff} \rangle}{E} = 0.019\%$$

$$\sigma_\delta = \frac{e^2 NL (W_z^{diff})_{rms}}{E} = 0.007\%$$

$$\Delta \varepsilon_n = 0.007\% \quad \text{for } 100 \mu\text{m oscillation}$$

Pump Slots

Gap Length : $g = 5 \text{ mm}$

Number Pumping Slots per segment: ~ 10

Total Number of Pumping Slots: $M = 360$

Slot width $w = 1 \text{ mm}$

Azimuthal Filling Factor: $w/2\pi a = 0.064$

$$\langle \delta \rangle = \frac{w}{2\pi a} \frac{e^2 NL \langle W_z^{diff} \rangle}{E} = 0.006\%$$

$$\sigma_\delta = \frac{w}{2\pi a} \frac{e^2 NL (W_z^{diff})_{rms}}{E} = 0.002\%$$

$$\Delta \varepsilon_n = 0.006\% \quad \text{for } 100 \mu\text{m oscillation}$$

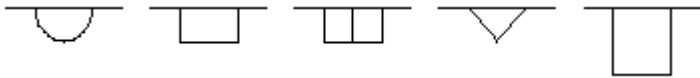
Shielded Bellows (Total Number: ~ 36)

Negligible due to Shielding

Amplitudes negligibly small.

Vacuum Chamber Surface Roughness

Initial Bump Model for Surface Roughness => Aspect Ratio ~ 1/1

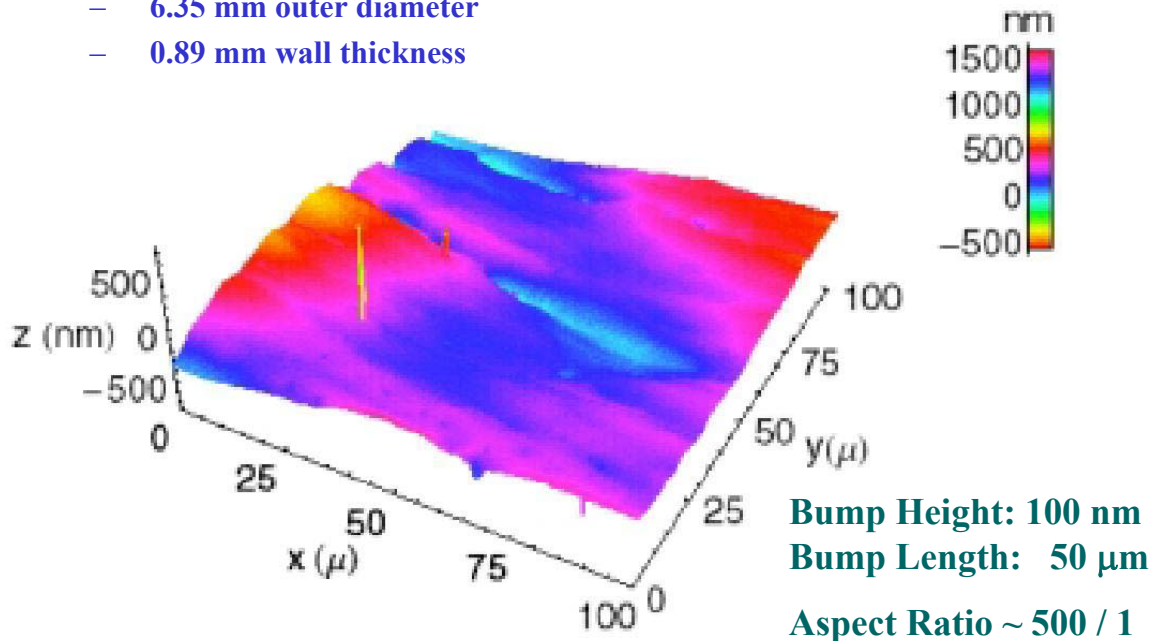


=> Large Wakefield Amplitudes

AFM Measurement of Surface Roughness

Type 316-L Stainless Steel Tubing VALEX Corp. (best commercial finish, A5)

- 6.35 mm outer diameter
- 0.89 mm wall thickness



=> Small Wakefield Amplitudes

Atomic Force Microscope (AFM) Measurements show much smaller Aspect Ratios Surface Roughness Wake becomes unimportant

Wall Roughness Wakefields

Sinusoidal Corrugation – Arbitrary Bunch Length Model (G. Stupakov, 2000)

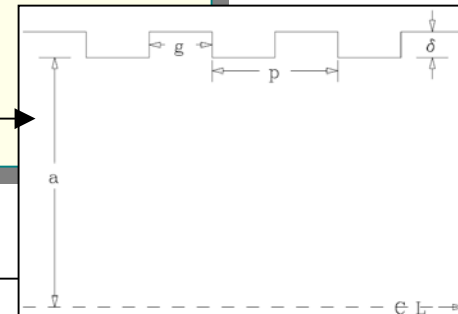
$$W_z(s) = cZ_0 e^2 \frac{h_0^2 \kappa^{3/2}}{a} \frac{1}{2\sqrt{\pi}} \frac{\partial}{\partial s} \frac{1}{\sqrt{s}} \left[\cos\left(\frac{\kappa s}{2}\right) + \sin\left(\frac{\kappa s}{2}\right) \right]$$

Synchronous Mode (A. Novokhatski, A. Mosnier, 1996)

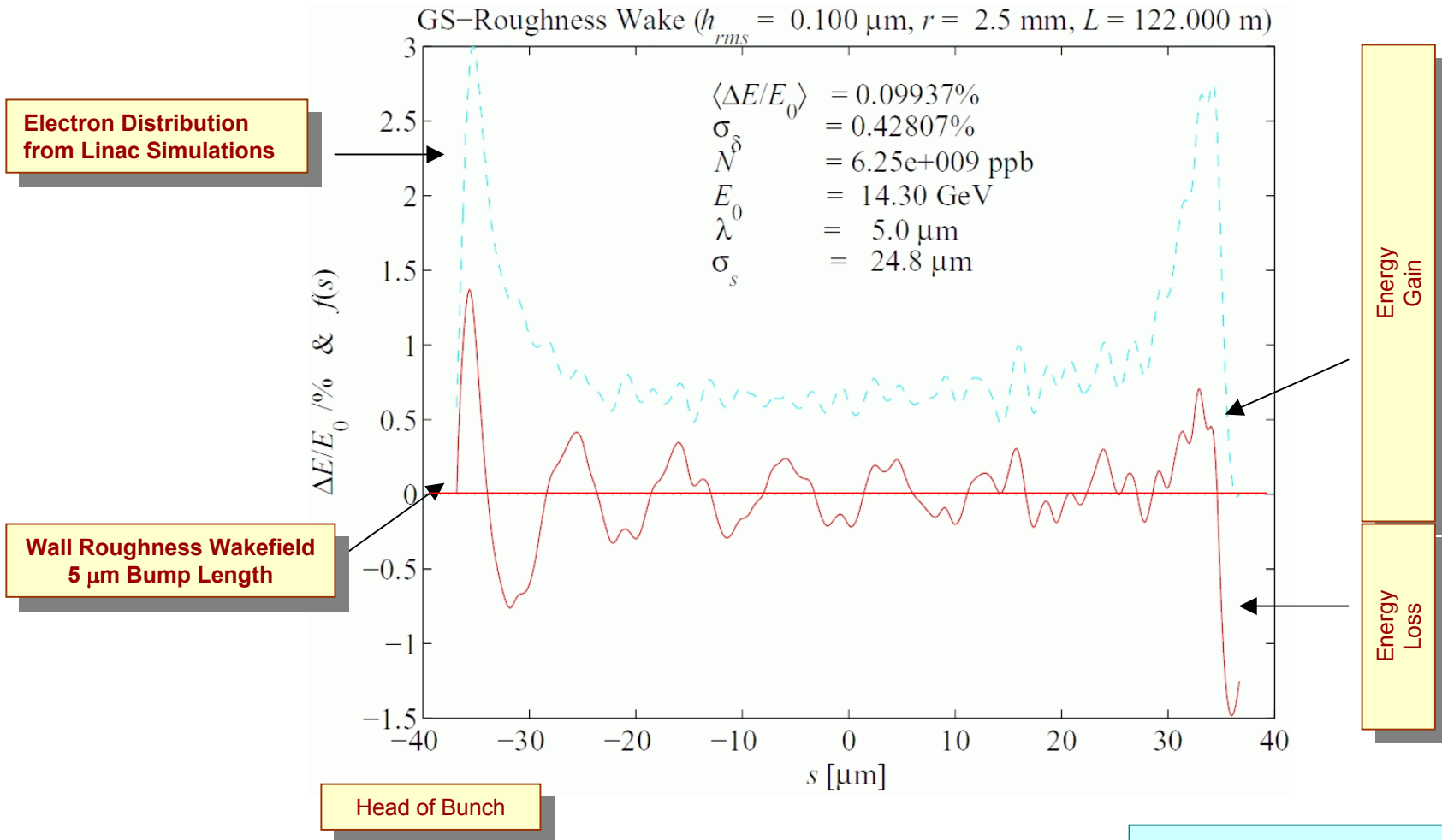
$$W_z(s) = -\frac{cZ_0 e^2}{\pi a^2} \cos(k_0 s)$$

Negligible for aspect ratios > 1 / 1 !

$W_z(s)$	Single Particle Wakefield
Z_0	Vacuum Impedance
a	Pipe Radius
h_0	Corrugation Amplitude
s	Longitudinal Distance from Test Particle to Generator
$p = 2\pi / \kappa$	Corrugation Period
$k_0 = \sqrt{2 p / \delta a g}$	

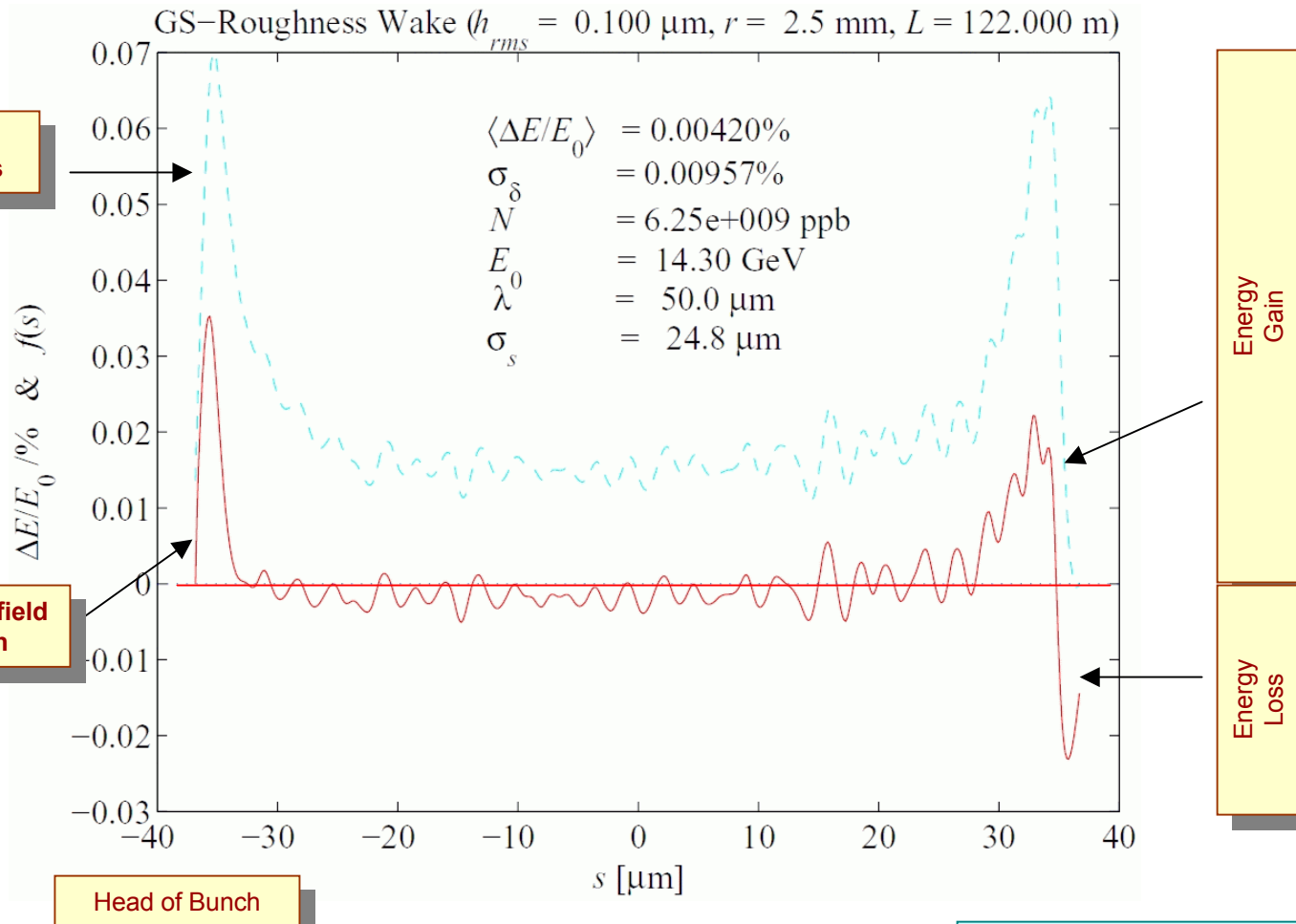


Wall Roughness Wakefield (5 μm / 0.1 μm Bumps) for Simulated Distribution



Courtesy of P. Emma, SLAC

Wall Roughness Wakefield (50 μm / 0.1 μm Bumps) for Simulated Distribution



Courtesy of P. Emma, SLAC

Resistive Wall Wakefield for Short Bunches

Ultra-Relativistic Approximation

$$E_z(s) = -\frac{4ceZ_0}{\pi a^2} \left(\frac{1}{3} e^{-s/s_0} \cos(\sqrt{3}s/s_0) - \frac{\sqrt{2}}{\pi} \int_0^\infty \frac{x^2}{x^6 + 8} e^{-sx^2/s_0} dx \right) \quad z > 0$$

$$E_z(s) = 0 \quad z < 0$$

$$s_0 = \sqrt[3]{\frac{2a^2}{Z_0\sigma}} = 8.3 \mu\text{m}$$

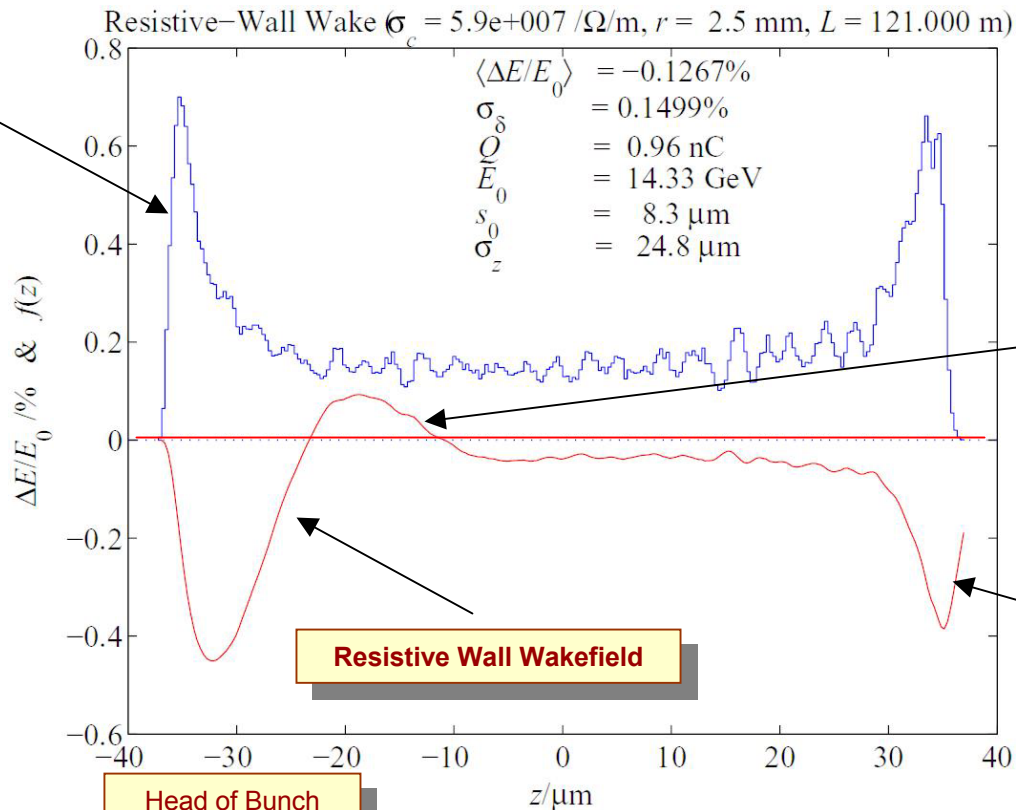
for LCLS Parameters, i.e.,

$a = 2.5 \text{ mm}$

Copper Plated Vacuum Chamber

$E_z(s)$	Wakefield Green's Function [V/C/m]
Z_0	Vacuum Impedance
a	Pipe Radius
σ	Conductivity of Vacuum Chamber Material ($5.9 \times 10^7 \Omega^{-1}\text{m}^{-1}$ for Copper)
s	Longitudinal Distance from Test Particle to Generator

Resistive Wall Wakefield for Simulated Distribution



Electron Distribution
from Linac Simulations

285 keV/m corresponds to 0.2 %
Slice Energy Change per 100 m.

Resistive Wall Wakefield

Head of Bunch

Energy
Gain

Energy
Loss

Courtesy of P. Emma, SLAC

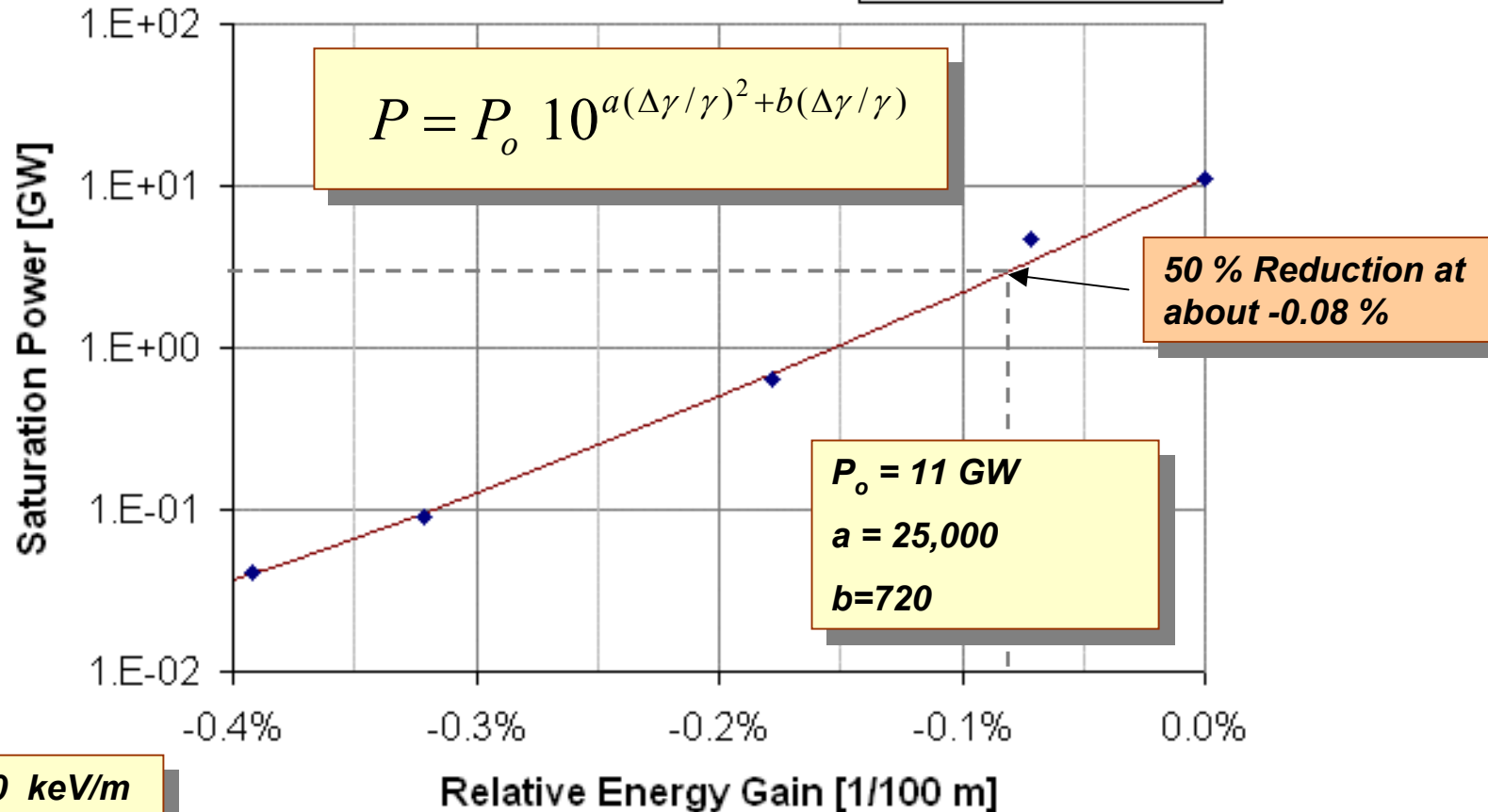
Undulator Wakefield Simulations

Continuous Change in Average Slice Energy along Undulator

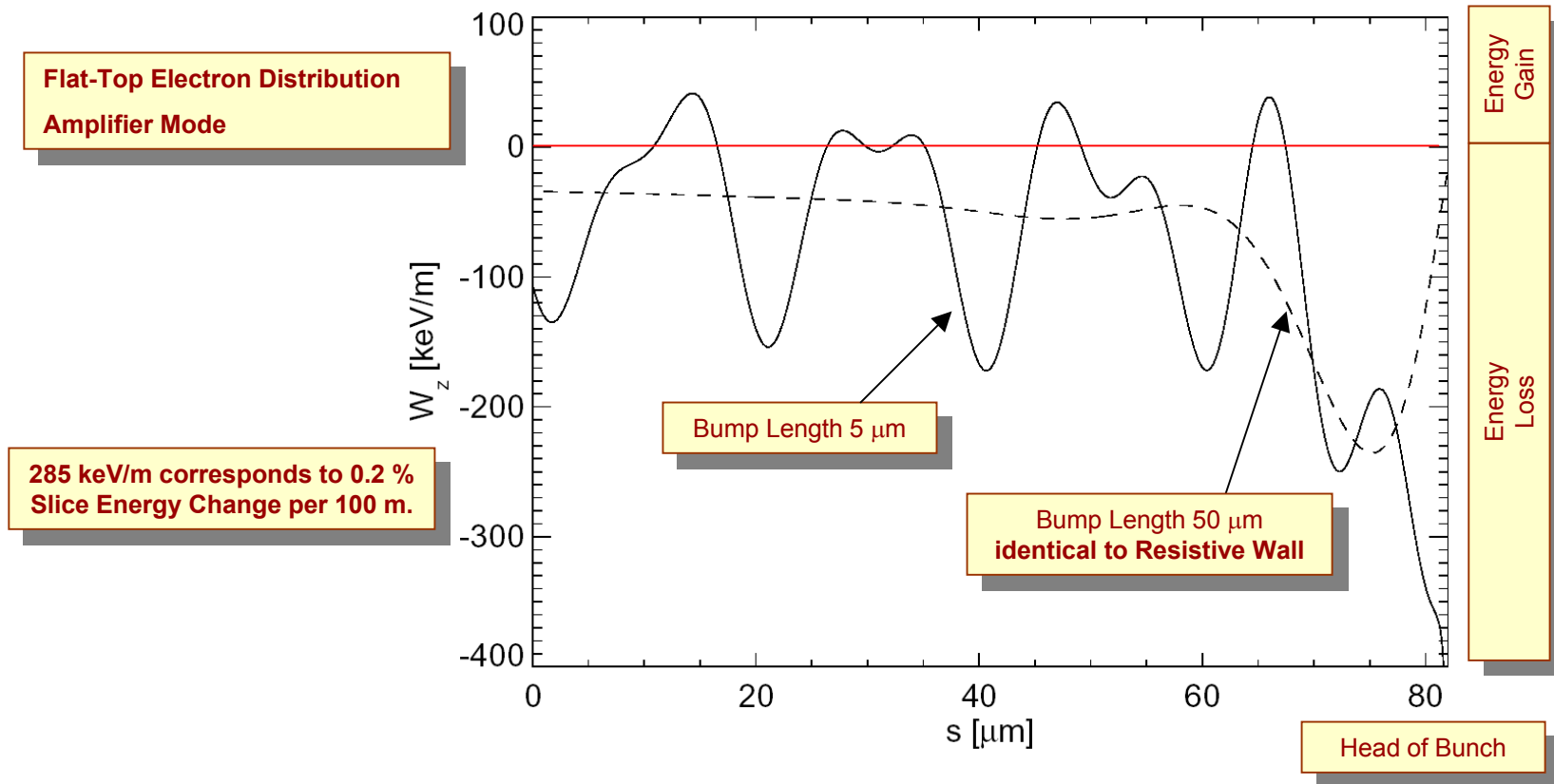
Undulator Wakefield Effects on FEL Performance

1.5 Å

GINGER Simulations



Wakefields used in FEL Simulations



- **Resistive Wall: Copper Plated Stainless Steel**
- **Surface Roughness: Both inductive model and synchronous mode, assuming a 1 nC electron bunch, a bump height of 100 nm**

Courtesy of S. Reiche, UCLA

Undulator Wakefield Simulations : Power Envelope

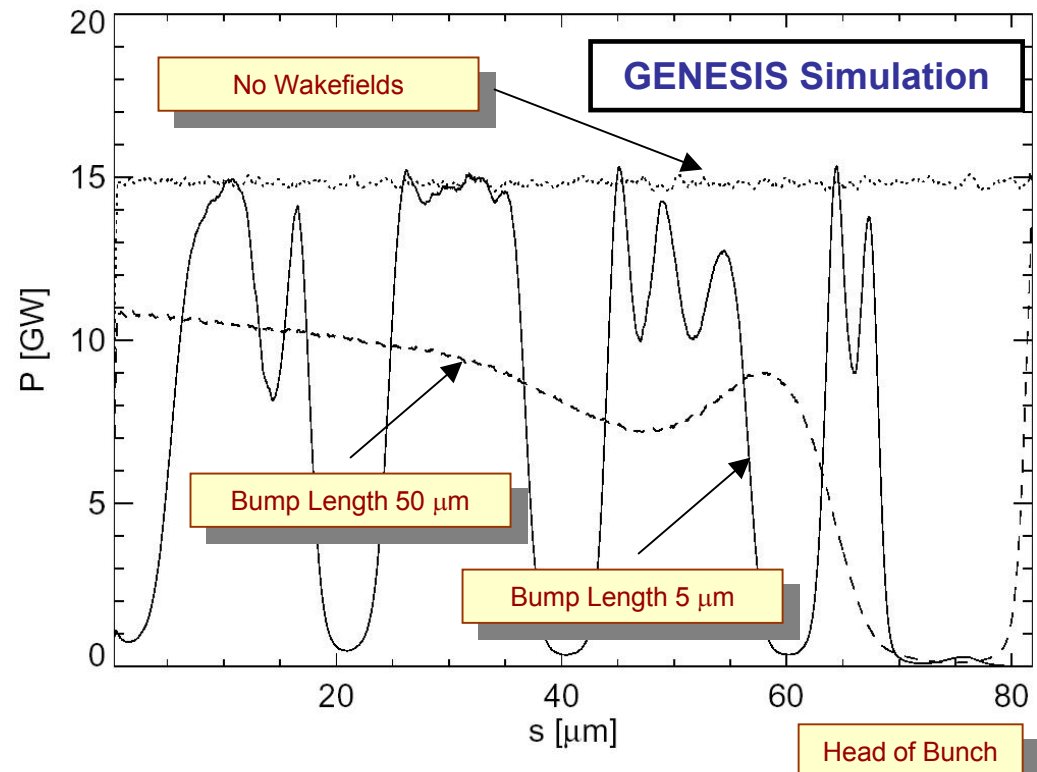
Flat-Top Electron Distribution
Amplifier Mode

Effect of Wakefields on
temporal Radiation Power Profile at
Undulator Exit

Dotted line: no wakefields;

Dashed line: long bump case;

Solid line: short bump case.



Wakefield Effects on LCLS Performance

Flat-Top Electron Distribution
Amplifier Mode

$\epsilon_n = 1.2 \mu\text{m rad}$
 $I_{pk} = 3.4 \text{ kA}$

No Wakefields

Power vs. undulator length
for the LCLS case

Saturation length ~ 92 m

Saturation power levels:

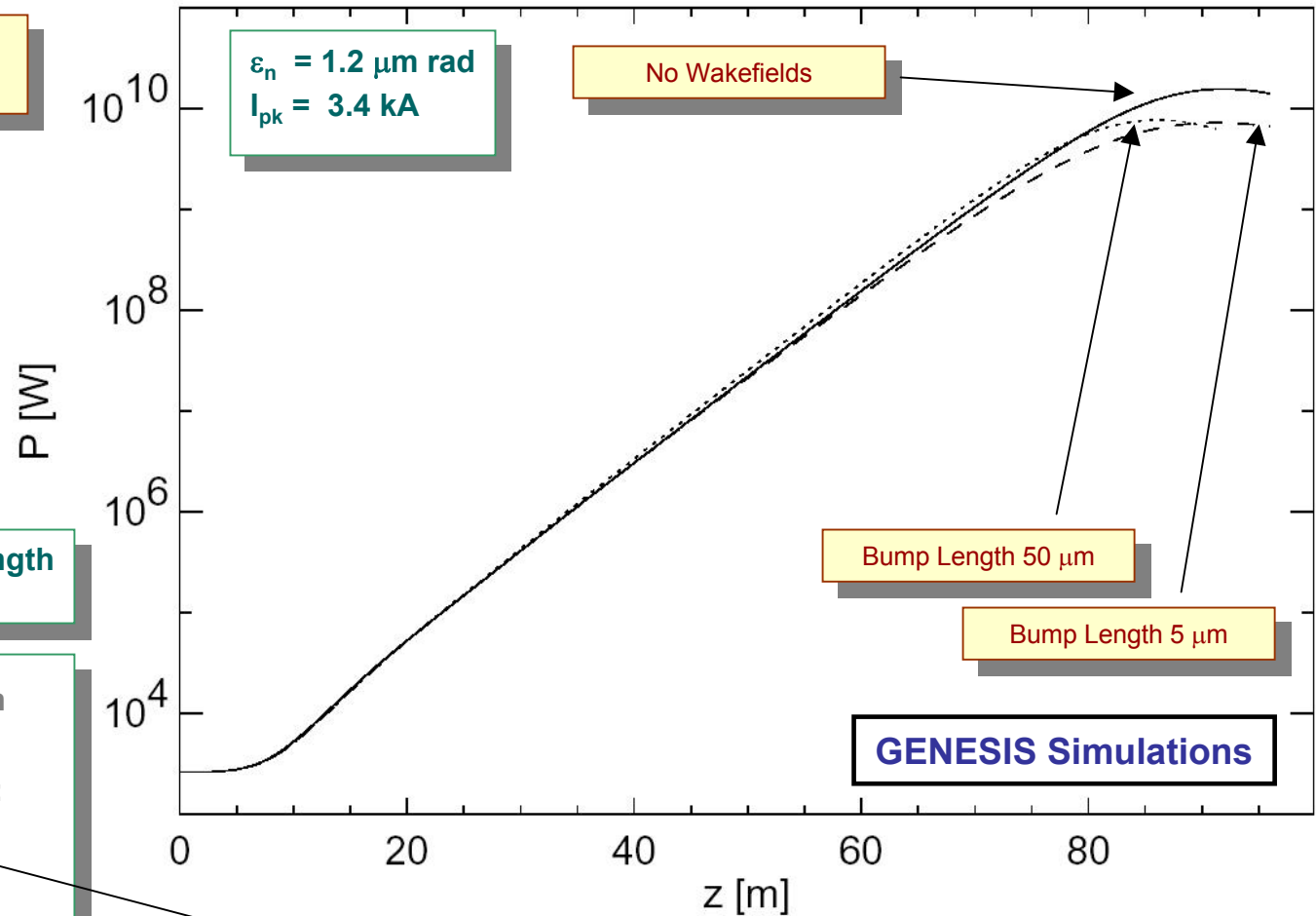
- 15 GW
- 8 GW
- 8 GW
- 7 GW

LCLS Goal Power Level

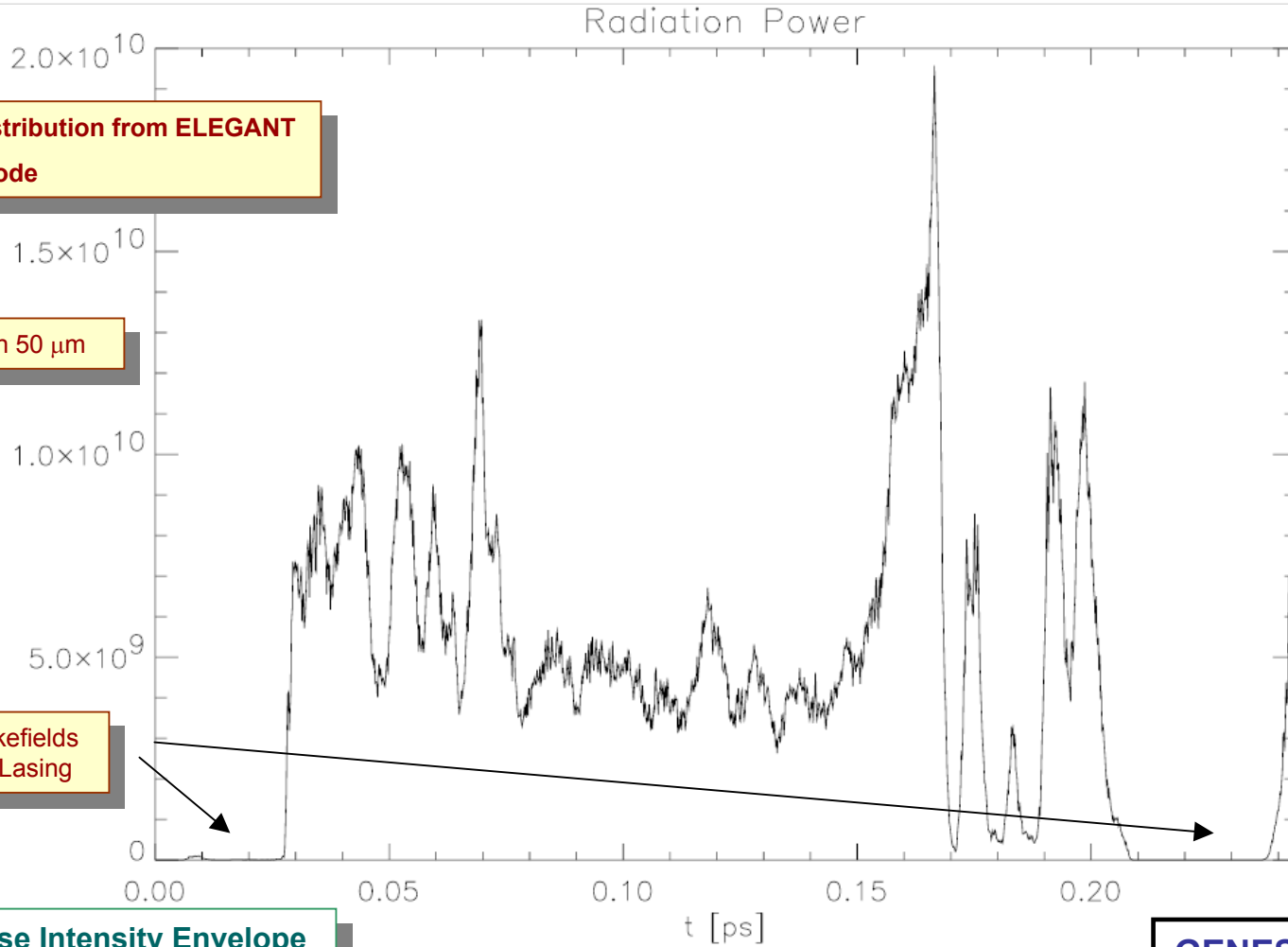
Bump Length 50 μm

Bump Length 5 μm

GENESIS Simulations



Wakefield Effects on LCLS Performance A



Electron Distribution from ELEGANT
Amplifier Mode

Bump Length 50 μm

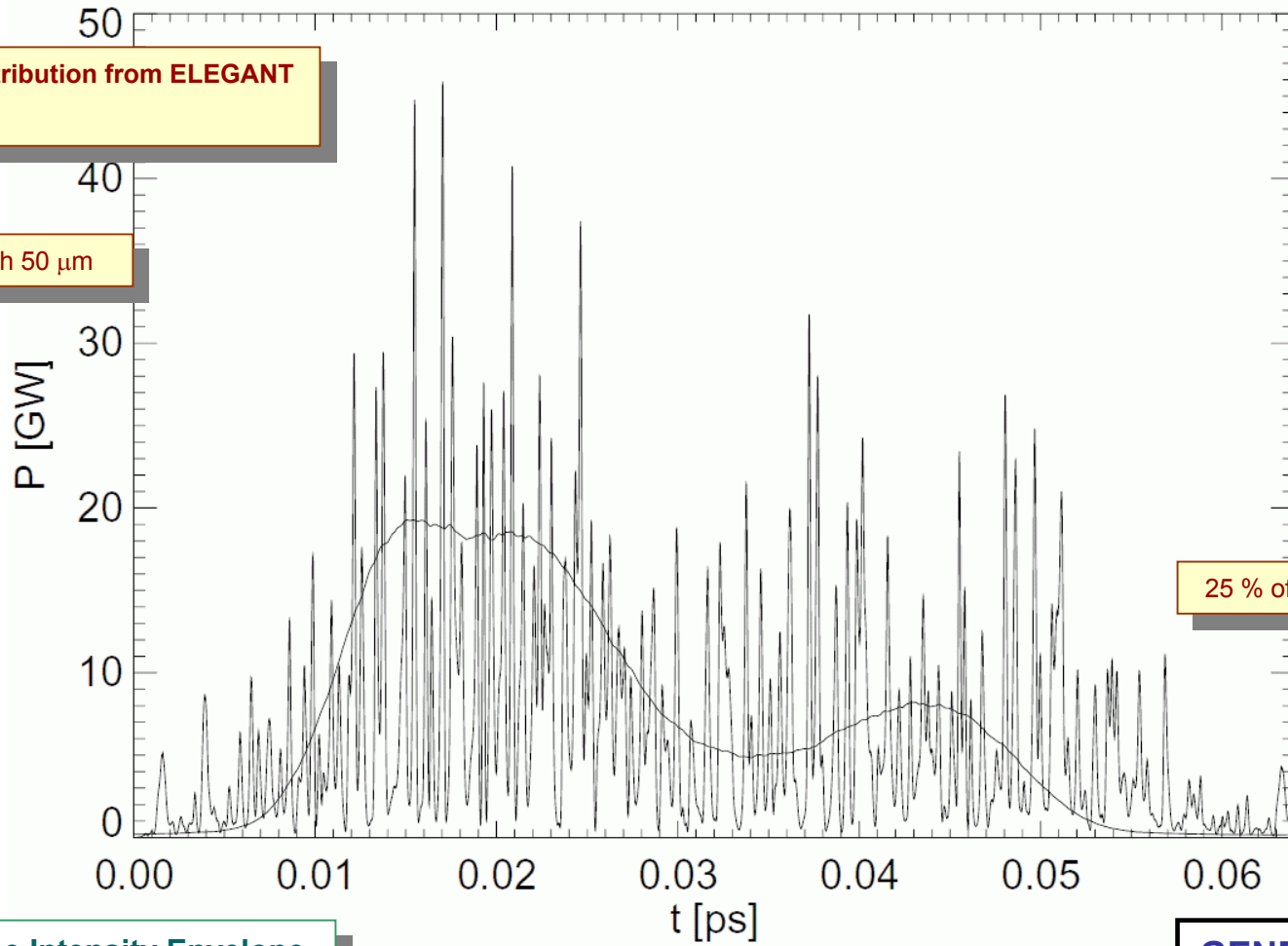
High Wakefields
suppress Lasing

$\epsilon_n = 1.2 \mu\text{m rad}$
 $I_{pk} = 3.4 \text{ kA}$

X-Ray Pulse Intensity Envelope

GENESIS Simulations

Wakefield Effects in SASE Simulations



Wakefield Effects on Electron Beam Slices

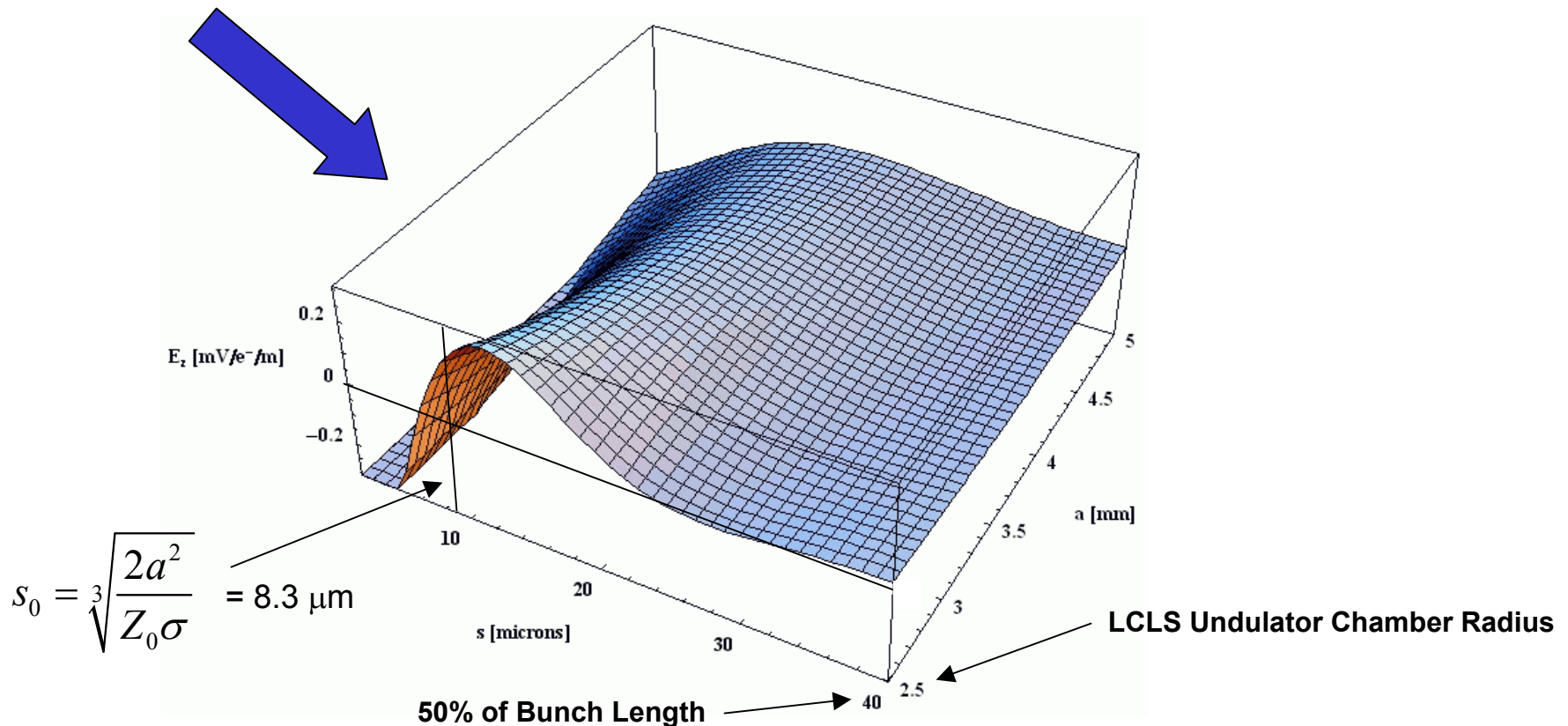
- ***Reduction of Total Pulse Power by about 50%***
7-8 GW instead of 15 GW
- ***Added Temporal Structure in x-ray intensity (Shorter Pulses)***
- ***Practically no Change in Saturation Length***
- ***Radiation Bandwidth increase small (< 30% for unchirped beam)***
- ***Small Decrease in Brightness***

PRESENT LCLS POSITION

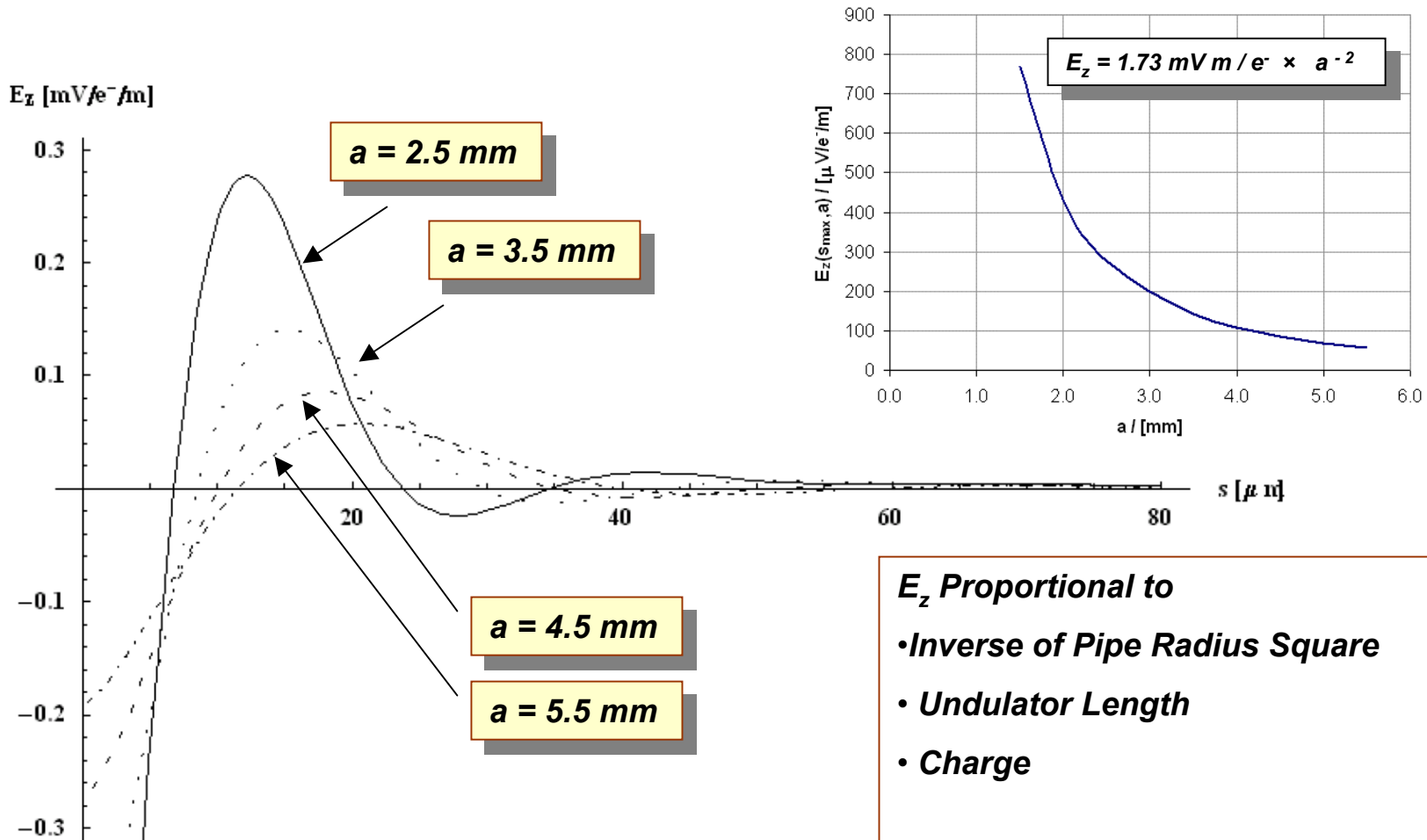
Wakefield Effects do not degrade performance below the design goal.

Resistive Wall Wakefield Sensitivity to Pipe Radius

$$E_z(s, a) = -\frac{4ceZ_0}{\pi a^2} \left(\frac{1}{3} e^{-s/s_0(a)} \cos(\sqrt{3}s / s_0(a)) - \frac{\sqrt{2}}{\pi} \int_0^\infty \frac{x^2}{x^6 + 8} e^{-sx^2/s_0(a)} dx \right)$$



Resistive Wall Wakefield Scaling



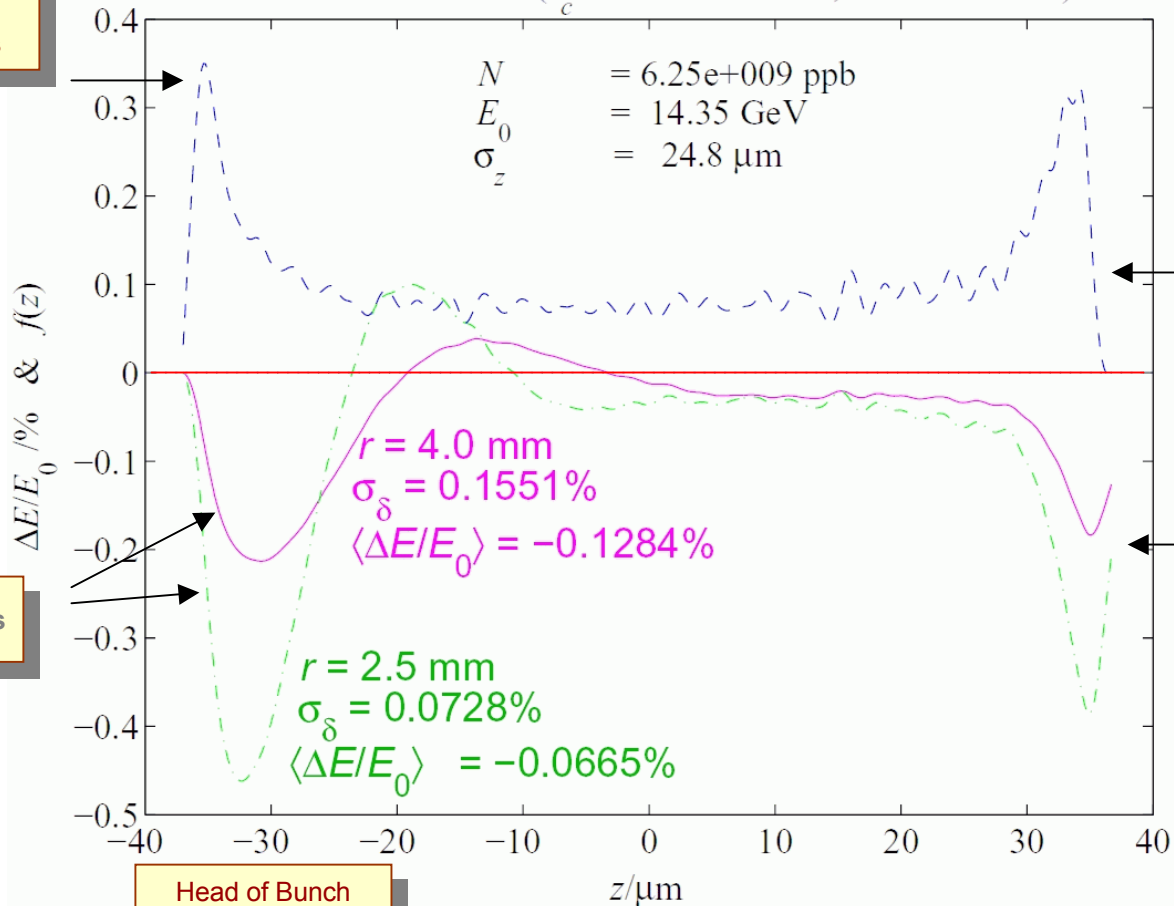
E_z Proportional to

- Inverse of Pipe Radius Square $\frac{1}{a^2}$
- Undulator Length L_u
- Charge Q

Resistive Wall Wakefield at 2.5 and 4 mm Radius for Simulated Distribution

Electron Distribution
from Linac Simulations

Resistive-Wall Wake ($\sigma_c = 5.9e+007 / \Omega/m, L = 121.000 \text{ m}$)



Energy Gain

Energy Loss

Reduction less
than quadratic

Head of Bunch

Courtesy of P. Emma, SLAC

Summary

- Considered Various Undulator Chamber Wakefields:
 - Geometric
 - Flange Gaps, Pump Slots, BPMs, Shielded Bellows → Negligible Effect
 - Surface Roughness
 - AFM Measurements indicate large Aspect Ratio → Small Effect
 - Resistive Wall
 - Copper Surface → Sizeable Effect
- Resistive wall wakefields in the undulator vacuum chamber effect FEL output for the parameters that are presently proposed for the CDR.
- Total output power expected to be at the goal values as described in the CDR.

Undulator Chamber Wakefields

Heinz-Dieter Nuhn, SLAC / SSRL - December 10, 2001