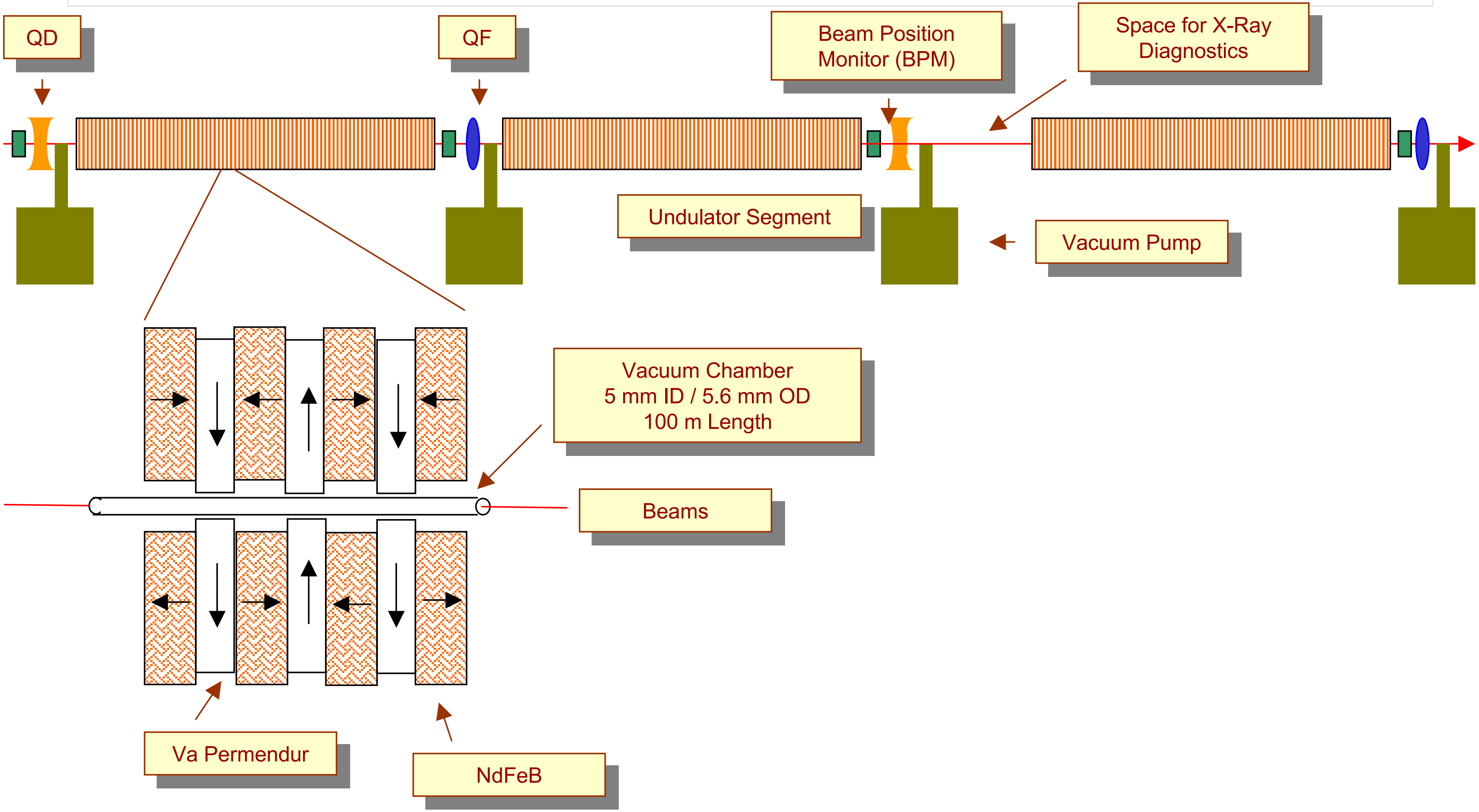
Undulator Chamber Wakefields

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

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

LCLS Undulator



QD

QF

Beam Position Monitor (BPM)

Space for X-Ray Diagnostics

Undulator Segment

Vacuum Pump

Vacuum Chamber
5 mm ID / 5.6 mm OD
100 m Length

Beams

Va Permendur

NdFeB

Undulator Chamber Wakefield Sources

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

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Geometric Undulator Chamber Wakefields

Calculations for Short Bunches Based on Diffraction Wakefield Model

$$\left\langle W_z^{diff} \right\rangle \approx \frac{\Gamma(1/4)}{4\pi^{5/2}} \frac{Z_0 cM}{aL} \sqrt{\frac{g}{\sigma_z}}, \qquad \sigma_z / a \ll 1$$

$$\left(W_z^{diff} \right)_{rms} \approx (0.40) \left\langle W_z^{diff} \right\rangle$$

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

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 × 10^7 Ω^{-1}m^{-1} for Copper)
M	Number of Gaps / BPMs / Pump Slots

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Geometric Undulator Chamber Wakefields

Flange Gaps

Gap Length : g = 0.25 mm
Number of Flange Gaps : M = 144

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

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

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

RF Cavitiy BPMs

Gap Length : g = 5 mm
Number of Flange Gaps : M = 72

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

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

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

Pump Slots

Gap Length : g = 5 mm
Number Pumping Slots per segment: ~10
Total Number of Pumping Slots: M = 360
Slot width w = 1 mm
Azimuthal Filling Factor: $w/2\pi a$ = 0.064

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

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

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

Shielded Bellows (Total Number: ~36)

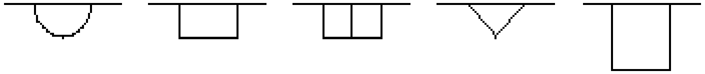
Negligible due to Shielding

Amplitudes negligibly small.

See LCLS Design Study Report

Vacuum Chamber Surface Roughness

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

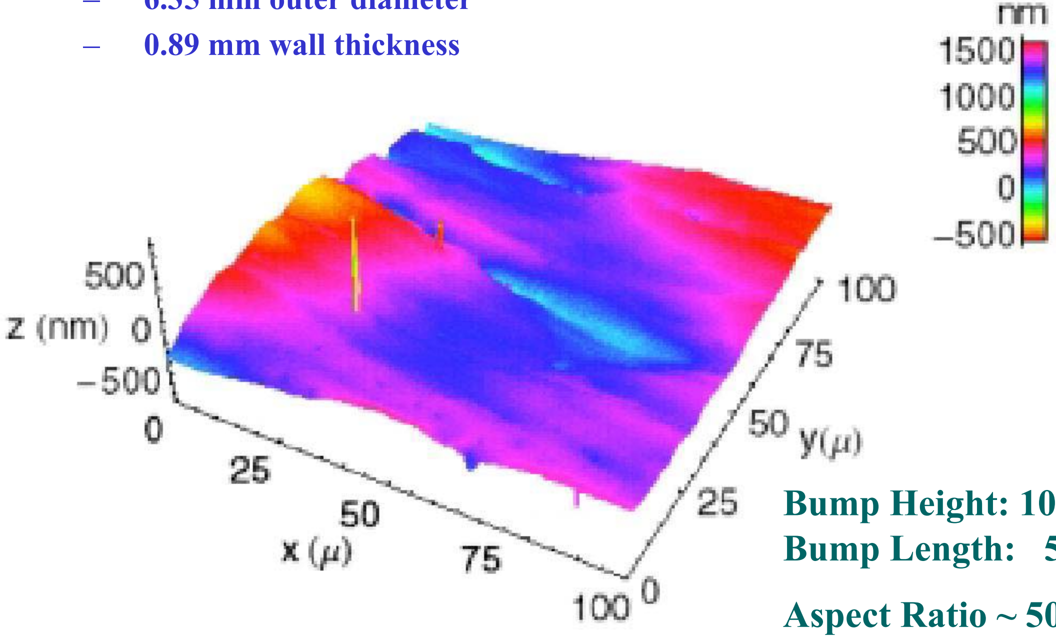


=> Large Wakefield Amplitudes

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**



Bump Height: 100 nm
Bump Length: 50 µm

Aspect Ratio ~ 500 / 1

=> 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)

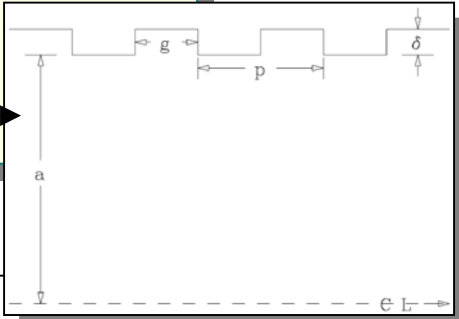
$$W_z(s) = cZ_0e^2 \frac{h_0^2\,\kappa^{3/2}}{a} \frac{1}{2\sqrt{\pi}} \frac{\partial}{\partial s} \frac{1}{\sqrt{s}} \left[\cos\left(\frac{\kappa s}{2}\right) + \sin\left(\frac{\kappa s}{2}\right) \right]$$

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

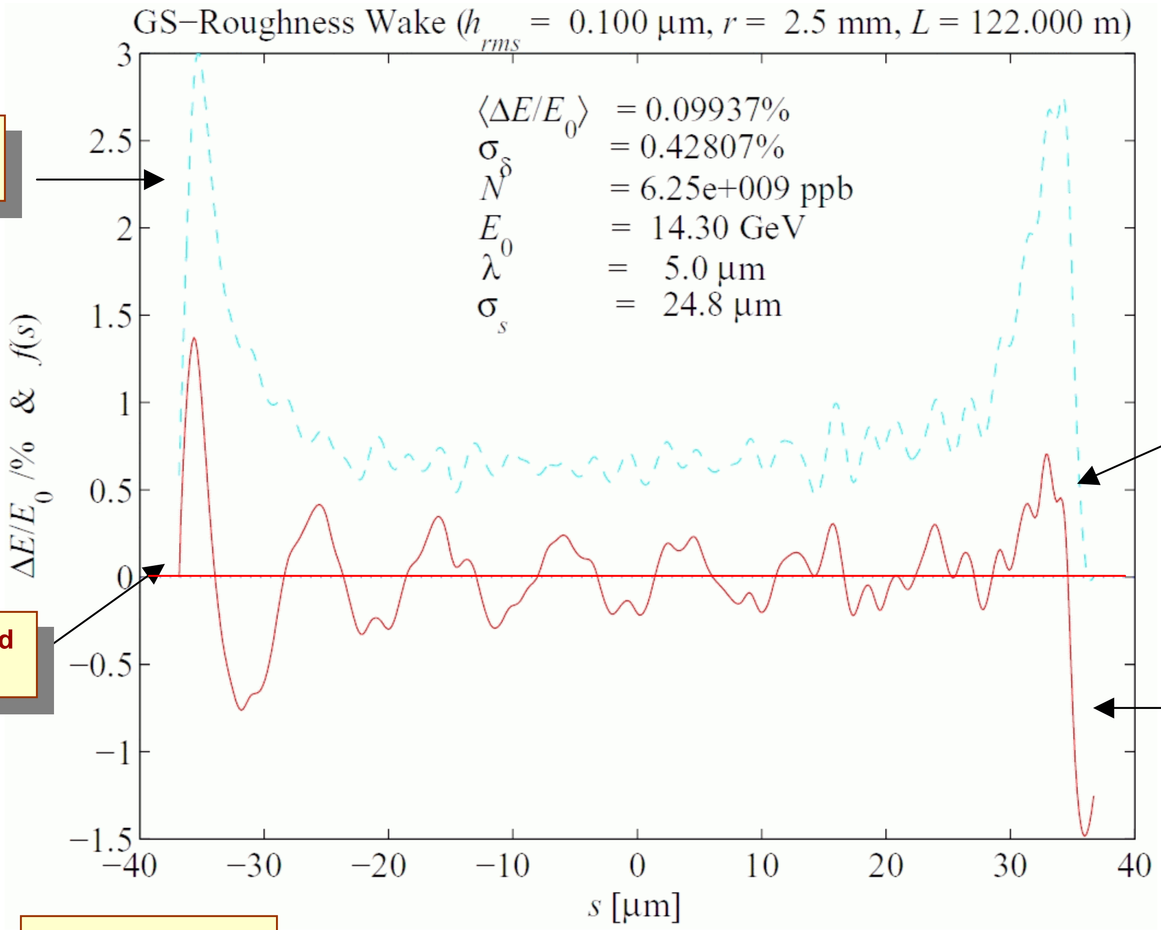
$$W_z(s) = -\frac{cZ_0e^2}{\pi a^2} \cos(k_0 s)$$

Negligible for aspect ratios > 1 / 1 !

$W_z(\mathrm{s})$	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



Electron Distribution from Linac Simulations

Wall Roughness Wakefield 5 μm Bump Length

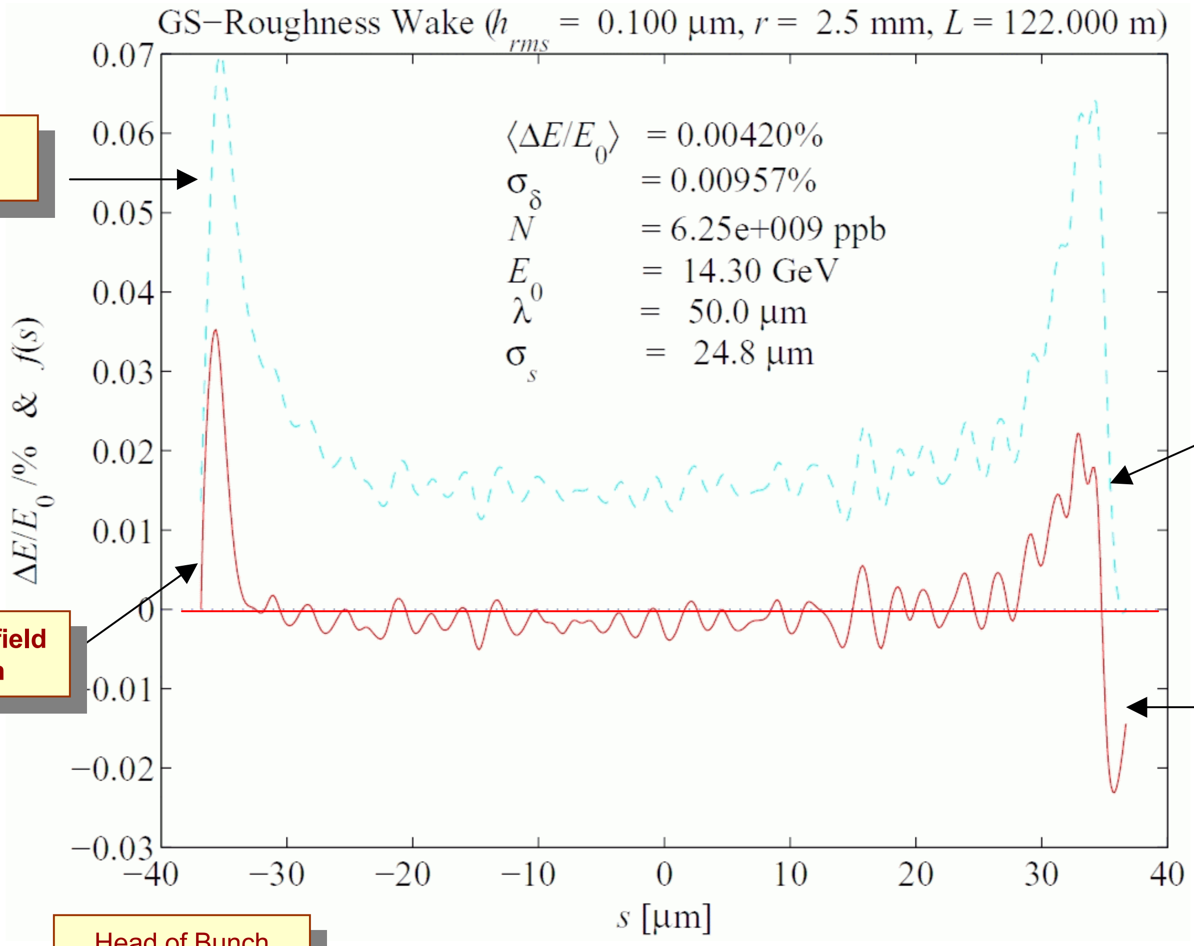
Head of Bunch

Energy Gain

Energy Loss

Courtesy of P. Emma, SLAC

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



Electron Distribution from Linac Simulations

Wall Roughness Wakefield 50 µm Bump Length

Head of Bunch

Energy Gain

Energy Loss

Courtesy of P. Emma, SLAC

December 10, 2001

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Resistive Wall Wakefield for Short Bunches

Ultra-Relativistic Approximation

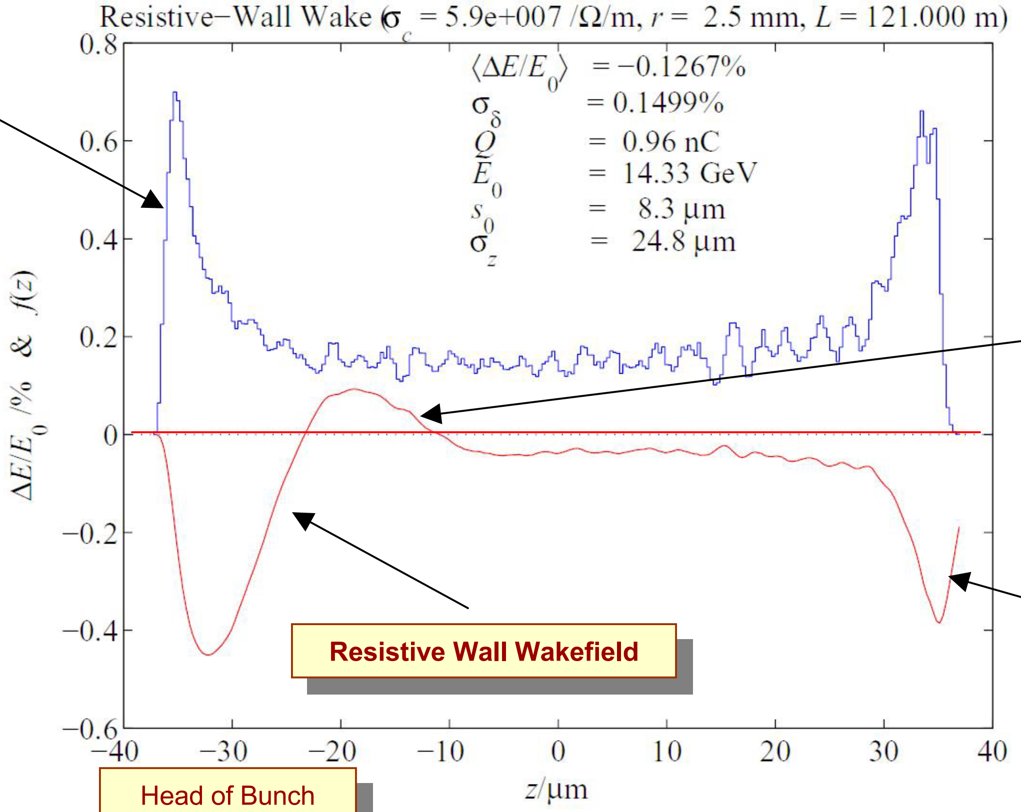
$E_z(s) = -\frac{4ceZ_0}{\pi a^2}\left(\frac{1}{3}\mathrm{e}^{-s/s_0}\cos(\sqrt{3}s/s_0) - \frac{\sqrt{2}}{\pi}\int_0^\infty \frac{x^2}{x^6+8}\mathrm{e}^{-sx^2/s_0}\,dx\right)$	$z > 0$
$E_z(s) = 0$	$z < 0$

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

for LCLS Parameters, i.e.,
a = 2.5 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 × 10^7 Ω^{-1}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

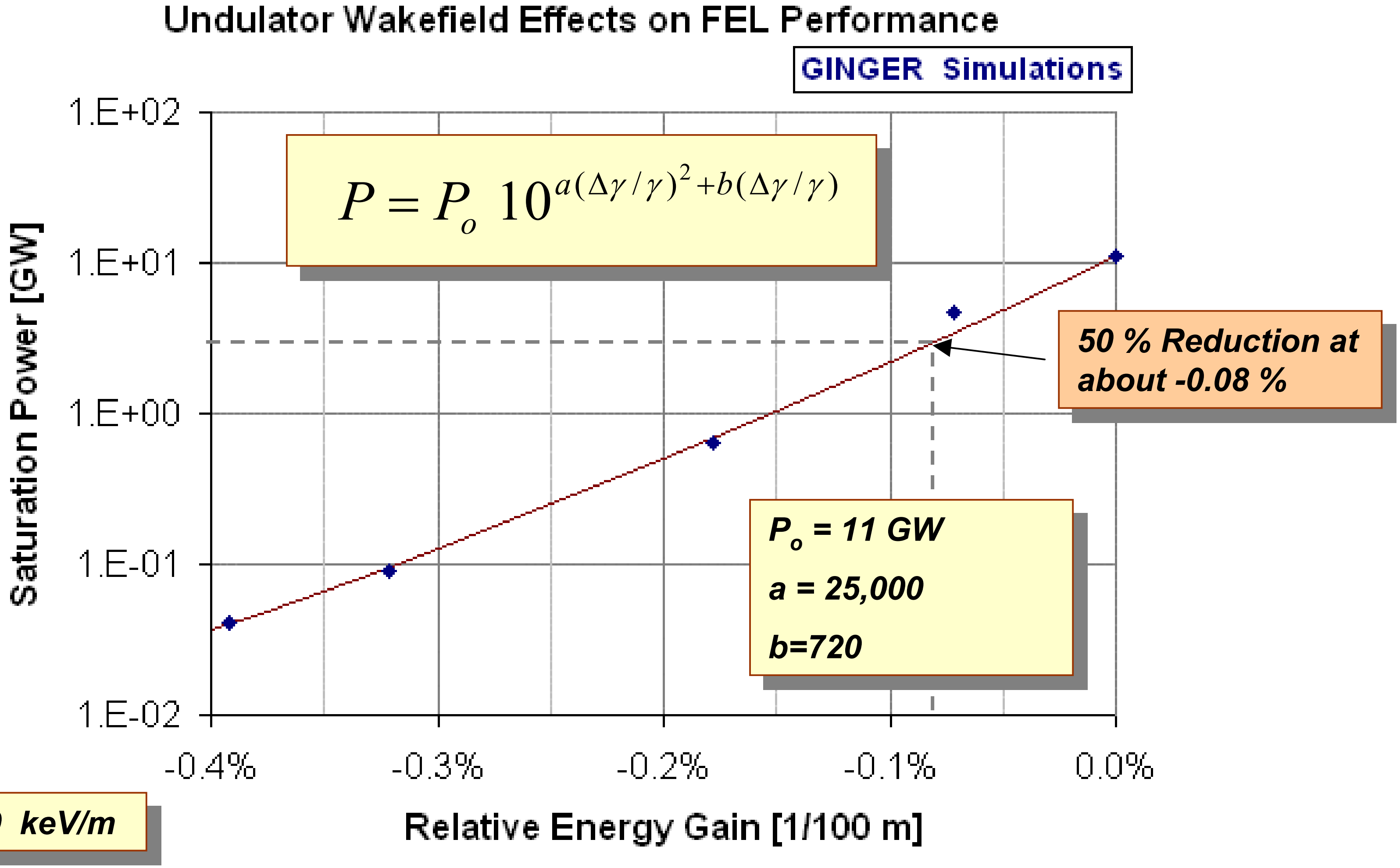
Energy Loss

Courtesy of P. Emma, SLAC

Undulator Wakefield Simulations

Continuous Change in Average Slice Energy along Undulator

1.5 Å



$$P = P_o\ 10^{a(\Delta\gamma/\gamma)^2 + b(\Delta\gamma/\gamma)}$$

50 % Reduction at about -0.08 %

P_o = 11 GW

a = 25,000

b=720

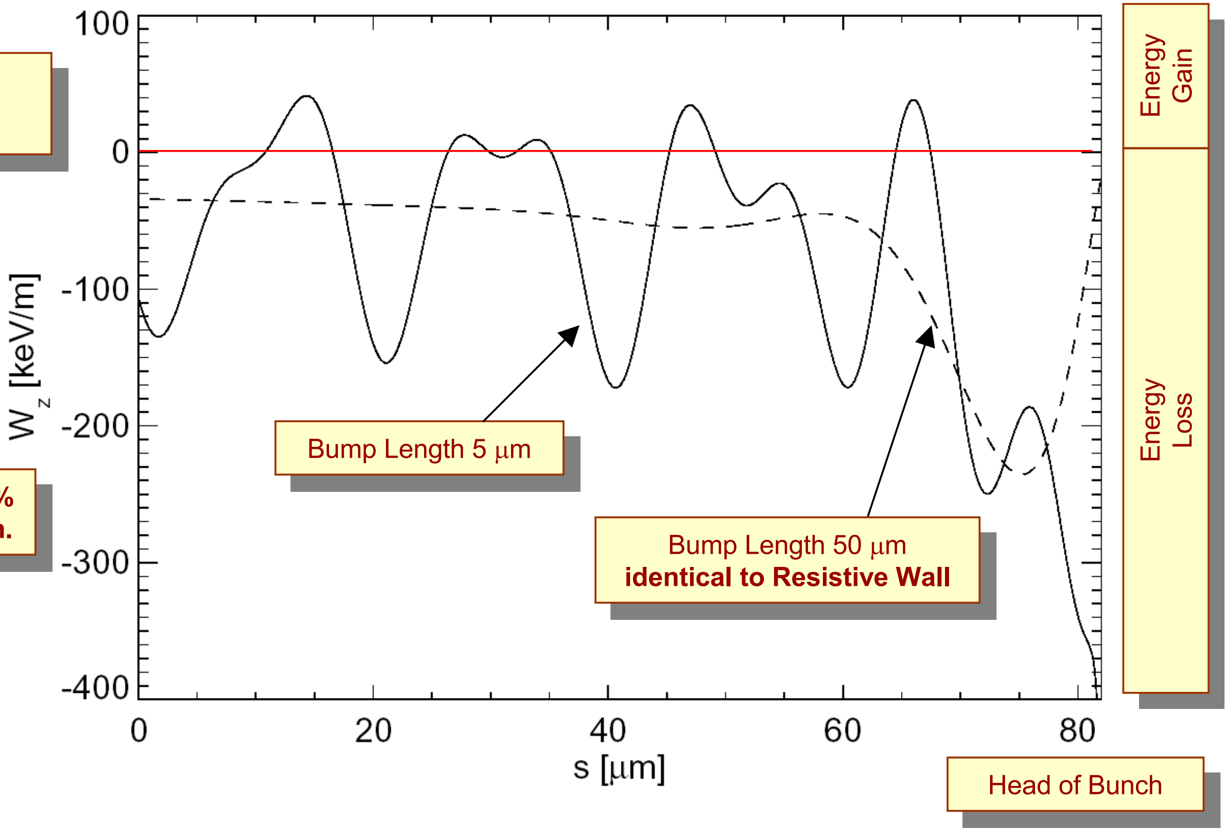
0.4 % ⇒ 570 keV/m

Wakefields used in FEL Simulations

Flat-Top Electron Distribution

Amplifier Mode

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



Bump Length 5 µm

Bump Length 50 µm
identical to Resistive Wall

Head of Bunch

- **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

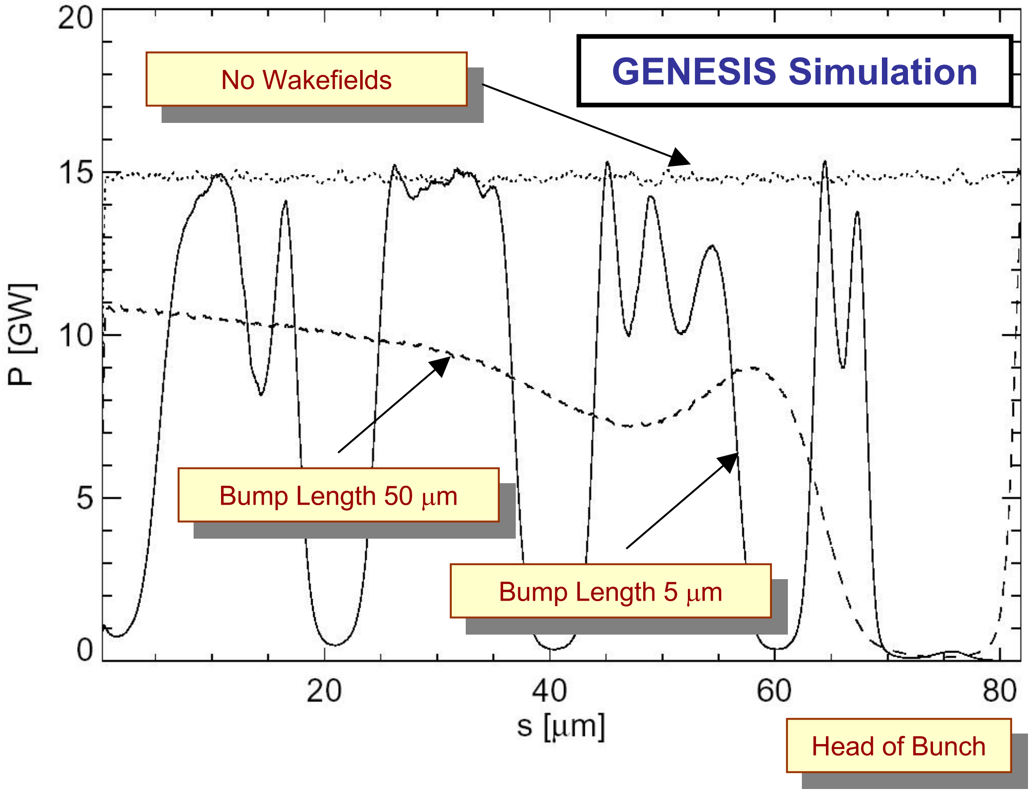
Amplifier Mode

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.


GENESIS Simulation

No Wakefields

Bump Length 50 μm

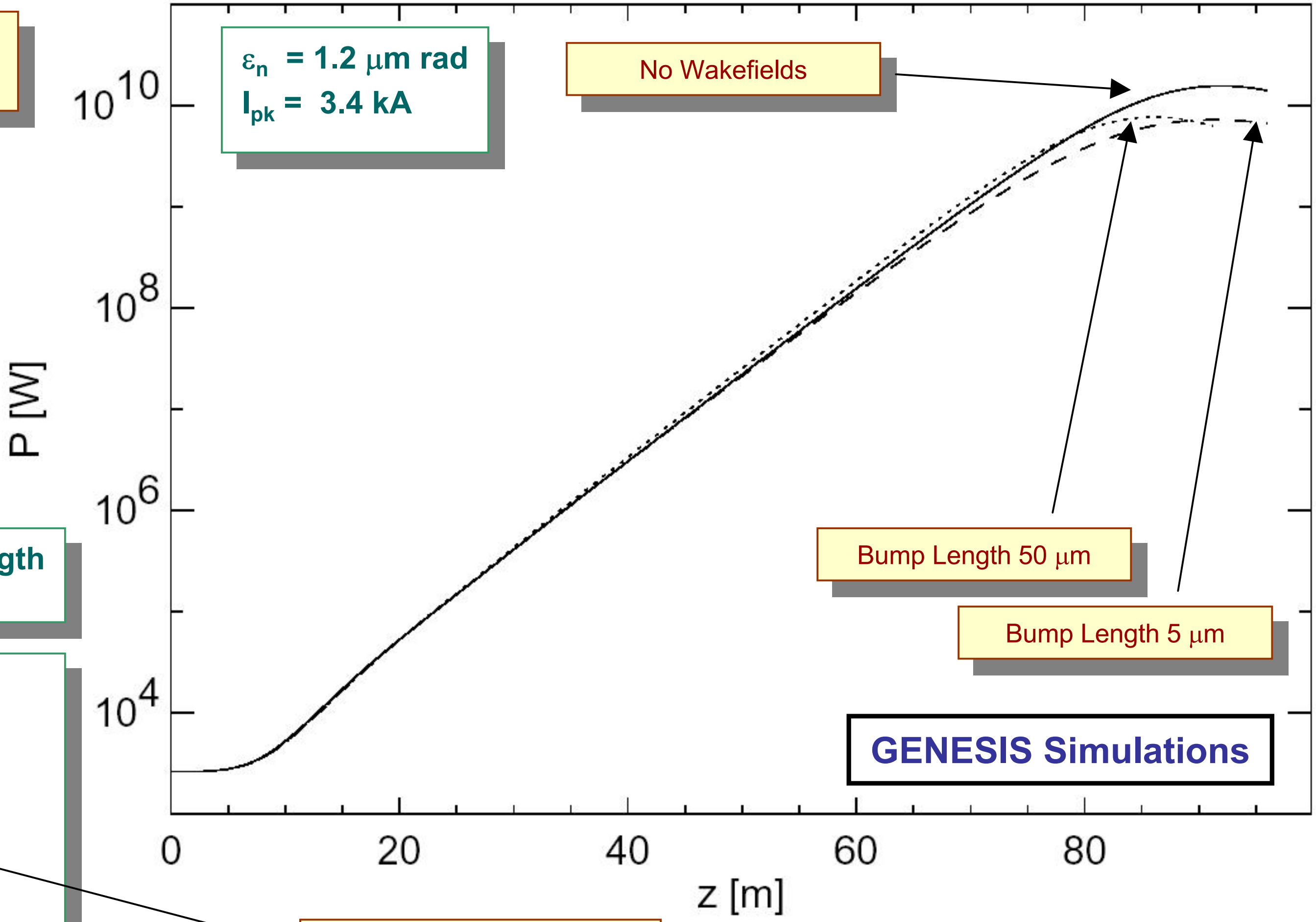
Bump Length 5 μm

Head of Bunch

Courtesy of S. Reiche, UCLA

Wakefield Effects on LCLS Performance

Flat-Top Electron Distribution
Amplifier Mode



ε_n = 1.2 μm rad
I_{pk} = 3.4 kA

No Wakefields

Bump Length 50 μm

Bump Length 5 μm

GENESIS Simulations

LCLS Goal Power Level

Power vs. undulator length for the LCLS case

Saturation length ~ 92 m

Saturation power levels:
15 GW
8 GW
7 GW

Courtesy of S. Reiche, UCLA

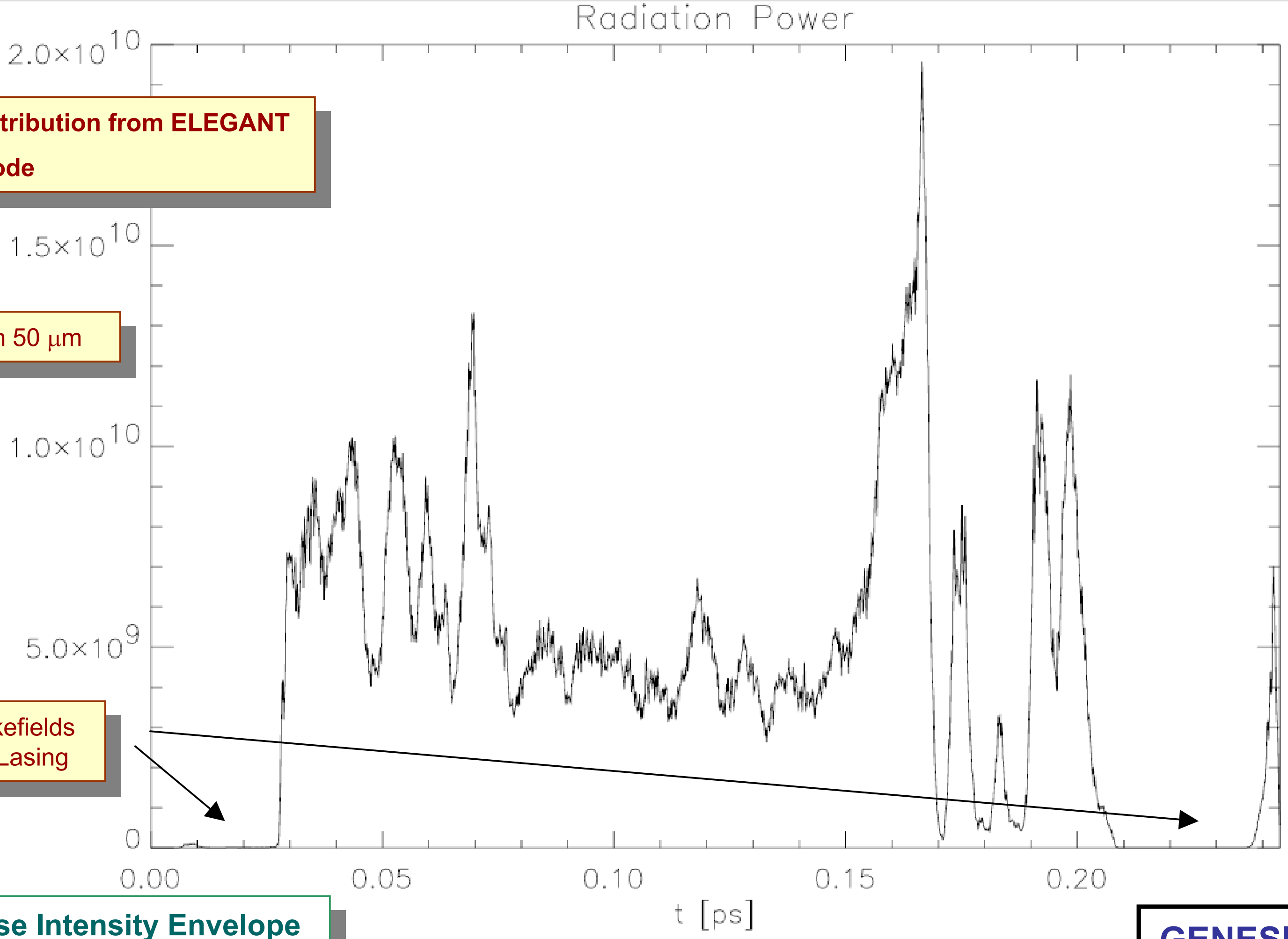
Wakefield Effects on LCLS Performance A

ε_n = 1.2 μm rad
I_{pk} = 3.4 kA

Electron Distribution from ELEGANT
Amplifier Mode

Bump Length 50 μm

High Wakefields supress Lasing



X-Ray Pulse Intensity Envelope

GENESIS Simulations

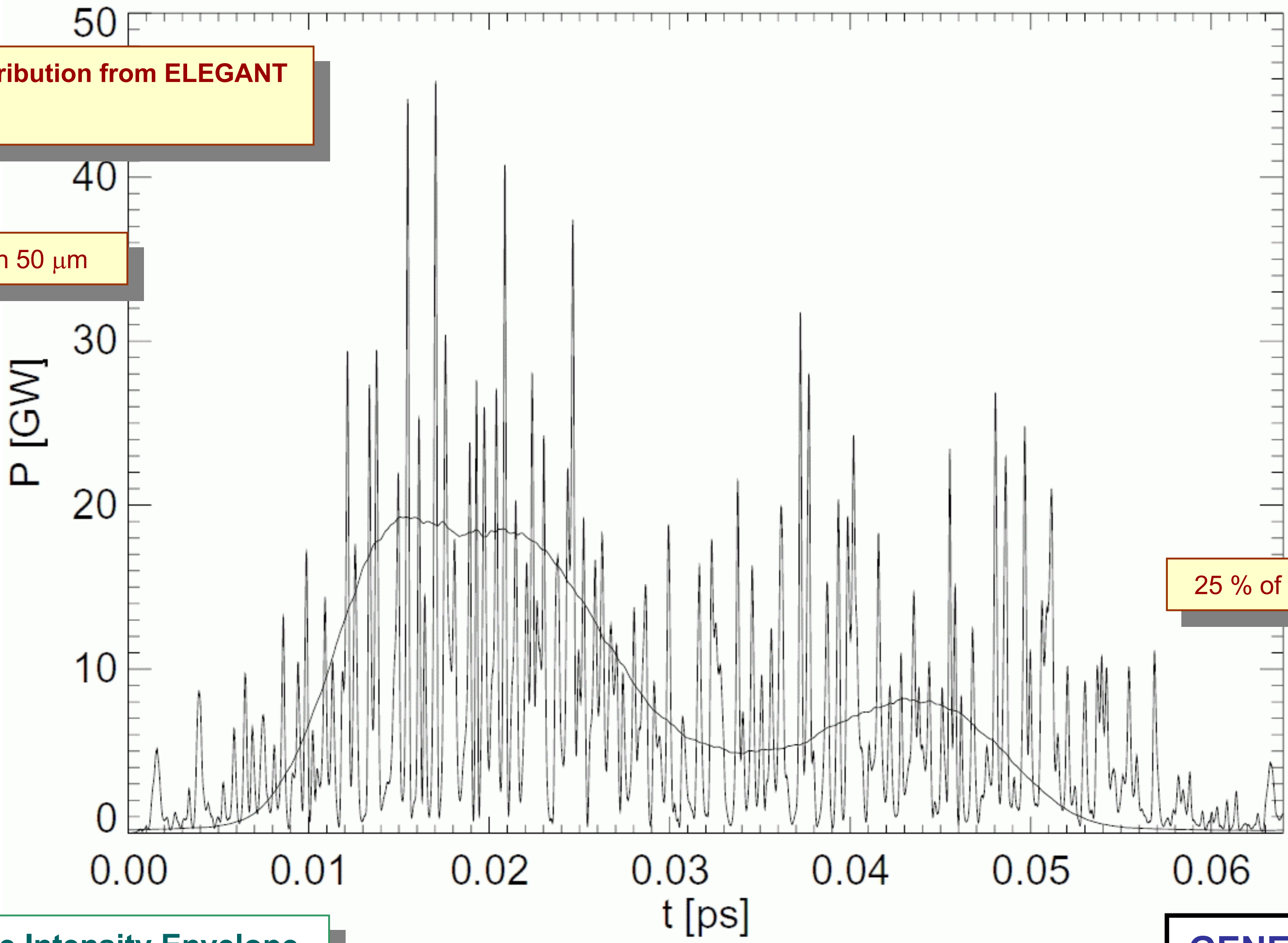
Courtesy of S. Reiche, UCLA

Wakefield Effects in SASE Simulations

Electron Distribution from ELEGANT
SASE Mode

Bump Length 50 μm

ε_n = 1.2 μm rad
I_{pk} = 3.4 kA



25 % of Total LCLS Pulse Length

X-Ray Pulse Intensity Envelope

GENESIS Simulations

Courtesy of S. Reiche, UCLA

Wakefield Effects on Electron Beam Slices

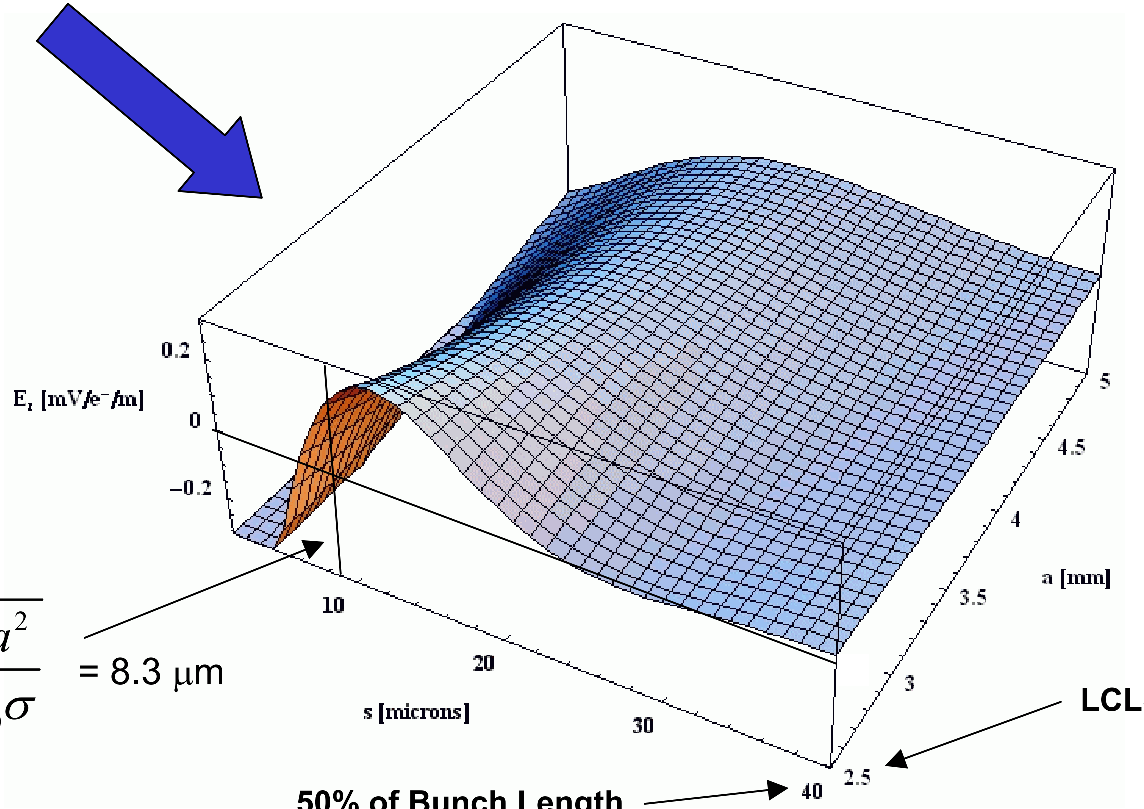
- *Reduction of Total Pulse Power by about 50%*
  7-8 GW instead of 15 GW
- *Added Temporal Structure in x-ray intensity (Shorter Pulses)*
- *Practically no Change in Saturation Length*
- *Radiation Bandwidth increase small (< 30% for unchirped beam)*
- *Small Decrease in Brightness*

PRESENT LCLS POSITION

Wakefield Effects do not degrade performance below the design goal.

Resistive Wall Wakefield Sensitivity to Pipe Radius

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

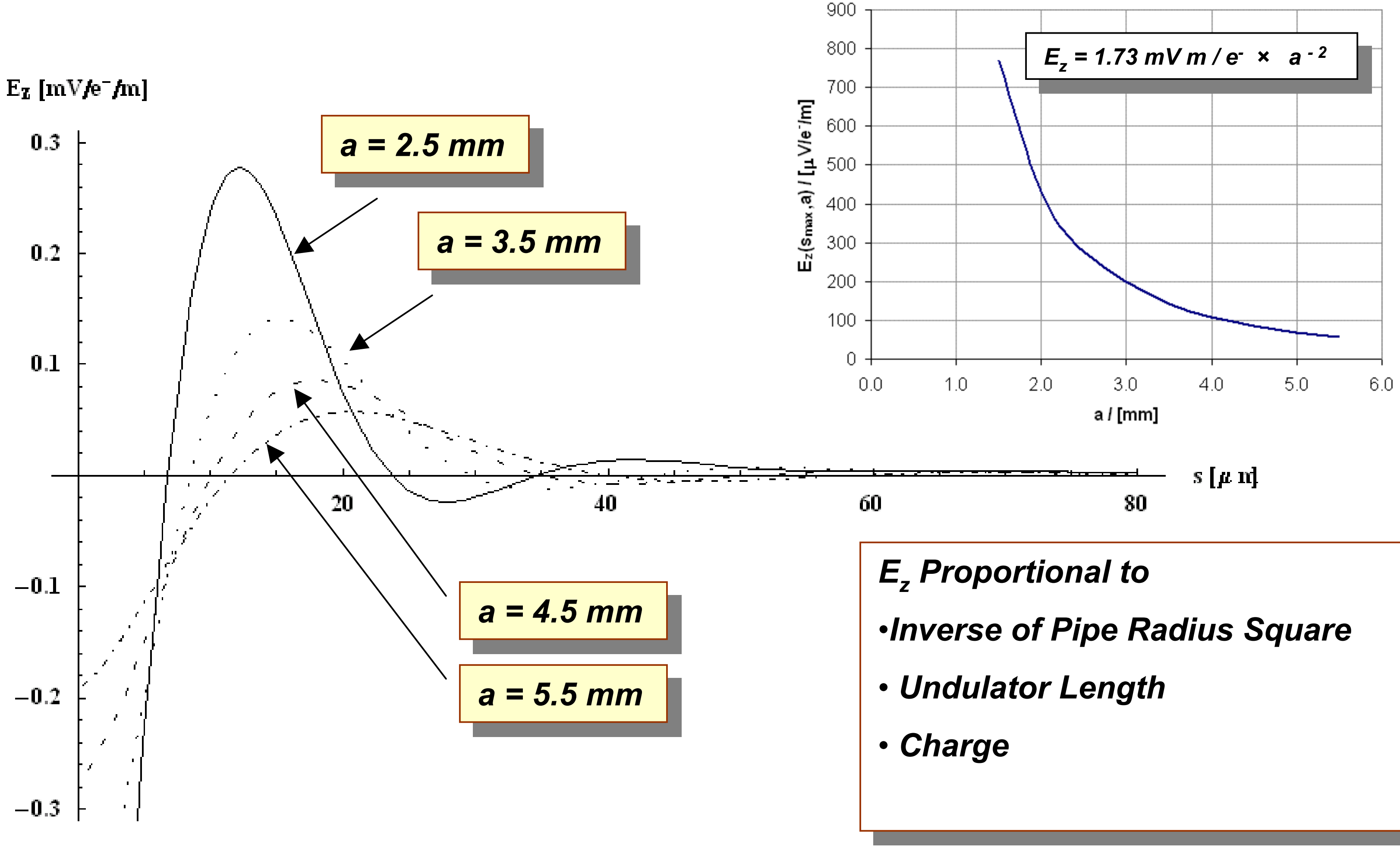


$$s_0 = \sqrt[3]{\frac{2a^2}{Z_0\sigma}}$$ = 8.3 µm

LCLS Undulator Chamber Radius

50% of Bunch Length

Resistive Wall Wakefield Scaling

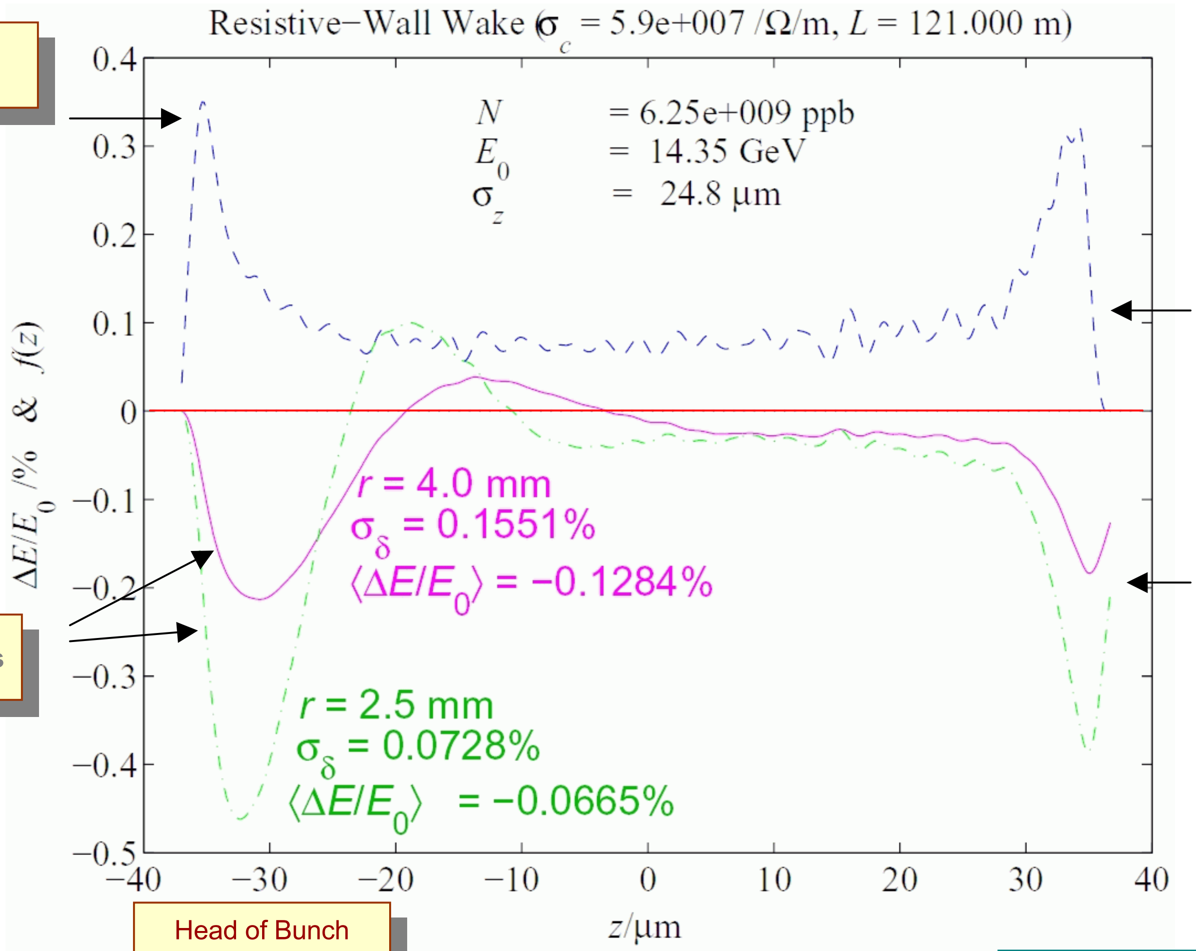


E_z Proportional to

- ***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



Energy Gain

Energy Loss

Reduction less than quadratic

Reduction less

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.

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Undulator Chamber Wakefields

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