# Wakefield effects in XFEL undulator

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Beam Dynamics Group Meeting

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# SASE 1-2 parameters

| name | symbol | unit | value |
|---|---|---|---|
| energy | $E$ | GeV | 20 |
| energy spread | $\Delta E$ | MeV | 2.5 |
| emmitance | $\varepsilon_n$ | $\pi$ mm-mrad | 1.4 |
| bunch charge | $Q$ | nC | 1 |
| bunch length | $\sigma$ | $\mu$m | 25 |
| peak current | $I_P$ | kA | 4.76 |
| undulator period | $\lambda_u$ | cm | 4.8 |
| undulator parameter | $a_u$ | | 2.33 |
| quadrupole length | $L_Q$ | cm | 20 |
| quadrupole gradient | $G_Q$ | T/m | 19.5 |
| section length | $L_u$ | m | 5 |
| beta function (waist) | $\beta_{x,}$<br>$\beta_{y,}$ | m | 42.5<br>29.3 |

Parameters (XFEL theory)

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + a_u^2\right) = 0.10072\,[\mathrm{nm}]$$

$$\sigma_{x,y} = \sqrt{\frac{\varepsilon_n}{\gamma}\beta_{x,y}} = \begin{pmatrix} 39 \\ 32.4 \end{pmatrix}[\mu m]$$

$$\sigma_r = 0.5(\sigma_x + \sigma_y) = 35.7\,[\mu m]$$

$$z_R = \frac{\pi w_0^2}{\lambda_s} = \frac{2\pi\sigma_r^2}{\lambda_s} = 79.5\,[m]$$

## Parameters (XFEL theory)

### Gain parameter

$$\Gamma_3 = \left[ \left( \frac{A_{JJ}\omega_s\theta_l}{c\gamma_l} \right)^2 \frac{I_P}{2\gamma I_A} \right]^{1/2} = 0.48\,[cm] \qquad \Gamma_1 = \Gamma_3 B^{-1/3} = 0.14\,[cm]$$

### Efficiency parameter

$$\rho_3 = \frac{c\gamma_l^2\Gamma_3}{\omega} = 18.5\text{e-4} \qquad \rho_1 = \frac{c\gamma_l^2\Gamma_1}{\omega} = 5.5\text{e-4}$$

### Diffraction parameter

$$B = \Gamma_3\sigma_r^2\frac{\omega_s}{c} = 38$$

Effective power of the input signal

$$P_{sh} = 3\rho_1 \frac{W_b}{N_c\sqrt{\pi \ln N_c}} = 7864\,[W]$$

Electron beam power

$$W_b = \gamma I_P \frac{mc^2}{e} = 9.56\text{e+13 [W]}$$

Number of cooperating electrons

$$N_c = \frac{N_\lambda}{2\pi\rho_1} = 2.9\text{e+6}$$

Number of electrons per wavelength

$$N_\lambda = \frac{I_P}{ec}\lambda_s = 1.0033\text{e+4}$$

Gain length[*]

$$L_g = L_{g0}(1+\delta) \approx 17.6\,[\mathrm{m}]$$

Optimal beta-function

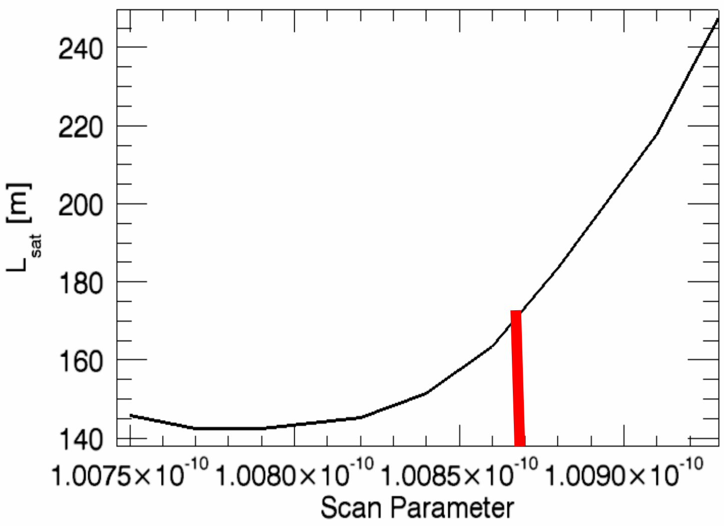
$$\beta_{opt} \approx 37\,[\mathrm{m}]$$

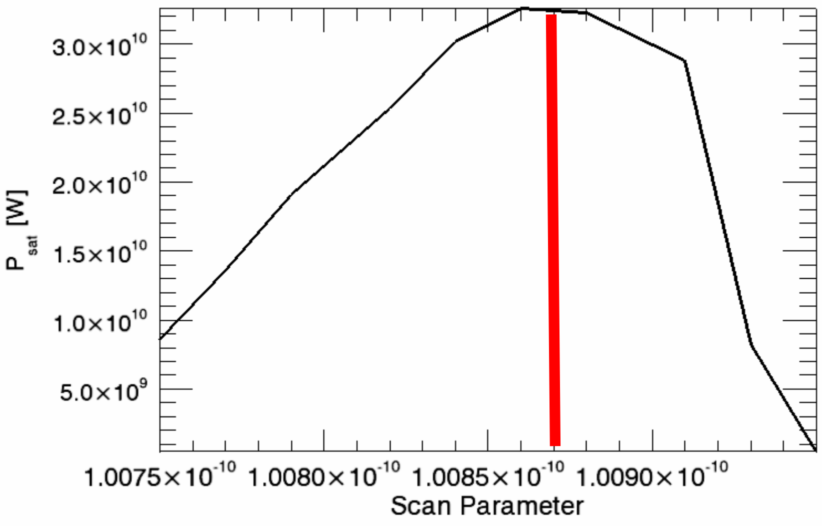
Saturation length

$$L_{sat} \approx 10 L_{g0} = 176\,[\mathrm{m}]$$

[*] E.L.Saldin et al./Optics Communications 235 (2004) 415-420

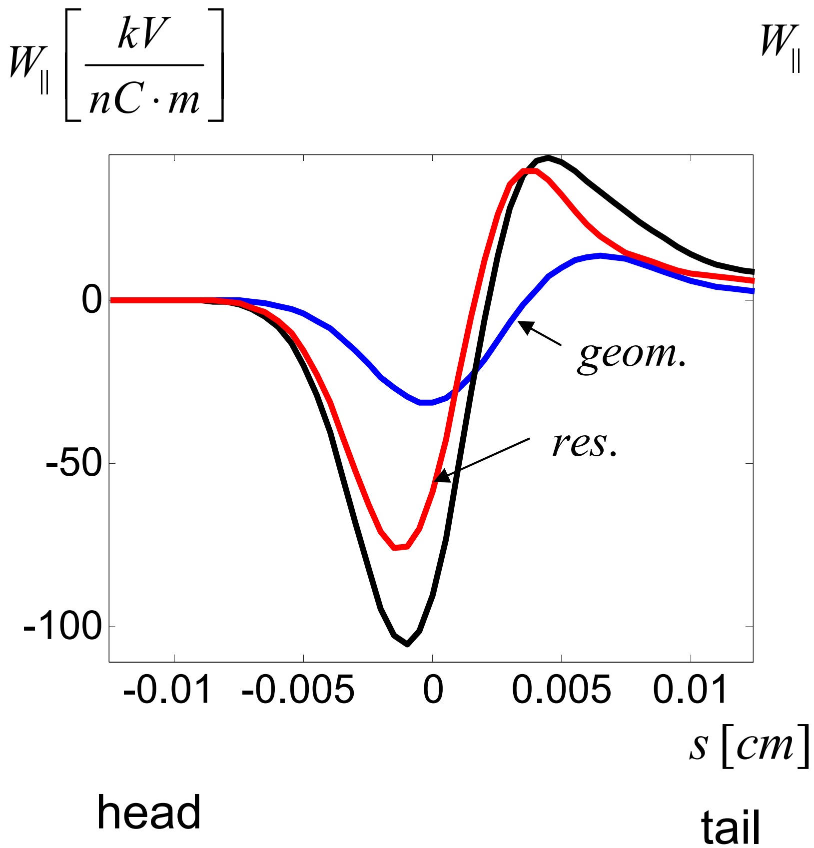
# Genesis steady state simulation

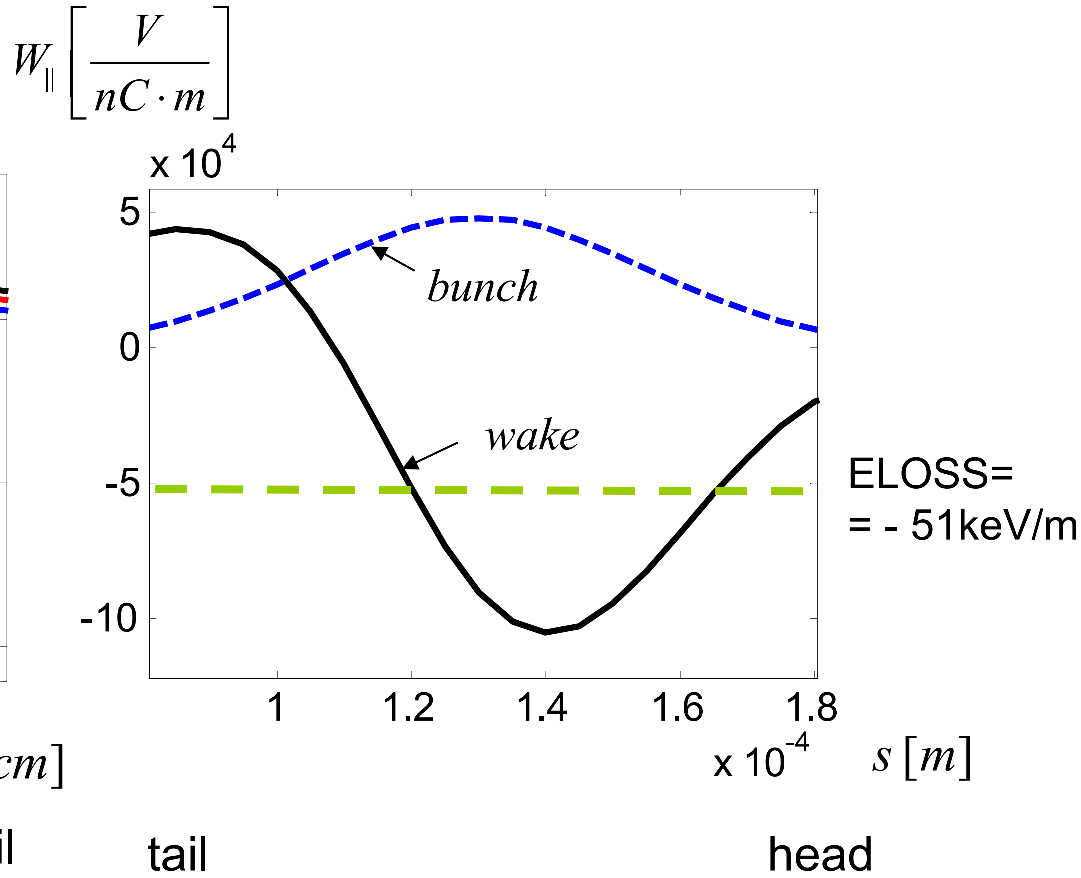



$$\lambda_s^{num} = 0.10087\,[\text{nm}]$$

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + a_u^2\right) = 0.10072\,[\text{nm}]$$

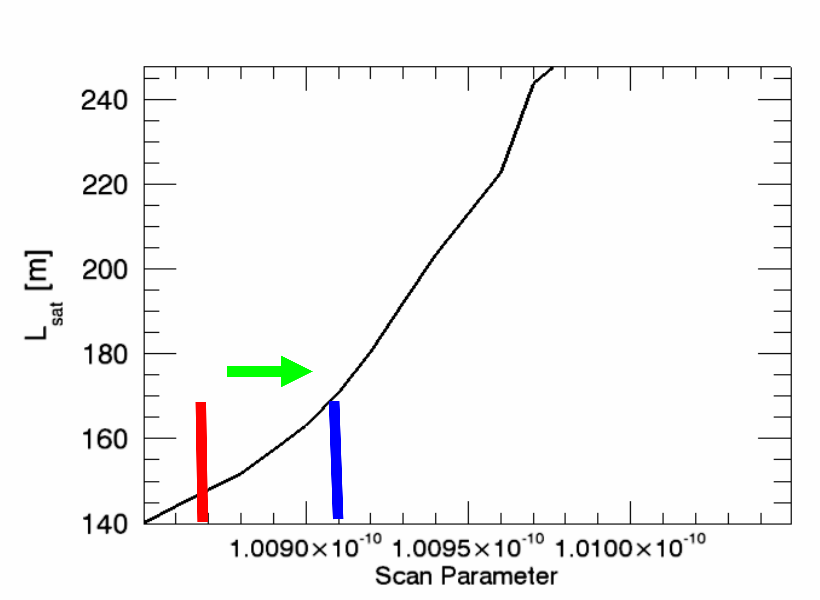


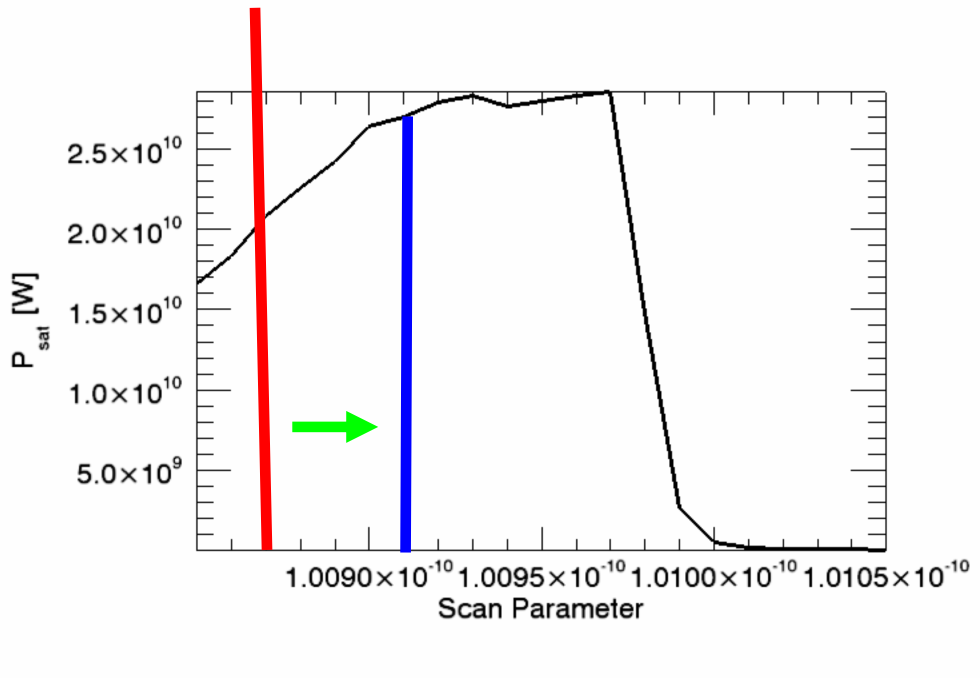




| | Loss, kV/nC/m | Spread, kV/nC/m | Peak, kV/nC/m |
|---|---|---|---|
| geometrical | 20 | 12 | -32 |
| resistive | 31 | 39 | -75 |
| total | **51** | 49 | -105 |

**Genesis steady state simulation**

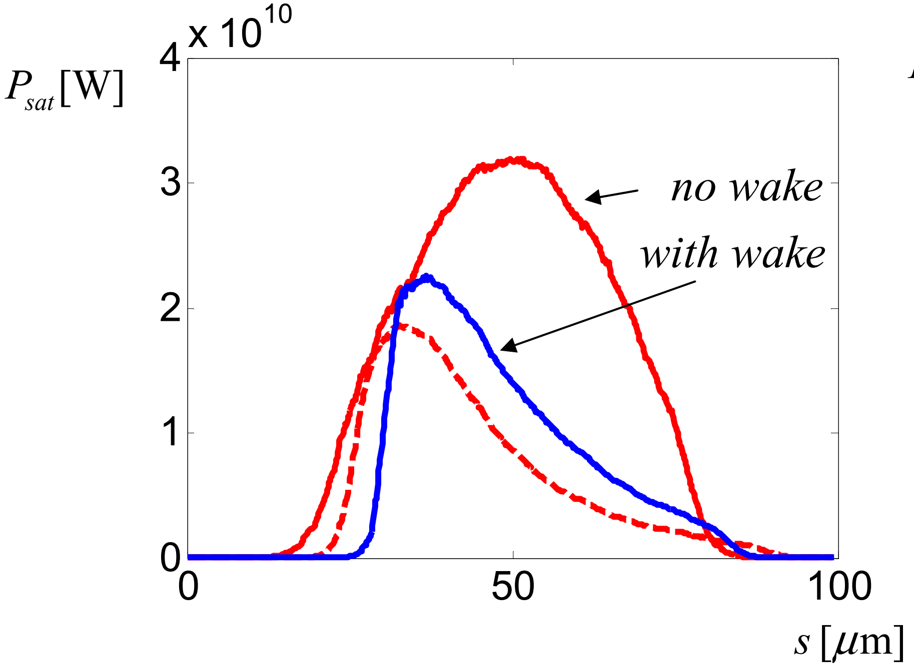
Scan with ELOSS = - 51keV/m

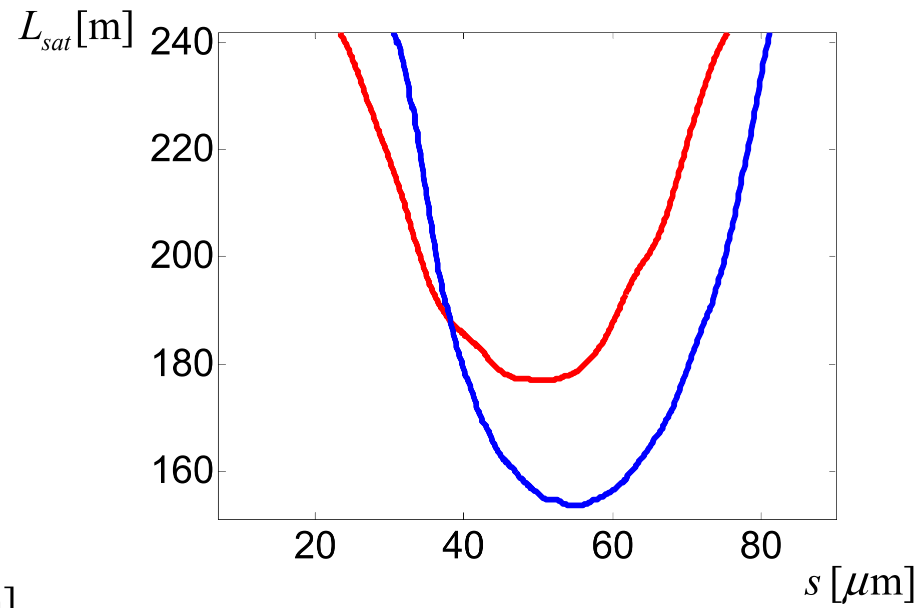


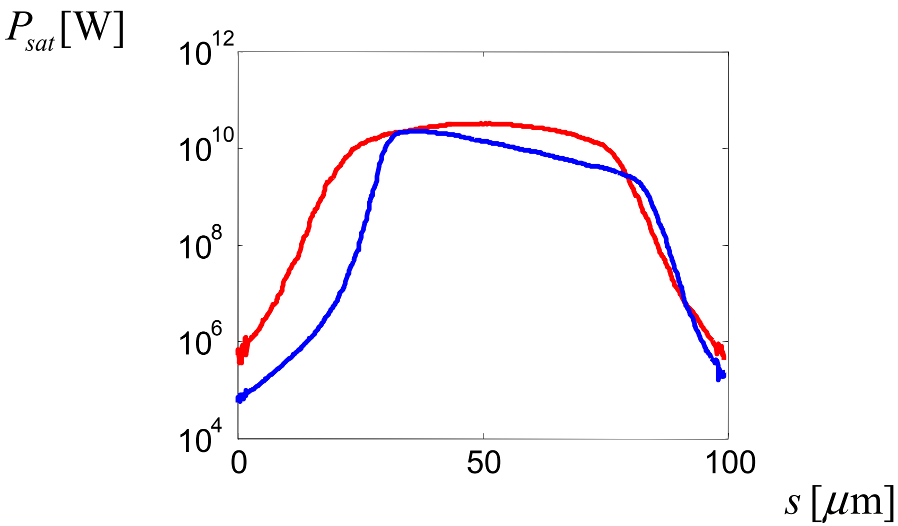



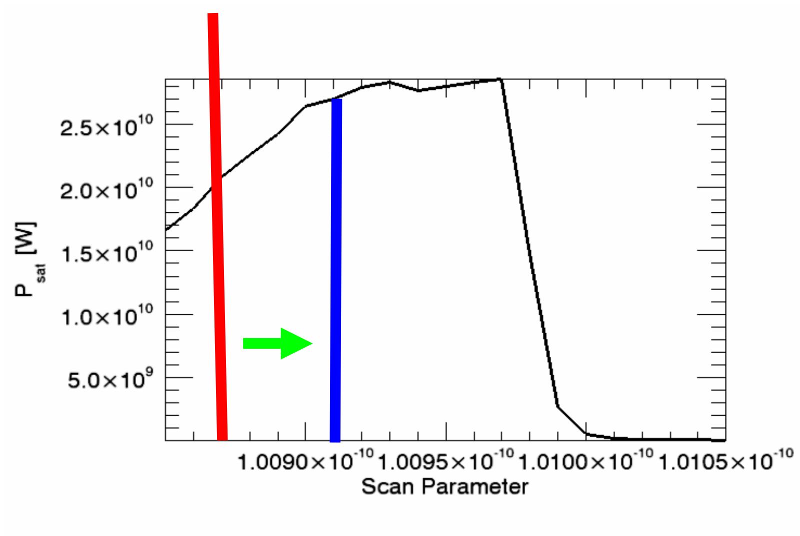

$$\lambda_s^{num} = 0.10087\,[\mathrm{nm}] \quad \rightarrow \quad 0.10091\,[\mathrm{nm}]$$

# Genesis time dependent simulation (amplifier)

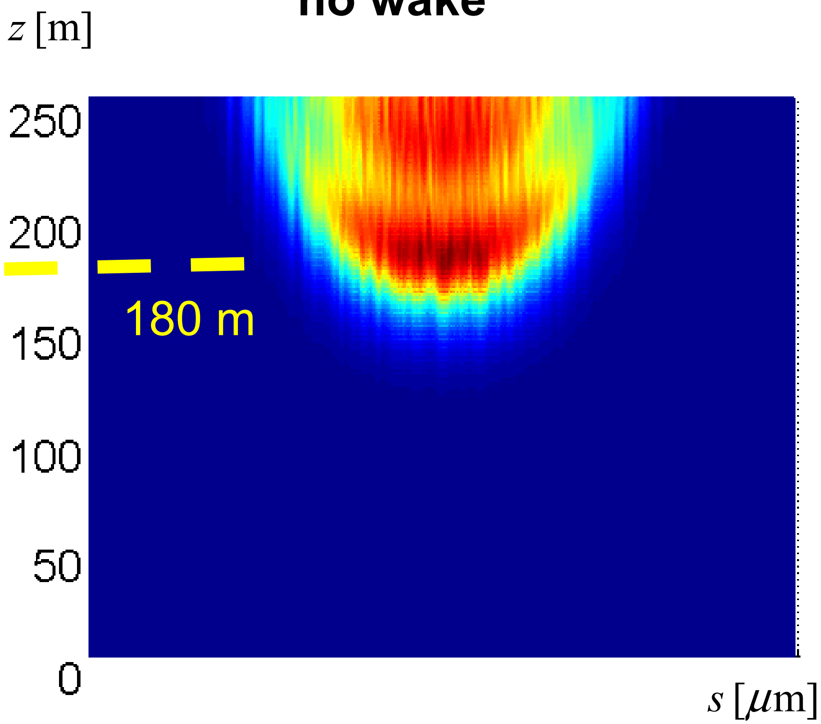


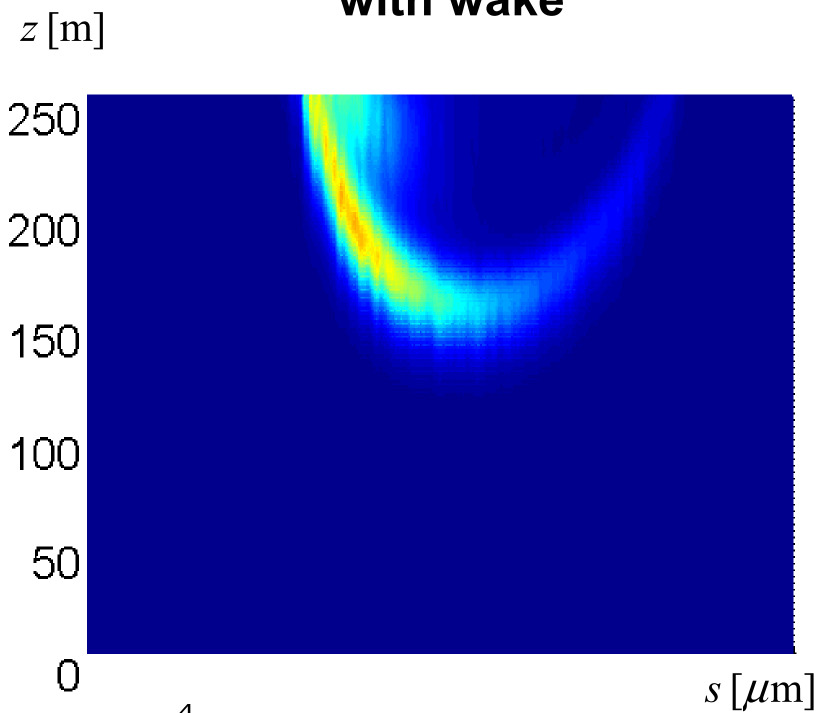



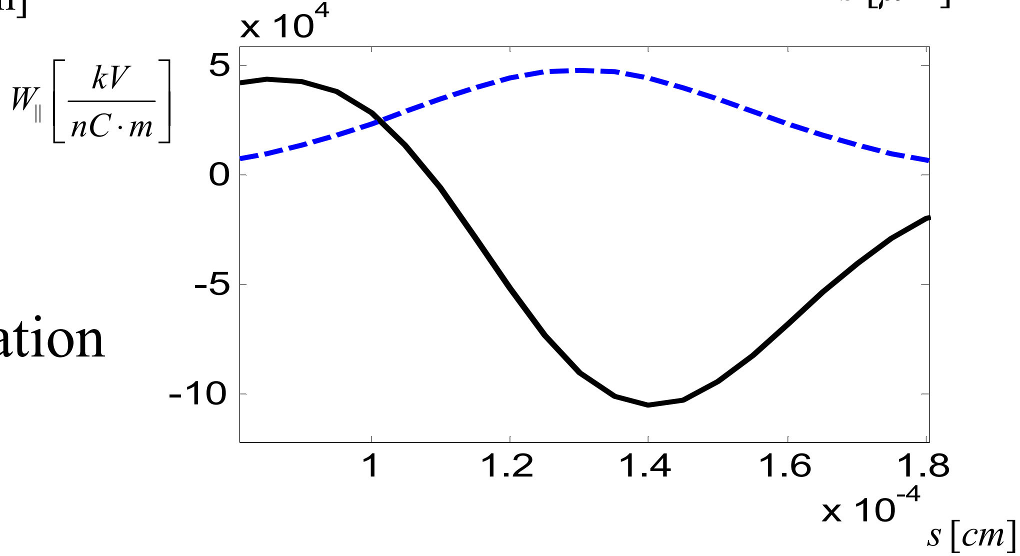



# Power

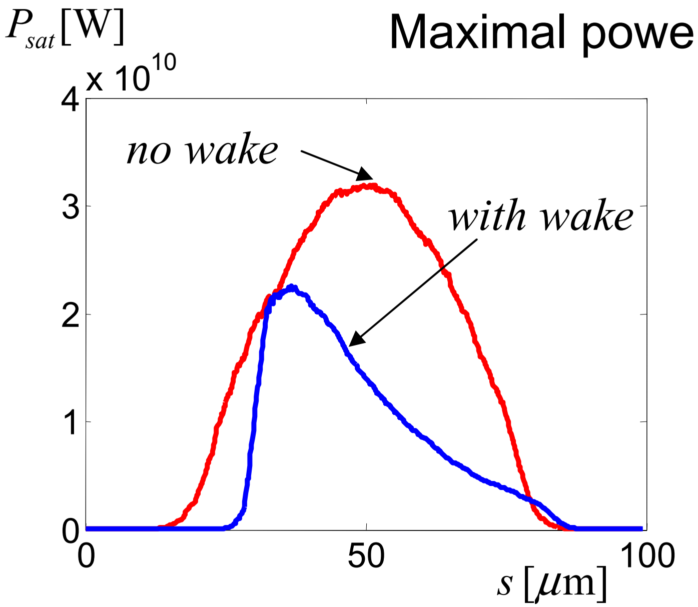


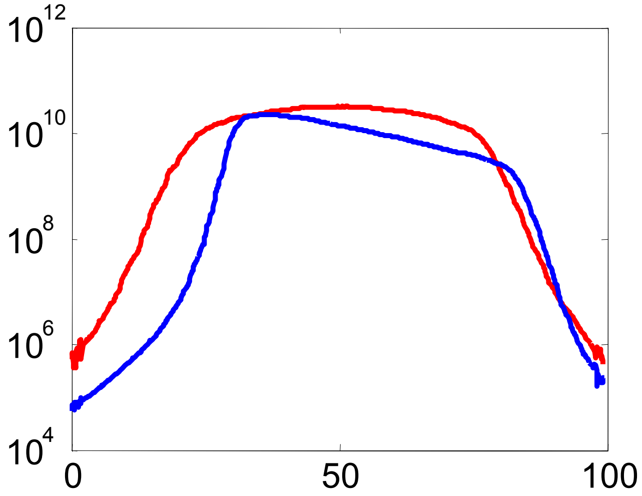



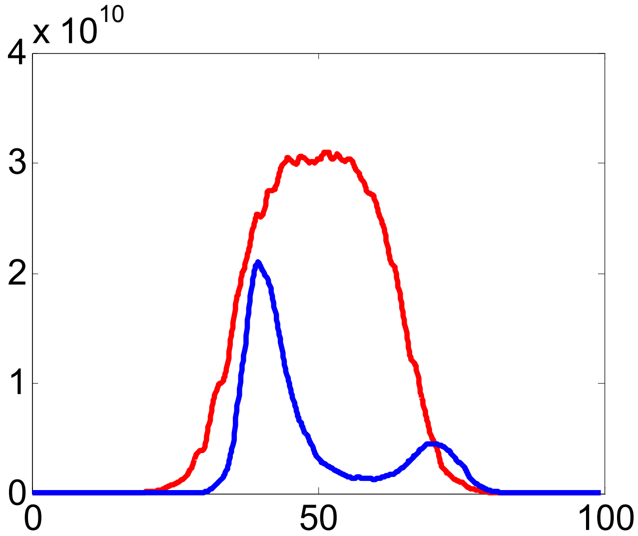

$$d = \frac{\langle P_{total} \rangle}{\langle P_{total}^{wake} \rangle} = 3.3 - \text{power degradation}$$

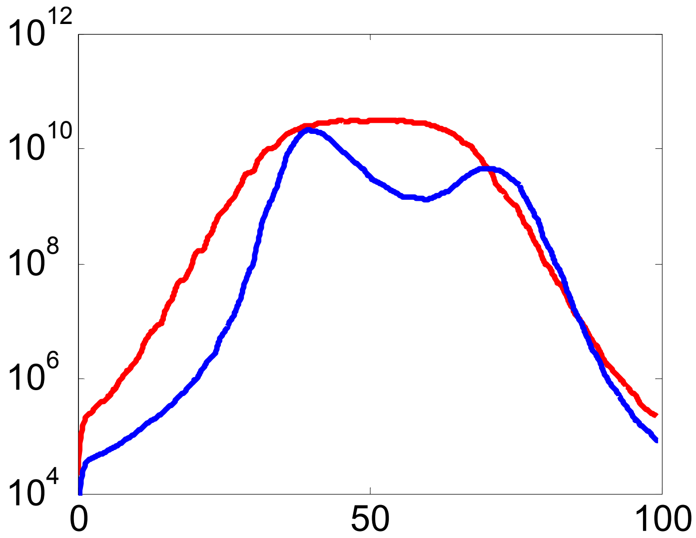
# Maximal power along the undulator up to z = 250 m




$$\frac{\langle P_{sat} \rangle}{\langle P_{sat}^{wake} \rangle} = 2.1$$



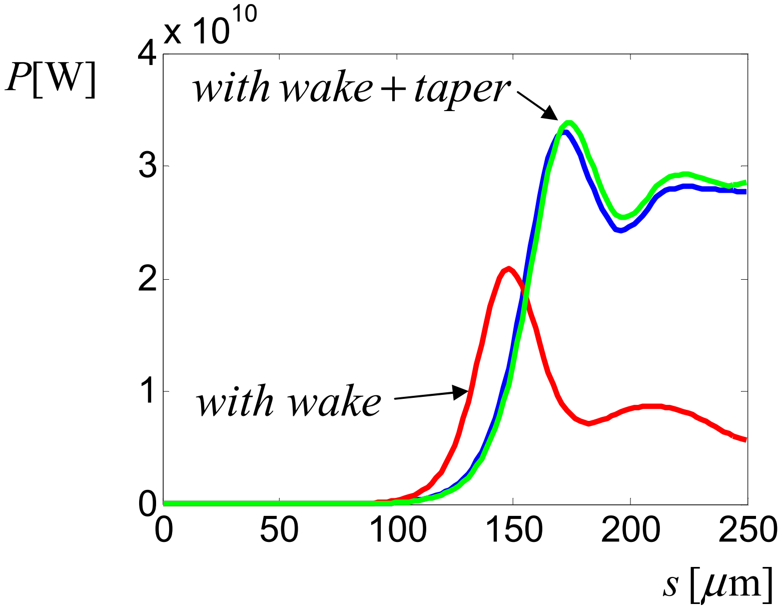



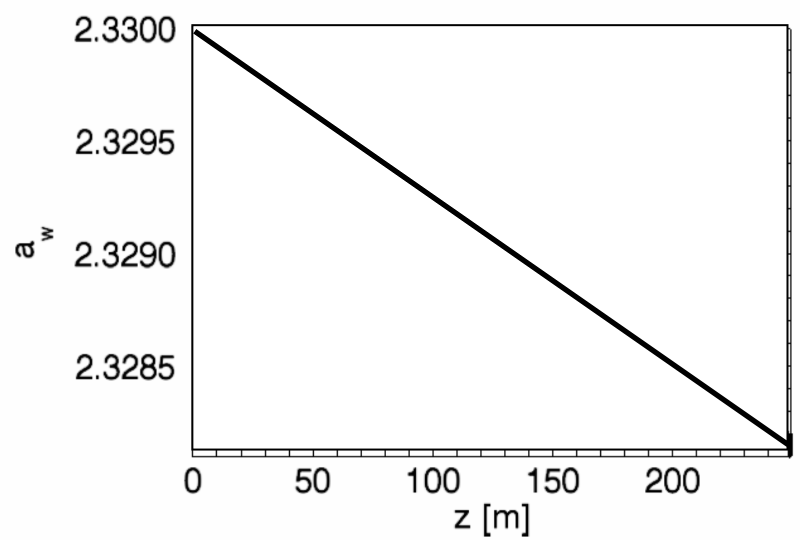

$$\frac{\langle P_{180} \rangle}{\langle P_{180}^{wake} \rangle} = 3.6$$

Power at z = 180 m

# Tapering (steady state)

with ELOSS = - 51keV/m

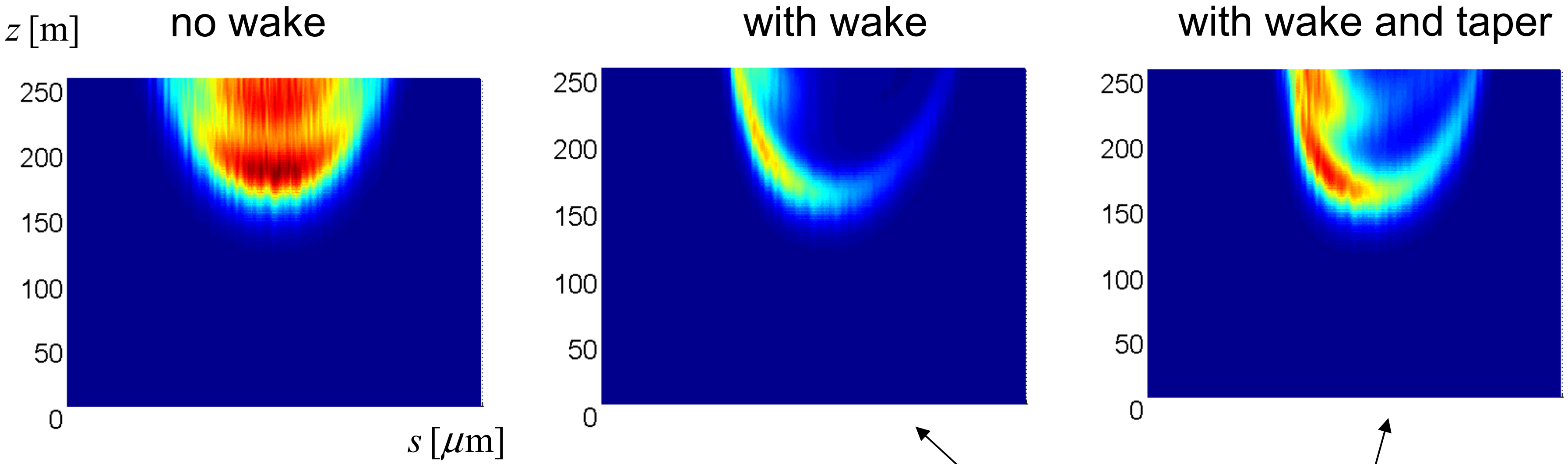


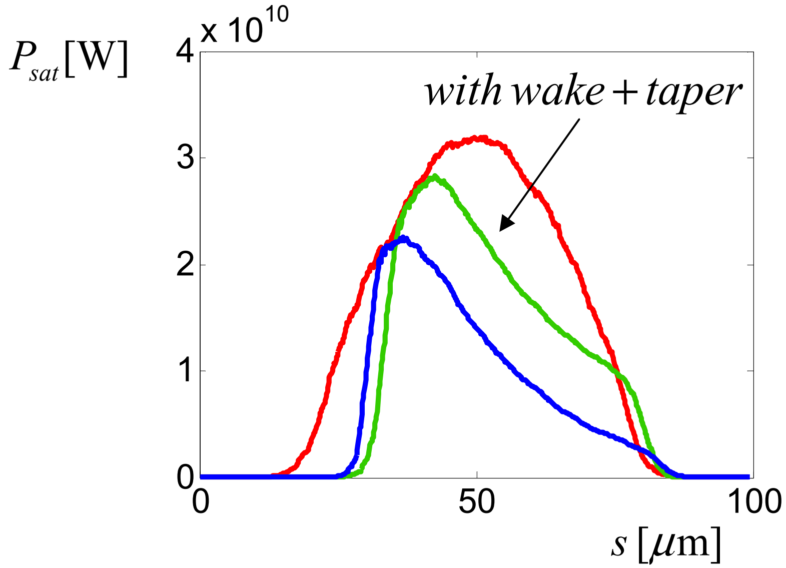




$$\frac{\Delta a_w}{a_w} \approx \frac{\Delta \gamma}{\gamma} = \frac{\Delta E}{E} = \frac{51[keV/m] \cdot 250[m]}{20[GeV]} = 6.375e-4$$

$$\frac{\Delta a_w}{a_w} = 8.0e-4 = 1.5\rho_1$$ → Taper ~ 64 keV/m

# Power with tapering (time-dependent)

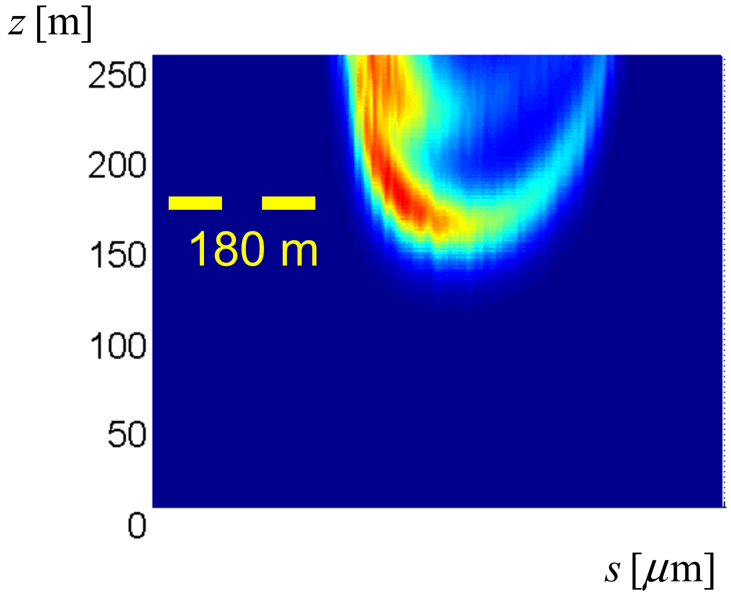


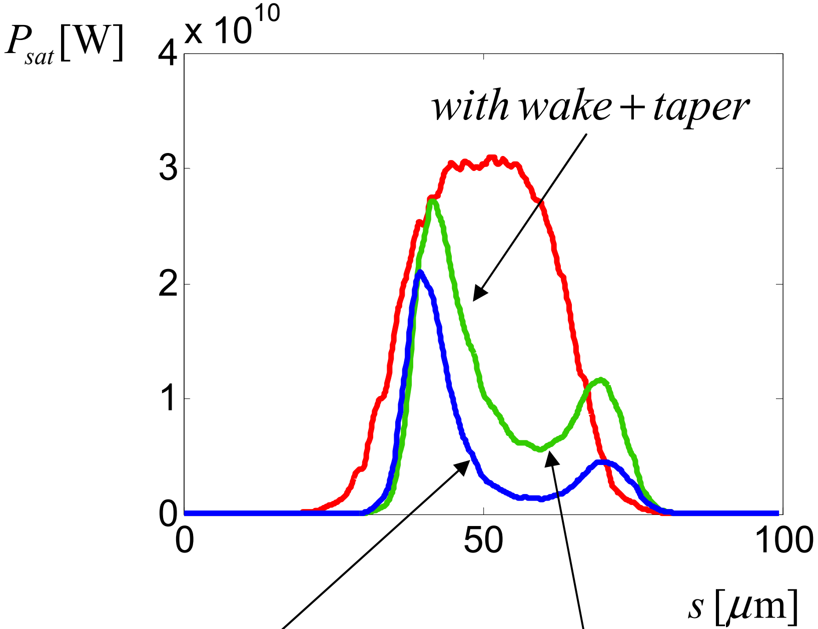




$$\frac{\langle P_{sat} \rangle}{\langle P_{sat}^{wake} \rangle} = 2.1$$

$$\frac{\langle P_{sat} \rangle}{\langle P_{sat}^{wake+taper} \rangle} = 1.5$$

# Tapering



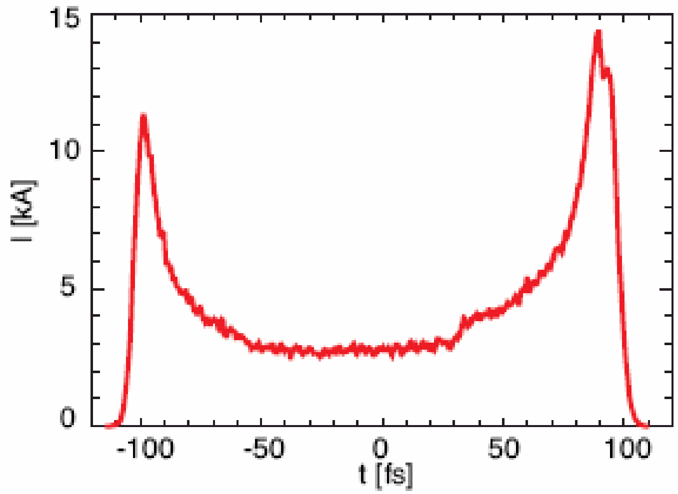

$$\frac{\Delta a_w}{a_w} = 8.0e-4 = 1.5\rho_1$$

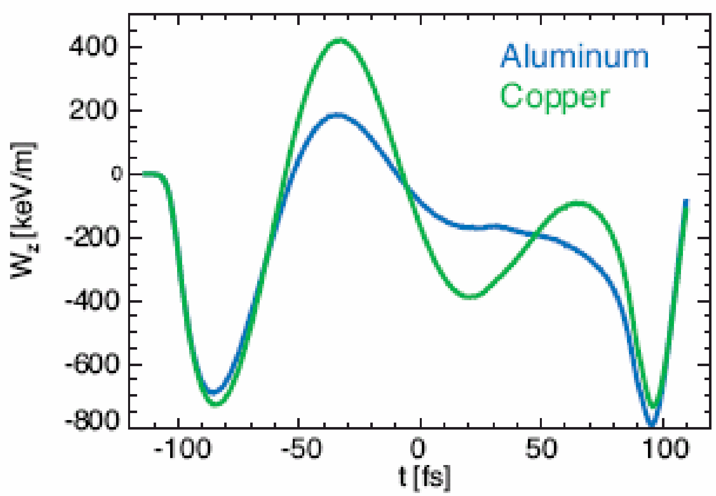
$$\frac{\langle P_{180} \rangle}{\langle P_{180}^{wake} \rangle} = 3.6$$

$$\frac{\langle P_{180} \rangle}{\langle P_{180}^{wake+taper} \rangle} = 1.9$$

# Comparison with LCLS

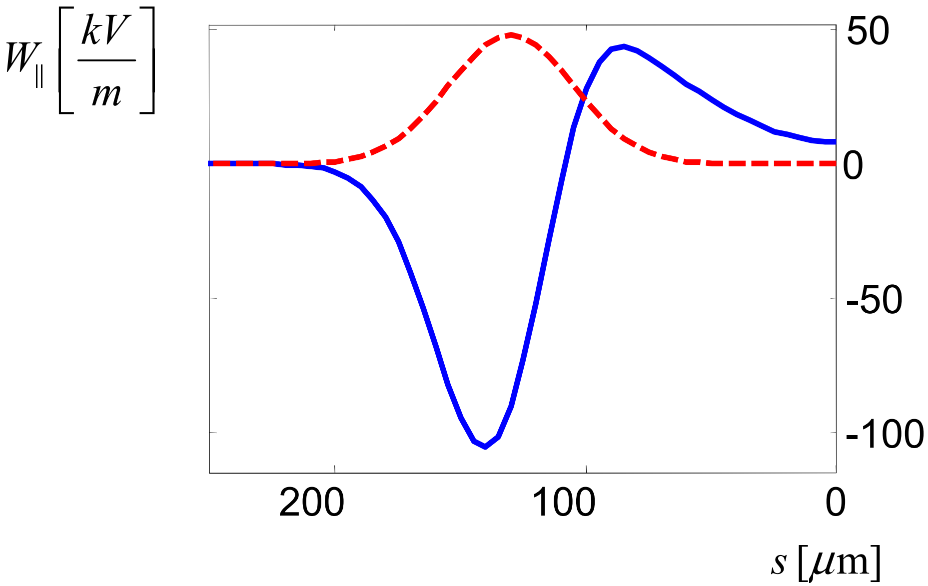
*K.Bane and G.Stupakov*




$$\delta_A = \frac{W_A L}{E \rho_1}$$ - fractional energy oscillation amplitude

| | LCLS | XFEL |
|---|---|---|
| $W_A$, kV/m | 400 | 100 |
| L, m | 100 | 200 |
| E, GeV | 14 | 20 |
| $\rho_1$ | 5e-4 | 5.5e-4 |
| **$\delta_A$** | **6** | **2** |



*Z.Huang and G.Stupakov*

## *Tapering (no wake)*

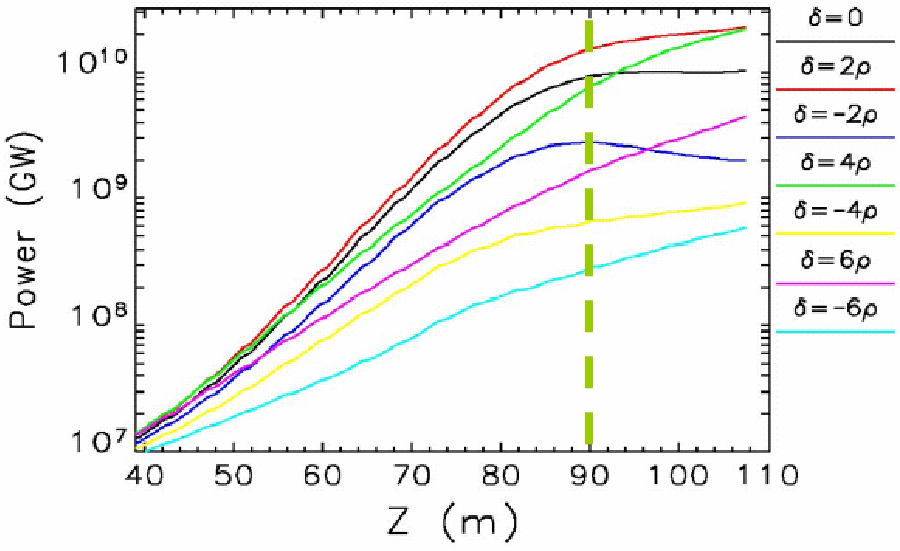



FIG. 9. (Color) LCLS power evolution obtained from GENESIS simulations for different fractional energy change $\delta(z = 90\text{ m})$.

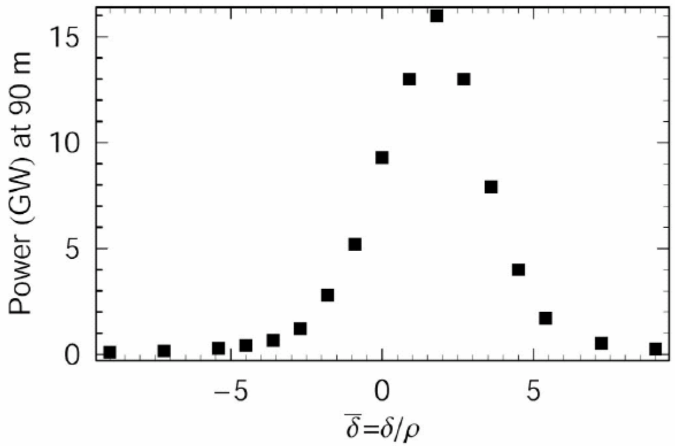
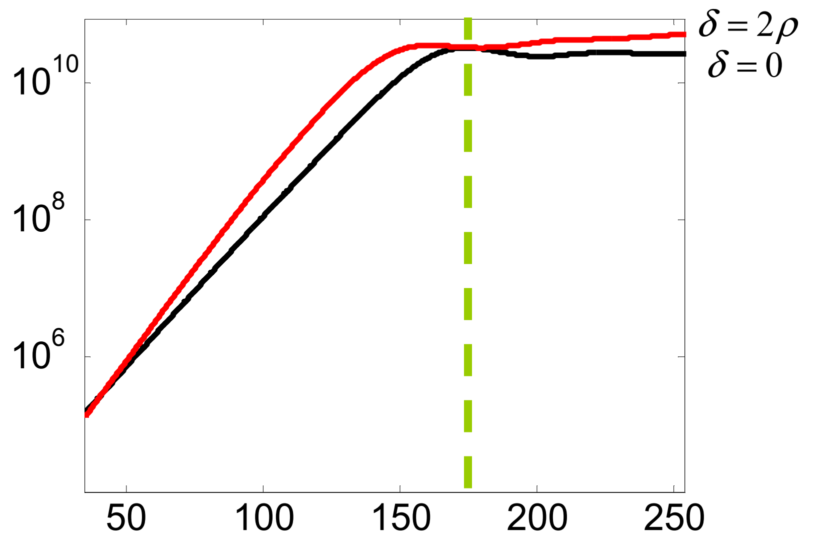
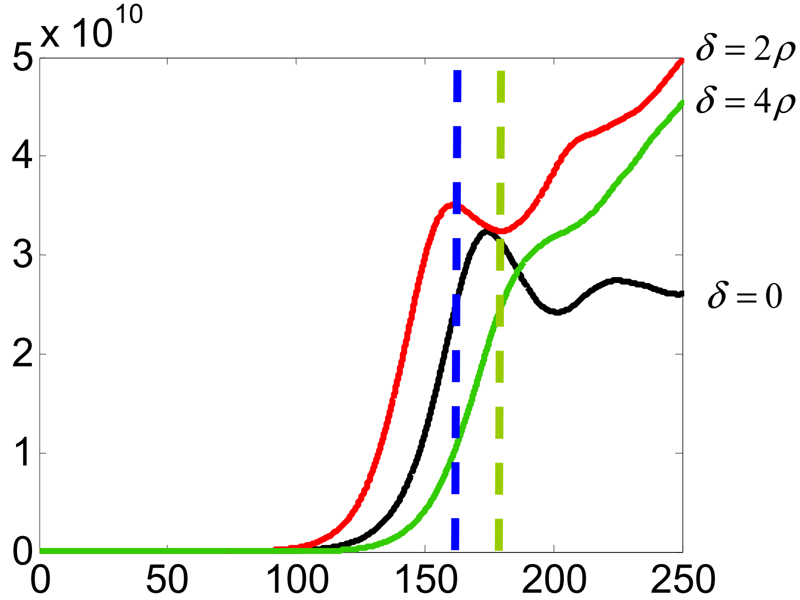



FIG. 10. LCLS power obtained from GENESIS simulations versus fractional energy change $\bar{\delta} = \delta/\rho$ at $z = 90$ m. The maximum power is reached when $\delta \approx 2\rho$, and the FWHM fractional energy change is about $4\rho$, in agreement with Eq. (50).



*Z.Huang and G.Stupakov*

*Taper $\delta$=2$\rho$ with wakes*

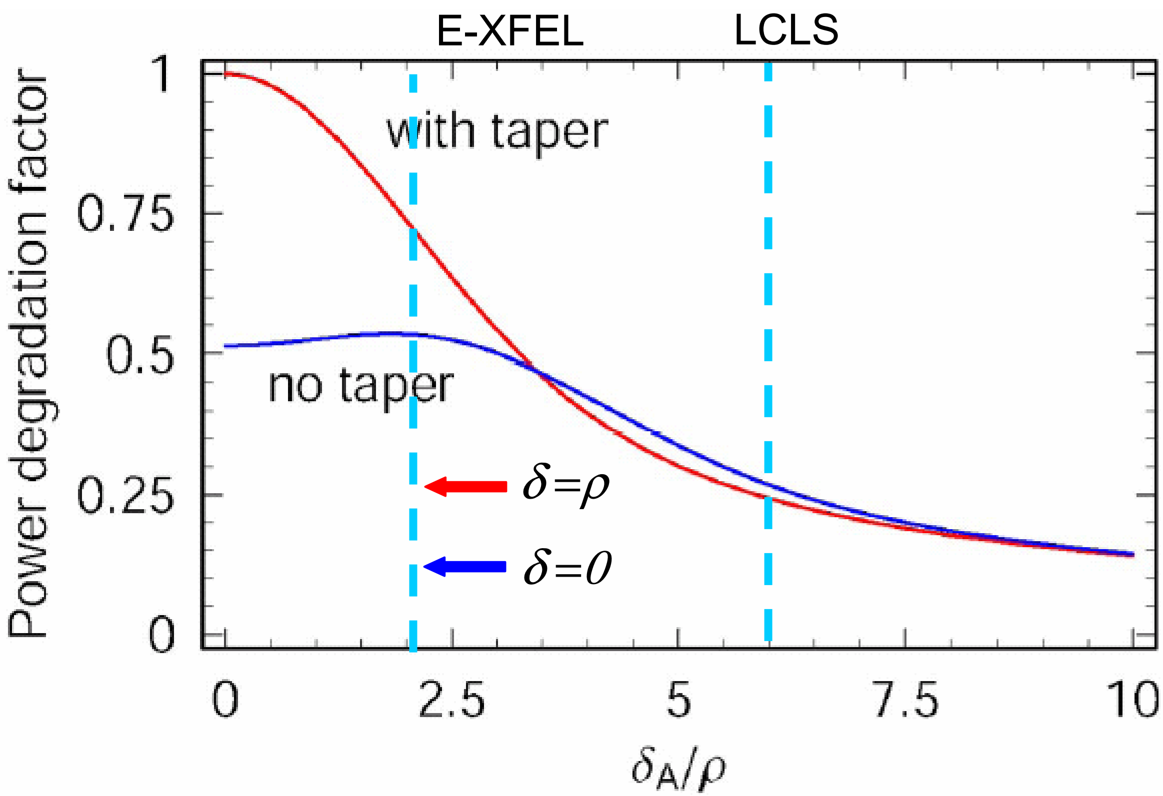



FIG. 11. (Color) Power degradation factor averaged over the core part of the bunch (with about 30 $\mu$m in length) versus the sinusoidal wake oscillation amplitude $\delta_A/\rho$ at the LCLS saturation ($z = 90$ m) for a prescribed tapered undulator (red) and without any taper (blue).

*S.Reiche et al. (PAC05) - optimal tapering for LCLS with wake field is considered*

# Conclusions

1. For smooth Gaussian bunch the wake field reduces the power at L=180 m by factor 3.6

$$\langle P_{180} \rangle / \langle P_{180}^{wake} \rangle = 3.6$$

2. The tapering allows to reduce the degradation

$$\langle P_{180} \rangle / \langle P_{180}^{wake+taper} \rangle = 1.9$$

3. The numerical simulations are required to find an optimal tapering.

4. The wake effect for the expected bunch shape should be analyzed .