GENESIS simulations with Wakefields for XFEL

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SASE 2 parameters

name	symbol	unit	value
energy	E	GeV	17.5
energy spread	ΔE	MeV	1.5
emmitance	ε_n	π mm-mrad	1.4
bunch charge	Q	nC	1
bunch length	σ	µm	25
peak current	I_P	kA	4.76
undulator period	λ_u	cm	4.8
undulator parameter	a_u		2.33
quadrupole length	L_Q	cm	20
quadrupole gradient	G_Q	T/m	17
section length	L_{sect}	m	5+1.1
total length	L_{total}	m	260
beta function (waist)	$\beta_{x,}$ $\beta_{y,}$	m	41.6 29.3

Parameters XFEL theory

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + a_u^2\right) = 0.13155\,[\mathrm{nm}]$$

$$\sigma_{x,y} = \sqrt{\frac{\varepsilon_n}{\gamma}\beta_{x,y}} = \begin{pmatrix} 41 \\ 34 \end{pmatrix}[\mu m]$$

$$\sigma_r = 0.5(\sigma_x + \sigma_y) = 37\,[\mu m]$$

$$z_R = \frac{\pi w_0^2}{\lambda_s} = \frac{2\pi\sigma_r^2}{\lambda_s} = 67\,[m]$$

Parameters XFEL theory

Gain parameter

$$\Gamma_3 = \left[\left(\frac{A_{JJ} \omega_s \theta_l}{c \gamma_l} \right)^2 \frac{I_P}{2 \gamma I_A} \right]^{1/2} = 0.52\,[cm] \qquad \Gamma_1 = \Gamma_3 B^{-1/3} = 0.16\,[cm]$$

Efficiency parameter

$$\rho_3 = \frac{c \gamma_l^2 \Gamma_3}{\omega} = 20\text{e-}4 \qquad \rho_1 = \frac{c \gamma_l^2 \Gamma_1}{\omega} = 6.1\text{e-}4$$

Diffraction parameter

$$B = \Gamma_3 \sigma_r^2 \frac{\omega_s}{c} = 34$$

Effective power of the input signal

$$P_{sh} = 3 \rho_1 \frac{W_b}{N_c \sqrt{\pi \ln N_c}} = 6444\,[W]$$

Gain length*

$$L_g = L_{g0}(1+\delta) \approx 14\,[\mathrm{m}]$$

Optimal beta-function

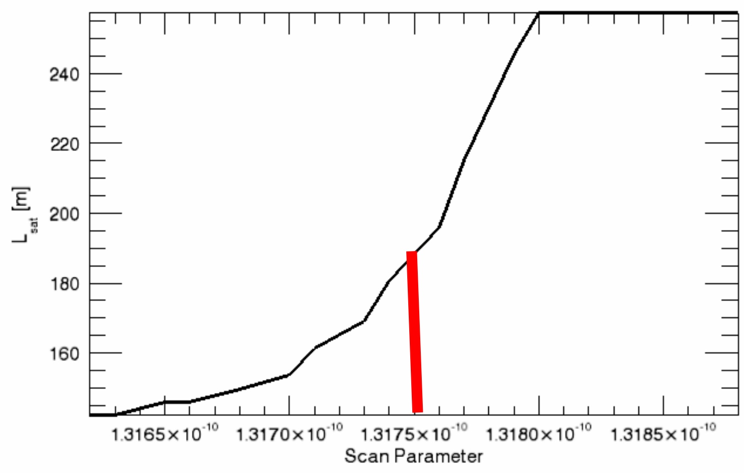
$$\beta_{opt} \approx 31\,[\mathrm{m}]$$

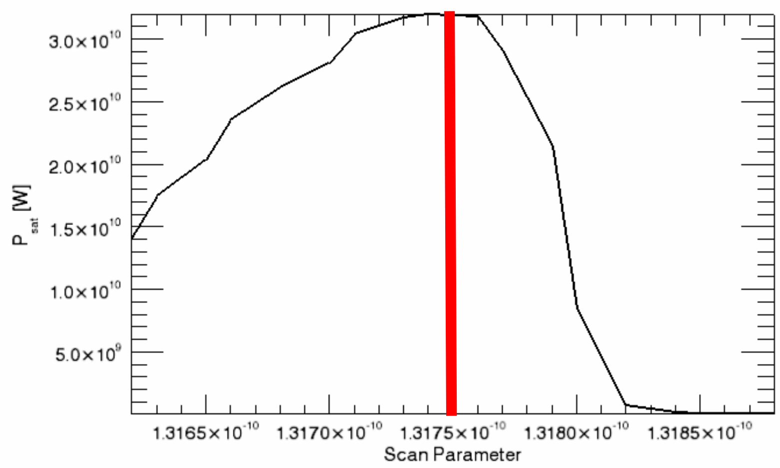
Saturation length

$$L_{sat} \approx 10 L_{g0} = 140\,[\mathrm{m}]$$

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

Genesis steady state simulation

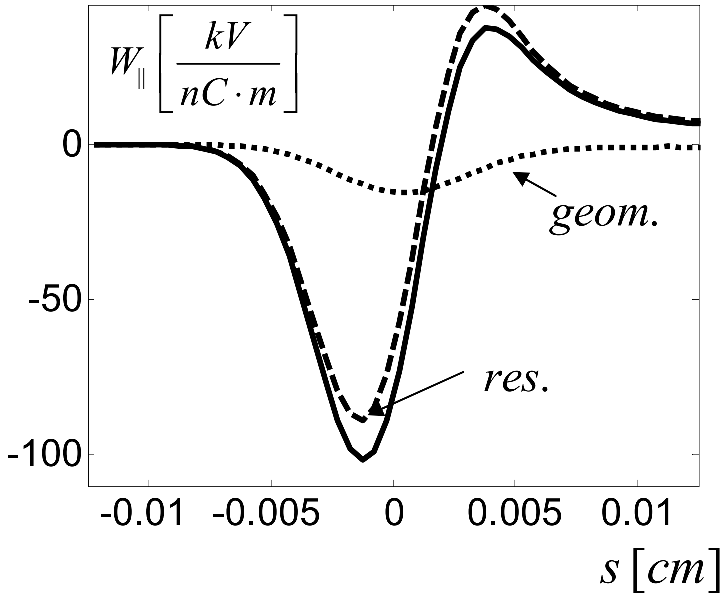


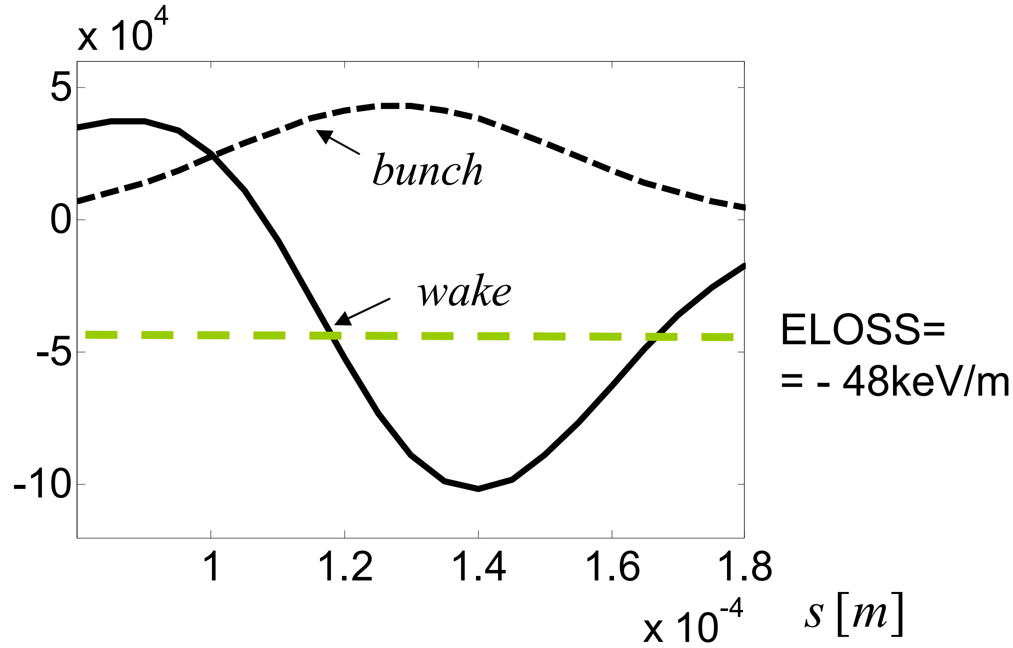


$$\lambda_s^{num} = 0.13175\,[\mathrm{nm}]$$

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + a_u^2\right) = 0.13155\,[\mathrm{nm}]$$

$$W_{\parallel}\left[\frac{V}{nC\cdot m}\right]$$





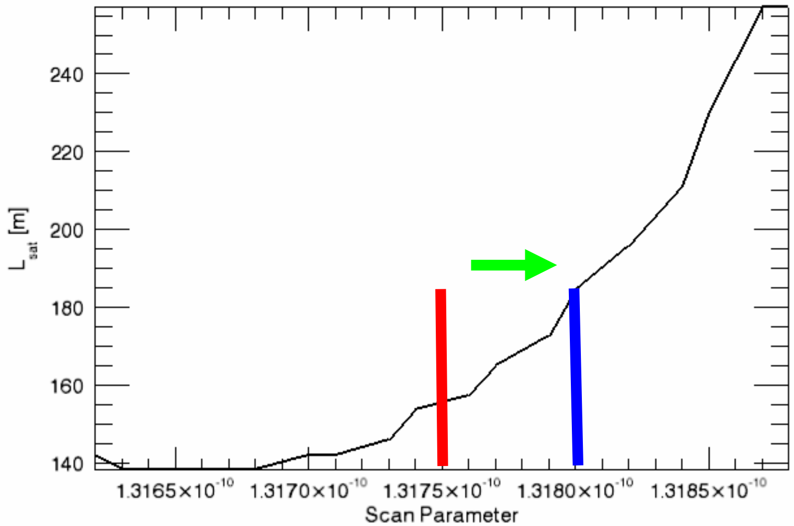
head tail tail head

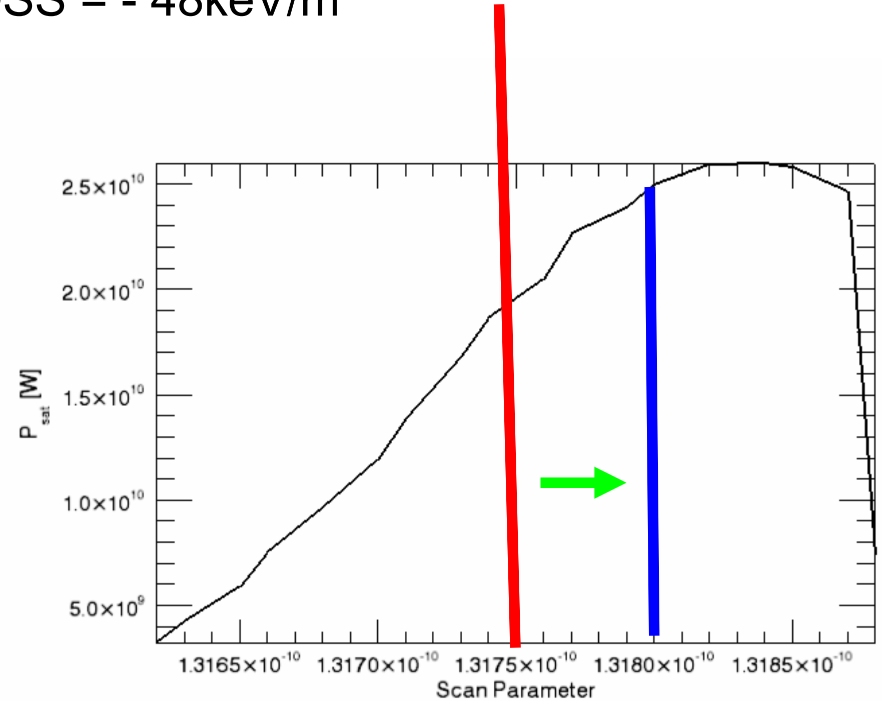
	Loss, kV/nC/m	Spread, kV/nC/m	Peak, kV/nC/m
total	**48**	47	-101

$cu: \quad \sigma_{cond} = 5.8e{+}7[\Omega^{-1}\cdot \mathrm{m}^{-1}], \quad \tau_{relax}=2.46e\text{-}14[\sec]$

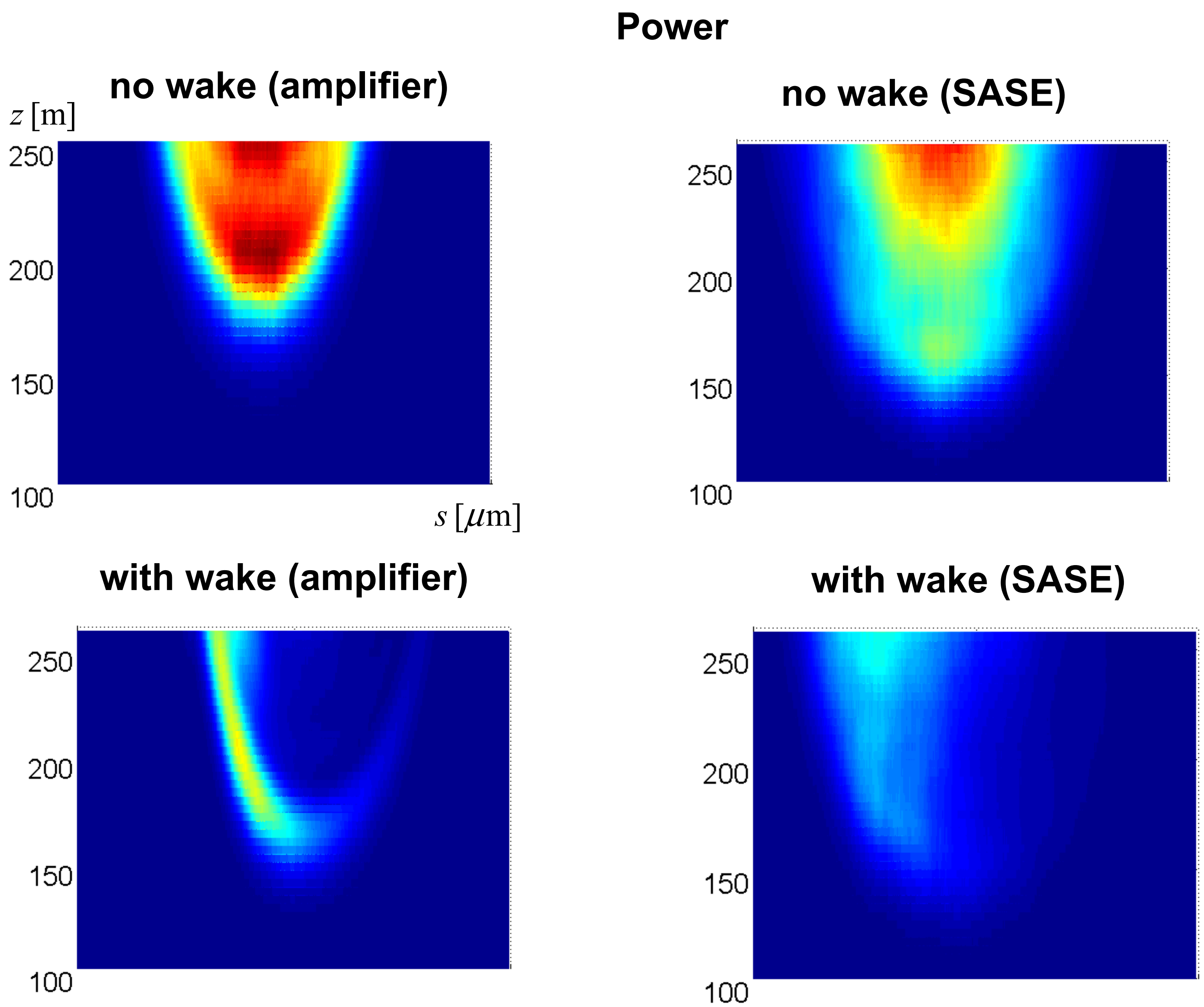
Genesis steady state simulation

Scan with ELOSS = - 48keV/m





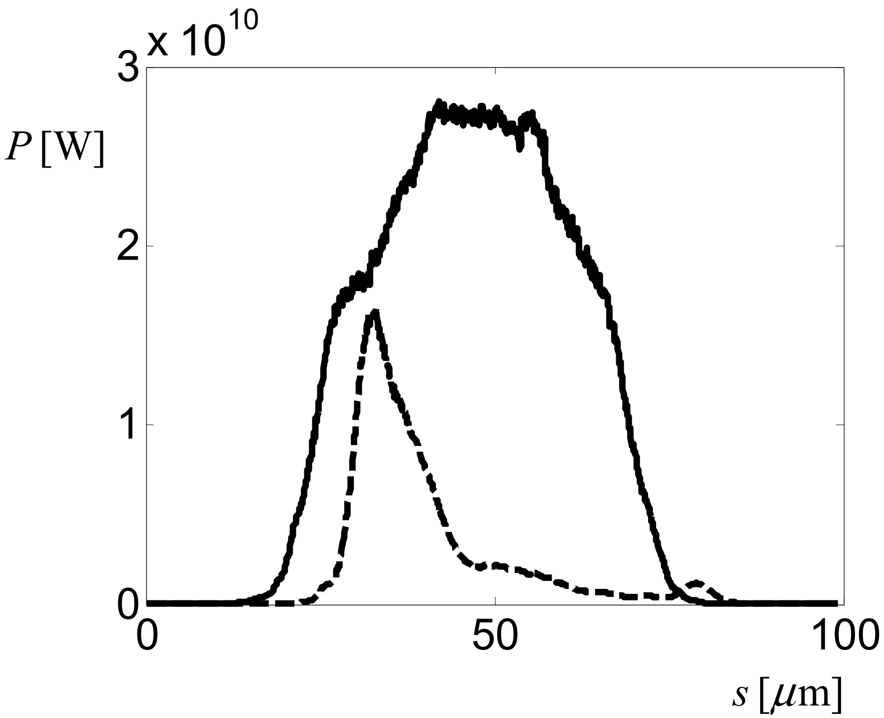
$$\lambda_s^{num} = 0.13175\,[\mathrm{nm}] \rightarrow 0.13180\,[\mathrm{nm}]$$


Power
no wake (amplifier)
z [m]
250
200
150
100
s [μm]
no wake (SASE)
250
200
150
100
with wake (amplifier)
250
200
150
100
with wake (SASE)
250
200
150
100

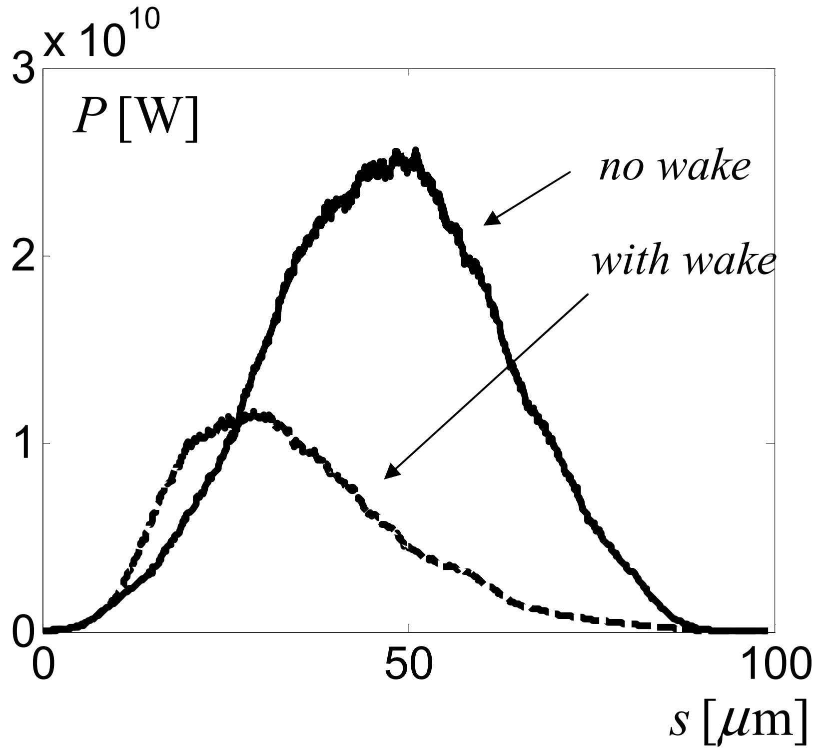
Genesis time dependent simulation

Amplifier model → **SASE model**

$\lambda_s^{num} = 0.13175\,[\mathrm{nm}]\;(\mathrm{P}_{\max}^{250\mathrm{m}})$ → $\lambda_s^{num} = 0.13165\,[\mathrm{nm}](\mathrm{P}_{\max}^{75\mathrm{m}})$



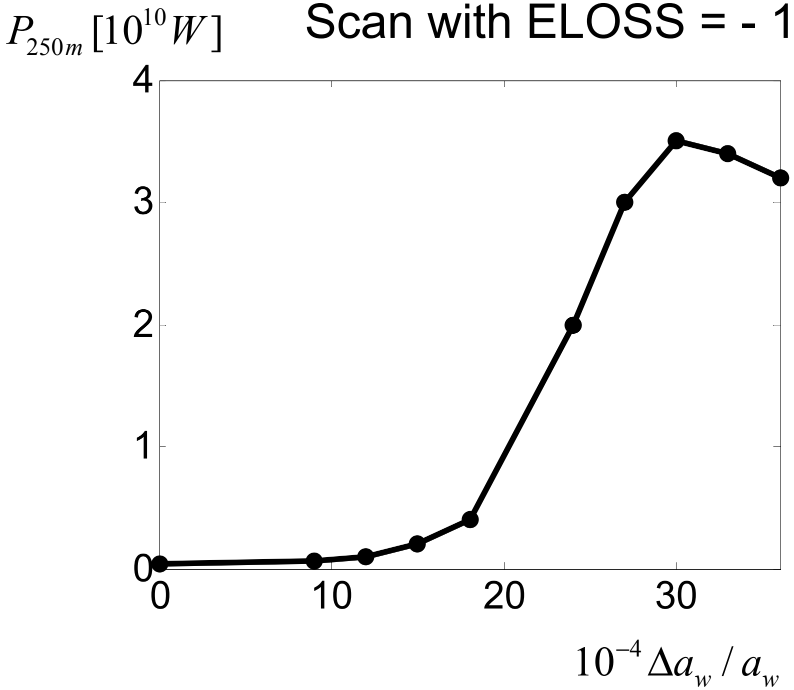
$$\frac{\langle P_{250m}^{wake}\rangle}{\langle P_{250m}\rangle} = 0.2$$

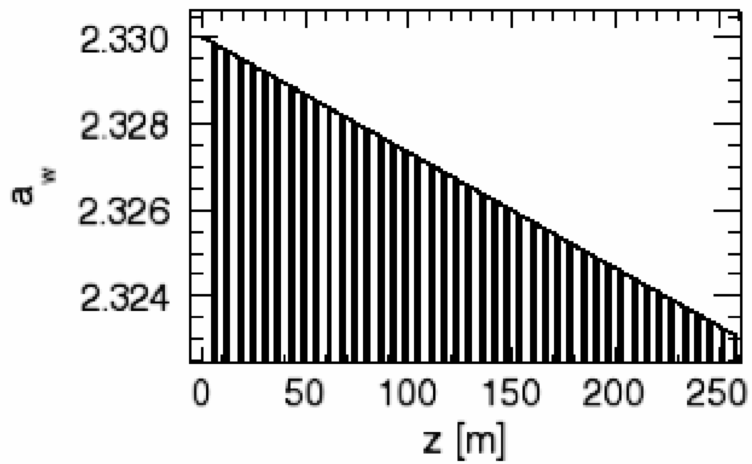


$$\frac{\langle P_{250m}^{wake}\rangle}{\langle P_{250m}\rangle} = 0.4$$

Taper optimization (steady state)

Scan with ELOSS = - 100keV/m





$$\frac{\Delta a_w}{a_w} = 3e-3 = 5\rho_1$$

$$B = 3.694\exp\left(-\frac{g}{\lambda_u}\left(5.068 - 1.520\frac{g}{\lambda_u}\right)\right)$$

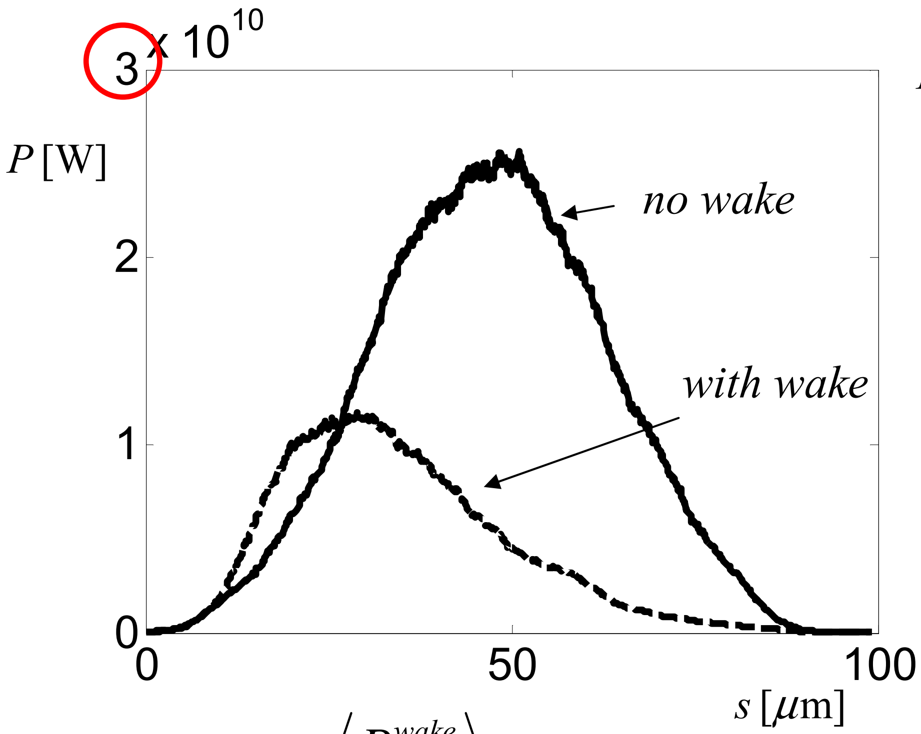
$$\frac{\Delta a_w}{a_w} \approx \frac{\Delta B}{B} \approx \left[-5.068\frac{g}{\lambda_w} + 3.04\left(\frac{g}{\lambda_w}\right)^2\right]\frac{\Delta g}{g}\Bigg|_{\substack{g=0.019m,\\ \lambda_w=0.048m}} = -80\Delta g(m)$$

$$\Delta g \approx 37.5\mu m$$

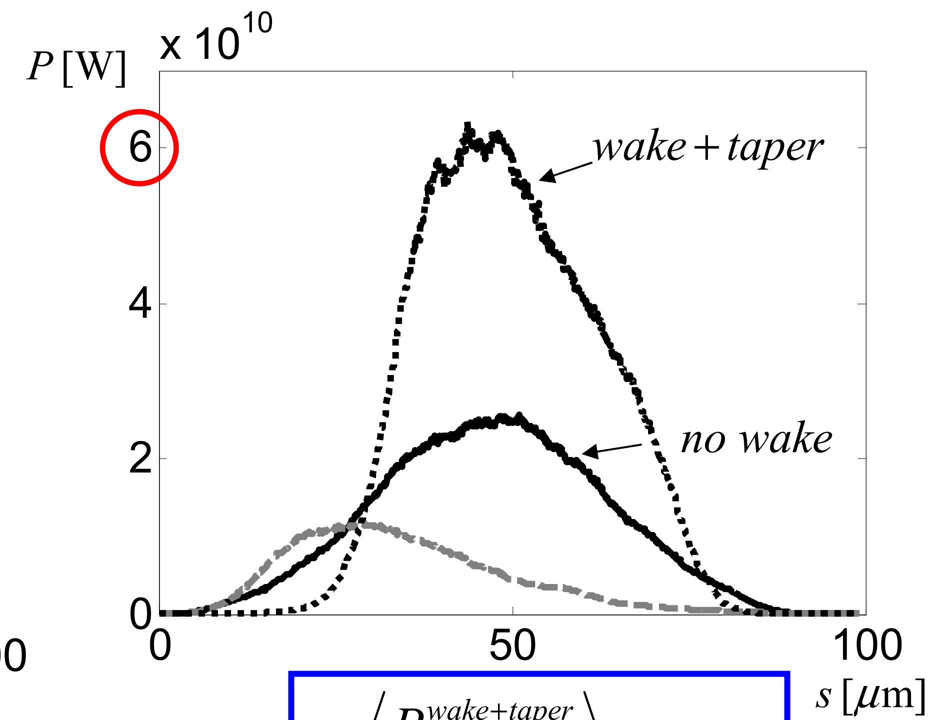
$$\Delta g / N_{\rm sec} \approx 0.9\mu\text{m/section}$$

Genesis time dependent simulation

SASE model

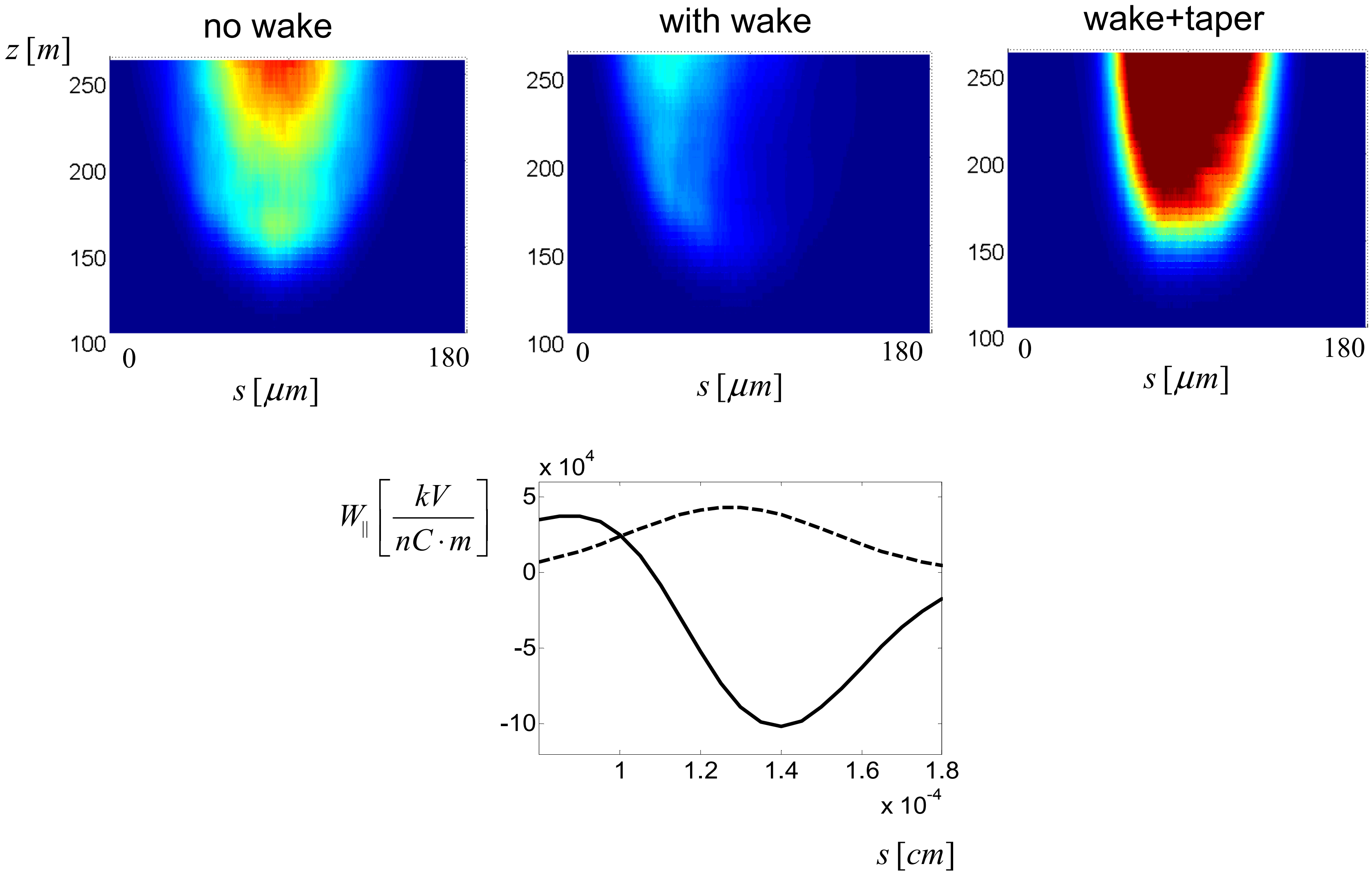


$$\frac{\langle P_{250m}^{wake} \rangle}{\langle P_{250m} \rangle} = 0.4$$

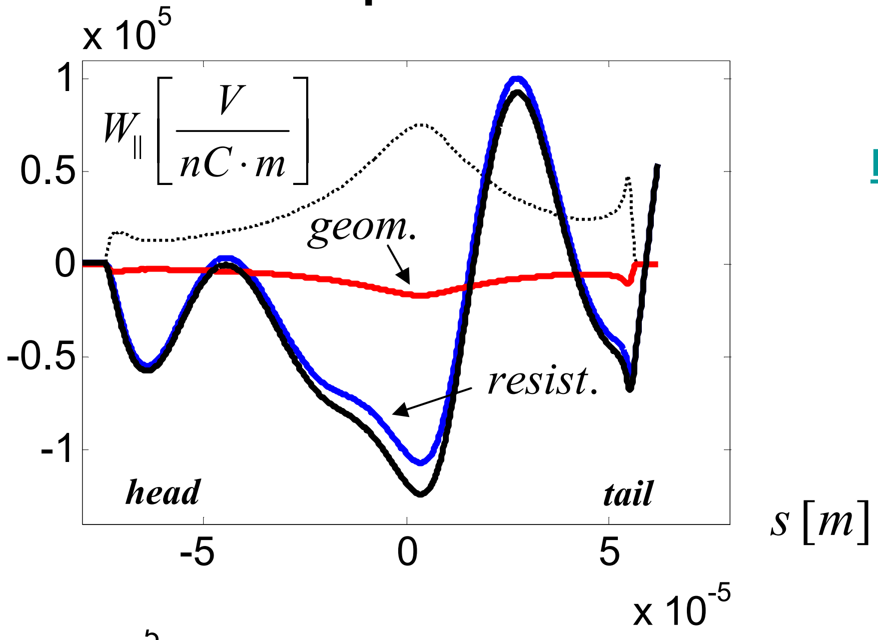


$$\frac{\langle P_{250m}^{wake+taper} \rangle}{\langle P_{250m} \rangle} = 2$$

Power (Gaussian bunch)



Shape 0



„Real“ shapes from Martin Dohlus

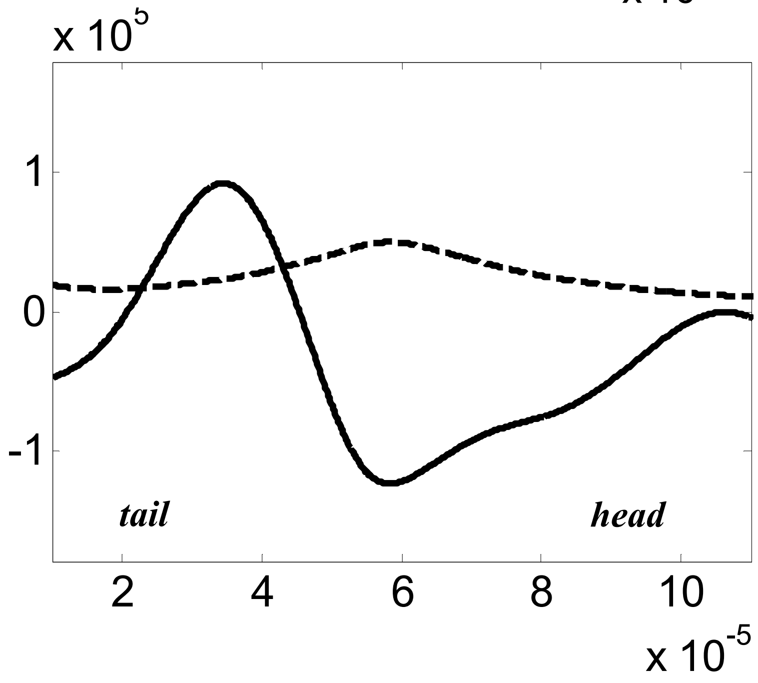
http://www.desy.de/~dohlus/2005.09.xfel_wakes

$$cu: \quad \sigma_{cond} = 5.8\text{e+}7[\Omega^{-1}\cdot \mathrm{m}^{-1}],$$

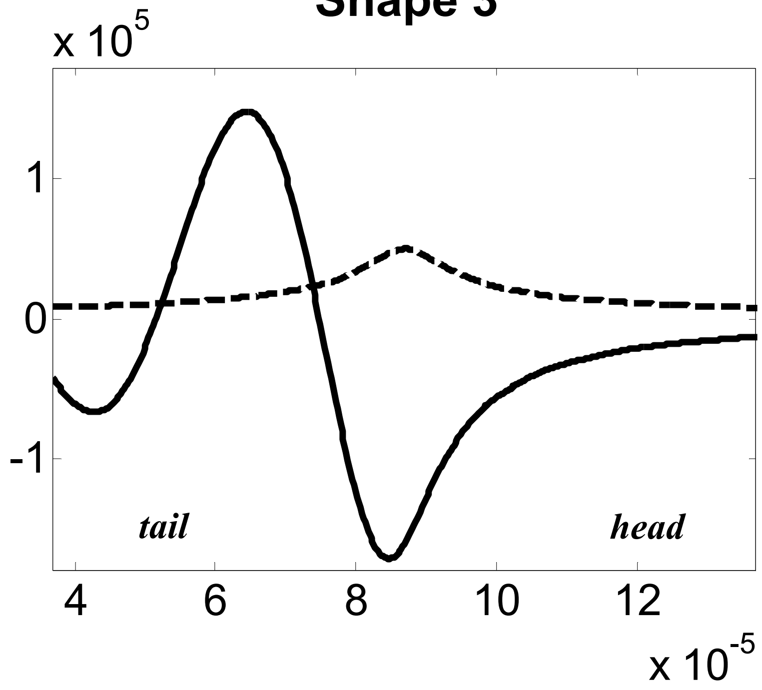
$$\tau_{relax} = 2.46\text{e-}14[\mathrm{sec}]$$

$$W_{\mathrm{P}}^{geom}(s) = cZ_{hi}\lambda(s)$$

$$Z_{hi} = 3.36[\Omega / m]$$

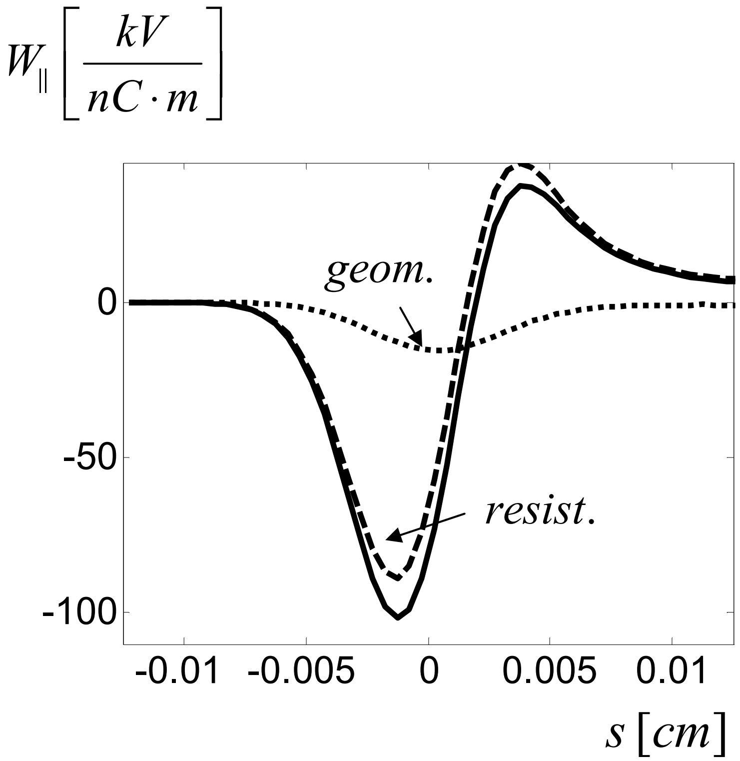


Shape 3



Geometric wake?

Longitudinal wake for the case of the elliptical pipe (3.8mm)



	pro section (6.1 m)	Loss, V/pC
absorber	1	42
pumping slot	1	<0.2
pump	1	9
BPM	1	
bellow	1	13
flange gap	1	6
Total geom.		**70**

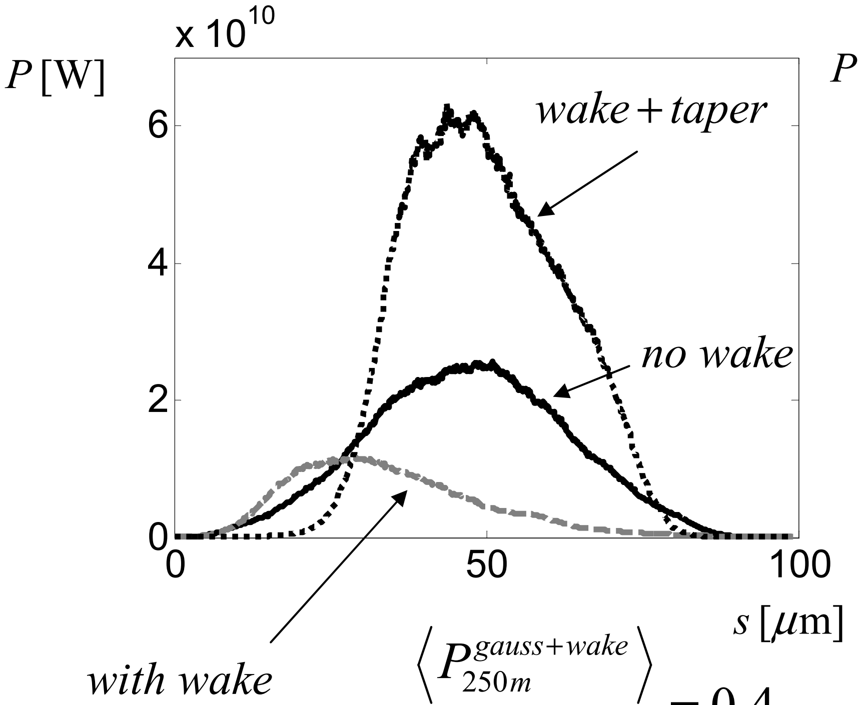
$$W_{\mathrm{P}}^{geom}(s) = cZ_{hi}\lambda(s)$$

$$Z_{hi} = 3.36[\Omega / m]$$

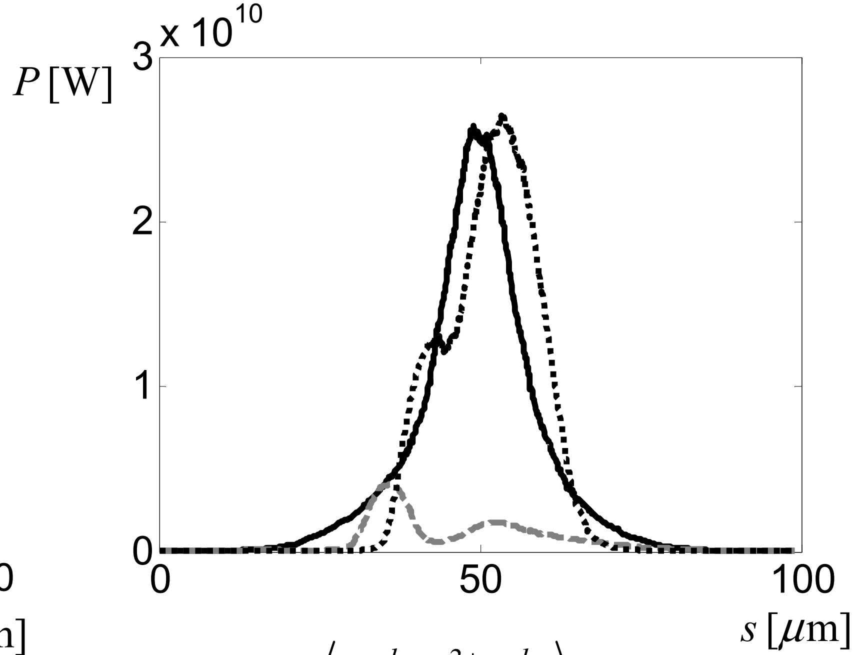
The wake repeats the bunch shape

Genesis time dependent simulation (SASE)

Gaussian



Shape 3



$$\frac{\left\langle P_{250m}^{gauss+wake} \right\rangle}{\left\langle P_{250m}^{gauss} \right\rangle} = 0.4$$

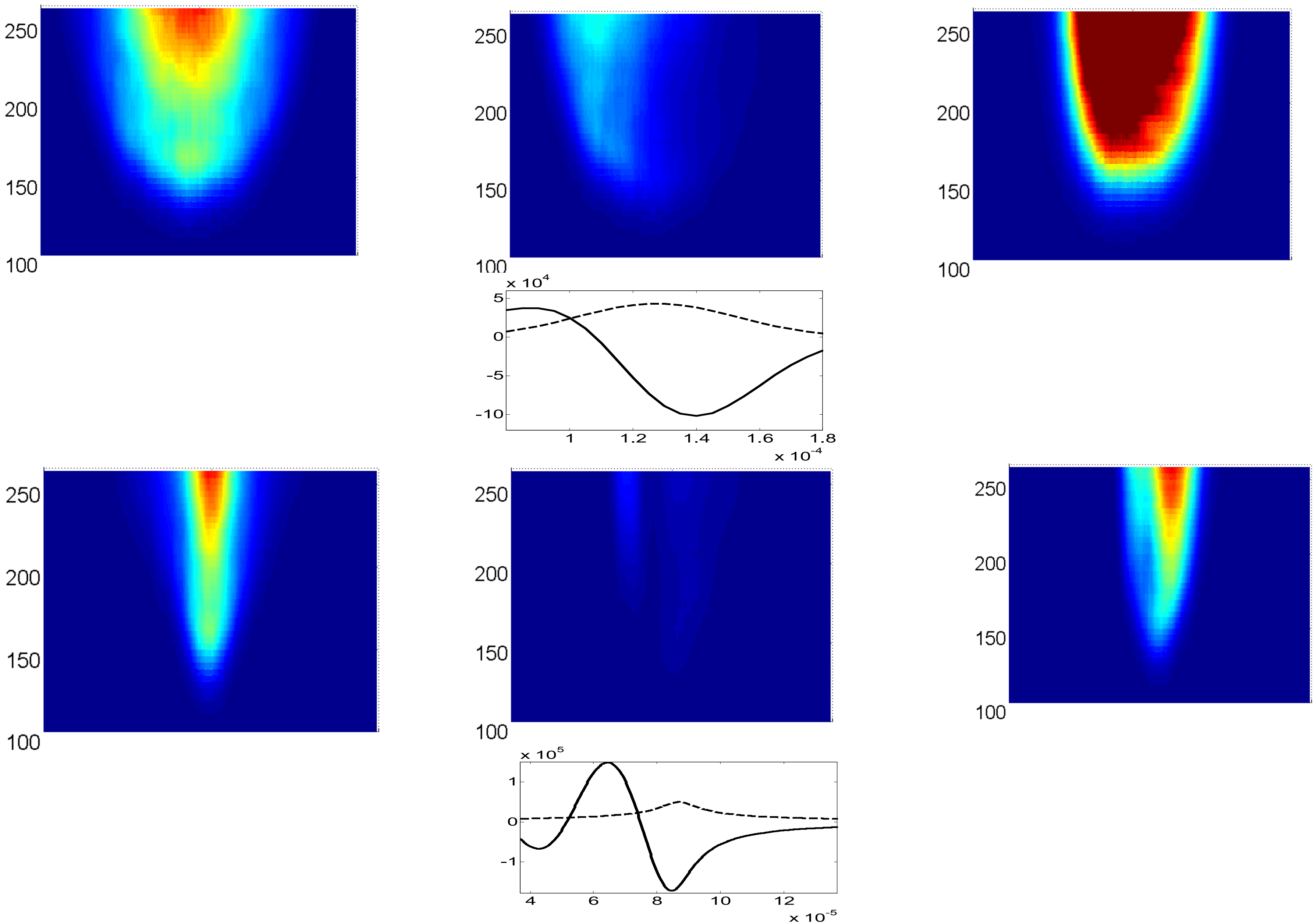
$$\frac{\left\langle P_{250m}^{shape3+wake} \right\rangle}{\left\langle P_{250m}^{shape3} \right\rangle} = 0.15$$

$$\frac{\left\langle P_{250m}^{gauss+wake} \right\rangle}{\left\langle P_{250m}^{gauss} \right\rangle} = 2$$

$$\frac{\left\langle P_{250m}^{shape3+wake} \right\rangle}{\left\langle P_{250m}^{shape3} \right\rangle} = 1$$

$$\frac{\left\langle P_{250m}^{gauss} \right\rangle}{\left\langle P_{250m}^{shape0} \right\rangle} = 0.41$$

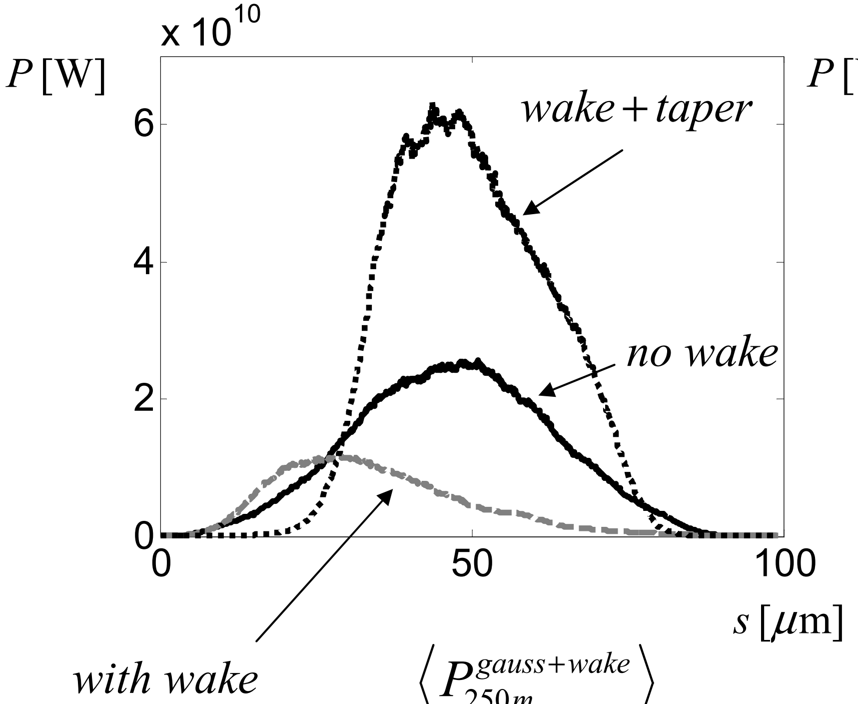
Power



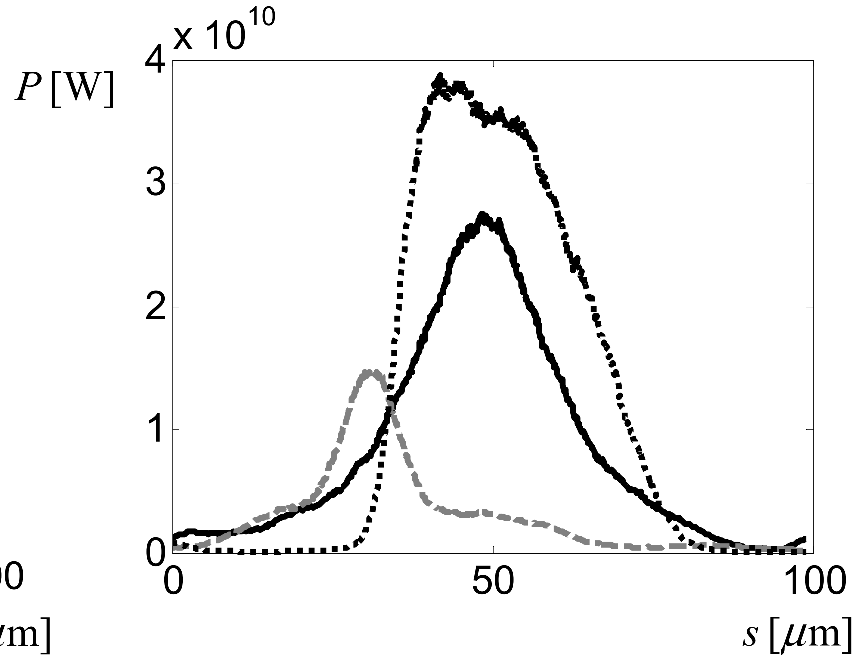
250
200
150
100
x 10^4
5
0
-5
-10
1
1.2
1.4
1.6
1.8
x 10^-4
x 10^5
1
0
-1
4
6
8
10
12
x 10^-5

Genesis time dependent simulation (SASE)

Gaussian



Shape 0



$$\frac{\left\langle P_{250m}^{gauss+wake}\right\rangle}{\left\langle P_{250m}^{gauss}\right\rangle}=0.4$$

$$\frac{\left\langle P_{250m}^{shape0+wake}\right\rangle}{\left\langle P_{250m}^{shape0}\right\rangle}=0.37$$

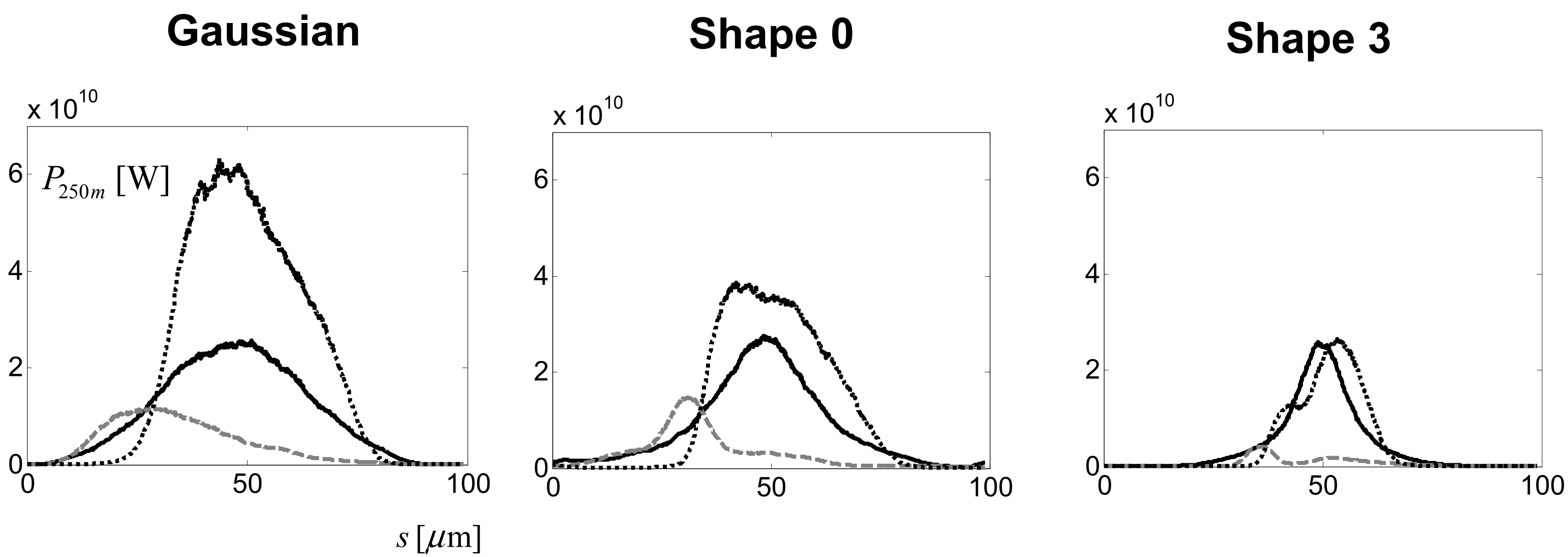
$$\frac{\left\langle P_{250m}^{gauss+wake}\right\rangle}{\left\langle P_{250m}^{gauss}\right\rangle}=2$$

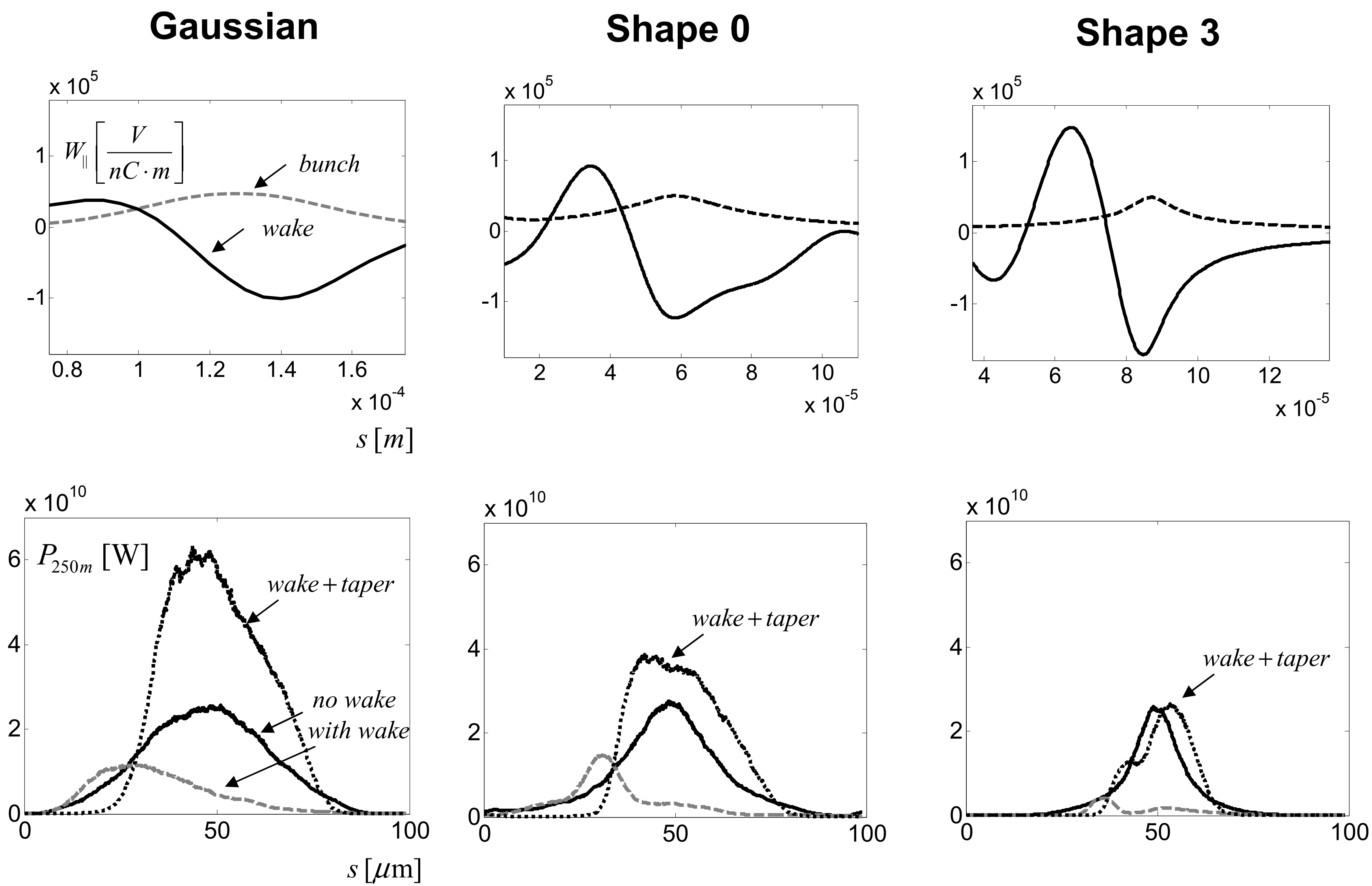
$$\frac{\left\langle P_{250m}^{shape0+wake}\right\rangle}{\left\langle P_{250m}^{shape0}\right\rangle}=1.4$$

$$\frac{\left\langle P_{250m}^{gauss}\right\rangle}{\left\langle P_{250m}^{shape0}\right\rangle}=0.78$$

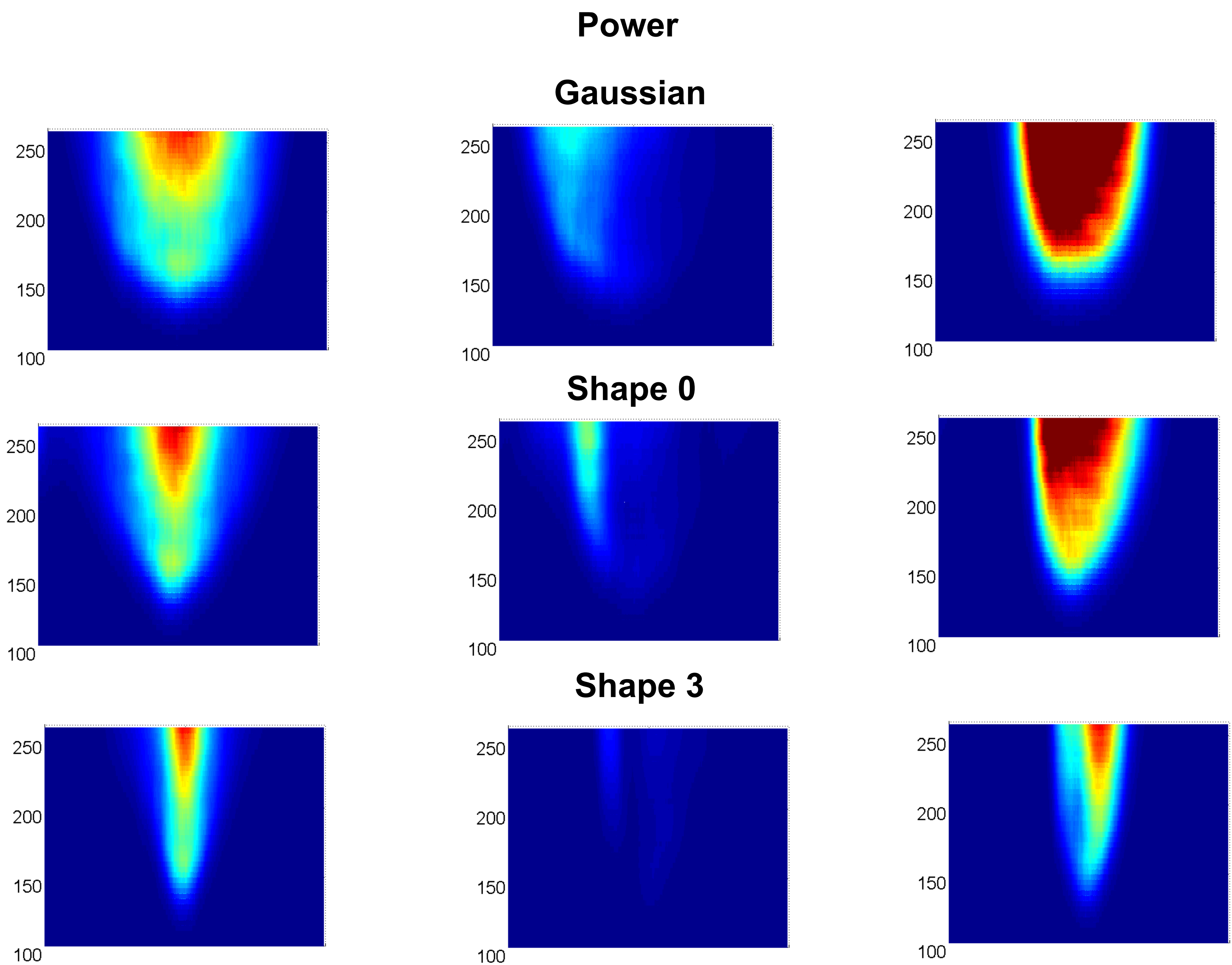
Power in a.u.

	Free space	With wake	With wake+taper (32mkm / 260m)
Gaussian	1	0.4	2
Shape 0	0.8	0.8*0.37=0.3	0.8*1.4=1.1
Shape 3	0.4	0.4*0.15=0.06	0.4*1=0.4





Taper: $$\frac{\Delta a_w}{a_w} = 3e-3 = 5\rho_1$$


Power
Gaussian
Shape 0
Shape 3
250
200
150
100

Conclusions

1. The wake field reduces the power at L=250 m by factor 2.5 for the Gaussian bunch and up to factor 7 by the “real” shape

2. The linear taper allows to avoid the degradation and to increase the power by factor 2 for the Gaussian bunch

3. The same taper allows to avoid the degradation for other shapes too

Acknowledgements to Evgeny Schneidmiller and Martin Dohlus for the help