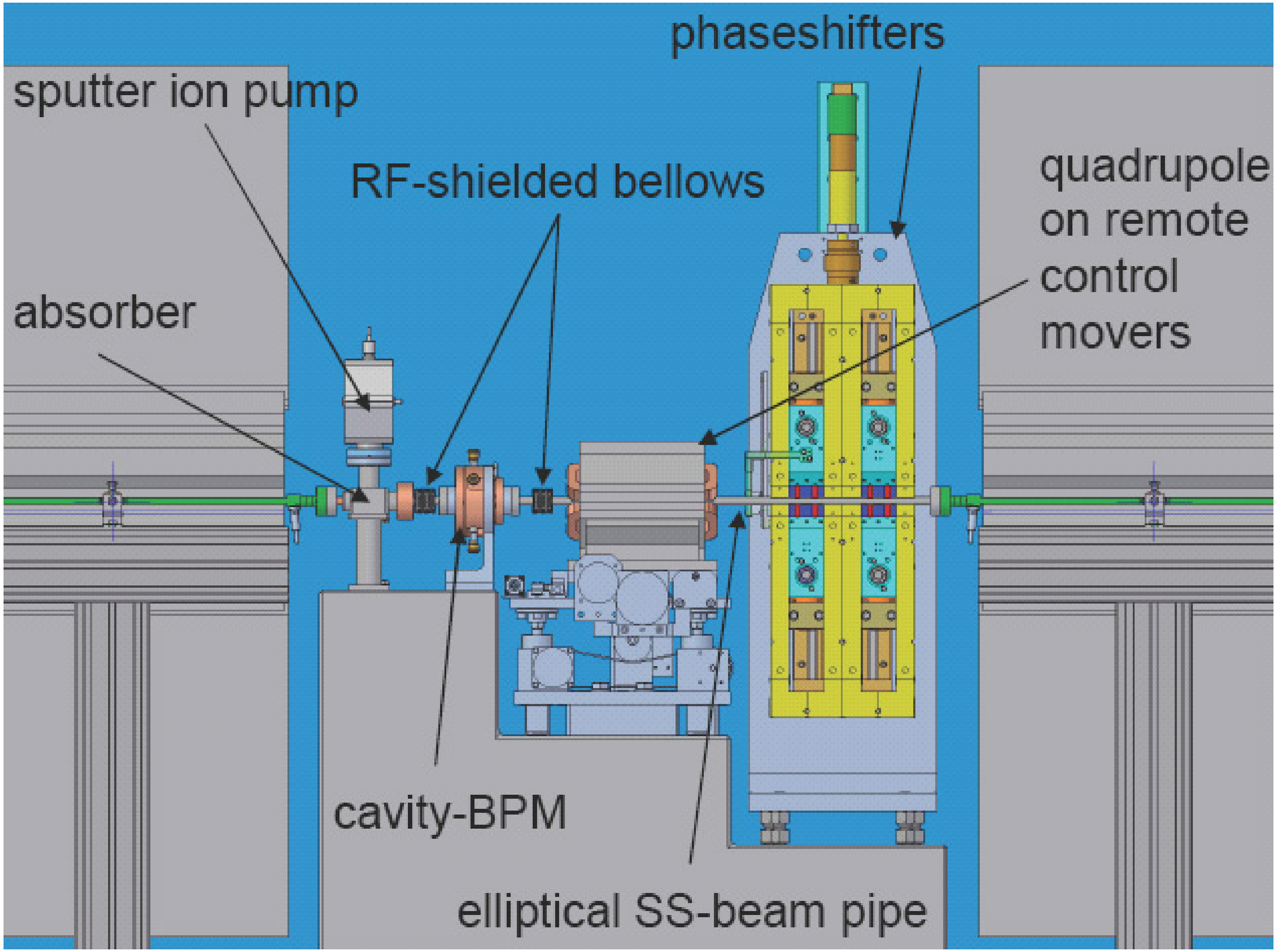
Wakefields impact on SASE2 XFEL performance

Igor Zagorodnov

Beam Dynamics Group Meeting

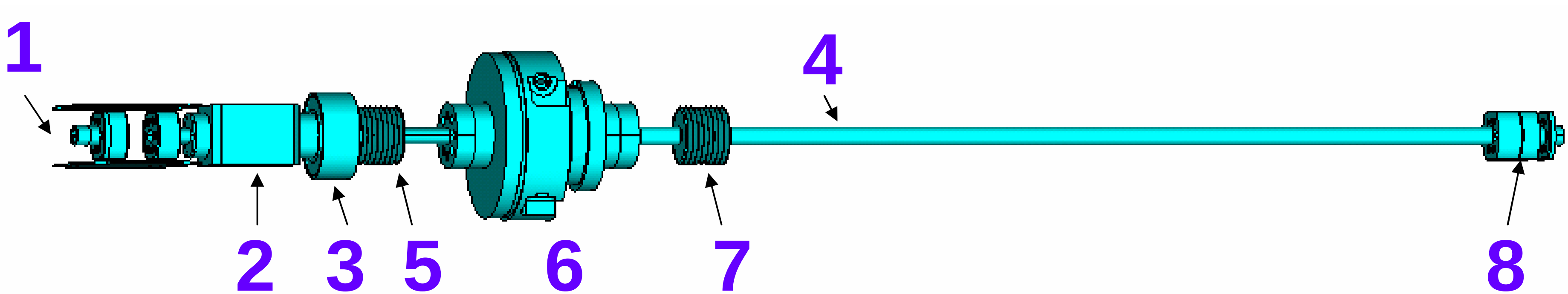
9.06.08



UNDULATOR- CELL(6.1m) = UNDULATOR (5m) + INTERSECTION (1.1m)

N	Element	from	to	Effective Length	Material	Conduct.	Relax. Time	Oxid layer	Rough ness
		mm	mm	mm		1/Omm/m	sec	nm	nm
1	Eliptical pipe	0	5288	5161	Aluminium	3,66E+07	7,10E-15	5	300
2	Pump	5161	5266	105	Aluminium	3,66E+08	7,10E-15	5	300
3	Absorber/Round transition	5266	5288	22	Copper	5,80E+07	2,46E-14	5	300
4	Round pipe	5288	6100	652	Copper	5,80E+07	2,46E-14	5	300
5	Below	5288	5318	30	BeCu 174	2,78E+07	2,46E-14	5	300
6	BPM	5373	5473	100	Stainless Steel 304	1,40E+06	2,40E-15	5	300
7	Below	5513	5543	30	BeCu 174	2,78E+07	2,46E-14	5	300
8	Round/Eliptical transition	6100	6100	0					

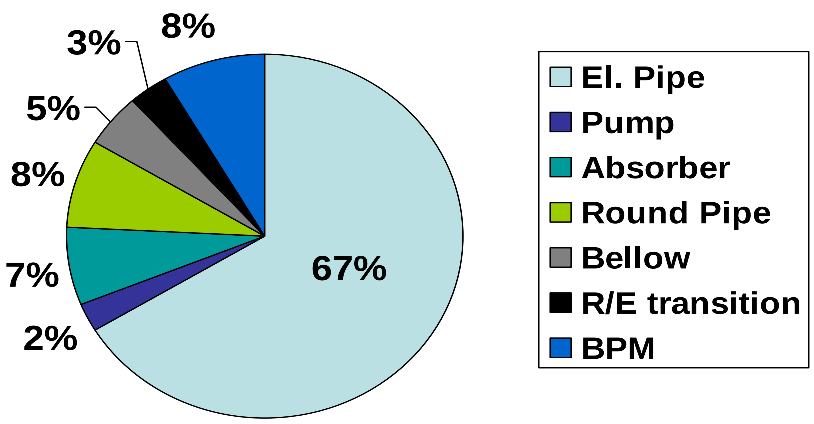
6100

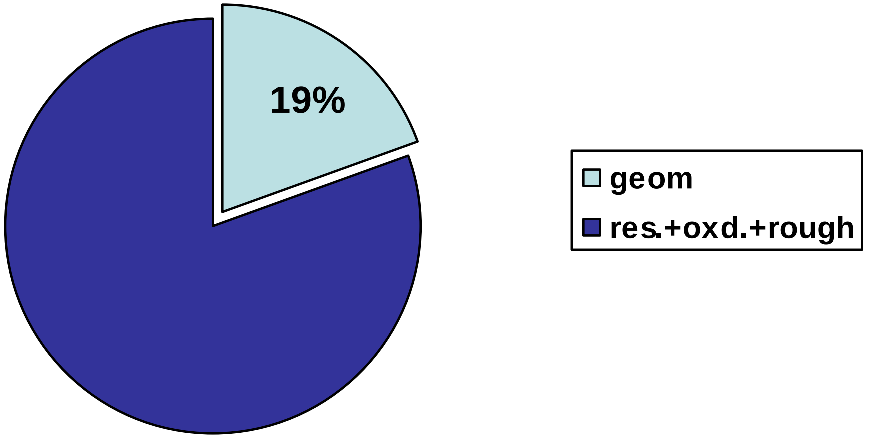


Katrin Schuett, ZM1
Dirk Lipka, MDI

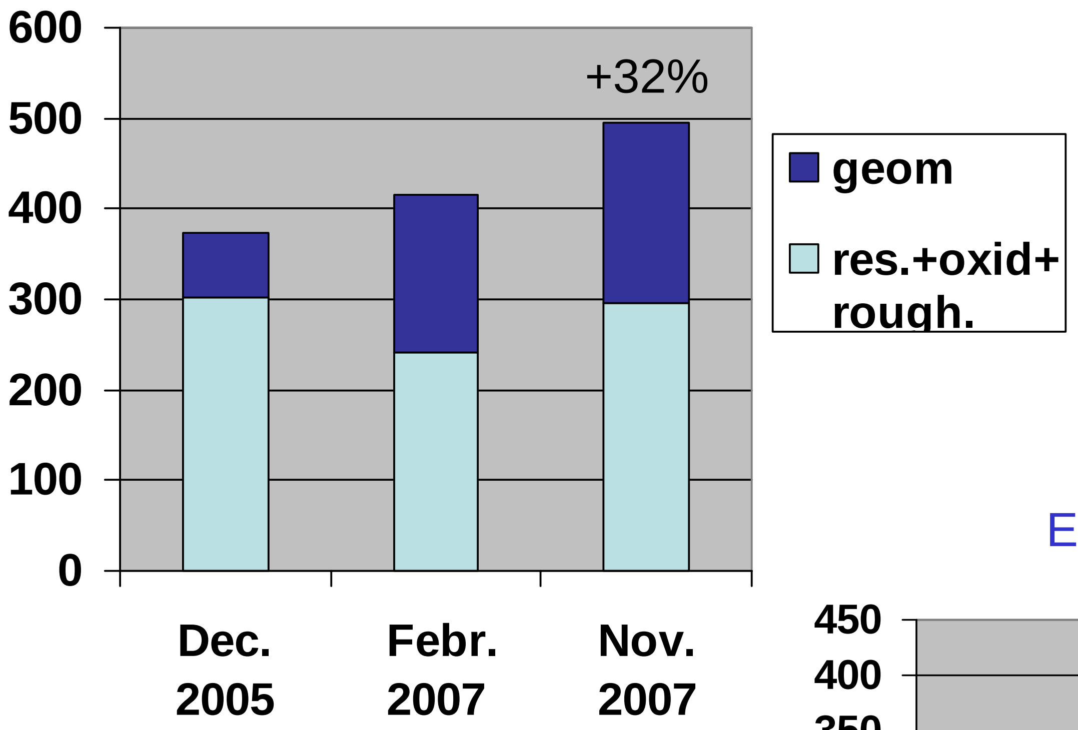
$$\sigma = 25\,\mu\mathrm{m} \quad q = 1\,\mathrm{nC}$$

N	Element	Geom Loss	Geom Spread	Loss	Spread
		kV	kV	kV	kV
1	Eliptical pipe	0	0	239	274
2	Pump	4,4	4,5	9	10
3	Absorber/Round transition	69	27	70	28
4	Round pipe	0	0	22	32
5	Below	24	9	25	10
6	BPM	42	17	70	34
7	Below	24	9	25	10
8	Round/Eliptical transition	36	14	36	14
	Energy Spread	199,4	80,5	496	412(365)





Enrgy Loss



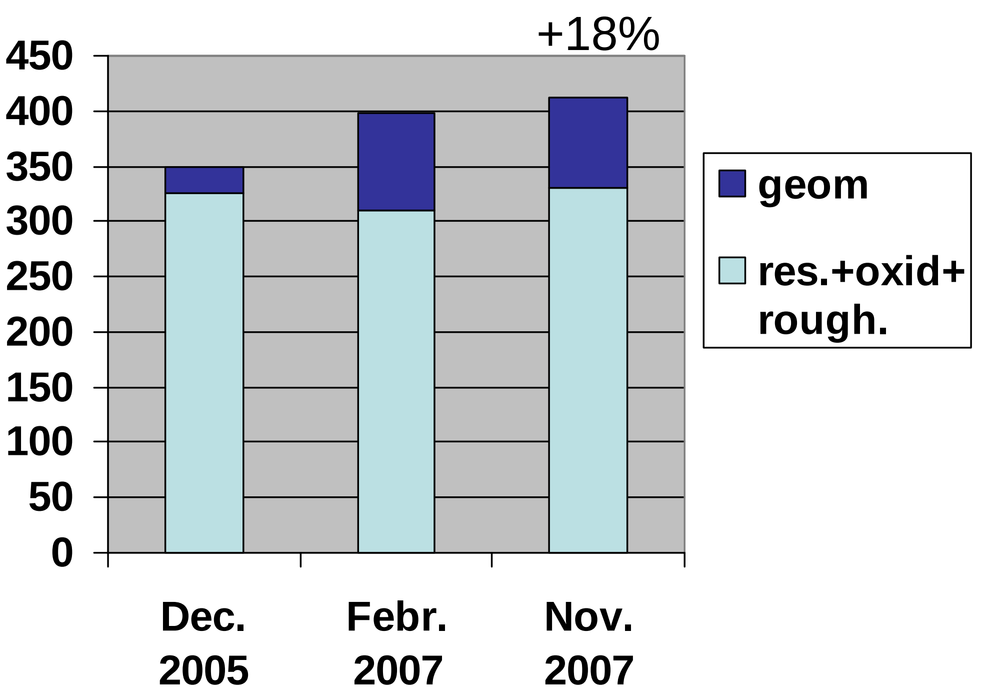
$$\sigma = 25\mu m$$

TESLA-FEL Report 2005-10

FEL simulations with

$$\varepsilon = 0.7\,\text{mm*mrad}$$

Energy Spread

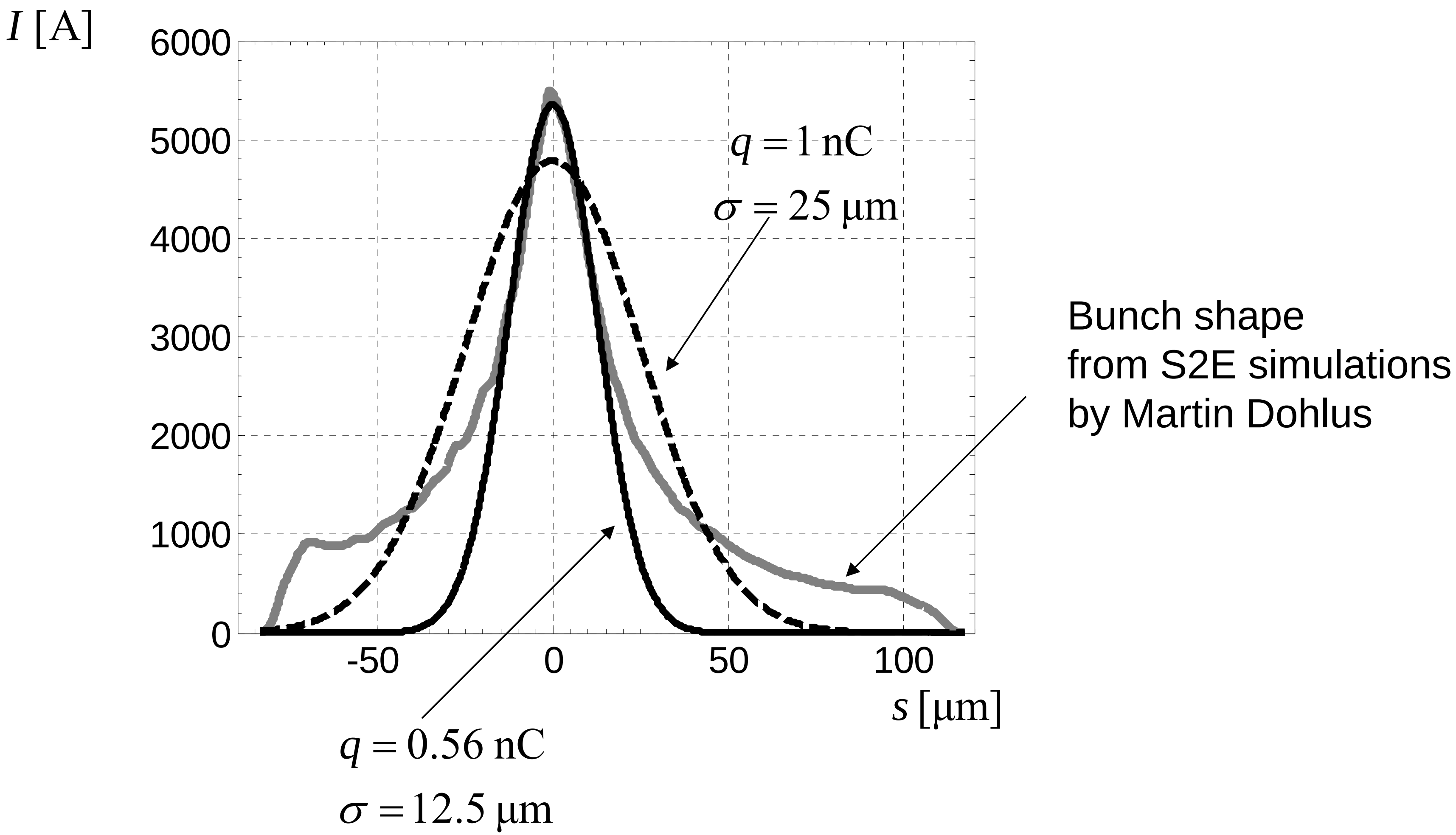


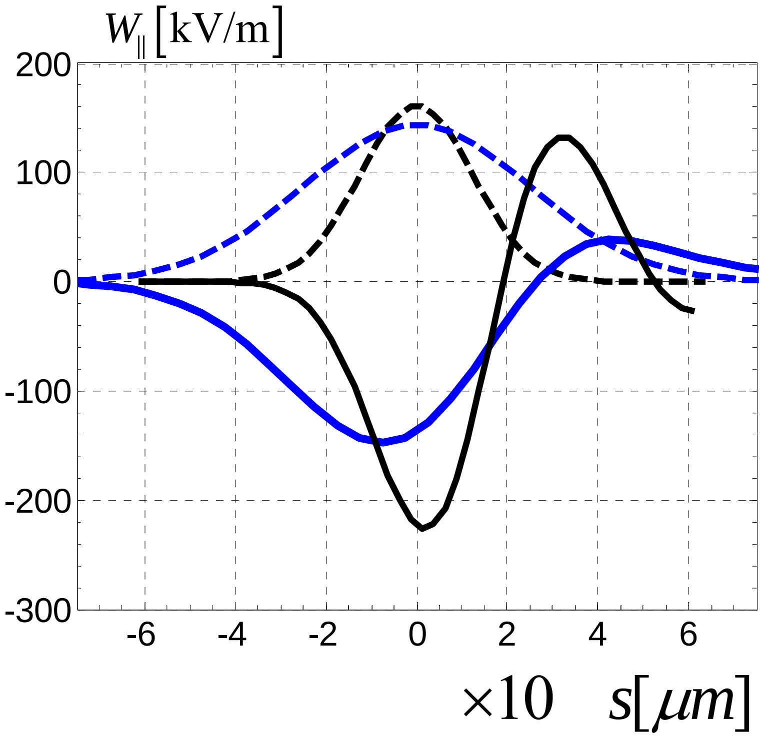
New FEL simulations with
new wakefields and

$$\varepsilon = 1.4\,\text{mm*mrad}$$

are required.

Gaussian fit of the bunch shape from S2E simulations

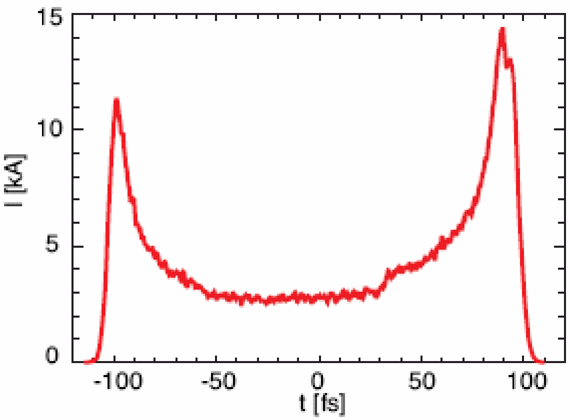


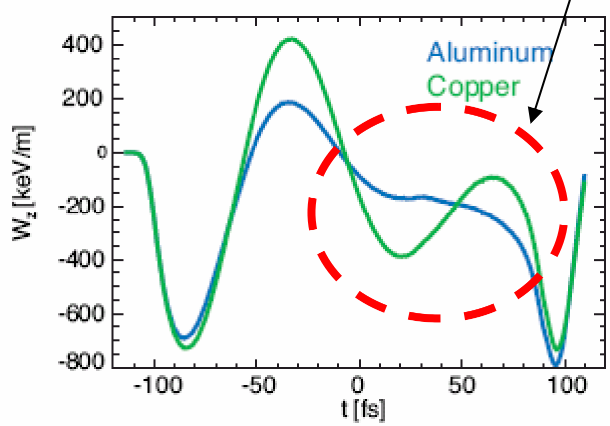


$$\delta_A = \frac{W_A L}{E \rho_1}$$ - fractional energy oscillation amplitude

	LCLS	XFEL SASE2 (q=1nC, sig=25mkm)	XFEL SASE2 (q=0.56nC, sig=12.5mkm)
W_A, kV/m	200	140	220
L, m (L_sat)	100 (90)	200 (175)	200 (175)
E, GeV	14	17.5	17.5
ρ_1	3.2e-4	4e-4	4e-4
δ_A	**4.5**	**4**	**6.3**

K. Bane and G.Stupakov





Genesis
(S.Reiche et al)

- only 3D
- 3D Cartesian field solver (ADI)
- Runge-Kutta integrator
- Dirichlet boundary conditions
- **transverse motion**
- many other physics
- parallel (MPI)

ALICE

- 1D/2D/3D
- 3D azimuthal field solver (Neumann)
- Leap-Frog integrator
- Perfectly Matched Layer
- **transverse motion**
- simplified model
- parallel (MPI)
- tested by me on the examples from the book of SSY

(~Saldin et al, 2000 „The Physics …“,)

XFEL Source Parameters

General properties of XFEL sources

- Operation at fixed electron energy 17.5 GeV
- Continuos covering of design wavelength range with three SASE FELs

Electron beam

	Units	
Energy	GeV	17.5
Bunch charge	nC	1
Peak current	kA	5
Bunch length (rms)	μm	25
Norm. emittance (rms)	mm-mrad	1.4
Energy spread (rms)	MeV	1.5
# bunches p. pulse	#	3250
Repetition rate	Hz	10

2.5 MeV?

Undulators:

	λ_r nm	λ_u mm	L_W m
SASE1	0.1	35.6	200
SASE2	0.1–0.4	48	260
SASE3	0.4–1.6	65	130
Possible XUV option			
SASE4	1.6–6.4	110	80

Genesis /ALICE Benchmarking, my talk 17.03.08

Genesis vs. ALICE with transverse motion

$C = 0$

P0 = 4 kW

$\sigma_E = 2.5\,\mathrm{MeV}$

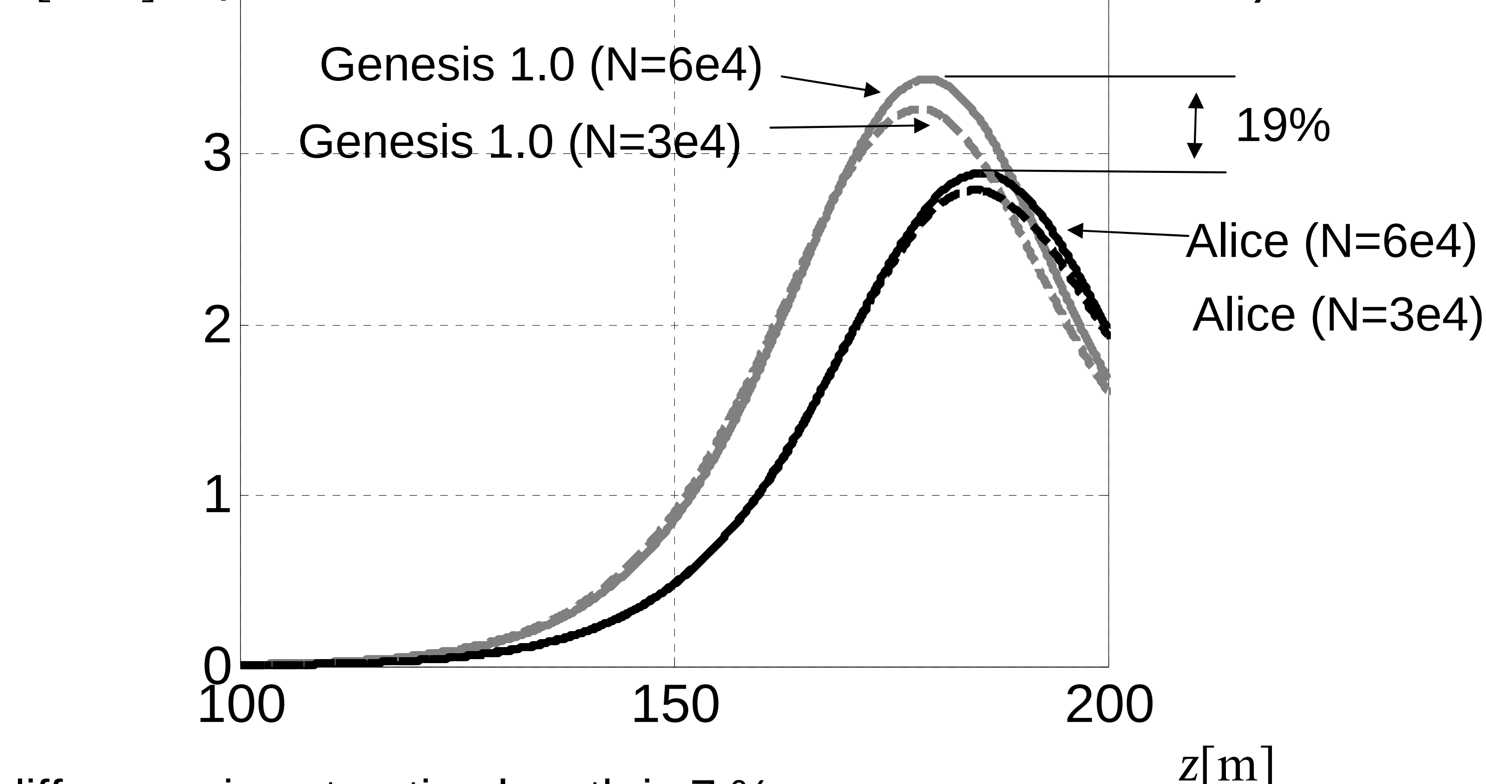
$\varepsilon = 1.4\,\mathrm{mm{*}mrad}$

I=5KA

N_λ ~10 400

$\lambda_s = 0.1\,\mathrm{nm}$

$\rho = 4.2e-4$



The difference in saturation length is 7 %.

The difference in power gain is 19 %.

The difference **does not reduce** with changing of the discrete model parameters ?!.

Genesis 2.0 released on 16.04.2008

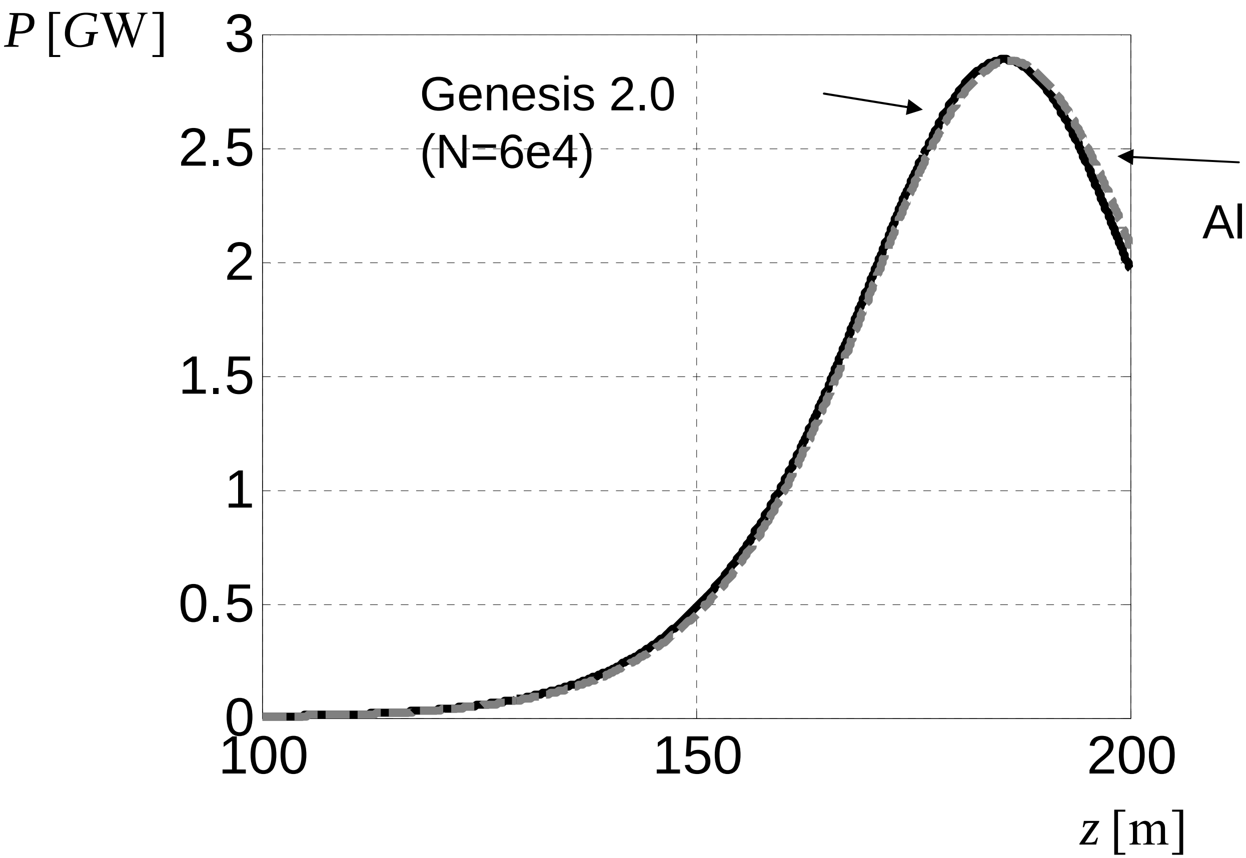
New Genesis 2.0 vs. ALICE with transverse motion

$C = 0$

P0 = 4000 Watt

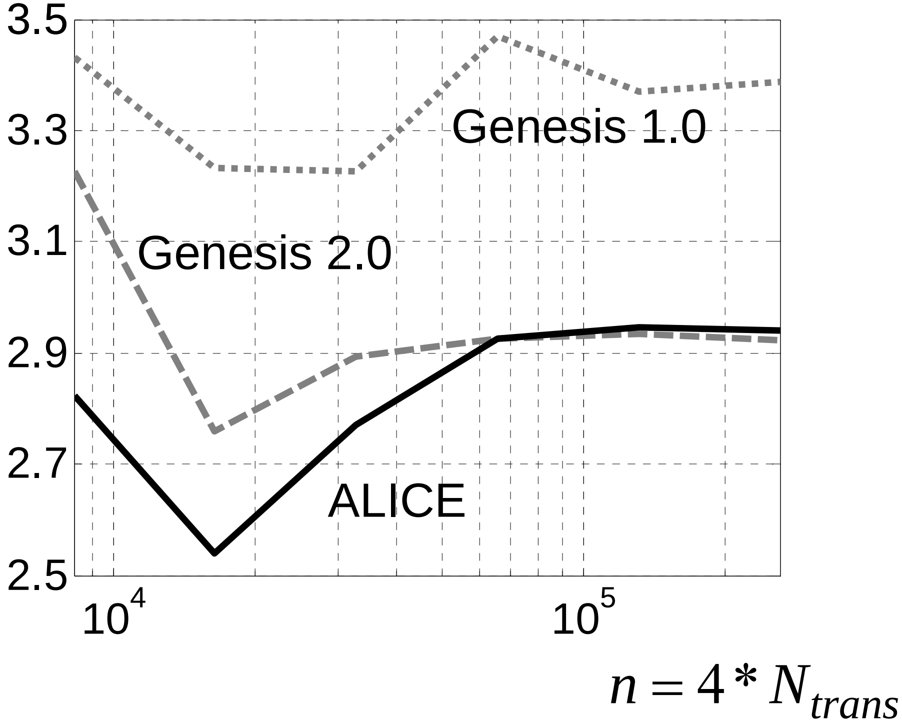
$\sigma_E = 2.5\,\mathrm{MeV}$

$\varepsilon = 1.4\,\mathrm{mm*mrad}$

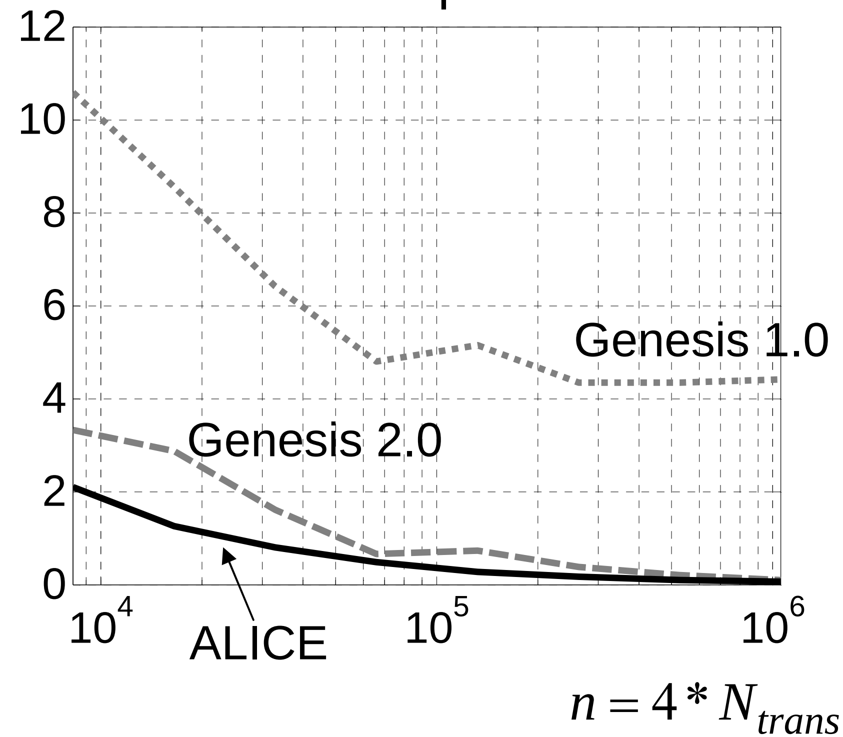


Convergence

$P\,[GW]$ at saturation



$$\delta = \frac{\left|\sigma_4 - \tilde{\sigma}_4\right|}{\sigma_4} 100\%$$



Genesis 1.0:	Hammersley and Box-Mueller
Genesis 2.0:	Hammersley and the inverse error function
ALICE:	Sobol and the inverse error function

$\varepsilon = 1.4\,\mathrm{mm{*}mrad}$

$\sigma_E = 2.5\,\mathrm{MeV}$

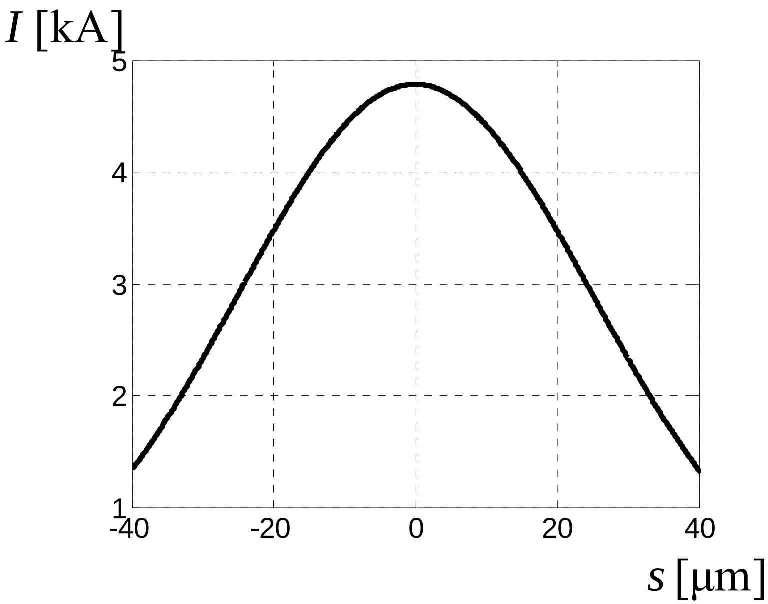
$C = 0$

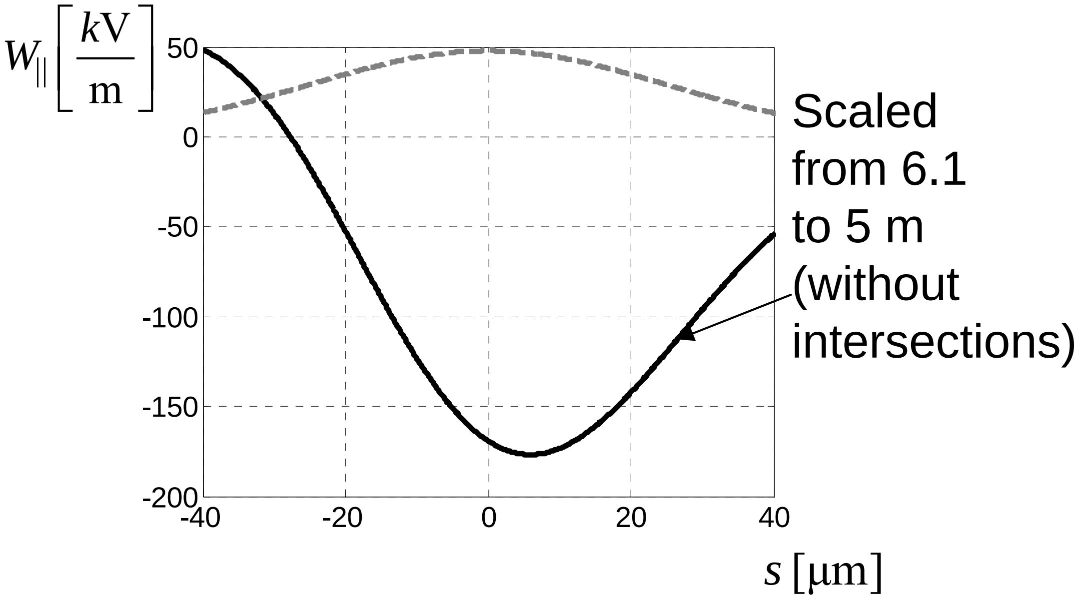
$\lambda_s = 0.1\,\mathrm{nm}$

I=5KA

N_λ ~10 400

Matched Gaussian Beam Parameters





$$\varepsilon_x = \varepsilon_y = 1.4 \text{ mm}\times\text{mrad}$$

$$\gamma = 34246.667$$

$$\sigma_E = 2.5 \text{ MeV}$$

$$\beta_y = 33 \text{ m}$$

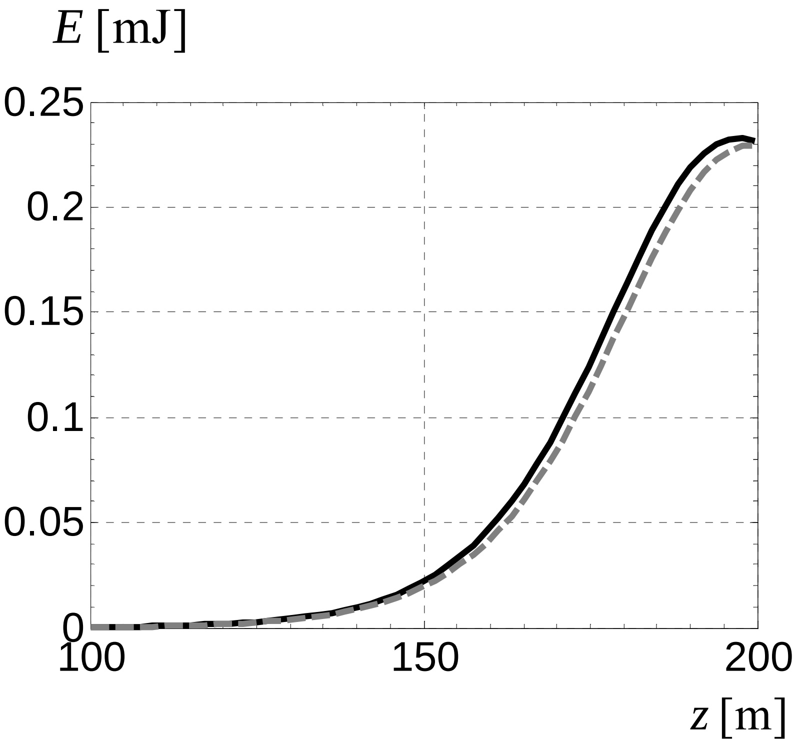
$$\beta_x = 47 \text{ m}$$

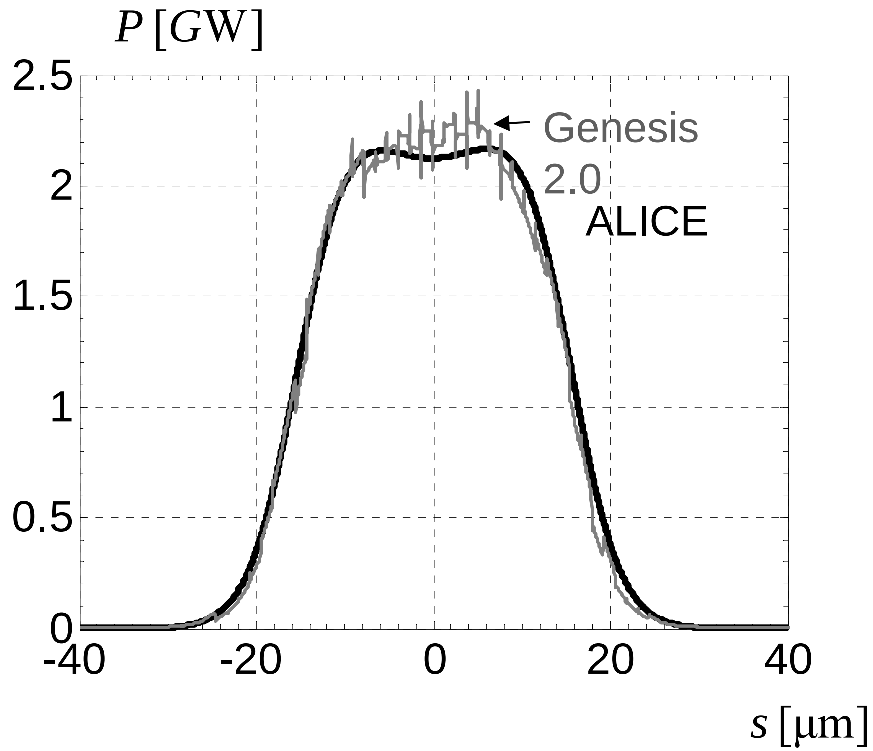
$$\alpha_x = \alpha_y = 0$$

$$\langle x \rangle = \langle y \rangle = 0$$

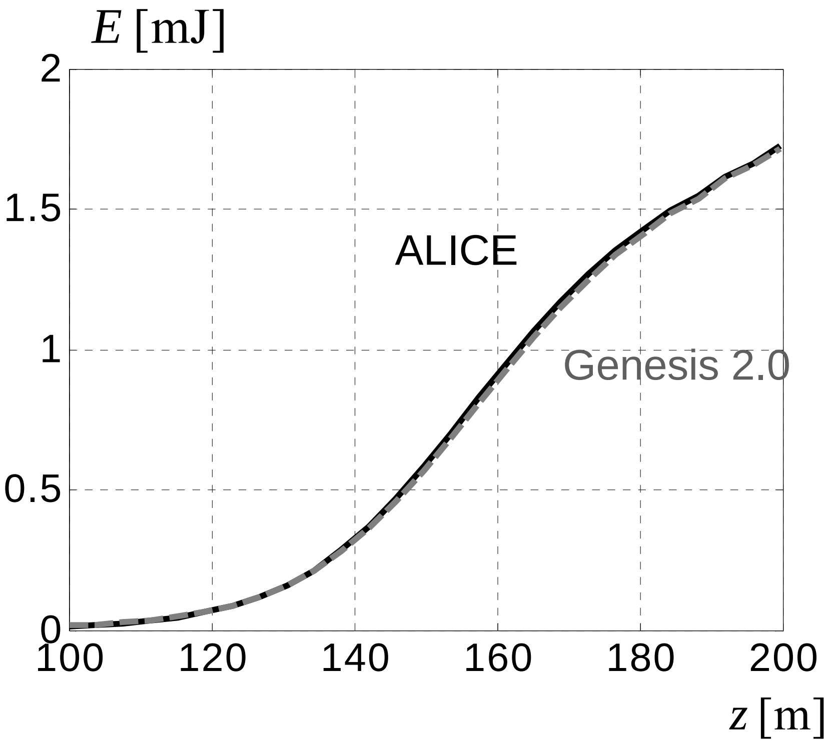
$$\langle x' \rangle = \langle y' \rangle = 0$$

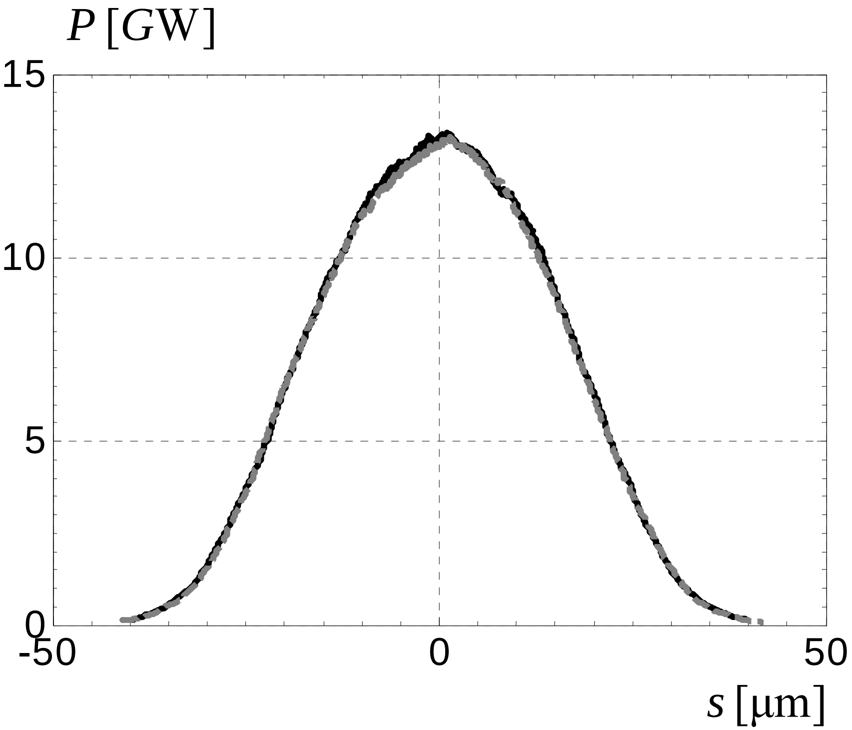
Amplifier with matched Gaussian beam





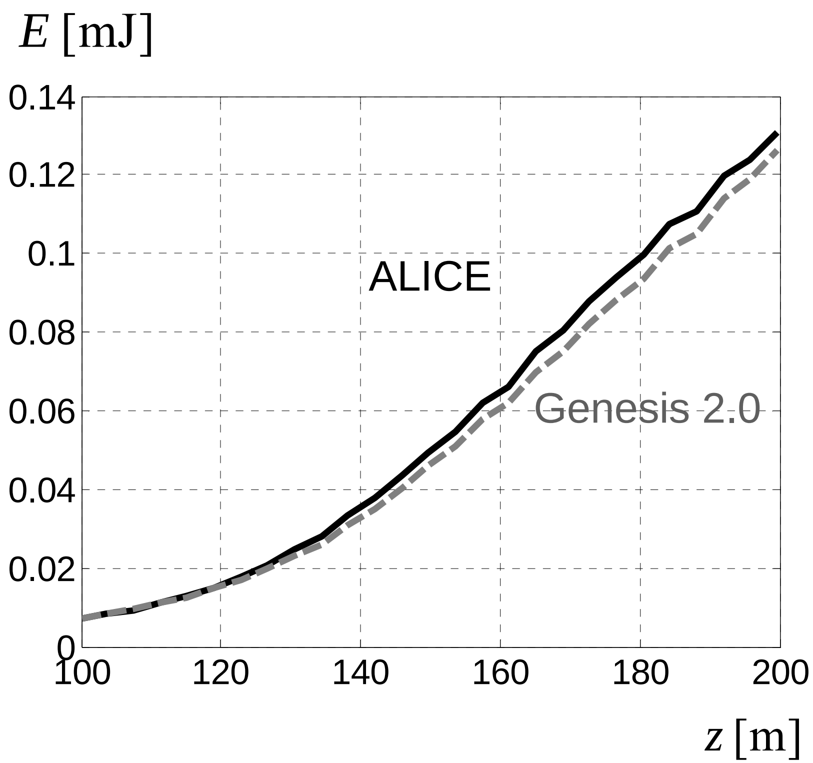
SASE with matched Gaussian beam

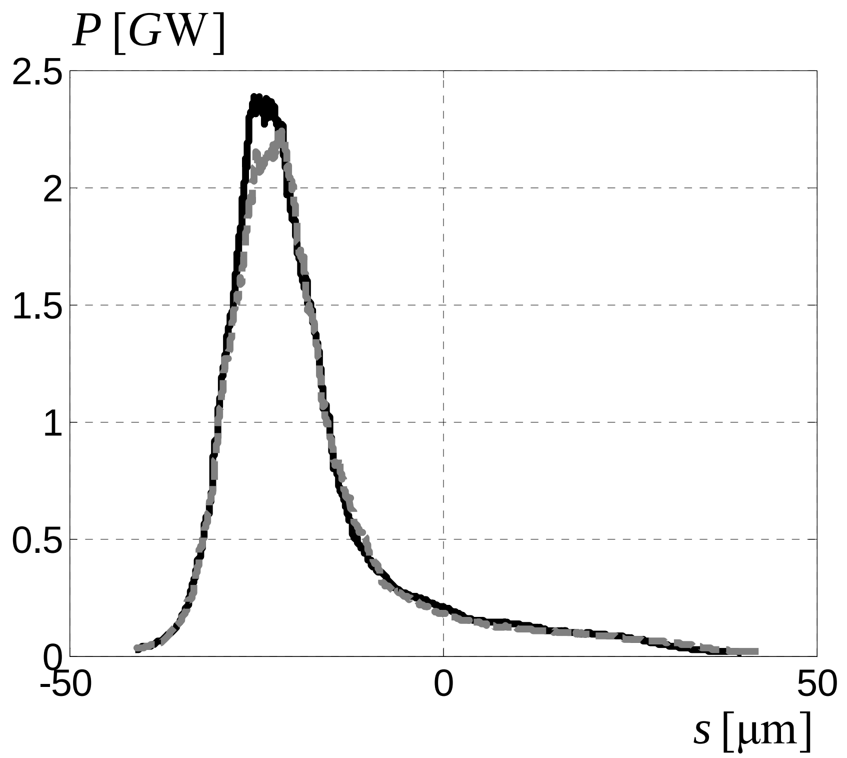




Averaged in space through 1500*56 slices

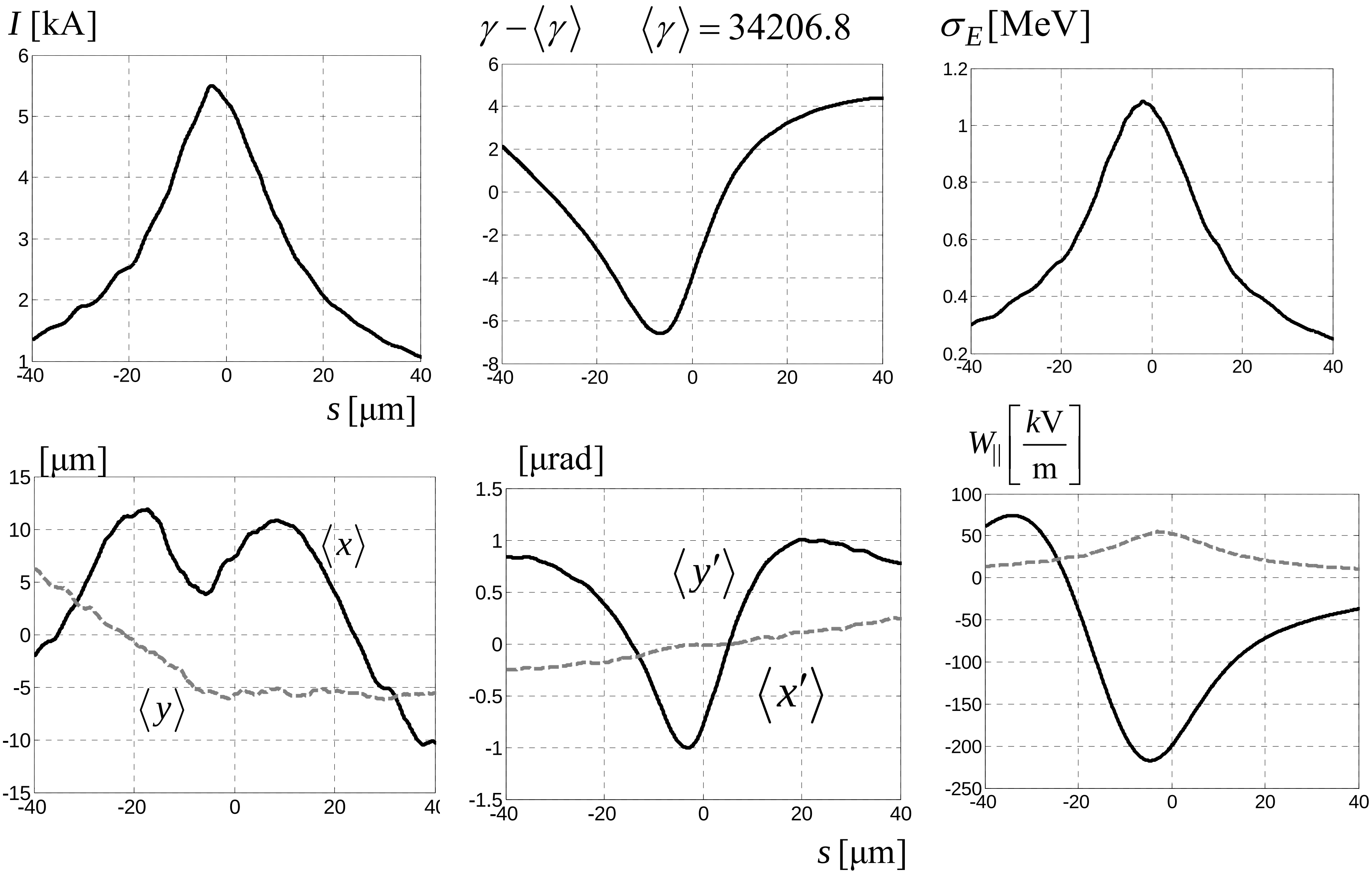
SASE with matched Gaussian beam and wake



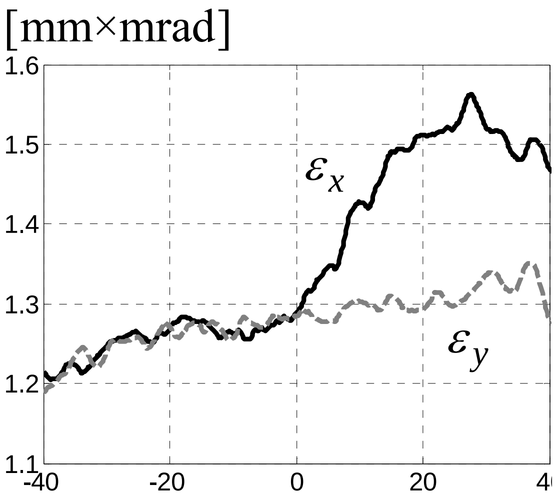


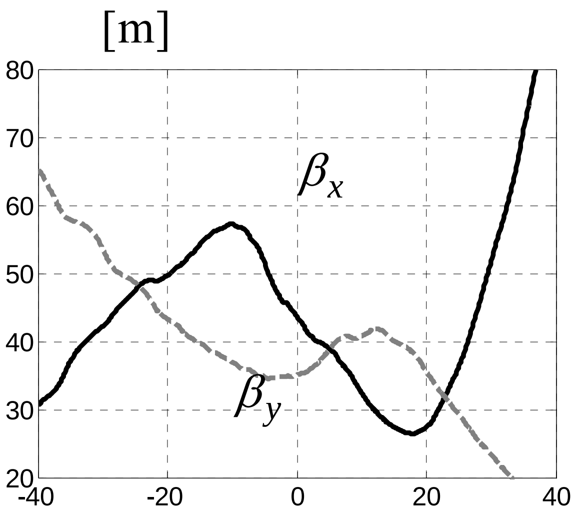
Averaged in space through 500*56 slices

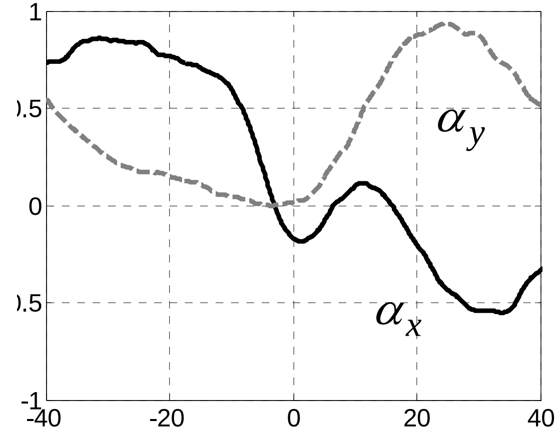
Beam parameters (S2E)



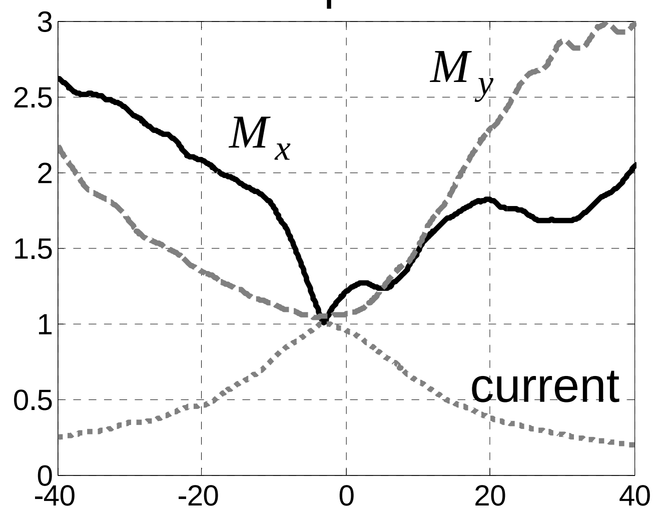
Beam parameters (S2E)







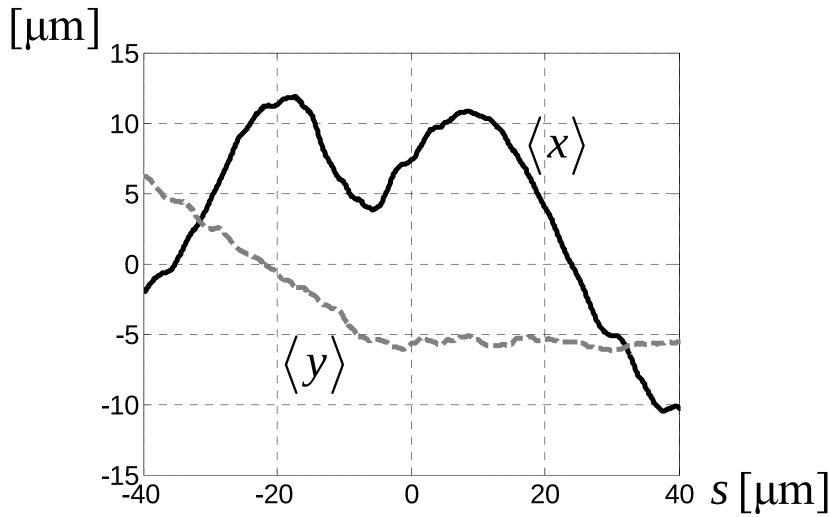
Mismatch parameters



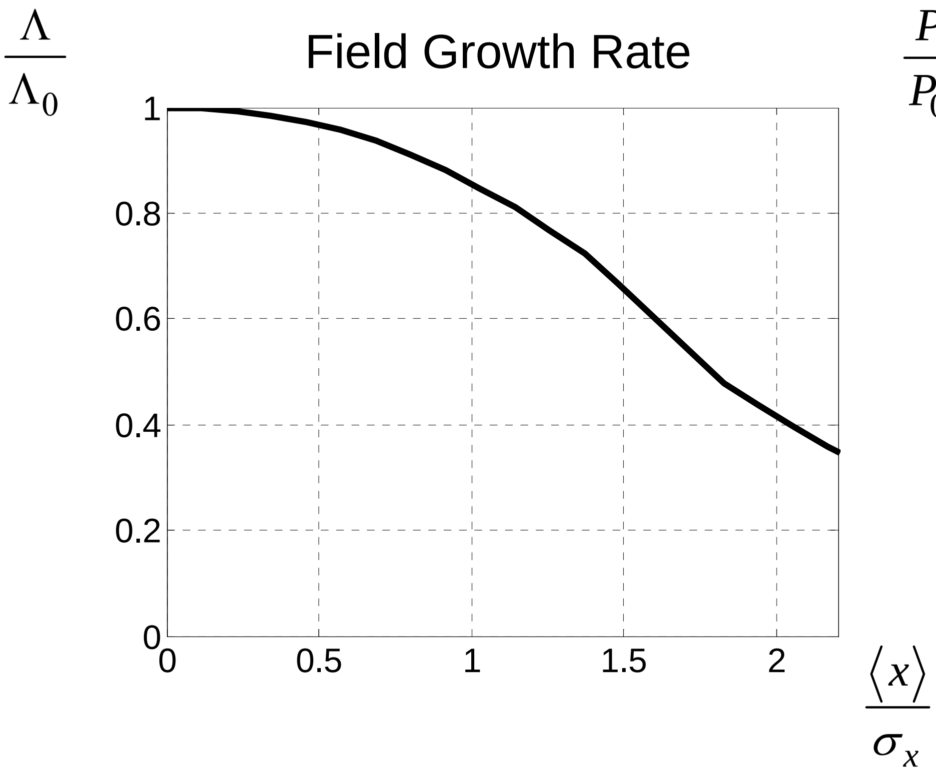
$$\beta_x^0 = 47$$

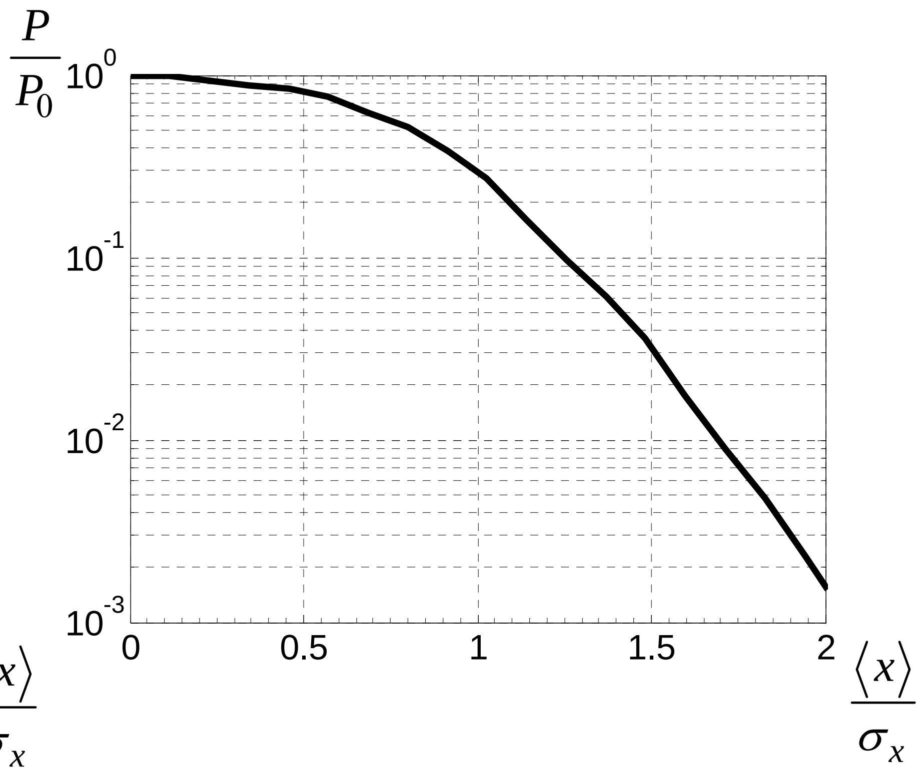
$$\beta_y^0 = 33$$

Beam parameters (S2E)

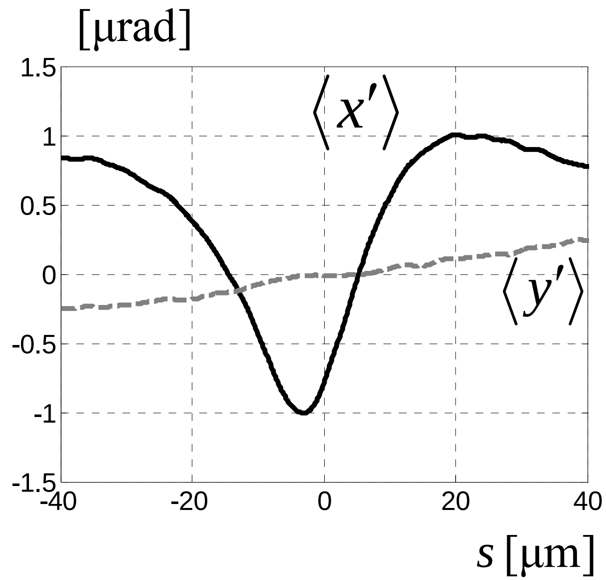


$$\sigma_x = 43.8\,\mu\text{m}$$
$$P_0 = 14.4\ \text{GW}$$
$$\Lambda_0 = 0.055$$





Beam parameters (S2E)

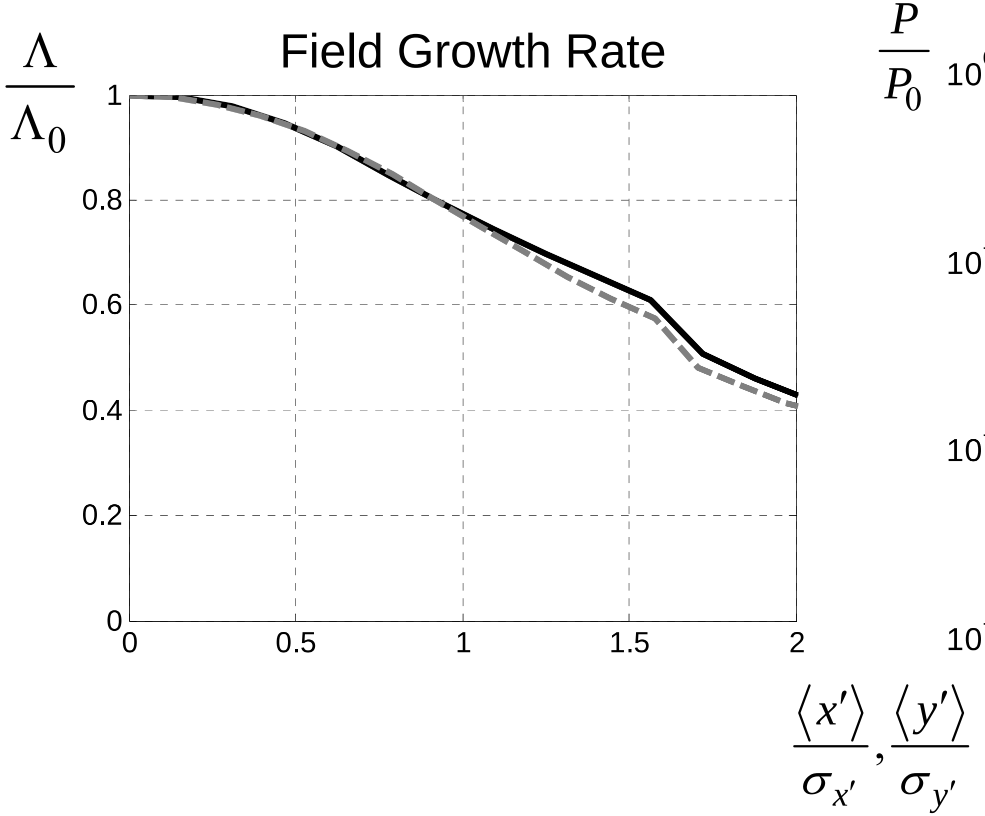


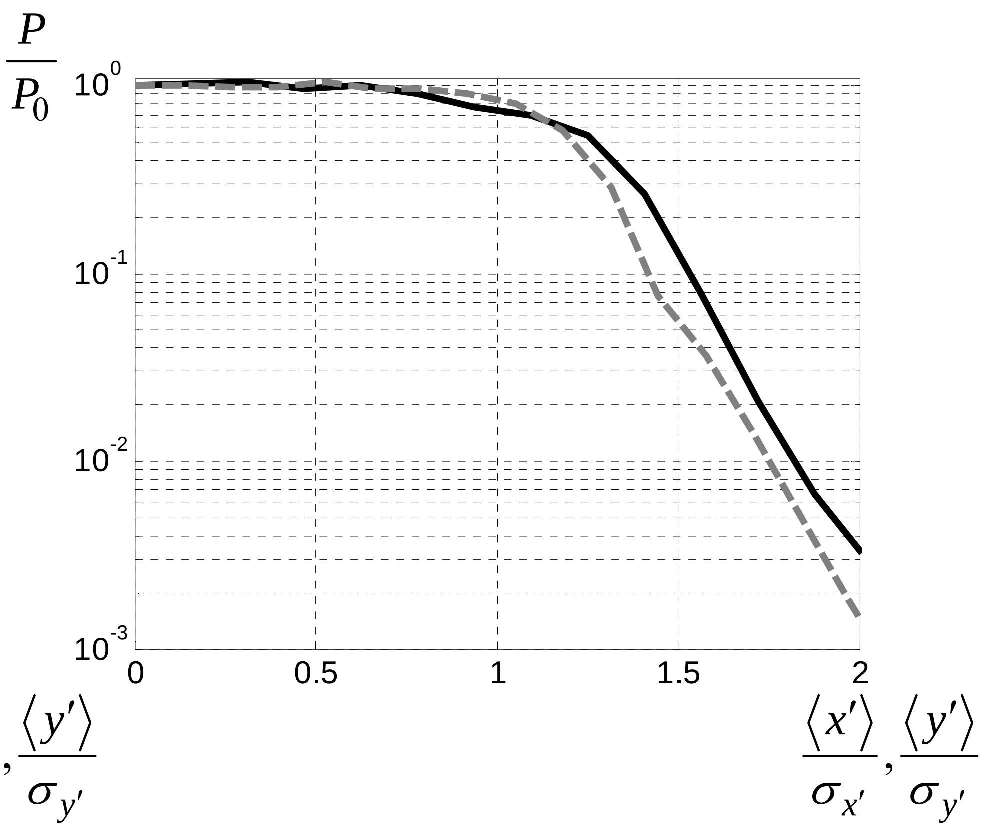
$$\sigma_{x'} = 0.93\,\mu\text{rad}$$

$$\sigma_{y'} = 1.1\,\mu\text{rad}$$

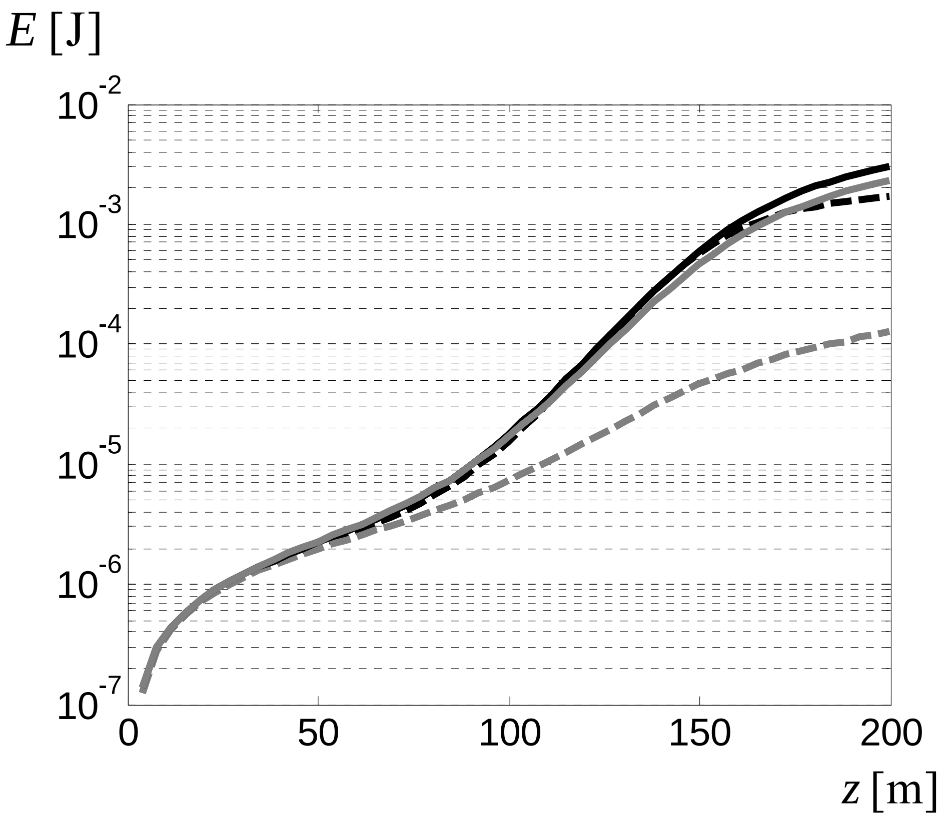
$$P_0 = 14.4\ \text{GW}$$

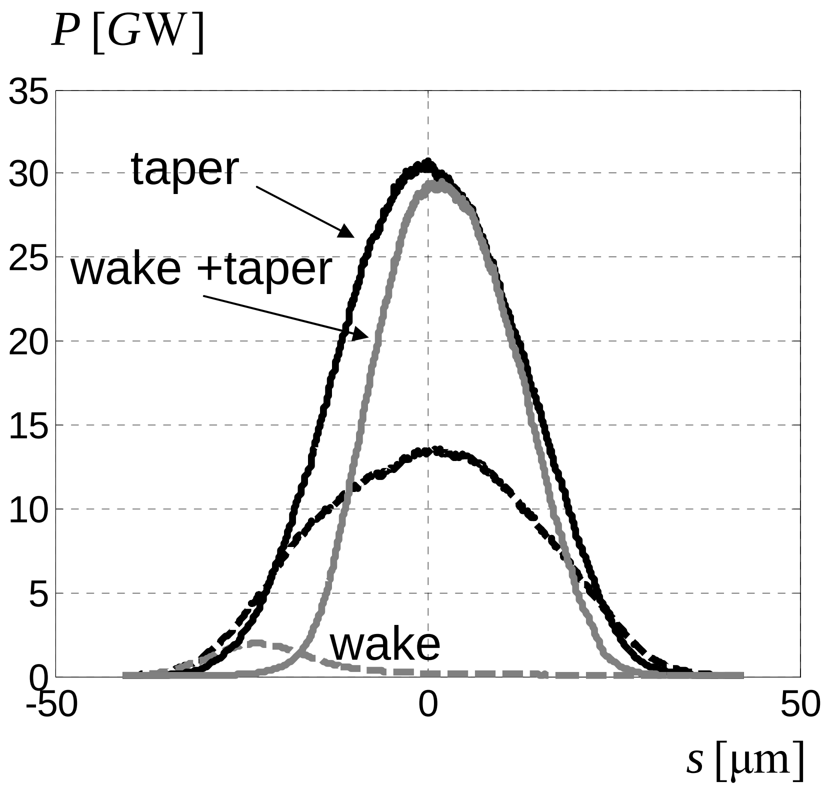
$$\Lambda_0 = 0.055$$





SASE with matched Gaussian beam



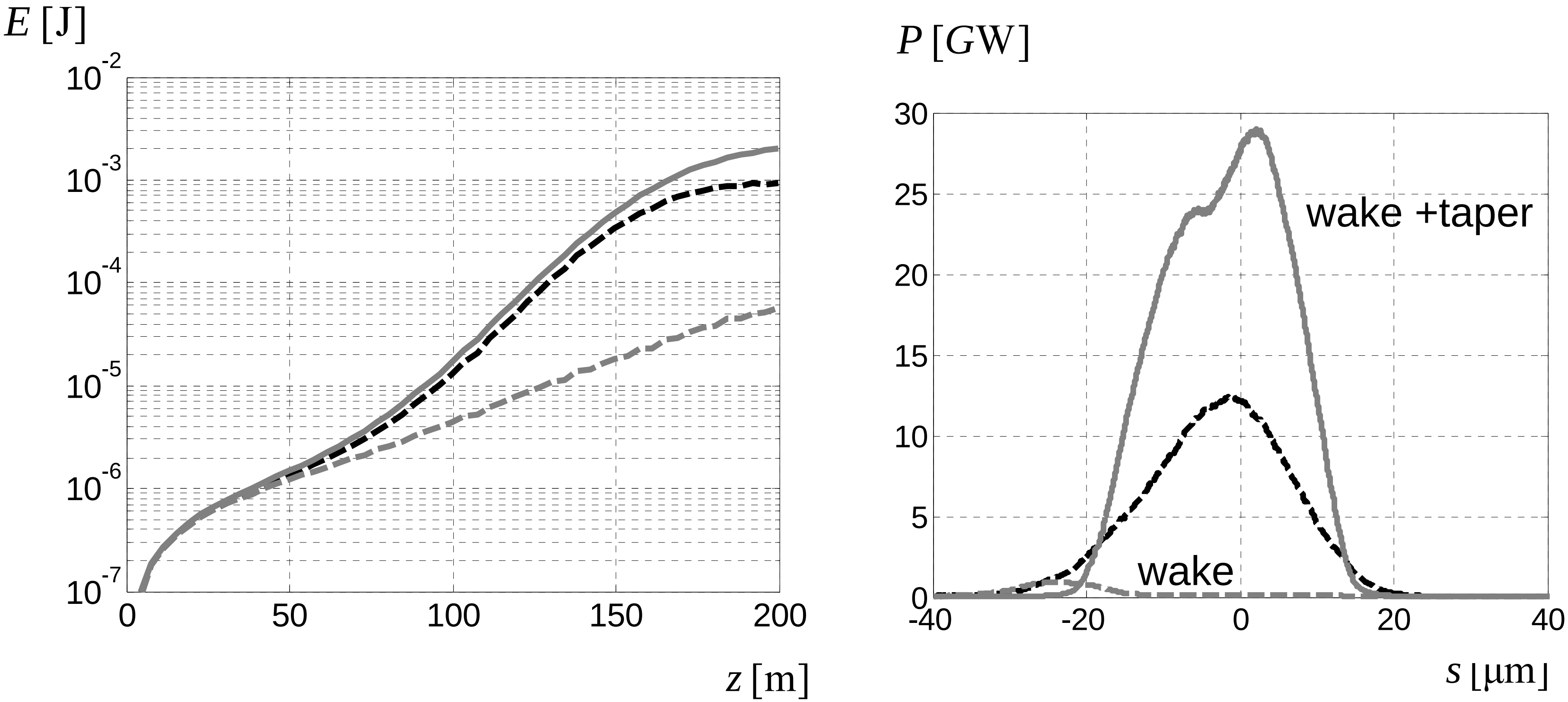


Averaged in space through 1000*56 slices

$E_0 = 1.7$ mJ

	without wake, without taper	with taper	with wake	with wake, with taper
Energy, mJ	1.7	3.1	0.13	2.3
E/E_0	100%	180%	7.3%	136%

SASE with S2E beam

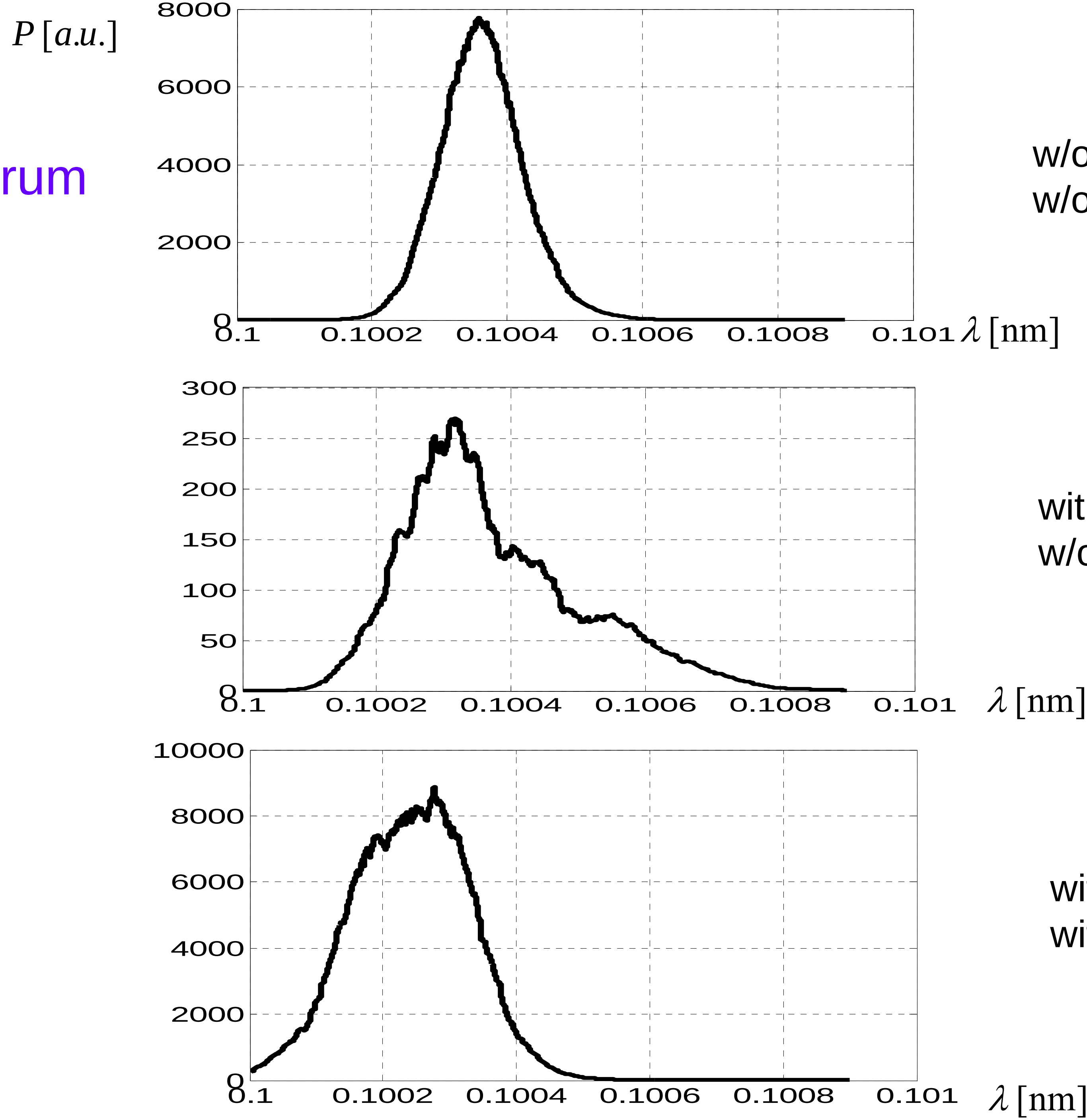


Averaged in space through 1000*56 slices

$$E_0 = 0.93 \text{ mJ}$$

	without wake, without taper	with wake	with wake, with taper
energy,mJ	0.93	0.06	2
E/E_0	100%	6.1%	220%

Spectrum (S2E)



w/o wake
w/o taper

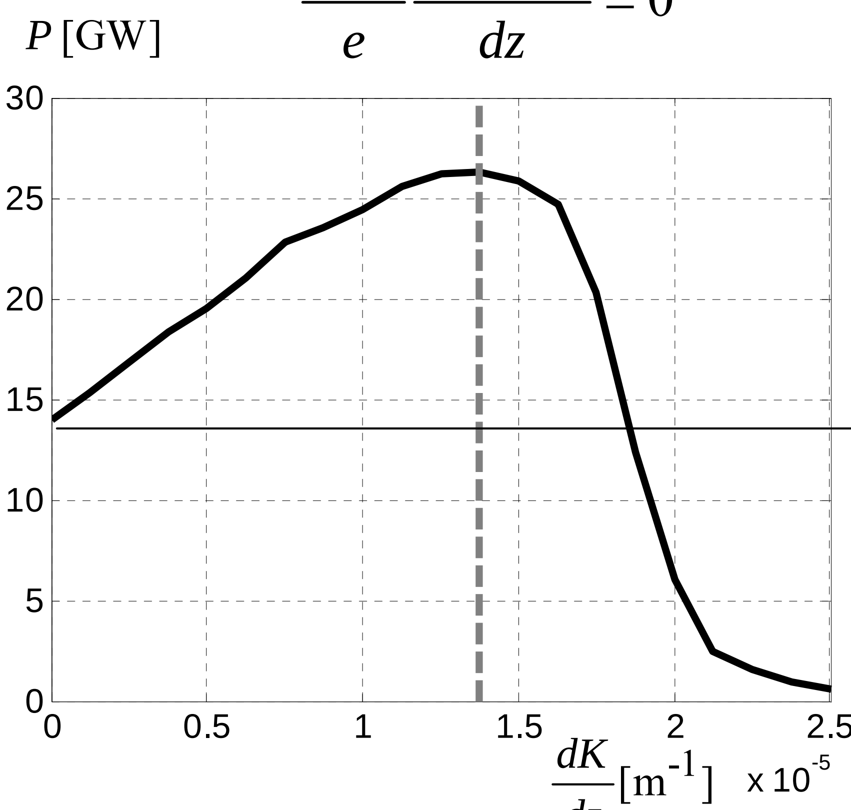
with wake
w/o taper

with wake
with taper

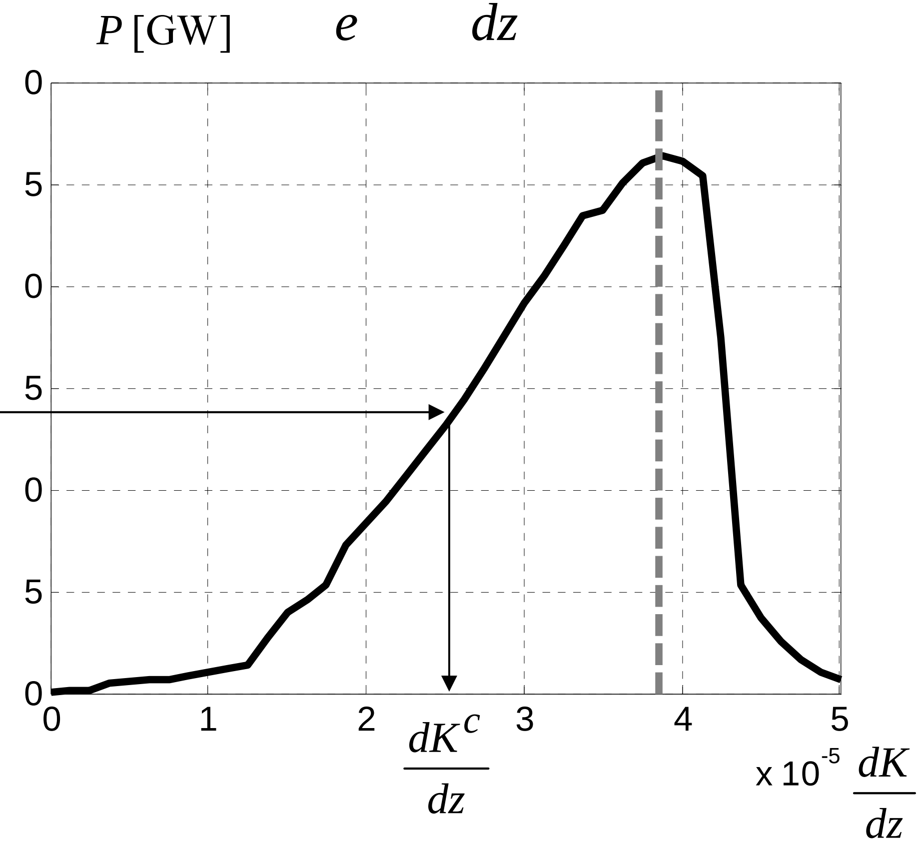
Optimal taper

$$\frac{\lambda_s}{\lambda_u} = \frac{1 + K_{av}^2}{2\gamma^2} \qquad \frac{dK}{dz} = 2\frac{\lambda_s}{\lambda_u}\frac{\gamma_0}{K_0}\frac{d\gamma}{dz} \qquad \frac{dK^c}{dz} = -2.5\cdot 10^{-5}\ \mathrm{m}^{-1}$$

$$\frac{mc^2}{e}\frac{d\gamma^{wake}}{dz} = 0$$



$$\frac{mc^2}{e}\frac{d\gamma^{wake}}{dz} = -180\,\mathrm{kV}$$

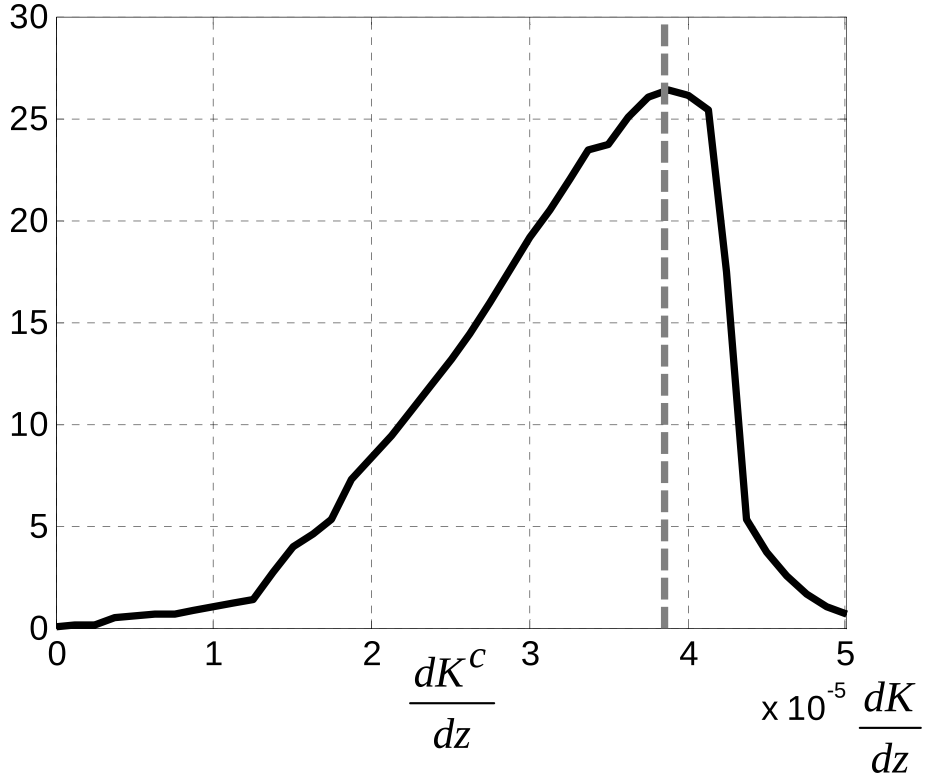


Optimal taper

$$\frac{mc^2}{e}\frac{d\gamma^{wake}}{dz} = -180\,\mathrm{kV}$$

$$\frac{dK}{dz} = -3.85\cdot 10^{-5}\ \ \mathrm{m}^{-1}$$

P [GW]



$$B_u = 3.694\exp\left(-5.068\frac{g}{\lambda_u} + 1.52\left(\frac{g}{\lambda_u}\right)^2\right)$$

$$\frac{\Delta K_{rms}}{K_{rms}} \approx -\frac{\Delta g}{g}\left(-5.068\frac{g}{\lambda_u} + 3.04\left(\frac{g}{\lambda_u}\right)^2\right)$$

$$K_{rms} = 93.4\lambda_u B_u / \sqrt{2}$$

$$\Delta g = -0.0124\,\Delta K_{rms} / K_{rms}$$

$$\Delta g = -0.0124\,\Delta K_{rms} / K_{rms} = 60\cdot 10^{-6}[m]$$

$$\Delta g = -0.0124\frac{\Delta K}{\mathrm{K}} \approx -50\,\mu m$$

$$\frac{dg}{dz} = -0.24\frac{\mu\mathrm{m}}{\mathrm{m}} \approx -1.2\frac{\mu\mathrm{m}}{\mathrm{module}}$$

Comparison with previous estimations

Undulator gap error tolerances for wakefield compensation in XFEL

Igor Zagorodnov

BDGM, DESY

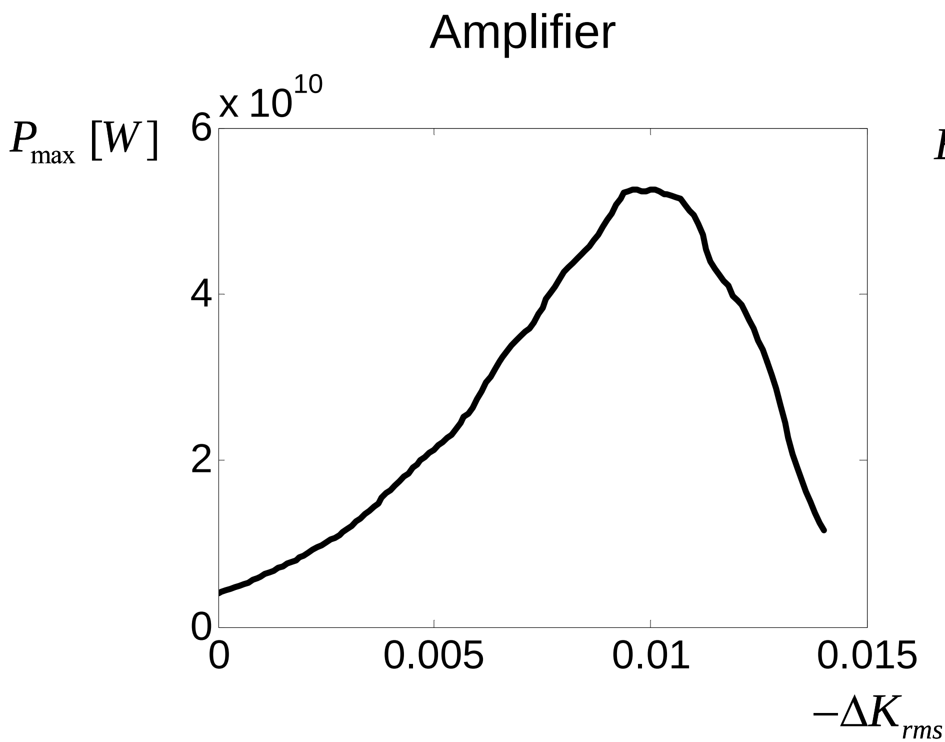
27.03.06/08.05.06

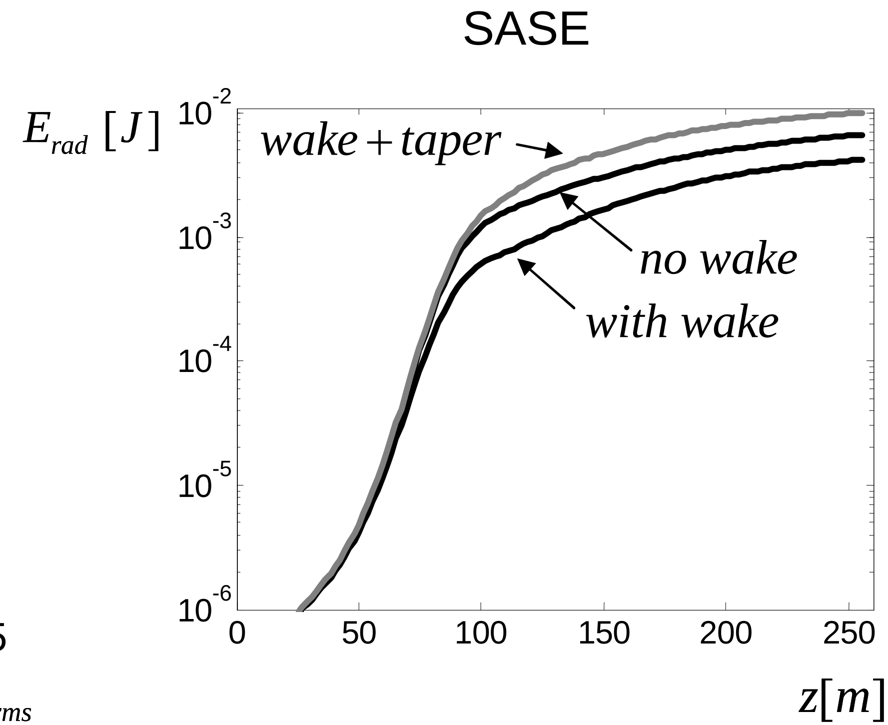
SASE (2005) $\varepsilon \approx 0.7\ \mathrm{mm}\times\mathrm{mrad}$

SASE 2 parameters

Parameter	symbol	unit	Value
radiation wavelength	λ	nm	0.1
Energy	E	GeV	17.5
energy spread	σ_E	MeV	1
undulator parameter	K_{rms}		1.97
Emmitance	ε_n	mm*mrad	0.7
peak current	I	kA	5
average beta function	β	m	17.25
undulator section length	L_{sect}	m	5
intersection length	L_{inters}	m	1.1
total length	L_{total}	m	260
undulator period	λ_u	m	0.048

$$\rho = 7.1\cdot 10^{-4}$$





The maximum power dependence on tapering (left) and the radiation power along the undulator (right)

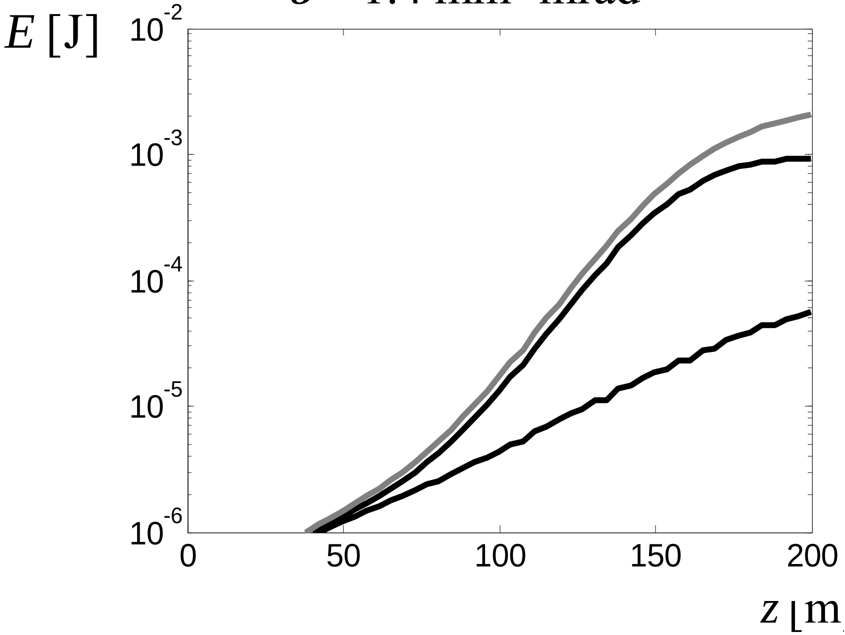
$$W_{sh} = 3\rho \frac{W_b}{N_c\sqrt{\pi \ln N_c}} = 11800[W]$$

$$W_{\|} = 150kV / nC / m$$

As one can see from this figure, in the absence of wakefields the radiation pulse energy is 2.3 mJ at 130m. It is reduced to 1.2 mJ by undulator wakefields. The optimal linear undulator tapering allows to avoid the degradation and to increase the radiation energy up to 3.5 mJ at 130m

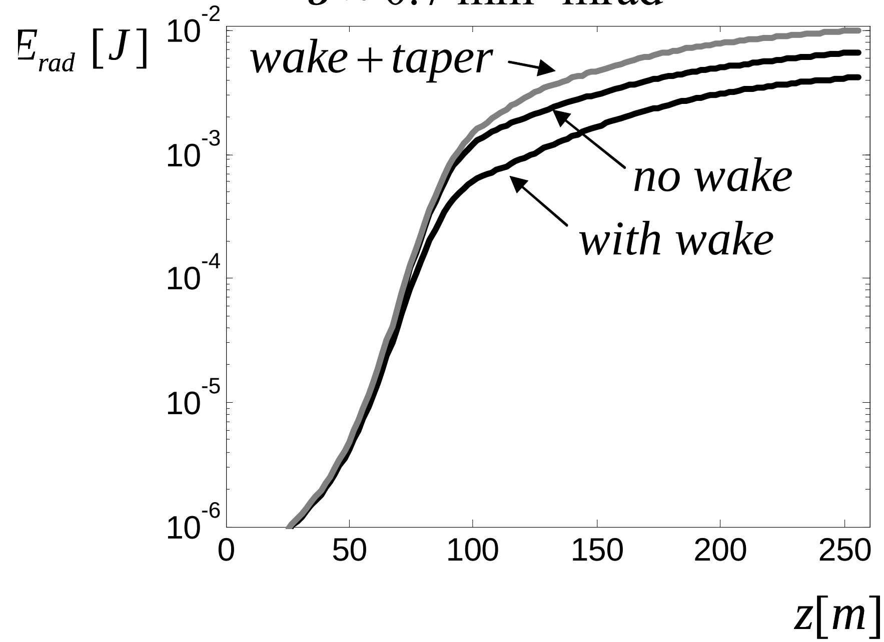
SASE (2008)

$\varepsilon \approx 1.4$ mm×mrad



SASE (2005)

$\varepsilon \approx 0.7$ mm×mrad



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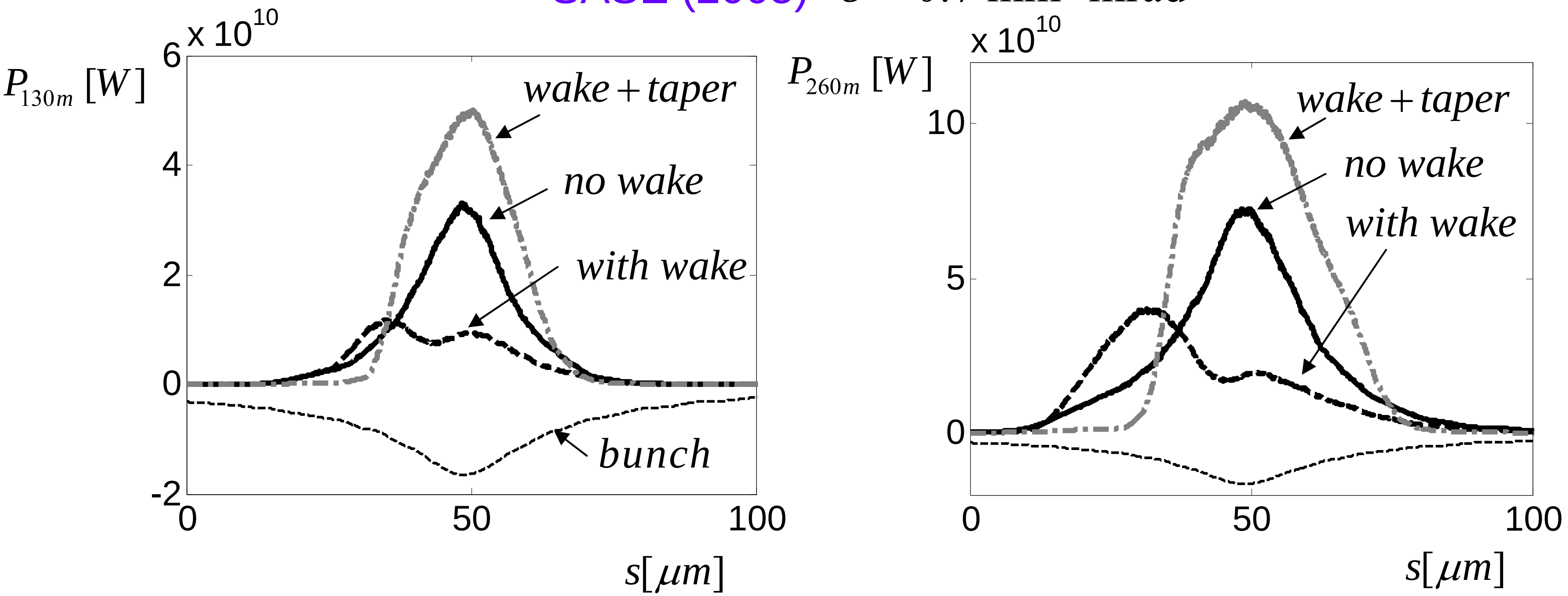
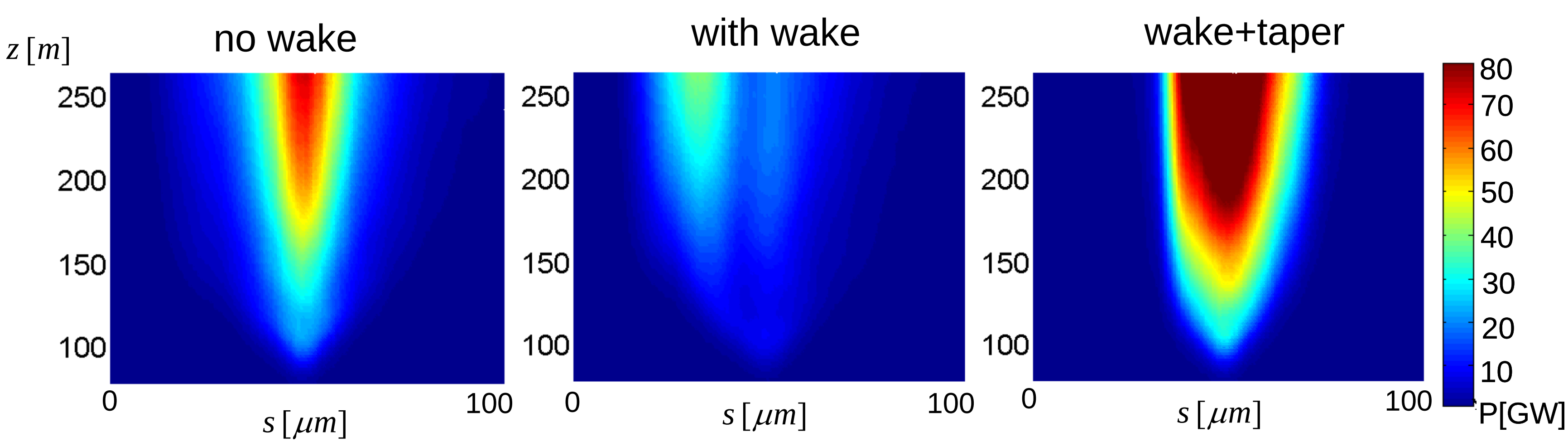
SASE (2005) $\varepsilon \approx 0.7$ mm×mrad



The radiation power in the middle (left) and at the end of the undulator (right)



SASE (2005) $\varepsilon \approx 0.7\ \mathrm{mm}\times\mathrm{mrad}$

$$B_u = 3.694 \exp\left(-5.068 \frac{g}{\lambda_u} + 1.52 \left(\frac{g}{\lambda_u} \right)^2 \right)$$

$$\frac{\Delta K_{rms}}{K_{rms}} \approx -\frac{\Delta g}{g} \left(-5.068 \frac{g}{\lambda_u} + 3.04 \left(\frac{g}{\lambda_u} \right)^2 \right)$$

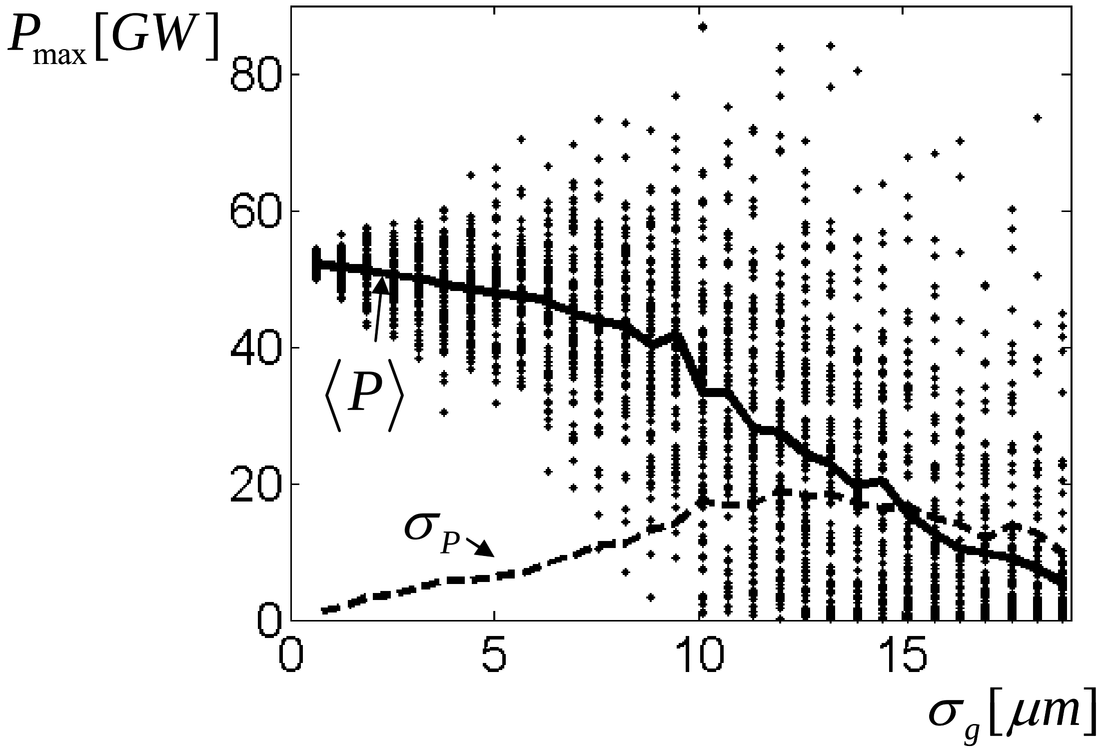
$$K_{rms} = 93.4 \lambda_u B_u / \sqrt{2}$$

$$\Delta g = -0.0124\, \Delta K_{rms} / K_{rms}$$

Optimal taper

$$\Delta g = -0.0124\, \Delta K_{rms} / K_{rms} = 60 \cdot 10^{-6} [m]$$

Steady-state SASE (2005) $\varepsilon \approx 0.7$ mm×mrad



$$f(\delta g) = \frac{1}{\sqrt{2\pi}\sigma_g} \exp\left(-\frac{\delta g^2}{2\sigma_g{}^2}\right)$$

Impact of statistical errors of undulator gap on power gain.

$$\frac{P_0 - \langle P \rangle}{P_0} 100\% \approx 20\% \qquad for \quad \sigma_g = 10\mu m$$

$$\frac{P_0 - \left[\langle P \rangle - 3\sigma_p\right]}{P_0} 100\% \approx 20\% \qquad for \quad \sigma_g = 2\mu m$$

SASE (2005) $\varepsilon \approx 0.7$ mm×mrad

For 5 mkm gap error at position z=130m

Steady-state

$$\frac{\left\langle P_{\max}^{\sigma_g} \right\rangle}{P_{\max}^{0}} = 0.91$$

$$\sigma_P = 0.22$$

SASE

$$\frac{\left\langle E_{\max}^{\sigma_E} \right\rangle}{E_{\max}^{0}} = 0.88$$

$$\sigma_E = 0.16$$