Beam Dynamics and SASE Simulations for XFEL

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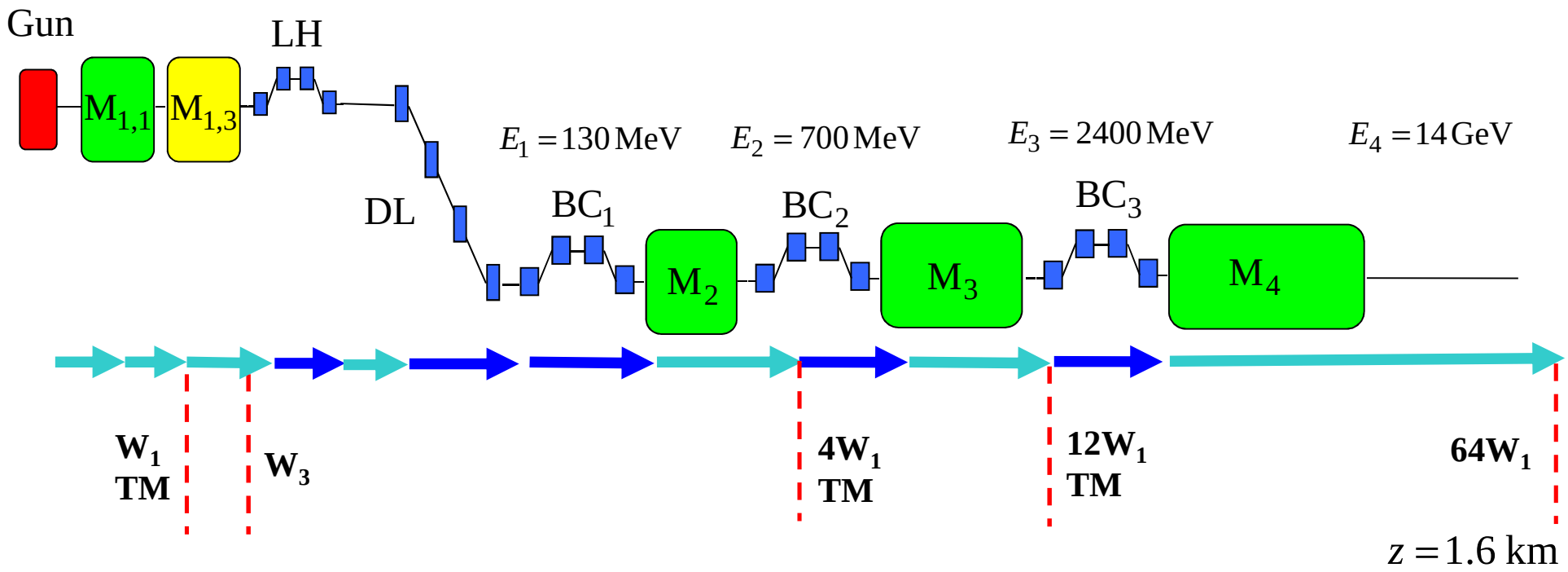
14.02.2011

DESY

Beam dynamics simulations for the European XFEL

Full 3D simulation method (**200 CPU, ~10 hours**)



ASTRA (tracking with **3D space charge**, DESY, K. Flötmann)

CSRtrack (tracking through dipoles, DESY, M. Dohlus, T. Limberg)

W1 -TESLA cryomodule wake (TESLA Report 2003-19, DESY, 2003)

W3 - ACC39 wake (TESLA Report 2004-01, DESY, 2004)

TM - transverse matching to the design optics

Choosing of machine parameters

Macro-parameters

Charge Q, nC	Momentum compaction factor in BC_1 $R_{56,1}$, [mm]	Compr. in BC_1 C_1	Momentum compaction factor in BC_2 $R_{56,2}$, [mm]	Compr. in BC_2 C_2	Momentum compaction factor in BC_3 $R_{56,3}$, [mm]	Total compr. C	First derivative Z', [m^{-1}]	Second derivative Z'', [m^{-2}]
1	-100	3.5	-54	8	-20	121	0	2000
0.5	-89	3.5	-50	8	-20	217	0	1000
0.25	-78	3.5	-50	8	-20	385	0	1000
0.1	-71	3.5	-50	8	-20	870	0	1000
0.02	-67	3.5	-50	8	-20	4237	0	500

$E_1 = 130\,\mathrm{MeV}$ $E_2 = 700\,\mathrm{MeV}$ $E_3 = 2400\,\mathrm{MeV}$

I. Zagorodnov, M. Dohlus, *A Semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects*, Physical Review STAB 14 (2011), 014403.

XFEL beam dynamic simulations for different charges

RF settings in accelerating modules

Charge, nC	$V_{1,1}$, [MV]	$\varphi_{1,1}$, [deg]	$V_{1,3}$, [MV]	$\varphi_{1,3}$, [deg]	V_2, [MV]	φ_2, [deg]	V_3, [MV]	φ_3, [deg]
1	145	5.4	22	164	656	29.7	1832	21.7
0.5	150	11.5	23.1	175.5	661	30.3	1826	21.3
0.25	157	18.9	25.1	189	652	29	1860	23.9
0.1	165	25	27.6	199.5	645	27.9	1885	25.6
0.02	164	23.4	28	194.6	640	27.1	1905	26.8

Tolerances (analytically) **without self fields** (10 % change of compression)

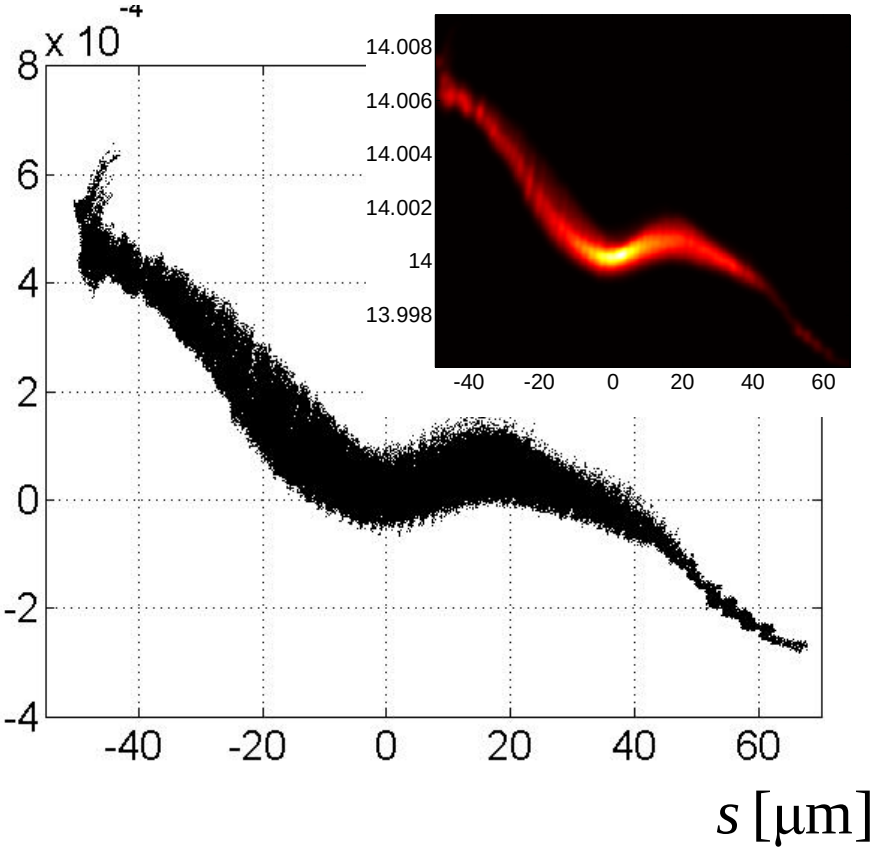
Q, nC	1	0.5	0.25	0.1	0.02
$\left\|\Delta\tilde{V}_{1,1}\right\| / V^0_{1,1}$	5e-4	3e-4	2e-4	1e-4	2.5e-5

XFEL beam dynamic simulations for different charges (full)

Q=1 nC

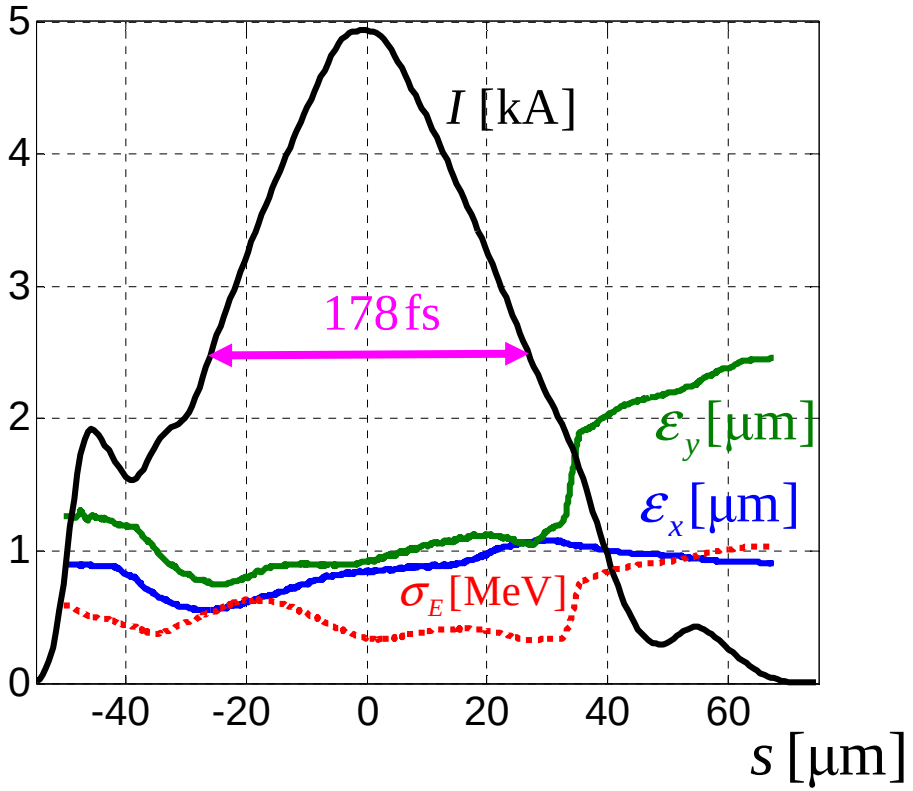
δ_E

Phase space



bunch head

Current, emittance, energy spread



$\varepsilon_x^{proj} = 0.9\,[\mu m]$

$\varepsilon_y^{proj} = 3.5\,[\mu m]$

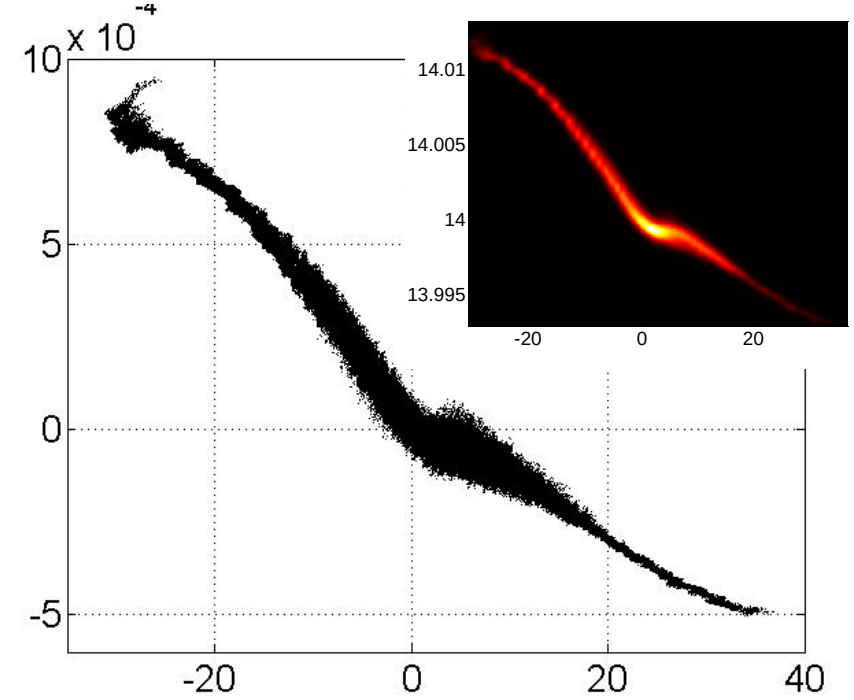
We have removed 6% of bad particles in the analysis

XFEL beam dynamic simulations for different charges (full)

Q=500 pC

δ_E

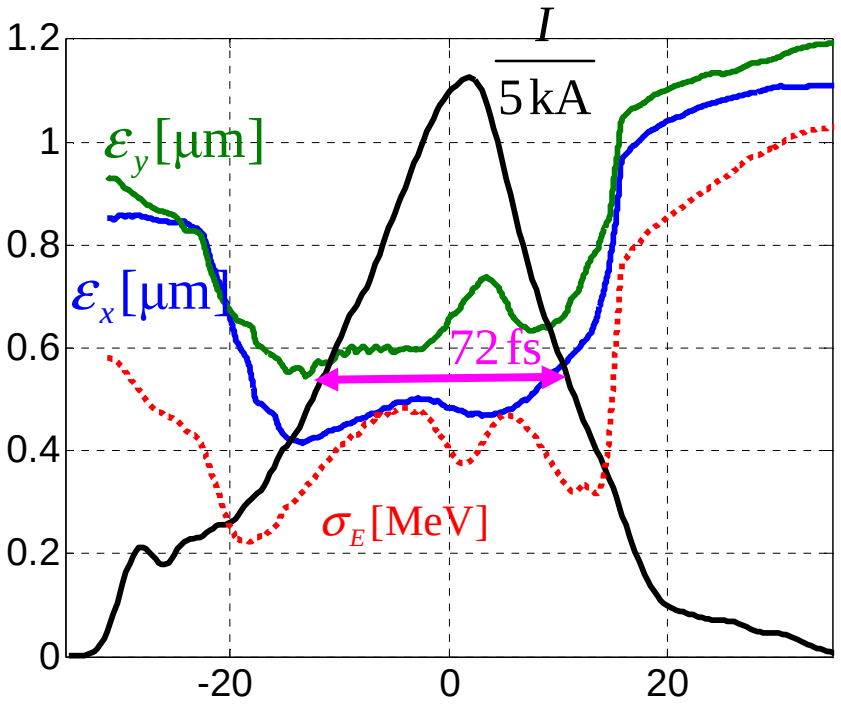
Phase space



s [μm]

bunch head

Current, emittance, energy spread



s [μm]

$\varepsilon_x^{proj} = 0.7\,[\mu m]$

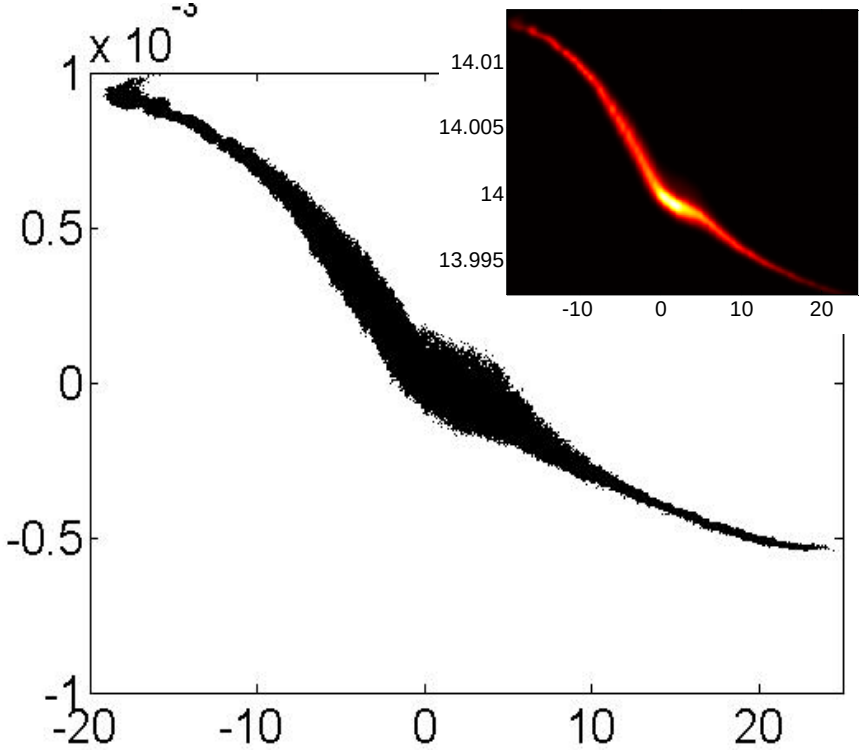
$\varepsilon_y^{proj} = 2.2\,[\mu m]$

XFEL beam dynamic simulations for different charges (full)

Q=250 pC

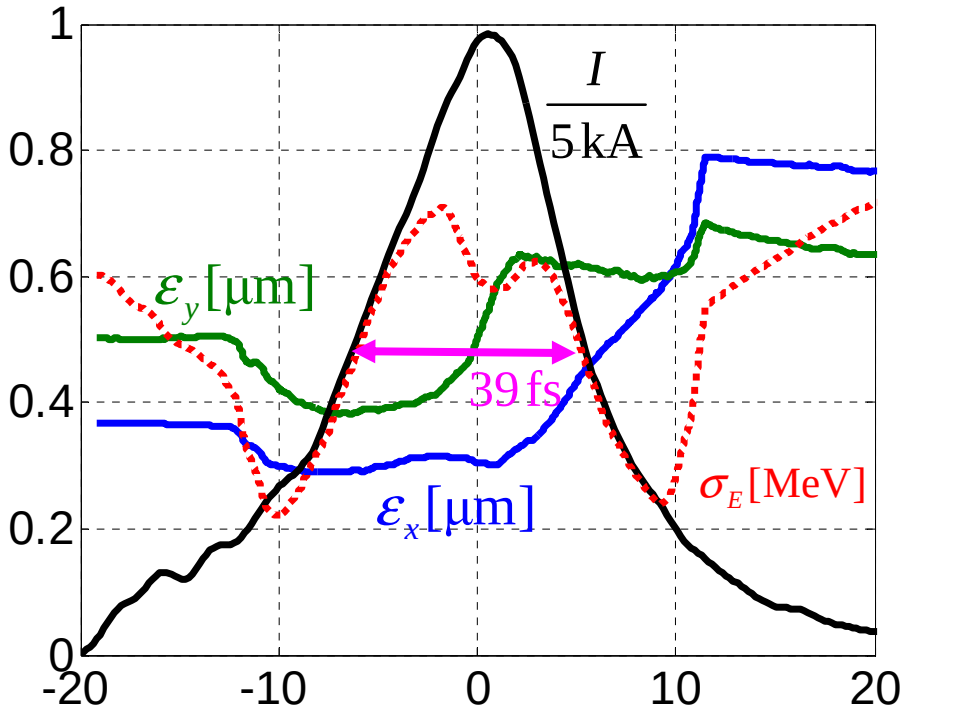
δ_E

Phase space



s [μm]

Current, emittance, energy spread



s [μm]

bunch head

$\varepsilon_x^{proj} = 0.45\,[\mu m]$

$\varepsilon_y^{proj} = 1.5[\mu m]$

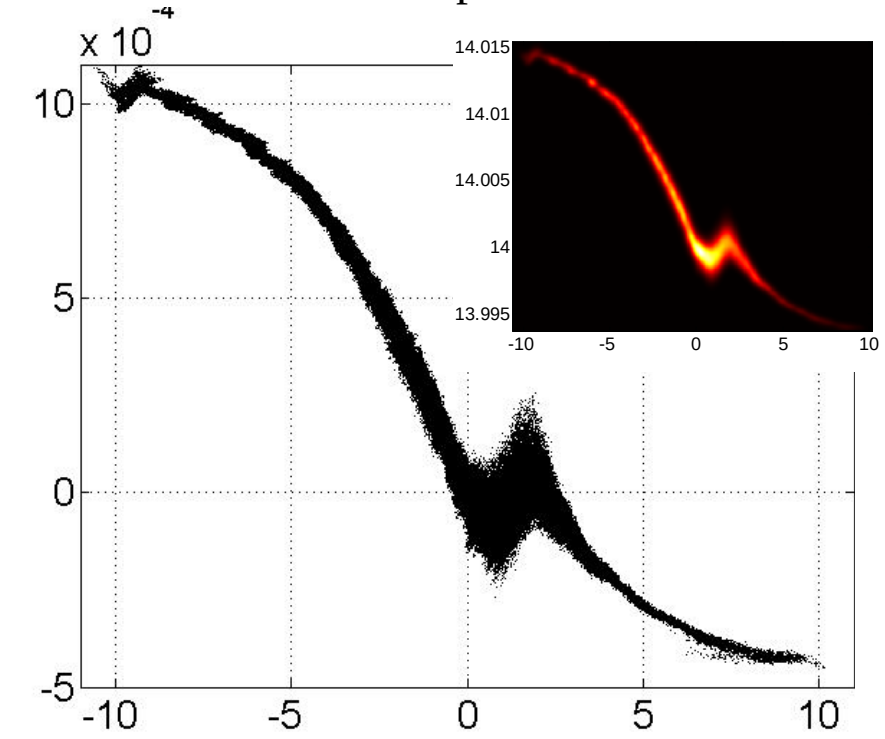
We have removed 6% of bad particles in the analysis (Q=235 pC!)

XFEL beam dynamic simulations for different charges (full)

Q=100 pC

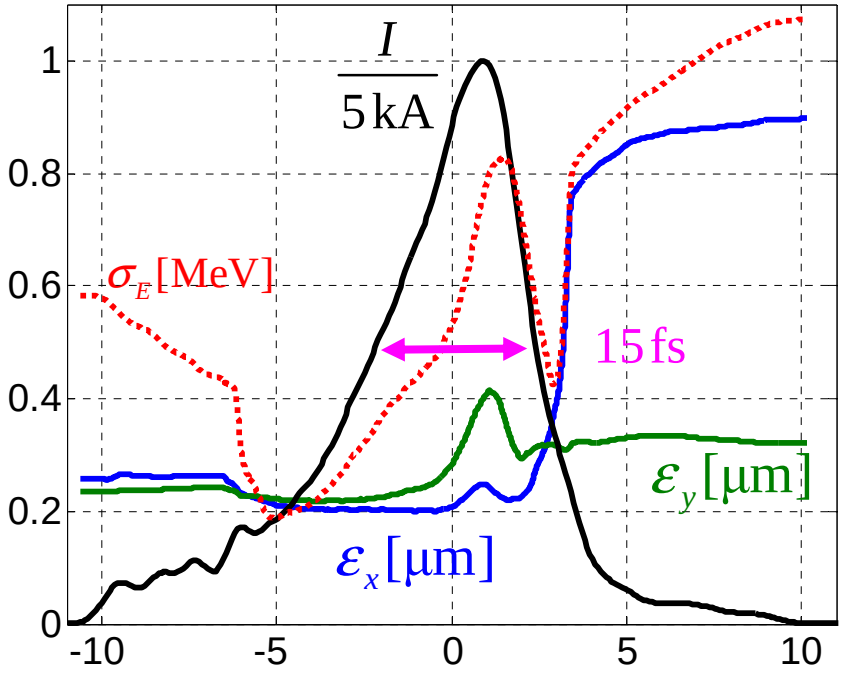
δ_E

Phase space



s [μm]

Current, emittance, energy spread



s [μm]

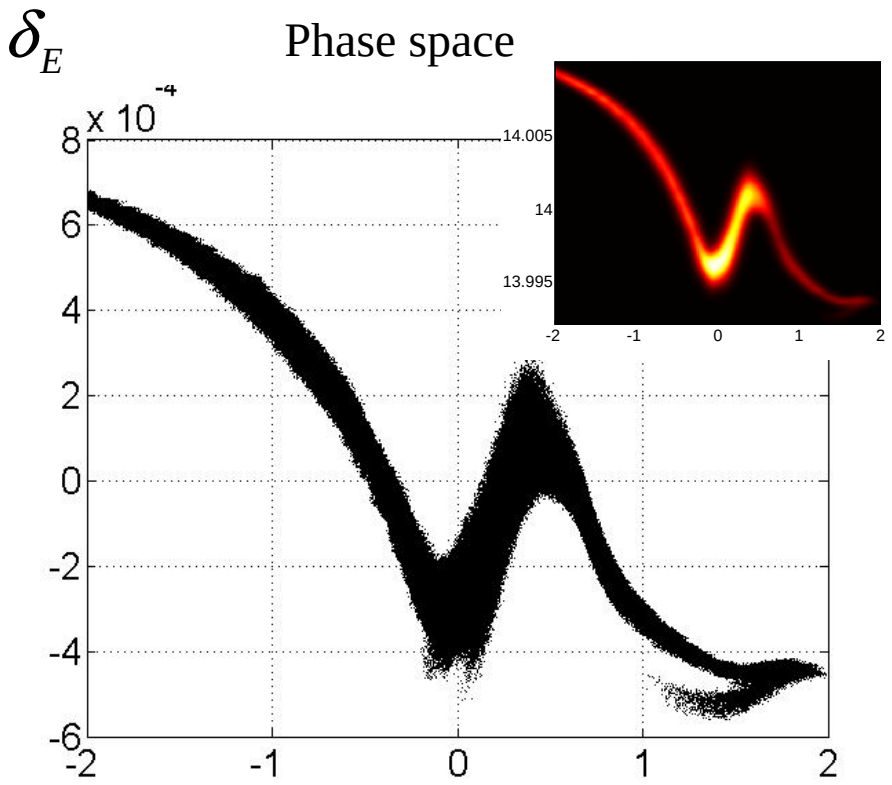
bunch head

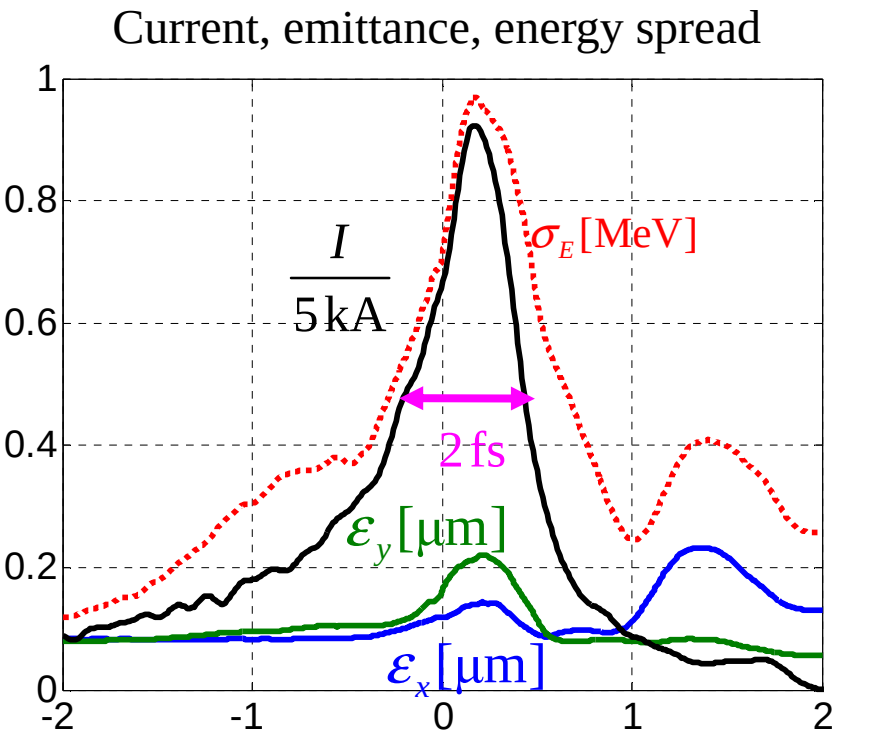
$$\varepsilon_x^{proj} = 0.35\,[\mu m]$$

$$\varepsilon_y^{proj} = 0.84\,[\mu m]$$

XFEL beam dynamic simulations for different charges (full)

Q=20 pC





s [μm]

bunch head

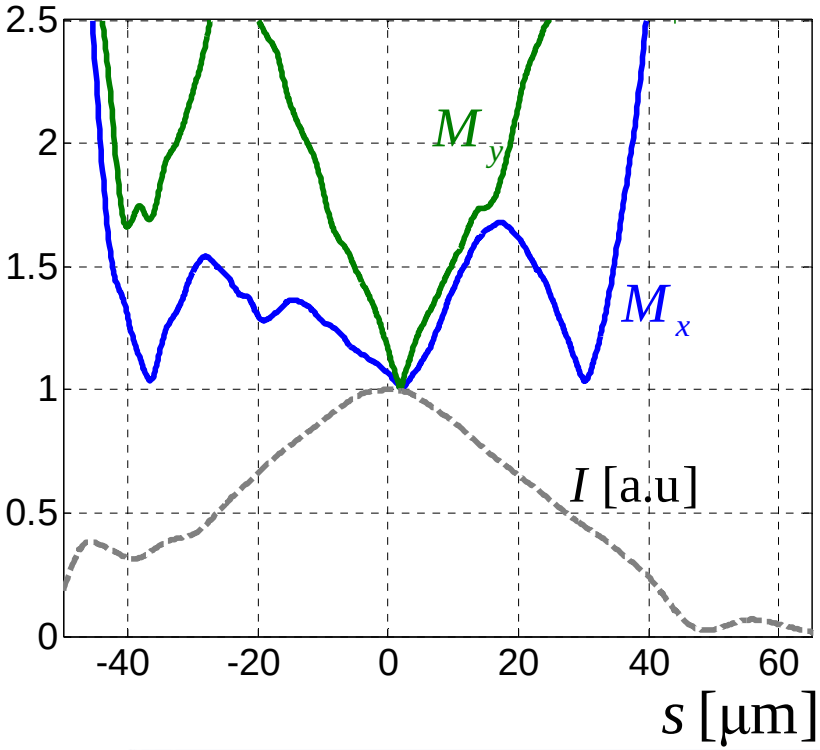
$$\varepsilon_x^{proj} = 0.14\,[\mu\mathrm{m}]$$

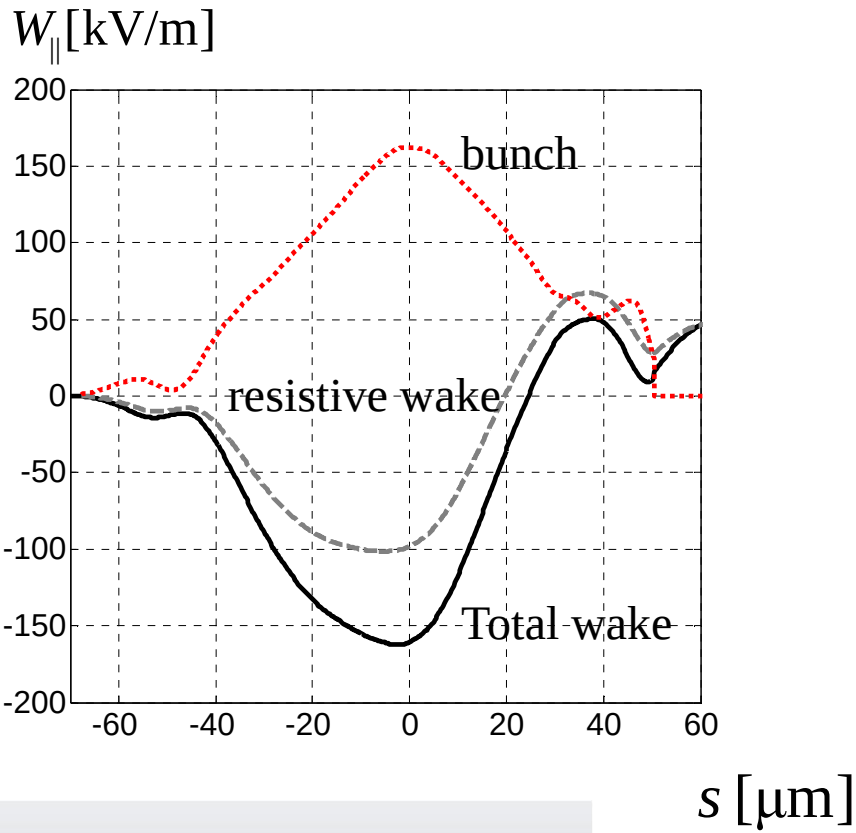
$$\varepsilon_y^{proj} = 0.26\,[\mu\mathrm{m}]$$

Beam parameters from S2E simulations

Parameter	Unit					
Bunch charge	nC	1	0.5	0.25	0.1	0.02
Peak current (gun)	A	43	24	13.5	5.7	1.2
Bunch length (gun, FWHM)	ps	25	22	20	17	17
Slice emittance (gun)	μm	0.8	0.5	0.3	0.21	0.09
Projected emittance (gun)	μm	1	0.7	0.6	0.3	0.1
Compression		114	233	363	877	3833
Peak current	kA	**4.9**	**5.6**	**4.9**	**5**	**4.6**
Bunch length (FWHM)	fs	178	72	39	12	2.2
Slice emittance	μm	**1**	**0.7**	**0.5**	**0.3**	**0.2**
Projected emittance	μm	3.5	2.2	1.5	0.84	0.26
Slice energy spread (**laser heater off**)	MeV	0.45	0.44	0.6	0.6	0.8

Mismatch and wake Q=1nC

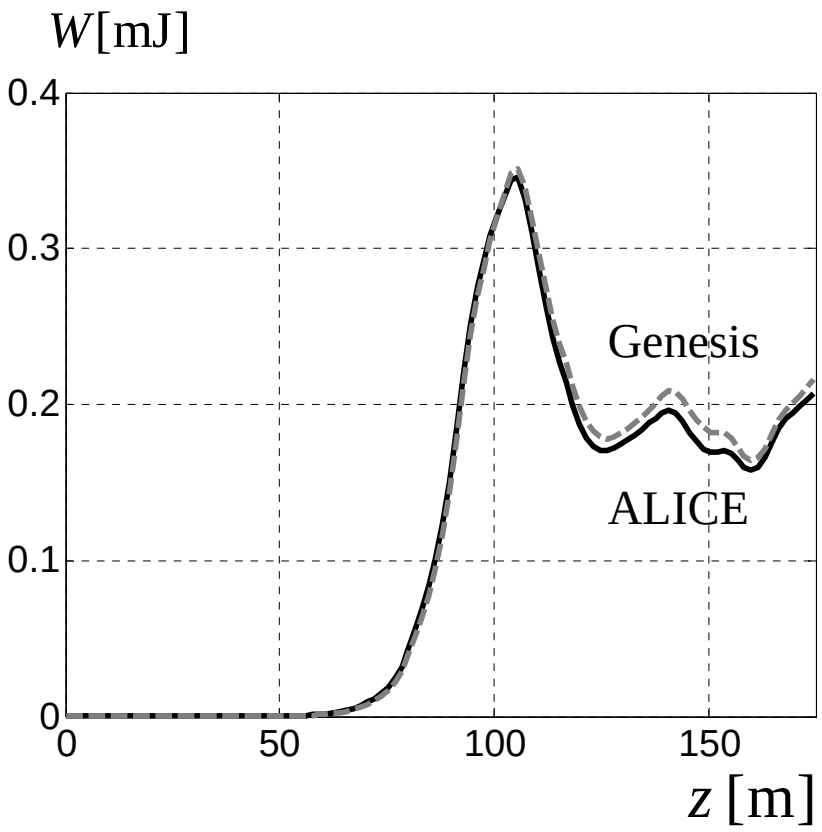


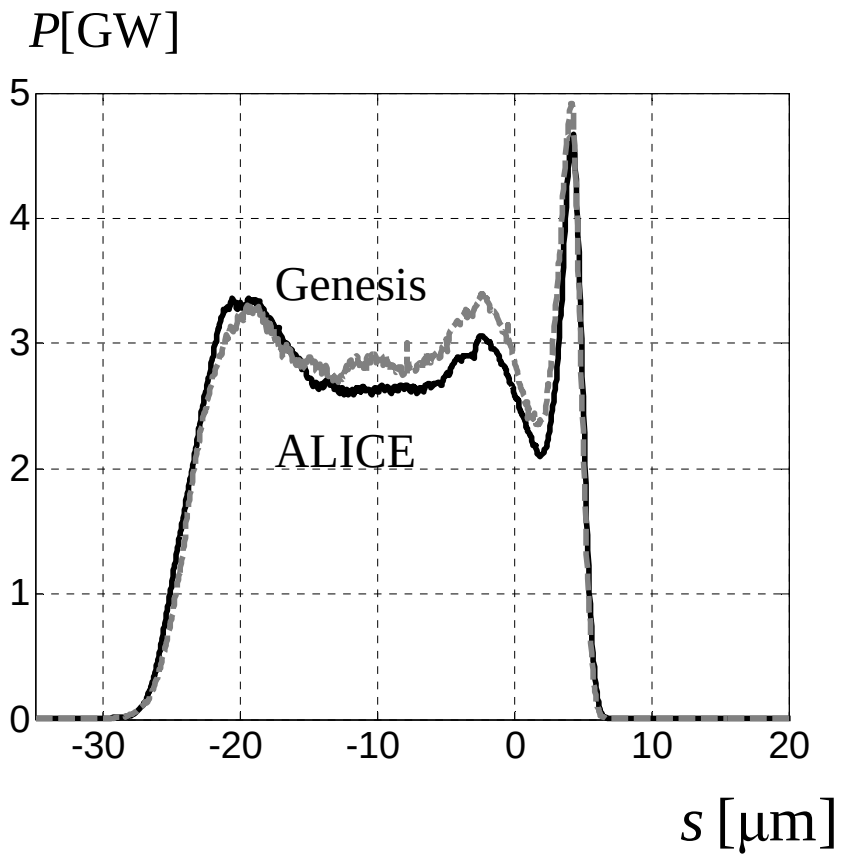


Loss, spread, peak parameters

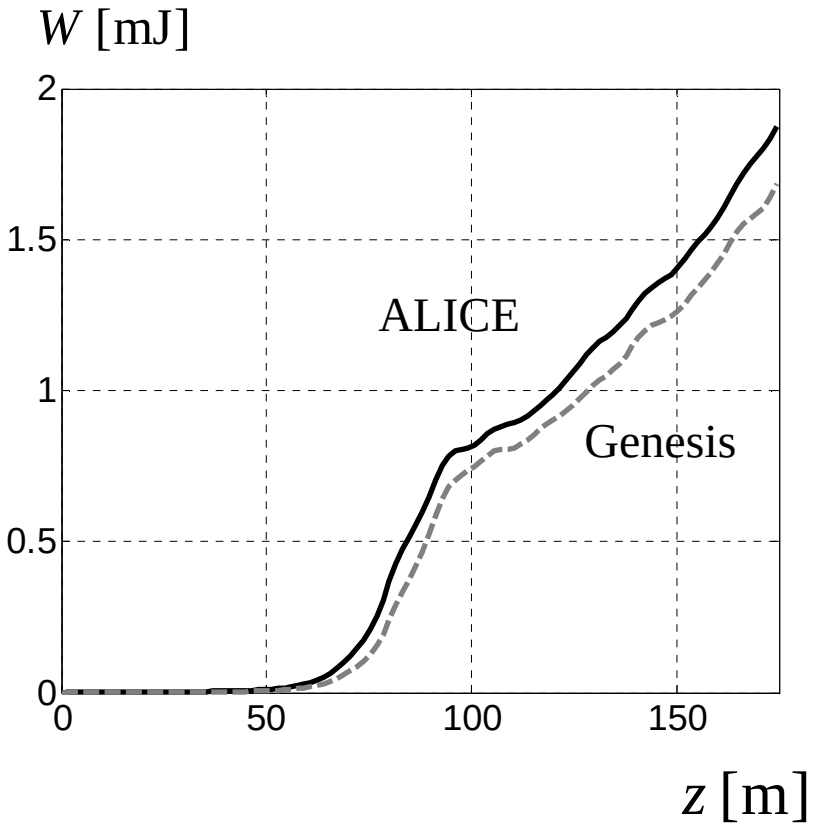
Section	Type of element	Number	Loss (V/pC)	%	Spread (V/pC/m)	%	Peak (V/pC/m)	%
SA1	ABS	32	2.389E+03	14	8.717E+02	7	3.451E+03	12
SA1	BEL	64	1.342E+03	8	4.476E+02	3	1.803E+03	6
SA1	BPME	33	1.780E+03	11	7.243E+02	6	2.598E+03	9
SA1	PIPE	33	8.730E+03	53	1.020E+04	80	1.844E+04	62
SA1	PIPR	32	7.812E+02	5	1.157E+03	9	2.069E+03	7
SA1	PUM	32	3.025E+02	2	2.383E+02	2	5.476E+02	2
SA1	RET	32	1.228E+03	7	4.422E+02	3	1.766E+03	6
SA1			1.655E+04	100	1.283E+04	100	2.951E+04	100
			1.655E+04	100	1.283E+04	100	2.951E+04	100

Radiation Q=1nC. Amplifier

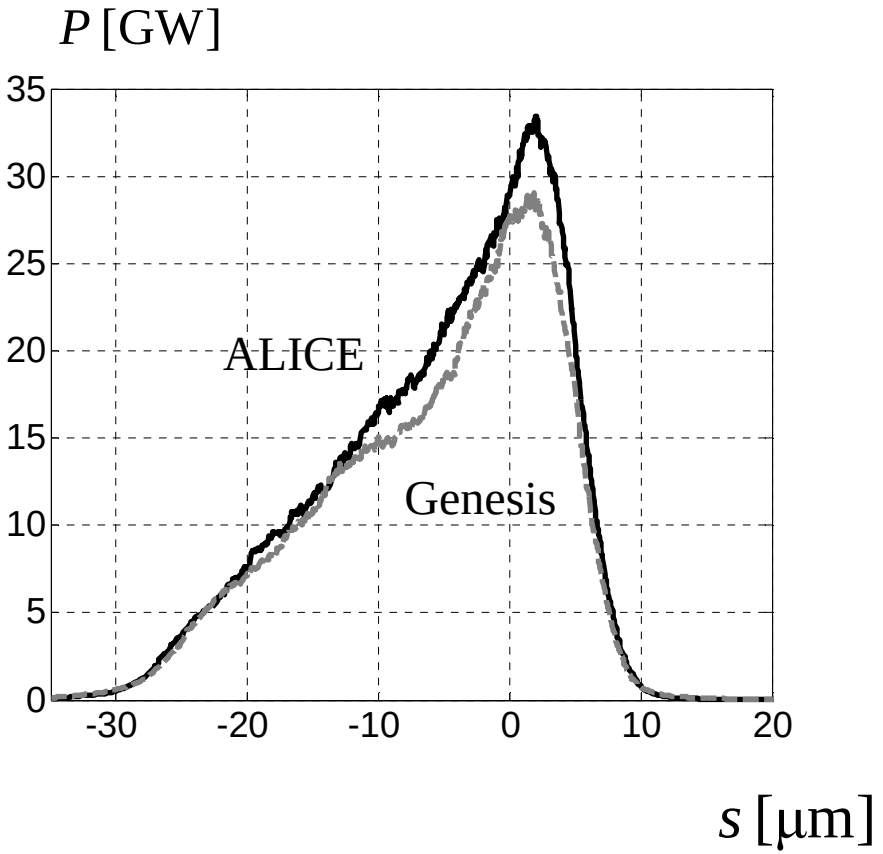




Radiation Q=1nC. SASE



One shot from different particle distributions



Averaged through 20000 slices

Radiation Q=1nC. SASE

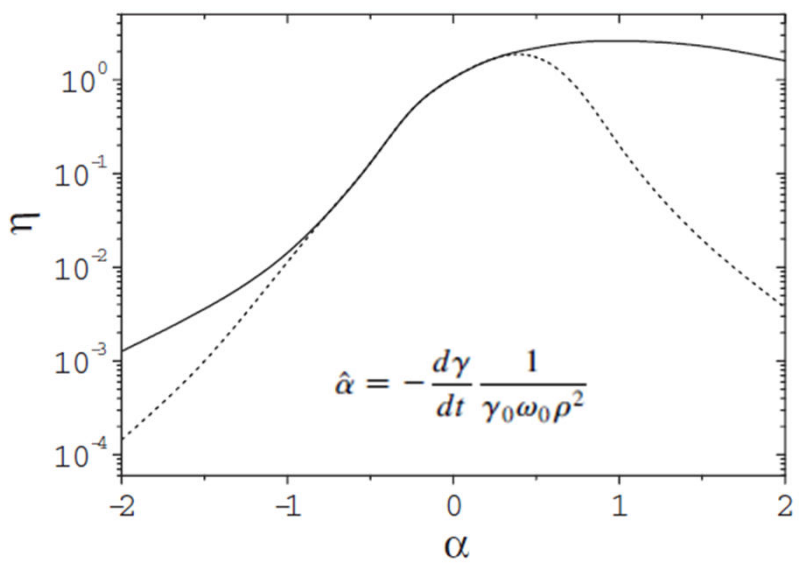


FIG. 2. Normalized output power versus parameter $\hat{\alpha}$. Solid: $\hat{z} = \hat{z}_{sat}(\hat{\alpha})$ (see Fig. 1); dashed: $\hat{z} = \hat{z}_{sat}(0) = 13$.

$$\hat{\alpha}_{opt} = 0.25$$

$$\hat{C}(\hat{z}) = \hat{b}\hat{z}$$

$$\hat{b}_{opt} = 0.5\alpha_{opt}$$

$$\hat{C}(\hat{z}) = 0.125\hat{z}$$

$$\frac{dK}{dz} \approx \frac{1}{kK}\left(2k_u\gamma\frac{d\gamma}{dz} - 0.5\left(k_u\rho\gamma\right)^2\right)$$

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9, 050702 (2006)

Self-amplified spontaneous emission FEL with energy-chirped electron beam and its application for generation of attosecond x-ray pulses

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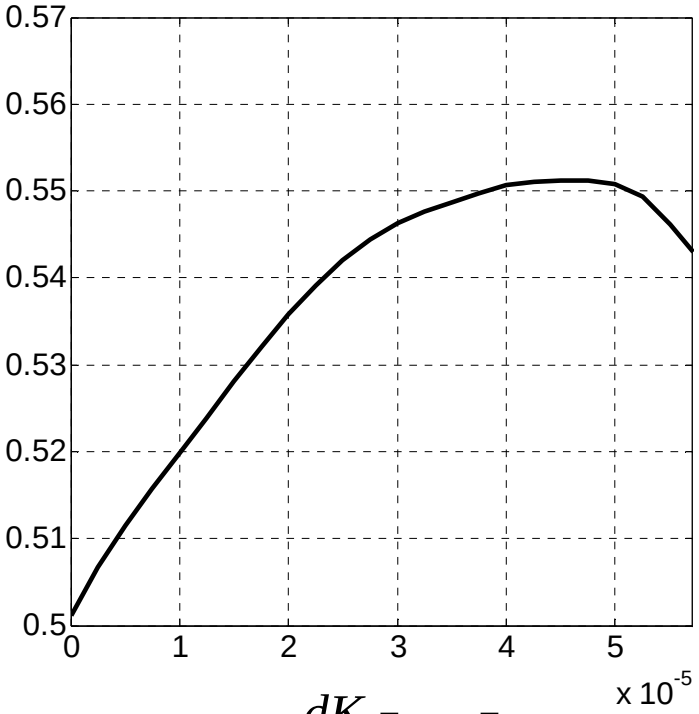
(Received 17 March 2006; published 3 May 2006)

Radiation Q=1nC. SASE

$$\frac{mc^2}{e}\frac{d\gamma}{dz} = -160\,\frac{\text{keV}}{\text{m}}$$

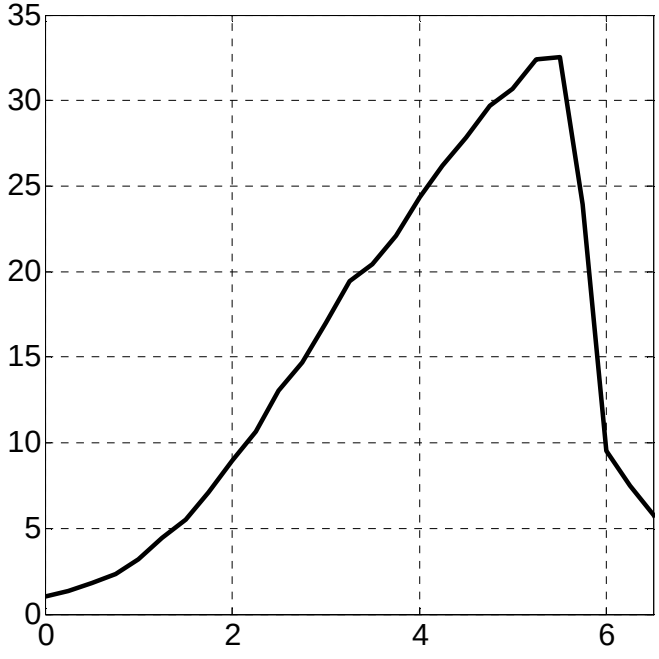
$$\left(\frac{dK}{dz}\right)_{opt} = -4.8\cdot 10^{-5}\,\text{m}^{-1}$$

$\hat{\Lambda}$



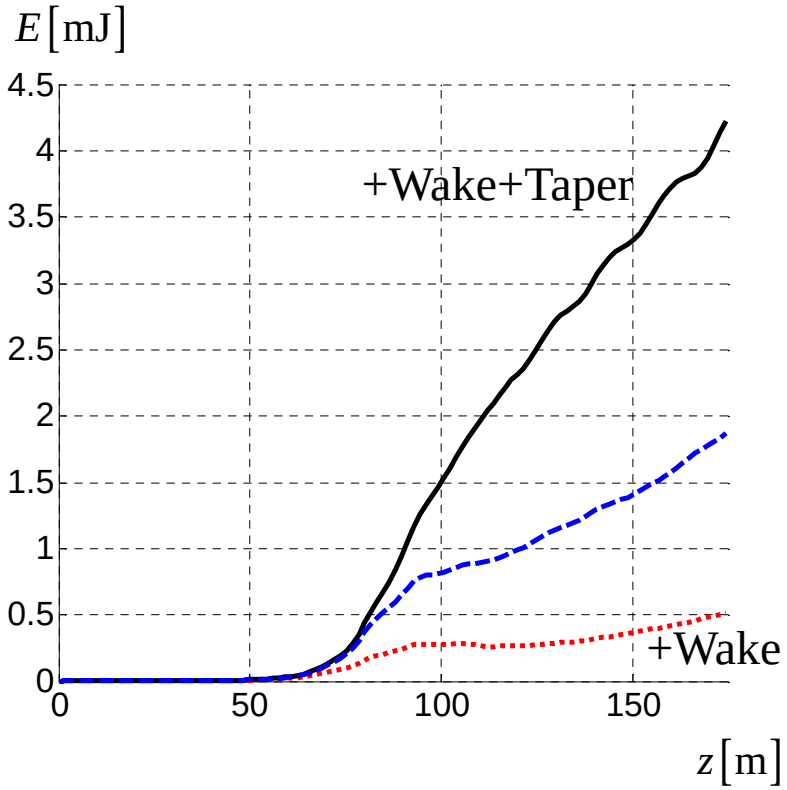
$$\frac{dK}{dz}\left[m^{-1}\right]$$

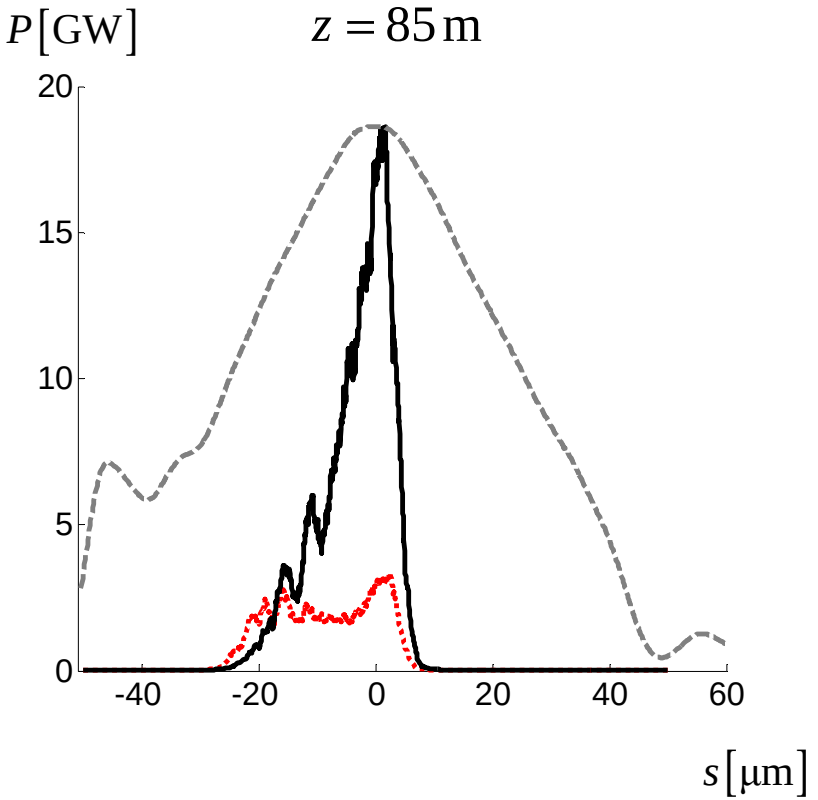
$P\,[\text{GW}]$



$$\frac{dK}{dz}\left[m^{-1}\right]$$

Radiation Q=1 nC

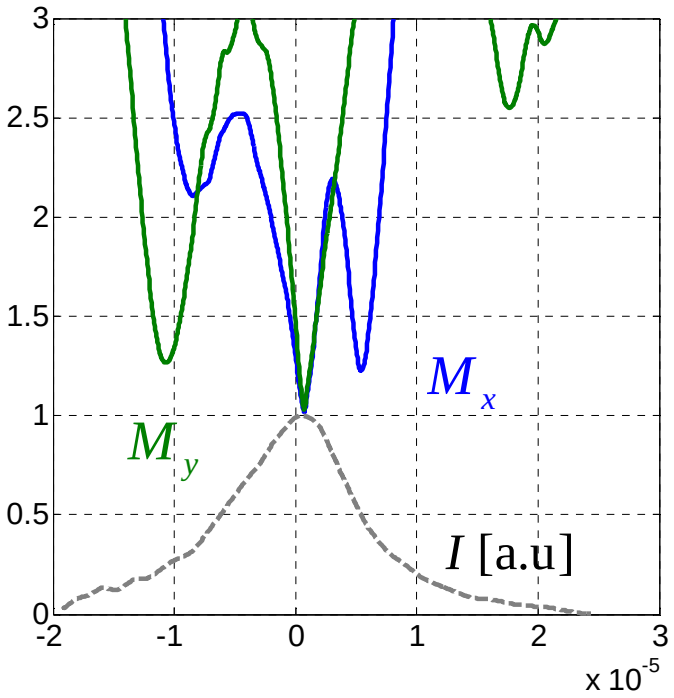




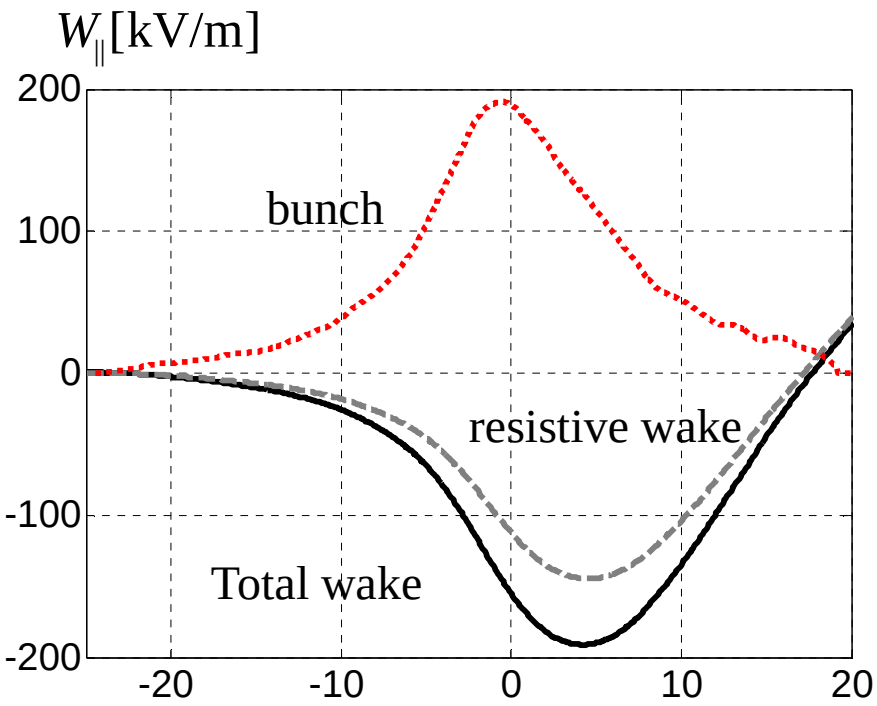
$$\left(\frac{dK}{dz}\right)_{opt} = -4.8 \cdot 10^{-5}\,\mathrm{m}^{-1}$$

Averaged through 8000 slices

Mismatch and wake Q=250 pC

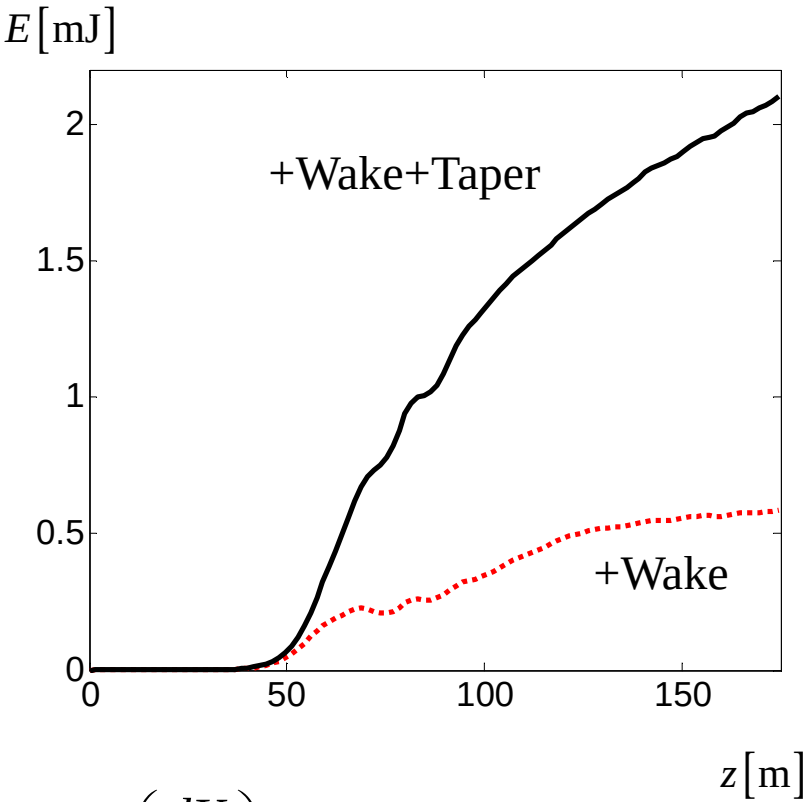


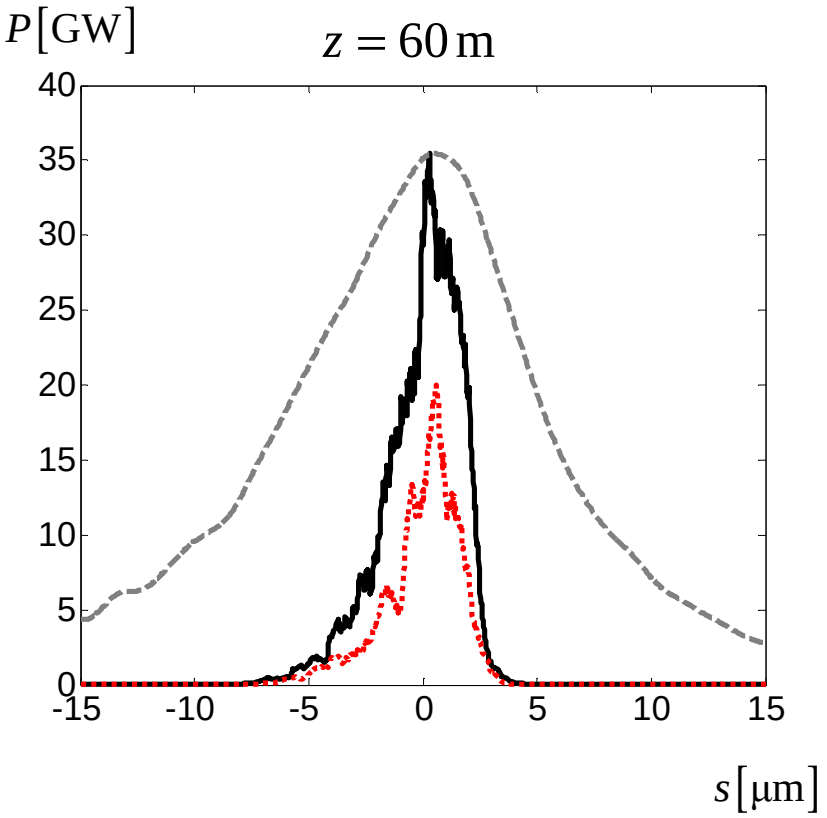
s [μm]



s [μm]

Radiation Q=250 pC

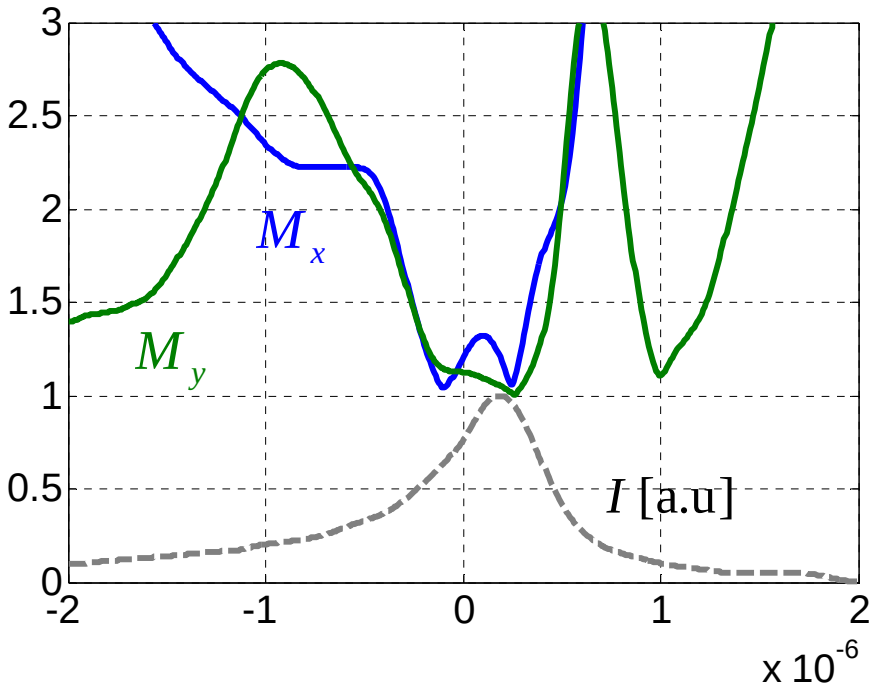




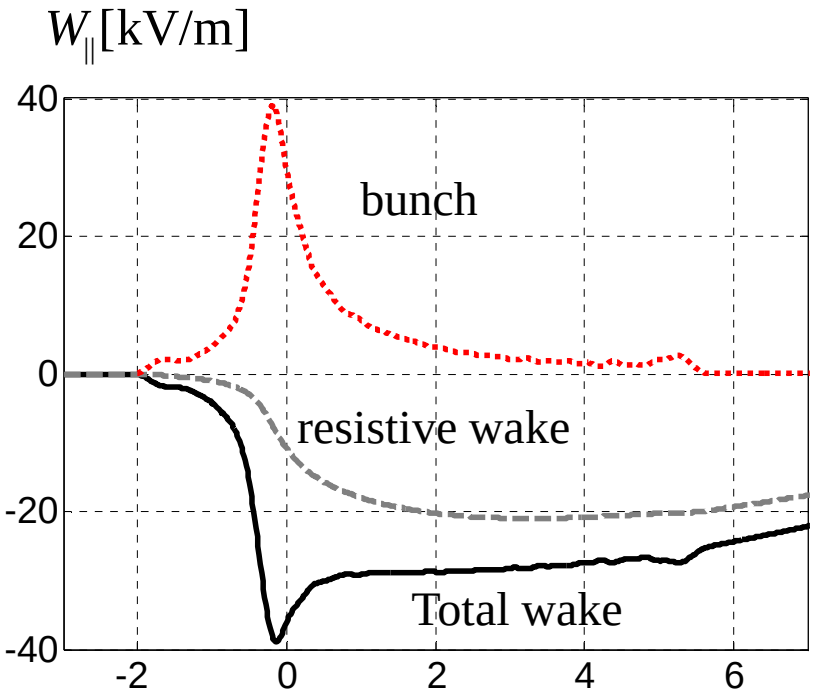
$$\left(\frac{dK}{dz}\right)_{opt} = -4.8\cdot 10^{-5}\,\mathrm{m}^{-1}$$

Averaged through 2400 slices

Mismatch and wake Q=20 pC



s [μm]

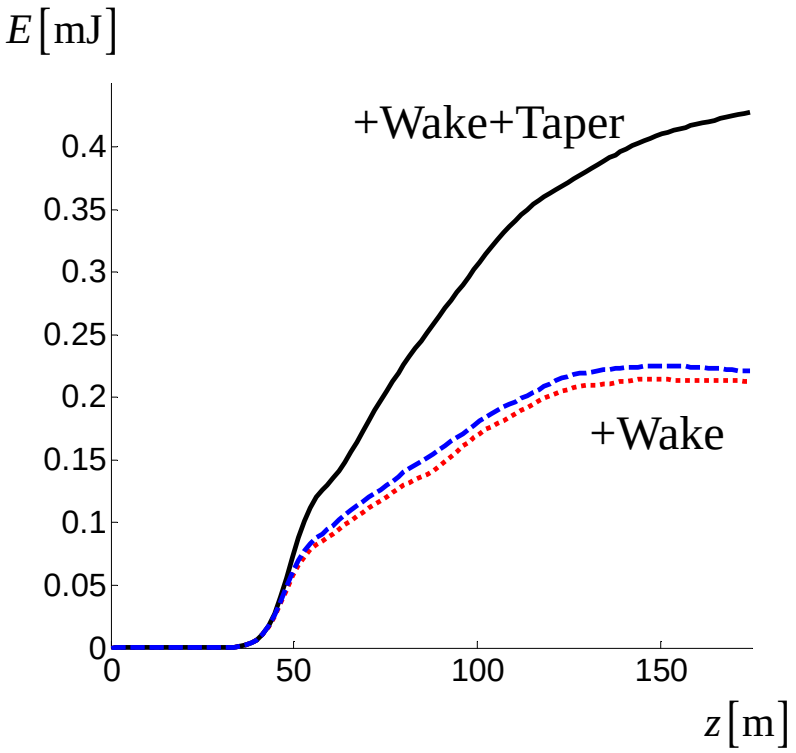


s [μm]

$$\frac{mc^2}{e}\frac{d\gamma}{dz} = -40\,\frac{\text{keV}}{\text{m}}$$

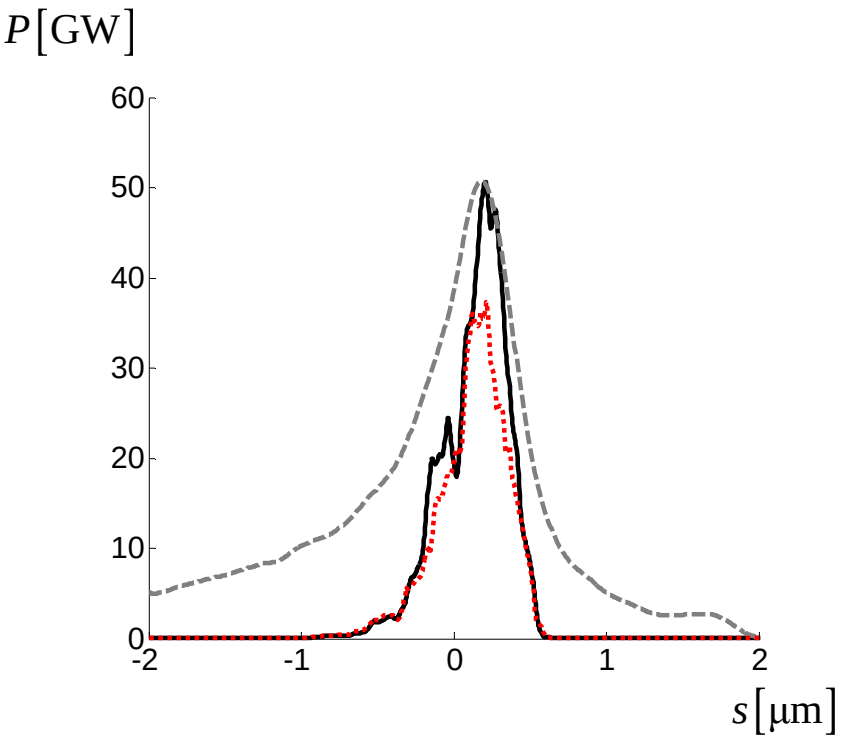
$$\left(\frac{dK}{dz}\right)_{opt} = -2.2\cdot 10^{-5}\,\text{m}^{-1}$$

Radiation Q=20 pC



$$\left(\frac{dK}{dz}\right)_{opt} = -4.8\cdot 10^{-5}\,\mathrm{m}^{-1}$$

$z = 50\,\mathrm{m}$



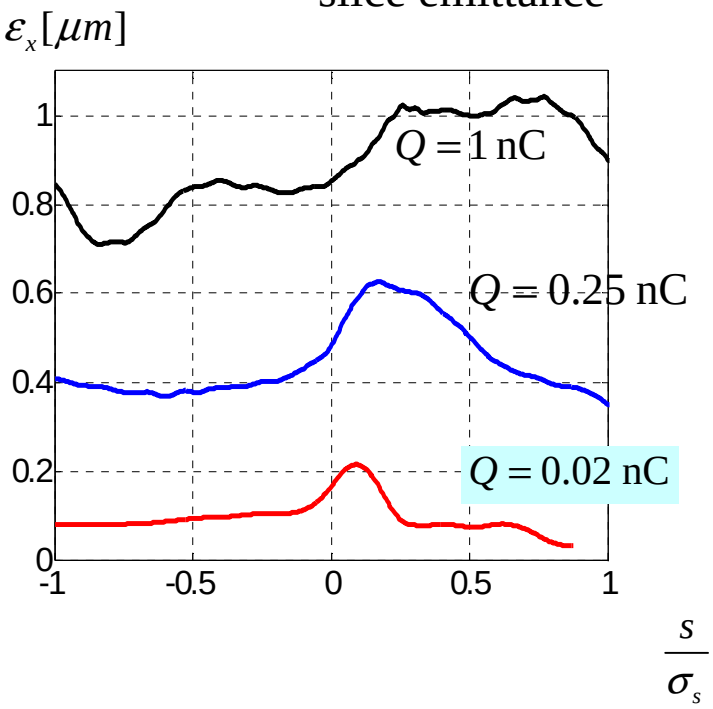
Averaged through 800 slices

Slice parameters for SASE simulations

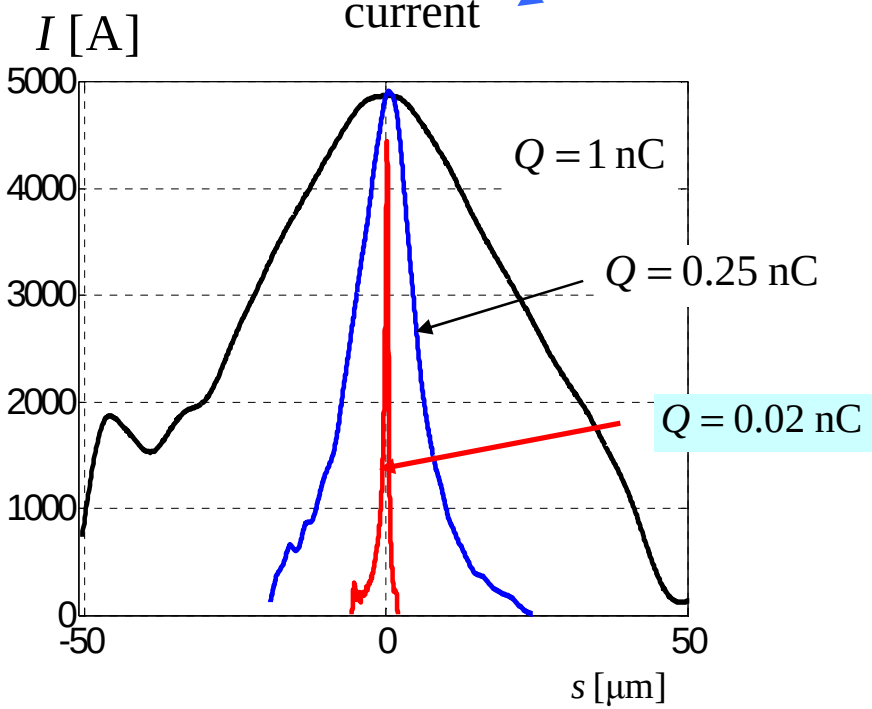
Slice parameters are extracted from S2E simulations for SASE simulations

$$\gamma \quad \Delta\gamma \quad \varepsilon_x \quad \varepsilon_y \quad \beta_x \quad \beta_y \quad \langle x \rangle \quad \langle y \rangle \quad \langle x' \rangle \quad \langle y' \rangle \quad \alpha_x \quad \alpha_y \quad I$$

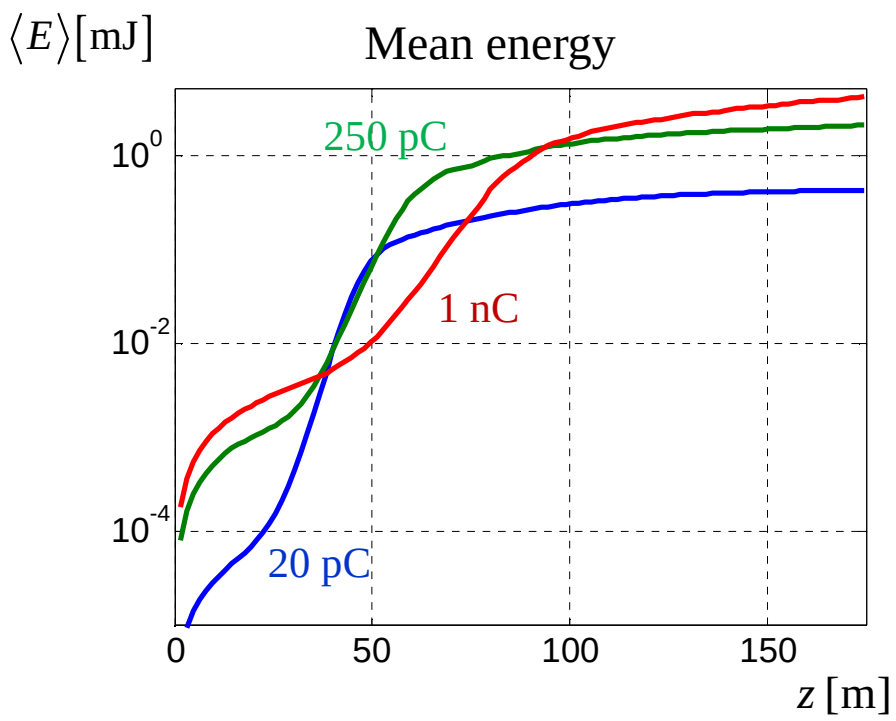
slice emittance

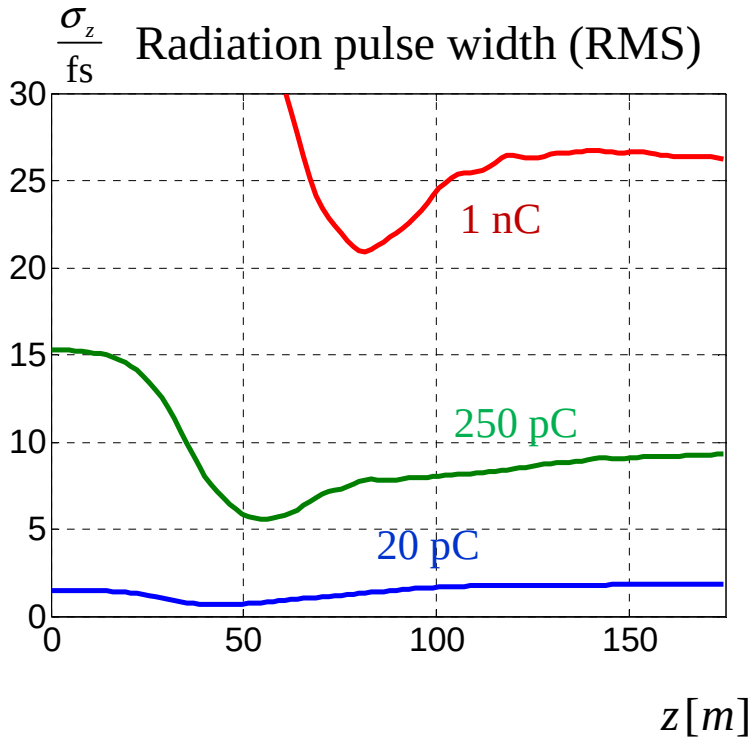


current



Radiation energy statistics (1-25-120 runs)



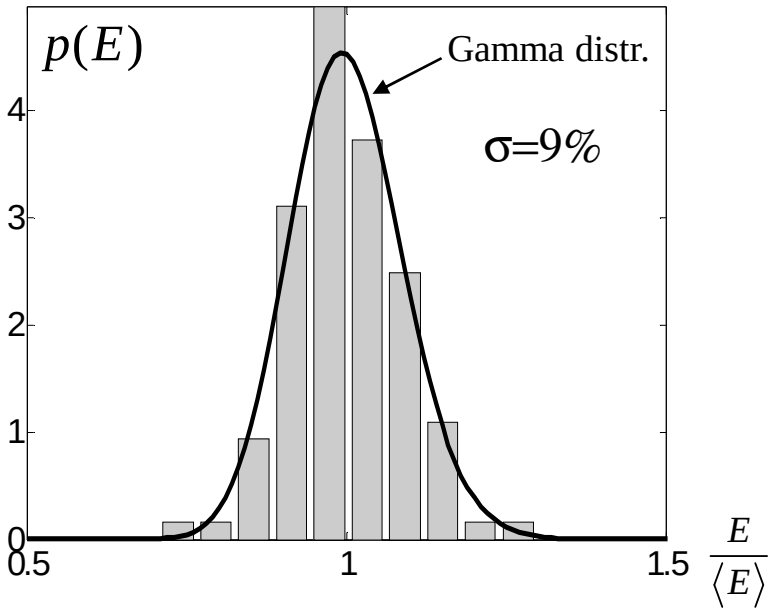


Charge, nC	1	0.25	0.02
Mean radiation energy, mJ	1-4	1-2	0.1-0.4
Pulse radiation width (FWHM), fs	**25-50**	**10-20**	**1-2**

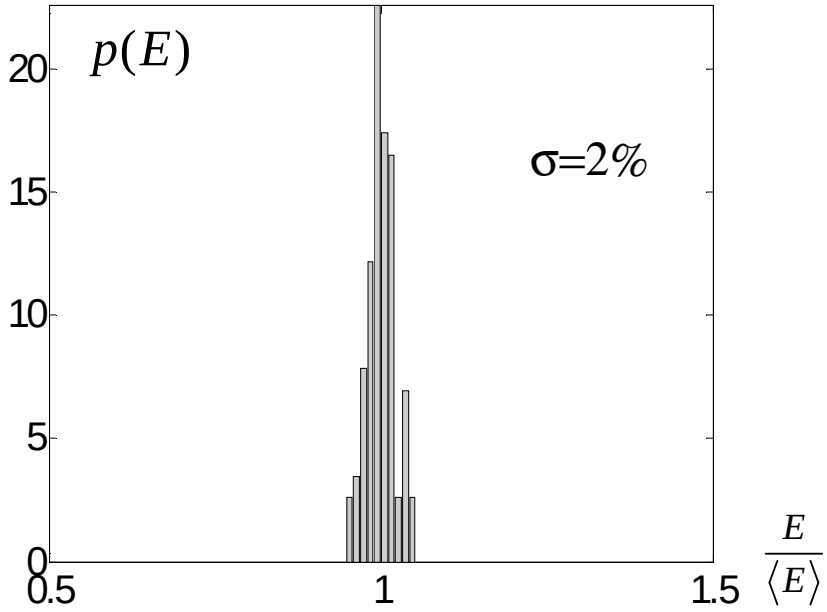
Radiation energy statistics

Q=20 pC (120 runs)

z=50m

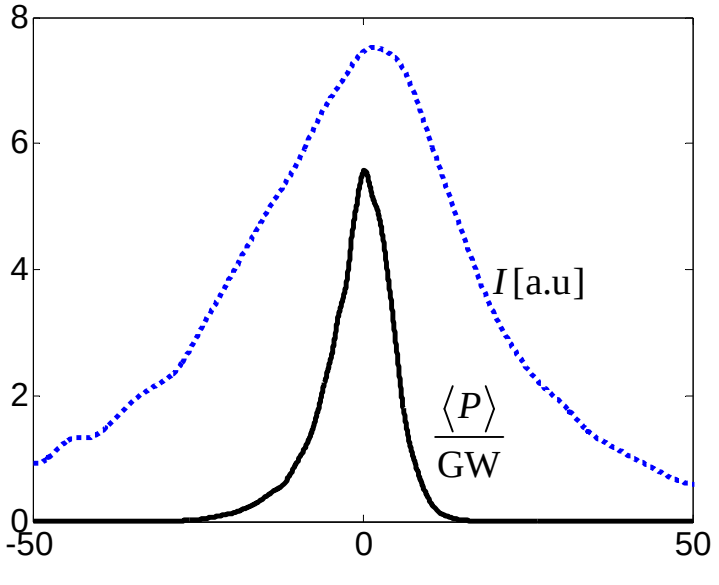


z=175m



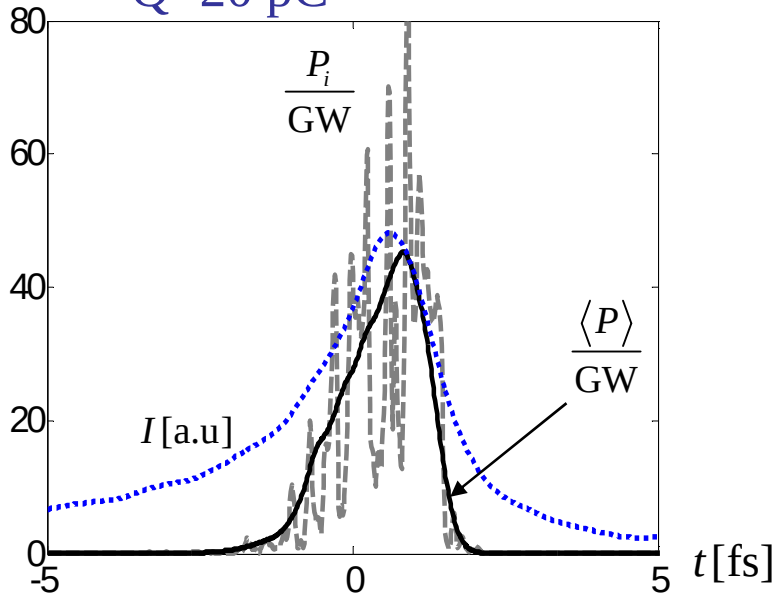
Temporal structure

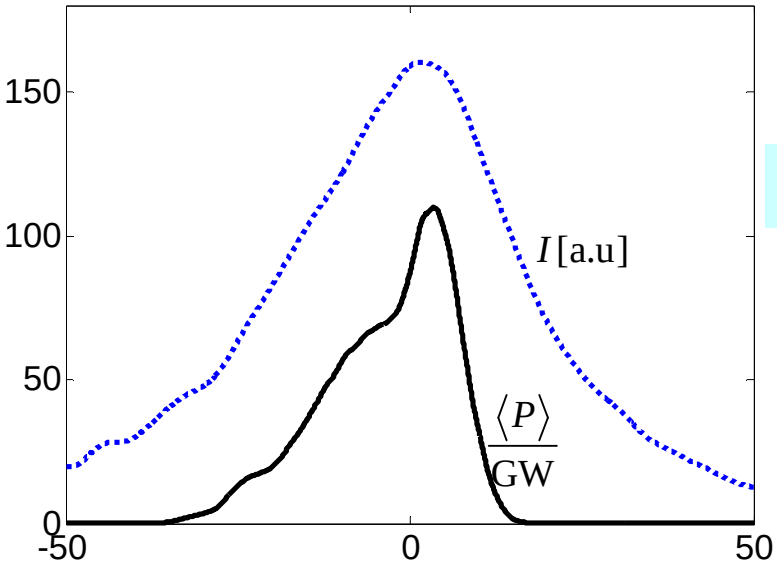
Q= 250 pC



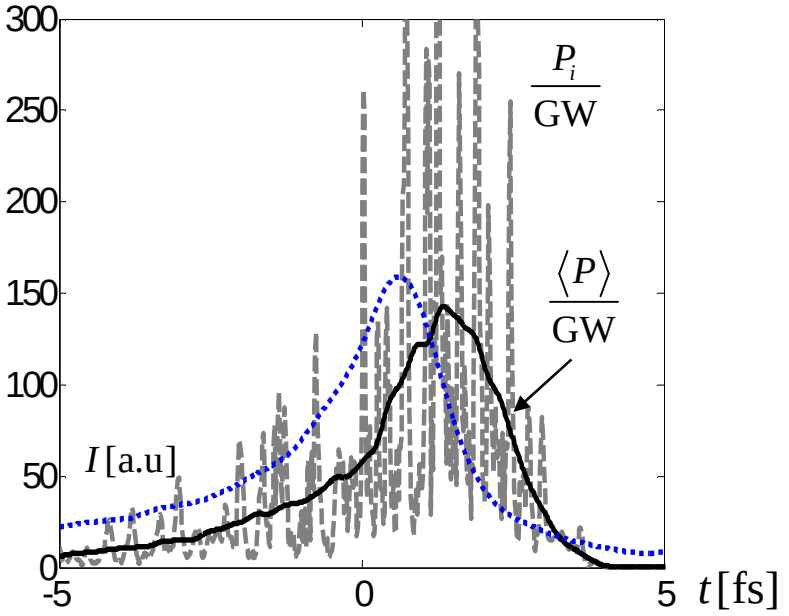
z=50m

Q=20 pC



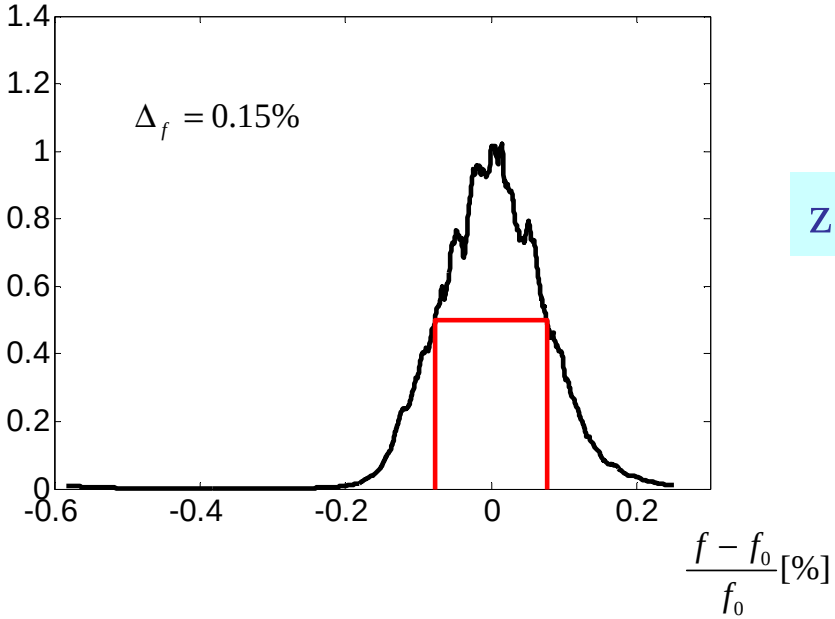


z=175m



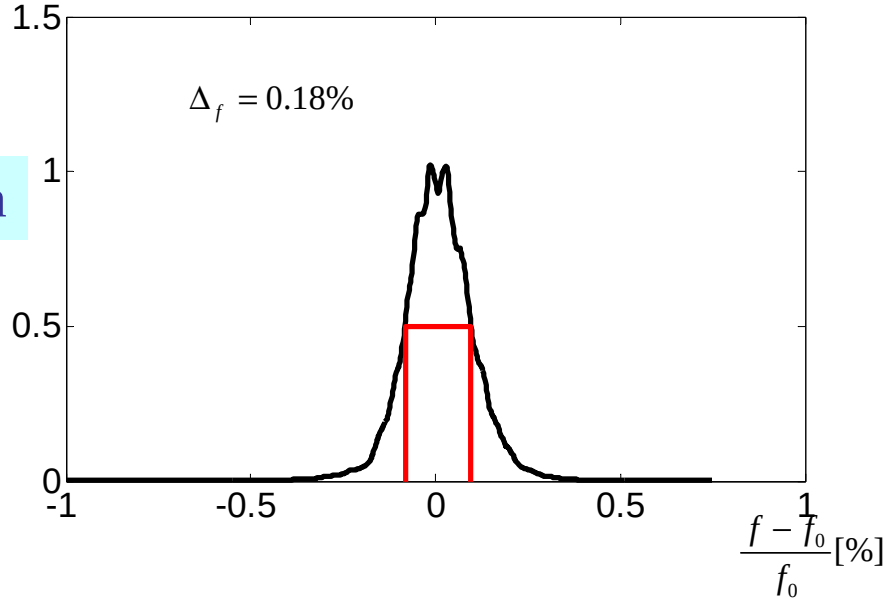
Spectrum

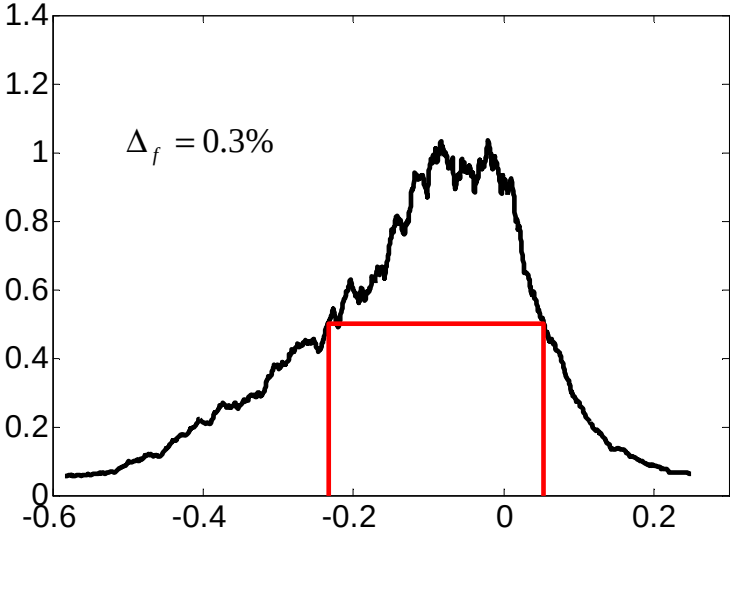
Q= 250 pC



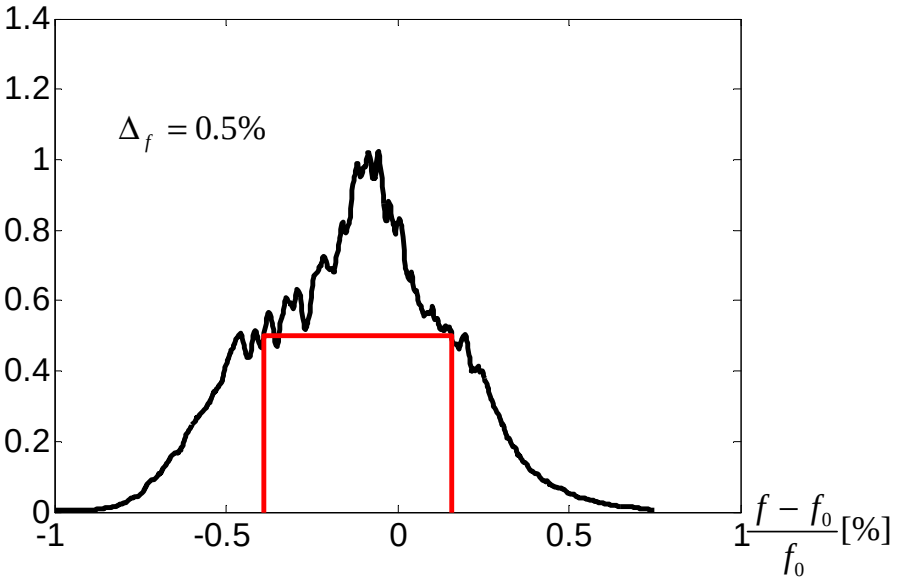
Q=20 pC

z=50m





z=175m



Summary

Bunch charge, nC	1	0.25	0.02
Wavelength, nm	0.1		
Beam energy, GeV	14		
Peak current, kA	**~ 5**		
Slice emmitance,mm-mrad	**1**	**0.5**	**0.2**
Saturation length, m	**85**	**60**	**45**
Energy in the rad. pulse, mJ	1-4	1-2	0.1-0.4
Radiation pulse duration FWHM, fs	**25-50**	**10-20**	**1-2**
Averaged peak power, GW	**10-50**	**10-100**	**50-150**
Spectrum width, %		**0.15-0.3**	**0.18-0.5**