Longitudinal Impedance Budget and Simulations for XFEL

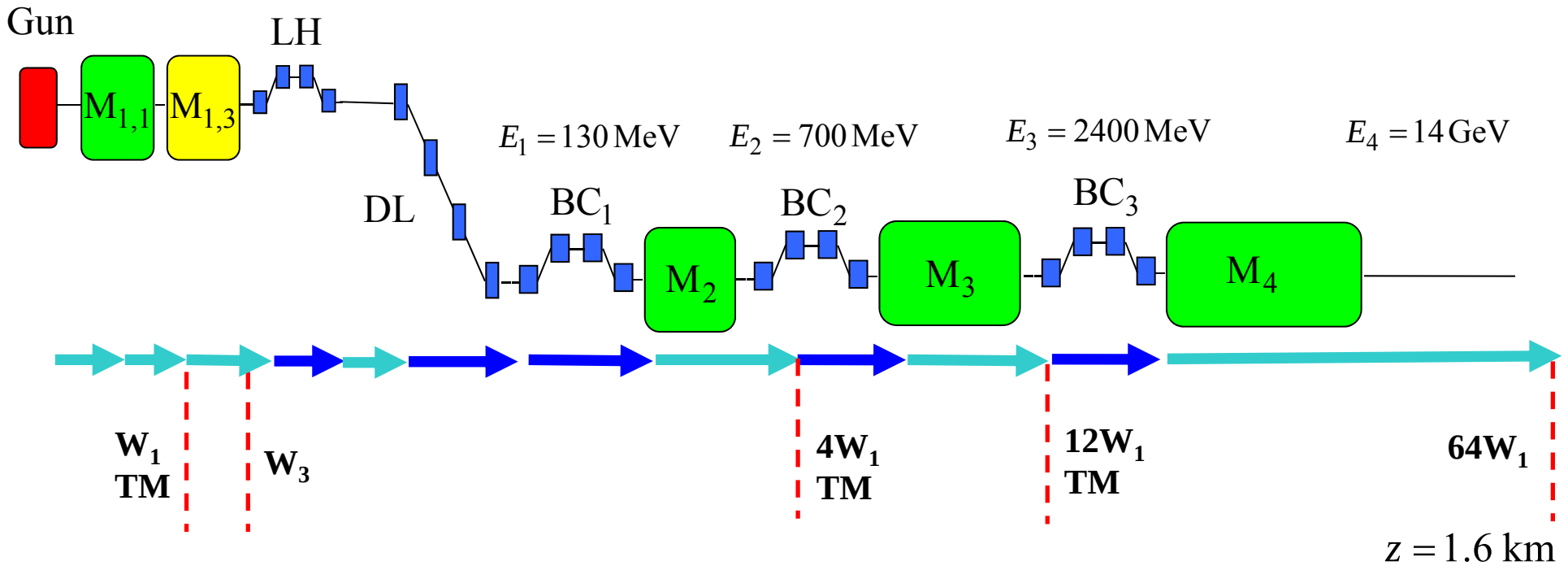
Igor Zagorodnov

14.03.2011

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

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

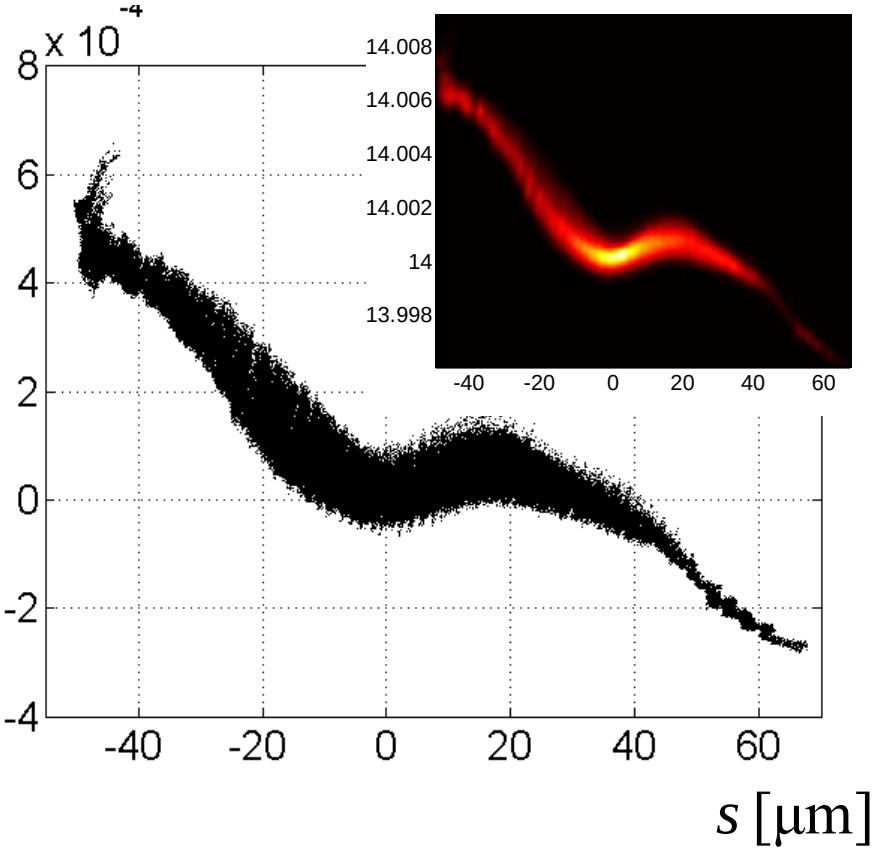
I. Zagorodnov, M. Dohlus, *A Semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects*, Physical Review STAB 14 (2011), 014403.

XFEL beam dynamic simulations for different charges (full)

Q=1 nC

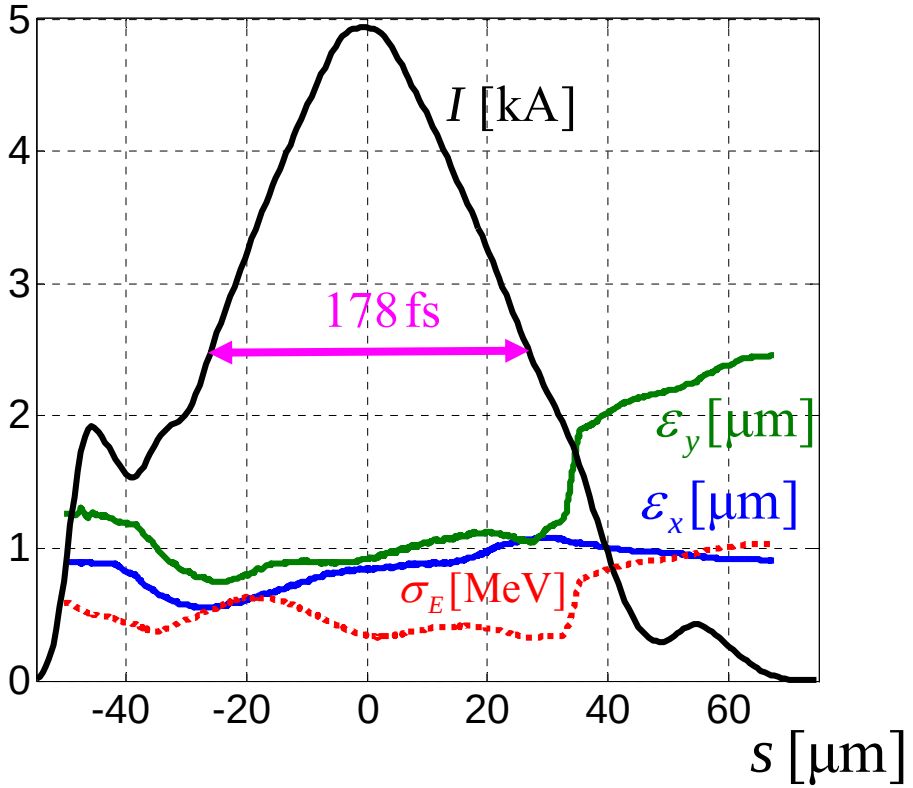
δ_E

Phase space



bunch head

Current, emittance, energy spread

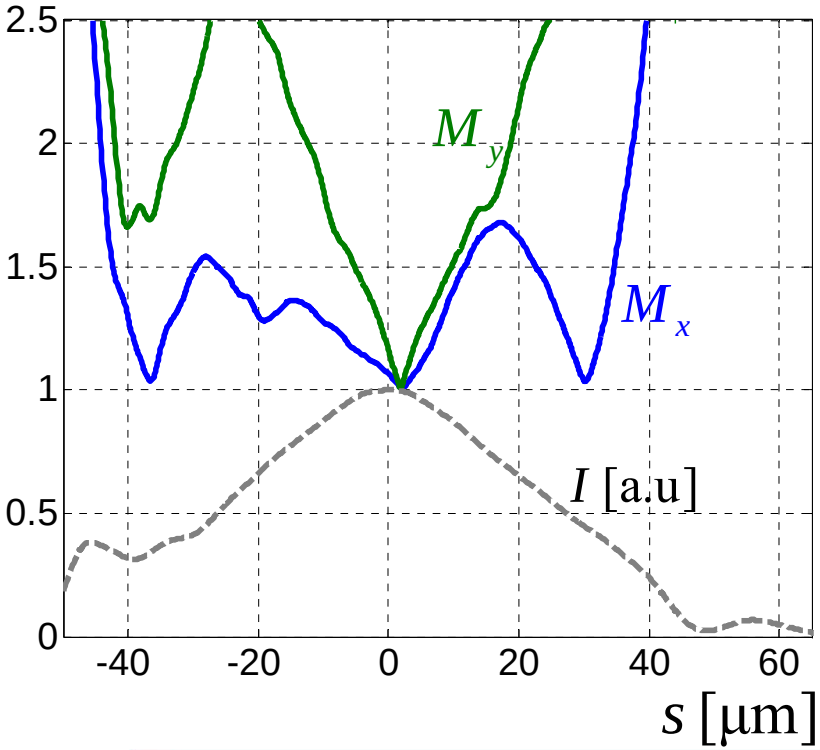


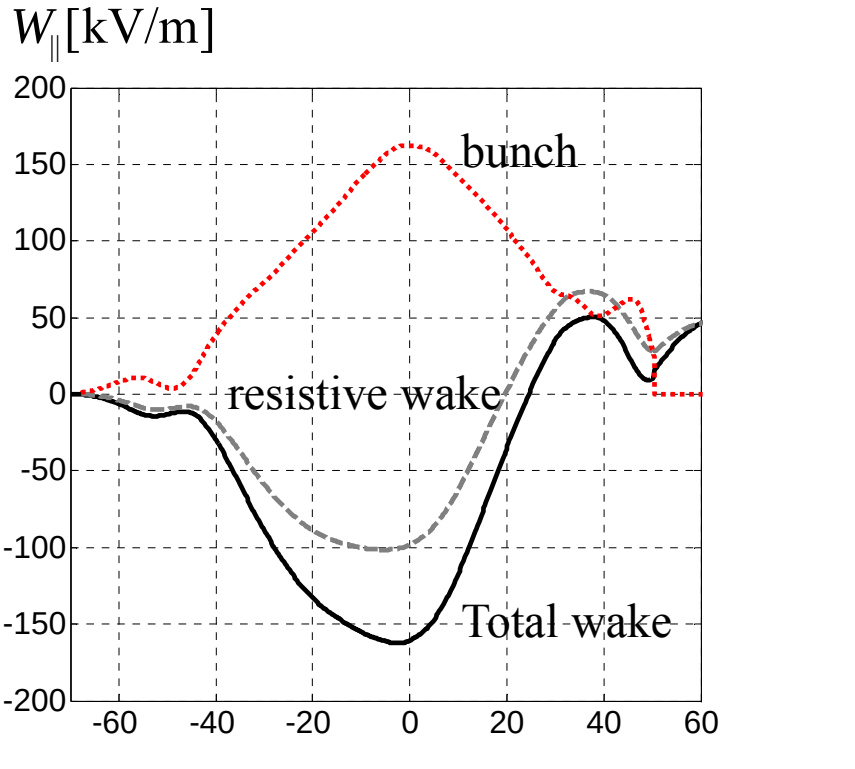
$\varepsilon_x^{proj} = 0.9\,[\mu m]$

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

We have removed 6% of bad particles in the analysis

Mismatch and **undulator** 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

Optimal taper for Q=1nC

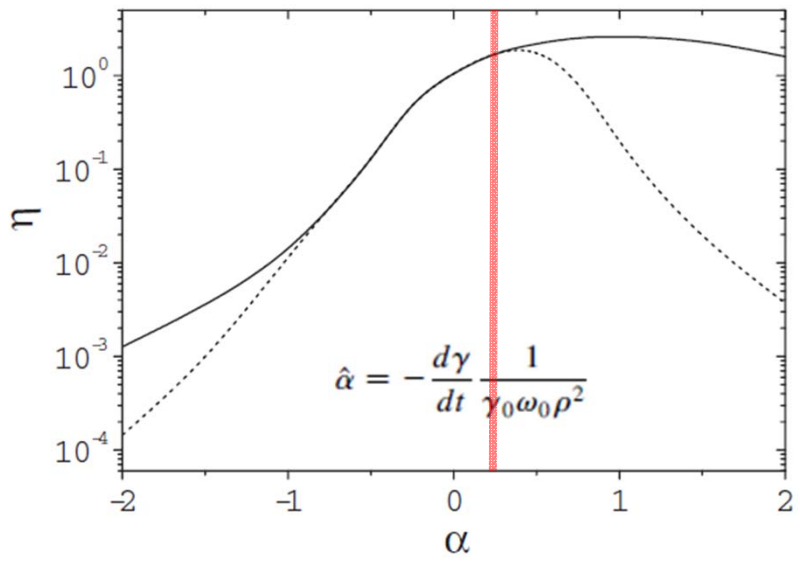


FIG. 2. Normalized output power versus parameter $\hat{\alpha}$. Solid: $\hat{z} = \hat{z}_{sat}(\hat{\alpha})$ (see Fig. 1); dashed: $\hat{z} = \hat{z}_{sat}(0) = 13$.

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

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

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

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

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

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

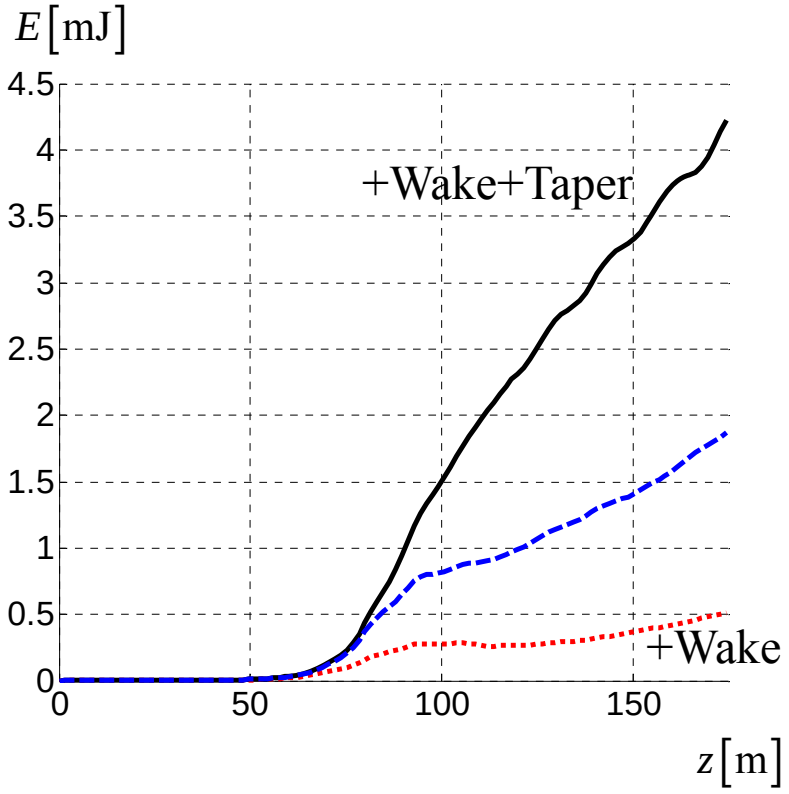
$$\left(\frac{dK}{dz}\right)_{opt} = -4.8\cdot10^{-5}\,\text{m}^{-1}$$

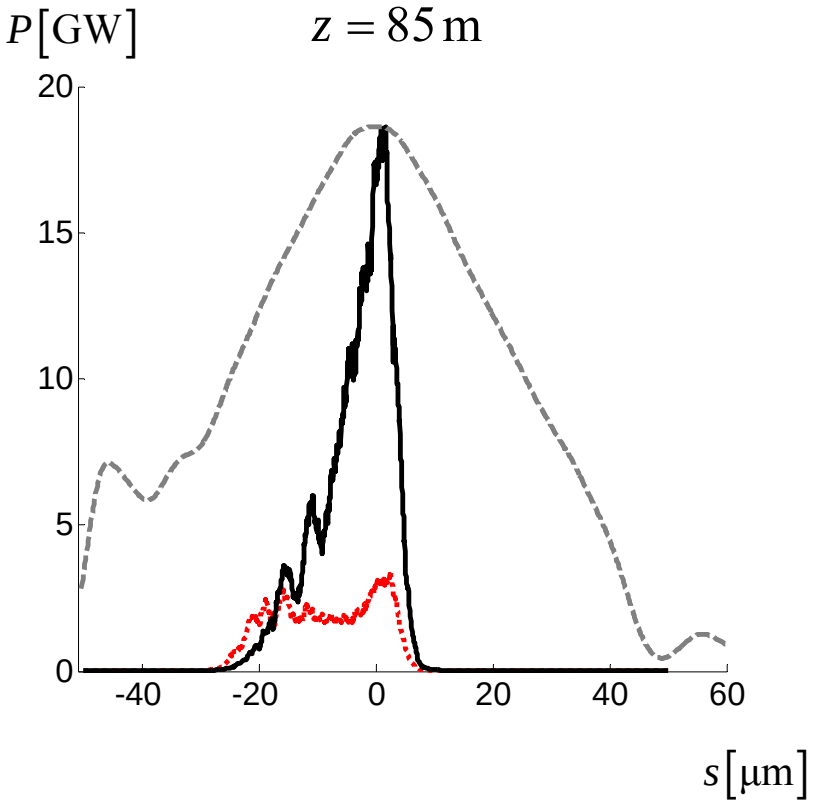
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
9, 050702 (2006)

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

E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
(Received 17 March 2006; published 3 May 2006)

SASE radiation Q=1 nC (ALICE, 360 CPU, ~30 min)



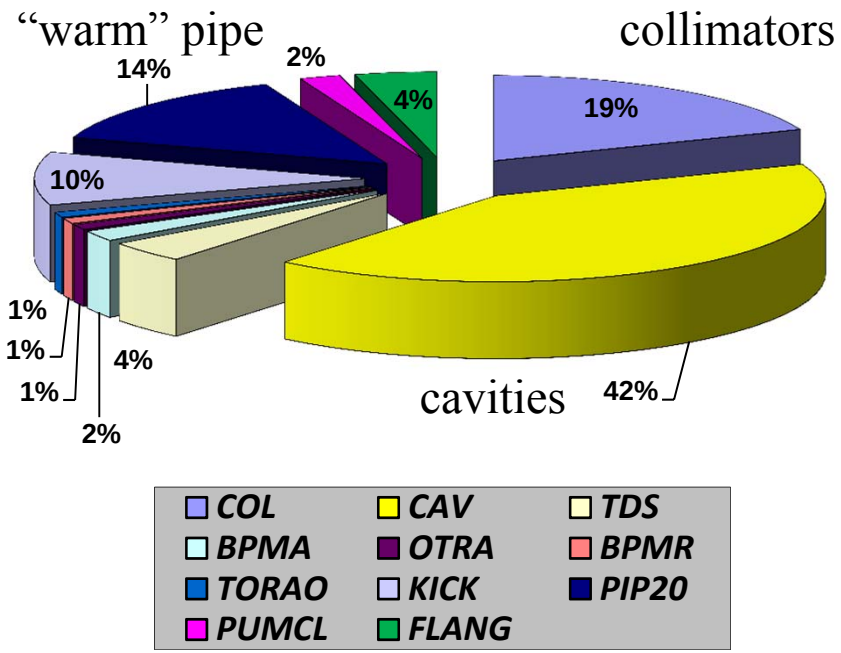


Averaged through 8000 slices

Accelerator wakes. Q=1nC

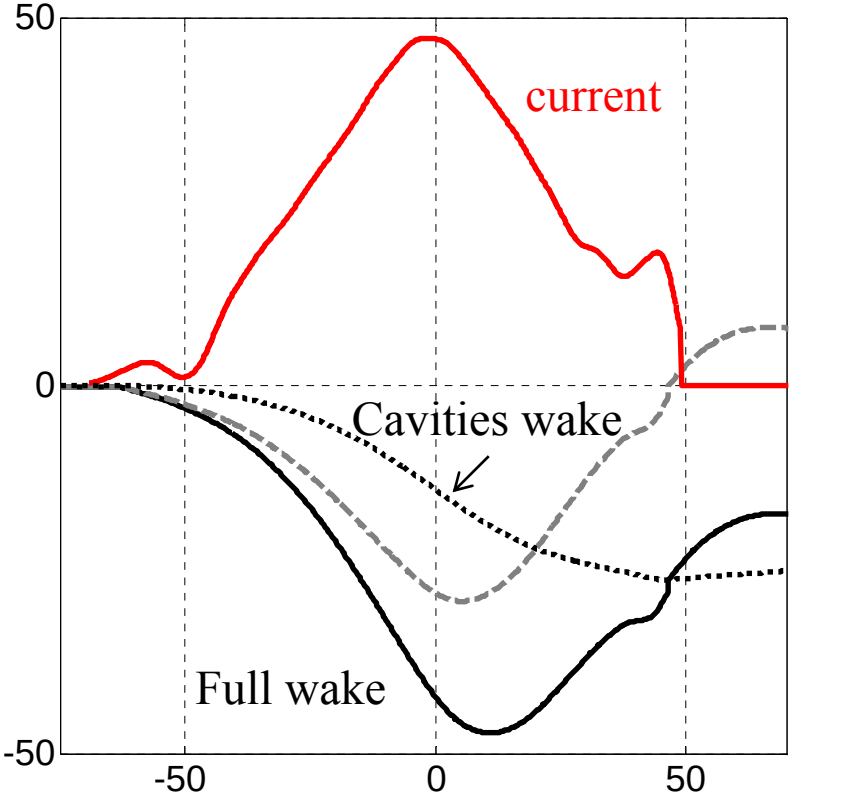
Impedance Budget (list of elements)

El.type	Num.	Loss (kV / nC)	%	Spread (kV / nC)	%	Peak (kV / nC)	%
BPMF	4	4.075E+01	0	1.858E+01	0	5.804E+01	0
COL	7	6.725E+03	19	3.373E+03	22	1.058E+04	21
KICK	3	3.645E+03	10	1.459E+03	9	5.283E+03	10
PIP20	1	5.116E+03	14	3.661E+03	24	8.959E+03	18
PUMCL	78	5.605E+02	2	2.363E+02	2	7.946E+02	2
CAV	808	1.481E+04	42	8.842E+03	57	2.814E+04	56
CAV3	8	8.084E+01	0	3.010E+01	0	1.117E+02	0
FLANG	500	1.330E+03	4	5.610E+02	4	1.886E+03	4
TDS	8	1.507E+03	4	7.348E+02	5	2.174E+03	4
OTRB	8	1.584E+02	0	7.251E+01	0	2.254E+02	0
STEP1	1	3.010E+00	0	5.969E-01	0	3.441E+00	0
BPMA	107	5.654E+02	2	2.896E+02	2	8.670E+02	2
OTRA	12	3.078E+02	1	1.274E+02	1	4.494E+02	1
BPMC	56	4.431E+01	0	2.138E+01	0	6.805E+01	0
BPMR	26	2.993E+02	1	1.304E+02	1	4.501E+02	1
DCM	4	1.644E+01	0	7.479E+00	0	2.315E+01	0
BPMB	27	5.744E-02	0	1.587E-01	0	6.023E-01	0
BAM	5	3.319E+00	0	1.494E+00	0	4.768E+00	0
TORA	3	3.147E+01	0	1.609E+01	0	4.763E+01	0
TORAO	6	1.856E+02	1	7.684E+01	0	2.700E+02	1
		3.530E+04	100	1.540E+04	100	5.037E+04	100



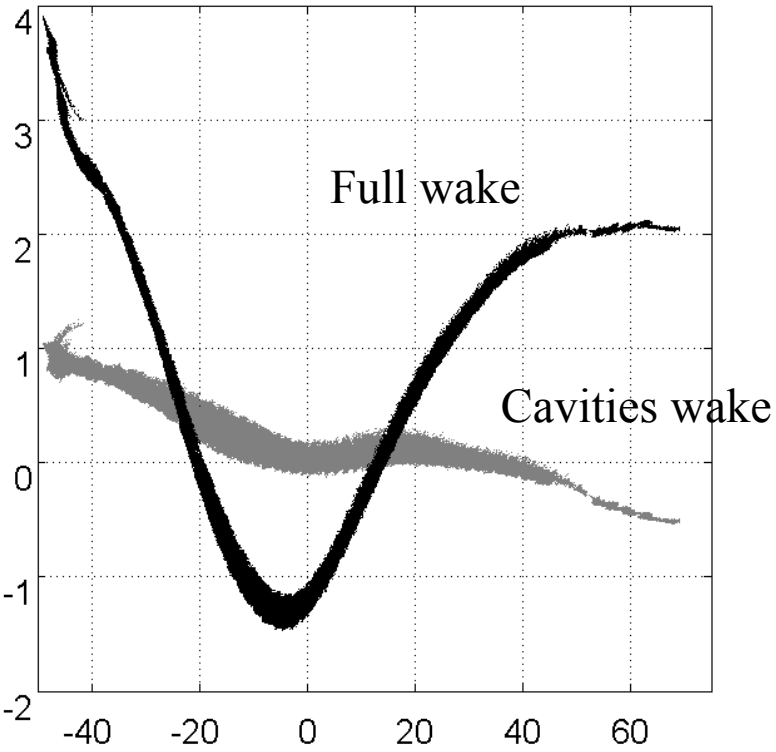
Accelerator wakes. Q=1nC

$W_{\|}$ [MV]



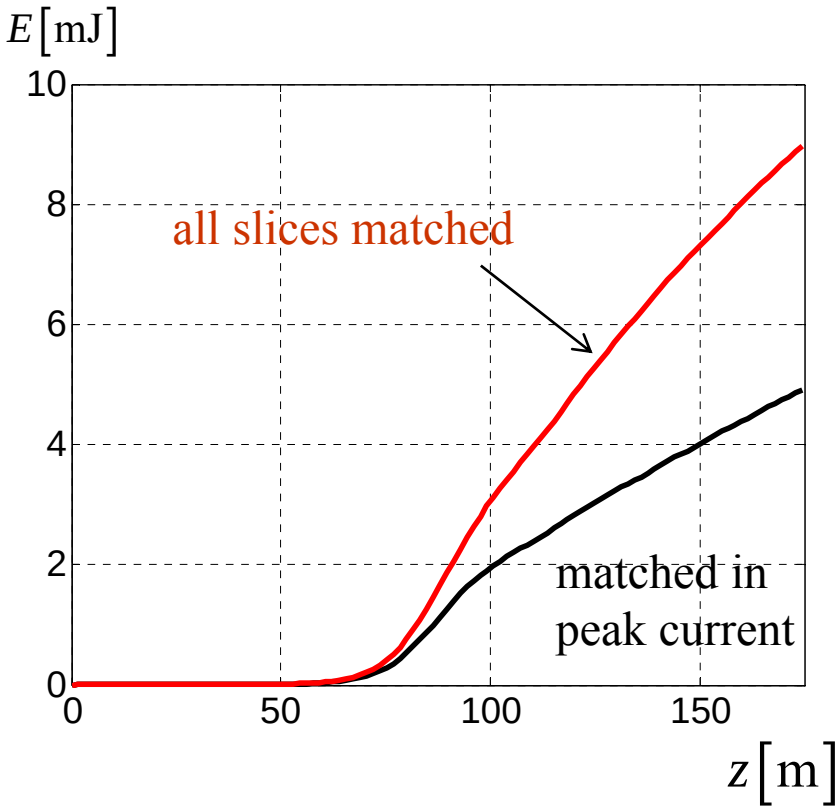
s [μm]

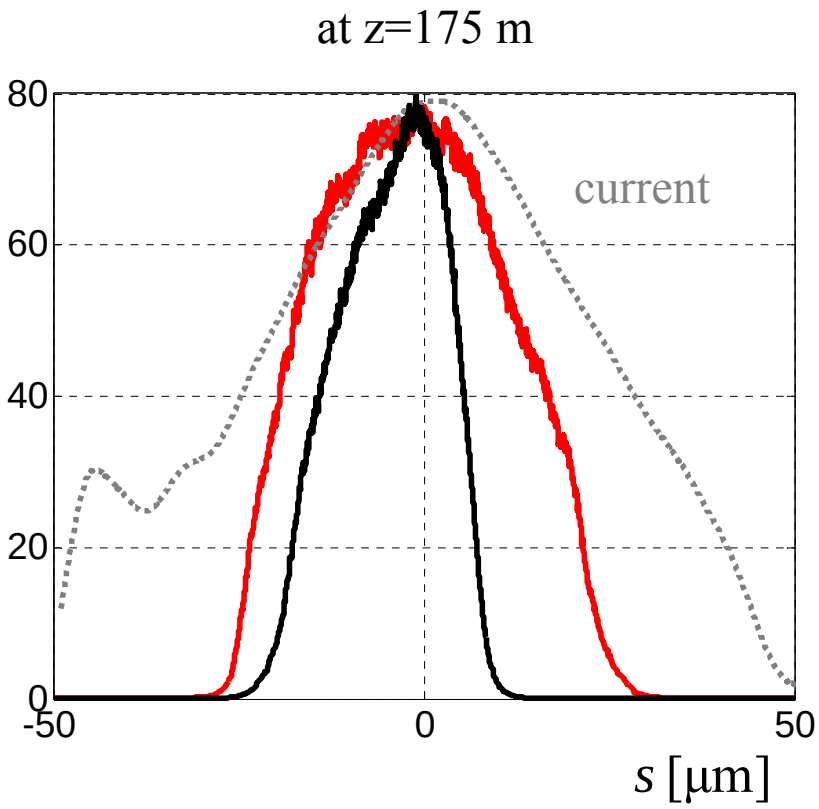
$$\frac{E - E_0}{E_0 \rho} \qquad \rho = 5.3e-4$$



s [μm]

“Artificially” matched beam. Q=1nC

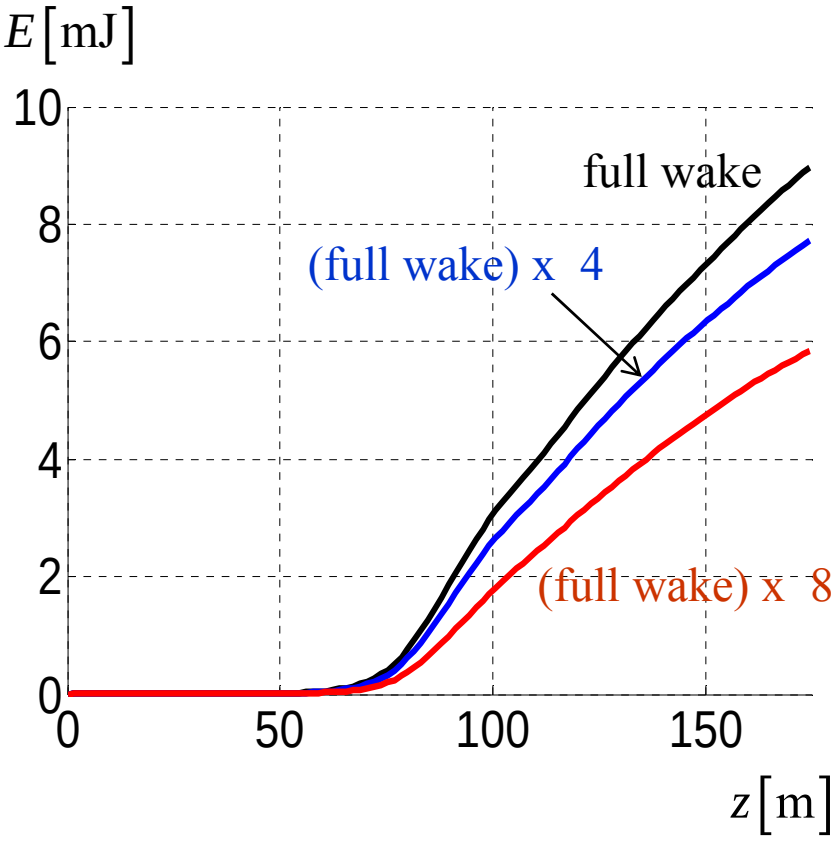


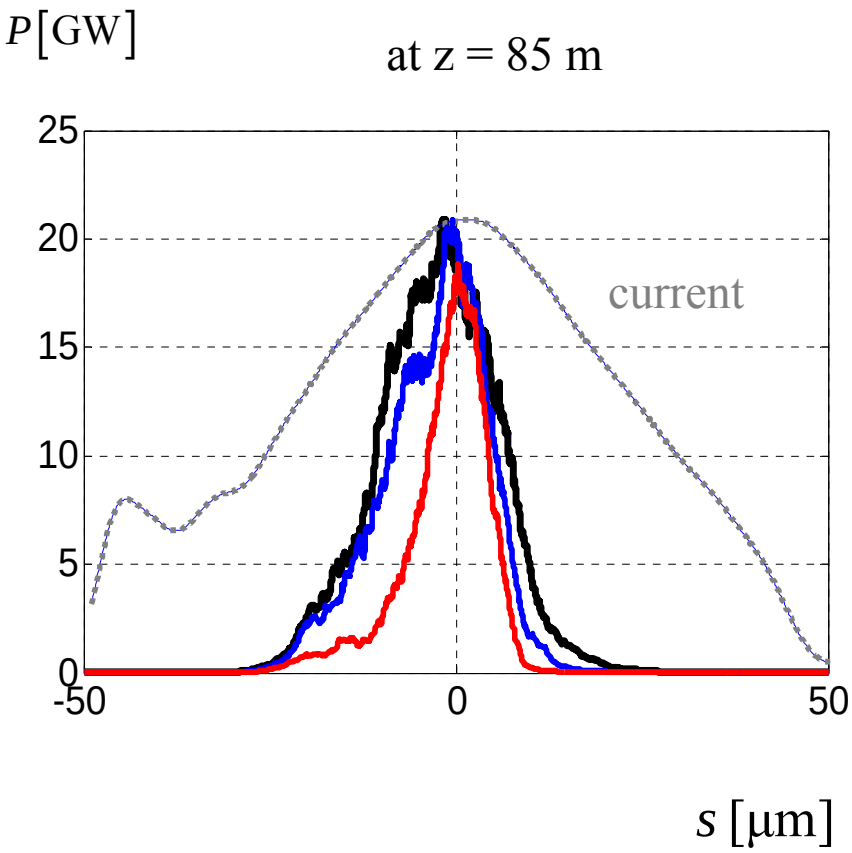


With full accelerator and undulator wake

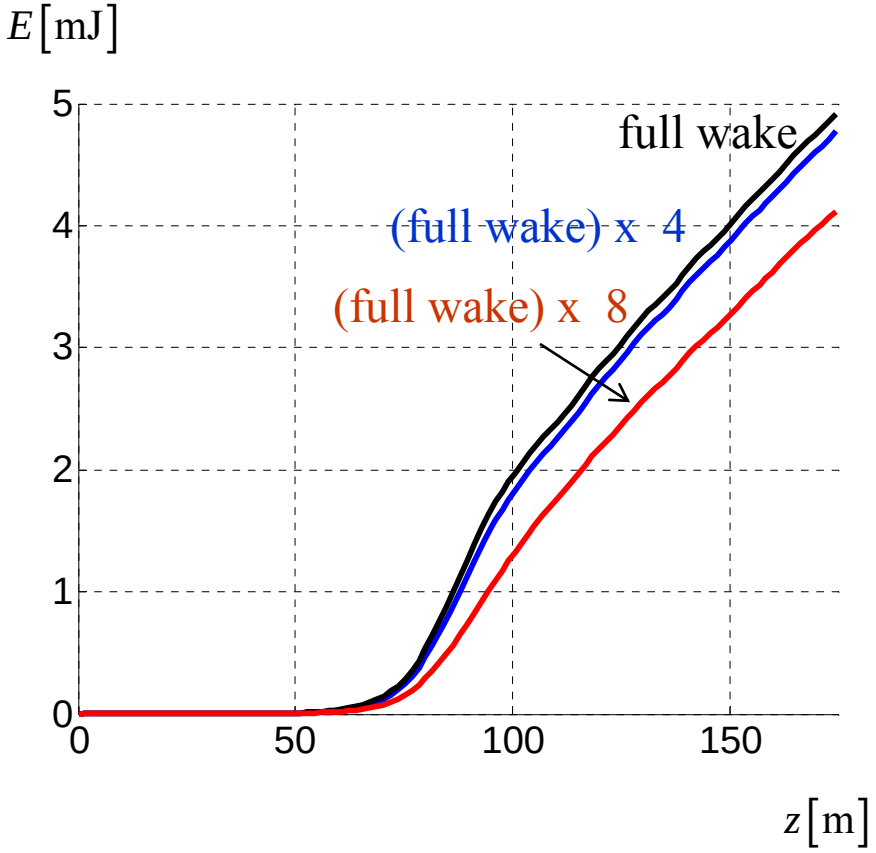
$$\left(\frac{dK}{dz}\right)_{opt} = -4.8 \cdot 10^{-5}\ \mathrm{m}^{-1}$$

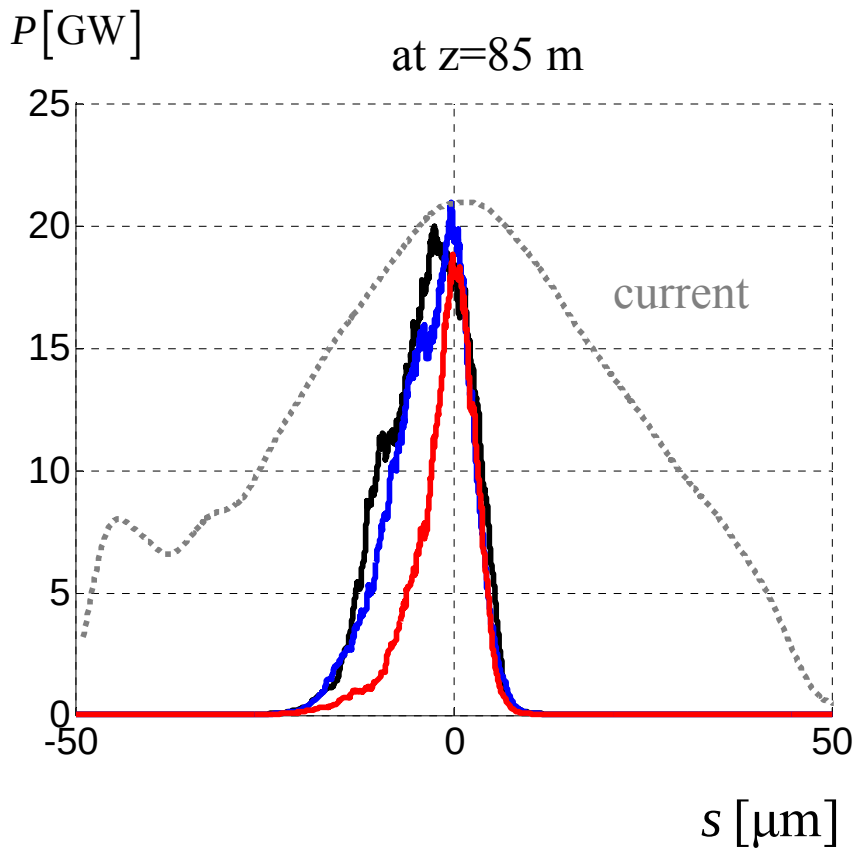
“Artificially” matched beam. Q=1nC



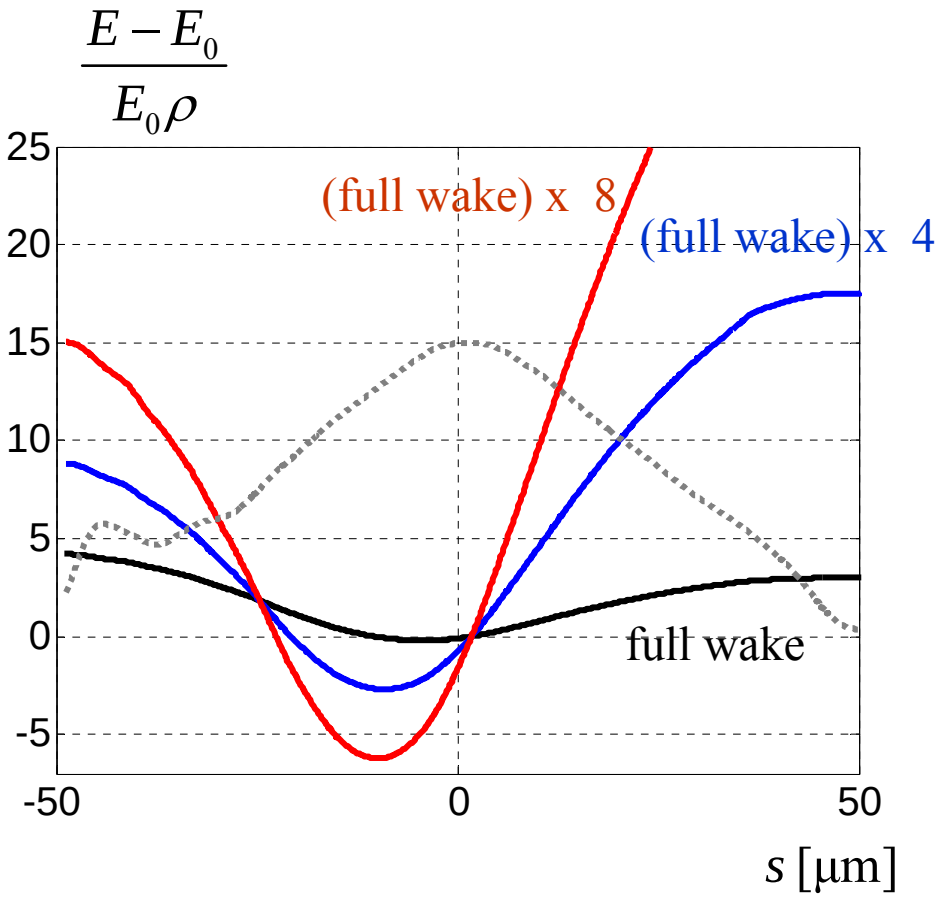


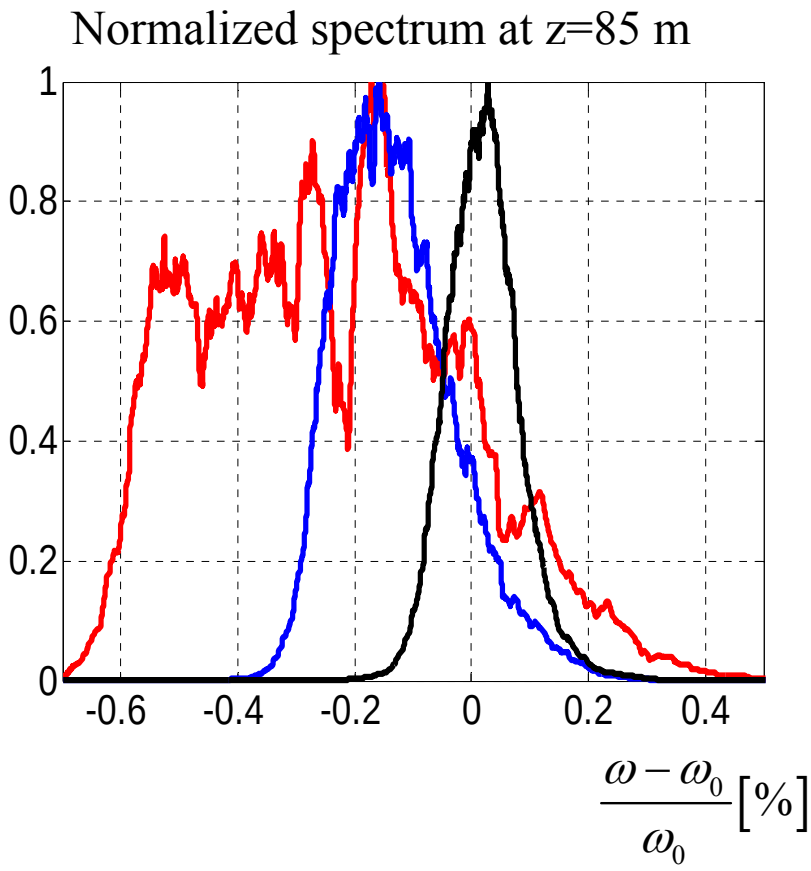
Beam matched in the peak current. Q=1nC





Beam matched in the peak current. Q=1nC





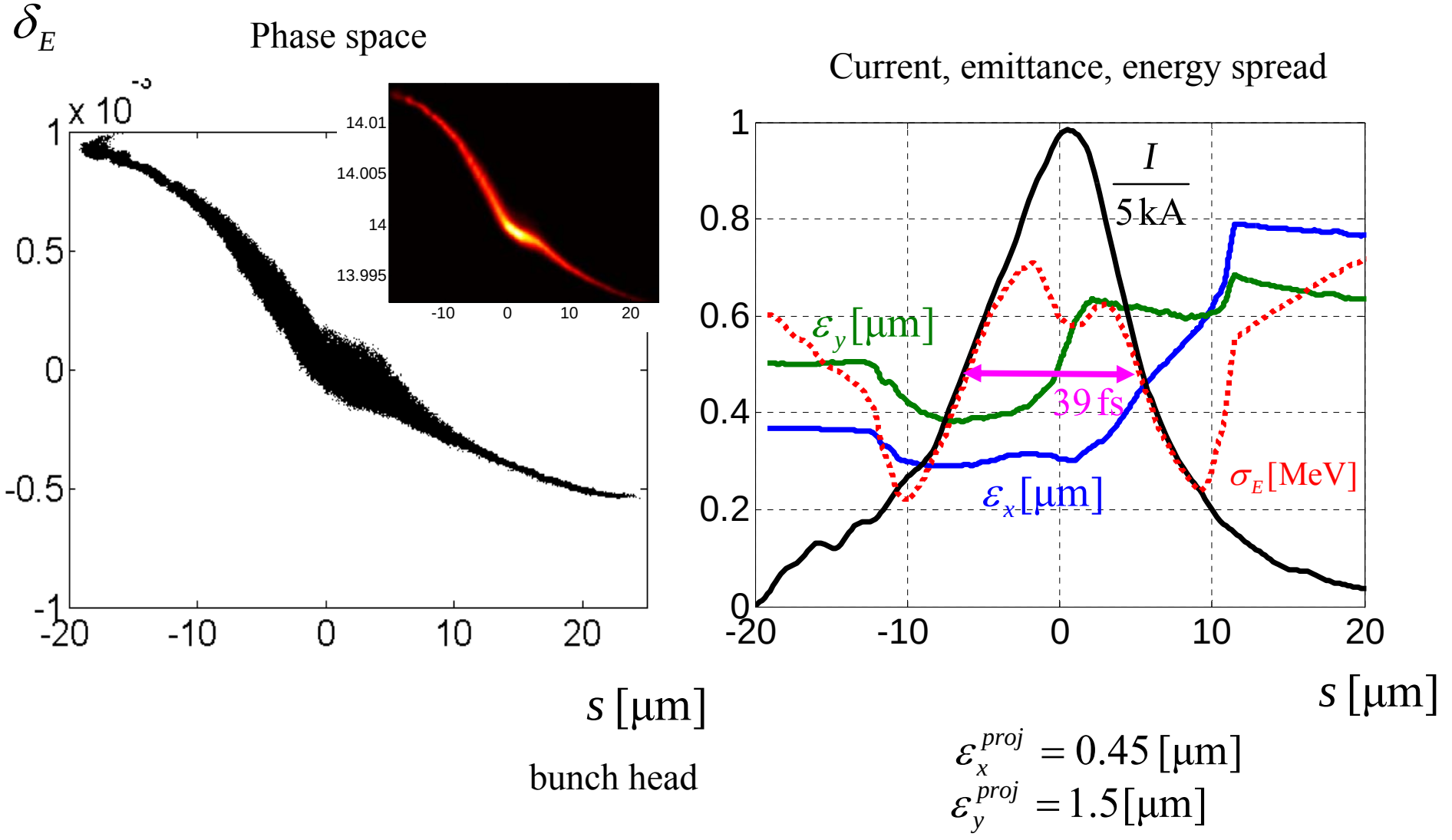
FWHM=0.14%

FWHM=0.23%

FWHM=0.6%

XFEL beam dynamic simulations for different charges (full)

Q=250 pC

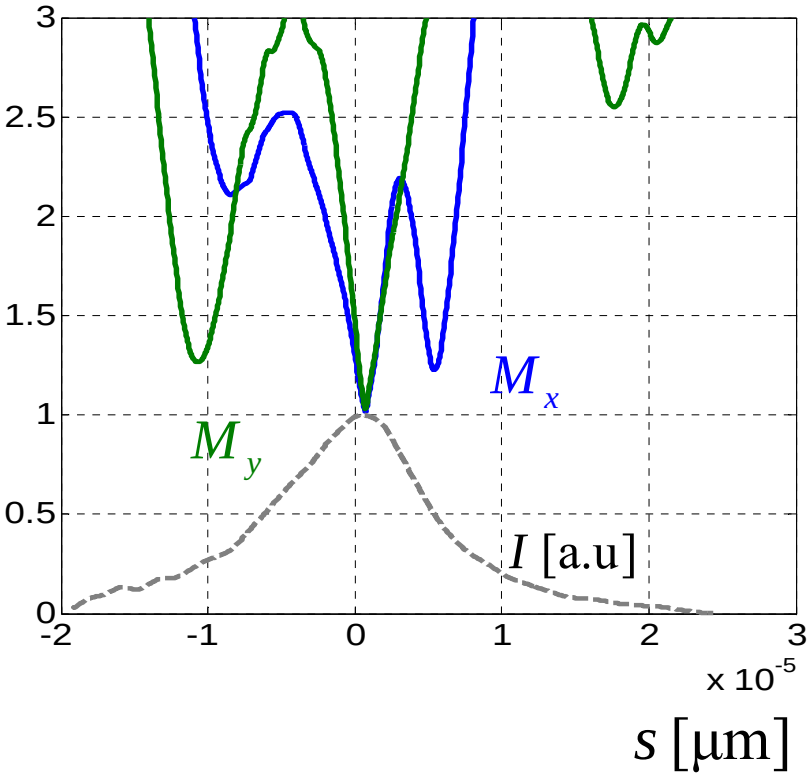


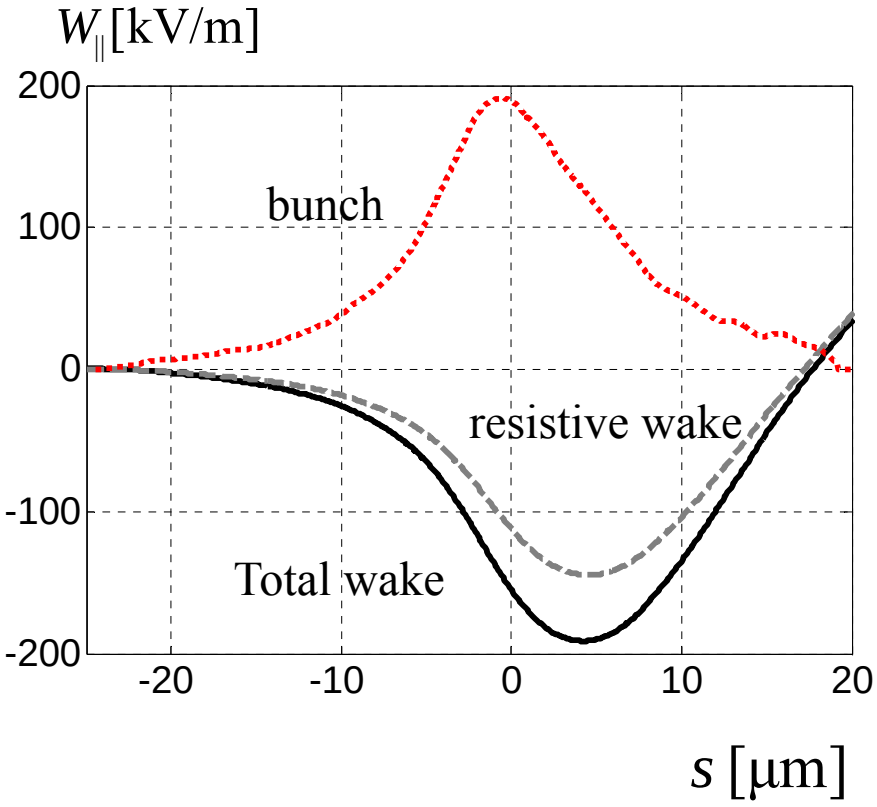
bunch head

$$\varepsilon_x^{proj} = 0.45\,[\mu\text{m}]$$
$$\varepsilon_y^{proj} = 1.5\,[\mu\text{m}]$$

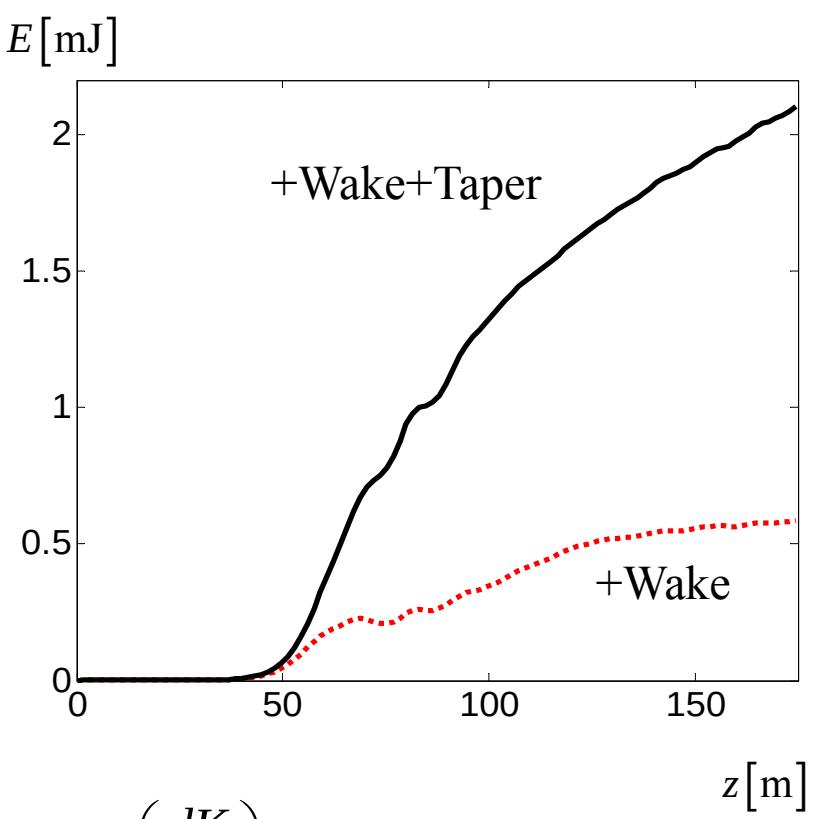
We have removed 6% of bad particles in the analysis (Q=235 pC!)

Mismatch and undulator wake. Q=250 pC

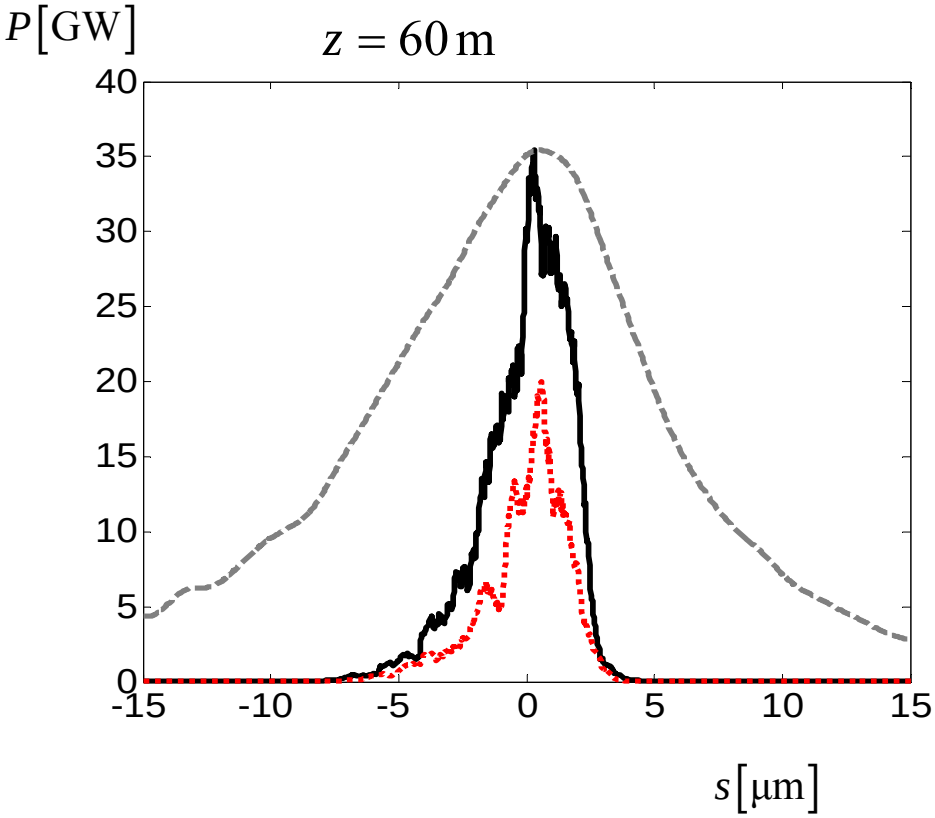




SASE radiation. Q=250 pC



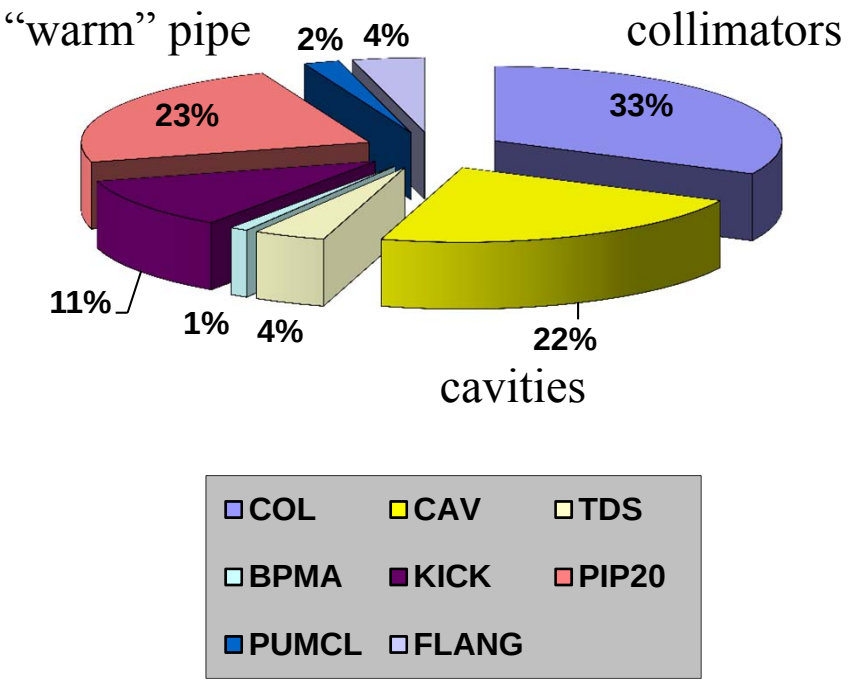
$$\left(\frac{dK}{dz}\right)_{opt} = -4.8 \cdot 10^{-5}\ \mathrm{m}^{-1}$$



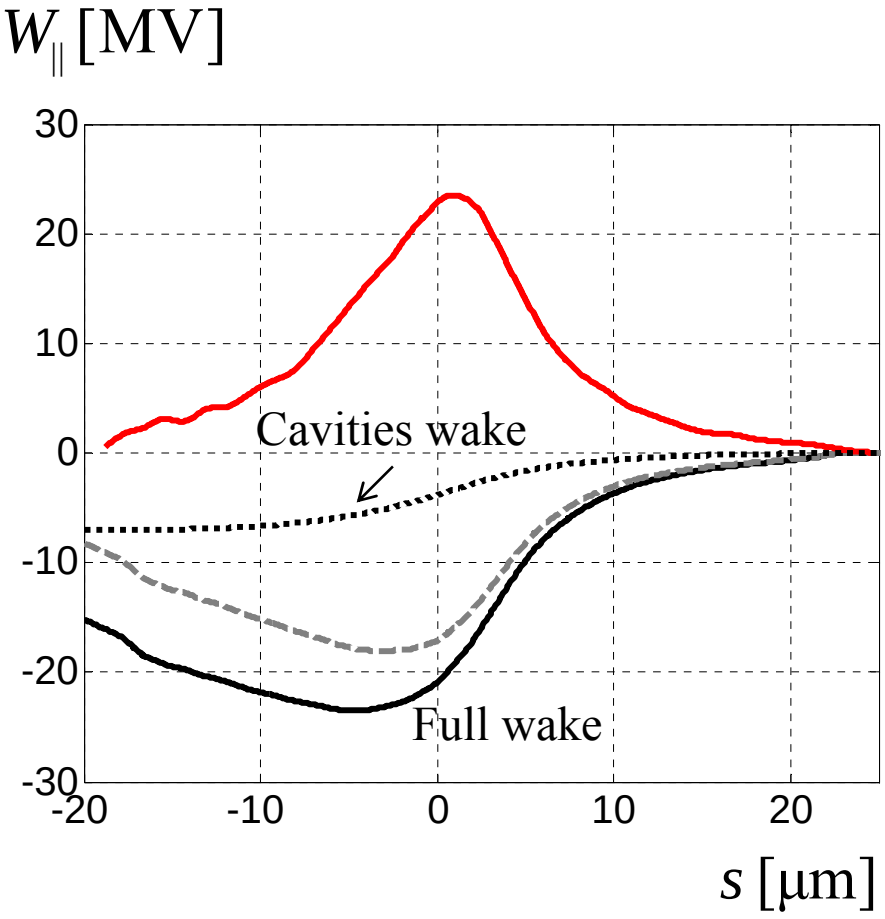
Averaged through 2400 slices

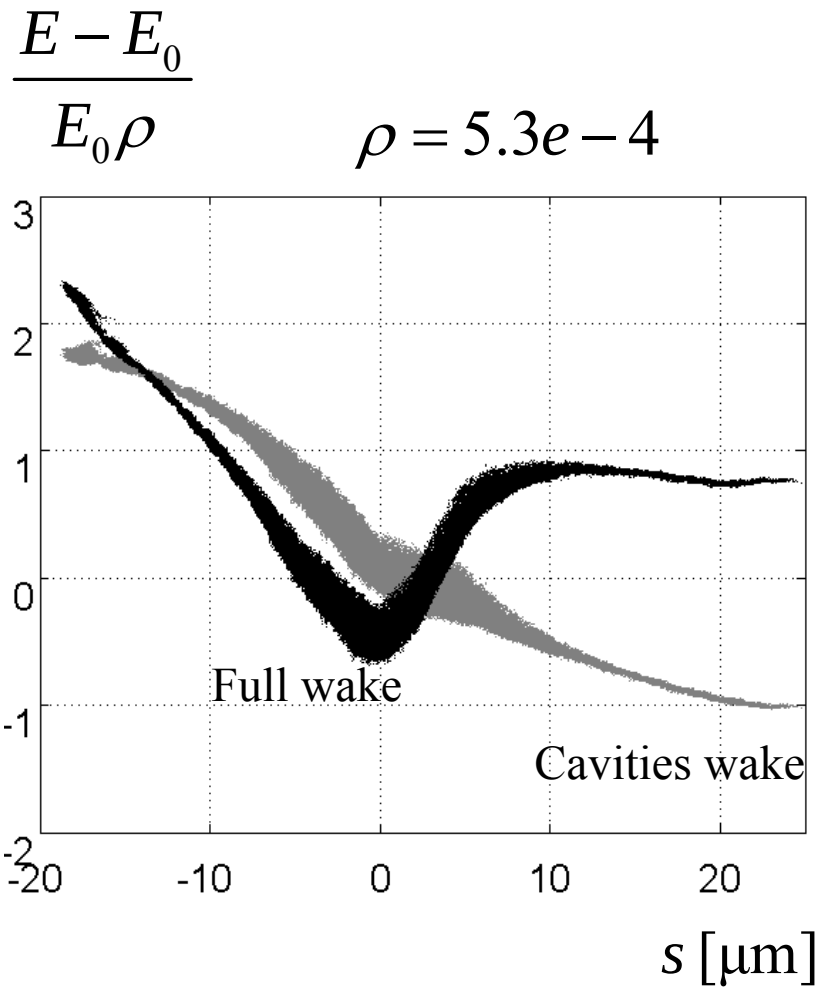
Accelerator wakes. Q=250 pC.

El.type	*Num.*	*Loss (kV / nC)*	*%*	*Spread (kV / nC)*	*%*	*Peak (kV / nC)*	*%*
BPMF	4	6.150E+01	0	2.891E+01	0	8.933E+01	0
COL	7	2.283E+04	32	1.022E+04	31	3.452E+04	35
KICK	3	7.893E+03	11	3.100E+03	9	1.052E+04	11
PIP20	1	1.652E+04	23	8.512E+03	26	2.730E+04	27
PUMCL	78	1.103E+03	2	4.743E+02	1	1.574E+03	2
CAV	808	1.574E+04	22	9.440E+03	29	2.987E+04	30
CAV3	8	9.280E+01	0	3.590E+01	0	1.316E+02	0
FLANG	500	2.619E+03	4	1.126E+03	3	3.736E+03	4
TDS	8	2.506E+03	4	1.229E+03	4	3.677E+03	4
OTRB	8	2.428E+02	0	1.137E+02	0	3.510E+02	0
STEP1	1	3.825E+00	0	6.815E-01	0	4.293E+00	0
BPMA	107	7.317E+02	1	4.231E+02	1	1.265E+03	1
OTRA	12	1.698E+02	0	8.118E+01	0	2.474E+02	0
BPMC	56	7.912E+01	0	4.531E+01	0	1.348E+02	0
BPMR	26	1.523E+02	0	7.506E+01	0	2.241E+02	0
DCM	4	2.533E+01	0	1.160E+01	0	3.612E+01	0
BPMB	27	1.247E-01	0	1.976E-01	0	7.440E-01	0
BAM	5	4.474E+00	0	2.180E+00	0	6.820E+00	0
TORA	3	4.681E+01	0	2.515E+01	0	7.275E+01	0
TORAO	6	1.107E+02	0	5.175E+01	0	1.598E+02	0
		7.063E+04	100	3.285E+04	100	1.000E+05	100

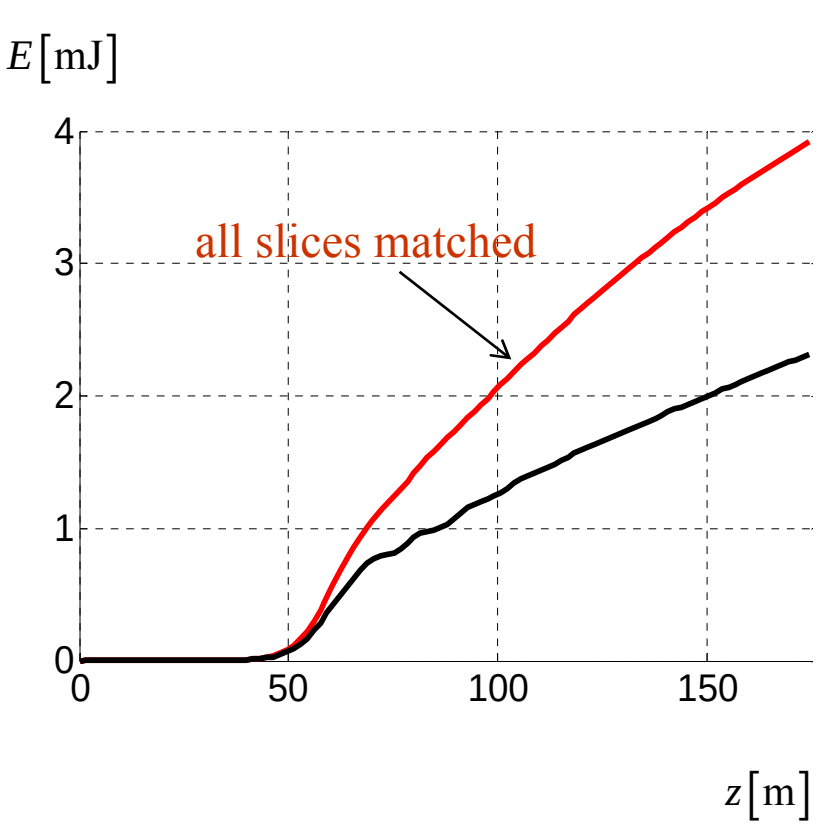


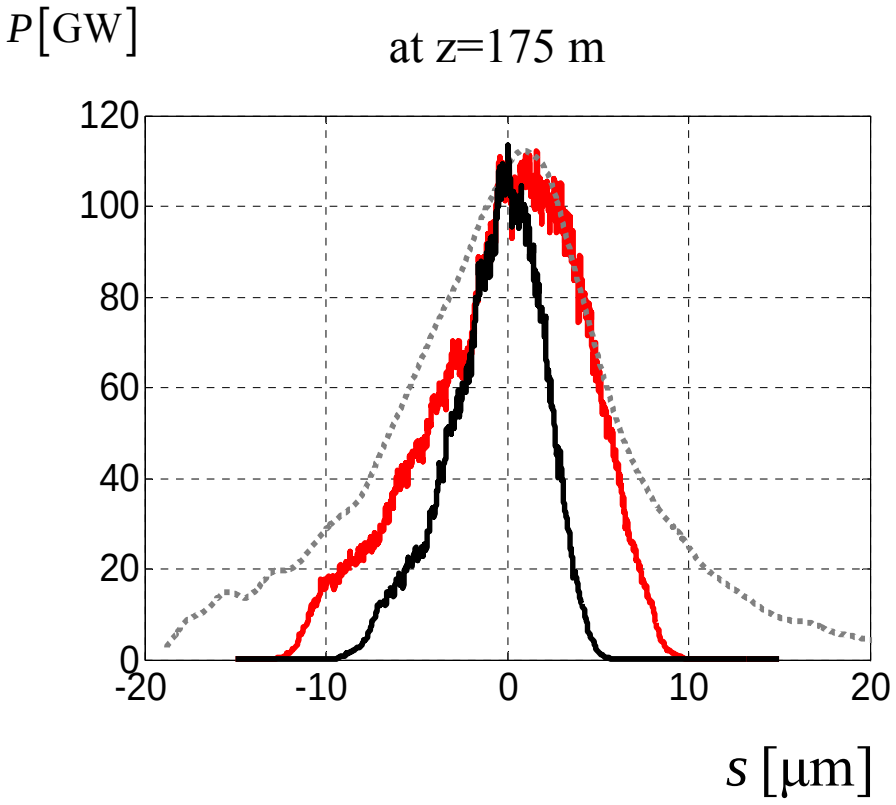
Accelerator wakes. Q=250 pC



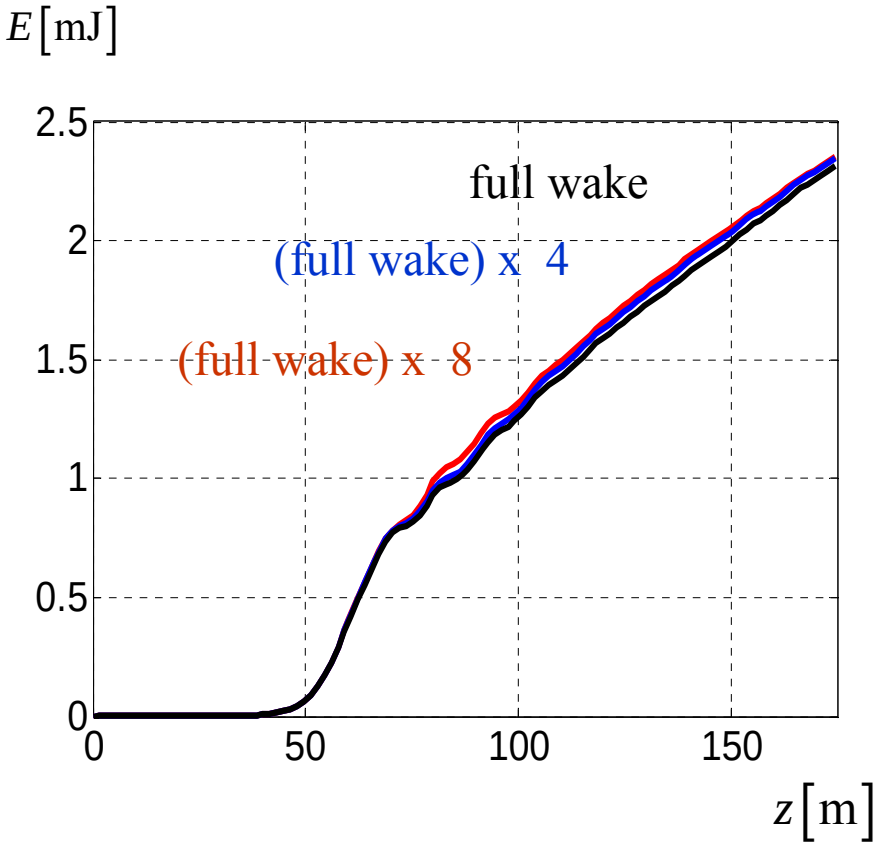


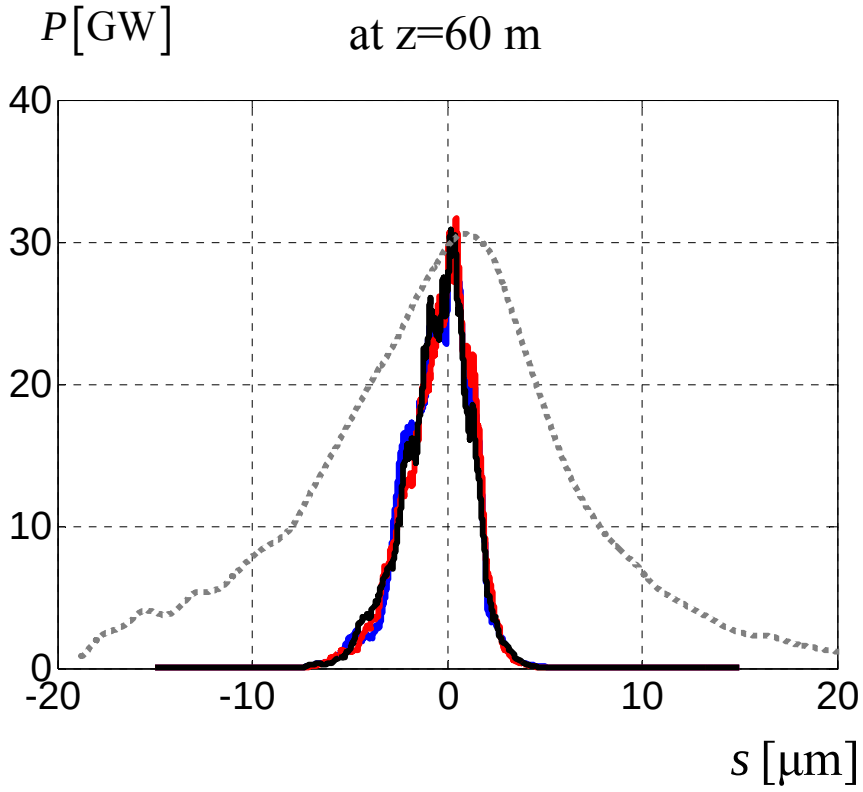
“Artificially” matched beam. Q=250 pC



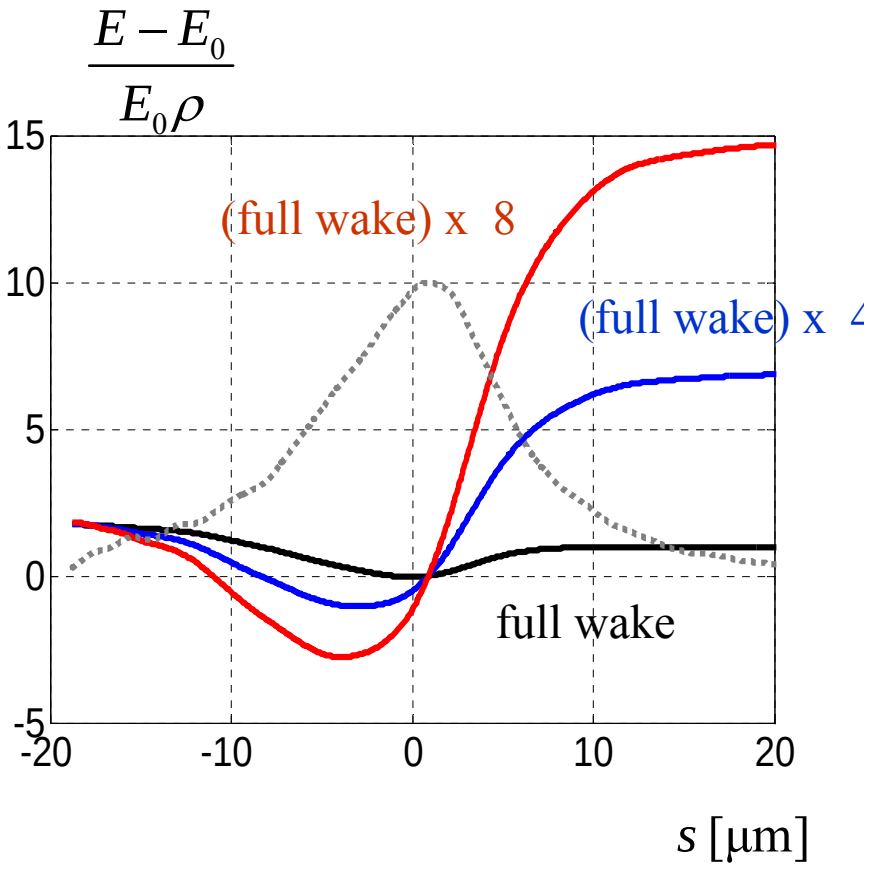


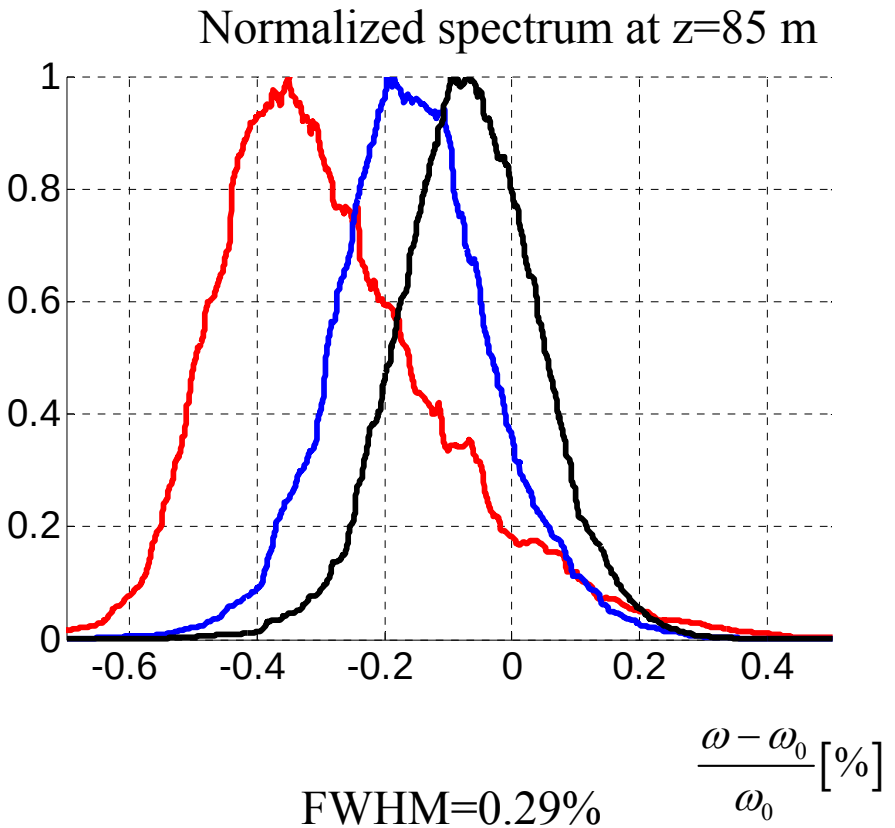
Beam matched in the peak current. Q=250 pC





Beam matched in the peak current. Q=250 pC





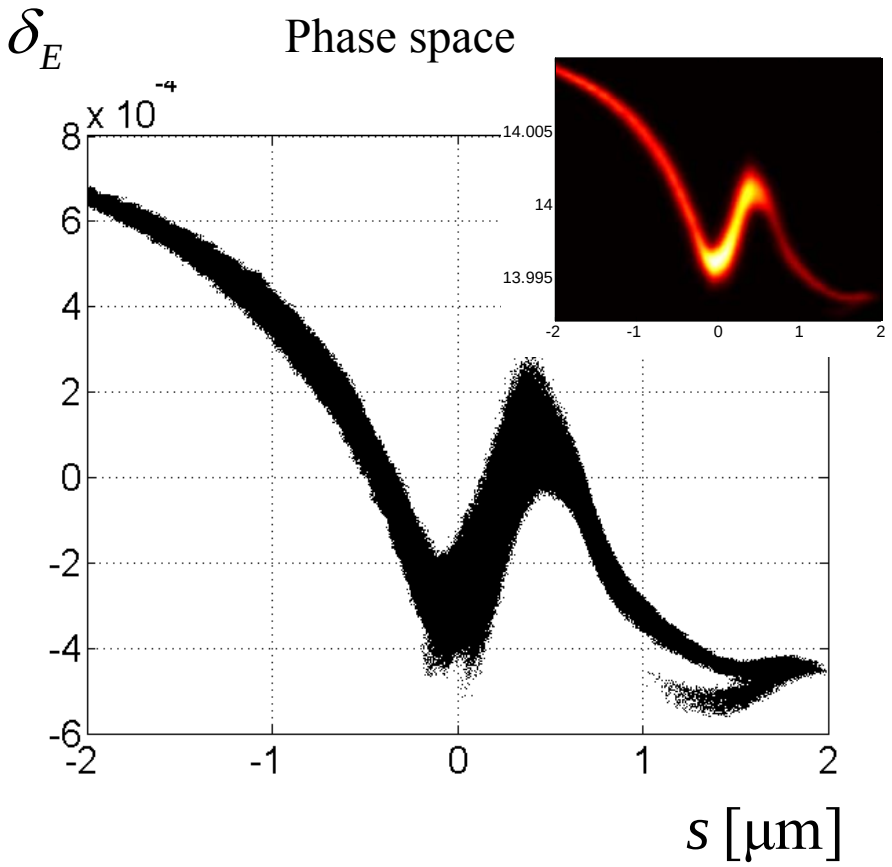
FWHM=0.29%

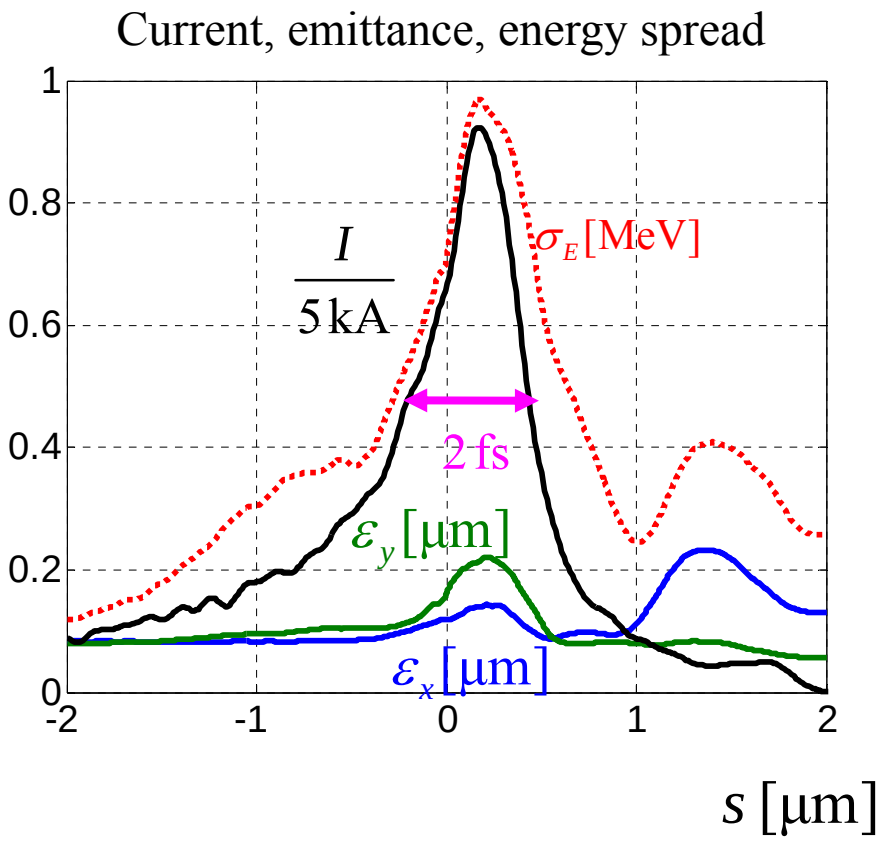
FWHM=0.30%

FWHM=0.38%

XFEL beam dynamic simulations for different charges (full)

Q=20 pC



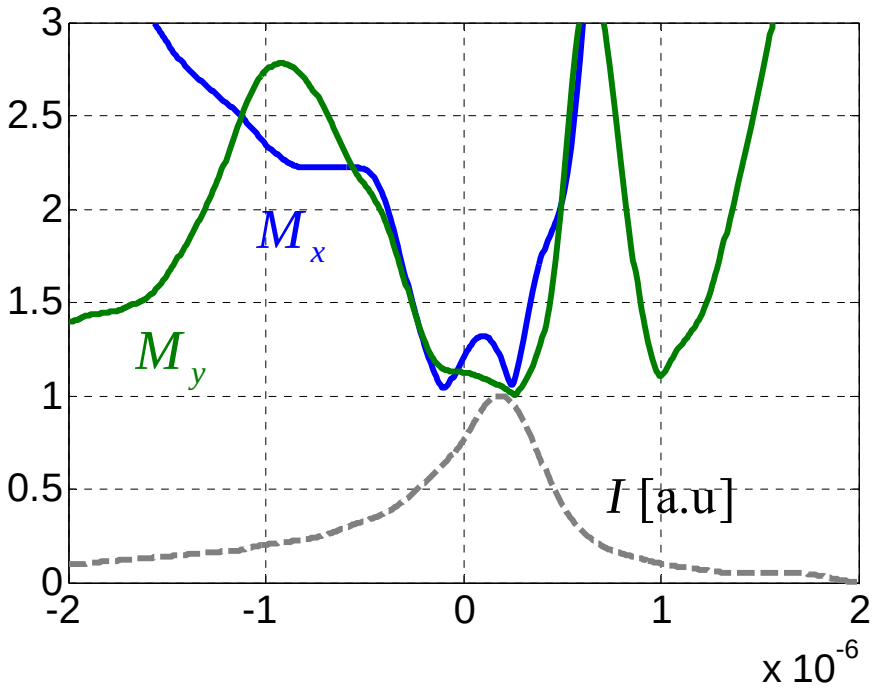


bunch head

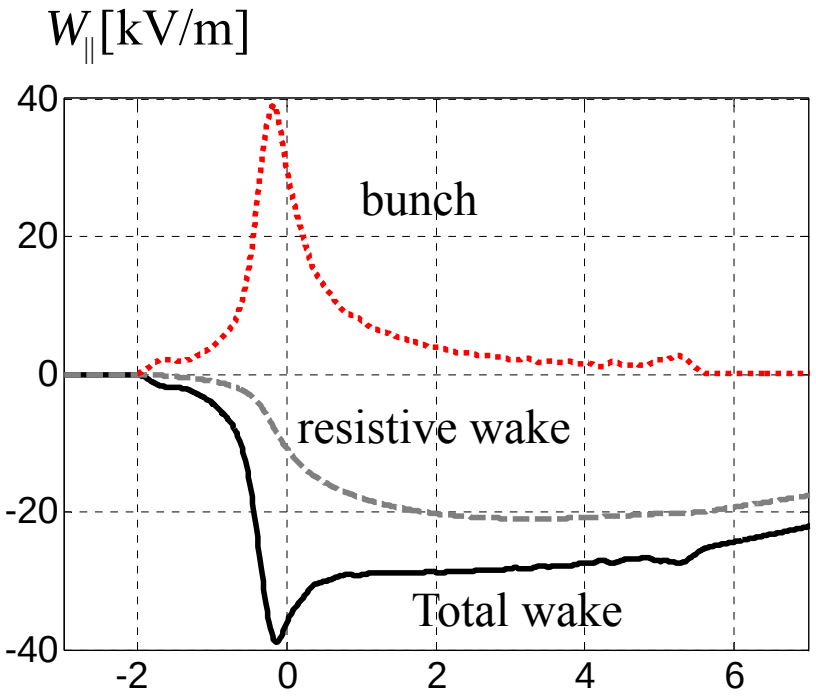
$$\varepsilon_x^{proj} = 0.14\,[\mu\mathrm{m}]$$

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

Mismatch and undulator wake. Q=20 pC

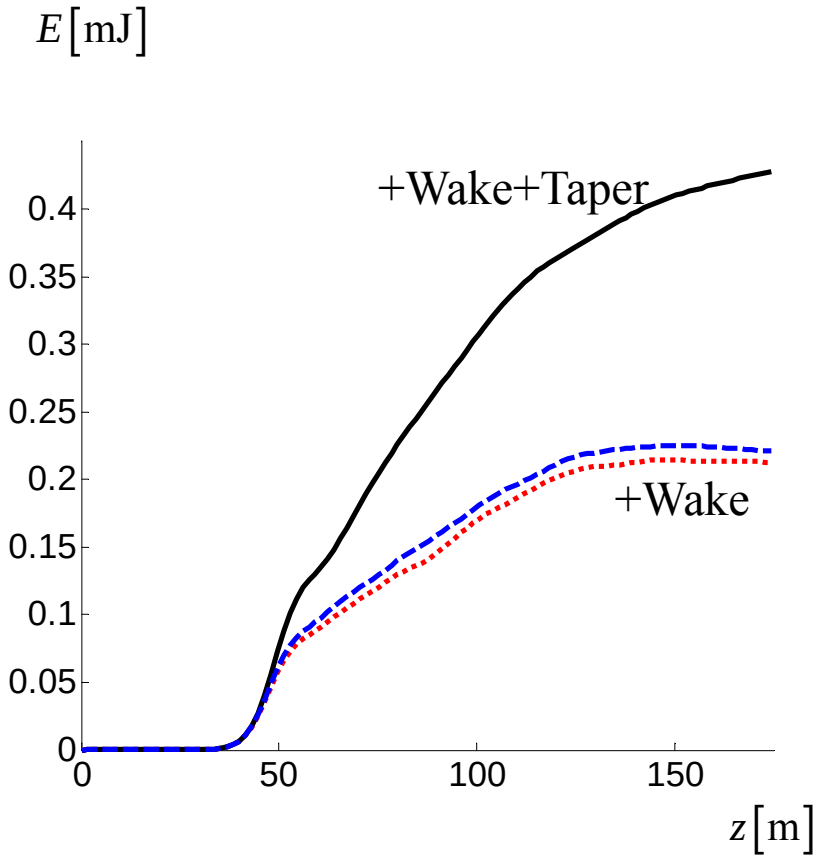


s [μm]

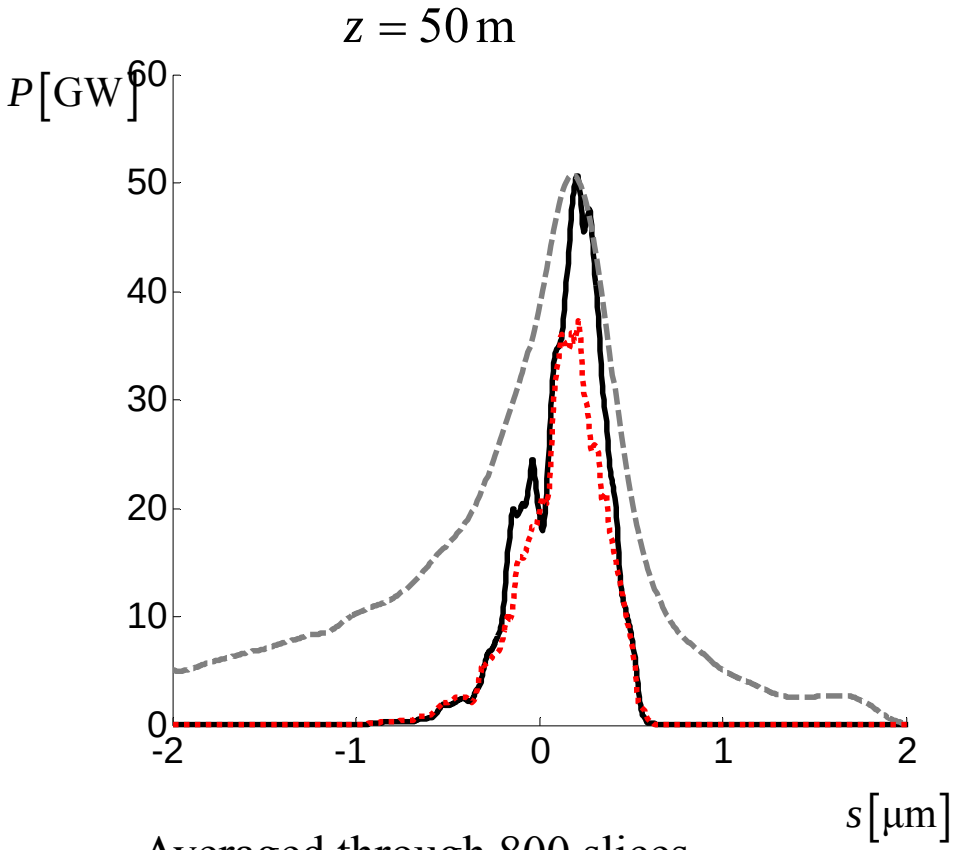


s [μm]

SASE radiation. Q=20 pC



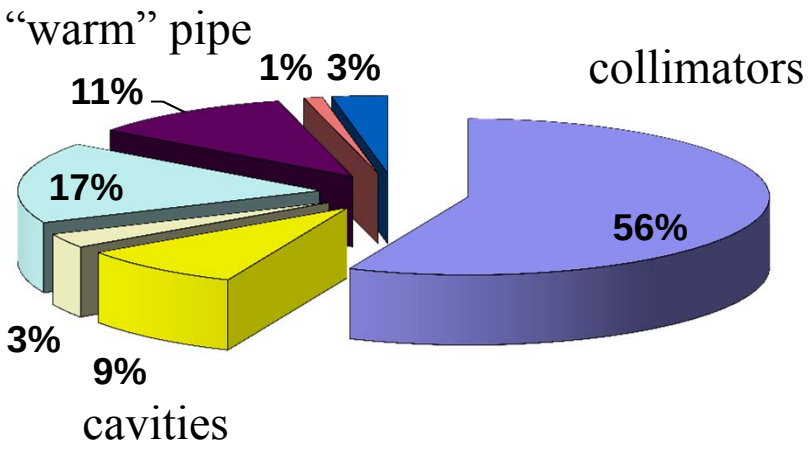
$$\left(\frac{dK}{dz}\right)_{opt} = -4.8 \cdot 10^{-5}\ \mathrm{m}^{-1}$$



Averaged through 800 slices

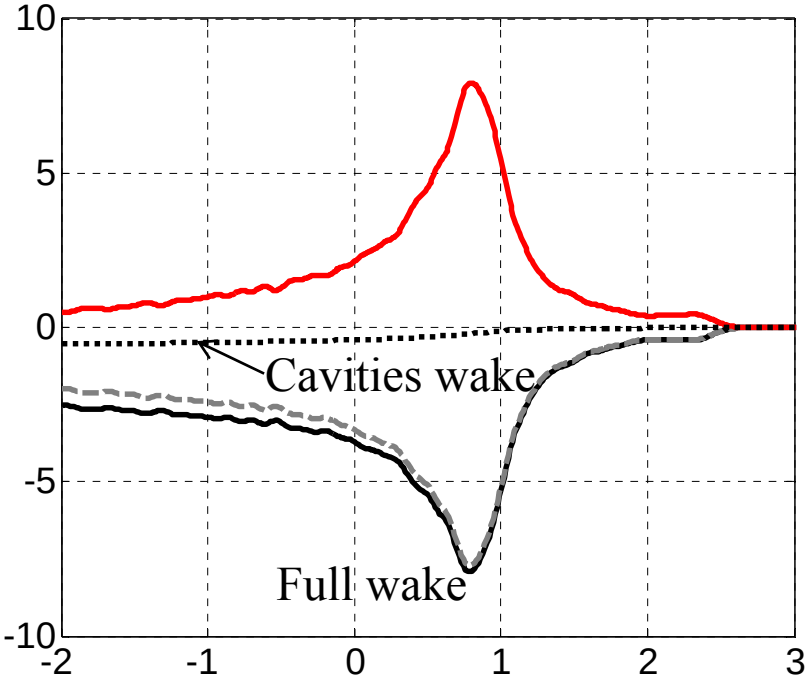
Accelerator wakes. Q=20 pC

El.type	Num.	Loss (kV / nC)	%	Spread (kV / nC)	%	Peak (kV / nC)	%
BPMF	4	1.028E+02	0	4.822E+01	0	1.602E+02	0
COL	7	1.040E+05	57	8.502E+04	83	2.999E+05	75
KICK	3	3.017E+04	17	1.808E+04	18	6.233E+04	16
PIP20	1	1.975E+04	11	1.126E+04	11	3.789E+04	9
PUMCL	78	2.666E+03	1	1.237E+03	1	4.514E+03	1
CAV	808	1.670E+04	9	9.809E+03	10	3.109E+04	8
CAV3	8	9.994E+01	0	3.871E+01	0	1.424E+02	0
FLANG	500	6.328E+03	3	2.937E+03	3	1.072E+04	3
TDS	8	4.847E+03	3	2.648E+03	3	8.072E+03	2
OTRB	8	4.257E+02	0	2.010E+02	0	6.740E+02	0
STEP1	1	4.406E+00	0	7.830E-01	0	4.846E+00	0
BPMA	107	7.840E+02	0	4.502E+02	0	1.352E+03	0
OTRA	12	3.035E+02	0	1.468E+02	0	4.863E+02	0
BPMC	56	8.884E+01	0	5.119E+01	0	1.636E+02	0
BPMR	26	3.036E+02	0	1.547E+02	0	5.074E+02	0
DCM	4	4.672E+01	0	2.190E+01	0	7.487E+01	0
BPMB	27	1.755E-01	0	2.488E-01	0	7.636E-01	0
BAM	5	5.023E+00	0	2.364E+00	0	7.486E+00	0
TORA	3	6.546E+01	0	3.326E+01	0	9.760E+01	0
TORAO	6	1.989E+02	0	9.429E+01	0	3.173E+02	0
		1.810E+05	100	1.019E+05	100	4.004E+05	100



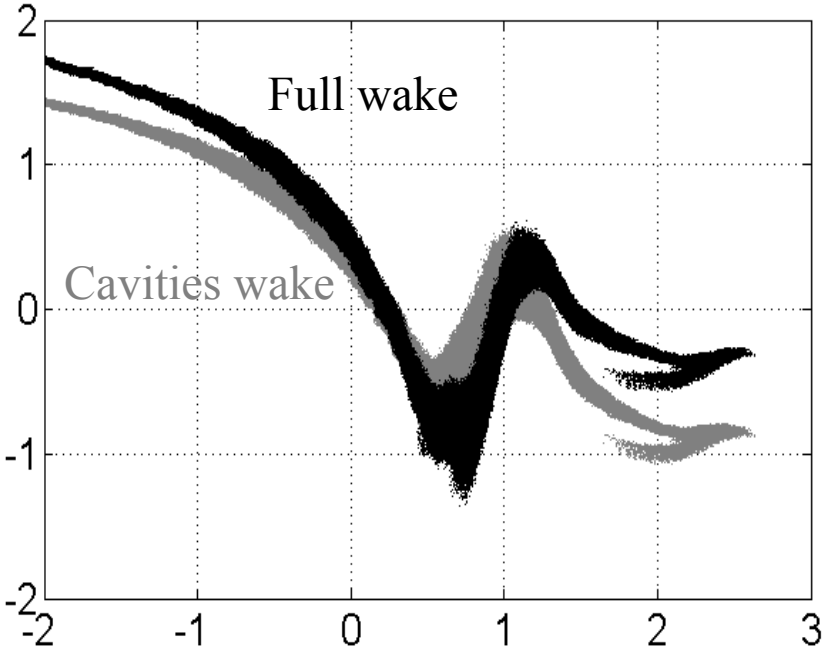
Accelerator wakes. Q=20 pC

$W_{\|}$ [MV]



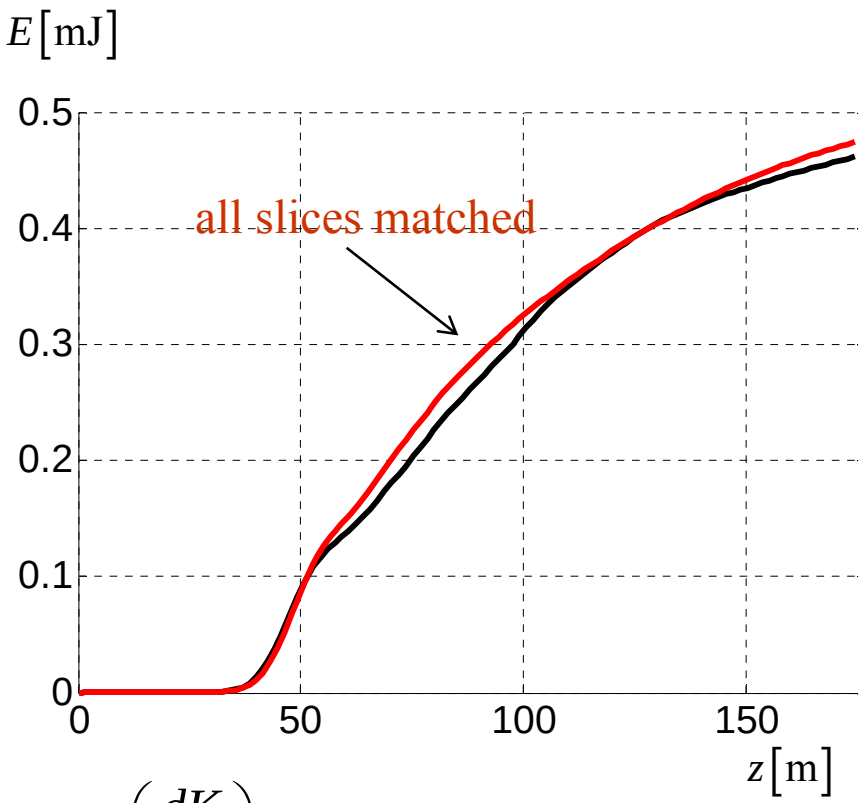
s [μm]

$$\frac{E - E_0}{E_0 \rho} \qquad \rho = 5.3e-4$$

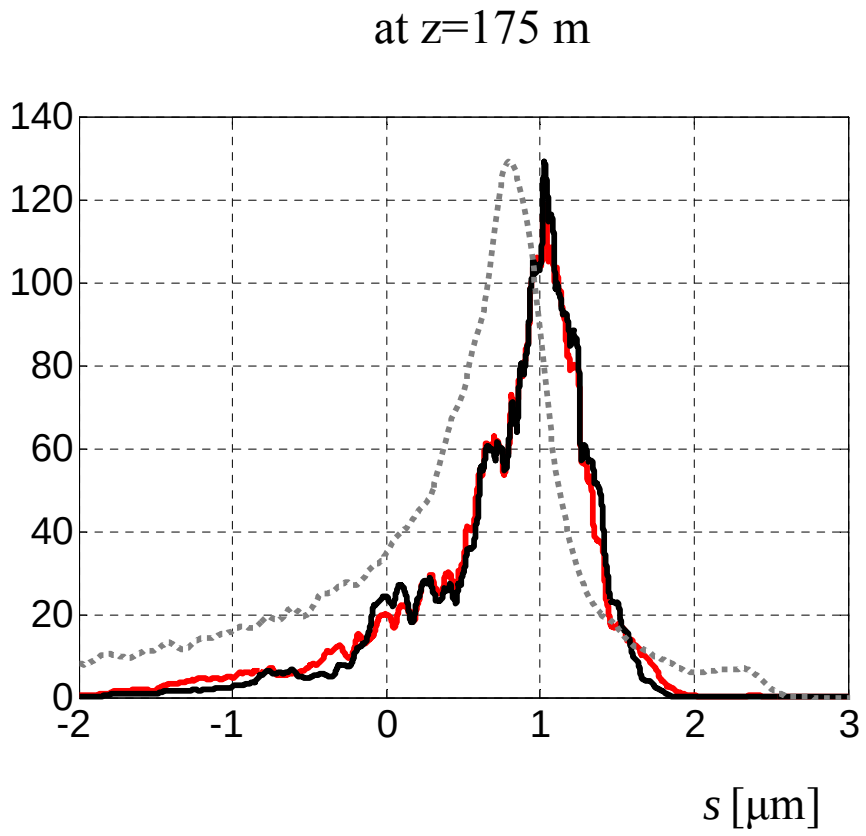


s [μm]

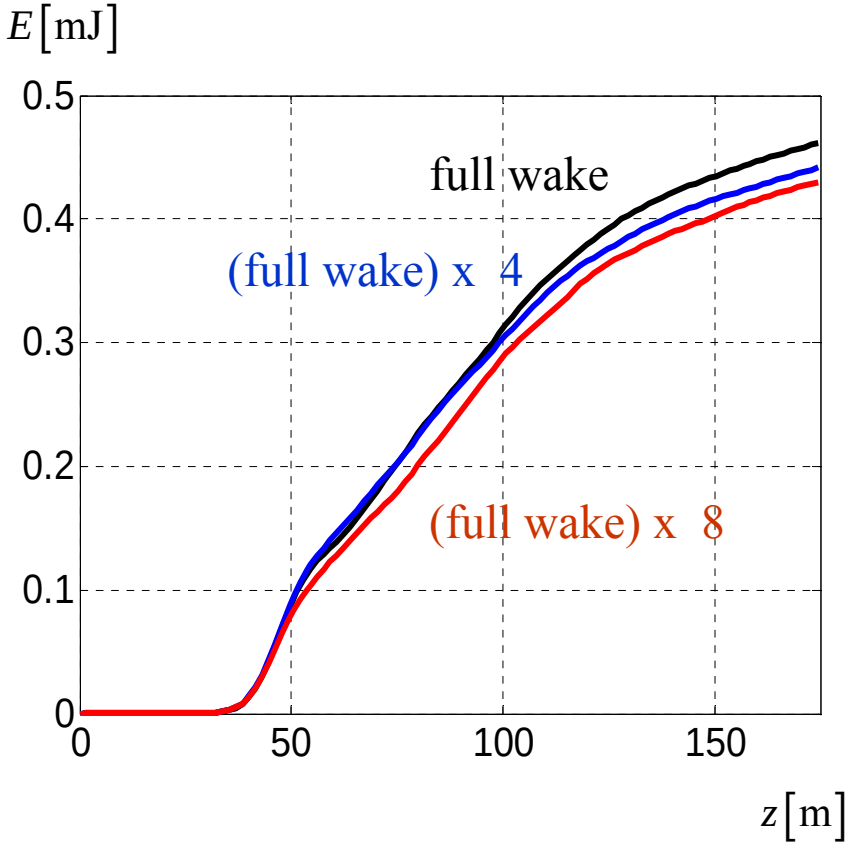
“Artificially” matched beam. Q=20 pC

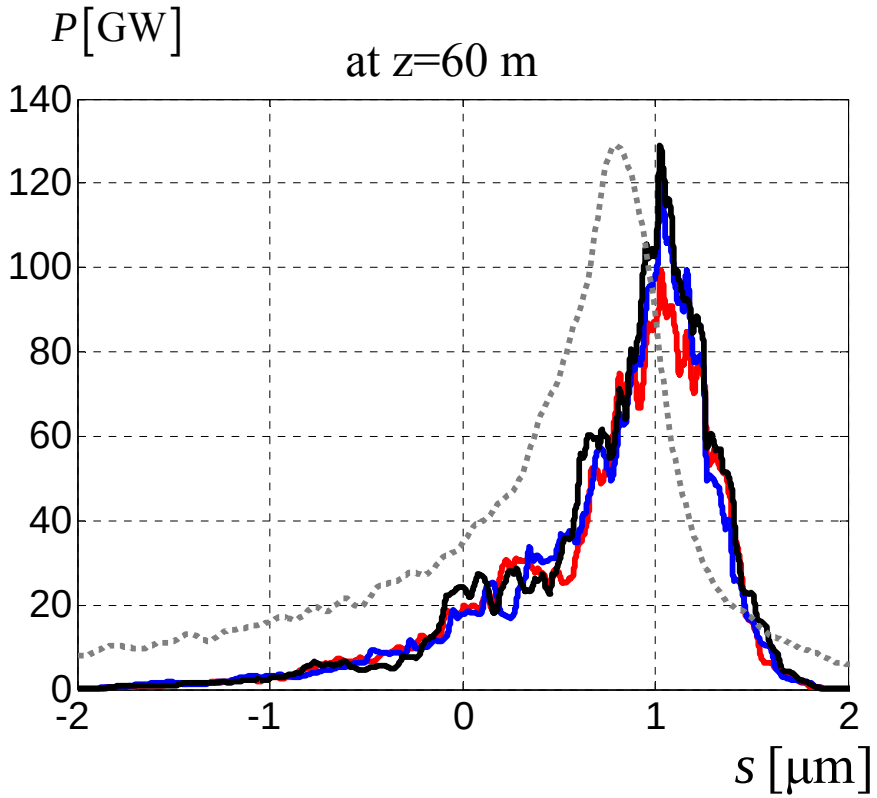


$$\left(\frac{dK}{dz}\right)_{opt} = -4.8\cdot 10^{-5}\,\mathrm{m}^{-1}$$

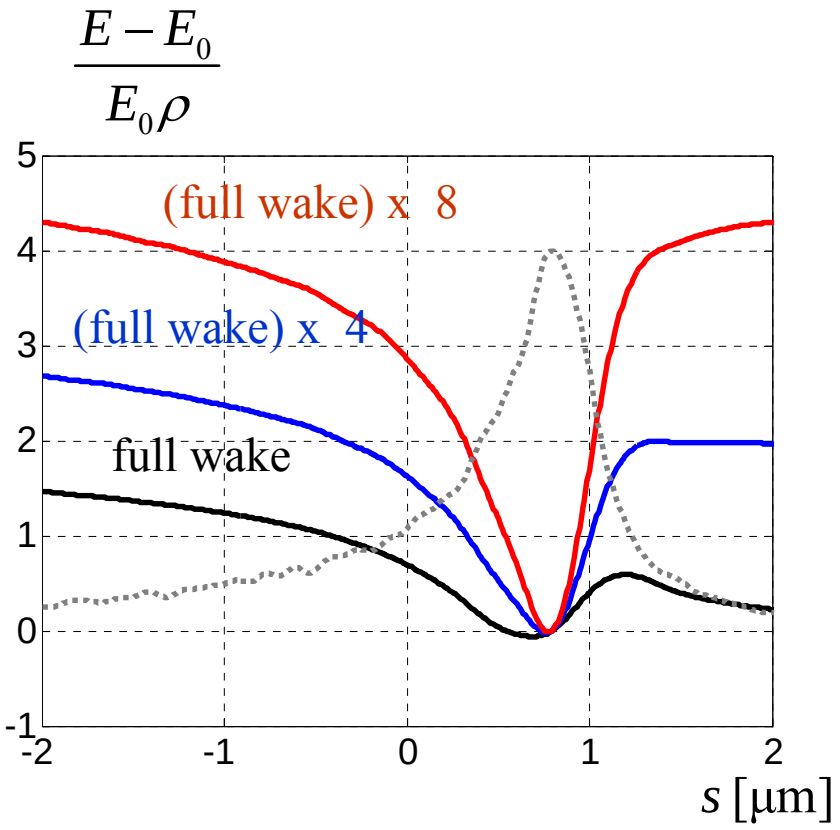


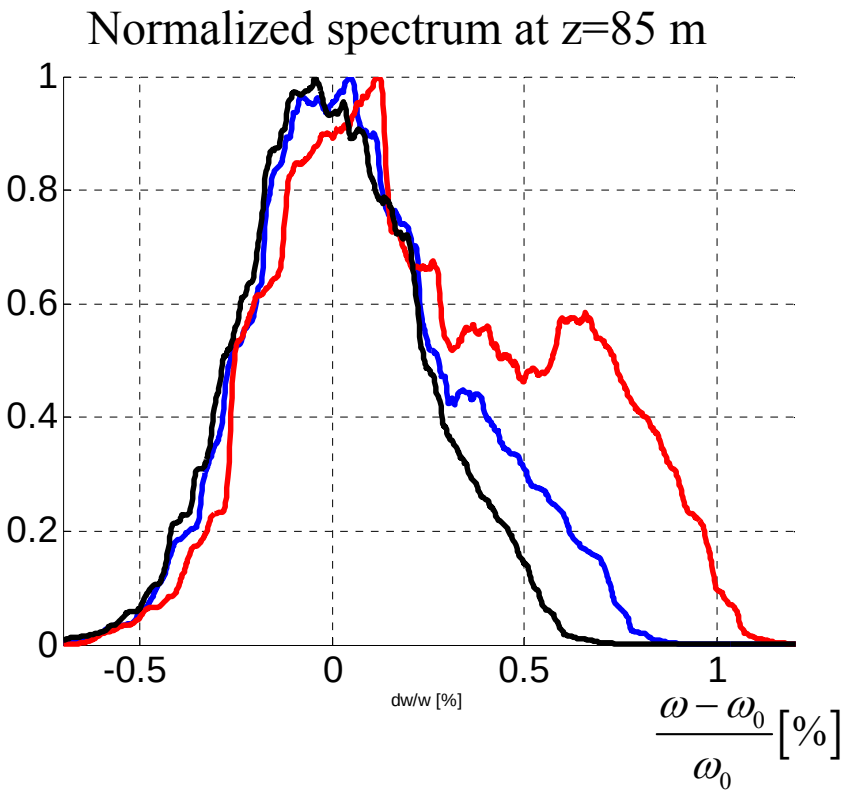
Beam matched in the peak current. Q=20 pC





Beam matched in the peak current. Q=20 pC





FWHM=0.55%

FWHM=0.58%

FWHM=1.0%

Summary

	Accelerator wake	Bunch charge, nC		
		1	0.25	0.02
Energy in the radiation pulse at z=175 m, mJ	x1	9	2.3	0.46
	x4	8	2.3	0.44
	x8	6	2.3	0.43
Spectrum width at z=85m, %	x1	0.14	0.29	0.55
	x4	0.23	0.30	0.58
	x8	0.6	0.38	1.0

We have considered only the **longitudinal** wake in a quite coarse model (adding the accelerator wake at the undulator entrance).
The **transverse** wakes are neglected.