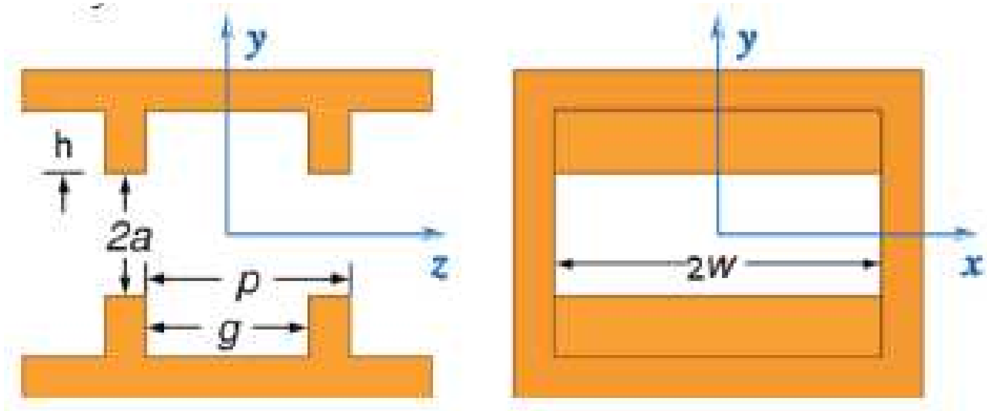
Large Bandwidth Radiation at XFEL

Usage of corrugated structure for increase of the energy chirp



Igor Zagorodnov

S2E Meeting

DESY

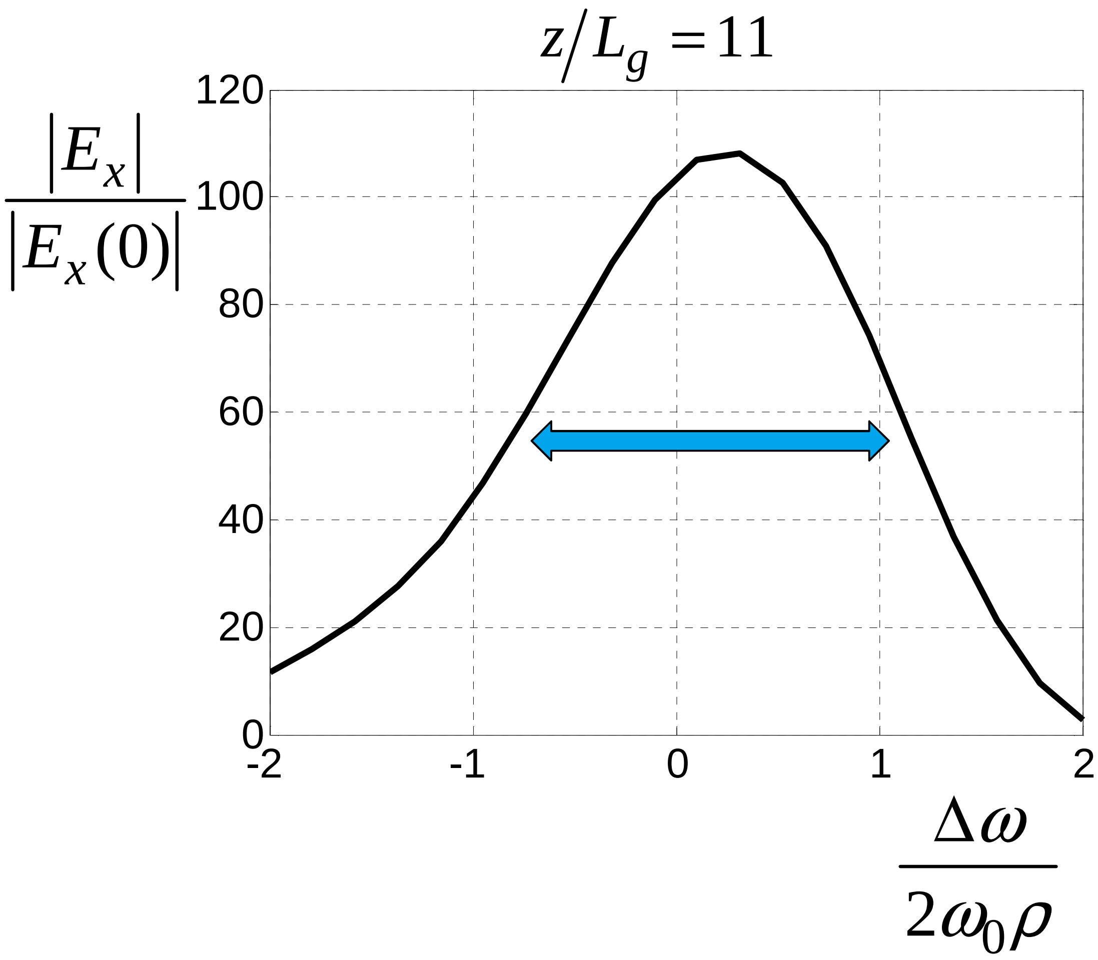
18. April 2016

HELMHOLTZ
GEMEINSCHAFT

DESY

Energy spread and Radiation Bandwidth

FEL bandwidth for negligible energy spread (1D simulation)



$$\frac{\Delta\omega}{\omega_0} \sim \rho$$

$$\rho \sim 10^{-3} \text{ at EXFEL}$$

Energy spread and Radiation Bandwidth

Comparative table of the properties of the radiation from SASE1 as of TDR 2006 and December 2010 revision (electron energy 17.5 GeV, wavelength 0.1 nm)

	Units	SASE1 2006	SASE1 (2010)		
Bunch charge	nC	1	1	0.25	0.02
Pulse energy	mJ	1.3	1.80	.697	.635E-01
Peak power	GW	11.7	16.8	30.0	37.8
Average power	W	35.2	48.7	18.8	1.71
FWHM spot size	μm	53.8	42.7	34.2	27.3
FWHM angular divergence	μrad	1.22	1.35	1.60	2.00
Coherence time	fs	0.29	.201	.164	.135
FWHM spectrum width, $\Delta\omega/\omega$	%	.081	.117	.144	.175
Degree of transverse coherence	#	.62	.820	.950	.960
FWHM pulse duration	fs	110	107.	23.2	1.68
Degeneracy parameter	#	.106E+10	.139E+10	.235E+10	.246E+10
Number oh photons per pulse	#	.656E+12	.907E+12	.351E+12	.319E+11
Average flux of photons	ph/sec	.177E+17	.245E+17	.947E+16	.862E+15
Peak brilliance*	#	.179E+34	.237E+34	.399E+34	.417E+34
Average brilliance*	#	.540E+25	.685E+25	.250E+25	.189E+24
Saturation length	m	131.	100.	70.6	57.6

$$\frac{\Delta\omega}{\omega_0} \sim 0.1\%$$

Photon beam properties at the European XFEL (December 2010 revision)

E.A. Schneidmiller, M.V. Yurkov

Energy spread and Radiation Bandwidth

The energy deviation (of electron) is equivalent to the wavelength deviation (of EM wave)

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \quad \Rightarrow \quad \frac{\gamma-\gamma_0}{\gamma_0} \approx \frac{\omega-\omega_0}{2\omega_0}$$

3% in bandwidth ~ 1.5% in energy spread

For 17.5 GeV we need energy spread of **260 MeV**.

S2E simulations with over-compression

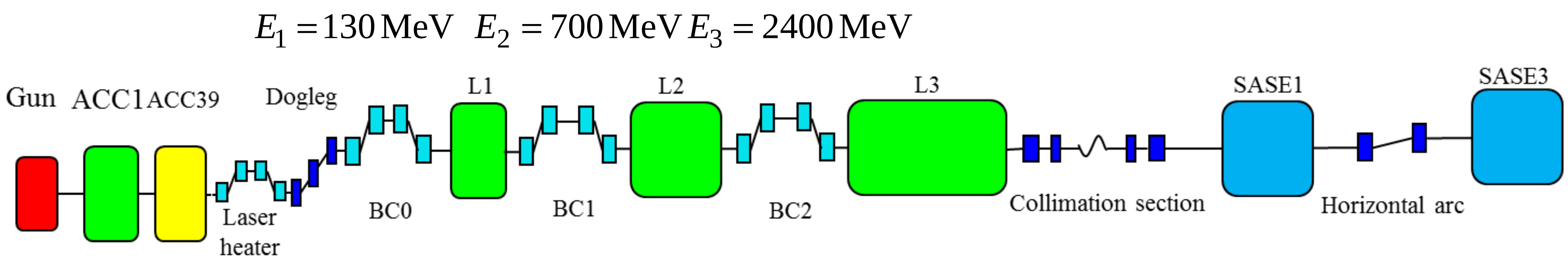
Start-to-End simulations done by Guangyao Feng, DESY.

❖ At the end of the linac

E=17.5 GeV ,

I_{peak}=~5.0kA, Q=0.5nC

❖ Beam energy at some key positions



ASTRA+CSRTrack

S2E simulations with over-compression

Start-to-End simulations done by Guangyao Feng, DESY.

Parameter settings for the bunch compressors

Charge Q, nC	Momentum compaction factor in Dogleg $R_{56,dogleg}$ [mm]	Momentum compaction factor in BC_0 $R_{56,0}$ [mm]	Total compr. Cdogleg*C0	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]	Over compression In BC_2
0.5	-30.1	-54.80	3.5	-50	8	-28.3	Ip = 5.0 kA

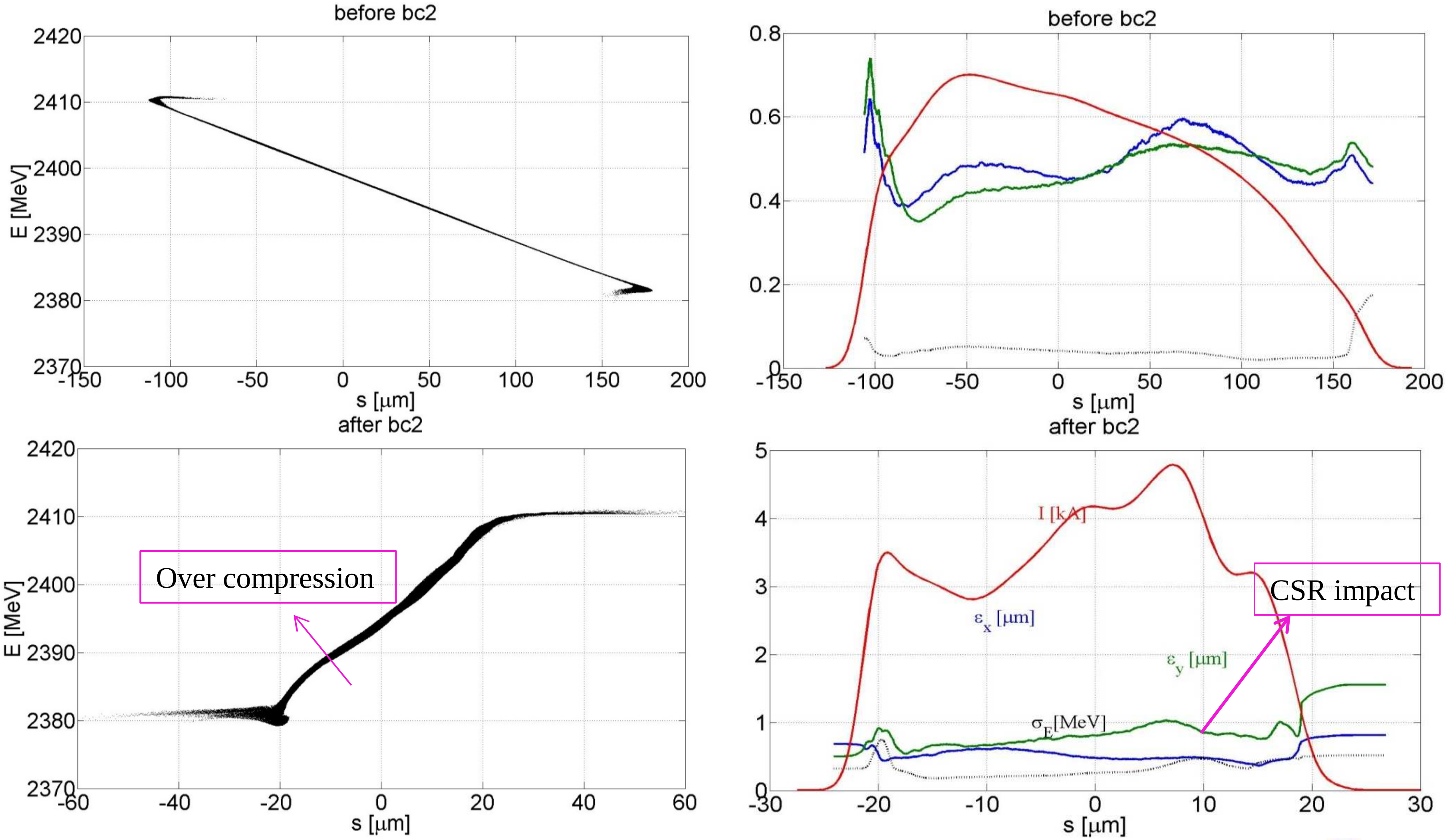
RF settings in accelerating modules

Charge nC	Vacc1 [MV]	φacc1 [deg]	Vacc39 [MV]	φacc39 [deg]	Vlinac1 [MV]	φlinac1 [deg]	Vlinac2 [MV]	Φlinac2 [deg]
0.5 (5kA)	157.31	21.76	24.67	203.82	673.54	32.16	1776.25	16.75

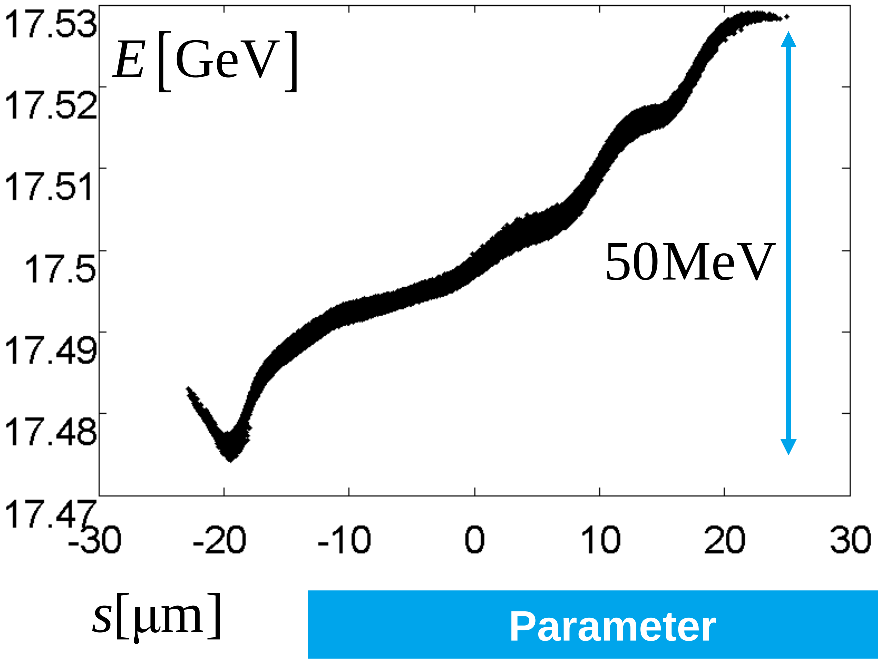
Linac3: accelerating on-crest

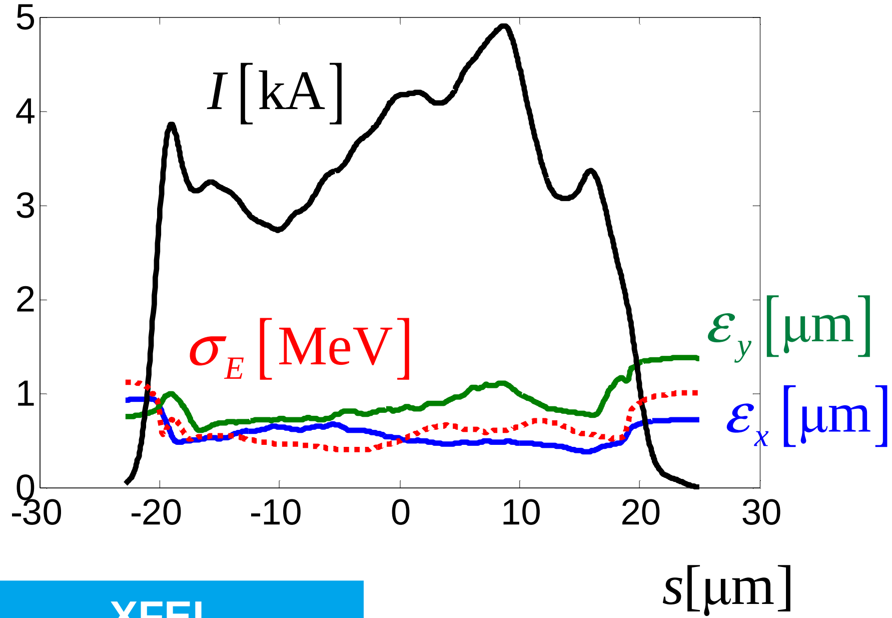
S2E simulations with over-compression

Start-to-End simulations done by Guangyao Feng, DESY.



S2E simulations with over-compression

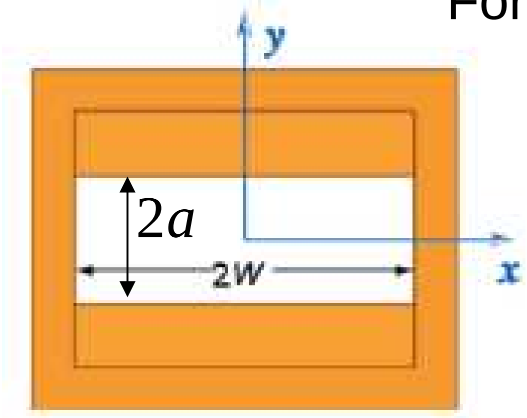




Parameter	XFEL
Beam energy, GeV	17.5
Charge, pC	500
Beam average current, kA	3.75
FWHM bunch length, um	40
Emittance $\varepsilon_x/\varepsilon_y$, um	0.64/1.09
Energy spread , keV	500

Flat structure with delayed layer

For **flat structure** (paper of Bane Stupakov, 2015)



$$Z^{cc}(k_x,k)=\frac{Z_0 c}{2a}\operatorname{sech}^2(X)\left[\eta^{-1}-ika\frac{\tanh(X)}{X}\right]^{-1},\; X=ak_x$$

$$Z^{ss}(k_x,k)=\frac{Z_0 c}{2a}\operatorname{csch}^2(X)\left[\eta^{-1}-ika\frac{\coth(X)}{X}\right]^{-1}$$

$$Z(y_0,y,k_x,k)=Z^{cc}(k_x,k)\cosh(k_x y_0)\cosh(k_x y)+Z^{ss}(k_x,k)\sinh(k_x y_0)\sinh(k_x y$$

For **rectangular structure**

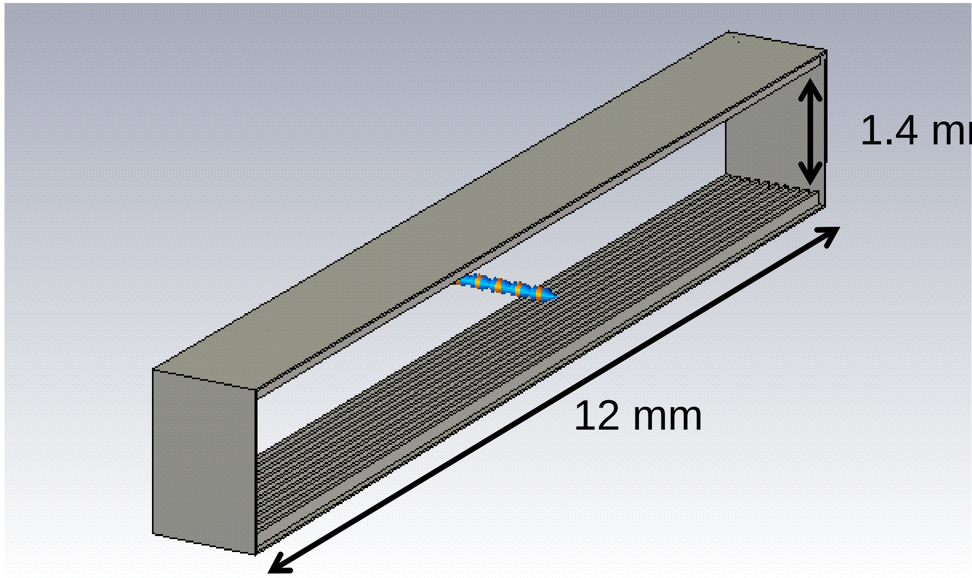
$$Z(x_0,y_0,x,y,k)=\frac{1}{w}\sum_{m=1}^{\infty}Z(y_0,y,k_{x,m},k)\sin(k_{x,m}x_0)\sin(k_{x,m}x),\quad k_x=\frac{\pi m}{2w}$$

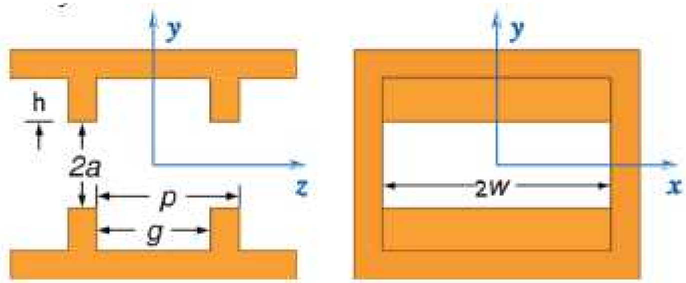
Surface impedance

$$\eta=\sqrt{\frac{i\omega\mu}{\kappa}}\text{ - conductive layer}$$

$$\eta=-2ikw\left(\mu-\varepsilon^{-1}\right)\text{ - dielectric layer}$$

Corrugated structure





g = 0.25 mm
p = 0.5 mm
2w = 12 mm
2a = 1.4 mm
h = 0.5 mm
Length = 2&3 m

$\eta = -2ikw\left(\mu - \varepsilon^{-1}\right), \mu = \frac{g}{p}, \varepsilon << 1$ - equivalent dielectric layer

$\eta^{-1} << k$ - high frequency behavior for any delayed layer

Corrugated structure wakes

$$Z^{cc}(k_x,k)=\frac{Z_0 c}{2a}\operatorname{sech}^2(X)\left[\eta^{-1}-ika\frac{\tanh(X)}{X}\right]^{-1},\ X=ak_x$$

$$Z^{ss}(k_x,k)=\frac{Z_0 c}{2a}\operatorname{csch}^2(X)\left[\eta^{-1}-ika\frac{\coth(X)}{X}\right]^{-1}$$

⇩ $\eta^{-1} << k$ K. Bane, G. Stupakov, LCLS-II, TN-16-01, 2016

$$Z^{cc}(k_x,k)=Z^{ss}(k_x,k)=i\frac{Z_0 c}{2ka^2}\frac{\mathrm{X}}{\cosh(\mathrm{X})\sinh(\mathrm{X})}$$

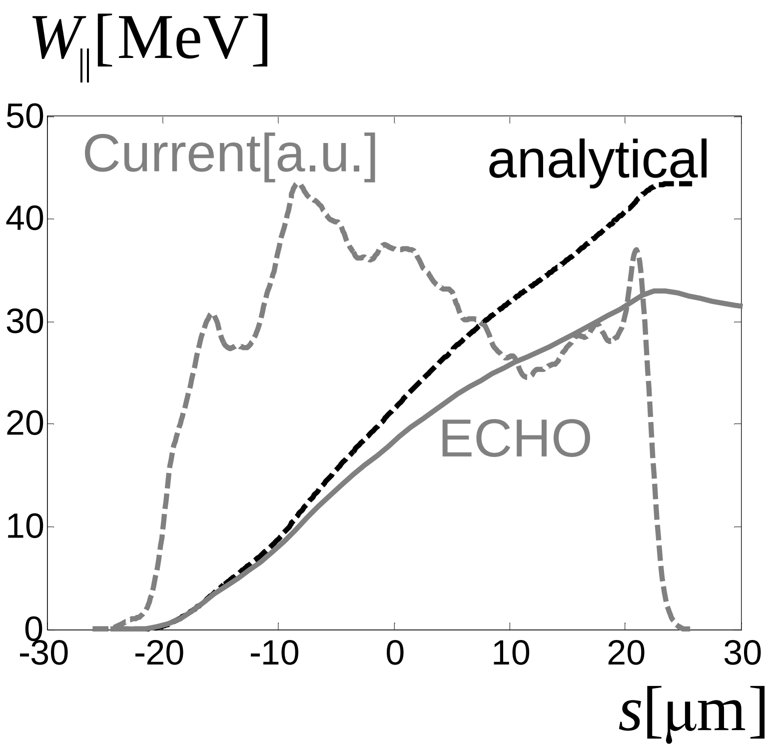
$$W^{cc}(k_x,s)=W^{ss}(k_x,s)=\frac{Z_0 c}{2a^2}\frac{\mathrm{X}}{\cosh(\mathrm{X})\sinh(\mathrm{X})}$$ - independent from s

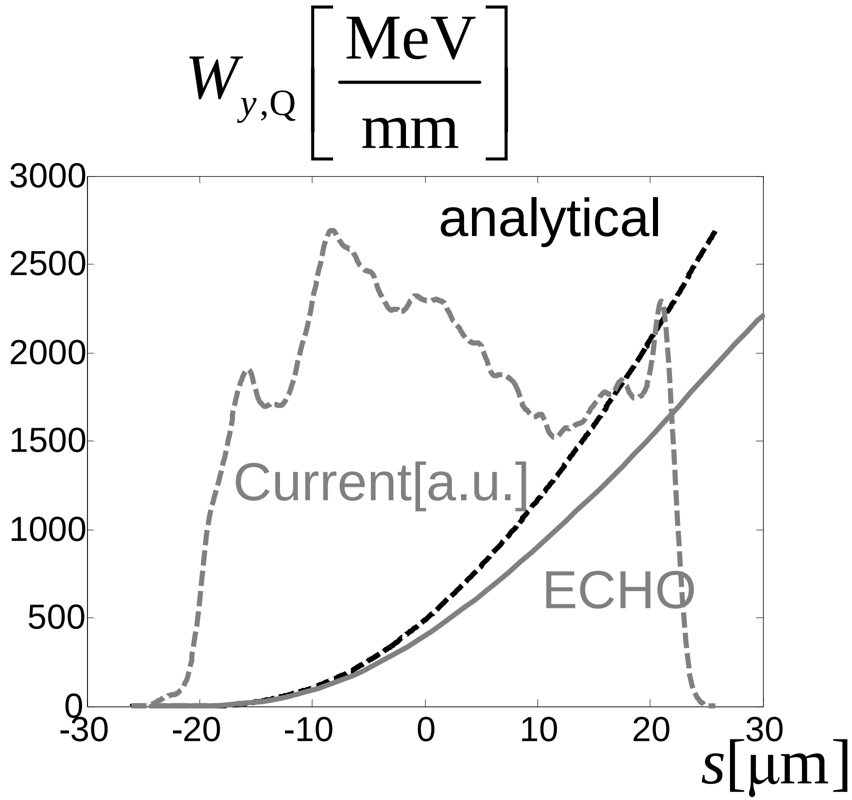
$$W(y_0,y,k_x,s)=W^{cc}(k_x,s)\cosh(k_x y_0)\cosh(k_x y)+W^{ss}(k_x,s)\sinh(k_x y_0)\sinh(k_x y)$$

$$W(x_0,y_0,x,y,s)=\frac{1}{w}\sum_{m=1}^{\infty}W(y_0,y,k_{x,m},s)\sin(k_{x,m}x_0)\sin(k_{x,m}x),\quad k_x=\frac{\pi m}{2w}$$

Corrugated structure wakes

"0-order" approximation





K. Bane, G. Stupakov, LCLS-II, TN-16-01, 2016

Corrugated structure wakes

From paper of K. Bane, K. Yokoya , PAC 1999 for chain of **pillbox cavities**

$$Z_{\parallel}(k) = i\frac{Z_0}{\pi k a^2}\left[1+(1+i)\frac{\alpha L}{a}\sqrt{\frac{\pi}{kg}}\right]^{-1} = \frac{Z_0 c}{4\pi}\frac{2}{ca}\left[\eta^{-1} - ik\frac{a}{2}\right]^{-1}$$

$$\eta = \frac{(1+i)}{\sqrt{k}}\left[\alpha L\sqrt{\frac{\pi}{g}}\right]^{-1}$$ - "surface" impedance

"First order" in paper of K. Bane, G. Stupakov, I. Zagorodnov, DESY 16-056

$$W_a^{cc}(k_x,s) = Z_0 c\frac{k_x}{\sinh(2k_x a)} e^{-\frac{k_x a}{\tanh(k_x a)}\sqrt{\frac{s}{4s_0}}}$$

$$s_0 = \frac{g}{2\pi}\left(\frac{a}{\alpha(g/p)p}\right)^2$$

$$W_a^{ss}(k_x,s) = Z_0 c\frac{k_x}{\sinh(2k_x a)} e^{-\frac{k_x a}{\coth(k_x a)}\sqrt{\frac{s}{4s_0}}}$$

"0-order

Corrugated structure wakes

from paper
of K.Bane SLAC-PUB-9663, 2003

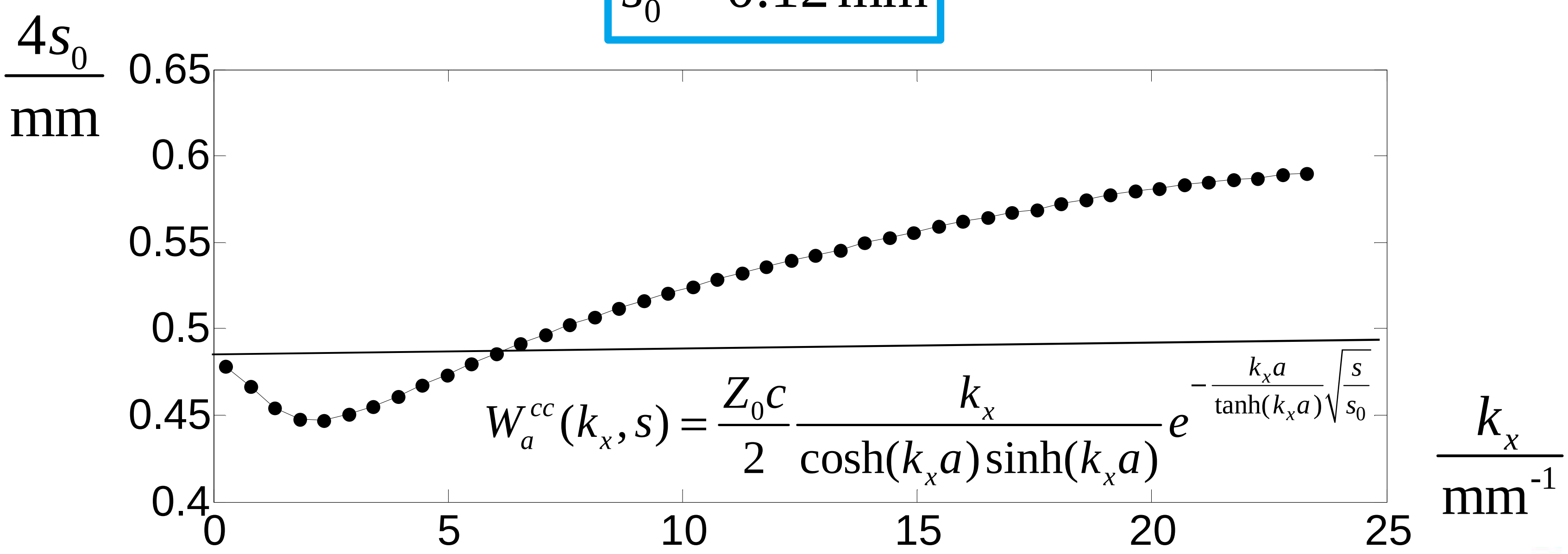
$$s_0 = \frac{g}{8}\left(\frac{a}{\alpha(g/p)p}\right)^2 = 0.1514\text{mm}$$

from Bane, Mosnier, Novokhatsky, Yokoya, ICAP 98.

$$s_0 = 0.41\frac{a^{1.8}g^{1.6}}{p^{2.4}} = 0.12\text{mm}$$

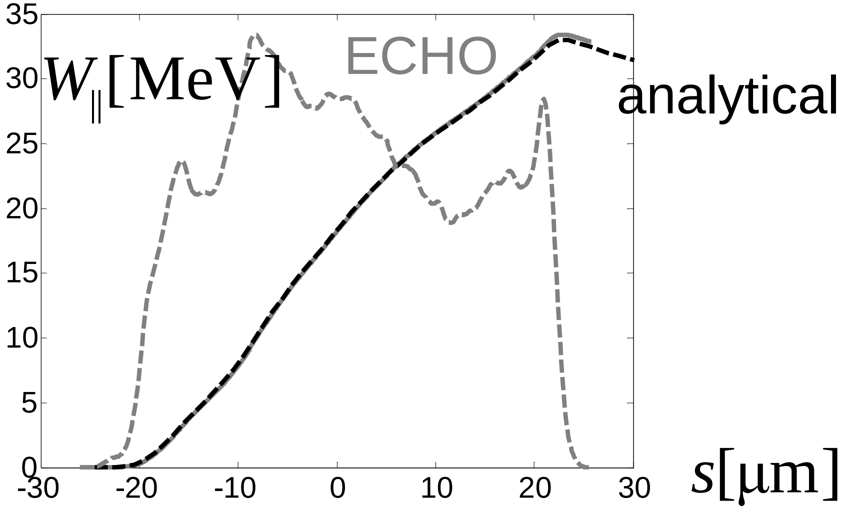
from fit to ECHO (calculations for bunches with up to 2um RMS)

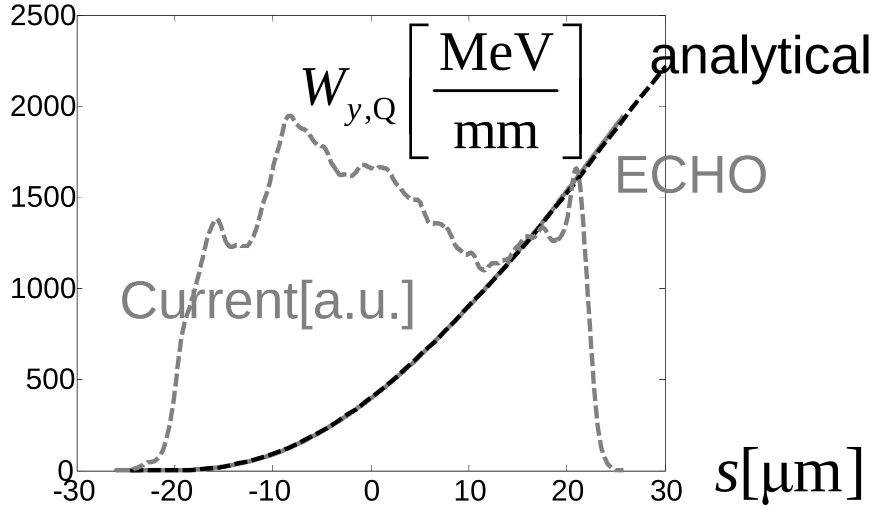
$$s_0 = 0.12\,\text{mm}$$

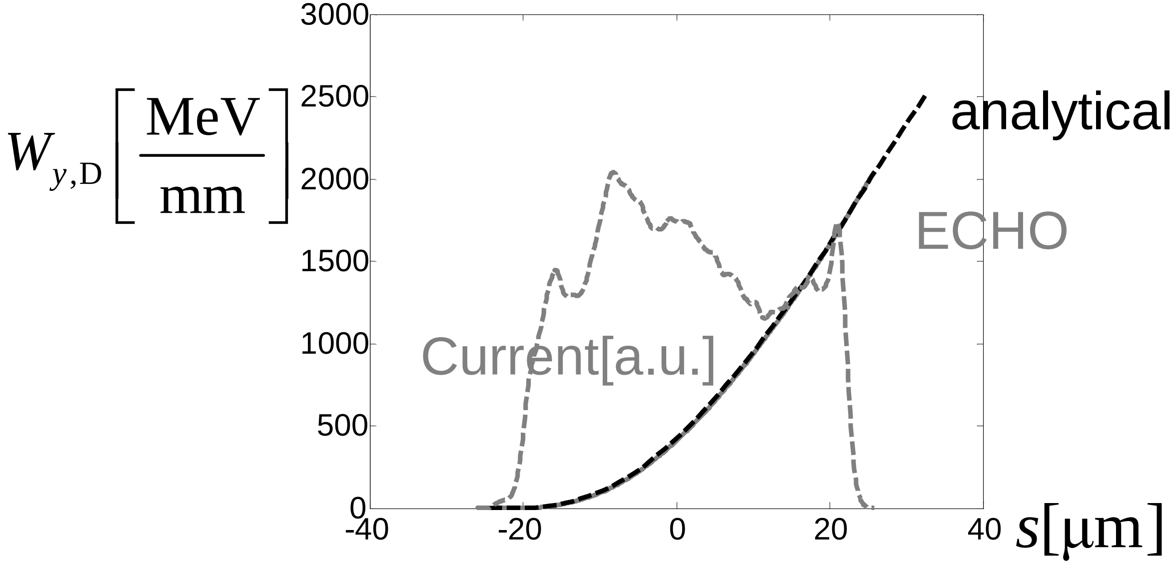


$$W_a^{cc}(k_x,s) = \frac{Z_0 c}{2}\frac{k_x}{\cosh(k_x a)\sinh(k_x a)}e^{-\frac{k_x a}{\tanh(k_x a)}\sqrt{\frac{s}{s_0}}}$$

Corrugated structure wakes







Beam dynamics in corrugated structure

Patrameter	Theoretical (0 order)	Numerical, ASTRA (0 order)	Numerical, ASTRA (1st order)
Emittance growth $\varepsilon/\varepsilon_0$	1.33	1.32	1.20
Energy spread in tail [keV]	67	66	45
Energy loss in tail [MeV]	45	**45**	**35**

$$\frac{\varepsilon}{\varepsilon_0} = \sqrt{1 + \left(\frac{\pi^3 Z_0 ceQ\beta Ll}{384\sqrt{5}a^4 E} \right)^2}$$

$$l = 40\mu\text{m}$$

$$\sigma_E(s) = \frac{\sqrt{2}\pi^3 Z_0 ceQLs}{256a^4 l} \sqrt{\sigma_x{}^4 + \sigma_y{}^4}$$

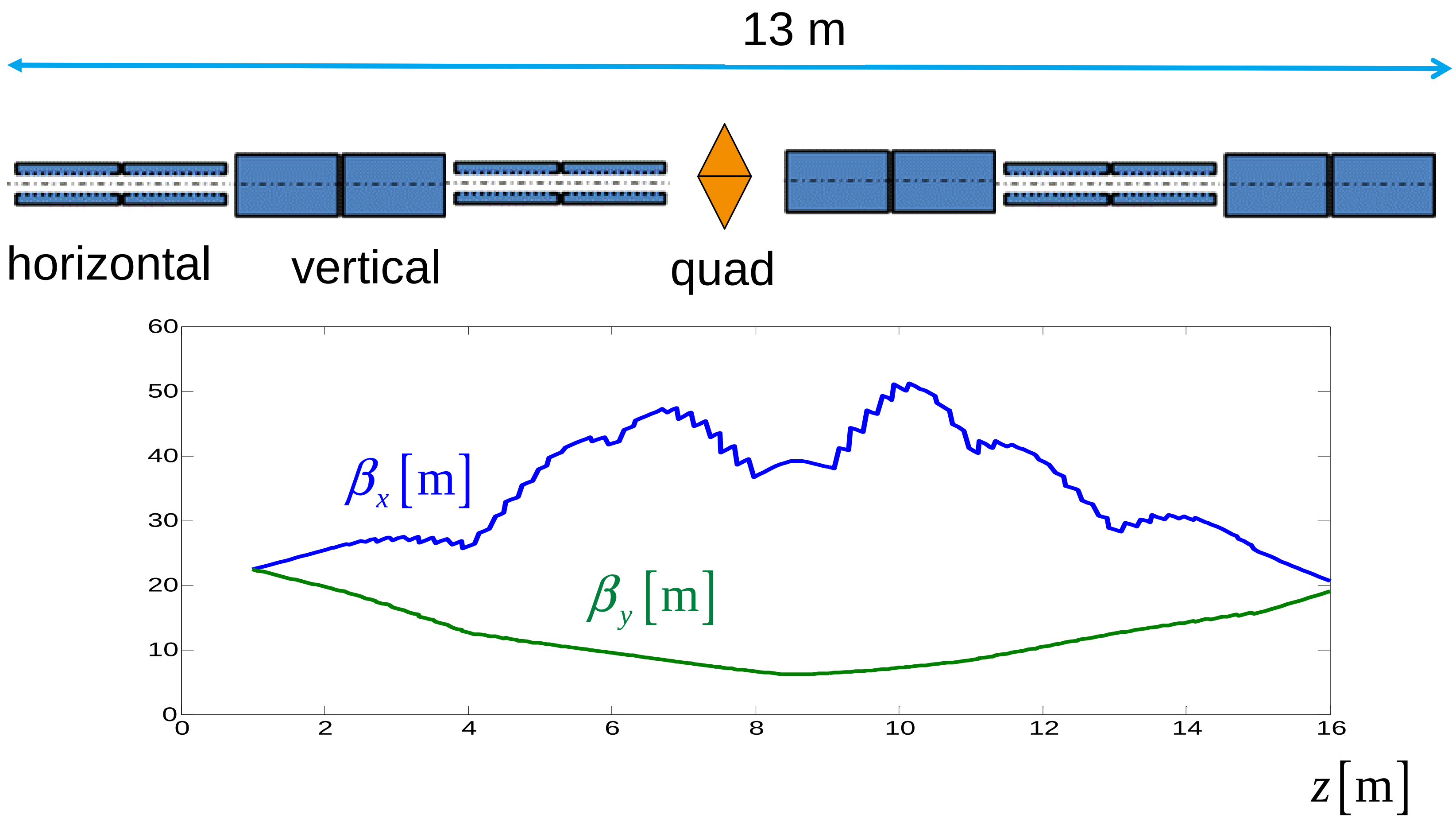
$$W_\parallel(l) = \frac{\pi Z_0 ceQL}{16a^2}$$

K. Bane, G. Stupakov, LCLS-II, TN-16-01, 2016

ASTRA tracking with wakefields.

M.Dohlus et al. Fast Particle Tracking with Wakefields, 2012

Beam dynamics in corrugated structure



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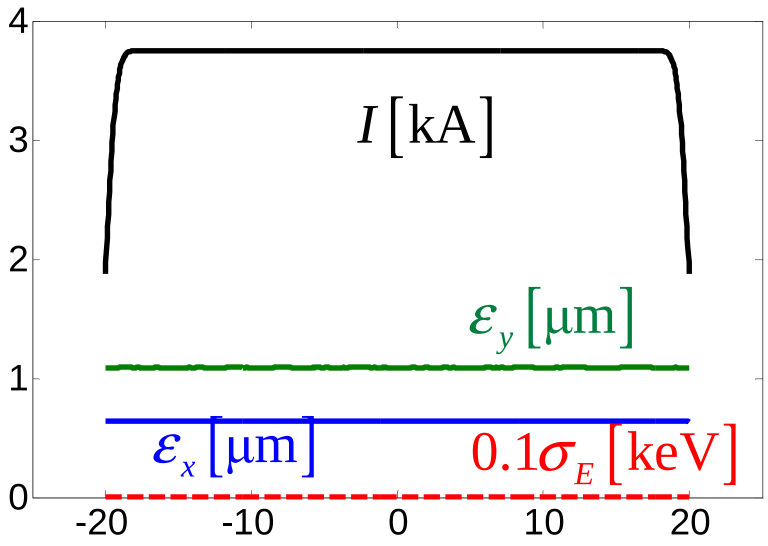
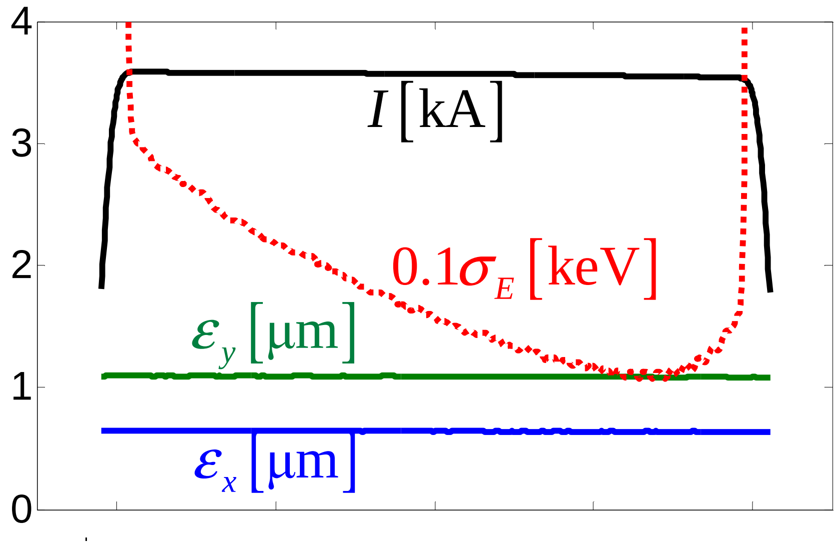
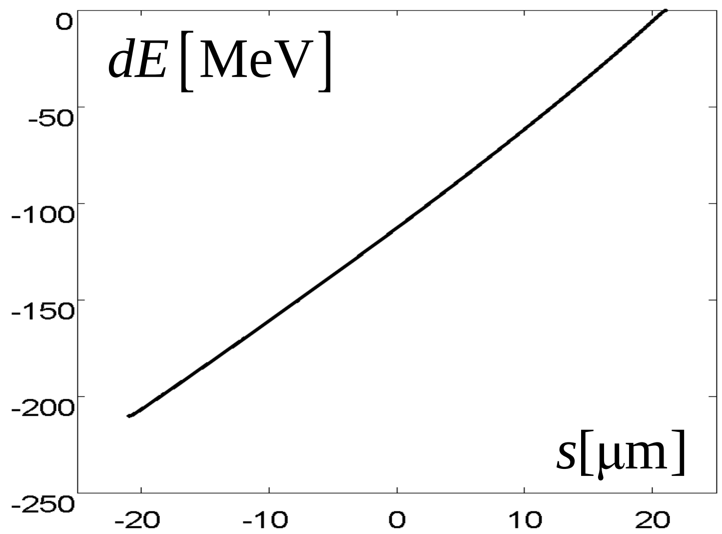
Beam dynamics in corrugated structure

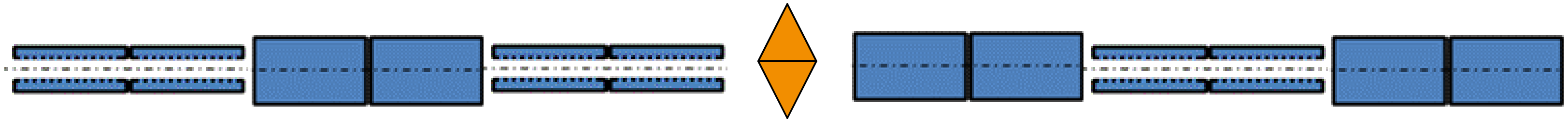


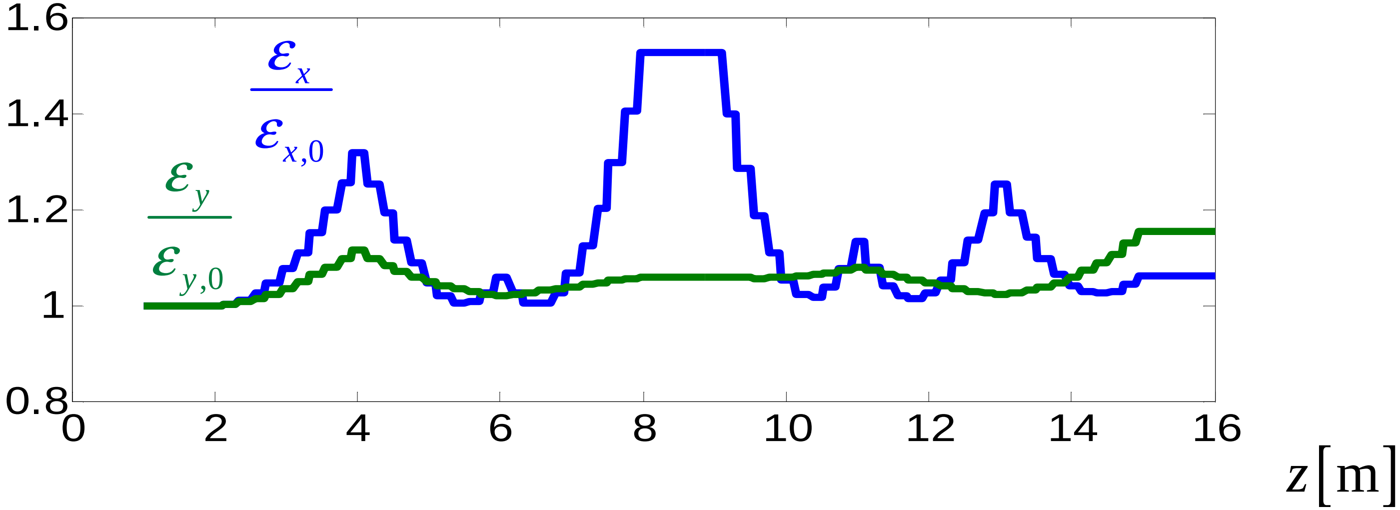


Parameter	Before	After 6 mod.
Emittance ε_x	0.64	0.68
Emittance ε_y	1.09	1.26
Energy spread in tail [keV]	0	30
Energy loss in tail [MeV]	0	**210**



Beam dynamics in corrugated structure

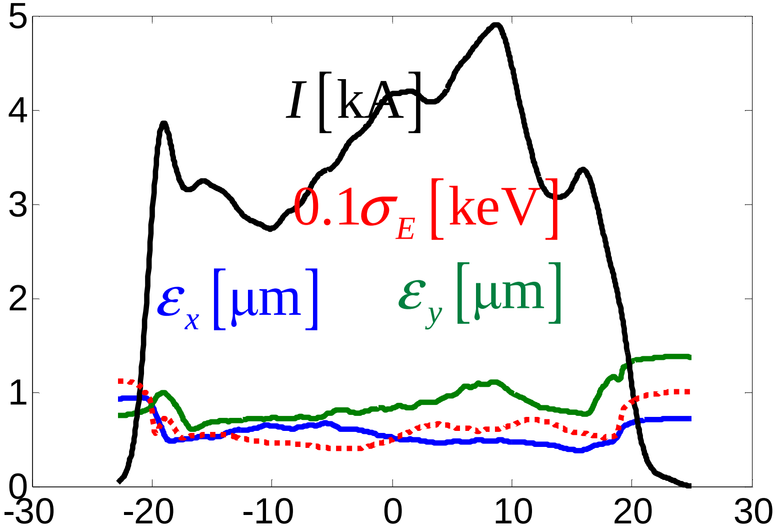


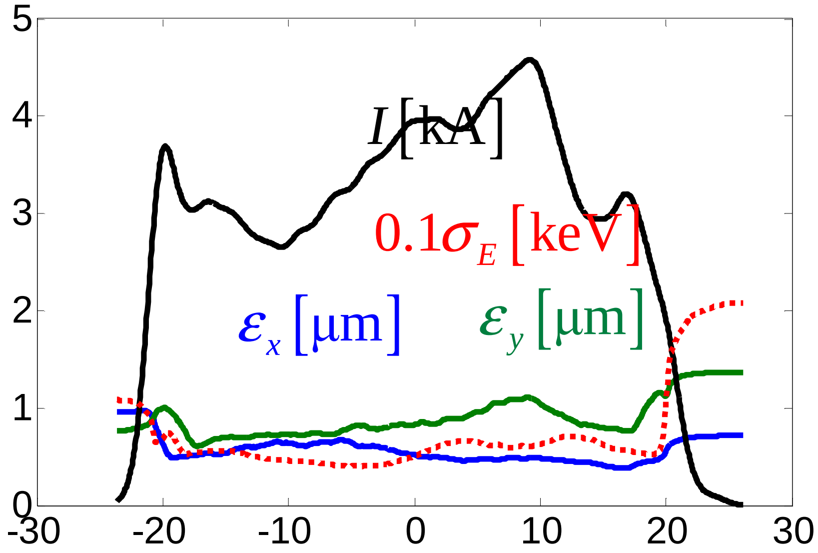


Beam dynamics in corrugated structure

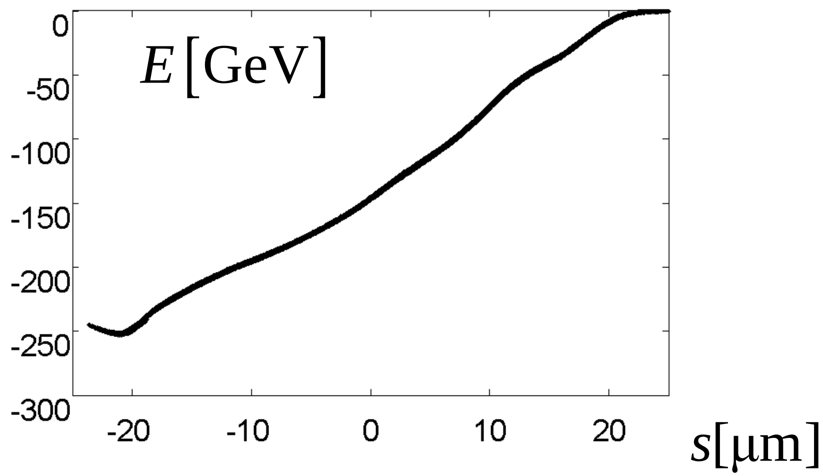
Parameter	after 1 module as 1 kick	after 1 module, 10 kicks	after 6 modules, 60 kicks
Emittance growth $\varepsilon_x / \varepsilon_{x,0}$	1.20	1.32	1.06
Emittance growth $\varepsilon_y / \varepsilon_{y,0}$	1.20	1.11	1.15
Energy spread in tail [keV]	45	45	30
Energy Loss in tail [MeV]	35	35	210

Beam dynamics in corrugated structure

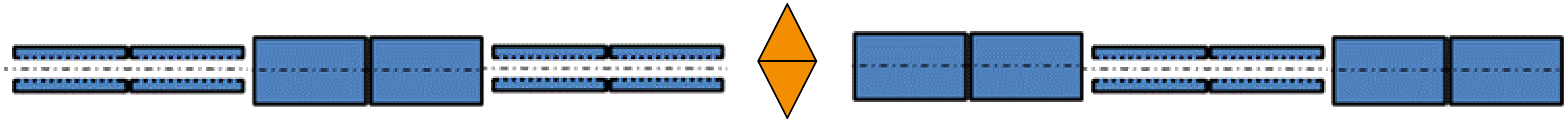


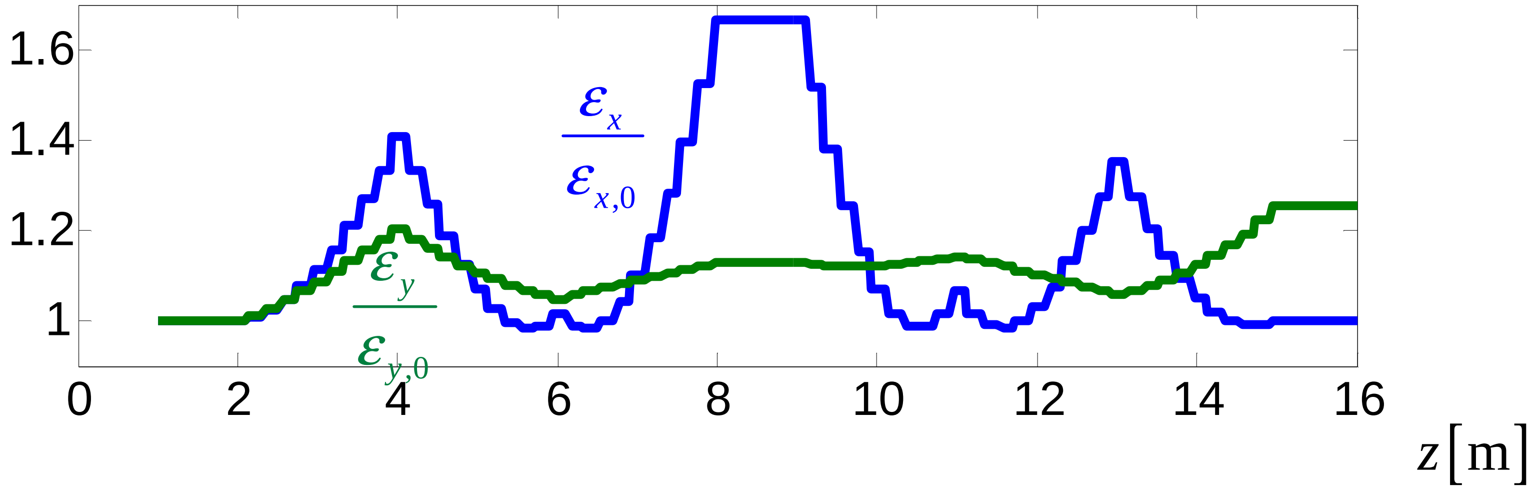


Parameter	Before	After
Emittance ε_x	0.64	0.64
Emittance ε_y	1.09	1.37
Energy spread in tail [keV]	500	530
Energy loss in tail [MeV]	50	250

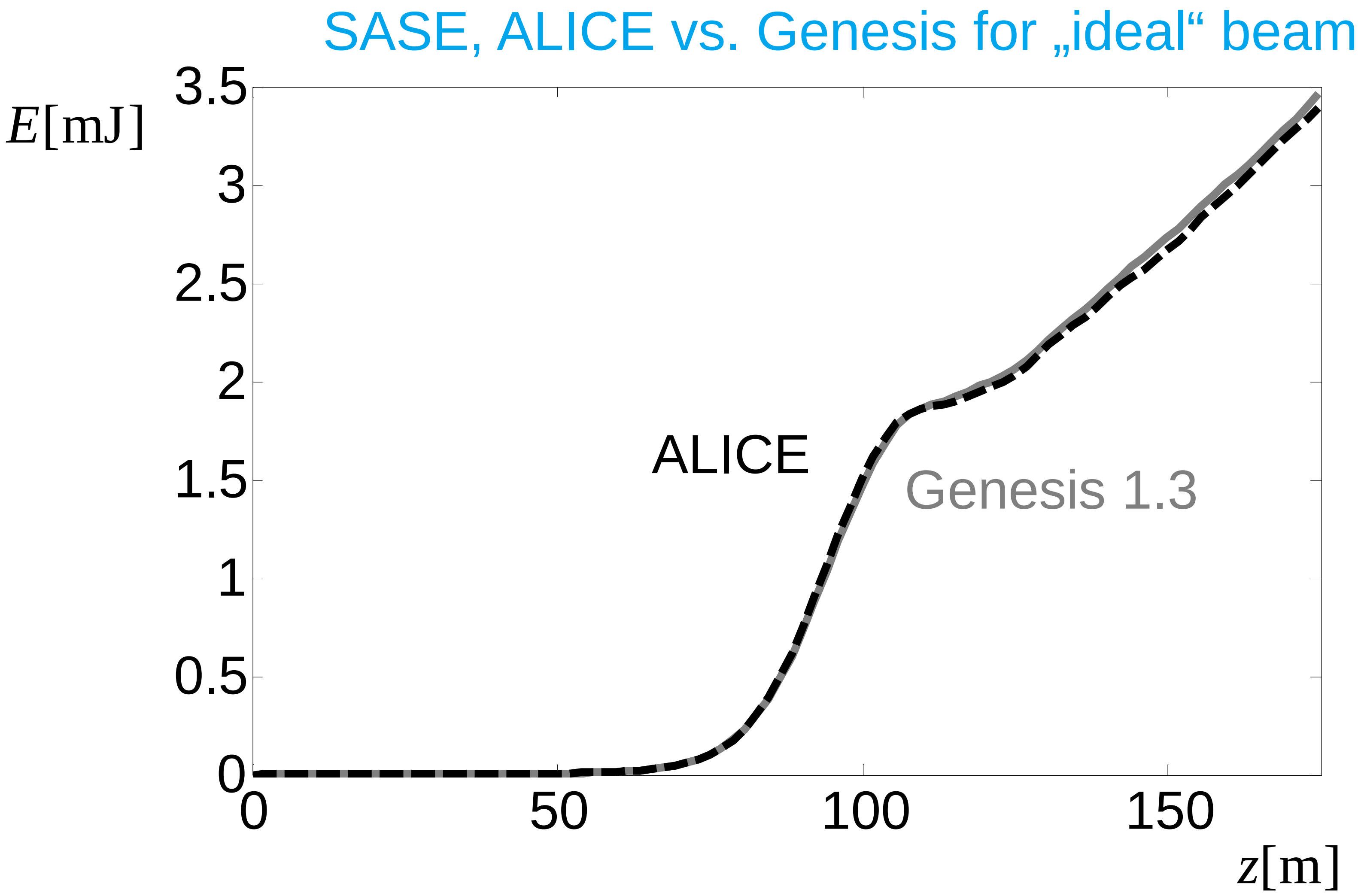


Beam dynamics in corrugated structure



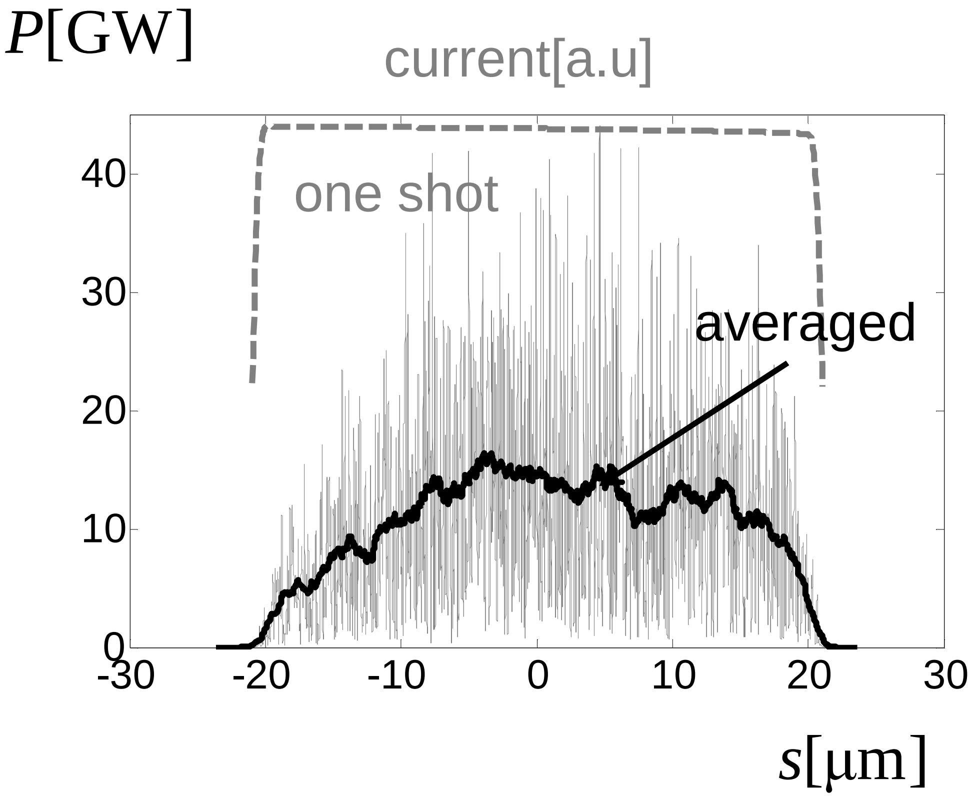


SASE ("ideal" beam)

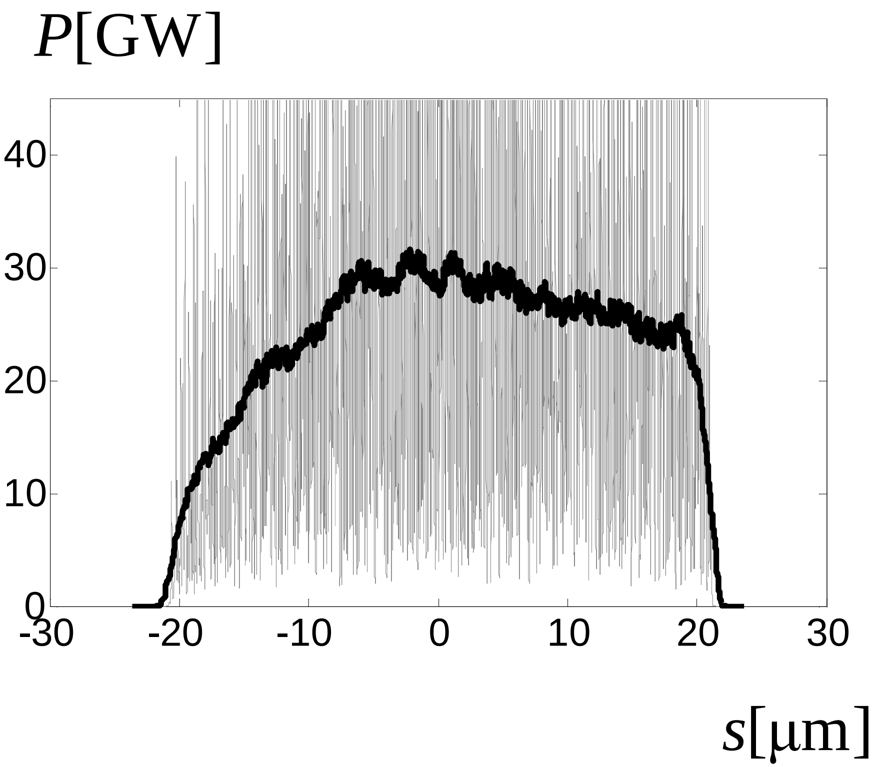


SASE (“ideal” beam)

Energy distribution at z=100 m

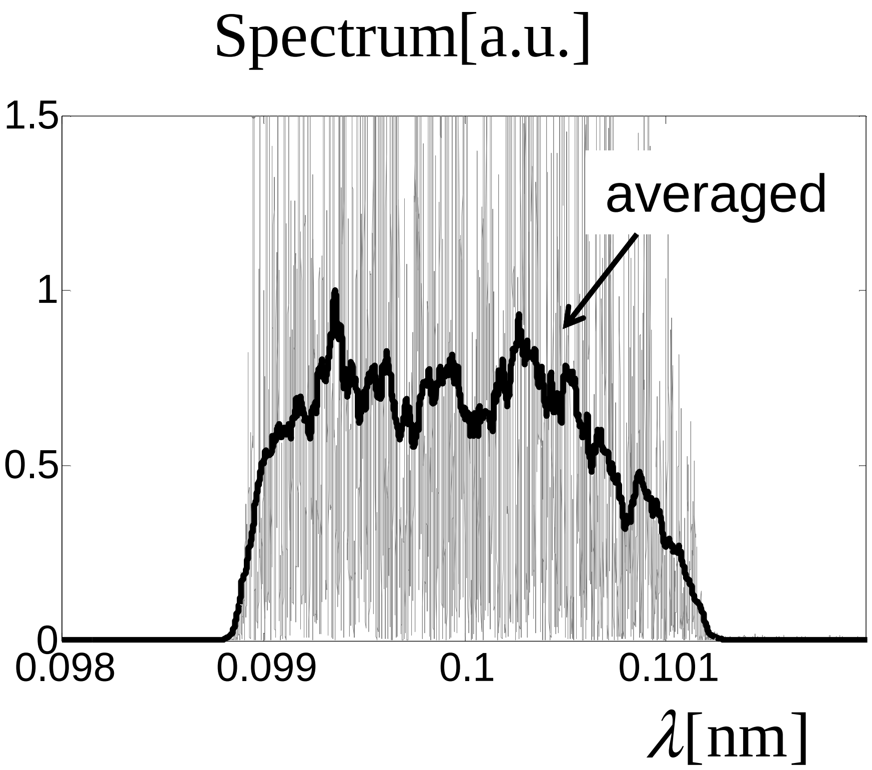


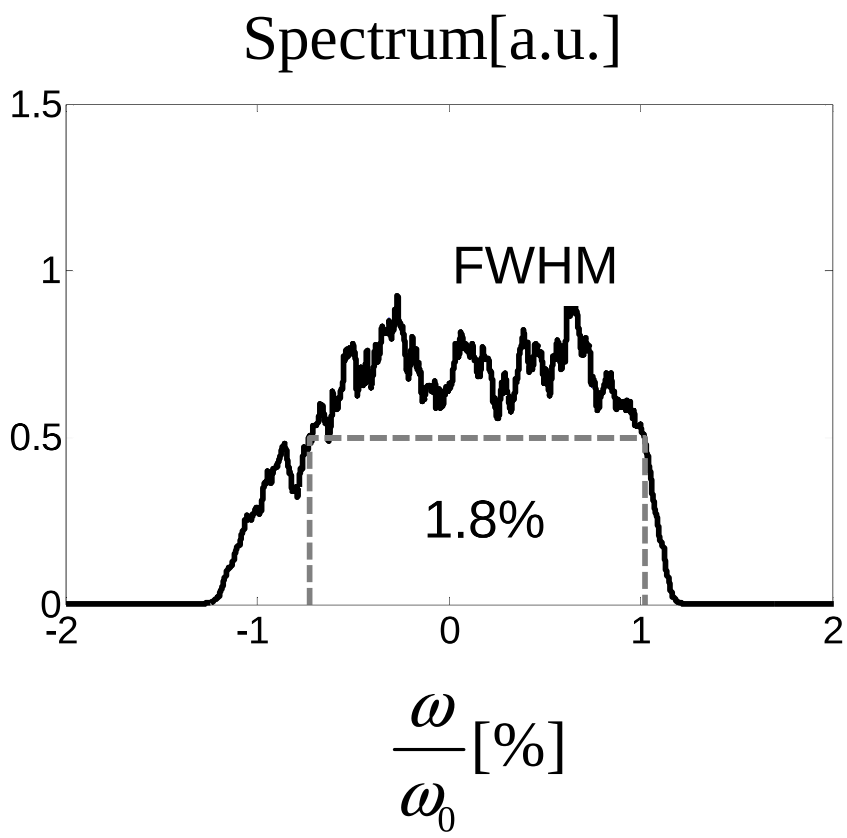
Energy distribution at z=175 m



SASE ("ideal" beam)

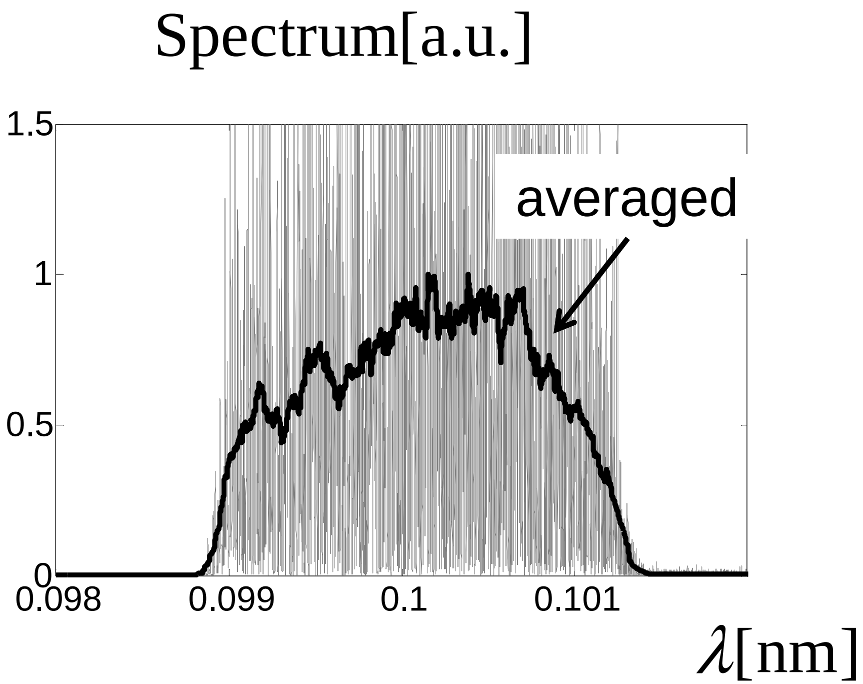
Spectrum at z=100 m

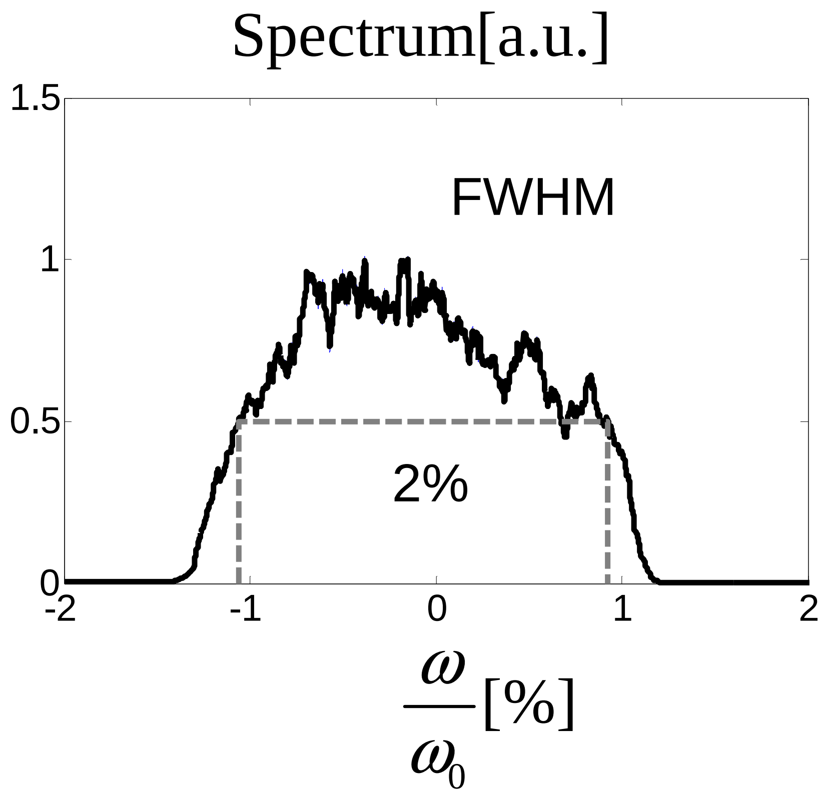




SASE ("ideal" beam)

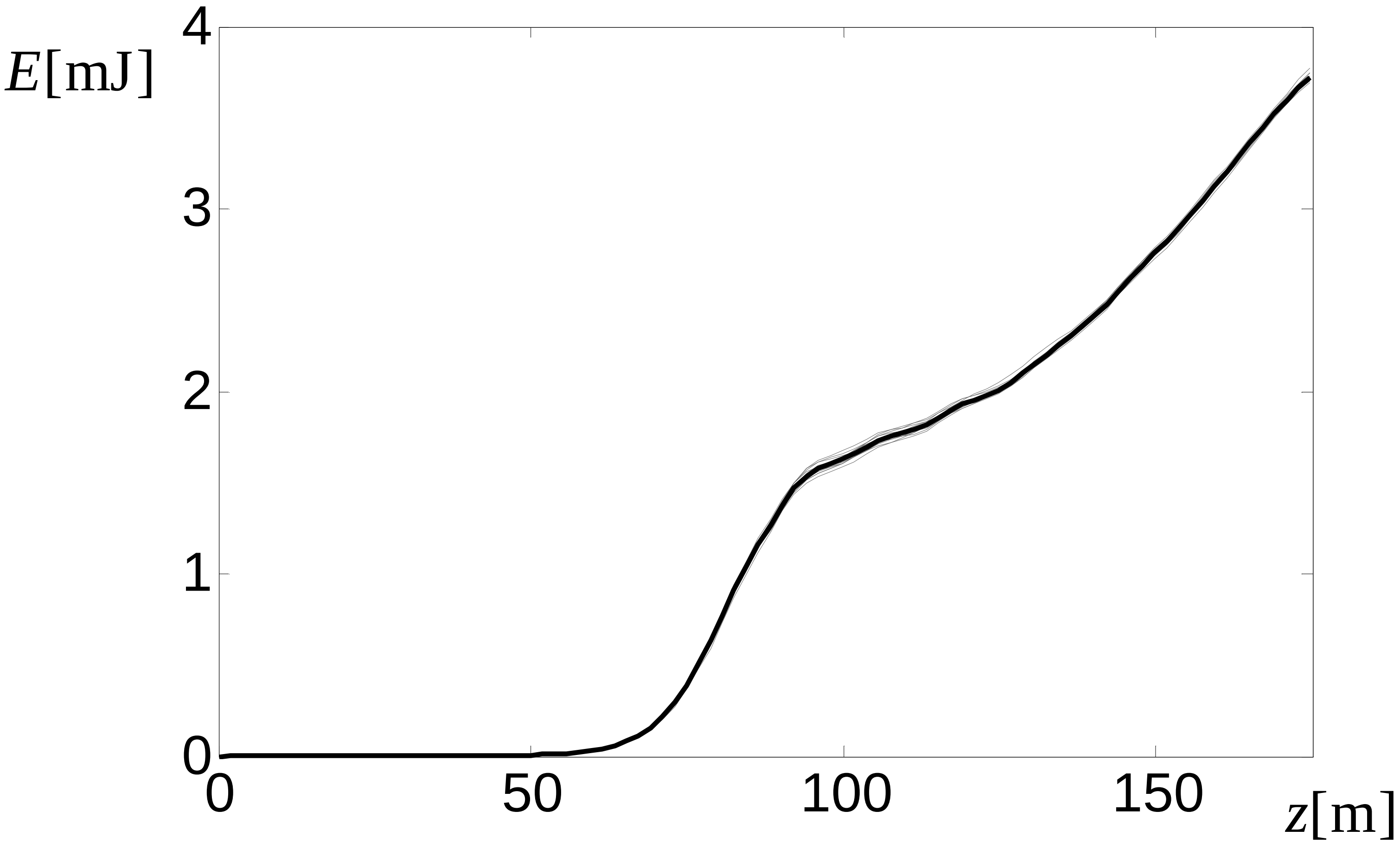
Spectrum at 175 m





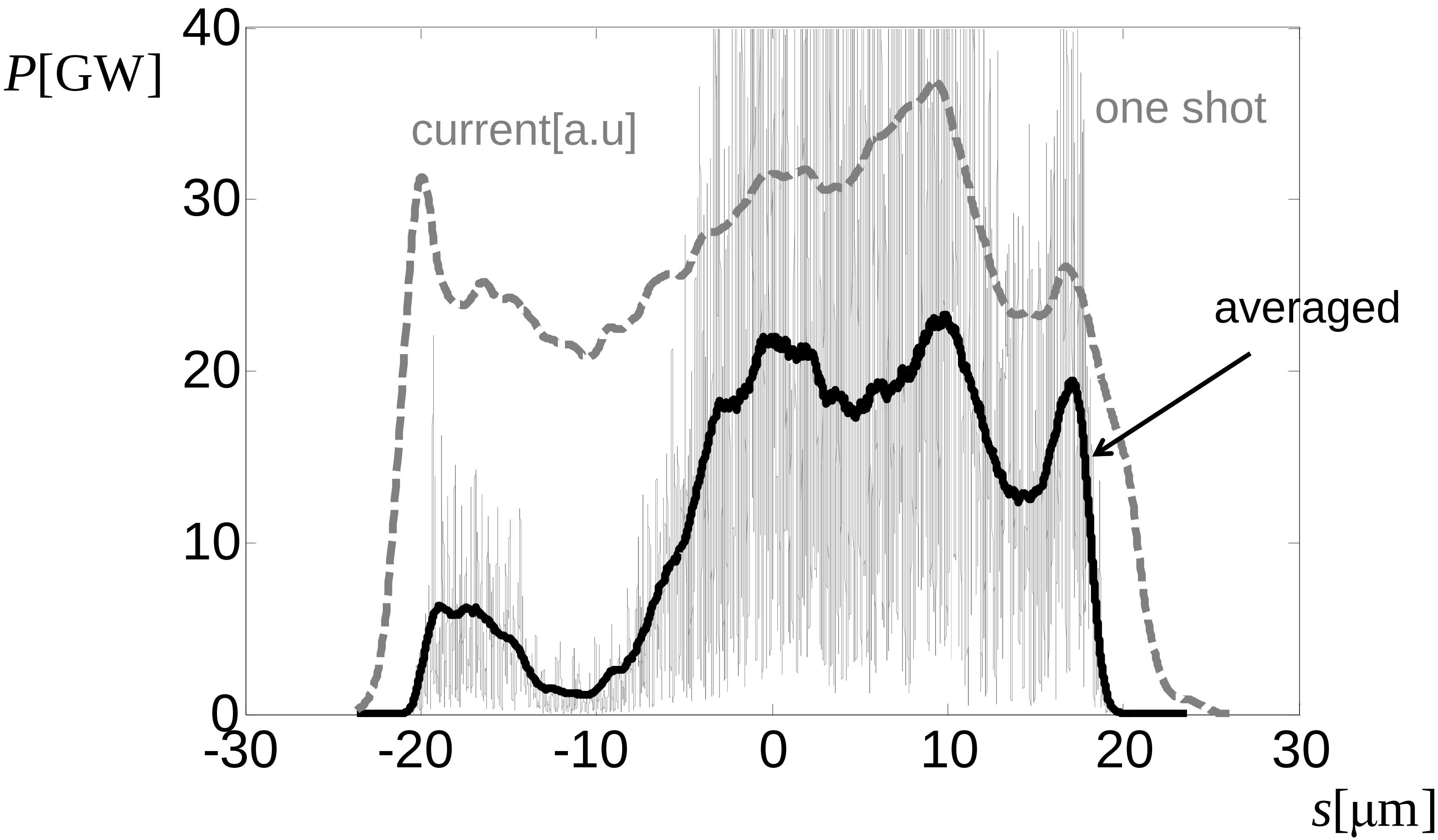
SASE

SASE, ALICE, for „real“ beam, 15 shots



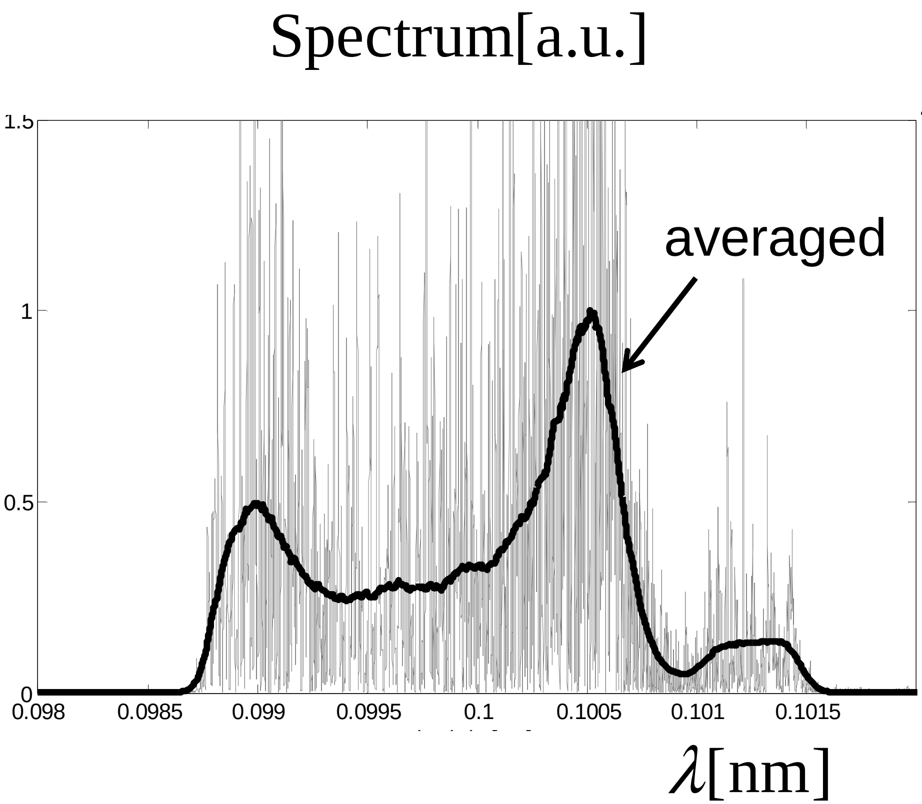
SASE

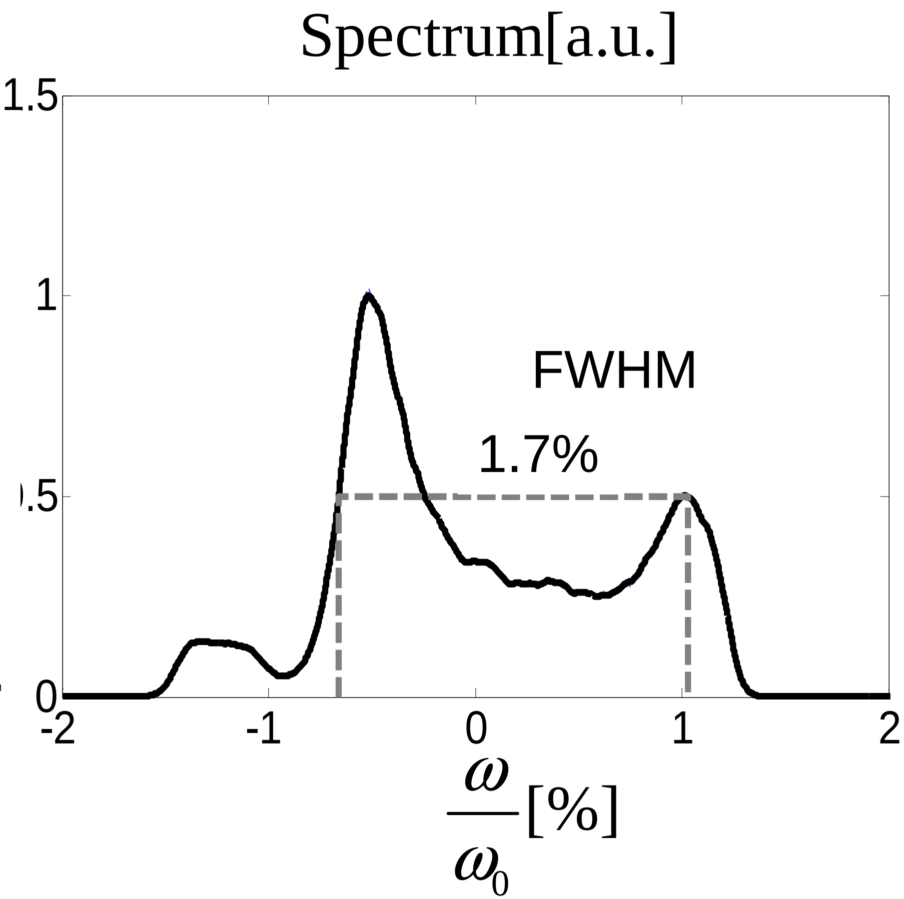
Energy distribution at z=100 m



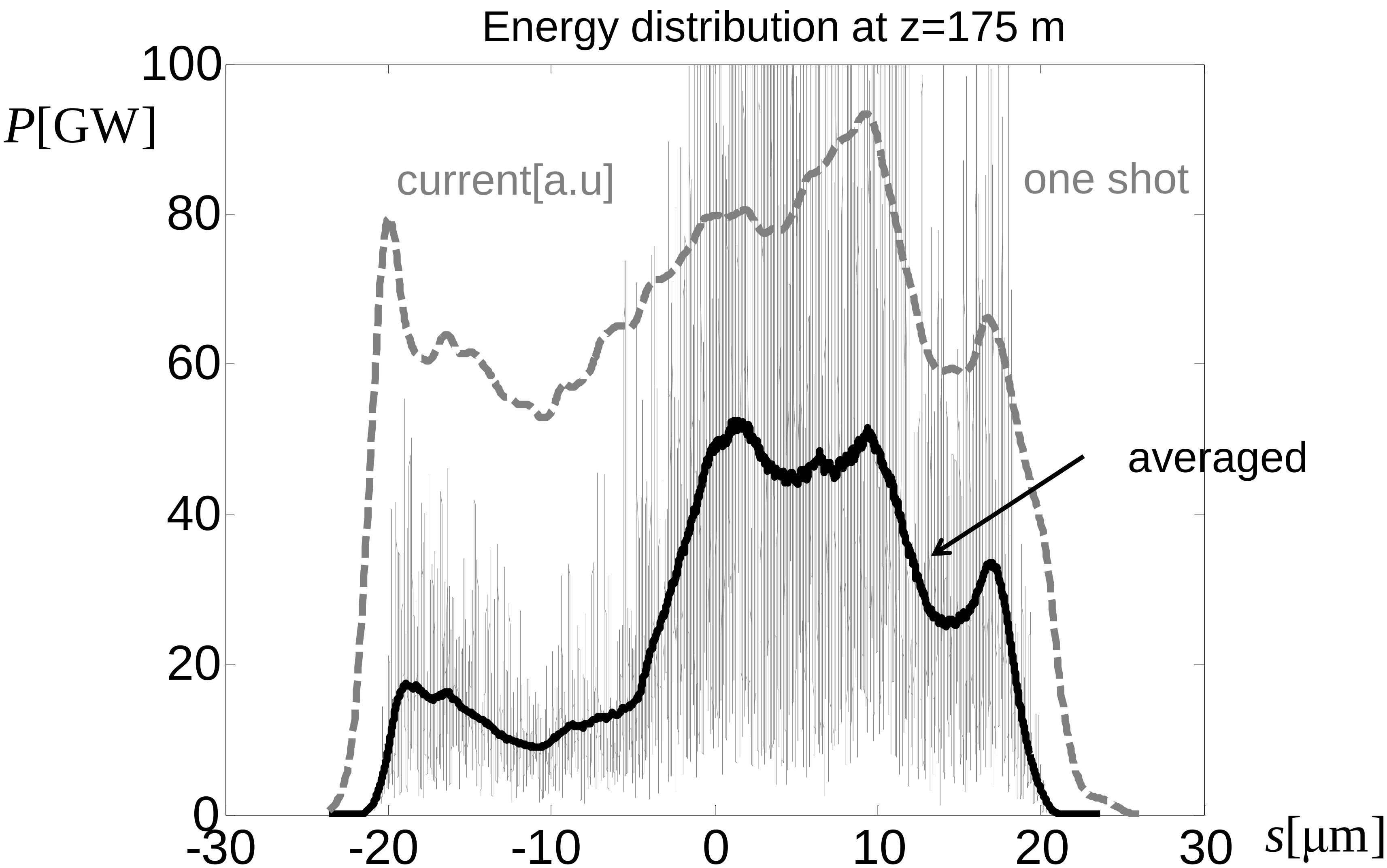
SASE

Spectrum at z=100 m





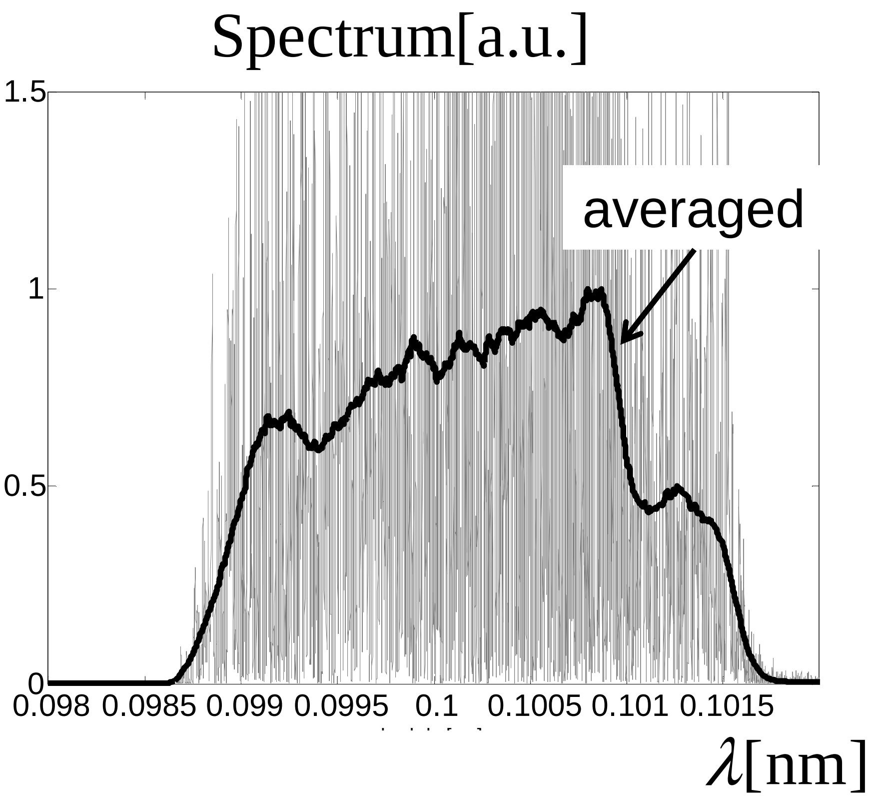
SASE

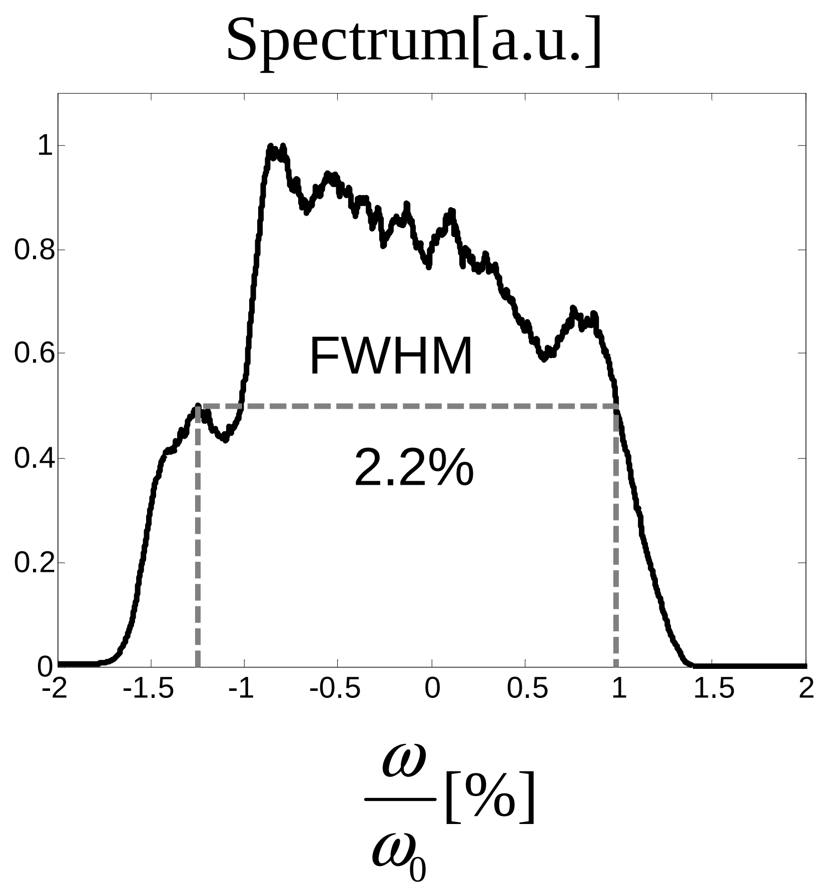


Energy distribution at z=175 m
100
80
60
40
20
0
P[GW]
current[a.u]
one shot
averaged
-30
-20
-10
0
10
20
30
s[µm]

SASE

Spectrum at z=175 m





Conclusion

With 6 corrugated modules of total length 12 m
we can obtain 2% radiation bandwidth
at 17.5 GeV (0.1 nm radiation wavelength).

Parameter	z=100 m	z=175 m
Bunch charge, pC	500	
Bunch energy, GeV	17.5	
Radiation wavelength, nm	0.1	
Bandwidth (FWHM), %	1.7	2.2
Radiation energy, mJ	2	3.5