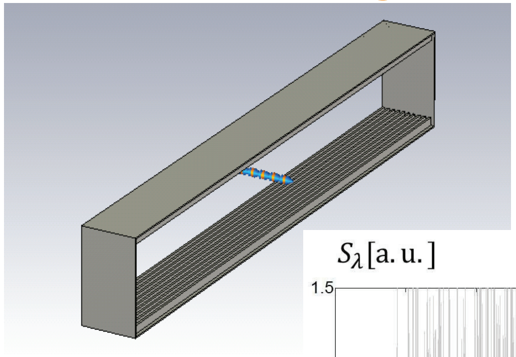
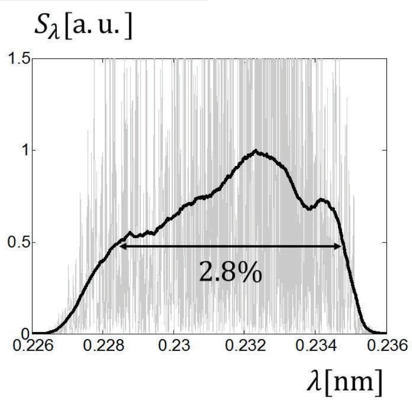
Corrugated structure insertion to extend SASE bandwidth up to 3% at the European XFEL

Beam Dynamics and FEL Simulations





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Chicago, USA
11. October 2016

HELMHOLTZ GEMEINSCHAFT

DESY

Motivation

- The natural bandwidth of the SASE-XFEL pulses is on the order of the Pierce parameter ρ, with values between 10e-3 and 10e-4 for the European XFEL.
- There is a scientific demand to obtain **broadband XFEL radiation** for certain applications such as
  - ✓ X-ray crystallography*,
  - ✓ X-ray absorption spectroscopy,
  - ✓ multi-wavelength anomalous diffraction,
  - ✓ stimulated Raman spectroscopy.

*C. Dejoie et al, ***Using a non-monochromatic microbeam for serial snapshot crystallography***, J. Appl. Crystallogr. 46, 791 (2013)

K. Ayyer et al, ***Perspectives for imaging single protein molecules with the present design of the European XFEL***, Structural Dynamics 2, 041702 (2015)

Motivation

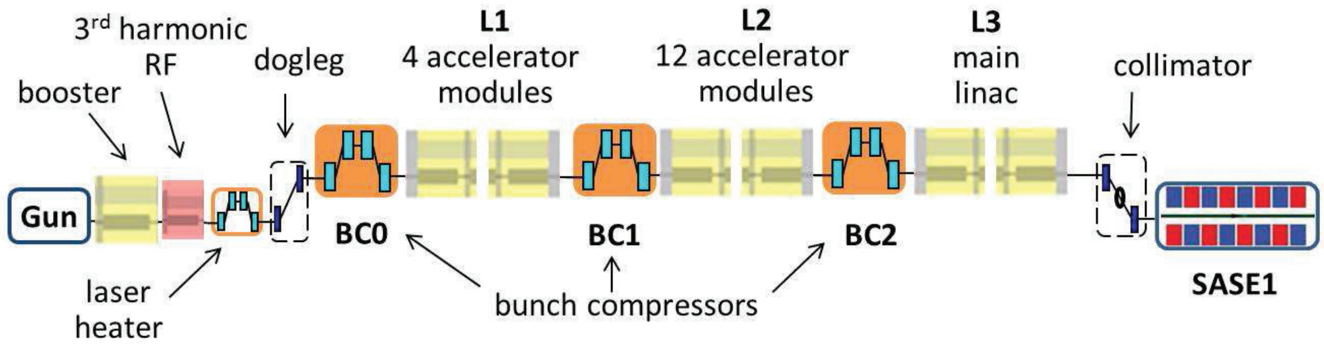
The energy deviation (of electron) is equivalent to the wavelength deviation (of EM wave)

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

3% in bandwidth ~ 1.5% in energy spread

For 14 GeV we need the energy spread above **210 MeV**.

Beam dynamics in linac



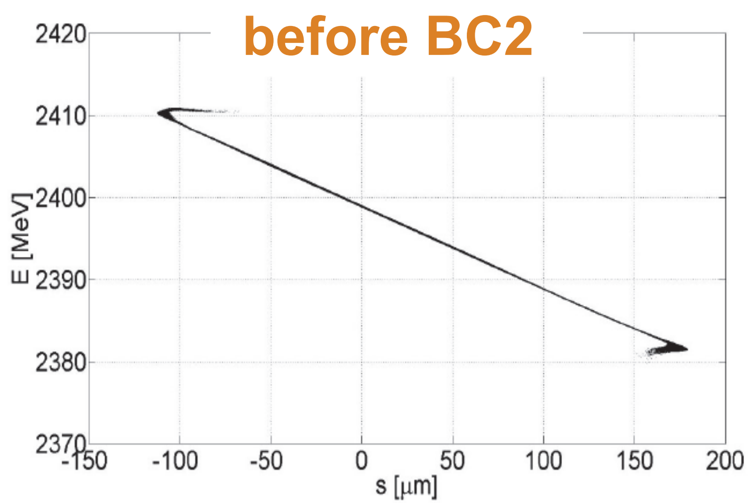
R_{56} = 30-90 mm | R_{56} = 20-80 mm | R_{56} = 10-60 mm

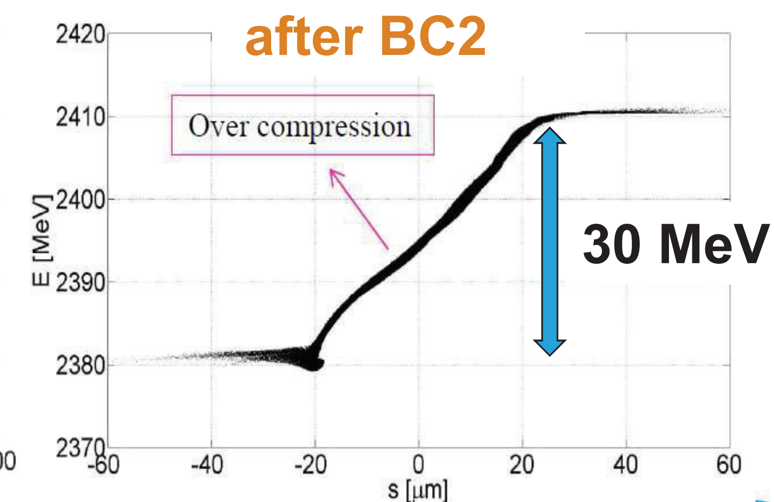
I_{peak} ~ 30 A
Q = 0.5 nC

I_{peak} ~ 100 A
E = 130 MeV

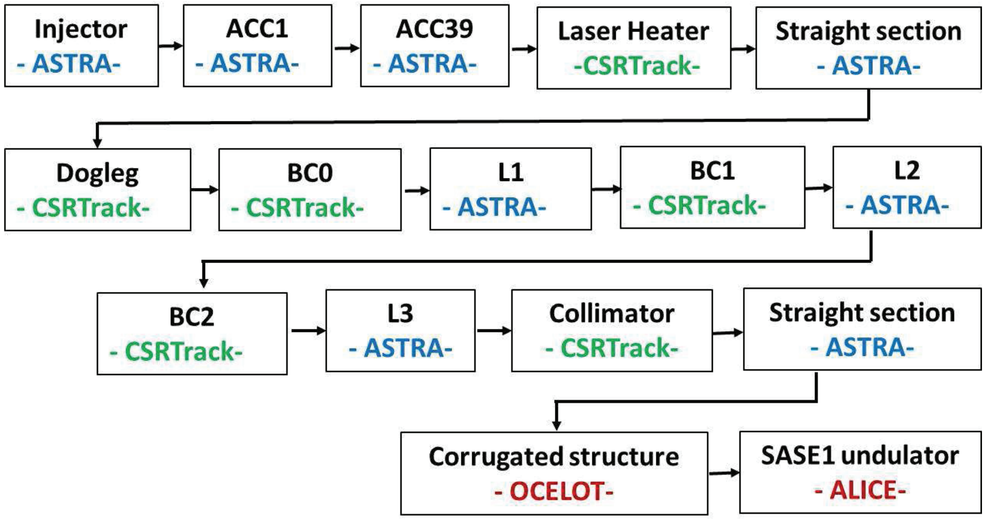
I_{peak} ~ 1 kA
E = 700 MeV

I_{peak} ~ 5 kA
E = 2400 MeV





Beam dynamics in linac

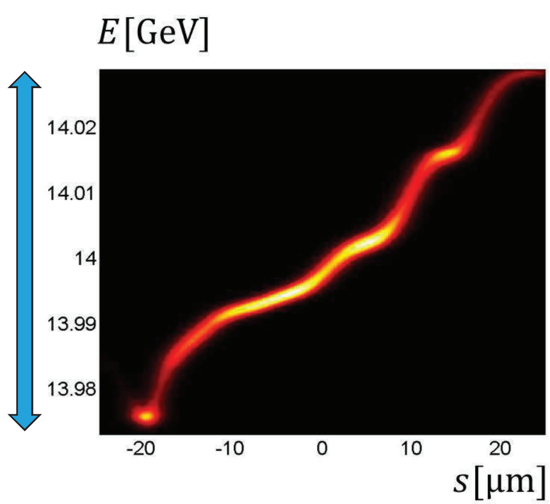


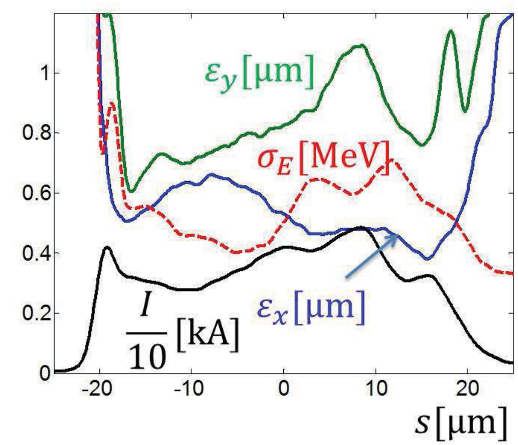
after collimator

projected emittance:
in x-plane - 0.72 µm
in y-plane - 1.17 µm.

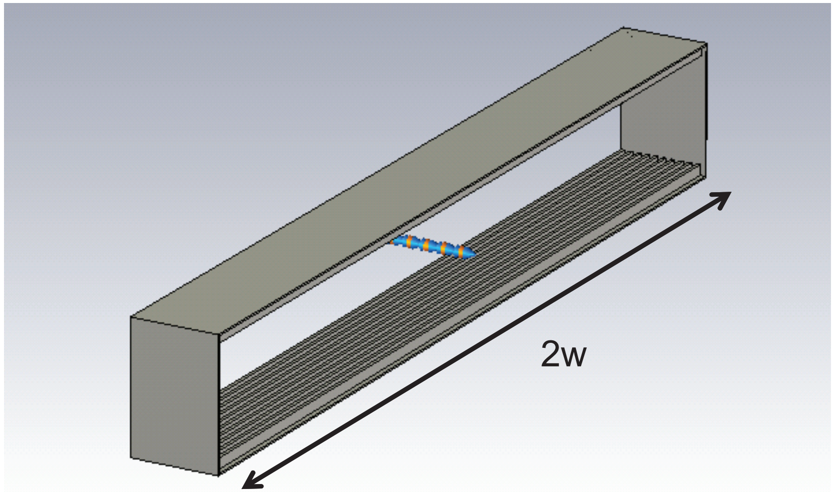
energy drop ~ 0.4%.

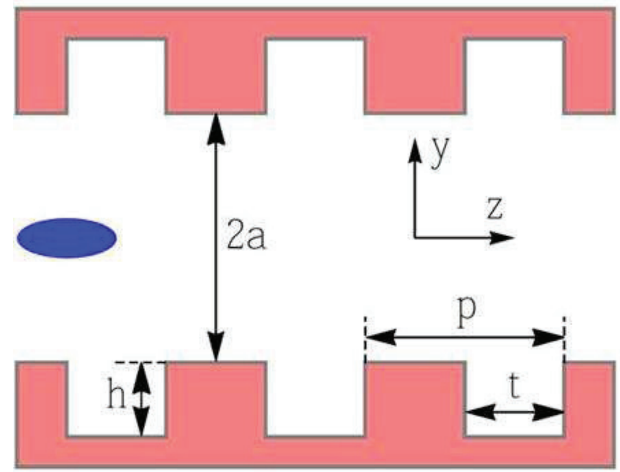
55 MeV





Wake function of the corrugated structure





K. Bane and G. Stupakov, ***Corrugated pipe as a beam dechirper***, NIM A **690** (2012) 106.

Z. Zhang et al, ***Electron beam energy chirp control with a rectangular corrugated structure at the Linac Coherent Light Source***, PR STAB **18** (2015) 010702.

Parameter	Value	Unit
Depth, *h*	0.5	mm
Gap, *t*	0.25	mm
Period, *p*	0.5	mm
Half aperture, *a*	0.7	mm
Half width, *w*	6	mm
Length, *L*	2	m

Wake function of the corrugated structure

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

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

0th - order model

K. Bane and G. Stupakov, ***Dechirper wakefields for short bunches***, NIM A **820** (2016) 156.

$$W_a^{cc}(k_x, s) = W_a^{ss}(k_x, s) = Z_0 c \frac{k_x}{\sinh(2k_x a)} \qquad s \equiv z_0 - z$$

1st - order model

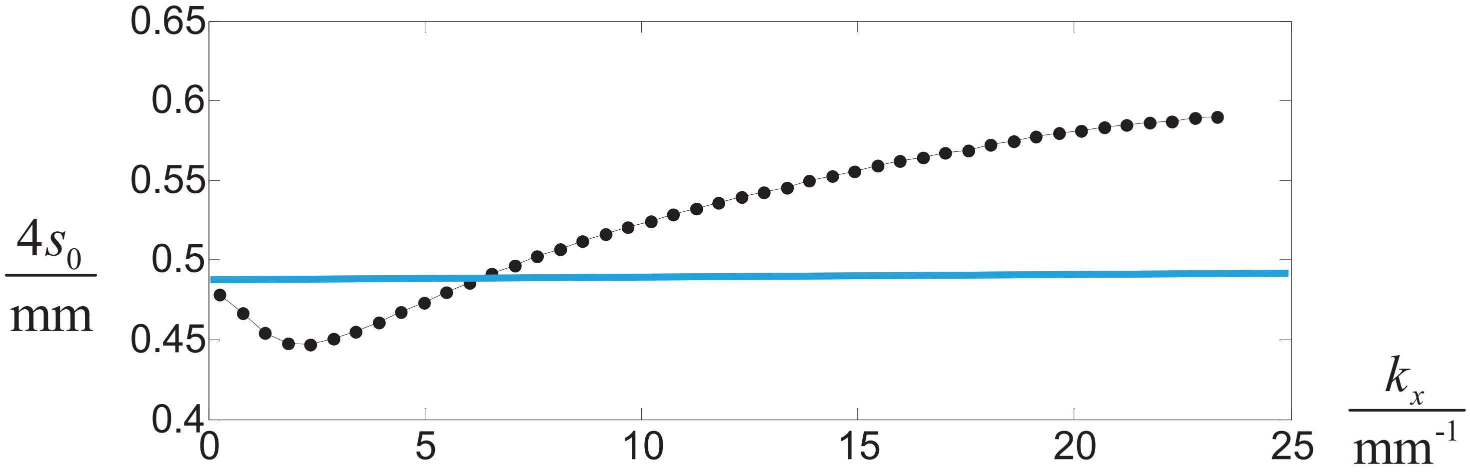
K. Bane, G. Stupakov, I. Zagorodnov, ***Analytical formulas for short bunch wakes in a flat dechirper***, PR STAB **19** (2016) 084401

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

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

Wake function of the corrugated structure

Fitting to ECHO calculations for bunches with up to 2μm RMS.



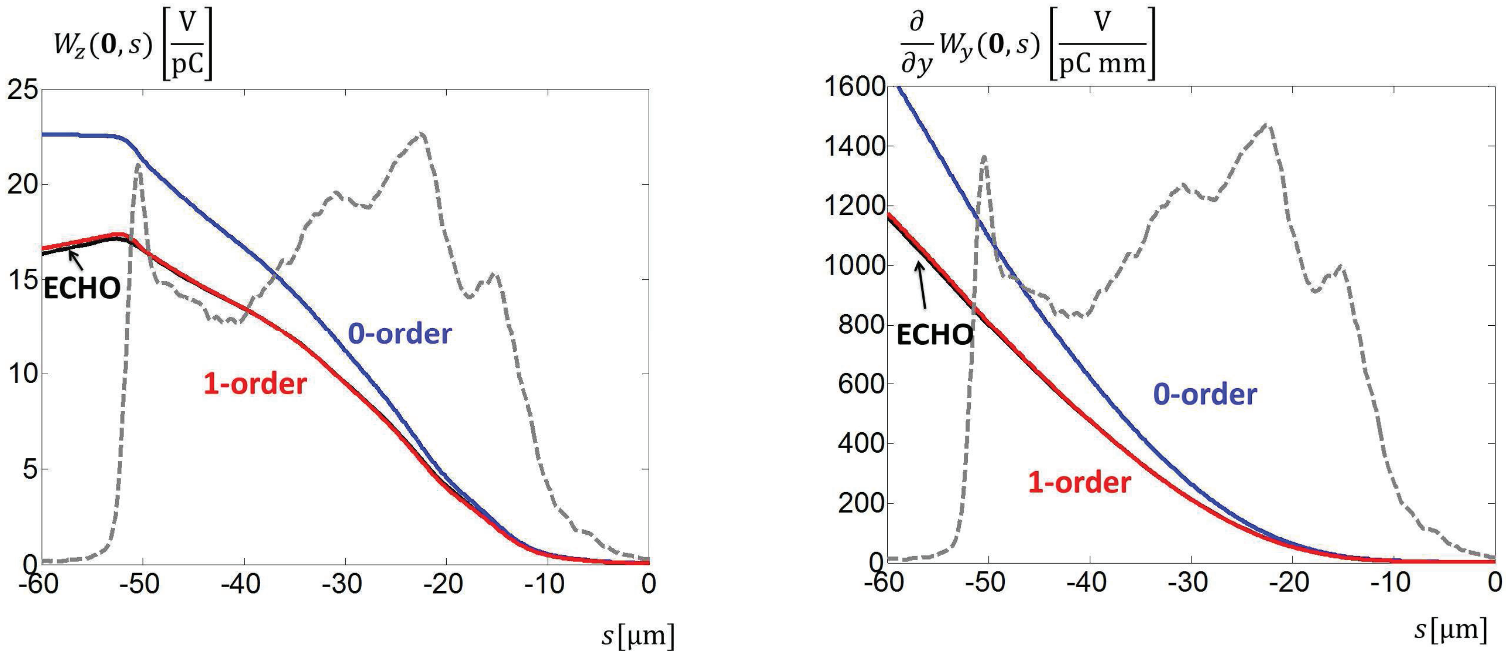
K.Bane, S***hort-range dipole wakefields in accelerating structures for the NLC***,SLAC-PUB-9663, 2003

$$s_0 = \frac{g}{8}\left(\frac{a}{\alpha(g/p)p}\right)^2 = 0.15\text{mm}$$

K. Bane et al, ***Calculations of the short-range longitudinal wake fields in the NLC Linac***, SLAC-PUB-7862, 1998.

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

Wake function of the corrugated structure

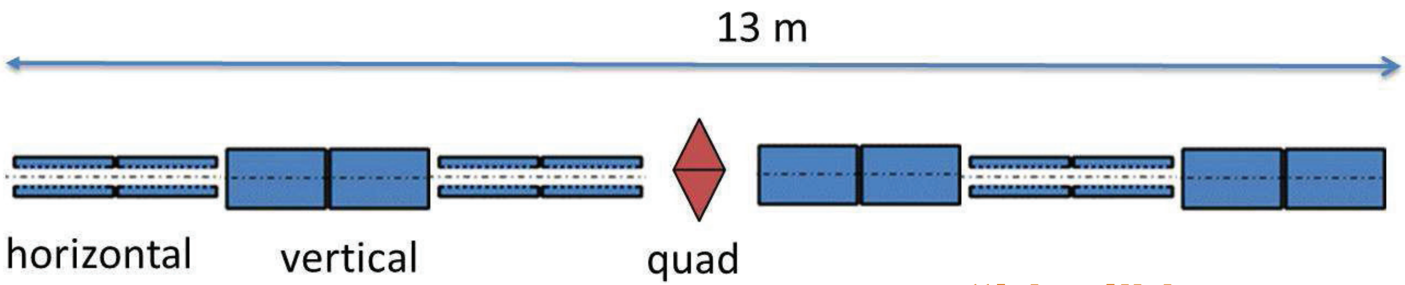


$$W_z(x_0,y_0,x,y,s) = W_z(\mathbf{0},s) + h_{11}(s)\left(x_0^{\ 2} - y_0^{\ 2} + x^2 - y^2\right) +$$
$$+ h_{13}(s)x_0x + h_{24}(s)y_0y + O(3)$$

M. Dohlus et al, ***Fast particle tracking with wake fields***, DESY 12-012, 2012.

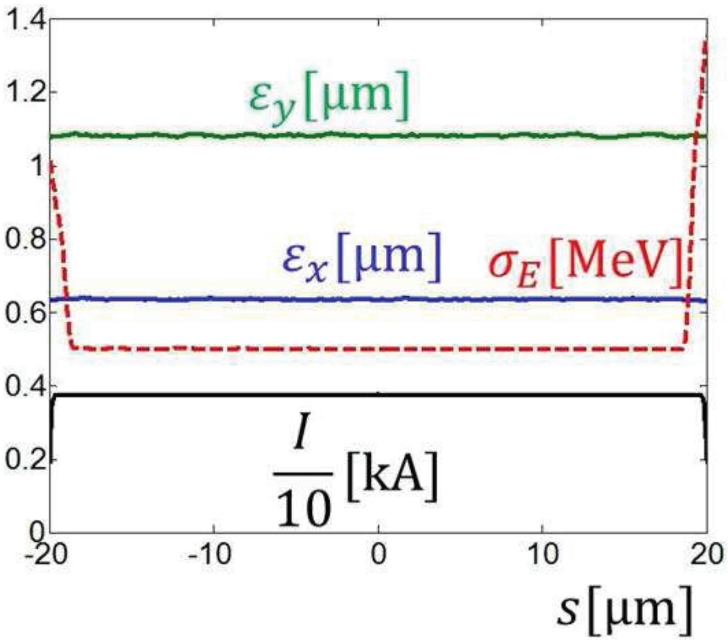
I. Agapov et al., ***OCELOT: a software framework for synchrotron light source and FEL studies***, NIM A **768** (2014)

Beam dynamics in corrugated structure



Parameter	Value	Unit
Emittance, $\epsilon_{0x}/\epsilon_{0y}$	0.64/1.09	µm
RMS size, σ_x/σ_y	30.9/16.8	µm
Beta function, β_x/β_y	22.6	m
Alpha function, α_x/α_y	-1.43/1.43	
Energy, E	14	GeV
Length, l	40	µm
Length, Q	0.5	nC

"Ideal" beam



Beam dynamics in corrugated structure

"Ideal" beam, only one kick without tracking

Parameter	Analytical (0 order)*	Numerical, OCELOT (0 order)	Numerical, OCELOT (1st order)	Units
Emittance growth, $\varepsilon/\varepsilon_0$	1.484	1.479	1.29	
Energy spread in tail, $\sigma_E(l)$	80.2	81	56	keV
Energy loss in tail, $W_{\|\|}(l)$	45.3	**45**	**35**	**MeV**

$$\frac{\varepsilon}{\varepsilon_0} = \sqrt{1 + \left(\frac{\pi^3 Z_0 c e Q \beta L l}{384\sqrt{5} a^4 E} \right)^2}$$

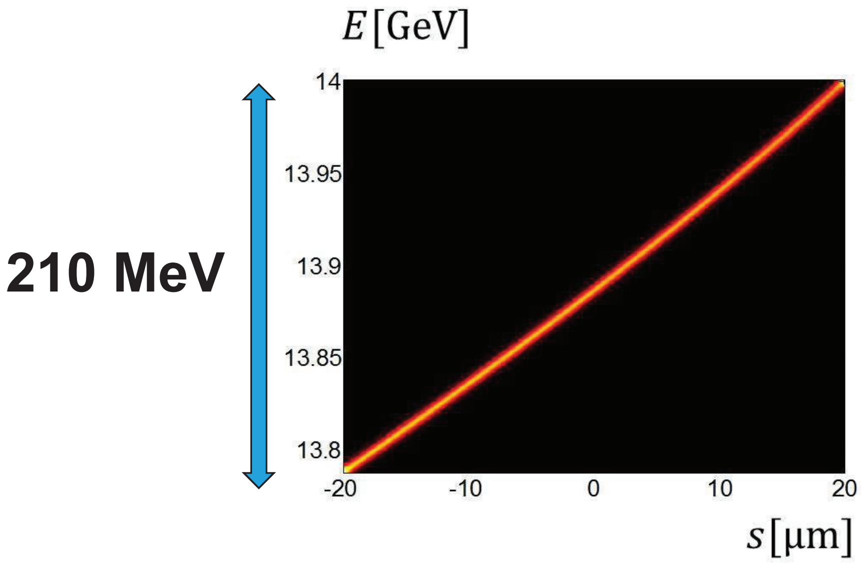
$$\sigma_E(l) = \frac{\sqrt{2}\pi^3 Z_0 c e Q L}{256 a^4} \sqrt{\sigma_x^4 + \sigma_y^4}$$

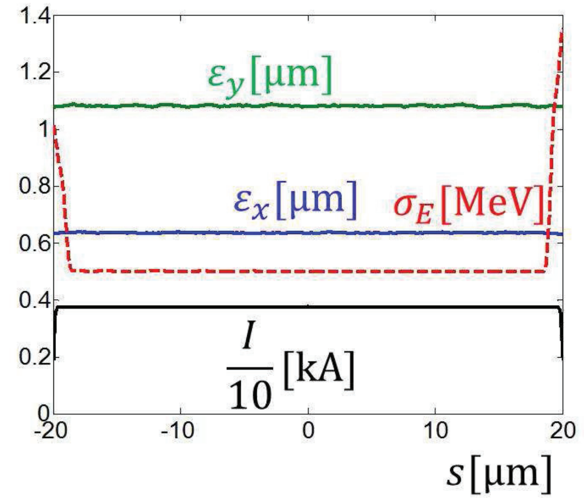
$$W_{\|}(l) = \frac{\pi Z_0 c e Q L}{16 a^2}$$

*K. Bane and G. Stupakov, ***Dechirper wakefields for short bunches***, NIM A **820** (2016) 156.

Beam dynamics in corrugated structure

"Ideal" beam after the insertion



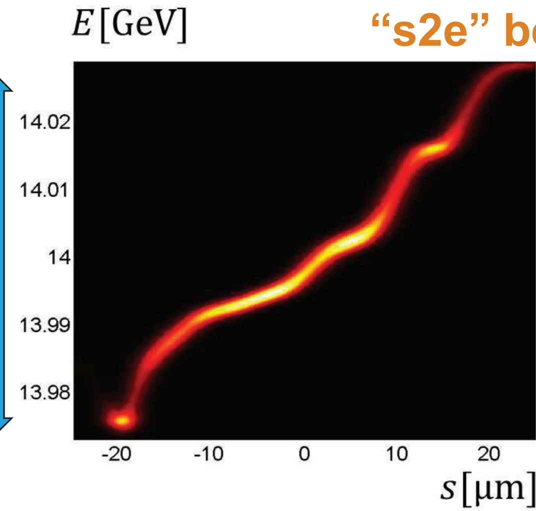


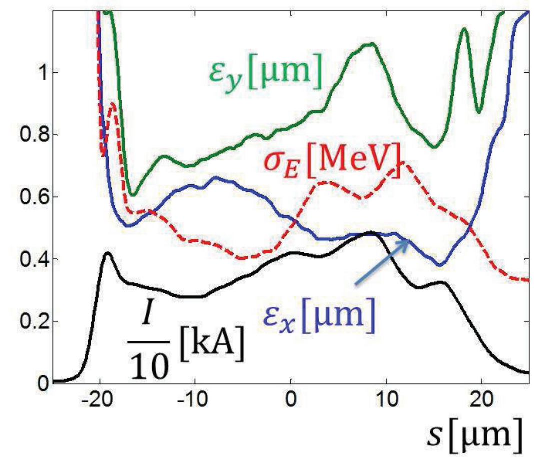
The change in the slice parameters is negligible.

Beam dynamics in corrugated structure

"s2e" beam before the insertion

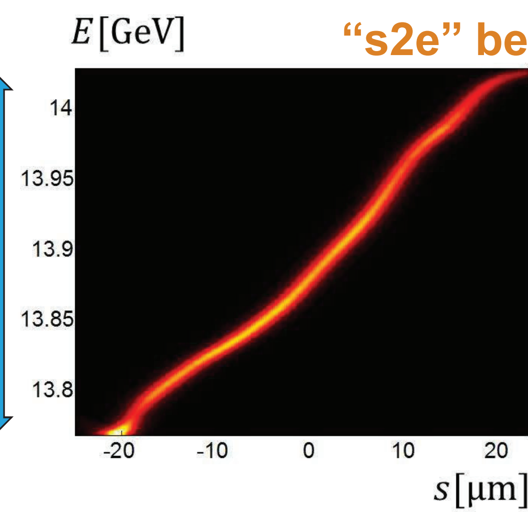
55 MeV

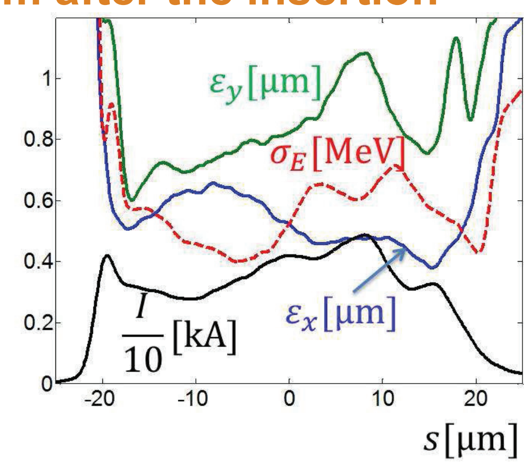




"s2e" beam after the insertion

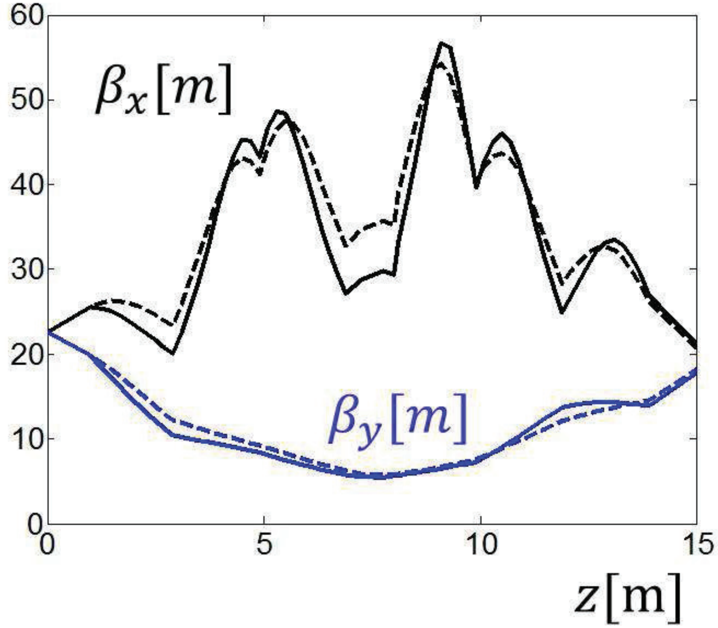
255 MeV



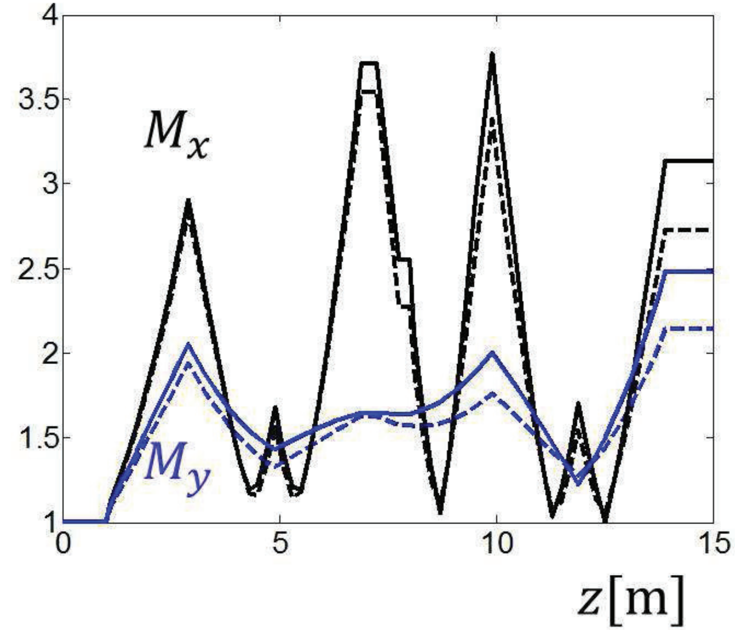


Beam dynamics in corrugated structure

Beta function



Beta mismatch parameter



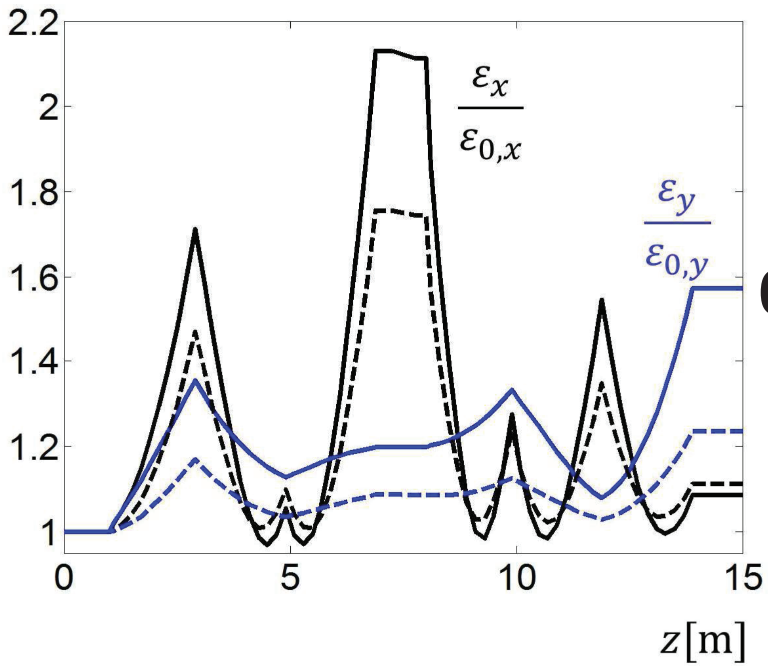
solid lines – "S2E" beam

dashed lines – "ideal" beam

$$M = \frac{1}{2}\left(\tilde{\beta}_e + \tilde{\gamma}_e + \sqrt{\left(\tilde{\beta}_e + \tilde{\gamma}_e\right)^2 - 4}\right)$$

$$\tilde{\gamma}_e = \frac{1 + \tilde{\alpha}_e^2}{\tilde{\beta}_e}, \quad \tilde{\alpha}_e = \alpha_e - \alpha\tilde{\beta}_e, \quad \tilde{\beta}_e = \frac{\beta_e}{\beta}$$

Beam dynamics in corrugated structure



Projected emittance growth

60%

solid lines – "S2E" beam

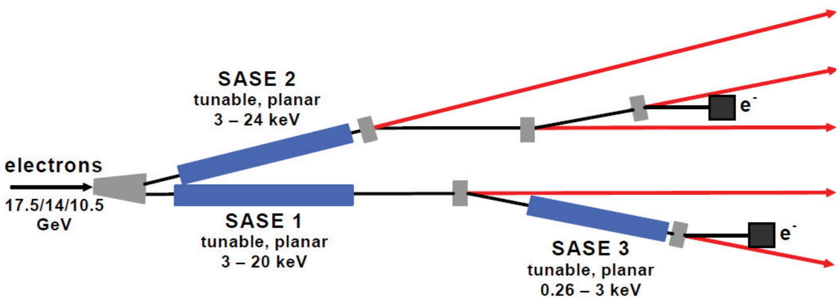
dashed lines – "ideal" beam

Parameter	"ideal" beam	"S2E" beam	Units
Initial/final projected x-emittance	0.64/0.70	0.72/0.77	µm
Initial/final projected y-emittance	1.09/1.33	1.18/1.82	µm
Initial/final energy loss in tail	0/212	50/**255**	MeV

Broadband SASE radiation

The European XFEL undulator lines

Parameter	SASE1/SASE2	SASE3	Units
Undulator wavelength	40	68	mm
K-range	3.9-1.65	99.3-4	
Wavelength at 17.5 GeV	0.147-0.040	1.22-0.27	nm
Wavelength at 14.0 GeV	**0.230-0.063**	1.90-0.42	nm
Wavelength at 8.5 GeV	0.625-0.171	5.17-1.15	nm
Active undulator length	175	105	m

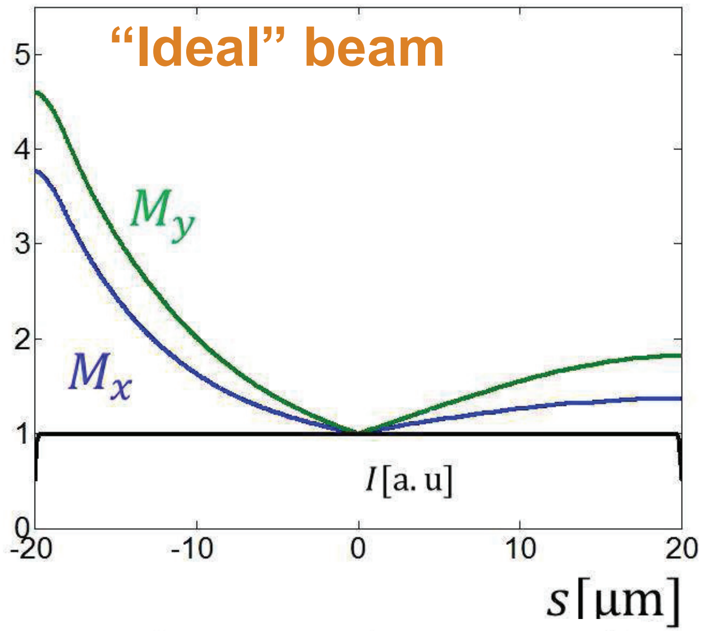


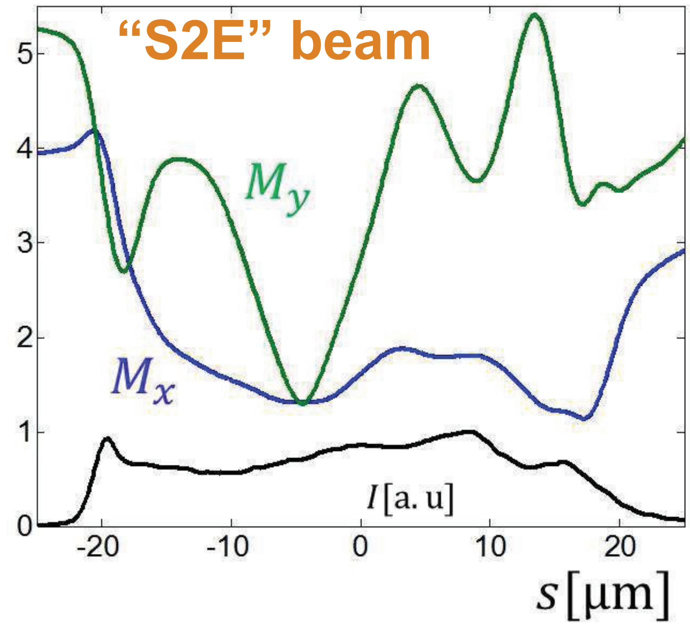
SASE1 line in the simulation

Parameter	Value	Units
Undulator wavelength	40	mm
K averaged	2.76	
Radiation wavelength	0.23	nm
Averaged beta function	16	m

Broadband SASE radiation

Beta mismatch parameter along the beams



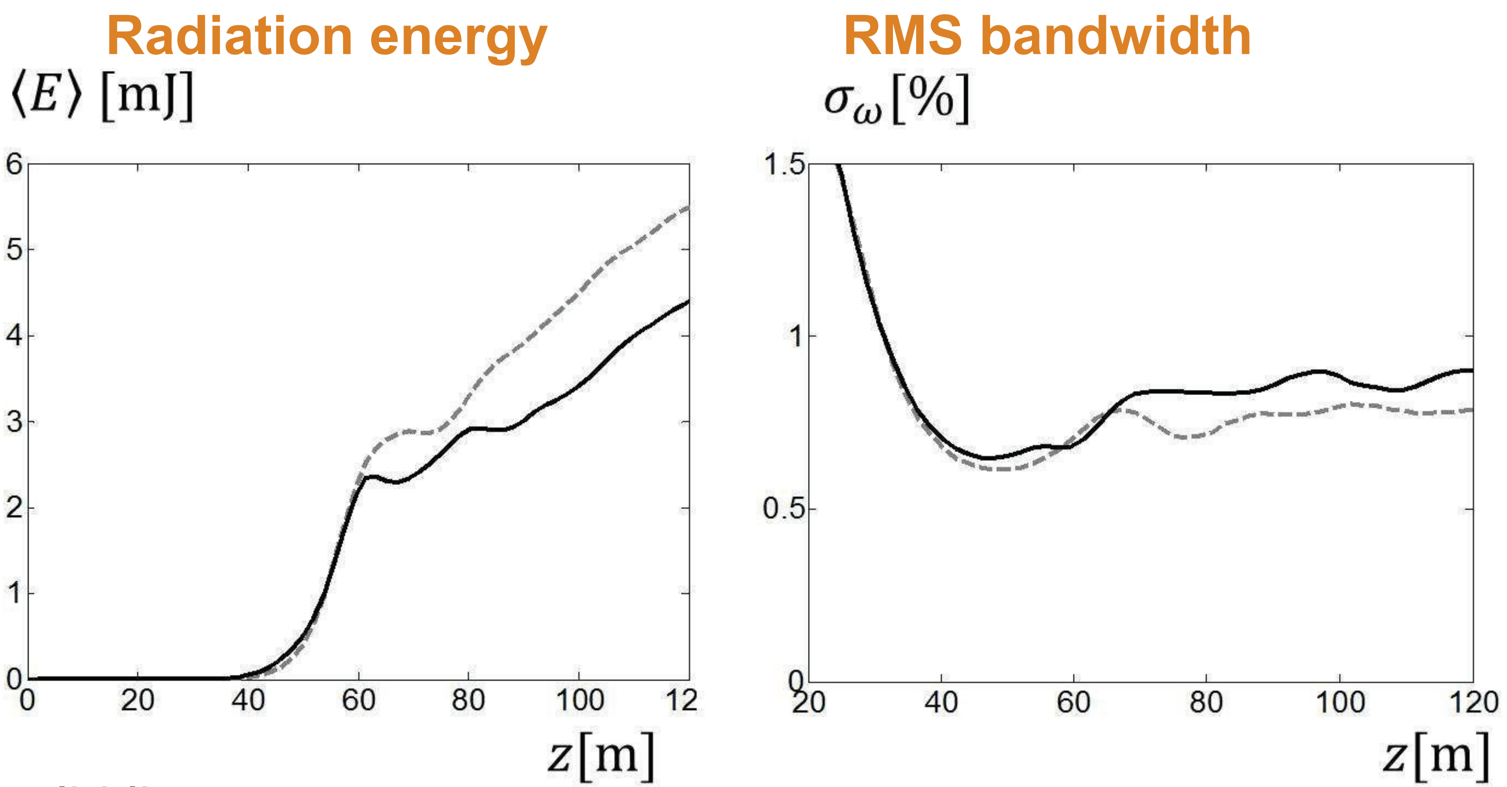


$$M = \frac{1}{2}\left(\tilde{\beta}_e + \tilde{\gamma}_e + \sqrt{\left(\tilde{\beta}_e + \tilde{\gamma}_e\right)^2 - 4}\right)$$

$$\tilde{\gamma}_e = \frac{1+\tilde{\alpha}_e^2}{\tilde{\beta}_e}, \quad \tilde{\alpha}_e = \alpha_e - \alpha\tilde{\beta}_e, \quad \tilde{\beta}_e = \frac{\beta_e}{\beta}$$

The "ideal" beam can be matched well even at the tail.
The “S2E” beam has a larger mismatch at the head and at the tail.

Broadband SASE radiation



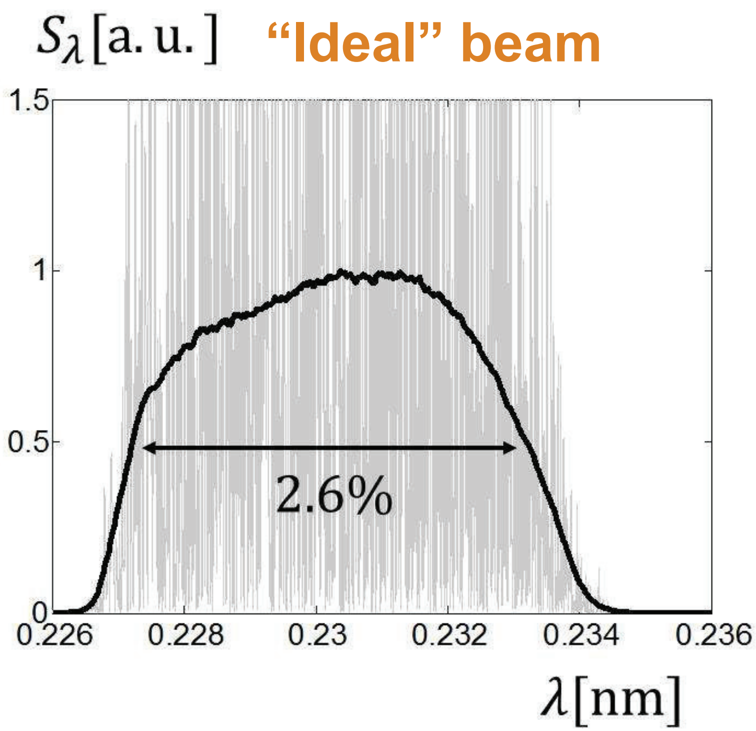
solid lines
– “S2E” beam

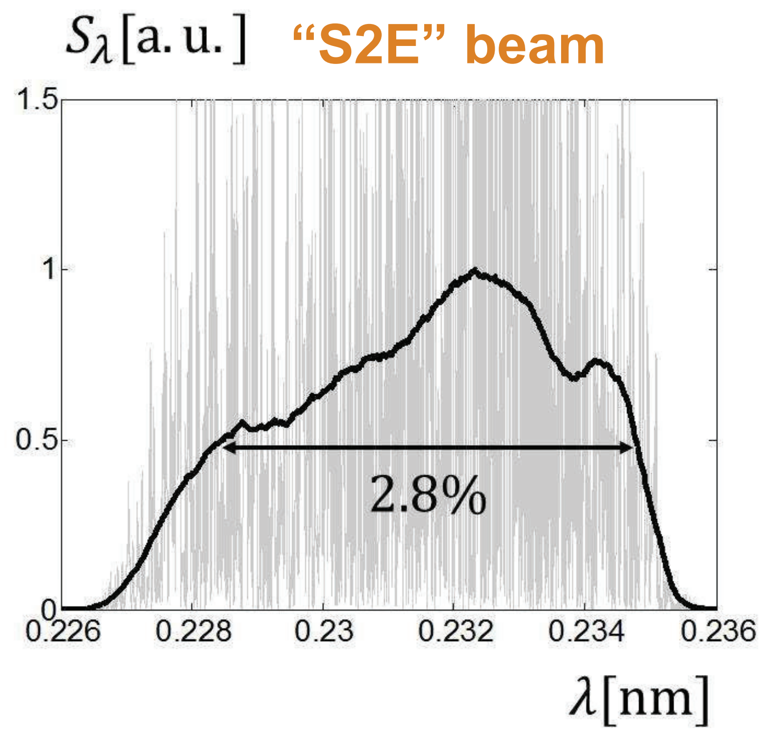
dashed lines
– “ideal” beam

We do not use an undulator tapering. The tapering could increase the radiation power yet by order of magnitude but the radiation bandwidth can be reduced because of it.

Broadband SASE radiation

Full-Width-Half-Maximum bandwidth at z= 115 m



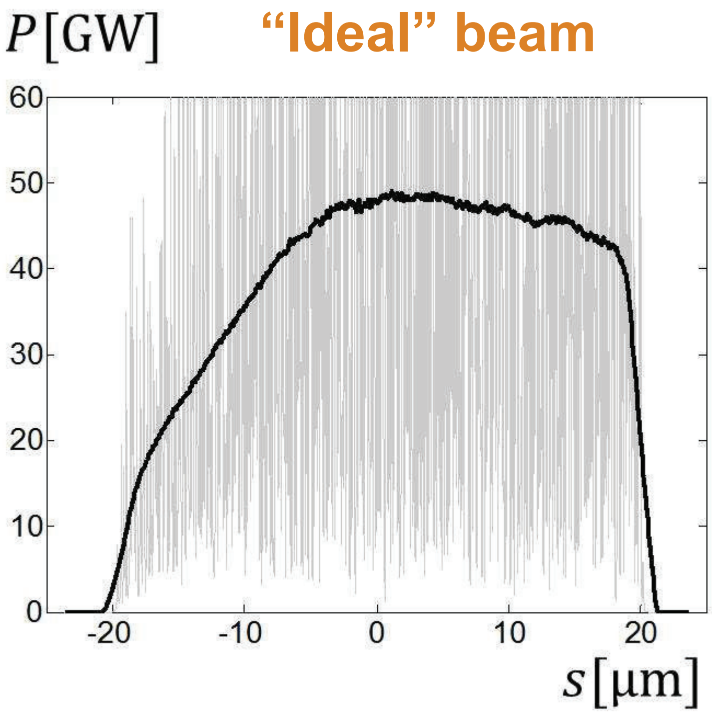


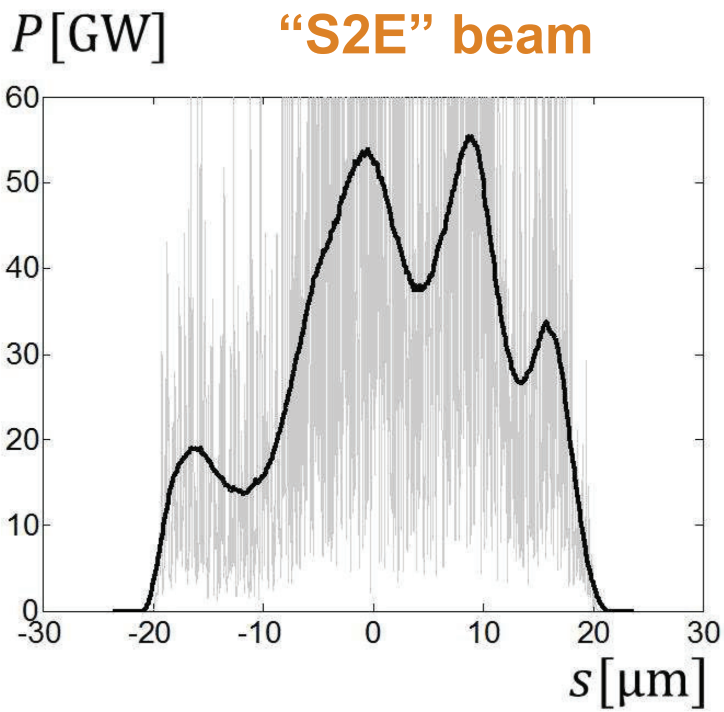
The solid lines present the spectrum averaged over many shots. The oscillating gray lines show an one shot spectrum.

DESY

Broadband SASE radiation

Radiation power at z= 115 m





The radiation from the beam tail and head are suppressed partially due to impact of the wake fields on the beam quality in the corrugated structure insertion. The solid lines present the averaging over many shots.

Conclusion

With 6 corrugated modules we can obtain 3% radiation bandwidth at 14 GeV (0.23 nm radiation wavelength).

Parameter	Value	Units
Bunch charge	500	pC
Bunch energy	14	GeV
Radiation wavelength	0.23	nm
Pulse energy	~4	mJ
Bandwidth	~3	%