XFEL Impedance Effects and Mitigation

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The European XFEL

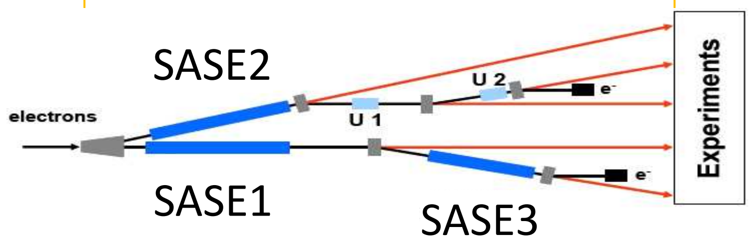
About FELs and Wakes

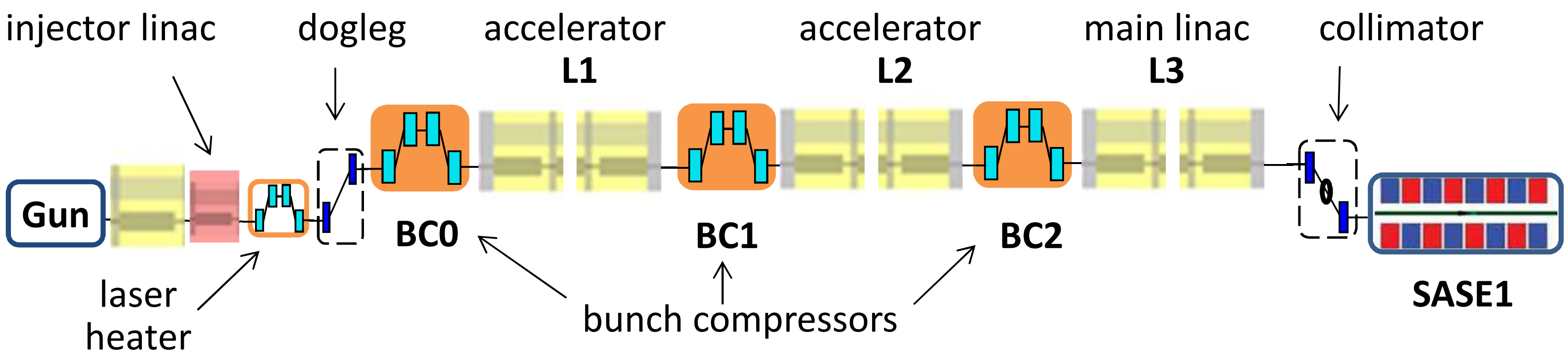
A Measurement

The European XFEL

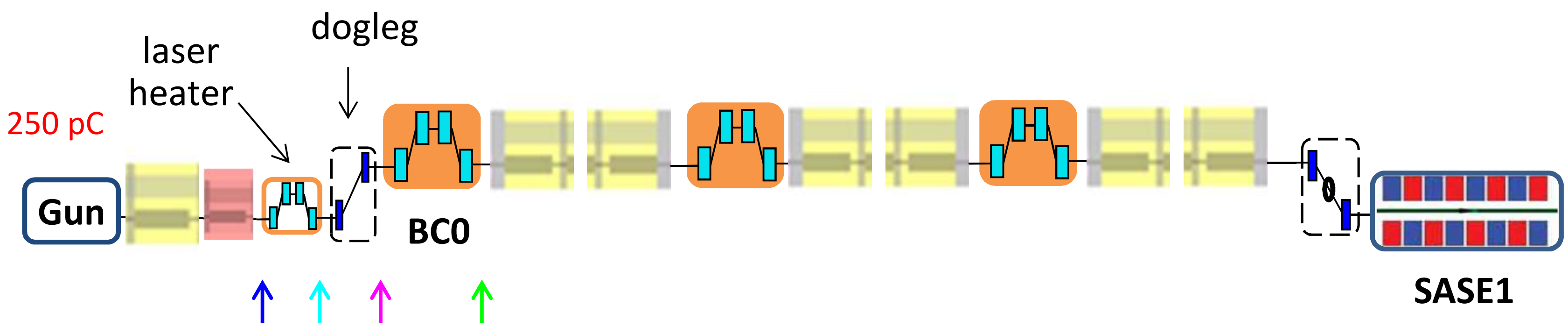
main linac, L_{tot} = 1179 m
L_{act} = 640 × 1.038 m = 664 m

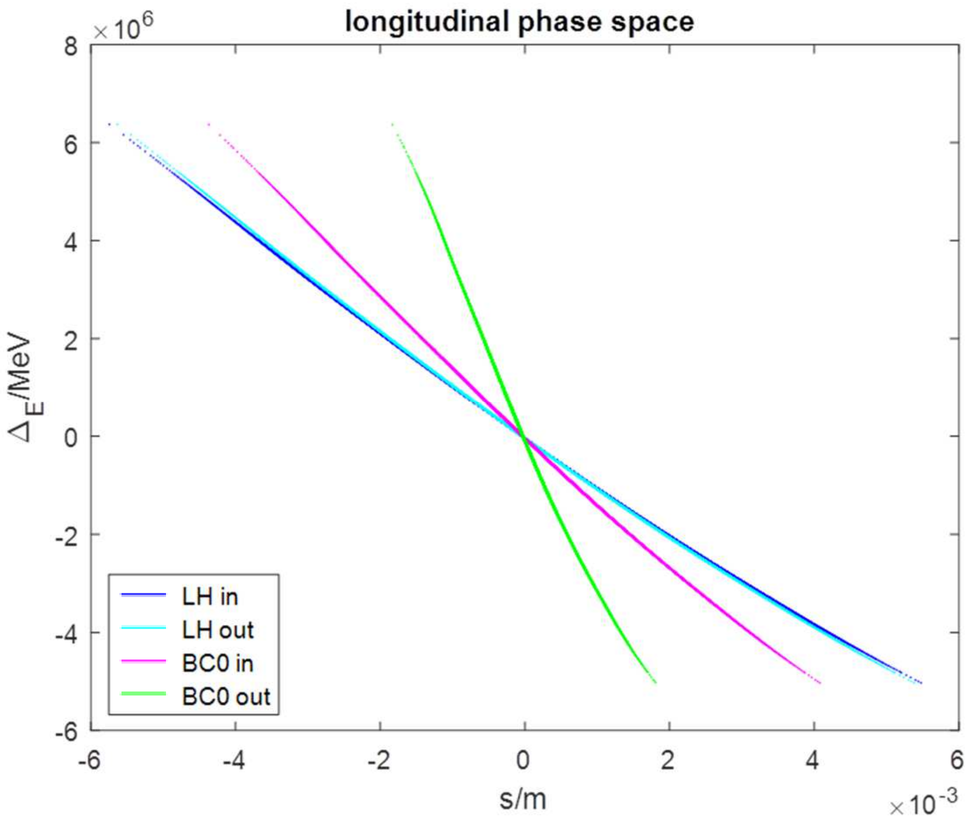
SASE1 L_{tot} = 225 m
L_{act} = 35 × 5 m = 175 m

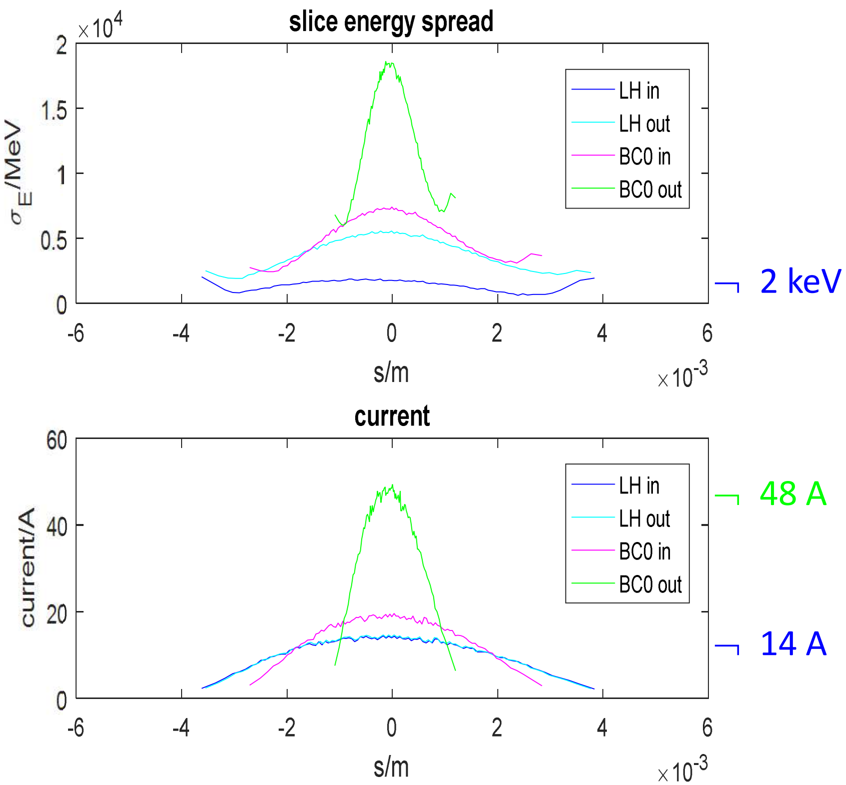




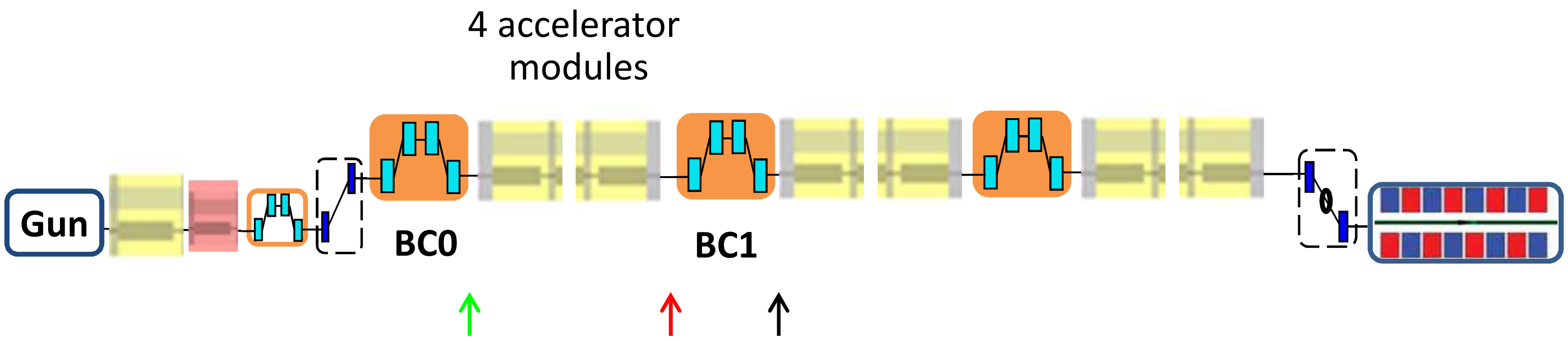
Compression Scenario → BC0 →

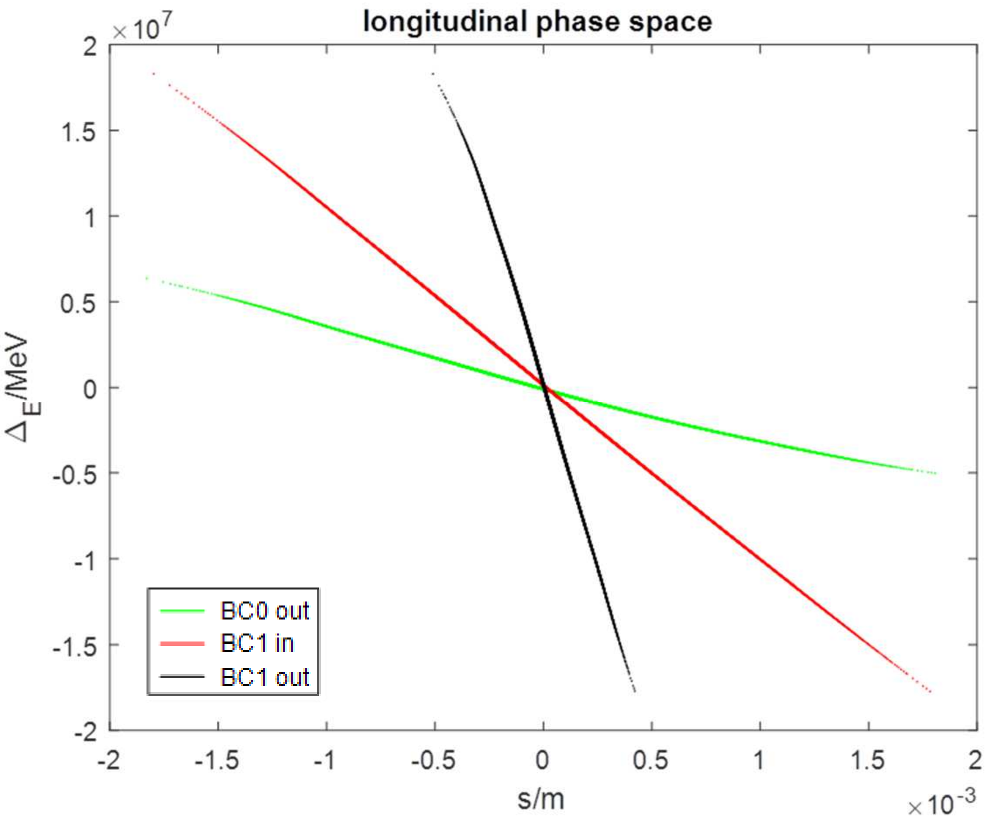


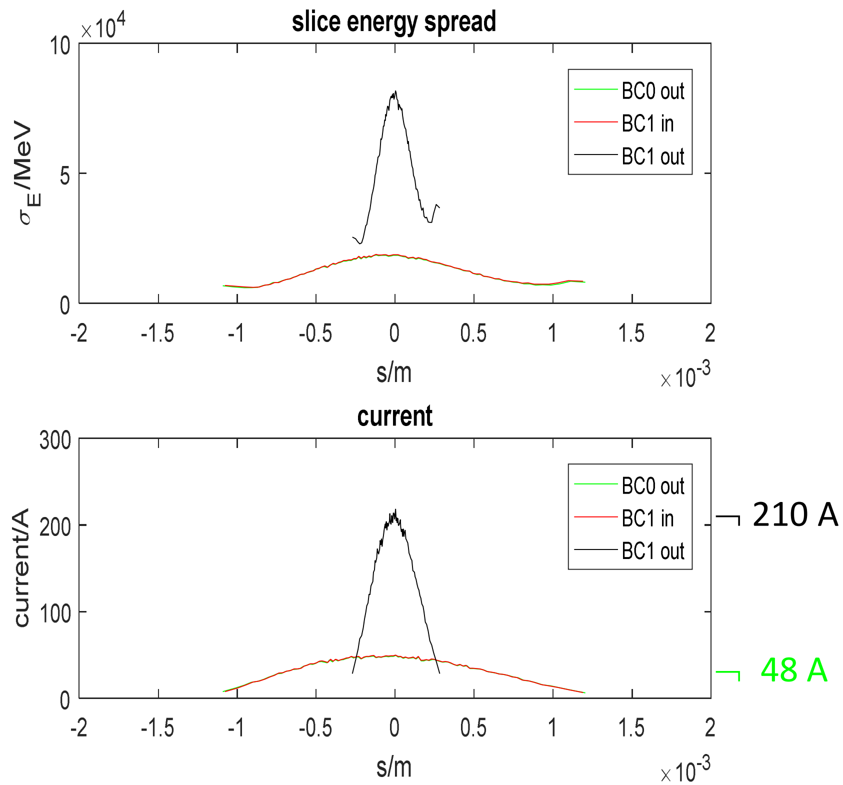




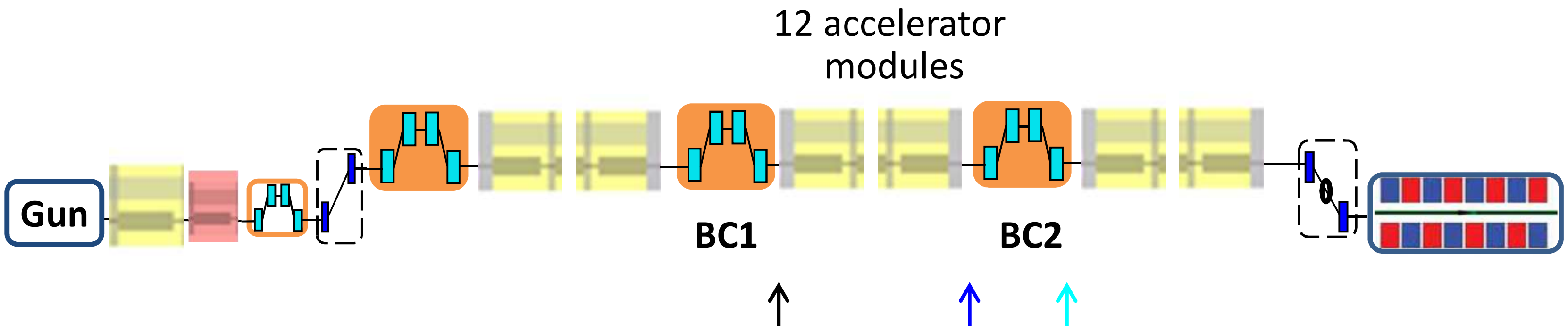
→ BC1 →


4 accelerator
modules
Gun
BC0
BC1

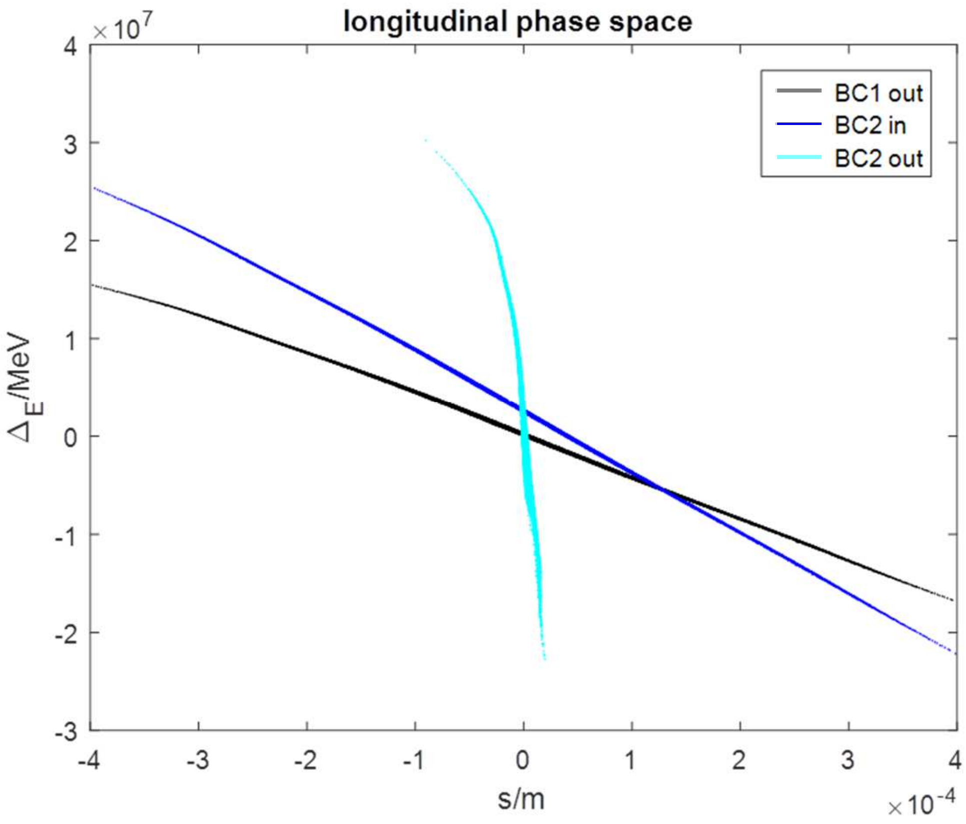

longitudinal phase space
$\times 10^7$
Δ_E/MeV
s/m
$\times 10^{-3}$
BC0 out
BC1 in
BC1 out


slice energy spread
$\times 10^4$
σ_E/MeV
s/m
$\times 10^{-3}$
BC0 out
BC1 in
BC1 out
current
current/A
s/m
$\times 10^{-3}$
BC0 out
BC1 in
BC1 out
210 A
48 A

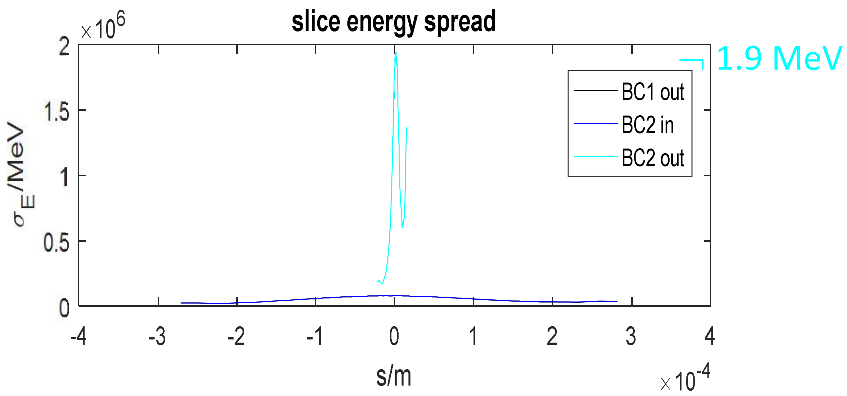
→ BC2 →



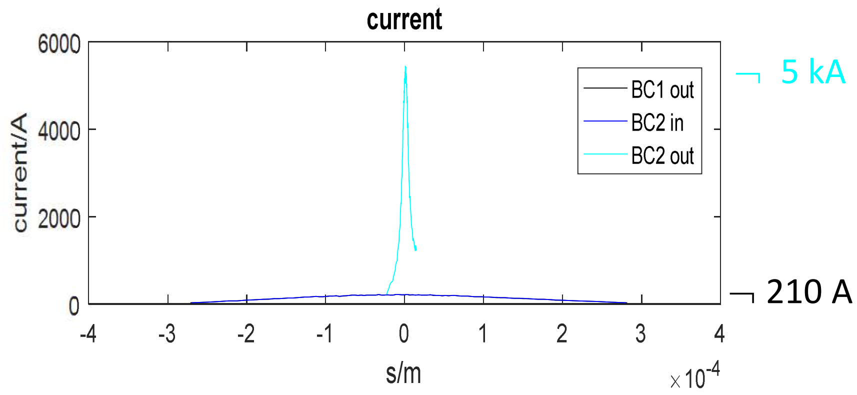
12 accelerator modules
Gun
BC1
BC2



longitudinal phase space
$\times 10^7$
Δ_E/MeV
s/m
$\times 10^{-4}$
BC1 out
BC2 in
BC2 out

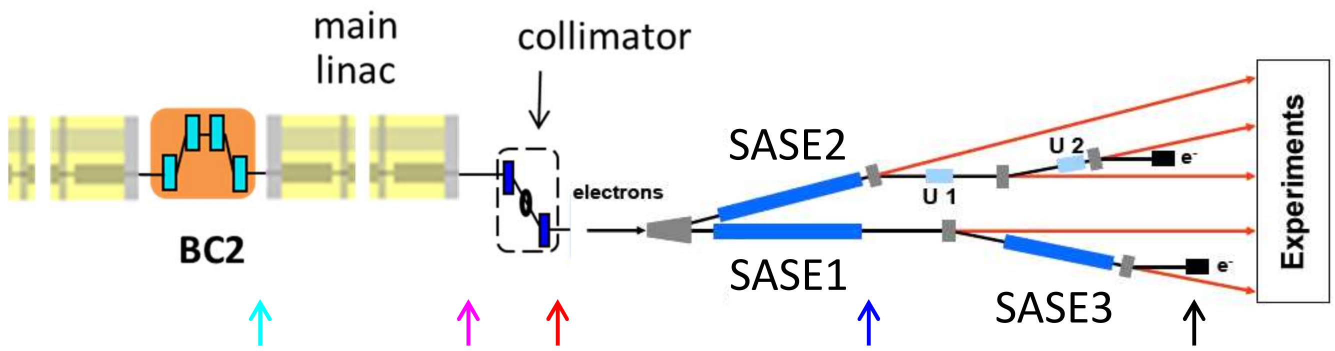


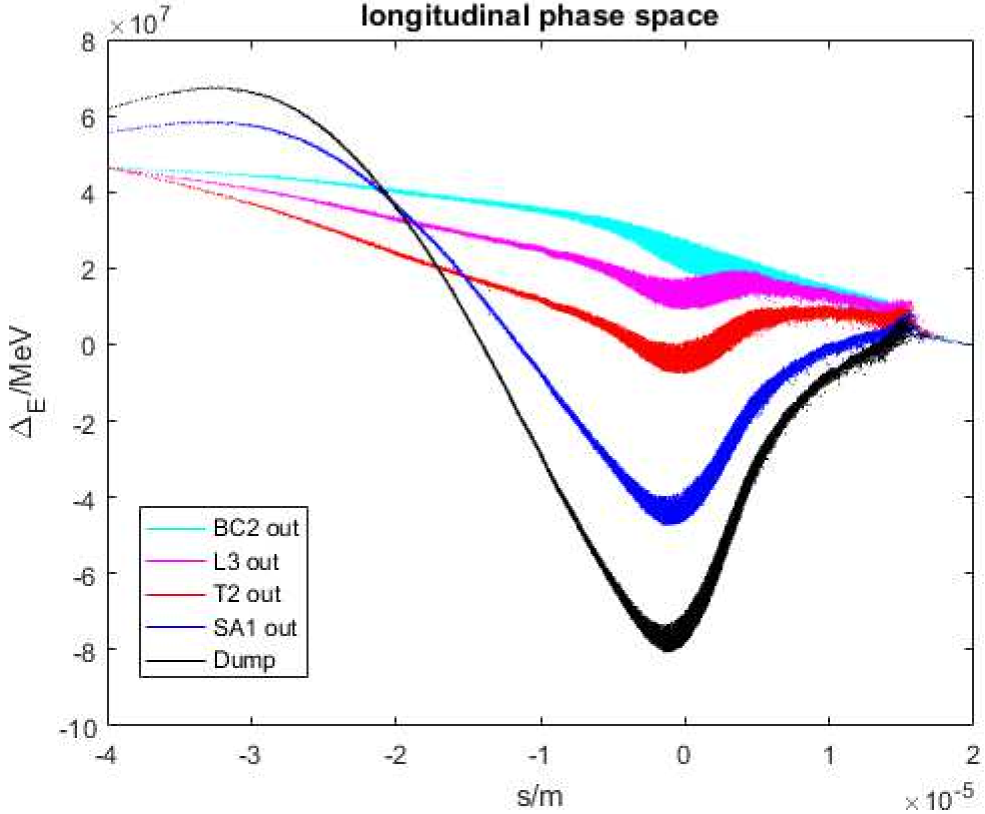
slice energy spread
$\times 10^6$
σ_E/MeV
s/m
$\times 10^{-4}$
BC1 out
BC2 in
BC2 out
1.9 MeV

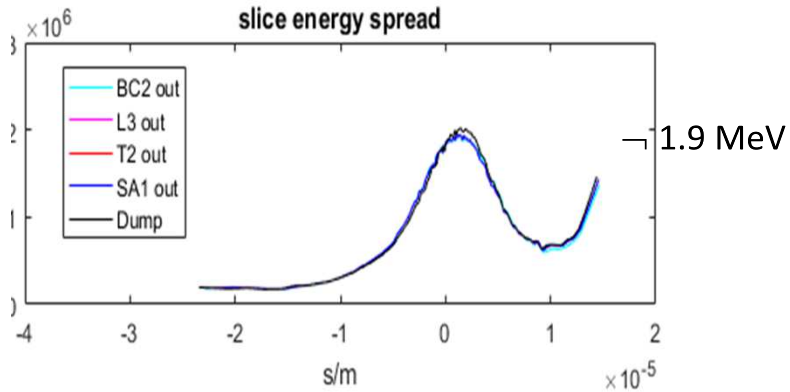


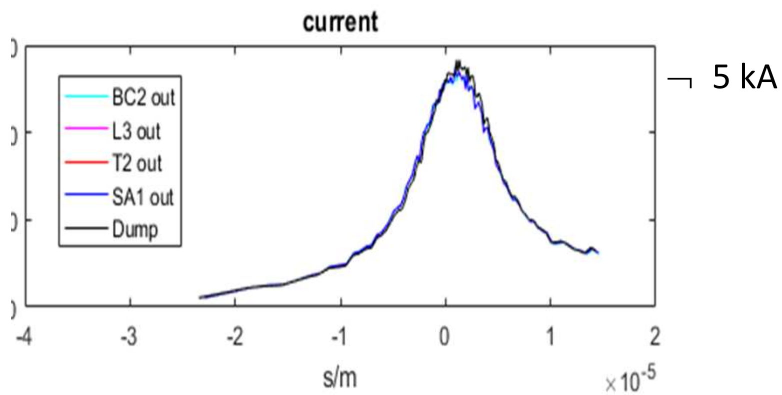
current
current/A
s/m
$\times 10^{-4}$
BC1 out
BC2 in
BC2 out
5 kA
210 A

BC1 → SASE1 → SASE3 → dump









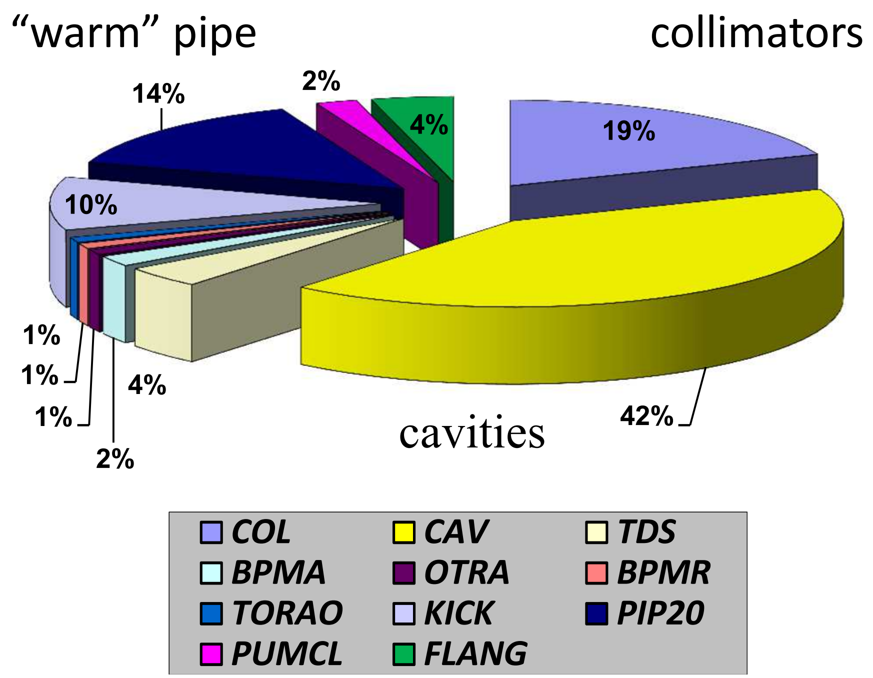
Impedance Budged before Undulator

accelerator wakes for Q = 1nC

about 2000 components
824 cavities (including TDS)
500 flanges
220 BPMs (5 types)
78 pumps
20 OTR screens
7 collimators
5 BAMs
3 kickers
warm pipe
…

total energy **loss** ≈ 35.3 MeV
total energy spread ≈ 15.4 MeV

loss

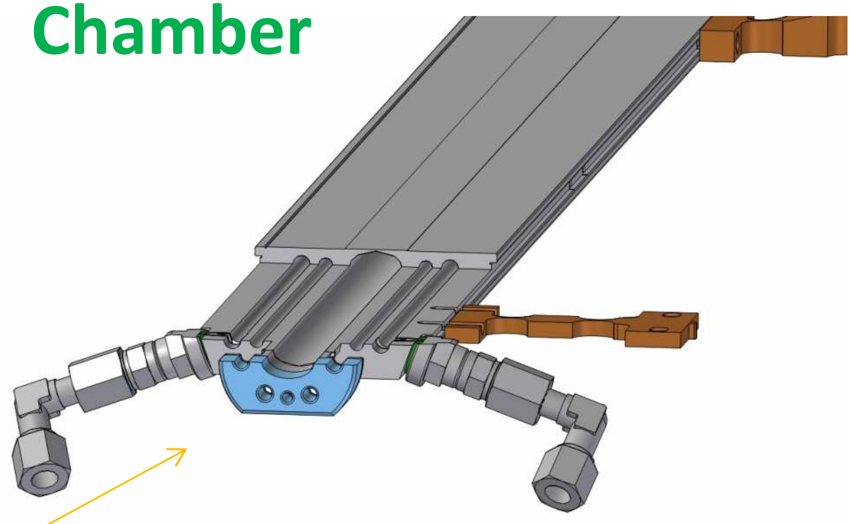


In the Undulator

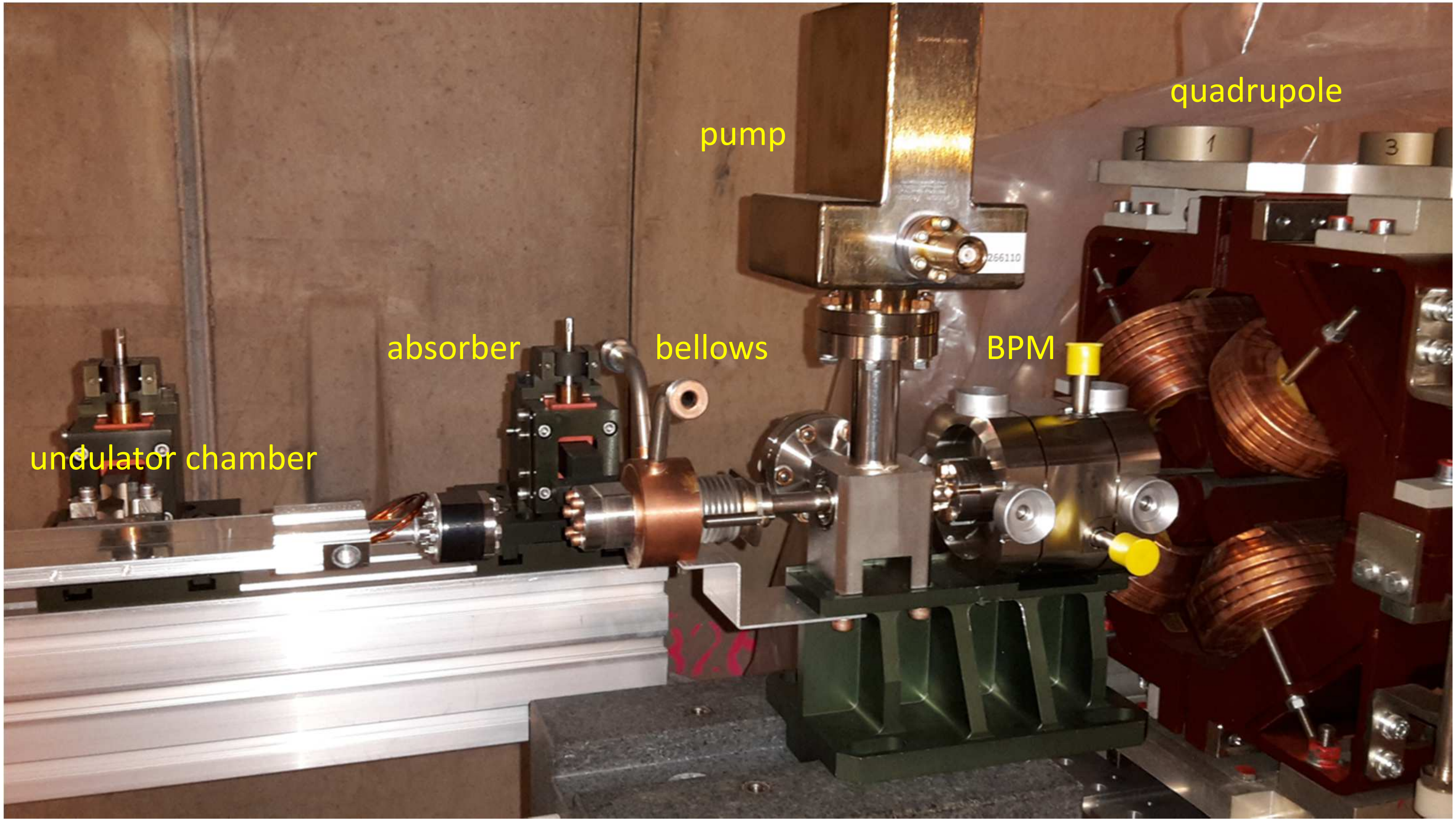
SASE1:
L_{tot} = 225 m
L_{act} = 35 × 5 m = 175 m

SASE3: 21 segments

Chamber



Intersection



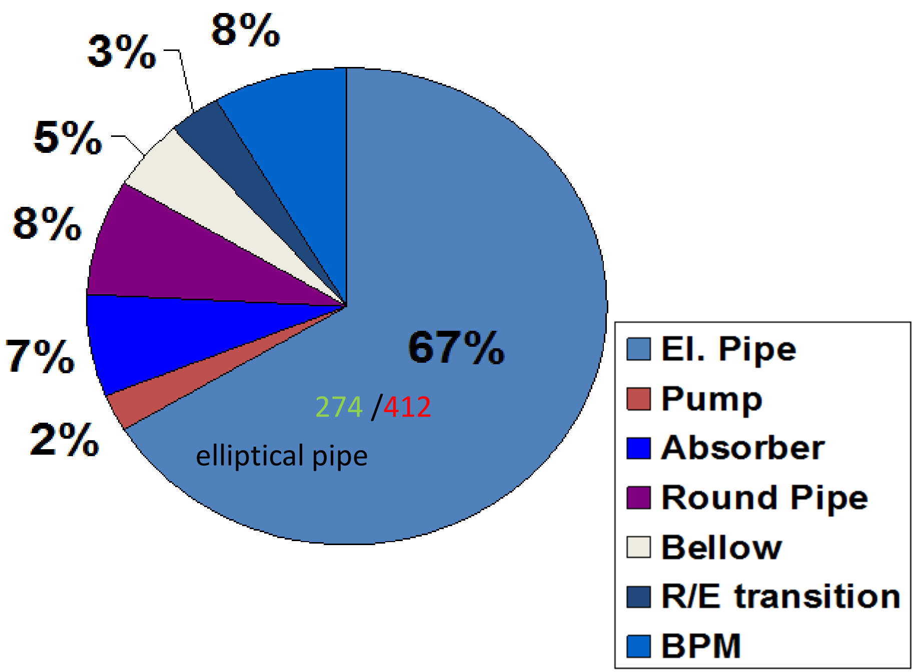
Impedance Budged for one Undulator Section

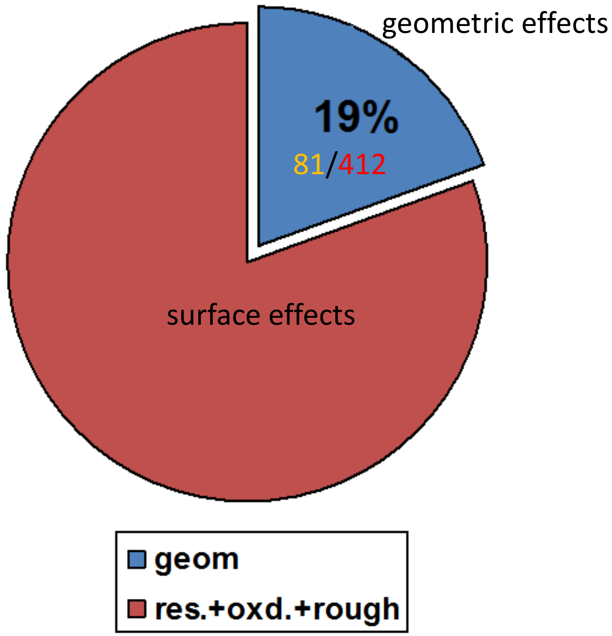
numbers for Q = 1nC, I_{peak} = 5 kA

SASE1 has 35 sections
SASE3 with 21 sections

energy spread

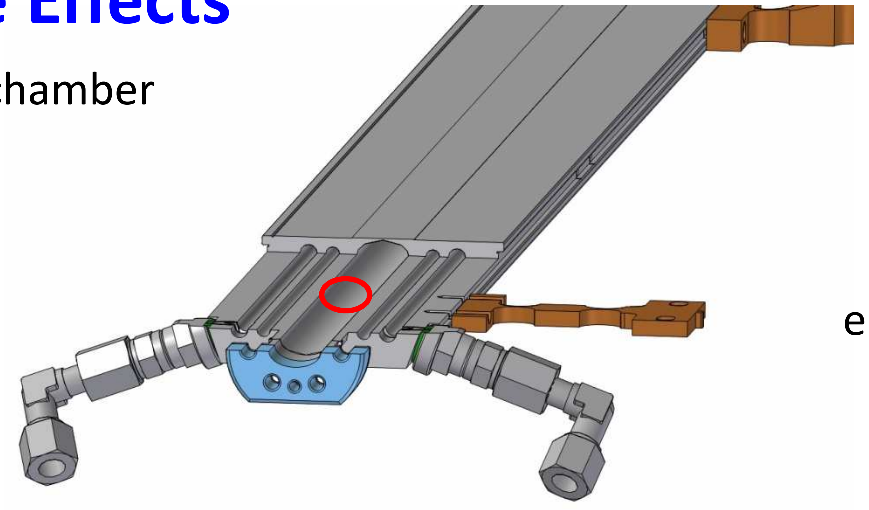
total energy spread (per section) ≈ 412 keV
elliptical pipe → 274 keV (pure surface effects)
surface effects → 331 keV
geometric effects → 81 keV



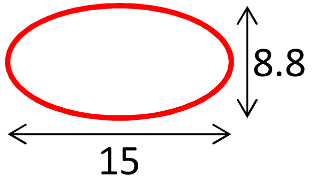


Surface Effects

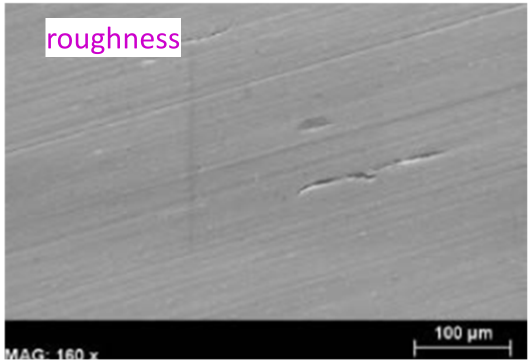
undulator chamber

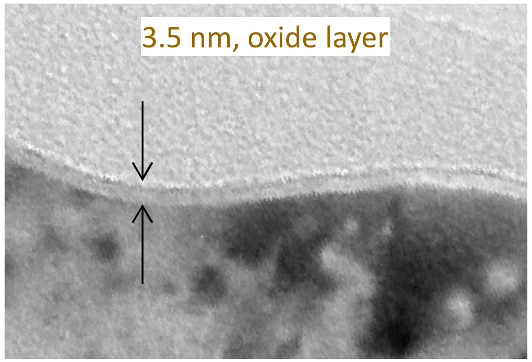


elliptical pipe



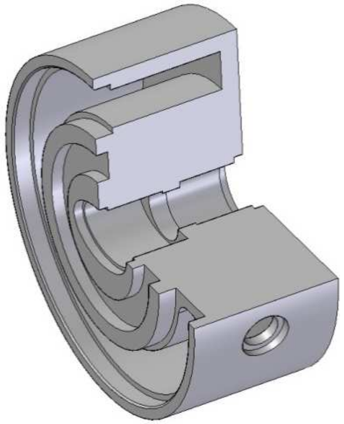
- shape: large cross-section (mirror currents & pumping) + small gap (undulator)
  $\longrightarrow$ elliptical pipe
- material: frequency dependent conductivity + anomalous skin effect
  $\longrightarrow$ aluminum profile
- more surface effects: roughness + oxide layer
  $\longrightarrow$ very tight tolerances 300 nm + 5 nm in undulators
  1000 nm + 5 nm in BC chambers



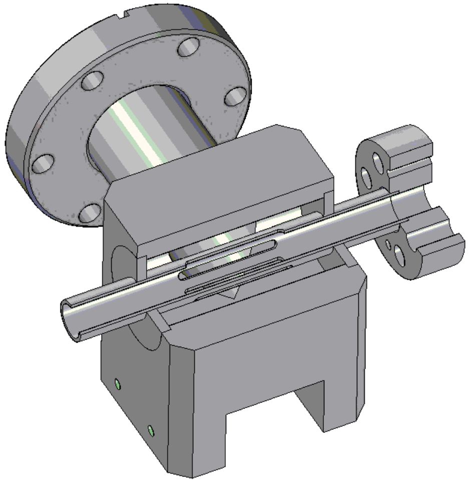


Geometric Effects

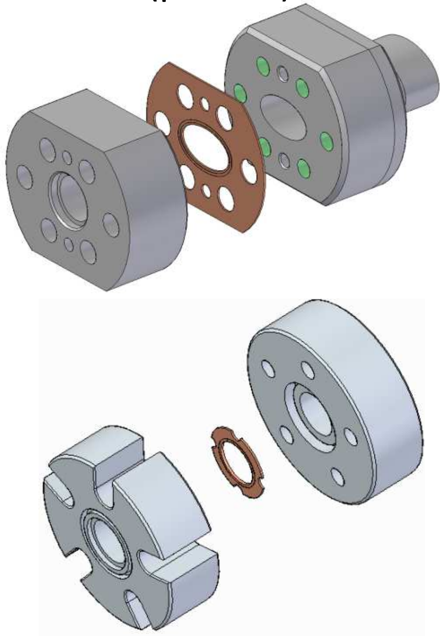
absorber



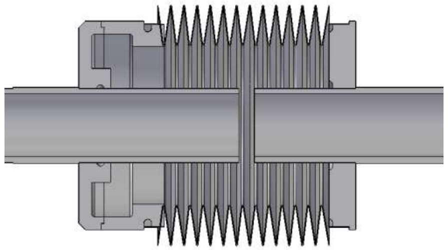
pump

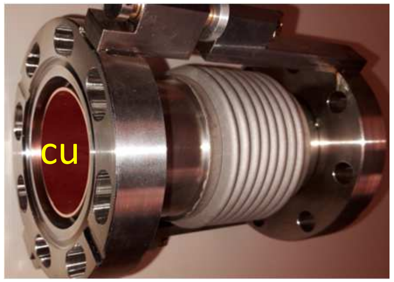


flange connections (pinned)

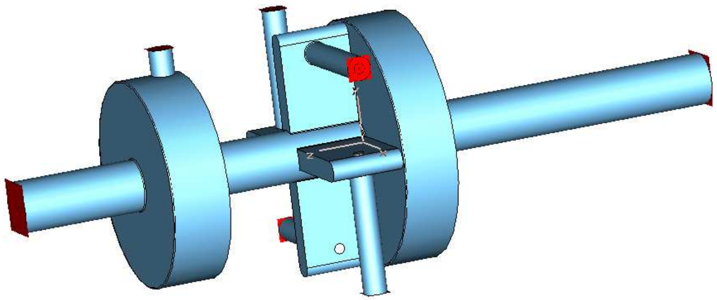


bellows (pipe with gaps)

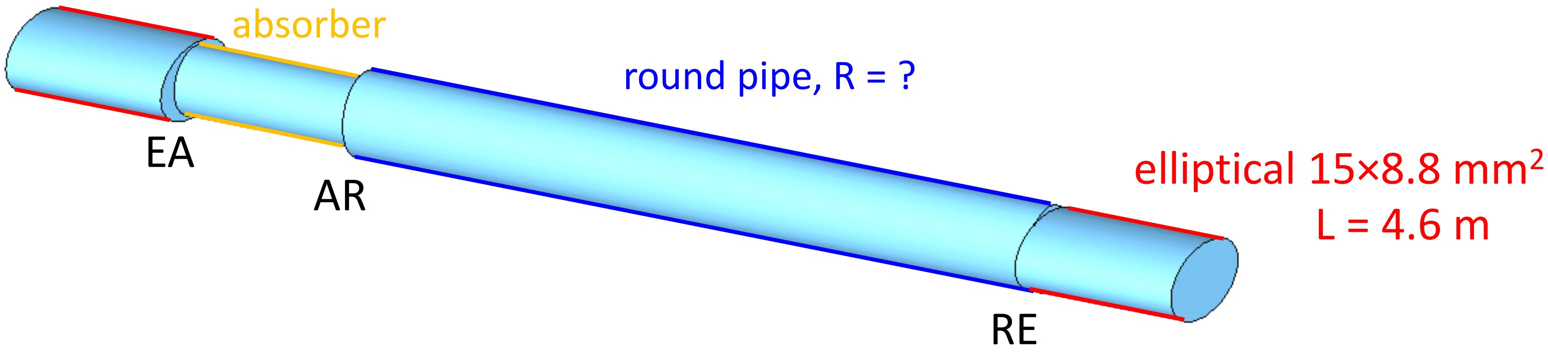


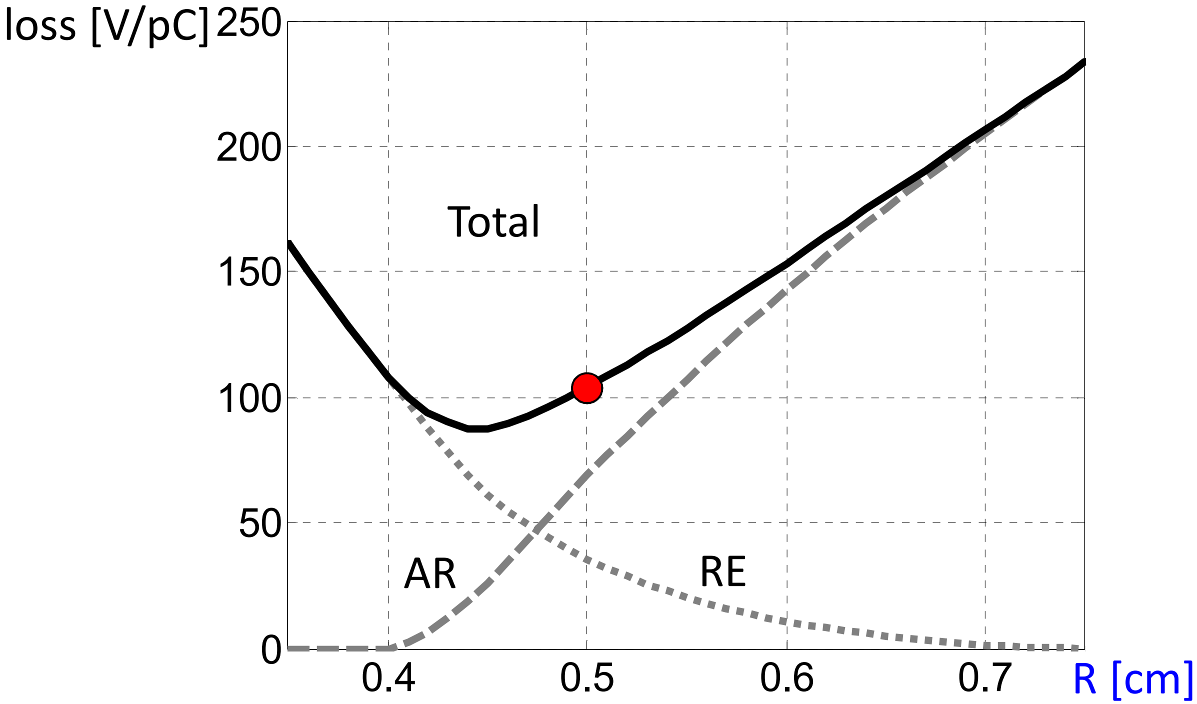


beam position monitor



optimize geometric effects





About FELs and Wakes

beam properties

energy, energy deviation ← wakes
emittance, optics ←
bunch charge, peak current ← compression

resonance condition

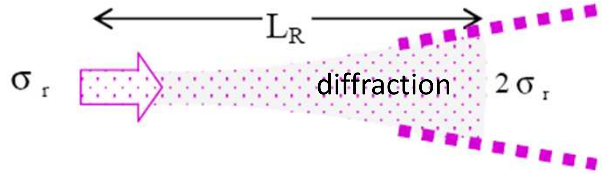
$$\lambda_l = \frac{\lambda_u}{2(\gamma_0 + \delta\gamma)^2}\left(1 + \frac{K^2}{2}\right) + \frac{\lambda_u}{2}\left(x'^2 + y'^2\right)$$

power gain length
(assuming optimal beta function)

$$L_g = 1.18\sqrt{\frac{I_A}{I_{\text{peak}}}\,\frac{(\varepsilon_n \lambda_w)^{5/6}}{\lambda_l^{2/3}}\,\frac{\left(1+\frac{K^2}{2}\right)^{1/3}}{KA_{JJ}}}\left(1 + \delta(\sigma_\gamma, \cdots)\right)$$

overlap electron – photon beam $\quad \sigma_r \approx \sigma_{r,l} \quad L_g \approx L_r$

$$\sigma_{r,l} \approx \sqrt{L_r \lambda_l / \pi}$$



Some Dimensions ≈ European XFEL

typical beam properties: energy ≈ 14 GeV (.. 17.5 GeV)
bunch charge ≈ 250 pC (.. 1 nC)
peak current ≈ 3 kA

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photon wavelength $\lambda_l \mu 10^{-10}\mathrm{m} \quad \mu\ \lambda_u/\gamma^2$

cooperation length $L_l \mu 10^{-8}\mathrm{m}$

transverse oscillation $\hat{x} \mu 10^{-6}\mathrm{m}$ (undulator trajectory)

bunch length $L_b \mu 10^{-5}\ \mathrm{m}$

bunch width $\sigma_w \mu \sqrt{\lambda_l L_g} \mu 10^{-5}\mathrm{m}$ (overlap electron-beam EM wave)

undulator (SASE1) $\lambda_u \approx 4\times 10^{-2}\mathrm{m}$

power gain length $L_g \approx 5\ \mathrm{m}$

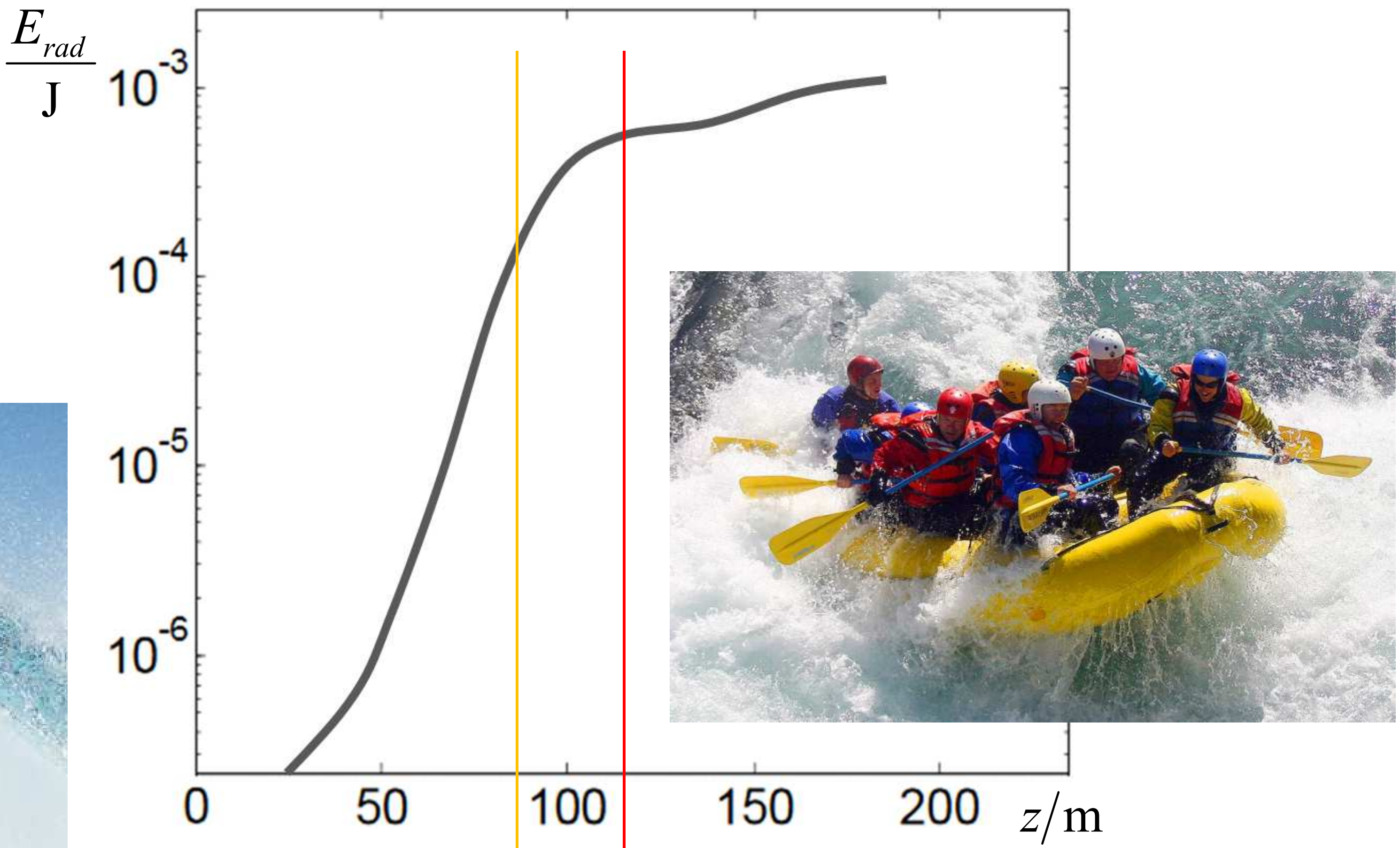
Rayleigh length $L_R \approx L_g$

(power gain length and Rayleigh length:) (overlap electron-beam EM wave)

linear operation $z < 8L_g$

saturation length $L_s \approx 10L_g .. 20L_g$

SASE

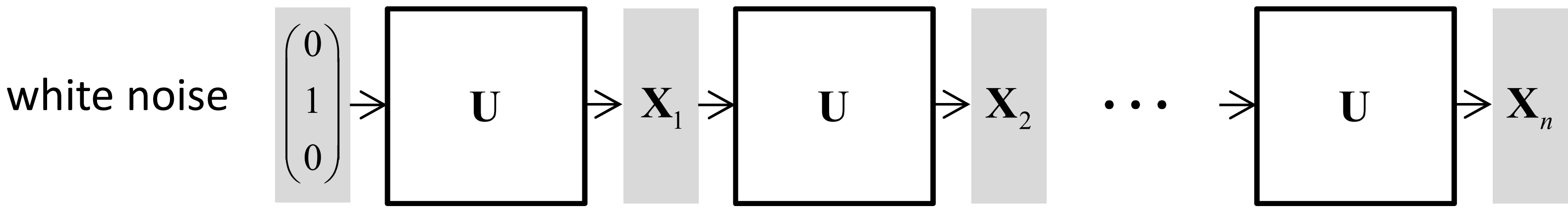


linear operation
(exponential gain)

saturation
(whitewater rafting)

Amplifier Model (linear operation)

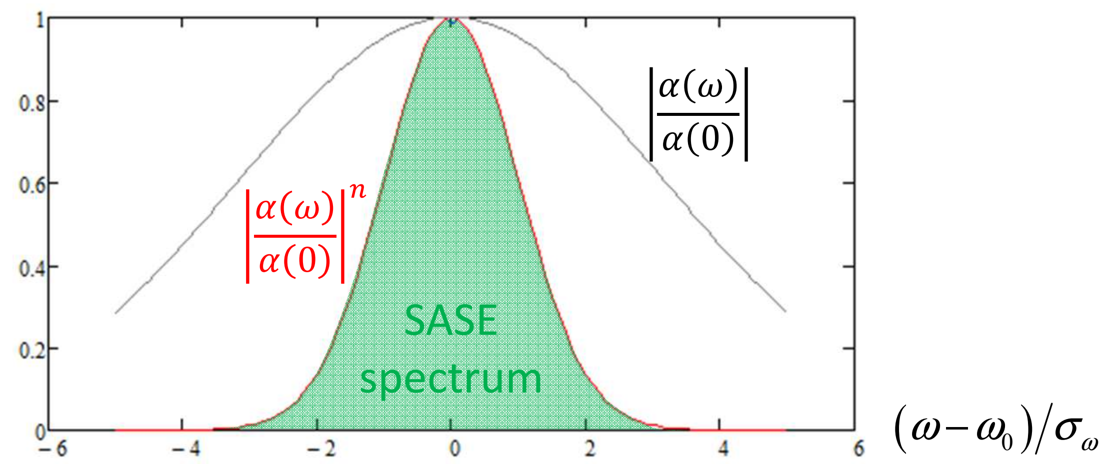
$$\mathbf{X} = \begin{pmatrix} \text{EM wave} \\ \text{beam, density modulation} \\ \text{beam, energy modulation} \end{pmatrix}$$



$$\mathbf{X}_2(\omega) = \mathbf{U}(\omega)\mathbf{X}_1(\omega)$$

$$\alpha(\omega)\mathbf{X}_e(\omega) = \mathbf{U}(\omega)\mathbf{X}_e(\omega)$$

only one eigenvector is amplified $\rightarrow \mathbf{X}_n(\omega) \sim (\alpha(\omega))^n \, \mathbf{X}_e(\omega)$

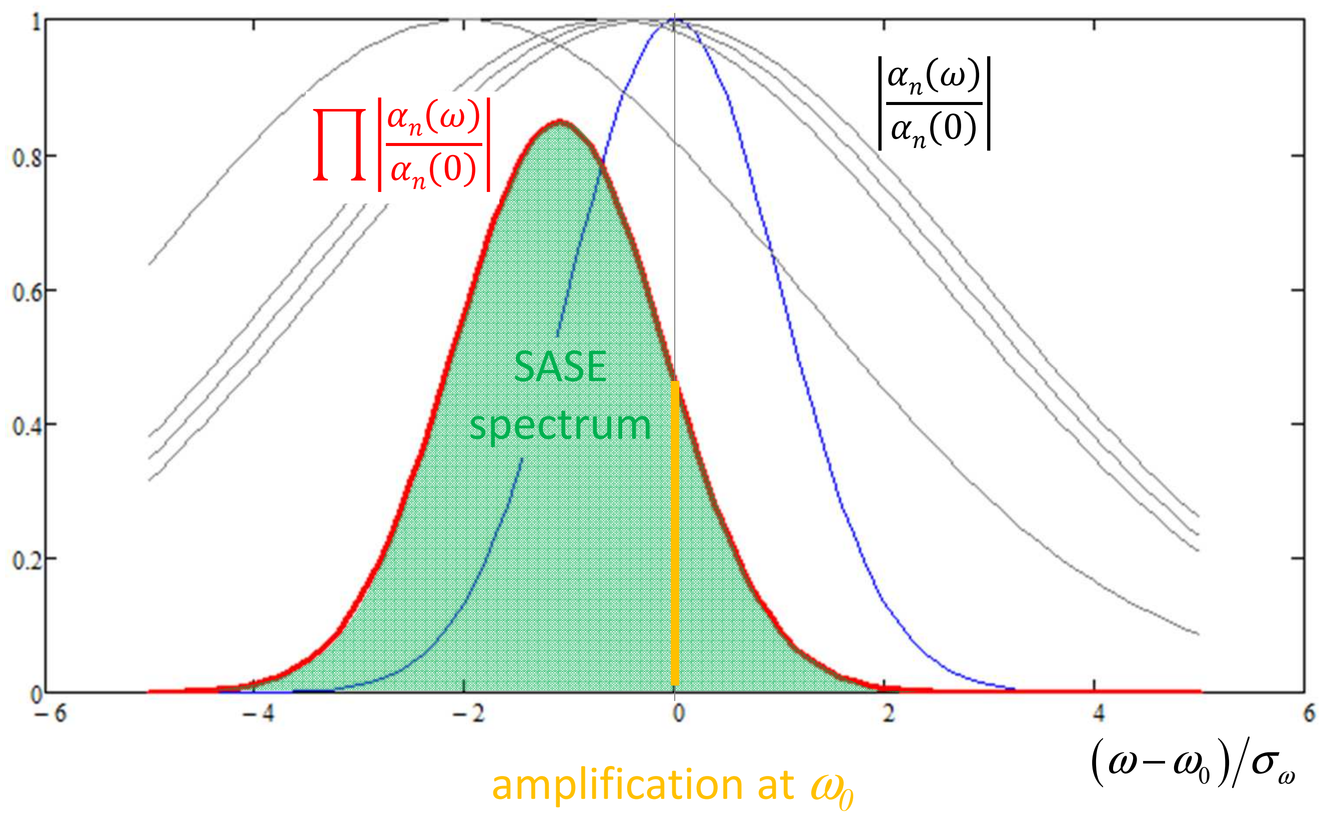


Amplifier Model (linear operation)

energy loss per stage $\gamma_n = \gamma_0 - n\delta\gamma$

shifted resonance condition $\lambda_l(n) = \frac{\lambda_u}{2\gamma_n^2}\left(1 + \frac{K^2}{2}\right)$

$$\alpha_n(\omega) \approx \alpha_0(\omega - n\delta\omega)$$



Amplifier Model (linear operation)

our parameters: $\frac{\sigma_\omega}{\omega_0} \approx 0.0005$ after 9 power gain length

$$\frac{\omega'}{\omega_0} 9L_g \approx 0.00045$$

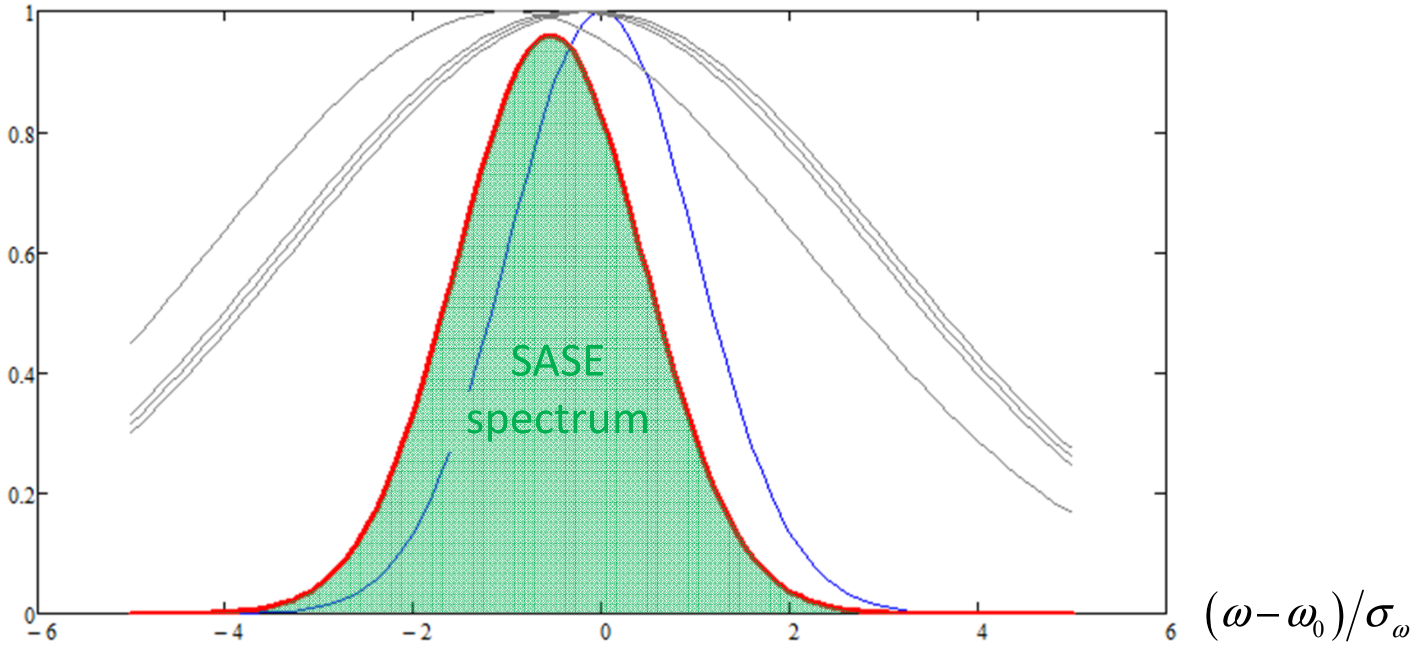
for Gaussian bunch with 250 pC, 5 kA

wake: $\approx -18\ \text{MeV}/(100\ \text{m})$

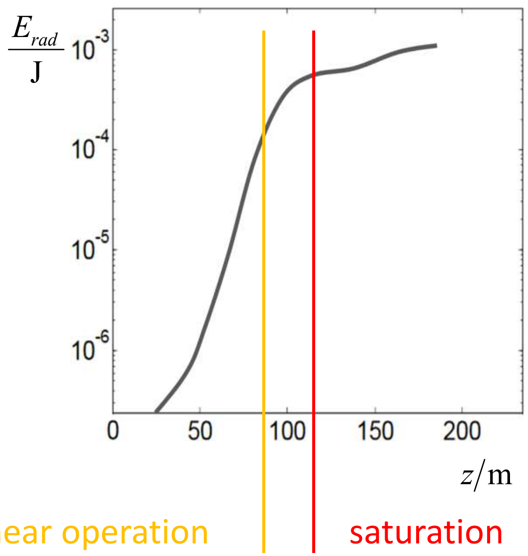
ISR: $\approx -5.7\ \text{MeV}/(100\ \text{m})$

with undulator intersections

CSR: exponentially increasing but smaller than wake + ISR



SASE in Non-Linear Regime



for our parameters (SASE1, 0.1nm, 250pC, 5kA):

linear regime: wakes + ISR > CSR (SASE)
mild shift of resonance condition

beyond linear regime: CSR > wakes + ISR
energy loss $\longrightarrow$ further shift of resonance
complicated interaction of kinetic- and field-energy
and micro-bunching

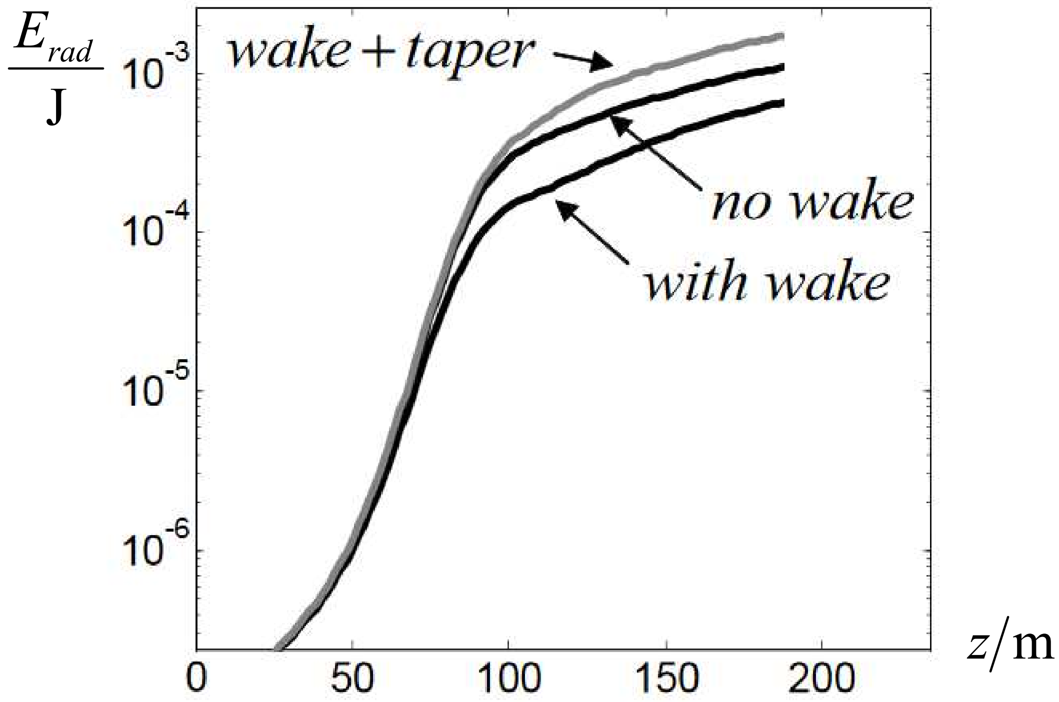
Tapered Undulator (Mitigation)

systematic energy loss $\gamma(S)$ can be compensated by tapering $K(S)$

keep resonance condition: $\lambda_l = \frac{\lambda_u}{2\left(\gamma(S)\right)^2}\left(1+\frac{K(S)^2}{2}\right)$

optimal tapering is more than compensation of resonance condition, it also considers the dynamics of the bunching process

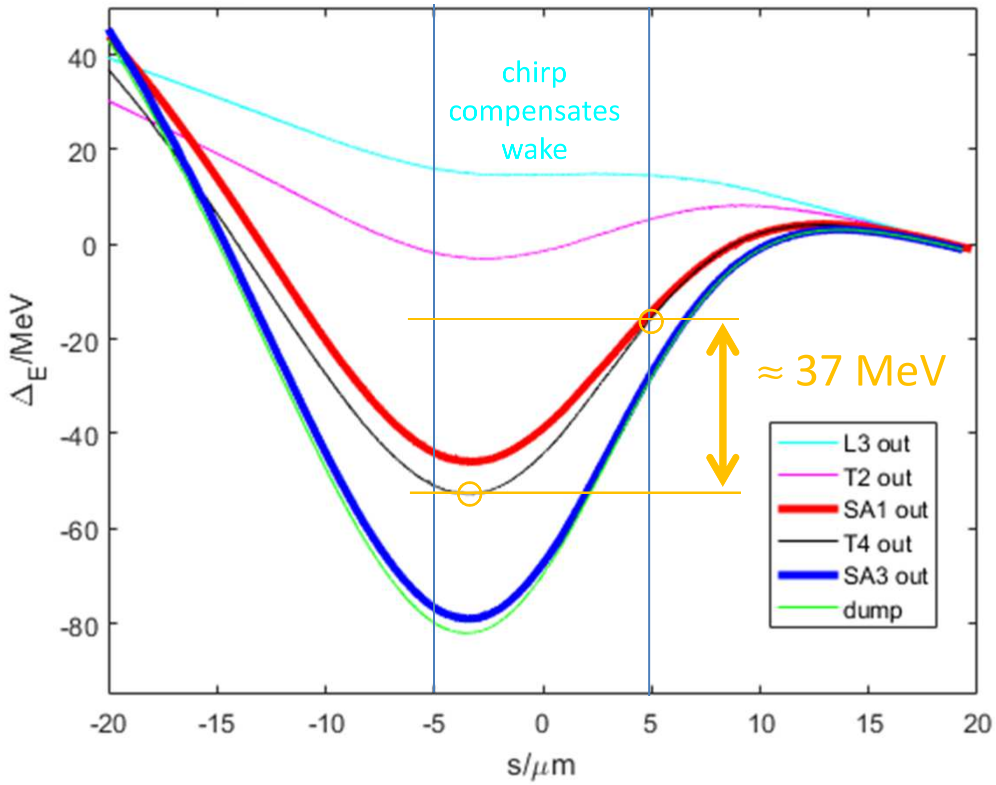
the optimal taper is non-linear in the range of saturation, it is usually adjusted empirically



Energy Profile before Undulator

the taper compensates **wake** effects **in the undulator**, but different parts of the bunch (~ cooperation length ≈ 10 nm) radiate on wavelengths defined by the **energy before the undulator** (+ some frequency shift)

idealized longitudinal phase space



Gaussian bunch with 250pC, 5kA

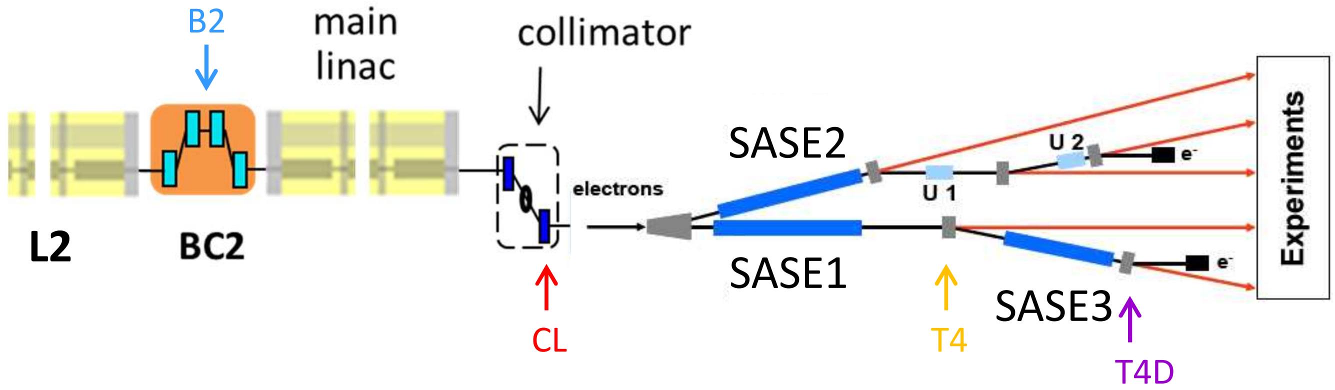
the initial energy width causes an **additional broadening of the SASE3 spectrum**

$$\frac{\Delta\gamma}{\gamma} \approx 0.0026$$

$$\Downarrow$$

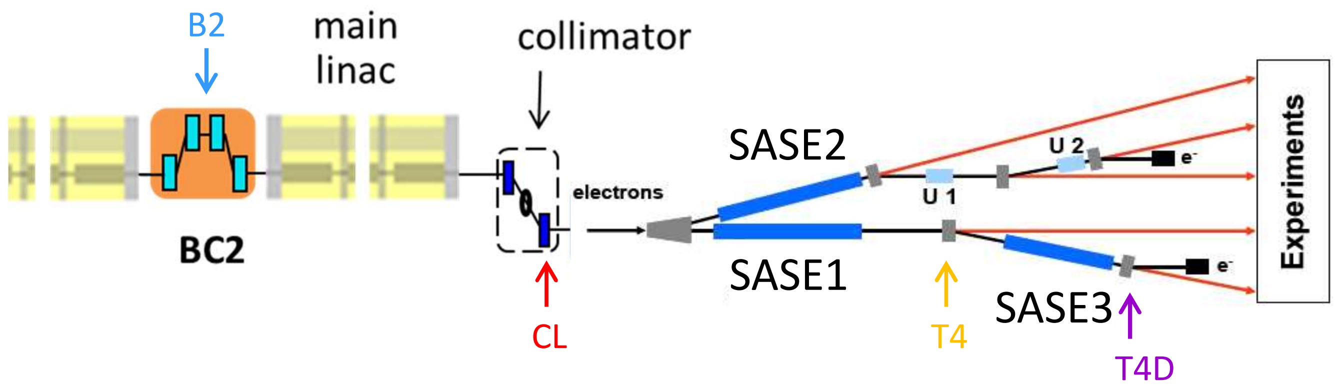
$$\frac{\Delta\omega}{\omega} \approx 0.0053$$

A Measurement



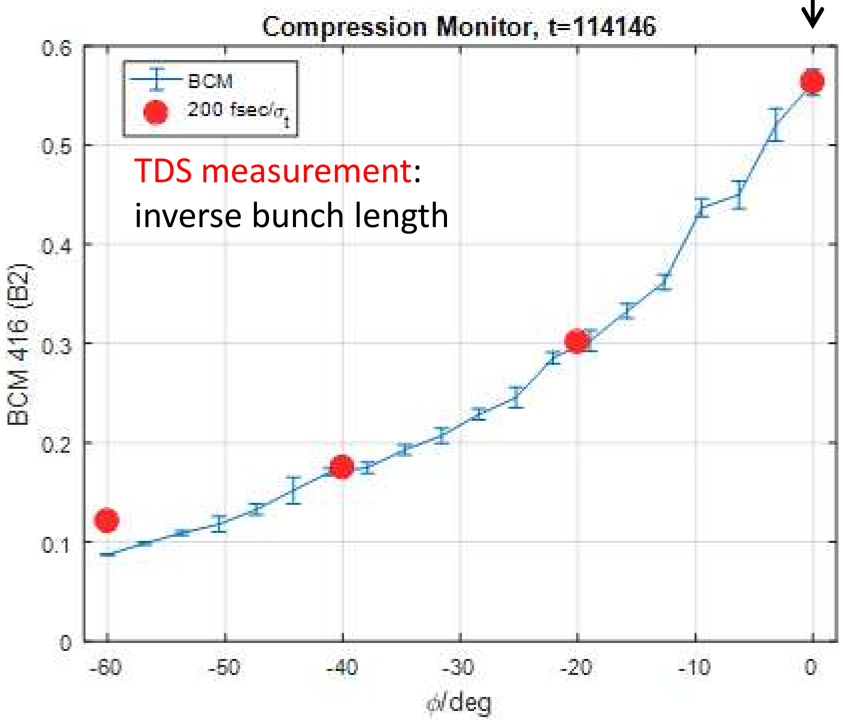
operation: 14 GeV, 250 pC, no SASE
change the compression (in BC2) by varying phase and amplitude of L2
$\longrightarrow$ variation of wakes due to different bunch length
measure energy loss (B2, CL, T4 and T4D) and keep BCM signal

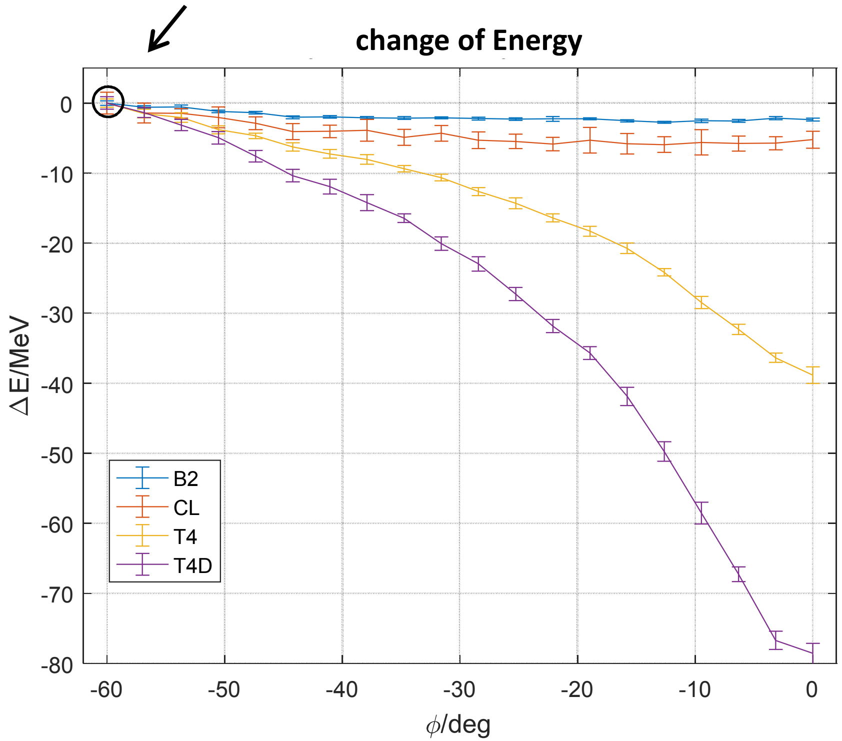
repeat measurement for few phase settings and measure rms bunch length with transverse deflecting structure

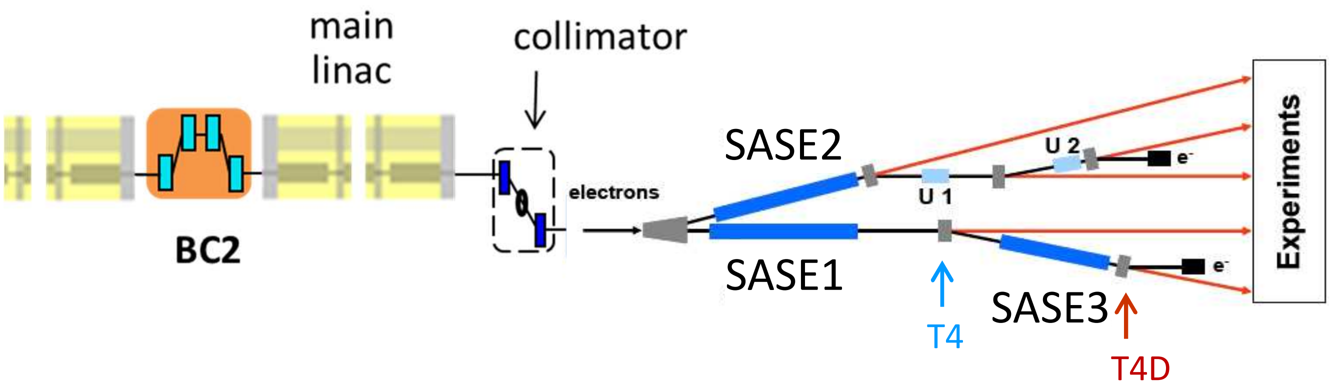


strong compression

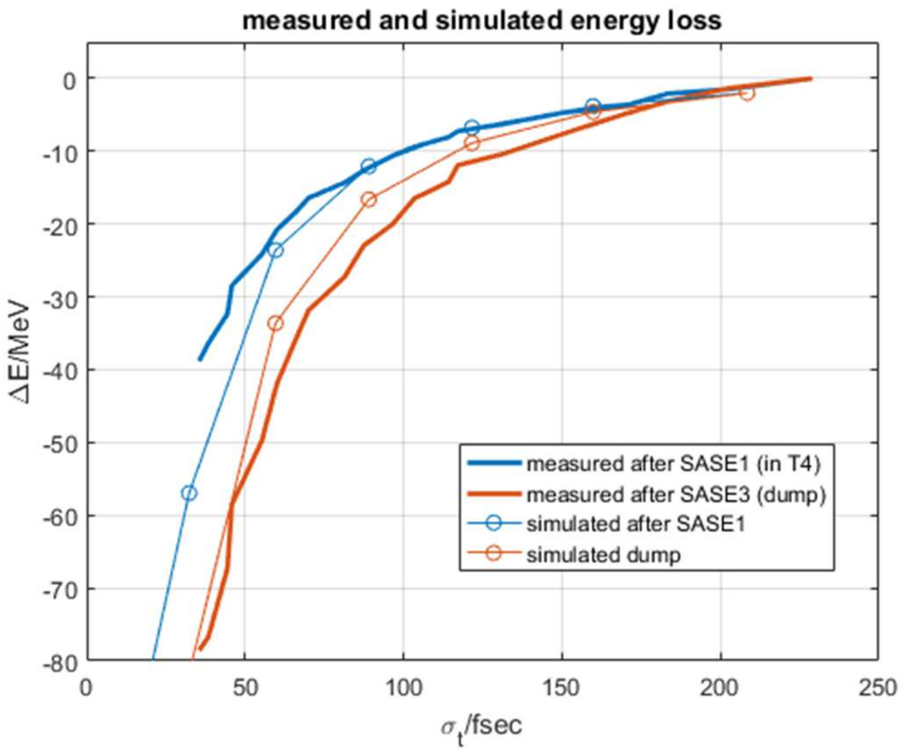
normalization







comparison with simulated compression (vs rms bunch length)



Summary/Conclusion

European XFEL

impedance data base with about 2000 components

before SASE1: major sources of wakes are cavities, collimators, warm pipes (L3 to undulator) and fast kickers

SASE1 and 3: optimized geometry (cross section, flanges, pumps, diagnostics, …) consider surface effects (material, roughness, oxide layers)

FELs and Wakes

wake before undulator causes broadening of SASE spectrum

mitigation: energy losses in undulator can be compensated by tapering
compensation of energy variation before undulator (wake versus chirp)

wake before SASE1 is small

SASE1 wake causes energy variation before SASE3

Measurement

measurements of energy losses (due to variation of bunch length) are in reasonable agreement with simulation based on impedance data base