XFEL impedance budget, energy losses/spread and released technical solutions to minimize the effects

European XFEL

FEL basics

before the undulator

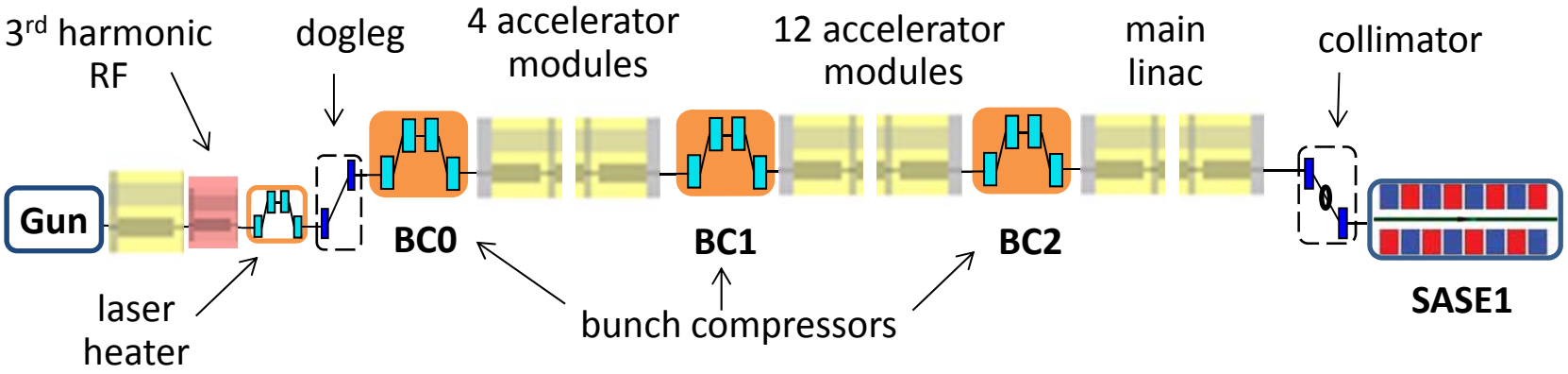
- bunch compression
- impedance budged

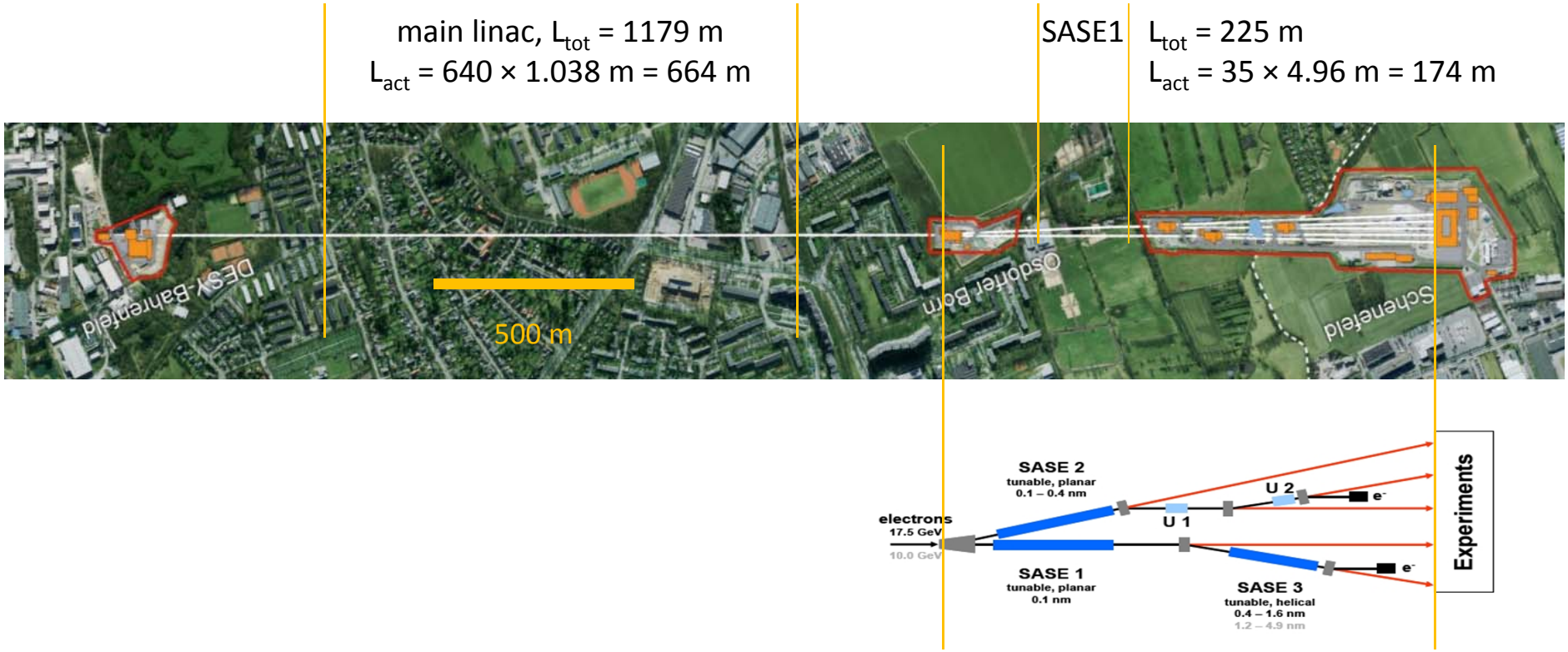
in the undulator

- energy loss
- undulator chamber, intersection
- impedance budged
- geometric effects
- surface effects

summary

European XFEL





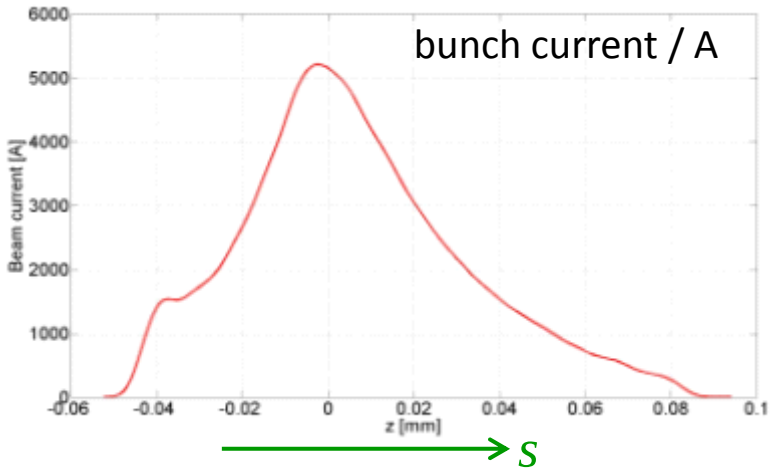
Fundamental FEL Equation

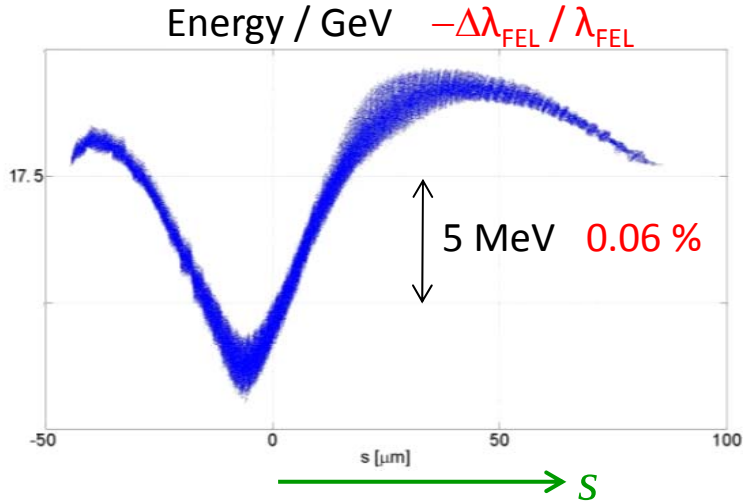
FEL resonance $$\lambda_{\mathrm{FEL}} = \frac{\lambda_{\mathrm{u}}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

but $\gamma = \gamma(s,S)$ with s = bunch coordinate

S = beamline coordinate

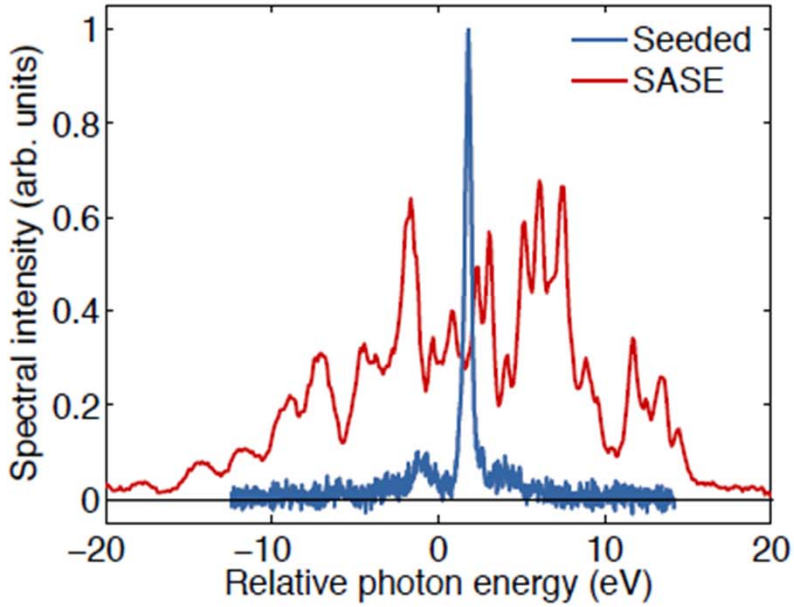
f.i. $S \approx 2200$ m (**start** of SASE1)



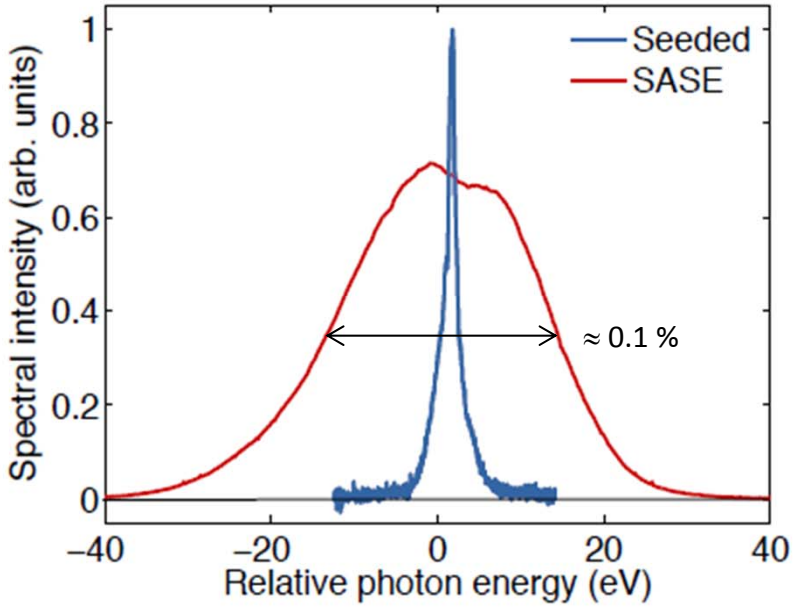


SASE and Seeding

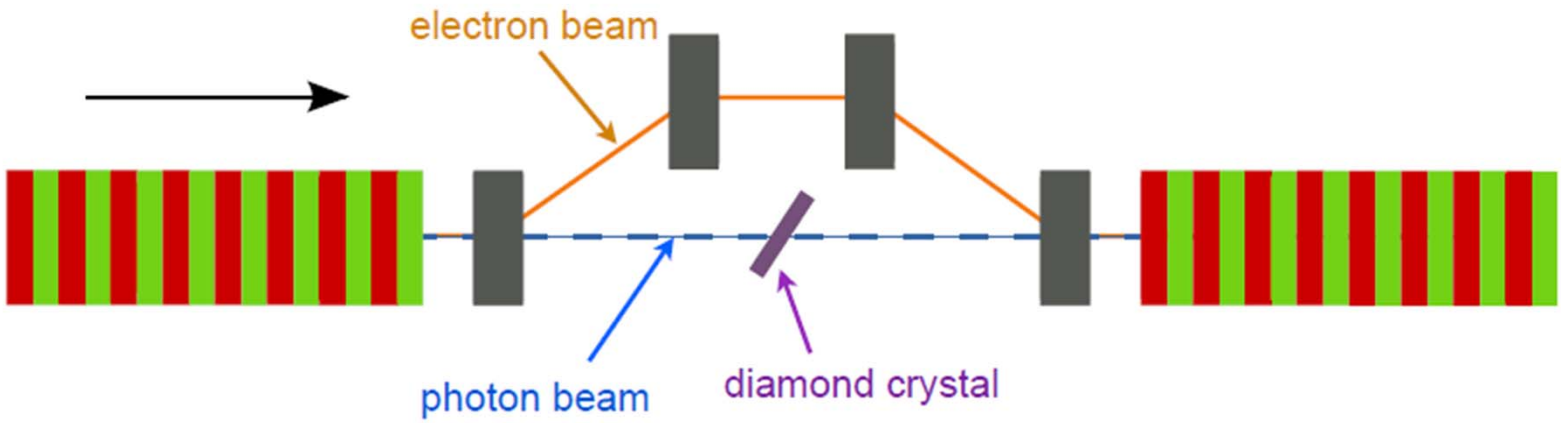
single shot



averaged

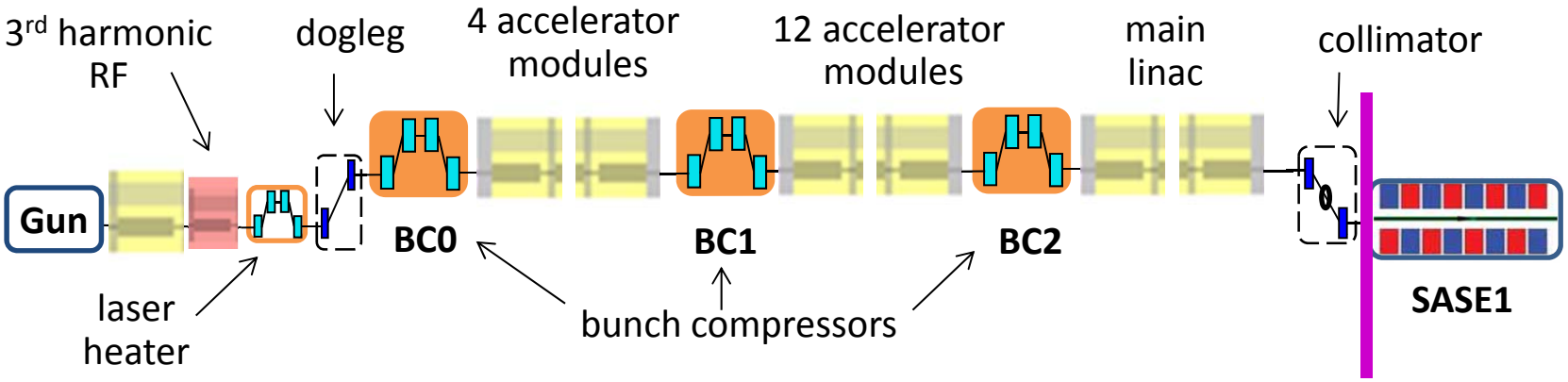


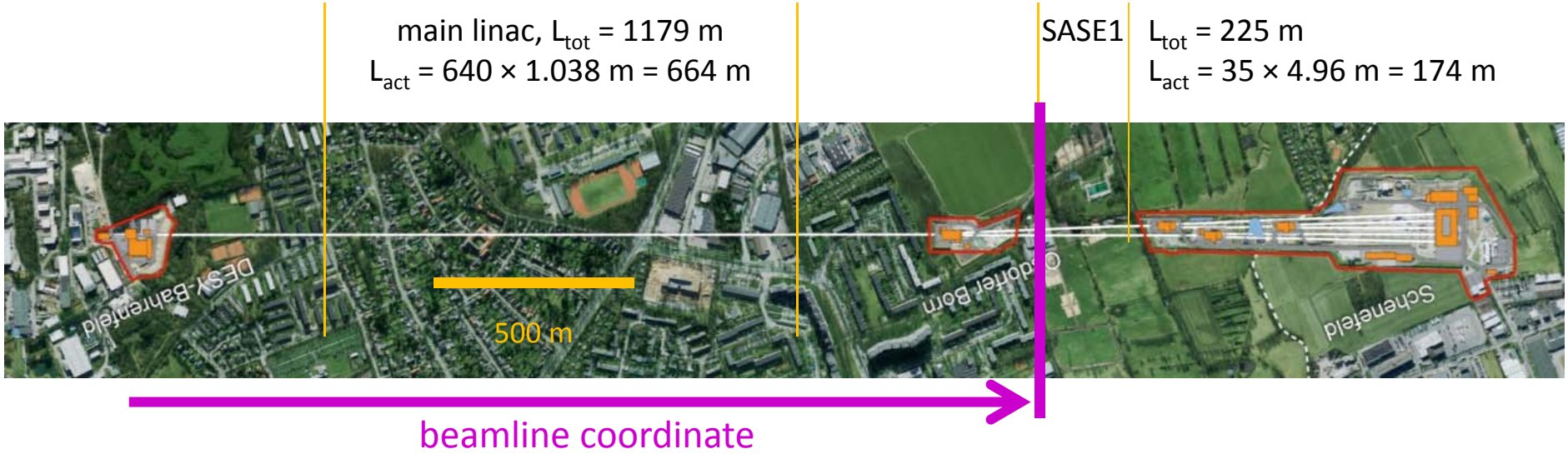
self seeding scheme:



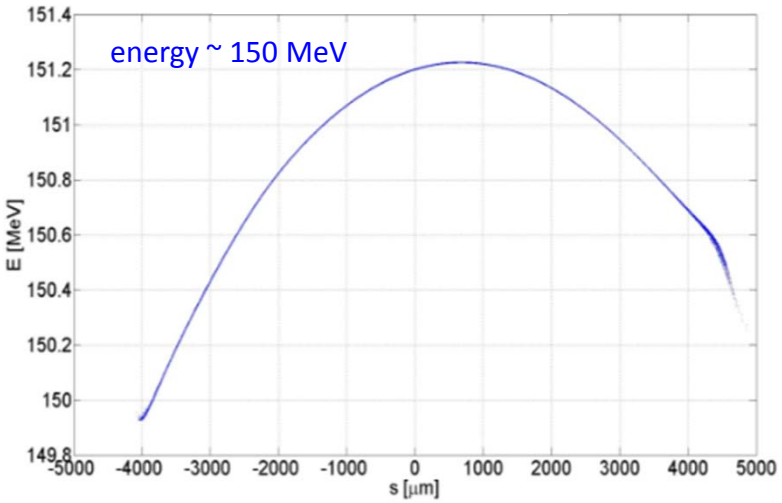
Before the Undulator

accelerator and bunch compression system



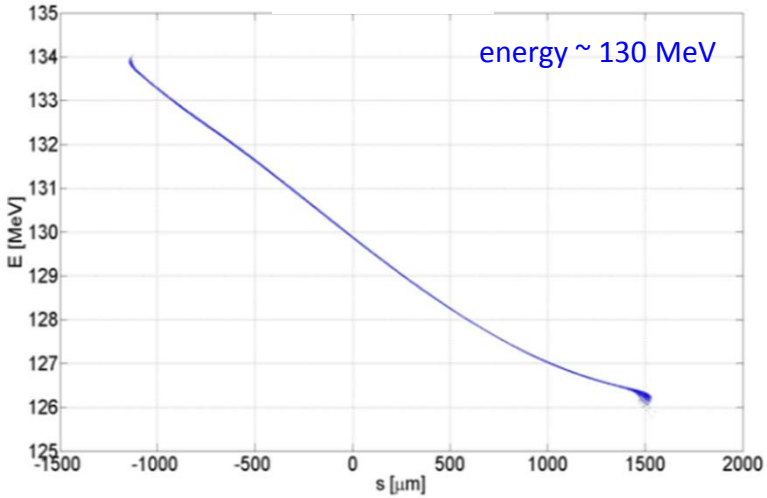


after 1st module



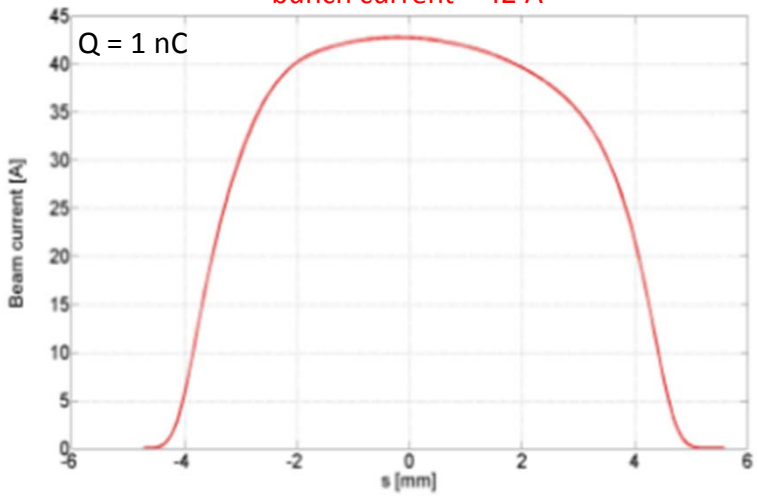
bunch coordinate → s

after BC0



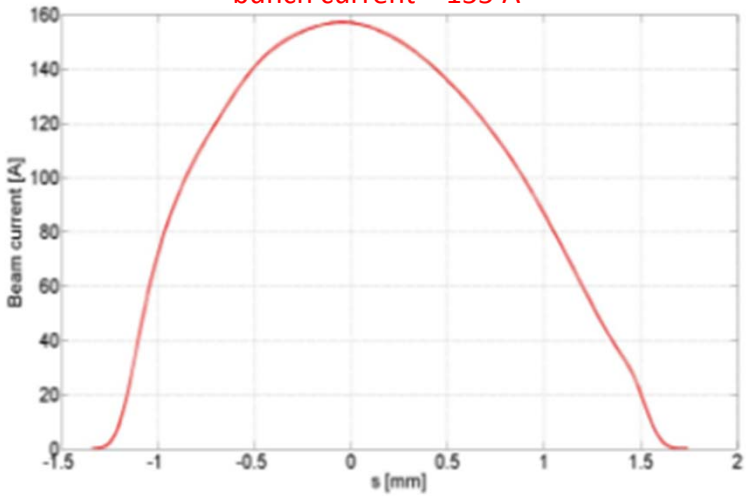
→ s

bunch current ~ 42 A

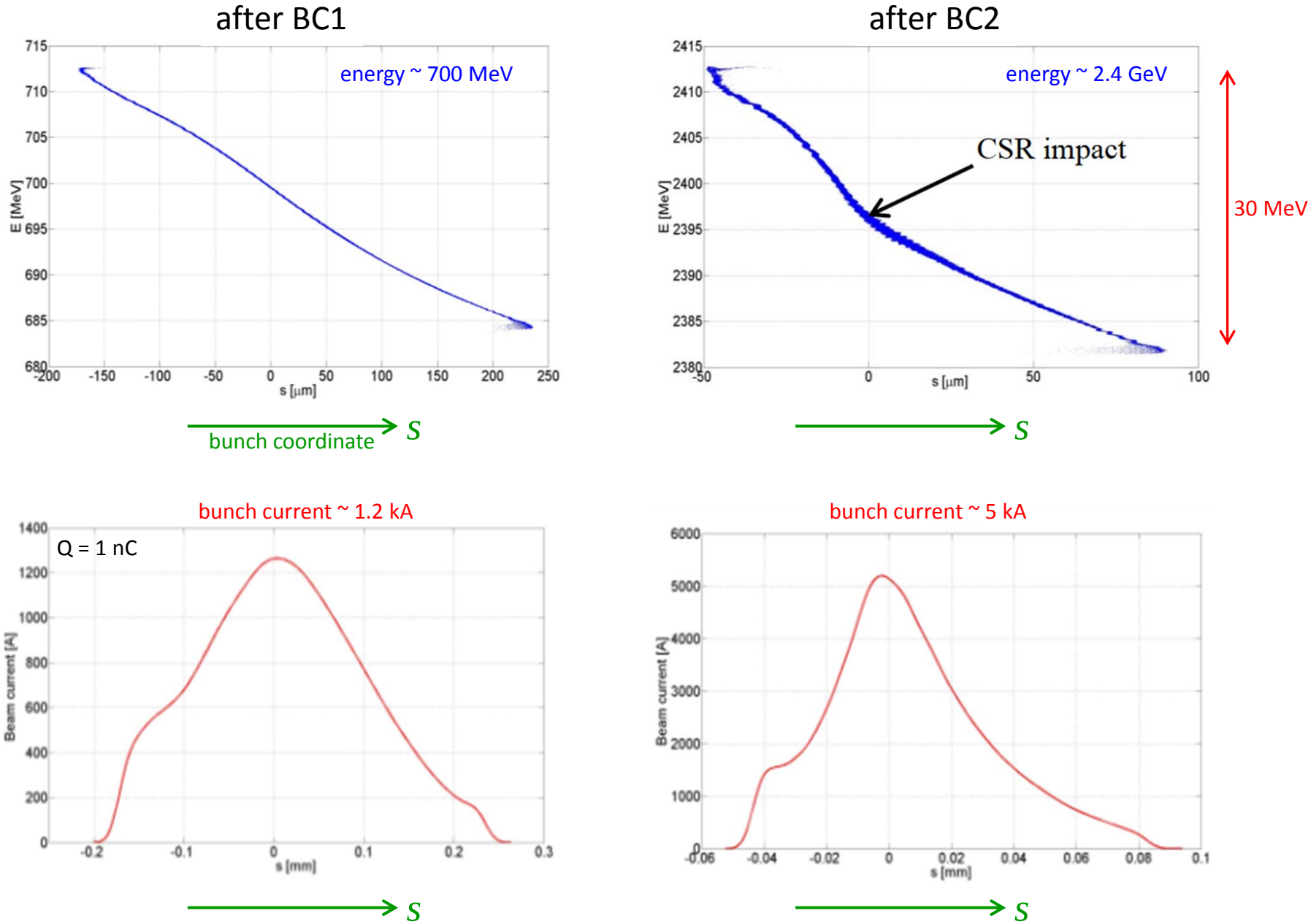


→ s

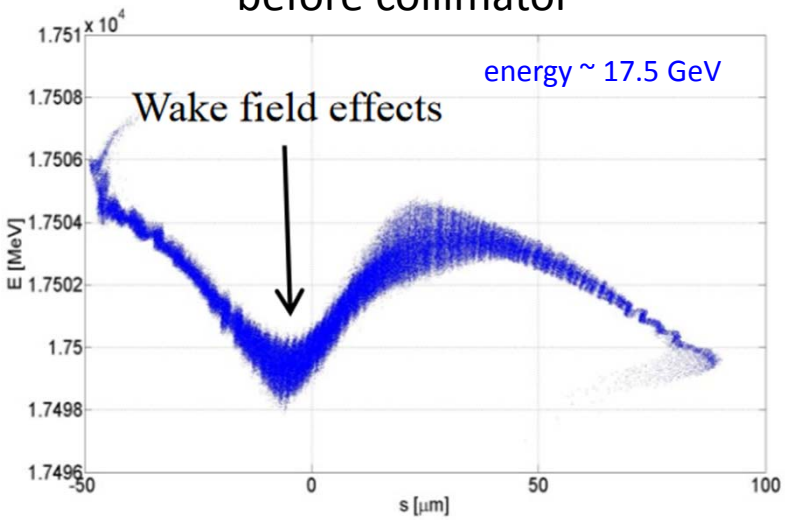
bunch current ~ 155 A



→ s

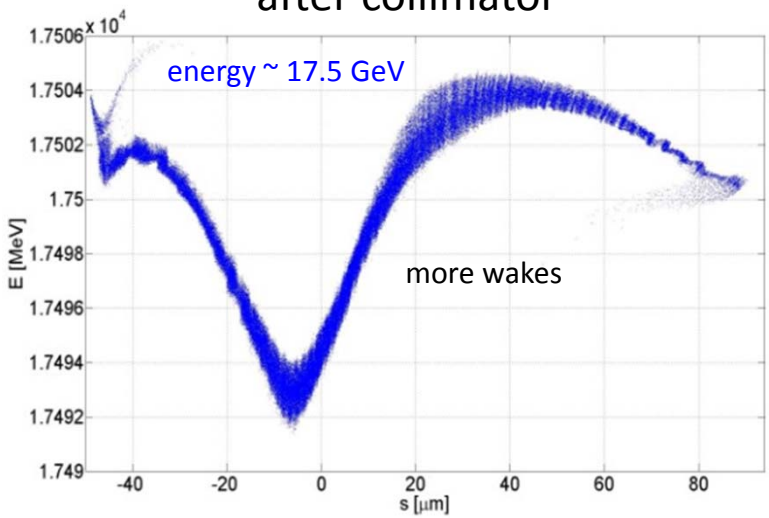

after BC1
energy ~ 700 MeV
E [MeV]
s [μm]
bunch coordinate
s
after BC2
energy ~ 2.4 GeV
CSR impact
30 MeV
E [MeV]
s [μm]
s
bunch current ~ 1.2 kA
Q = 1 nC
Beam current [A]
s [mm]
s
bunch current ~ 5 kA
Beam current [A]
s [mm]
s

before collimator



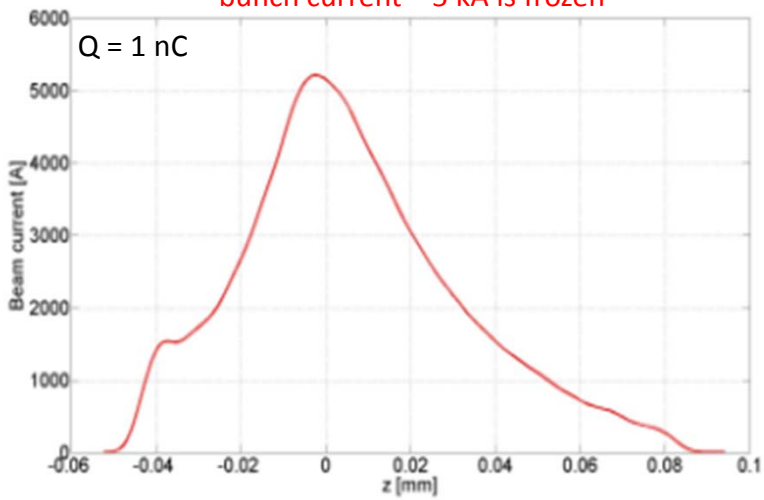
bunch coordinate → s

after collimator



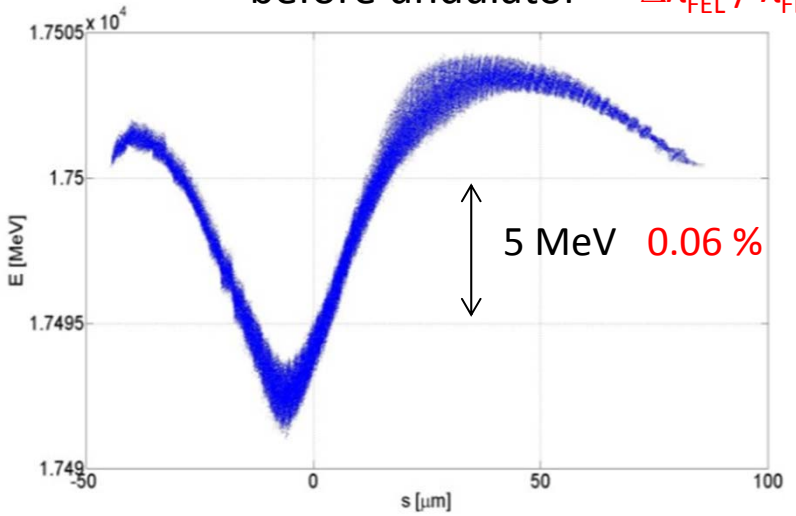
→ s

bunch current ~ 5 kA is frozen



→ s

before undulator $-\Delta\lambda_{FEL} / \lambda_{FEL}$



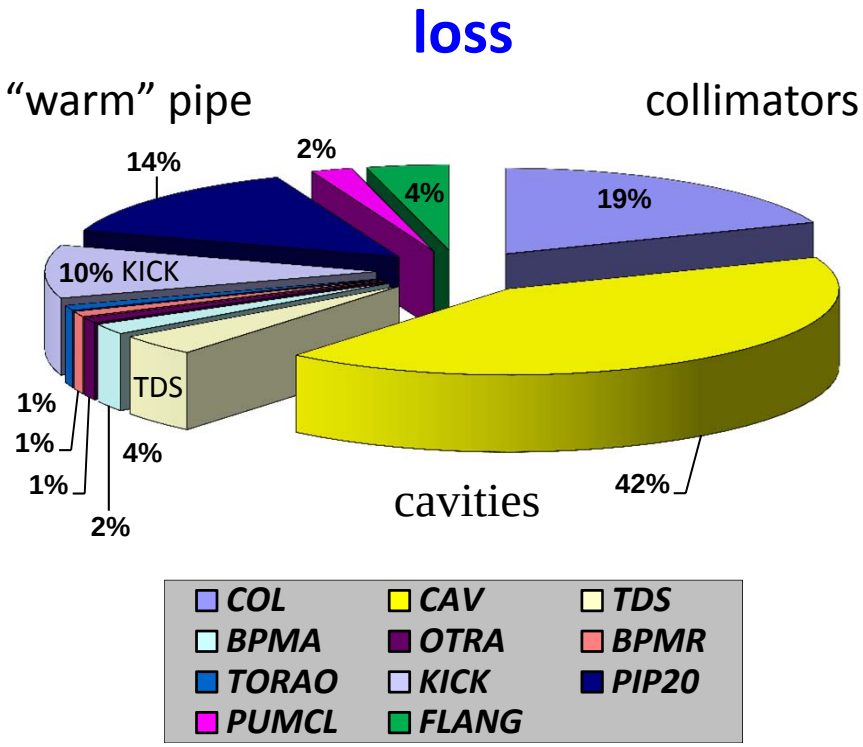
→ s

Before the Undulator: Impedance Budged

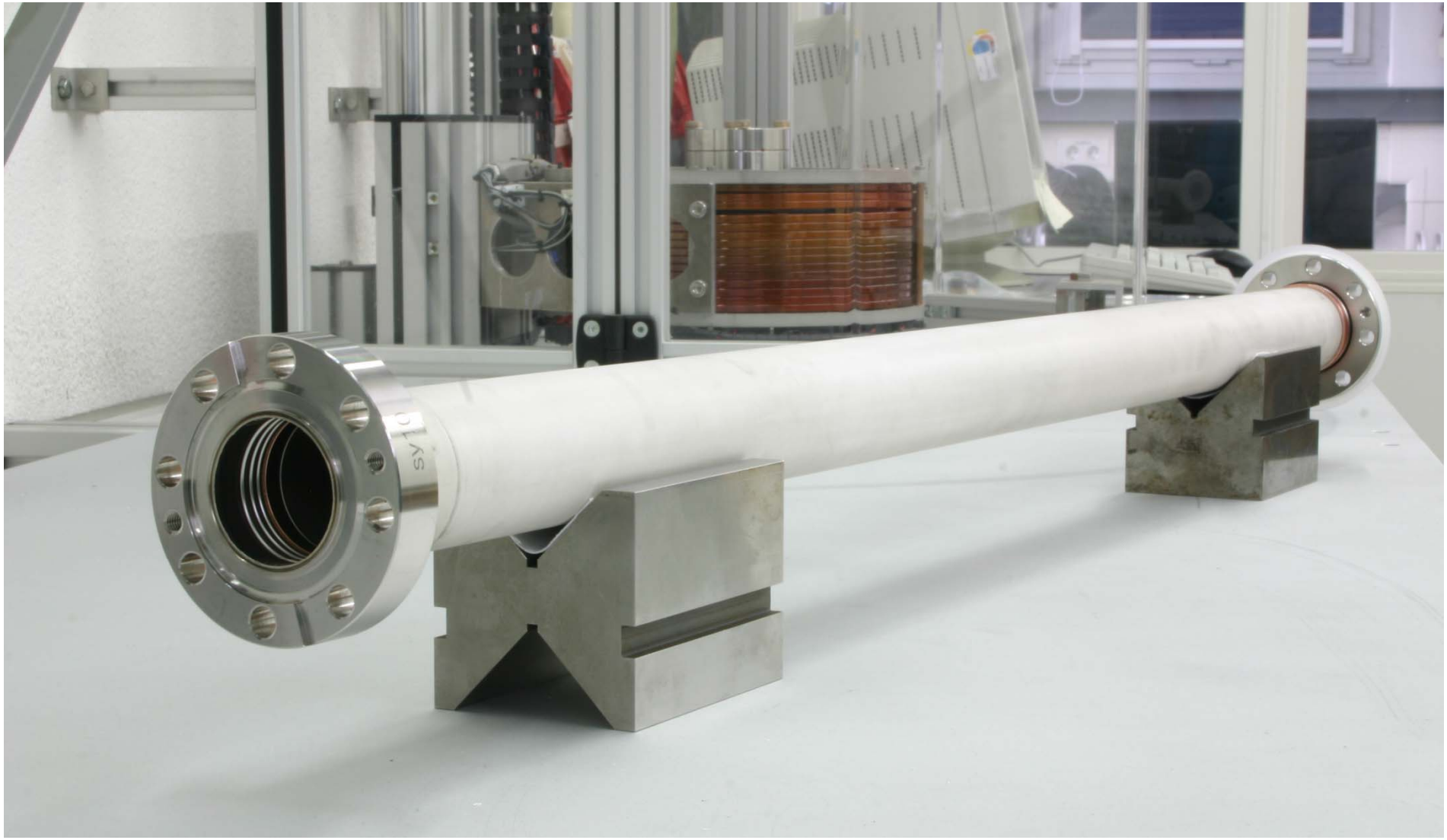
accelerator wakes for Q = 1nC

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



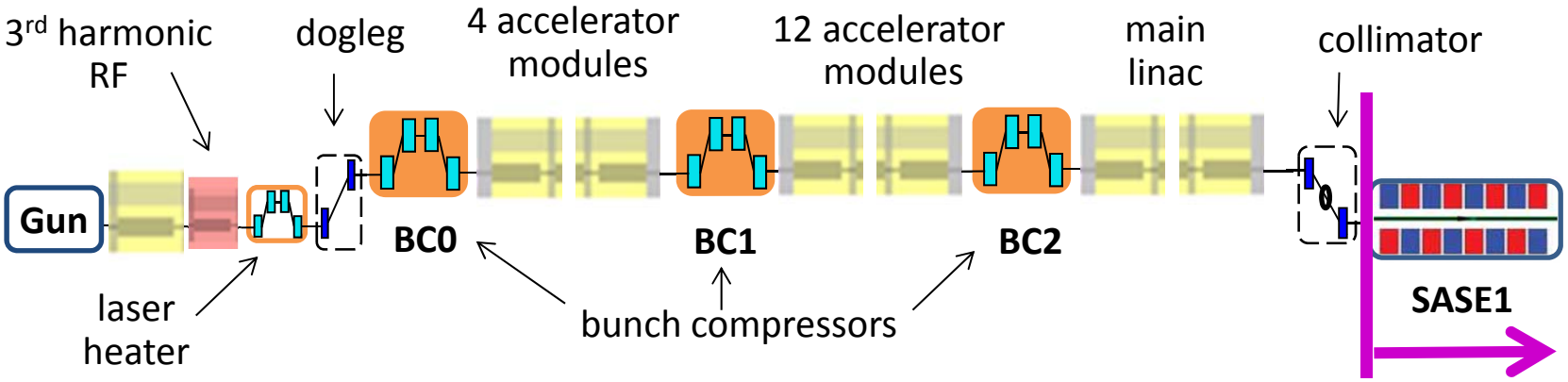
fast kicker (in beam distribution system)

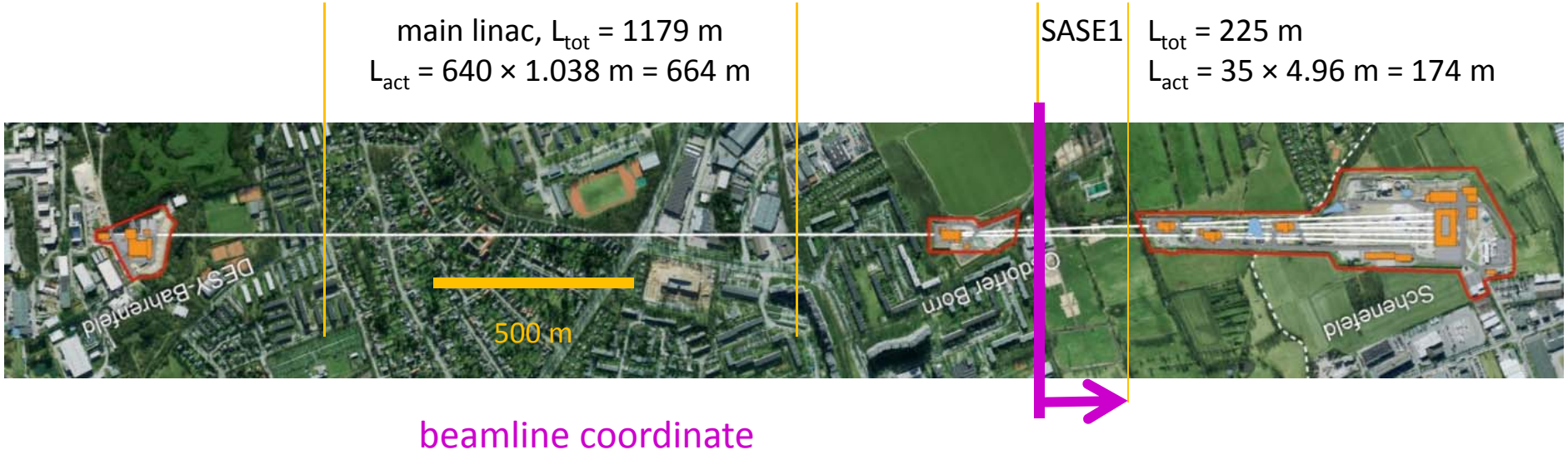


ceramic pipe with thin metallic layer

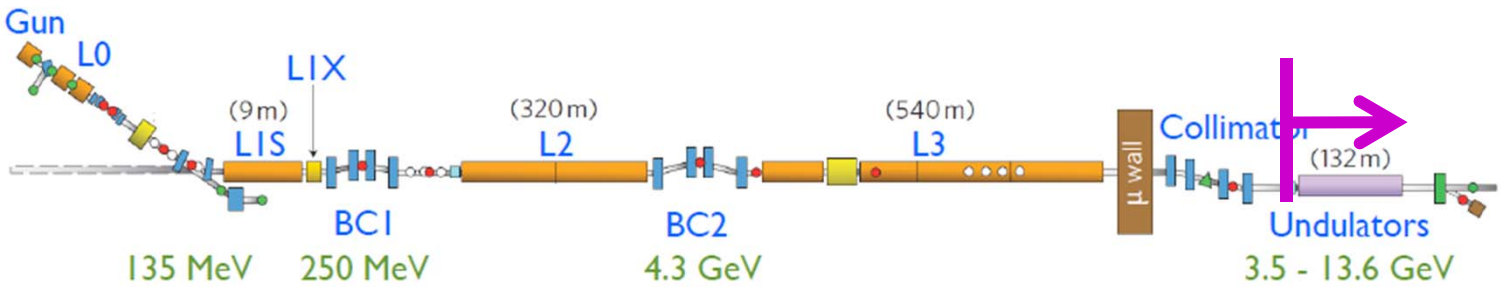
In the Undulator

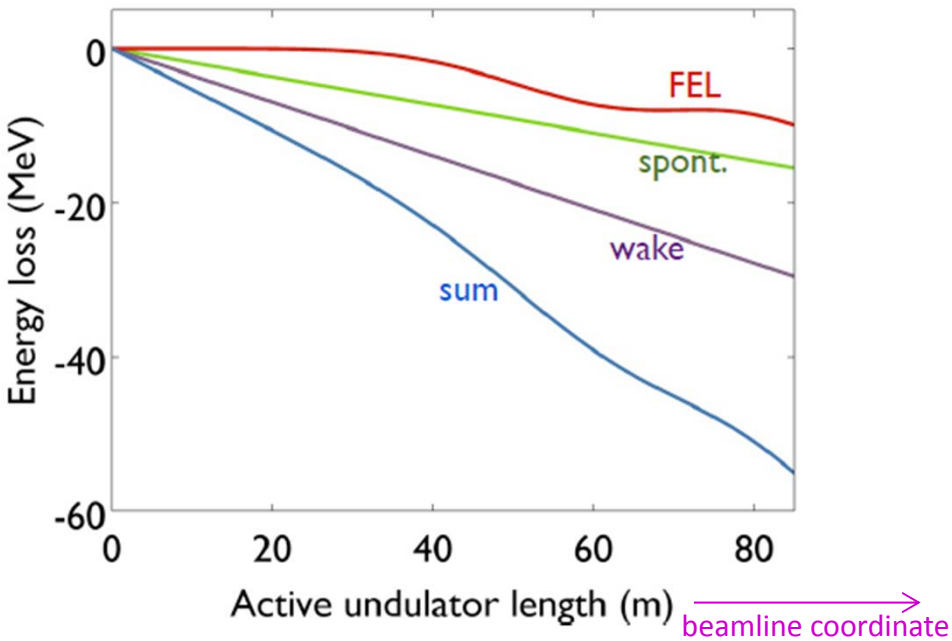
SASE1

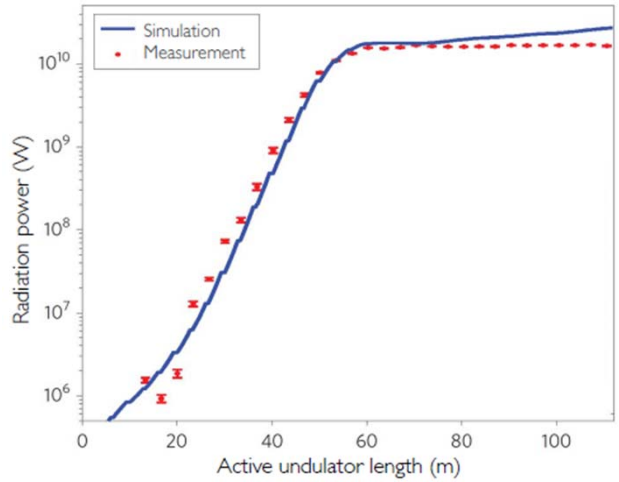




example: LCLS





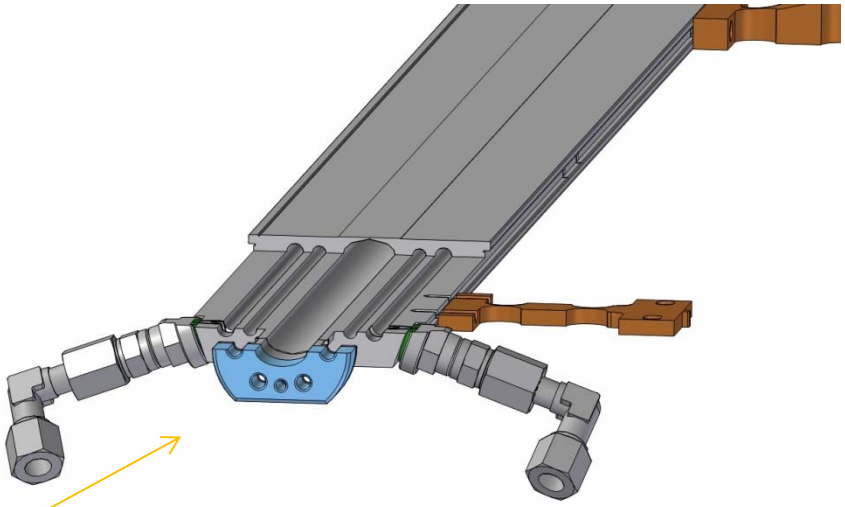


taper undulator parameter
to compensate energy loss

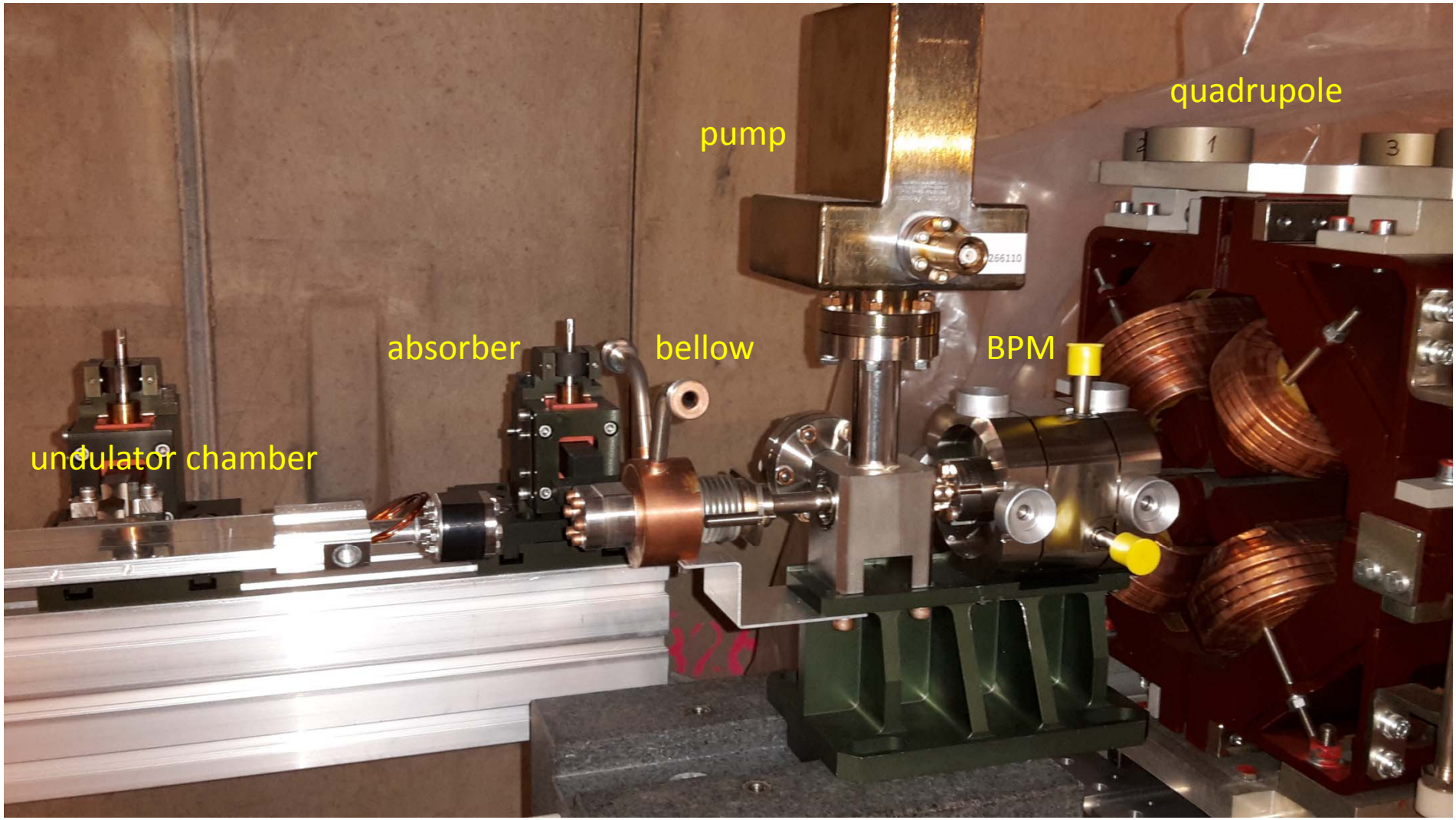
$$\lambda_{\mathrm{FEL}} = \frac{\lambda_{\mathrm{u}}}{2\gamma(s,S)^2}\left(1+\frac{K(S)^2}{2}\right)$$

Undulator chamber

SASE1:
L_{tot} = 225 m
L_{act} = 35 × 4.96 m = 174 m



Intersection

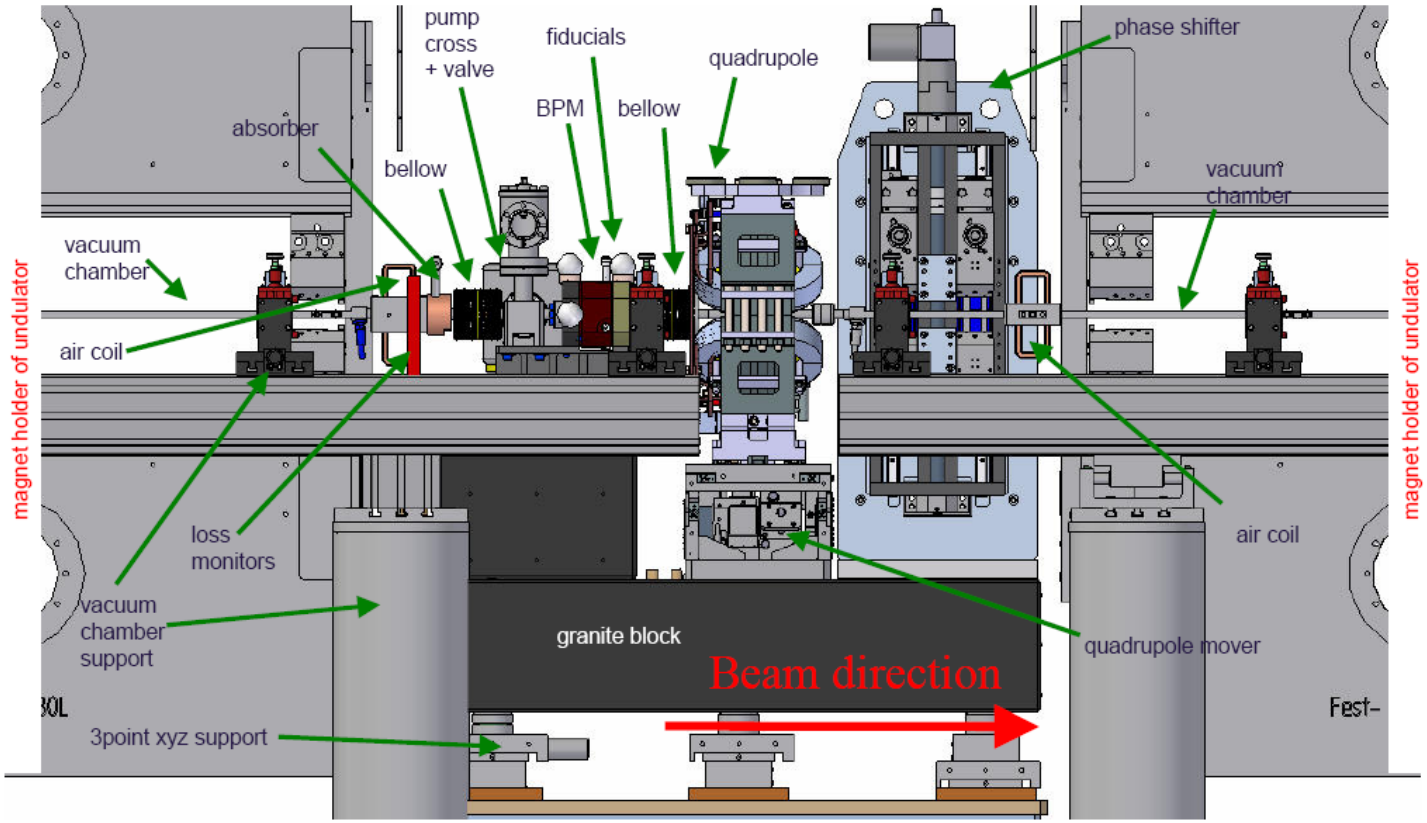


European XFEL, Undulator chamber & Intersection

SASE1:

L_{tot} = 225 m

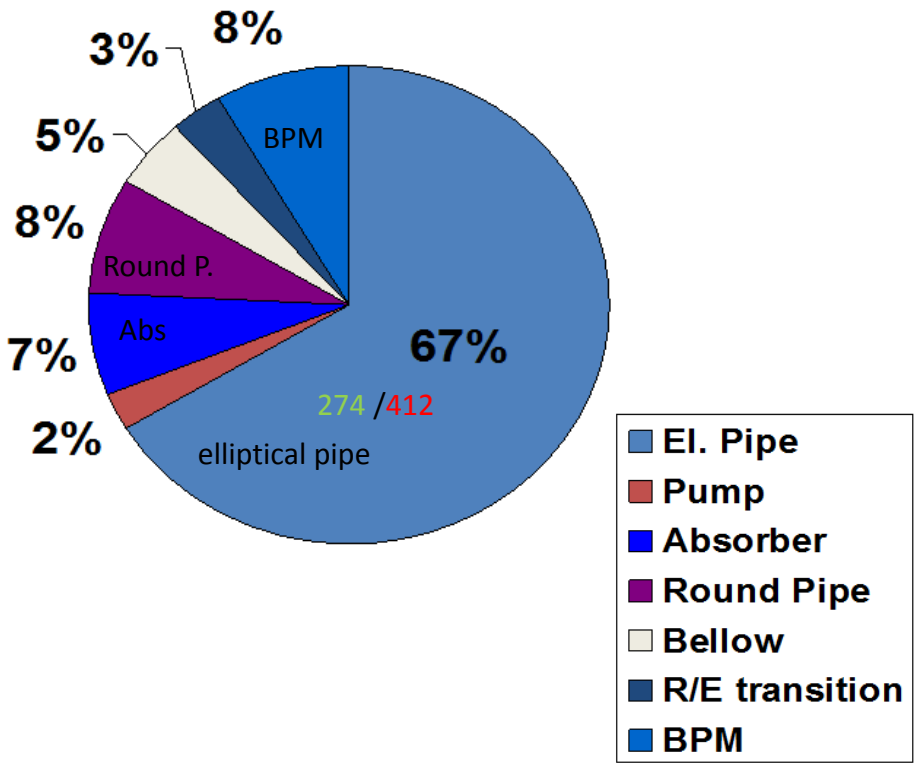
L_{act} = 35 × 4.96 m = 174 m

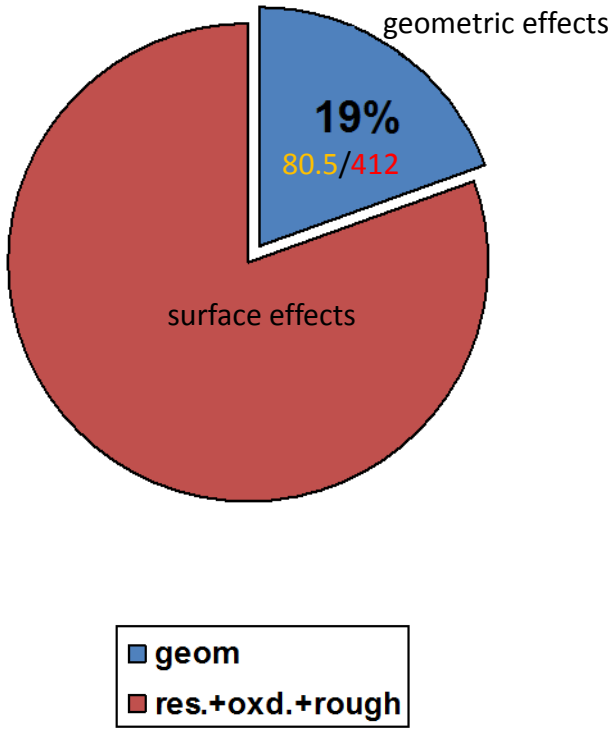


SASE1 undulator (one of 35 sections) for Q = 1nC, I_{peak} = 5 kA

total energy spread (per section) ≈ 412 keV
elliptical pipe → 274 keV (pure surface effects)
surface effects → 331 keV
geometric effects → 80.5 keV

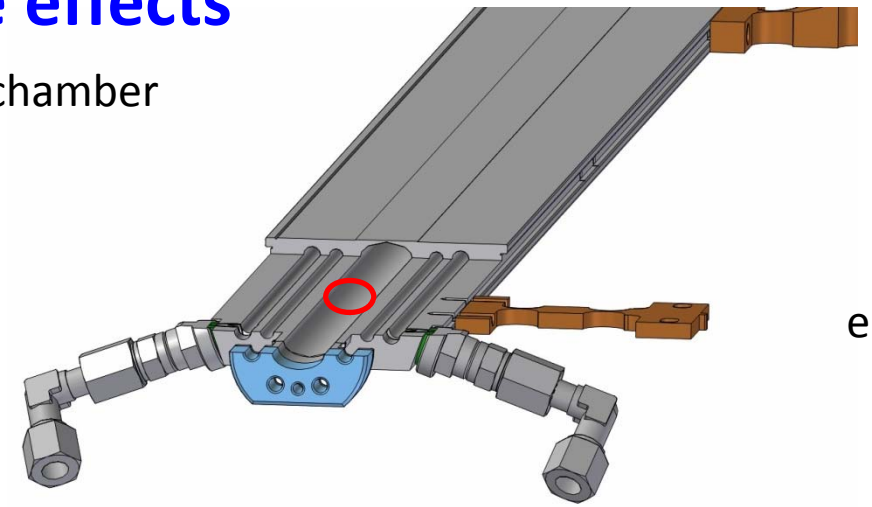
energy spread



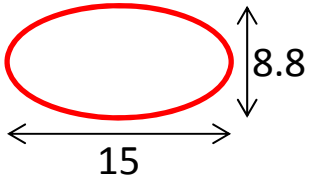


surface effects

undulator chamber



elliptical pipe

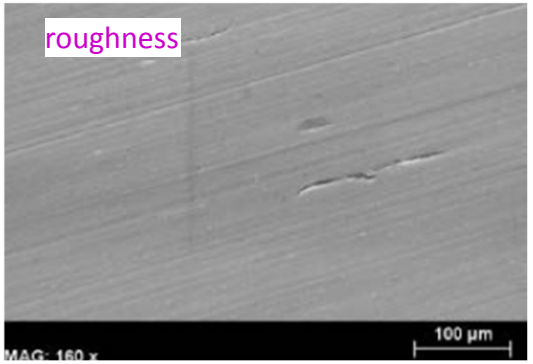


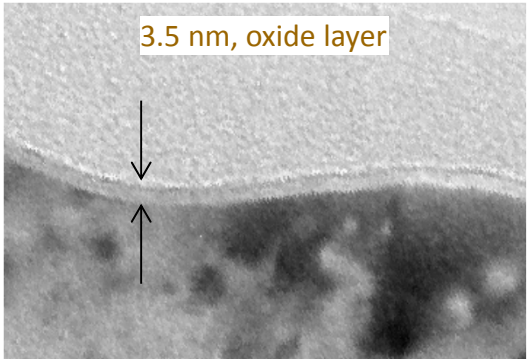
- shape: large cross-section (mirror currents & pumping) + small gap (undulator)
  → elliptical pipe
- material: frequency dependent conductivity + anomalous skin effect
  → aluminum profile
- more surface effects: roughness + oxide layer
  → very tight tolerances 300 nm + 5 nm in undulators
  1000 nm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

≈ 75 %

≈ 25 %

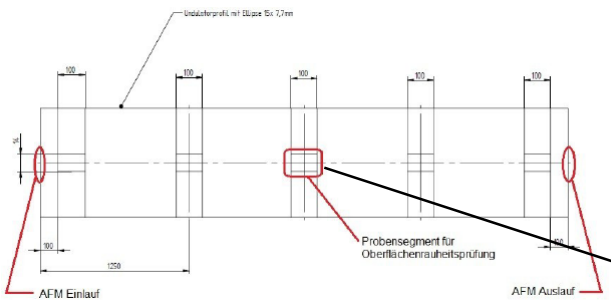
of surface impedance



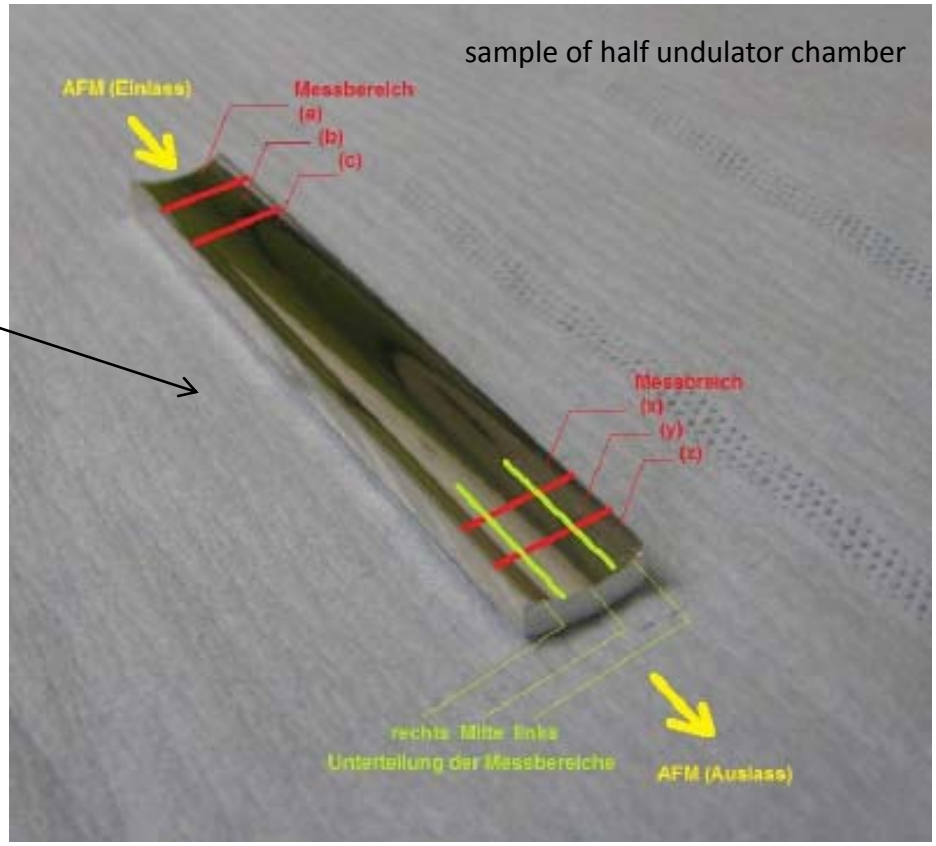


roughness

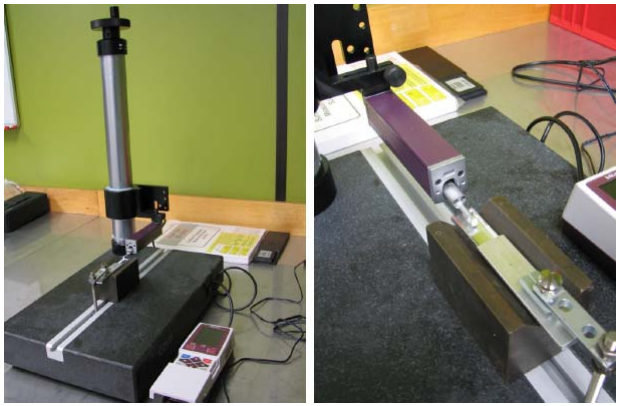
AFM treatment on a 5 m long test chamber
measurement preparation and equipment



sketch of sample preparation



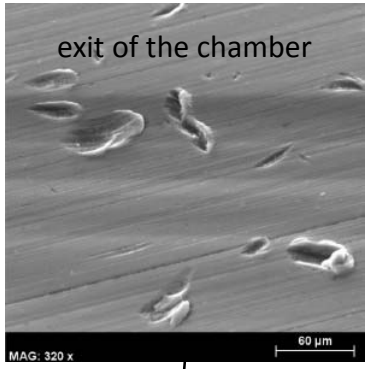
sample of half undulator chamber

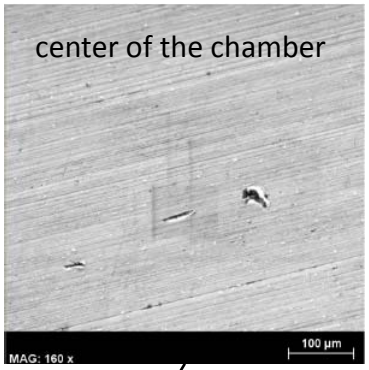


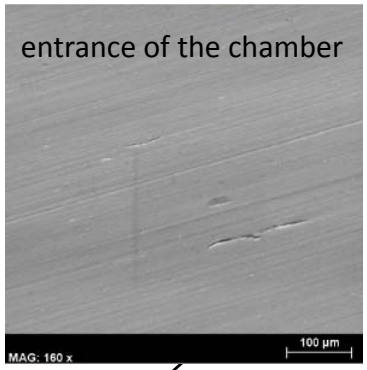
Mitutoyo (Surftest SJ-210)

result of the AFM treatment on a 5 m long test chamber polished with unidirectional flow

results show that it is essential to polish in both directions







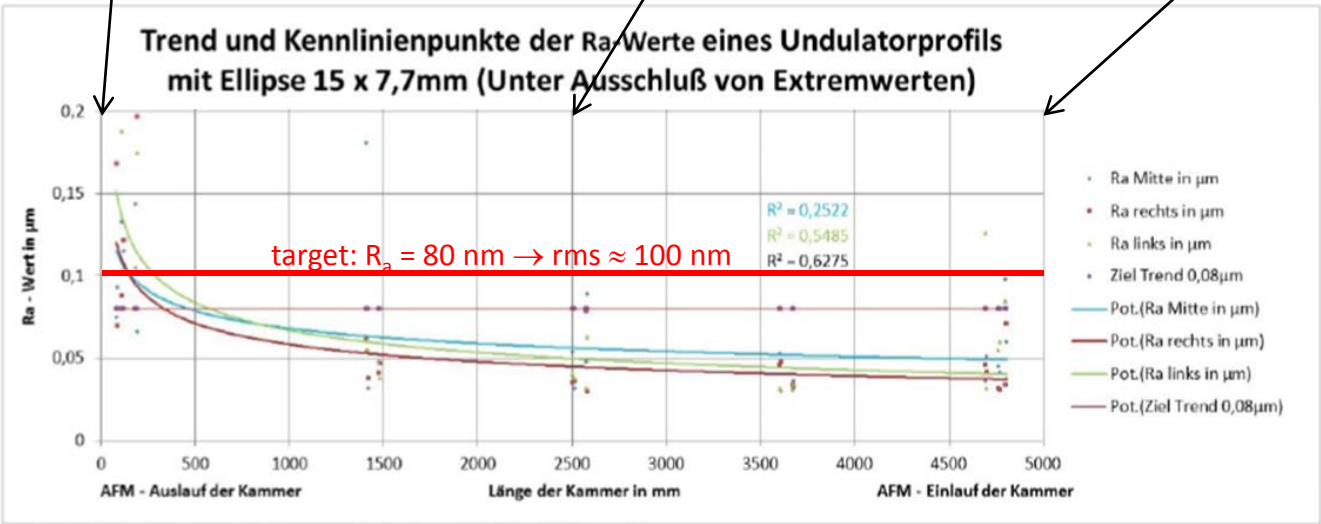
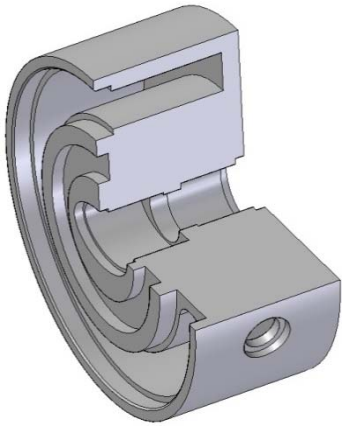


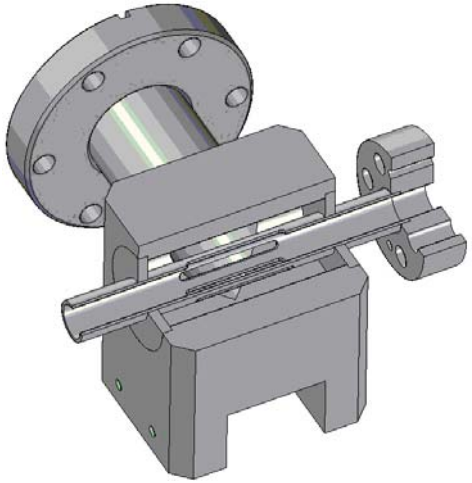
Bild 8: Trend und Kennlinien der Ra-Werte unter Ausschluß von Extremwerten

geometric effects

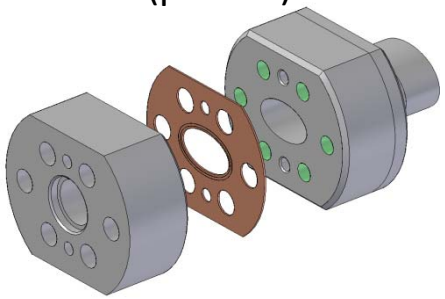
absorber

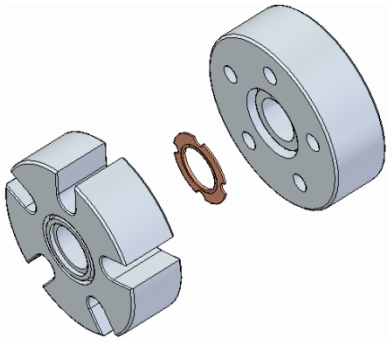


pump

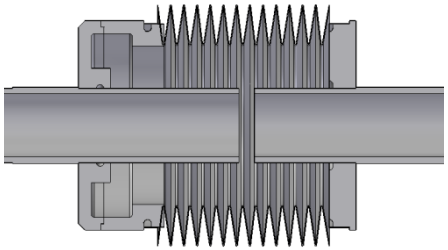


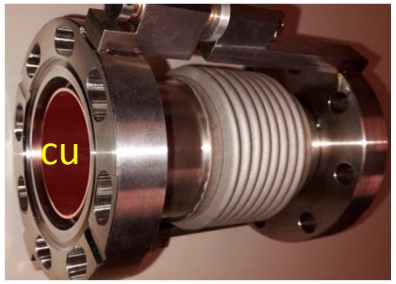
flange connections (pinned)



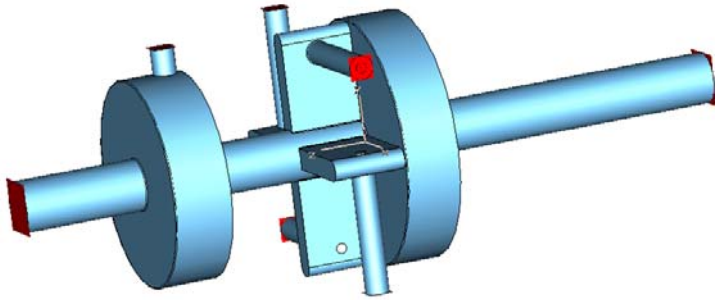


bellows (pipe with gaps)



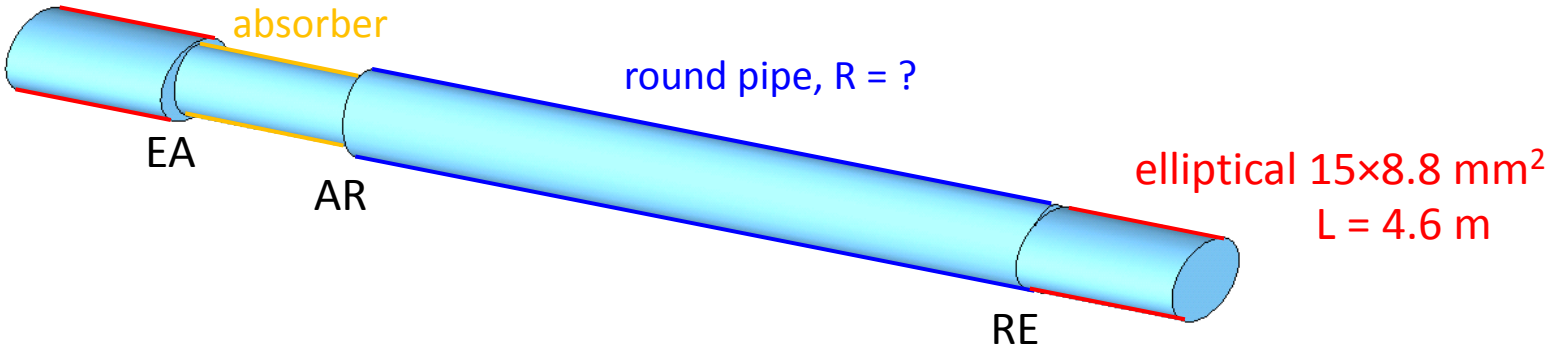


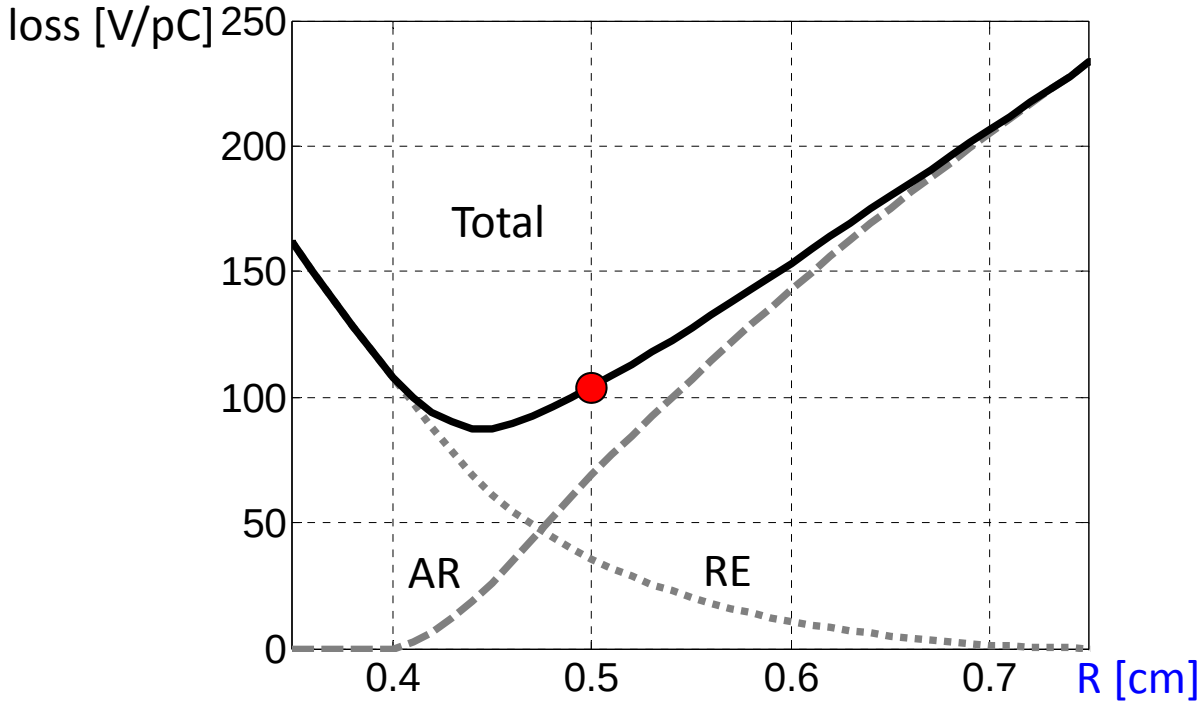
beam position monitor



a good survey and alignment concept is essential due to the small aperture of the beam pipe!

optimize geometric effects





Summary

challenging beam dynamics before and in the undulator

high peak current
low transverse emittance
low correlated energy spread

before the undulator: about 2000 components, ●, major sources are

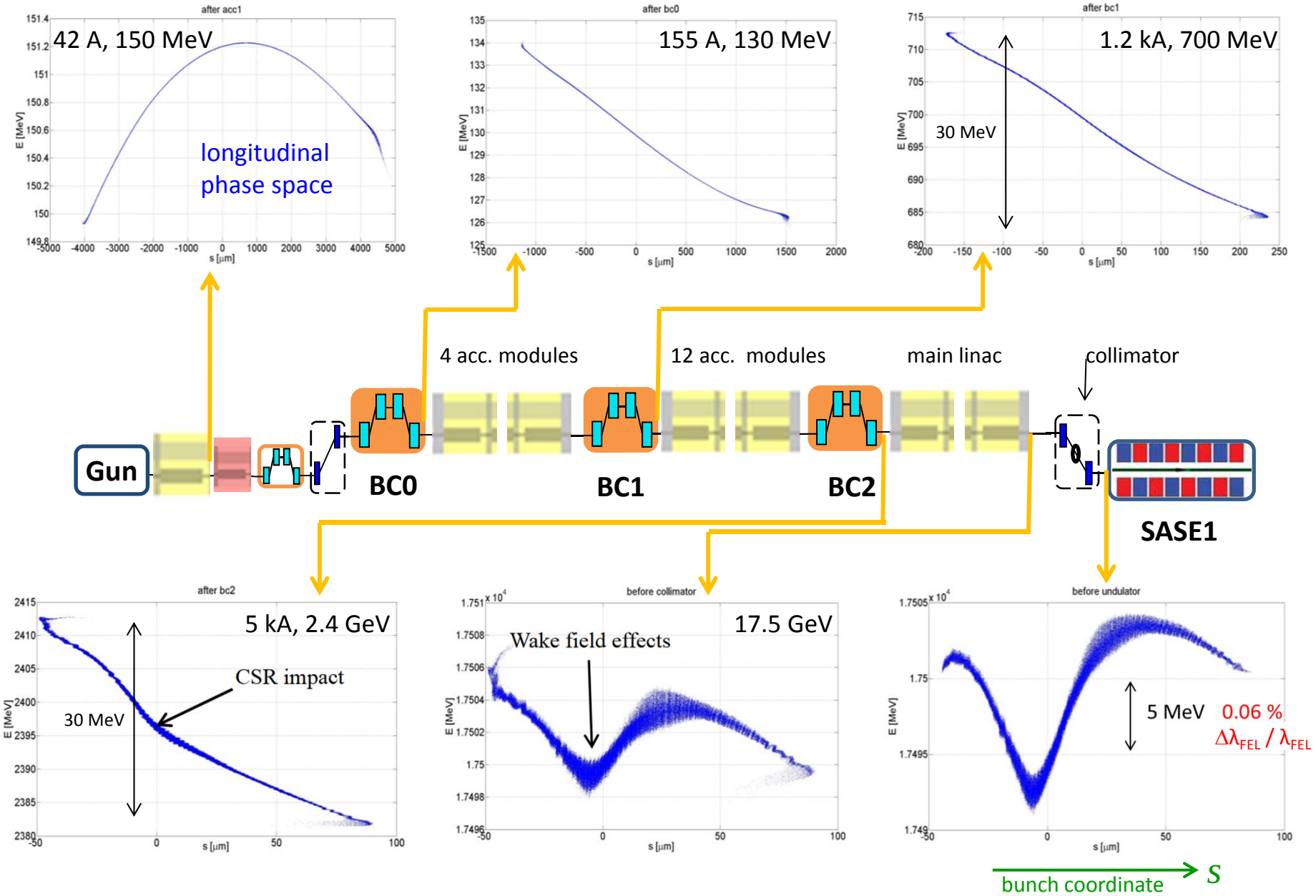
cavities
collimators
warm pipes (L3 to undulator)
fast kickers (beam distribution system)

undulator and intersections: geometric wakes → optimized geometry, ●
surface effects → material, roughness, oxide layers

● **carful design of all geometric details**: flanges, pumps, steps, diagnostics, …

my special thank to Igor Zagorodnov
Guangjao Feng
Sven Lederer
Torsten Wohlenberg for their support and material

Bunch Compression



Before the Undulator: Impedance Budged

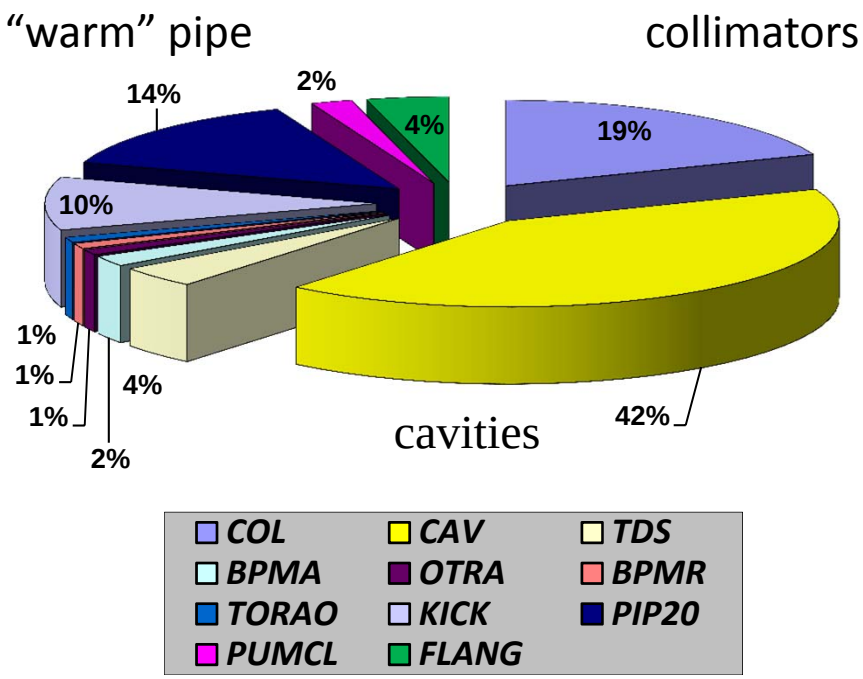
accelerator wakes for Q = 1nC

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

→ 15.4 MeV

loss

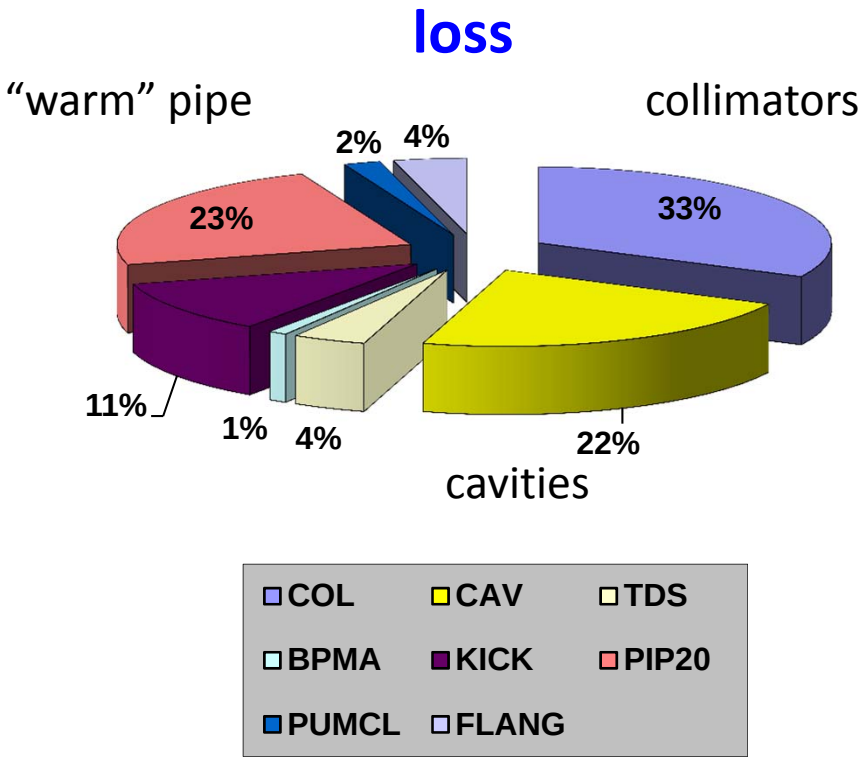


Before the Undulator: Impedance Budged

accelerator wakes for 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

→ 8.2 MeV



SASE1 undulator (one of 35 sections) for Q = 1nC, I_{peak} = 5 kA

N	element	geom loss	geom spread	loss	spread
		kV	kV	kV	kV
1	elliptical pipe	0	0	239	274
2	pump	4,4	4,5	9	10
3	absorber → round transition	69	27	70	28
4	round pipe	0	0	22	32
5	below	24	9	25	10
6	BPM	42	17	70	34
7	below	24	9	25	10
8	round → elliptical transition	36	14	36	14
		199,4	80,5	496	412

energy spread