Beam Dynamics at the European XFEL up to SASE4/5

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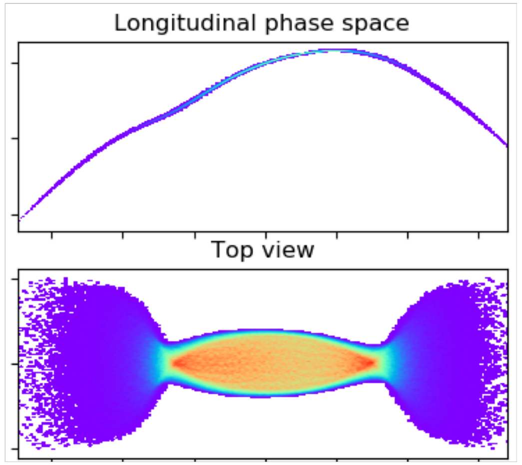
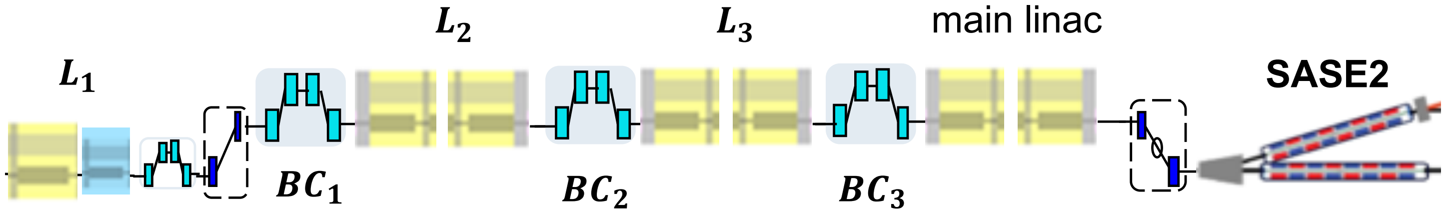
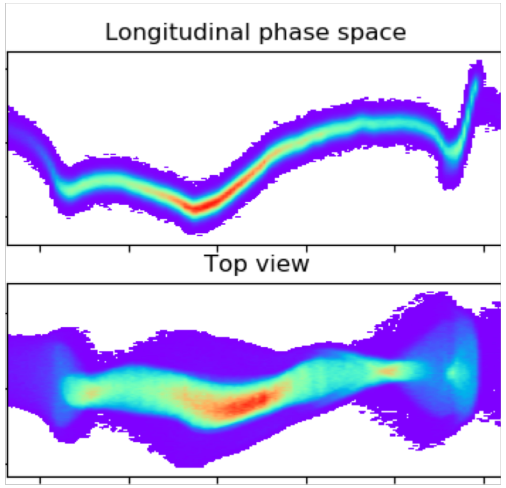
Workshop „Shaping the Future of the European XFEL:
Options for the SASE4/5 Tunnels“
Schenefeld
December 6, 2018





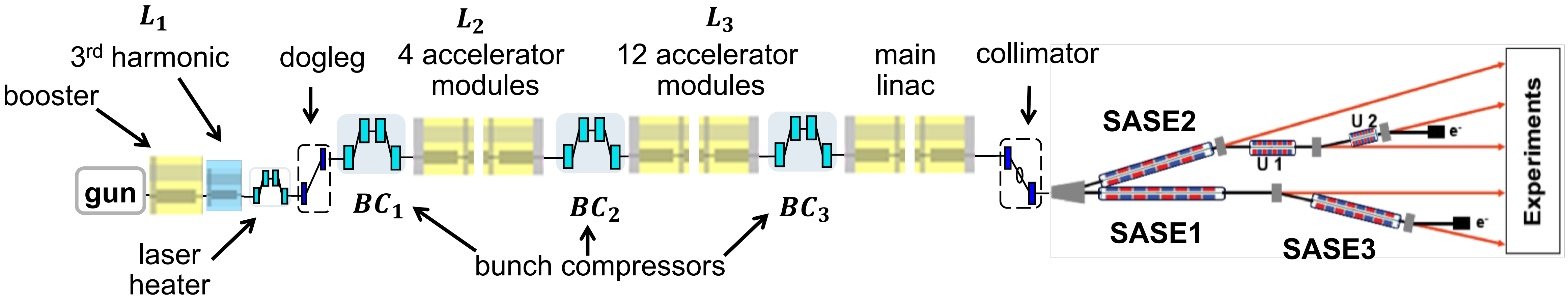


Outline

- Layout, optics, technical constraints
- Numerical approach
- RF tolerances, collective effects and the choice of the working point
- Beam dynamics for
  - 500 pC
  - 250 pC
  - 100 pC
- Accuracy of the results
- Summary

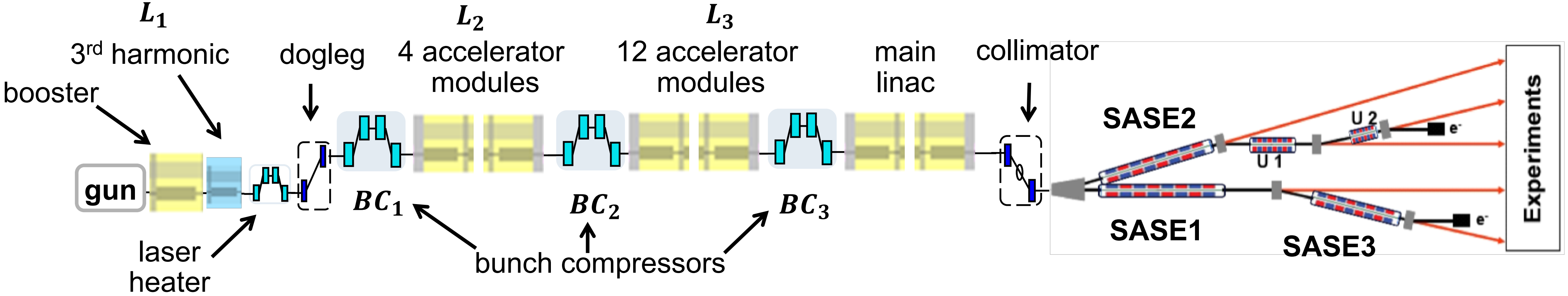
Layout, optics, technical constraints

17.5 GeV , I ~ kA’s



- the injector contains a **high harmonic module** to linearize the longitudinal phase space
- there are **three bunch compressors** to compress the bunch to several kA’s and to mitigate collective effects
- the **design optics** has a special phase advance between the bunch compressors to reduce effects due to coherent synchrotron radiation (CSR) kicks at them

Layout, optics, technical constraints



Section name	booster	3rd harmonic	L2	L3
Maximal voltage, MV	180	40	680	2470

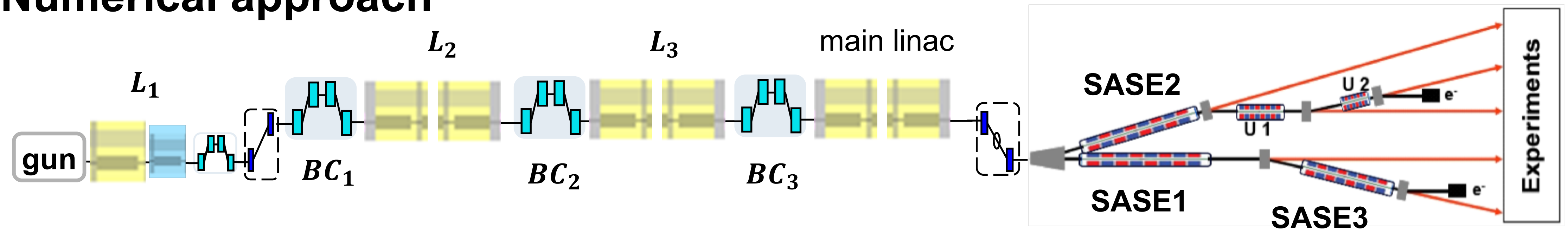
Section name	BC1	BC2	BC3
|r56|, mm	30-90	20-80	10-60

- high beam energy E
- high peak current I
- small emittance ε
- low energy spread σ_E

$$\lambda \sim \frac{1}{\gamma^2}$$

$$L_g \sim \frac{\varepsilon^{5/6}}{\sqrt{I}}\left(1+O(\sigma_E{}^2)\right)$$

Numerical approach



17.5 GeV , I ~ kA's

gun environment
photo cathode
cavity, solenoid,
drift …

straight
cavity,
quadrupole,
drift …

dispersive
bend,
quadrupole,
drift …

FEL
undulator,
quadrupole,
wakes …

cathode physics
self-fields ~ external fields
Poisson or Maxwell

external fields > self fields,
space charge (Poisson)
chamber wakes

CSR for non-straight parts

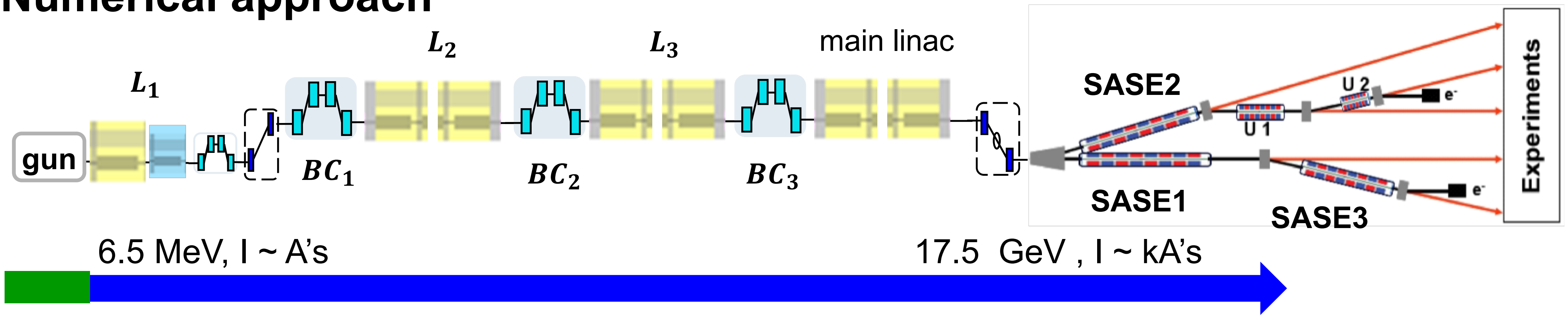
FEL effects
slippage & wave propagation
mono- or multi-frequent

Astra, **Krack3**, GPT, CST, Impact, Opal, Parmela, …

Ocelot, Xtrack, CSRtrack, Astra, GPT, Elegant, Impact, Opal, …

Genesis, Alice, Fast, Ginger, …

Numerical approach



Astra / Krack3

- cathode physics
- external fields by field maps
- self-fields with 2D/3D Poisson equation
- particle motion with finite-difference method
- cathode through mirror charge
- no chamber (no wakes)

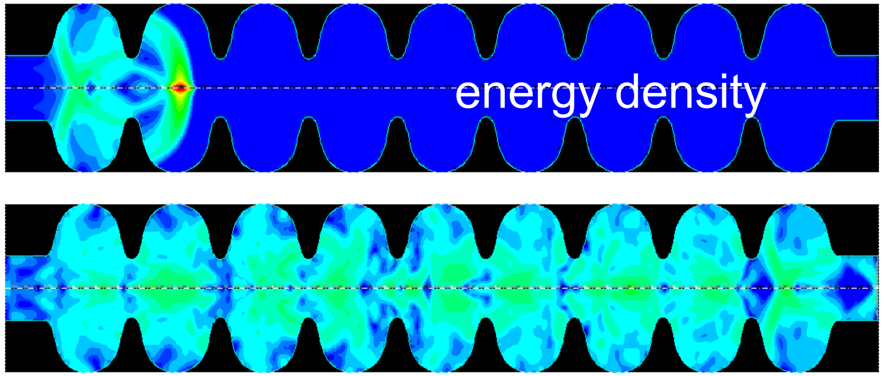
Ocelot / Xtrack

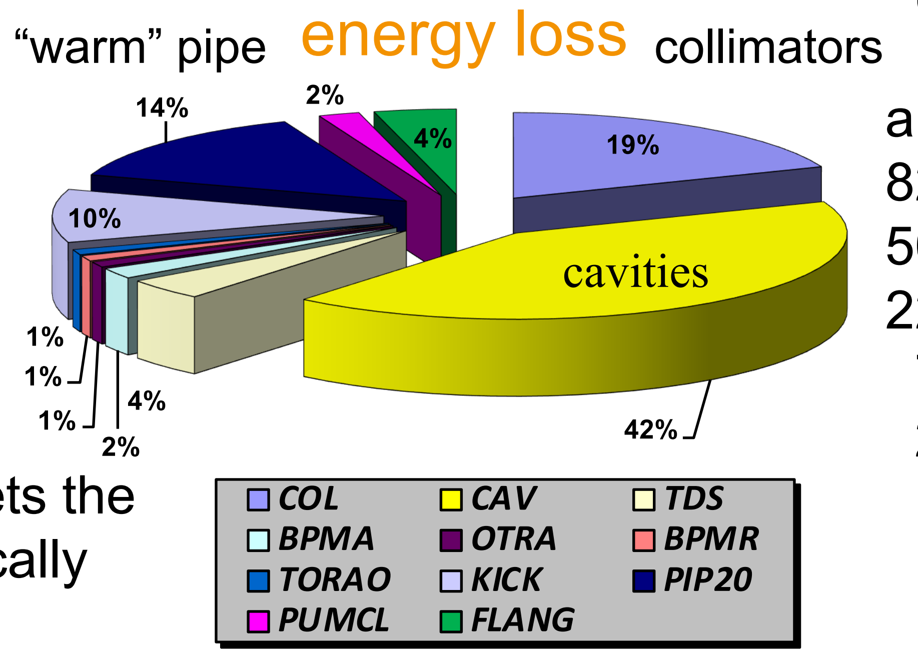
- external RF fields analytically
- self-fields with 3D Poisson equation
- CSR fields with 1D projected model
- particle motion with transport matrices of second order
- Chamber with wakes

S.Tomin, I.Agapov, M.Dohlus, I.Zagorodnov, *Ocelot as framework for beam dynamics simulations of x-ray sources, in Proceedings of IPAC 2017, WEPAB031*

Numerical approach

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





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

Source particle creates fields, test particle gets the integrated kick. Wakes are calculated analytically and with electromagnetic code **ECHO***.

- update of transverse wakes: length << betatron wavelength
- update of longitudinal wakes: length << wavelength of longitudinal oscillations
- in accelerator effects due to transverse wakes are minor; effects due to longitudinal wakes are essential → long. phase space and compression

*I. Zagorodnov, *T. Weiland, TE/TM field solver for particle beam simulations without numerical Cherenkov radiation, Phys. Rev. STAB 8, 042001 (2005)*

Numerical approach

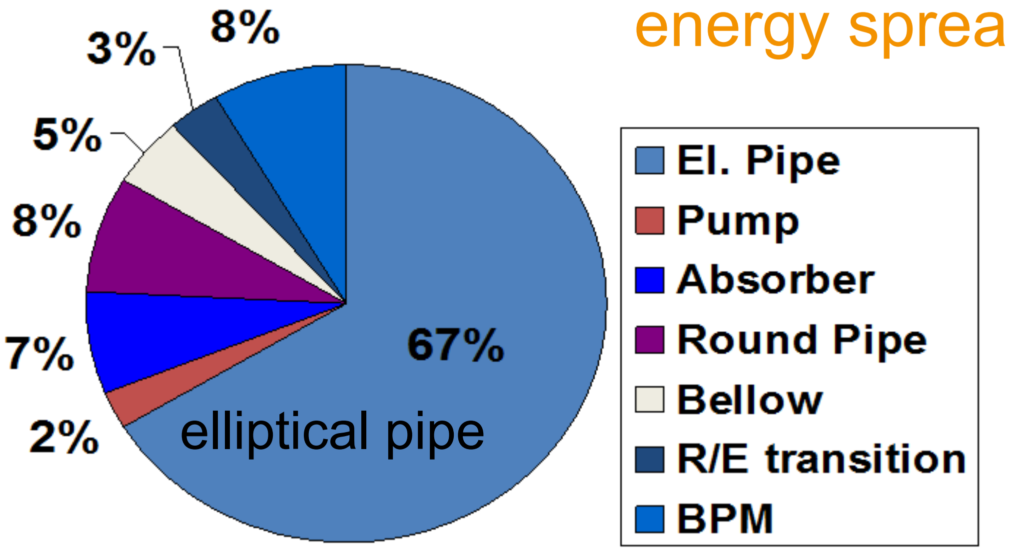
Undulator wakes

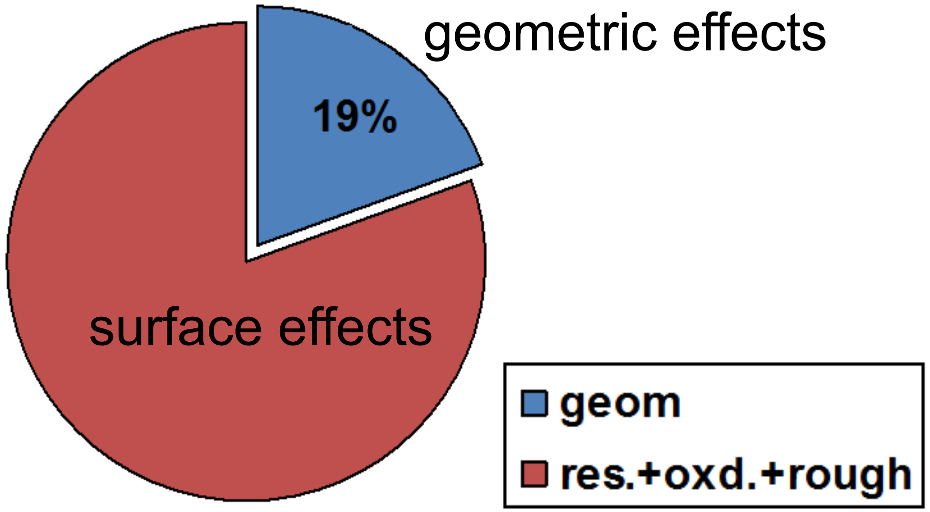
Q = 1nC, I_{peak} = 5 kA

total (correlated) energy spread (per section) ≈ 412 keV

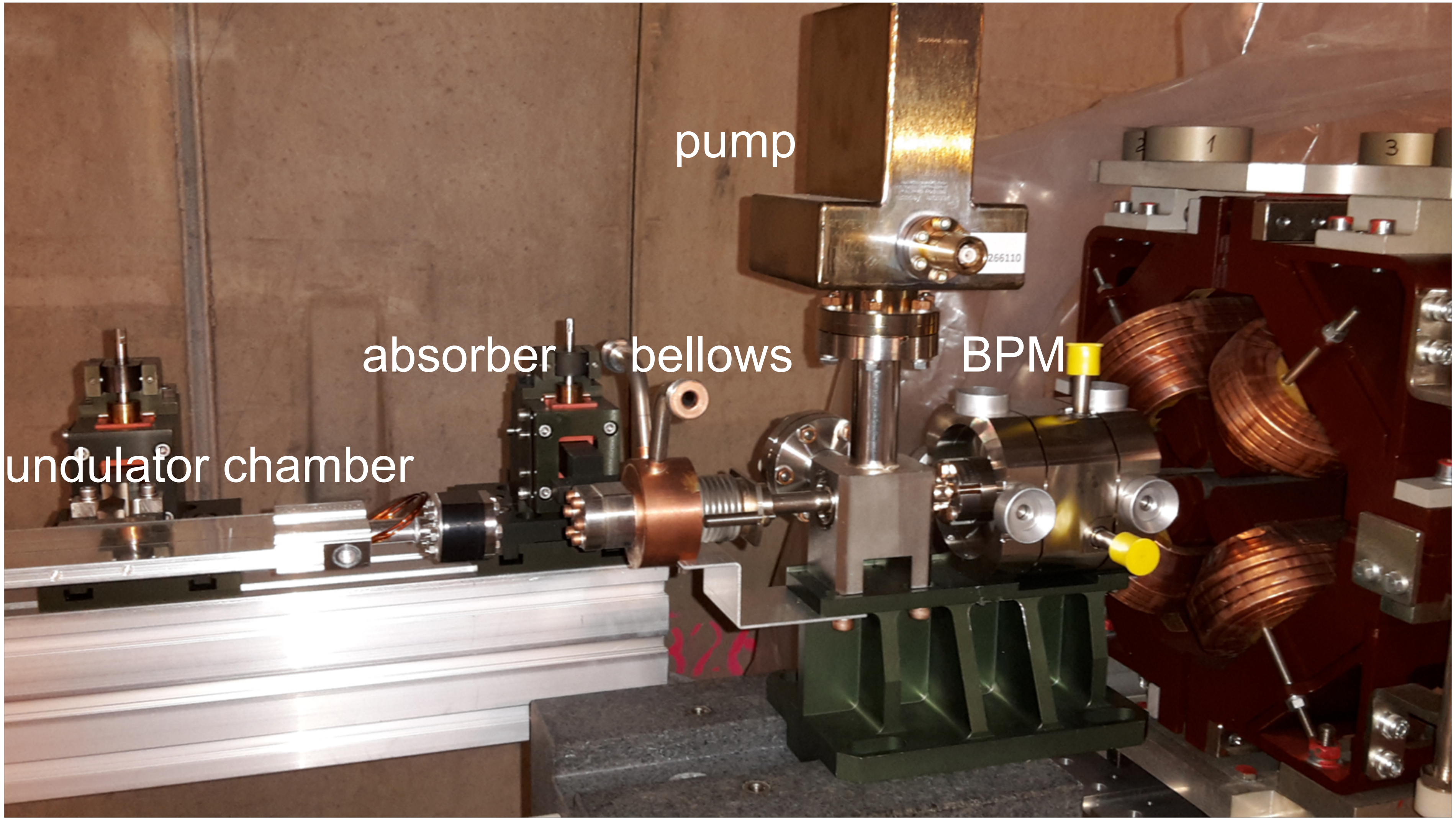
SASE1/2 has 35 sections
SASE3 with 21 sections

energy spread



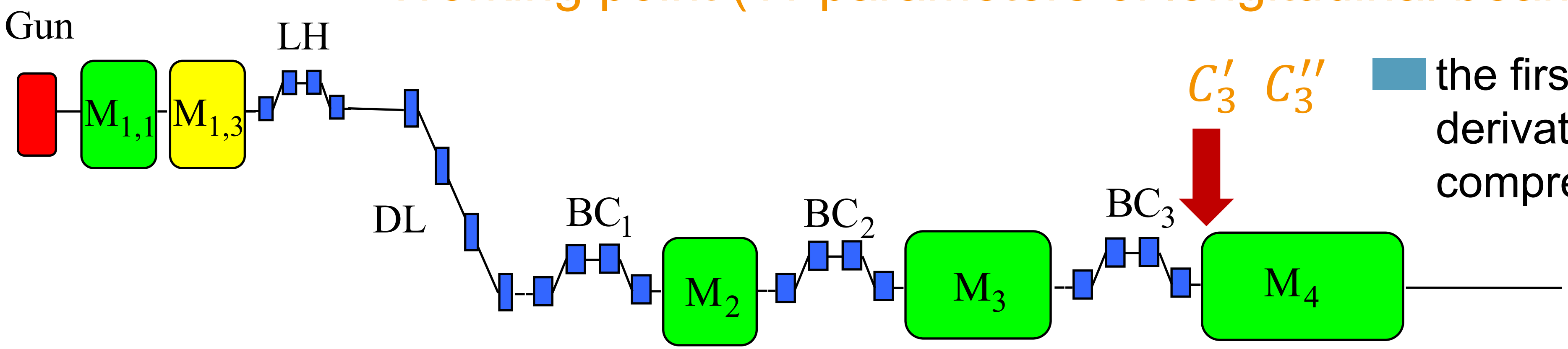


Numerical approach



RF tolerances, collective effects and the choice of the working point

Working point (11 parameters of longitudinal beam dynamics)



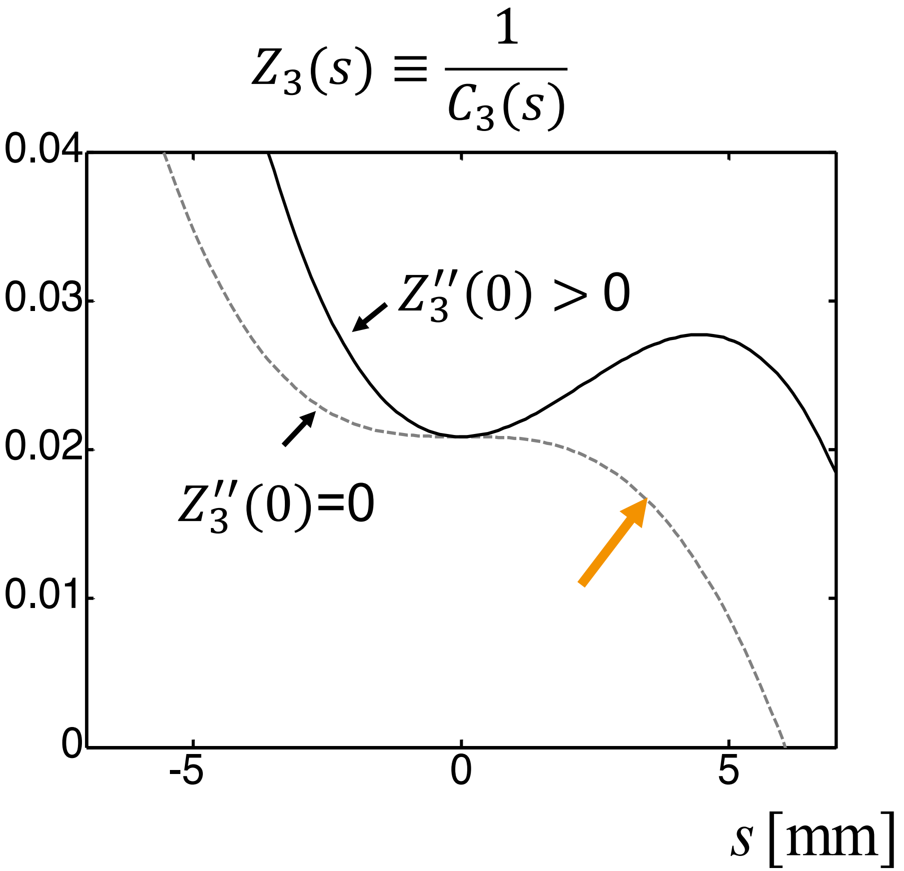
C'_3 C''_3 the first and the second derivatives of the global compression

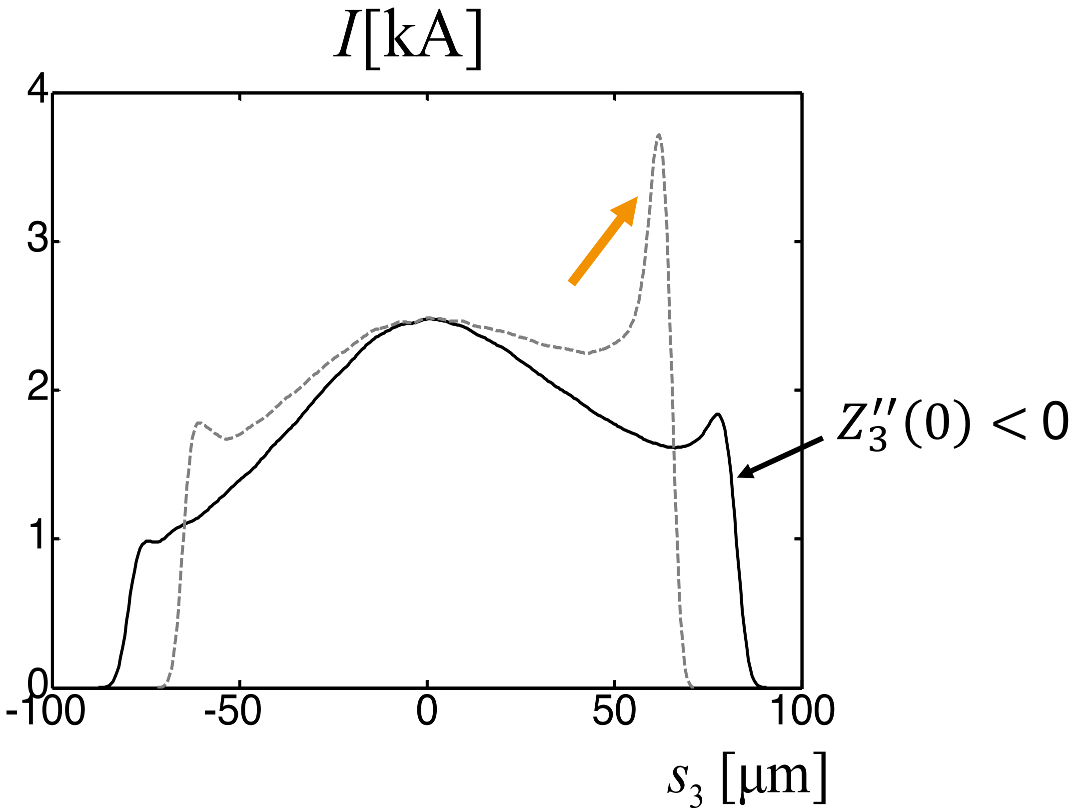
energy in BC:	$E_1 = 130$ MeV	$E_2 = 700$ MeV	$E_3 = 2400$ MeV
deflecting radius:	$r_1 = ?$	$r_2 = ?$	$r_3 = ?$
compression factor:	$C_1 = ?$	$C_2 = ?$	$C_3 = I_{\mathrm{final}}/I_{\mathrm{gun}}$

What is the optimal choice?

I. Zagorodnov, M. Dohlus, S.Tomin, *Accelerator Beam Dynamics at the European XFEL*, Phys. Rev. STAB, submitted.

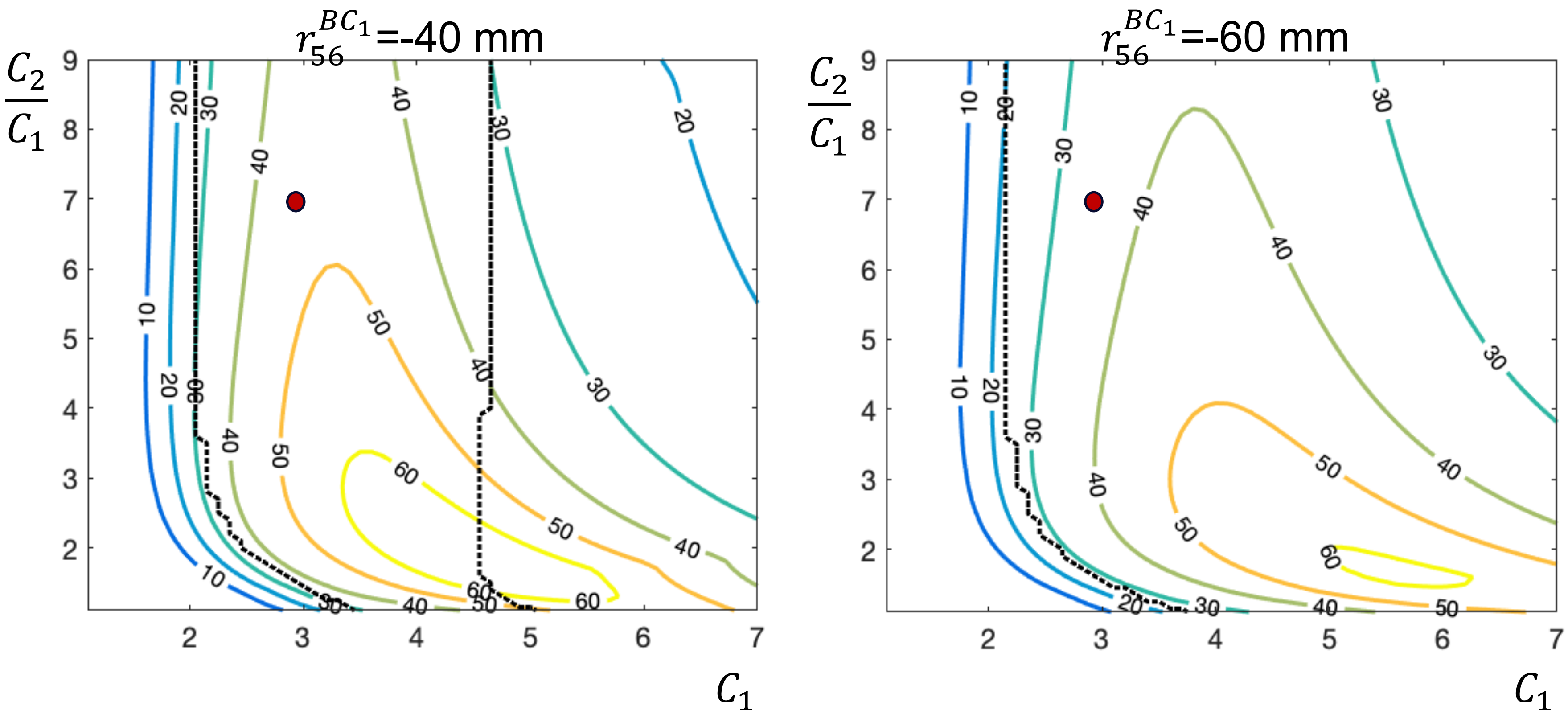
RF tolerances, collective effects and the choice of the working point





- very strong compression at the bunch head (spike)
- the first and the second derivatives of the global compression are special parameters which allow to tune the flatness and the symmetry of the current profile

RF tolerances, collective effects and the choice of the working point



$$\theta_{11} \equiv \frac{\Theta}{V_{11}^0 C_3 \left|\nabla_{\boldsymbol{v}_{11}} Z_3\right|}$$

$$\boldsymbol{v}_{11} = (X_{11}, Y_{11})^T$$

$$X_{11} + iY_{11} = V_{11} e^{i\varphi_{11}}$$

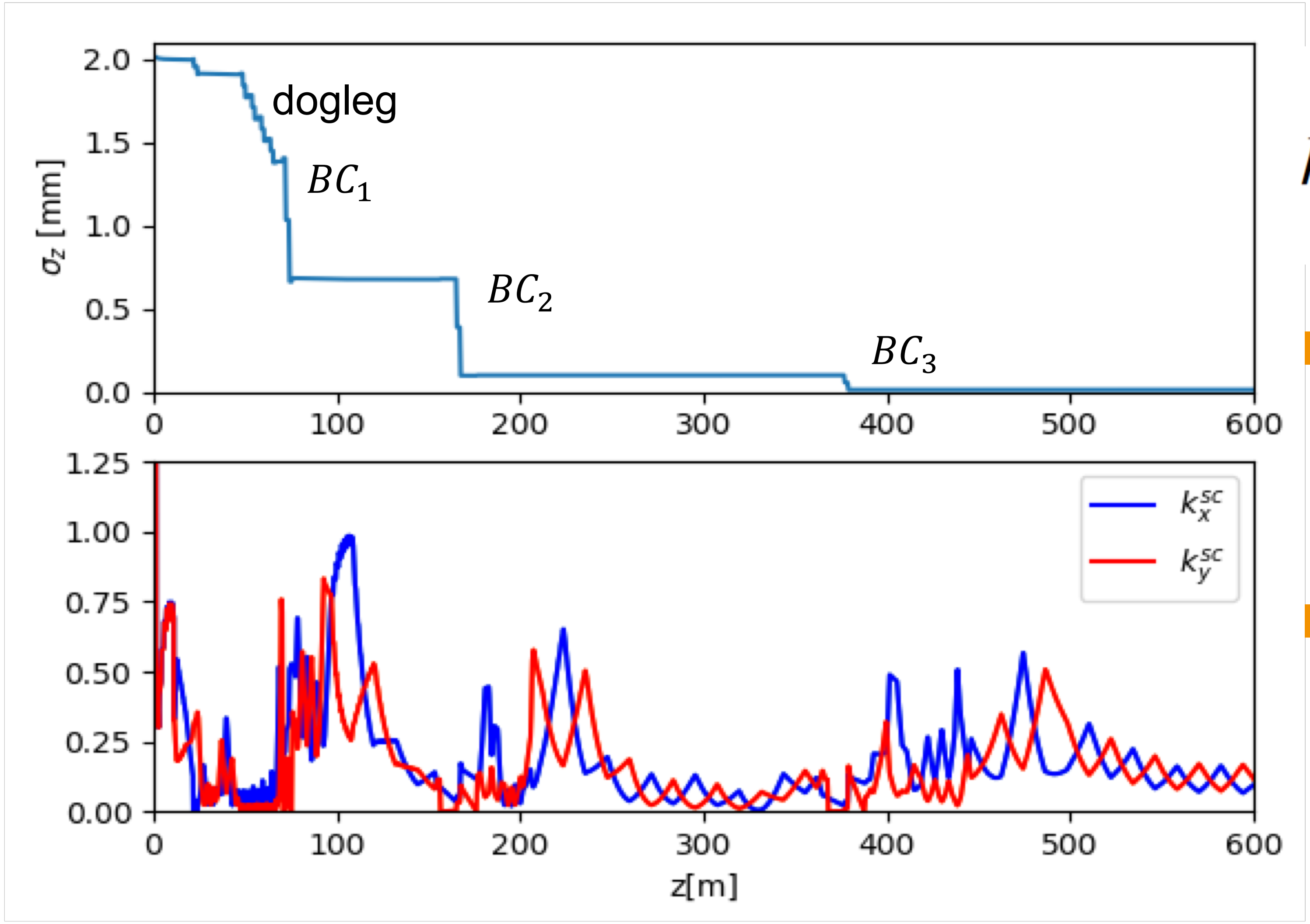
We always show the tolerances for

$$\Theta = 0.1$$

which means that the total compression deviation is restricted by 10 %.

The RF tolerance of the booster $\theta_{11} 10^5$ for two different compaction factors in BC1 for 500 pC, 5 kA. The red point shows the working point. The dashed black lines show the limits of available RF voltage.

RF tolerances, collective effects and the choice of the working point



$$k_x^{sc} = \frac{I_0\beta_x}{I_A\gamma^2\epsilon_x}, \qquad k_y^{sc} = \frac{I_0\beta_y}{I_A\gamma^2\epsilon_y}$$

- the space charge parameters relate the space charge forces to the averaged focusing in the magnetic lattice
- at the chosen working point the de-focussing due to the space charge forces is less than the focusing of the quadrupoles

RF tolerances, collective effects and the choice of the working point

- Longitudinal dynamics parameters

parameter	500 pC, 5kA	500 pC, 10 kA	250 pC, 5 kA	100 pC, 5 kA
E_1, MeV	130			
r_1, m	4.12			
C_1	3			3.5
E_2, MeV	700			
r_2, m	8.39			8.68
C_2	21			28
E_3, MeV	2400			
r_3, m	14.80	14.36	14.41	15.27
C_3	192	384	345	862
Z_3', 1/m	0			
Z_3'', 1/m/m	1000	1500	700	600

RF tolerances, collective effects and the choice of the working point

Analytical solution without self-fields

$$\mathbf{x}_0 = \mathbf{A}_0^{-1}(\mathbf{f}_0)$$

$$\mathbf{f}_0 = \begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ C_1 \\ C_2 \\ C \\ C' \\ C'' \end{pmatrix} \Rightarrow \mathbf{x} = \begin{pmatrix} V_{1,1} \\ \varphi_{1,1} \\ V_{1,3} \\ \varphi_{1,3} \\ V_2 \\ \varphi_2 \\ V_3 \\ \varphi_3 \end{pmatrix}$$

I. Zagorodnov, M. Dohlus, *Semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects*, Phys. Rev. STAB, 2011.

Solution with self-fields

nonlinear operator
(numerical tracking with self-fields)

$$\mathbf{A}(\mathbf{x}) = \mathbf{f}_0$$

$$\mathbf{x}_n = \mathbf{A}_0^{-1}\left(\mathbf{A}_0(\mathbf{x}_{n-1}) + \mathbf{f}_0 - \mathbf{A}(\mathbf{x}_{n-1})\right)$$

numerical tracking $\mathbf{f}_{n-1} = \mathbf{A}(\mathbf{x}_{n-1})$

residual in parameters $\Delta\mathbf{f}_{n-1} = \mathbf{f}_0 - \mathbf{f}_{n-1}$

analytical correction of RF parameters $\mathbf{g}_n = \mathbf{g}_{n-1} + \Delta\mathbf{f}_{n-1}$

$$\mathbf{x}_n = \mathbf{A}_0^{-1}(\mathbf{g}_n)$$

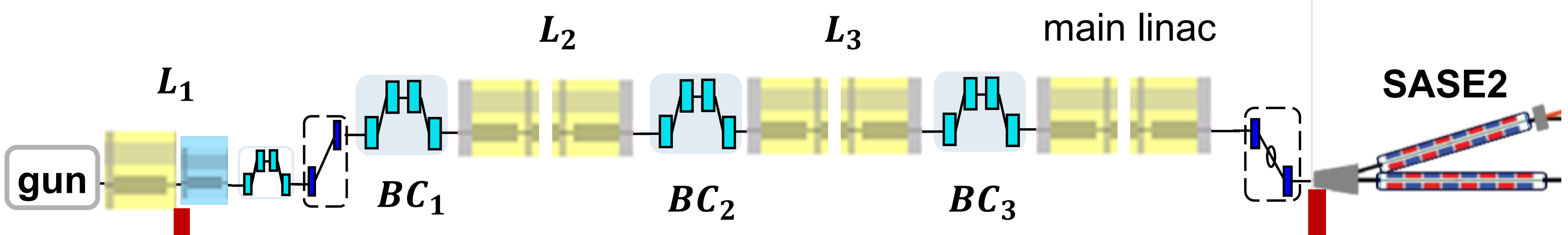
RF tolerances, collective effects and the choice of the working point

- The RF tolerances for 10% change of the global compression

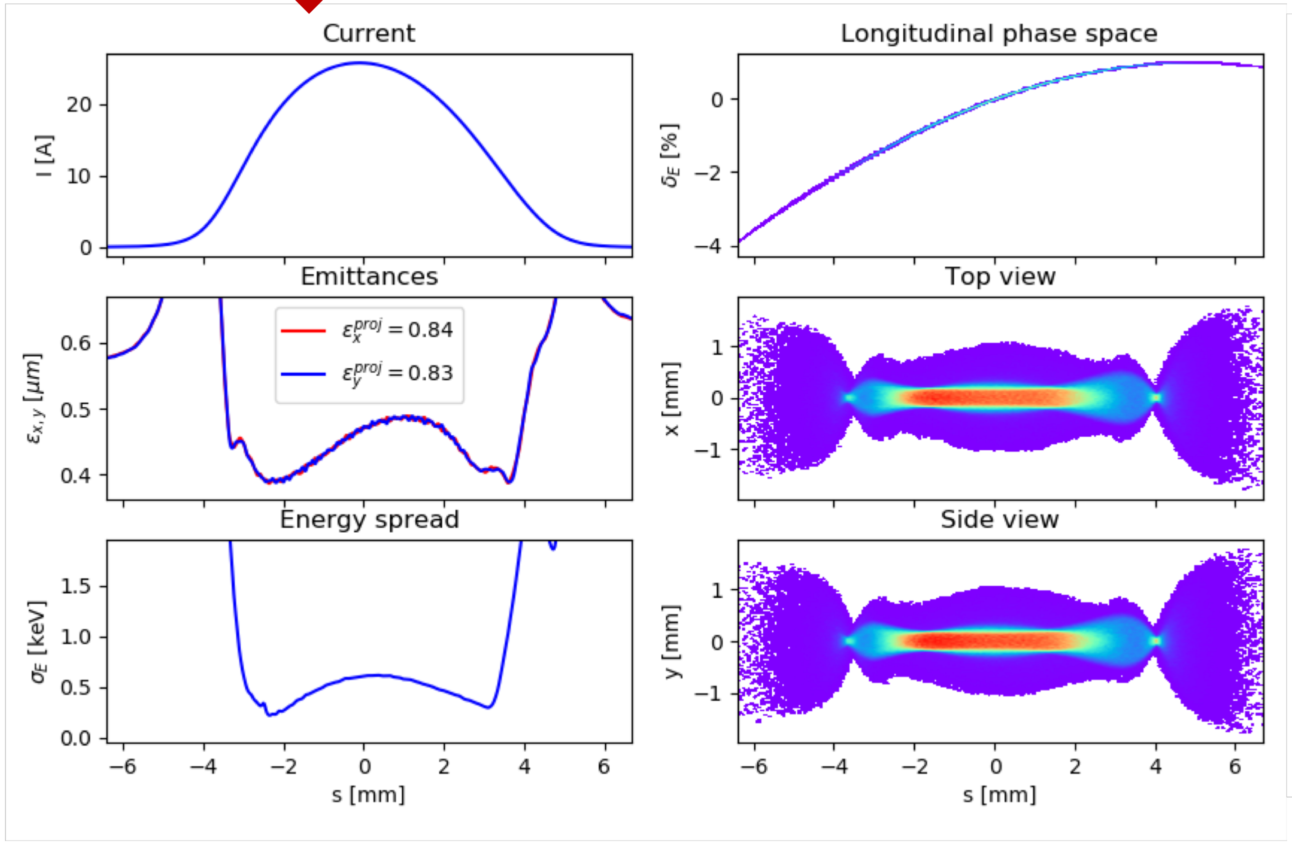
	$V_{11}\theta_{11}^{V}$	θ_{11}^{φ}	$V_{13}\theta_{13}^{V}$	θ_{13}^{φ}	$V_{2}\theta_{2}^{V}$	θ_{2}^{φ}	$V_{3}\theta_{3}^{V}$	θ_{3}^{φ}
	MV	deg	MV	deg	MV	deg	MV	deg
500 pC, 5 kA	0.11	0.04	0.17	0.07	1.4	0.06	16	0.3
500 pC, 10 kA	0.06	0.02	0.79	0.03	0.8	0.03	7	0.2
250 pC, 5 kA	0.06	0.02	0.14	0.04	0.8	0.03	8	0.2

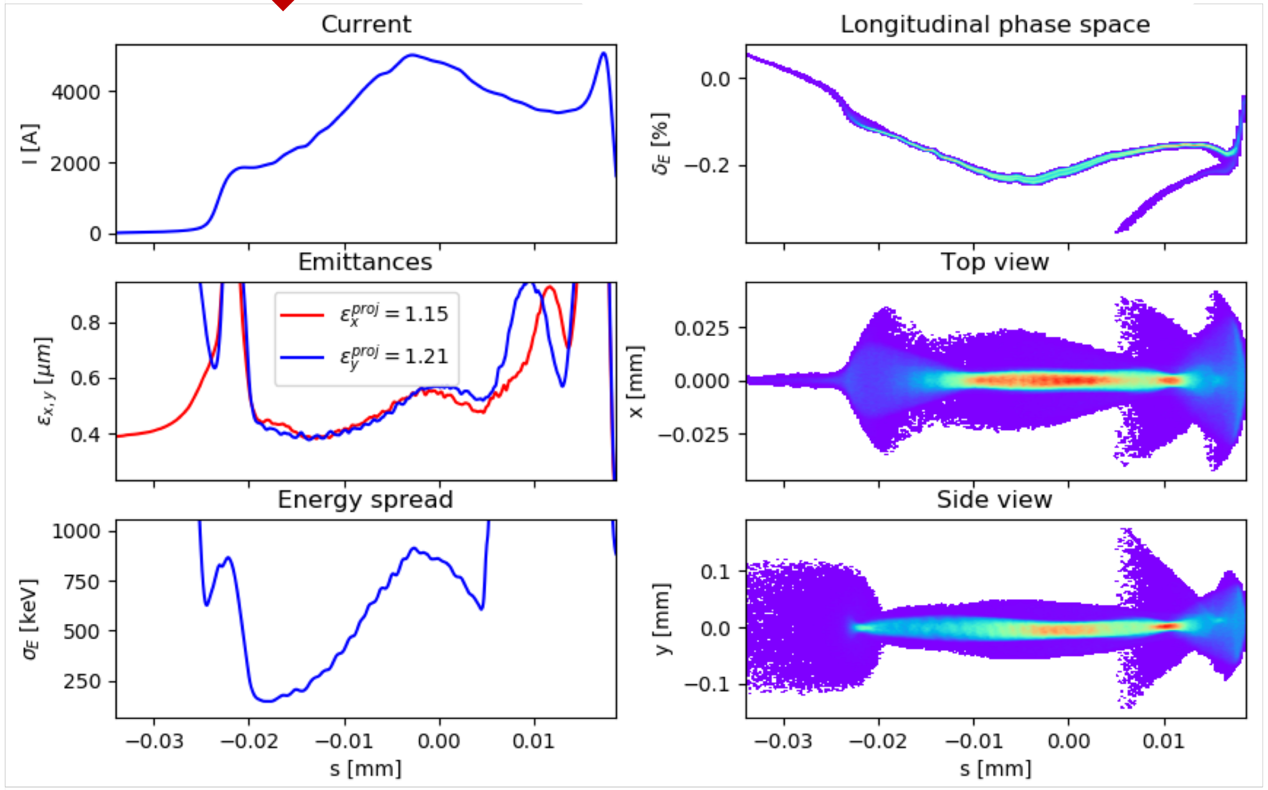
- In the simulations we use the laser heater in the injector to provide 1 MeV slice energy spread after the full compression (after BC2)

Beam dynamics for 500 pC, 5 kA



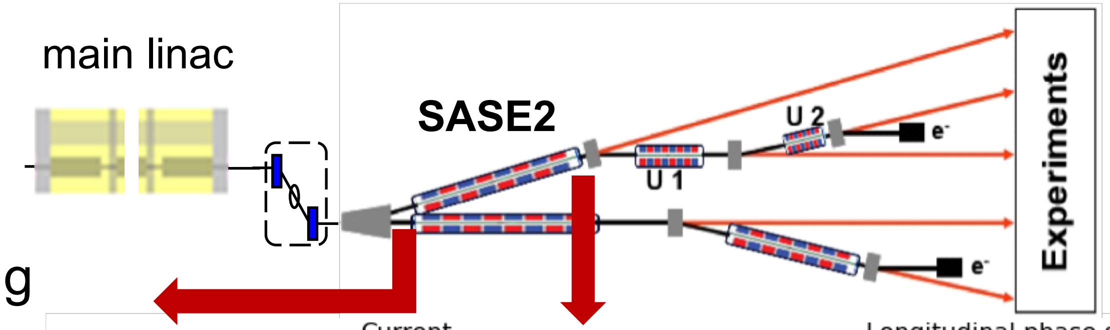
- projected x-emittance growth by 37%
- projected y-emittance growth by 44%

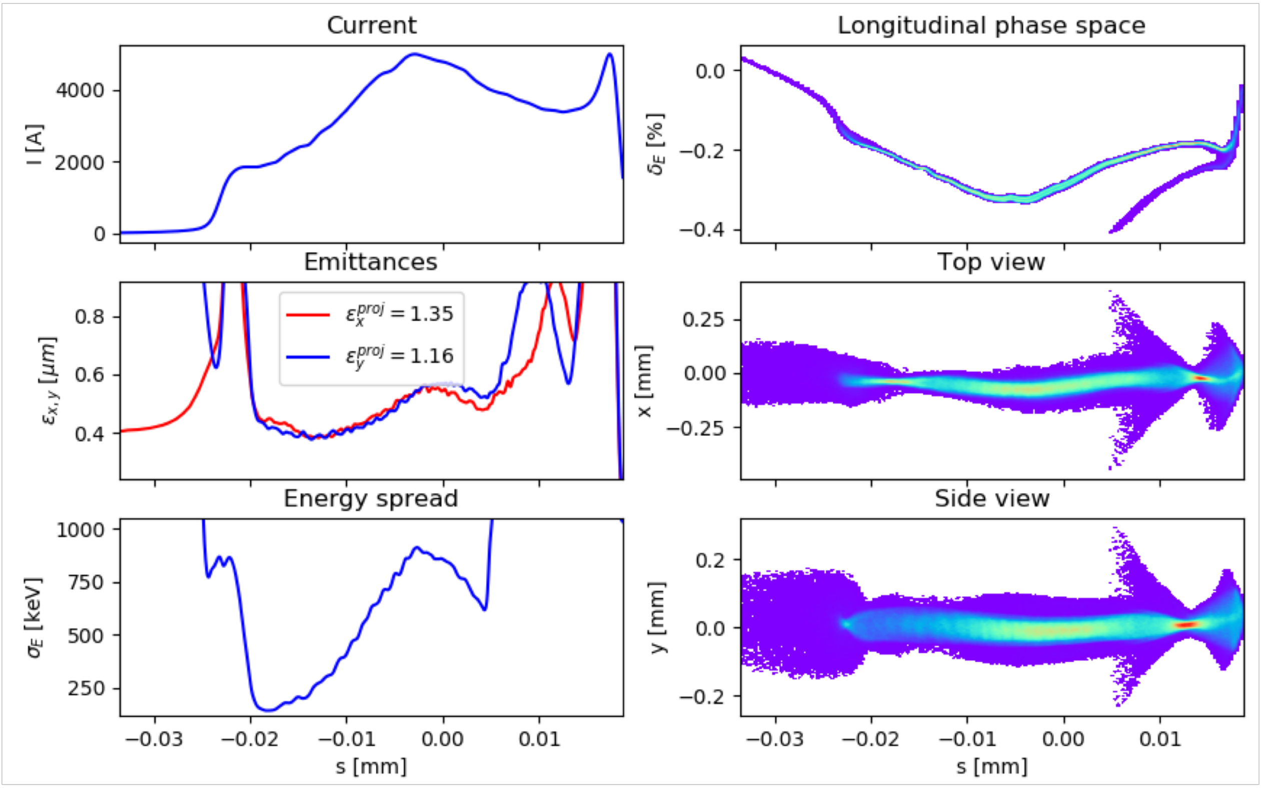


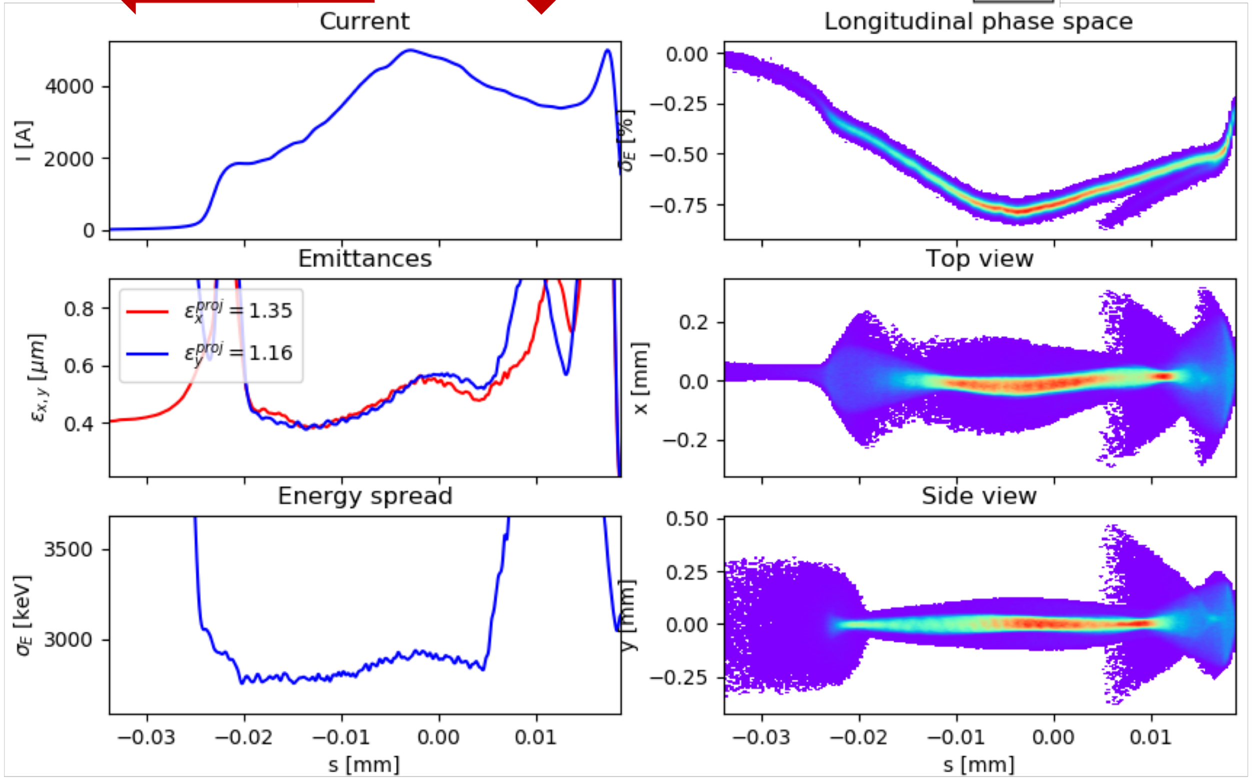


Beam dynamics for 500 pC, 5 kA

- projected x-emittance growth by 60%
- slice energy spread growth due to quantum fluctuations in SASE2 (K=3.9)
- correlated energy spread growth due to strong wakefields in SASE2

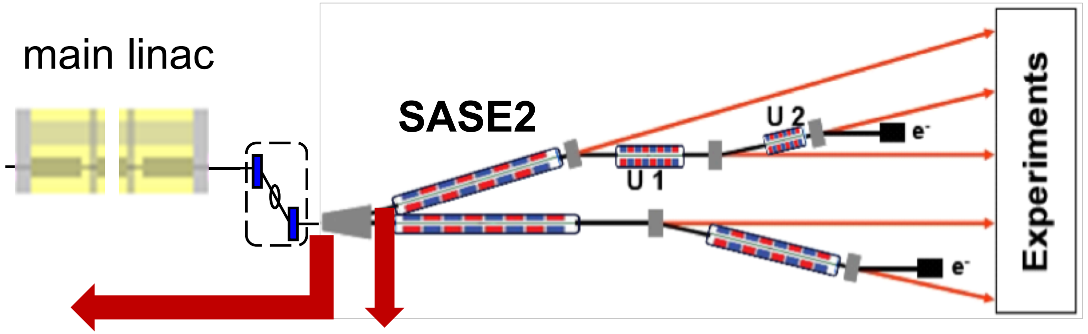


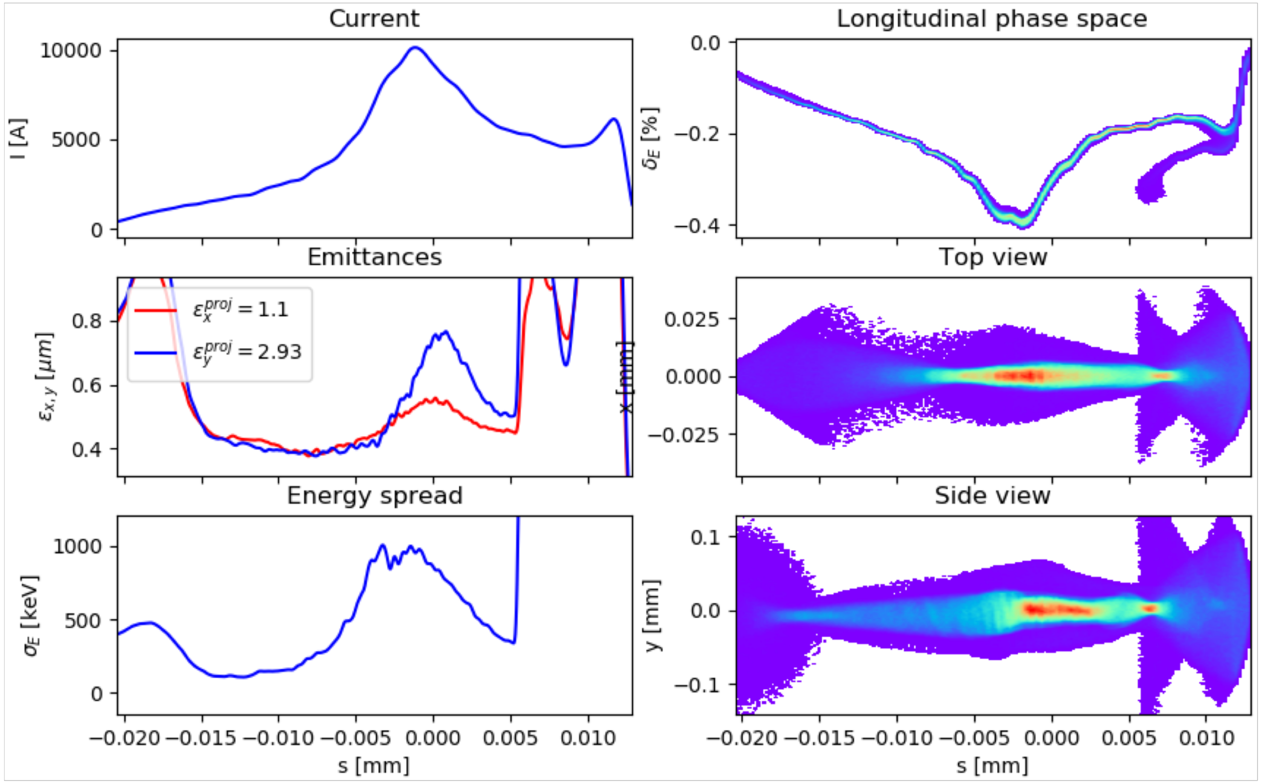


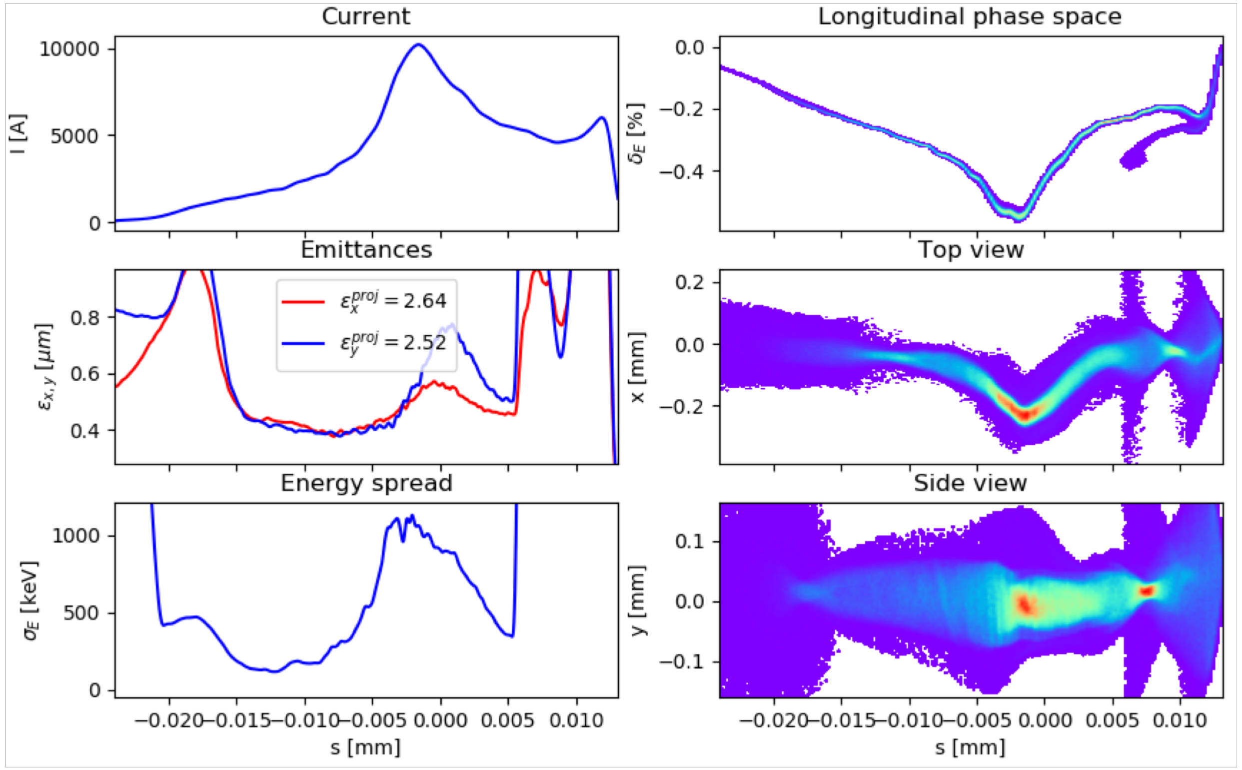


Beam dynamics for 500 pC, 10 kA

- projected x-emittance growth by 210%
- projected y-emittance growth by 200%
- slice y-emittance growth by 50%

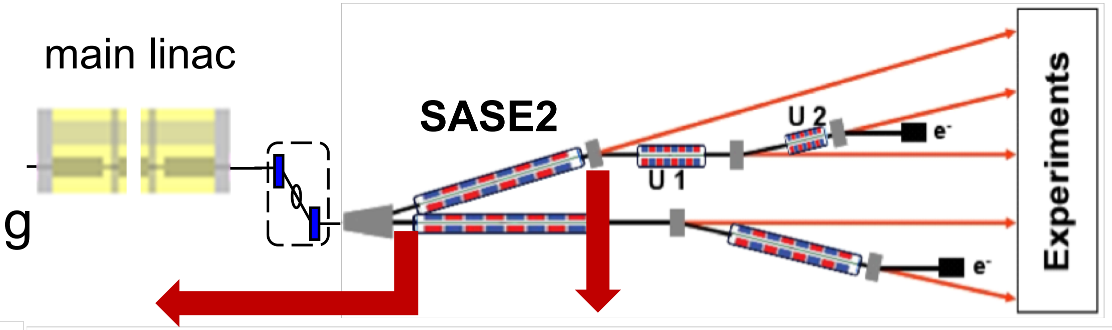


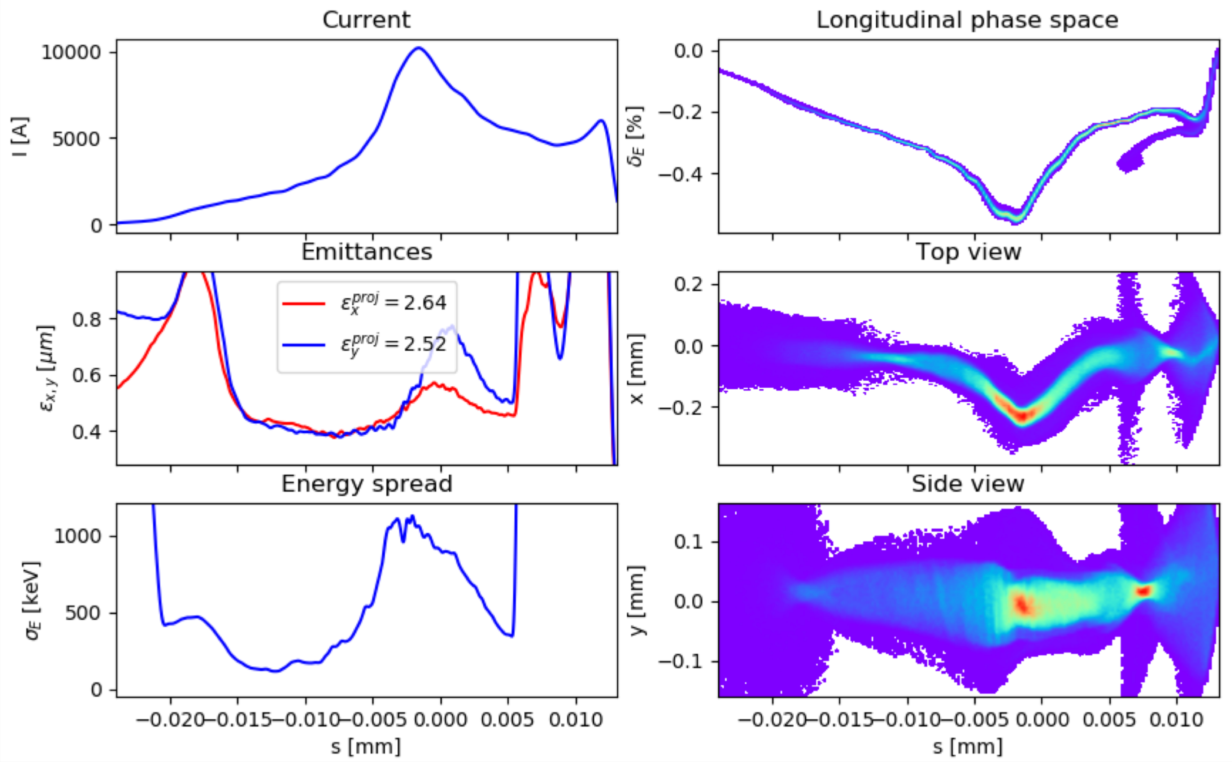


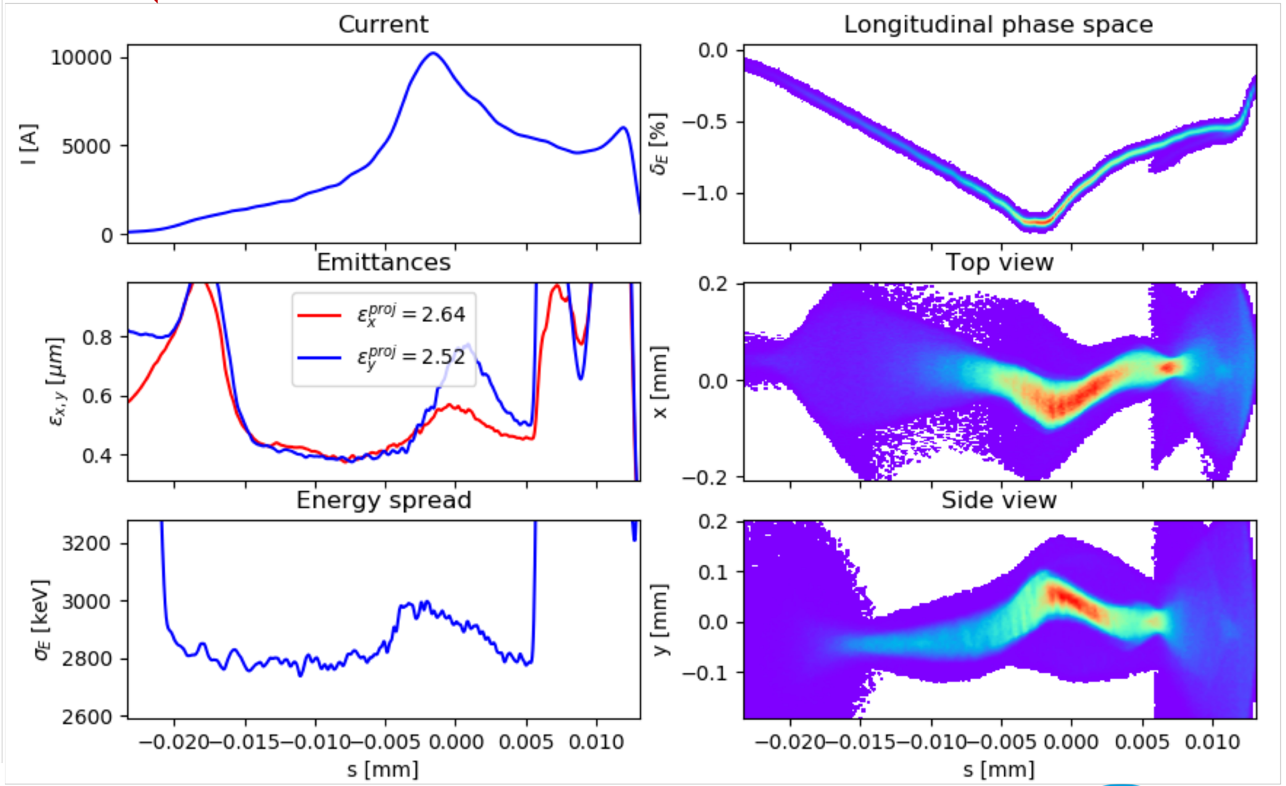


Beam dynamics for 500 pC, 10 kA

- slice energy spread growth due to quantum fluctuations in SASE2 (K=3.9)
- correlated energy spread growth due to strong wakefields in SASE2

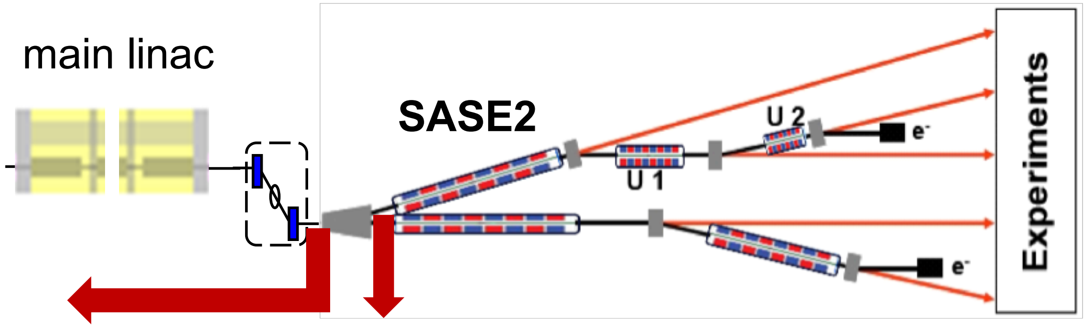


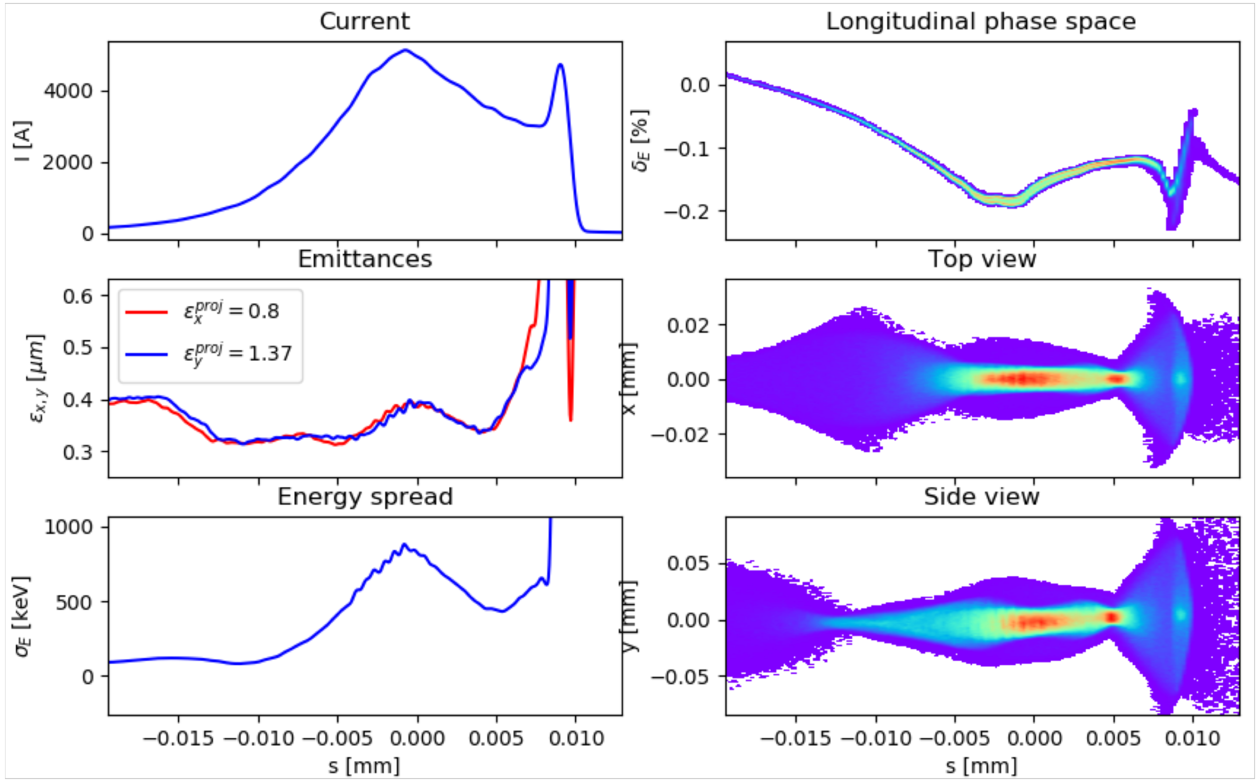


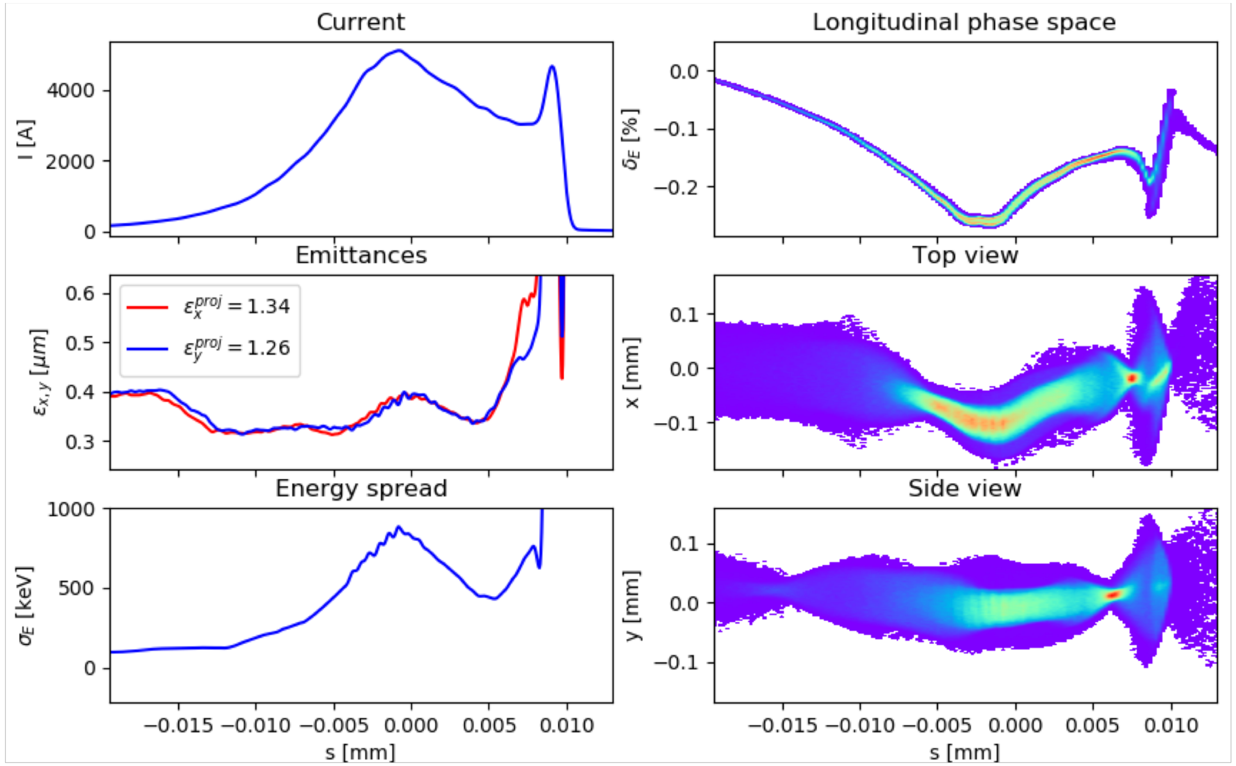


Beam dynamics for 250 pC, 5 kA

- projected x-emittance growth by 100%
- projected y-emittance growth by 90%

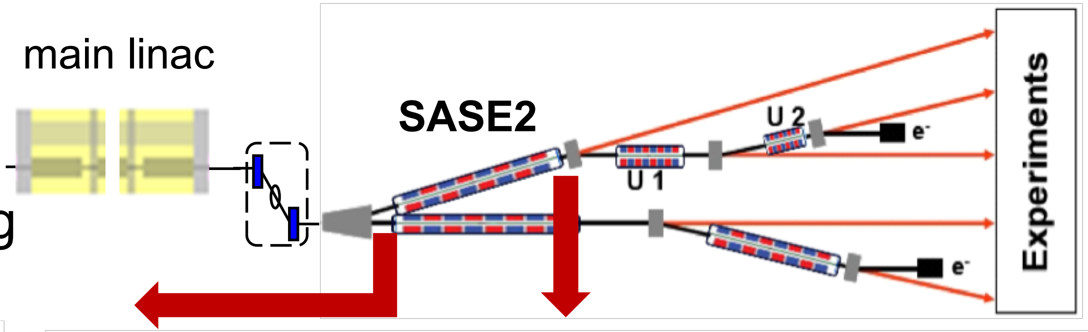


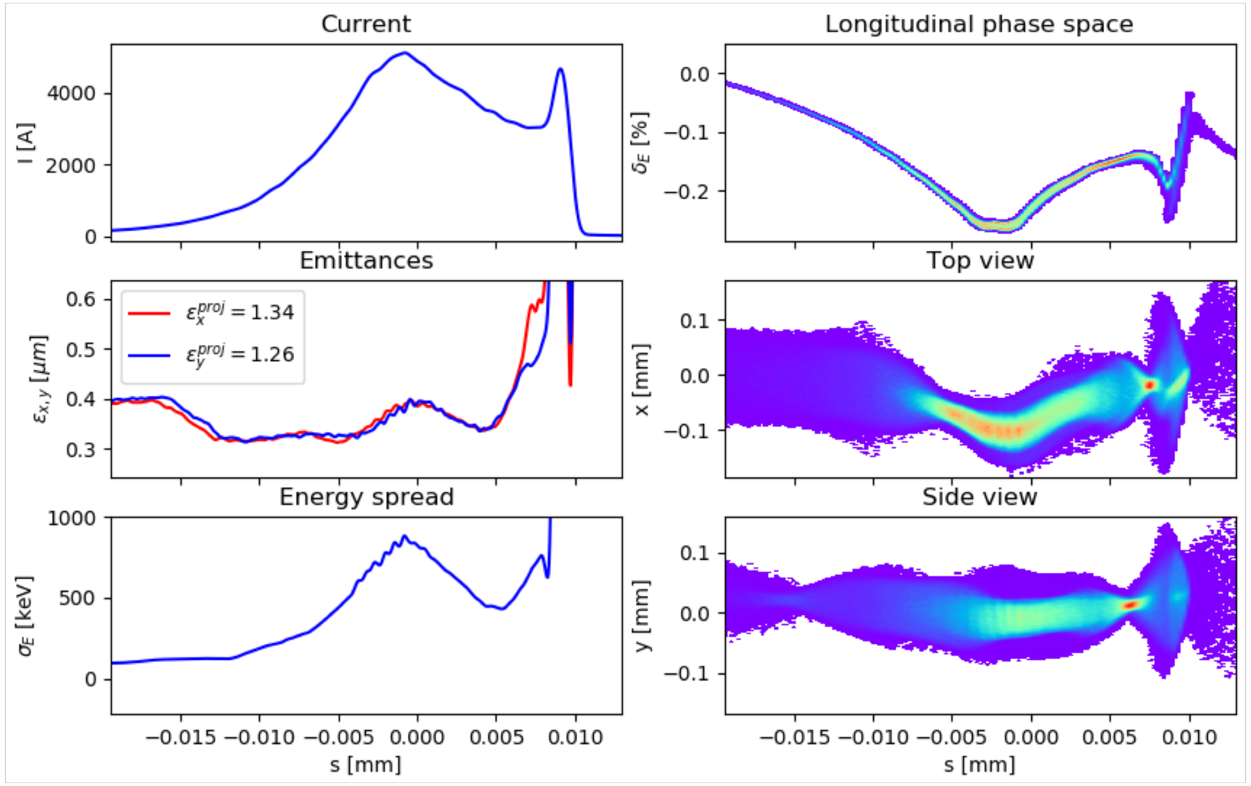


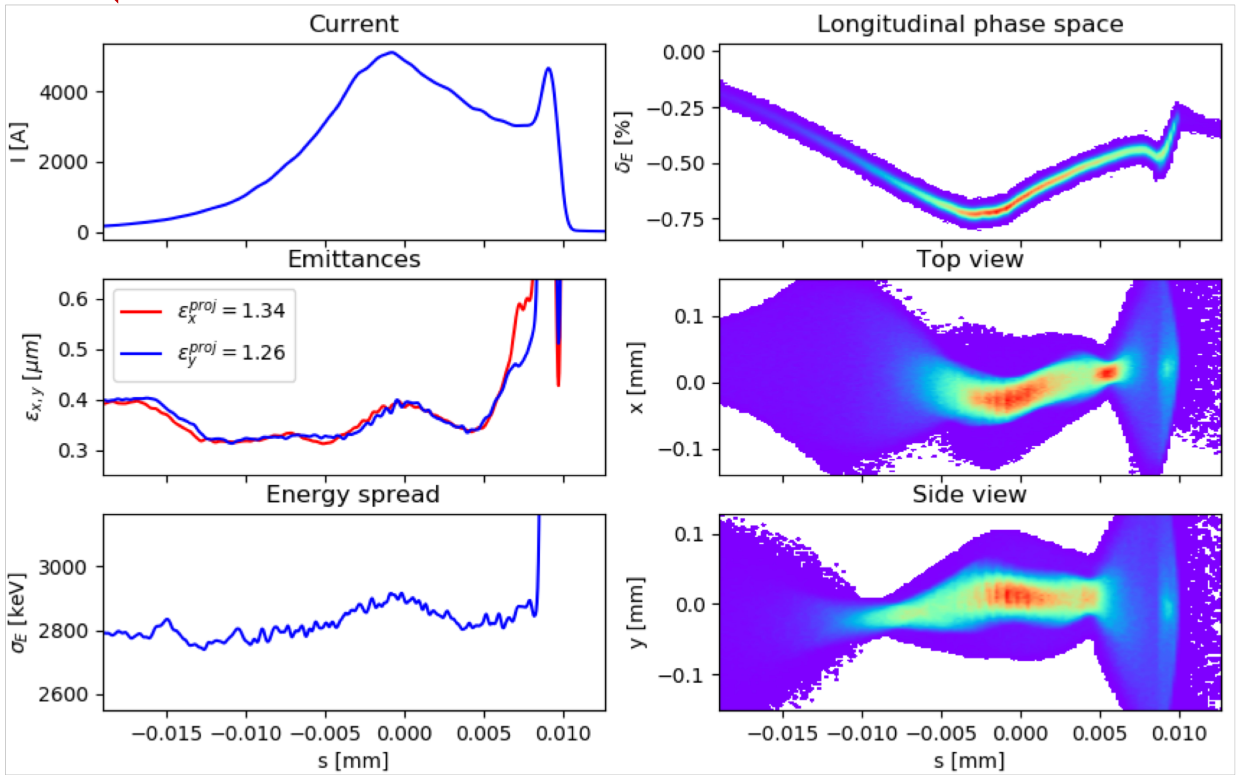


Beam dynamics for 250 pC, 5 kA

- slice energy spread growth due to quantum fluctuations in SASE2 (K=3.9)
- correlated energy spread growth due to strong wakefields in SASE2

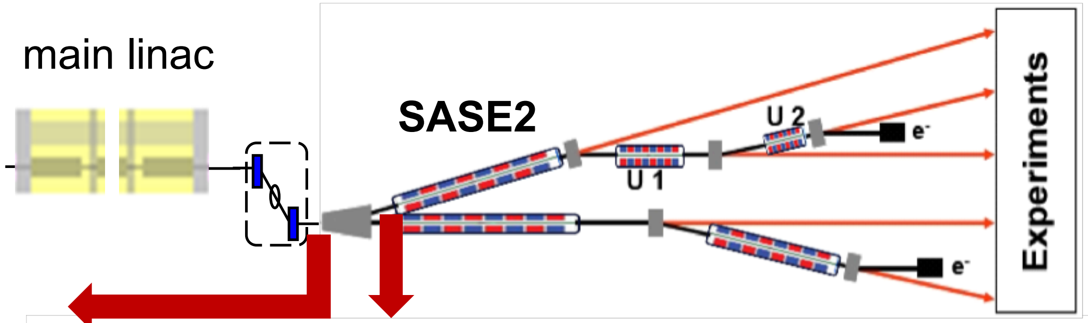


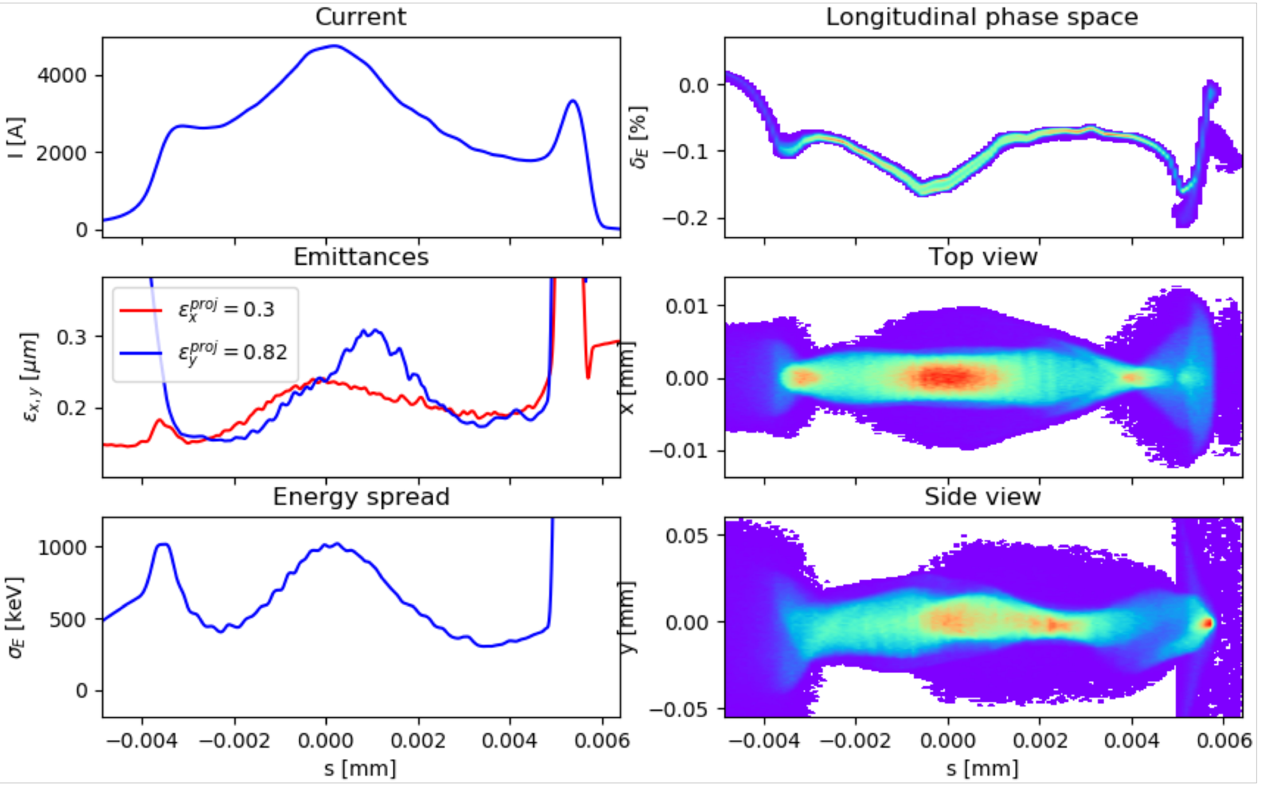


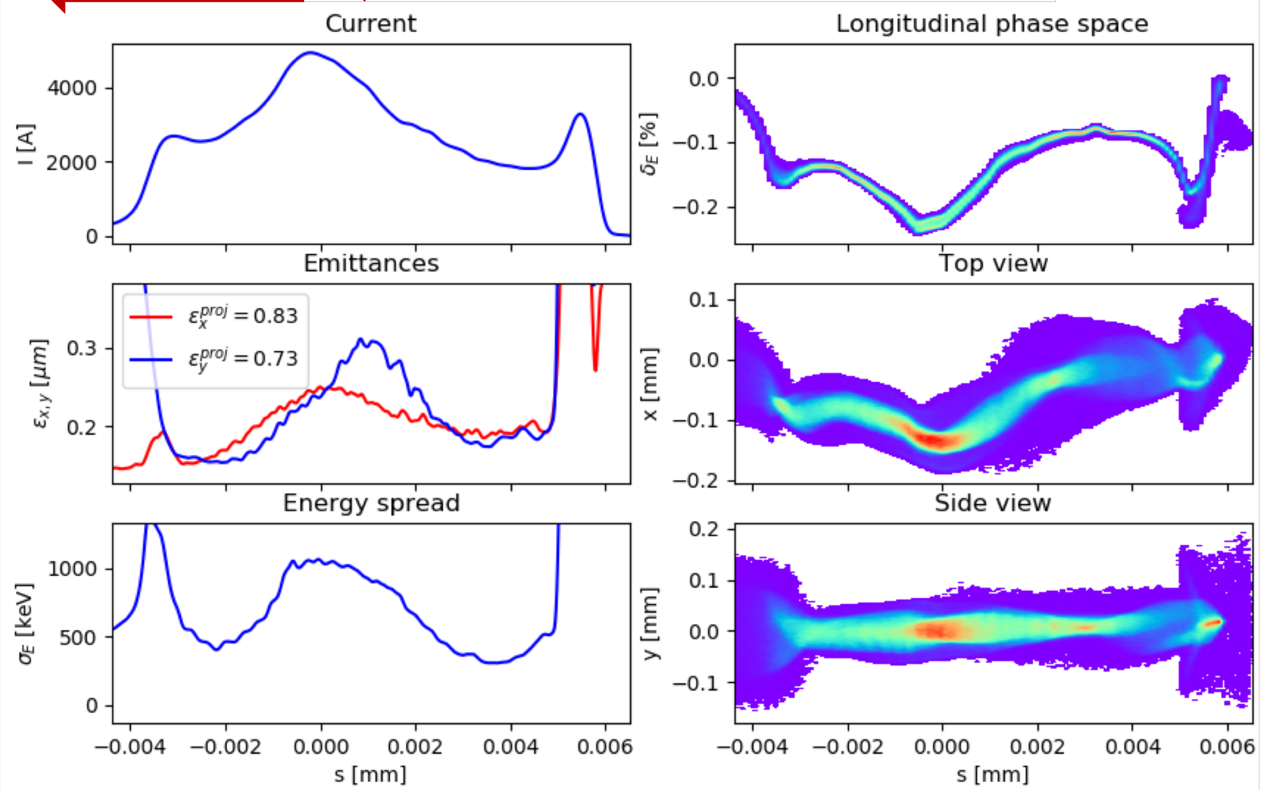


Beam dynamics for 100 pC, 5 kA

- projected x-emittance growth by 180%
- projected y-emittance growth by 140%

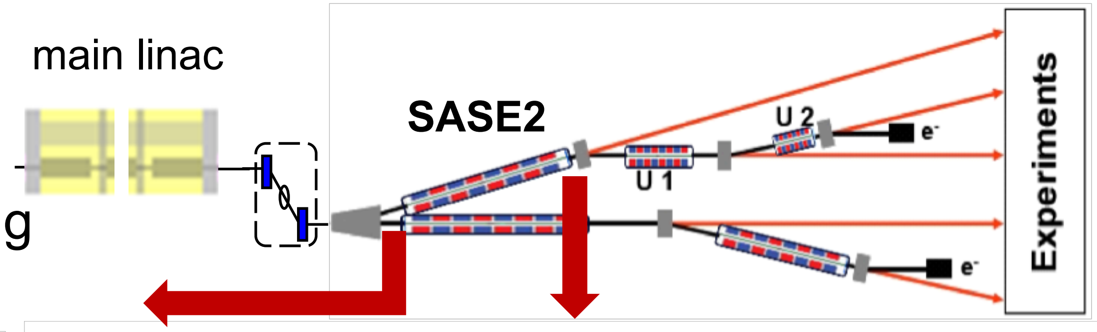


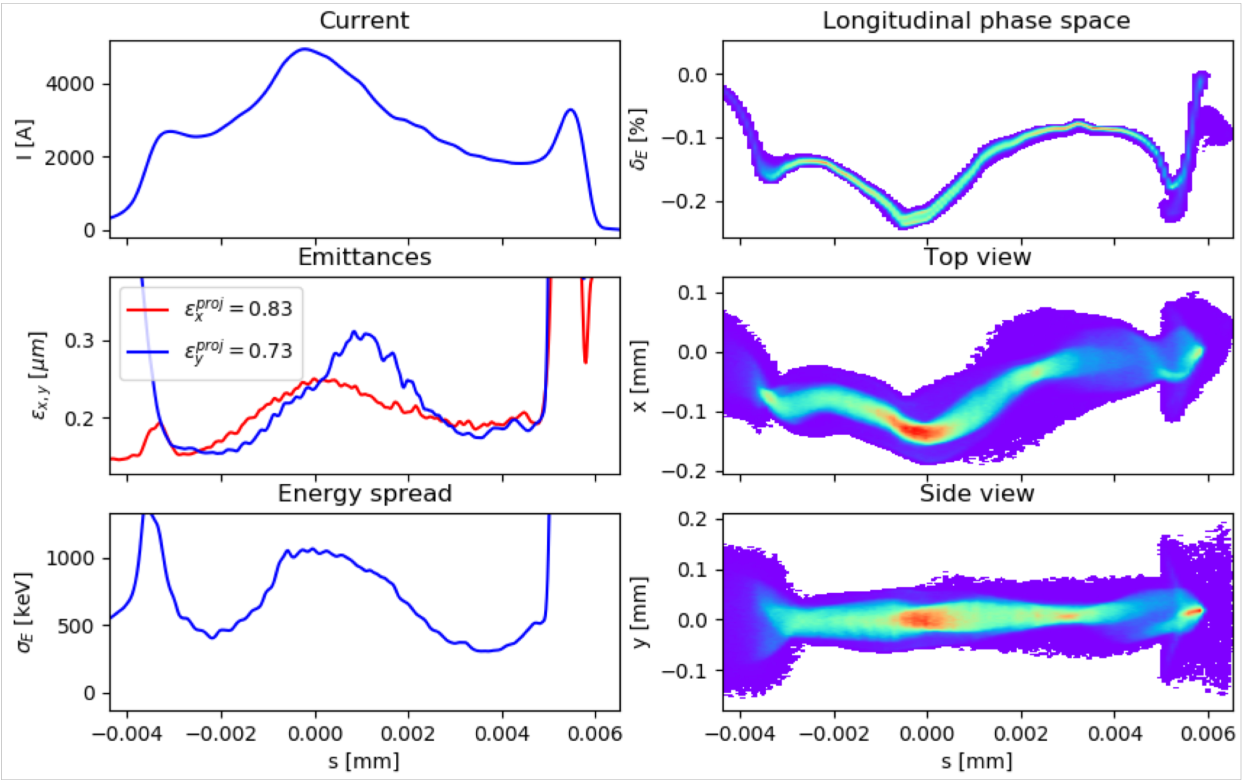


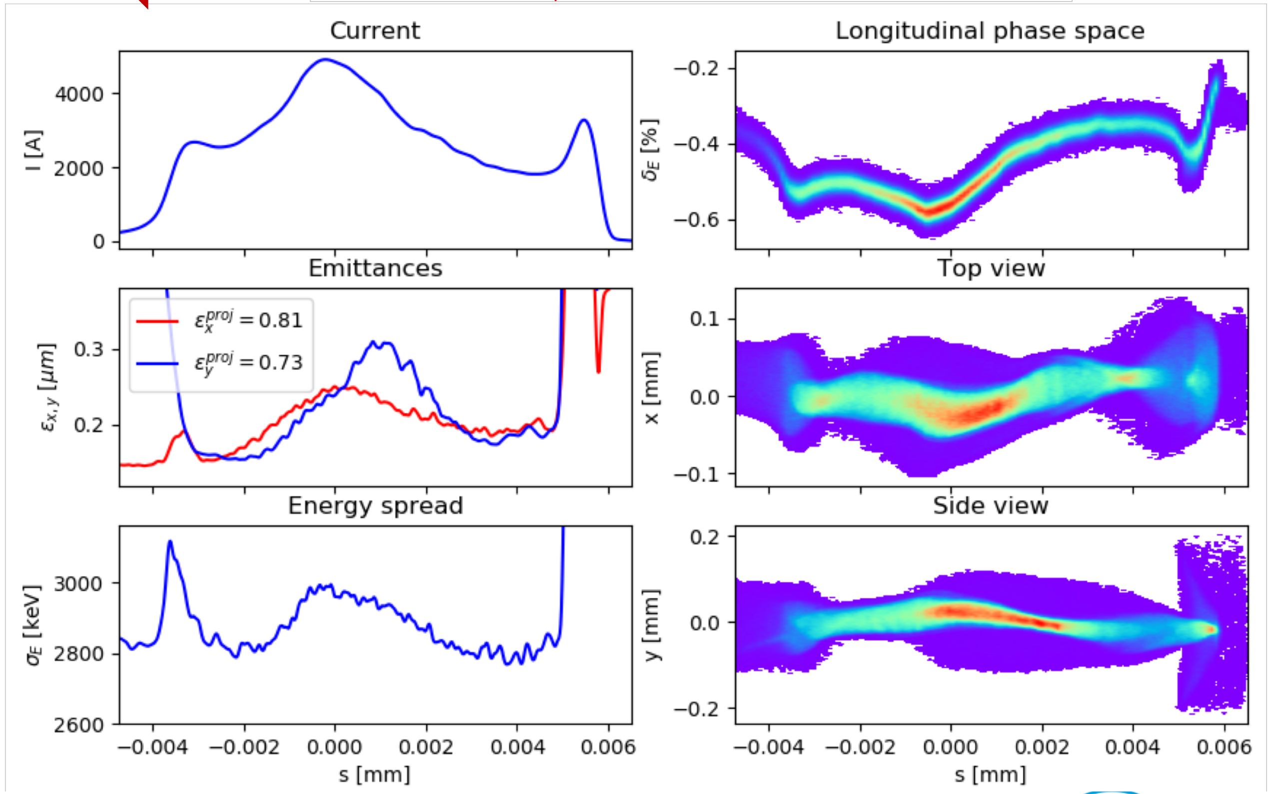


Beam dynamics for 100 pC, 5 kA

- slice energy spread growth due to quantum fluctuations in SASE2 (K=3.9)
- correlated energy spread growth due to strong wakefields in SASE2







Accuracy of the results

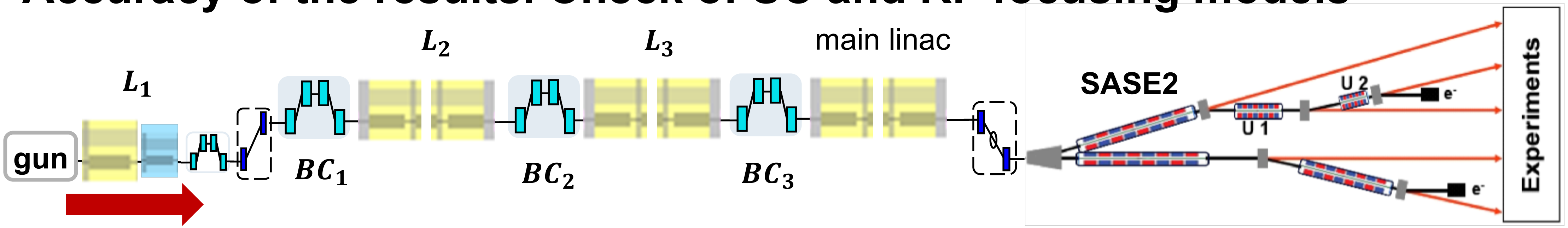
- Beam dynamics without collective effects
  - the second-order optics cross-checked with MAD
  - the chromatic effects in dispersive sections are cross-checked with CSRtrack

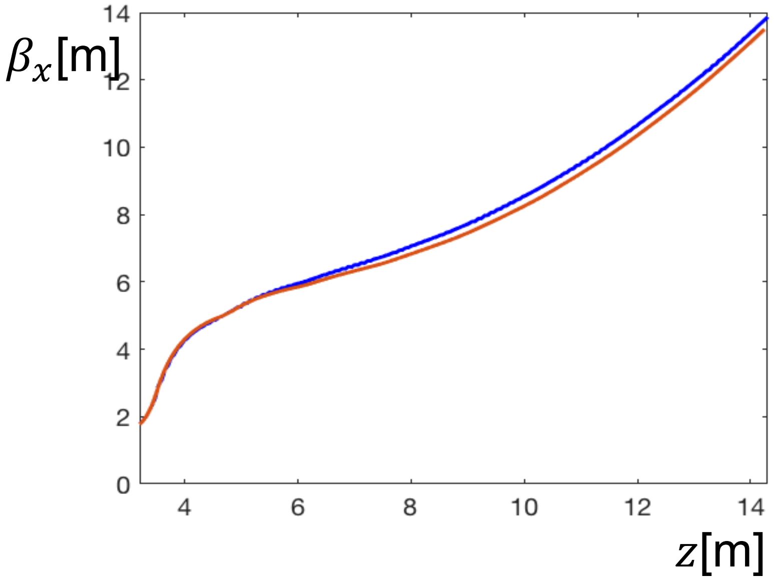
- Beam dynamics with collective effects
  - the space charge is cross-checked with ASTRA and with analytical estimations
  - CSR in dispersive sections is cross-checked with CSRtrack
  - the results are checked by increasing of macroparticle number 200k -> 2M
  - the results are checked by varying of sampling/mesh parameters in wakes, CSR, space-charge

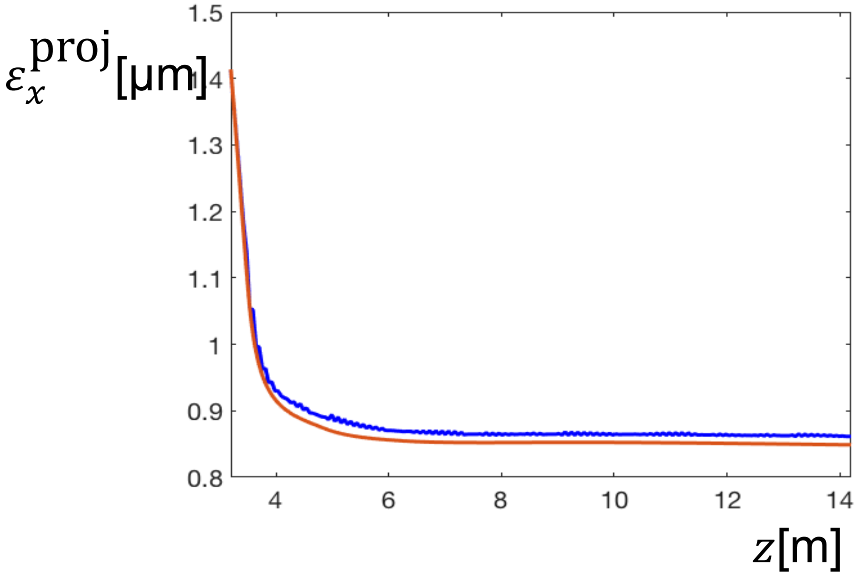
- The results are optimized
  - with gun and laser parameters,
  - with optics re-matching at several points along the accelerator

- What is missing?
  - the transverse wakes are taken into account only in RF modules
  - only 1D CSR model is used; the vacuum chambers in BC's are not present

Accuracy of the results. Check of SC and RF focusing models

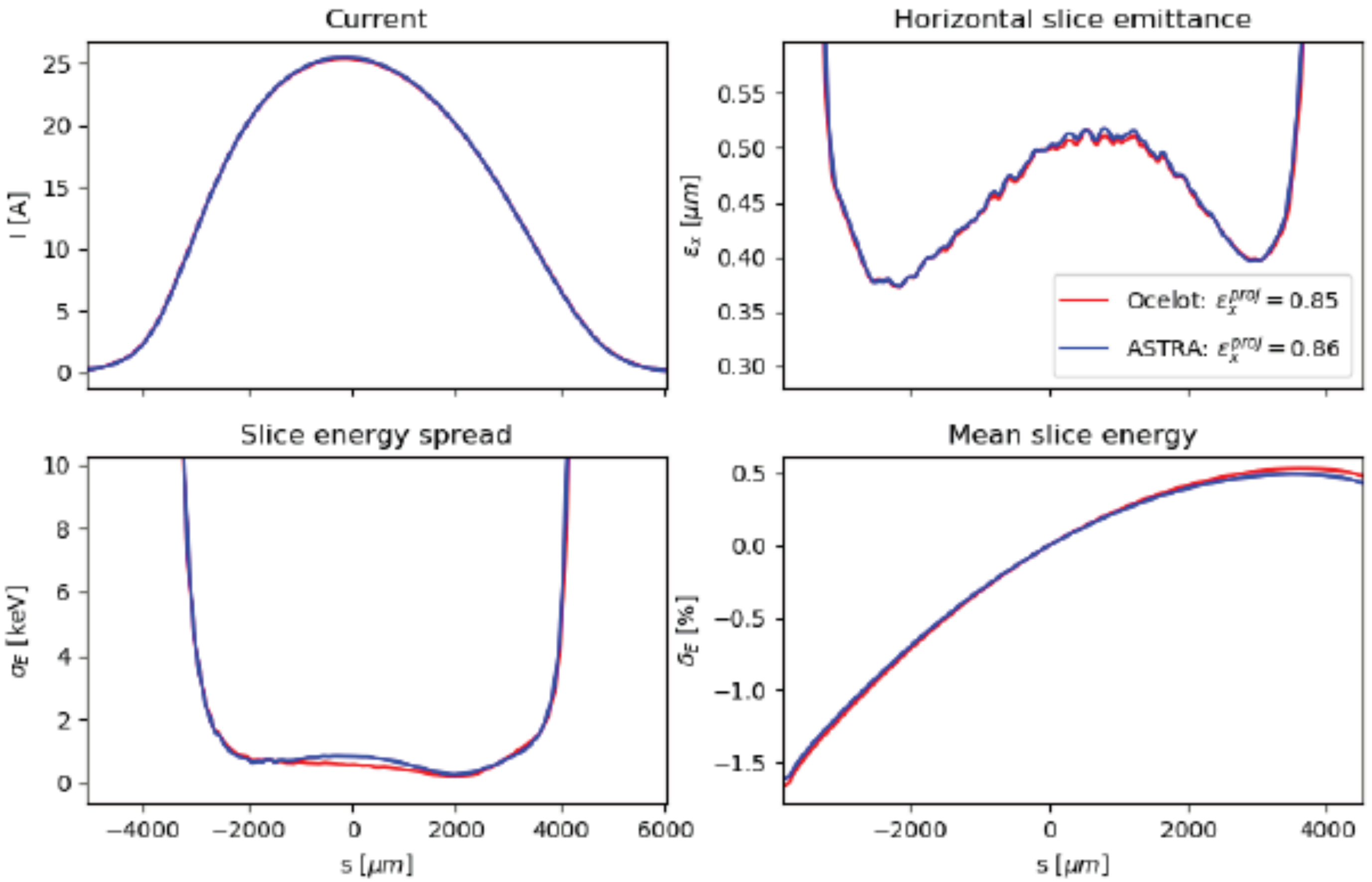






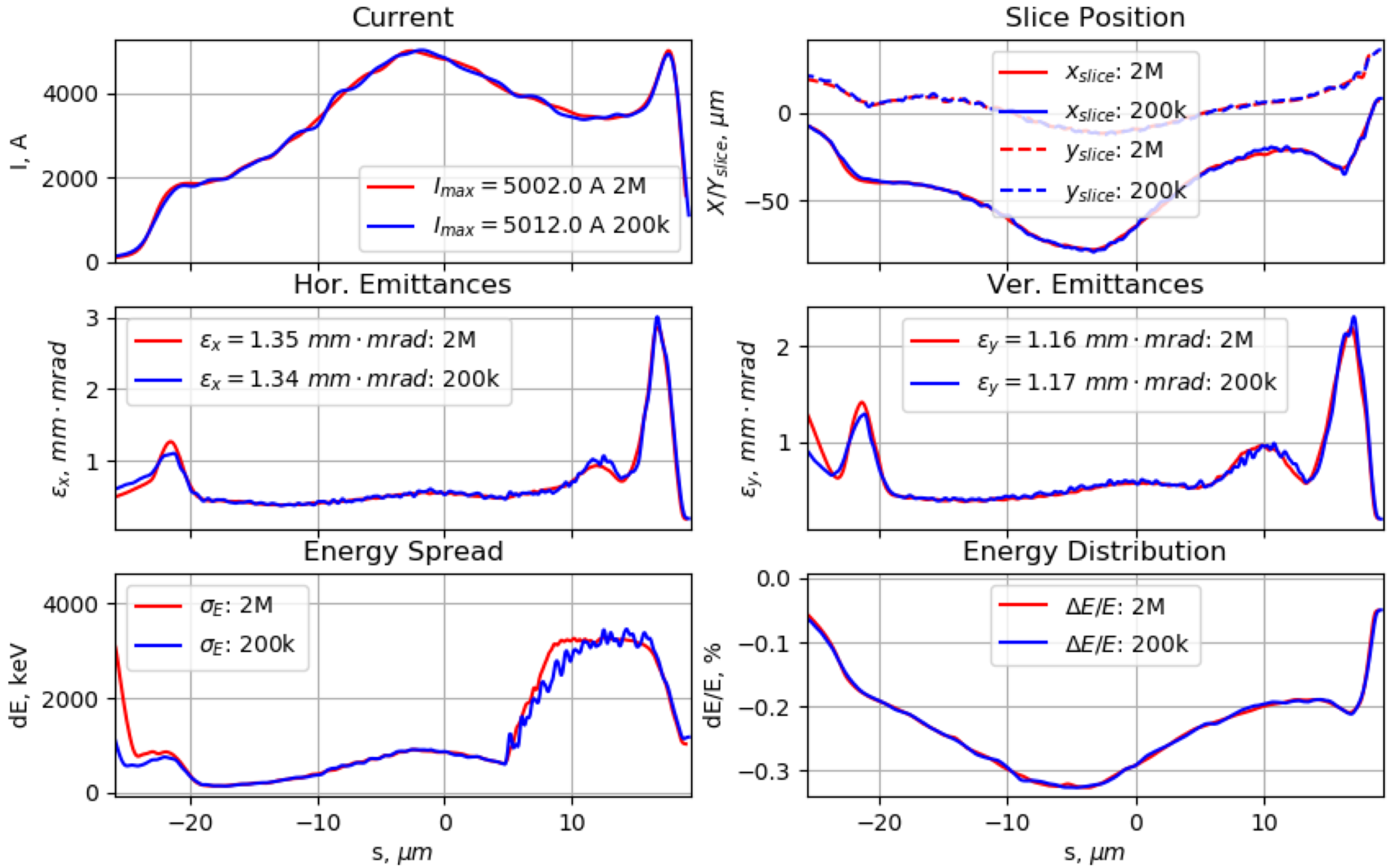
- Comparison of ***β***-function and projected emittance in the booster calculated by ASTRA (in blue) and Ocelot (in red)

Accuracy of the results. Check of SC and RF focusing models



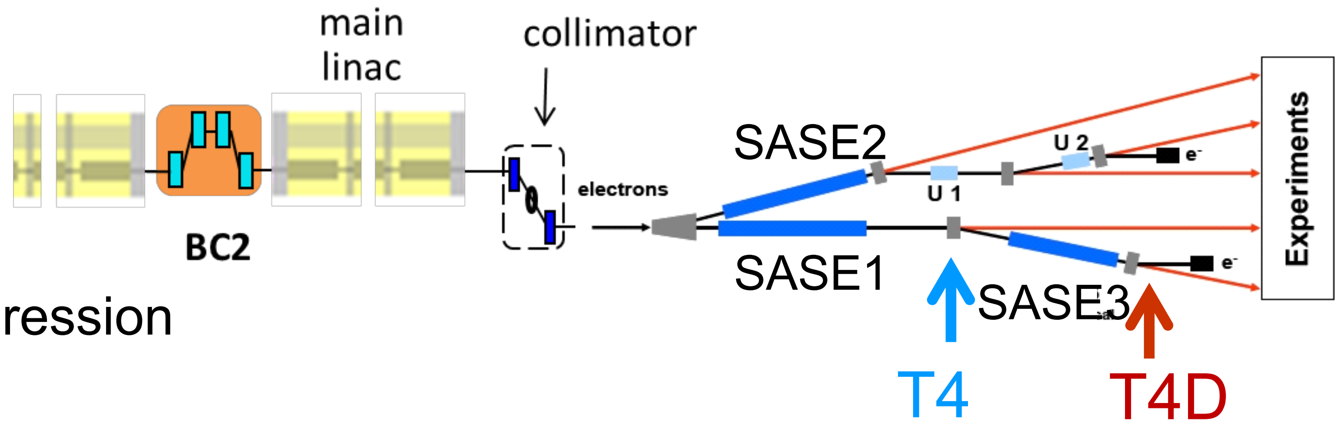
- Comparison of the slice parameters after the booster calculated by ASTRA (in blue) and Ocelot (in red)

Accuracy of the results. Increase of number of macroparticles

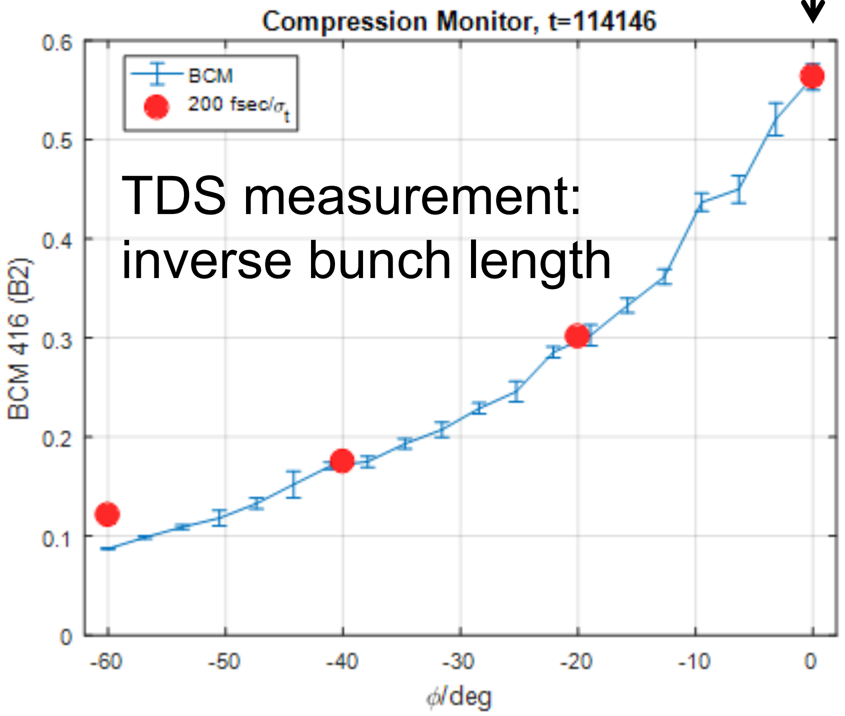


- increase of the macroparticle number by factor 10: from 200k to 2M
- the slice and projected parameters do not change

Accuracy of the results. Impedance database (simulations / experiment)

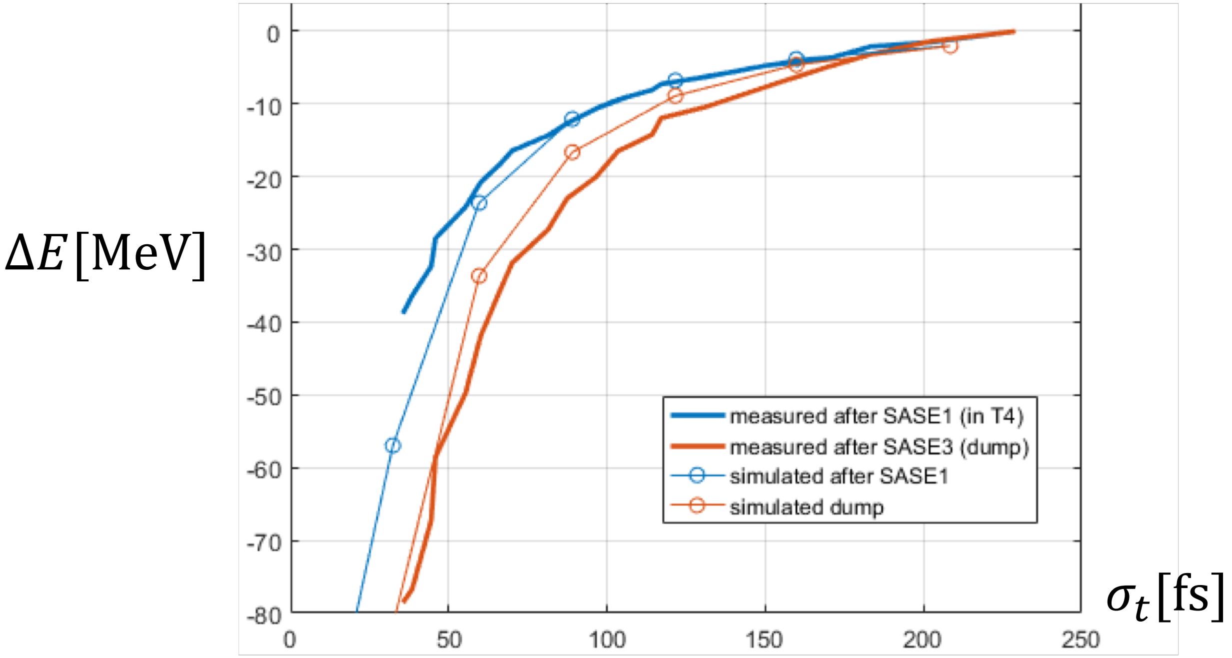


strong compression



Compression monitor calibration

Energy loss vs the bunch length (measured / simulated)



Summary

- Slice emittance in x / y plane, μm

Position	500 pC, 5kA	500 pC, 10 kA	250 pC, 5 kA	100 pC, 5 kA
after injector booster	0.50	0.50	0.36	0.18
after collimator	0.57	0.57 / 0.75	0.40	0.24 / 0.30
after T1 arc (before SASE2)	0.57	0.57 / 0.75	0.40	0.24 / 0.30

- Projected emittance in x / y plane, μm

Position	500 pC, 5kA	500 pC, 10 kA	250 pC, 5 kA	100 pC, 5 kA
after injector booster	0.84	0.84	0.67	0.30
after collimator	1.15 / 1.21	1.10 / 2.93	0.80 / 1.37	0.30 / 0.82
after T1 arc (before SASE2)	1.35 / 1.16	2.64 / 2.52	1.34 / 1.26	0.83 / 0.73

- In the simulations we have used the laser heater in the injector to provide 1 MeV slice energy spread after BC2

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