Beam Dynamics in SASE2 Arc

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MAC, Hamburg
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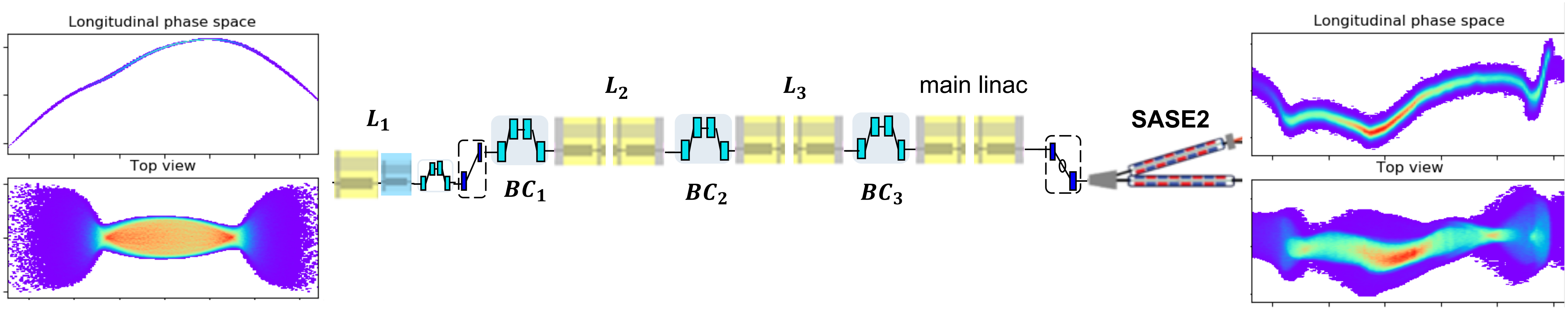
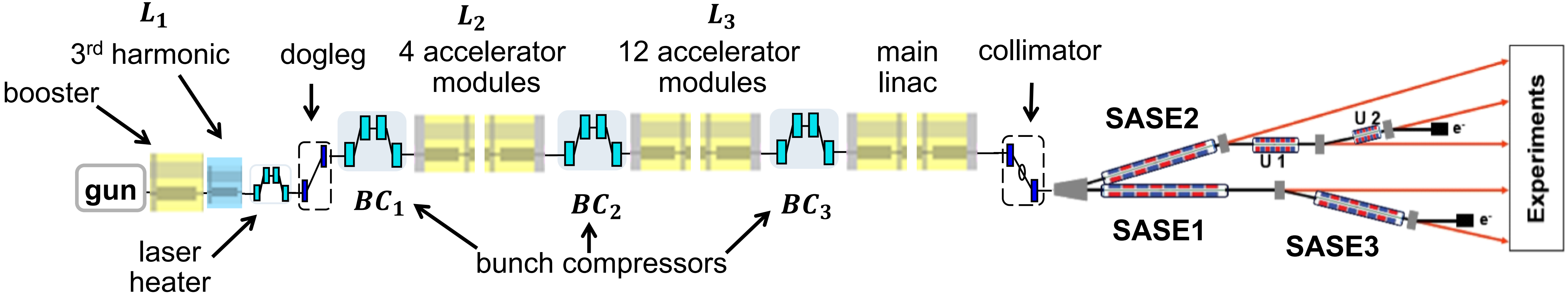


Outline

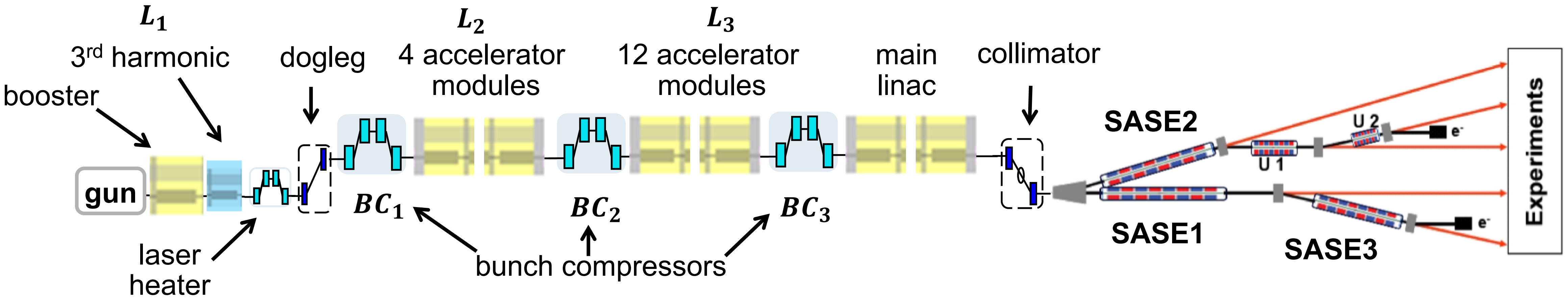
- Layout, optics, technical constraints
- Numerical approach
- RF tolerances, collective effects and the choice of the working point
- Beam dynamics up to SASE1/SASE2 for 250 pC compressed to 3-7 kA
- SASE simulations for SASE1/SASE2 for 250 pC compressed to 3-7 kA
- Accuracy of the results
- Summary

Layout, optics, technical constraints



- 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

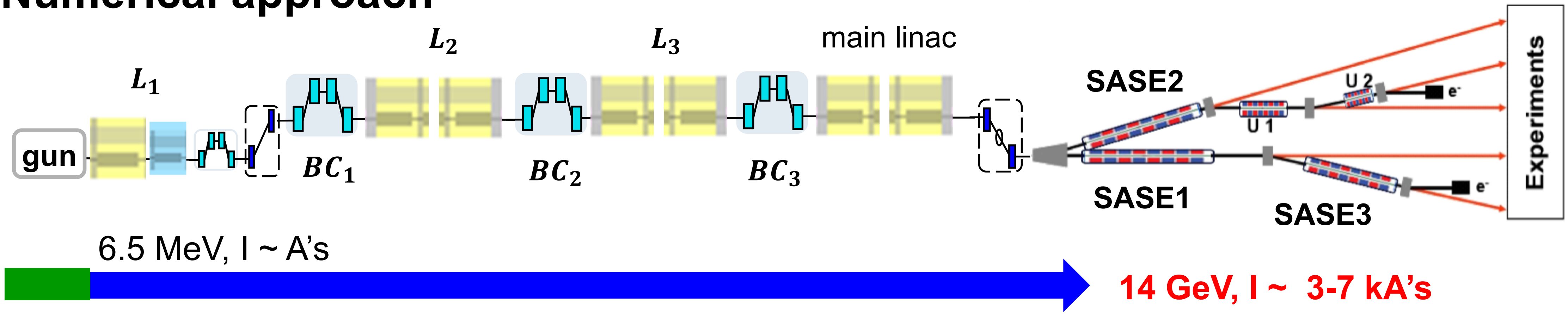
Section name	BC1	BC2	BC3
|r56|, mm	30-90	20-80	10-60

- 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

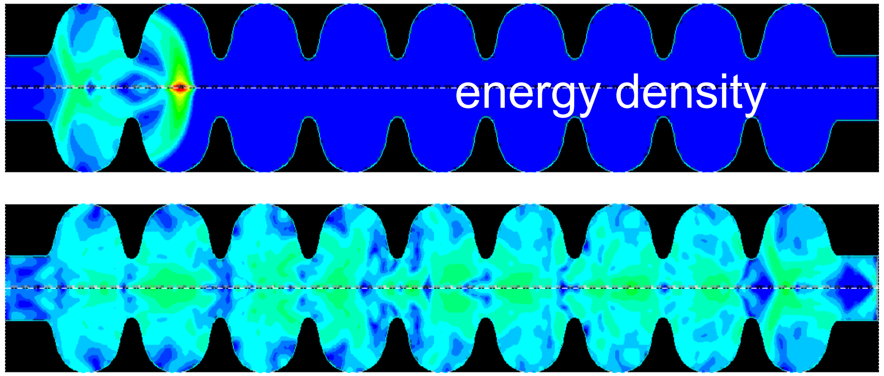


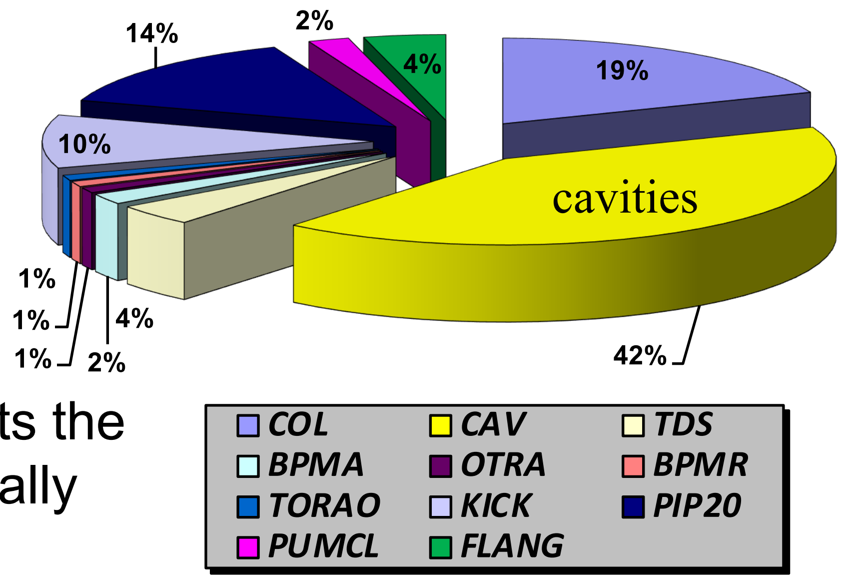
- **Krack3**
  - cathode physics
  - external fields by field maps
  - self-fields with 2D/3D Poisson equation
  - particle motion with finite-difference method
  - cathode through mirror charge
  - no chamber (no wakes)

- **Ocelot***
  - 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
  - ISR effects

*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, …

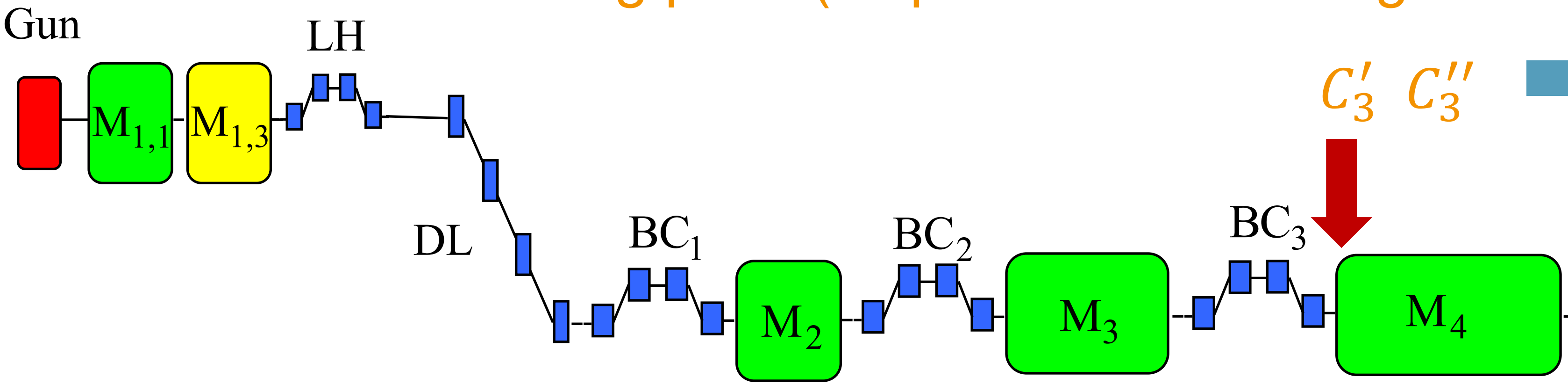
Source particle creates fields, test particle gets the integrated kick. Wakes are calculated analytically and with electromagnetic code **ECHO***.

- 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)*

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

Working point (11 parameters of longitudinal beam dynamics)



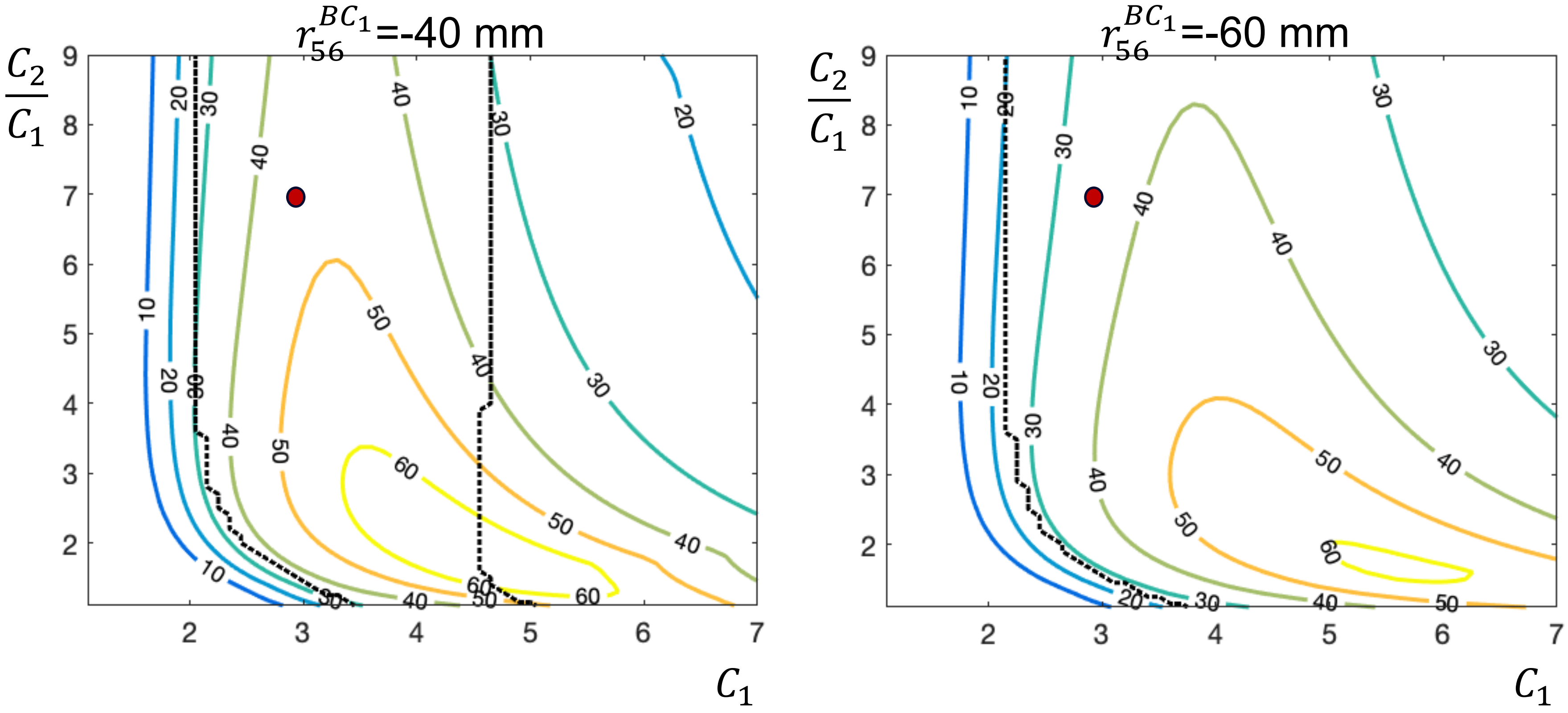
- the first and the second derivatives of the global compression

- energy in BC: $E_1 = 130$ MeV, $E_2 = 700$ MeV, $E_3 = 2400$ MeV
- deflecting radius: $r_{56,1} = ?$, $r_{56,2} = ?$, $r_{56,3} = ?$
- compression factor: $C_1 = ?$, $C_2 = ?$, $C_3 = I_{\text{final}}/I_{\text{gun}}$

What is the optimal choice?

I. Zagorodnov, M. Dohlus, S.Tomin, *Accelerator Beam Dynamics at the European XFEL*, Phys. Rev. STAB, 2019.

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



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

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

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

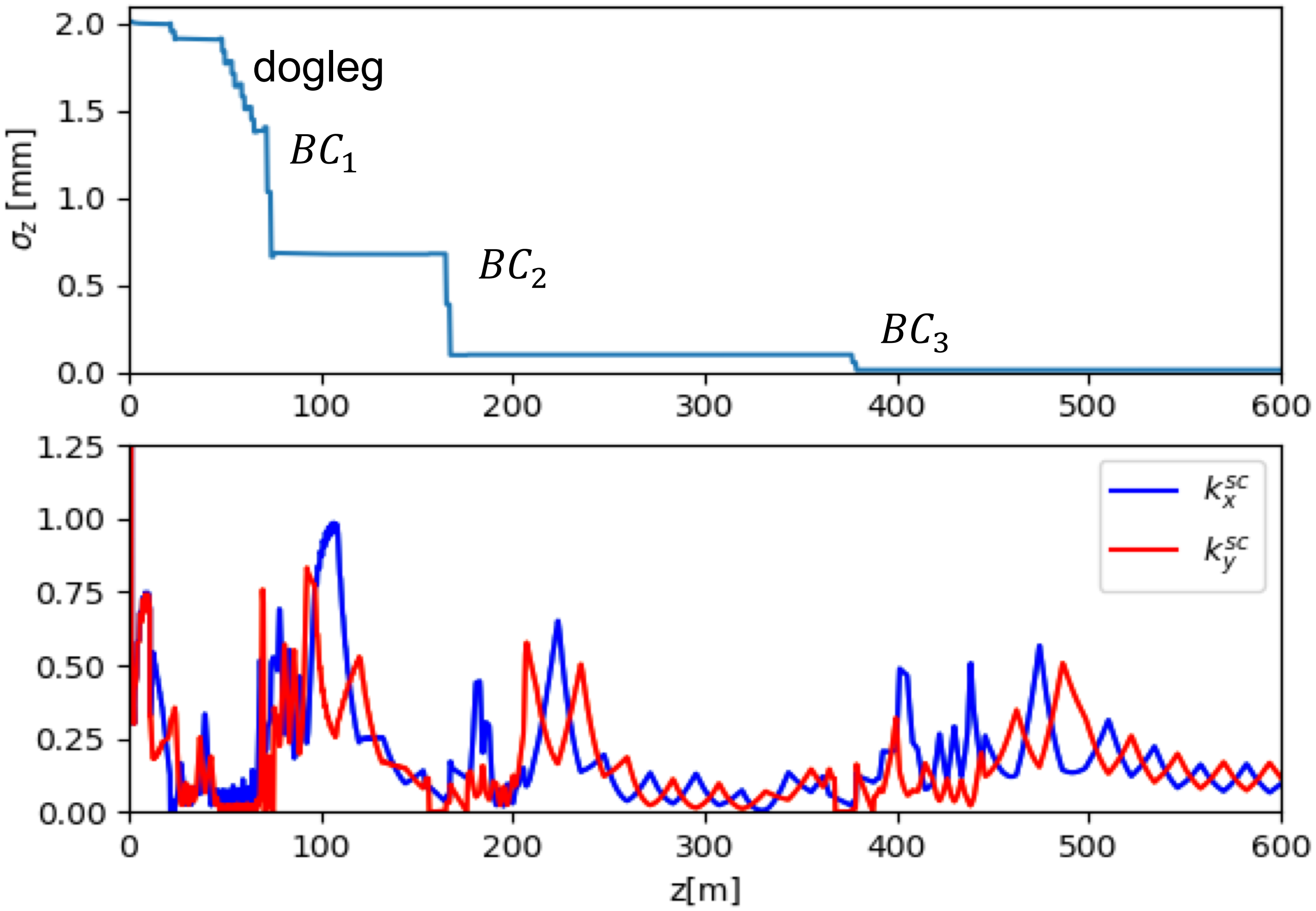
We always show the tolerances for

$$\Theta = 0.1$$

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	250 pC, 3kA	250 pC, 5 kA	250 pC, 7 kA	real setup (29.04.2019)
E_1, MeV		130		130
$r_{56,1}$, mm		40		50
C_1		3		
E_2, MeV		700		700
$r_{56,2}$, mm		63		51
C_2		21		
E_3, MeV		2400		2400
$r_{56,3}$, mm		21		30
C_3	**210**	**350**	**490**	
Z_3', 1/m		0		
Z_3'', 1/m/m	700	900	1000	

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

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

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

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

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

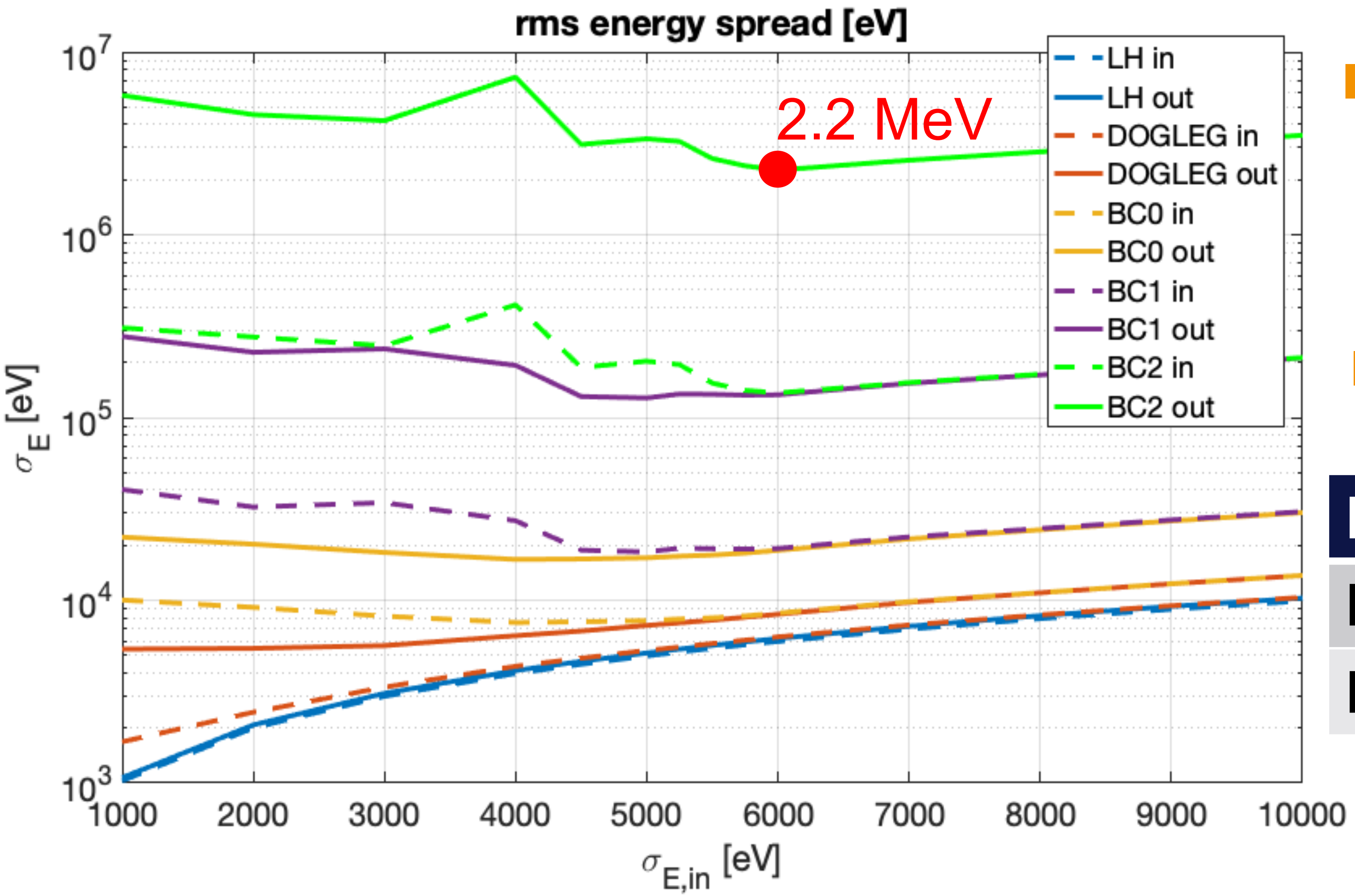
- The RF tolerances for 10% change of the global compression

	$V_{11}\theta_{11}^{V}$	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
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 **2.2 MeV** slice energy spread after the full compression (after BC2). This corresponds to the minimal energy spread as found in microbunching studies done by M. Dohlus (next slide).

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

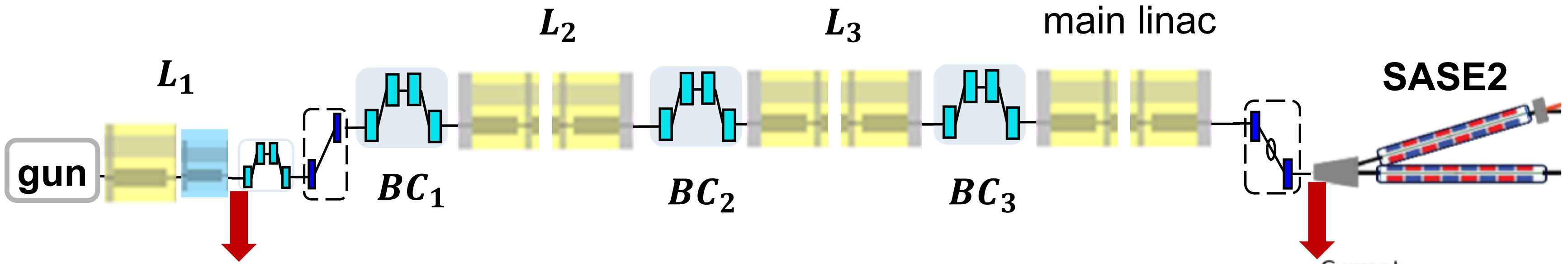
- Microbunching. Minimal slice energy spread at the working point of 5 kA



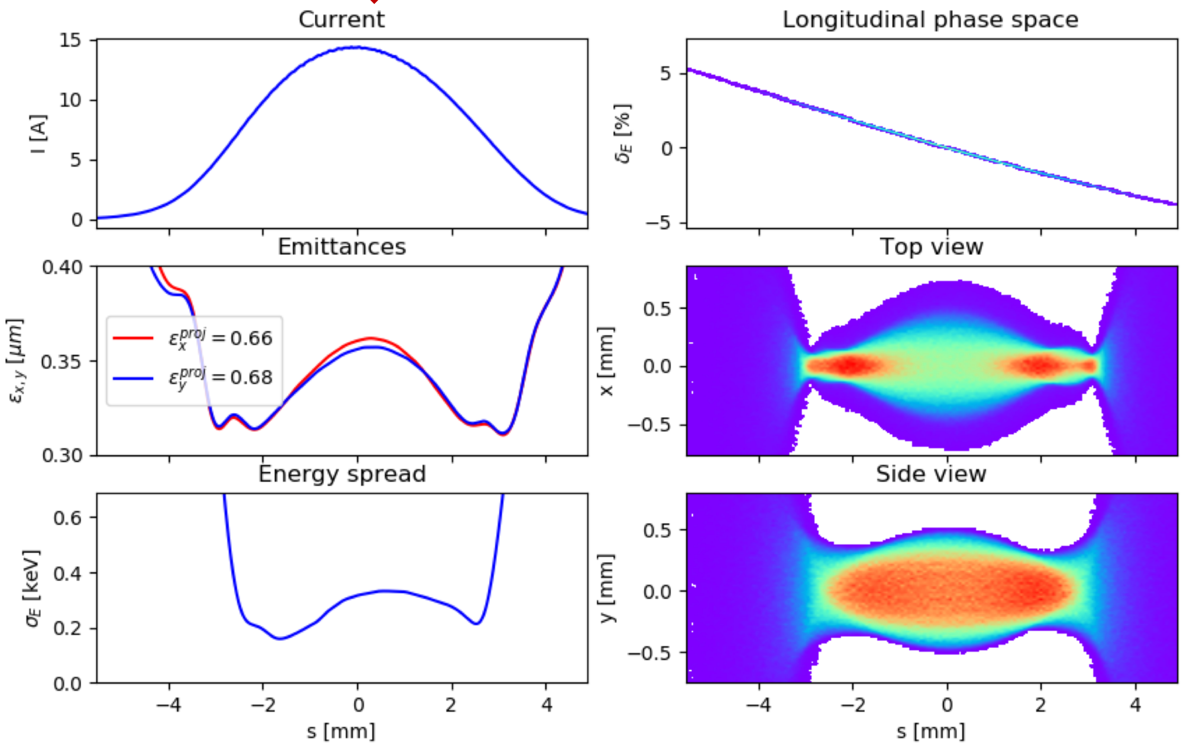
- The results are obtained by M. Dohlus numerically by tracking of real number of electrons (periodic model).
- Quantum fluctuations. Spread due to ISR only negligible.

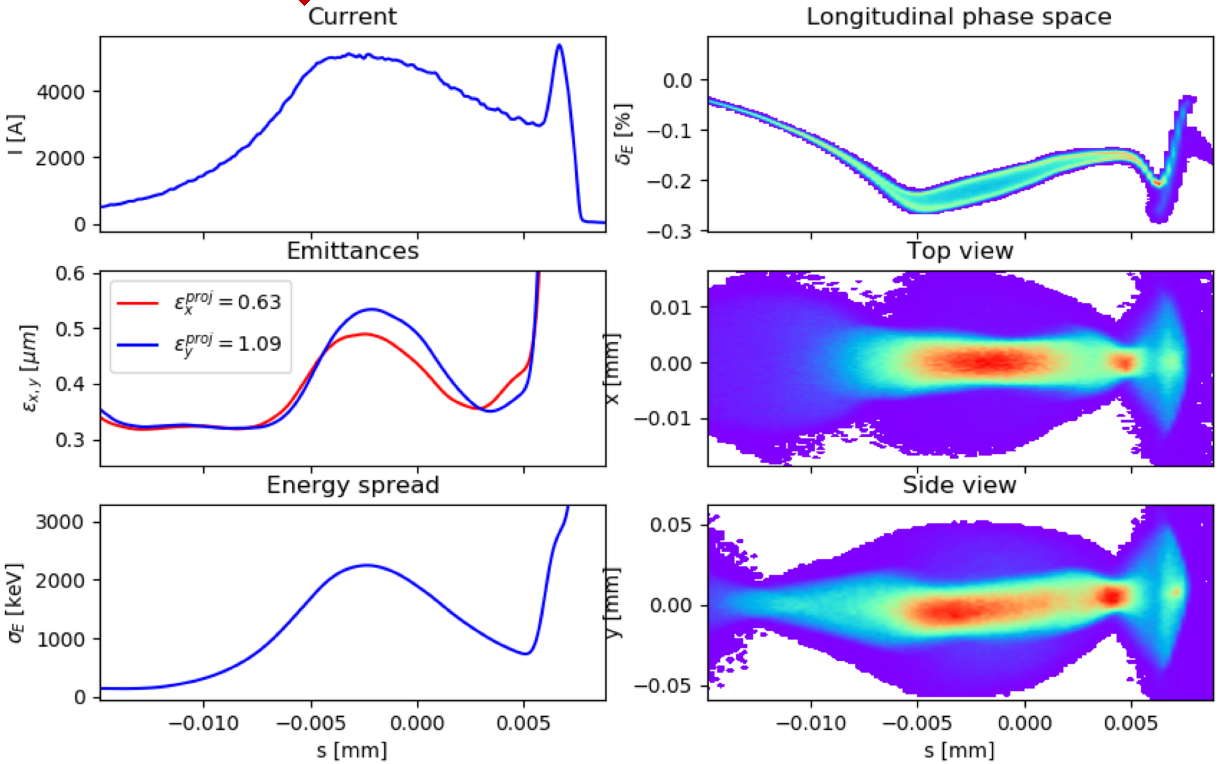
Position	Spread, keV
Before SASE1	40
Before SASE2	90

Beam dynamics for 5 kA (Gun → Collimator)

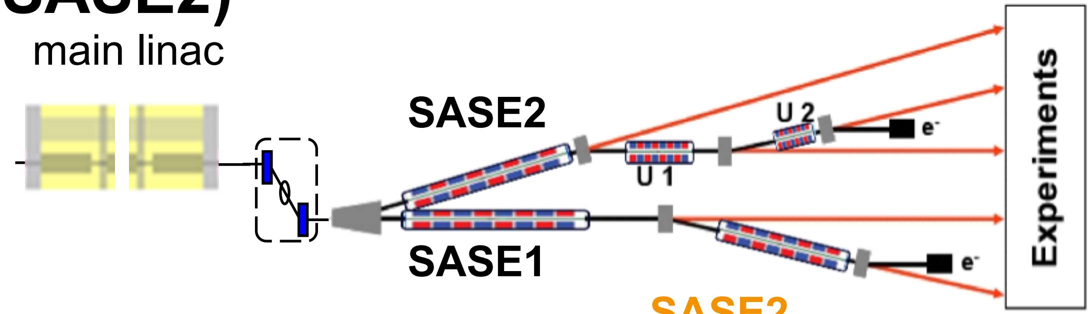


- slice emittance growth by 20%
- projected y-emittance growth by 50%

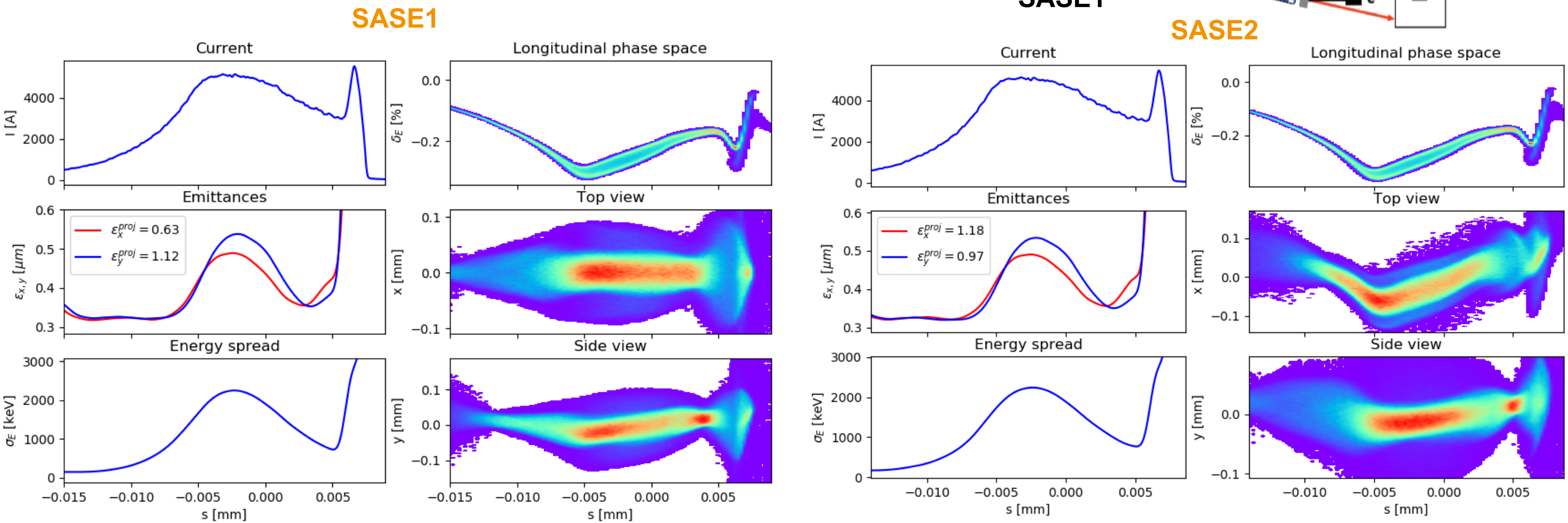




Beam dynamics for 5 kA (SASE1 vs. SASE2)

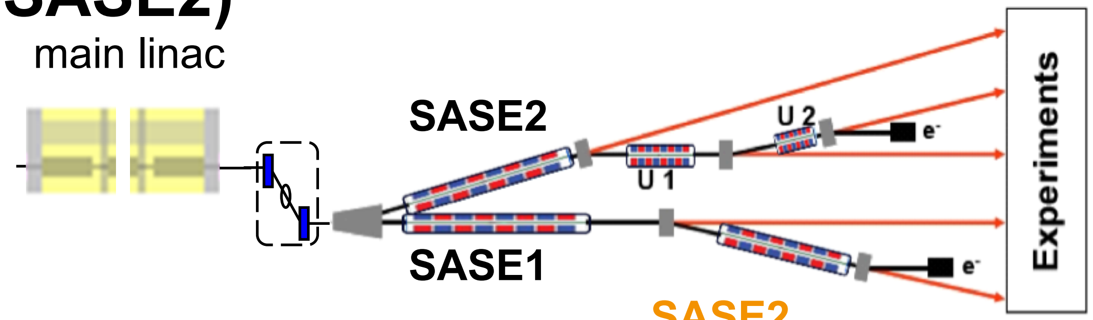


- projected x-emittance growth in SASE2 arc by 90 %

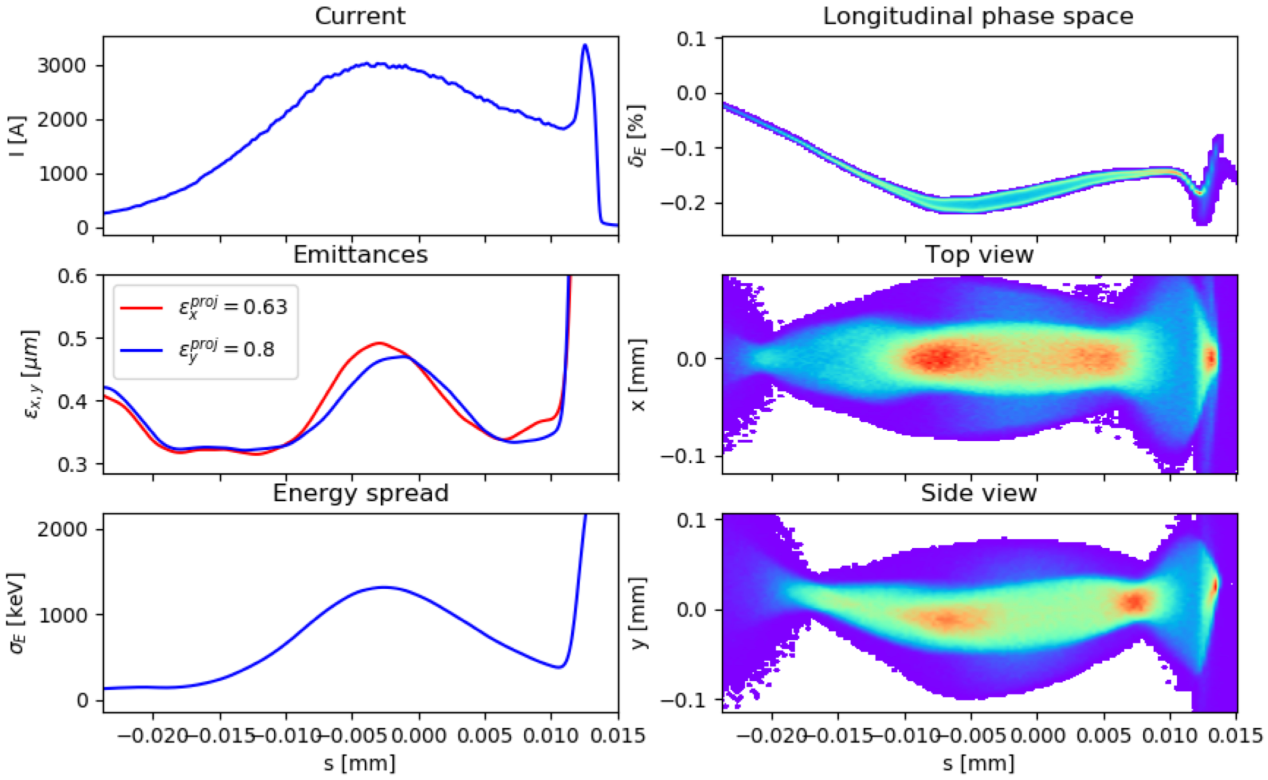


Beam dynamics for 3 kA (SASE1 vs. SASE2)

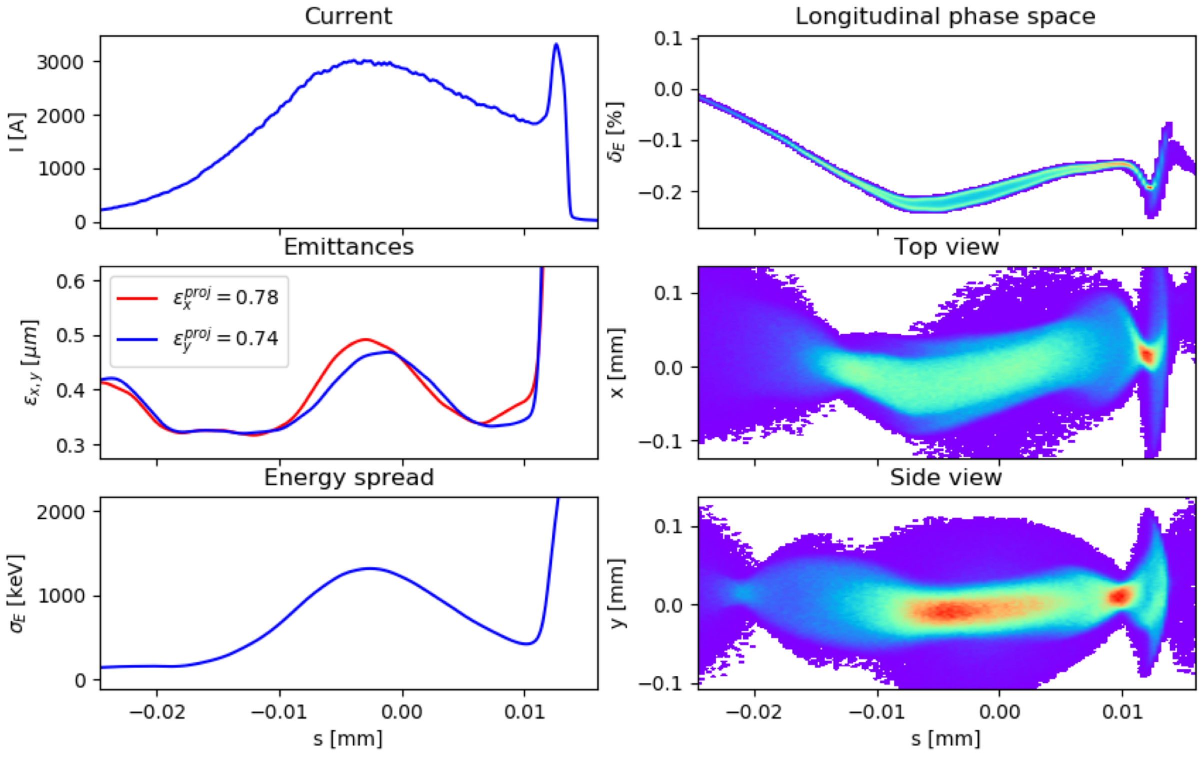
- projected x-emittance growth in SASE2 arc by 20 %



SASE1

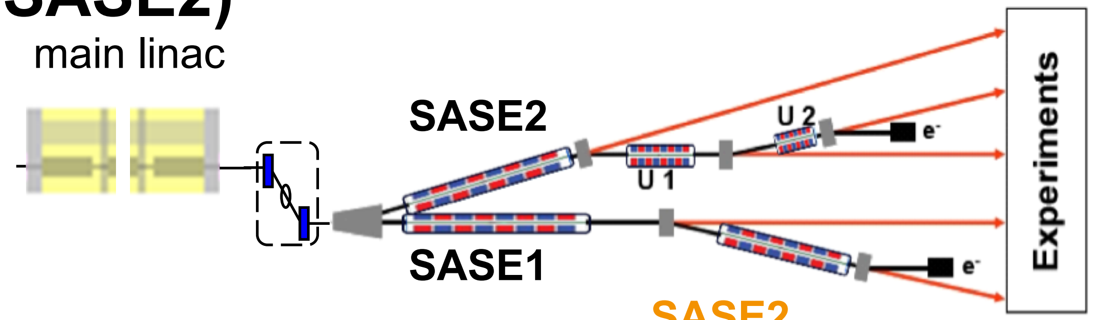


SASE2

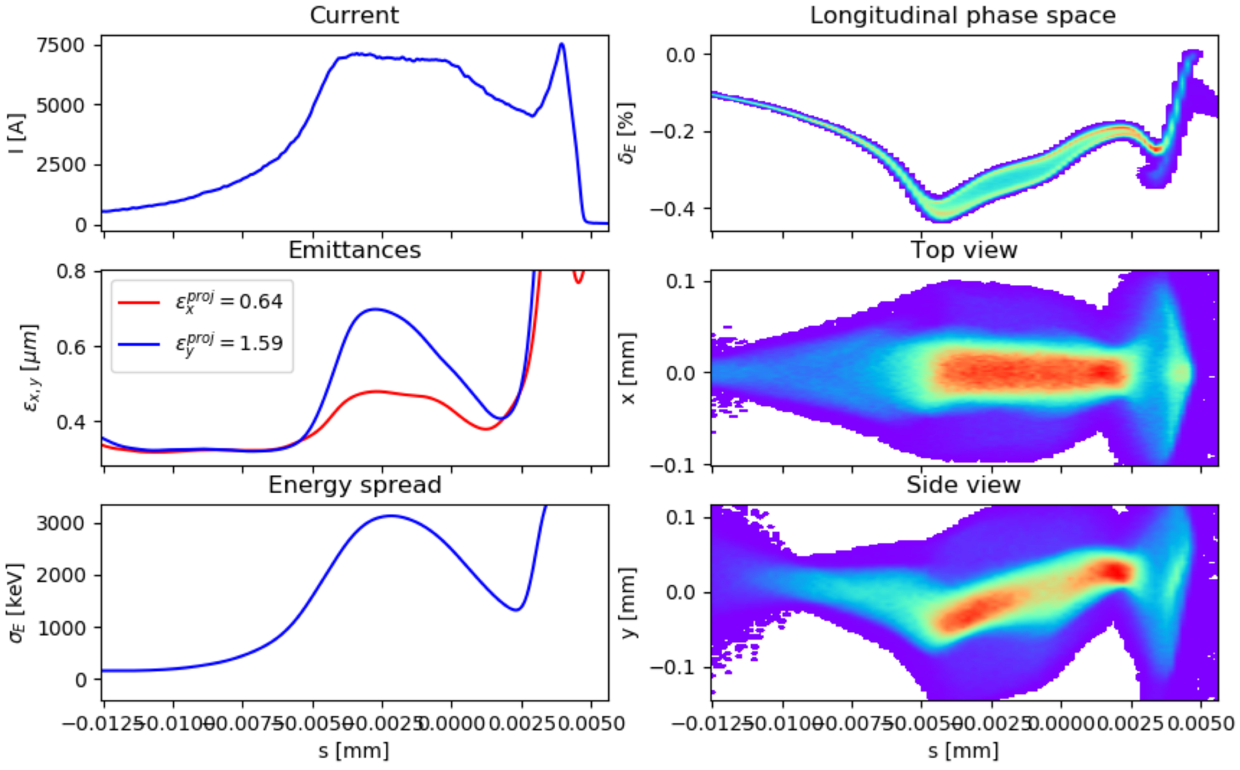


Beam dynamics for 7 kA (SASE1 vs. SASE2)

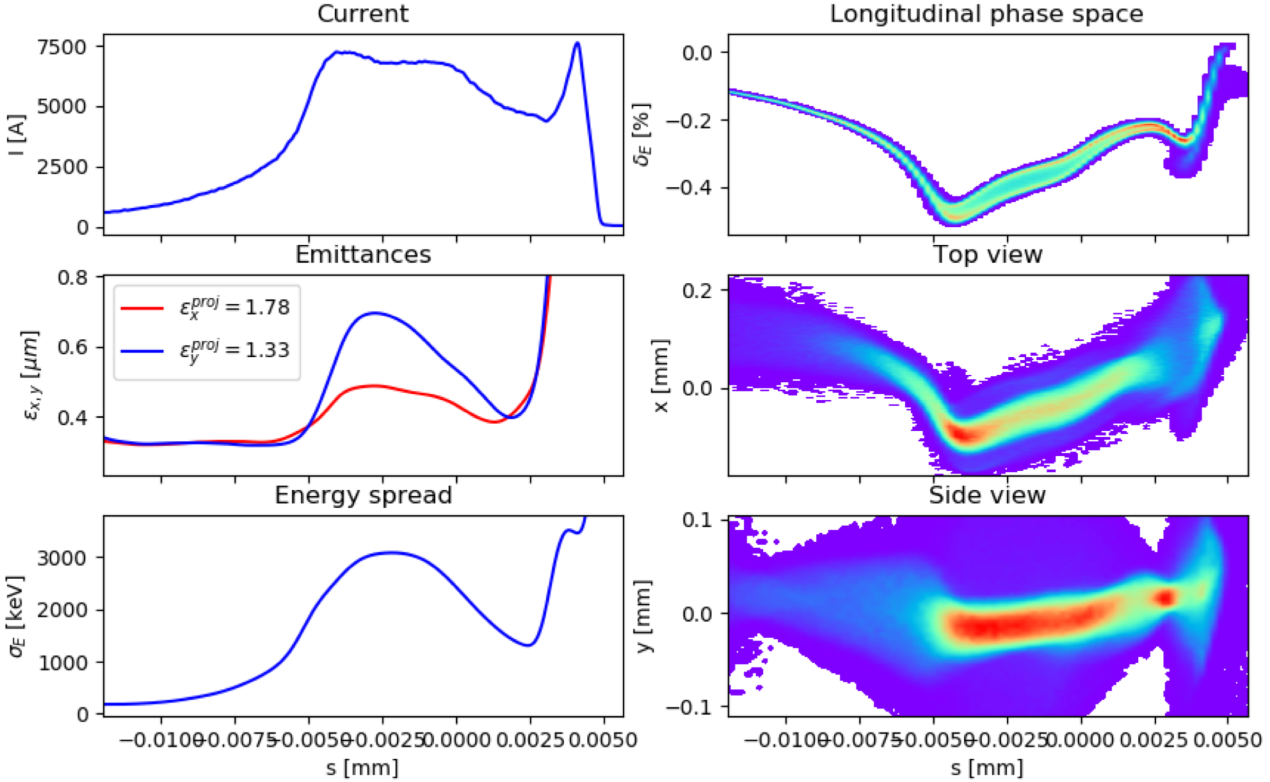
- slice y-emittance growth in BC3
- projected x-emittance growth in SASE2 arc by 180 %



SASE1



SASE2



Beam dynamics for 250 pC compressed to 3-7 kA

- Beam parameters at SASE2 vs SASE1

Parameter	3 kA		5 kA		7 kA	
	SASE1	SASE2	SASE1	SASE2	SASE1	SASE2
Projected x-emittance, μm	**0.63**	**0.78**	**0.63**	**1.18**	**0.64**	**1.78**
Projected y-emittance, μm	0.80	0.74	1.12	0.97	1.59	1.33
Slice x-emittance, μm	0.48		0.50		0.50	
Slice y-emittance, μm	0.45		0.55		0.70	
Slice energy spread, MeV	1.4		2.2		3	

- The main effect of SASE2 arc is an increase of the projected horizonal emittance due to CSR.

SASE simulations for 250 pC compressed to 3-7 kA

- code ALICE*
- cross-checks with Genesis 1.3
- longitudinal wake included
- ISR and quantum fluctuations included
- optimal **linear** taper used
- non-linear taper is not considered

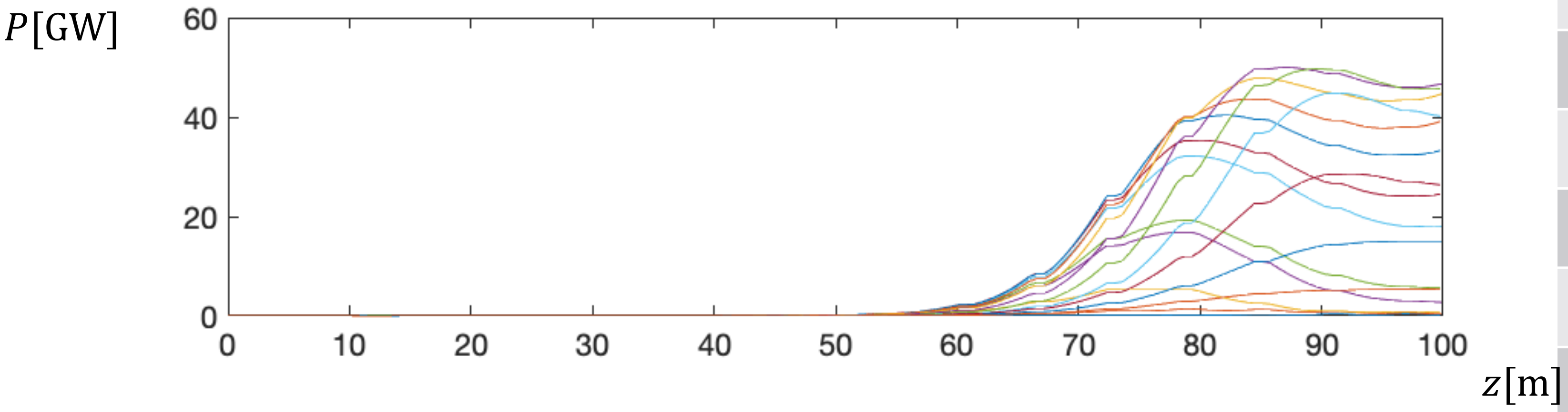
*I. Zagorodnov, Numerical modeling of collective effects in free electron laser, Proceedings of ICAP2012, Rostock-Warnemünde, Germany, TUACI1, pp. 81-85, 2012.

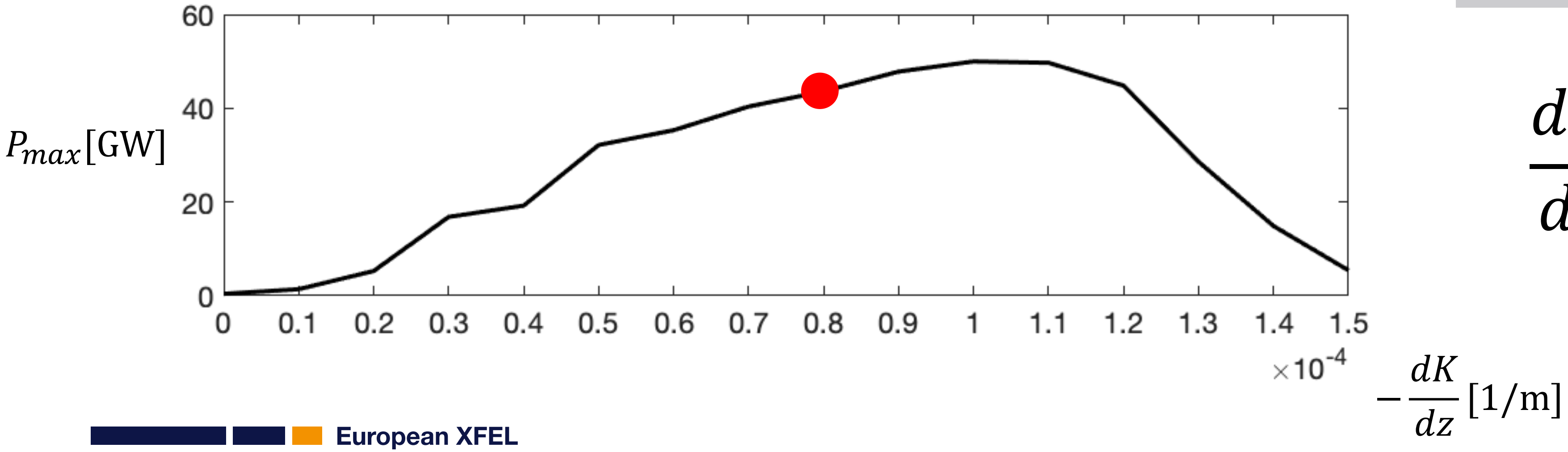
Table 1: Numerical Methods in Different Codes

	FAST	Genesis 1.3	ALICE
Equations of motion	Runge-Kutta		Leap-frog
EM field solver	Integral representation	Finite-difference, ADI	Finite-difference, Neumann
Boundary condition	Free space	Dirichlet	Free space with PML

SASE simulations for 250 pC compressed to 3-7 kA

Scan to choose a linear taper (amplifier model)



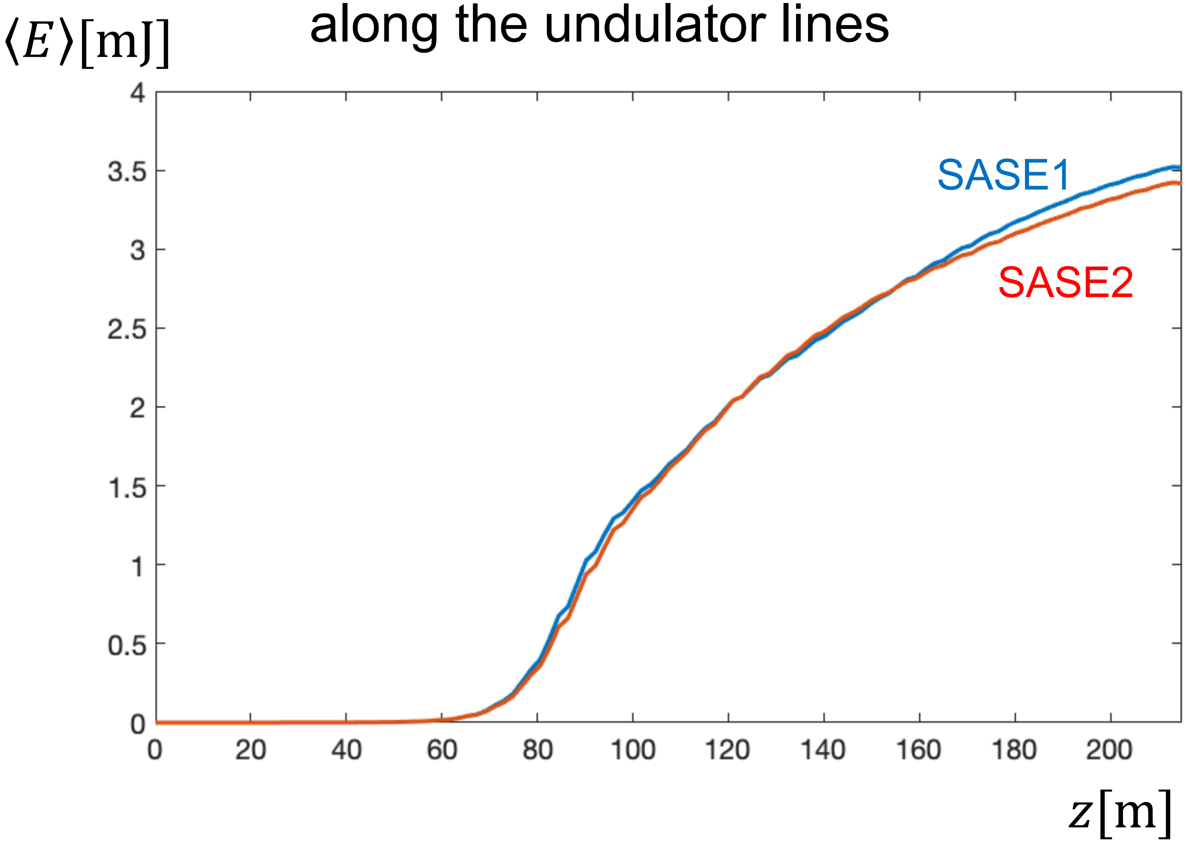


Parameter	Value
Beam energy, GeV	14
Energy spread, MeV	2.2
Slice emittance, μm	0.5
Peak current, kA	5
Wake loss, keV/m	200
Averaged beta function, m	32
Photon energy, eV	9300

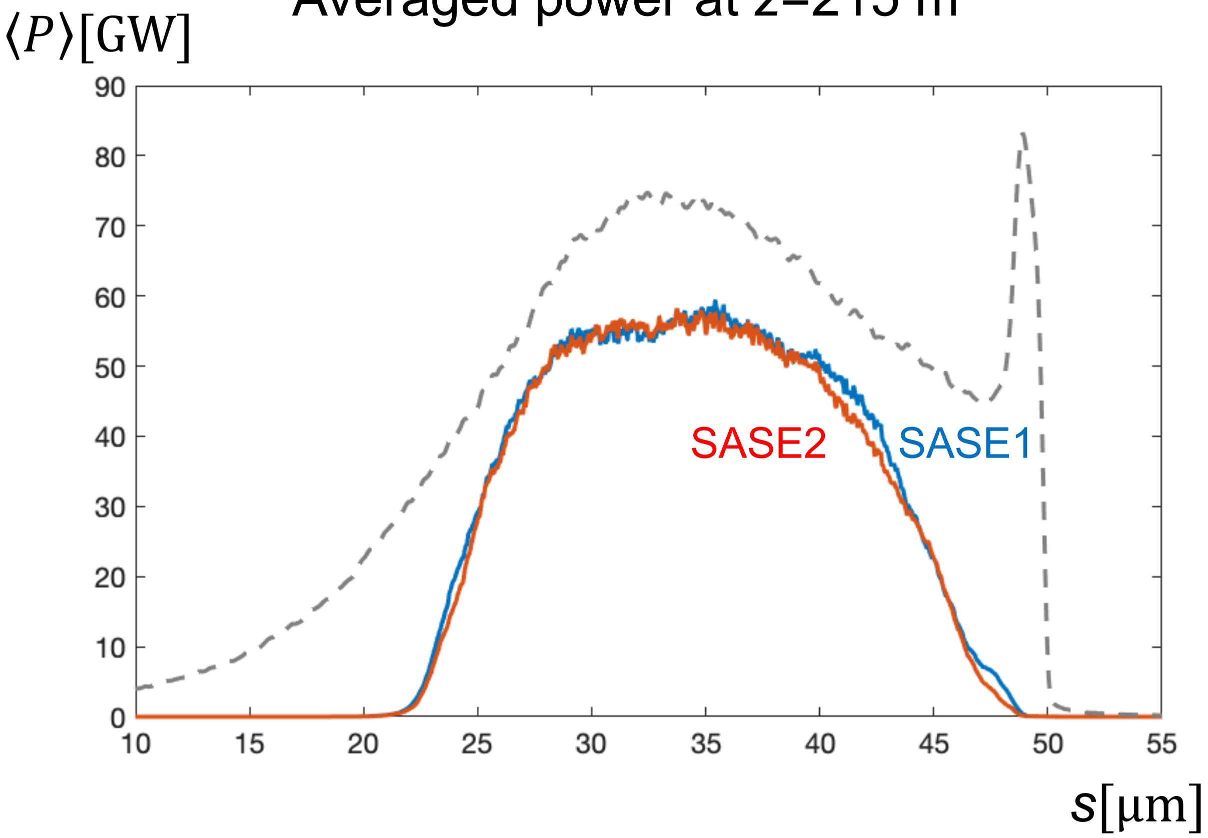
$$\frac{dK}{dz} = -8 \cdot 10^{-5} \ [1/\mathrm{m}]$$

SASE simulations for 3 kA

Averaged photon energy along the undulator lines



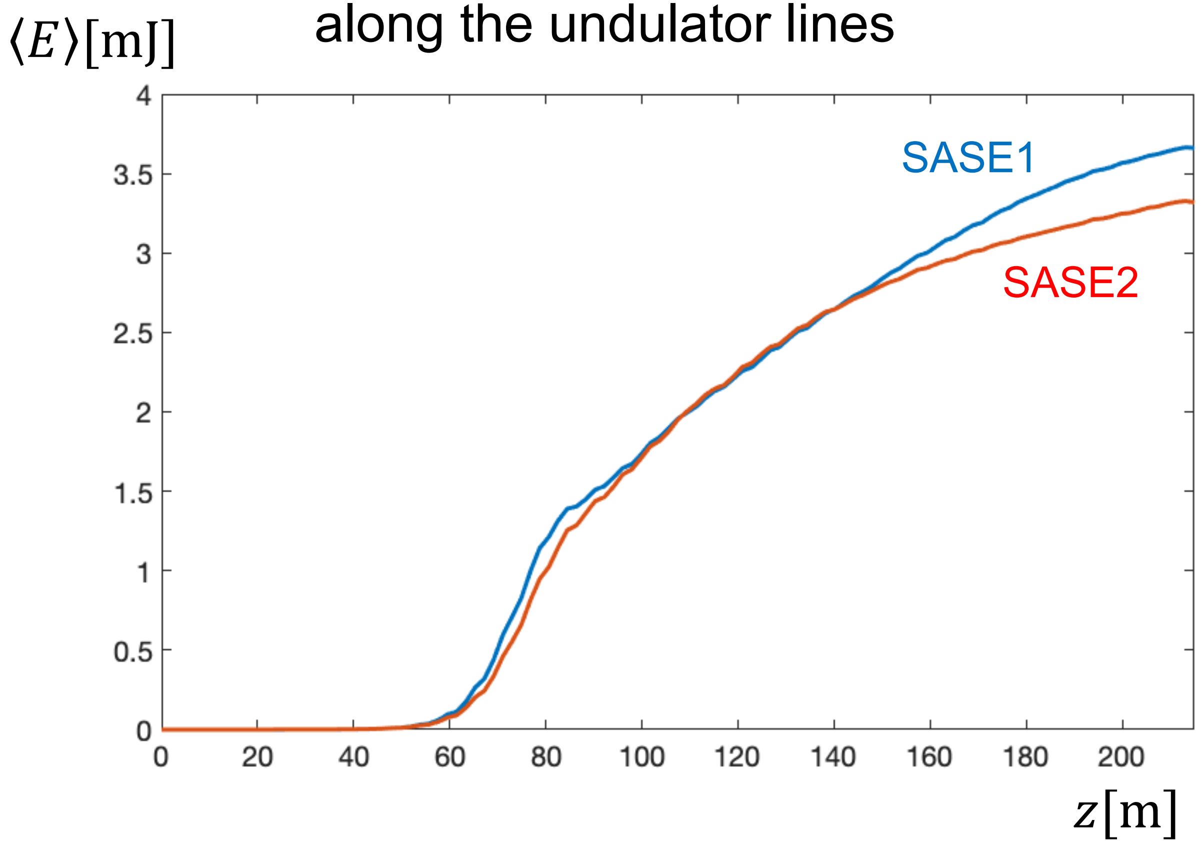
Averaged power at z=215 m



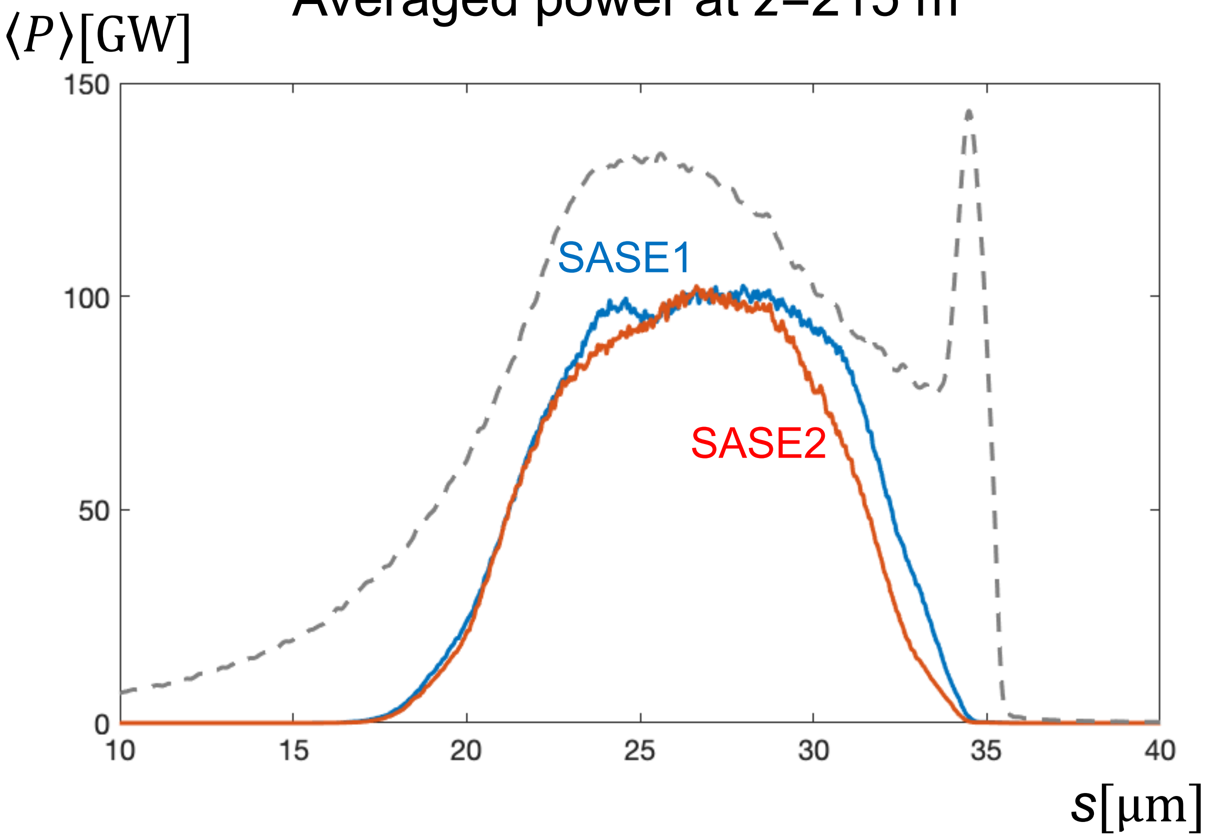
- No degradation at SASE level for 3 kA case.

SASE simulations for 5 kA

Averaged photon energy along the undulator lines



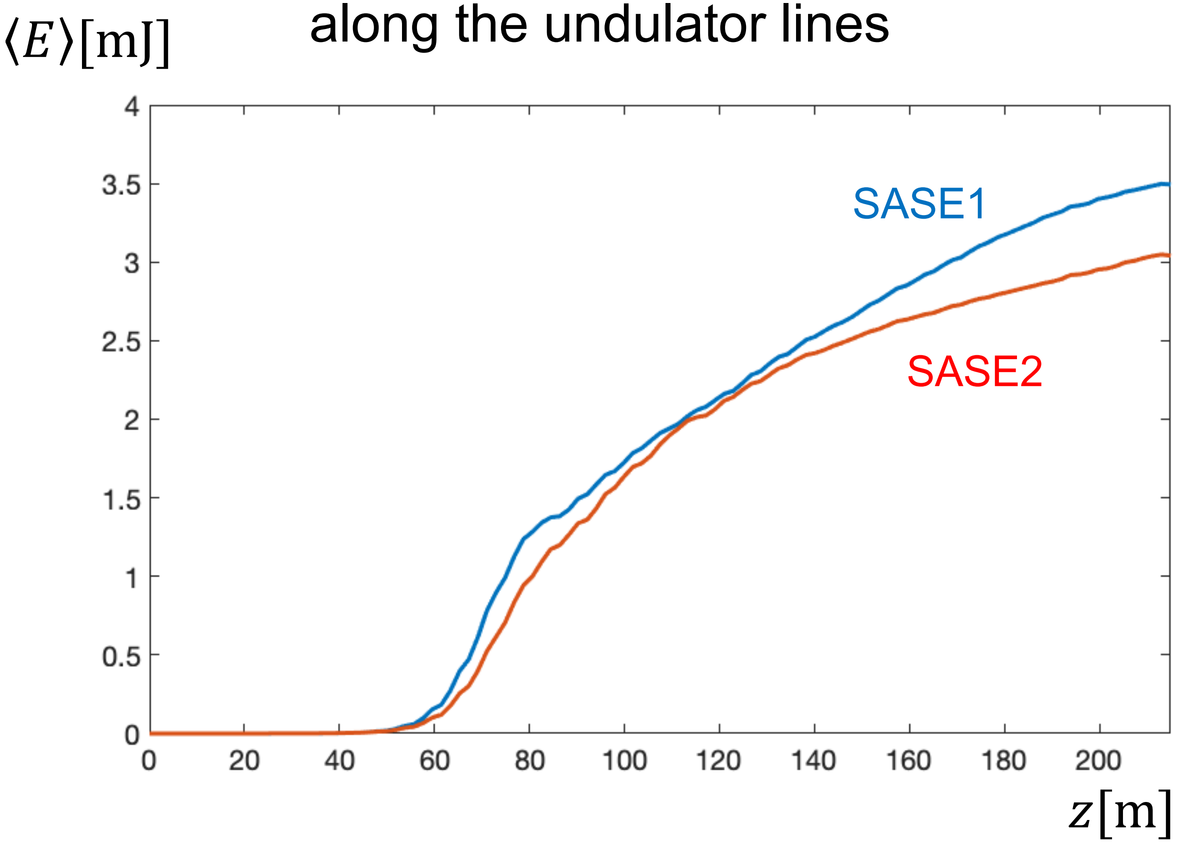
Averaged power at z=215 m



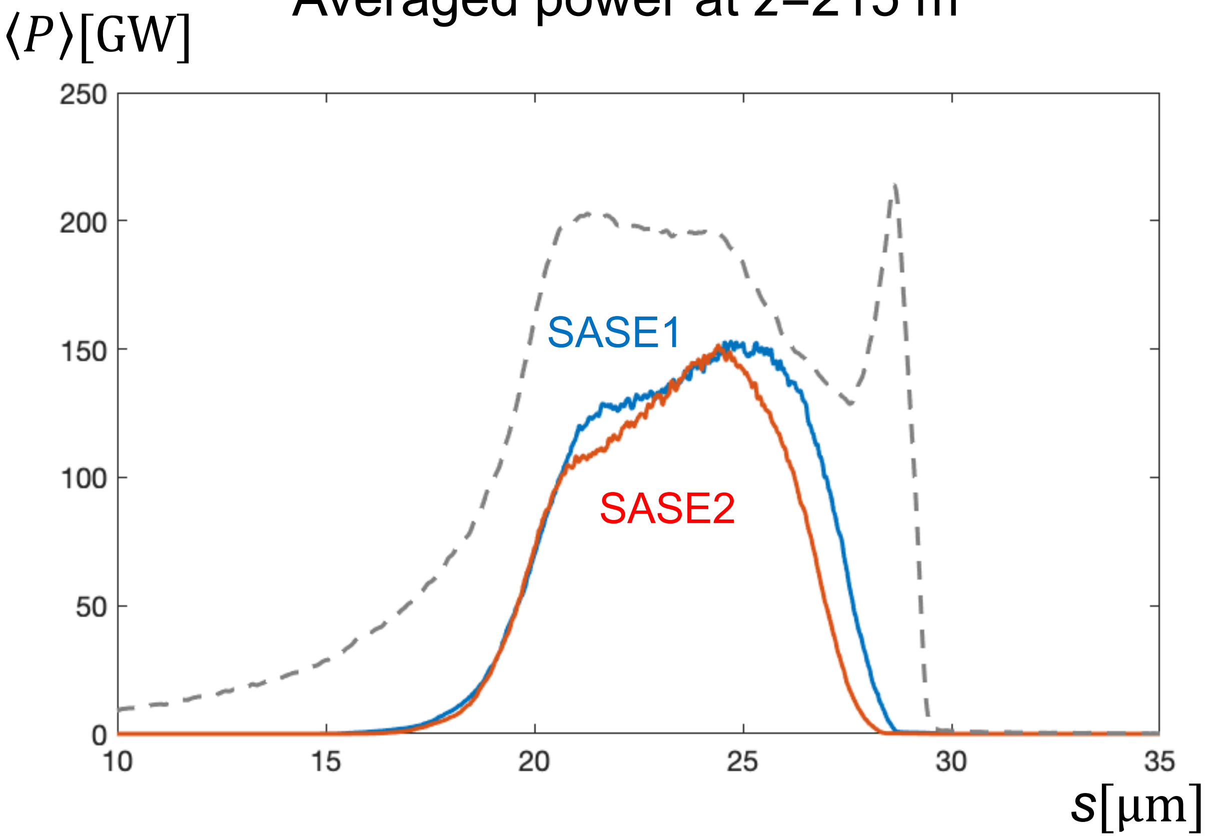
- 10% degradation at SASE energy level for 5 kA case.

SASE simulations for 7 kA

Averaged photon energy along the undulator lines



Averaged power at z=215 m



- 15% degradation at SASE energy level for 3 kA case.

SASE simulations for 250 pC compressed to 3-7 kA

- SASE radiation parameters at SASE2 vs SASE1.

Parameter	3 kA		5 kA		7 kA	
	SASE1	SASE2	SASE1	SASE2	SASE1	SASE2
Saturation length, m	100		85	90	85	90
Saturation energy, mJ	1.4					
Final energy at 215 m, mJ	3.5	3.4	3.7	3.3	3.5	3.0
Final power, GW	55		100		150	
Pulse width FWHM, fs	63	62	37	34	24	22

- The effect of SASE2 arc on SASE energy level for 250 pC compressed to 3-7 kA is below 15 %.

Accuracy of the results

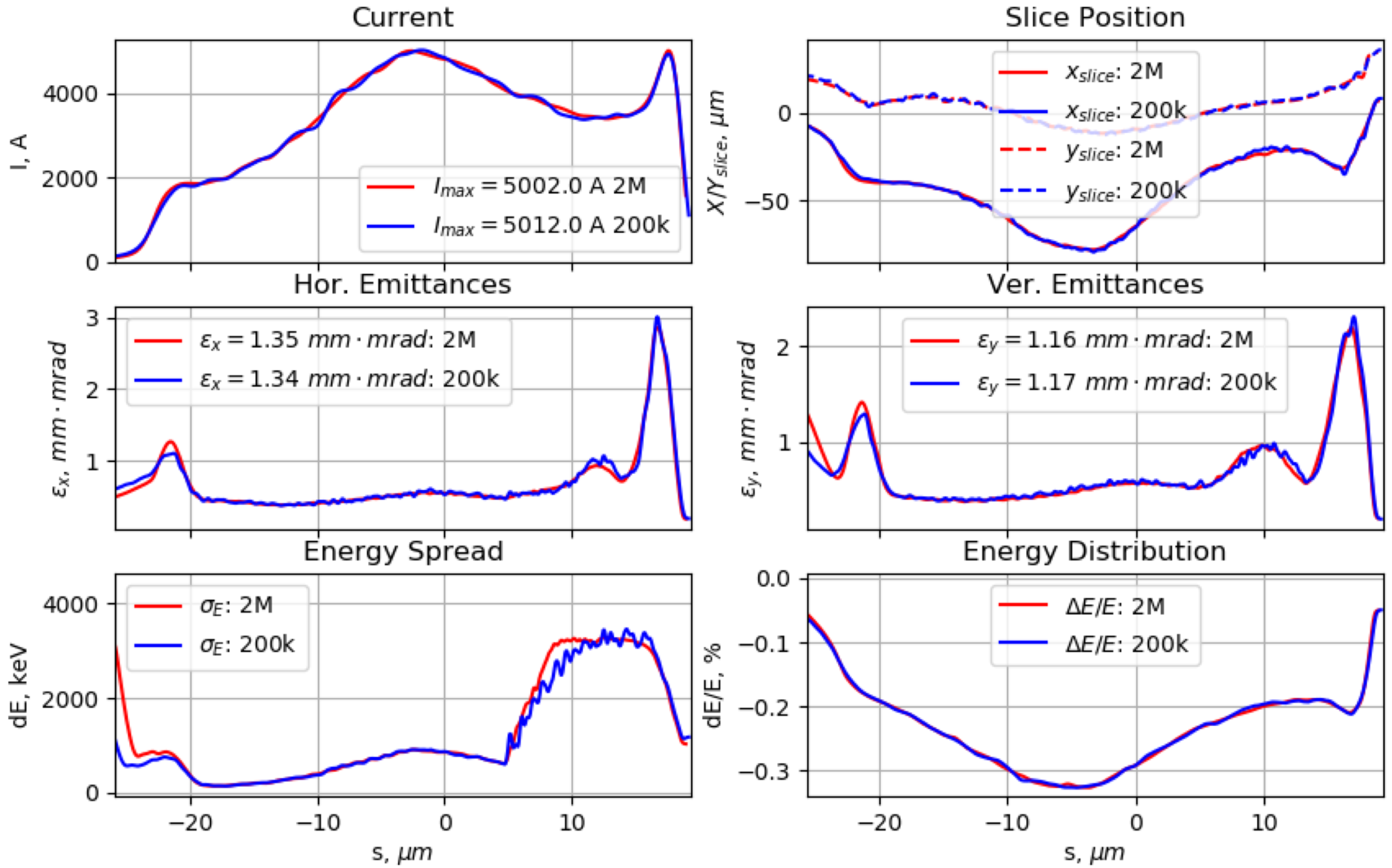
- Beam dynamics without collective effects
  - the second-order optics cross-checked with MAD
  - the chromatic effects in dispersive sections are cross-checked with CSRtrack
  - ISR effects are cross-checked with analytics

- 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

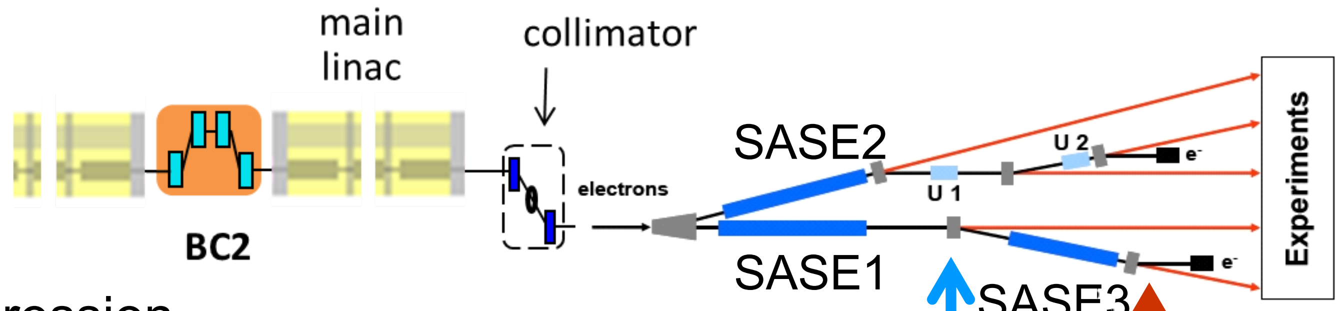
- What is missing?
  - the transverse wakes are taken into account only in RF modules
  - only 1D CSR model is used; the vacuum chambers in BC’s are not present

Accuracy of the results. Increase of number of macroparticles (500 pC)

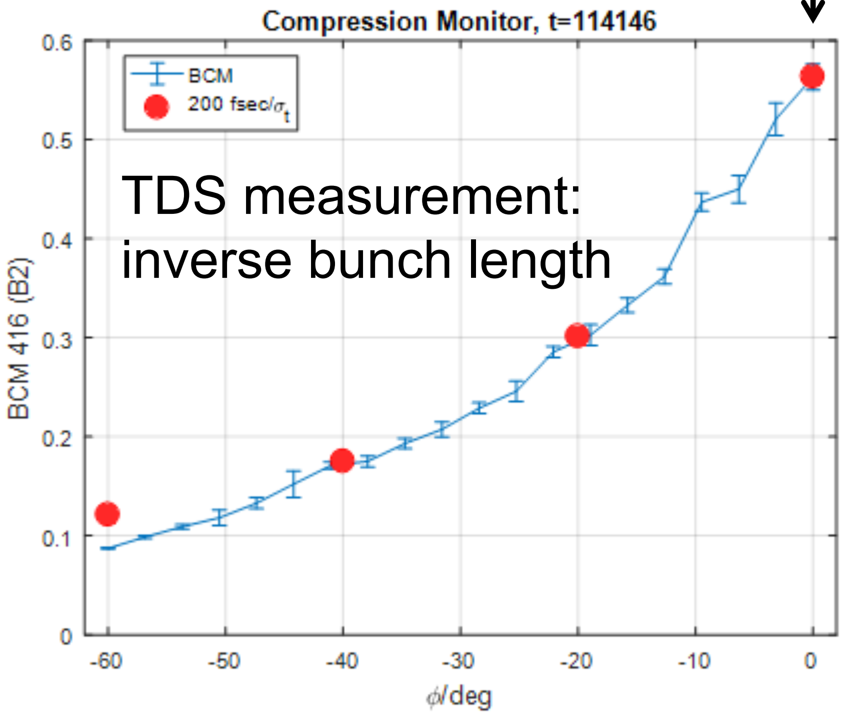


- increase of the macroparticle number by factor 10: from 200k to 2M
- the slice and the projected parameters do not change

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



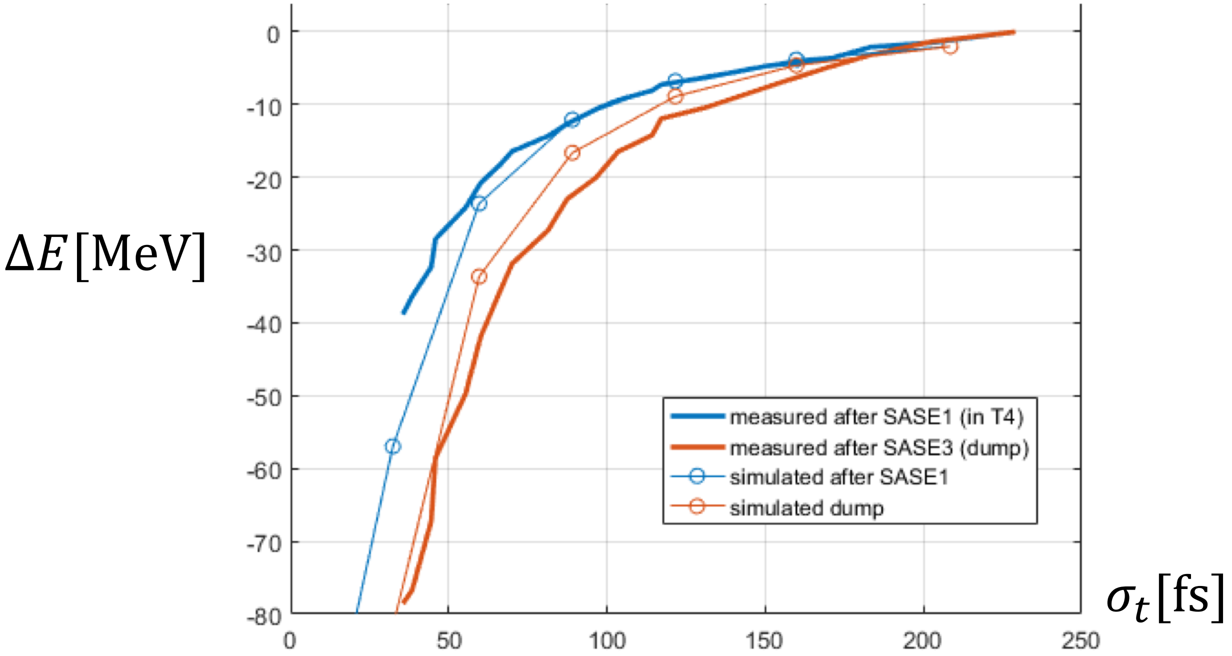
strong compression



TDS measurement:
inverse bunch length

Compression monitor calibration

Energy loss vs the bunch length (measured / simulated)



Summary

- The main effect of SASE2 arc is increase of the projected horizonal emittance due to CSR.
- SASE2 arc has a negligible impact on the slice emittance and the slice energy spread.
- The effect of SASE2 arc on SASE energy level for 250 pC compressed to 3 - 7 kA is below 15%.