Ultra-Short Low Charge Operation at FLASH and the European XFEL

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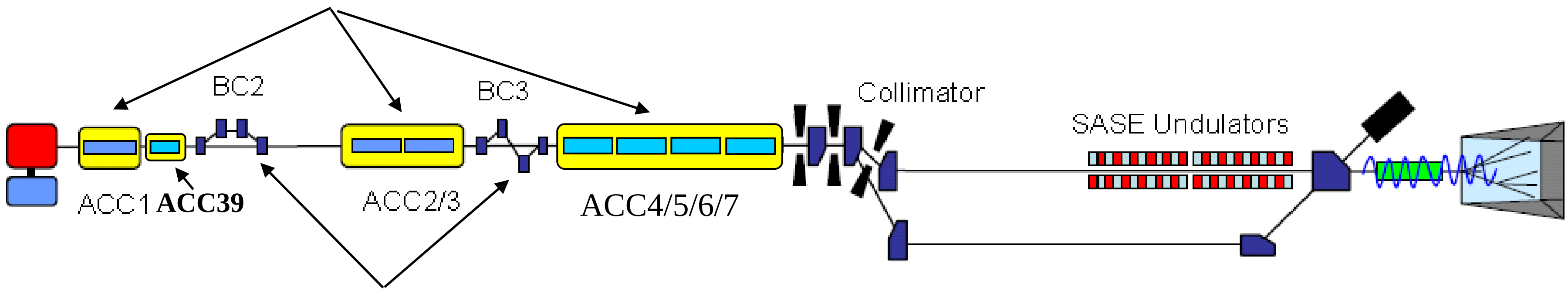
Outline

- FLASH layout and **desired beam parameters**
- Technical constraints and **choosing of machine parameters**
- **Simulation methods**
- FLASH beam dynamic **simulations for different charges**
- **Radiation properties** for different charges at FLASH
- First **experimental results** for low charges at FLASH
- Beam dynamics **simulations for European XFEL**

FLASH layout and desired beam parameters

short radiation wavelength $\lambda \sim \frac{1}{\gamma^2}$ high electron energy

In accelerator modules ACC1, ACC2,..., ACC7 the e**nergy** of the electrons is increased from 5 MeV (gun) upto **1200 MeV** (undulator).



In compressors **the peak current *I*** is increased from 1.5-50 A (gun) to **2500 A** (undulator).

short gain length $L_g \sim \frac{\varepsilon^{5/6}}{\sqrt{I}}\left(1+O(\sigma_E{}^2)\right)$ (for the optimal beta function)

high peak current

FLASH layout and desired beam parameters

small emittance

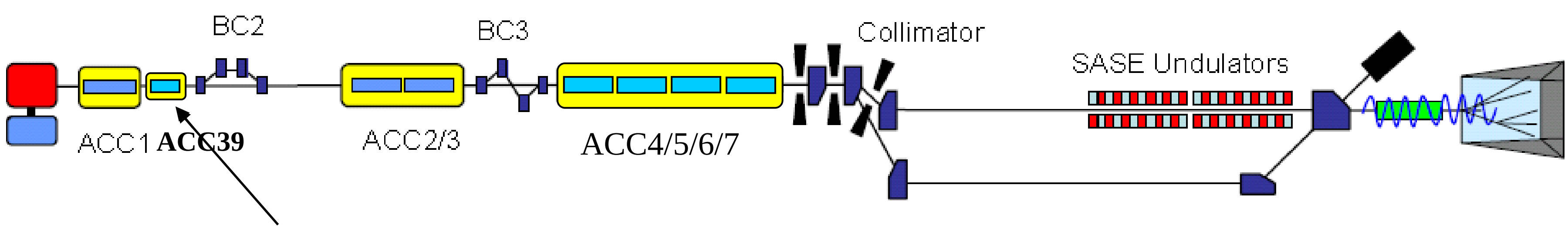
short gain length $$L_g \sim \frac{\varepsilon^{5/6}}{\sqrt{I}}\left(1+O(\sigma_E{}^2)\right)$$ (for the optimal beta function)

small energy spread

high peak current

Electron beam properties for good lasing

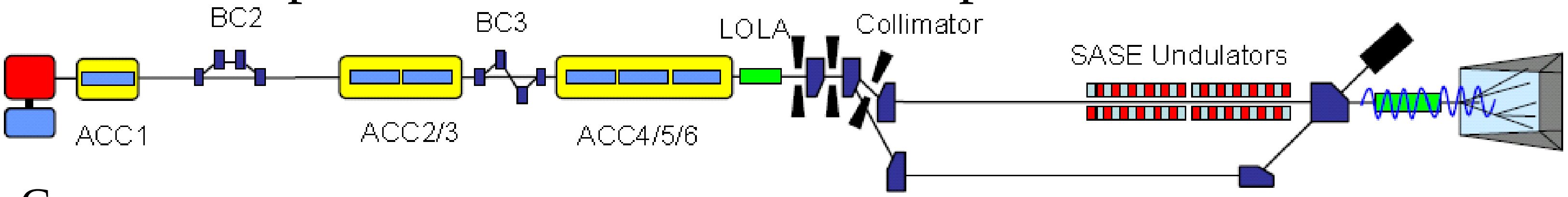
High **peak current** ~ **2500 A.**
Small slice **emittance** ε (**0.3-1 μm**).
Small slice **energy spread** σ_E (**< 300 keV**).



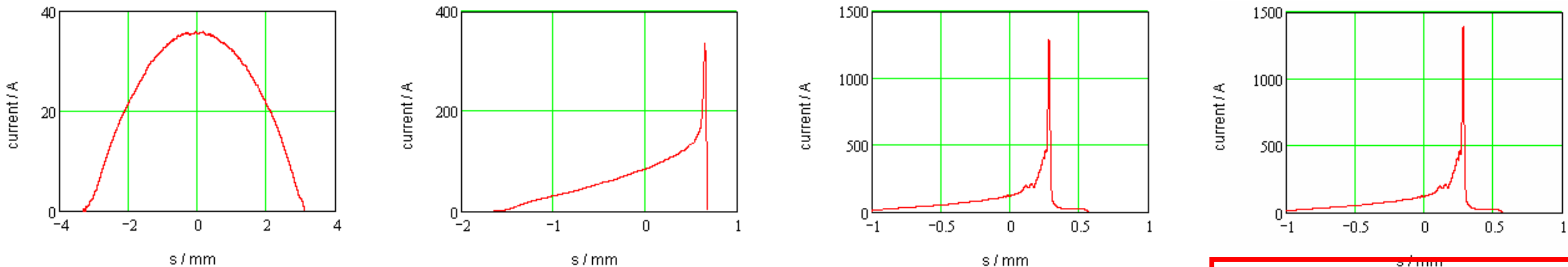
High harmonic module installed in 2010

FLASH layout and desired beam parameters

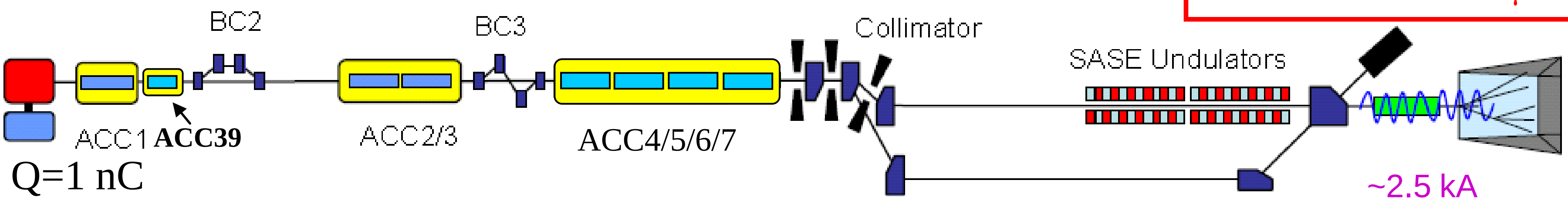
rollover compression vs. linearized compression



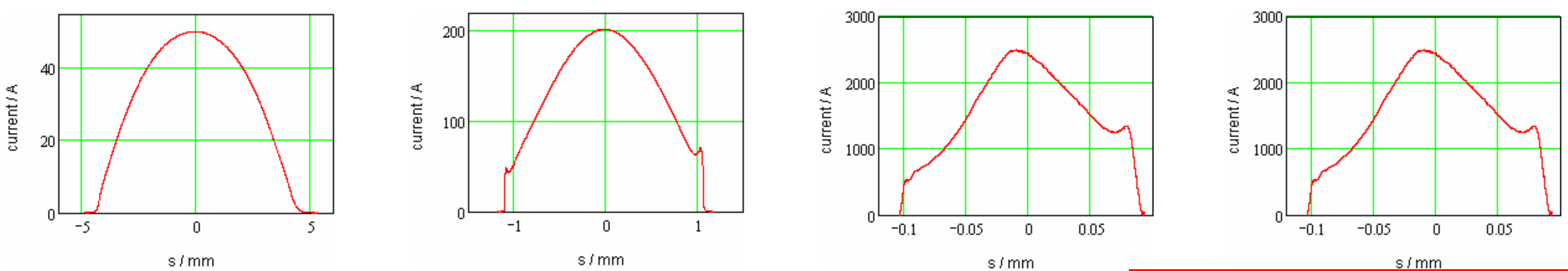
Q=0.5 nC



slice emittance > 2μm



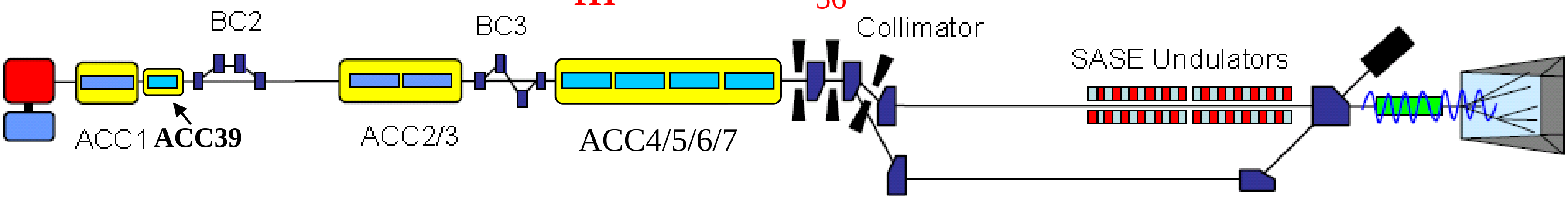
Q=1 nC



slice emittance ~ 0.3 - 1μm

Technical constraints and choosing of machine parameters

$$1.4 \le \frac{r_1}{m} \le 1.93 \qquad 5.3 \le \frac{r_2}{m} \le 16.8 \qquad r_{56} \approx 0 \dots -0.56 \text{ mm}$$



$V_1 \le 150$ MV

$V_{39} \le 26$ MV

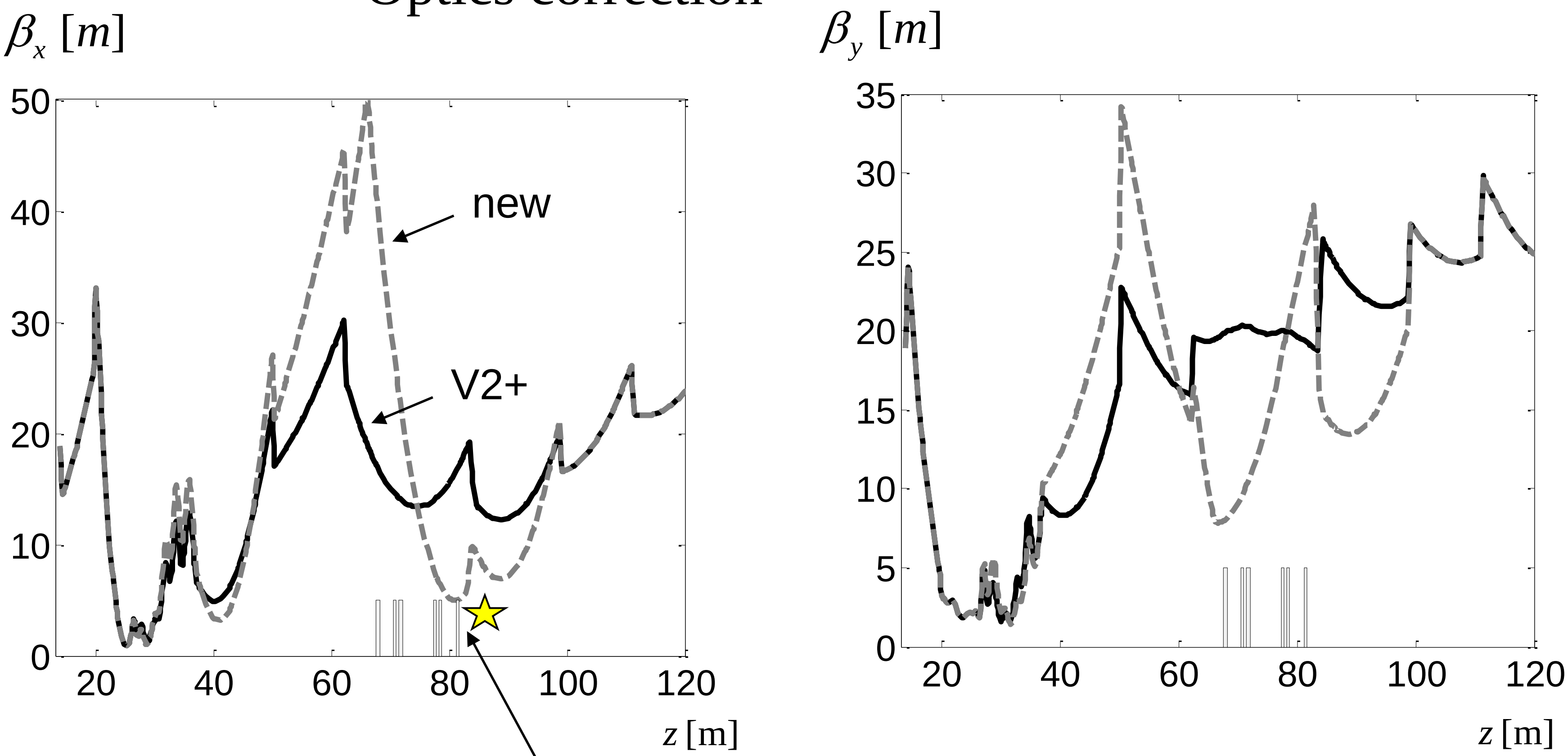
$V_2 \le 360$ MV

How to provide (1) a well conditioned electron beam and (2) what are the properties of the radiation?

(1) Self consistent beam dynamics simulations.
(2) FEL simulations.

Technical constraints and choosing of machine parameters

Optics correction



a small transverse bunch size before the last dipole

M.Dohlus, T. Limberg, *Impact of optics on CSR-related emittance growth in bunch compressor chicanes*, PAC 05, 2005

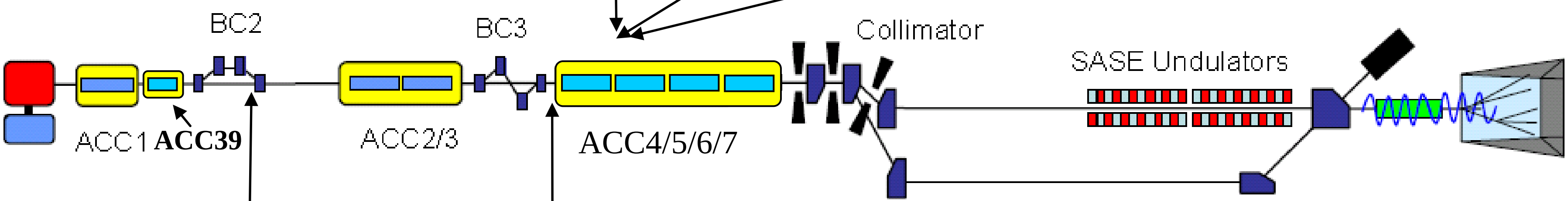
Technical constraints and choosing of machine parameters

Working points (8 macroparameters)

inverse compression factors

$$Z_1 \equiv \frac{\partial s_1}{\partial s}(0) \qquad Z_2 \equiv \frac{\partial s_2}{\partial s}(0) \qquad Z_2' \qquad Z_2''$$

?



E_1	E_2
r_1	r_2

s - particle position before BC2

s_1 - particle position between BC2 and BC3

s_2 - particle position after BC3

$s=s_1=s_2=0$ for the reference particle

What is the optimal choice?

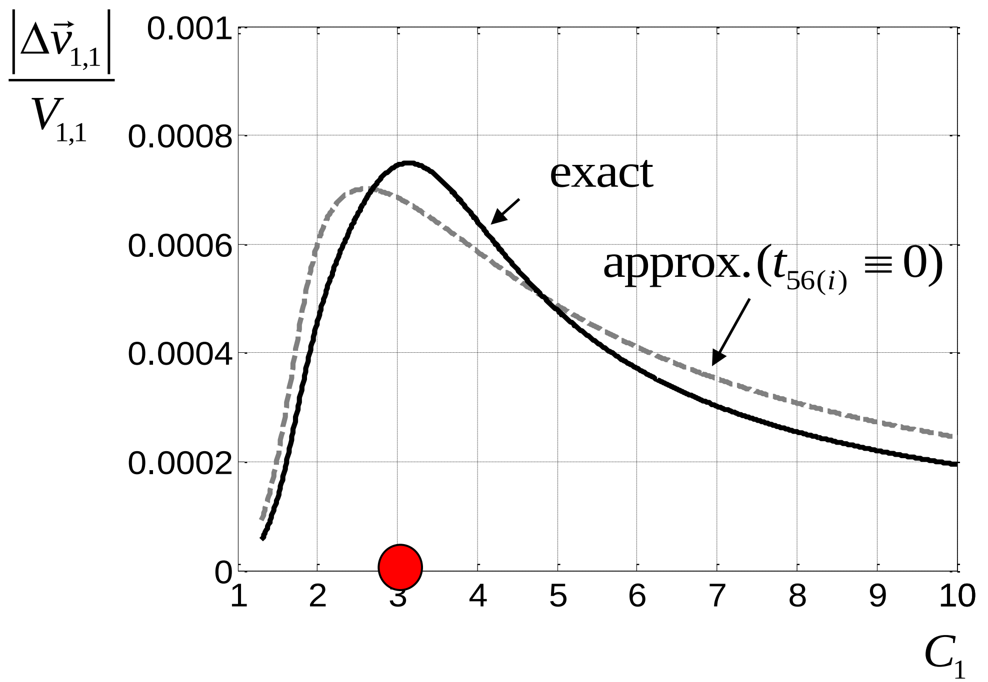
$$E_1 = 130\text{MeV}, \quad E_2 = 450\text{MeV}, \quad r_1 = 1.93\text{m}, \quad r_2 = 6\text{m},$$

$$Z_2^{-1} = 48, \quad Z_1^{-1} = ?, \quad Z_2' = ?, \quad Z_2'' = ?$$

Technical constraints and choosing of machine parameters

RF tolerance in ACC1 for 10% change of the compression

$$\frac{|\Delta \mathbf{v}_{1,1}|}{|\mathbf{v}_{1,1}^0|} \equiv \frac{|\Delta \mathbf{v}_{1,1}|}{V_{1,1}} \le \frac{0.1 Z_2^0}{V_{1,1} |\nabla_{\mathbf{v}_{1,1}} Z_2|}$$



$$|\nabla_{\mathbf{v}_{1,1}} Z_2| = k \frac{|r_{56(1)} r_{56(2)}|}{E_1 E_2} \sqrt{A_2^{\ 2} + B_2^{\ 2}}$$

$$A_2 = \left(E_2 r_{56(2)}^{-1} + E_1 r_{56(1)}^{-1} + k Y_2 \right)$$

$$B_2 = \left(\begin{array}{l} k X_2 Z_1 + 2 \frac{t_{56(1)}}{r_{56(1)}} \left(\frac{E_2}{r_{56(2)}} + k Y_2 \right) \frac{\delta_1'}{k} + \\ +2 \frac{t_{56(2)}}{r_{56(2)}} \left(\frac{E_1}{r_{56(1)}} + k Y_2 \right) \frac{\delta_2'}{k} \end{array} \right)$$

$$\Delta \mathbf{v}_{1,1} \equiv (\Delta X_{1,1}, \Delta Y_{1,1})^T$$

$$X_{1,1} = V_{1,1} \cos \varphi_{1,1} \qquad Y_{1,1} = Y_{1,1} \sin \varphi_{1,1}$$

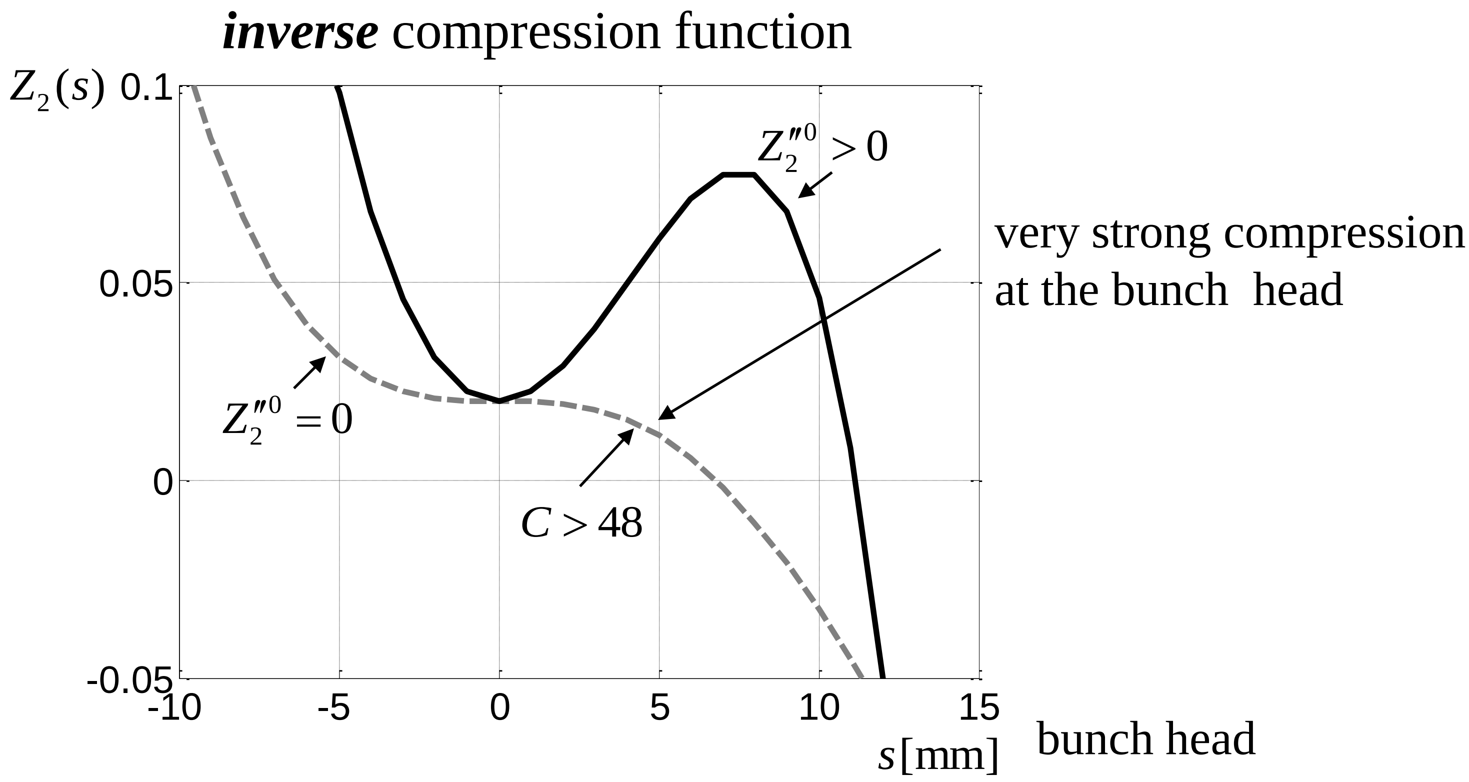
Optimum from the approximate solution

$$Z_1 = \sqrt{\frac{-r_{56(2)} E_1 - r_{56(1)} E_2 Z_2}{k r_{56(1)} r_{56(2)} (E_2 - E_1)}}$$

$$C_1 \equiv \frac{1}{Z_1} \approx 3$$

- optimal compression in BC2

Technical constraints and choosing of machine parameters



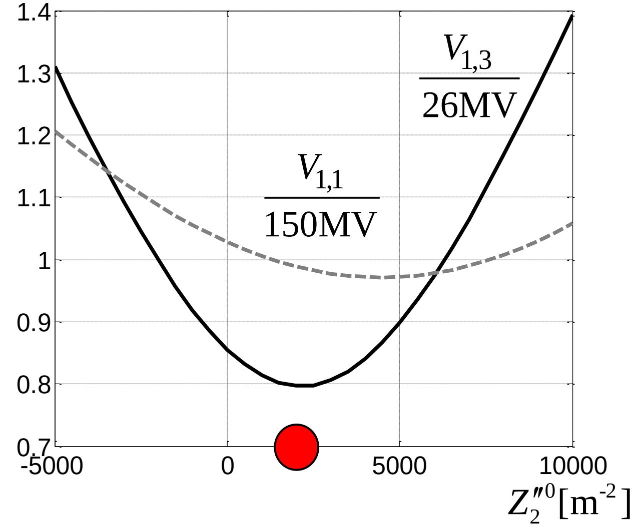
To avoid very strong compression at the bunch head

$$Z_2'' > 0$$

Technical constraints and choosing of machine parameters

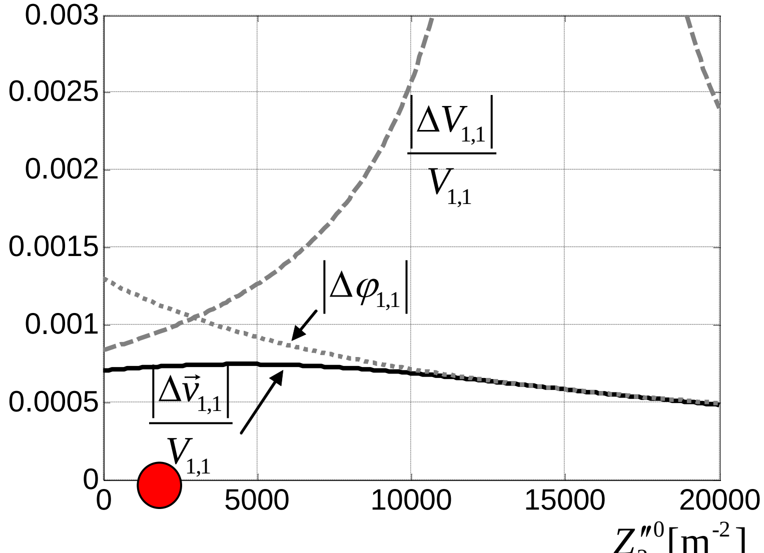
$$Z_2'' = 2000\,\mathrm{m}^{-2}$$

Voltage requirements

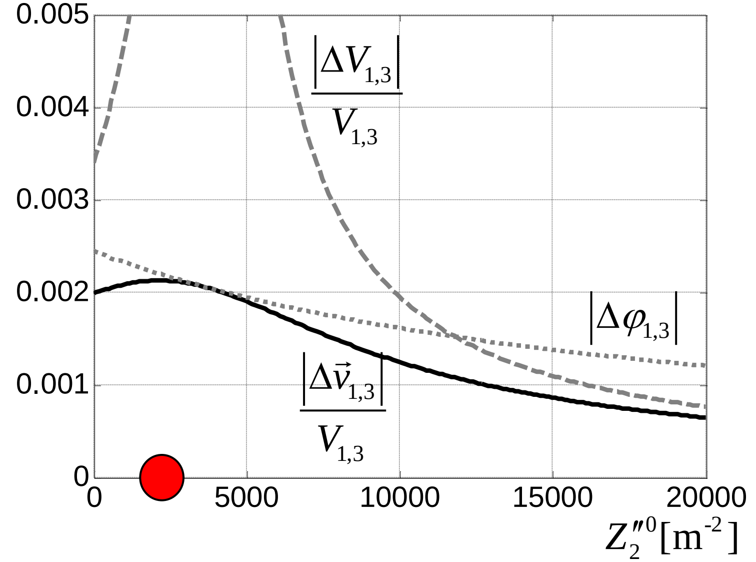


Tolerances (10 % change of compression)

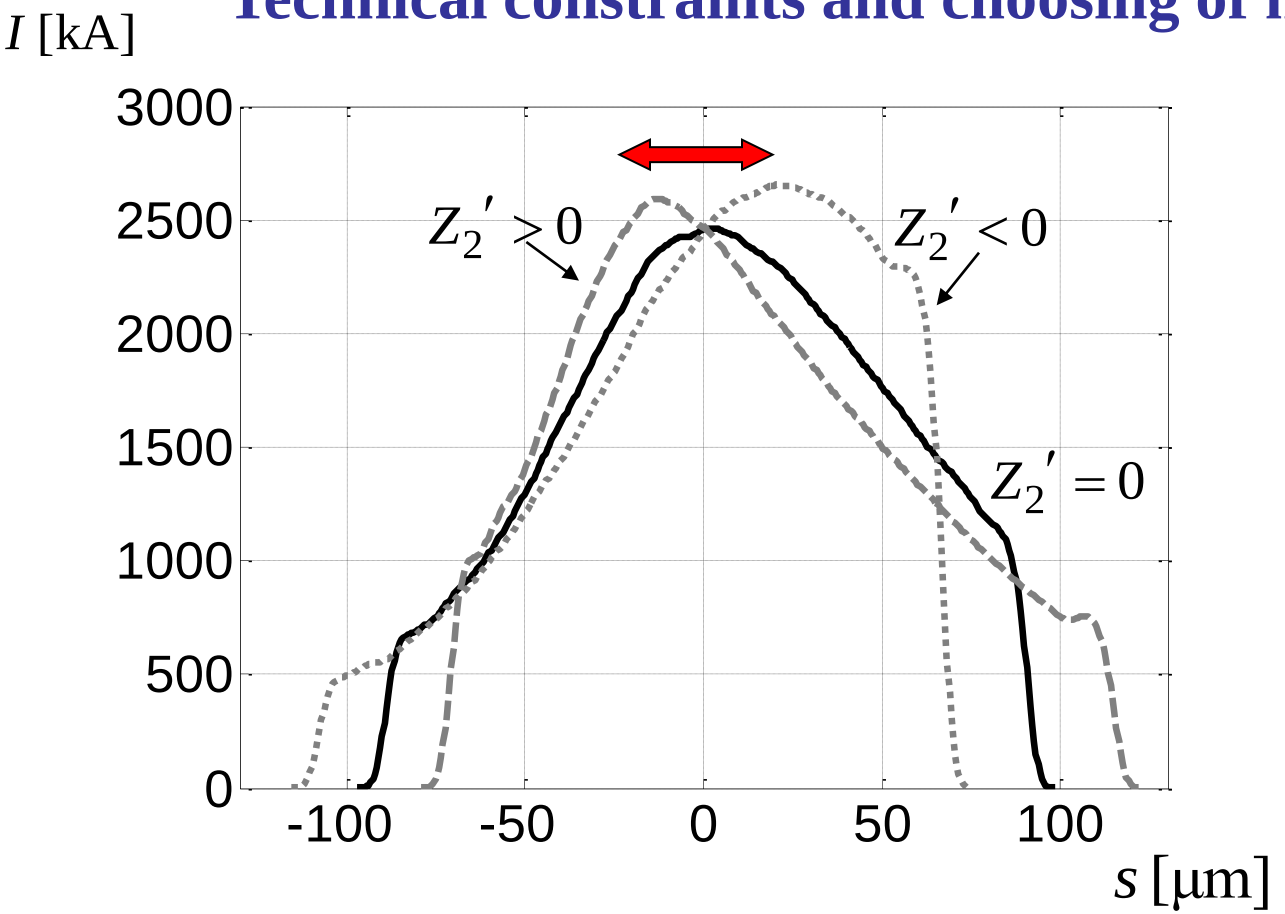
RF tolerances at ACC1



RF tolerances at the third harmonic module



Technical constraints and choosing of machine parameters



$E_1 = 130\text{MeV}$

$E_2 = 450\text{MeV}$

$r_1 = 1.93\text{m}$

$C \equiv Z_2^{-1} = 48$

$C_1 \equiv Z_1^{-1} = 2.84$

$r_2 = 6\text{m}$

$Z_2'' = 2000\text{m}^{-2}$

$$-1 \le \frac{Z_2'}{\text{m}^{-1}} \le 1$$

- a free parameter to move the peak

Technical constraints and choosing of machine parameters

Working points (8 macroparameters)

Charge Q, nC	Energy in BC2 E_1, [MeV]	Energy in BC3 E_2, [MeV]	Deflecting radius in BC2 r_1, [m]	Deflecting radius in BC3 r_2, [m]	Compression in BC2 C_1	Total compression C	First derivative Z_2', [m^{-1}]	Second derivative Z_2'', [m^{-2}]
1	130	450	1.93	6	2.84	48	1	2e3
0.5				6.93	4.63	90	1	3.5e3
0.25				7.8	6.57	150	0.7	4e3
0.1				9.3	10.3	240	0	4e3
0.02				15.17	31.8	1000	-0.5	5e3

C_1 : scaling for different charges

$$x'' + k_x x = \frac{1}{I_A \beta^3 \gamma^3} \frac{I}{\sigma_x(\sigma_x + \sigma_y)} x \quad \Longrightarrow \quad C_1(Q) \propto \frac{1}{\sqrt{Q}}$$

(trajectory equation in FODO cell)

We have used a more aggressive scaling.

Technical constraints and choosing of machine parameters

8 macroparameters define 6 equations

$$\begin{cases} E_2(0) = E_{20}, \quad E_1(0) = E_{10} \quad \dfrac{\partial s_1}{\partial s}(0) = Z_1, \\ \dfrac{\partial s_2}{\partial s}(0) = Z_2, \quad \dfrac{\partial^2 s_2}{\partial s^2}(0) = Z_2', \quad \dfrac{\partial^3 s_2}{\partial s^3}(0) = Z_2''. \end{cases}$$

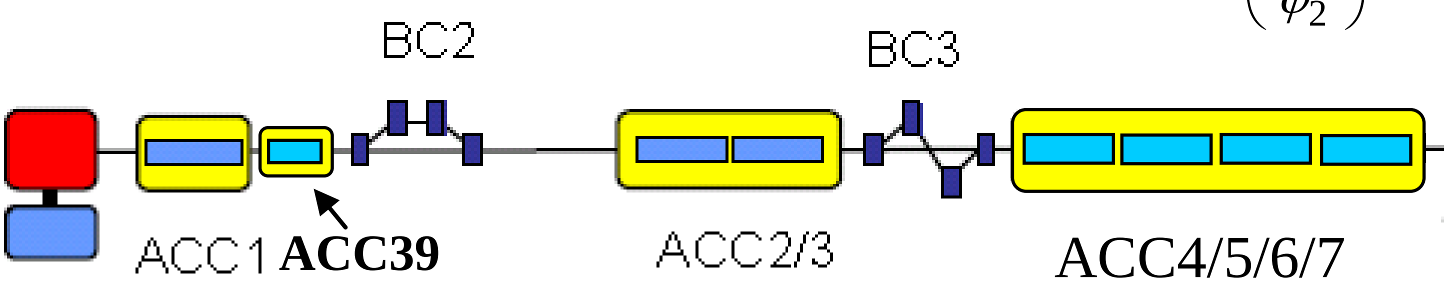
Analytical solution without self-fields*

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

nonlinear operator (defined analytically)

$$\mathbf{x}_0 = \begin{pmatrix} V_{1,1} \\ \varphi_{1,1} \\ V_{1,3} \\ \varphi_{1,3} \\ V_2 \\ \varphi_2 \end{pmatrix} \qquad \mathbf{f}_0 = \begin{pmatrix} E_{10} \\ E_{20} \\ Z_1 \\ Z_2 \\ Z_2' \\ Z_2'' \end{pmatrix}$$

*I.Zagorodnov and M.Dohlus, Multistage bunch compression, WEPB30



$V_{1,1}, \varphi_{1,1}$ $\quad$ $V_{1,3}, \varphi_{1,3}$ $\quad$ V_2, φ_2

Technical constraints and choosing of machine parameters

Analytical solution without self-fields

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

Solution with self-fields

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

nonlinear operator
(tracking with self-fields)

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

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

numerical tracking

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

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

$$\mathbf{g}_n = \mathbf{g}_{n-1} + \Delta\mathbf{f}_{n-1}$$

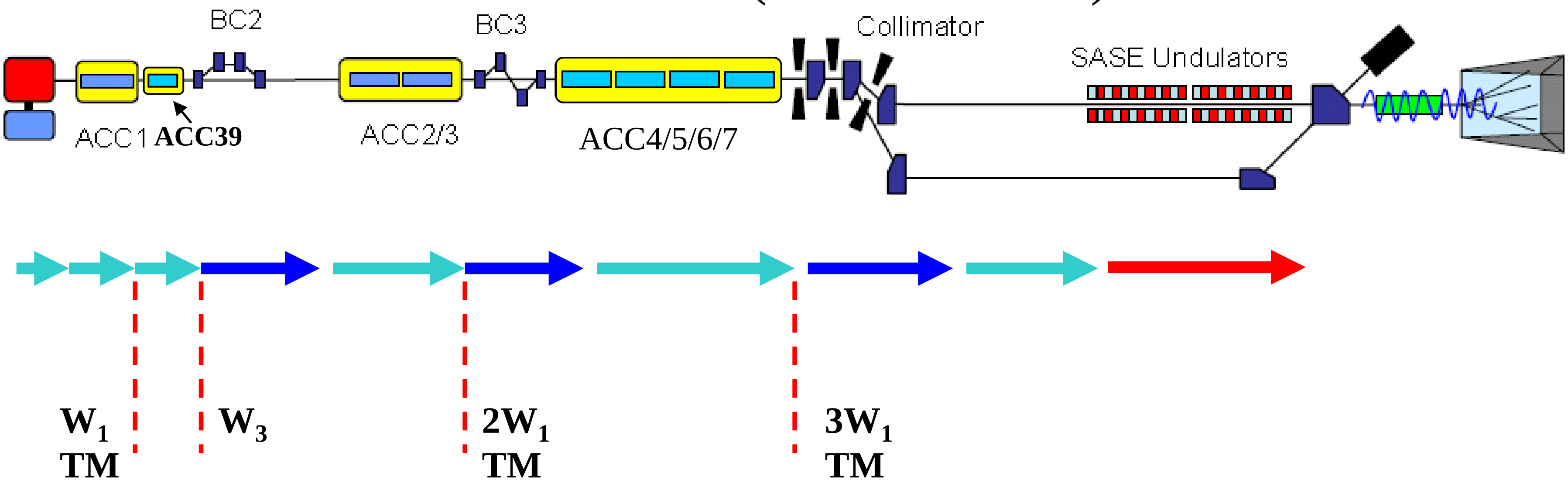
$$\mathbf{x}_n = \mathbf{A}_0^{-1}(\mathbf{g}_n)$$

residual in macroscopic parameters

analytical correction of RF parameters

FLASH beam dynamic simulations for different charges

3d simulation method (self-consistent)



ASTRA (tracking with space charge, DESY, K. Flötmann)

CSRtrack (tracking through dipoles, DESY, M. Dohlus, T. Limberg)

ALICE (3D FEL code, DESY, I. Zagorodnov, M. Dohlus)

W1 -TESLA cryomodule wake (TESLA Report 2003-19, DESY, 2003)

W3 - ACC39 wake (TESLA Report 2004-01, DESY, 2004)

TM - transverse matching to the design optics

FLASH beam dynamic simulations for different charges

simulation methods (looking for working points)

1d analytical solution without collective effects
(8 macroparameters -> 6 RF settings)

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

1d tracking with space charge and wakes

~ **seconds**
(1 cpu)

- accelerator: $E_1(s_1) = E_0(s_0) + V\cos(ks_0 + \varphi)$, $s_1 = s_0$
- compressor: $E_1(s_1) = E_0(s_0)$, $s_1(s_0) = s_0 + (r_{56}\delta + t_{566}\delta^2 + u_{5666}\delta^3)$

$\mathbf{A}_1(\mathbf{x}_1) = \mathbf{f}_0$ ~ 5 iterations

quasi 3d tracking with all collective effects

~ **30 min**
(1 cpu)

- accelerator: $E_1(s_1) = E_0(s_0) + V\cos(ks_0 + \varphi)$, $s_1 = s_0$, matrix transport for x & y
- **CSRtrack**

$\mathbf{x}_0 = \mathbf{x}_1$ ~ 5 iterations

$\mathbf{A}_2(\mathbf{x}_2) = \mathbf{f}_0$

3d tracking with all collective effects

~ **10 h**
(46 cpu-s)

- **Astra**
- **CSRtrack**

$\mathbf{A}(\mathbf{x}_2) \to \mathbf{f}$

$\mathbf{f} \approx \mathbf{f}_0$ final result

FLASH beam dynamic simulations for different charges

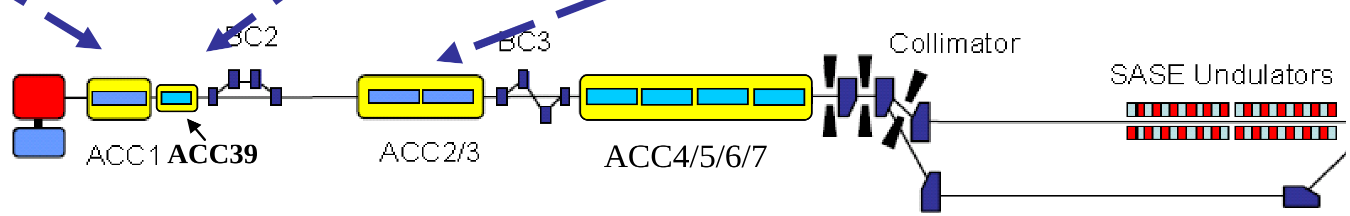
8 macroparameters
define 6 equations

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

Analytical solution without self-fields
+ iterative procedure with them

RF settings in accelerating modules

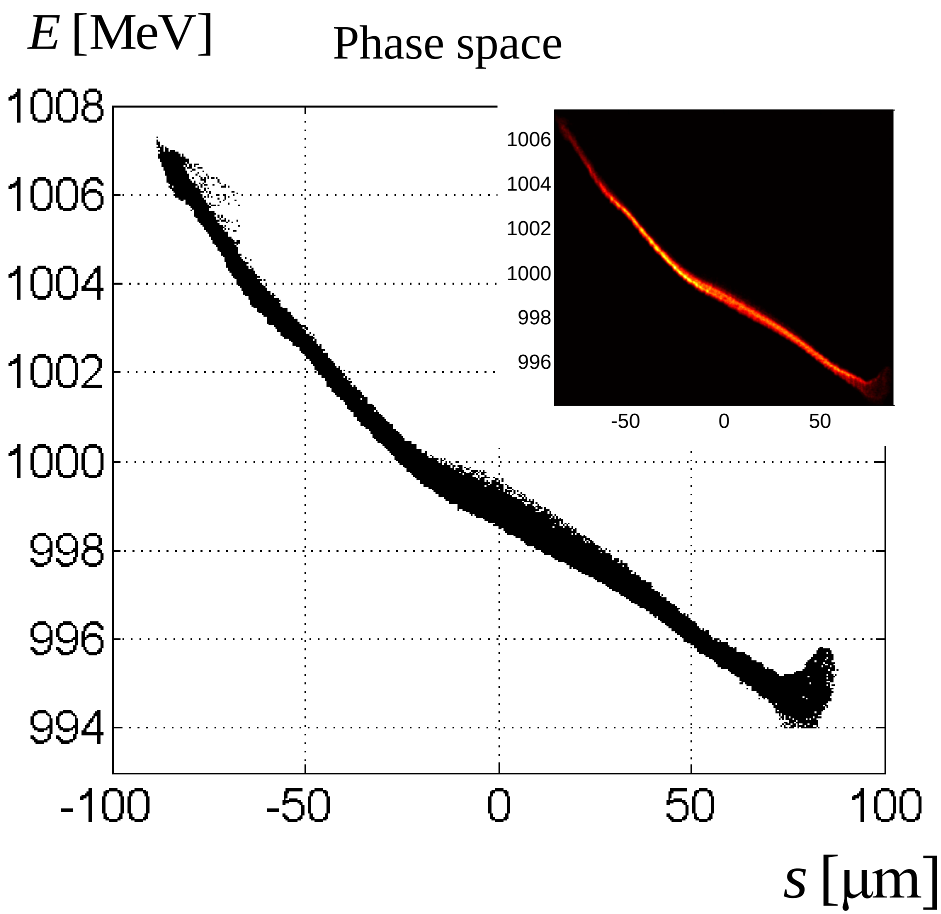
Charge, nC	$V_{1,1}$, [MV]	$\varphi_{1,1}$, [deg]	$V_{1,3}$, [MV]	$\varphi_{1,3}$, [deg]	V_2, [MV]	φ_2, [deg]
1	144	-4.66	22.6	145	350	23.4
0.5	143.7	4.042	19.65	158.4	351	23.65
0.25	143.36	2.493	20.81	153.9	352.6	23.96
0.1	144.8	-6.31	25.6	137.5	356.5	25.62
0.02	144.9	-3.894	25.58	141.65	339.8	19.385



FLASH beam dynamic simulations for different charges

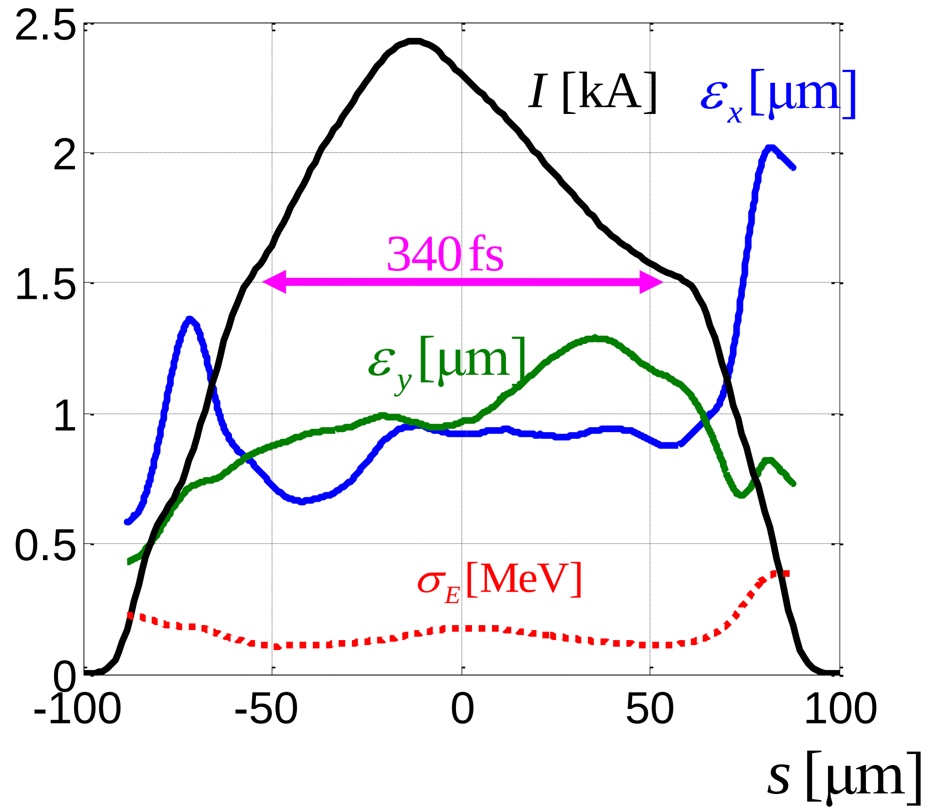
Q=1 nC

Phase space



bunch head

Current, emittance, energy spread

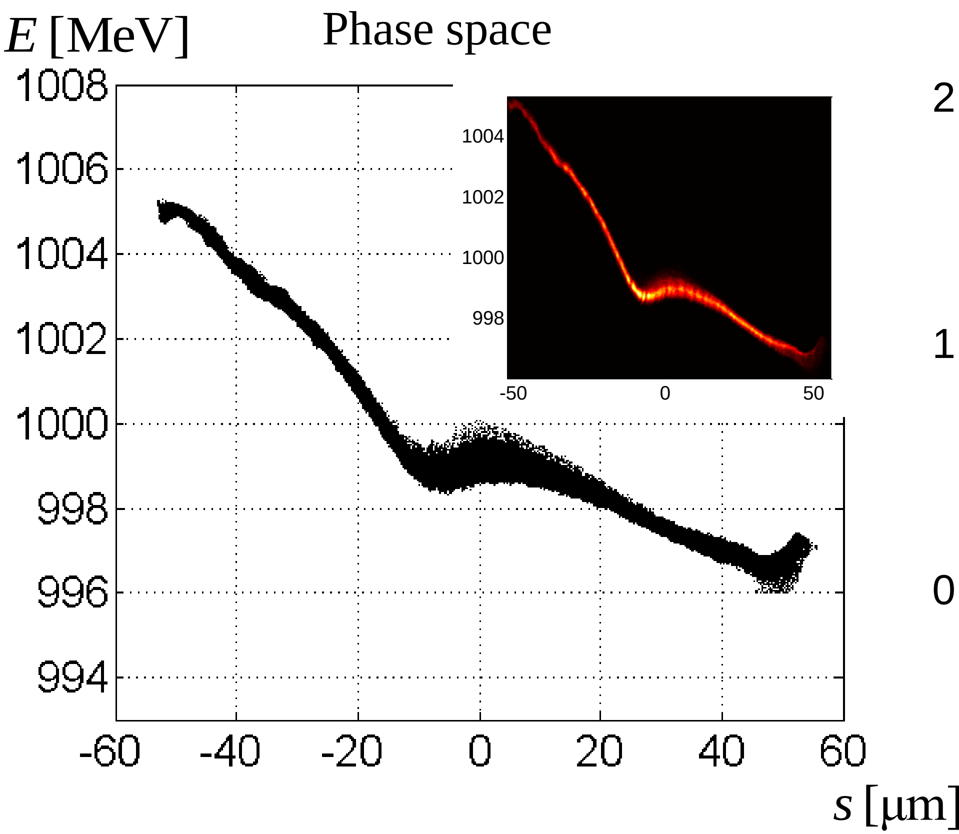


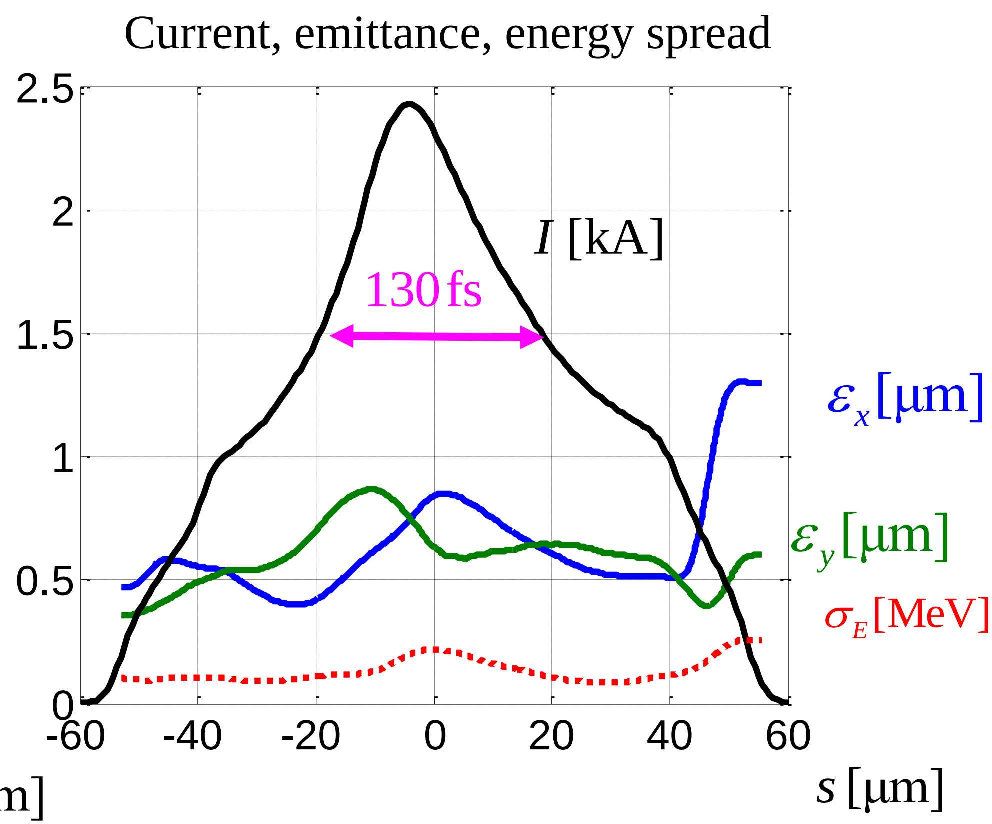
$$\varepsilon_x^{proj} = 3\,[\mu m]$$

$$\varepsilon_y^{proj} = 1.4\,[\mu m]$$

FLASH beam dynamic simulations for different charges

Q=0.5 nC





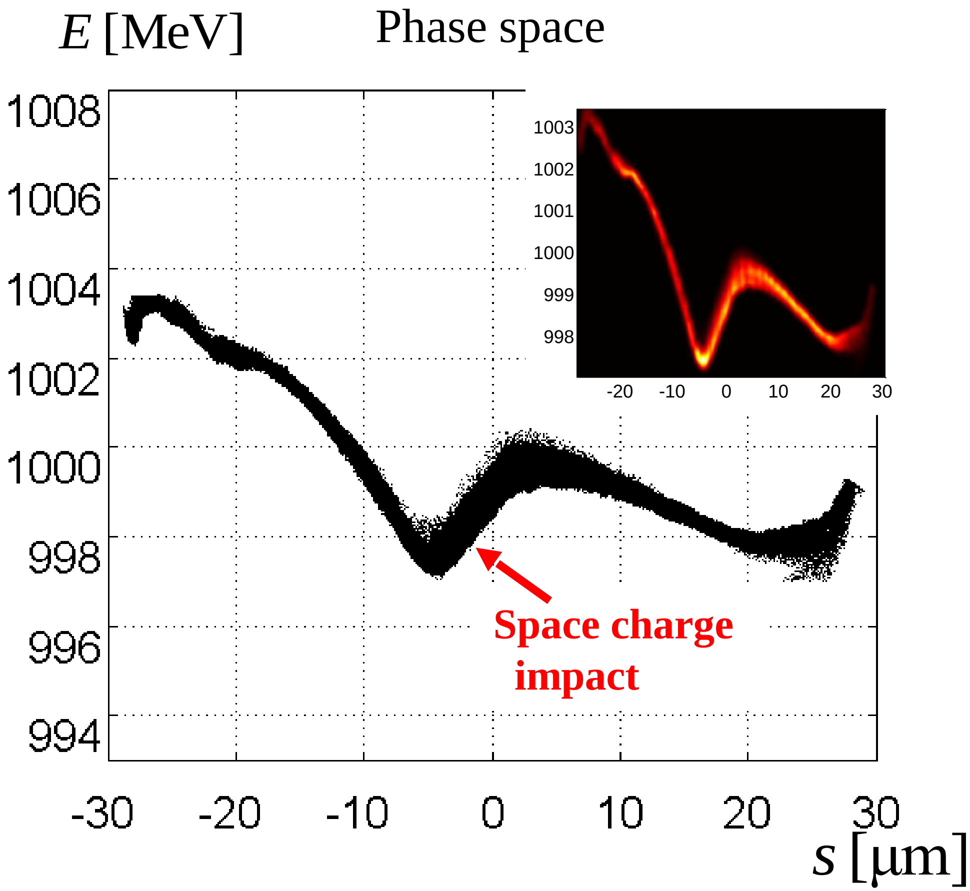
bunch head

$$\varepsilon_x^{proj} = 2.5\,[\mu m]$$

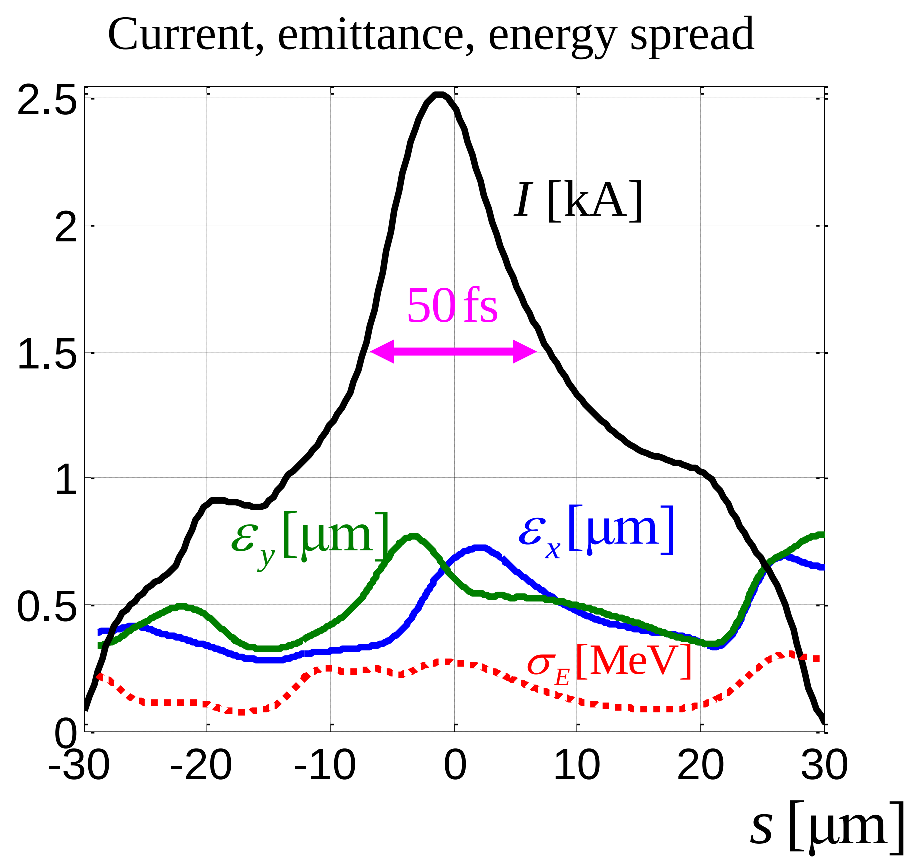
$$\varepsilon_y^{proj} = 0.84\,[\mu m]$$

FLASH beam dynamic simulations for different charges

Q=0.25 nC



bunch head

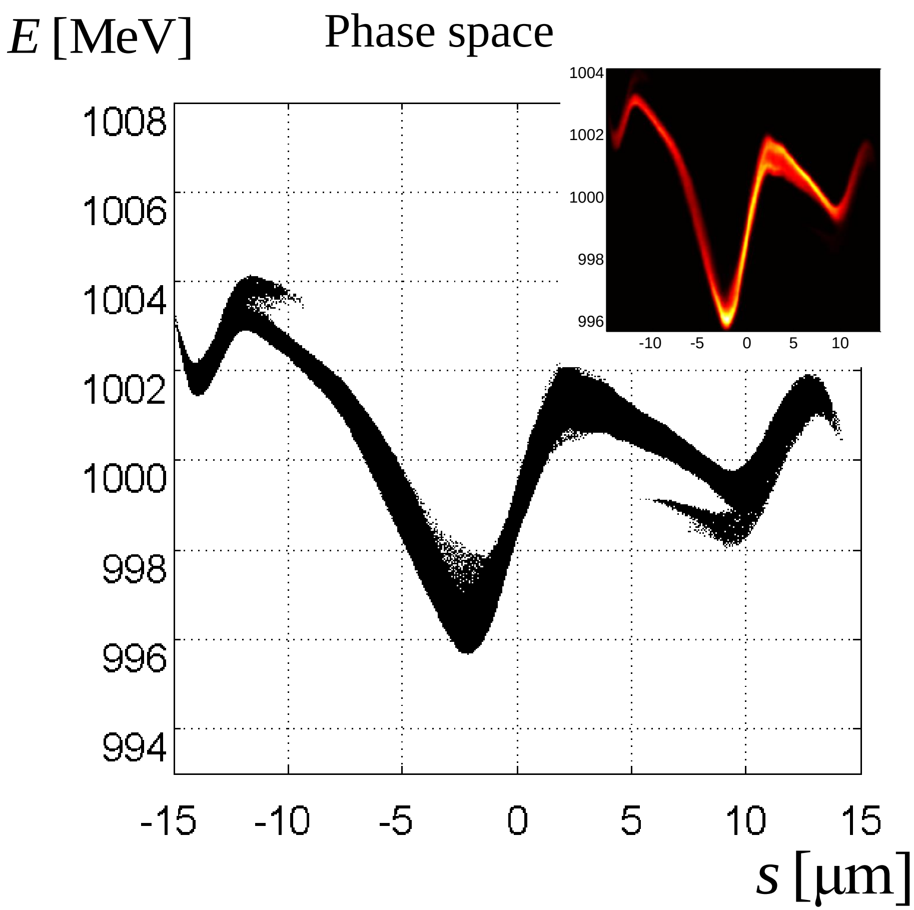


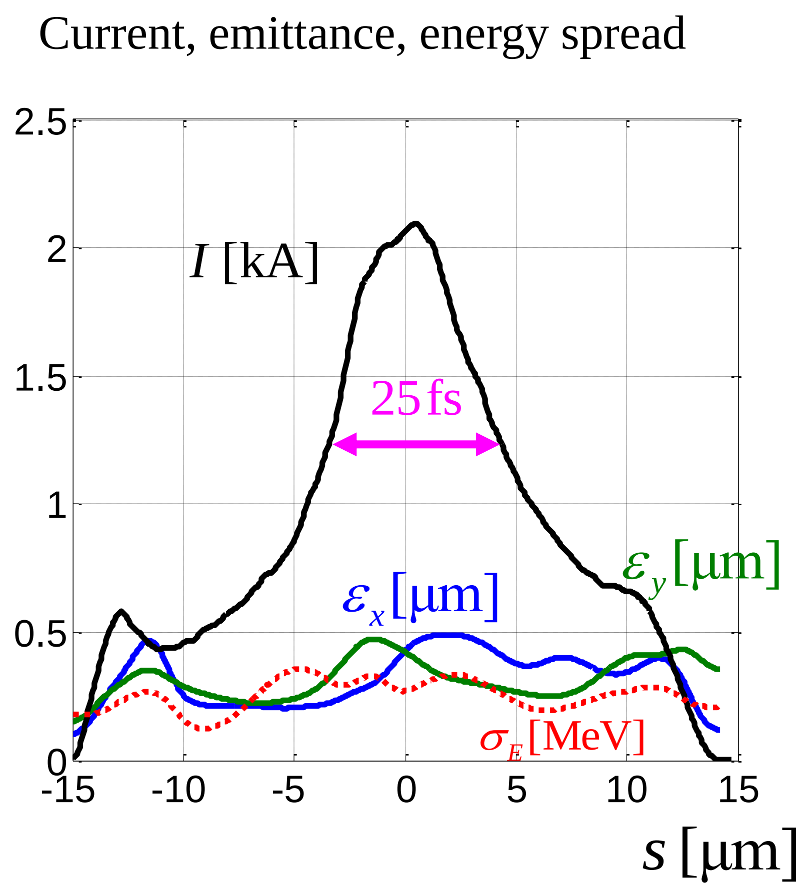
$$\varepsilon_x^{proj} = 1.14\,[\mu m]$$

$$\varepsilon_y^{proj} = 0.74\,[\mu m]$$

FLASH beam dynamic simulations for different charges

Q=0.1 nC





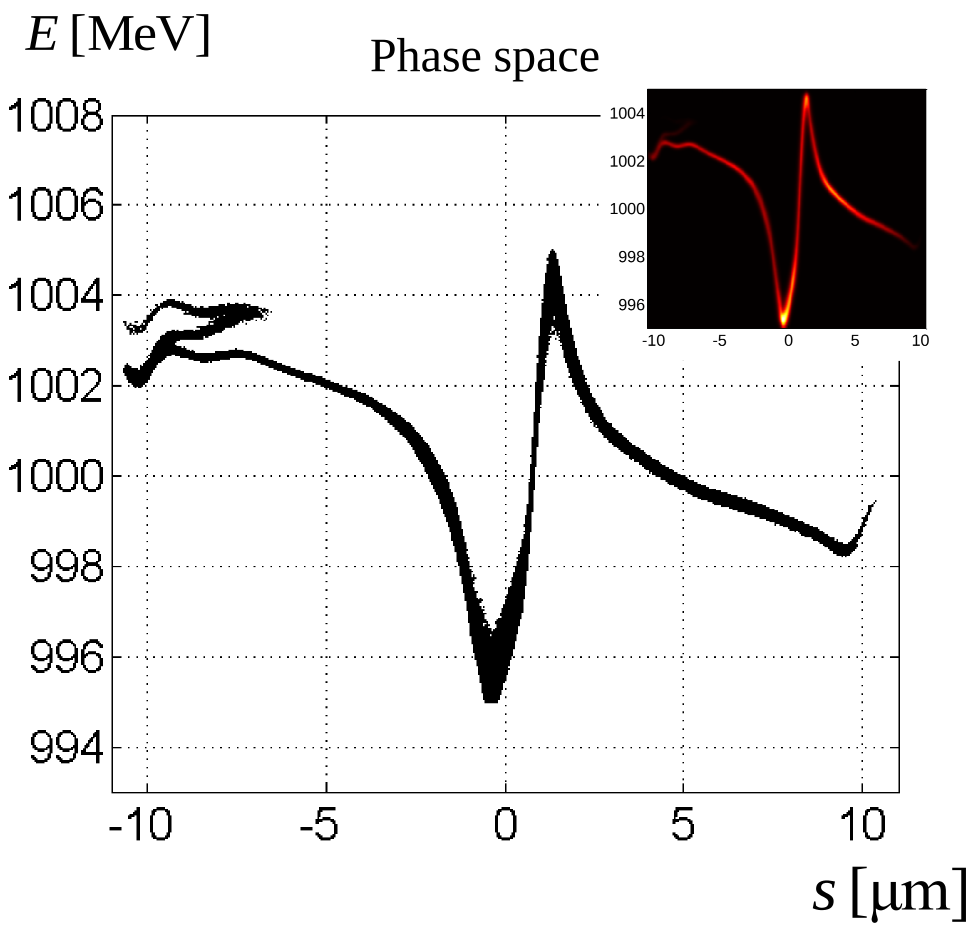
bunch head

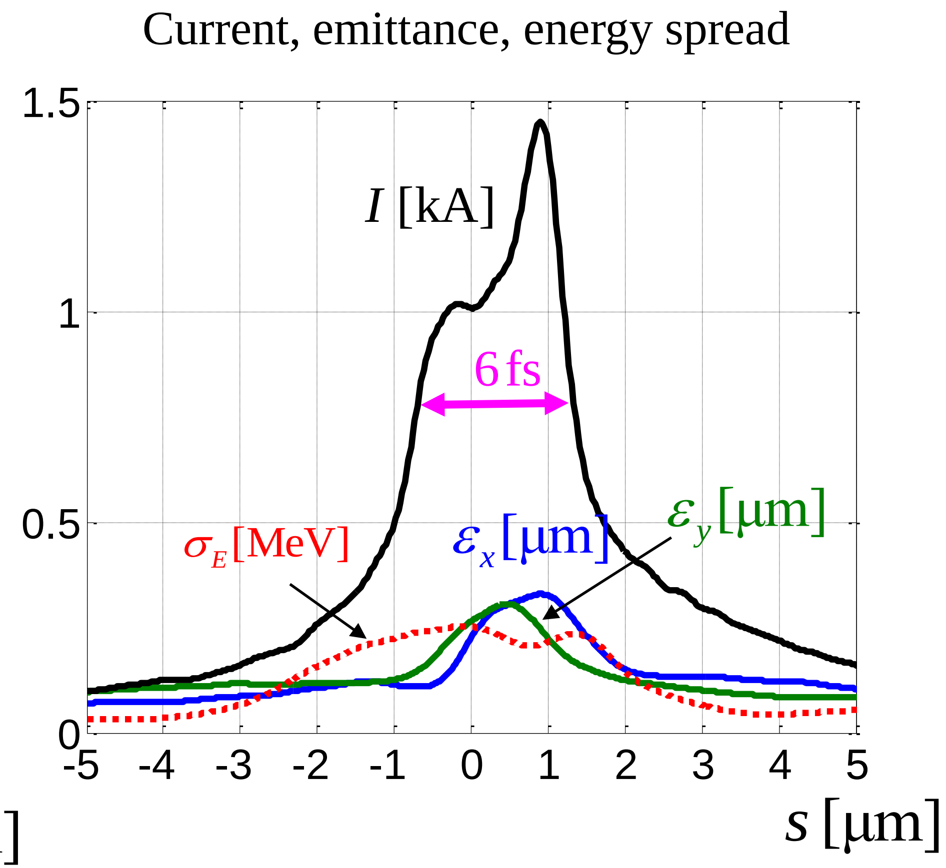
$$\varepsilon_x^{proj} = 2\,[\mu m]$$

$$\varepsilon_y^{proj} = 0.6\,[\mu m]$$

FLASH beam dynamic simulations for different charges

Q=0.02 nC



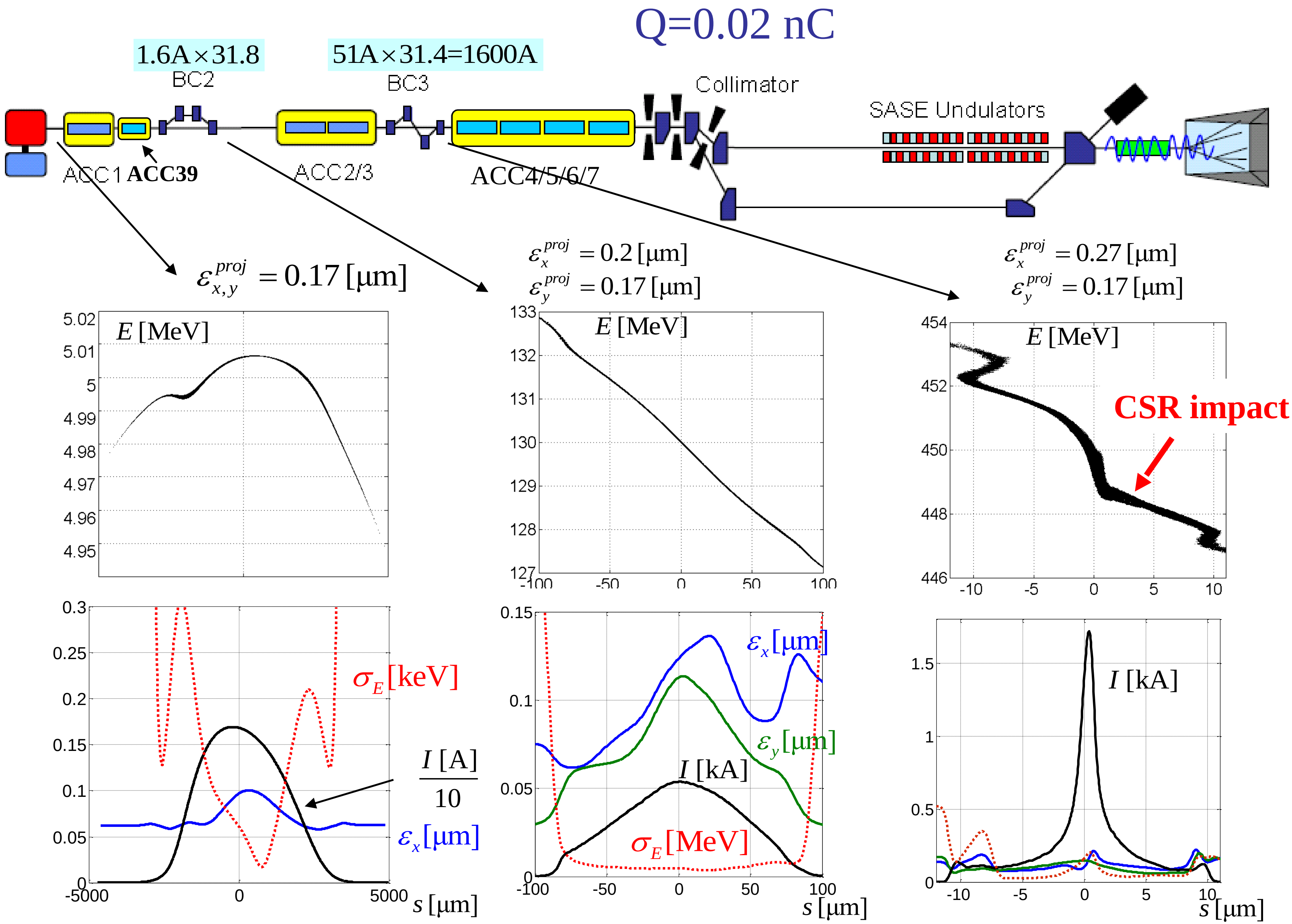


bunch head

$$\varepsilon_x^{proj} = 0.48\,[\mu m]$$

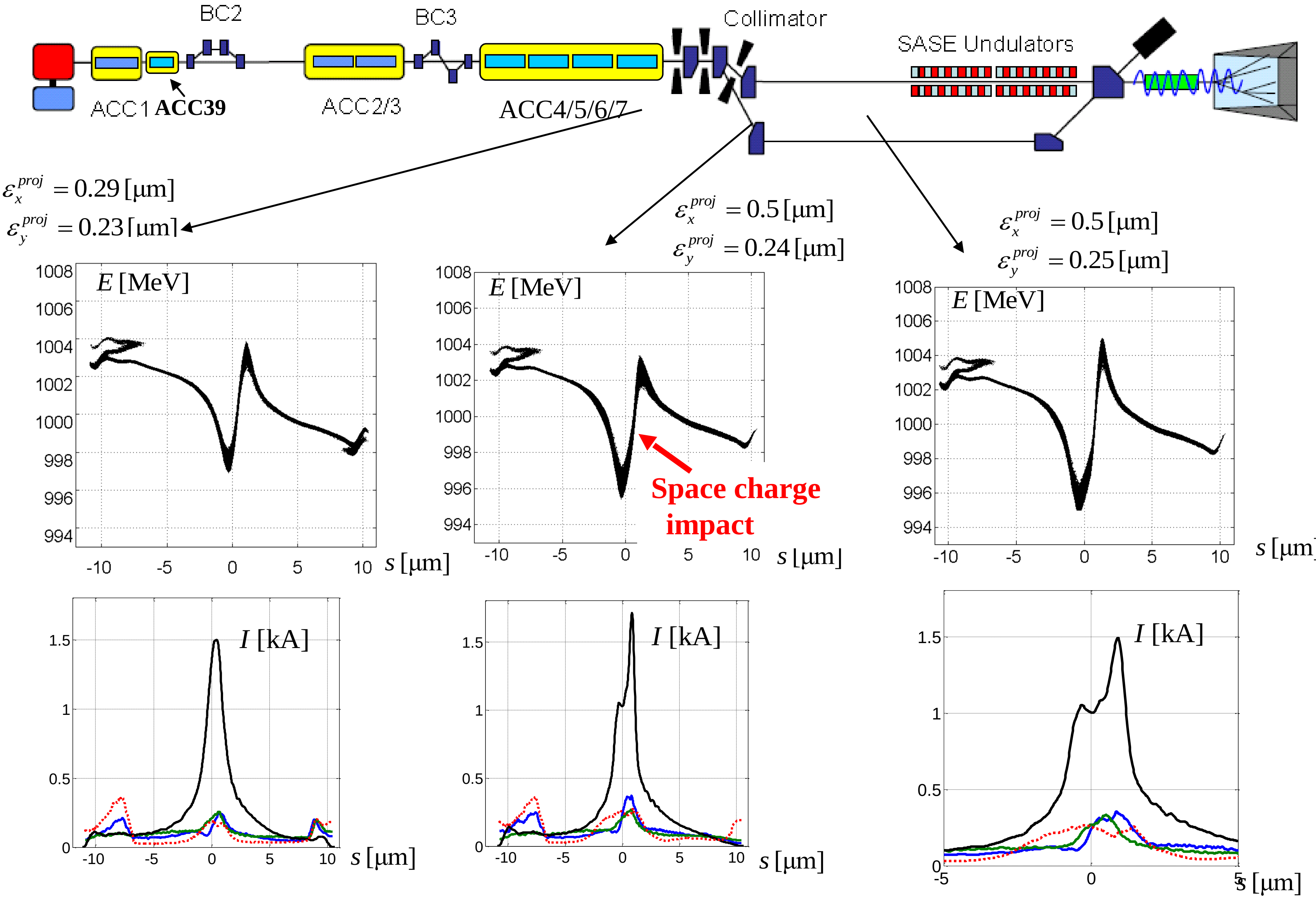
$$\varepsilon_y^{proj} = 0.25\,[\mu m]$$

FLASH beam dynamic simulations for different charges



FLASH beam dynamic simulations for different charges

Q=0.02 nC



FLASH beam dynamic simulations for different charges

Tolerances (analytically) **without self fields** (10 % change of compression)

Q, nC		1	0.5	0.25	0.1	0.02
ACC1	|ΔV|/V	**0.001**	**0.004**	**0.0012**	**0.0003**	**0.00004**
	|Δφ|, degree	**0.065**	**0.025**	**0.013**	**0.007**	**0.0014**
ACC39	|ΔV|/V	0.008	0.01	0.0026	0.0008	0.00013
	|Δφ|, degree	0.13	0.061	0.033	0.02	0.004
ACC2/3	|ΔV|/V	0.0042	0.0033	0.0026	0.0024	0.0016
	|Δφ|, degree	0.15	0.15	0.15	0.17	0.17

Tolerances (from tracking) **with self fields** agree with this table

Radiation properties for different charges

How to provide (1) a well conditioned electron beam and (2) what are the properties of the radiation?

(1) Self consistent beam dynamics simulations.

We are able to provide the well conditioned electron beam for different charges.

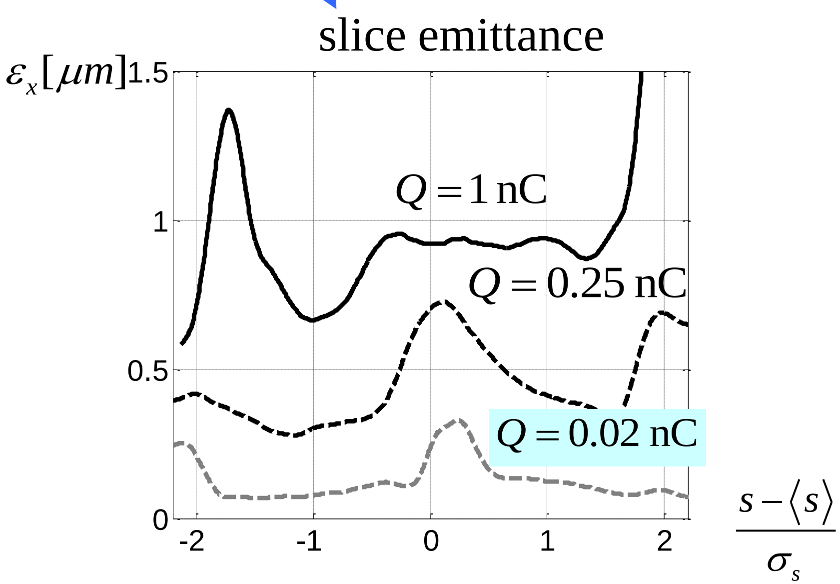
But RF tolerances for low charges are tough.

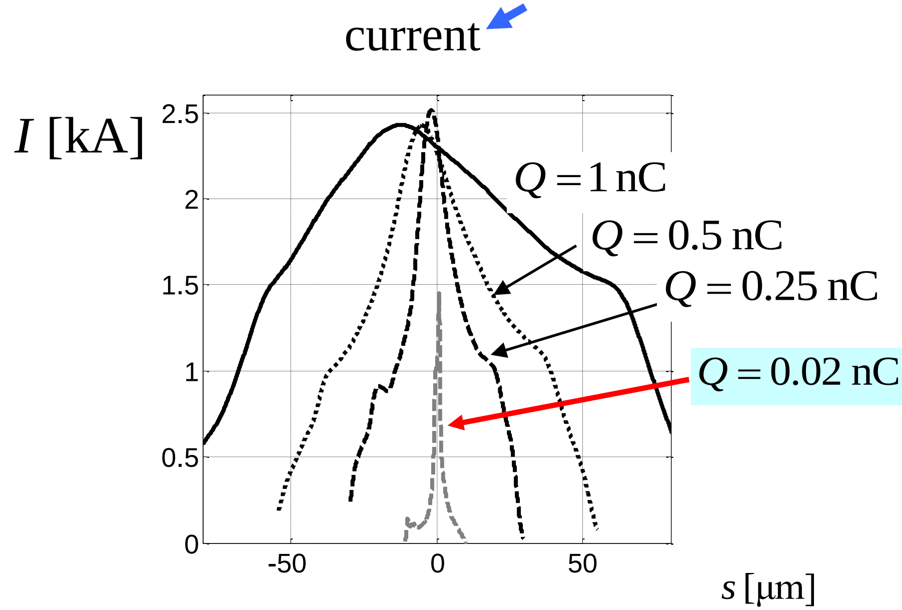
(2) FEL simulations (next slides).

Radiation properties for different charges

Slice parameters are extracted from S2E simulations for SASE simulations

$$\gamma \quad \Delta\gamma \quad \varepsilon_x \quad \varepsilon_y \quad \beta_x \quad \beta_y \quad \langle x \rangle \quad \langle y \rangle \quad \langle x' \rangle \quad \langle y' \rangle \quad \alpha_x \quad \alpha_y \quad I$$

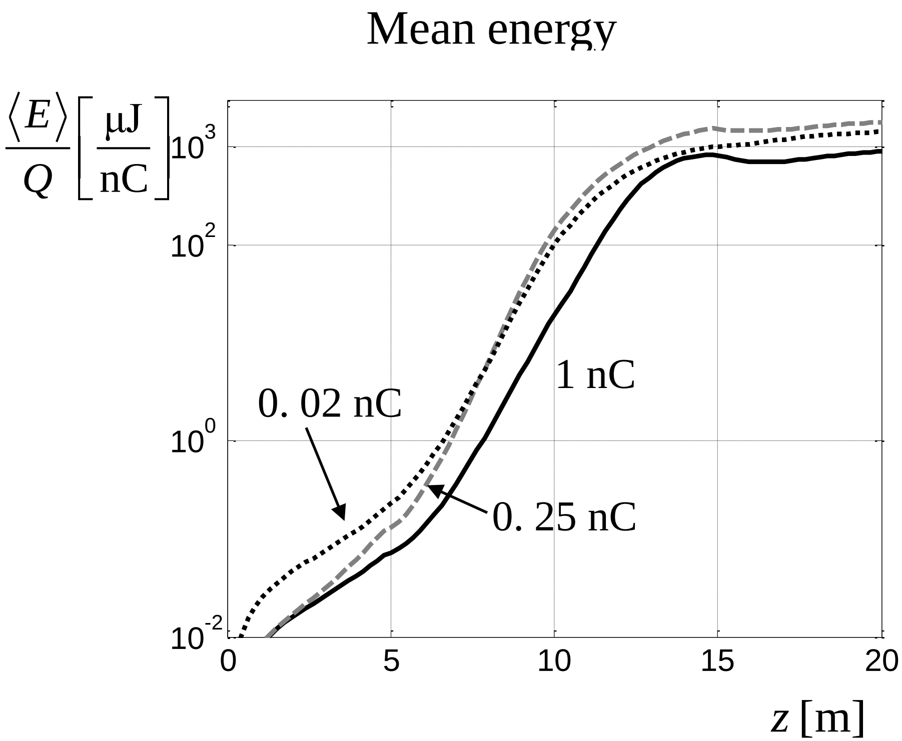


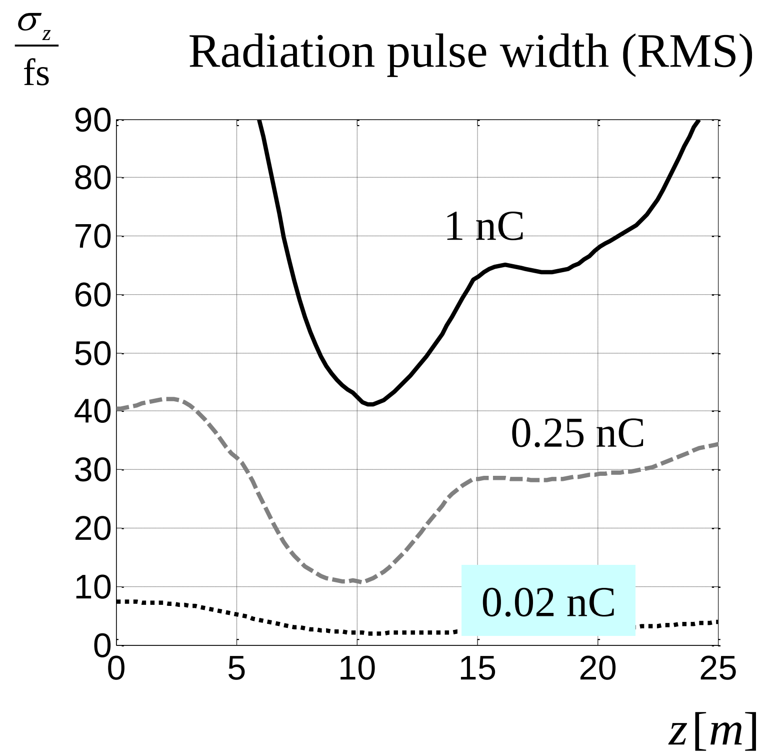


Charge Q, nC	1	0.25	0.02
Longitudinal electron beam size σ_s, μm	42	13	3.6
Transverse electron beam size σ_r, μm	80	68	36

Radiation properties for different charges

Radiation energy statistics (200-500 runs)





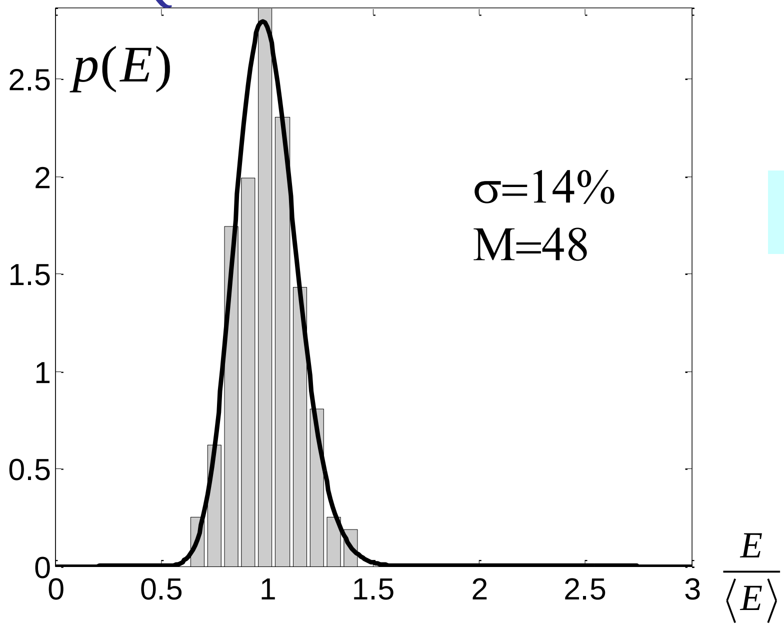
Charge, nC	1	0.5	0.25	0.1	0.02
Mean radiation energy, μJ	1000-1400	700	500	200	30
Pulse radiation width (FWHM), fs	**70**	**30**	**17**	**7**	**2**

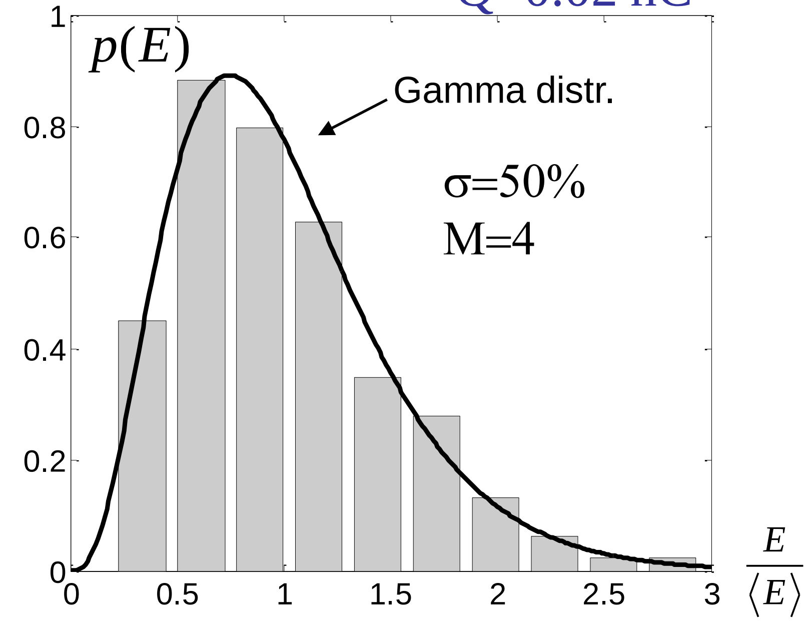
Radiation properties for different charges

Q=1 nC

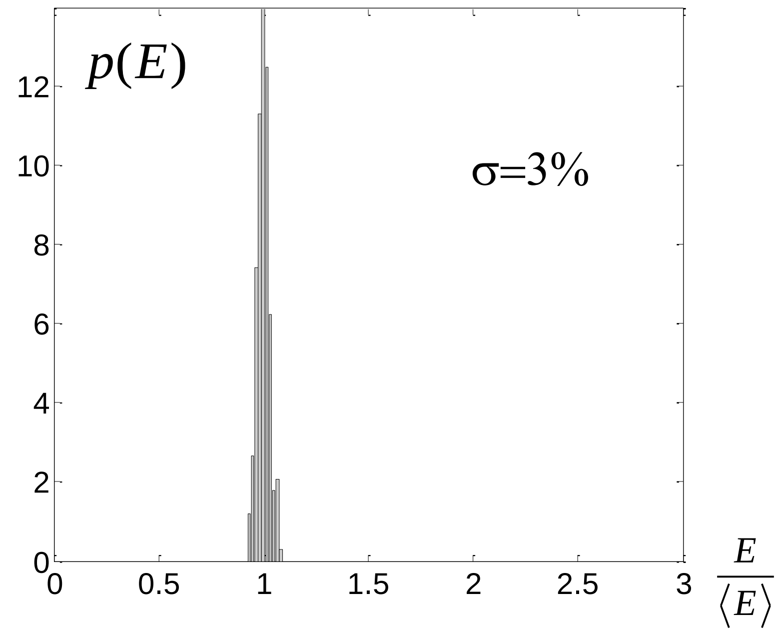
Q=0.02 nC

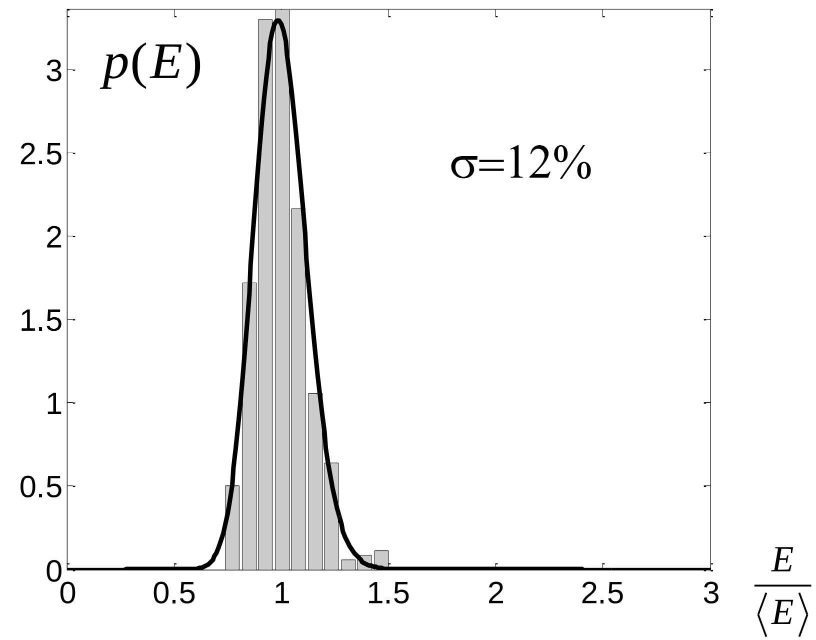
z=10m





z=20m

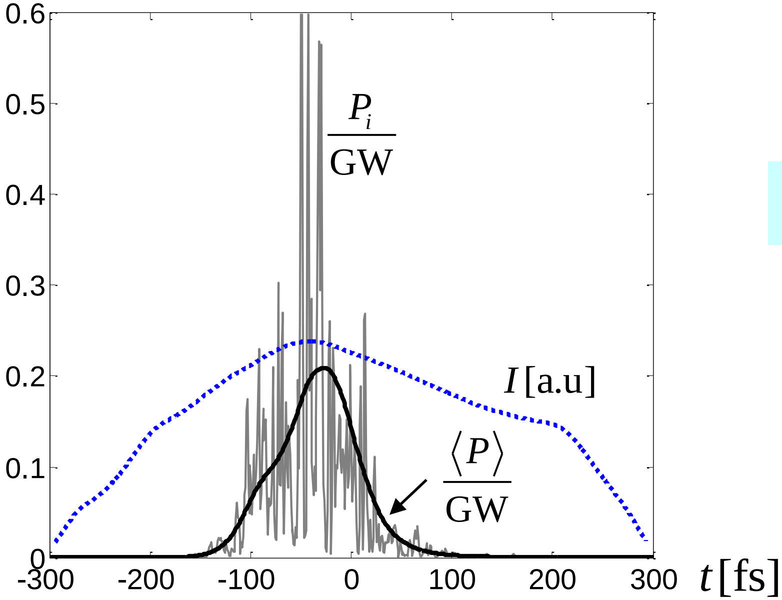


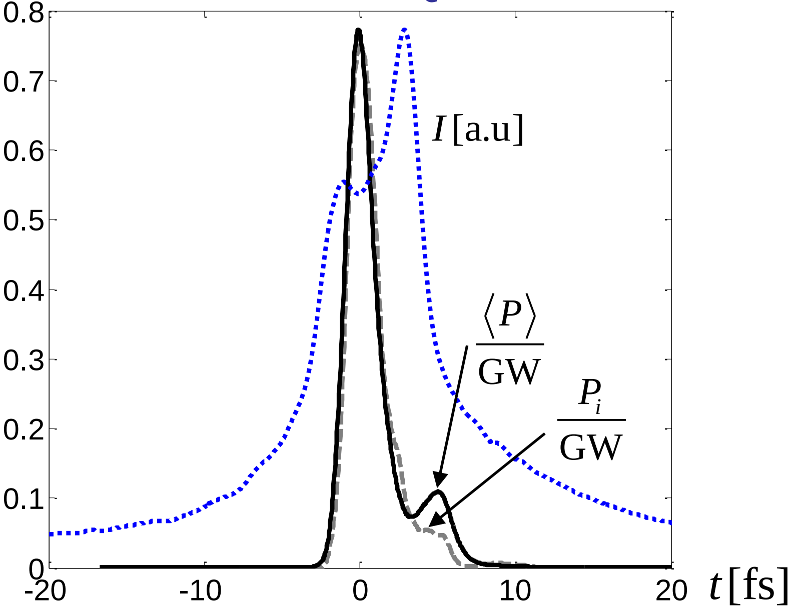


Radiation properties for different charges

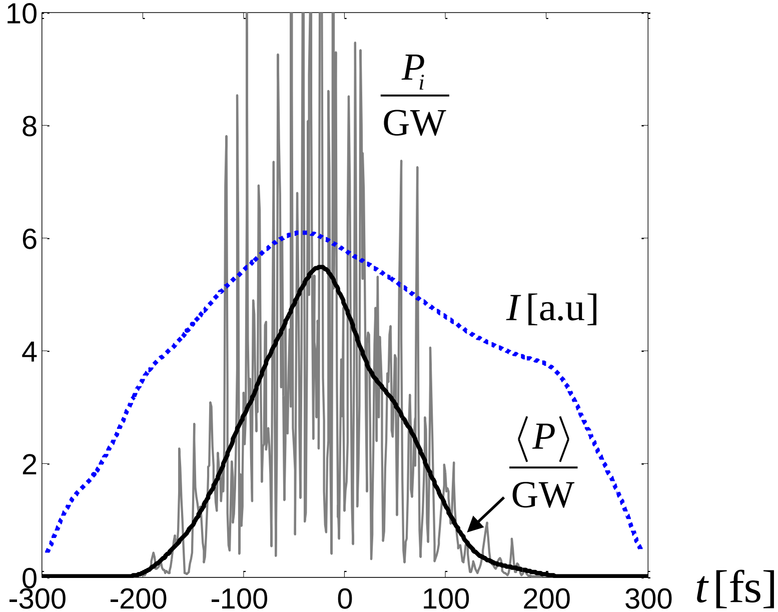
Q= 1 nC

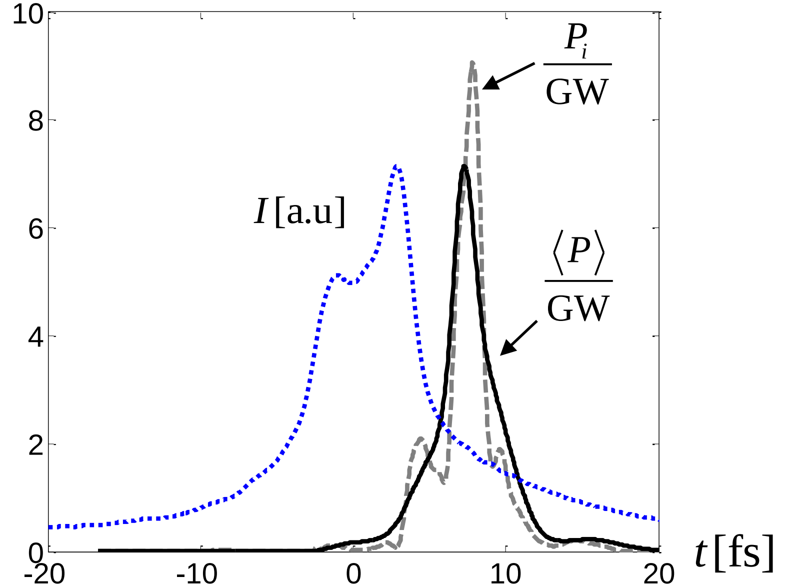
Q=0.02 nC





z=10m





z=20m

Radiation properties for different charges at FLASH

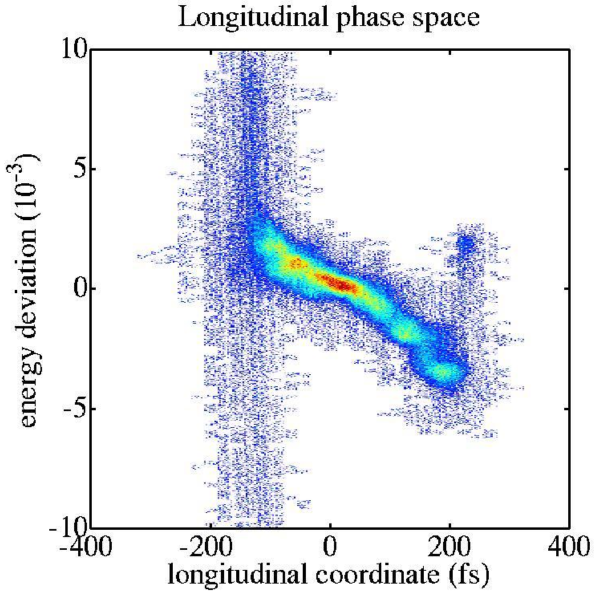
	with harmonic module					without*
Bunch charge, nC	1	0.5	0.25	0.1	0.02	0.5-1
Wavelength, nm	6.5					6
Beam energy, MeV	1000					1000
Peak current, kA	**2.5**			**2.1**	**1-1.5**	1.3-2.2
Slice emmitance,mm-mrad	**1-1.3**	**0.7-0.9**	**0.5-0.7**	**0.4-0.5**	**0.3-0.4**	1.5-3.5
Slice energy spread, MeV	0.1-0.2	0.1-0.2	0.25	0.2-0.4	0.25	0.3
Saturation length, m	**13**	**12**	**11**	**10**	**11**	22-32
Energy in the rad. pulse, μJ	1000-1400	700	500	200	30	50-150
Radiation pulse duration FWHM, fs	**70**	**30**	**17**	**7**	**2**	15-50
Averaged peak power, GW	5-7					2-4
Spectrum width, %	0.4-0.6			0.8-1		0.4-0.6
Coherence time, fs	4-5			-	-	-

*) E.L.Saldin at al, Expected properties of the radiation from VUV-FEL at DESY, TESLA FEL 2004-06, 2004.

First experimental results for low charges at FLASH

acknowledgments to Ch. Behrens

Q=0.4 nC



C.Behrens, C.Gerth, Measurement of Sliced-Bunch Parameters at FLASH, MOPC08.

strong compression at the bunch head

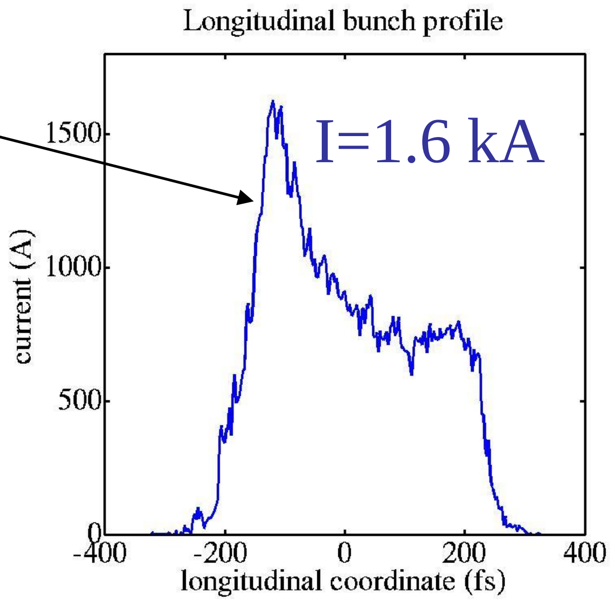
⇓

we need

$$Z_2'' > 0, Z_1' \approx 0$$

⇓

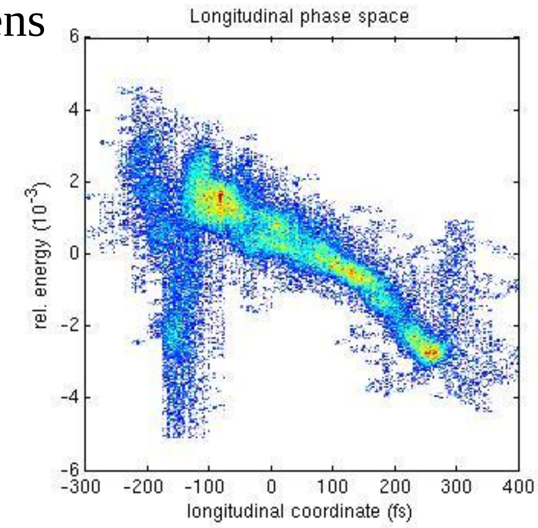
increase third harmonic voltage or reduce BC2 energy

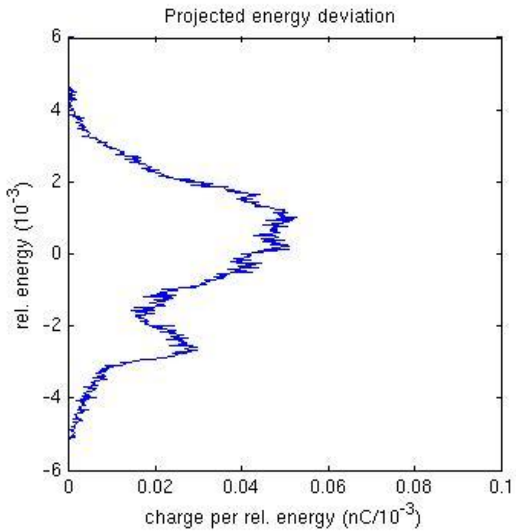


First experimental results for low charges at FLASH

acknowledgments to Ch. Behrens

Q=0.2 nC





strong compression at the bunch head

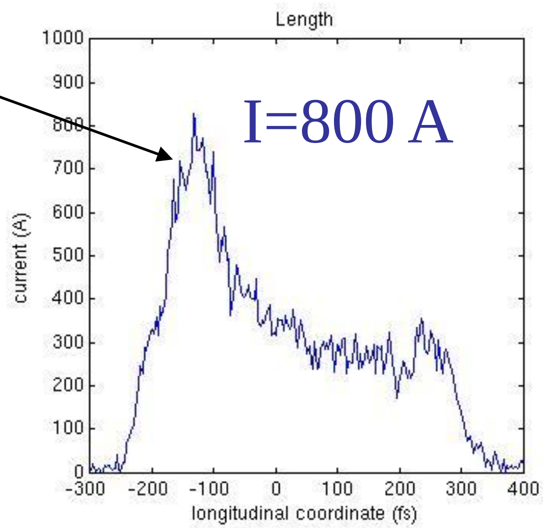
⇩

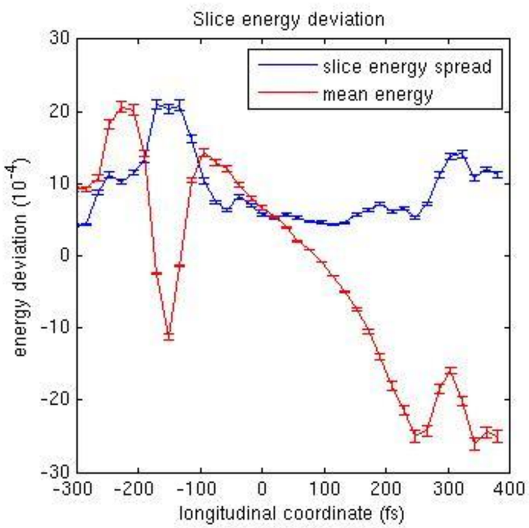
we need

$$Z_2'' > 0, Z_1' \approx 0$$

⇩

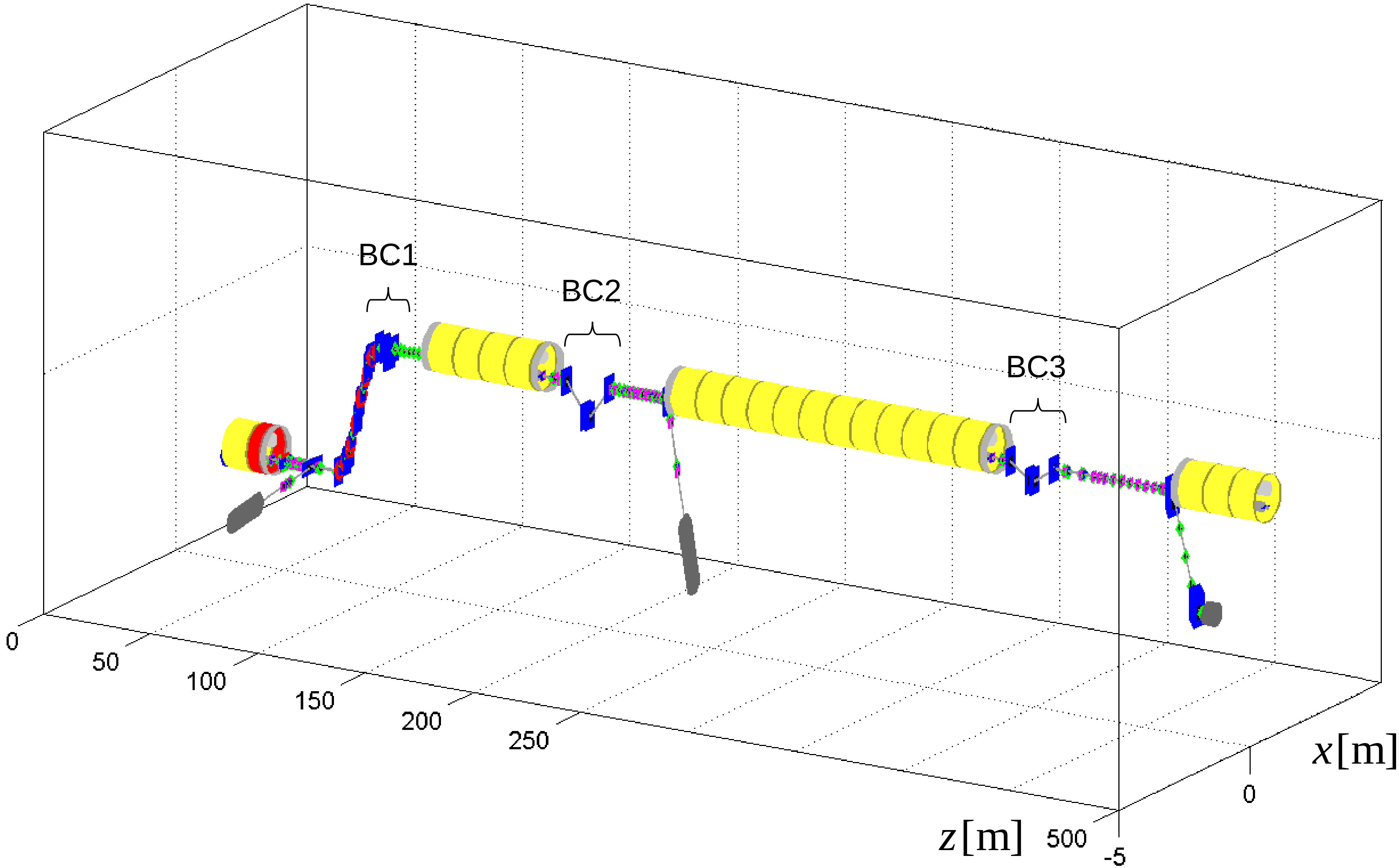
increase third harmonic voltage or reduce BC2 energy





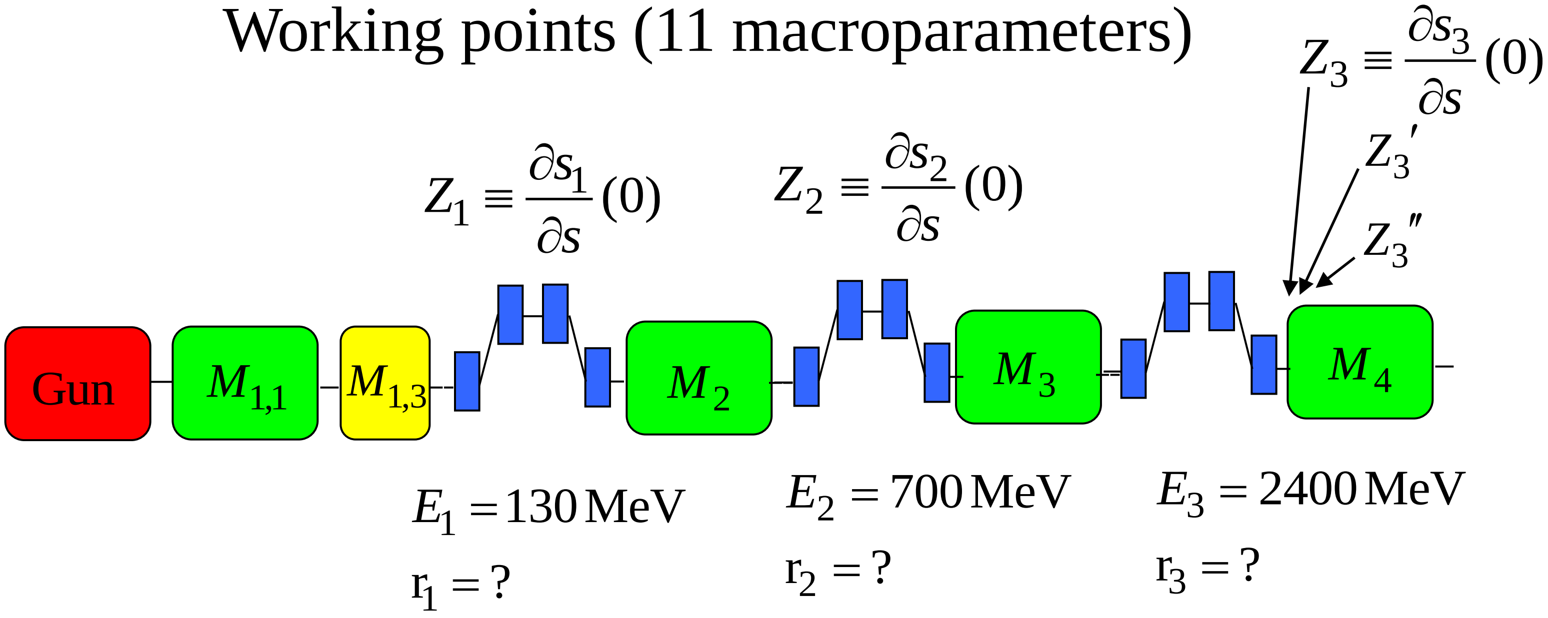
Beam dynamics simulations for the European XFEL

3 stage bunch compression system:



Beam dynamics simulations for the European XFEL

Working points (11 macroparameters)



What is the optimal choice?

$$r_1 = ?, \quad r_2 = ?, \quad r_3 = ?, \quad C_1 = ?, \quad C_2 = ?$$

Beam dynamics simulations for the European XFEL

$$r_1 = ?, \quad r_2 = ?, \quad r_3 = ?, \quad C_1 = ?, \quad C_2 = ?$$

Wake compensation

$$r^0_{56(3)} = -\left(\frac{1}{C_1 C_2} - \frac{1}{C}\right)\frac{L_0 E_3}{\Delta W_3} < 0$$

$$r_{56(3)} = \max(r^0_{56(3)}, \min r_{56(3)})$$

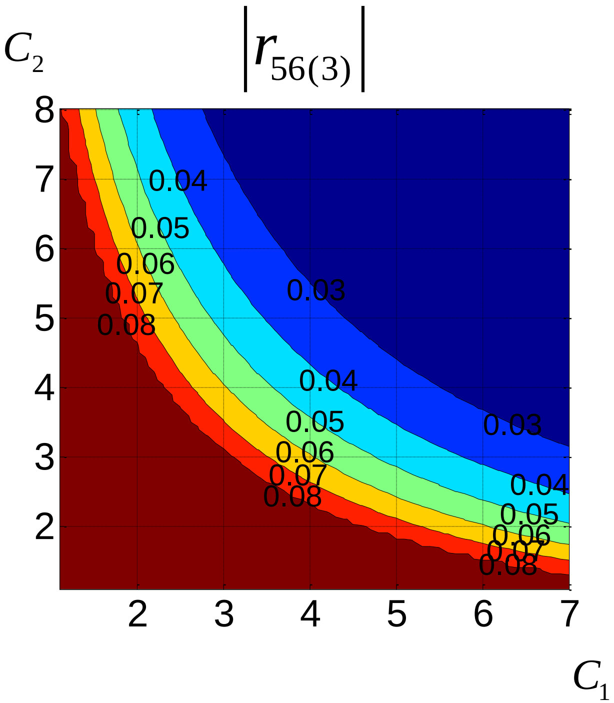
Restriction on maximal energy chirp at BCs

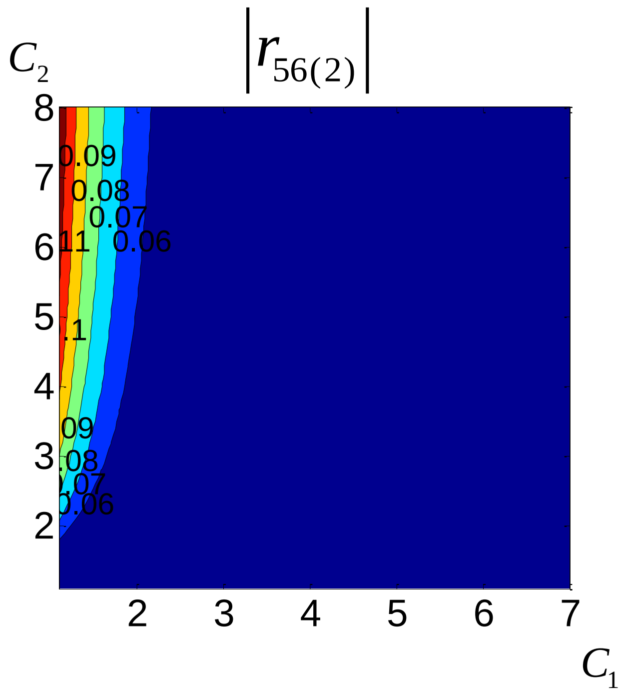
$$r^0_{56(2)} = \frac{L_0}{\delta_{E_2}} \frac{1}{C_1}\left(1 - \frac{1}{C_2}\right)$$

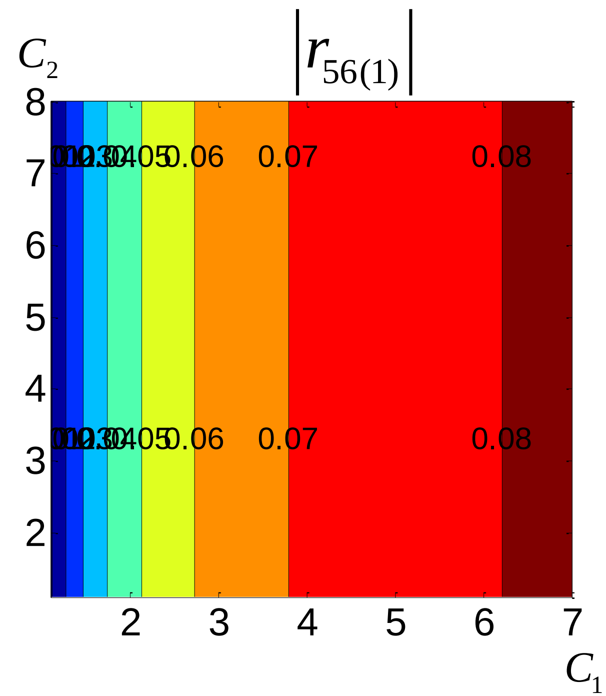
$$r_{56(2)} = \max(r^0_{56(2)}, \min r_{56(2)})$$

$$r^0_{56(1)} = \frac{L_0}{\delta_{E_1}}\left(1 - \frac{1}{C_1}\right)$$

$$r_{56(1)} = \max(r^0_{56(1)}, \min r_{56(1)})$$



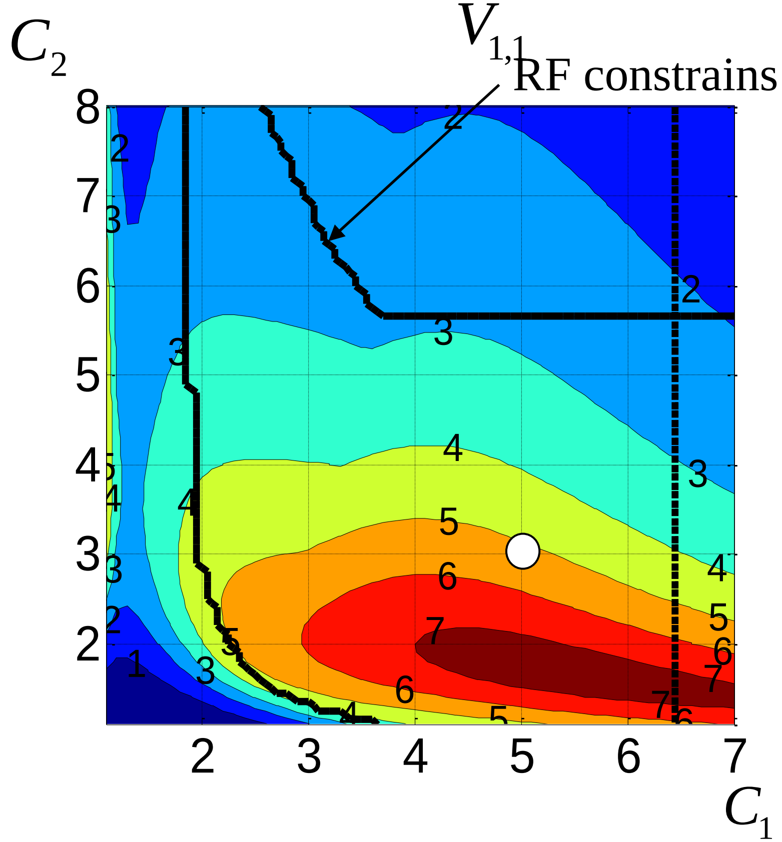




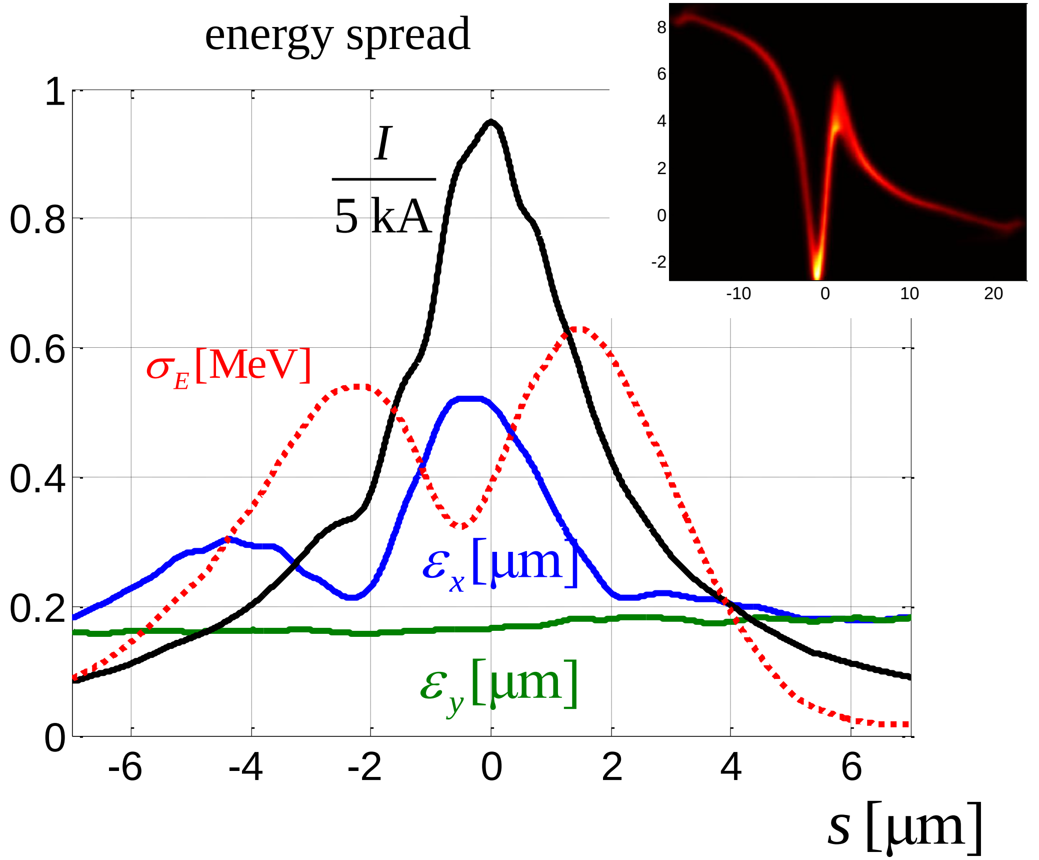
Beam dynamics simulations for the European XFEL

Q=0.1 nC

RF tolerance $\frac{|\Delta \mathbf{v}_{1,1}|}{V_{1,1}} 10^5$



Current, emittance, energy spread



Longitudinal phase space

$\delta_{E_1} = 4\%$ $\delta_{E_2} = 2.5\%$

$$\delta_{E_i} = \frac{\max_s E_i(s) - \min_s E_i(s)}{E_i^0}$$

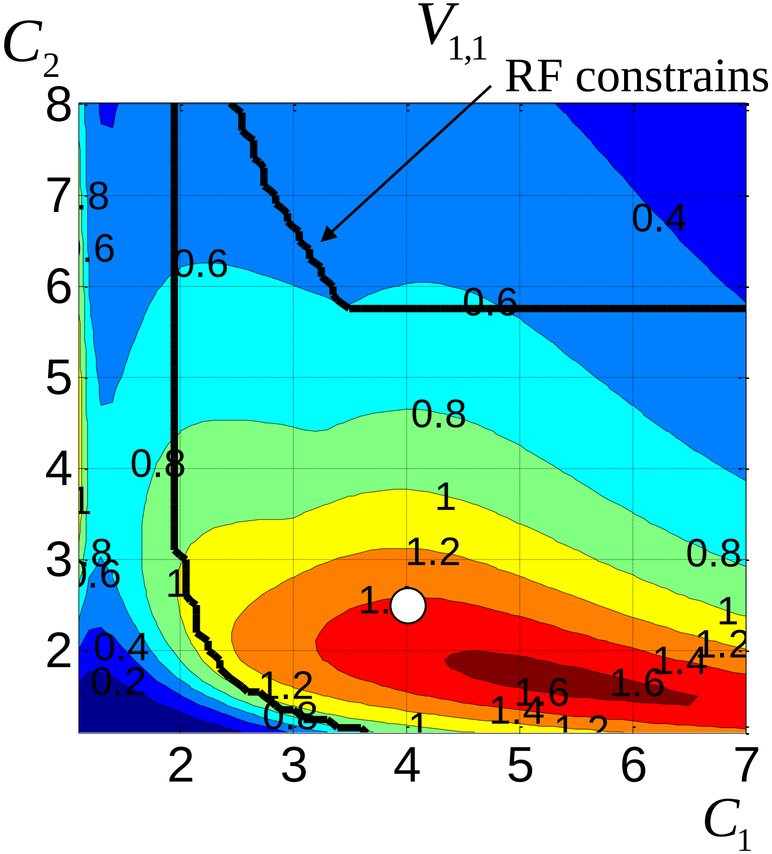
$$\varepsilon_x^{proj} = 1.6\,[\mu m]$$

$$\varepsilon_y^{proj} = 0.22\,[\mu m]$$

Beam dynamics simulations for the European XFEL

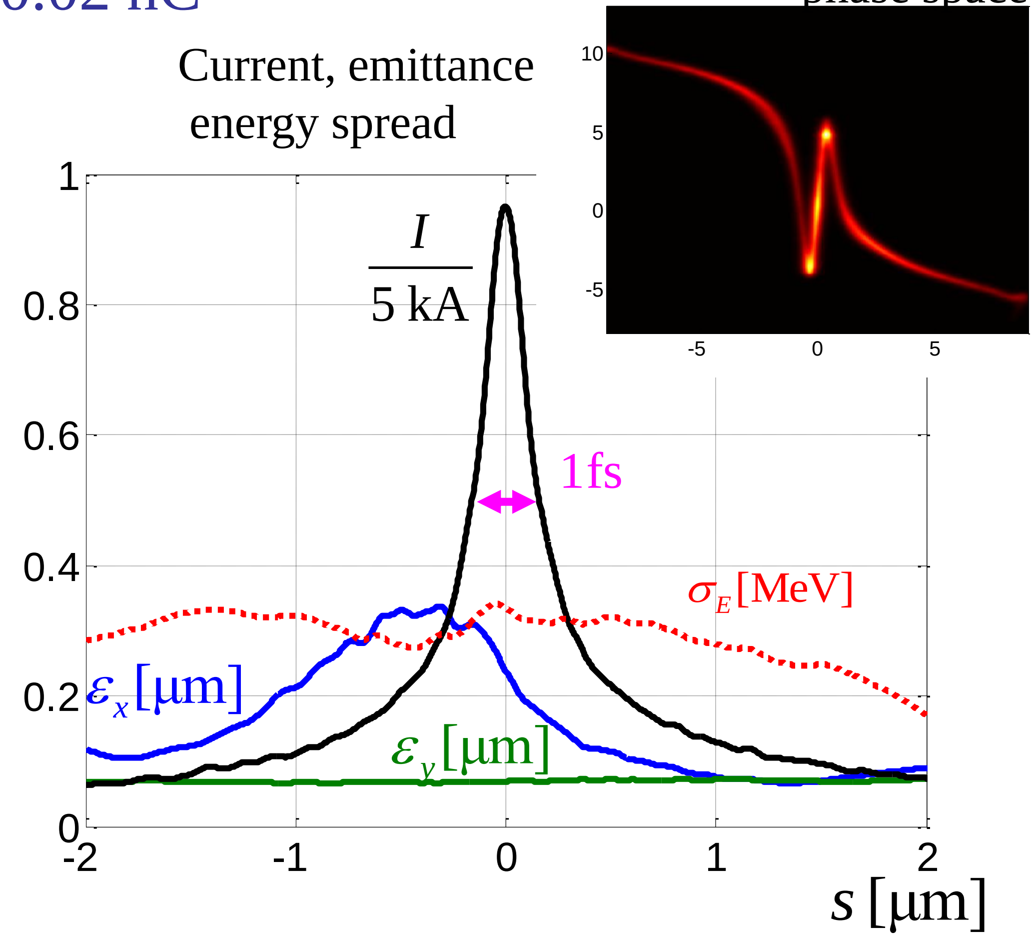
Q=0.02 nC

RF tolerance $\frac{|\Delta \mathbf{v}_{1,1}|}{V_{1,1}} 10^5$



Current, emittance energy spread

Longitudinal phase space



$\delta_{E_1} = 4\%$ $\qquad$ $\delta_{E_2} = 2.5\%$

$$\delta_{E_i} = \frac{\max_s E_i(s) - \min_s E_i(s)}{E_i^0}$$

$$\varepsilon_x^{proj} = 0.5\,[\mu\text{m}]$$

$$\varepsilon_y^{proj} = 0.1\,[\mu\text{m}]$$

Beam dynamics simulations for the European XFEL

Beam properties for different charges

Bunch charge, nC	1	0.5	0.25	0.1	0.02
Peak current, kA	**~ 5**				
Slice emmitance,mm-mrad	**0.7**	**0.4-0.5**	**0.3-0.5**	**0.2-0.5**	**0.1-0.4**
Slice energy spread, MeV (without laser heater)	0.1-0.2	0.1-0.2	0.2-0.3	0.3	0.3
Bunch length FWHM, fs	**160**	**80**	**40**	**10**	**1-2**

E. Schneidmiller, M.V.Yurkov, Expected Properties of the Radiation from the European XFEL Operating at the Energy of 14 GeV, MOPC05.

Summary

(1) Self consistent beam dynamics simulations for FLASH and European XFEL

We are able to provide the well conditioned electron beam for different charges.
But RF tolerances for low charges are tough.

(2) FEL simulations for FLASH

The charge tuning (20-1000 pC) in SASE mode allows to tune
- the radiation pulse energy (30-1400 mJ)
- the pulse width (FWHM 2-70 fs).

Acknowledgements to my colleagues from DESY Beam Dynamics Group.