Beam Dynamics Simulations for XFEL

Igor Zagorodnov

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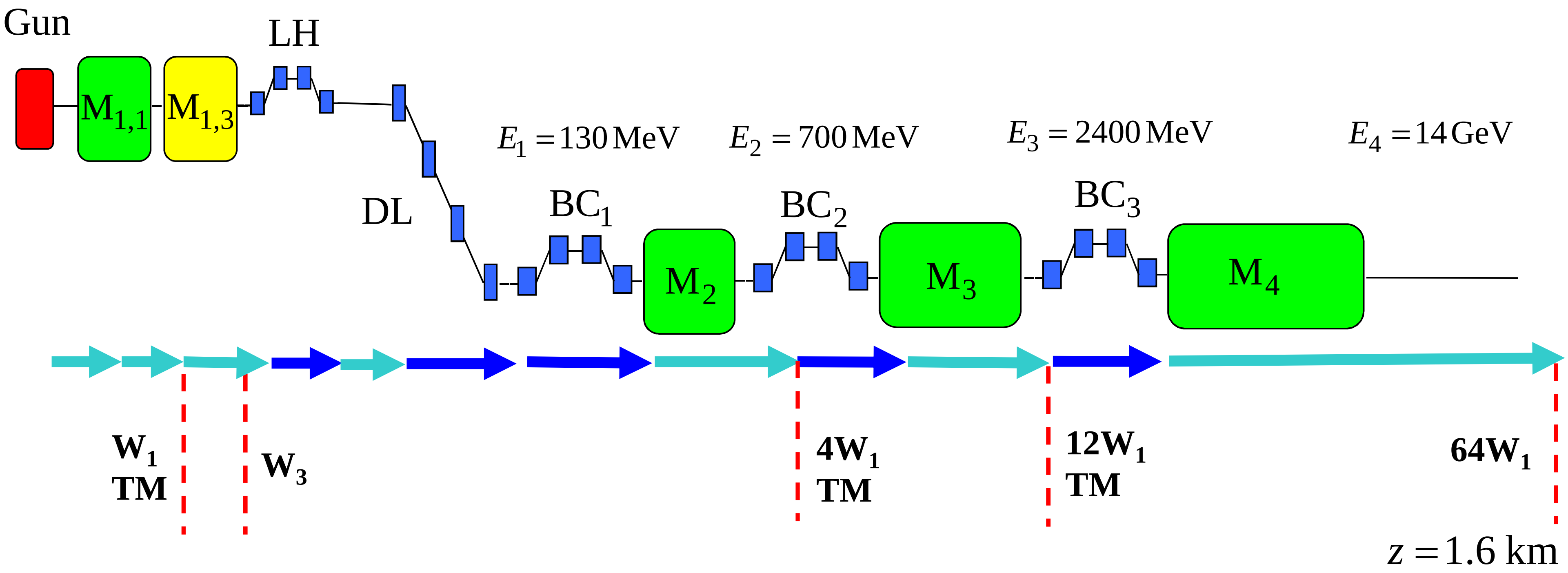
DESY

Beam dynamics simulations for the European XFEL

Full 3D simulation method (**200 CPU, ~10 hours**)



ASTRA (tracking with **3D space charge**, DESY, K. Flötmann)

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

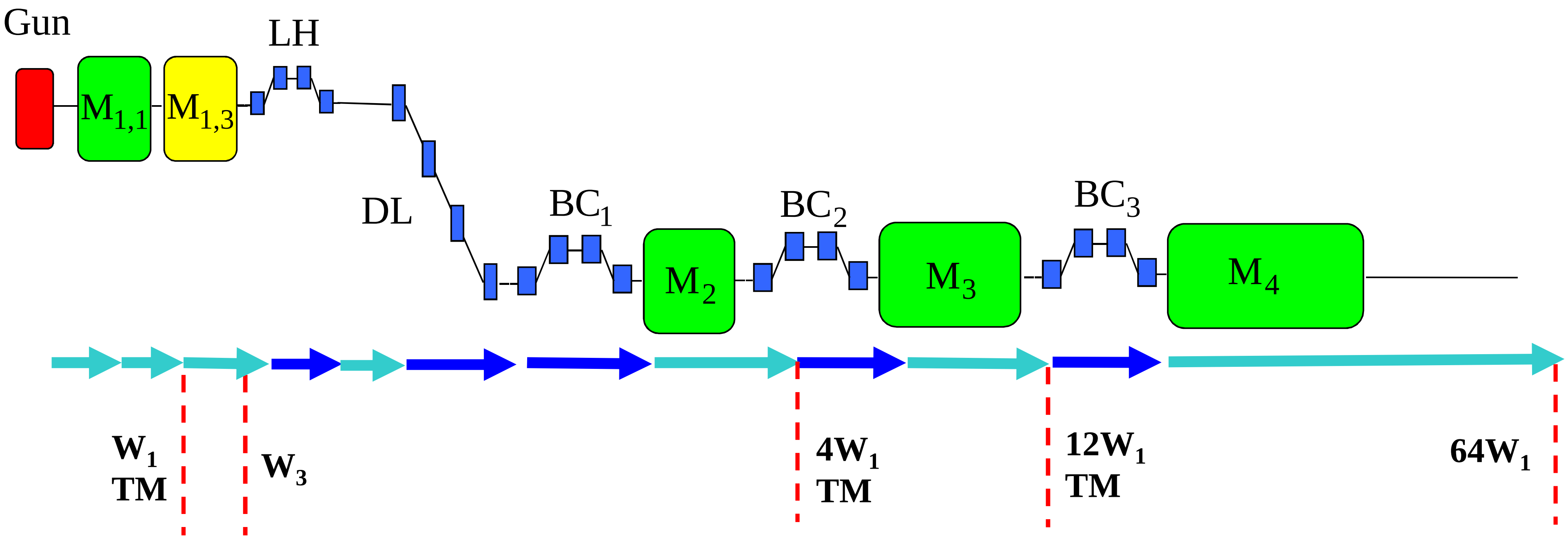
W1 -TESLA cryomodule wake (TESLA Report 2003-19, DESY, 2003)

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

TM - transverse matching to the design optics

Beam dynamics simulations for the European XFEL

Fast 3D simulation method (**1 CPU, ~10 min**)

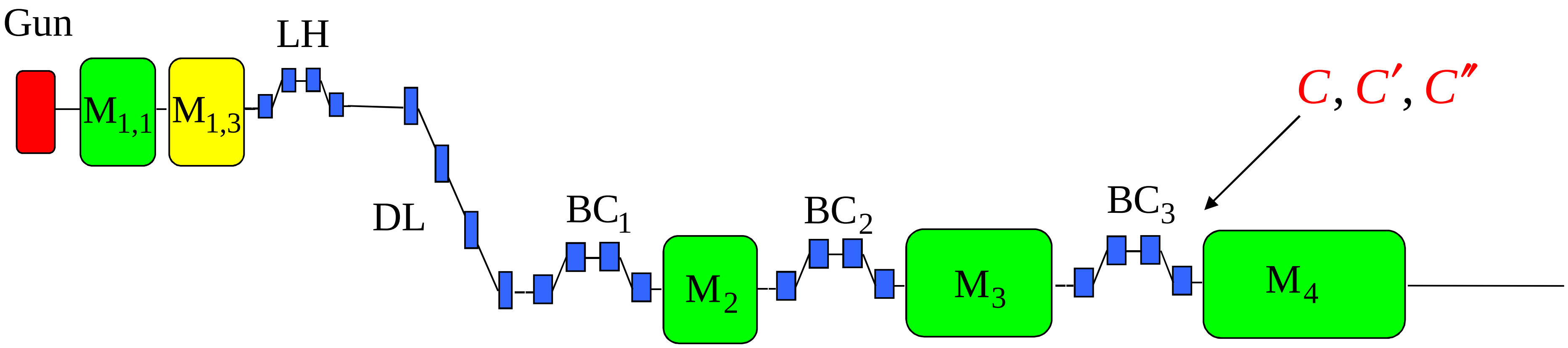


Transport Matrix + analytical longitudinal space charge wake

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

Beam dynamics simulations for the European XFEL

Working points (11 macro-parameters)



$E_1 = 130\,\mathrm{MeV}$	$E_2 = 700\,\mathrm{MeV}$	$E_3 = 2400\,\mathrm{MeV}$
$r_{56,1} = ?$	$r_{56,2} = ?$	$r_{56,3} = ?$
$C_1 = ?$	$C_2 = ?$	

What is the optimal choice?

$$r_{56,1} = ?,\quad r_{56,2} = ?,\quad r_{56,3} = ?,\quad C_1 = ?,\quad C_2 = ?$$

$$-120 \le \frac{r_{56,1}}{\mathrm{mm}} \le 0$$

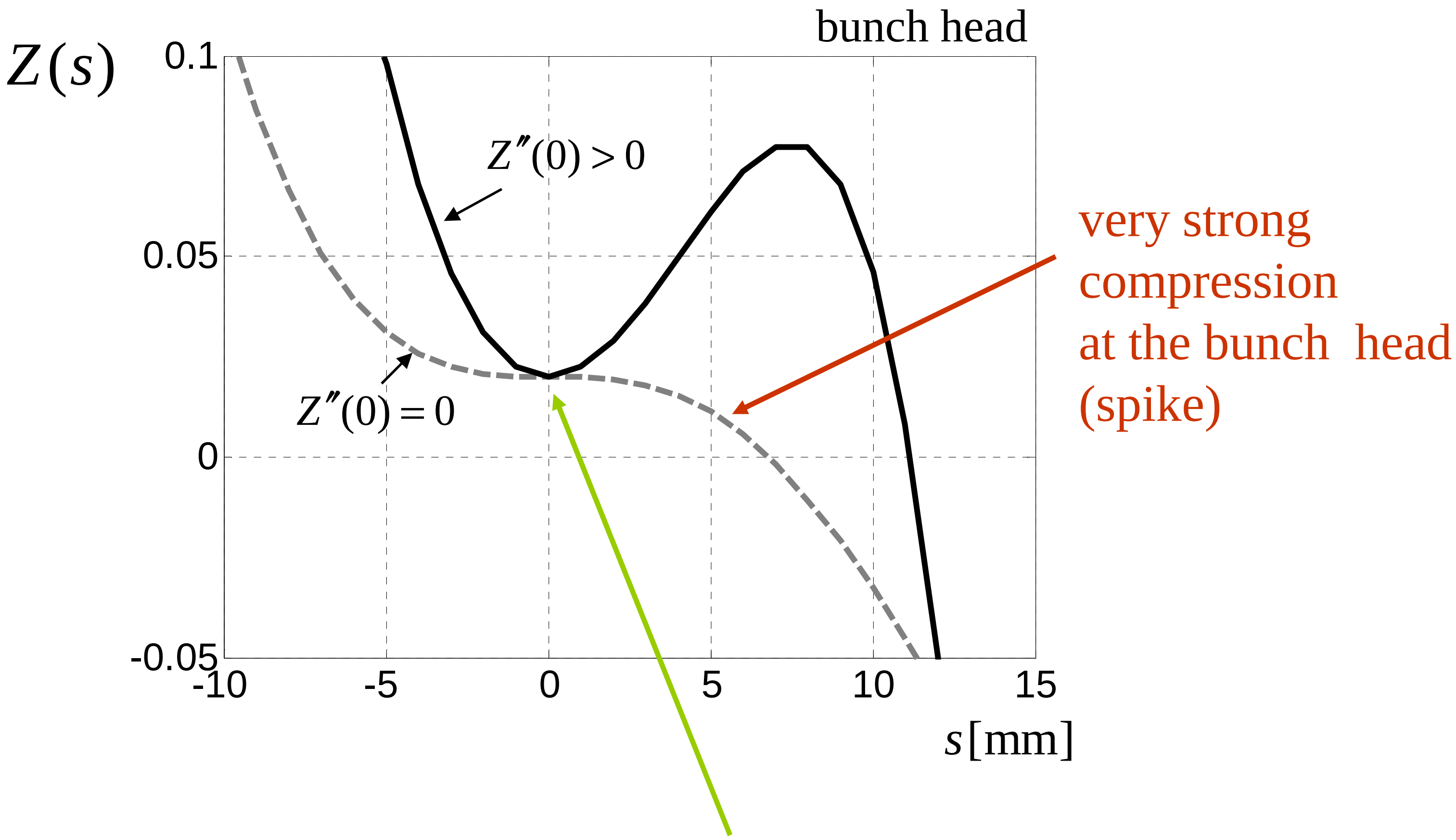
$$-120 \le \frac{r_{56,2}}{\mathrm{mm}} \le -50$$

$$-80 \le \frac{r_{56,3}}{\mathrm{mm}} \le -20$$

I. Zagorodnov, M. Dohlus, DESY 10-102, 2010

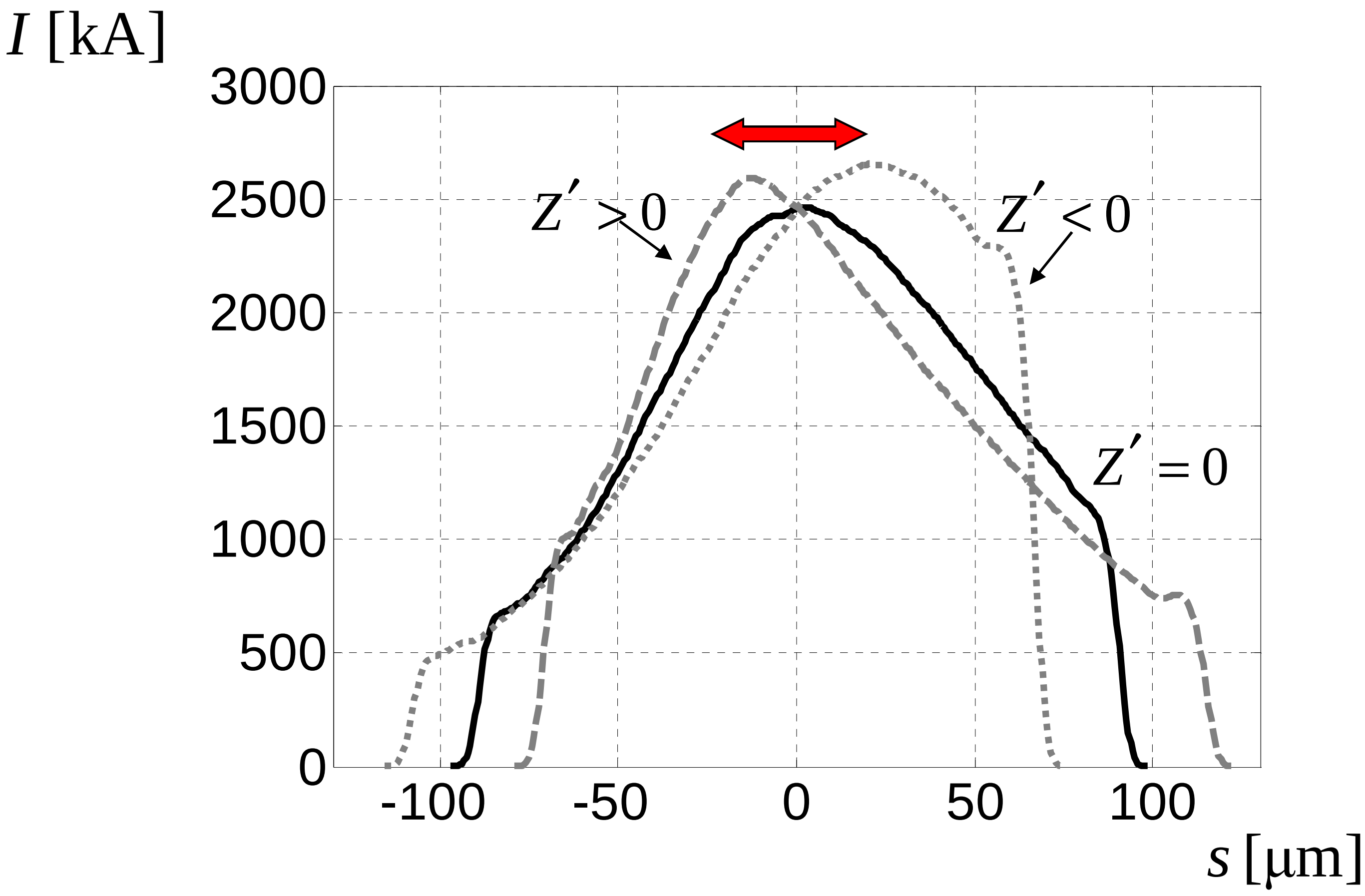
Choosing of machine parameters

$$Z(s) = \frac{1}{C(s)} = \frac{\partial s_3}{\partial s}$$ - *inverse* compression function



Local maximum of the compression $Z' = 0, Z'' > 0$

Choosing of machine parameters



Z' - a free parameter to move the peak

Beam dynamics simulations for the European XFEL

$$r_{56,1} = ?, \quad r_{56,2} = ?, \quad r_{56,3} = ?, \quad C_1 = ?, \quad C_2 = ?$$

Restriction on maximal energy chirps at BCs $\delta_{E_i} = \dfrac{\sigma_{E_i}}{E_i}$

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

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

$$r^0_{56(3)} = -\frac{\sigma_z^0}{\delta_{E_3}}\frac{1}{C_1 C_2}\left(1 - \frac{1}{C_3}\right)$$

Wake compensation?

$$\delta_{E_3} = \frac{1}{\sqrt{3}}\frac{QW_{\text{Linac}}}{E_3}$$

$$\left(\delta_{E_1}, \delta_{E_2}, \delta_{E_3}\right)$$

+ scan of the RF tolerance vs. C_1 and C_2

$$\textit{if} \quad r^0_{56(i)} > \max(r_{56(i)}), \quad \textit{then} \quad r^0_{56(i)} = \max r_{56(i)}$$

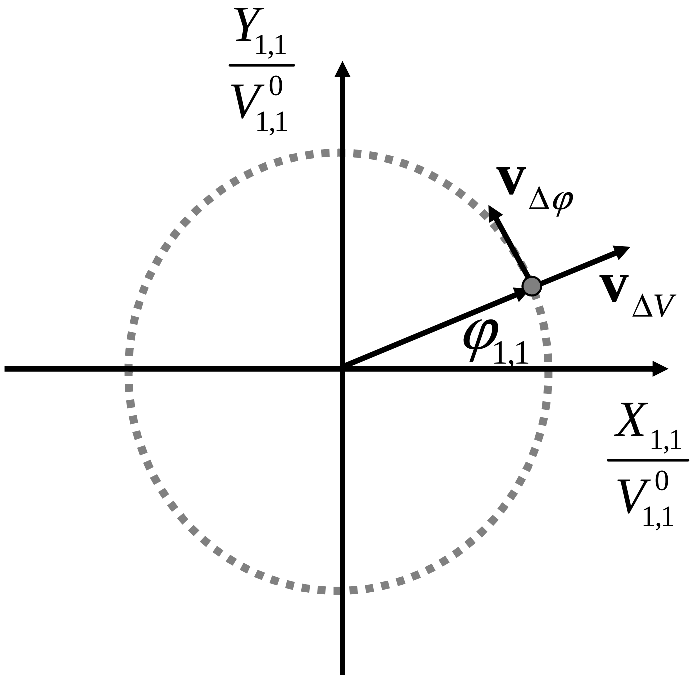
$$\textit{if} \quad r^0_{56(i)} < \min(r_{56(i)}), \quad \textit{then} \quad \text{reject}$$

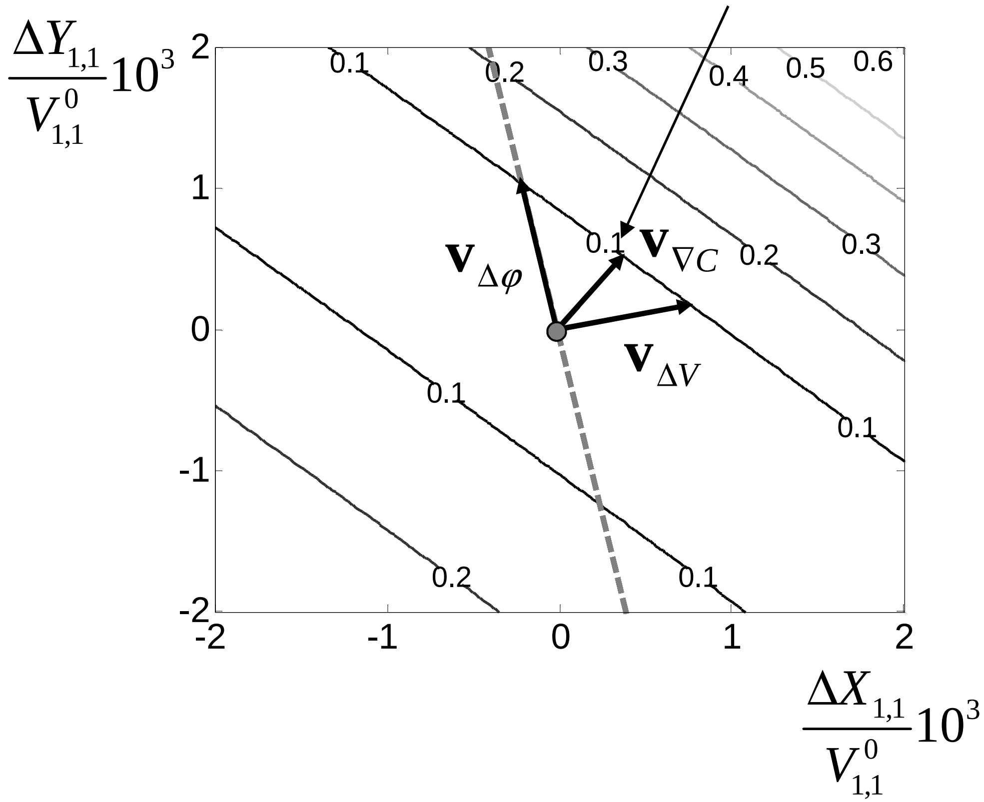
RF tolerance

$\mathbf{v}_{\Delta\varphi}$ – only the phase changes

$\mathbf{v}_{\Delta V}$ – only the voltage changes

$\mathbf{v}_{\nabla C}$ – gradient gives the worst direction





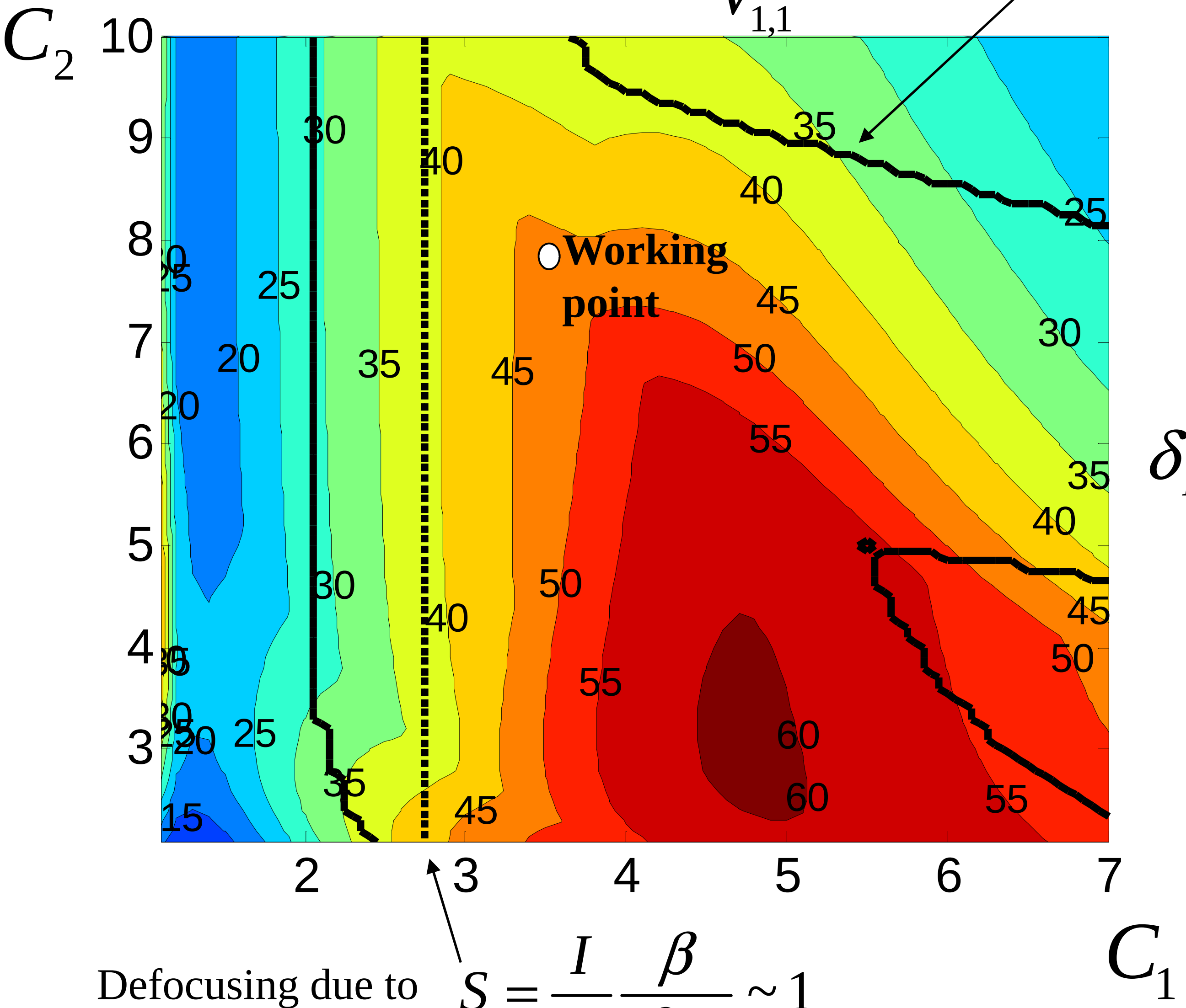
$$\tilde{V}_{1,1} = V_{1,1}e^{i\varphi_{1,1}} = X_{1,1} + iY_{1,1}$$

$$\frac{\left|\Delta\tilde{V}_{1,1}\right|}{V_{1,1}^0} = \frac{\Theta\bar{E}_1\bar{E}_2\bar{E}_3}{kV_{1,1}^0 C_3 C_2^2 C_1^3\sqrt{A_3^{\ 2} + B_3^{\ 2}}}$$

I. Zagorodnov, M. Dohlus, DESY 10-102, 2010

RF tolerance $\frac{\left|\Delta \tilde{V}_{1,1}\right|}{V_{1,1}^{0}} 10^{5}$

Maximal RF voltage



$$\delta_{E_i} = \begin{pmatrix} 0.015 \\ 0.01 \\ 0.003 \end{pmatrix}$$

Defocusing due to space charge $S = \frac{I}{I_A} \frac{\beta}{\gamma^2 \varepsilon_n} \sim 1$

Choosing of machine parameters

Macro-parameters

Charge Q, nC	Momentum compaction factor in BC_1 $R_{56,1}$, [mm]	Compr. in BC_1 C_1	Momentum compaction factor in BC_2 $R_{56,2}$, [mm]	Compr. in BC_2 C_2	Momentum compaction factor in BC_3 $R_{56,3}$, [mm]	Total compr. C	First derivative Z', $[m^{-1}]$	Second derivative Z'', $[m^{-2}]$
1	-100	3.5	-54	8	-20	121	0	2000
0.5	-89	3.5	-50	8	-20	217	0	1000
0.25	-78	3.5	-50	8	-20	385	0	1000
0.1	-71	3.5	-50	8	-20	870	0	1000
0.02	-67	3.5	-50	8	-20	4237	0	500

$E_1 = 130\,\mathrm{MeV}$ $E_2 = 700\,\mathrm{MeV}$ $E_3 = 2400\,\mathrm{MeV}$

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)

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

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

$$\mathbf{f}_0 = \begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ C_1 \\ C_2 \\ C_3 \\ Z_2' \\ Z_2'' \end{pmatrix} \Rightarrow \mathbf{x} = \begin{pmatrix} V_{1,1} \\ \varphi_{1,1} \\ V_{1,3} \\ \varphi_{1,3} \\ V_2 \\ \varphi_2 \\ V_3 \\ \varphi_3 \end{pmatrix}$$

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

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XFEL beam dynamic simulations for different charges

simulation methods (looking for RF parameters)

1d analytical solution without collective effects
(11 macroparameters -> 8 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

fast 3d tracking with all collective effects

~ **10 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**

$\mathbf{x}_0 = \mathbf{x}_1$

$\mathbf{A}_2(\mathbf{x}_2) = \mathbf{f}_0$ ~ 5 iterations

full 3d tracking with all collective effects

~ **10 h** (200 cpu-s)

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

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

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

XFEL beam dynamic simulations for different charges

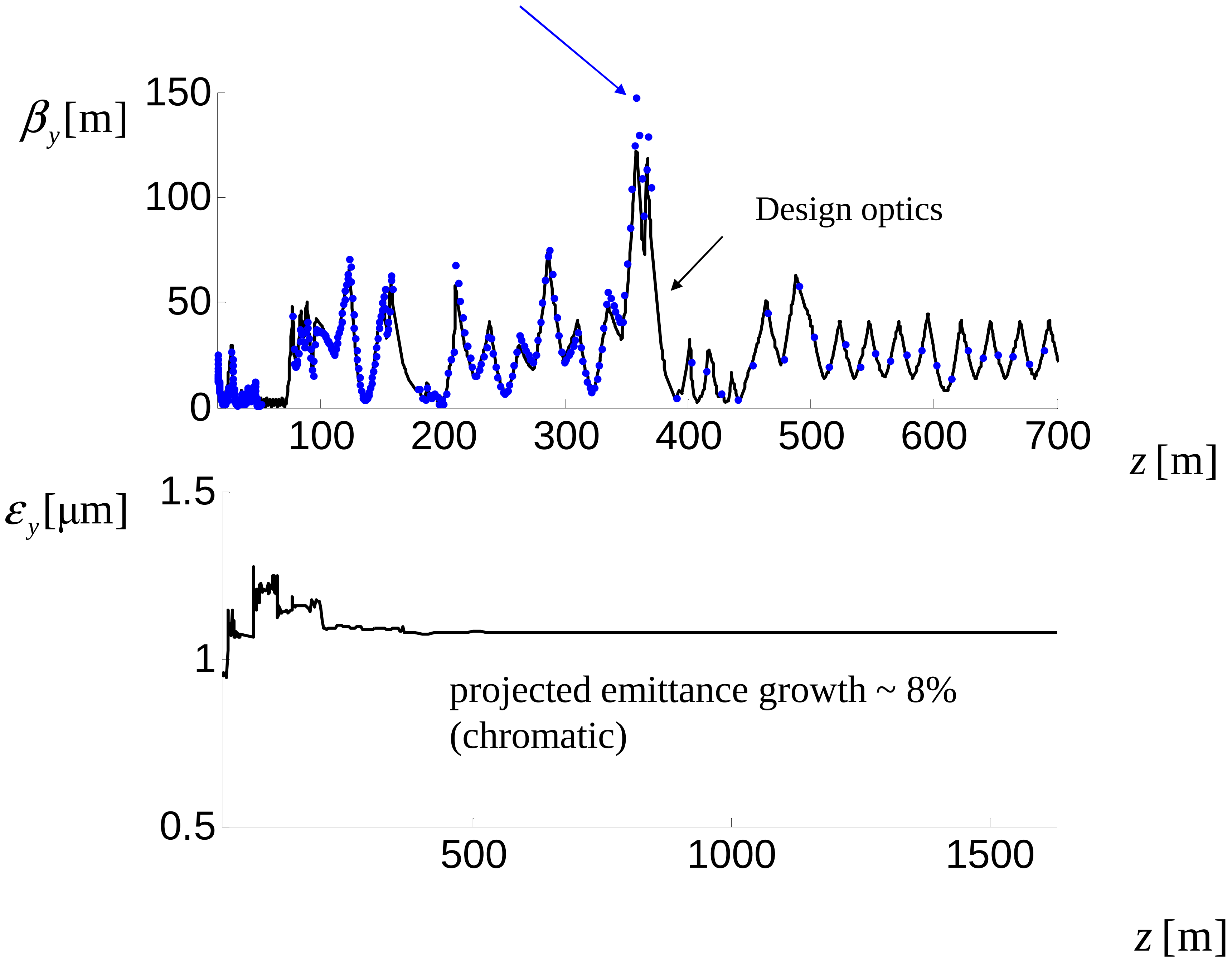
RF settings in accelerating modules

Charge, nC	$V_{1,1}$, [MV]	$\varphi_{1,1}$, [deg]	$V_{1,3}$, [MV]	$\varphi_{1,3}$, [deg]	V_2, [MV]	φ_2, [deg]	V_3, [MV]	φ_3, [deg]
1	145	5.4	22	164	656	29.7	1832	21.7
0.5	150	11.5	23.1	175.5	661	30.3	1826	21.3
0.25	157	18.9	25.1	189	652	29	1860	23.9
0.1	165	25	27.6	199.5	645	27.9	1885	25.6
0.02	164	23.4	28	194.6	640	27.1	1905	26.8

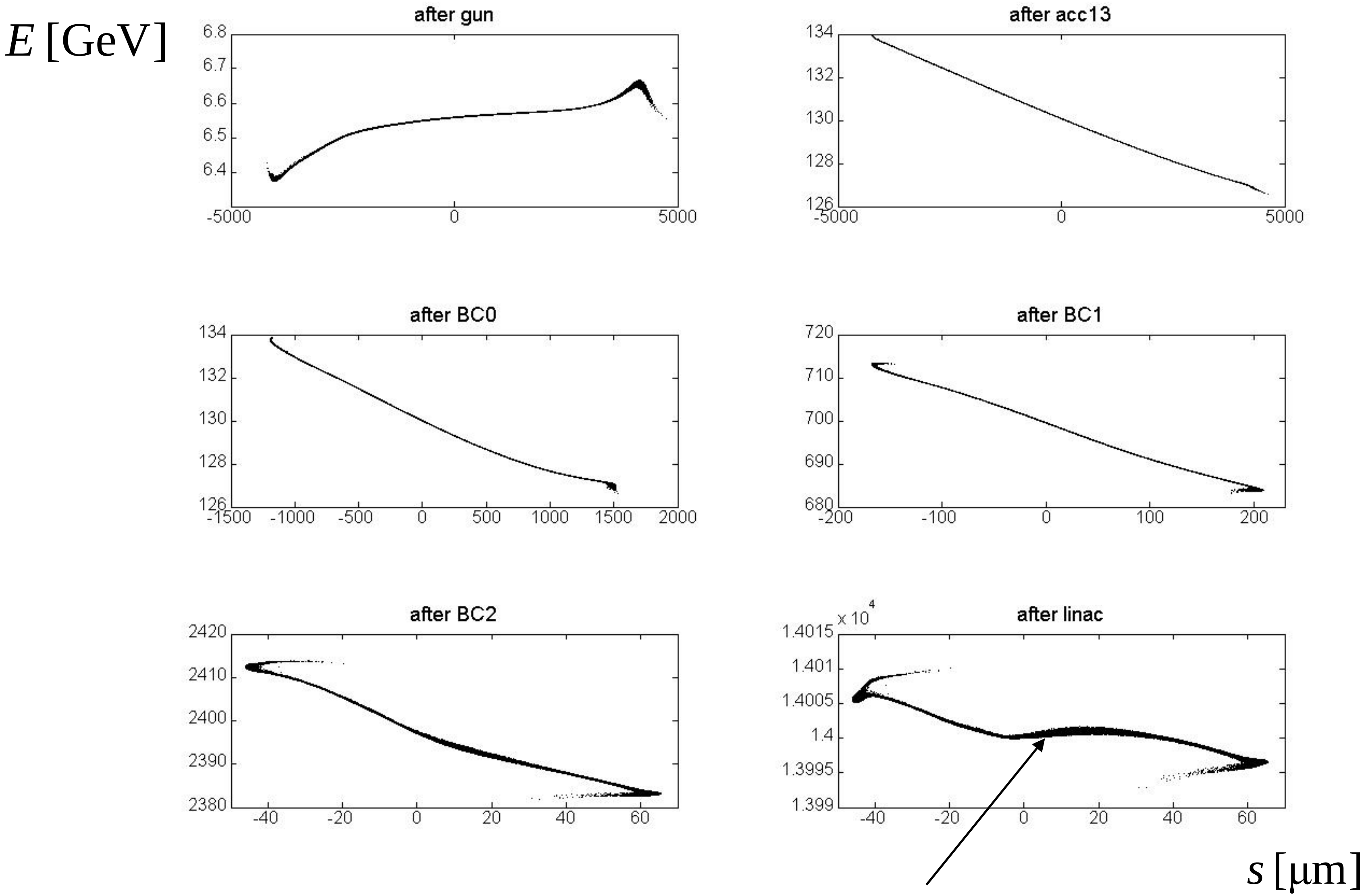
Tolerances (analytically) **without self fields** (10 % change of compression)

Q, nC	1	0.5	0.25	0.1	0.02
$\left\|\Delta\tilde{V}_{1,1}\right\|/V_{1,1}^0$	5e-4	3e-4	2e-4	1e-4	2.5e-5

Optics for Q=1nC without collective effects (full)

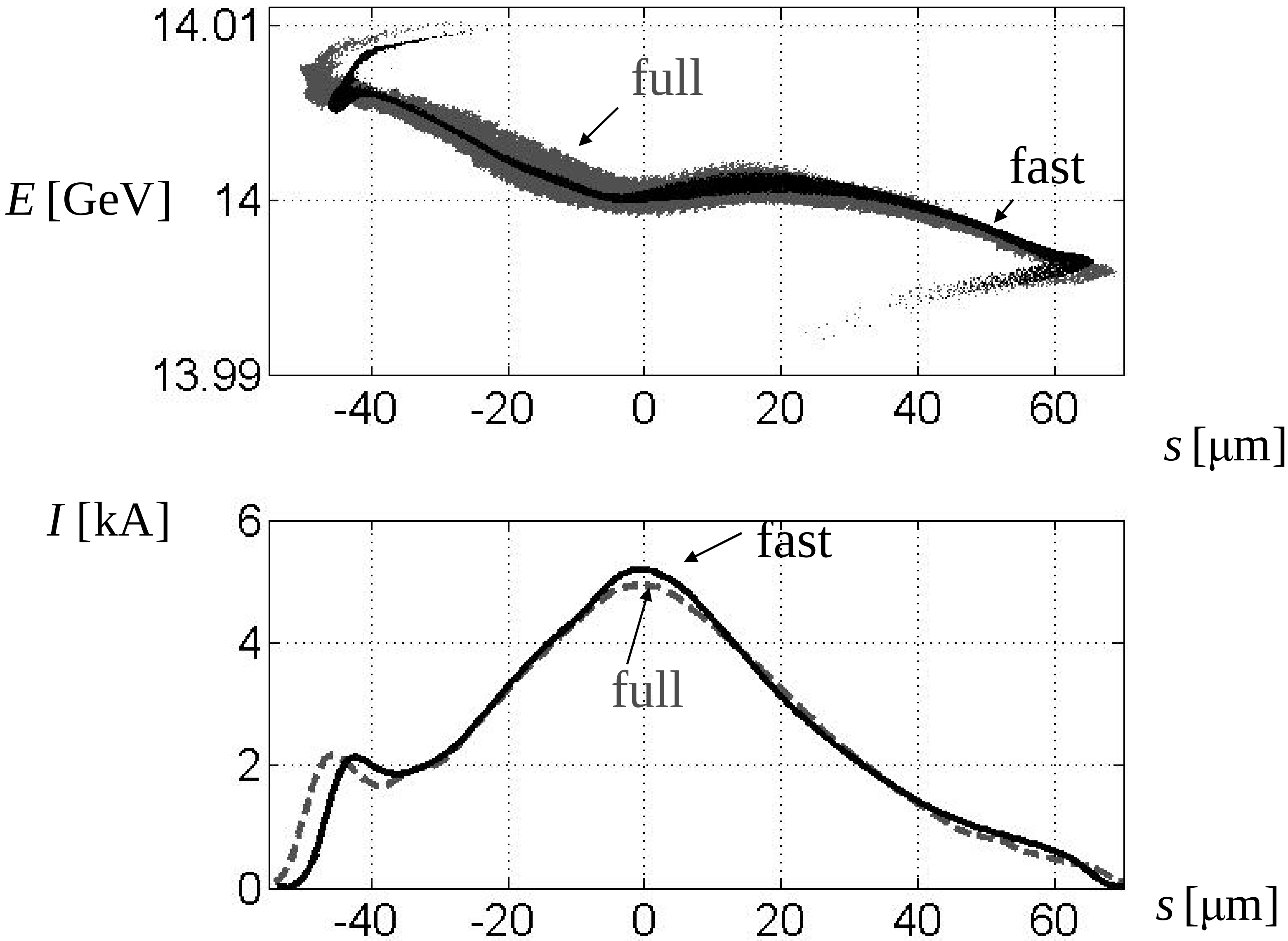


Longitudinal phase space for Q=1nC with collective effects (fast)



The chirp is compensated
by the linac wake

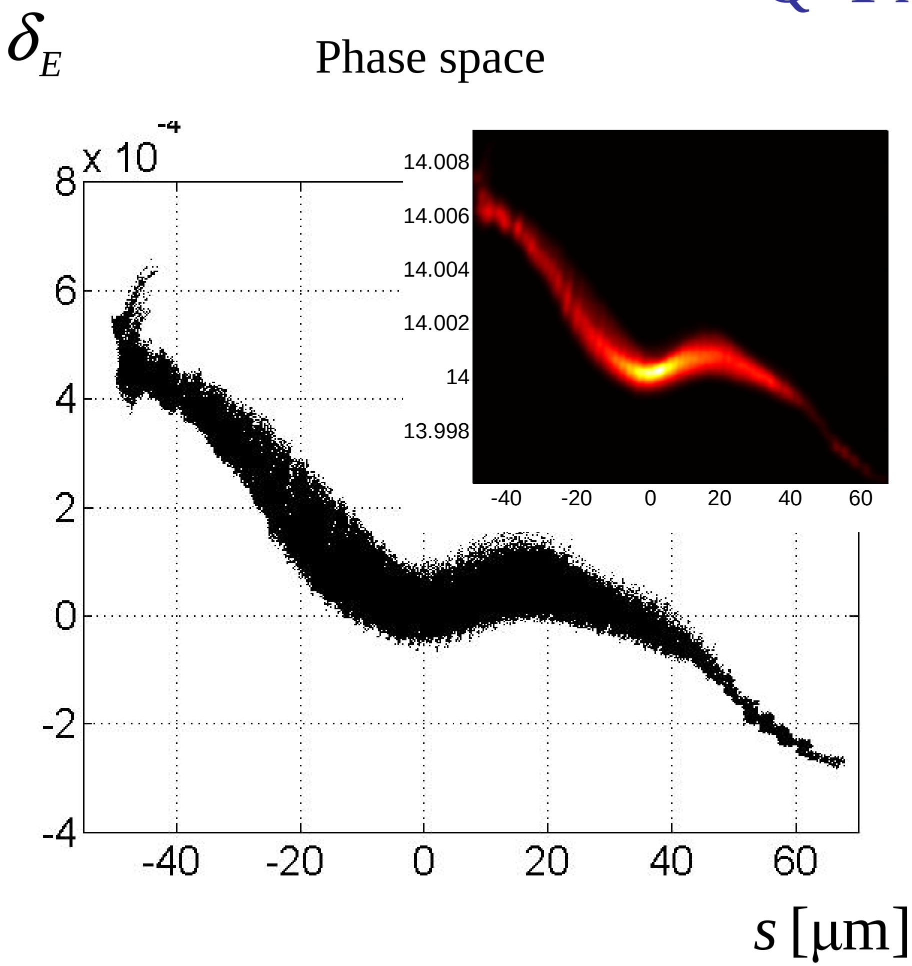
Cross-check of the models (**fast** vs. **full**), Q=1nC with collective effects



XFEL beam dynamic simulations for different charges (full)

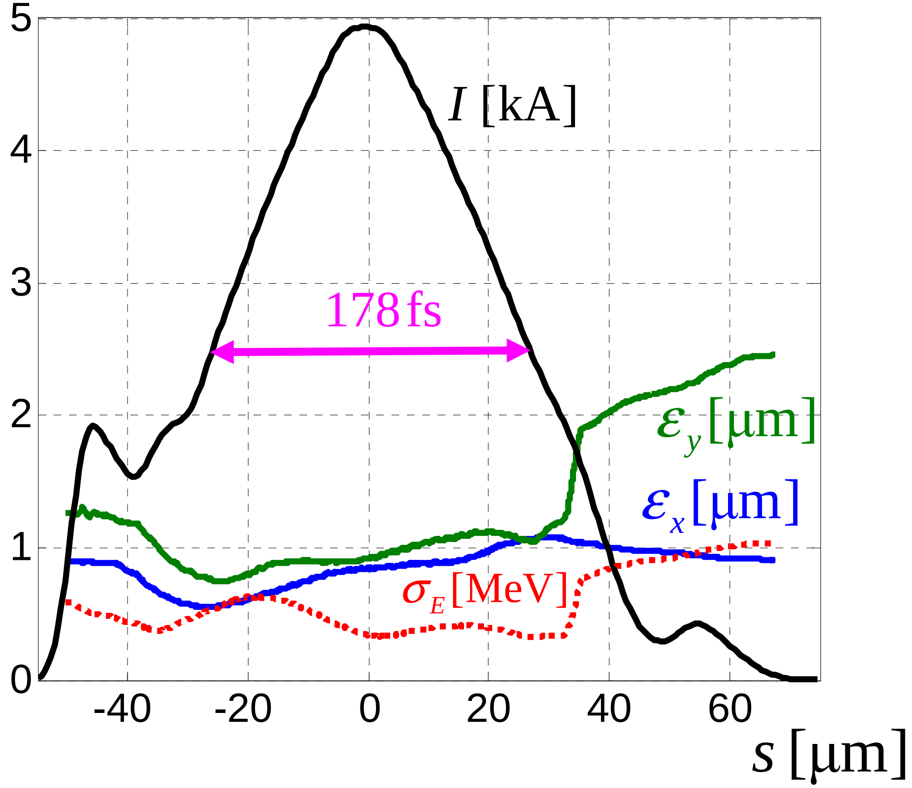
Q=1 nC

Phase space



bunch head

Current, emittance, energy spread



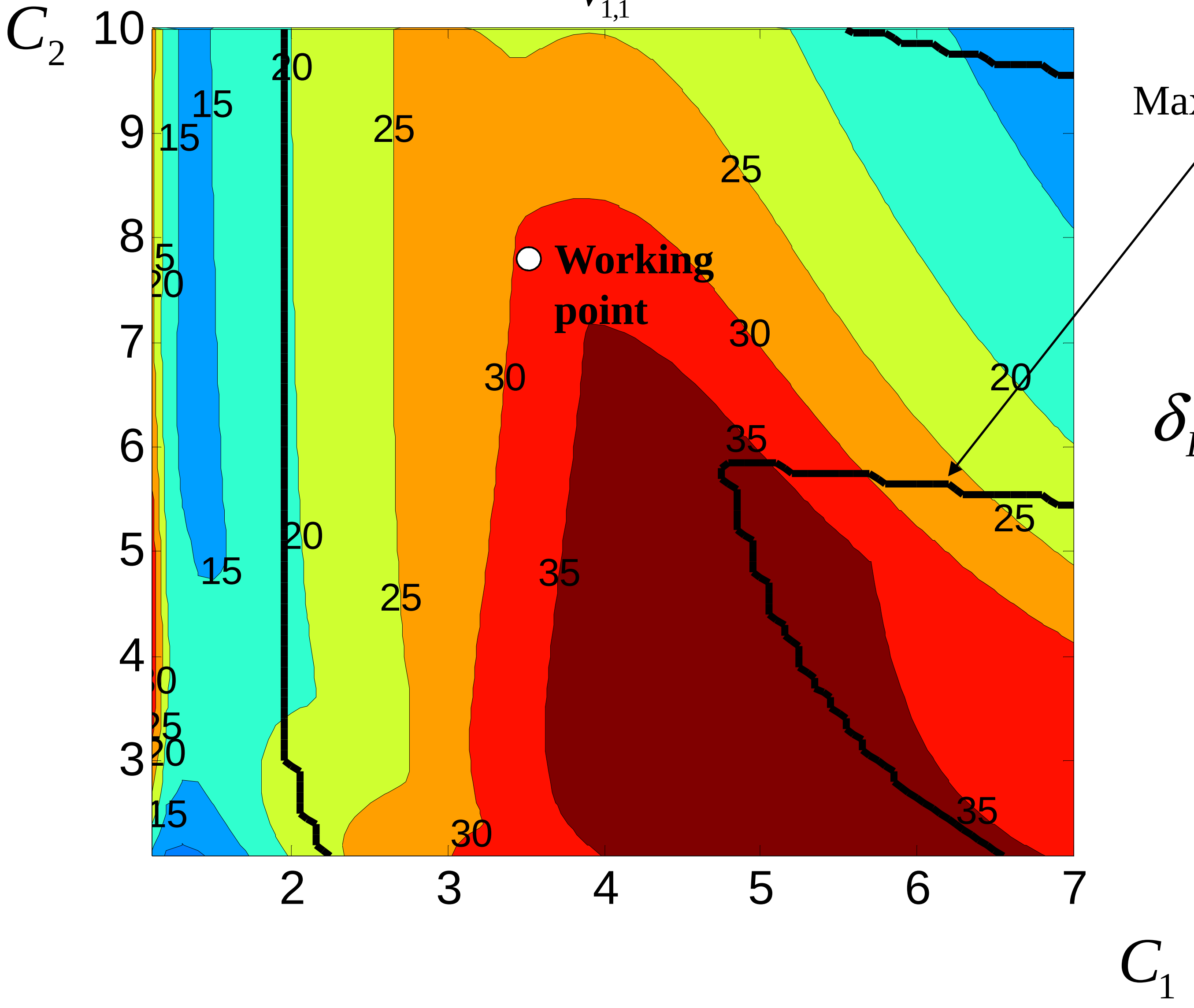
$$\varepsilon_x^{proj} = 0.9\,[\mu m]$$

$$\varepsilon_y^{proj} = 3.5\,[\mu m]$$

We have removed 6% of bad particles in the analysis

XFEL beam dynamic simulations for Q=500 pC

RF tolerance $\dfrac{\left|\Delta \tilde{V}_{1,1}\right|}{V_{1,1}^{0}} 10^5$



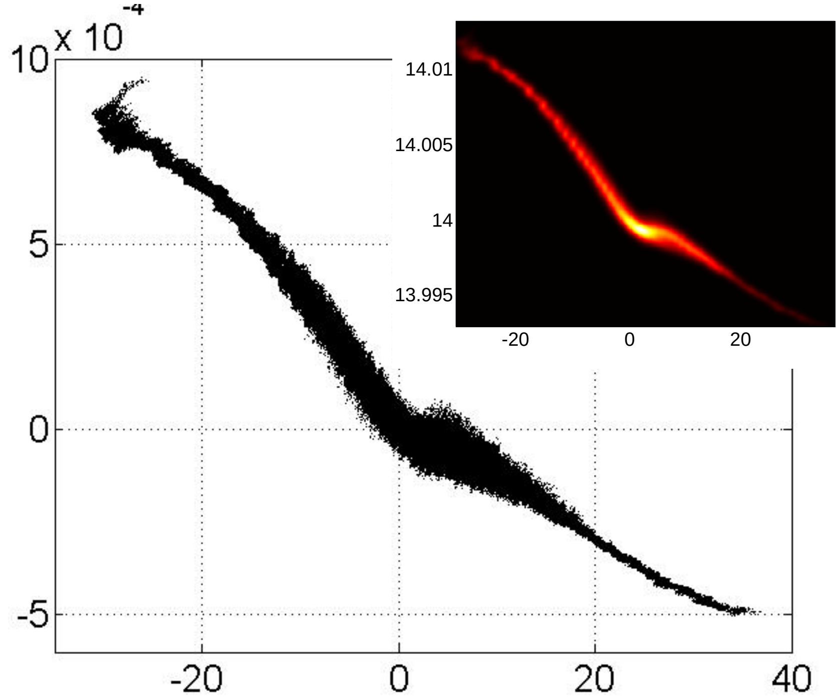
$$\delta_{E_i} = \begin{pmatrix} 0.015 \\ 0.01 \\ 0.003 \end{pmatrix}$$

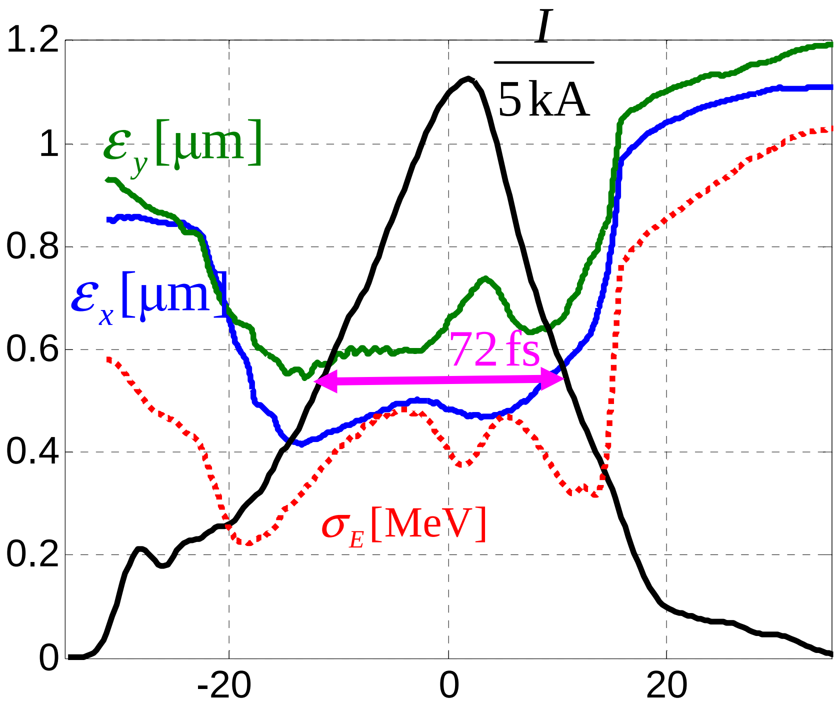
XFEL beam dynamic simulations for different charges (full)

Q=500 pC

δ_E Phase space

Current, emittance, energy spread





s [μm]

s [μm]

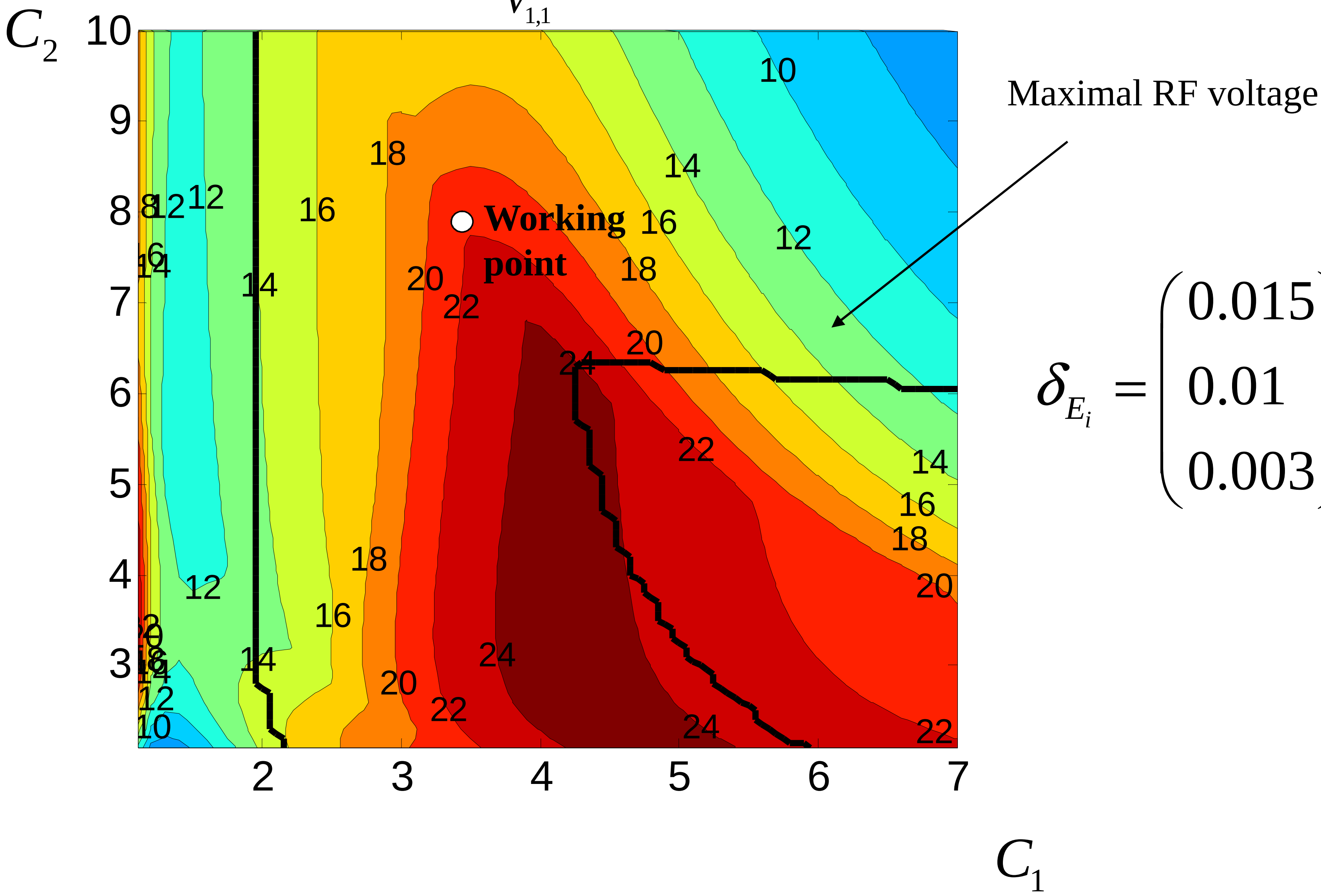
bunch head

$$\varepsilon_x^{proj} = 0.7\ [\mu\mathrm{m}]$$

$$\varepsilon_y^{proj} = 2.2\ [\mu\mathrm{m}]$$

XFEL beam dynamic simulations for Q=250 pC

RF tolerance $\frac{\left|\Delta \tilde{V}_{1,1}\right|}{V_{1,1}^{0}} 10^{5}$

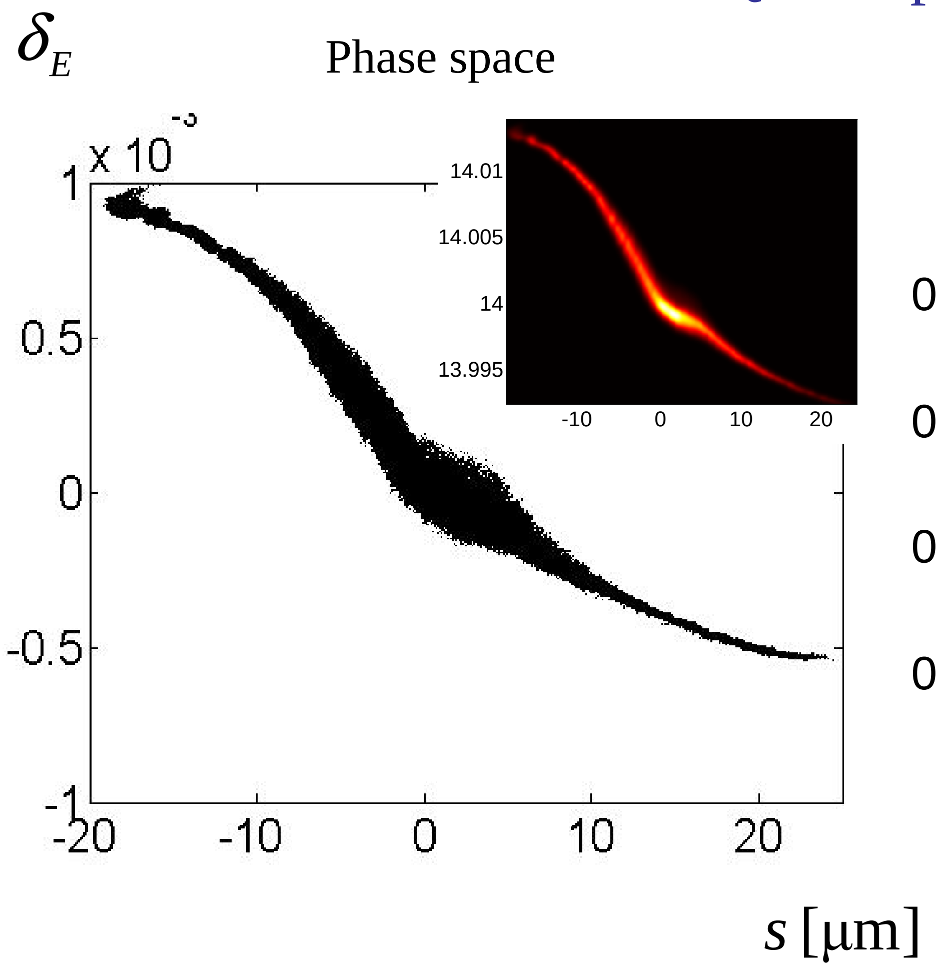


$$\delta_{E_i} = \begin{pmatrix} 0.015 \\ 0.01 \\ 0.003 \end{pmatrix}$$

XFEL beam dynamic simulations for different charges (full)

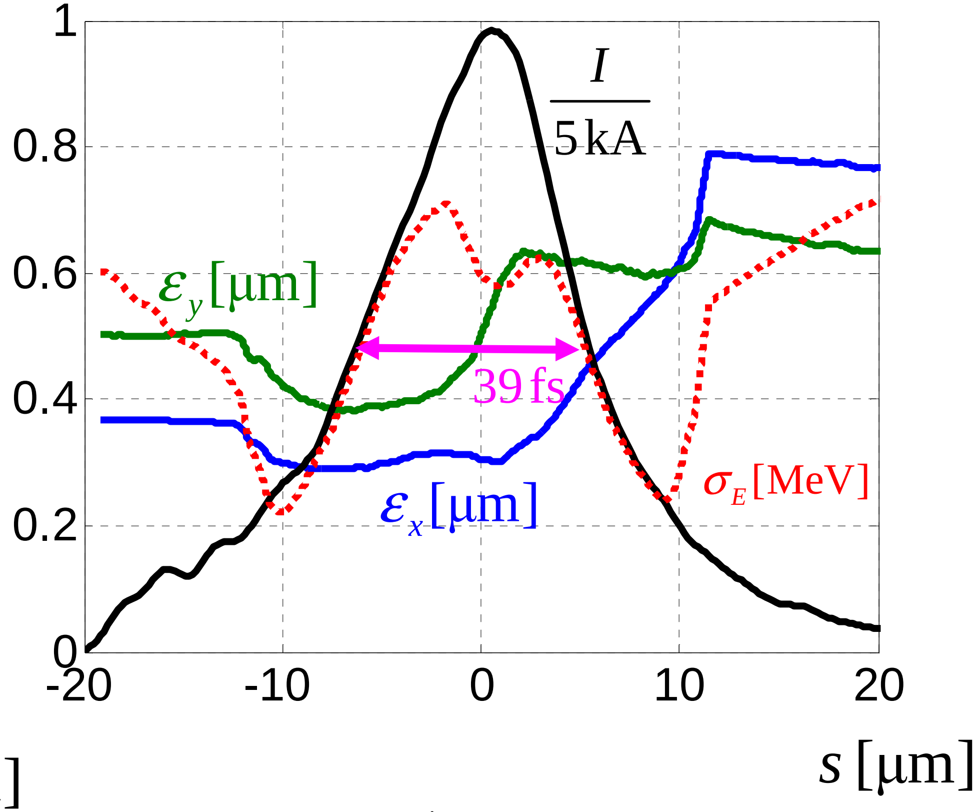
Q=250 pC

Phase space



bunch head

Current, emittance, energy spread

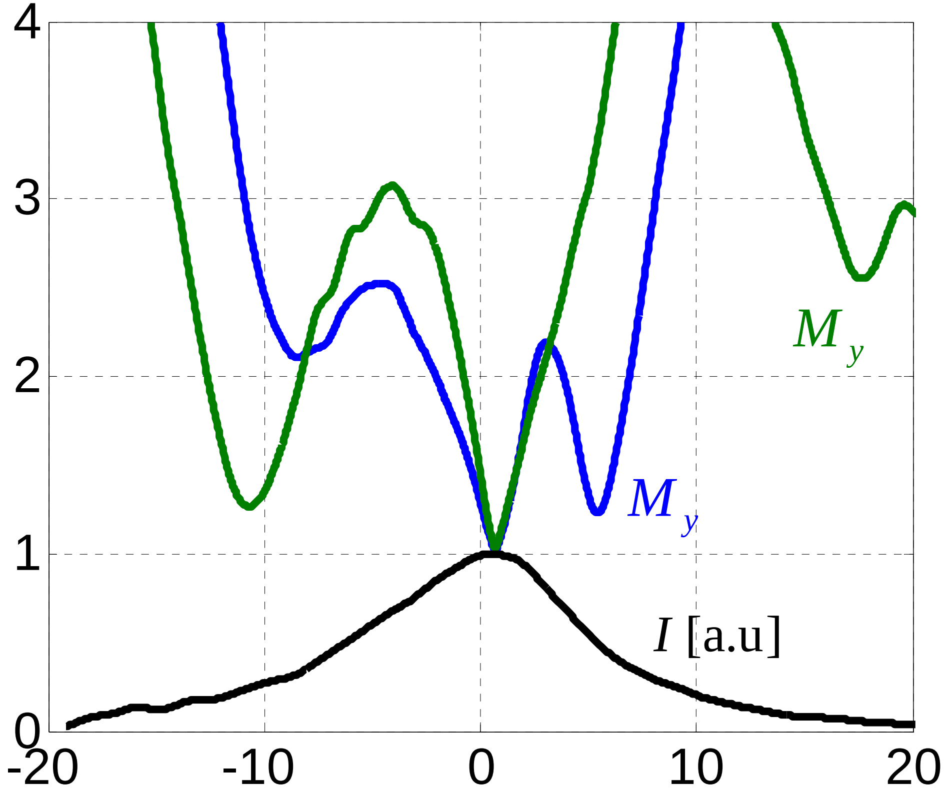


$$\varepsilon_x^{proj} = 0.45\,[\mu m]$$
$$\varepsilon_y^{proj} = 1.5\,[\mu m]$$

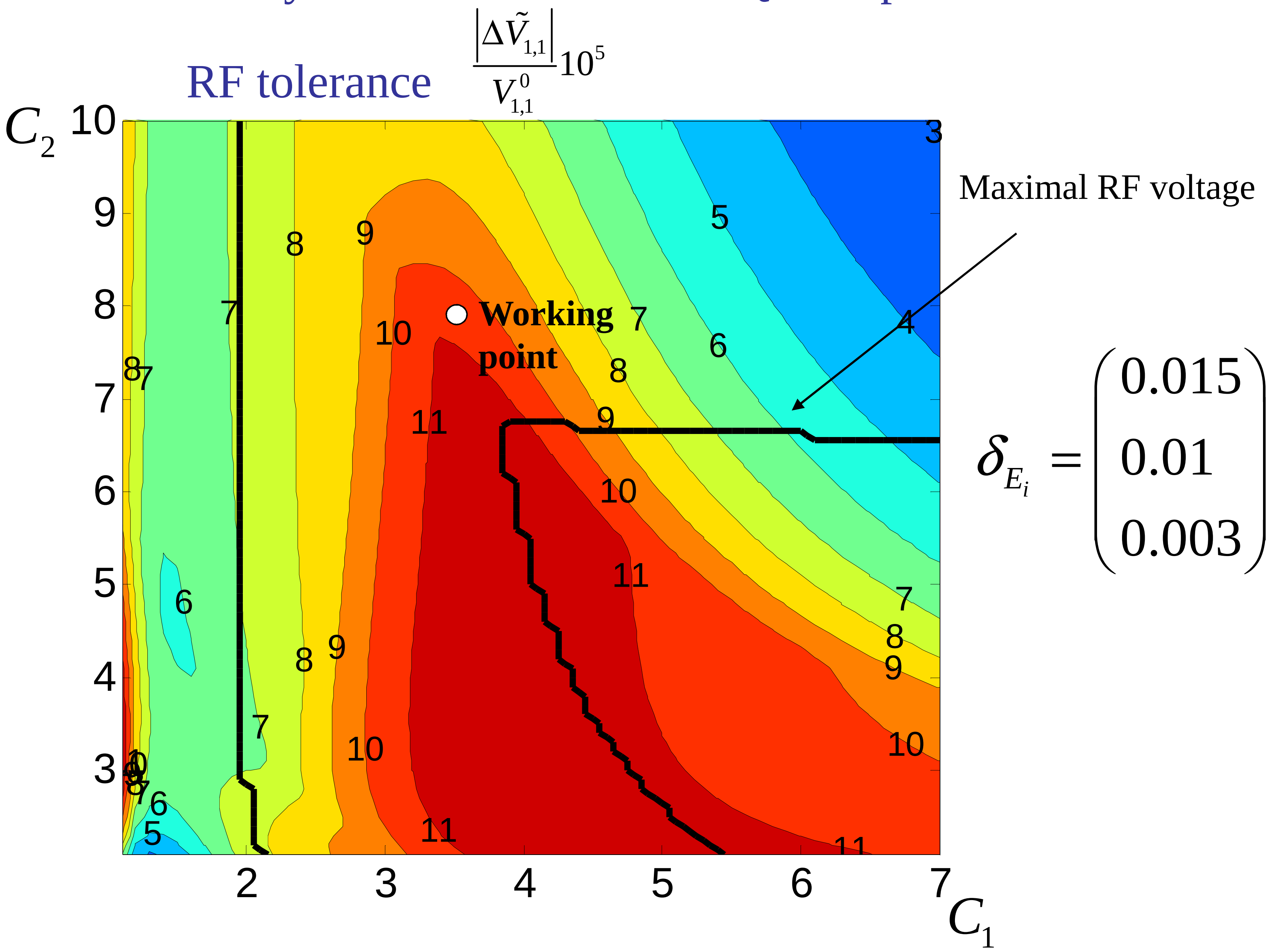
We have removed 6% of bad particles in the analysis (Q=235 pC!)

XFEL beam dynamic simulations for different charges (full)

Q=250 pC



XFEL beam dynamic simulations for Q=100 pC

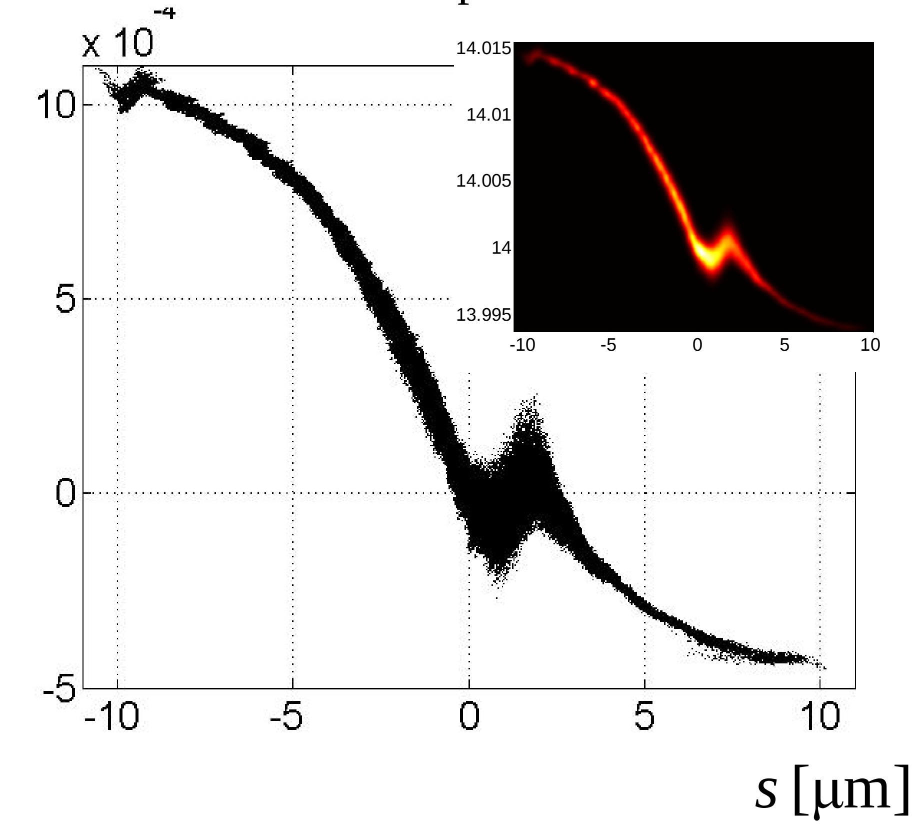


$$\delta_{E_i} = \begin{pmatrix} 0.015 \\ 0.01 \\ 0.003 \end{pmatrix}$$

XFEL beam dynamic simulations for different charges (full)

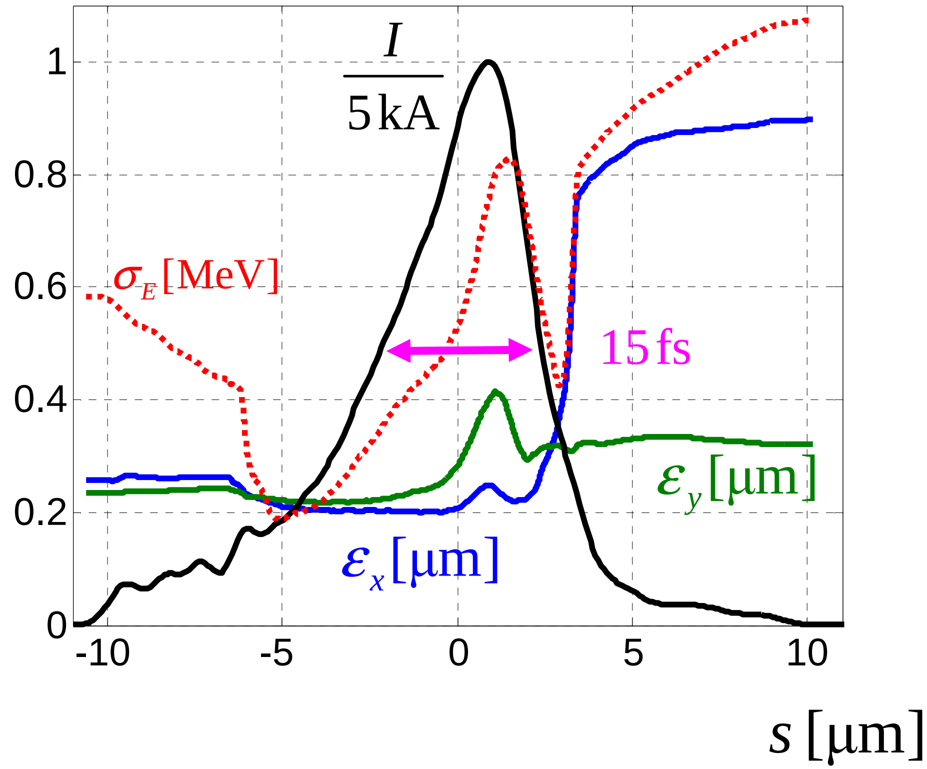
Q=100 pC

Phase space



bunch head

Current, emittance, energy spread

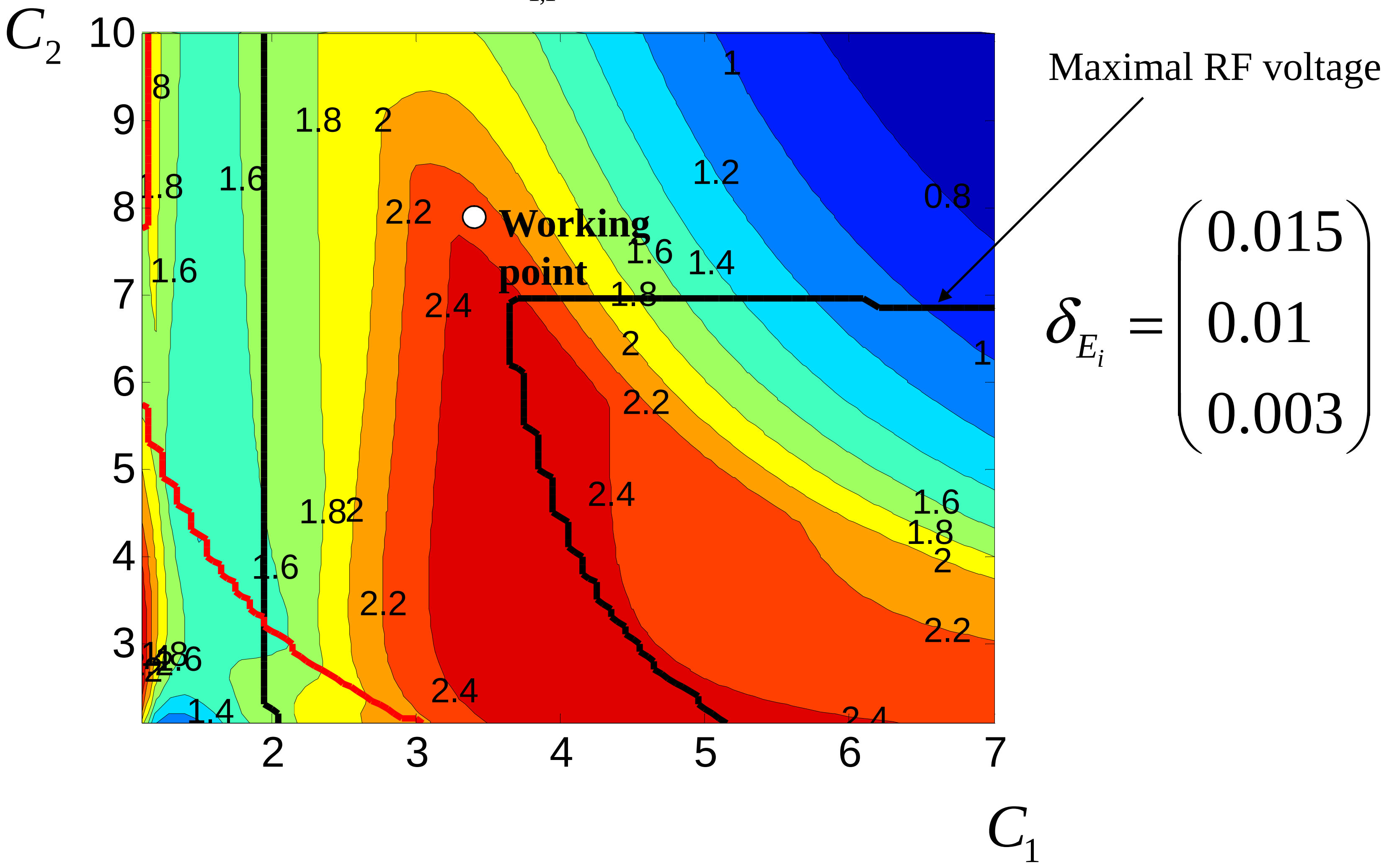


$$\varepsilon_x^{proj} = 0.35\,[\mu m]$$

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

XFEL beam dynamic simulations for Q=20 pC

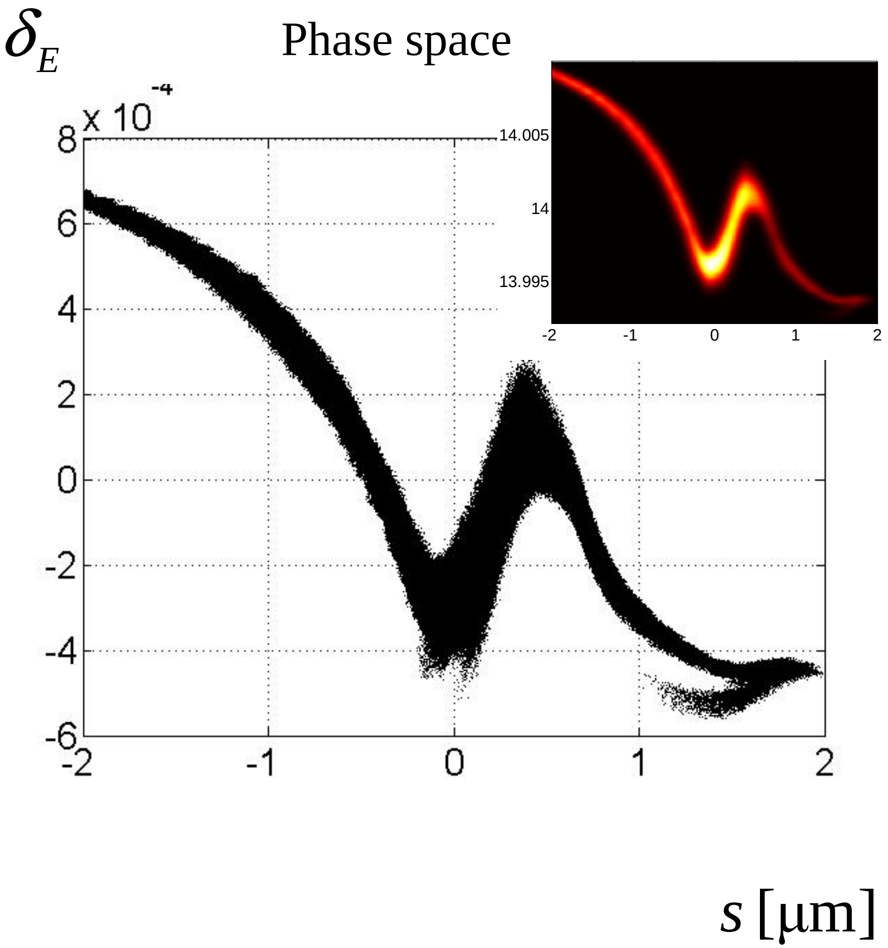
RF tolerance $\frac{\left|\Delta \tilde{V}_{1,1}\right|}{V_{1,1}^{0}} 10^{5}$



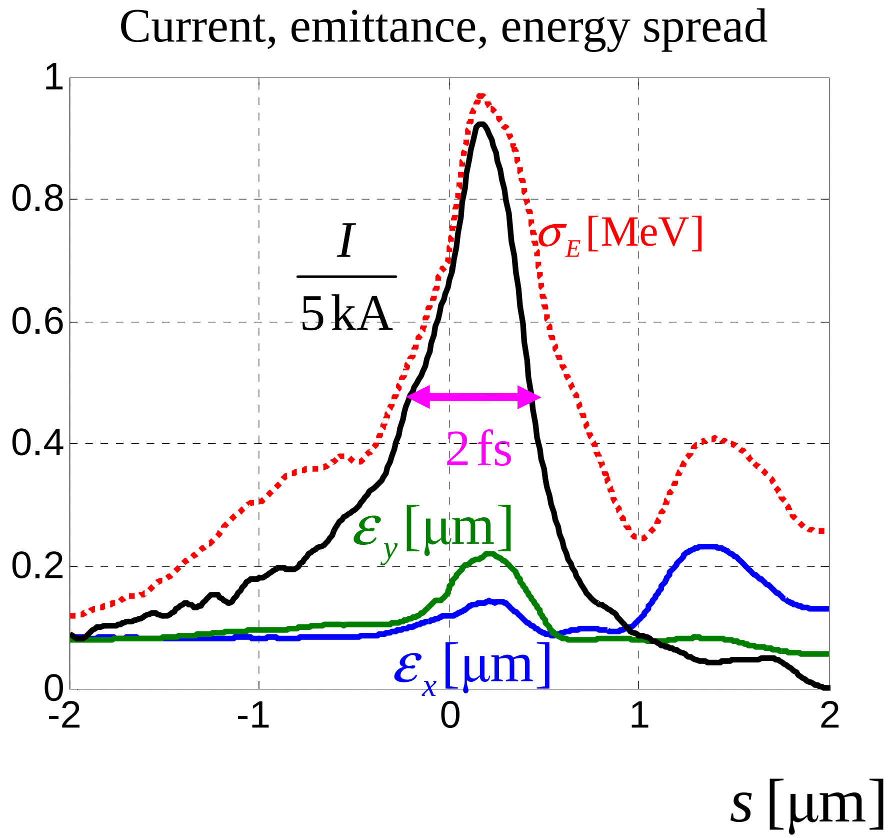
$$\delta_{E_i} = \begin{pmatrix} 0.015 \\ 0.01 \\ 0.003 \end{pmatrix}$$

XFEL beam dynamic simulations for different charges (full)

Q=20 pC



bunch head



$$\varepsilon_x^{proj} = 0.14\,[\mu m]$$

$$\varepsilon_y^{proj} = 0.26\,[\mu m]$$

Beam parameters from S2E simulations

Parameter	Unit					
Bunch charge	nC	1	0.5	0.25	0.1	0.02
Peak current (gun)	A	43	24	13.5	5.7	1.2
Bunch length (gun, FWHM)	ps	25	22	20	17	17
Slice emittance (gun)	µm	0.8	0.5	0.3	0.21	0.09
Projected emittance (gun)	µm	1	0.7	0.6	0.3	0.1
Compression		114	233	363	877	3833
Peak current	kA	**4.9**	**5.6**	**4.9**	**5**	**4.6**
Bunch length (FWHM)	fs	178	72	39	12	2.2
Slice emittance	µm	**1**	**0.7**	**0.5**	**0.3**	**0.17**
Projected emittance	µm	3.5	2.2	1.5	0.84	0.26
Slice energy spread (**laser heater off**)	MeV	0.45	0.44	0.6	0.6	0.8