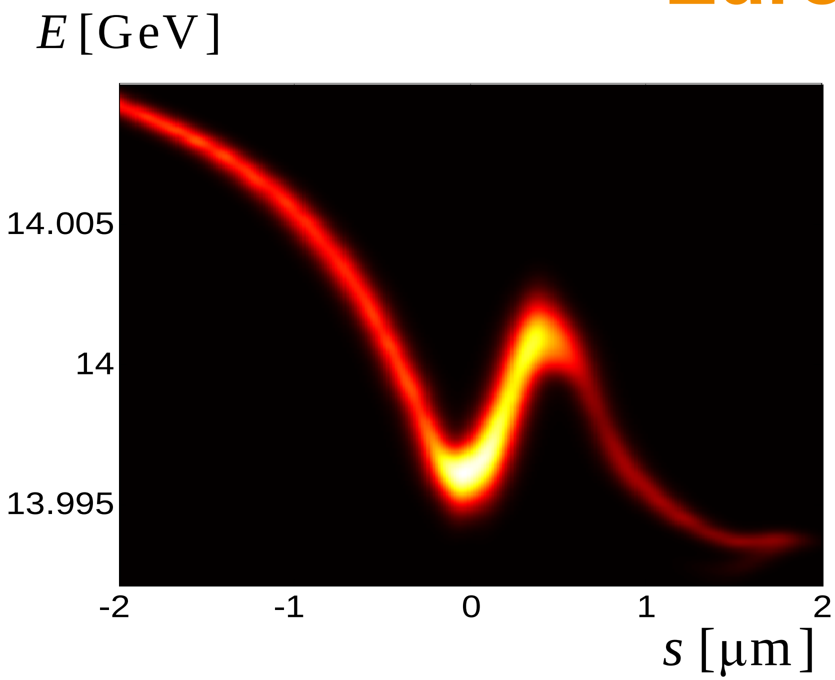
Beam Dynamics Simulations at DESY

Compression Scenarios for FLASH and the European XFEL



Igor Zagorodnov

Collaboration Meeting at PAL

Pohang, Korea
2-6. September 2013

HELMHOLTZ GEMEINSCHAFT

DESY

Overview

- FLASH Simulations
  - layout and desired beam parameters
  - machine parameters
  - simulation methods and results
  - low energy spread for FLASH 2
  - comparison with Elegant
- The European XFEL Simulations
  - layout and machine parameters
  - nominal scenarios
  - strong compression
  - new results and comparison with Elegant

Layout and Desired Beam Parameters

Electron beam properties for good lasing

small emittance

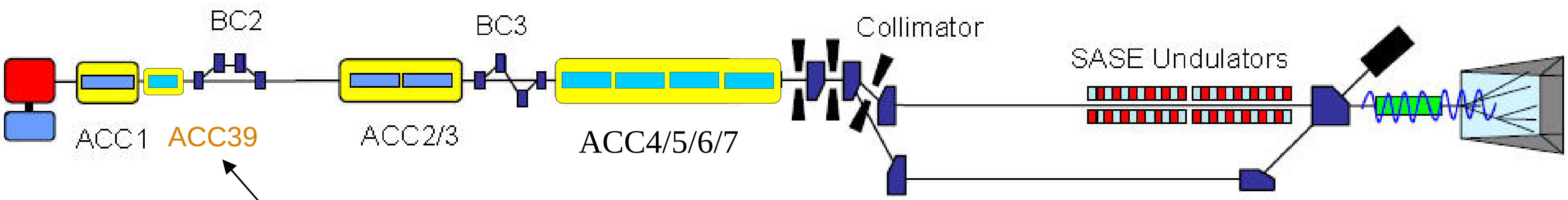
short gain length

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

small energy spread

high peak current

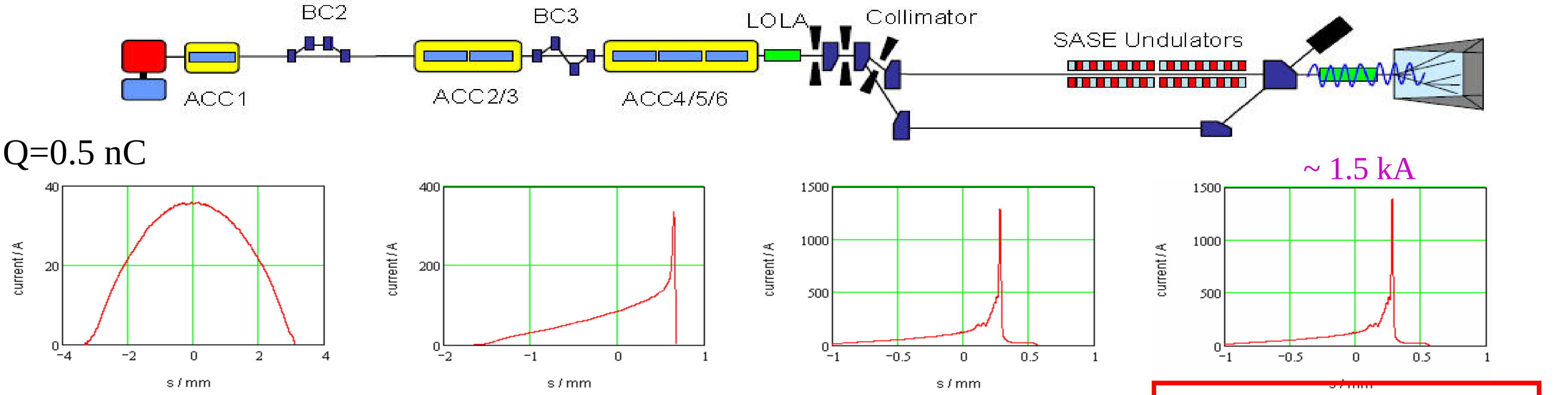
High **peak current** ~ **2500 A.**
Small slice **emittance** ε **(0.3-1 μm**).
Small slice **energy spread** σ_E (**< 300 keV**).



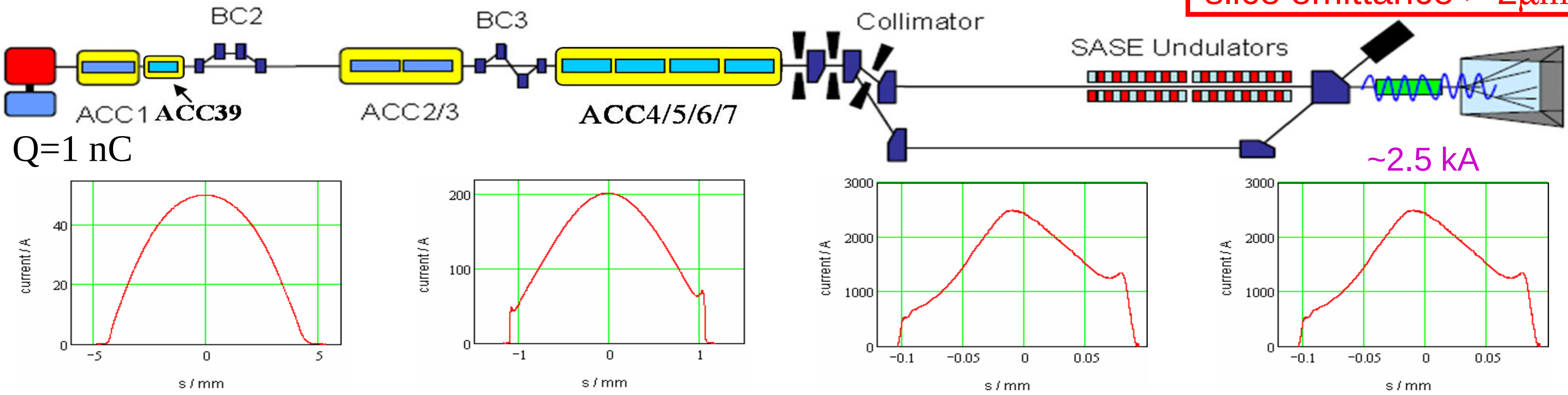
High harmonic module installed in 2010

Layout and Desired Beam Parameters

Rollover Compression vs. Linearized (FLASH)



slice emittance > 2μm



slice emittance ~ 0.3 - 1μm

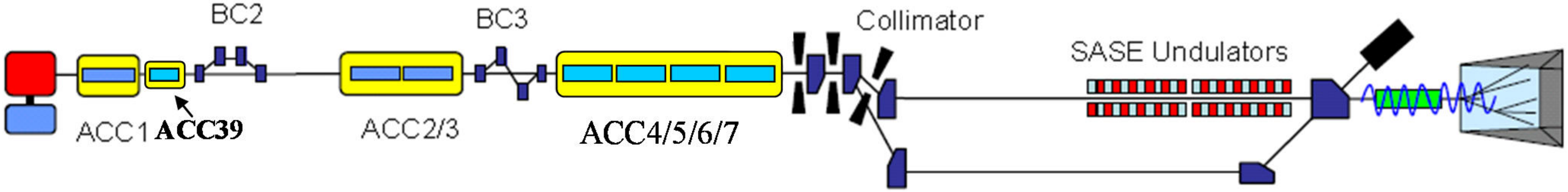
DESY

Machine Parameters

Technical constrains

$$1.4 \leq \frac{r_1}{\mathrm{m}} \leq 1.93 \qquad 5.3 \leq \frac{r_2}{\mathrm{m}} \leq 16.8$$

$r_{56} \approx 0... -0.56$ mm



$V_1 \leq 150$ MV

$V_2 \leq 360$ MV

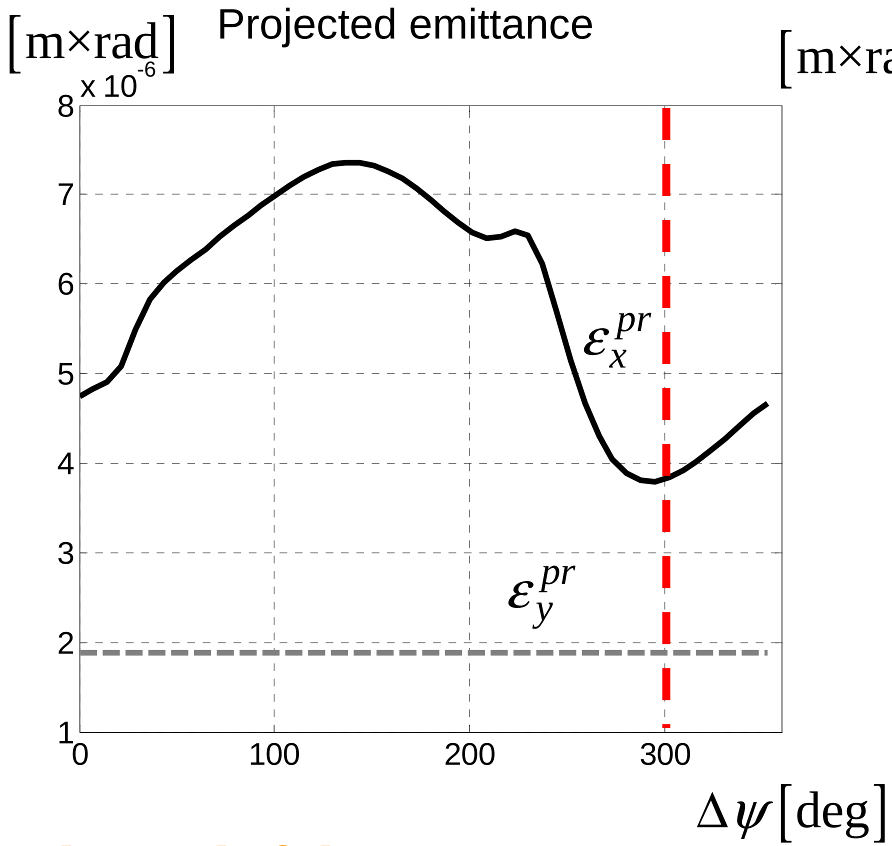
$V_{39} \leq 26$ MV

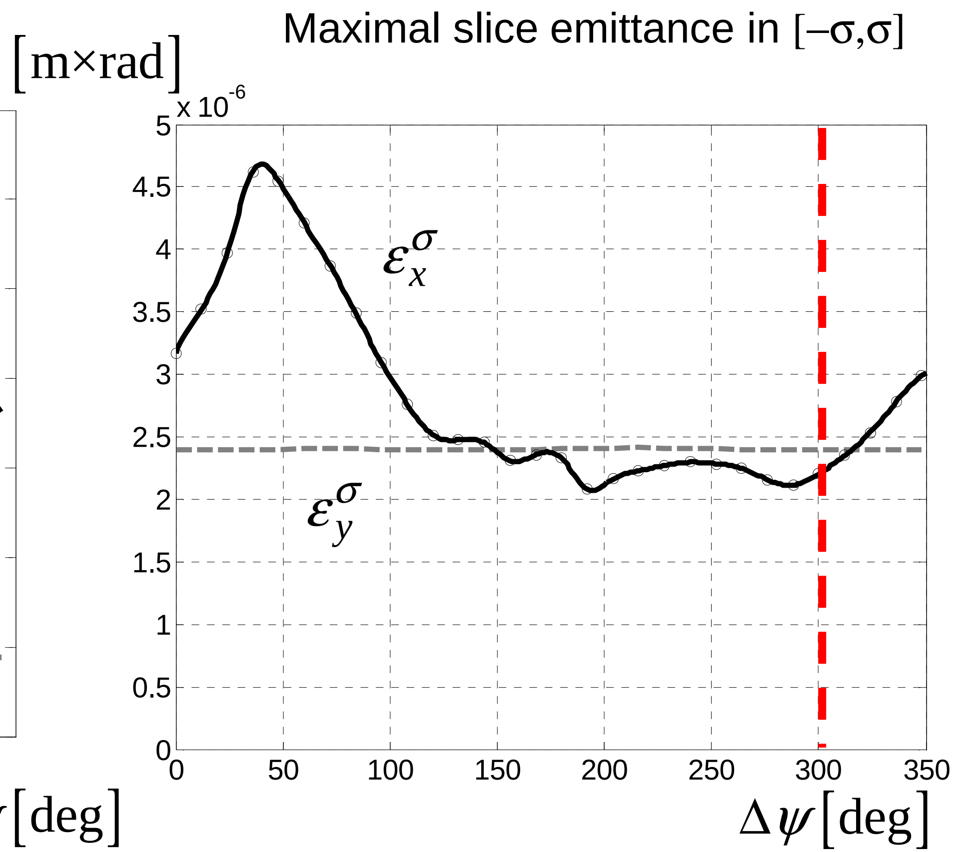
How to provide (1) a well conditioned electron beam and (2) what are the properties of the radiation?

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

Machine Parameters

Optics correction



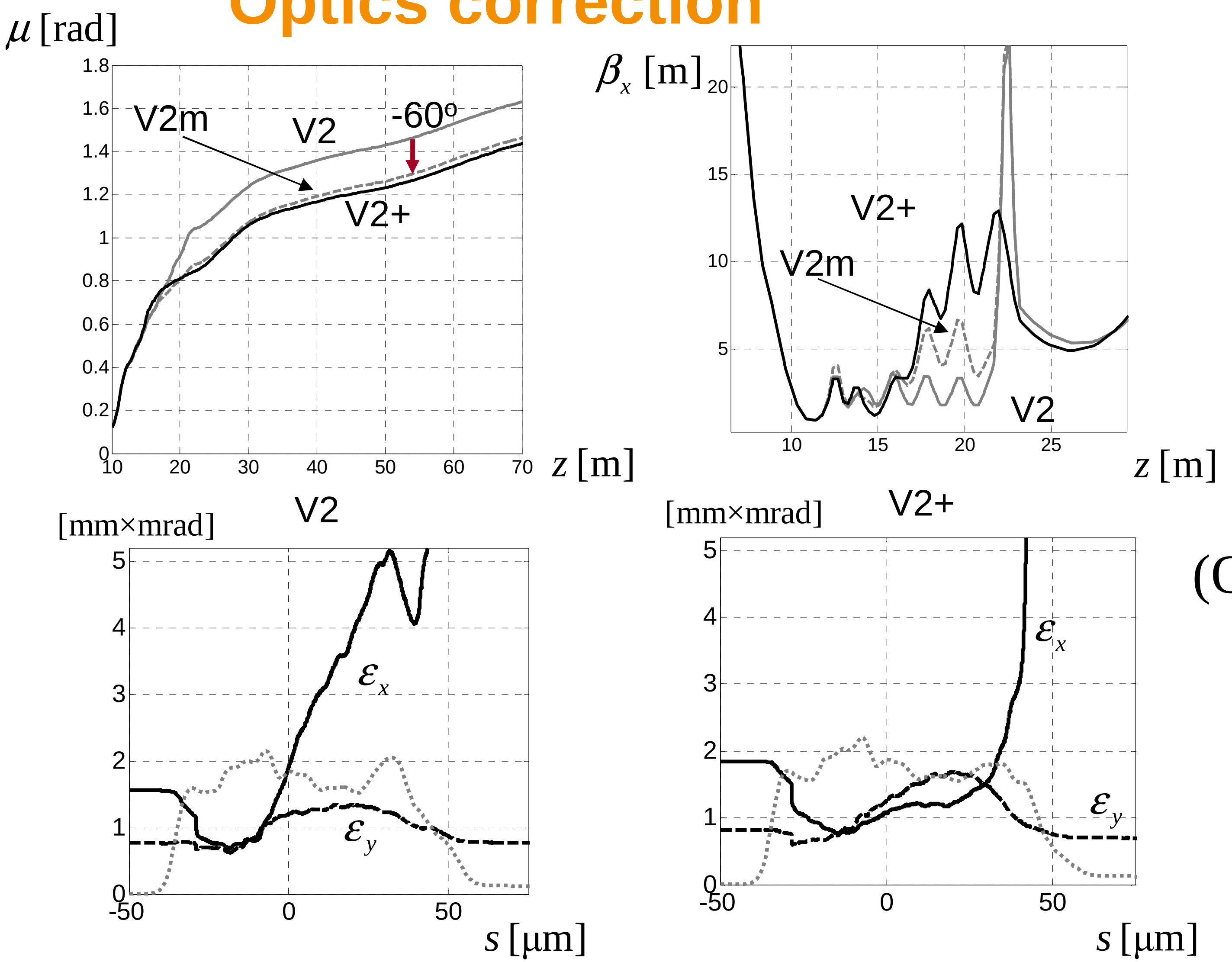


Phase shift between
BCs (Q=1nC, optics V2).

$$\Delta\psi = -60[\text{deg}] - ?$$

Machine Parameters

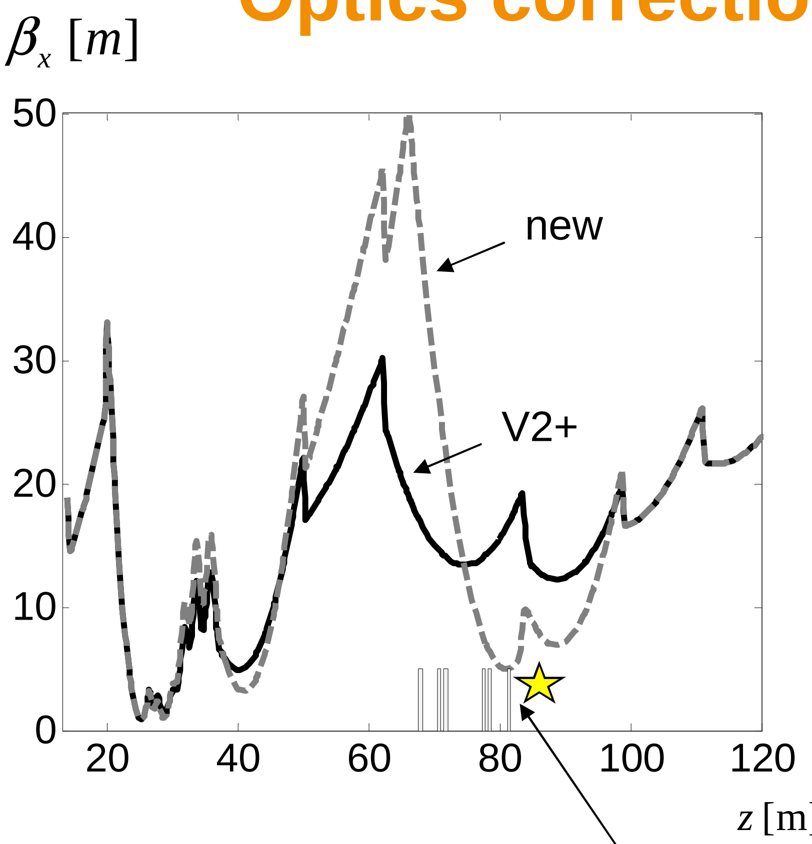
Optics correction

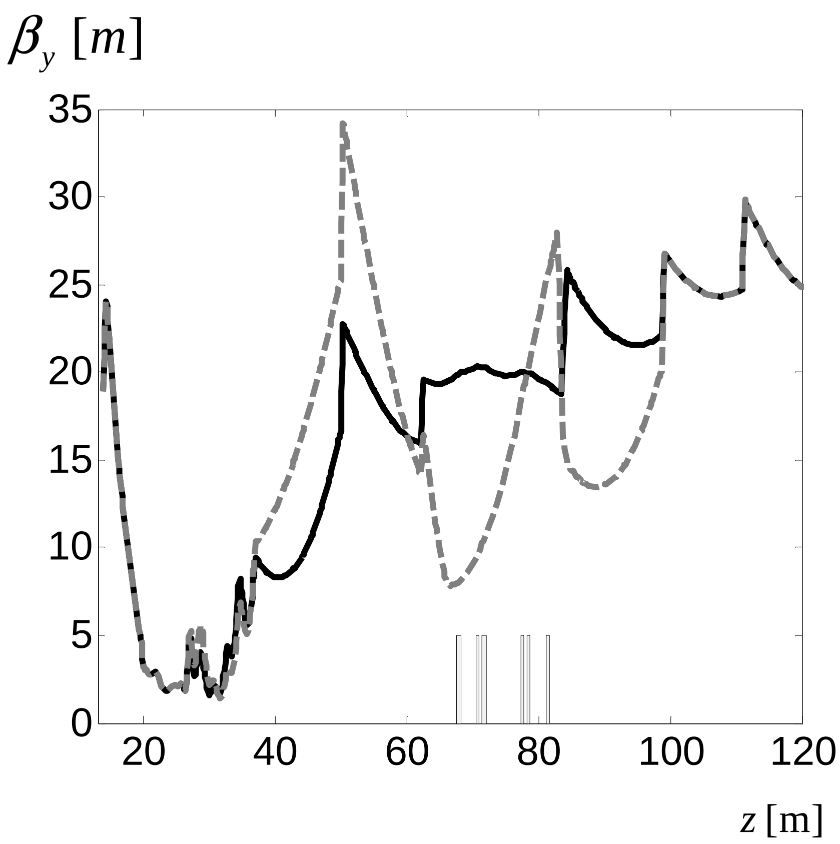


(Q=0.5nC).

Machine Parameters

Optics correction





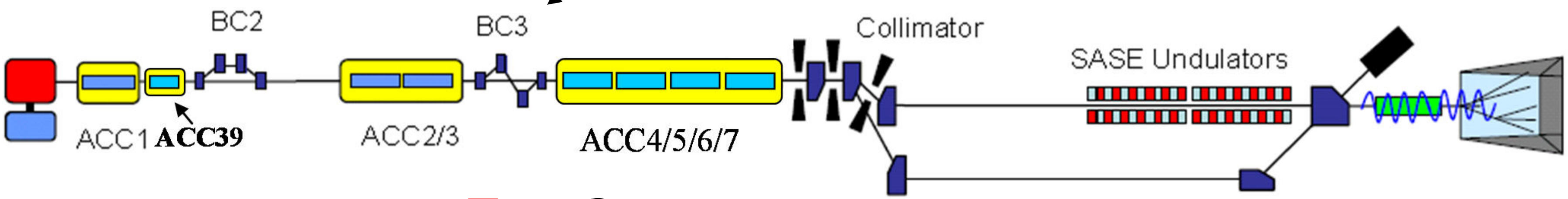
a small transverse bunch size before the last dipole

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

Machine Parameters

Working points (8 macroparameters)

$C' = ?, C'' = ?$



$E_1 = ?$ $E_2 = ?$

$r_1 = ?$ $r_2 = ?$

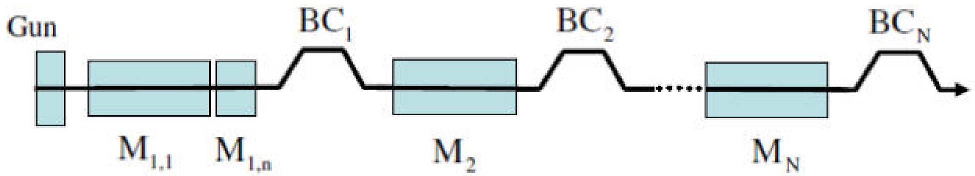
$C_1 = ?$ $C = ?$

What is the optimal choice?

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

Machine Parameters

How to convert to the machine parameters?



Initial longitudinal phase-space:

$$\delta_0(s) \equiv \delta_0'(0)s + \frac{\delta_0''(0)}{2}s^2 + \frac{\delta_0'''(0)}{6}s^3$$

Energy gain in linac section:

$$\Delta E_{1,1} = eV_{1,1}\cos(ks + \varphi_{1,1}),$$
$$\Delta E_{1,n} = eV_{1,n}\cos(nks + \varphi_{1,n}),$$
$$\Delta E_i = eV_i\cos(ks_{i-1} + \varphi_i), \qquad i > 1$$

Long. phase-space after acceleration:

$$\delta_1 = \frac{(1+\delta)E_0^0 + \Delta E_{1,1} + \Delta E_{1,n}}{E_1^0} - 1,$$
$$\delta_i = \frac{(1+\delta_{i-1})E_{i-1}^0 + \Delta E_i}{E_i^0} - 1, \qquad i = 2, \ldots, N.$$

Path length effects of the chicanes:

$$s_i = s_{i-1} - (r_{56i}\delta_i + t_{56i}\delta_i^2 + u_{56i}\delta_i^3), \qquad i = 1, \ldots, N$$

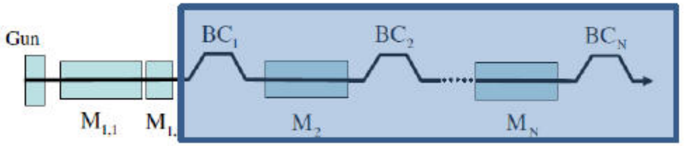
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 014403 (2011)

Semianalytical modeling of multistage bunch compression with collective effects

Igor Zagorodnov* and Martin Dohlus
Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, 22603 Hamburg, Germany
(Received 6 July 2010; published 13 January 2011)

Machine Parameters

How to convert to the machine parameters?



Linac Setup:

- Problem to be solved:
  What RF setings and initial phase-space distribution is required to achive the requested bunch shape?

$$\delta_i(\mathbf{X}) = 0, \quad i = 2, 3, \ldots, N,$$
$$s_i'(\mathbf{X}, \mathbf{Y}, \alpha_1) = Z_i, \quad i = 1, 2, \ldots, N,$$
$$s_N''(\mathbf{X}, \mathbf{Y}, \alpha_1, \alpha_2) = Z_N', \quad s_N'''(\mathbf{X}, \mathbf{Y}, \boldsymbol{\alpha}) = Z_N''$$
$$\mathbf{X} = (X_2, \ldots, X_N)^T, \ \mathbf{Y} = (Y_2, \ldots, Y_N)^T$$

- Example solution for a two stage compression setup:

$$X_2 = \bar{E}_2 - \bar{E}_1, \quad \alpha_1 = \frac{1 - Z_1}{r_{561}}, \quad Y_2 = \frac{\alpha_1 \bar{E}_1 - \delta_2' \bar{E}_2}{k Z_1}, \quad \delta_2' = \frac{Z_1 - Z_2}{r_{562}}, \quad \alpha_2 = \frac{y_1}{\bar{E}_1}, \quad y_1 = \frac{Z_2' - \tilde{x}_2}{\bar{x}_2}$$

$$\tilde{x}_2 = \tilde{x}_1 - \frac{r_{562}}{\bar{E}_2} \tilde{y}_2 - 2 t_{562} (\delta_2')^2, \quad \tilde{y}_2 = -k^2 Z_1^2 X_2 - k Y_2 \tilde{x}_1, \quad \tilde{x}_1 = -2 t_{561} \alpha_1^2, \quad \bar{x}_2 = \bar{x}_1 - \frac{r_{562}}{\bar{E}_2} \bar{y}_2,$$

$$\bar{y}_2 = 1 - k Y_2 \bar{x}_1, \quad \bar{x}_1 = -\frac{r_{561}}{\bar{E}_1}, \quad \alpha_3 = \frac{\hat{y}_1}{\bar{E}_1}, \quad \hat{y}_1 = \frac{Z_2'' - \hat{\tilde{x}}_2}{\bar{x}_2}, \quad \hat{\tilde{x}}_2 = \hat{\tilde{x}}_1 - \frac{r_{562}}{\bar{E}_2} \hat{\tilde{y}}_2 - 6 u_{562} (\delta_2')^3 - 6 t_{562} \delta_2' \delta_2'',$$

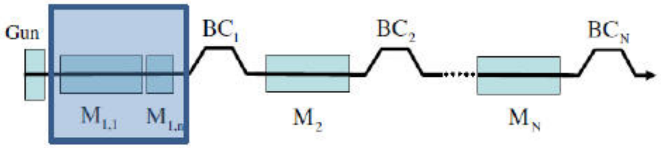
$$\delta_2'' = \frac{\alpha_2 \bar{E}_1 \bar{y}_2 + \tilde{y}_2}{\bar{E}_2}, \quad \hat{\tilde{y}}_2 = k^3 Z_1^3 Y_2 - 3 k^2 Z_1 Z_1' X_2 - k Y_2 \hat{\tilde{x}}_1, \quad \hat{\tilde{x}}_1 = -6 u_{561} \alpha_1^3 - 6 t_{561} \alpha_1 \alpha_2,$$

$$Z_1' = -r_{561} \alpha_2 - 2 t_{561} \alpha_1^2.$$

As a result we obtain the required phase-space after the injector **α** and the RF setup **X**, **Y**. $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \alpha_3)^T \quad \alpha_i = \frac{\partial^i \delta_1}{\partial s^i}$

Machine Parameters

How to convert to the machine parameters?



Injector Setup:

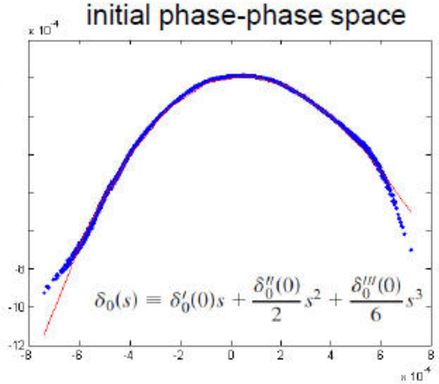
- Problem to be solved:
  What RF settings in the injector generate the required phase-space distribution before the first chicane?

$$\delta_1(X_{1,1}, Y_{1,1}, X_{1,n}, Y_{1,n}) = 0,$$
$$\delta_1'(X_{1,1}, Y_{1,1}, X_{1,n}, Y_{1,n}) = \alpha_1,$$
$$\delta_1''(X_{1,1}, Y_{1,1}, X_{1,n}, Y_{1,n}) = \alpha_2,$$
$$\delta_1'''(X_{1,1}, Y_{1,1}, X_{1,n}, Y_{1,n}) = \alpha_3.$$

- Problem can be formulates as:

$$\begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & -k & 0 & -nk \\ -k^2 & 0 & -(nk)^2 & 0 \\ 0 & k^3 & 0 & (nk)^3 \end{pmatrix} \begin{pmatrix} X_{1,1} \\ Y_{1,1} \\ X_{1,n} \\ Y_{1,n} \end{pmatrix} = \frac{1}{e} \begin{pmatrix} E_1 - E_0 \\ E_1\alpha_1 - E_0\delta_0' \\ E_1\alpha_2 - E_0\delta_0'' \\ E_1\alpha_3 - E_0\delta_0''' \end{pmatrix}.$$

initial phase-phase space



with the solution:

$$X_{1,1} = \frac{F_3 + F_1(kn)^2}{k^2(n^2-1)}, \qquad Y_{1,1} = -\frac{F_4 + F_2(kn)^2}{k^3(n^2-1)},$$
$$X_{1,n} = -\frac{F_3 + F_1k^2}{k^2(n^2-1)}, \qquad Y_{1,n} = \frac{F_4 + F_2k^2}{k^3n(n^2-1)},$$

$$F_1 = \bar{E}_1 - \bar{E}_0, \qquad F_i = \bar{E}_1\alpha_{i-1} - \bar{E}_0\frac{\partial^{i-1}\delta_0}{\partial s^{i-1}},$$
$$i = 2, 3, 4.$$

Machine Parameters

Working points (8 macroparameters)

$V_1 \leq 150$ MV

$$E_1 = 0.95\left[E_0 + e\left(1-\left(\frac{\omega}{\omega_3}\right)^2\right)\max V_1\right] \approx 130\text{MeV}$$

$V_2 \leq 360$ MV

5% reserve

$$E_2 = 0.95\left[E_1 + e\max V_2\right] \approx 450 \text{ MeV}$$

$E_1 = 130$ MeV
$\mathrm{E}_2 = 450$ MeV
$r_1 = ?$
$r_2 = ?$
$C_1 = ?$
$C = ?$
$\partial_s C^{-1} = ?$
$\partial_s^2 C^{-1} = ?$

Machine Parameters

Working points (8 macroparameters)

$$1.4 \le \frac{r_1}{\mathrm{m}} \le 1.93$$

- low compression in BC1 and high compression in BC2
- maximal energy chirp transported through BC1 for the same C_1

$$r_1 = 1.93\mathrm{m}$$

$$I_0 = 52\mathrm{A} \qquad I_f = 2500\mathrm{A}$$

$$C = \frac{I_f}{I_0} = 48$$

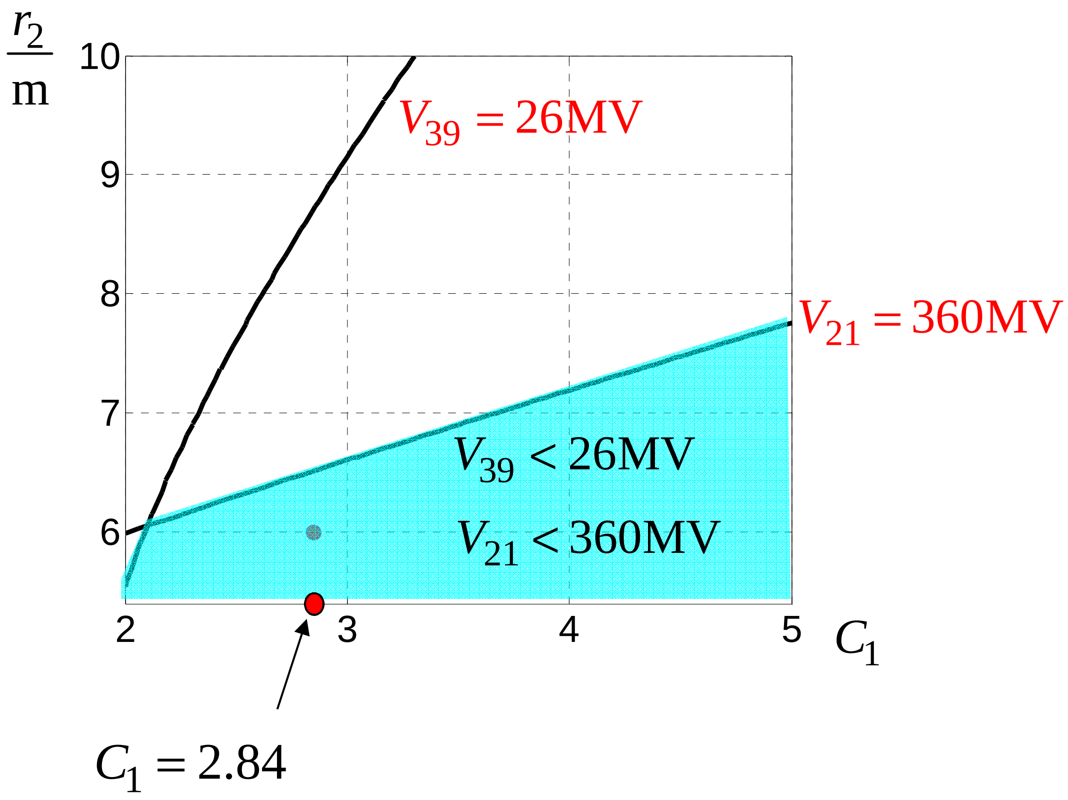
$$E_1 = 130\ \mathrm{MeV}$$
$$\mathrm{E}_2 = 450\ \mathrm{MeV}$$
$$r_1 = 1.93\ \mathrm{m}$$
$$r_2 = ?$$
$$C_1 = ?$$
$$C = 48$$
$$\partial_s C^{-1} = ?$$
$$\partial_s^2 C^{-1} = ?$$

Machine Parameters

Working points (8 macroparameters)

$p_1 = \partial_s C^{-1} = 0$

$p_2 = \partial_s^2 C^{-1} = 0$



$E_1 = 130$ MeV

$E_2 = 450$ MeV

$r_1 = 1.93$ m

$r_2 = ?$

$C_1 = 2.84$

$C = 48$

$\partial_s C^{-1} = ?$

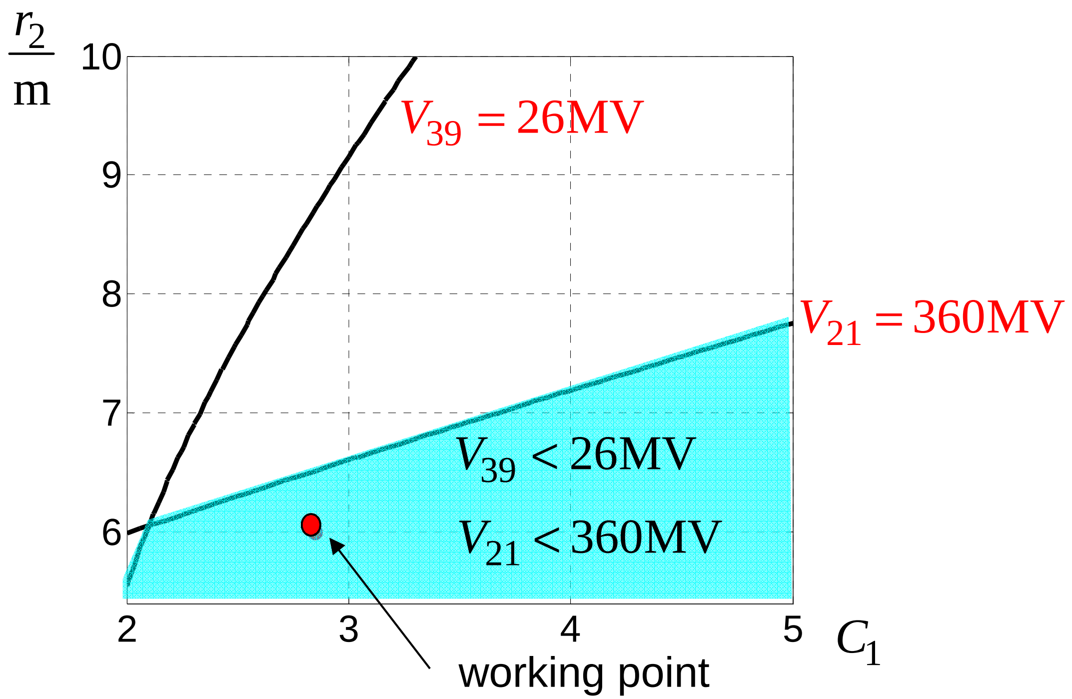
$\partial_s^2 C^{-1} = ?$

Machine Parameters

Working points (8 macroparameters)

$$\varphi_2 = \text{acos}\left(\frac{E_2 - E_1}{\max(V_2)\cdot 0.95}\right) \approx 22^o \qquad r_{562} = \frac{(C-1)r_{561}}{C((C_1-1)E_1E_2^{-1} - g)}$$

$$g = k\frac{V_2}{E_2} r_{562} \sin\varphi_2 \qquad r_2 \approx \frac{L_B}{\sin\sqrt{-r_{562}/(3L_B + 4L_D)}} = 6\text{ m}$$



$E_1 = 130$ MeV

$E_2 = 450$ MeV

$r_1 = 1.93$ m

$r_2 = 6$ m

$C_1 = 2.84$

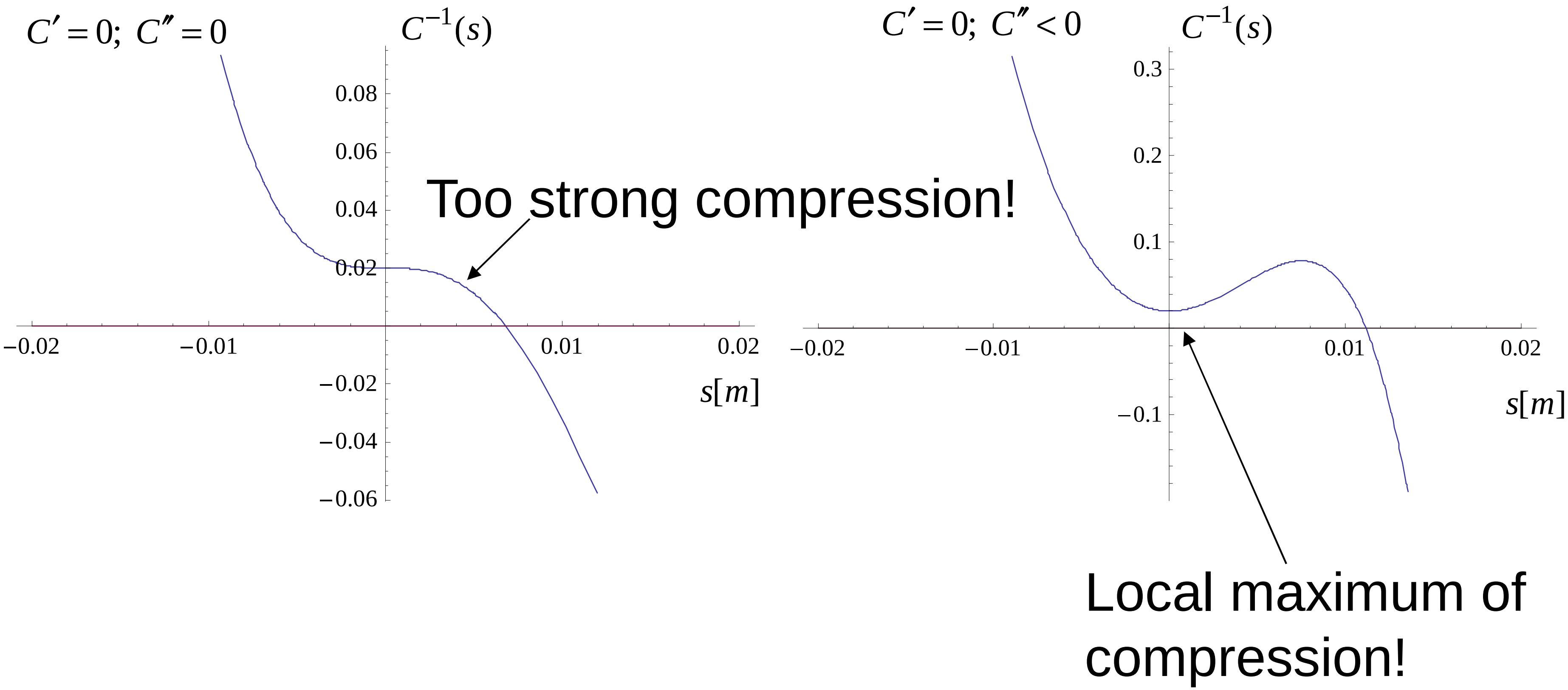
$C = 48$

$\partial_s C^{-1} = ?$

$\partial_s^2 C^{-1} = ?$

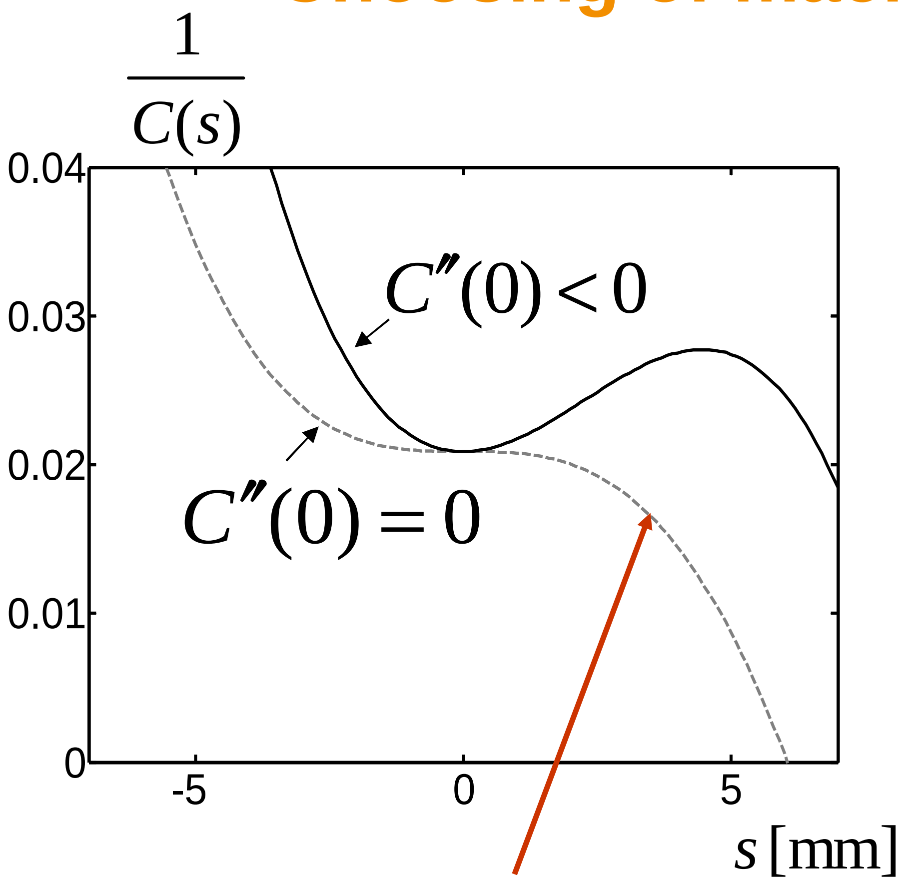
Machine Parameters

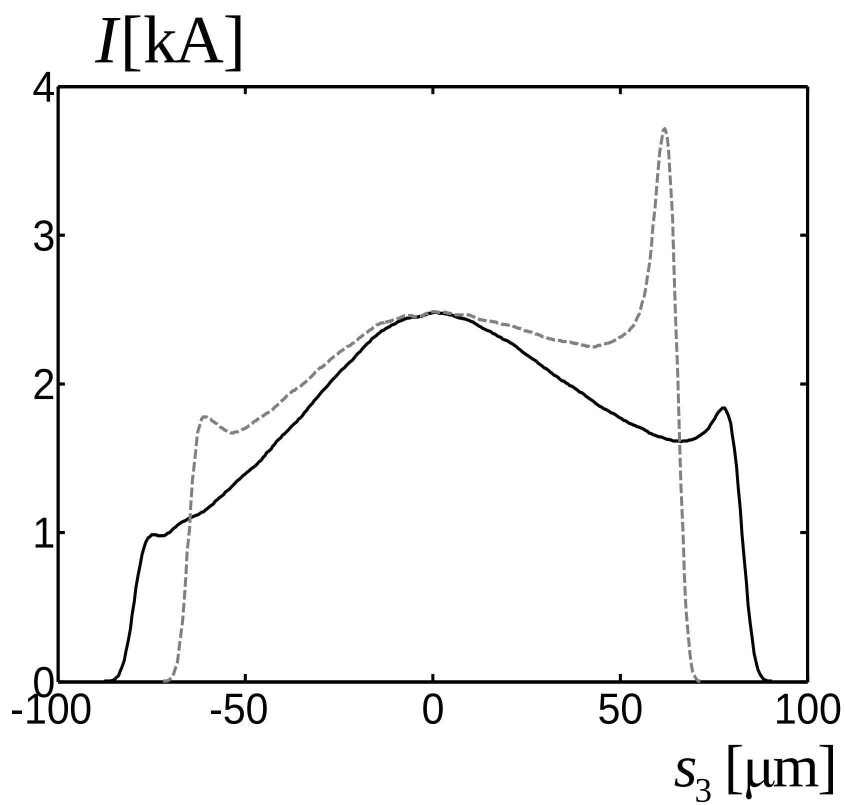
Working points (8 macroparameters)



Machine Parameters

Choosing of machine parameters



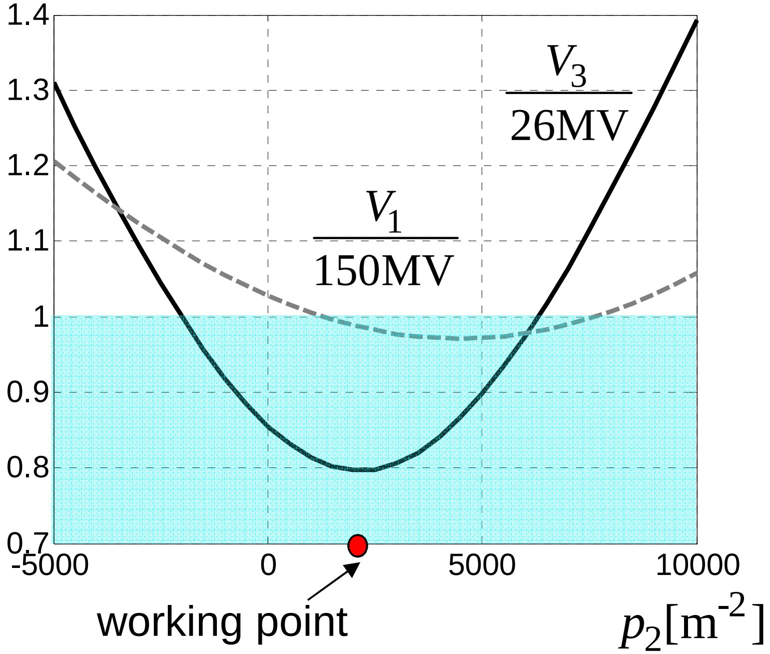


very strong compression
at the bunch head (spike)

$\partial_s^2 C^{-1} \geq 0$

Machine Parameters

Working points (8 macroparameters)



$E_1 = 130$ MeV

$E_2 = 450$ MeV

$r_1 = 1.93$ m

$r_2 = 6$ m

$C_1 = 2.84$

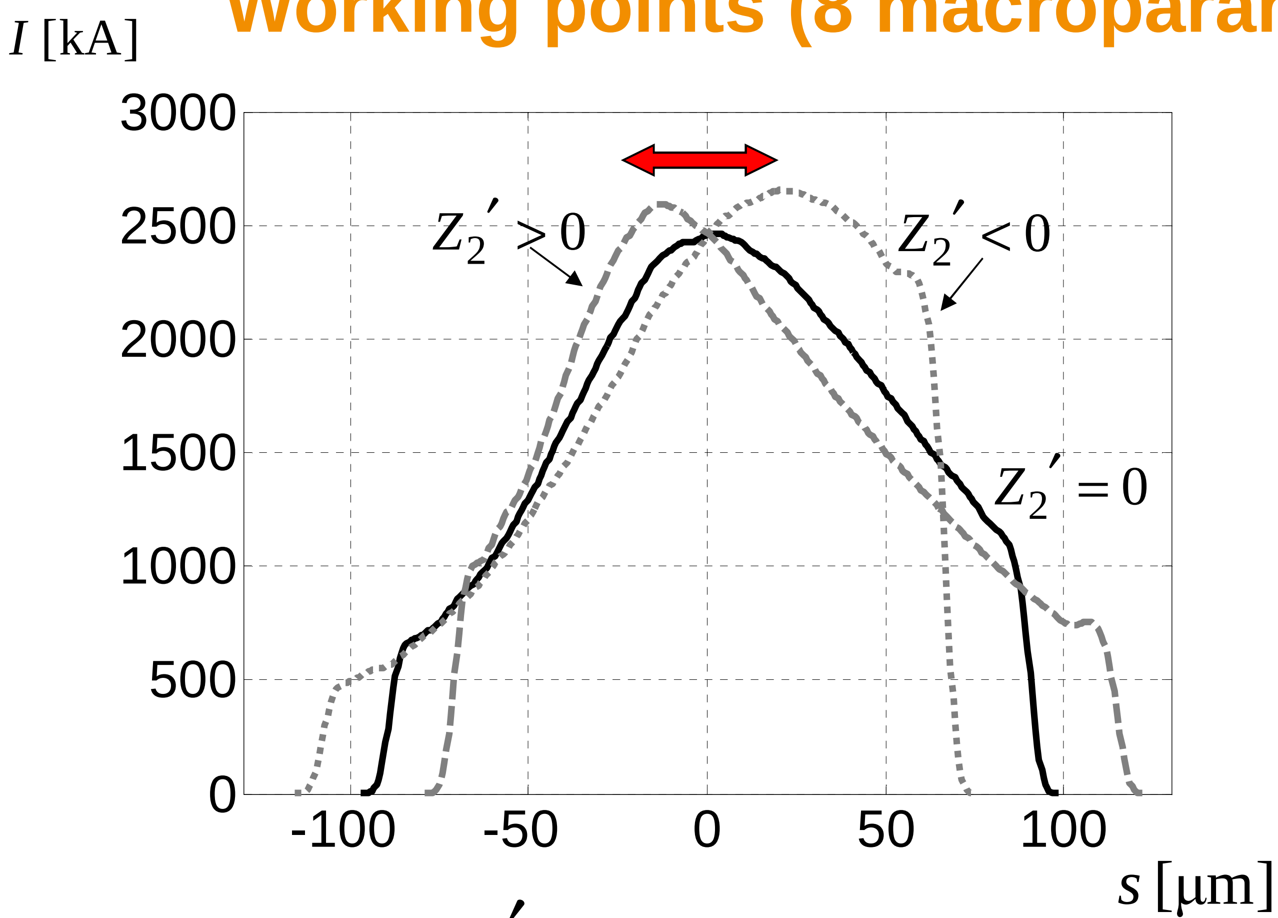
$C = 48$

$\partial_s C^{-1} = ?$

$\partial_s^2 C^{-1} = 2000 \text{ m}^{-2}$

Machine Parameters

Working points (8 macroparameters)



$E_1 = 130$ MeV

$E_2 = 450$ MeV

$r_1 = 1.93$ m

$r_2 = 6$ m

$C_1 = 2.84$

$C = 48$

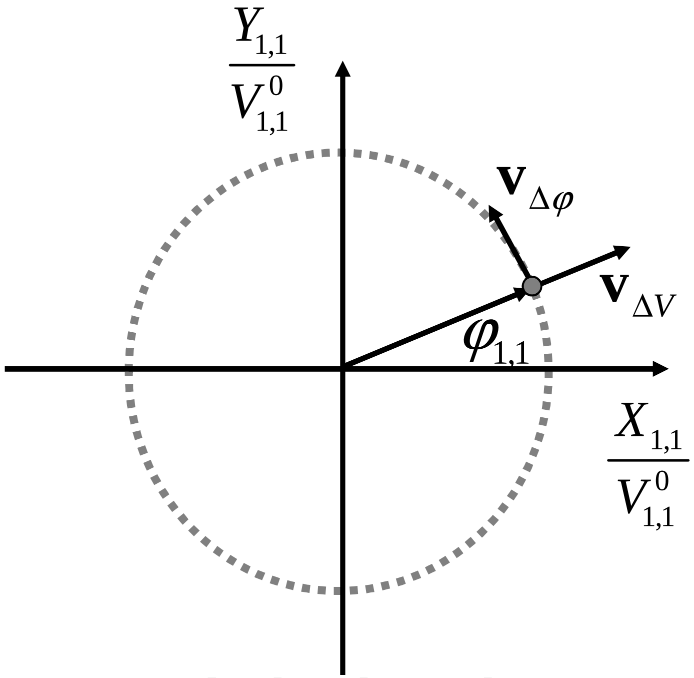
$\partial_s C^{-1} = 1\ \mathrm{m}^{-1}$

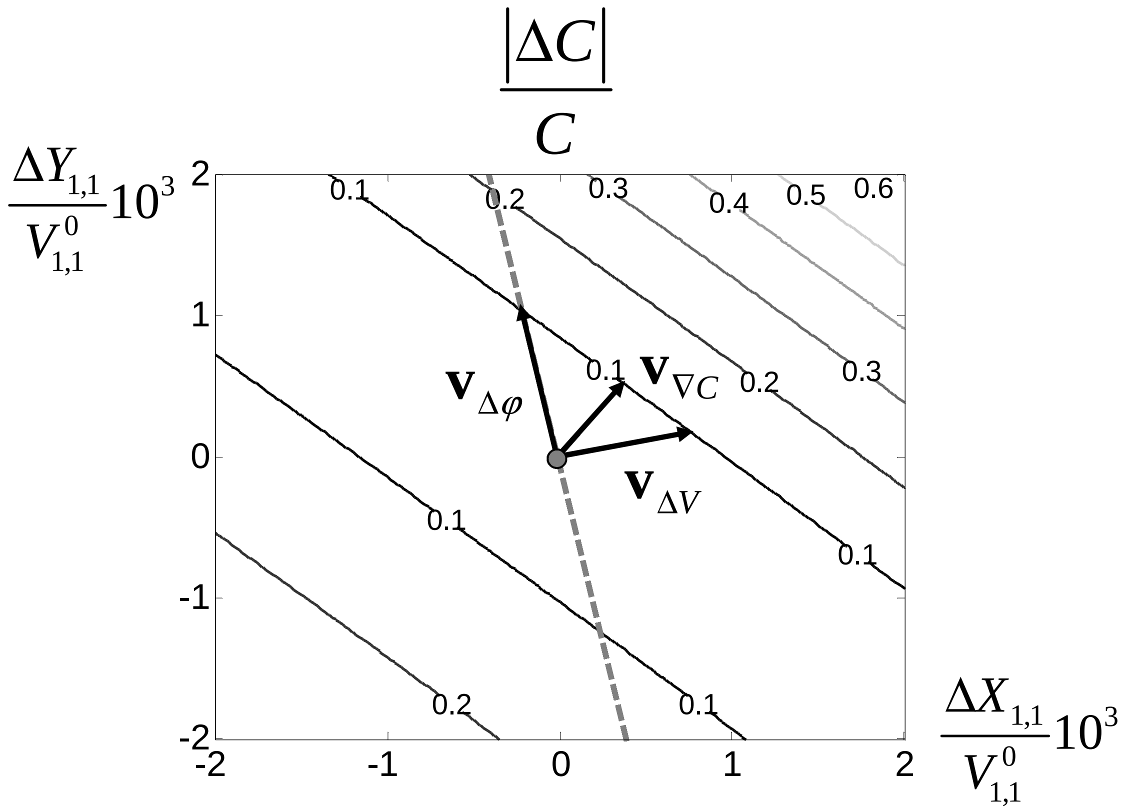
$\partial_s^2 C^{-1} = 2000\ \mathrm{m}^{-2}$

$Z' = \left(C^{-1}\right)'$ - a free parameter to move the peak

Machine Parameters

RF tolerance





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

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

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

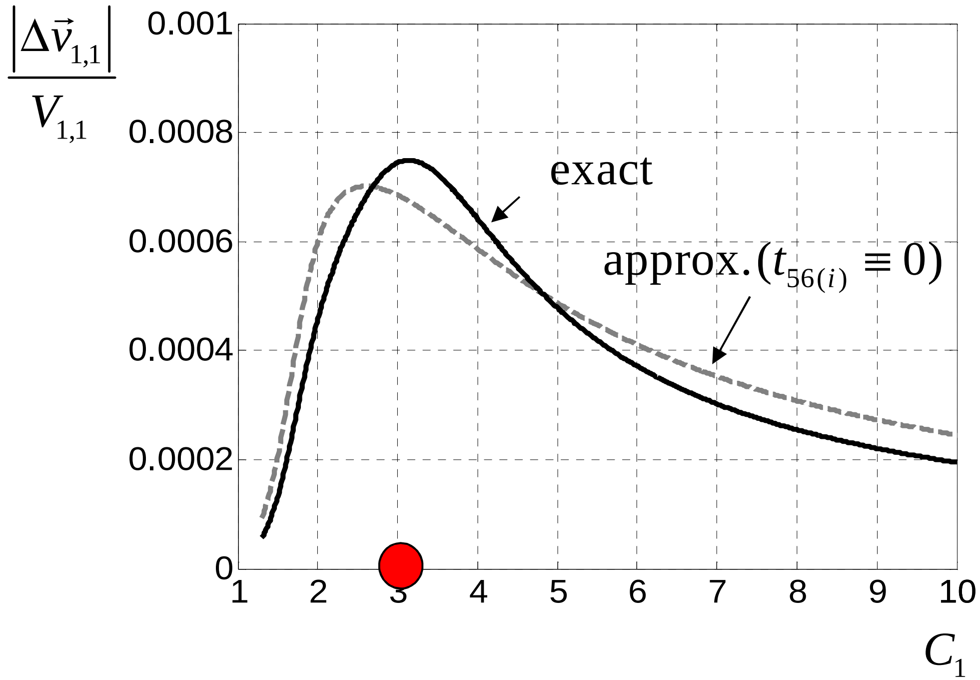
$\mathbf{v}_{\nabla C}$ – gradient gives the worst direction

$$\frac{\left|\Delta \tilde{V}_{1,1}\right|}{V_{1,1}^{0}} = \frac{\Theta E_1 E_2}{k V_{1,1}^{0} C C_1 \sqrt{A_2{}^2 + B_2{}^2}}$$

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

Machine Parameters

RF tolerance in ACC1 (10% change of C)



optimal compression in BC2

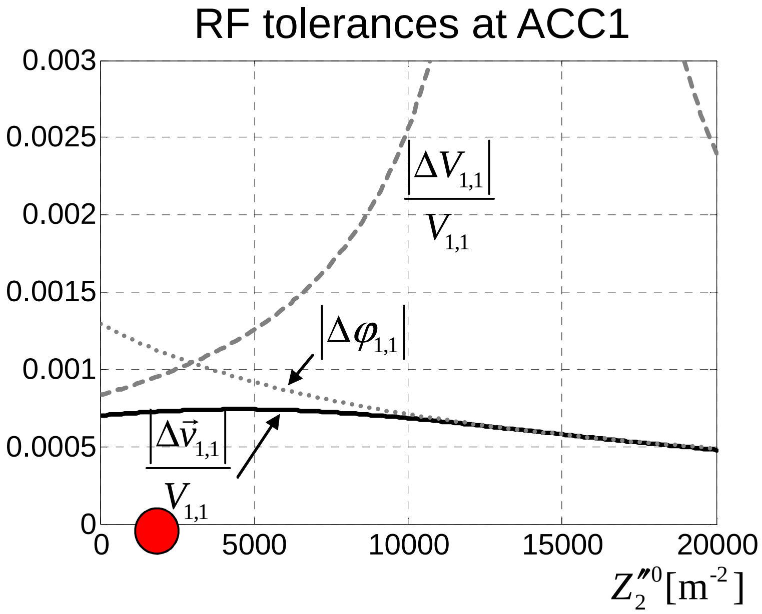
$$C_1 \equiv \frac{1}{Z_1} \approx 3$$

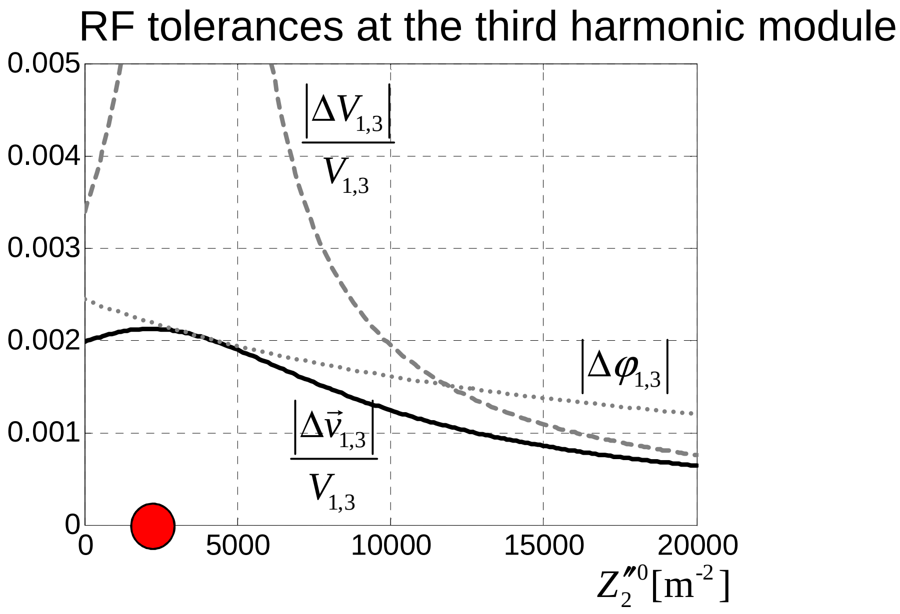
Optimum from the approximate solution

$$C_1^{-1} = \sqrt{\frac{-r_{56(2)}E_1 - r_{56(1)}E_2C^{-1}}{kr_{56(1)}r_{56(2)}(E_2 - E_1)}}$$

Machine Parameters

Tolerances (10 % change of compression)





$$\partial_s^2 C^{-1} = 2000 \text{ m}^{-2}$$

Machine Parameters

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

$$x'' + k_x x = \frac{1}{I_A \beta^3 \gamma^3} \frac{I}{\sigma_x(\sigma_x + \sigma_y)} x \quad \Rightarrow \quad \frac{\max[I_1(Q)]}{\sigma_r^2(Q)} \sim \frac{\max[I_1(Q)]}{\varepsilon(Q)} \sim \frac{\max[I_0(Q)]\, C_1(Q)}{\sqrt[2]{Q}} \sim const$$

(trajectory equation in FODO cell)

we have used a more aggressive scaling

$$\frac{\max[I_0(Q)]\, C_1(Q)}{\sqrt[4]{Q}} \sim const$$

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)

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

DESY

Simulation Methods and Results

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

Analytical solution without self-fields

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

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

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

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

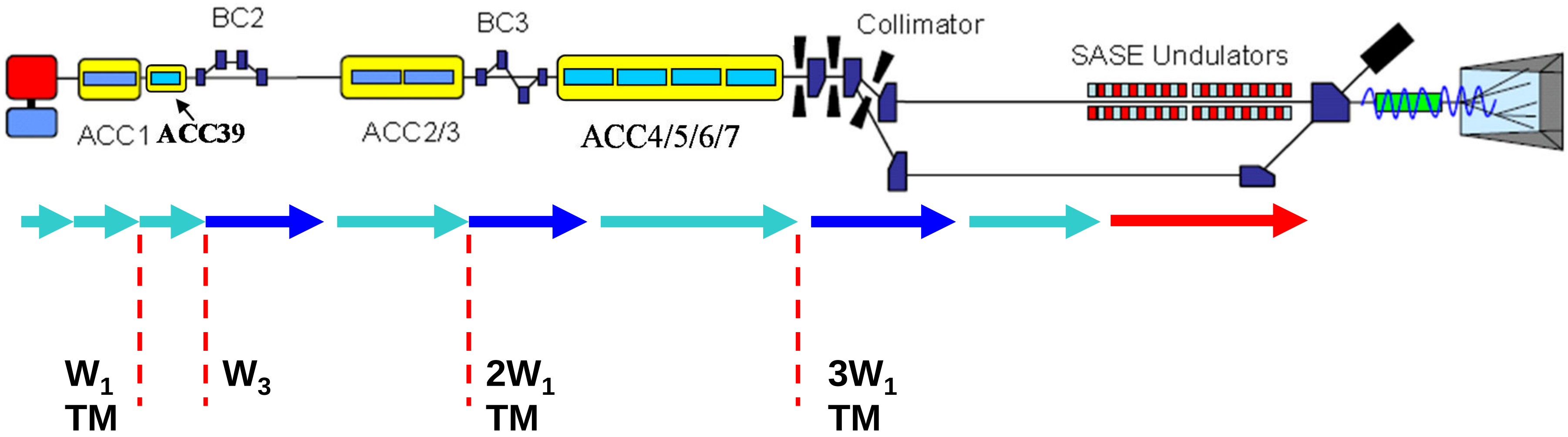
$$\mathbf{x}_n = \mathbf{A}_0^{-1}(\mathbf{g}_n)$$

residual in macroscopic parameters

analytical correction of RF parameters

Simulation Methods and Results

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

Simulation Methods and Results

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: $E_1(s_1) = E_0(s_0)$, $s_1(s_0) = s_0 + \left(r_{56}\delta + t_{566}\delta^2 + u_{5666}\delta^3\right)$

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

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

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

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

Simulation Methods and Results

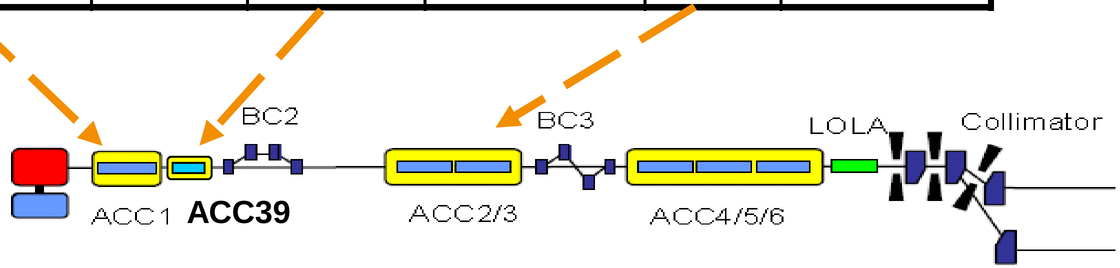
8 macroparameters
define 6 equations

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

Analytical solution without self-fields
+ iterative procedure with them

RF settings in accelerating modules

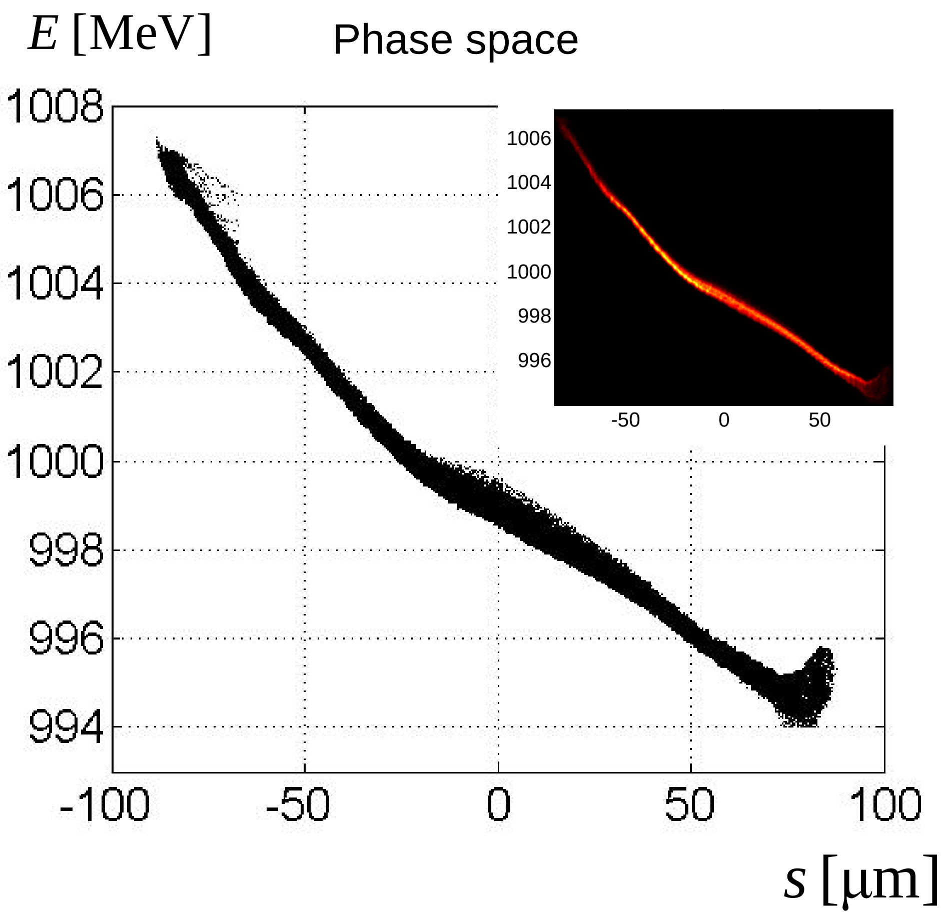
Charge, nC	$V_{1,1}$, [MV]	$\varphi_{1,1}$, [deg]	$V_{1,3}$, [MV]	$\varphi_{1,3}$, [deg]	V_2, [MV]	φ_2, [deg]
1	144	-4.66	22.6	145	350	23.4
0.5	143.7	4.042	19.65	158.4	351	23.65
0.25	143.36	2.493	20.81	153.9	352.6	23.96
0.1	144.8	-6.31	25.6	137.5	356.5	25.62
0.02	144.9	-3.894	25.58	141.65	339.8	19.385



Simulation Methods and Results

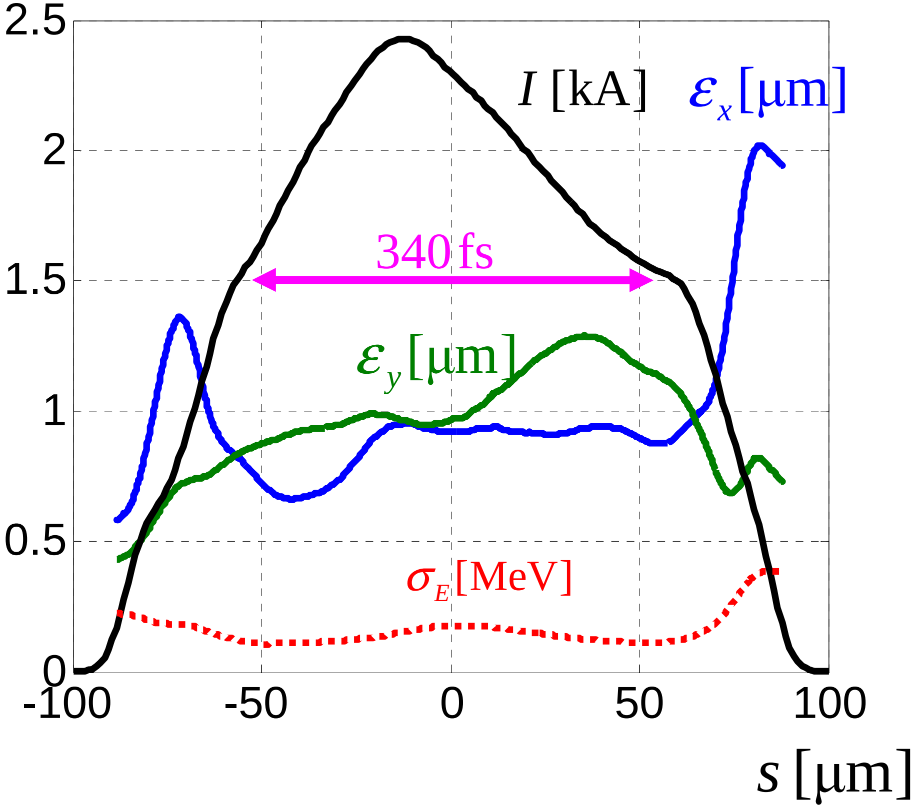
Q=1 nC

Phase space



bunch head

Current, emittance, energy spread

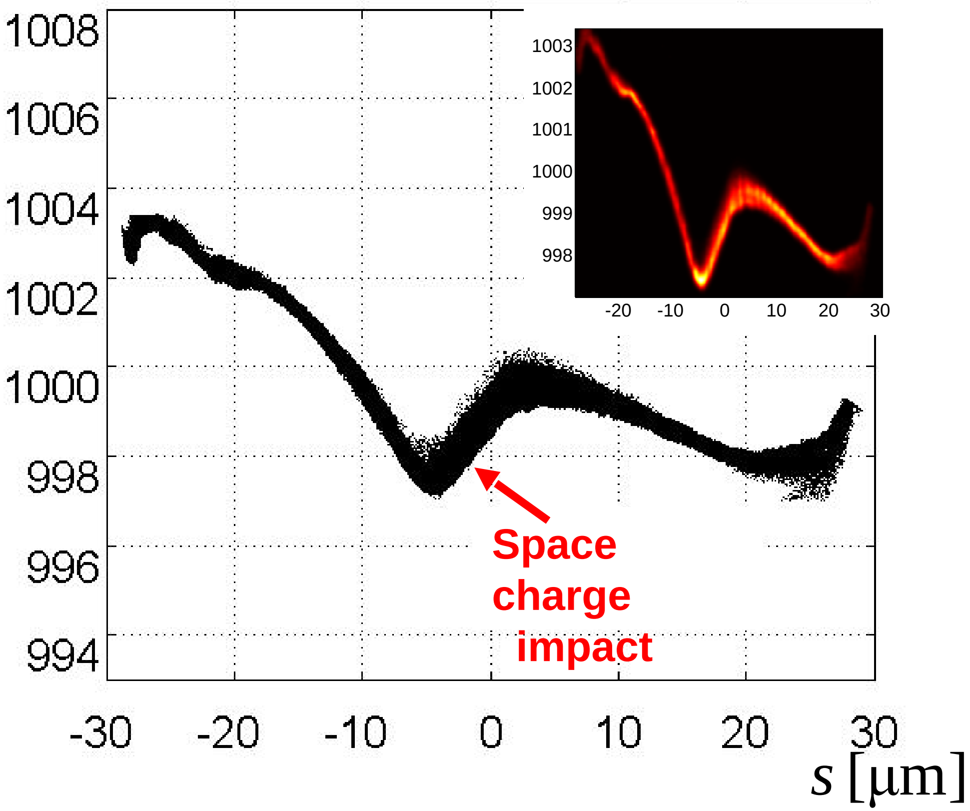


$$\varepsilon_x^{proj} = 3\,[\mu m]$$

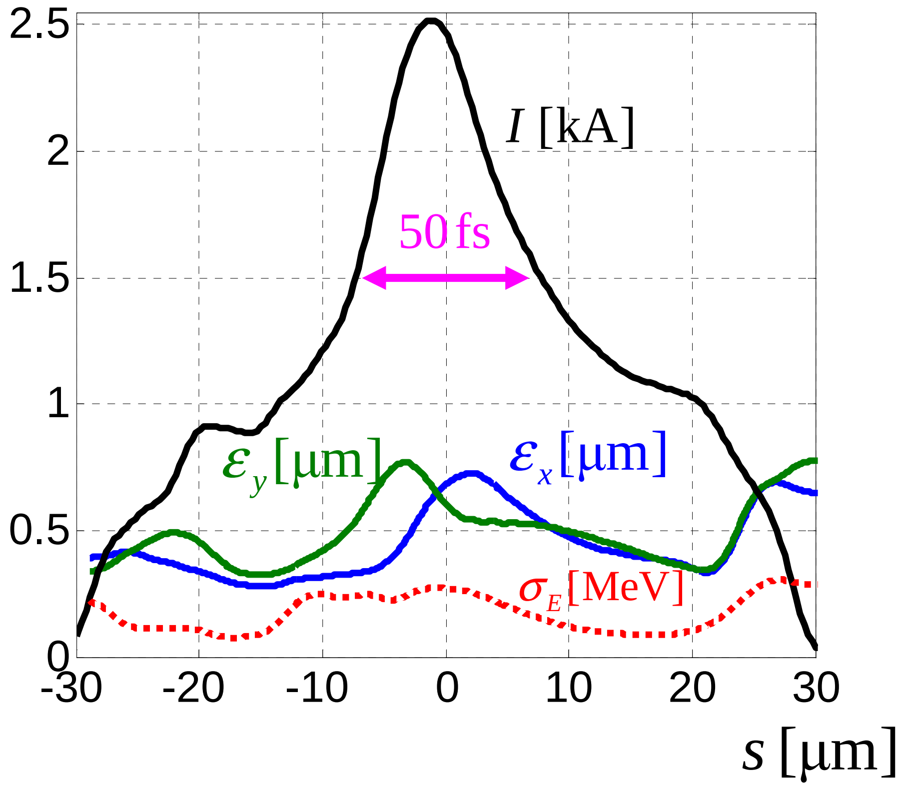
$$\varepsilon_y^{proj} = 1.4\,[\mu m]$$

Simulation Methods and Results

Q=0.25 nC



bunch head

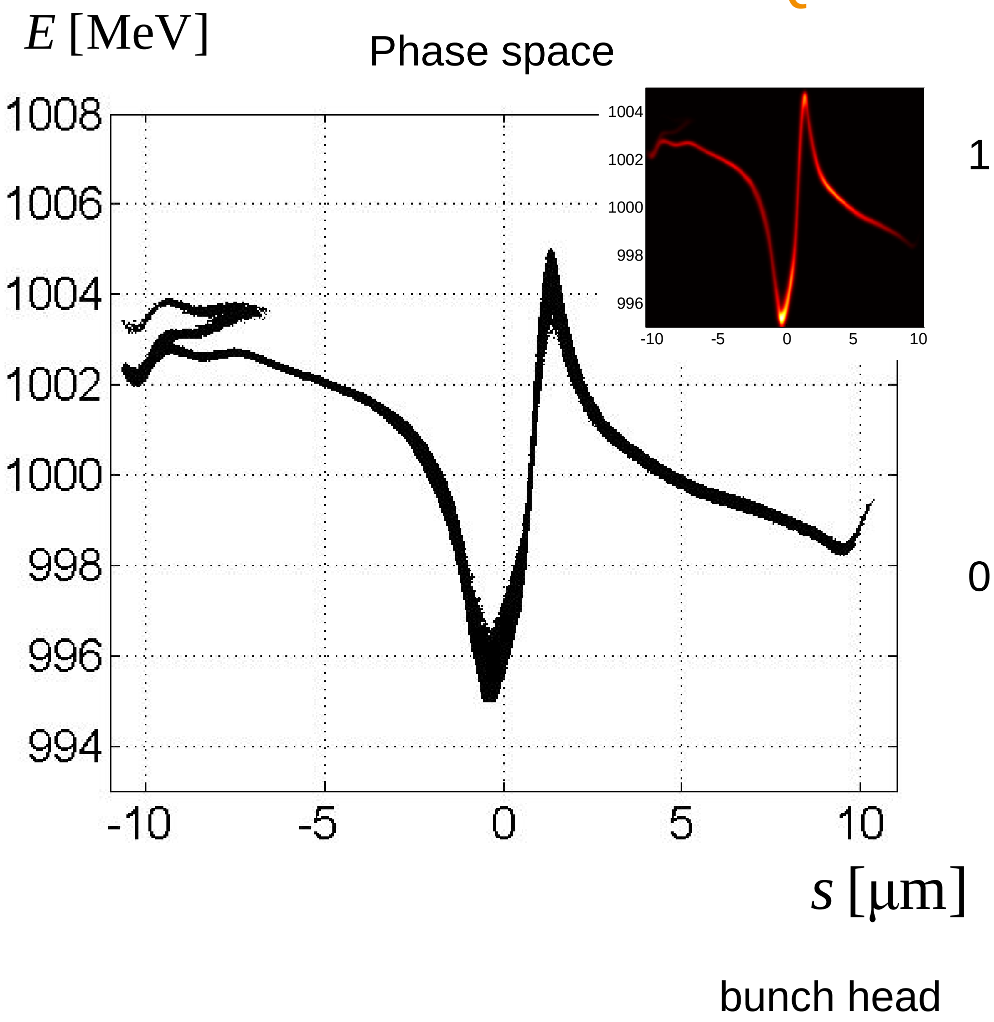


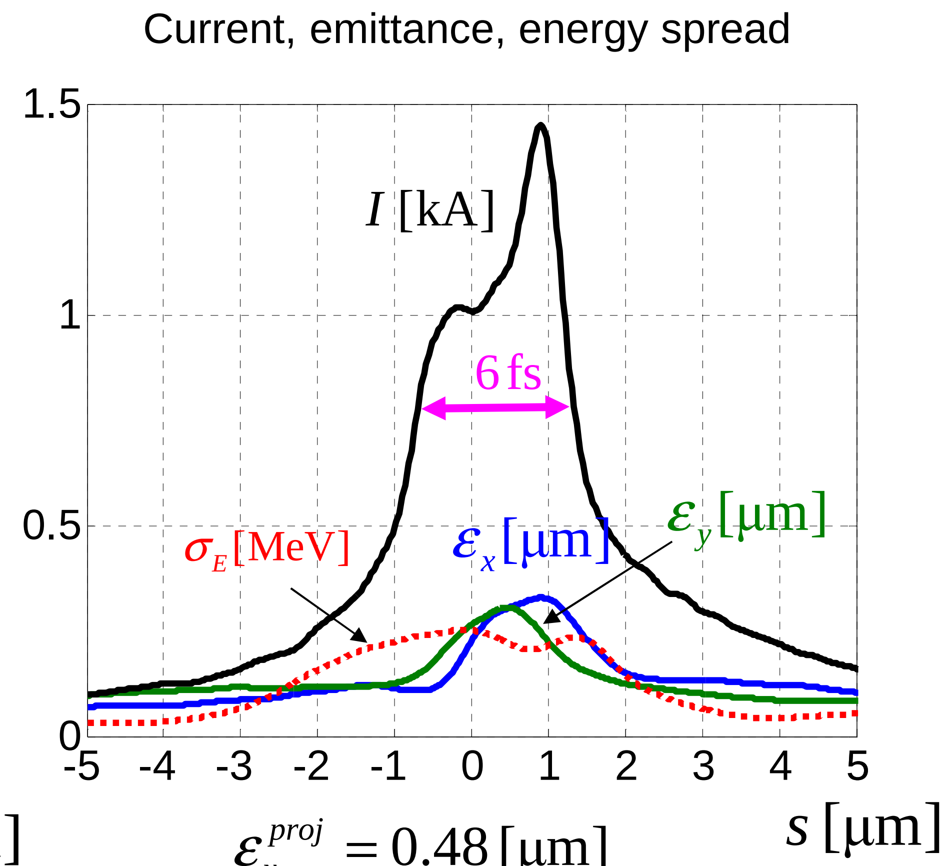
$$\varepsilon_x^{proj} = 1.14\,[\mu m]$$

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

Simulation Methods and Results

Q=0.02 nC

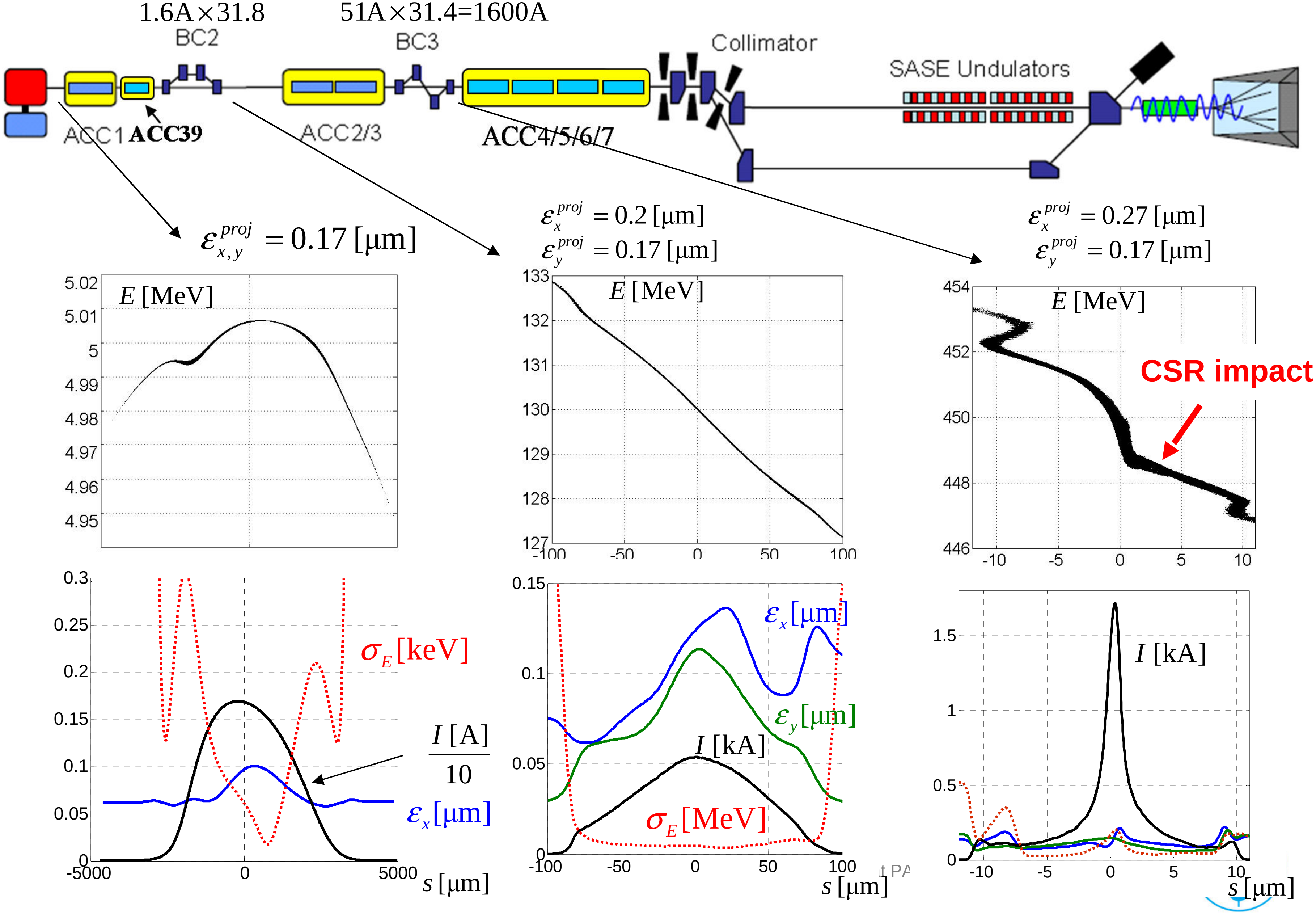




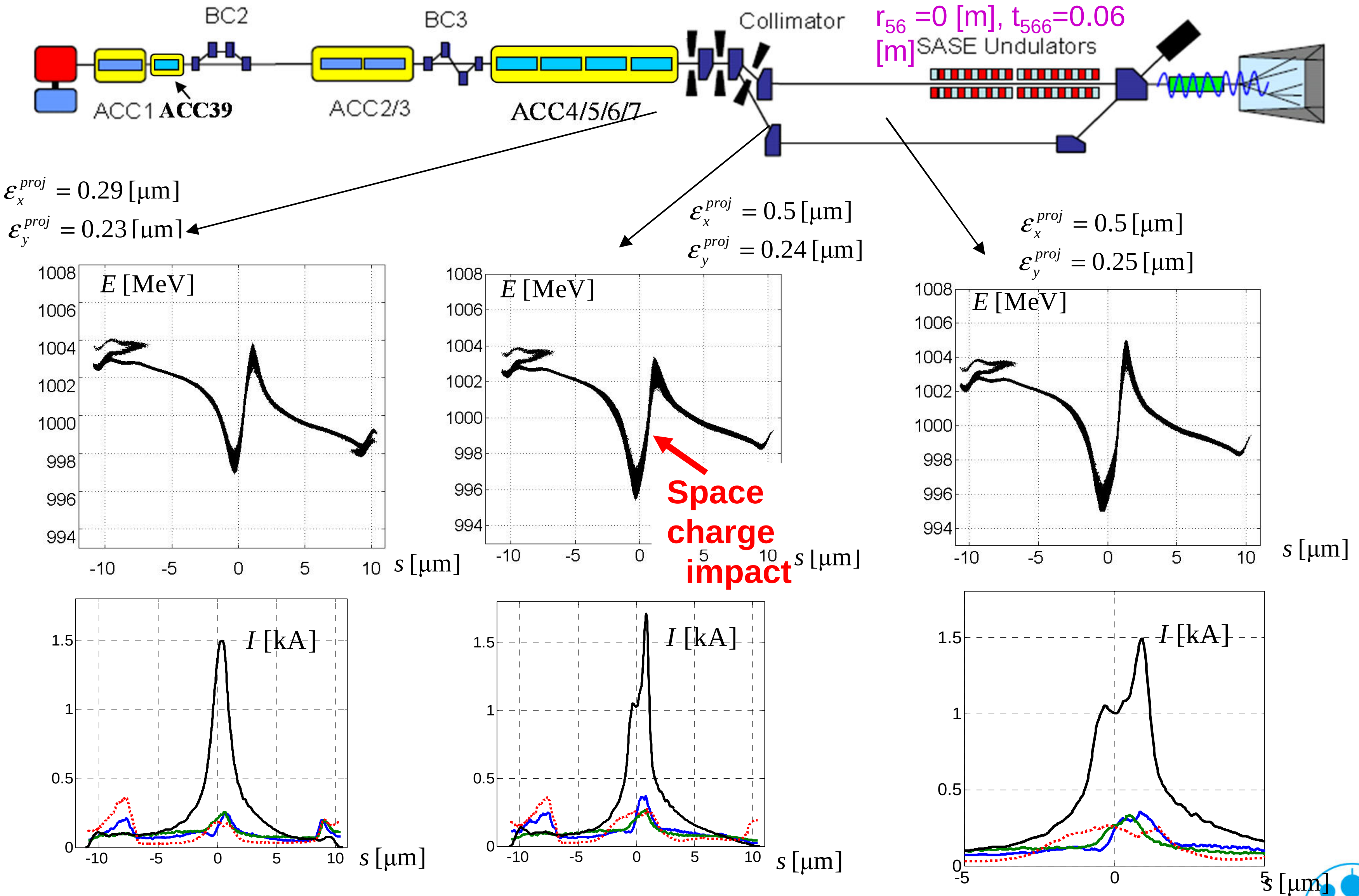
$$\varepsilon_x^{proj} = 0.48\,[\mu\text{m}]$$

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

Simulation Methods and Results



Simulation Methods and Results



Simulation Methods and Results

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

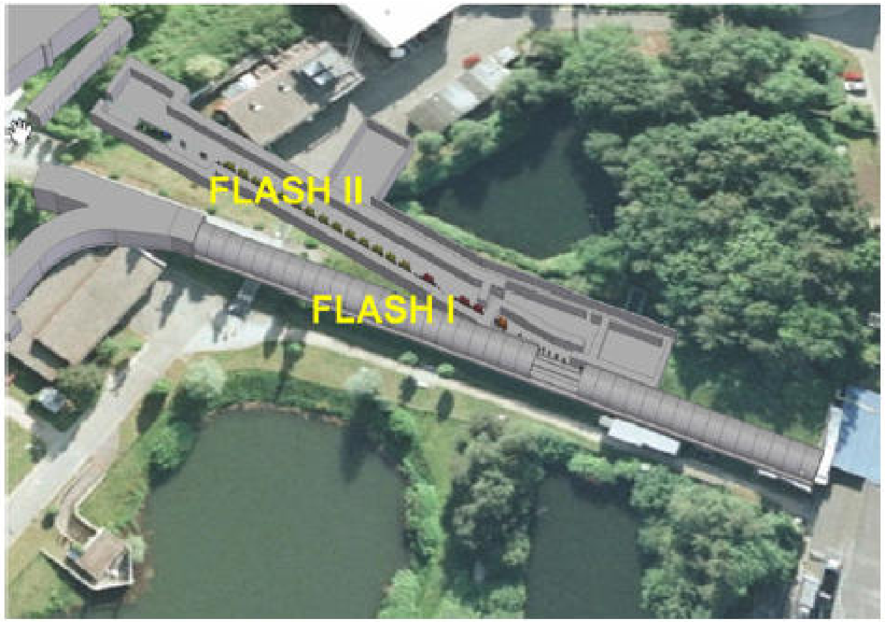
Tolerances (from tracking) **with self fields** agree with this table

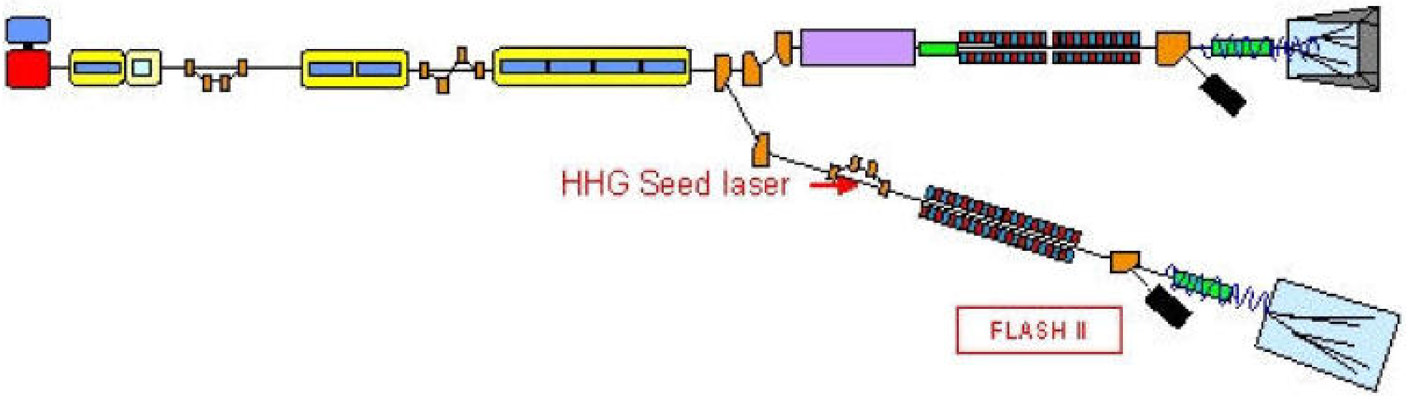
Simulation Methods and Results

	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			-	-	-

Low Energy Spread for FLASH 2

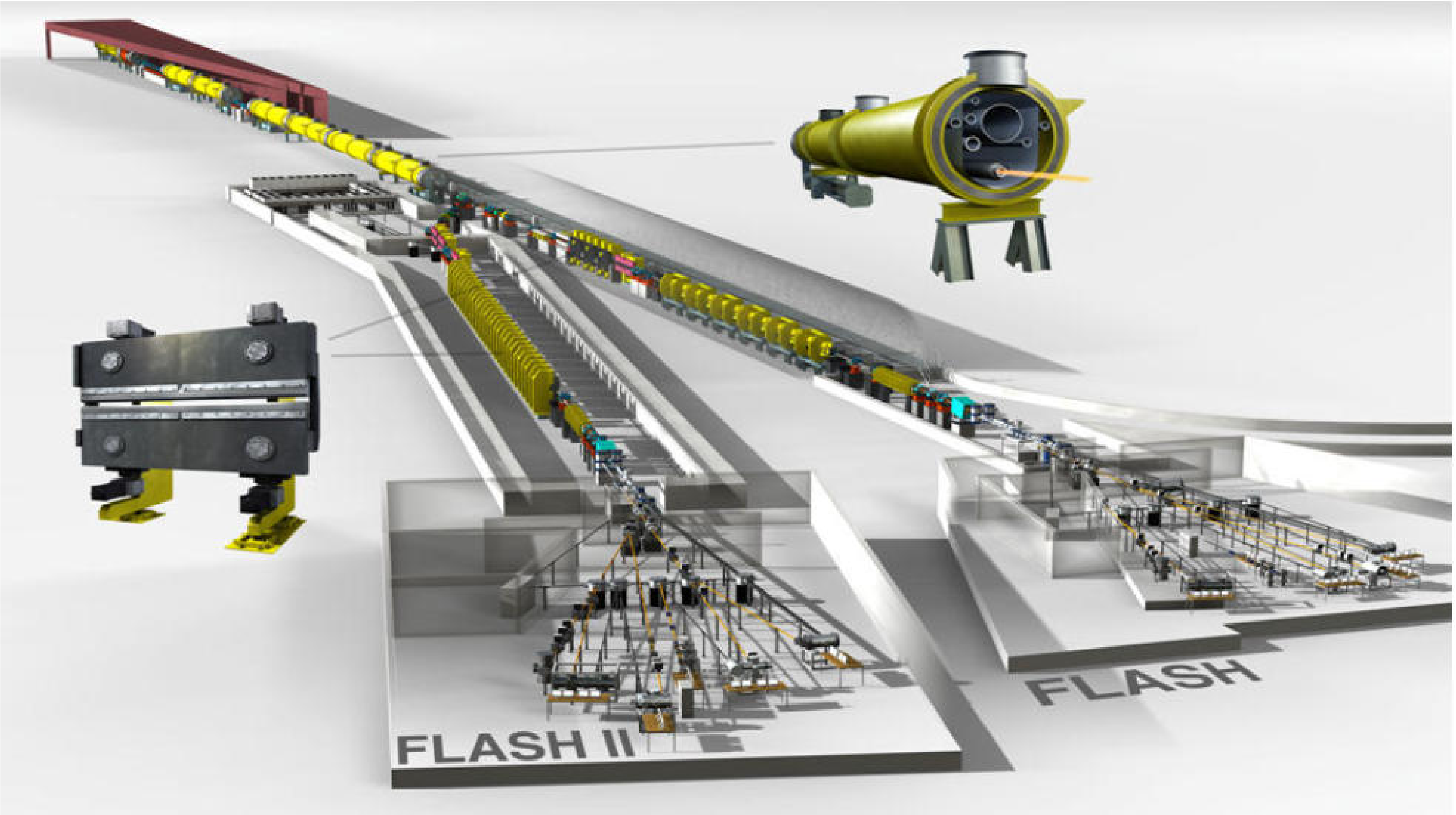
FLASH 2 (from 2013)





Low Energy Spread for FLASH 2

FLASH 2 (from 2013)



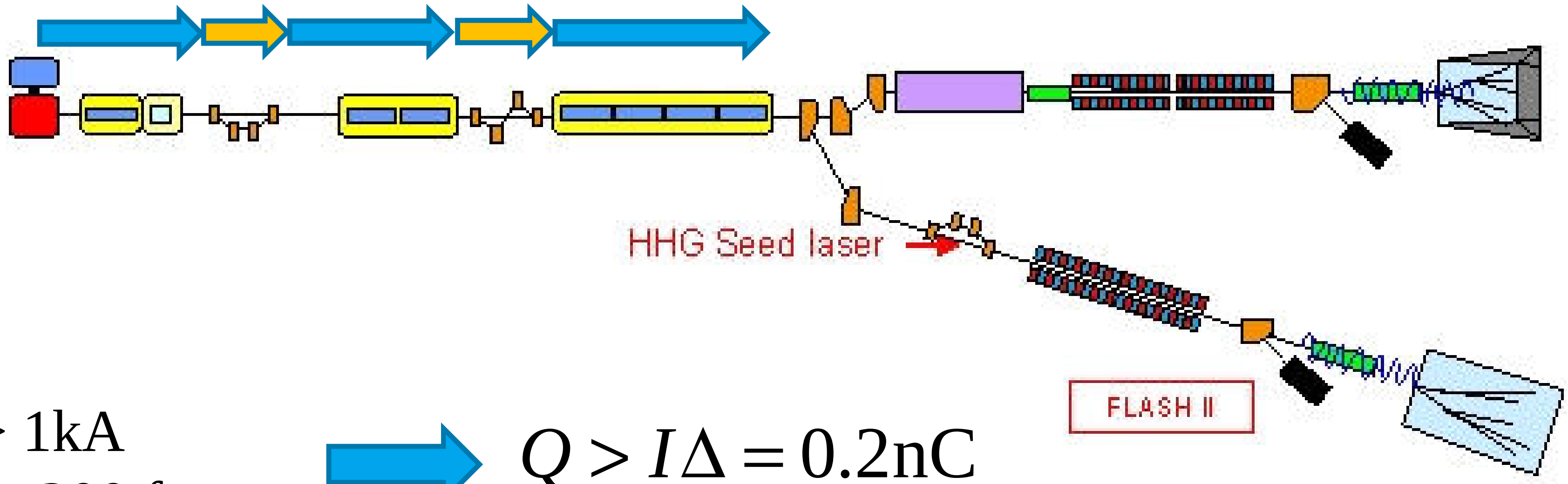
Low Energy Spread for FLASH 2

FLASH 2

Photon Beam	HHG	SASE
Wavelength range (fundamental)	10 - 40 nm	4 - 80 nm
Average single pulse energy	1 – 50 µJ	1 – 500 µJ
Pulse duration (FWHM)	<15 fs	10 – 200 fs
Peak power (from av.)	1 – 5 GW	1 – 5 GW
Spectral width (FWHM)	0.1 – 1 %	0.5 – 1.5 %
Peak Brilliance*10 - 40 nm	10^{28} - 10^{31}	10^{28} - 10^{31}

Low Energy Spread for FLASH 2

ASTRA+CSRtrack



I > 1kA
Δ > 200 fs

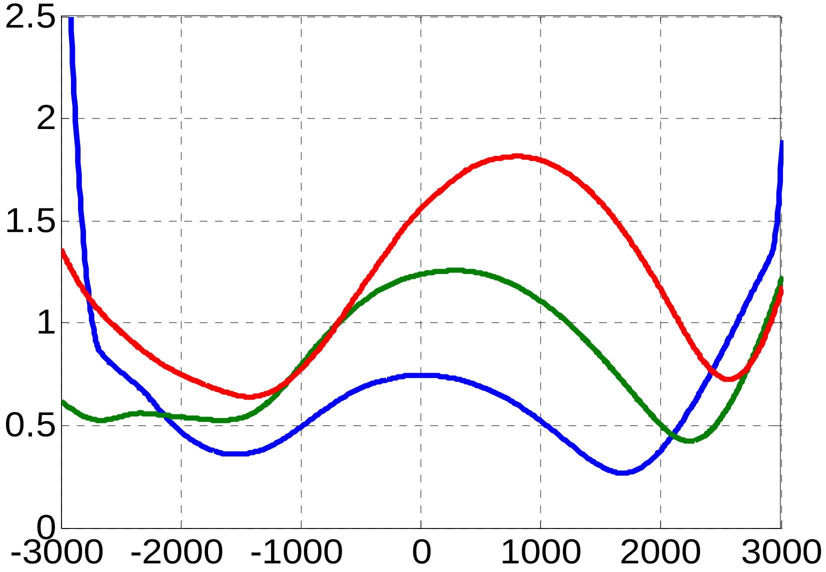
$$Q > I\Delta = 0.2\text{nC}$$

Energy spread < 120keV

Low Energy Spread for FLASH 2

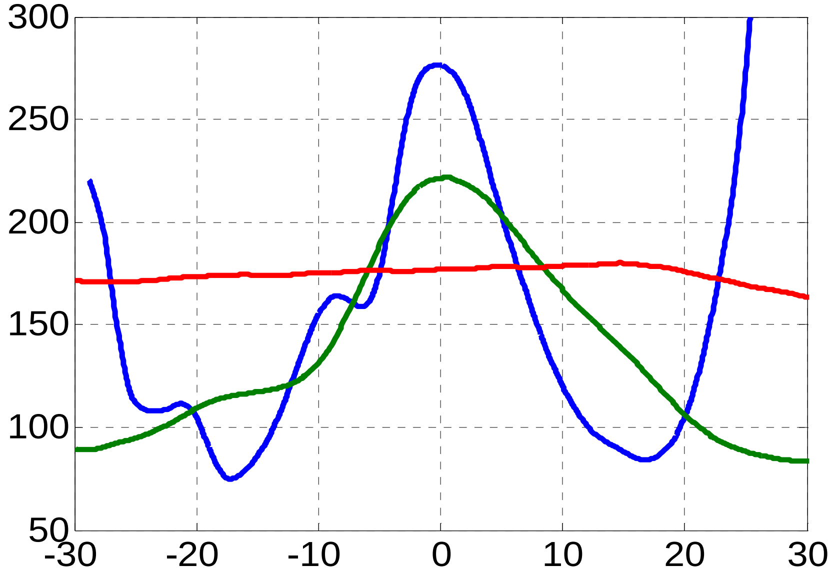
Energy spread vs. charge?

Slice emittance [um]



s [μm]

Slice energy spread [keV]



s [μm]

$Q = 1\,\mathrm{nC}$ $\quad Q = 0.5\,\mathrm{nC}$ $\quad Q = 0.25\,\mathrm{nC}$

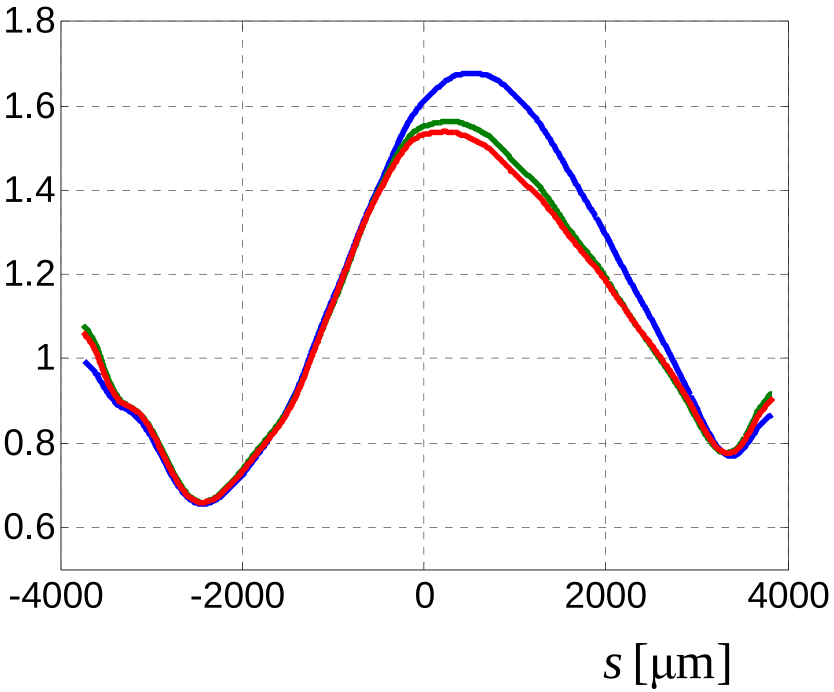
Low Energy Spread for FLASH 2

E in BC 2 = 145 MeV, ACC1 (50%, 50 %)

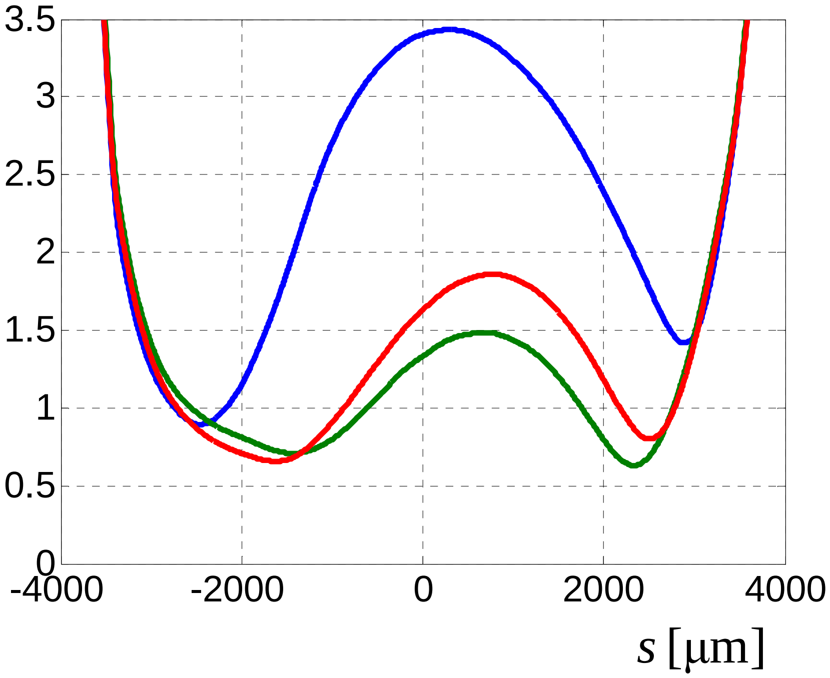
E in BC 2 = 145 MeV, ACC1 (37.5%, 62.5 %)

E in BC 2 = 130 MeV, ACC1(40%, 60 %)

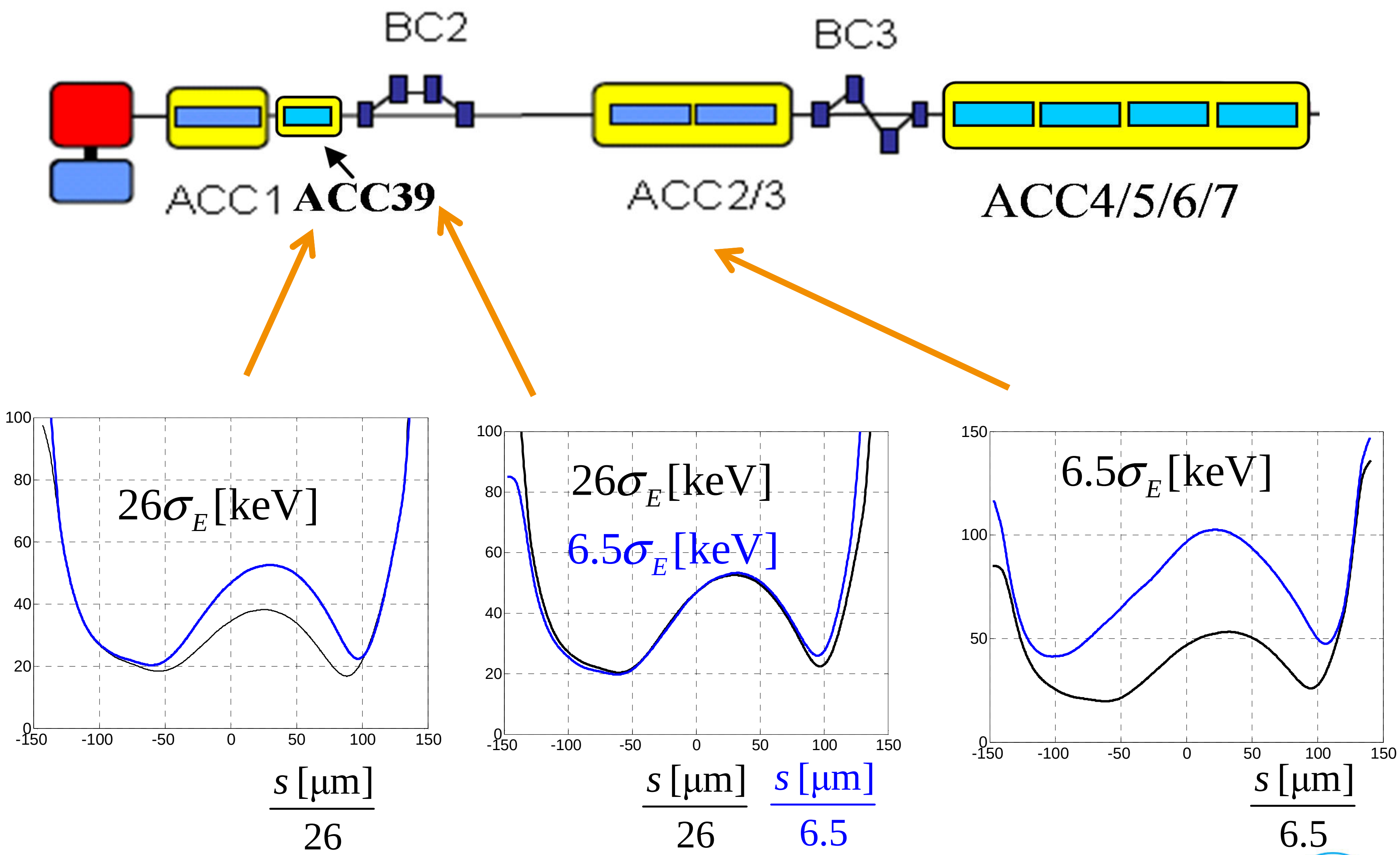
Slice emittance [um]



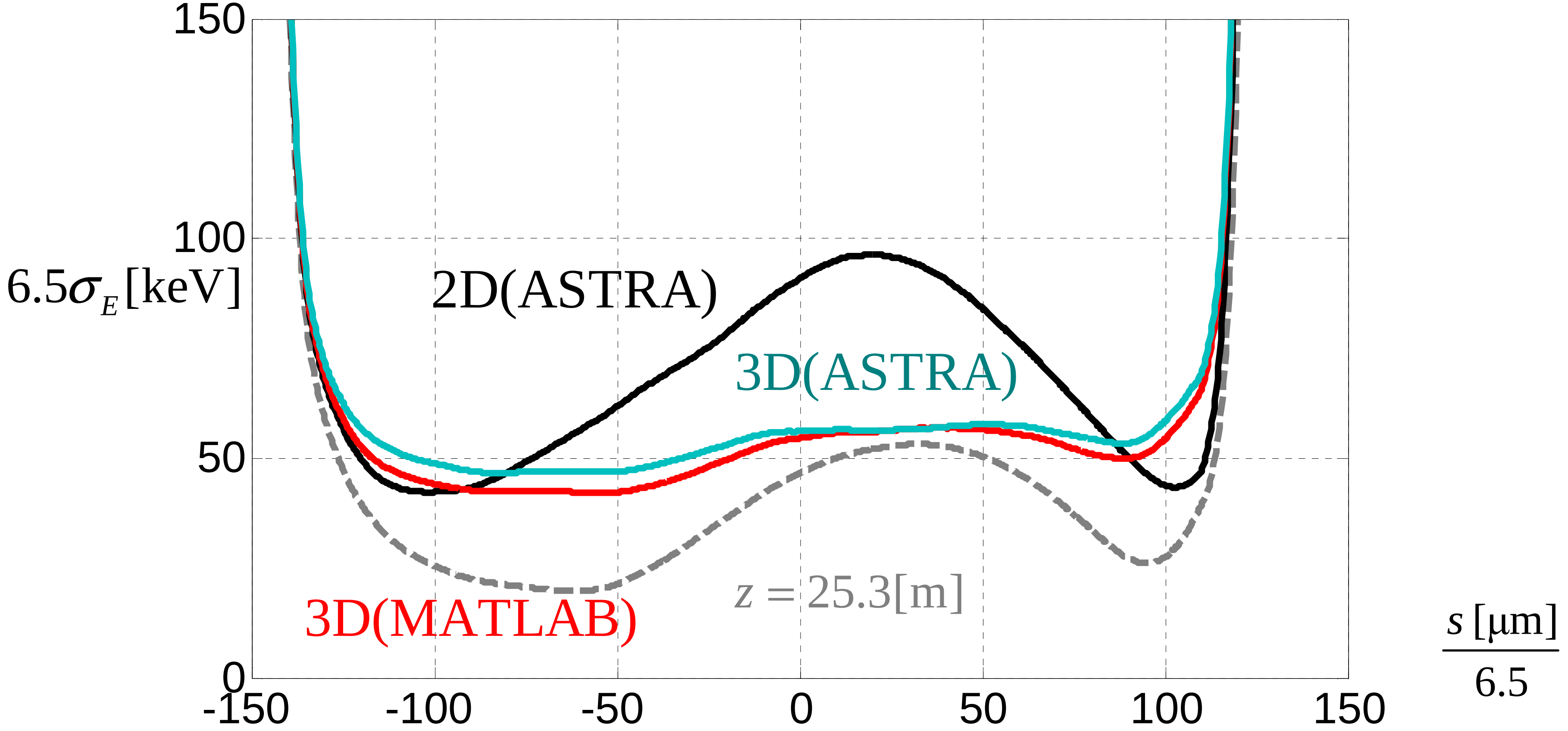
Slice energy spread [keV]



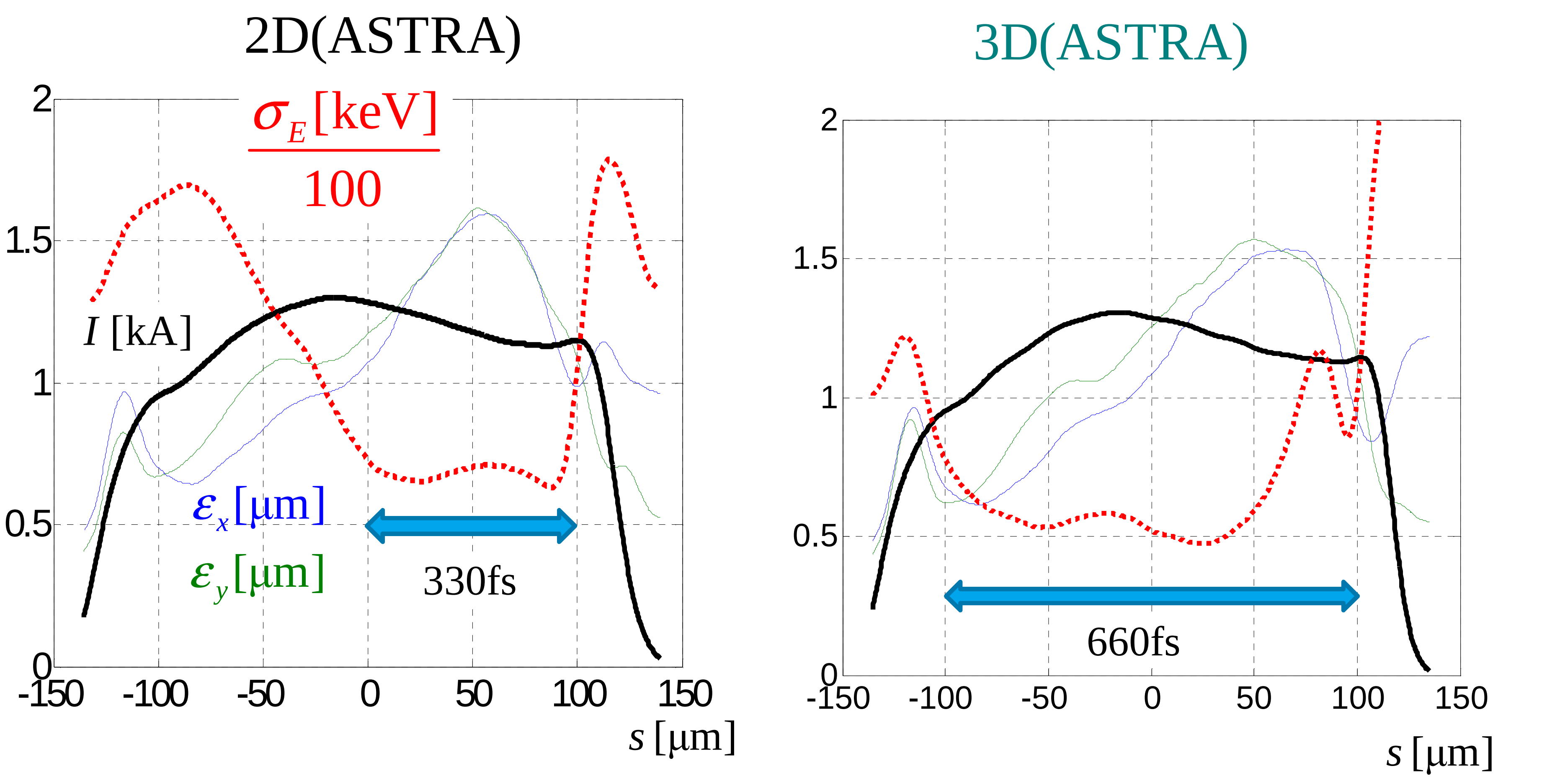
Low Energy Spread for FLASH 2



Low Energy Spread for FLASH 2



Low Energy Spread for FLASH 2



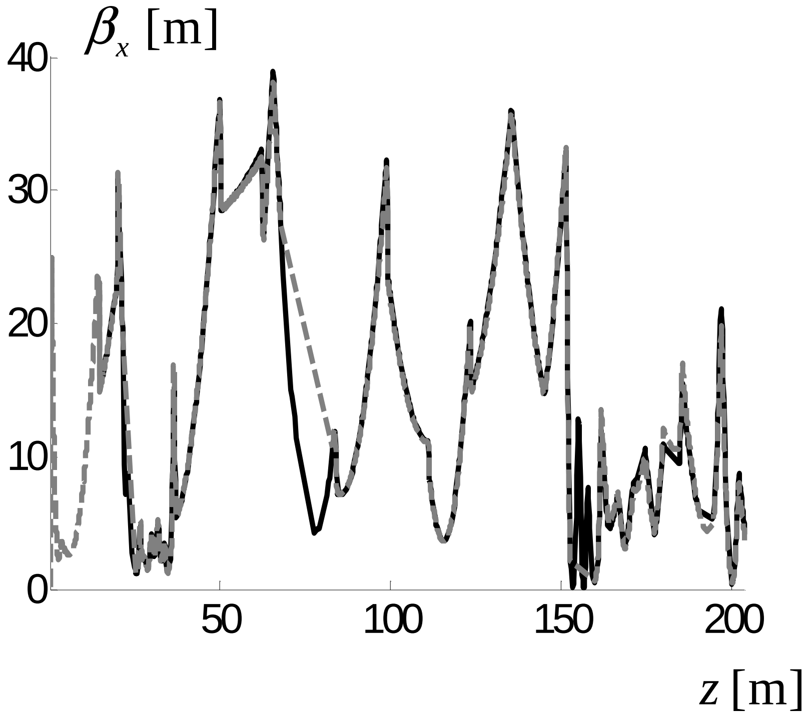
Comparison with Elegant

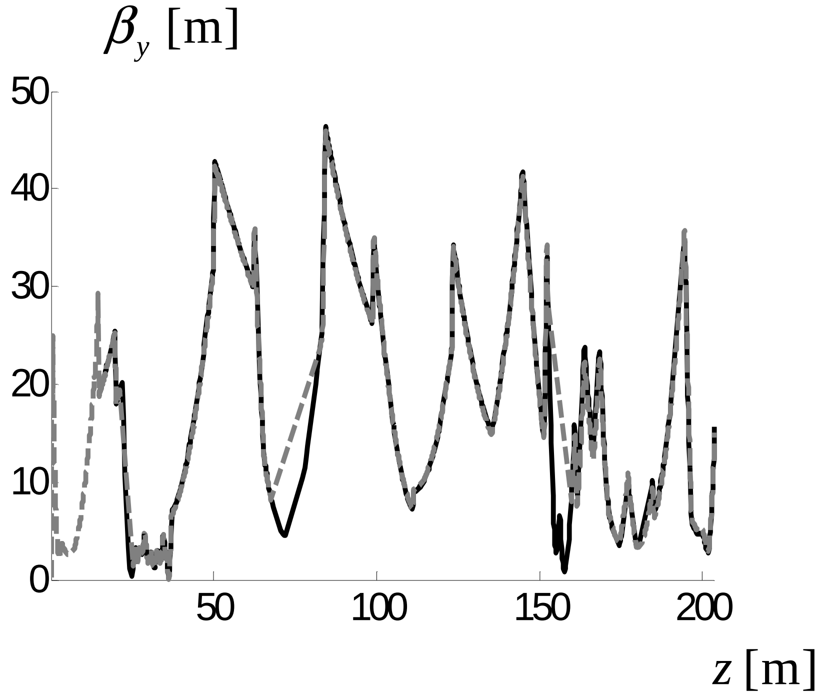
RF settings in accelerating modules (without self fields)

Charge, nC	$V_{1,1}$, [MV]	$\varphi_{1,1}$, [deg]	$V_{1,3}$, [MV]	$\varphi_{1,3}$, [deg]	V_2, [MV]	φ_2, [deg]
Track1D	162.41	9.34	20.32	183.17	332.67	23.53
Elegant	162.41	9.34	20.32	183.17	332.51	23.47
ASTRA	162.47	9.41	20.32	183.17	332.41	23.41

Comparison with Elegant

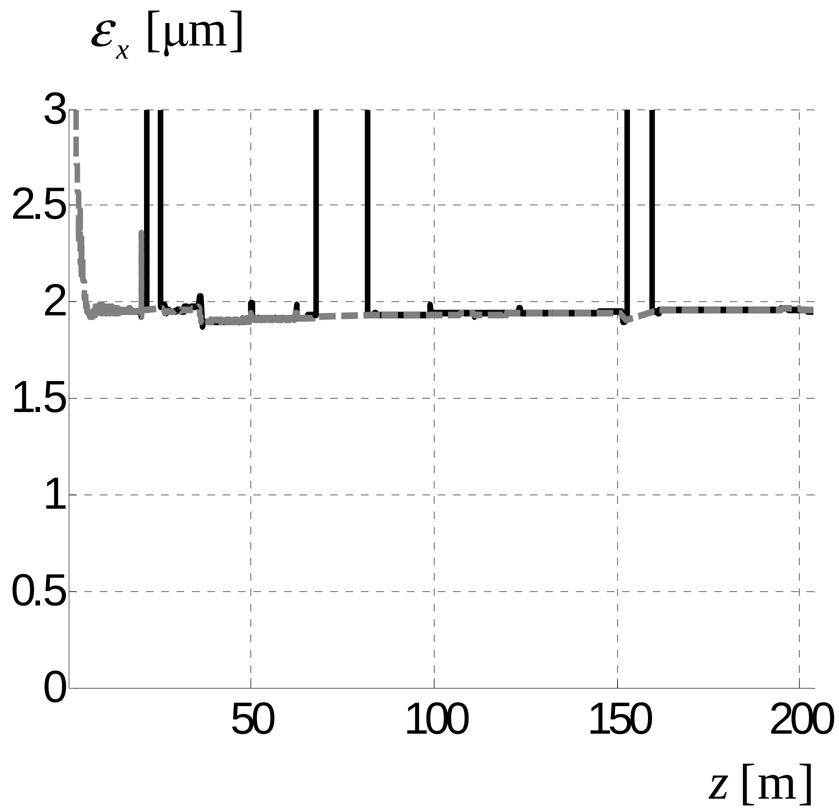
Elegant vs ASTRA without self-fields

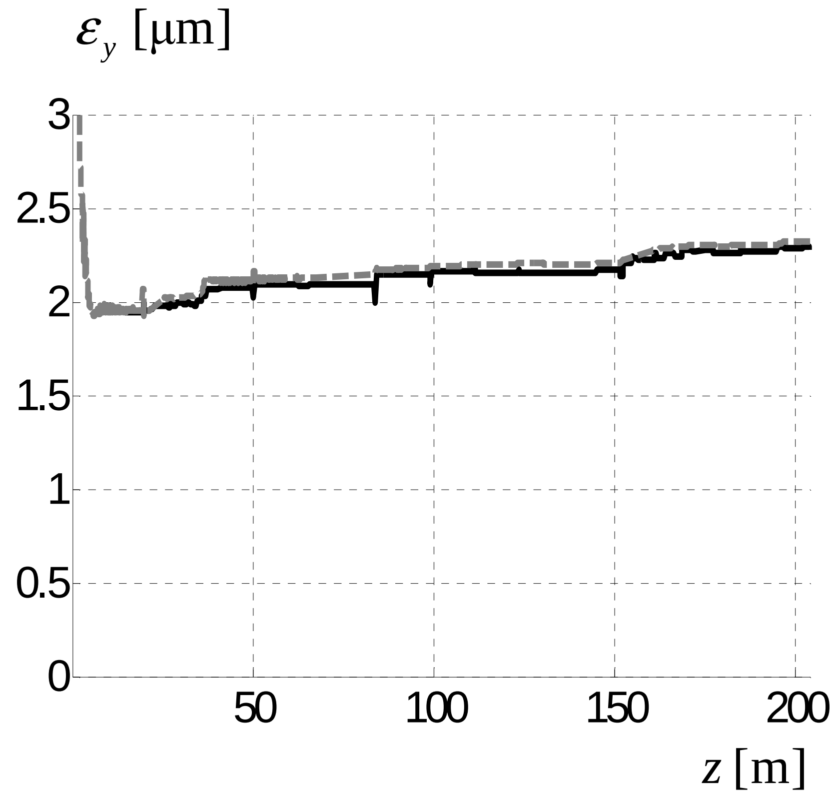




Comparison with Elegant

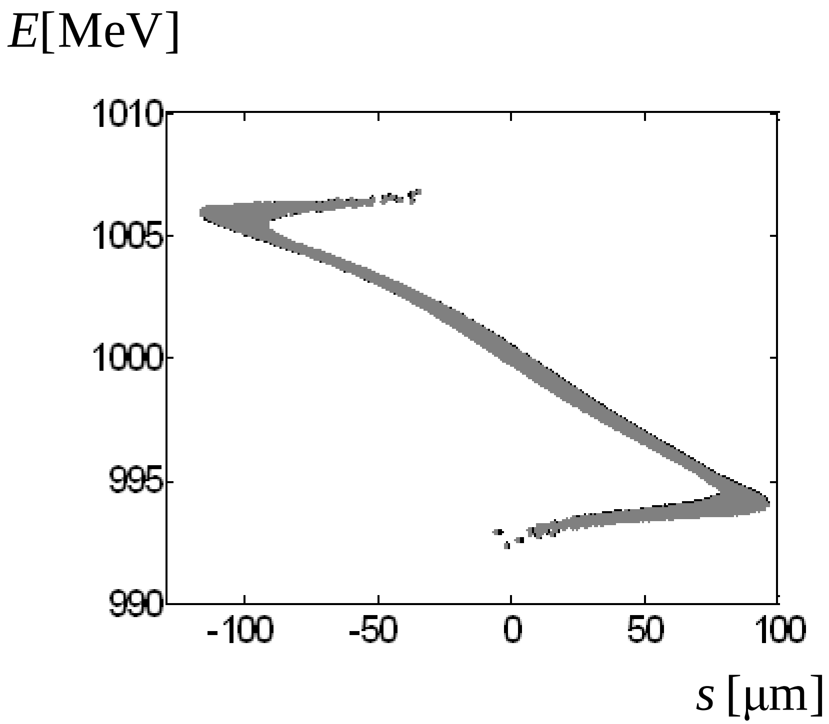
Elegant vs ASTRA without self-fields

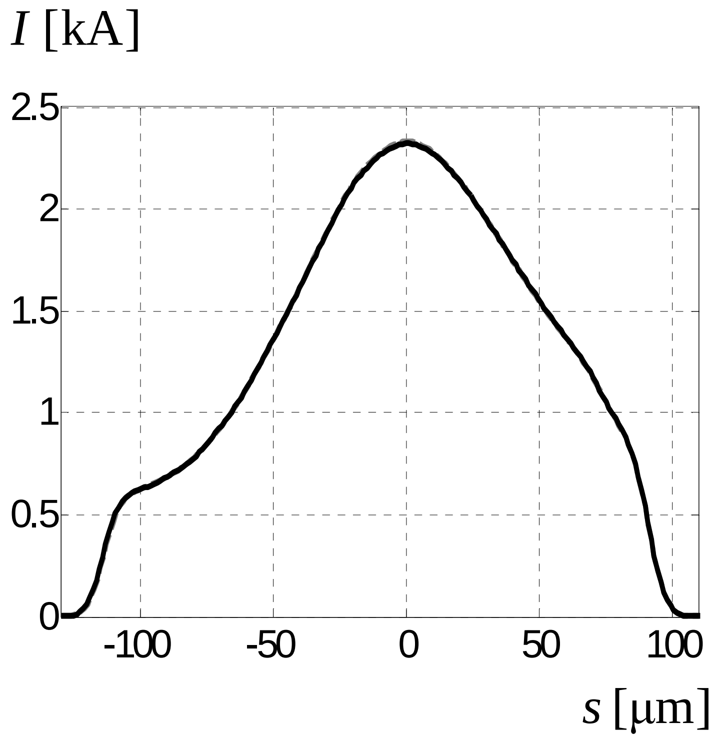




Comparison with Elegant

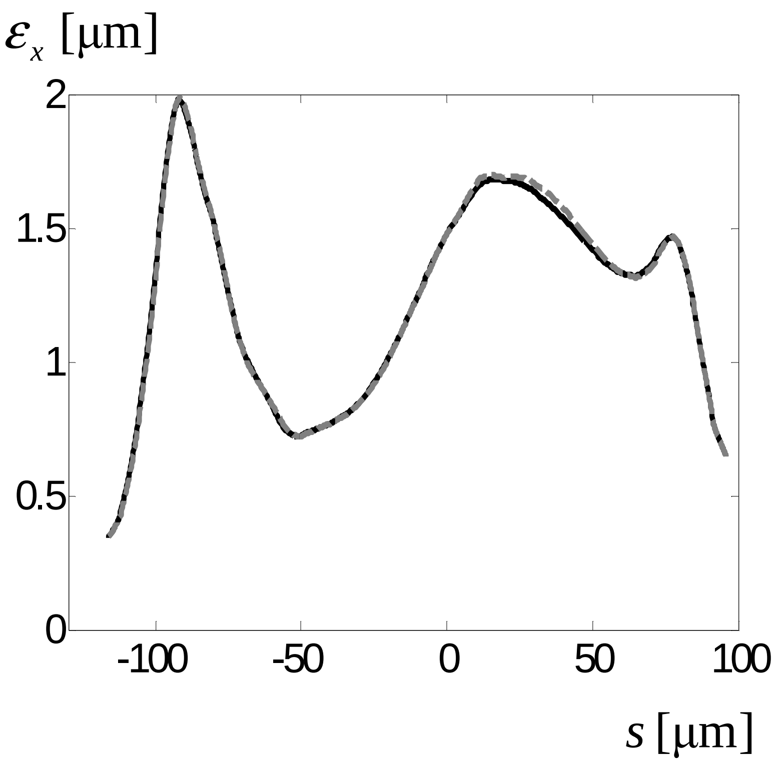
Elegant vs ASTRA without self-fields

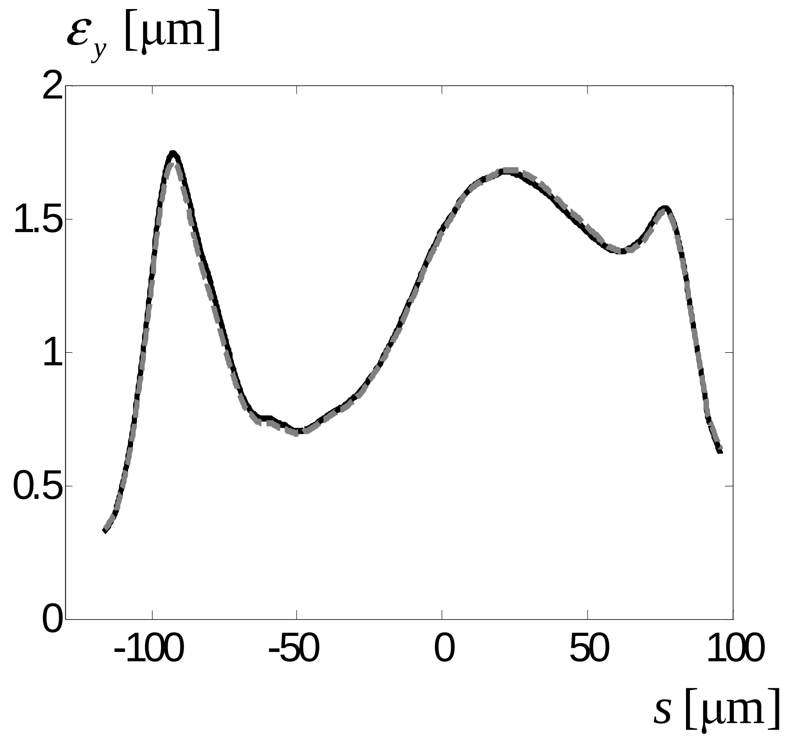




Comparison with Elegant

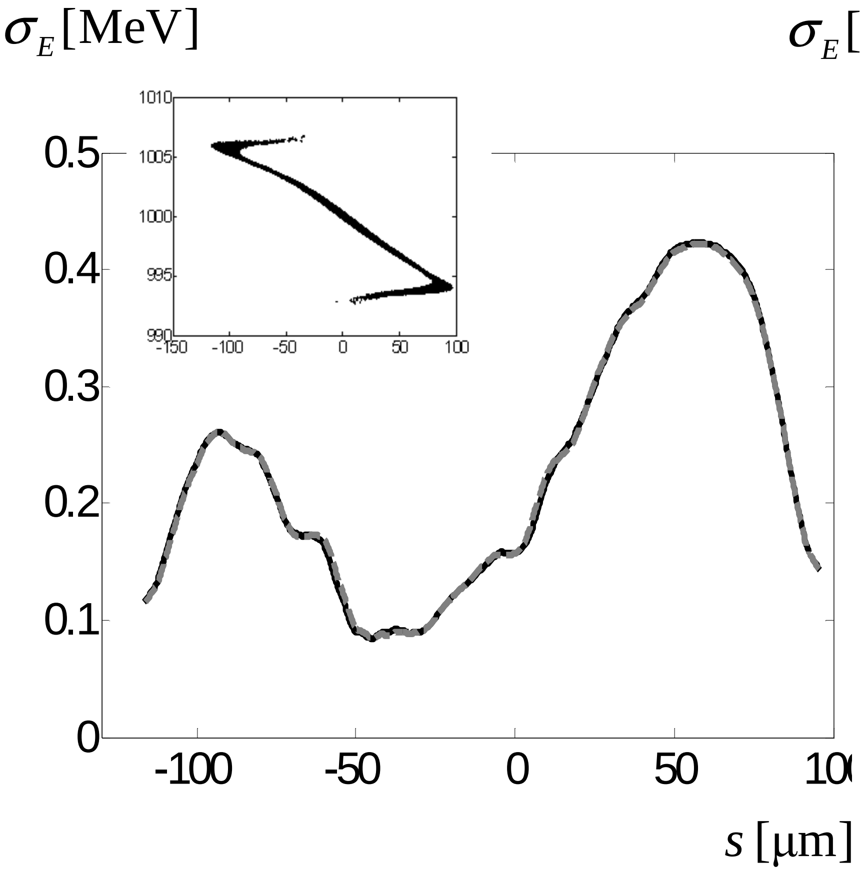
Elegant vs ASTRA without self-fields

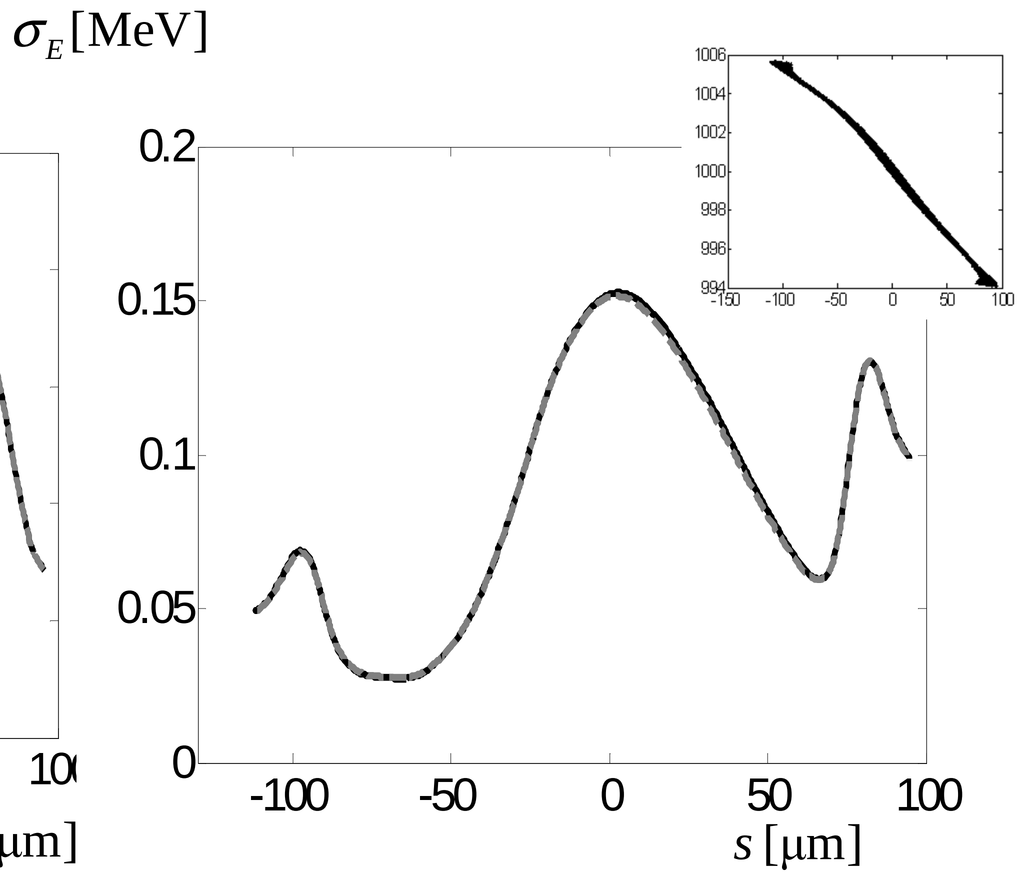




Comparison with Elegant

Elegant vs ASTRA without self-fields





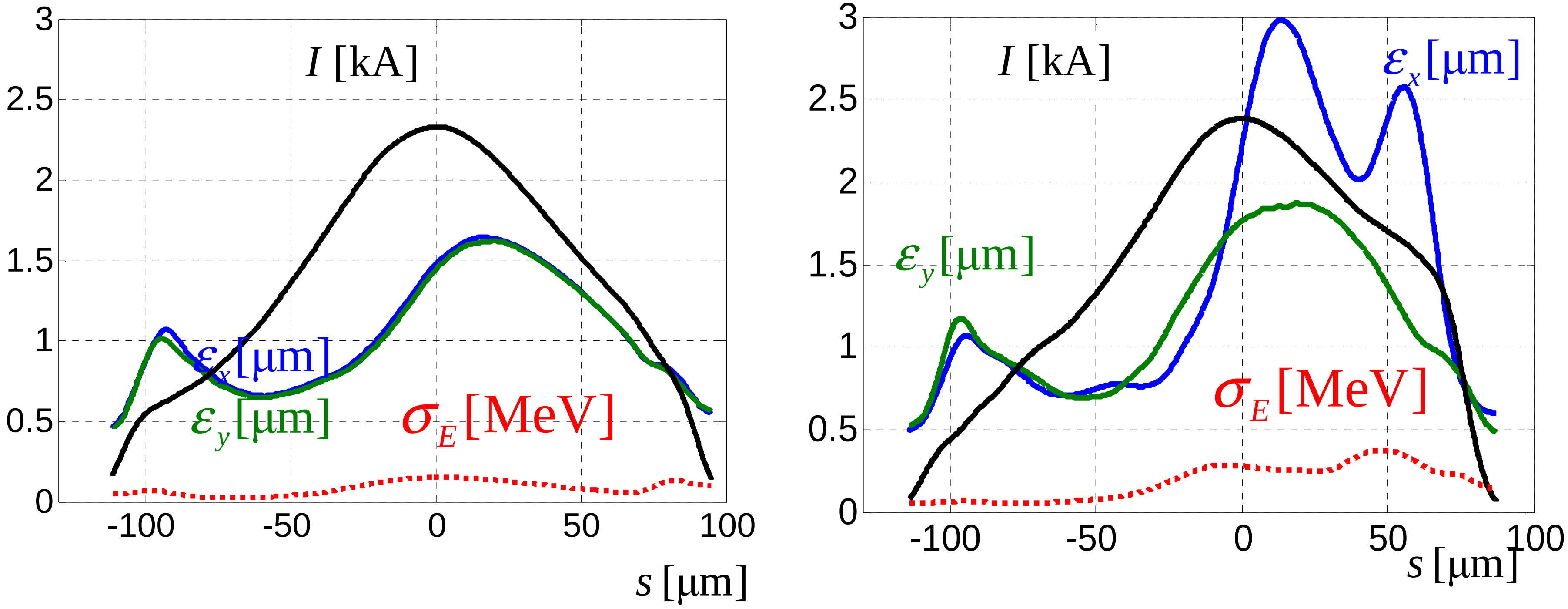
Comparison with Elegant

RF settings in accelerating modules (with self fields)

Charge, nC	$V_{1,1}$, [MV]	$\varphi_{1,1}$, [deg]	$V_{1,3}$, [MV]	$\varphi_{1,3}$, [deg]	V_{2}, [MV]	φ_{2}, [deg]
Track1D (without)	162.41	9.34	20.32	183.17	332.67	23.53
Track1D (selffield)	157.81	-3.92	20.81	145.89	339.19	25.86
Elegant	157.81	-3.92	20.81	145.90	339.01	25.79
ASTRA	157.84	-3.96	20.81	145.92	338.42	25.58

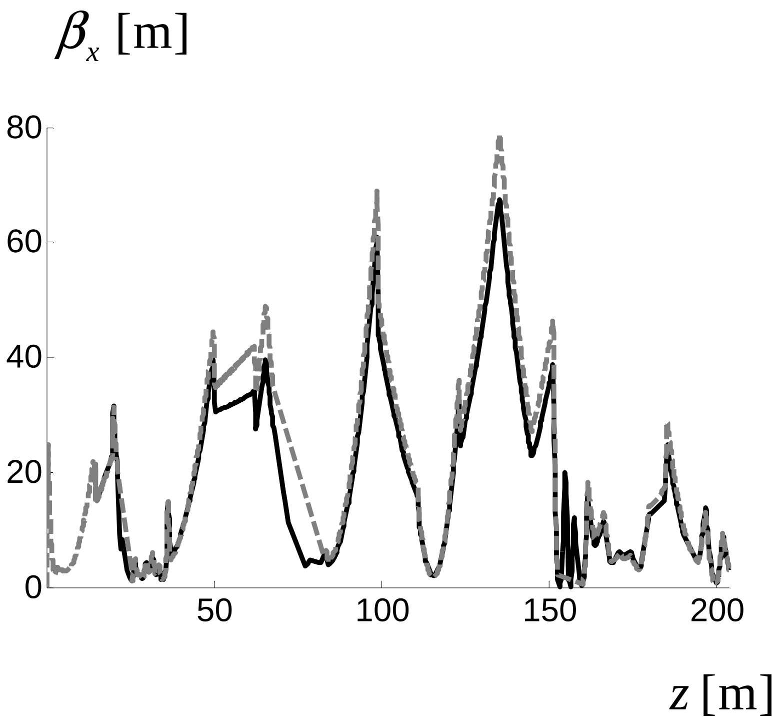
Comparison with Elegant

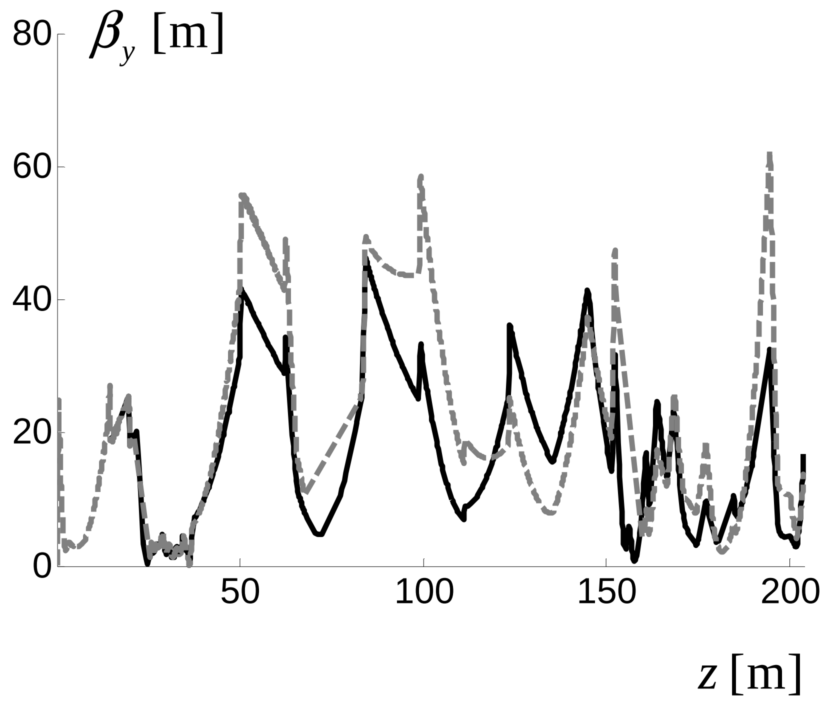
ASTRA without and with self-fields



Comparison with Elegant

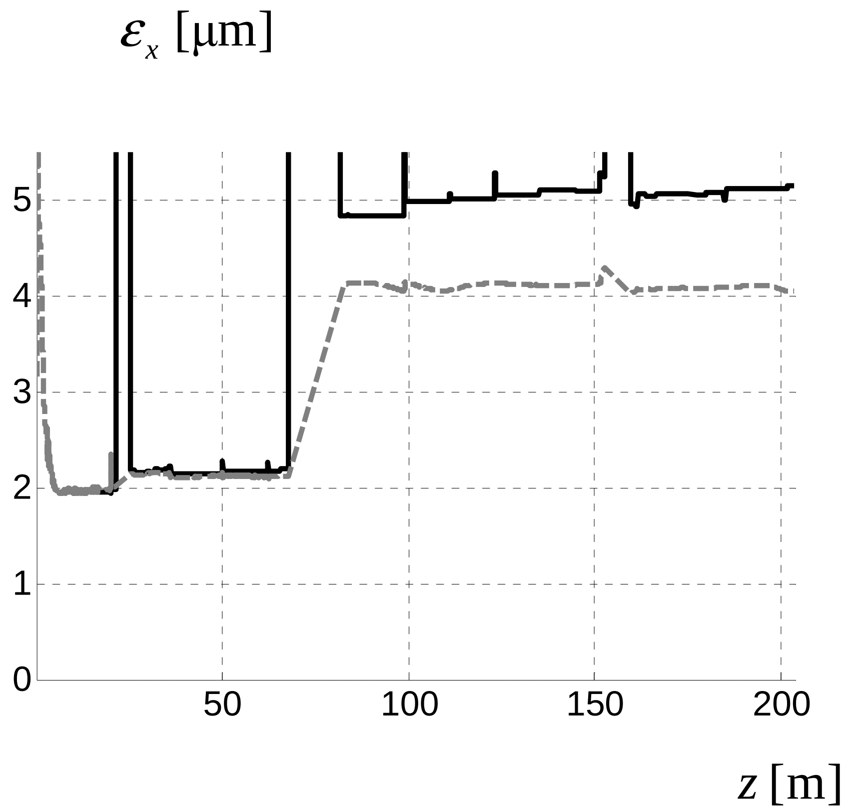
Elegant vs ASTRA with self-fields

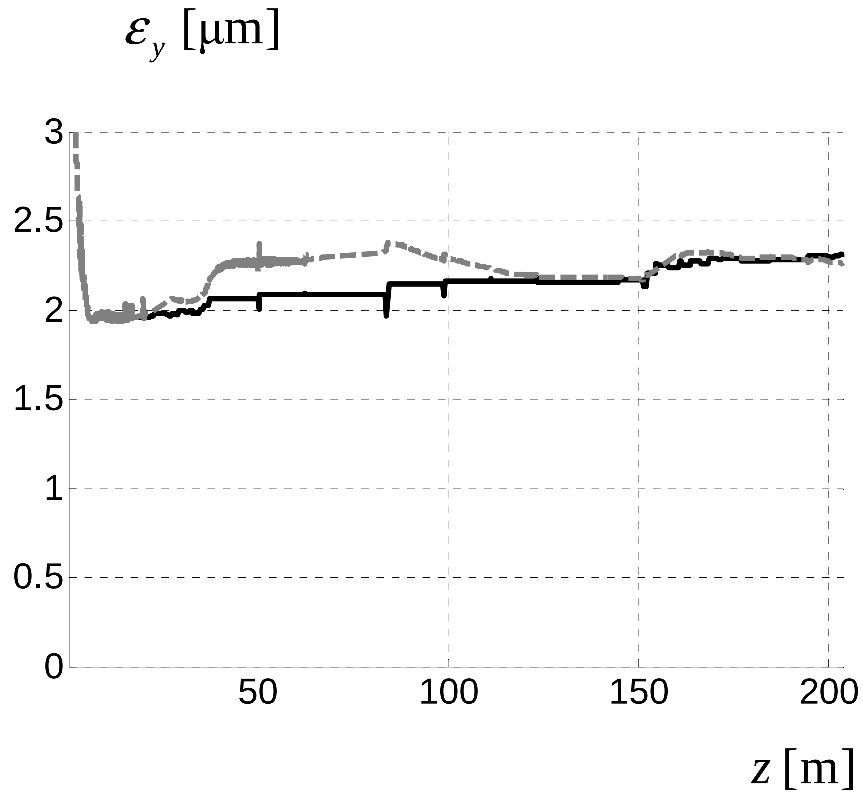




Comparison with Elegant

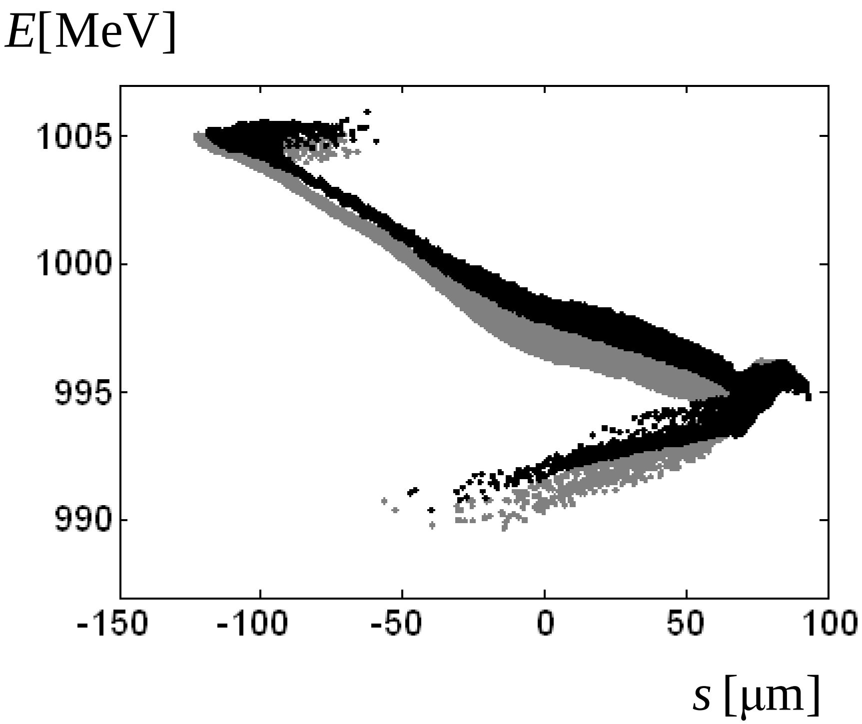
Elegant vs ASTRA with self-fields

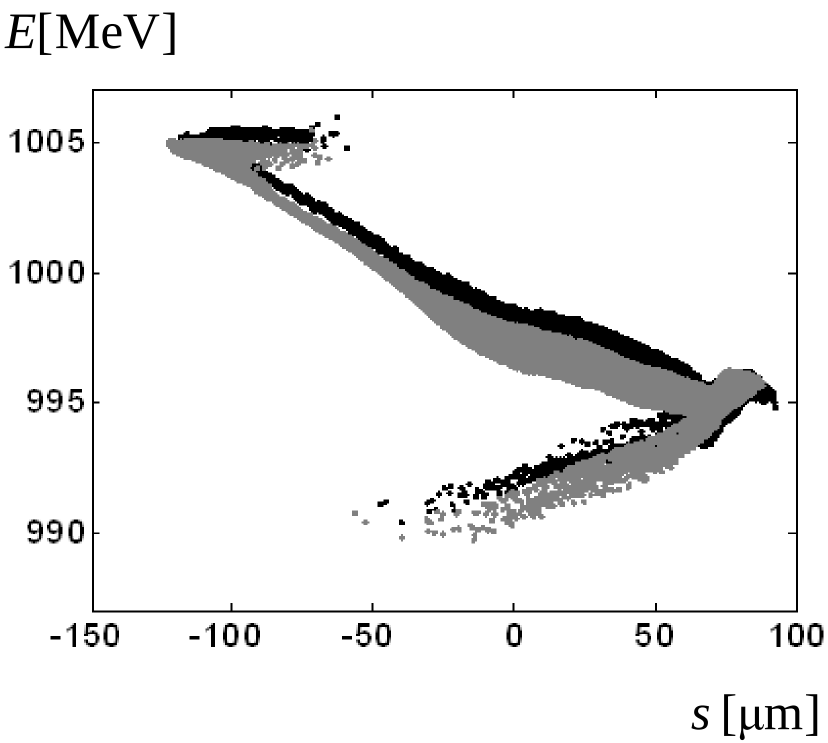




Comparison with Elegant

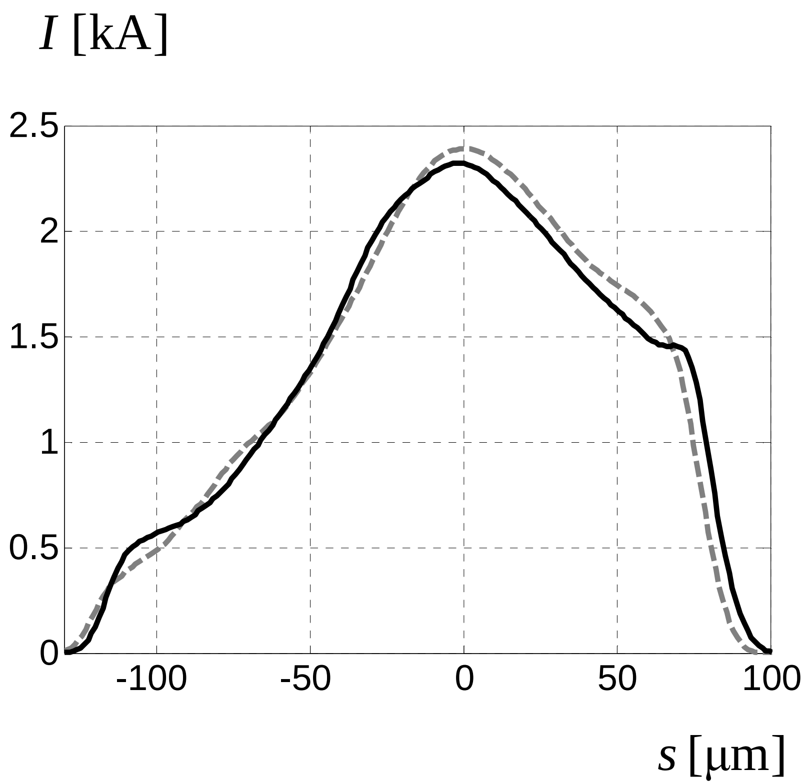
Elegant vs ASTRA with self-fields

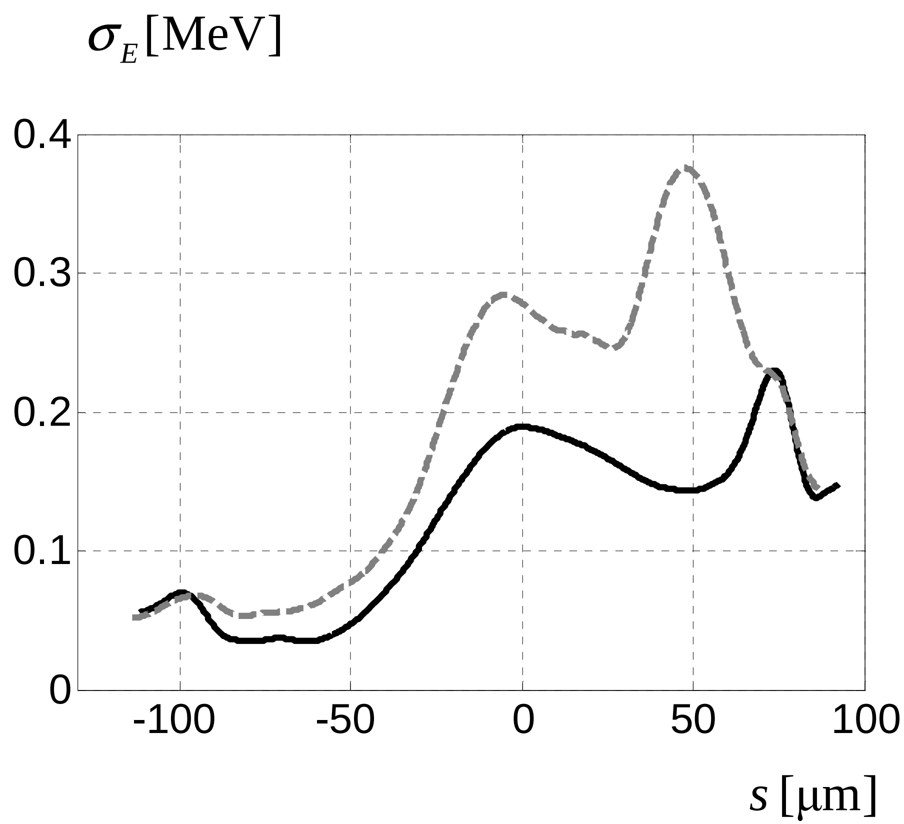




Comparison with Elegant

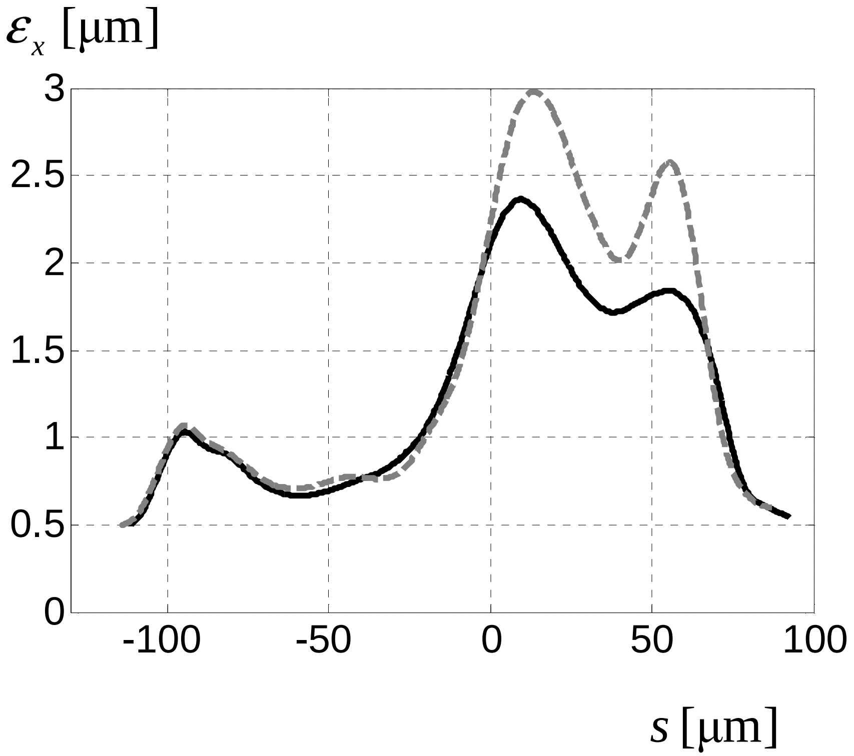
Elegant vs ASTRA with self-fields

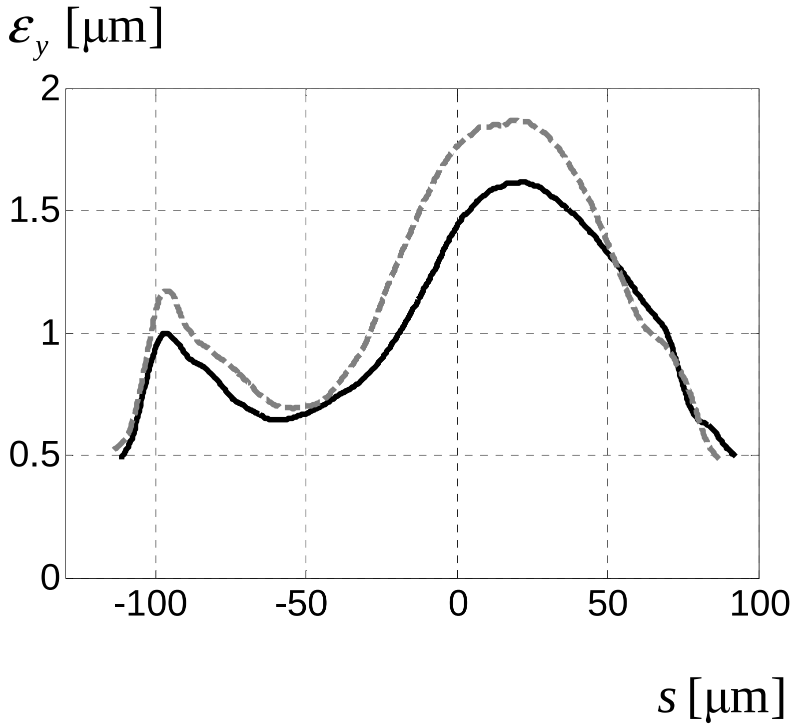




Comparison with Elegant

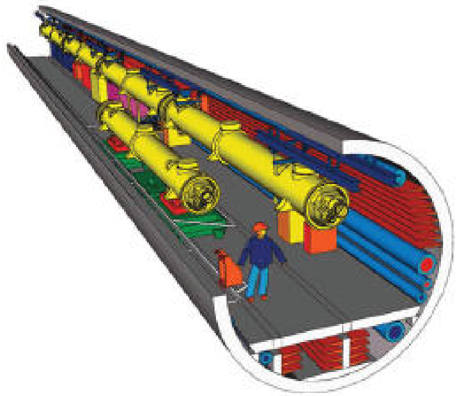
Elegant vs ASTRA with self-fields

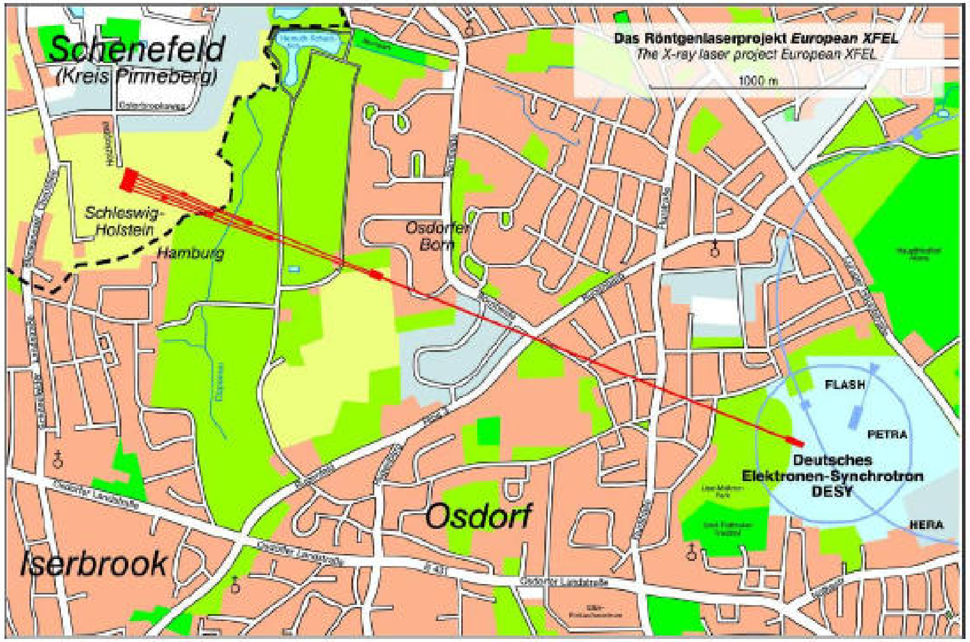


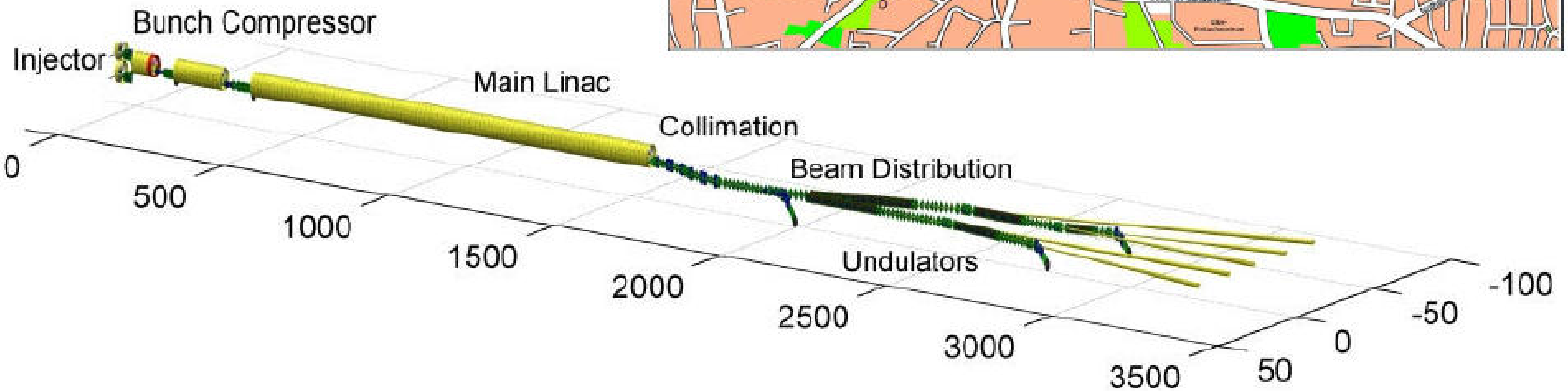


Layout and Machine Parameters of EXFEL

European XFEL







Layout and Machine Parameters of EXFEL

June 2007: Official project start announced on basis of start version at 850M€/y2005 construction cost

Early 2009: Start of construction

30.11.2009: Signing of international state treaty which provides the basis for the foundation of the **European XFEL GmbH** in charge of the construction and operation of the XFEL facility

DESY leads the consortium that constructs the accelerator

End 2013: First beam in injector

End 2014: First beam in main linac

End 2015: Ready for users

Accelerator Challenges at the European XFEL

Winfried Decking (DESY)
LBNL, May 5 2011

Layout and Machine Parameters of EXFEL

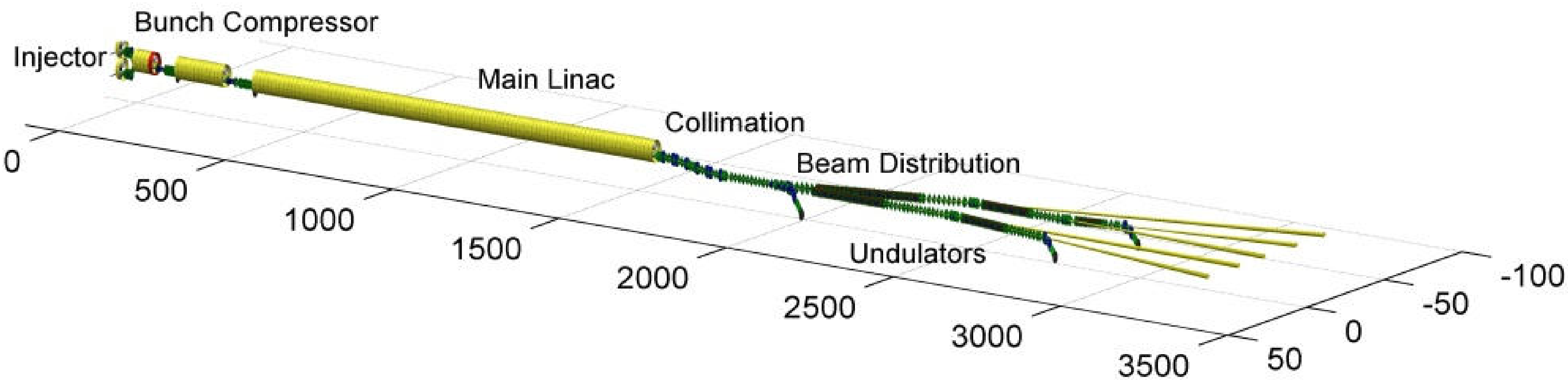
	Baseline	New Parameter Set
Electron Energy	17.5 GeV	10.5/14/17.5 GeV
Bunch charge	1 nC	0.02 - 1 nC
Peak current	5 kA	2 - 5 kA
Slice emittance	< 1.4 mm mrad	0.4 - 1.0 mm mrad
Slice energy spread	1.5 MeV	4 - 2 MeV
Shortest SASE wavelength	0.1 nm	0.05 nm
Pulse repetition rate	10 Hz	10 Hz
Bunches per pulse	3000	2700

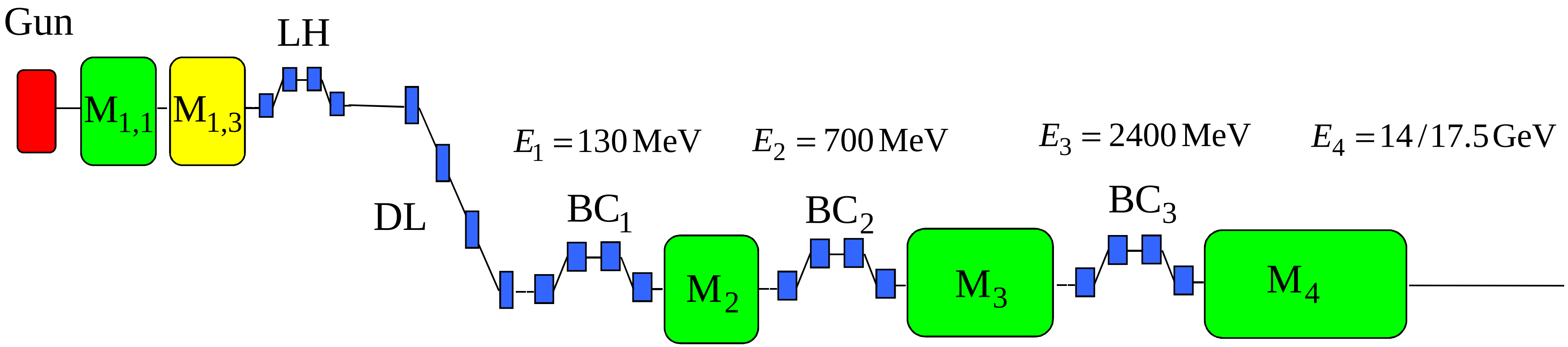
Accelerator Challenges at the European XFEL

Winfried Decking (DESY)
LBNL, May 5 2011

Layout and Machine Parameters of EXFEL

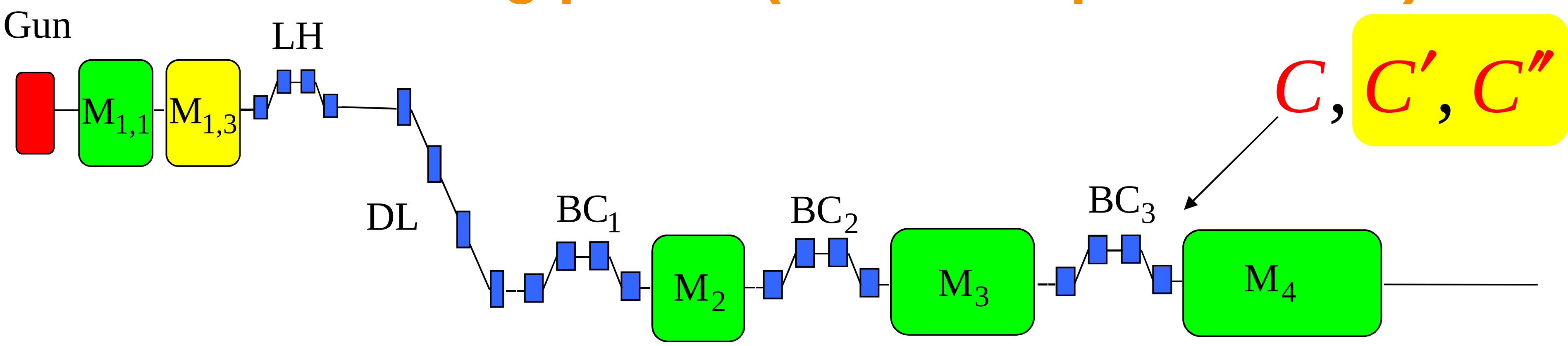
Layout





Layout and Machine Parameters of EXFEL

Working points (11 macro-parameters)



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

$R_{56,1} = ?$ $\quad R_{56,2} = ?$ $\quad R_{56,3} = ?$

$C_1 = ?$ $\quad C_2 = ?$

What is the optimal choice?

Layout and Machine Parameters of EXFEL

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

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

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

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

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

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

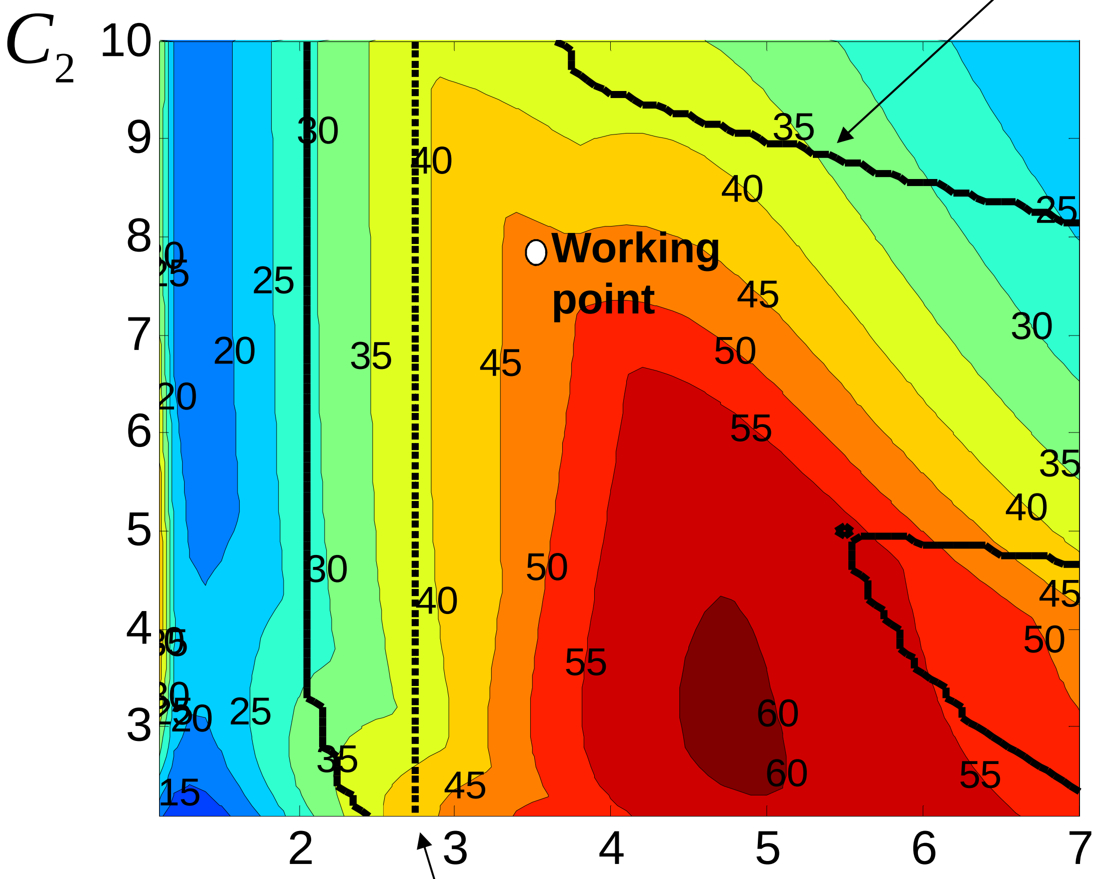
$$if \quad r^0_{56(i)} > \max(r_{56(i)}), \quad then \quad r^0_{56(i)} = \max r_{56(i)}$$

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

Layout and Machine Parameters of EXFEL

RF tolerance

Maximal RF voltage



C_1

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

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

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

Nominal Scenarios of EXFEL

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	2100	0	1000

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

Nominal Scenarios of EXFEL

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	154	15.9	24.8	185.6	661	30.4	1824	21.1
0.25	159	19.4	26.6	190.4	652	29	1860	23.9
0.1	160	19.2	27	187.8	645	27.9	1887	25.7
0.02	158	17	28	181.9	640	27.1	1893	26.1

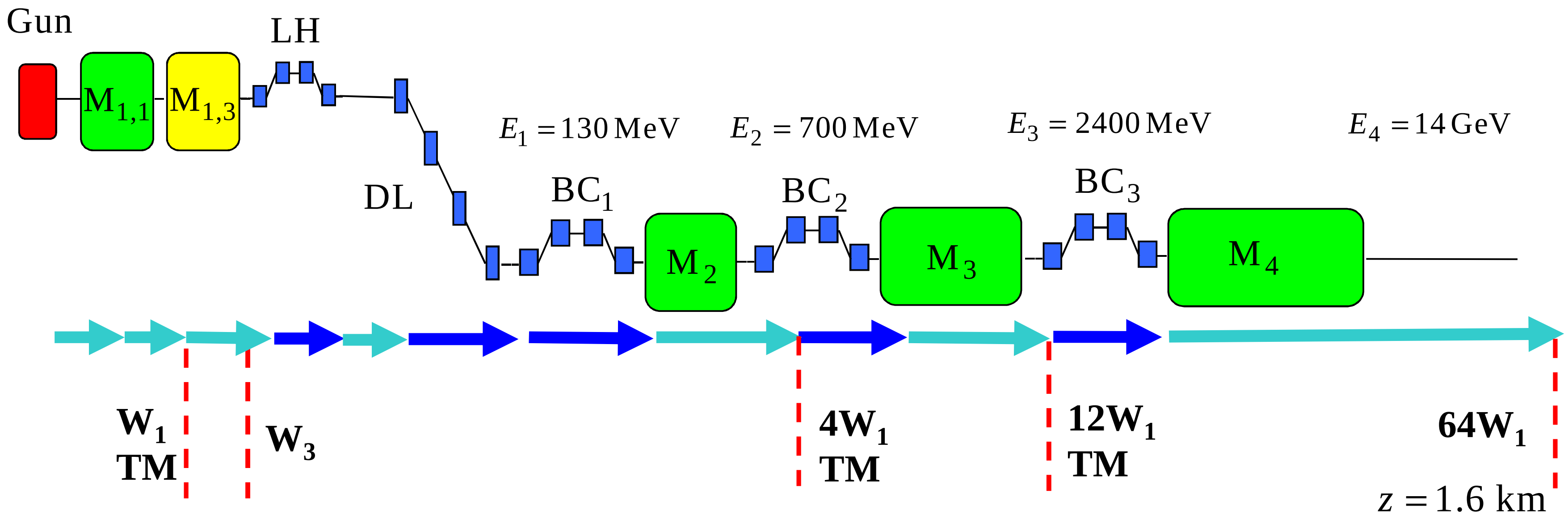
Tolerances (analytically 10 % change of C)

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	5e-5

Nominal Scenarios of EXFEL

Beam dynamics simulation

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)

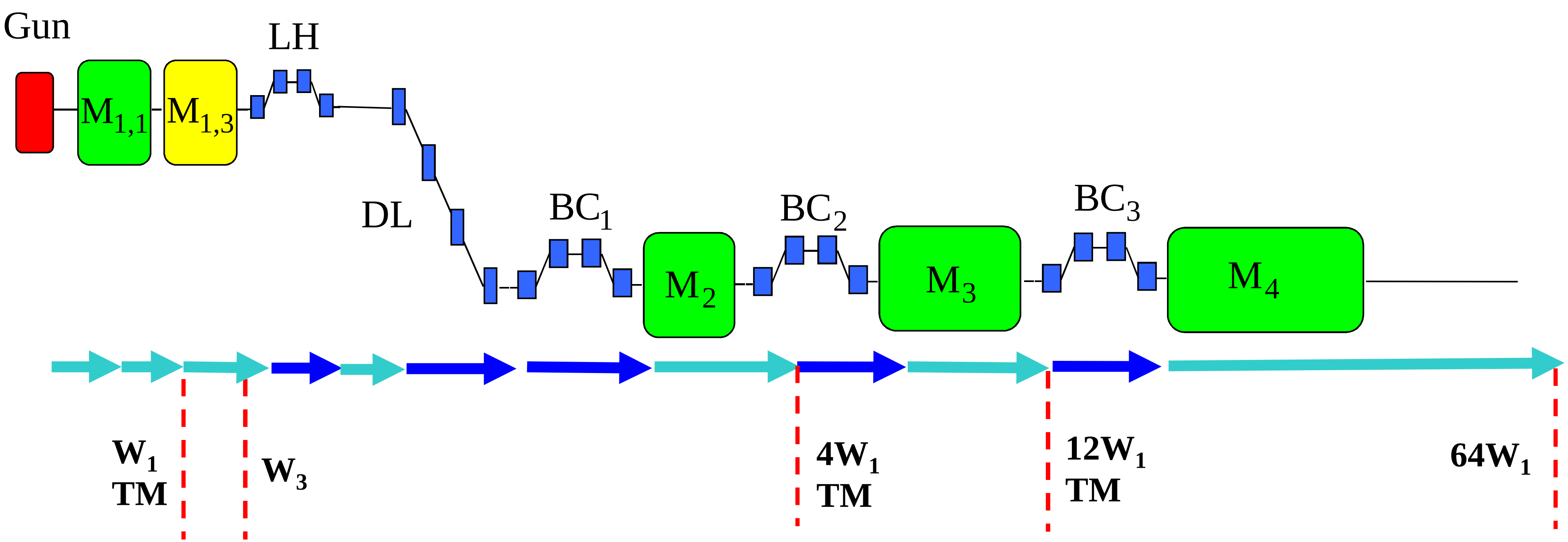
W3 - ACC39 wake (TESLA Report 2004-01, DESY, 2004)

TM - transverse matching to the design optics

Nominal Scenarios of EXFEL

Beam dynamics simulation

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

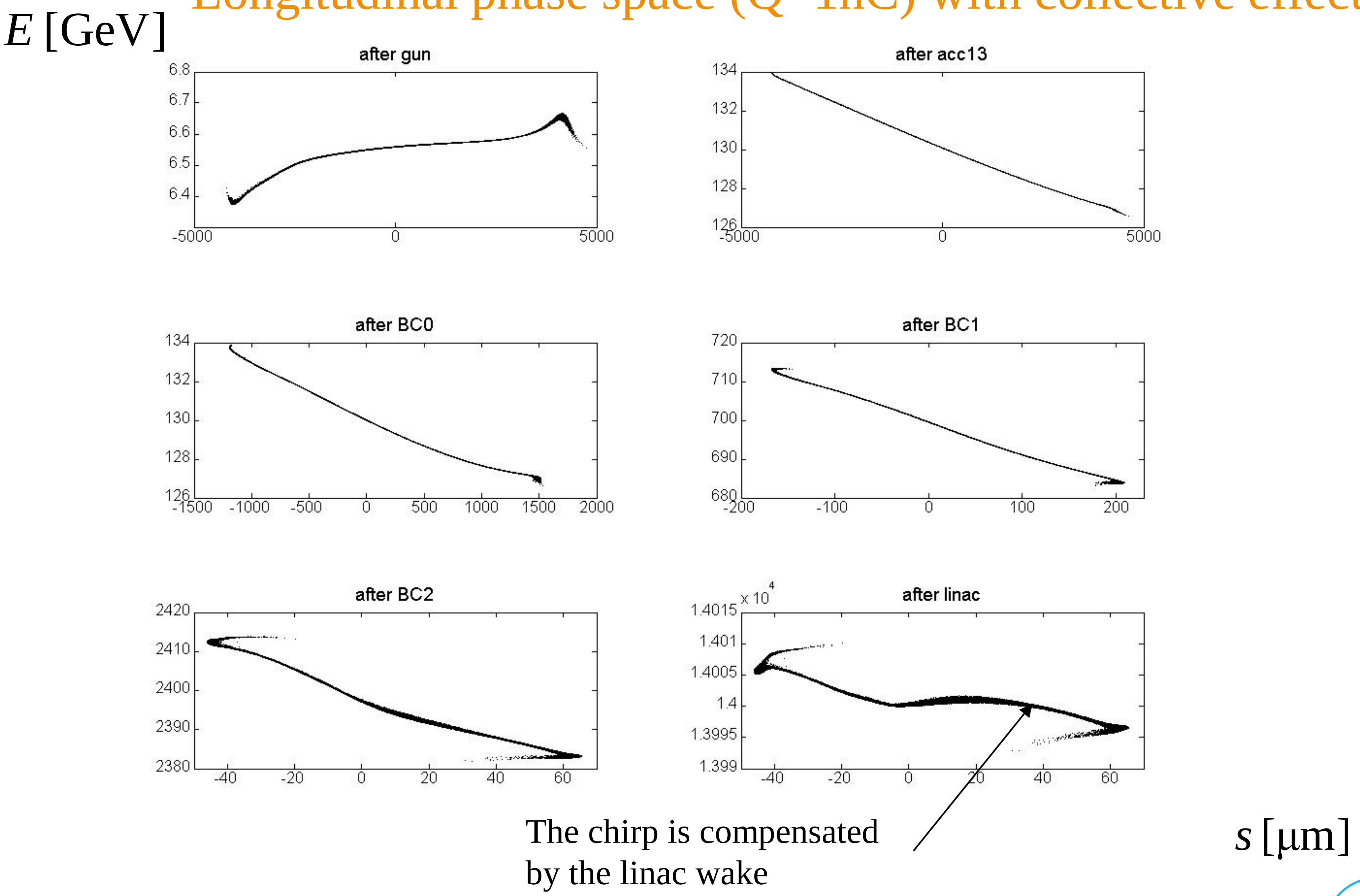


Transport Matrix + analytical longitudinal space charge wake

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

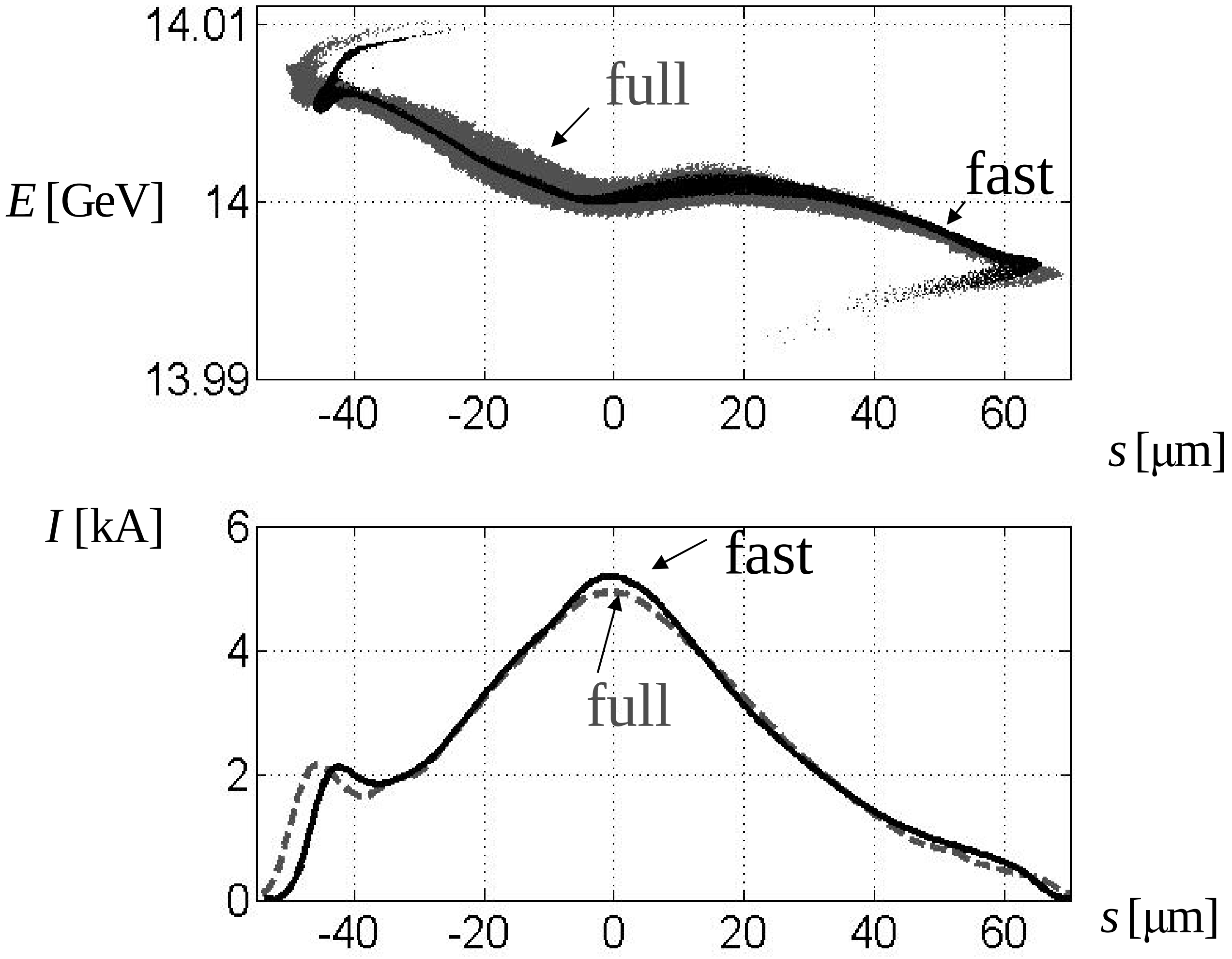
Nominal Scenarios of EXFEL

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



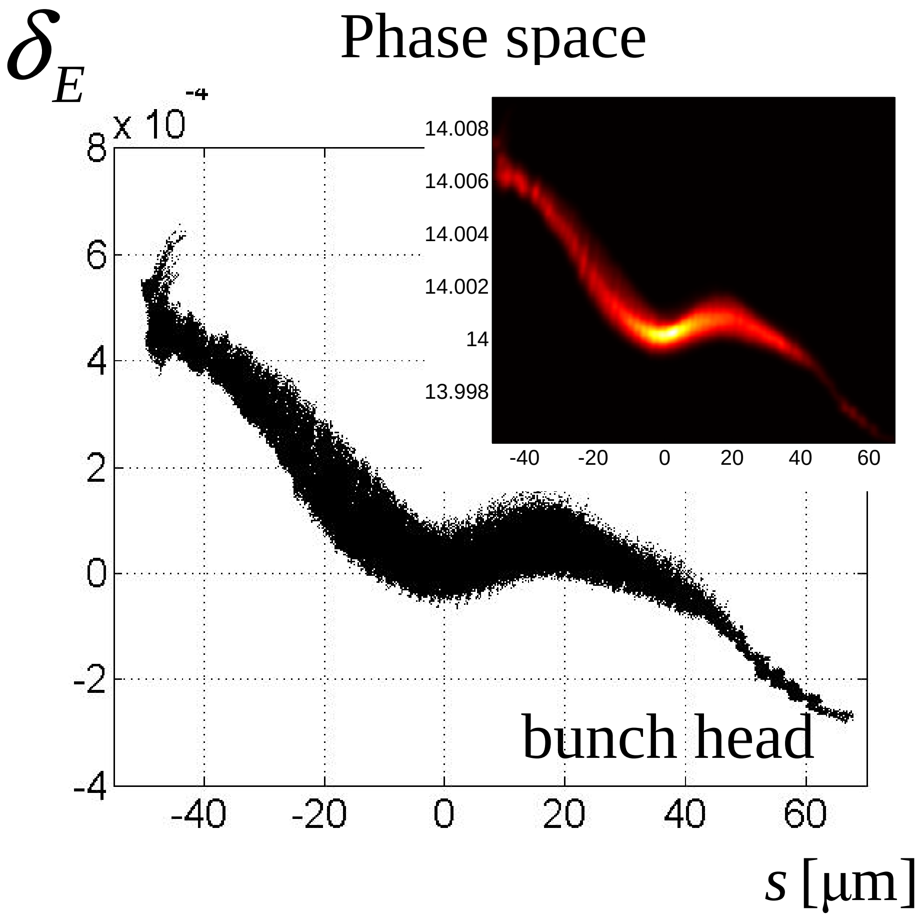
Nominal Scenarios of EXFEL

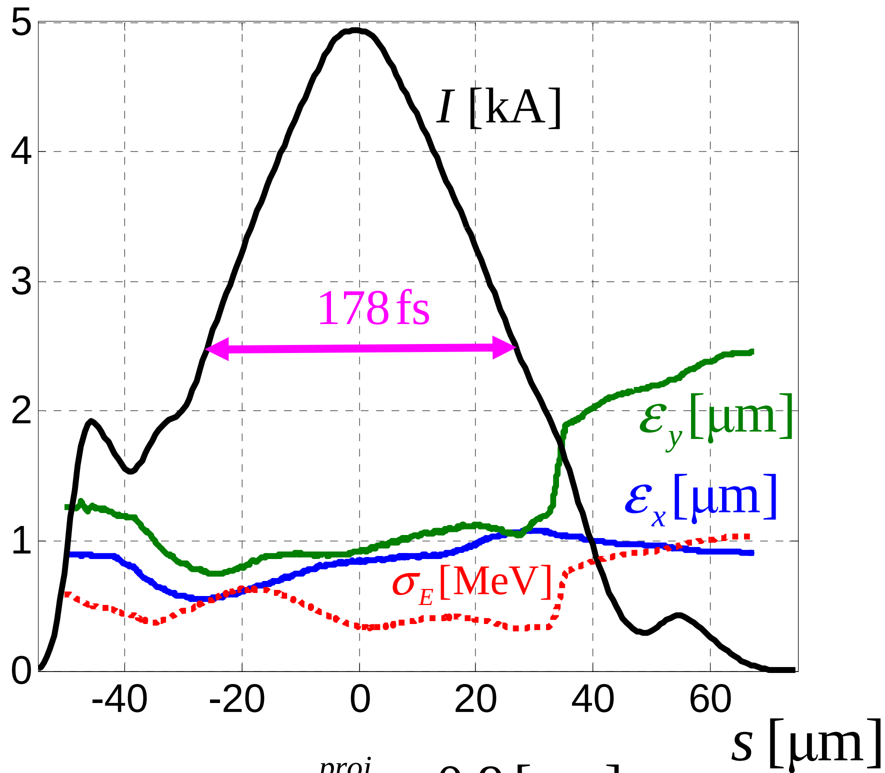
Cross-check of the models (**fast** vs. **full**),
Q=1nC with collective effects



Nominal Scenarios of EXFEL

Q=1 nC



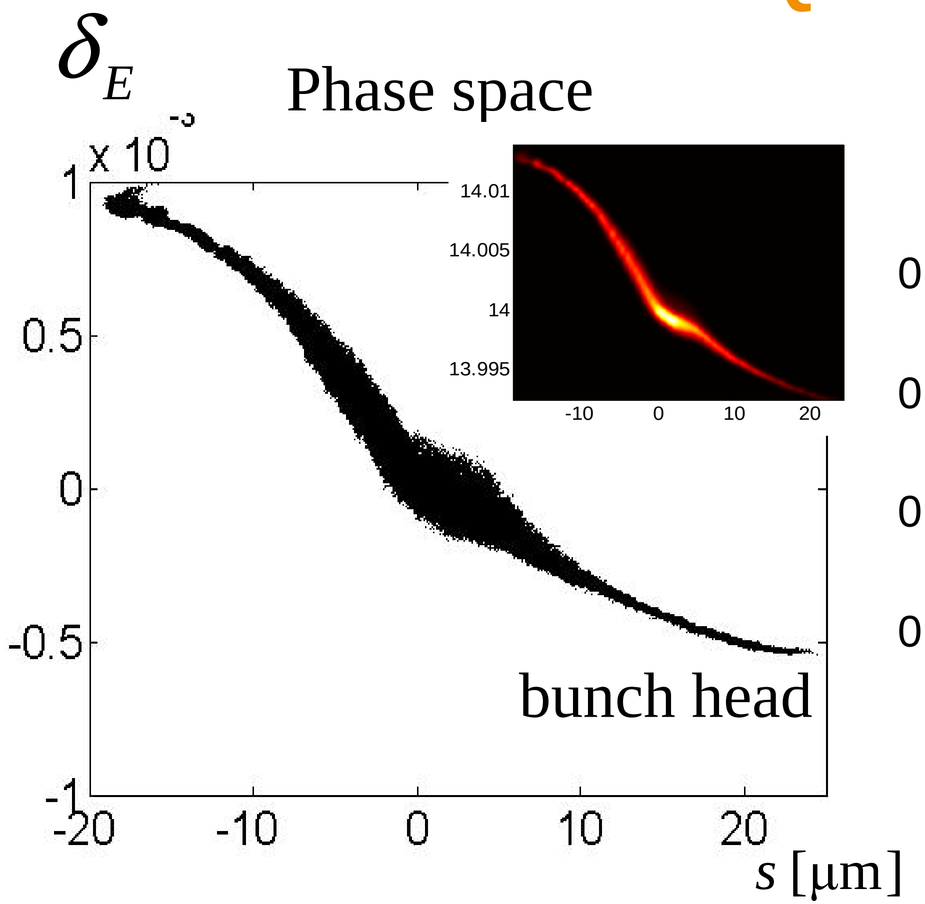


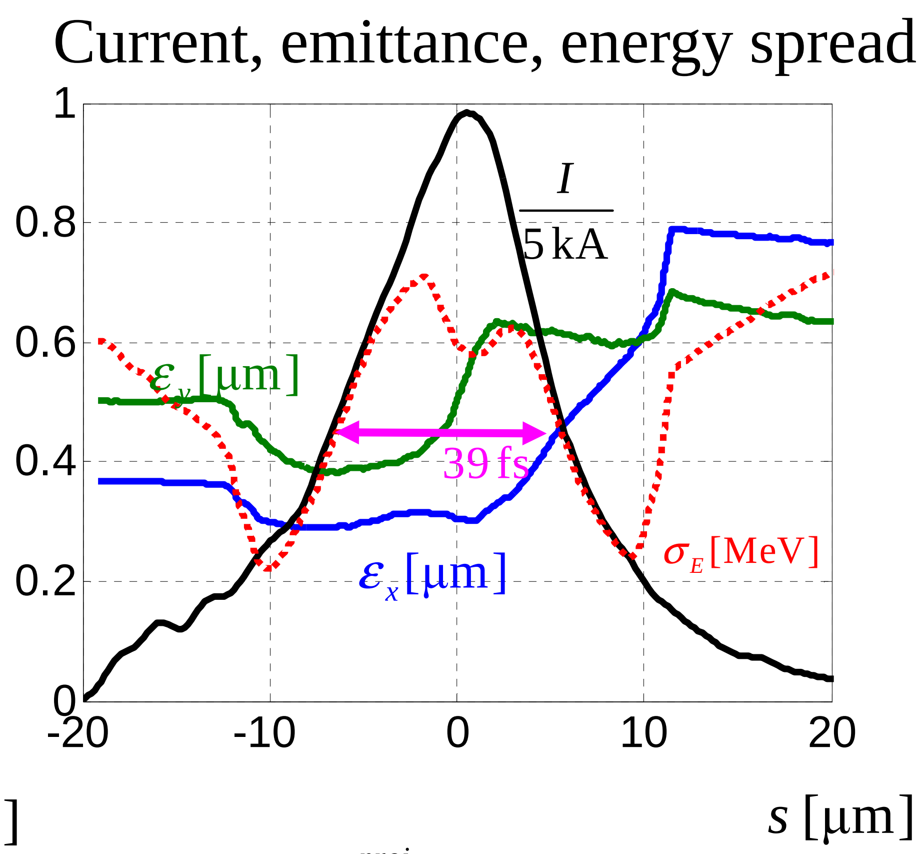
$$\varepsilon_x^{proj} = 0.9\,[\mu m]$$

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

Nominal Scenarios of EXFEL

Q=250 pC



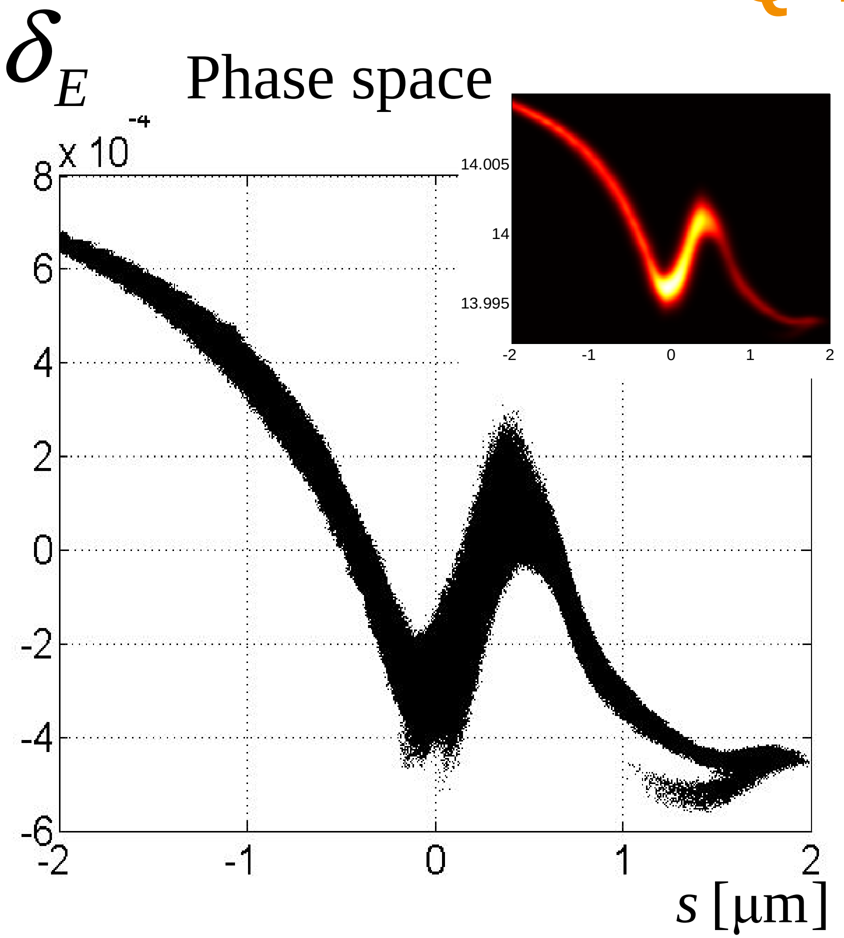


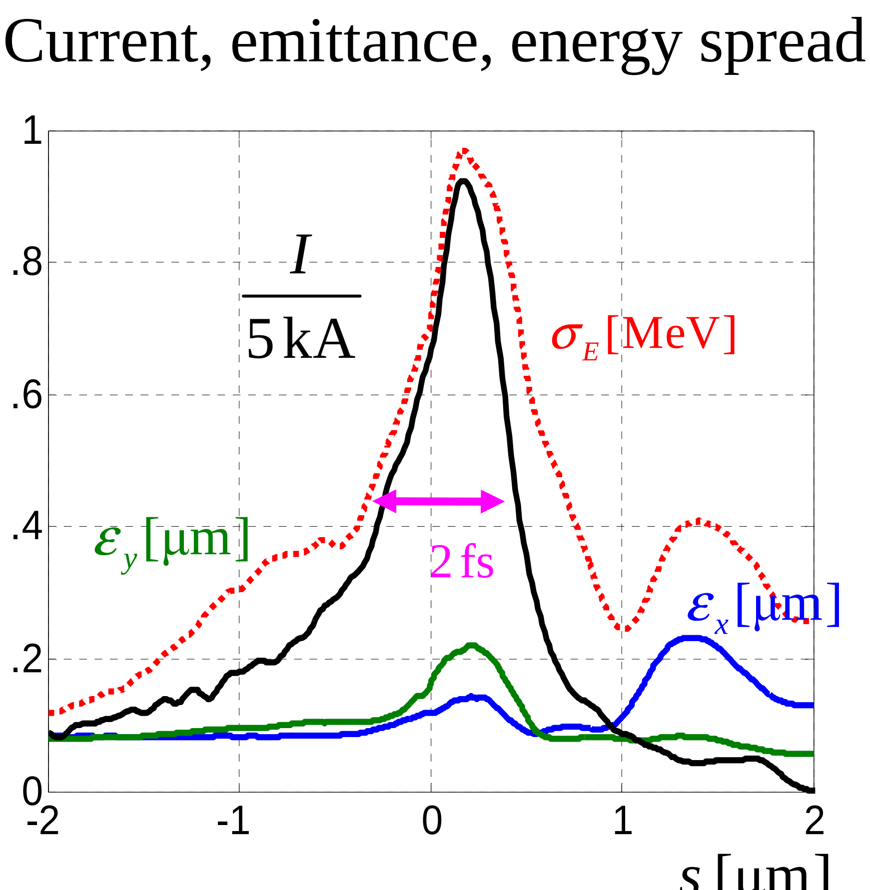
$$\varepsilon_x^{proj} = 0.45\,[\mu m]$$

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

Nominal Scenarios of EXFEL

Q=20 pC





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

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

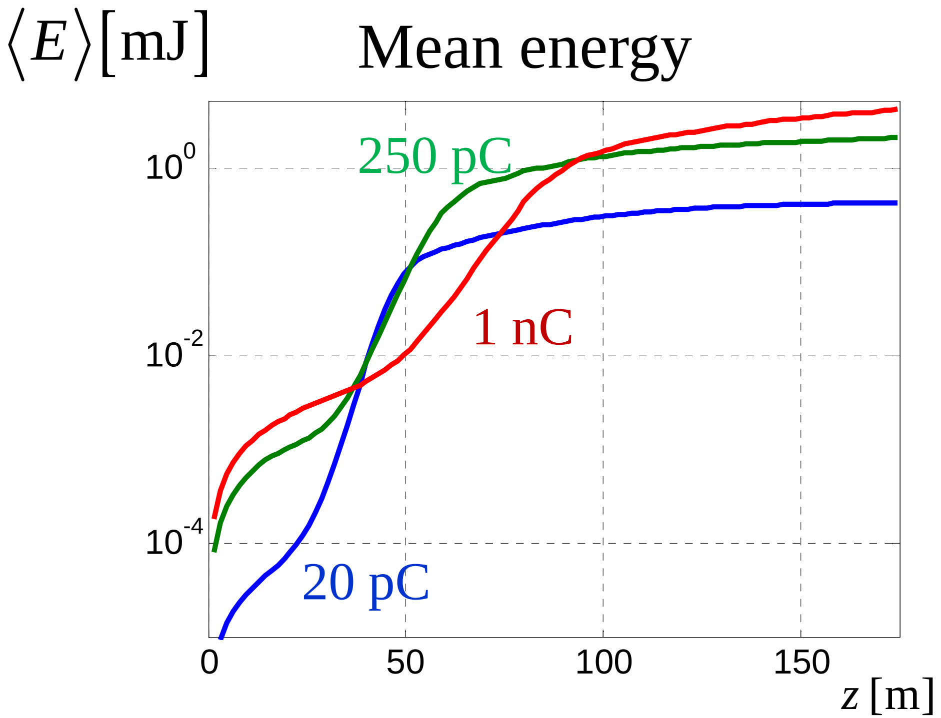
Nominal Scenarios of EXFEL

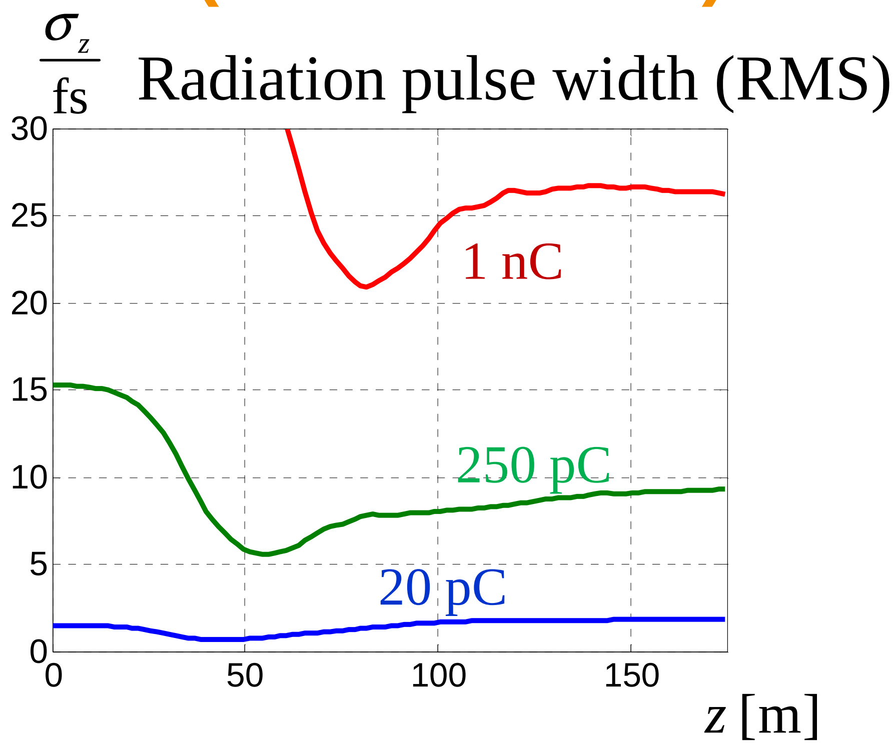
Beam parameters from S2E simulations

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

Nominal Scenarios of EXFEL

Radiation energy statistics (1-25-120 runs)





Charge, nC	1	0.25	0.02
Mean radiation energy, mJ	1-4	1-2	0.1-0.4
Pulse radiation width (FWHM), fs	**25-50**	**10-20**	**1-2**

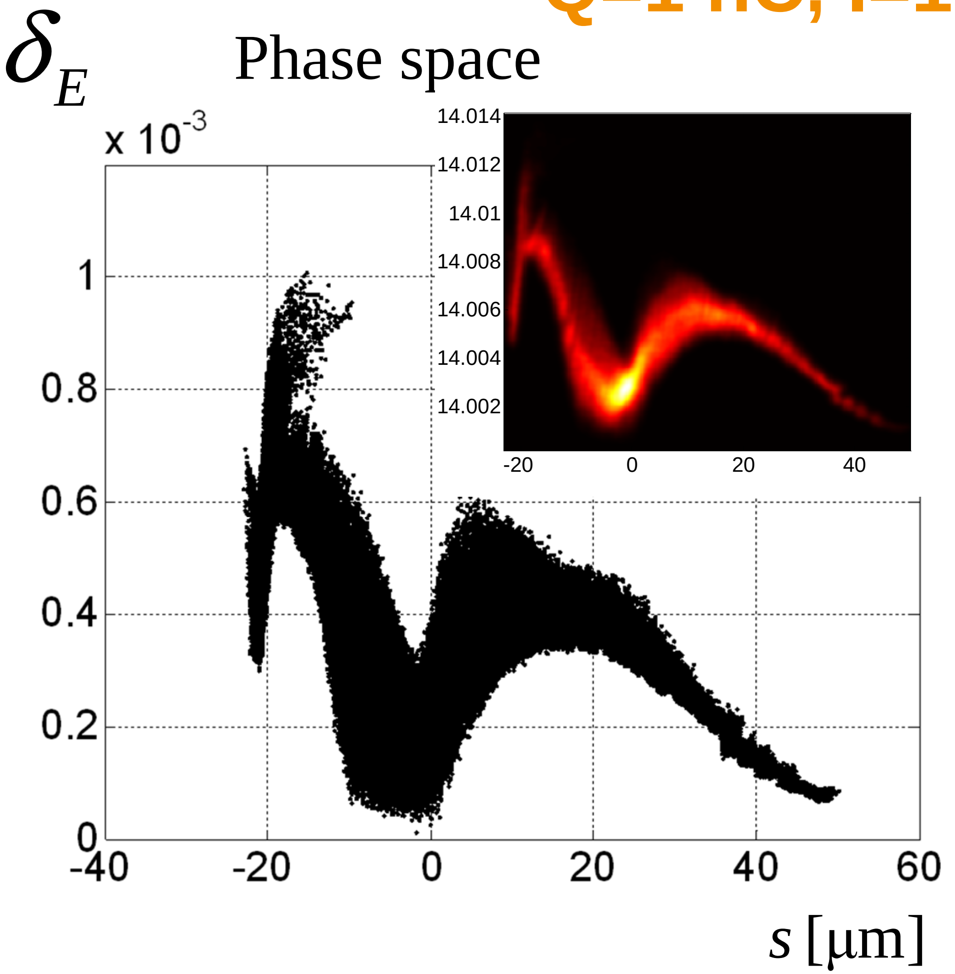
Nominal Scenarios of EXFEL

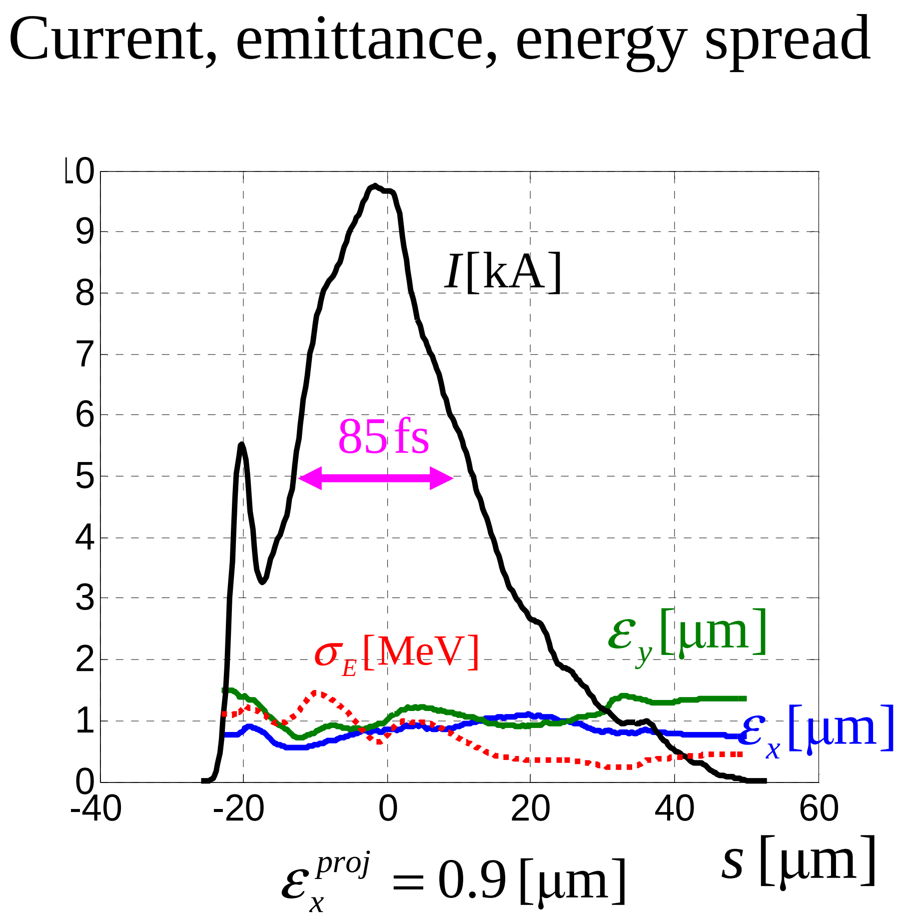
Radiation Properties from S2E

Bunch charge, nC	1	0.25	0.02
Wavelength, nm	0.1		
Beam energy, GeV	14		
Peak current, kA	**~ 5**		
Slice emmitance,mm-mrad	**1**	**0.5**	**0.2**
Saturation length, m	**85**	**60**	**45**
Energy in the rad. pulse, mJ	1-4	1-2	0.1-0.4
Radiation pulse duration FWHM, fs	**25-50**	**10-20**	**1-2**
Averaged peak power, GW	**10-50**	**10-100**	**50-150**
Spectrum width, %		0.15-0.3	0.18-0.5

Strong Compression

Q=1 nC, I=10kA





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

$$\varepsilon_y^{proj} = 8\,[\mu m]$$

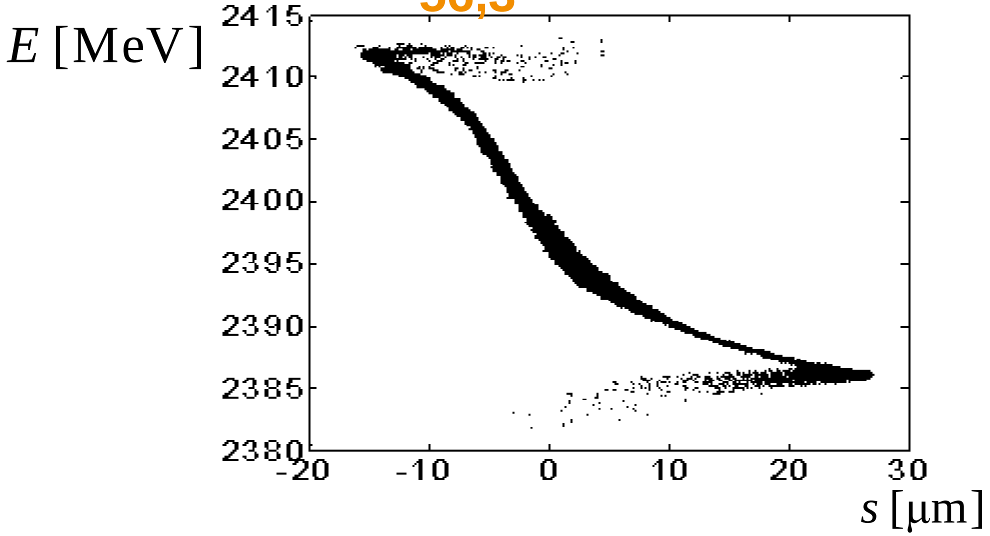
Strong Compression

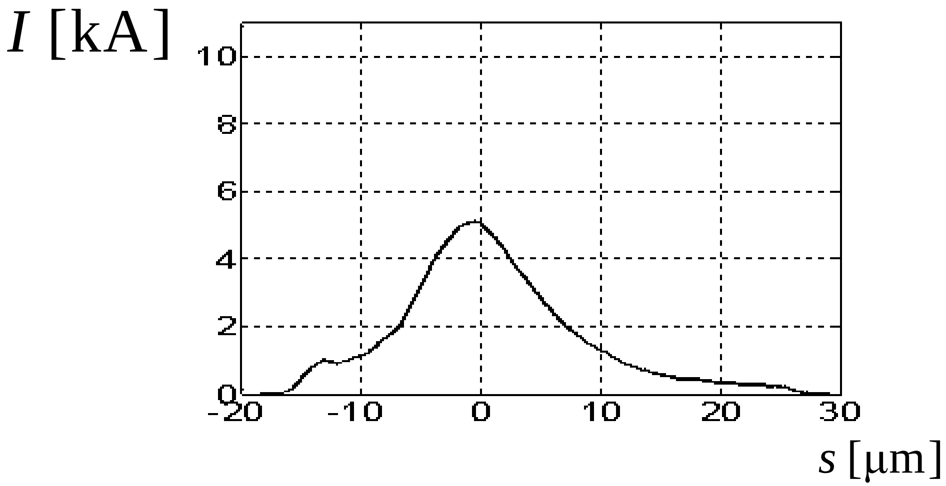
Q=1 nC

Parameter	Unit		
Bunch charge	nC	1	
Peak current (gun)	A	43	
Compression		116	**228**
Peak current	kA	**5**	**9.8**
Bunch length (FWHM)	fs	178	75
Slice emittance	µm	**1**	**1**
Projected emittance	µm	3.5	8
Slice energy spread **(laser heater off)**	MeV	0.45	1

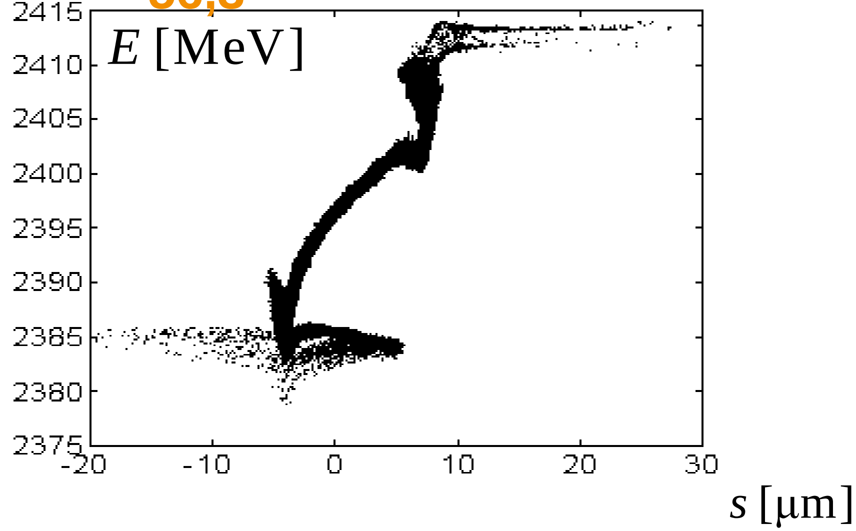
Strong Compression for 250 pC

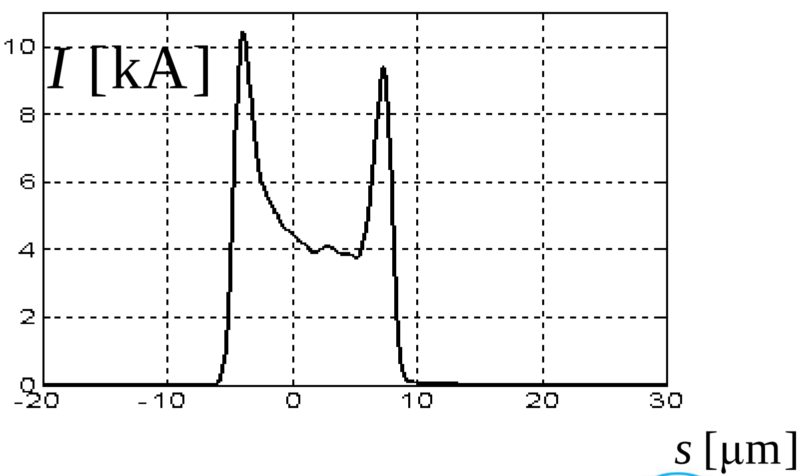
$R_{56,3}$= -20 mm





$R_{56,3}$= -23.8 mm





Strong Compression for 250 pC

Macro-parameters

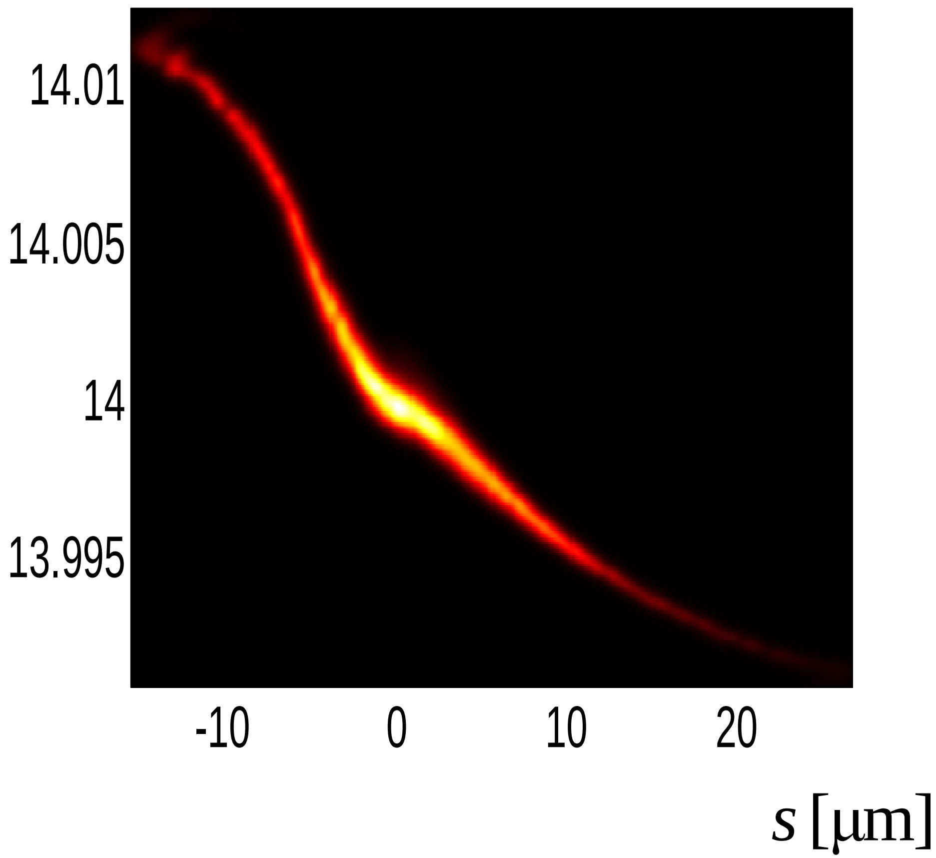
Momentum compaction factor in BC_1 $R_{56,1}$, [mm]	Compr. in BC_1 C_1	Momentum compaction factor in BC_2 $R_{56,2}$, [mm]	Compr. in BC_2 C_2	Momentum compaction factor in BC_3 $R_{56,3}$, [mm]	Total compr. C	Second derivative $(C^{-1})''$, $[m^{-2}]$
-78	3.5	-50	8	**-20,…,-24**	385	1000

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

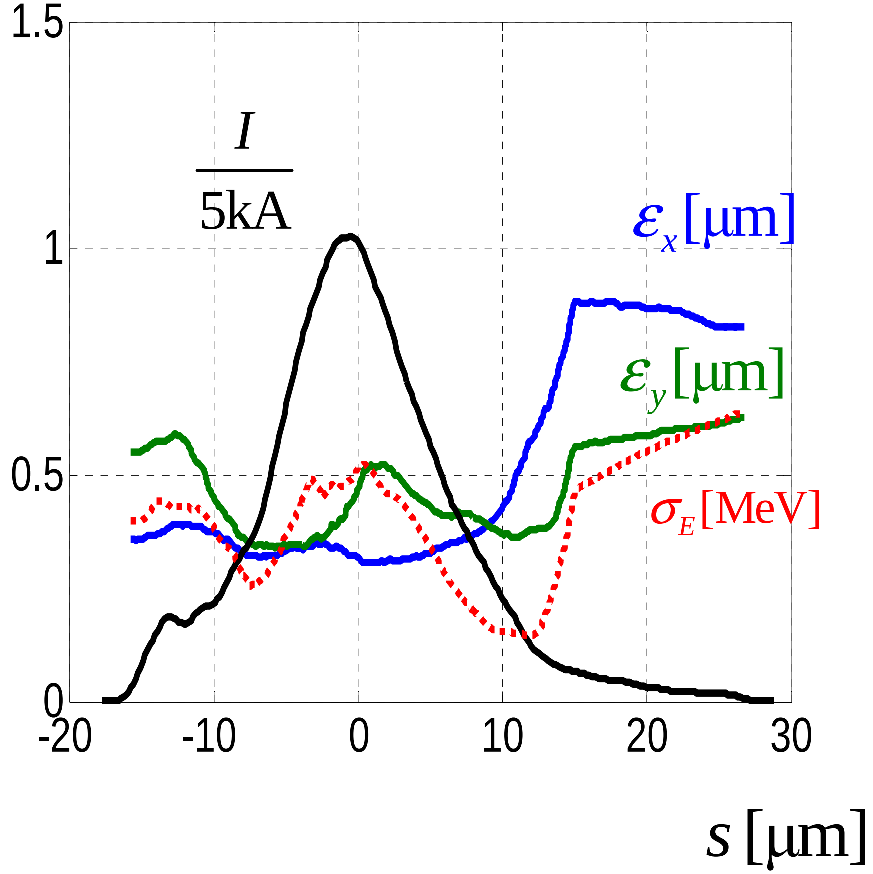
Strong Compression for 250 pC

$R_{56,3}$=-20mm

Phase space

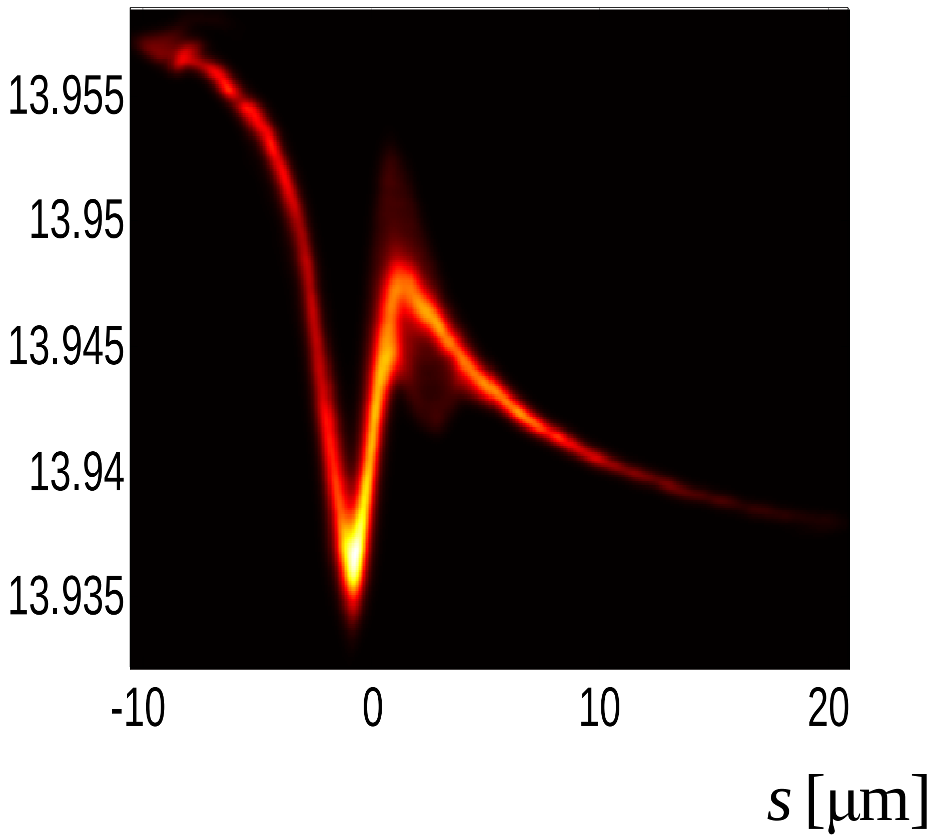


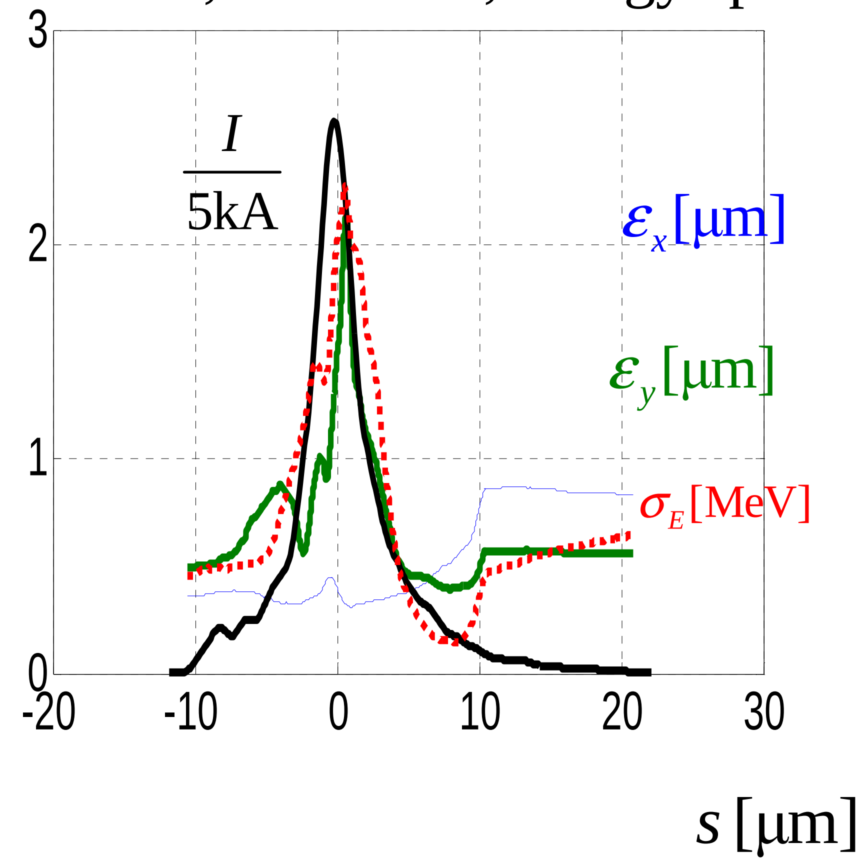
Current, emittance, energy spread



Strong Compression for 250 pC

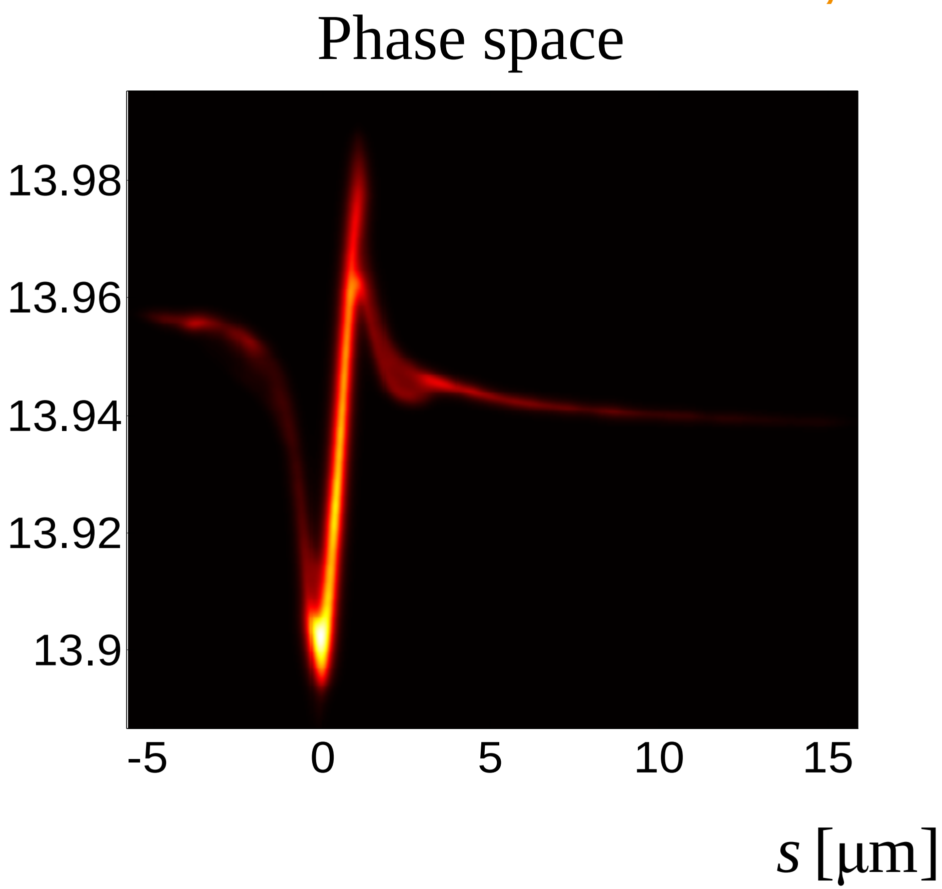
$R_{56,3}$ =-21 mm

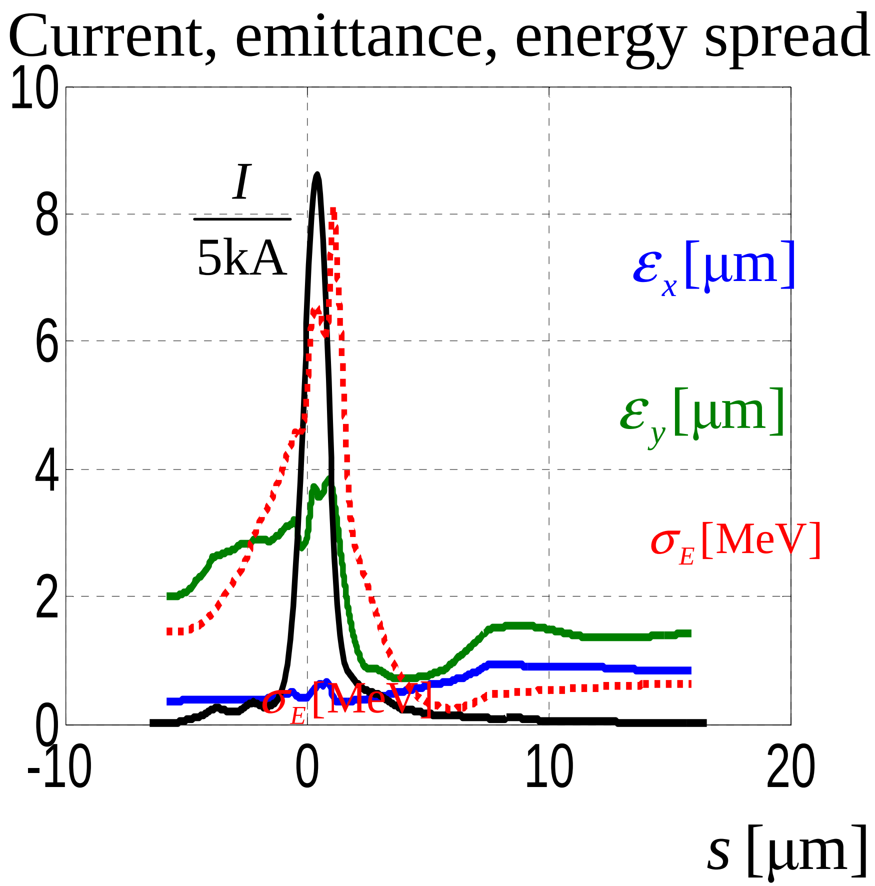




Strong Compression for 250 pC

$R_{56,3}$ =-21.9 mm



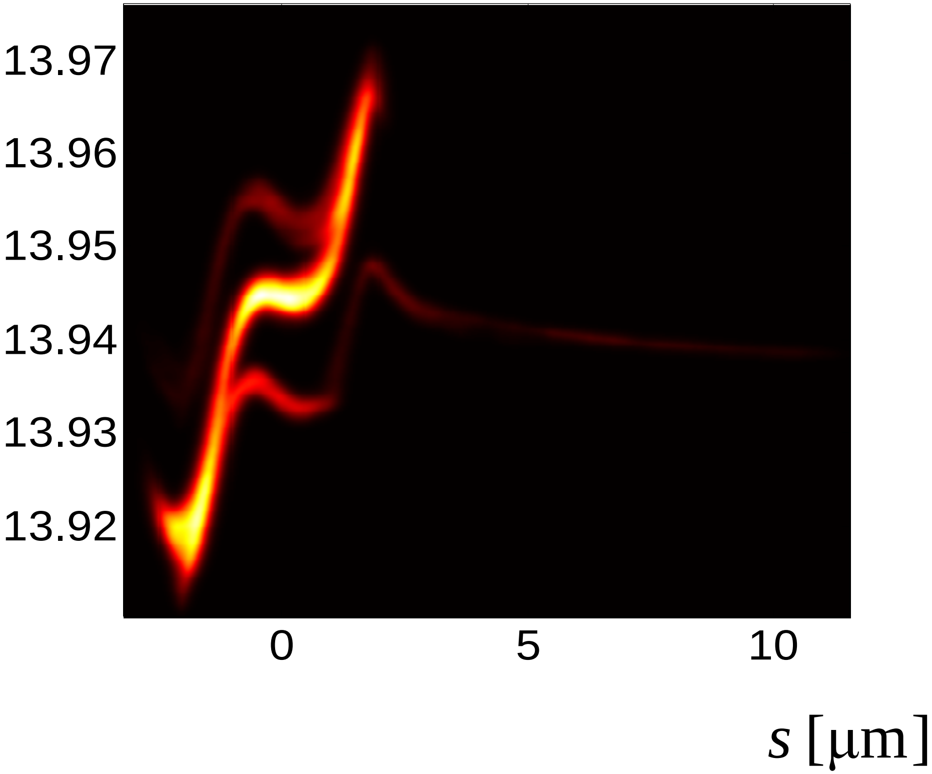


DESY

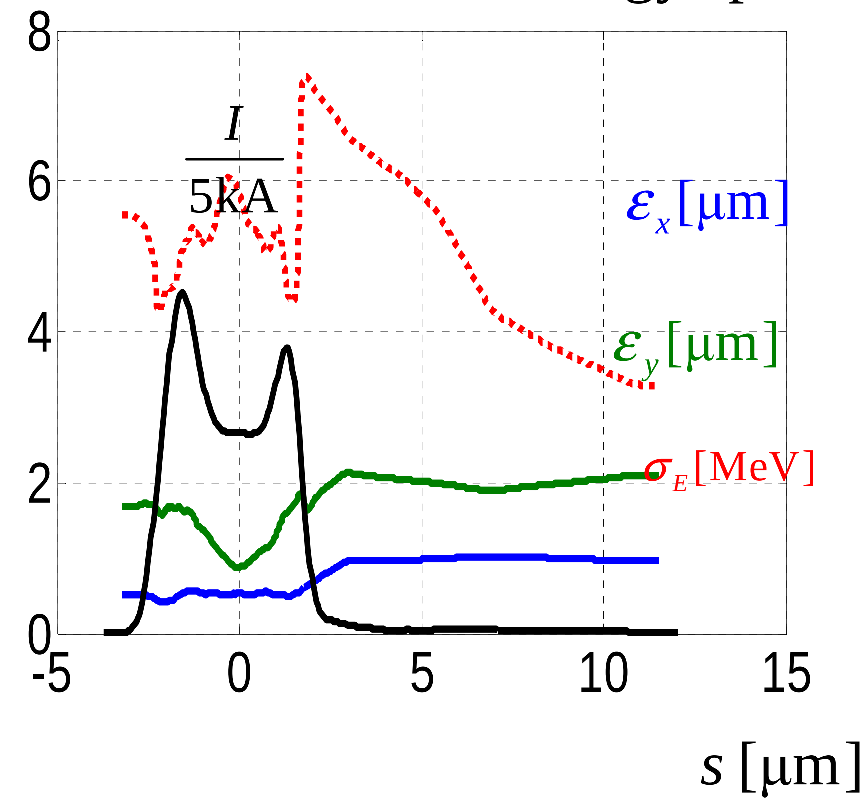
Strong Compression for 250 pC

$R_{56,3}$ =-22.6 mm

Phase space

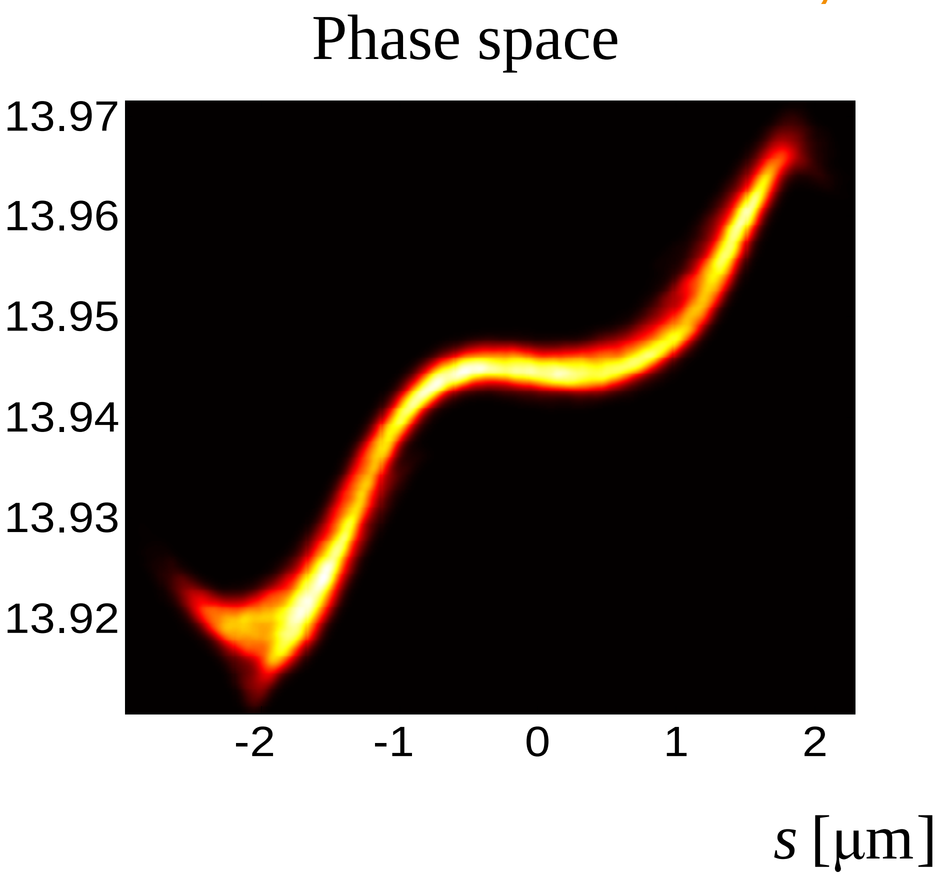


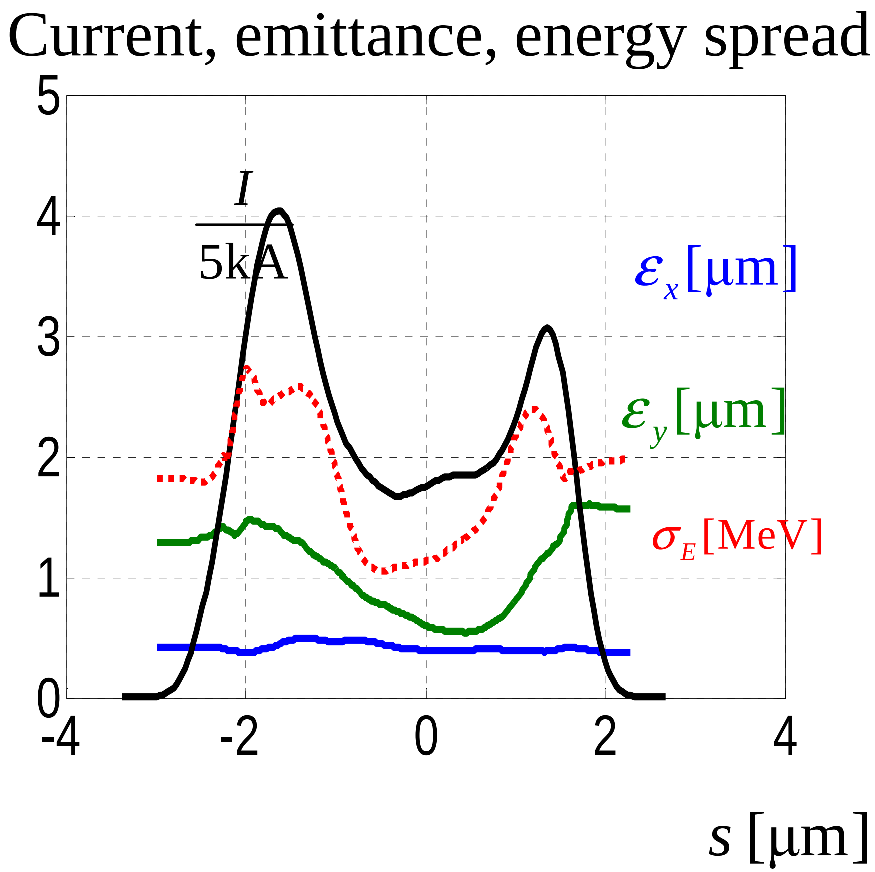
Current, emittance, energy spread



Strong Compression for 250 pC

$R_{56,3}$ =-22.6 mm (70% of particles)

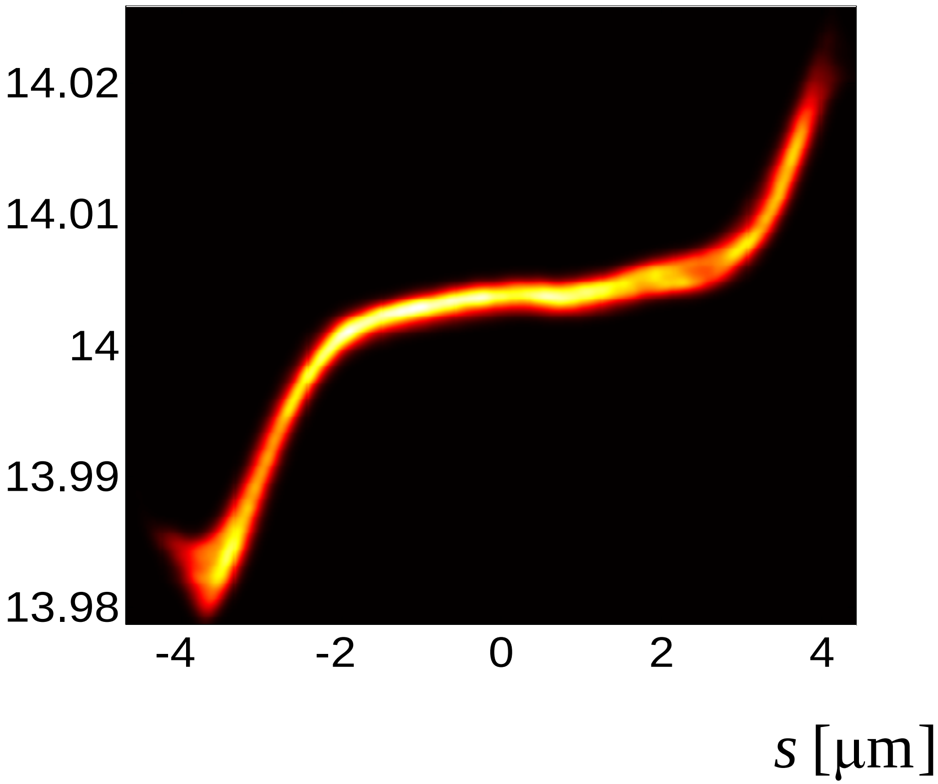




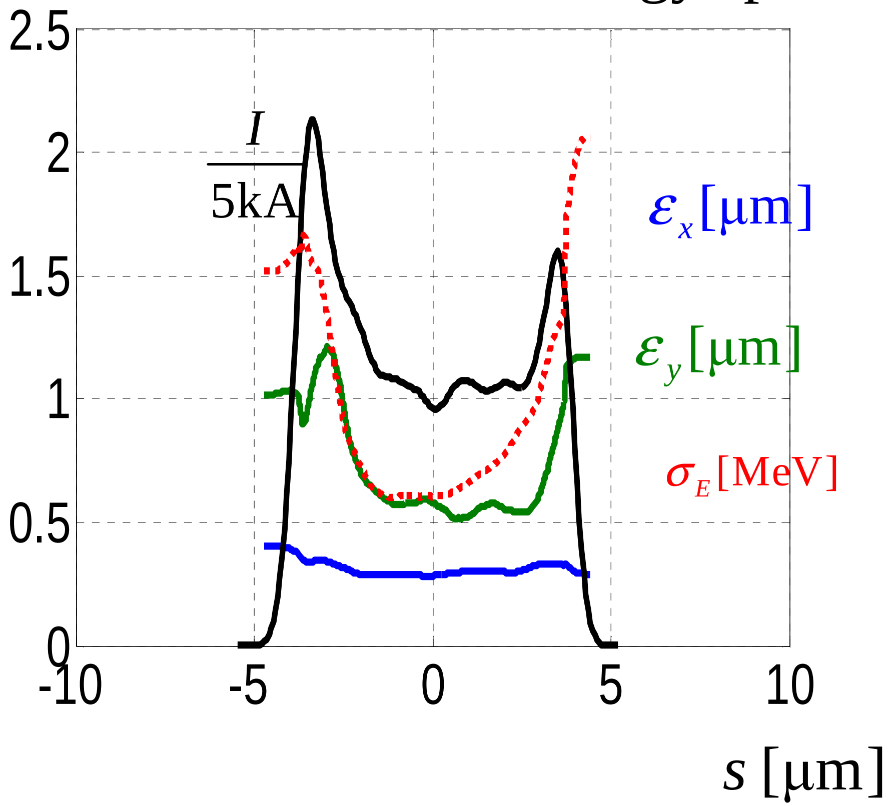
Strong Compression for 250 pC

$R_{56,3}$ =-23.2 mm (70% of particles)

Phase space



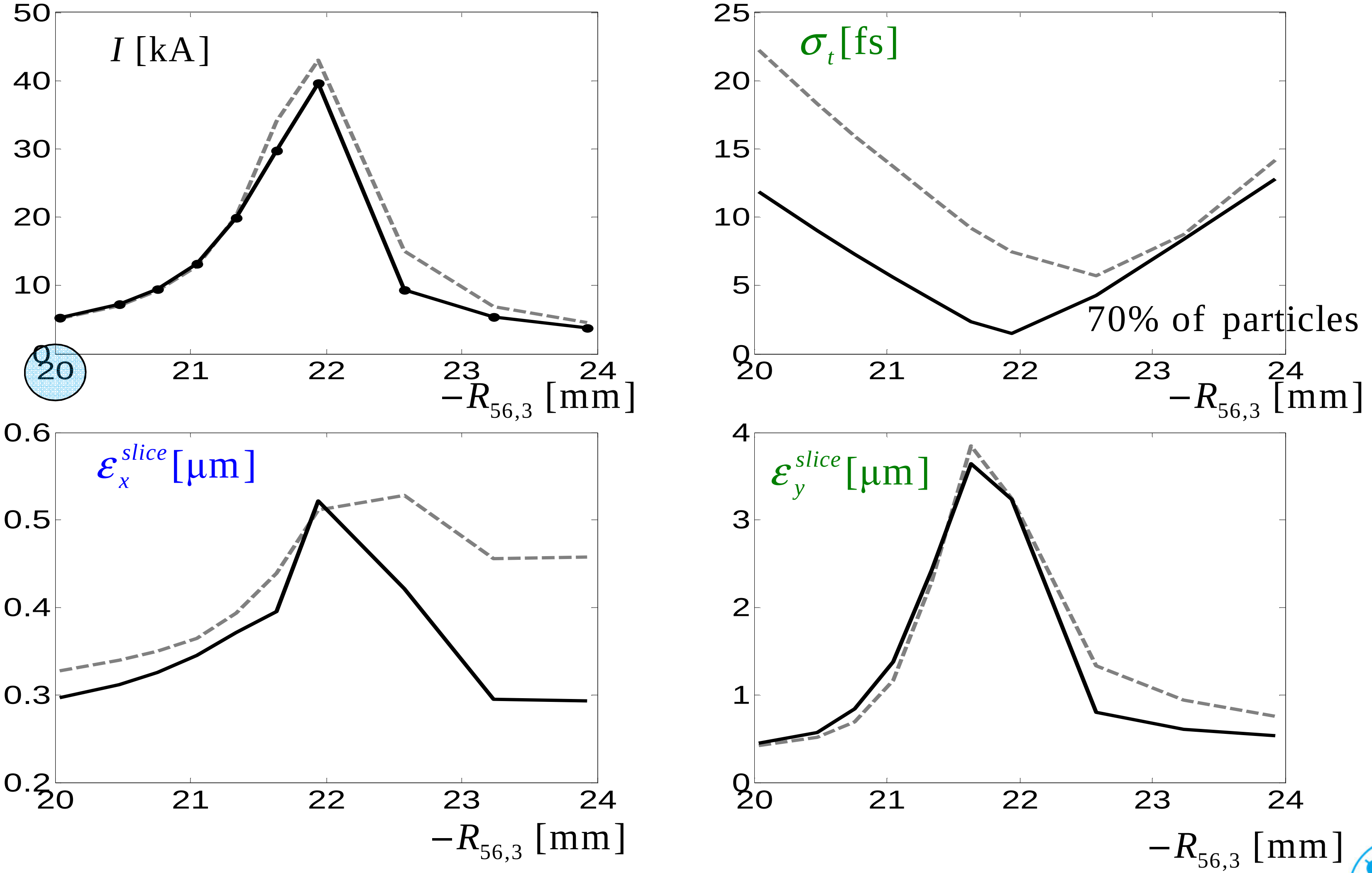
Current, emittance, energy spread



DESY

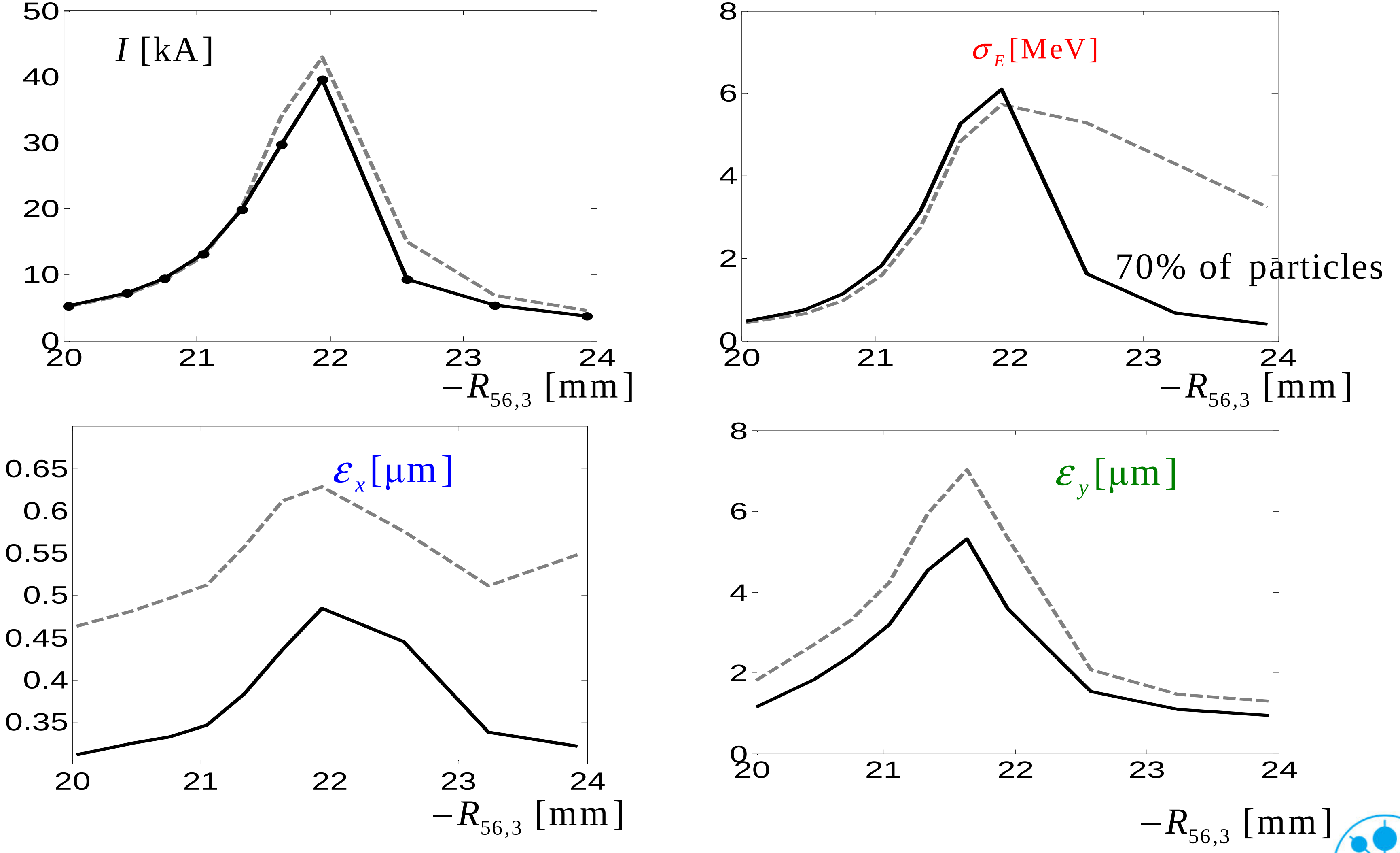
Strong Compression for 250 pC

Beam core parameters vs. R_{56}



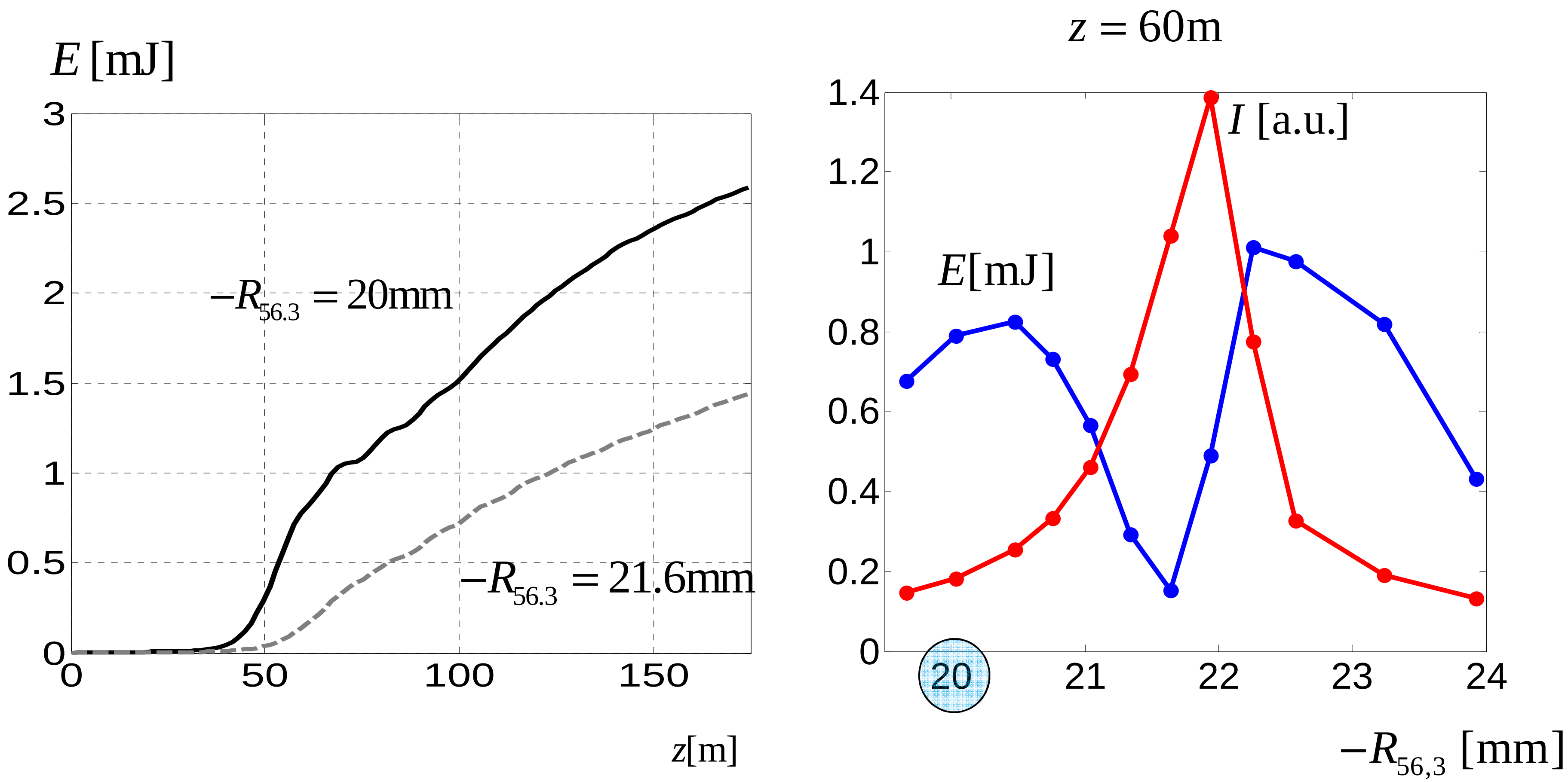
Strong Compression for 250 pC

Beam core parameters vs. R_{56}



Strong Compression for 250 pC

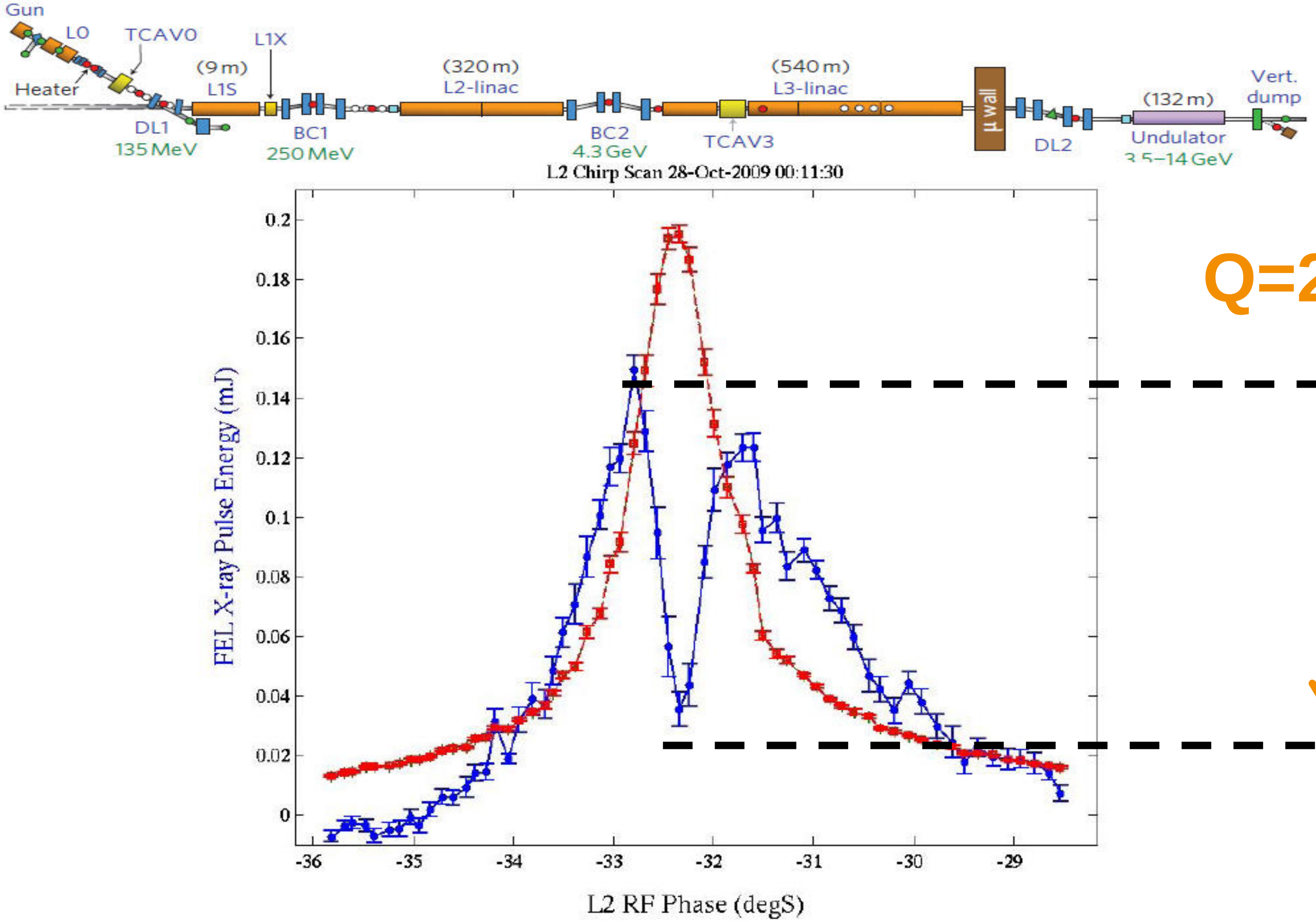
Radiation energy vs. R_{56} (with und. wake and taper)



Strong Compression (SLAC)

SLAC-PUB-14234

FEMTOSECOND OPERATION OF THE LCLS FOR USER EXPERIMENTS*

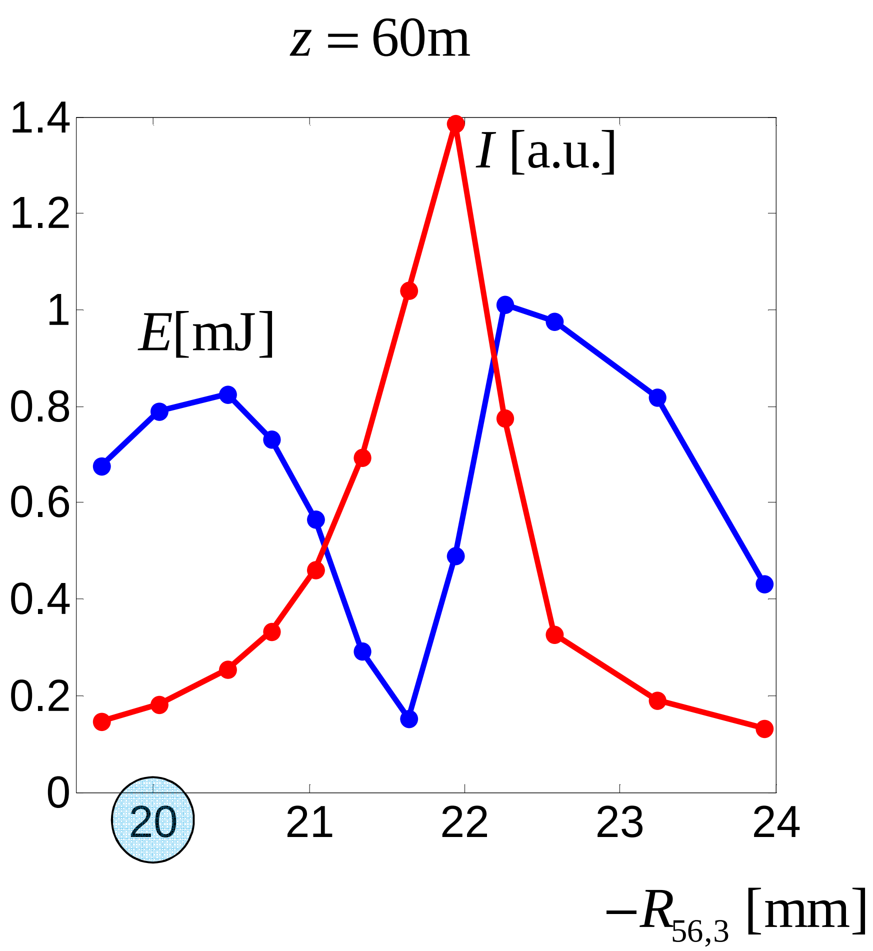


$$\frac{0.15}{0.03} = 5$$

Figure 2: FEL power (blue) and Ipk(red) vs. compression

Strong Compression for 250 pC

Radiation energy vs. compression rate



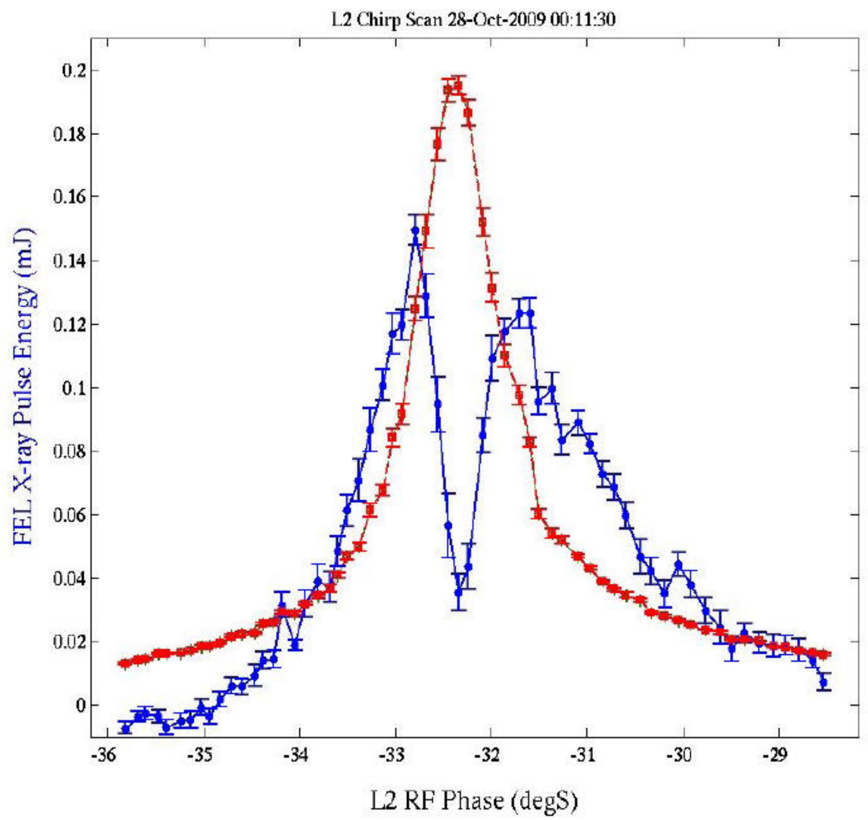
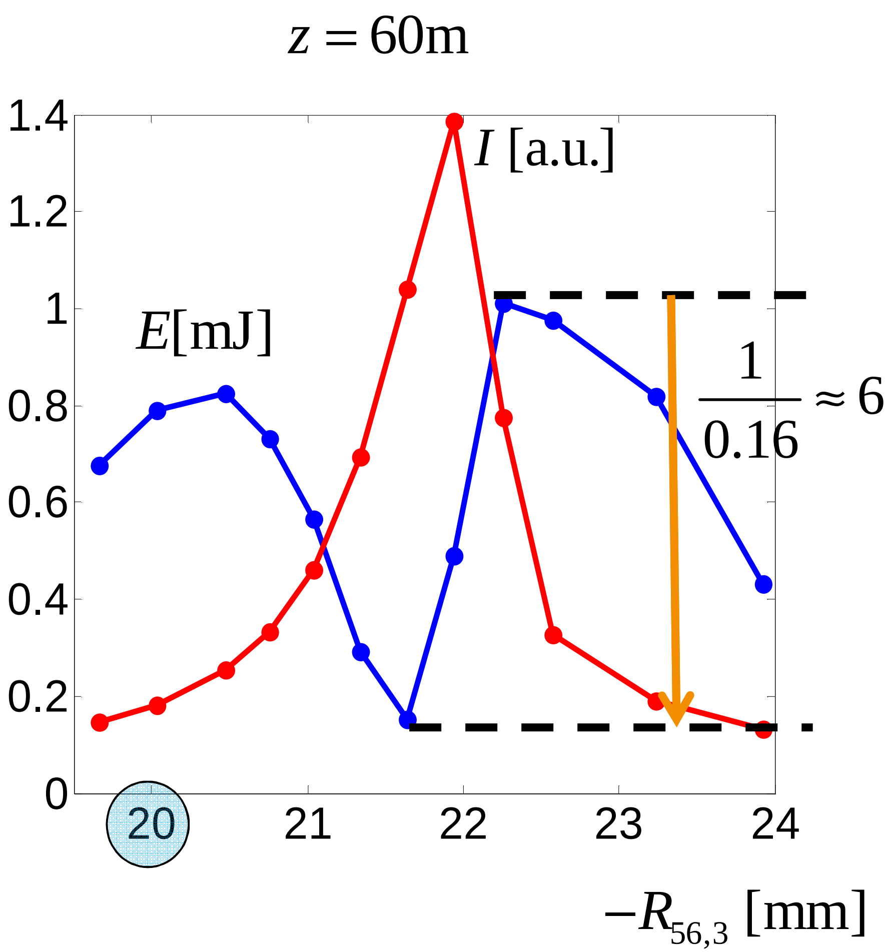


Figure 2: FEL power (blue) and Ipk(red) vs. compression

Strong Compression for 250 pC

Radiation energy vs. compression rate



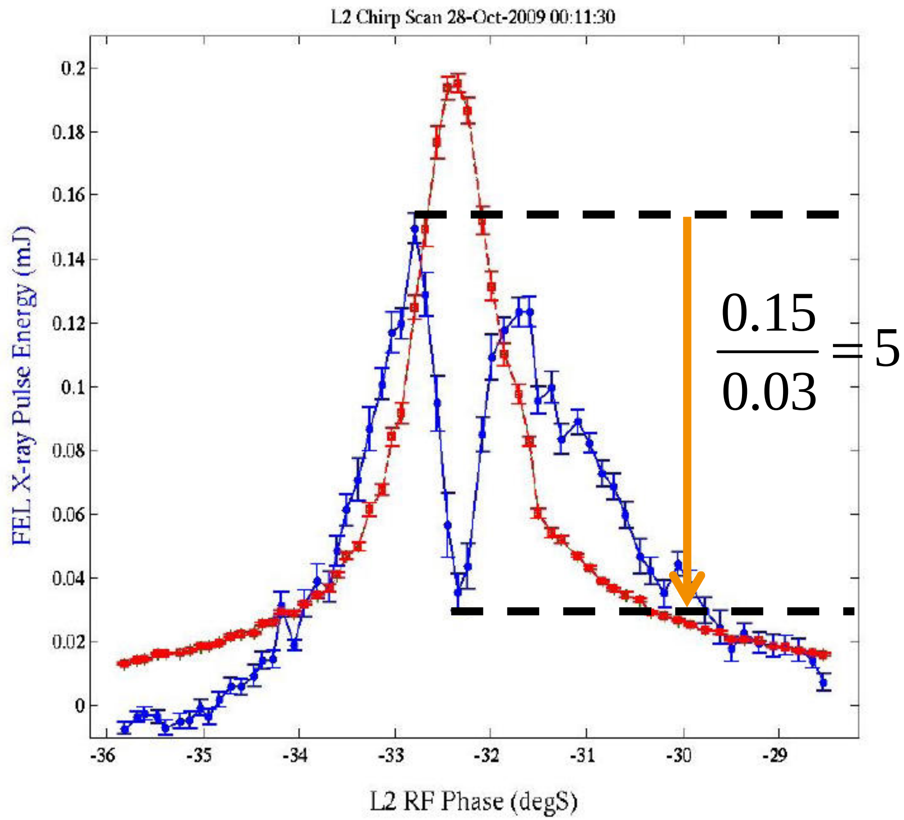
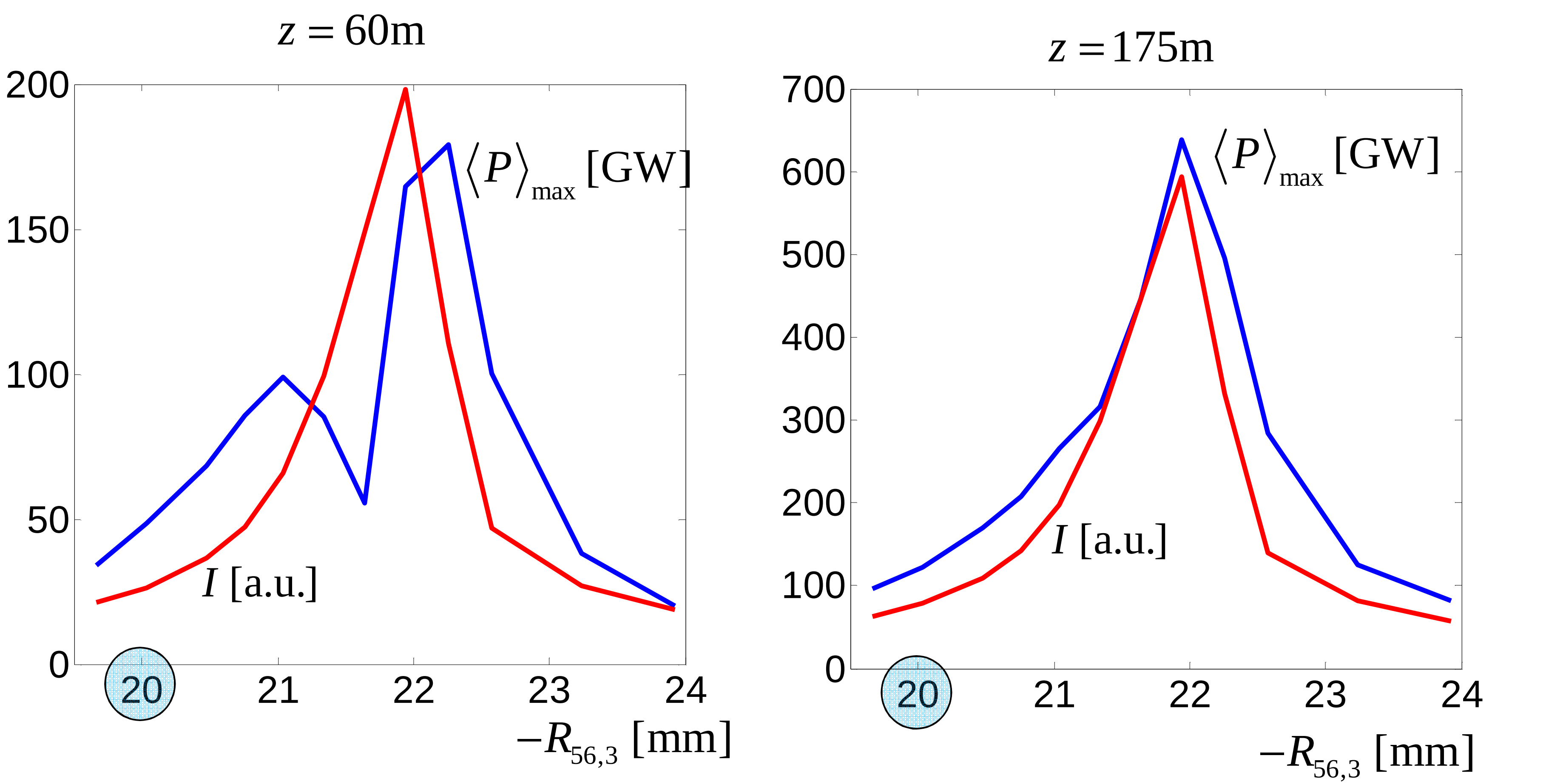


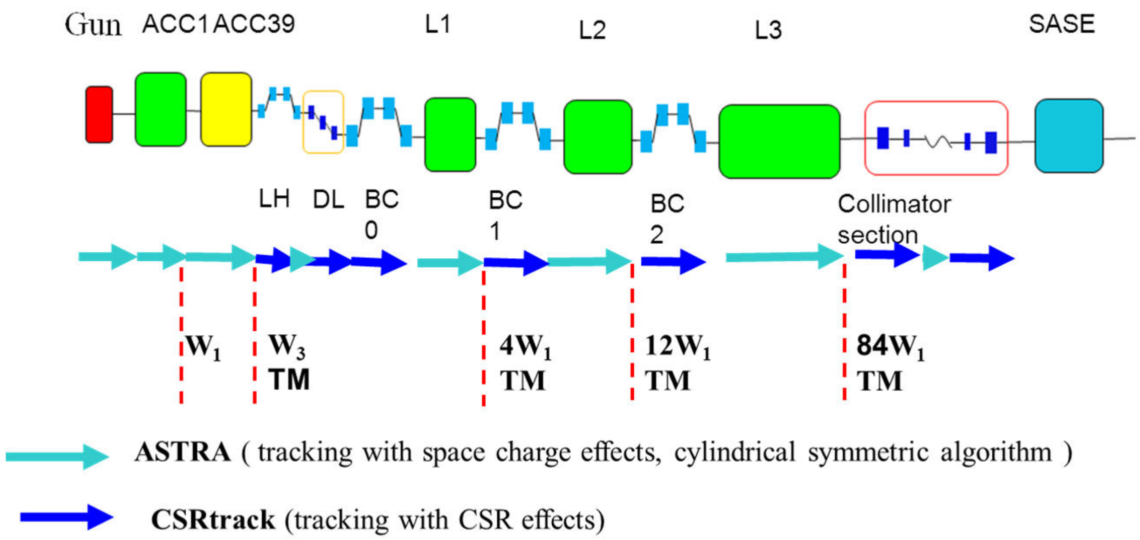
Figure 2: FEL power (blue) and Ipk(red) vs. compression

Strong Compression for 250 pC

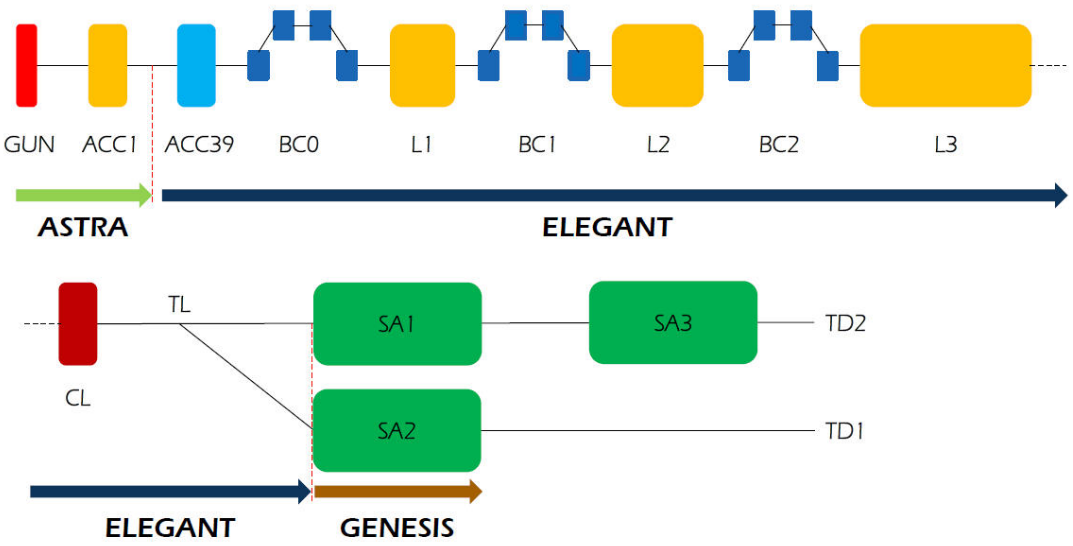
Radiation power vs. compression rate



New Results and Comparison with Elegant



CSRtrack+ASTRA (Guangyao Feng)

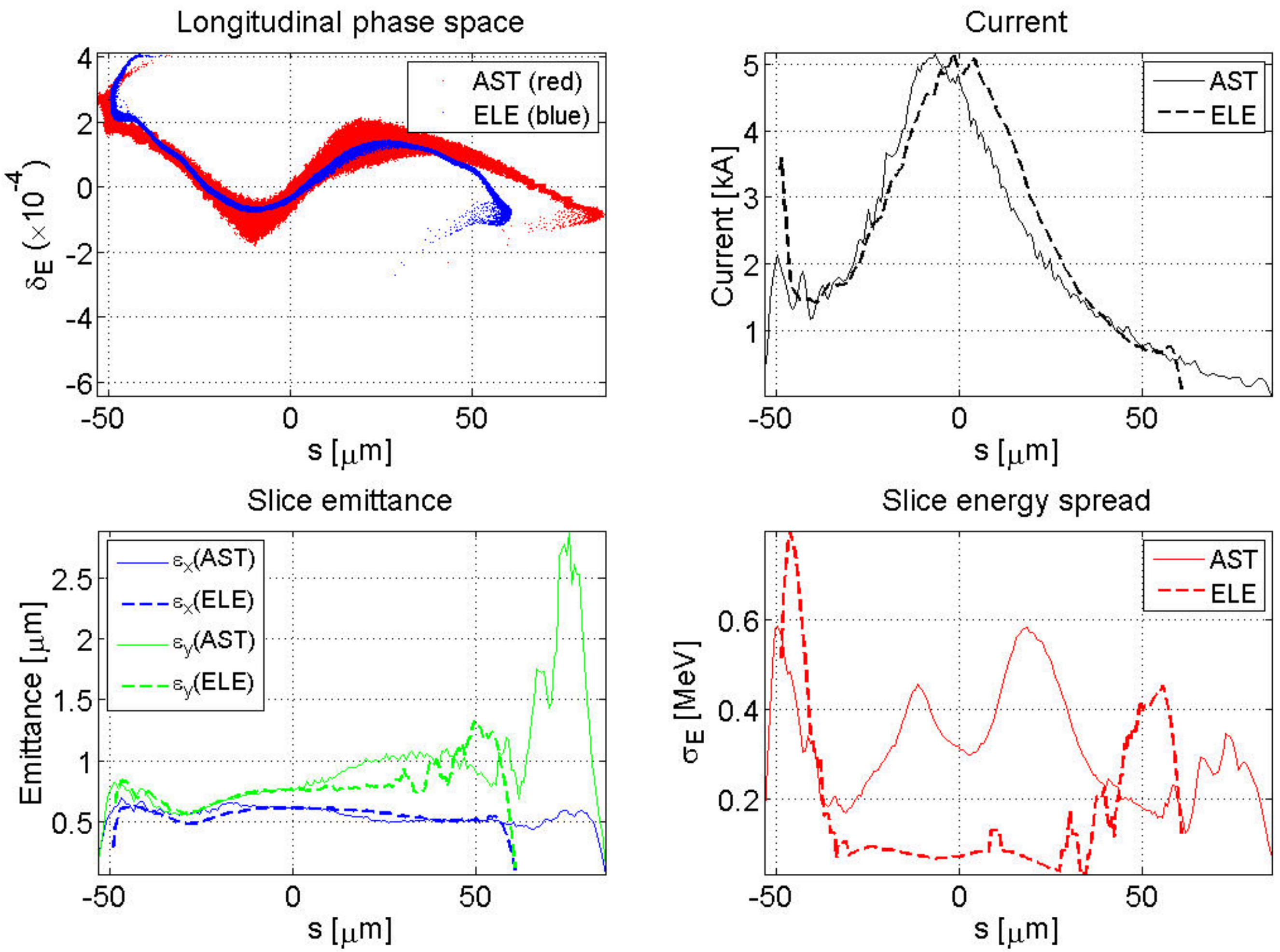


Elegant (Hyunchang Jin)

DESY

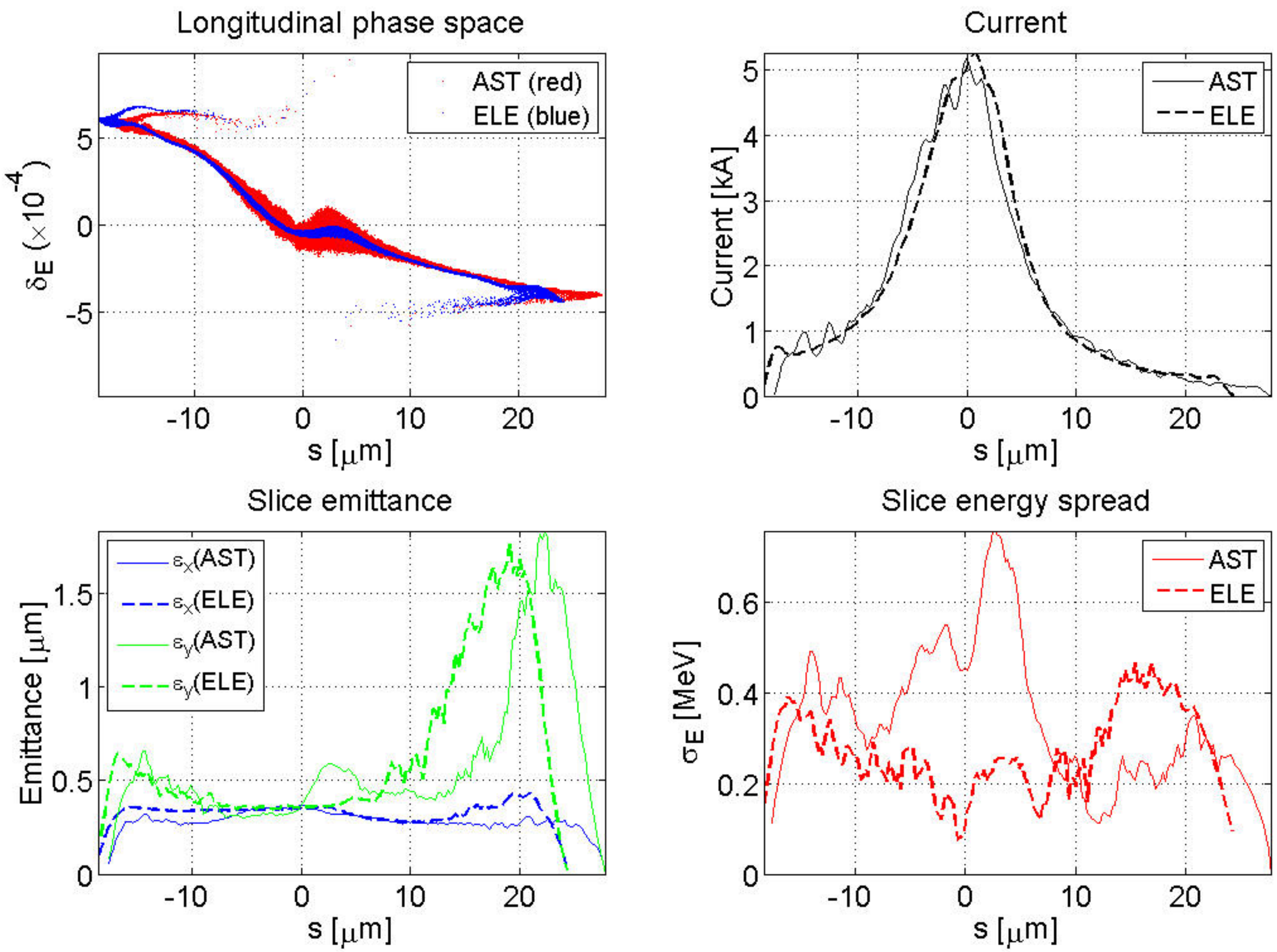
New Results and Comparison with Elegant

Q=1nC

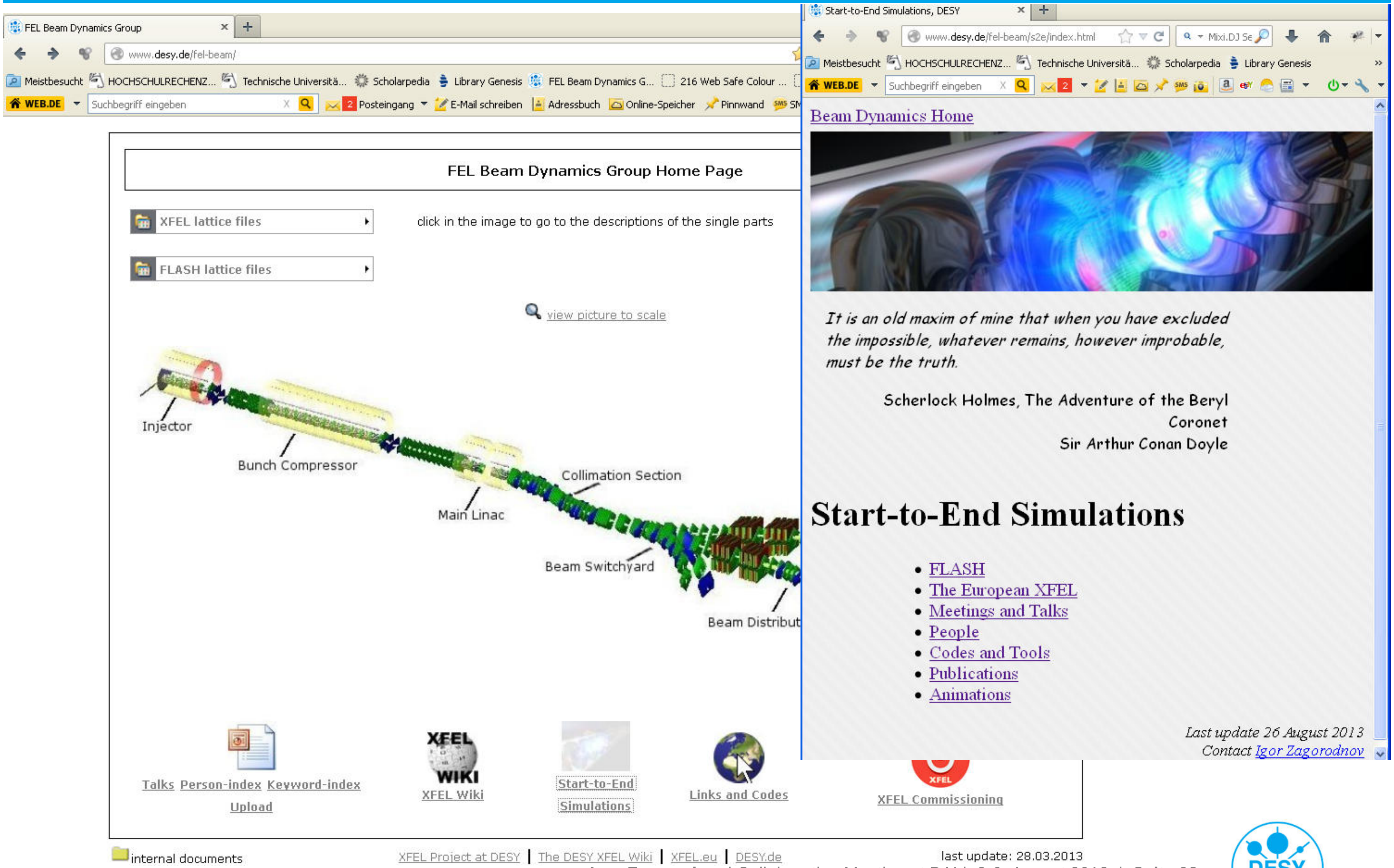


New Results and Comparison with Elegant

Q=250 pC



Outlook


FEL Beam Dynamics Group
www.desy.de/fel-beam/
FEL Beam Dynamics Group Home Page
XFEL lattice files
FLASH lattice files
click in the image to go to the descriptions of the single parts
view picture to scale
Injector
Bunch Compressor
Main Linac
Collimation Section
Beam Switchyard
Beam Distribut
Talks Person-index Keyword-index
Upload
XFEL Wiki
Start-to-End Simulations
Links and Codes
XFEL Commissioning
internal documents
XFEL Project at DESY | The DESY XFEL Wiki | XFEL.eu | DESY.de
last update: 28.03.2013
Start-to-End Simulations, DESY
www.desy.de/fel-beam/s2e/index.html
Beam Dynamics Home
It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth.
Scherlock Holmes, The Adventure of the Beryl Coronet
Sir Arthur Conan Doyle
Start-to-End Simulations
FLASH
The European XFEL
Meetings and Talks
People
Codes and Tools
Publications
Animations
Last update 26 August 2013
Contact Igor Zagorodnov