Beam Energy Dechirping Study for EXFEL

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S2e meeting

DESY

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Motivation

In general case, magnetic bunch compression needs an energy chirp in the electron bunch, which can broaden the FEL bandwidth and decrease FEL gain.

How to remove the energy chirp to improve FEL performance?

(1) **Using off crest acceleration in the linac section downstream of the last chicane.**
This method will need more additional RF power and be costly for a superconducting linac driving FEL.

(2) **Using beam self-induced wakefields to remove head-to-tail chirp.**
This method can benefit cost saving.

- resistive pipe with small radius
- Dielectric-lined waveguide
- metallic structure with corrugated walls* : SLAC, PAL, LBNL

* [1] Karl Bane, Corrugated Structures for Terahertz Generation and Beam Dechirping, NaPAC 2013, Pasadena, California
[2] Heung-Sik Kang, Dechirper and Its Applications, 23 May 2014
[3] K.L.F. Bane and G. Stupakov, Corrugated Pipe as a Beam Dechirper, SLAC-PUB-14925, April 2012
[4] Gennady Stupakov, Using wakefields for control of longitudinal phase space in FEL beams, February 18, 2014, KEK, Japan

Motivation

Beam dynamics study for energy dechirping for EXFEL

As the first step, doing beam dynamics simulation from the RF gun to the exit of the collimator section to generate proper particle distribution for the next energy dechirping with dechirper.

Considering the wakefiled effect in the main linac L3, the CSR impact on the bunch in the collimator section and the resistive wall wakefield in a structure with corrugated walls, an electron bunch with a flat top current profile and a linear energy distribution may meet the requirement.

Parameter Settings

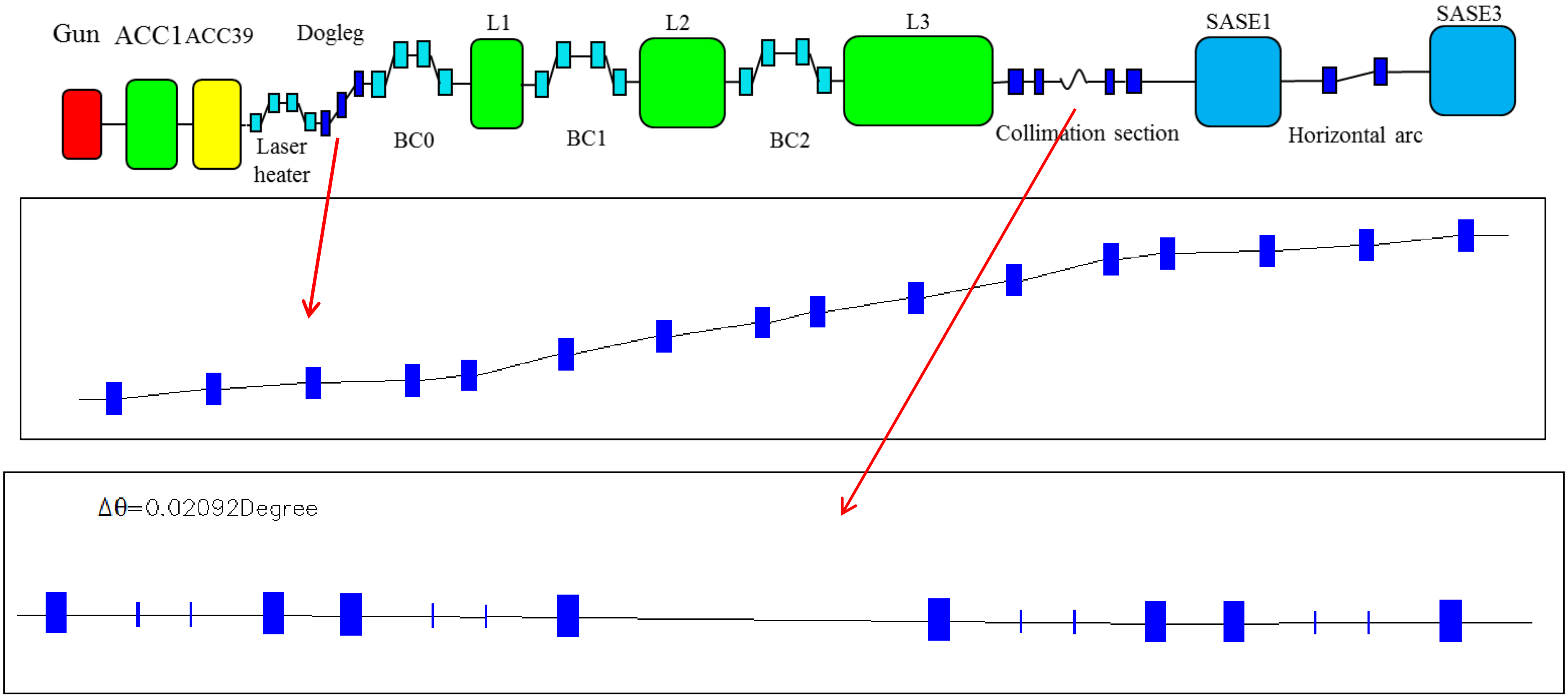
- **At the end of the linac**

  E=12GeV ,

  I_{peak}=~5.0kA, 3.5 kA, 2.5 kA   Q=0.5nC, 0.25nC

- **Beam energy at some key positions**

$E_1 = 130\,\text{MeV}$ $E_2 = 700\,\text{MeV}$ $E_3 = 2400\,\text{MeV}$ E_4=12.0GeV



Parameter Settings

Parameter settings for the bunch compressors [1] [2]

Charge Q, nC	Momentum compaction factor in Dogleg $R_{56,dogleg}$ [mm]	Momentum compaction factor in BC_0 $R_{56,0}$ [mm]	Total compr. $C_{dogleg}*C_0$	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]	Total compr. C
0.5	-30.1	-54.80	3.5	-50	8	-18.7	109 (2.5 kA)
0.5	-30.1	-54.80	3.5	-50	8	-20	152 (3.5 kA)
0.5	-30.1	-54.80	3.5	-50	8	-21	217 (5.0 kA)
0.25	-30.1	-48.20	3.5	-50	8	-20	385 (5.0 KA)

[1] Igor Zagorodnov, M. Dohlus, A semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects, Physical Review STAB 14(2011), 014403

[2] Igor Zagorodnov, Beam Dynamics Simulations for XFEL, BD meeting, 2011

Transformation of the longitudinal coordinate in the *i*th bunch compressor

$$s_i = s_{i-1} - \left(R_{56i}\delta_i + T_{566i}\delta_i^2 + U_{5666i}\delta_i^3\right) \qquad i = 1,2,3$$

For the fixed values of RF parameters and momentum compaction factors, the global compression function [1]

$$C_N = \frac{1}{Z_N}, \qquad Z_N = \frac{\partial s_N}{\partial s}$$

Three stages bunch compression scheme

$$\begin{cases} E_1 = E_1(V_1, \varphi_1, V_{39}\ \ \varphi_{39}) = V_1 Cos(k \cdot s + \varphi_1) + V_{39} Cos(3k \cdot s + \varphi_{39}) & \textbf{before BC0} \\ E_2 = E_2(V_1, \varphi_1, V_{39}, \varphi_{39}, V_2, \varphi_2) & \textbf{before BC1} \\ E_3 = E_3(V_1, \varphi_1, V_{39}, \varphi_{39}, V_2, \varphi_2, V_3, \varphi_3) & \textbf{before BC2} \\ Z_1 = \frac{\partial s_1}{\partial s}(0) & \\ Z_2 = \frac{\partial s_2}{\partial s}(0) & \\ Z_3 = \frac{\partial s_3}{\partial s}(0) & \\ Z_1' = \frac{\partial^2 s_1}{\partial s^2}(0) & \\ Z_1'' = \frac{\partial^3 s_1}{\partial s^3}(0) & \end{cases}$$

[1] I. Zagorodnov, M. Dohlus, "A semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects", Physical Review STAB 14 (2011).

Parameter Settings

$$\vec{x}_0 = \begin{pmatrix} V_1 \\ \varphi_1 \\ V_{39} \\ \varphi_{39} \\ V_2 \\ \varphi_2 \\ V_3 \\ \varphi_3 \end{pmatrix} \qquad \vec{f}_0 = \begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_1' \\ Z_1'' \end{pmatrix}$$

$$\vec{f}_0 = A_0(\vec{x}_0)$$

In order to take collective effects into account, a fast tracking code has been used for the RF parameters calculation.

Parameter Settings

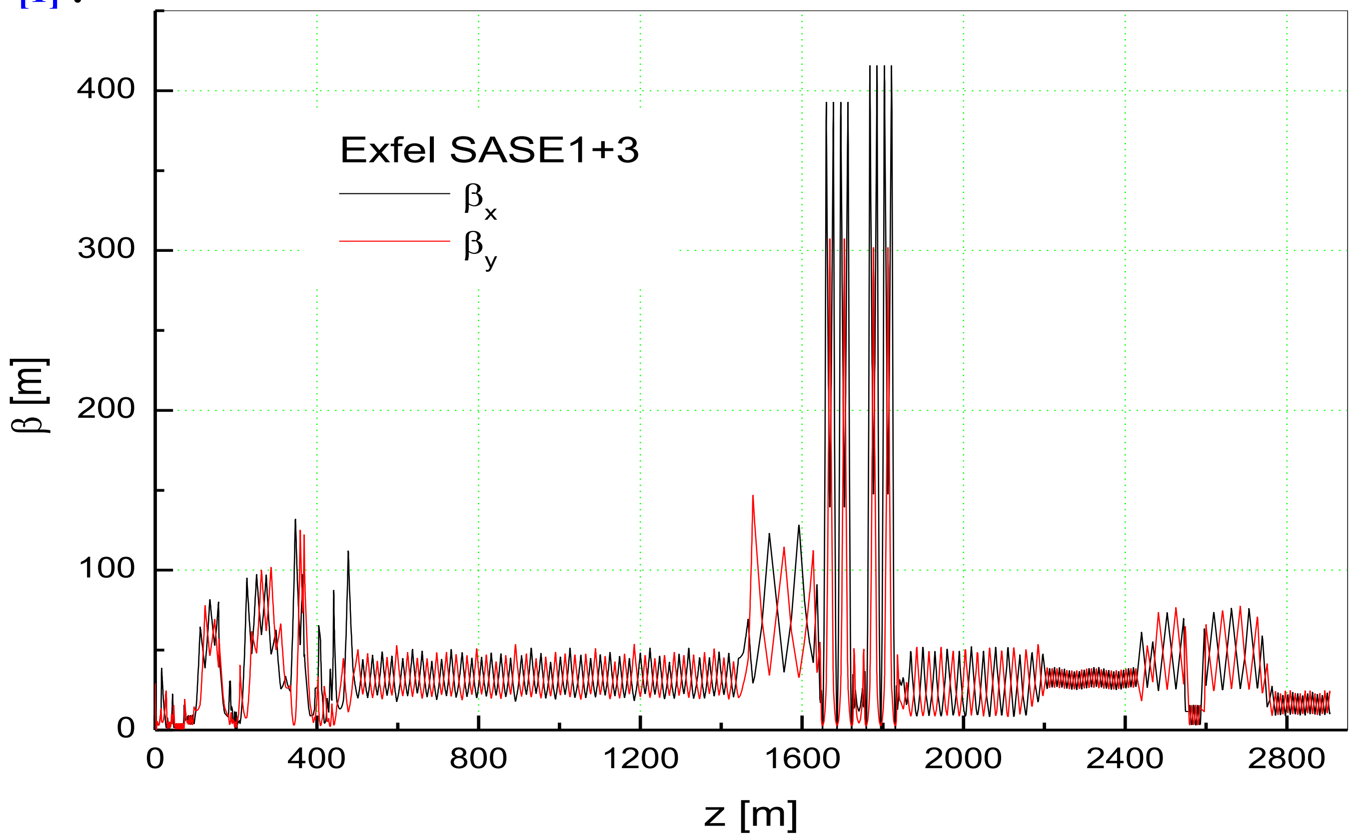
RF settings in accelerating modules for different bunch charge cases

Charge nC	V_{acc1} [MV]	φ_{acc1} [deg]	V_{acc39} [MV]	φ_{acc39} [deg]	V_{linac1} [MV]	φ_{linac1} [deg]	V_{linac2} [MV]	Φ_{linac2} [deg]
0.5 (2.5kA)	170.39	30.85	30.06	220.82	673.49	32.15	1773.14	16.41
0.5 (3.5kA)	158.82	23.28	25.11	207.13	673.52	32.15	1775.27	16.64
0.5 (5kA)	157.31	21.76	24.67	203.82	673.54	32.16	1776.25	16.75
0.25 (5kA)	155.55	19.87	23.96	197.95	667.15	31.29	1820.19	20.90

Linac3: accelerating on crest

Parameter Settings

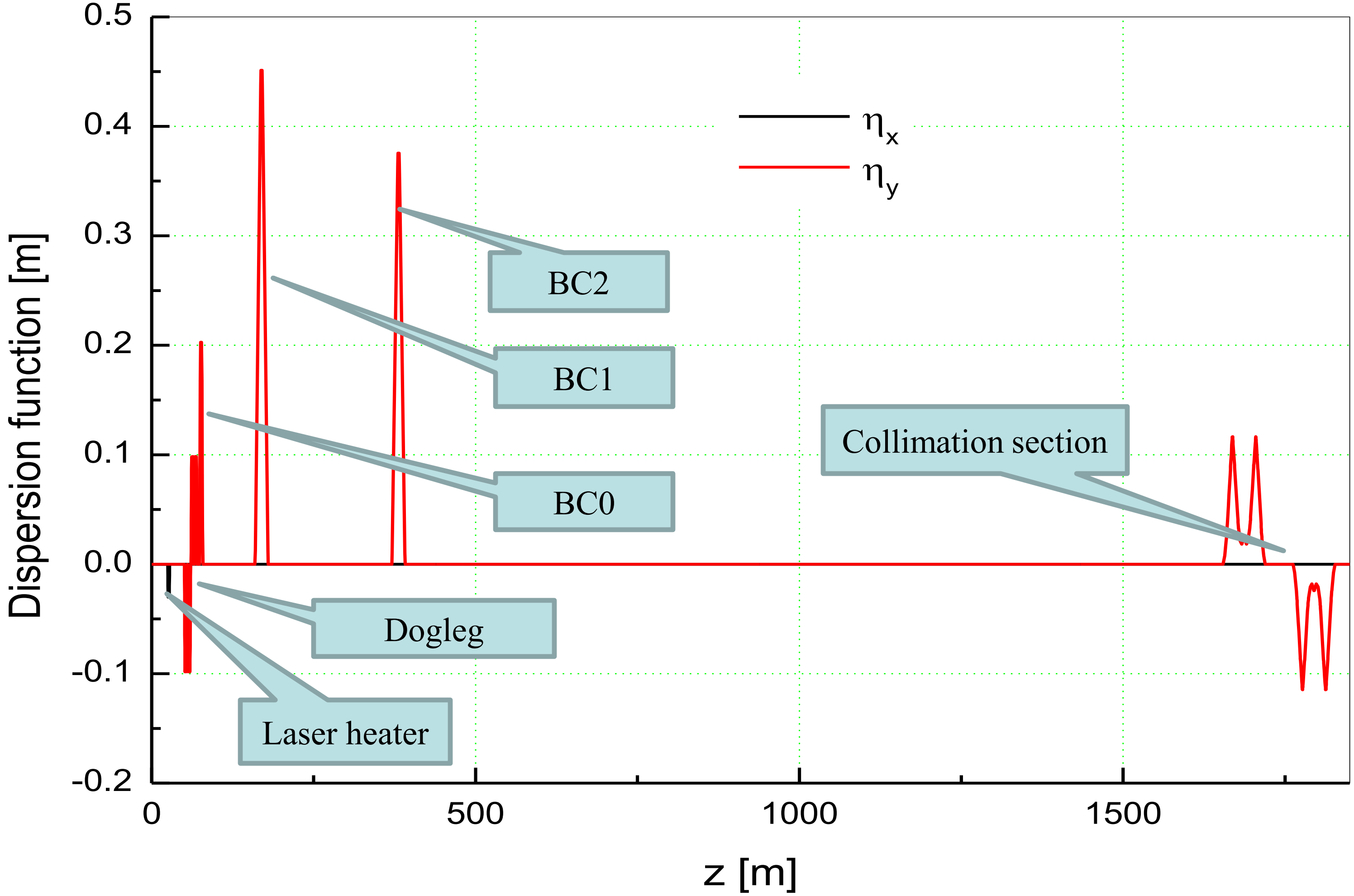
❖ Parameter values of the magnets are from the Elegant lattice file [1] .



New design optics for EXFEL SASE1+3 (Elegant)

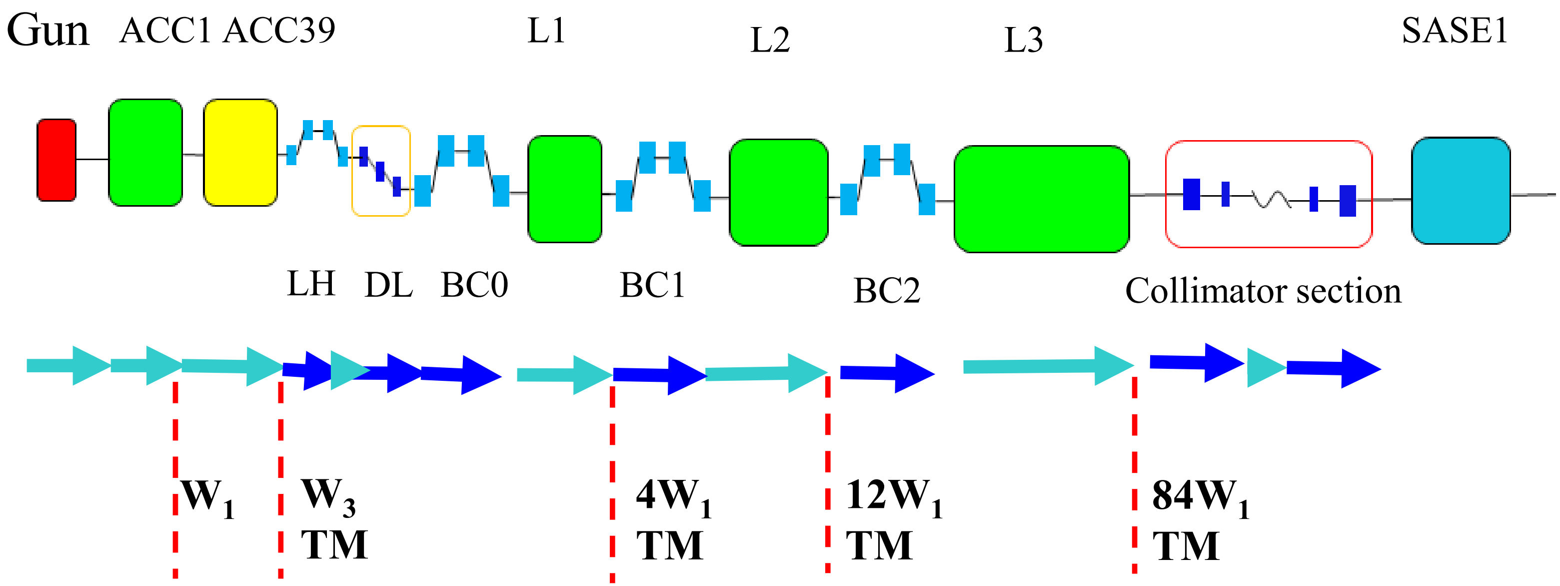
[1] http://www.desy.de/fel-beam/

Parameter Settings



Dispersion for EXFEL SASE1 (Elegant)

Beam dynamics simulation for energy dechirping for two charge cases



L1: ACC2
L2: ACC3+ ACC4+ ACC5
L3: ACC6+ …+ ACC26

1 Million particles
150CPUs, ~20 hours

ASTRA (tracking with space charge effects, cylindrical symmetric algorithm)

CSRtrack (tracking with CSR effects)

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

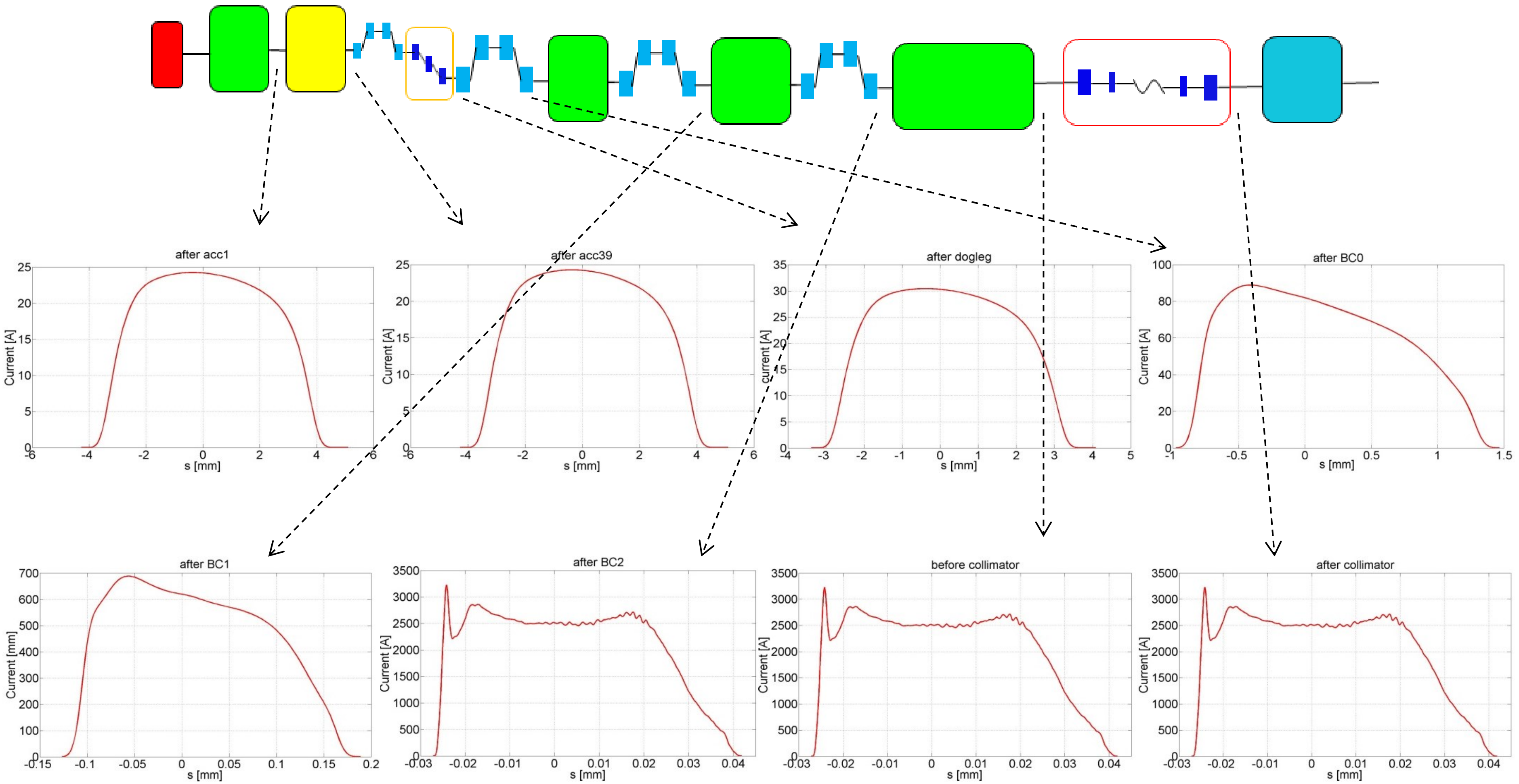
W3 - ACC39 wake (TESLA Report 2004-01, DESY, 2004)

TM - transverse matching to the design optics

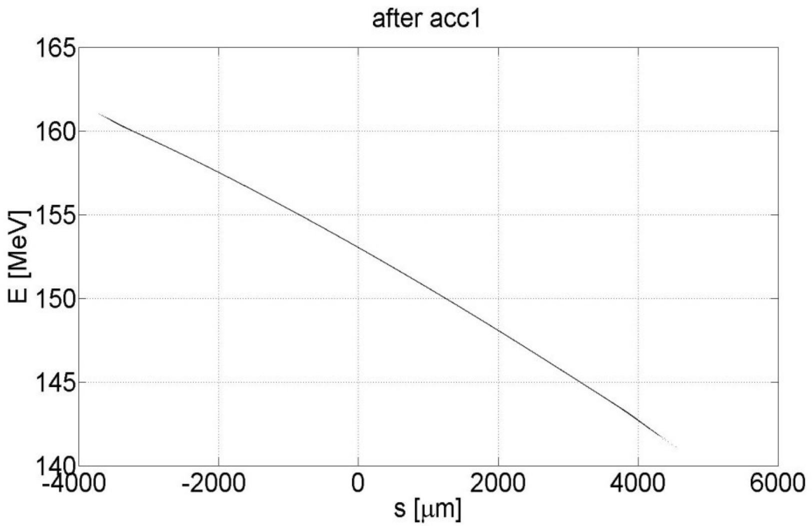
Beam dynamics simulation for energy dechirping for two charge cases

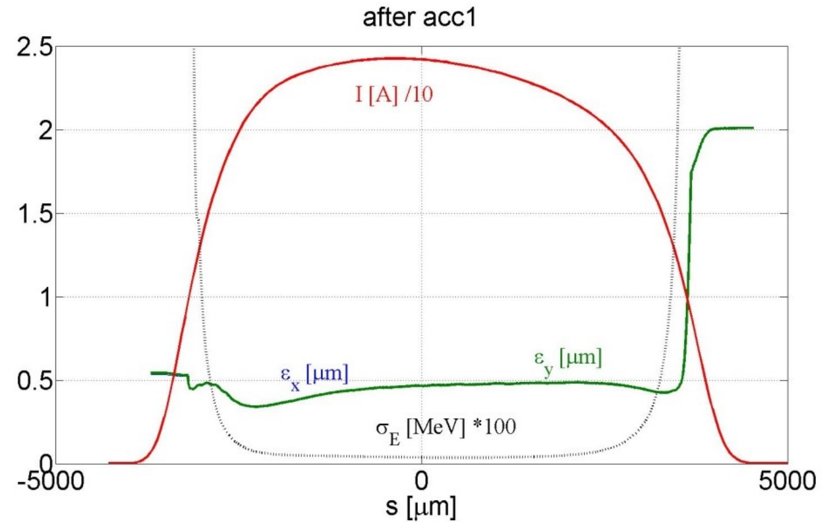
Q=0.5 nC, I_{peak}= 2.5 kA

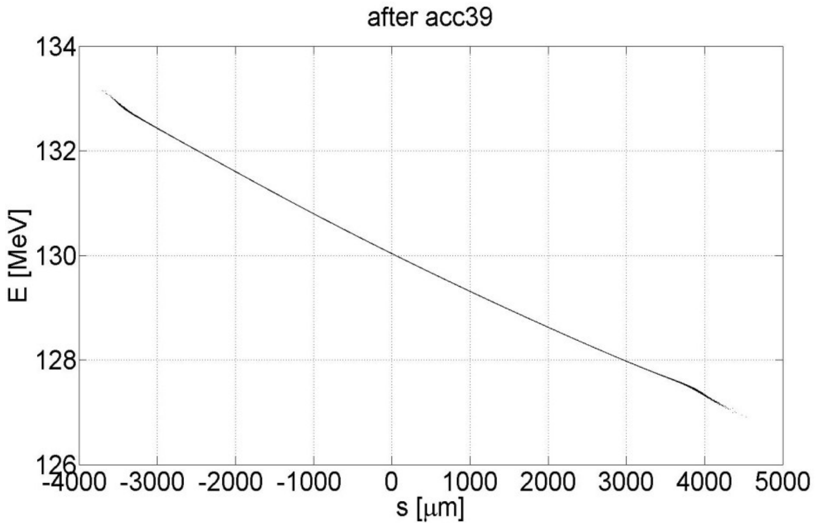
Current profile along the beam line

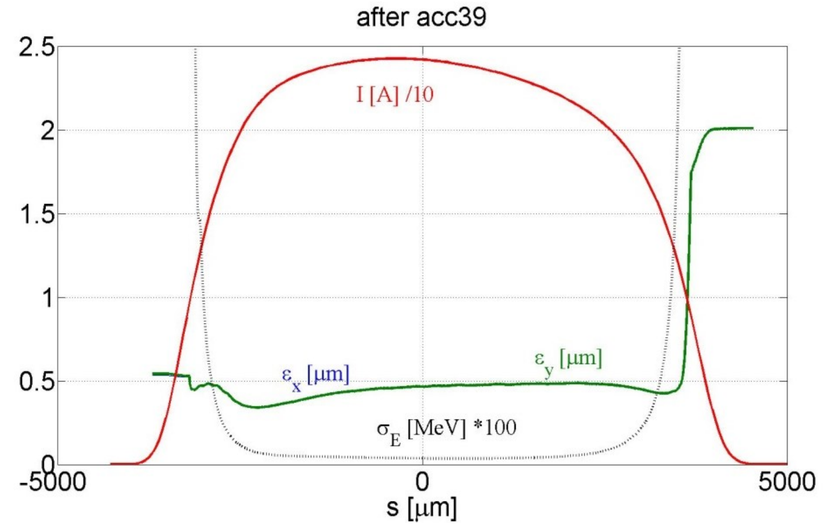


Beam dynamics simulation for energy dechirping for two charge cases

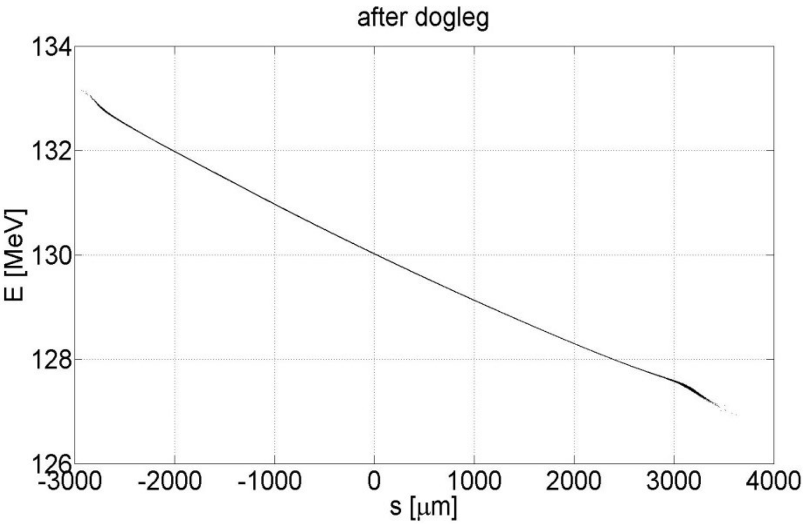


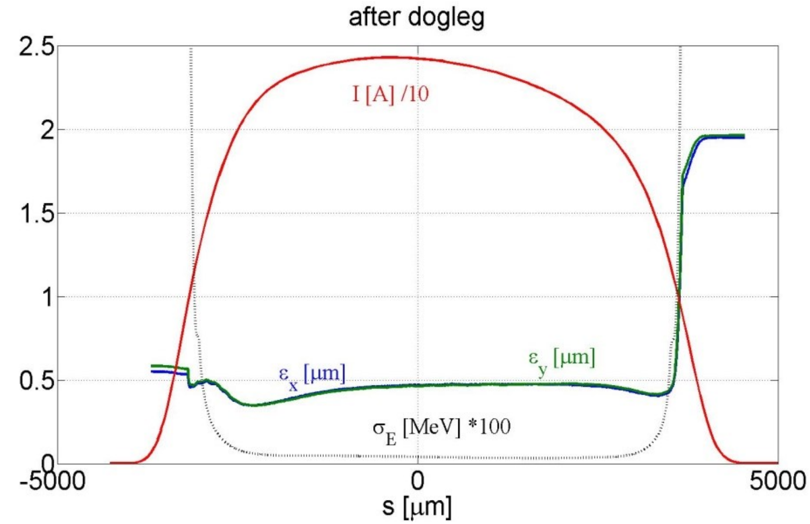


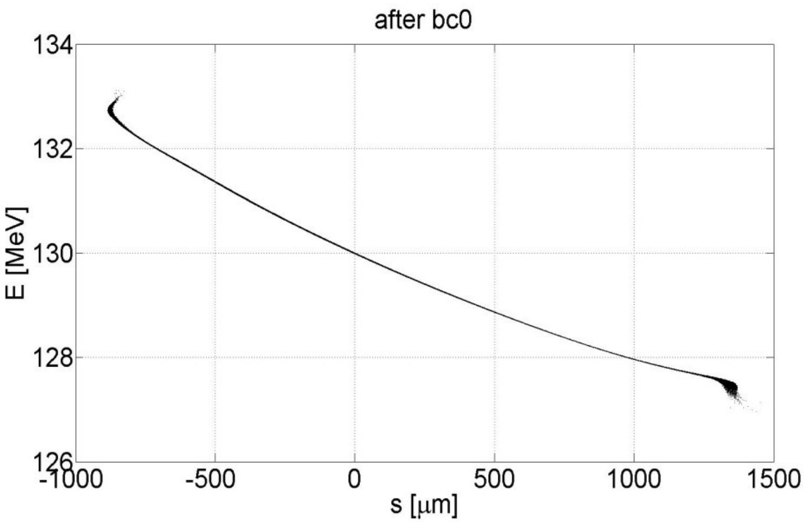


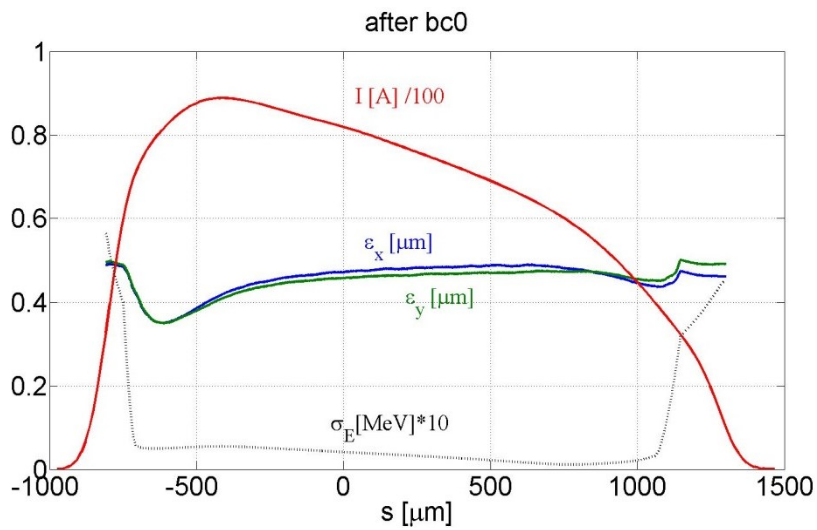


Beam dynamics simulation for energy dechirping for two charge cases

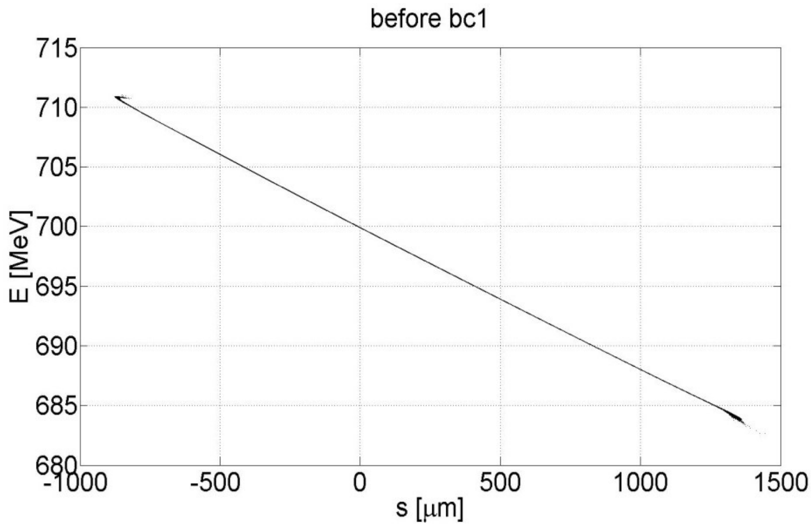


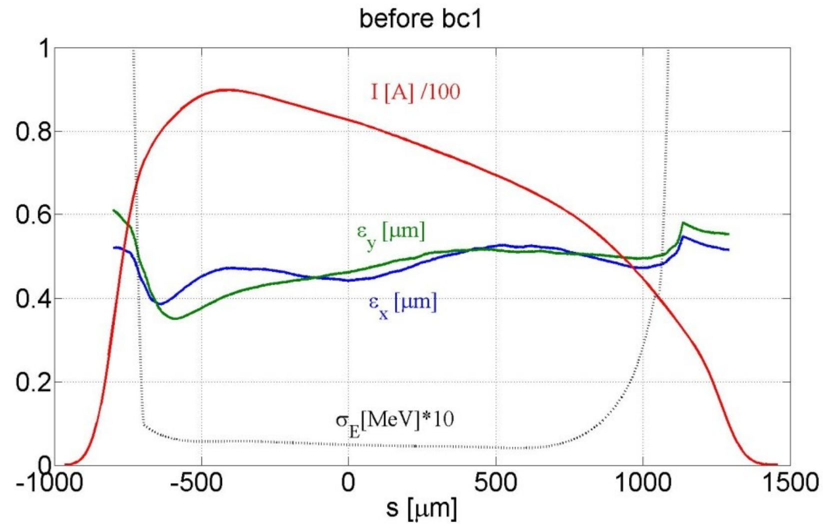


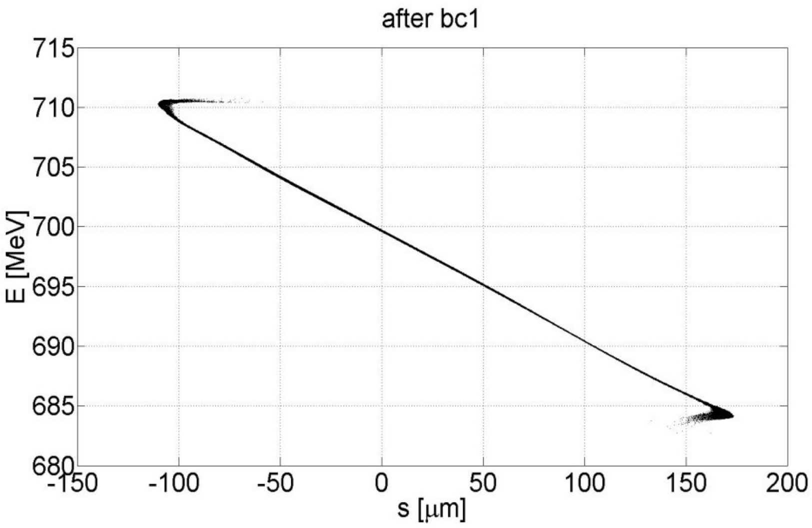


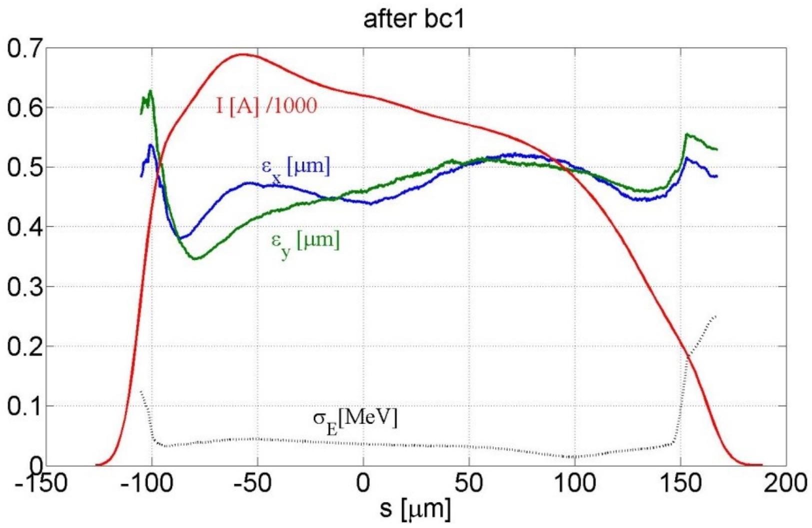


Beam dynamics simulation for energy dechirping for two charge cases

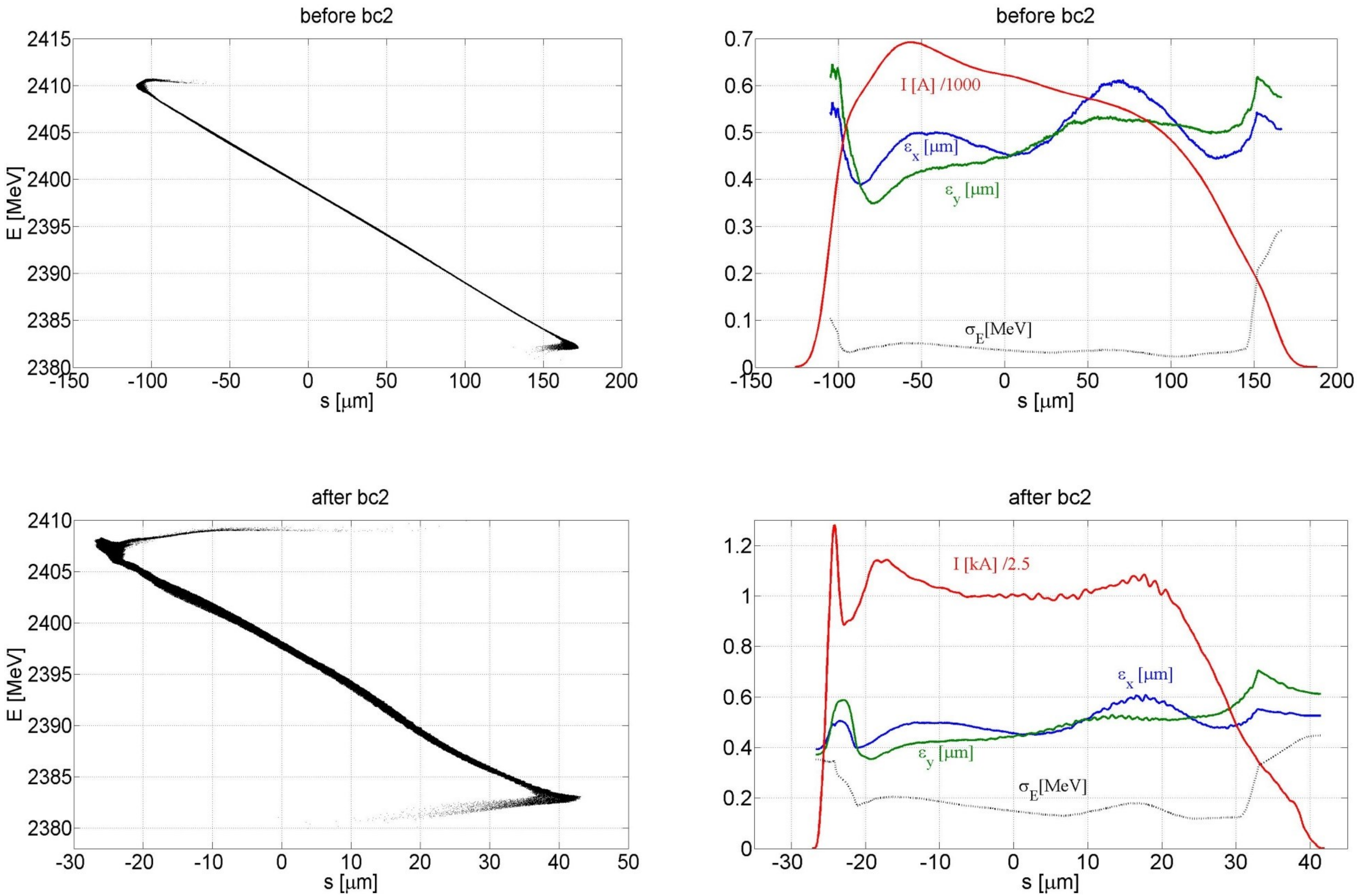




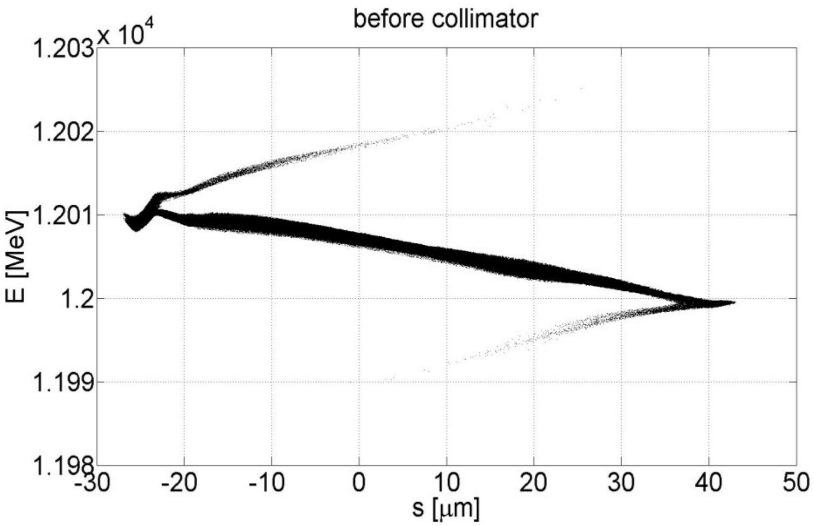


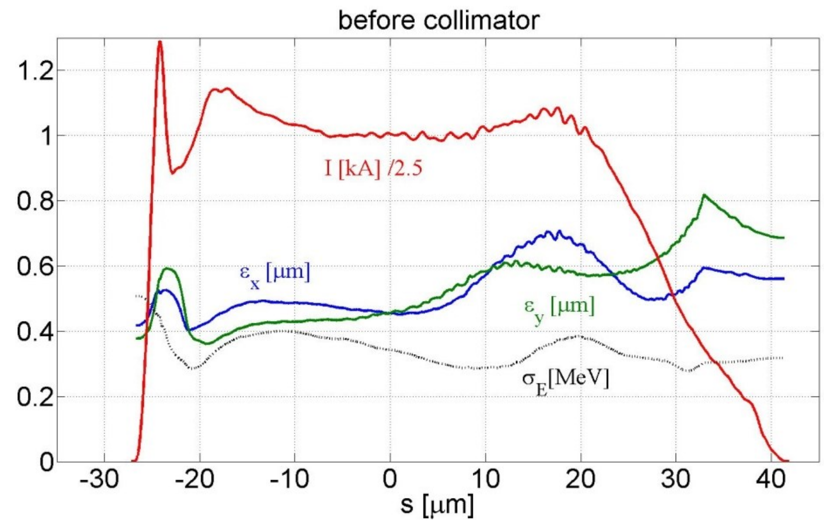


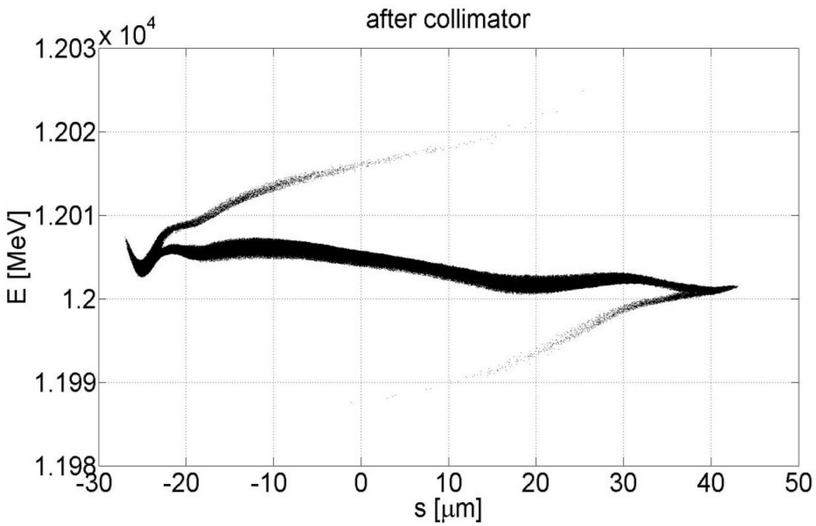
Beam dynamics simulation for energy dechirping for two charge cases

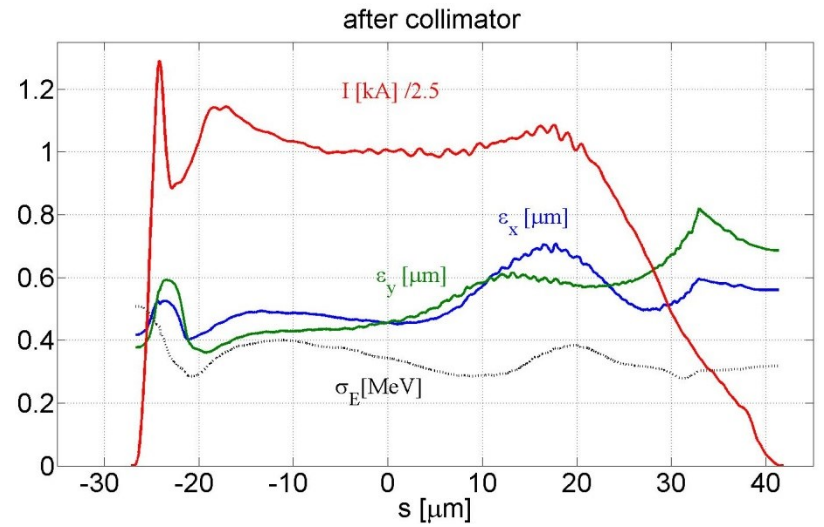


Beam dynamics simulation for energy dechirping for two charge cases



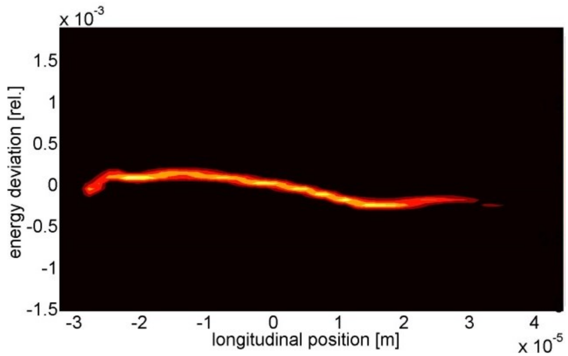




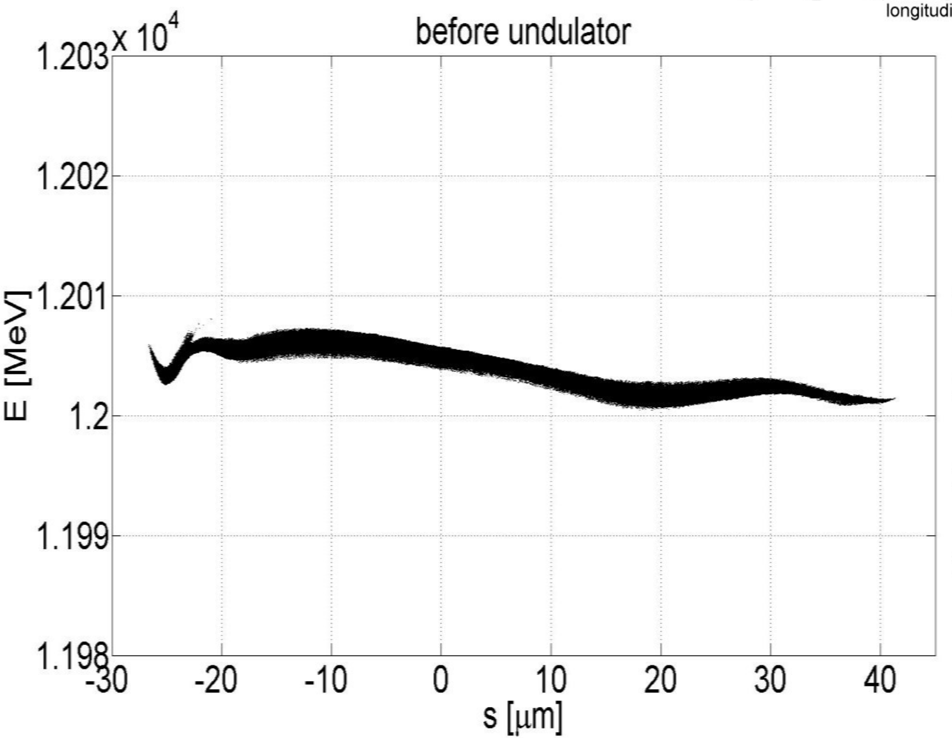


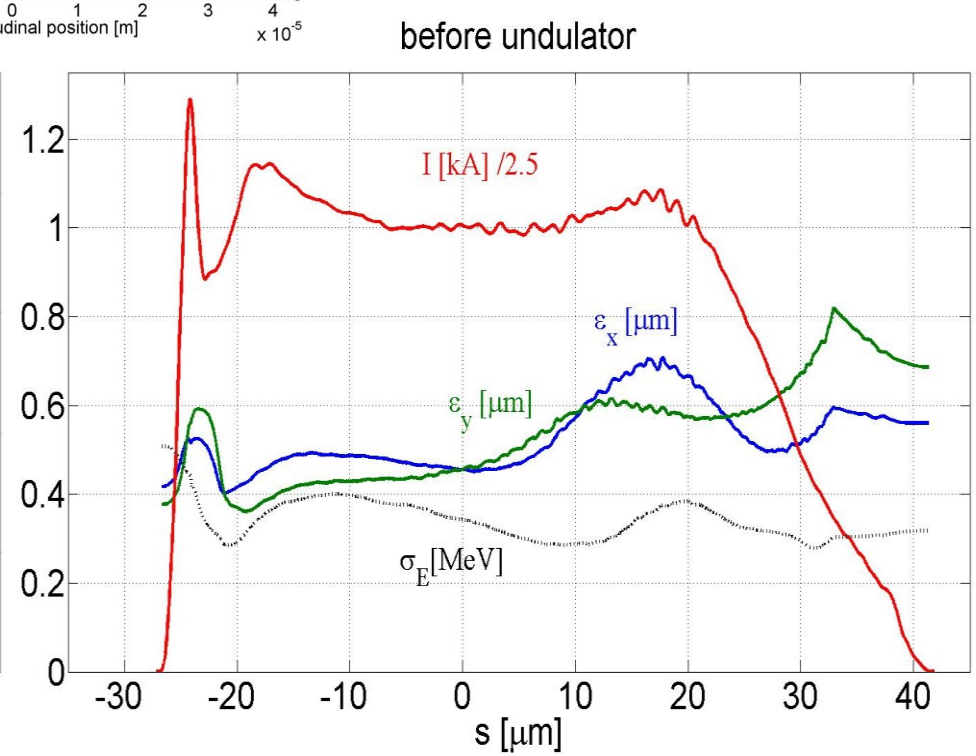
Beam dynamics simulation for energy dechirping for two charge cases

Q=0.5nC, Ipeak=2.5 kA



$\boldsymbol{\delta_{rms} = 1.49 \times 10^{-4}}$





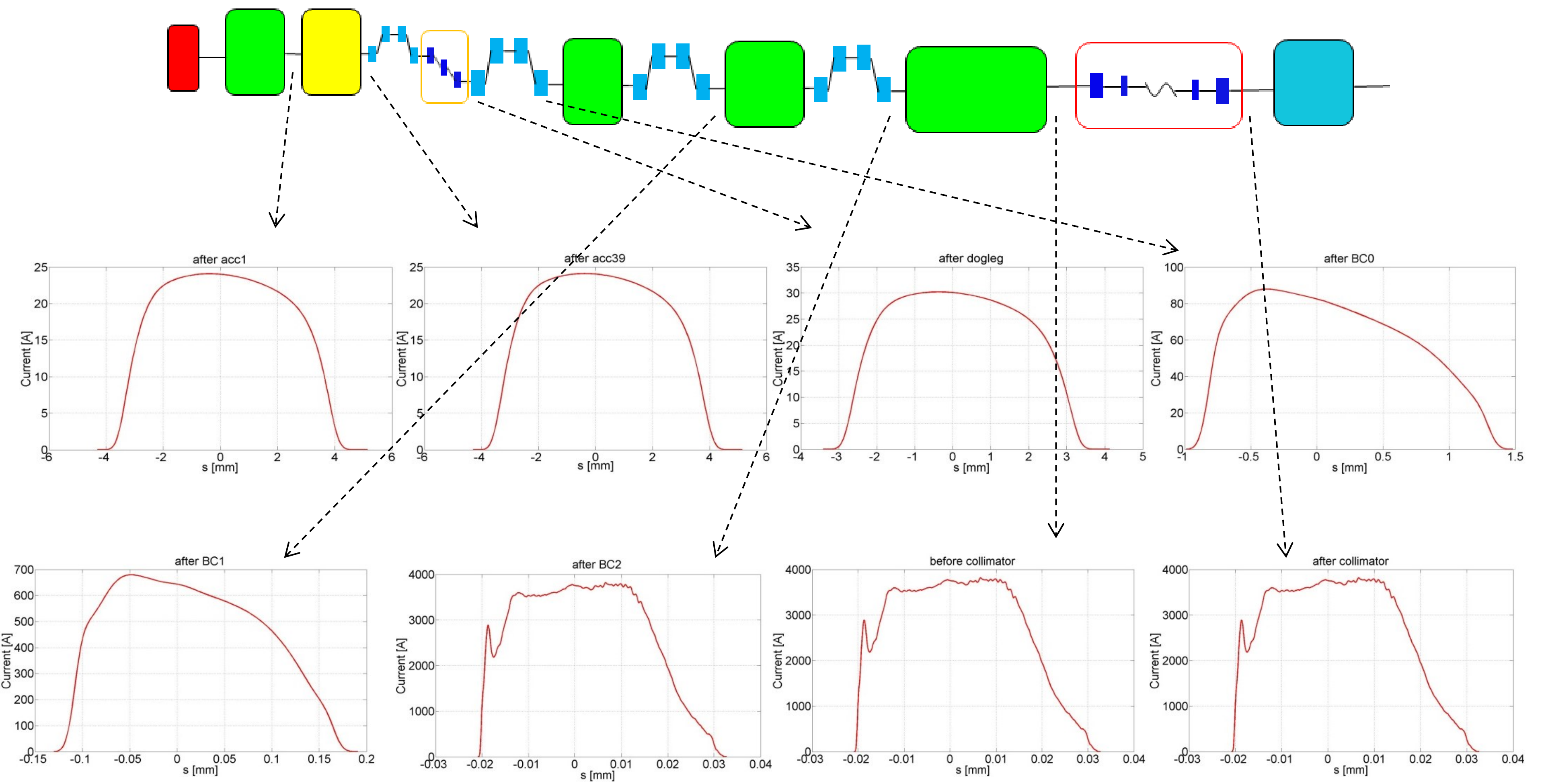
$\varepsilon_x{}^{proj} = 0.68\mu m \cdot rad, \varepsilon_y{}^{proj} = 0.80\mu m \cdot rad$

4% bad particles are removed

Beam dynamics simulation for energy dechirping for two charge cases

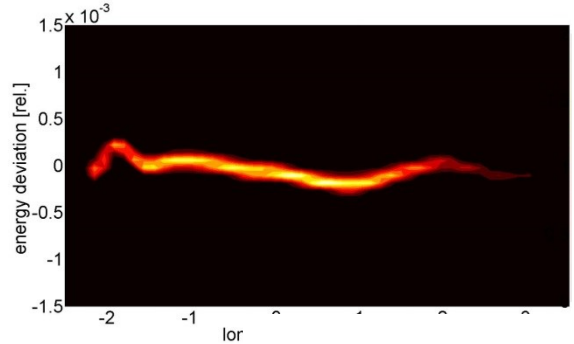
Q=0.5 nC, Ipeak= 3.5 kA

Current profile along the beam line

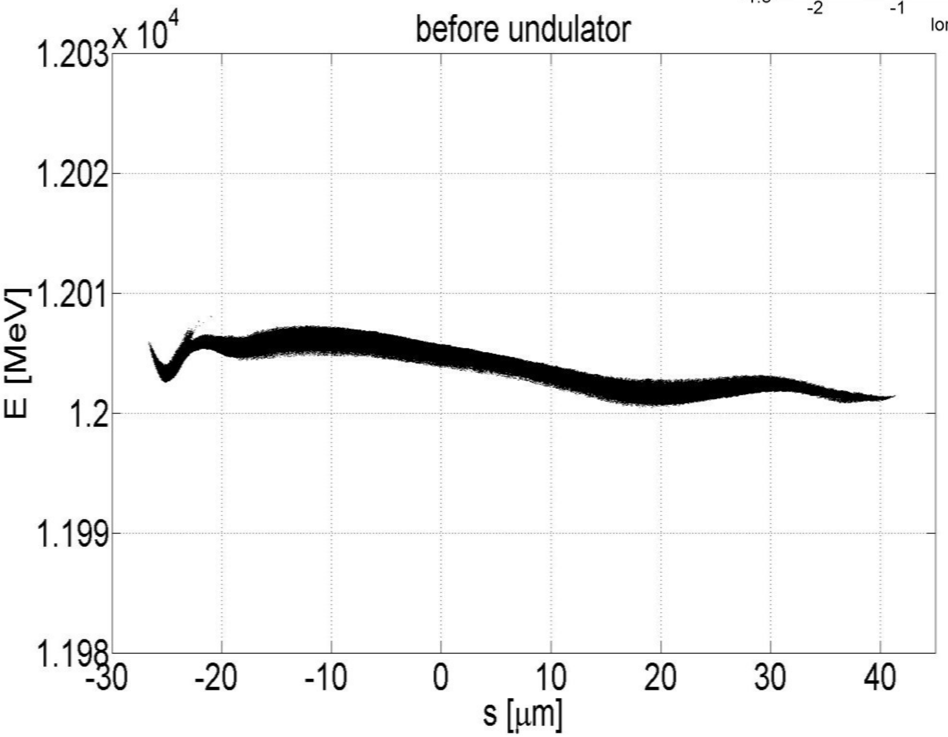


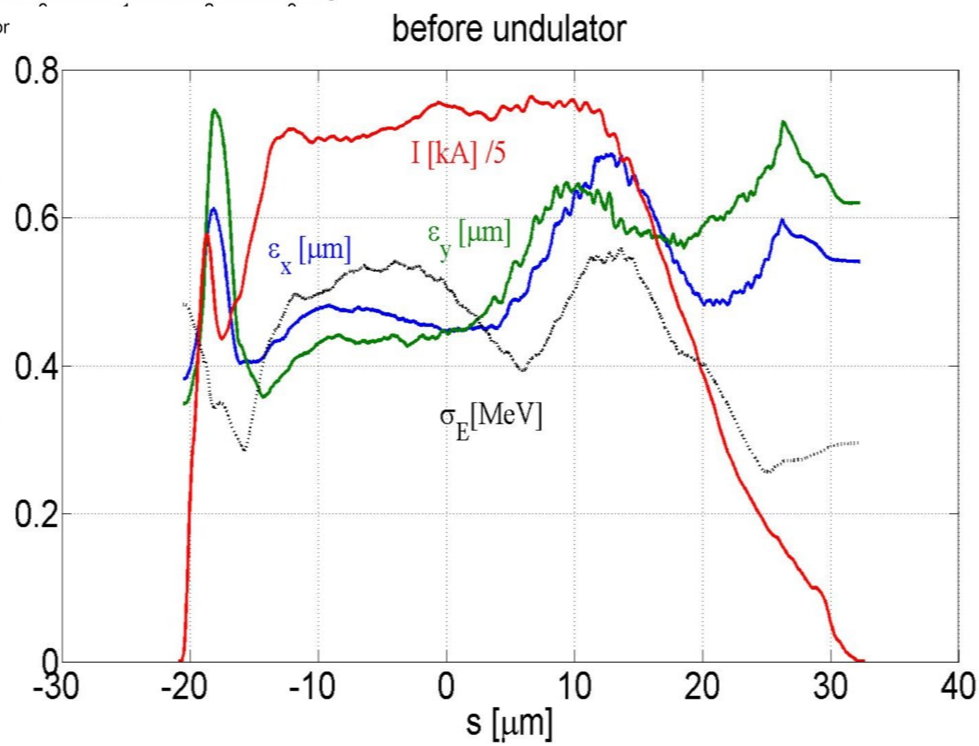
Beam dynamics simulation for energy dechirping for two charge cases

Q=0.5nC, Ipeak=3.5 kA



$$\delta_{rms} = 1.16 \times 10^{-4}$$





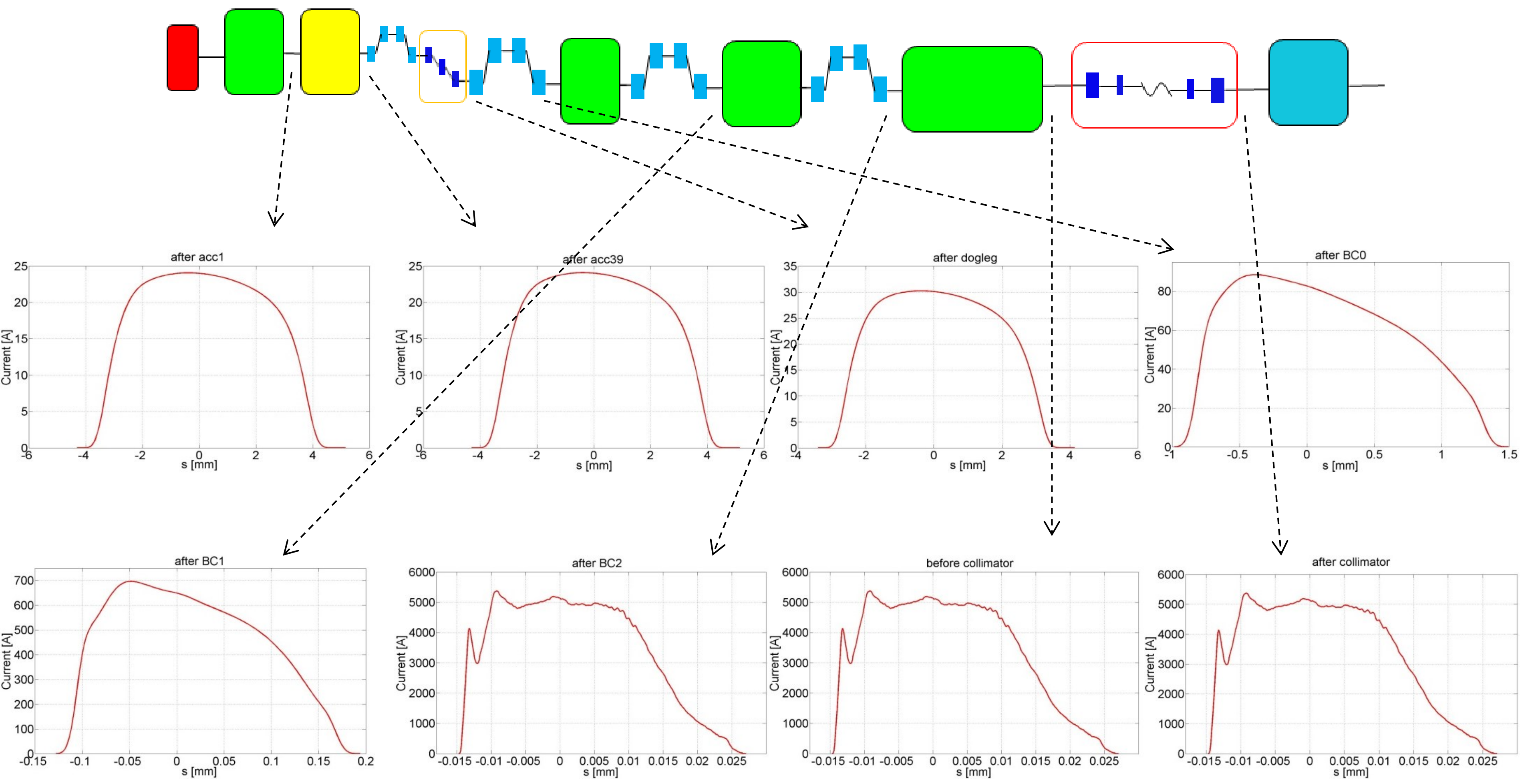
$$\varepsilon_x{}^{proj} = 0.65\mu m \cdot rad, \varepsilon_y{}^{proj} = 0.80\mu m \cdot rad$$

4% bad particles are removed

Beam dynamics simulation for energy dechirping for two charge cases

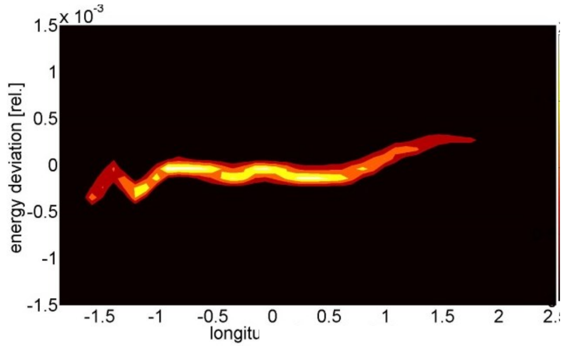
Q=0.5 nC, Ipeak= 5.0 kA

Current profile along the beam line

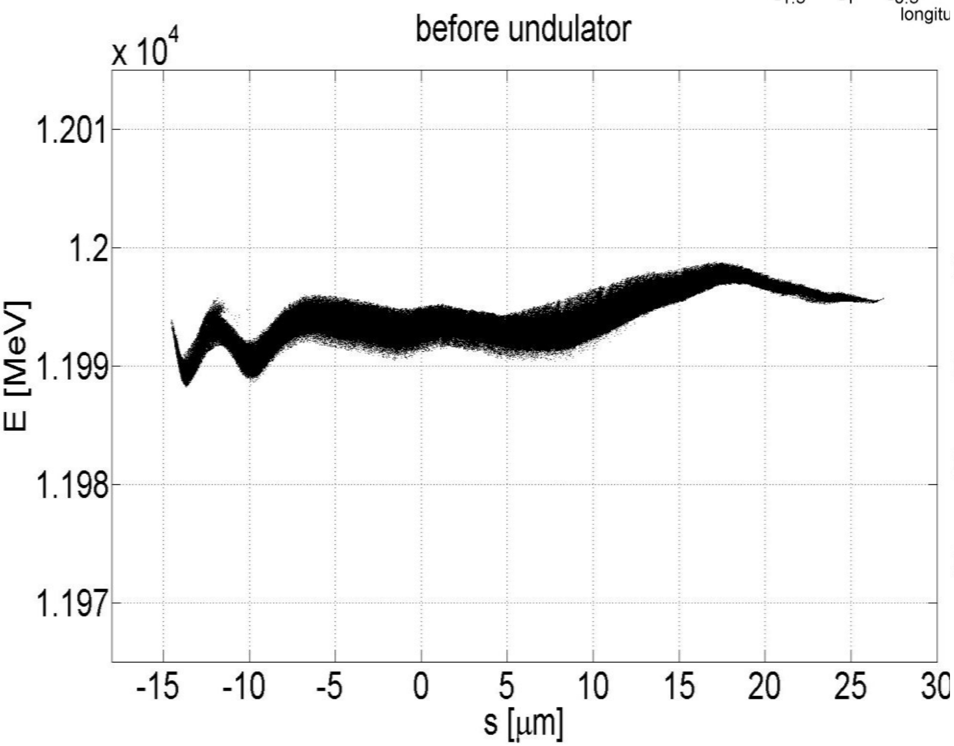


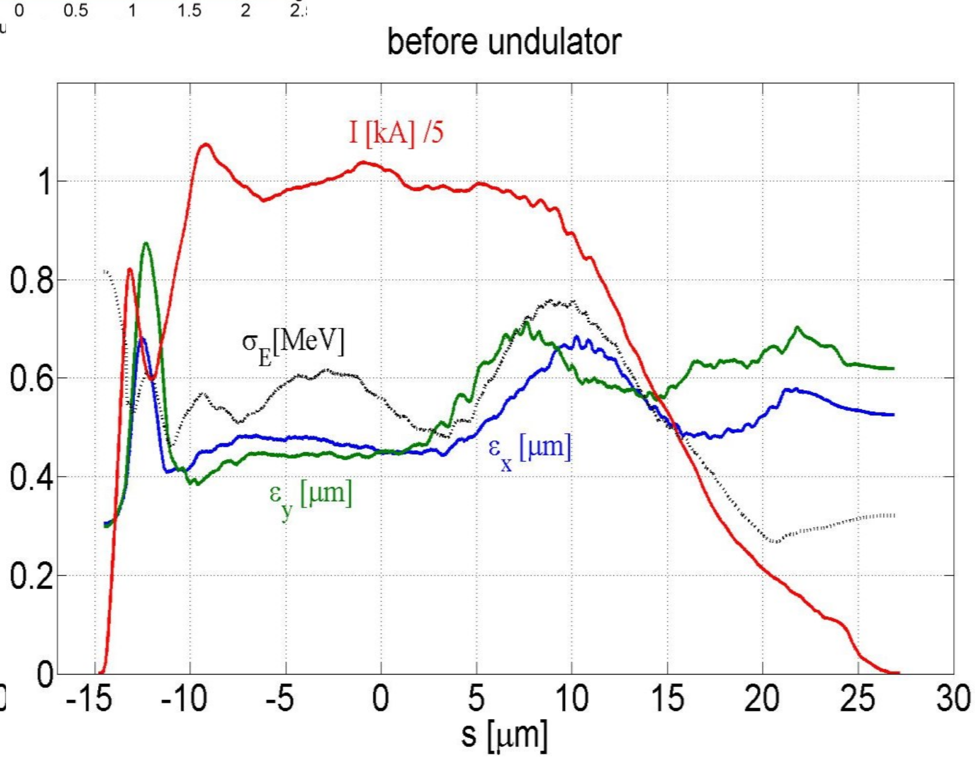
Beam dynamics simulation for energy dechirping for two charge cases

Q=0.5nC, Ipeak=5.0 kA



$$\boldsymbol{\delta_{rms} = 1.5 \times 10^{-4}}$$





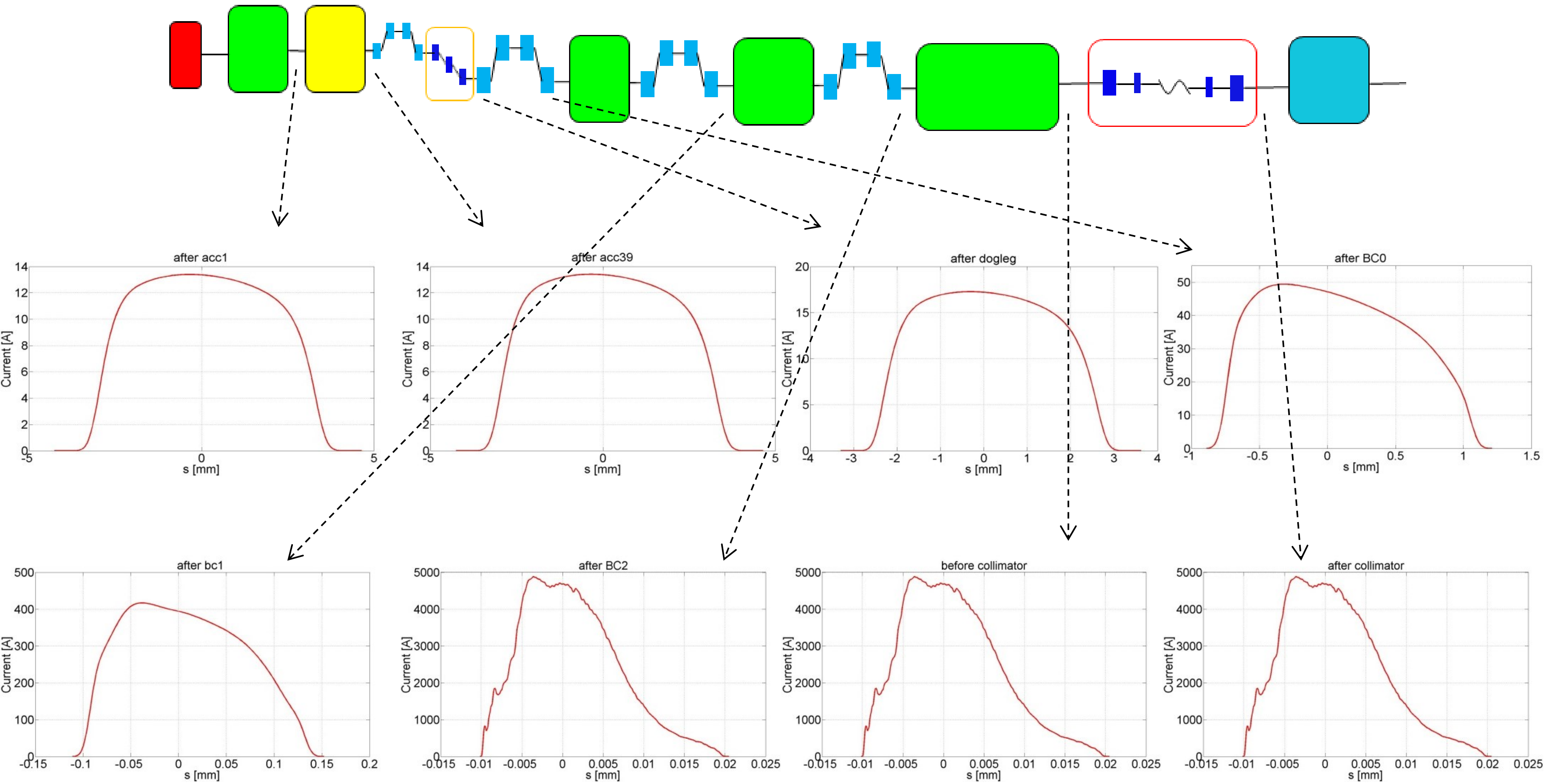
$$\varepsilon_x{}^{proj} = 0.64\mu m \cdot rad, \varepsilon_y{}^{proj} = 0.84\mu m \cdot rad$$

4% bad particles are removed

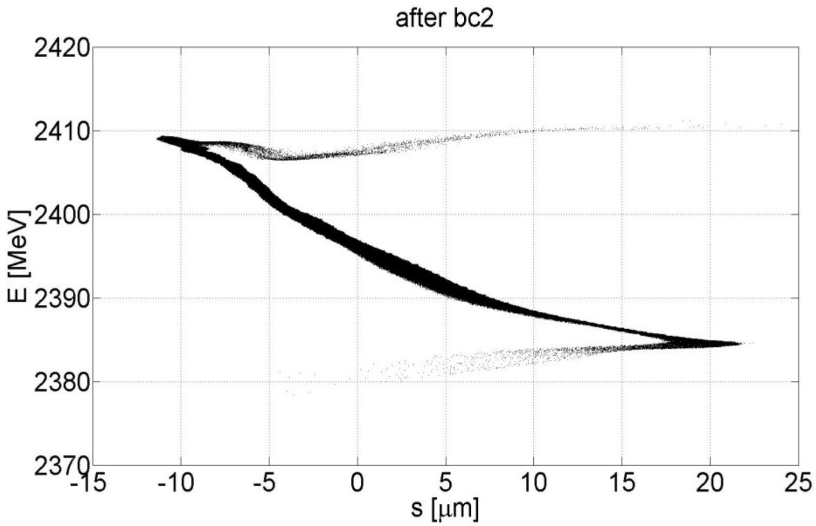
Beam dynamics simulation for energy dechirping for two charge cases

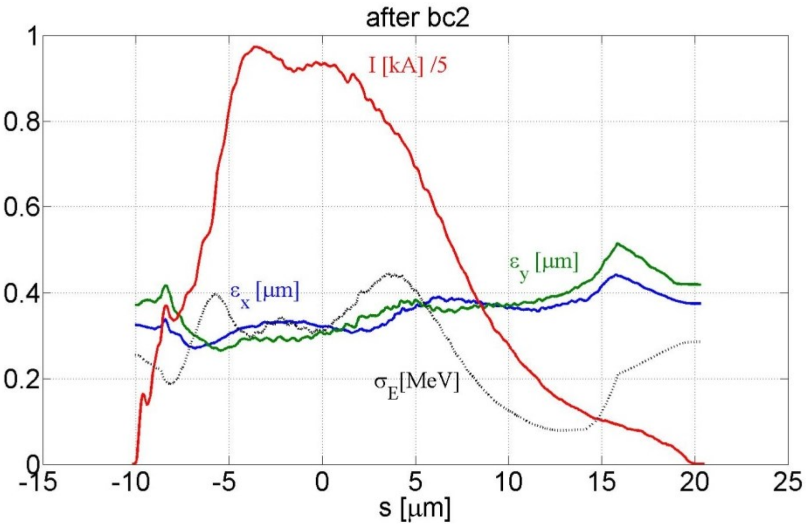
Q=0.25 nC, Ipeak= 5.0 kA

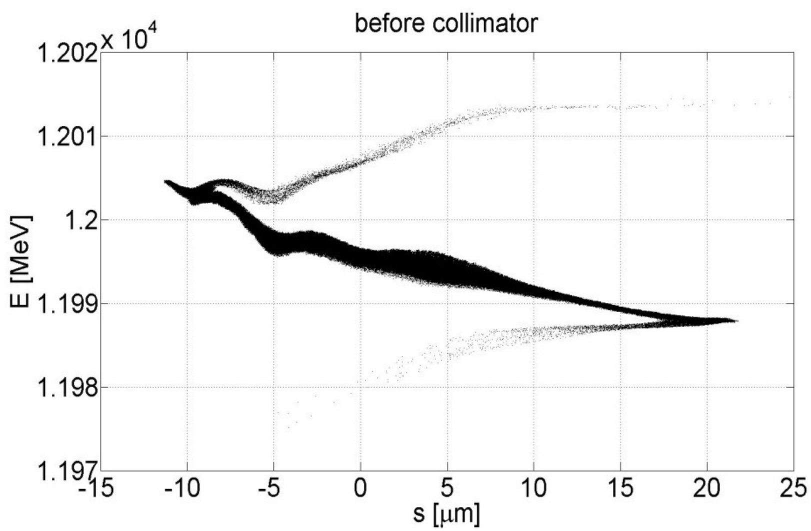
Current profile along the beam line

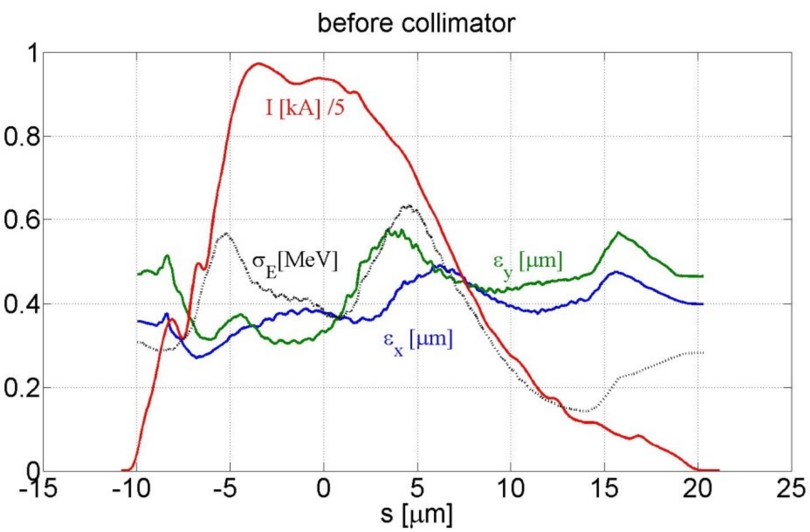


Beam dynamics simulation for energy dechirping for two charge cases



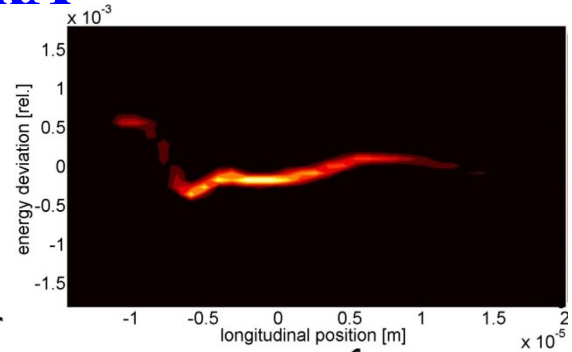






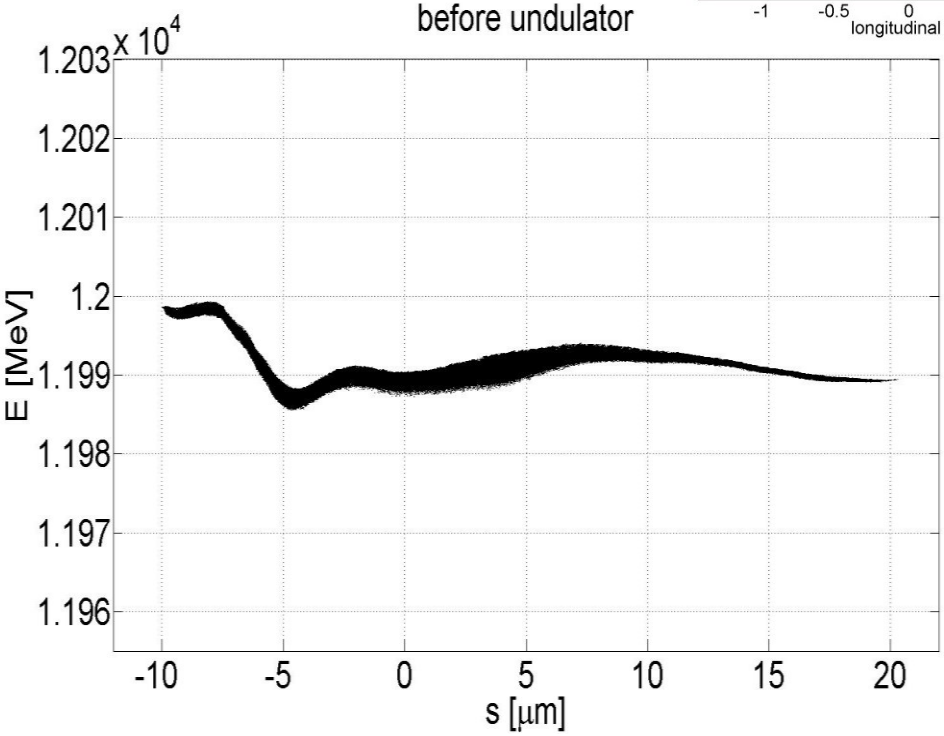
Beam dynamics simulation for EXFEL for different bunch charge cases

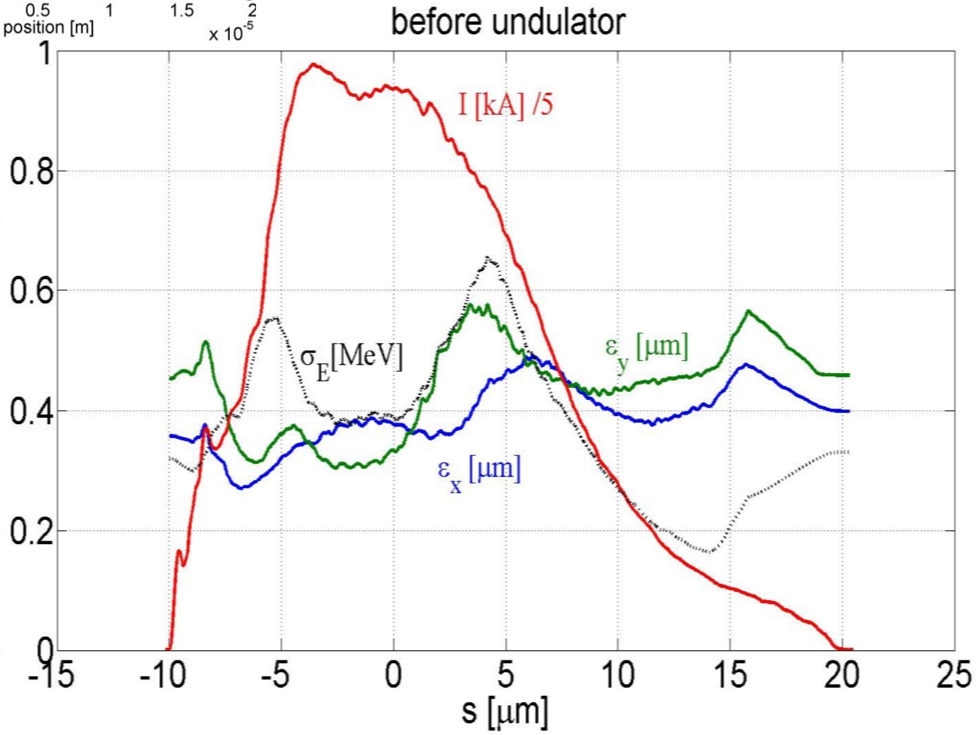
Q=0.25nC, Ipeak=5.0 kA



$\delta_{rms} = 2.3 \times 10^{-4}$ **for all particles**

$\delta_{rms} = 1.3 \times 10^{-4}$ **within FWHM**





$\varepsilon_x{}^{proj} = 0.50\mu m \cdot rad, \varepsilon_y{}^{proj} = 0.71\mu m \cdot rad$

4% bad particles are removed

Summary

1. Beam dynamics simulations from the RF gun to the entrance of SASE1 have been done for energy dechirping study.

   (1) Parameters optimization for the accelerating modules and the bunch compressors to obtain electron bunch with flat top and linear energy distribution.

   (2) Space charge, CSR and longitudinal cavity wakefield effects were taken into account in the simulation.

2. After parameters optimization, it is possible to obtain electron bunch with relative energy spread of <0.03% without a dechirper structure at 12 GeV for EXFEL.

   (1) A strong longitudinal geometric wakefield is generated in the main linac (L3) where the head of the bunch loads the tail. This loading is nearly linear for a uniform temporal distribution (flat top) and can be used to reduce the linearly correlated energy spread of the third bunch compressor chicane (BC2).

   (2) CSR impact in the collimator section is also helpful to reduce the energy spread.