TESLA-FEL 2013-04

Beam Dynamics Simulations for European XFEL

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Abstract

The European x-ray free electron laser (EXFEL) which is under construction will be a free electron laser facility based on self-amplified spontaneous emission (SASE). This facility can produce hard X-ray photons with 1 angstrom wavelength in undulator section SASE1, hard X-ray photons with 0.1-0.4 nm wavelength in section SASE2, and soft X-ray photons with 0.4-1.6 nm wavelength in section SASE3. Injector, 17.5 GeV superconducting linear accelerator, beam distribution system, undulator systems, photon beam lines and experimental stations are the main components of the facility. In this report, the results of beam dynamics simulations and radiation calculations for EXFEL sections SASE1 and SASE3 are presented. In the beam dynamics simulations, different numerical codes are used. The injector and the accelerator are studied with help of codes Astra, CSRTack and Elegant. Code Genesis 1.3 is used to simulate the physics in the undulator sections. This work describes beam optics comparison between the Astra+CSRTrack results and the Elegant results, parameter settings for bunch compressor chicanes, radio frequency (RF) parameters calculation for the accelerating modules, beam dynamics simulations for different bunch charge cases (1.0 nC, 0.5 nC, 0.25 nC, 0.1 nC and 0.02 nC) and SASE FEL radiation calculations for SASE1 and SASE3. During the simulations, space charge, coherent synchrotron radiation (CSR) and cavity wake field effects are included.

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1 INTRODUCTION

The European XFEL which is under construction will be a free electron laser facility based on SASE FEL. This facility will produce hard X-ray photons with 0.1nm wavelength in undulator section SASE1, hard X-ray photons with 0.1-0.4 nm wavelength in section SASE2, and soft X-ray photons with 0.4-1.6 nm wavelength in section SASE3. Injector, L-band superconducting linear accelerator, beam distribution system, undulators, photon beamlines and experimental stations are the main components of this facility. In this report, some results of beam dynamics simulations and radiation calculations for section SASE1 with codes Astra, CSRTrack and Genesis are given. This work includes beam optics comparison between the Astra+CSRTrack results and the Elegant results, parameter settings for bunch compressor chicanes, RF parameters calculation, beam dynamics simulations and radiation calculations for different bunch charge cases (1.0 nC, 0.5 nC, 0.25 nC, 0.1 nC and 0.02 nC) for SASE1. During the simulations, space charge, CSR and cavity wake field effects are included. In order to estimate the SASE1 impacts on the radiation properties of SASE3, the simulation from SASE1 to SASE3 has also been done for 0.5 nC case with SASE1 switched on and switched off. This simulation includes particle distribution conversion from Genesis to Astra, beam dynamics simulation for the extraction arc and FEL radiation calculation for SASE3.

2 START TO END SIMULATIONS FOR SASE1

A. Layout of European XFEL

Injector which includes a photocathode RF gun, L-band superconducting linac, beam distribution system, undulator systems, photon beam lines and experimental stations are the main components of EXFEL facility.

In the injector the electron bunches are produced from a photo cathode by a laser beam and accelerated to 6 MeV by a normal conducting 1.3 GHz RF gun which has 1.5 cell. After the gun the electron bunches are accelerated in an L-band superconducting accelerating section named ACC1 which has the same structure as the one for FLASH linac [1]. This section has 8 cavities. Each cavity is composed of 9 cells. Downstream of ACC1 section, a third harmonic (3.9 GHz) RF system named ACC39 can linearize the RF curvature distortion and minimize the beam tails in the next chicanes. ACC39 is a deaccelerating section. It consists of eight 9-cell cavities.

In the L-band superconducting linear accelerator, there are three accelerating sections with 1.3 GHz which named L1, L2, and L3 respectively. L1 has 1 unit (ACC2). This unit includes 4 modules and there are 8 cavities for each module. L2 has 3 units (ACC3-5, 12 modules) and each unit has the same structure as the one for L1. As the last accelerating section, L3 has 21 units (ACC6-26, 84 modules). Usually, the L3 will operate on crest.

The electron bunches generated from the injector will go through a laser heater and a diagnostic section. After the diagnostic section, the dogleg shifts the beam path by 2.75 m from the injector level to the main linac level. The laser heater has four 0.2 m dipole magnets and the reflection angle in horizontal plane in every dipole magnet is 5.7°. The momentum compaction factors of the laser heater are -0.0047 m for R56, 0.007 m for T566 and -0.0095 m for U5666 respectively. In the dogleg section, sixteen vertical dipole, fifteen quadrupole and sixteen sextupole magnets are used. For this section, R56 is -0.03009 m, T566 is 0.09942 m and U5666 is -0.14195 m.

There are three bunch compressor chicanes of C-type in vertical plane along the main linac. The first bunch compressor BC0 is located between the dogleg section and L1. Effective length of the dipole magnets in BC0 is 0.5 m and the distance between the first two dipole magnets is 1.0 m. The second bunch compressor BC1 is after L1. The effective length of the four dipole magnets in BC1 is 0.5 m and the distance between the first two magnets is 8.5 m. Between L2 and L3, BC2 also has four bending magnets with 0.5 m effective length. The distance between the first two magnets is same as the one in BC1. In principle, a proper energy distribution at the entrances of the bunch compressor chicanes can reduce the space charge effects. At the same time for a given beam bunch the lower momentum compaction factor for the chicanes can decrease coherent synchrotron radiation impacts on the beam bunch.

The main linac is followed by the collimation section and the beam distribution system. The collimation section for EXFEL can remove bad particles with off momentum. These bad particles could be lost inside the undulator and the relevant radiation may demagnetize the undulator permanent magnets. The collimation section can accept the electron bunches with different energies and transport them without any deterioration of both transverse and longitudinal beam parameters. This section includes 16 vertical bending magnets and the total deflection angle is 0.0209 degree. It is achromatic and isochronous. After that, the fast kicker system will direct the bunches to electron beam line 1 or beam line 2. After passing through beam line1, the beam bunches will go into SASE1 undulator system and produce hard X-ray radiation with 1 angstrom wavelength. There is a horizontal arc downstream of SASE1. This arc is achromatic but not isochronous with a small R56 of -0.11 mm, T566 of -0.0022 m and U5666 of 0.0066 m. After the arc section, the beam bunches will pass through the SASE3 undulator system and generate soft X-ray radiation with 0.4-1.6 nm. The layout of the main components for SASE1 and SASE3 is shown in Figure 1.

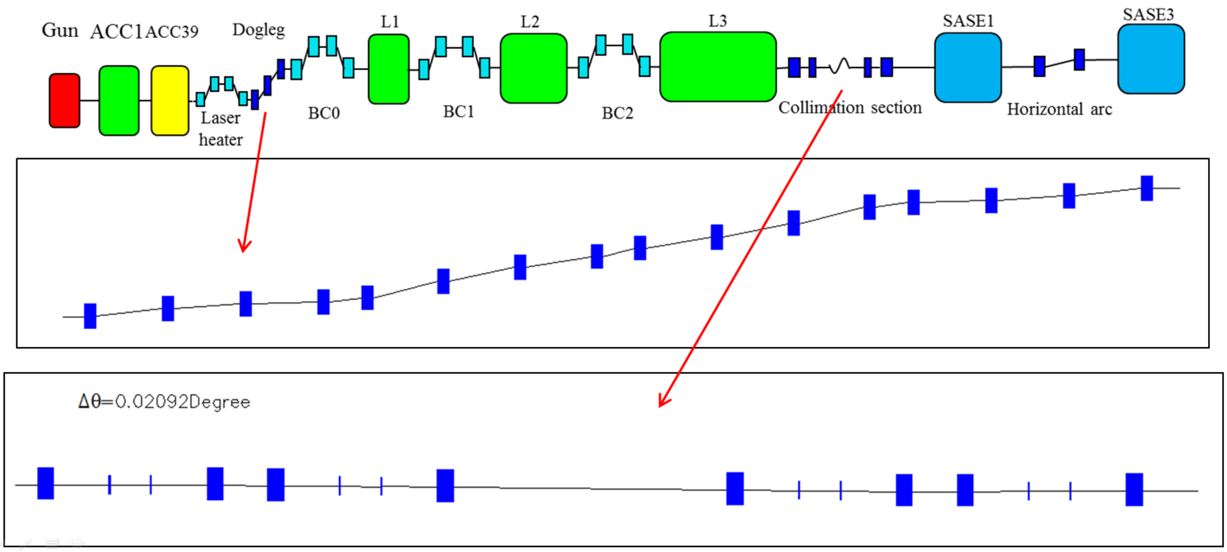


Figure 1. Main components layout for EXFEL SASE1 and SASE3

As to the electron bunches which are directed to beam line 2, they will pass through the SASE2 undulator system and hard X-ray radiation with 0.1-0.4 nm wavelength will be produced.

B. Input files Conversion from Elegant to Astra and CSRTrack

During the beam dynamics simulations for EXFEL, Astra, CSRTrack codes have been used. Space charge effects are included in the Astra calculation, coherence synchrotron radiation impacts are considered in the CSRTrack calculation and cavity wake field effects have been added at the end of each accelerating section by using the matlab scripts.

The description of the RF cavities and magnets is from the new version of EXFEL lattice definition [2] which has been written in MAD format. The file convertor [3] has been used for Excel to Elegant conversion. Figures 2 and 3 give the design optics for EXFEL SASE1 and SASE3. Astra preprocessor [4] has been used for the input files conversion from Elegant to Astra.

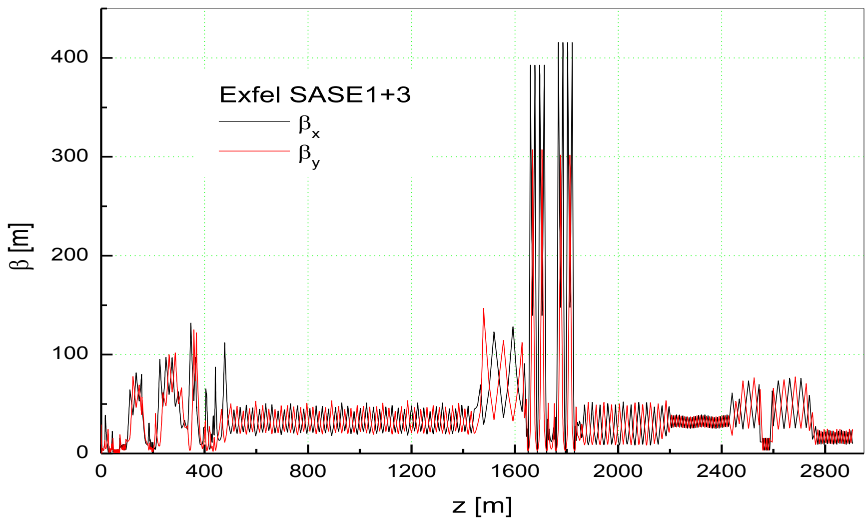


Figure 2. Betatron functions for EXFEL SASE1&3

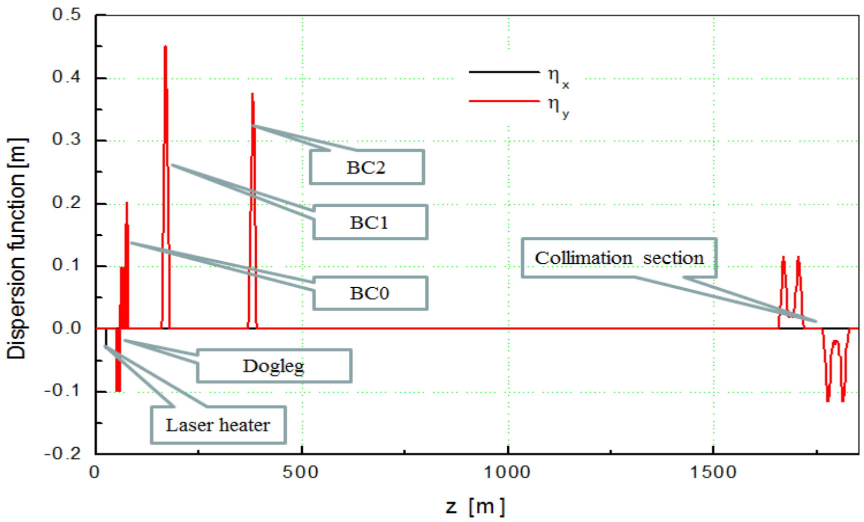


Figure 3. Dispersion functions for EXFEL SASE1

C. Beam Optics Comparison Between Elegant and Astra&CSRTrack Results

In order to make sure that the exact field strength and locations of the RF cavities and magnets were used in the Astra and CSRTrack calculation the beam optics comparison between Elegant and Astra&CSRTrack results has been done for 500 pC bunch charge case. During the calculation the exact parameters values of accelerating modules and bunch compressor chicanes have been used, which can affect the beam optics to a certain extent, especially the parameter settings of ACC1 and BC0. Collective effects were not included in the beam optics calculation. For Astra and CSRTrack calculation a thin beam bunch without energy spread has been used to exclude the chromatic aberration impact on the bunch. Figure 4 shows the betatron function comparison between elegant results and Astra+CSRTrack results. One can see, they are in good agreement with each other.

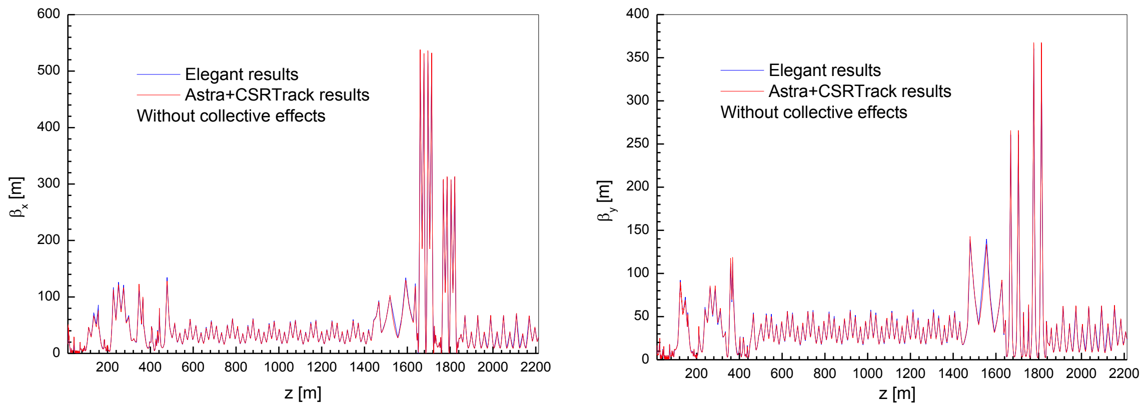


Figure 4. Betatron function comparison between Elegant and Astra+CSRTrack

D. Parameter Settings for Bunch Compressor Chicanes and RF Parameters Calculation for the accelerating modules

In order to get SASE FEL radiation with about 0.1 nm wavelength from SASE1, beam energy at the end of the linac should be about 17.5 GeV. Considering the requirement of short gain length: $L_g \sim \frac{\varepsilon^{5/6}}{\sqrt{I}}\left(1 + O(\sigma_E{}^2)\right)$, at the entrance of the undulator system, the bean bunches with high peak current, small slice emittance and low energy spread are needed. For EXFEL, the peak current before SASE1 is 5 kA. During the simulation, the nominal energies before BC0, BC1 and BC2 are fixed as follows: E_1=130 MeV, E_2=700 MeV, E_3= 2.4 GeV. The technical constraints on the RF power for the accelerating modules have been considered for these parameter settings.

As we know, the dogleg section is a weak longitudinal compression section. The momentum compaction factor R56 in the dogleg is about 30.1 mm. Following approach of [5], the total compression in the dogleg and BC0 is set to 3.5. The compression in BC1 is set to 8 like the one in the work mentioned before [5]. These parameter settings have been obtained considering the maximum RF voltage restriction and the RF tolerance for ACC1. For the three-stage bunch compression scheme, the estimation of the RF tolerance in ACC1 can be described by the following formula [7]:

$$\frac{|\Delta\widetilde{V_{11}}|}{{V_{11}}^{0}} = \frac{\Theta\bar{E}_1\bar{E}_2\bar{E}_3}{kV_{1,1}^{0}C_3C_2C_1\sqrt{A_3^2+B_3^2}}$$

Where

$$A_3 = r_{560}\bar{E}_2\,\bar{E}_3\,C_2^{-1}C_3^{-1} + r_{561}\bar{E}_1\bar{E}_3C_3^{-1} + r_{562}\bar{E}_1\bar{E}_2C_1^{-1}$$

$$B_3 \approx k[r_{560}(\bar{E}_2-\bar{E}_1)C_1^{-2}(\bar{E}_3r_{561}C_3^{-1}) + r_{562}(\bar{E}_3-\bar{E}_2)C_2^{-2}(\bar{E}_2r_{560}C_2^{-1}+\bar{E}_1r_{561})]$$

Θ is the tolerance for relative change of compression. $\bar{E}_i$ is the beam energy after the ith accelerating modules divided by the electron charge. C_i is the partial compression functions describing the compression for the ith bunch compressor. r_{56i} is the momentum compaction factor for the ith bunch compressor and k is the wave number of the fundamental RF frequency .

From [5] [6], we can also get the momentum compaction factor restrictions for the bunch compressors:

$$-120 \le \frac{r_{56,0}}{mm} \le 0 \text{ for BC0}$$

$$-120 \le \frac{r_{56,1}}{mm} \le -50 \text{ for BC1}$$

$$-80 \le \frac{r_{56,2}}{mm} \le -20 \text{ for BC2}$$

In order to reduce the space charge effects between the BC0 and BC1, a weak compression (smaller R_{56}) in BC0 has been used. RF power restrictions for ACC1 and ACC39 have also been considered during $R_{56,0}$ choice. For BC1 and BC2, the minimum values of R_{56} (-50 mm and -20 mm respectively) have been used to reduce the CSR impacts on the beam in the bunch compressors. Parameter settings for the bunch compressors for different bunch charge cases are shown in Table 1.

Table 1. Parameter settings for the bunch compressors

Charge Q, nC	$R_{56,dogleg}$ [mm]	$R_{56,BC0}$ [mm]	Compr. $C_{dogleg}\times C_0$	$R_{56,BC1}$ [mm]	Compr. in BC1, C1	$R_{56,BC2}$ [mm]	Total compr. C
1.0	-30.1	-62.00	3.5	-54	8	-20	118
0.5	-30.1	-54.80	3.5	-50	8	-20	217
0.25	-30.1	-48.20	3.5	-50	8	-20	385
0.10	-30.1	-43.90	3.5	-50	8	-20	870
0.02	-30.1	-41.40	3.5	-50	8	-20	4237

Before calculating the RF parameters of the accelerating modules, some parameters definition should be introduced. The transformation of the longitudinal coordinate in bunch compressor i can be described by

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

If the RF parameters and momentum compaction factors are fixed, the global compression function can be defined:

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

Where, the function $C_N(s)$ describes the increase of the peak current in the slice with initial position s and $Z_N(s)$is the inverse global compression function. For the linear compression in the middle of the bunch, the first and second derivatives of the global compression can be set to zero. Considering the relation between the derivative of the global compression and the derivative of the inverse global compression function [7], we also can set $Z'_N = 0$ and $Z''_N = 0$ for the same purpose. As we know, Z'_N can decide the symmetry of the current profile and Z''_N can decide the FWHM value of the bunch length. In other words, one can symmetrize the current profile and avoid spikes at the head and tail of the bunch by adjusting Z'_N and Z''_N respectively.

For the three stage bunch compression scheme, when the collective effects are not included, we can get the relation among the RF parameters, the beam energy and the inverse global compression functions.

$$E_1 = E_1(V_1, \varphi_1, V_{39}\ \ \varphi_{39})$$

$$E_2 = E_2(V_1, \varphi_1, V_{39}, \varphi_{39}, V_2, \varphi_2)$$

$$E_3 = E_3(V_1, \varphi_1, V_{39}, \varphi_{39}, V_2, \varphi_2, V_3, \varphi_3)$$

$$E_4 = E_4(V_1, \varphi_1, V_{39}, \varphi_{39}, V_2, \varphi_2, V_3, \varphi_3, V_4)$$

$$Z_1 = \frac{\partial s_1}{\partial s}(0)$$

$$Z_2 = \frac{\partial s_2}{\partial s}(0)$$

$$Z_3 = \frac{\partial s_3}{\partial s}(0)$$

$$Z'_3 = \frac{\partial^2 s_3}{\partial s^2}(0)$$

$$Z''_3 = \frac{\partial^3 s_3}{\partial s^3}(0)$$

Where, E_1, E_2, E_3, E_4 are the beam energies after ACC39, after L1, after L2 and after L3 respectively. V_{39} and φ_{39} are the voltage amplitude and phase shift of ACC39. V_i and φ_i, i=1, 2, 3, are the RF parameters of ACC1, L1 and L2. The beam bunch will be accelerated on crest in L3 module, which means φ_4=0.

So, if we define the vectors $\vec{x}_0$ and $\vec{f}_0$ as follows.

$$\vec{x}_0 = \begin{pmatrix} V_1 \\ \varphi_1 \\ V_{39} \\ \varphi_{39} \\ V_2 \\ \varphi_2 \\ V_3 \\ \varphi_3 \\ V_4 \end{pmatrix} \quad \text{and} \quad \vec{f}_0 = \begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ Z_1 \\ Z_2 \\ Z_3 \\ Z_3' \\ Z_3'' \end{pmatrix}$$

The relation between $\vec{x}_0$ and $\vec{f}_0$ can be written by using nonlinear operator A_0

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

If the beam energies and the inverse global compression functions are fixed, the RF parameters can be obtained by using

$$\vec{x}_0 = A_0^{-1}(\vec{f}_0)$$

In reality the RF parameters solution obtained above will not produce the required compression because of the collective effects like space charge and CSR. In order to take these effects into account the fast 3D tracking simulation has been carried out [7]. By using an iterative procedure, the proper RF parameters for the accelerating modules are obtained by using

$$\vec{x}_n = A_0^{-1}\left[A_0(\vec{x}_{n-1}) + \vec{f}_0 - A_x(\vec{x}_{n-1})\right] \qquad n>0$$

$$\vec{x}_0 = A_0^{-1}(\vec{f}),$$

where nonlinear operator $A_x(\vec{x})$ is realized by a fast 3D tracking procedure for the given RF parameters vector $\vec{x}$.

The RF parameter settings for the accelerating modules for different bunch charge cases are shown in Table 2.

Table 2. RF parameter settings 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]
1.0	144.64	-0.77	24.51	148.68	643.83	27.5	1837.42	22.0
0.5	153.47	16.71	23.49	184.54	651.95	29.0	1864.74	24.0
0.25	156.24	18.73	24.64	187.07	646.70	28.1	1812.60	20.0
0.1	156.72	17.99	25.64	184.13	639.57	27.2	1831.21	21.5
0.02	162.24	22.88	26.69	193.72	638.63	26.81	1871.54	24.62

E. Beam Dynamics Simulations for EXFEL SASE1 Including Collective Effects

The beam dynamics simulations from start to the entrance of SASE1 undulator system have been done for different bunch charge cases. For all of the arc sections, like laser heater, dogleg, BC0, BC1, BC2 and the collimation section, CSRTrack code has been used taking into account the CSR impact. The beam tracking in the straight sections (including RF accelerating modules) with space charge effects has been simulated using Astra code. During the Astra simulation, the cylindrical symmetric algorithm was used in order to save time. The cavity wake field effects [8] [9] have been taken into account at the exit of each accelerating section by using the matlab scripts. For the simulations, transverse matching to the design optics has been done before the bunch compressors. 200000 particles were used for the simulations. Models of RF gun which can generate flat top current profile with different bunch charge are from the work [10].

For 1nC case the current profiles along the beam line are shown in Figure 5. One can see that the peak current is about 5 kA after BC2 and the symmetry of the current profile is not very good because of the collective effects.

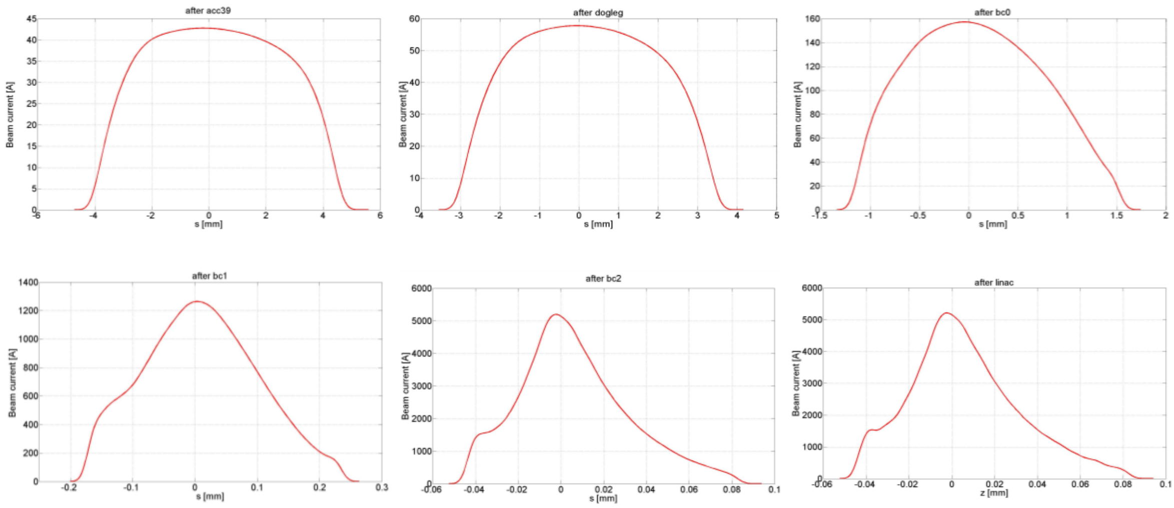
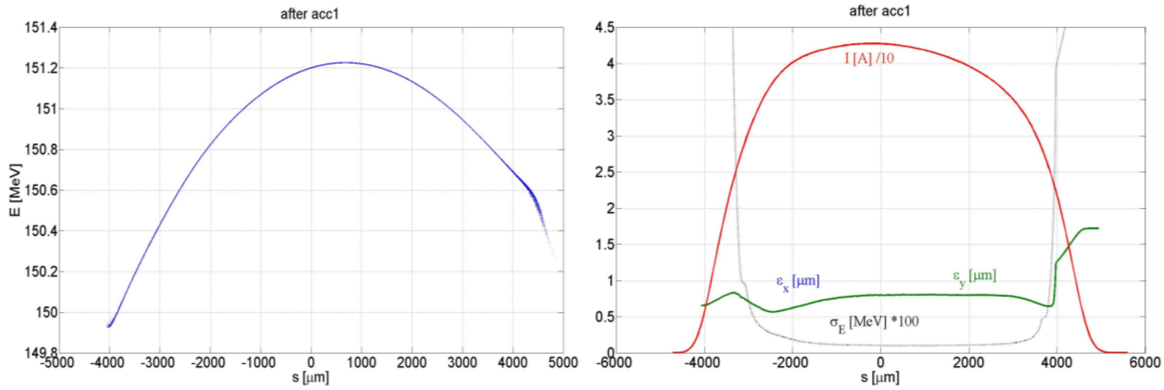
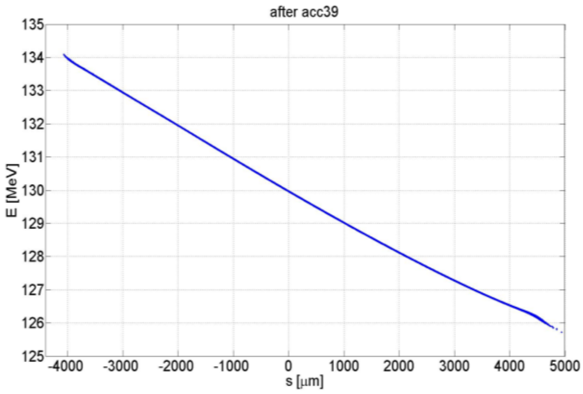
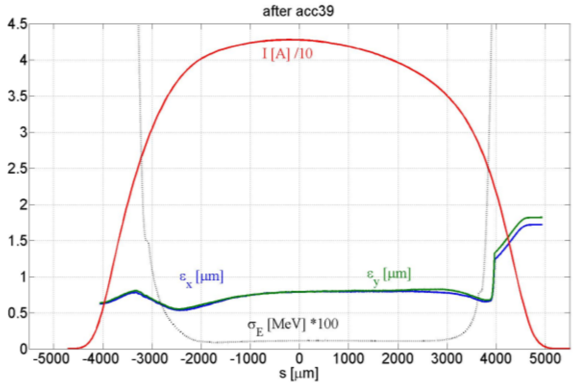


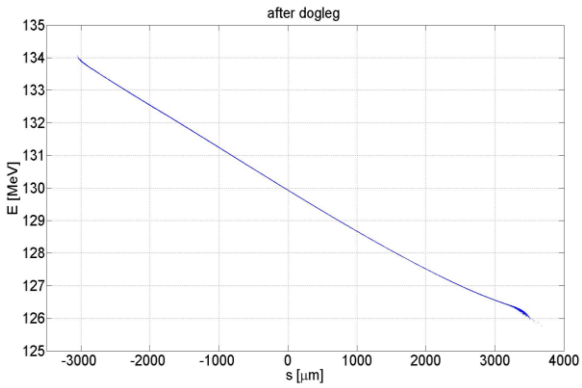
Figure 5. Current profile along the beam line for 1 nC case

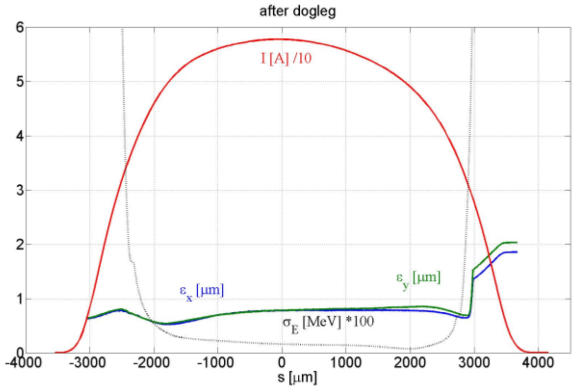
Figure 6 gives information about the current profile, longitudinal phase space, slice emittance and slice energy spread at some key positions: after ACC1, after ACC39, after dogleg, after BC0, before and after BC1, before and after BC2, before and after collimation section. One can see that the particle energy distribution has been linearized after ACC39. The dogleg is a weak compression section with a compression factor about 1.29. In BC0 and BC1 the CSR impacts are not very strong. But we can see the CSR impacts on the vertical slice emittance along the bunch. In BC2 the longitudinal phase space is distorted by CSR impact. This distortion becomes larger after L3 because of the cavity wake field effects. One also can see the CSR impact on the beam in the collimation section.

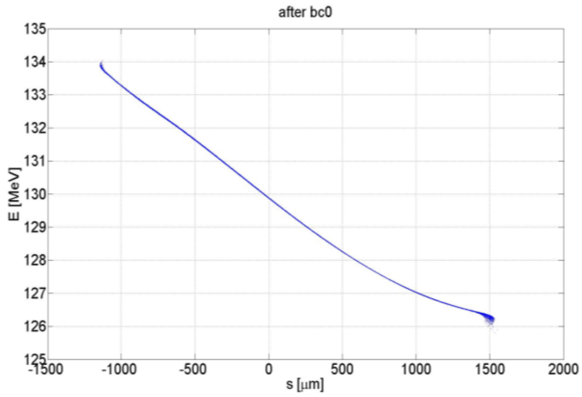


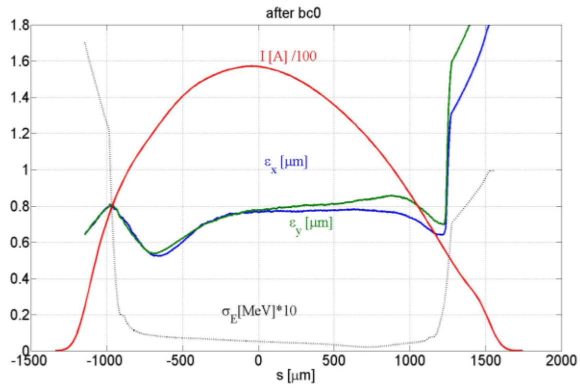

after acc39
E [MeV]
s [µm]

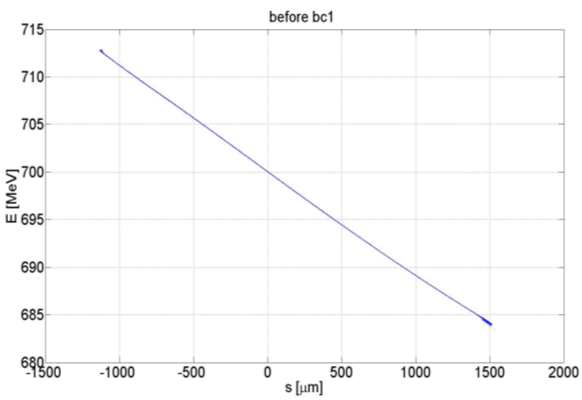

after acc39
I [A] /10
εx [µm]
εy [µm]
σE [MeV] *100
s [µm]

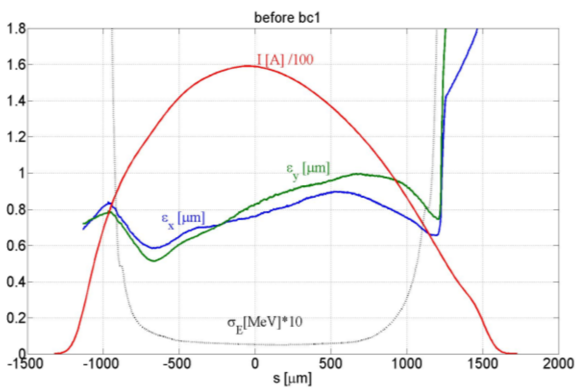

after dogleg
E [MeV]
s [µm]

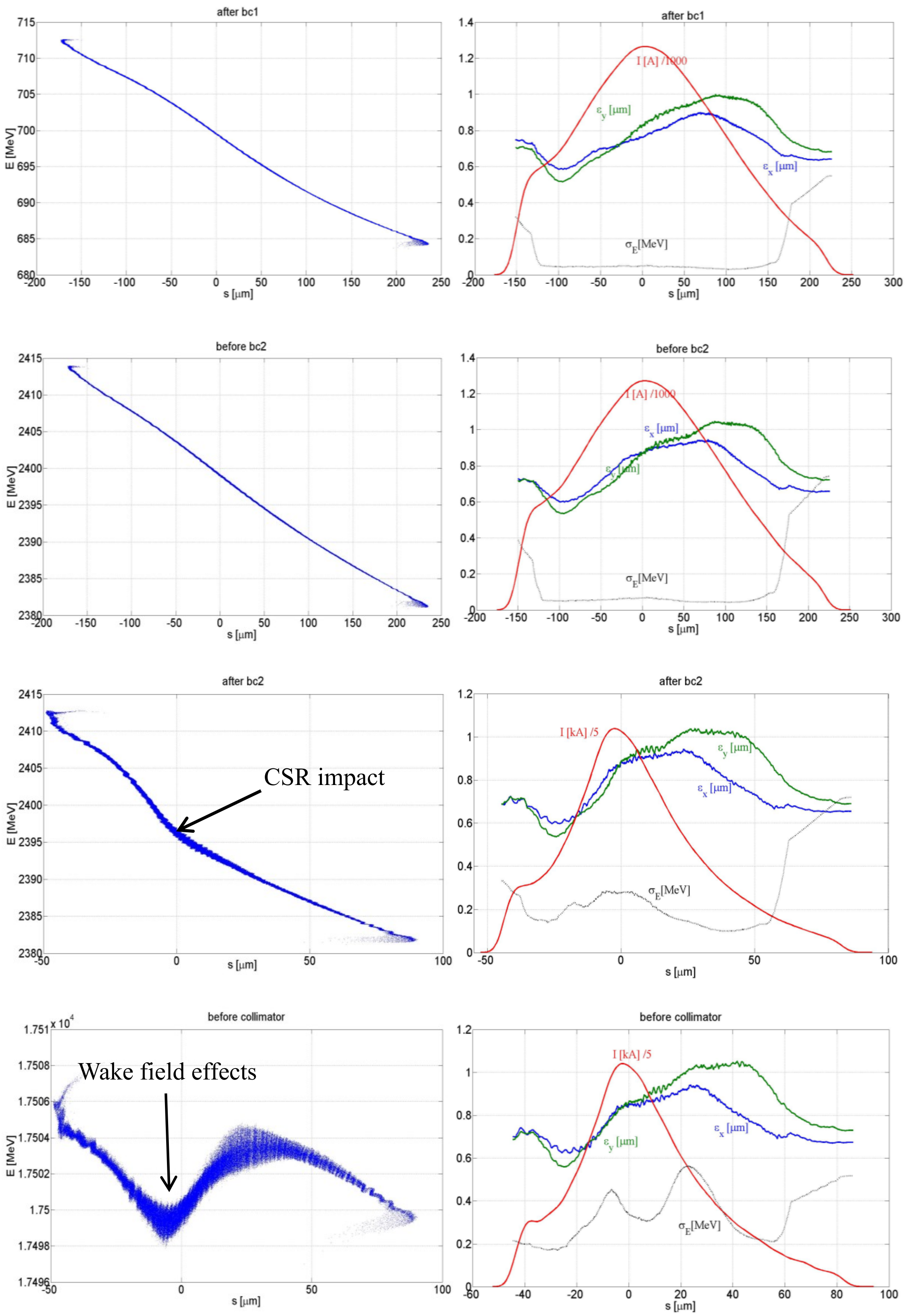

after dogleg
I [A] /10
εx [µm]
εy [µm]
σE [MeV] *100
s [µm]


after bc0
E [MeV]
s [µm]


after bc0
I [A] /100
εx [µm]
εy [µm]
σE[MeV]*10
s [µm]


before bc1
E [MeV]
s [µm]


before bc1
I [A] /100
εy [µm]
εx [µm]
σE[MeV]*10
s [µm]


after bc1
E [MeV]
s [µm]
I [A] /1000
εy [µm]
εx [µm]
σE[MeV]
before bc2
after bc2
I [kA] /5
CSR impact
before collimator
x 10^4
Wake field effects

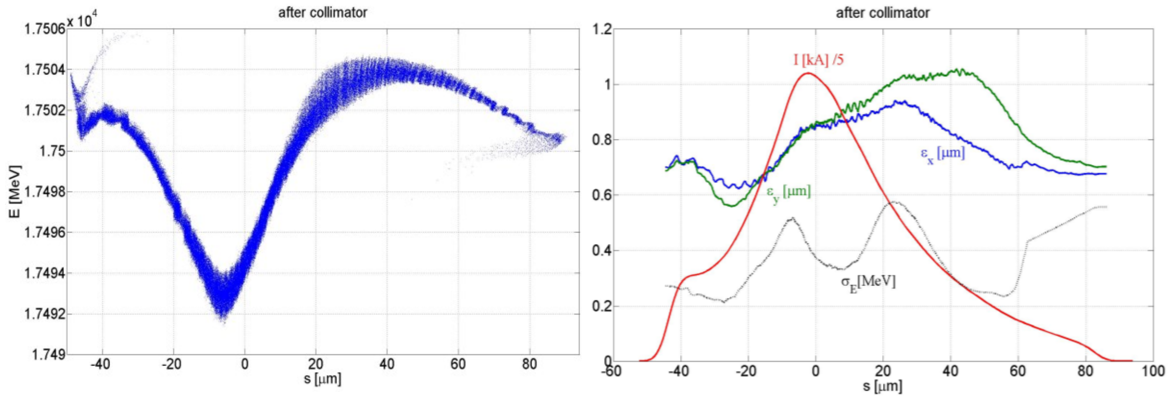


Figure 6. Longitudinal phase space, slice emittance and energy spread for 1 nC

The beam bunch properties at the entrance of SASE1 undulator system are shown in Figure 7. The projected emittance in horizontal plane is 0.9 μm and 2.4 μm in vertical plane. About 4% bad particles at the head and tail of the bunch have been removed from the analysis when these two plots had been prepared.

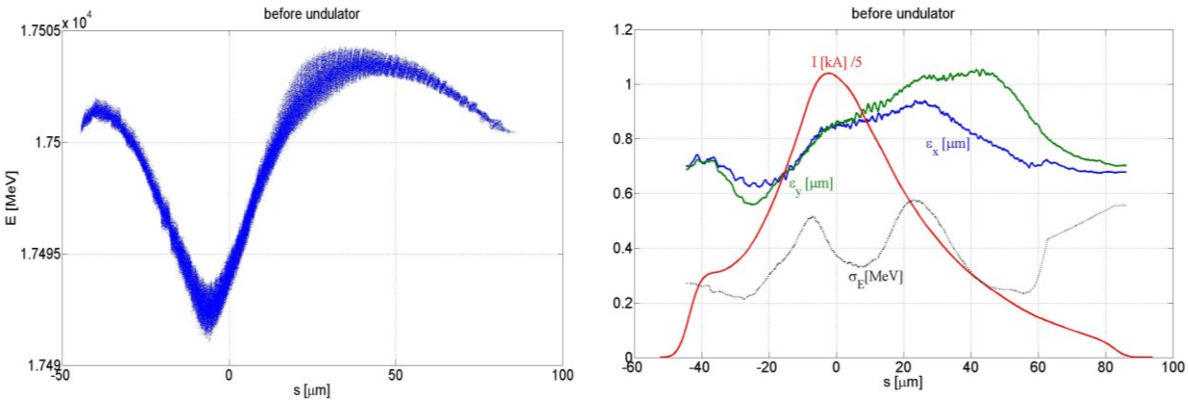
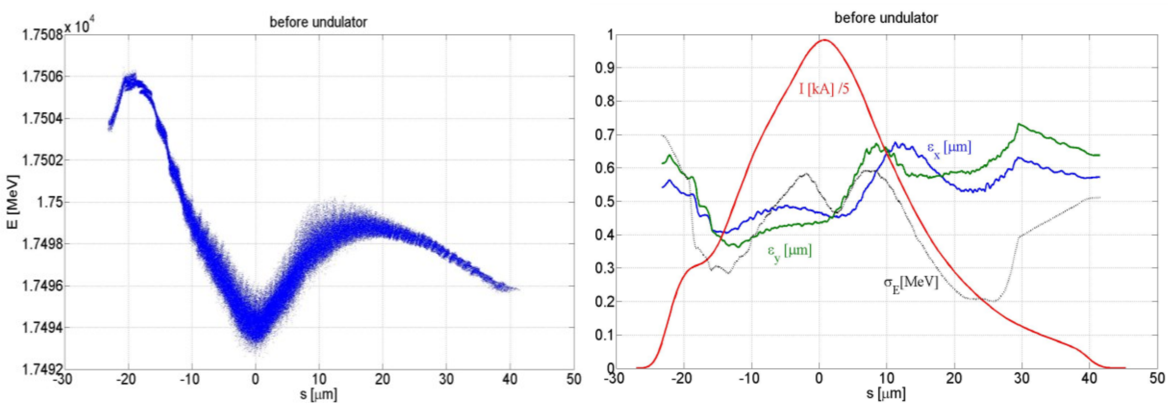
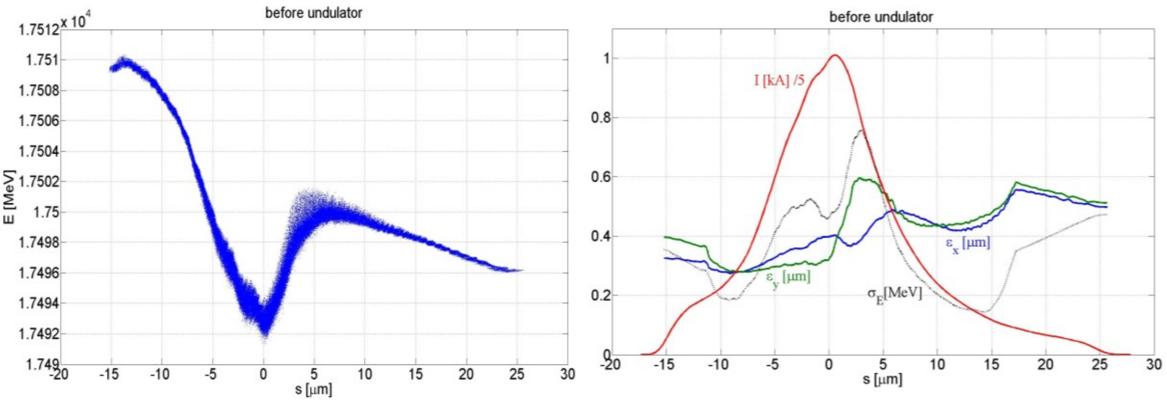


Figure 7. Beam properties before SASE1 for 1 nC case

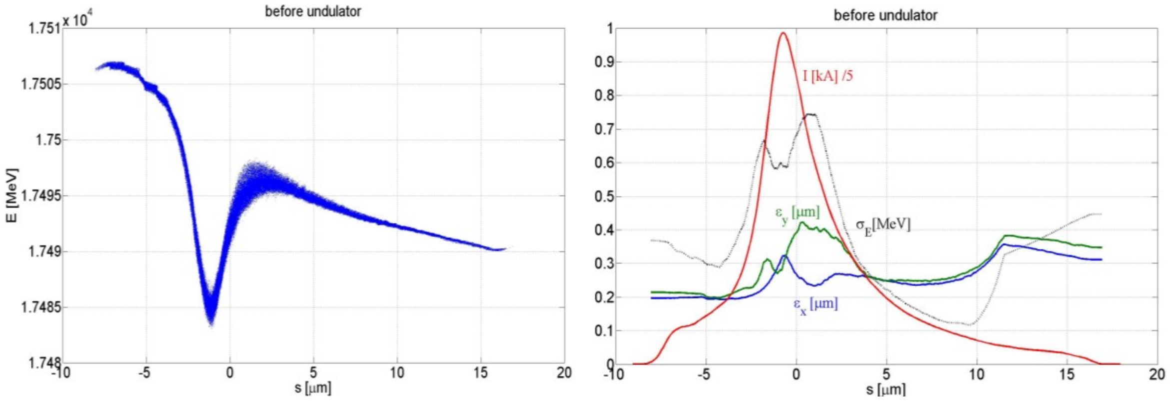
The current profile, the longitudinal phase space, the slice emittance and the slice energy spread before SASE1 undulator system for other bunch charge cases (0.5 nC, 0.25 nC, 0.1 nC and 0.02 nC) are shown in Figure 8. The plots for beam properties along the beam line for these cases can be found in the Appendix.



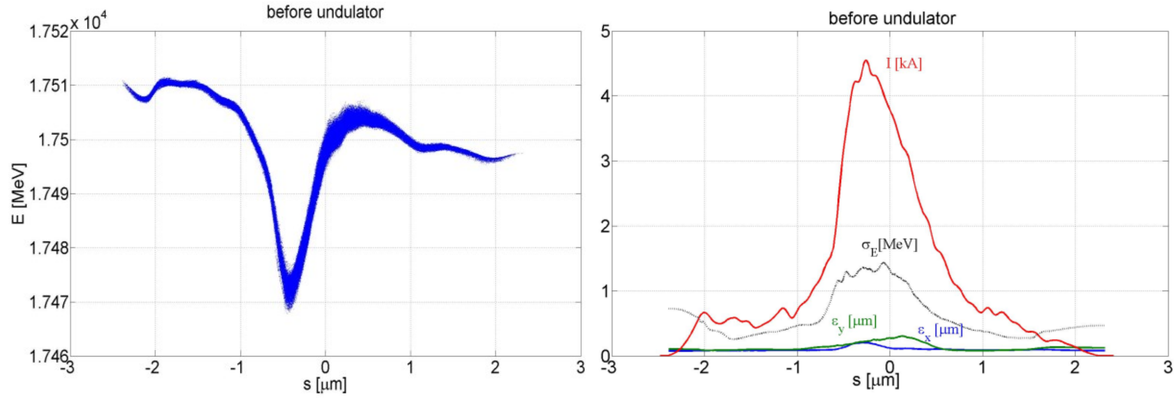
(a)



(b)



(c)



(d)

Figure 8. Beam properties before SASE1 for other bunch charge cases

(a: 0.5 nC, b:0.25 nC, c:0.1 nC, d:0.02 nC)

Table 3 gives a summary of beam parameters after the gun and before SASE1 from the beam dynamics simulations.

Table 3. Beam parameters from the beam dynamics simulations

Parameter	Unit					
Bunch charge	nC	1	0.5	0.25	0.1	0.02

Peak current (gun)	A	43	23.8	13.5	5.7	1.18
Bunch length (gun, FWHM)	ps	24.8	22.3	20.0	18.5	17.4
Projected emittance (gun)	μm	1.1	0.60	0.43	0.26	0.11
Compression		121	208	374	842	3814
Peak current	kA	5.2	4.95	5.05	4.8	4.5
Bunch length (FWHM)	fs	154	86	38.4	12.0	3.0
Projected emittance (y)	μm	2.4	1.8	1.6	0.64	0.37

F. Comparison with Elegant simulation results

The results of Astra and CSRTrack calculations have been compared with outputs of Elegant calculations. Using the beam distribution of the Astra calculation from the gun to the end of ACC1 cavity the Elegant calculation is carried out to the entrance of SASE1 undulators.

Collective effects have been included in the Elegant calculation. The longitudinal space charge effect and the coherent synchrotron radiation impact are taken into account and cavity wake fields are added at the end of each accelerating section. However, the transverse space charge effect is not applied in these calculations.

A CPU time of Elegant calculation is shorter than one of Astra and CSRTrack calculations. It takes about 10 minutes for one Elegant calculation with 64 CPUs.

The identical settings of the bunch compressors as shown in Table 1 are used in Elegant calculations, and the RF parameters are adjusted for each bunch charge case to achieve some compression conditions. Table 4 gives the RF parameter settings for the accelerating modules for different bunch charge cases used in Elegant calculations. These RF parameter settings are slightly different from ones of Astra and CSRTrack calculations.

Table 4. RF parameter settings for different bunch charge cases in Elegant calculation

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]
1.0	147.4	9.50	22.01	171.15	649.40	28.5	1838.38	22.1
0.5	153.8	16.90	23.76	185.99	657.43	29.8	1810.49	19.9
0.25	160.7	22.90	25.73	196.79	650.00	28.7	1844.06	22.6
0.1	164.2	25.00	27.10	199.44	644.62	27.8	1865.57	24.2
0.02	163.4	23.86	27.29	195.89	641.41	27.3	1888.46	25.7

Figure 9 shows the comparison of longitudinal phase spaces, beam currents, transverse slice emittances, and slice energy spreads between the Elegant and the Astra & CSRTrack calculations after L3 for bunch charge 1 nC. About 4 % bad particles are removed at the head and tail of the bunch in the analysis. The total bunch length of the Elegant calculation is shorter than one of Astra and CSRTrack calculations, but rms bunch lengths are identical in both calculations. Peak beam currents and transverse slice emittances are also similar in both calculations. However, the slice energy spread of the Elegant calculation is smaller than one of Astra and CSRTrack calculation because of the transverse space charge effect. In spite of different collective effects calculations, the Elegant calculation produces a similar output distribution for 1 nC case.

Figure 10 shows the comparison of longitudinal phase spaces, beam currents, transverse slice emittances, and slice energy spreads between the Elegant and the Astra & CSRTrack calculations after L3 for a bunch charge 250 pC. The beam profiles acquired by Elegant calculations are also comparable to the results of Astra and CSRTrack calculations for this bunch charge. For other bunch charges, 0.5, 0.1, and 0.02 nC, the similar results are obtained in both calculations.

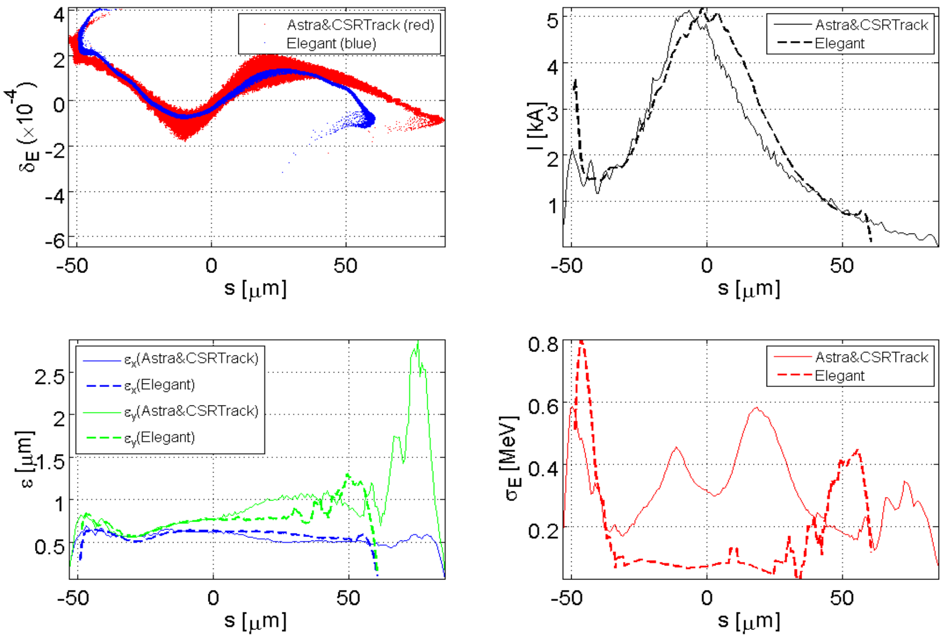


Figure 9. Comparison of longitudinal phase spaces (top-left), current profiles (top-right), transverse slice emittances (bottom-left), and slice energy spreads (bottom-right) along the beam line between Elegant and Astra & CSRTrack calculations after L3 for 1 nC case

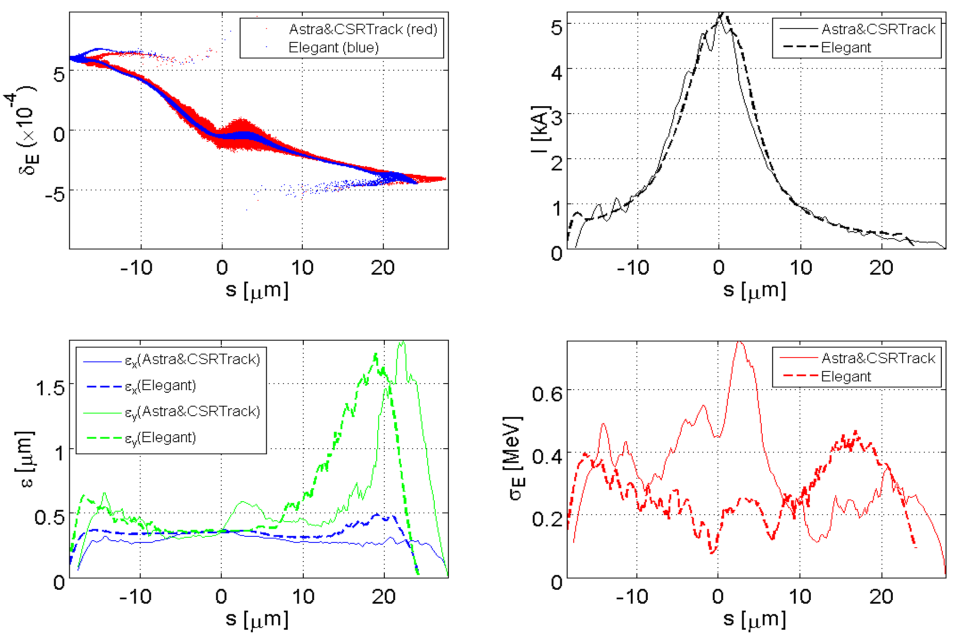


Figure 10. Comparison of longitudinal phase spaces (top-left), current profiles (top-right), transverse slice emittances (bottom-left), and slice energy spreads (bottom-right) along the beam line between Elegant and Astra & CSRTrack calculations after L3 for 0.25 nC case.

G. FEL Radiation Calculations for SASE1

For SASE1 undulator system the periodic length of undulator is 0.04 m. The value 2.13676 of normalized dimensionless undulator parameter has been used. SASE FEL radiation calculations have been done using code Genesis. During the calculation 10 random seeds have been used for each bunch charge case. The mean single pulse radiation energies along the undulator for different bunch charge cases are shown in Figure 11 and Table 5 gives the radiation properties from Genesis calculations. One also can see from Figure 11 that the different transverse emittances lead to different saturation lengths.

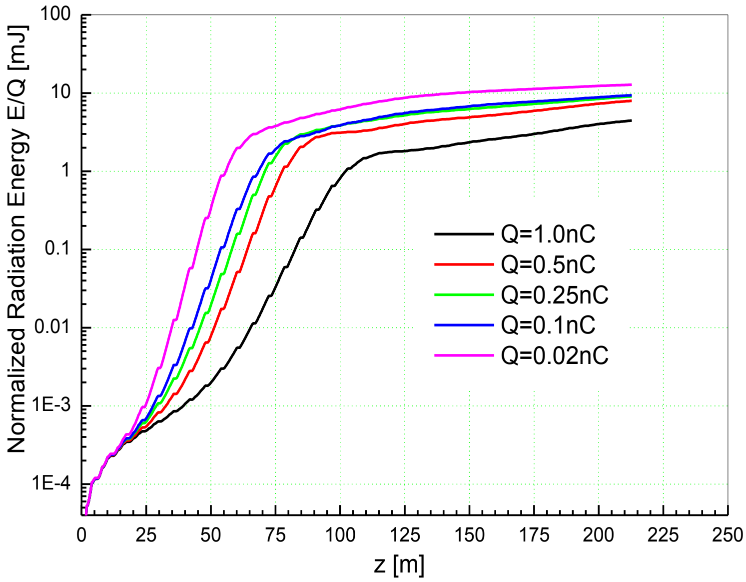


Figure 11. Mean radiation energies for different bunch charge cases

Table 5. SASE1 FEL Radiation properties from Genesis calculations

Bunch charge, nC	1.0	0.5	0.25	0.1	0.02
Wavelength, nm	0.1				
Beam energy, GeV	17.5				
Peak current, kA	5.0				
Saturation length, m	110	88	80	75	62
Mean radiation energy in the pulse, mJ	4.5	4.0	2.3	0.9	0.3
Averaged peak power, GW	41	55	69	80	110

3 SIMULATION FOR SASE3

In order to study the SASE1 impact on the radiation properties of SASE3, beam dynamics simulation has been done from SASE1 to the entrance of SASE3 for 500 pC bunch charge case, as well as the radiation calculation for SASE3.

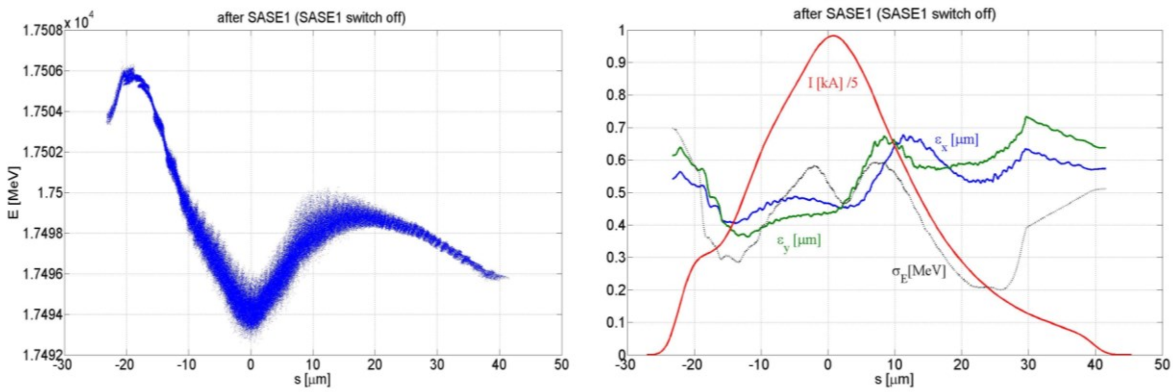
A. Particle Distribution Conversion from Genesis to Astra

Particle distribution file conversion from Genesis output to Astra input should be done to get the input particle file for the next beam dynamics simulation.

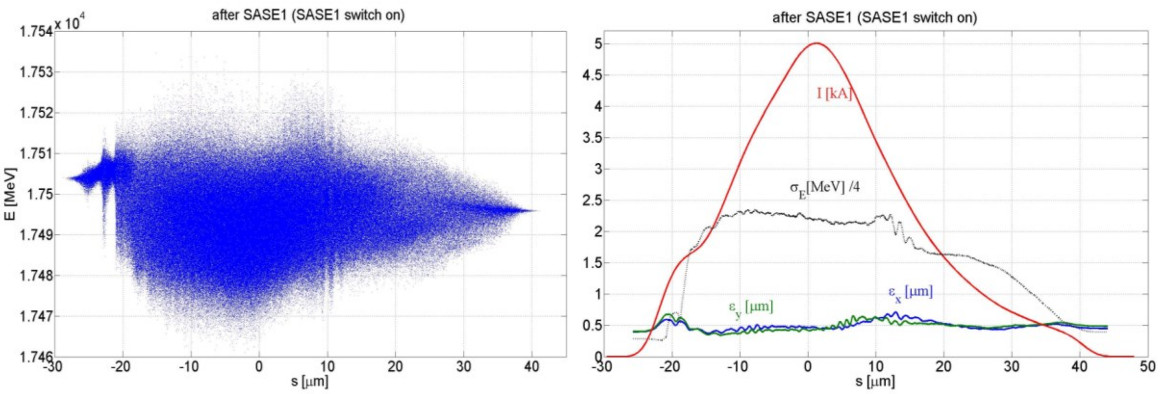
For this special purpose of Genesis calculation the newest version of the code (Version 3) has been used. For the new version of Genesis the output files are produced in HDF5 format to reduce their sizes.

In order to make sure that macro particles have the same charge, parameter IONE4ONE has been set to 1.

Beam properties at the entrance of SASE1 undulator system for 500 pC case are shown in Figure 8 (a). To study the SASE1 undulator impact on the beam properties two operation modes have been calculated: (1) SASE1 is switched off; (2) SASE1 is switched on. Beam properties after SASE1 for the two cases are shown in Figure 12. One can see that when SASE1 is switched on the transverse emittance changes little. But the slice energy spread becomes larger. The maximum value is about 9 MeV.



(a)



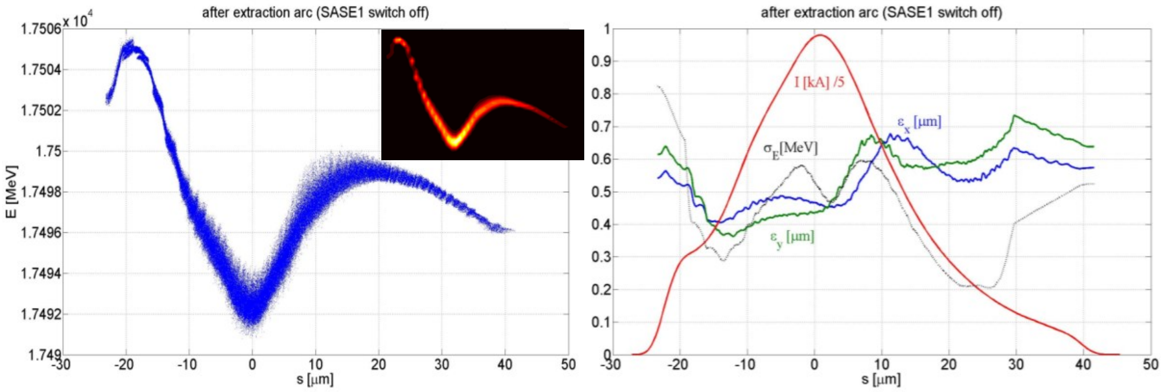
(b)

Figure 12. Beam properties after SASE1 for 0.5 nC case

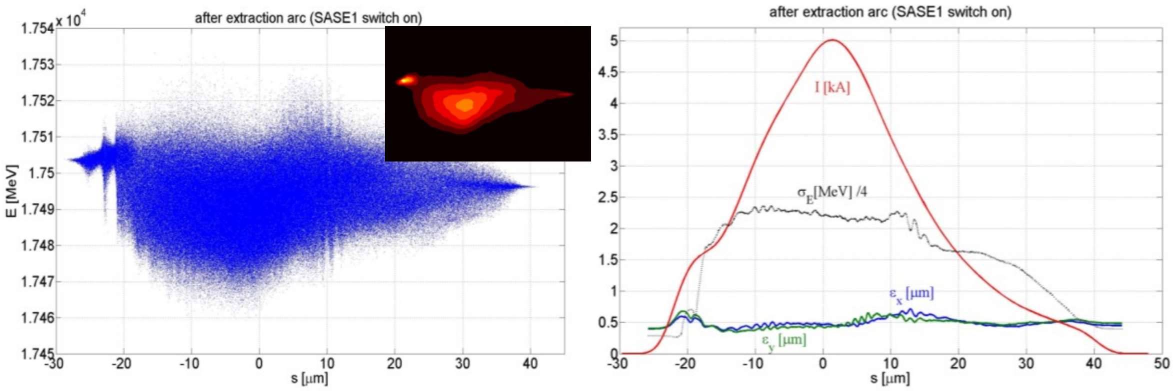
(a: SASE1 switched off, b: SASE1 switched on)

B. Beam Dynamics Simulation for the Extraction Arc before SASE3

Between SASE1 and SASE3 undulator systems there is an extraction arc which includes two horizontal bending magnets. The effective length of each dipole magnet is 2.5 m and the total reflection angle in the horizontal plane for the extraction arc is 1.3182°. Code Astra has been used for the straight section and code CSRTack for the arc section. The results after the extraction arc with SASE1 switched off and switched on are shown in Figure 13. It can be seen that the impact of extraction arc on the beam is not strong.



(a)



(b)

Figure 13. Beam properties after the extraction arc for 0.5 nC case

(a: SASE1 switched off, b: SASE1 switched on)

C. Radiation Calculation for SASE3

In SASE3 undulator system the periodic length of undulator is 0.068 m and the value of normalized dimensionless undulator parameter is 3.63497. Code Genesis has been used for an estimation of SASE3 radiation. The radiation wave length is about 0.4 nm. The mean single pulse radiation energies along the undulator for two cases (with SASE1 switched on and switched off) are shown in Figure 14. One can see that when SASE1 switched on the radiation energy is about 3 times lower than the one when SASE1 switched off.

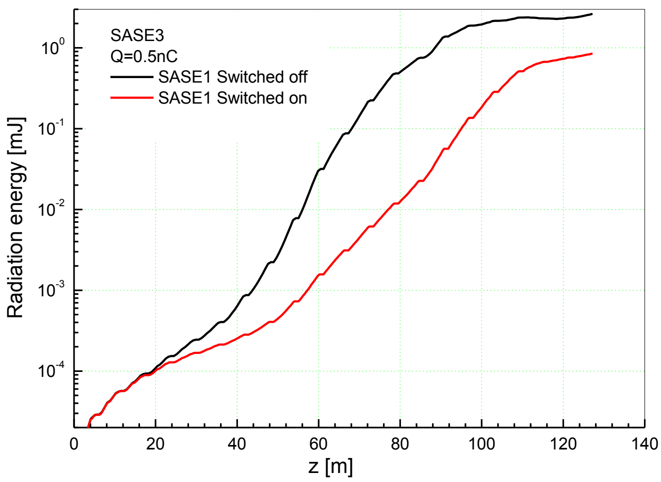


Figure 14. Comparison of mean radiation energy for 0.5 nC bunch charge case

4 SUMMARY

The beam dynamics simulations and SASE FEL radiation calculations have been done for EXFEL SASE1 for different bunch charge cases. Code Astra has been used for the straight sections and code CSRTack for the arc sections. The radiation calculations have been done using code Genesis. During the simulations space charge, CSR and cavity wake field effects are considered. In order to estimate the SASE1 impact on the radiation properties of SASE3, the simulation from SASE1 to SASE3 has also been done for 0.5 nC case with SASE1 switched on and switched off.

5 ACKNOWLEDGEMENTS

We are grateful to Vladimir Balandin, Nina Golubeva, Sascha Meykopff, Olga Zagorodnova and Matthias Scholz for their support and help for this work.

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APPENDIX

1. 0.5nC bunch charge case

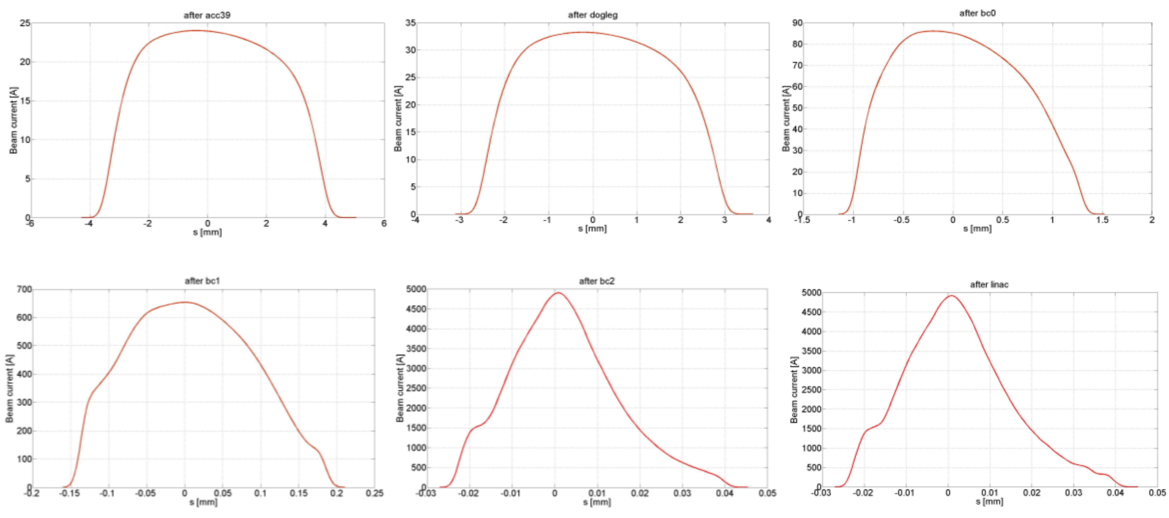
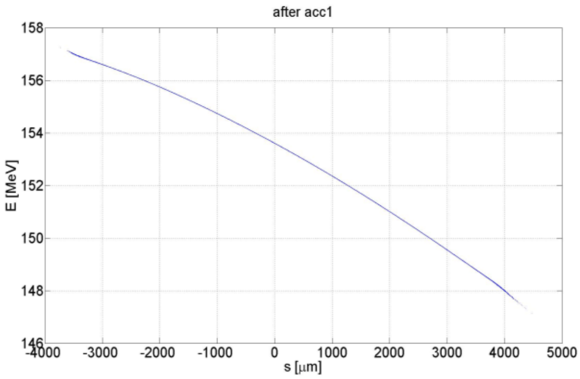
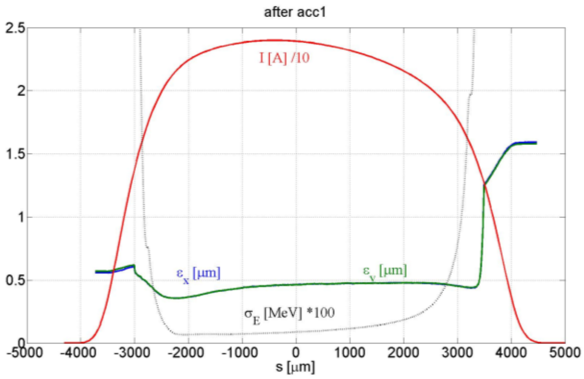
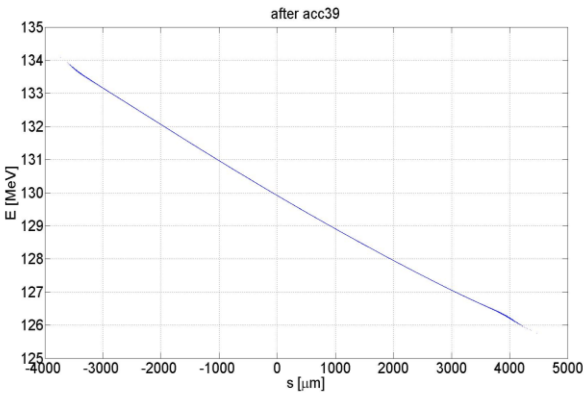
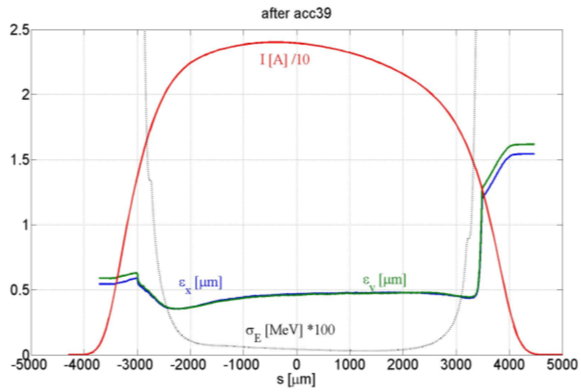


Figure 15. Current profile along the beam line for 0.5nC case


after acc1
E [MeV]
s [μm]


after acc1
I [A] /10
ε_x [μm]
ε_y [μm]
σ_E [MeV] *100
s [μm]


after acc39
E [MeV]
s [μm]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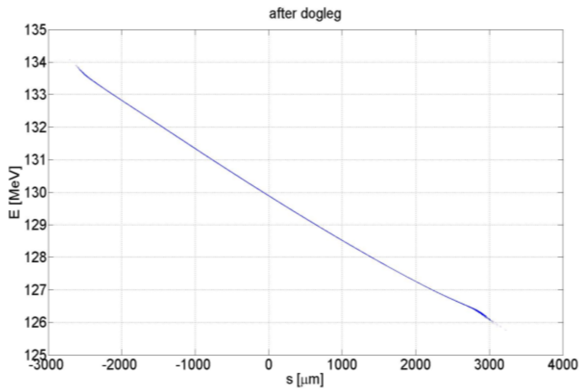
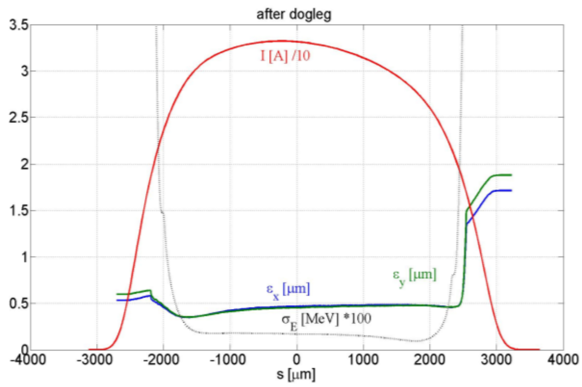
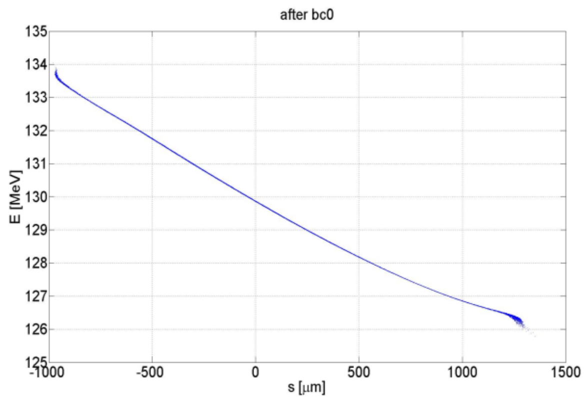
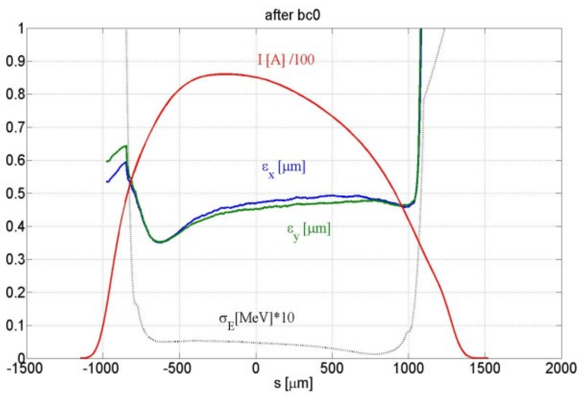
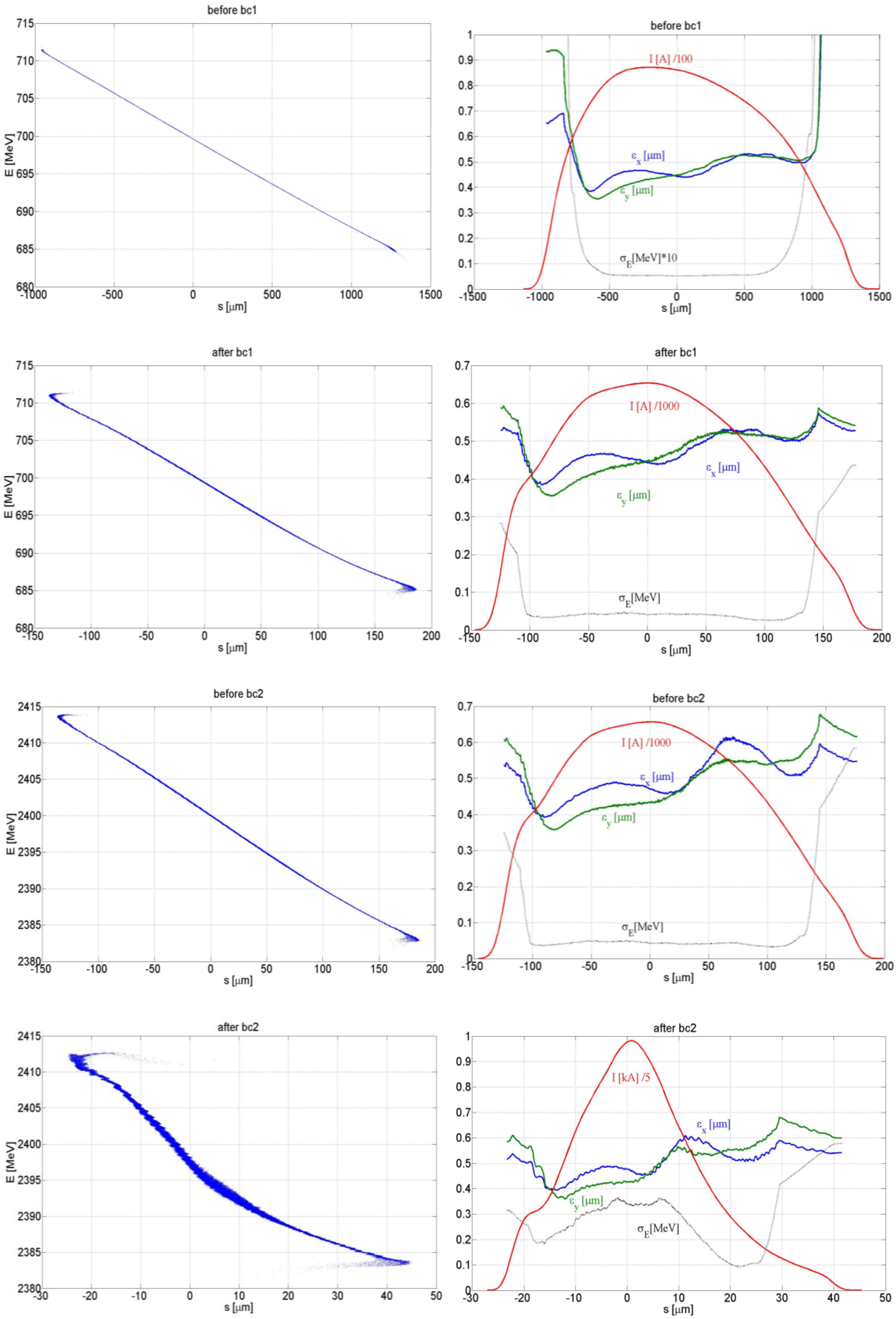
I [A] /10
ε_x [μm]
ε_y [μm]
σ_E [MeV] *100
s [μm]


after dogleg
E [MeV]
s [μm]


after dogleg
I [A] /10
ε_x [μm]
ε_y [μm]
σ_E [MeV] *100
s [μm]


after bc0
E [MeV]
s [μm]


after bc0
I [A] /100
ε_x [μm]
ε_y [μm]
σ_E[MeV]*10
s [μm]


before bc1
E [MeV]
s [μm]
I [A] /100
εx [μm]
εy [μm]
σE[MeV]*10
after bc1
I [A] /1000
σE[MeV]
before bc2
after bc2
I [kA] /5

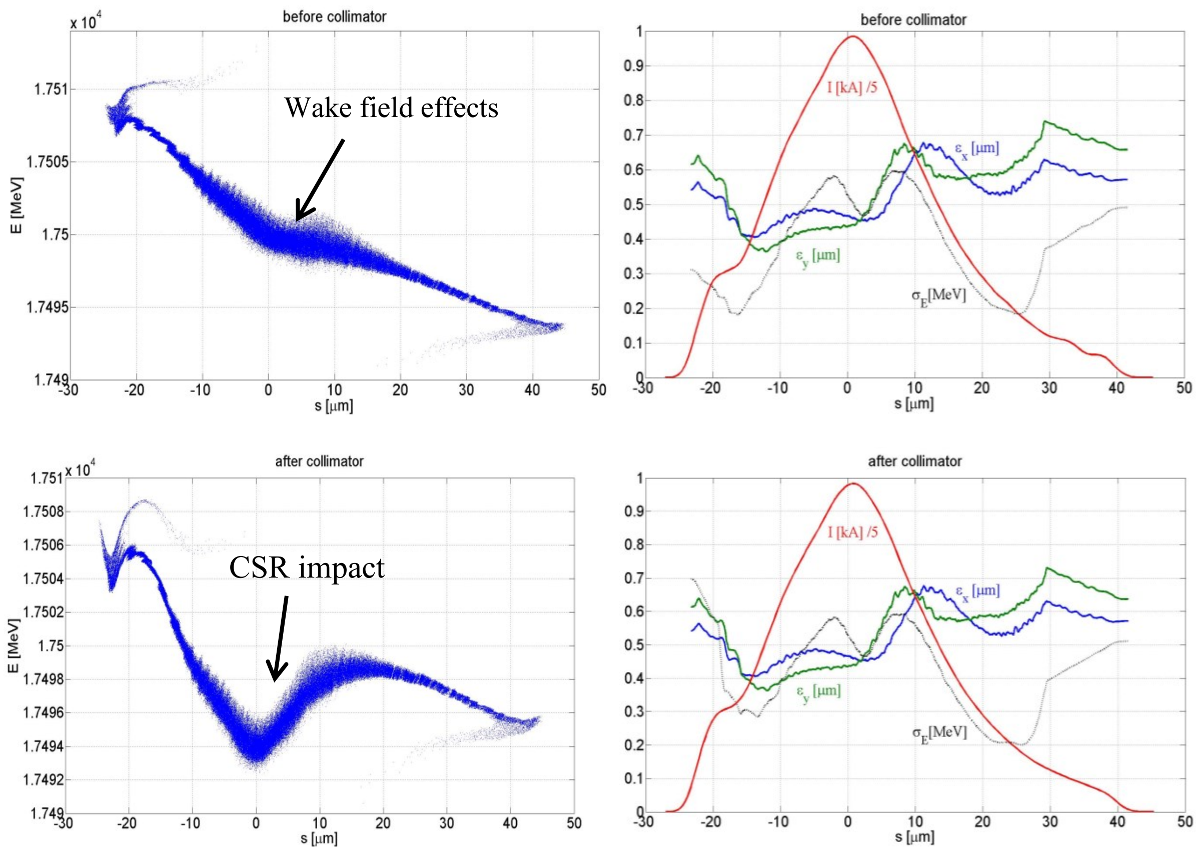


Figure 16. Longitudinal phase space, slice emittance and energy spread for 0.5nC case

2. 0.25nC bunch charge case

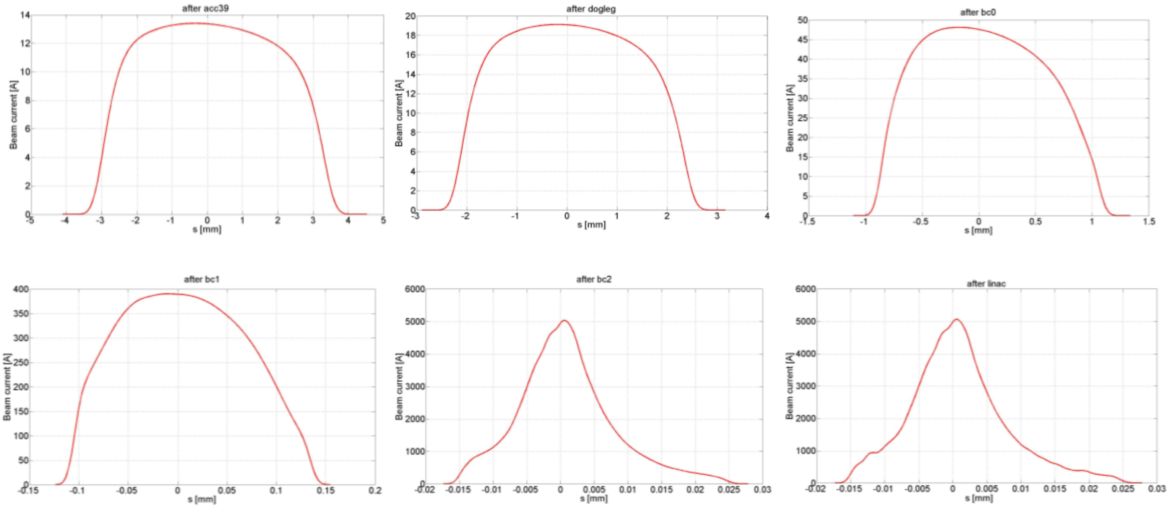
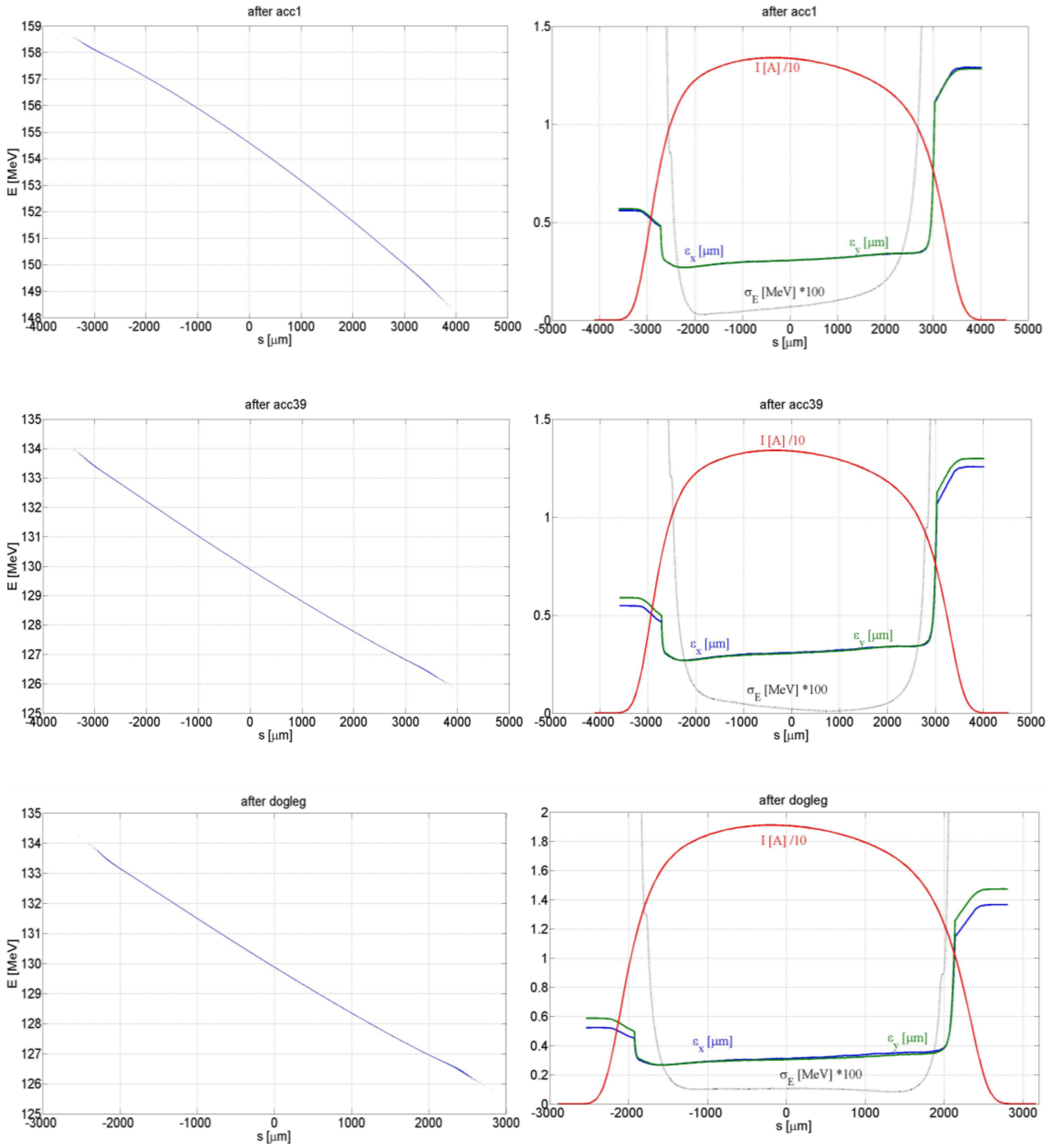
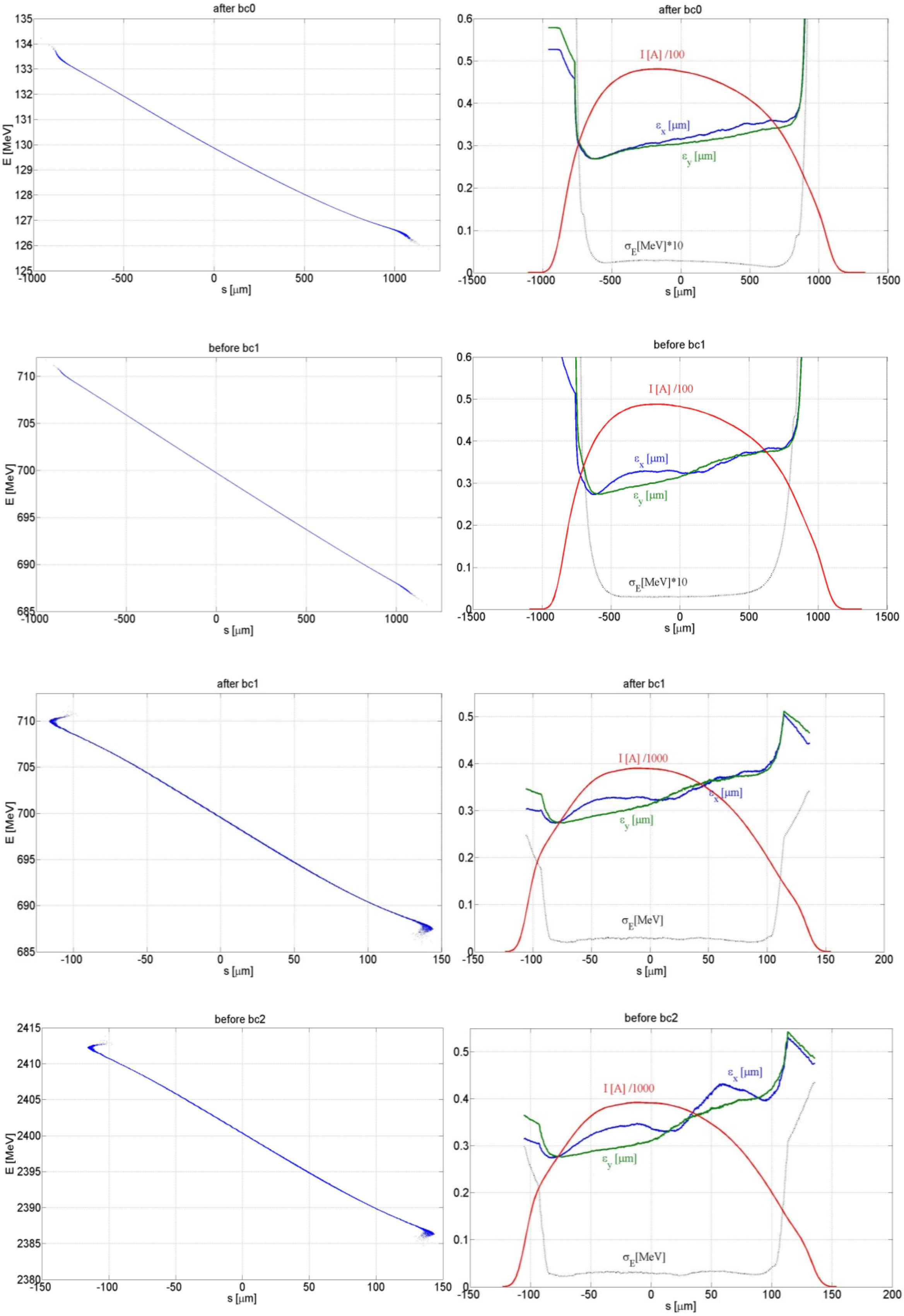


Figure 17. Current profile along the beam line for 0.25nC case




after bc0
E [MeV]
s [µm]
after bc0
I [A] /100
ε_x [µm]
ε_y [µm]
σ_E[MeV]*10
s [µm]
before bc1
E [MeV]
s [µm]
before bc1
I [A] /100
ε_x [µm]
ε_y [µm]
σ_E[MeV]*10
s [µm]
after bc1
E [MeV]
s [µm]
after bc1
I [A] /1000
ε_x [µm]
ε_y [µm]
σ_E[MeV]
s [µm]
before bc2
E [MeV]
s [µm]
before bc2
I [A] /1000
ε_x [µm]
ε_y [µm]
σ_E[MeV]
s [µm]

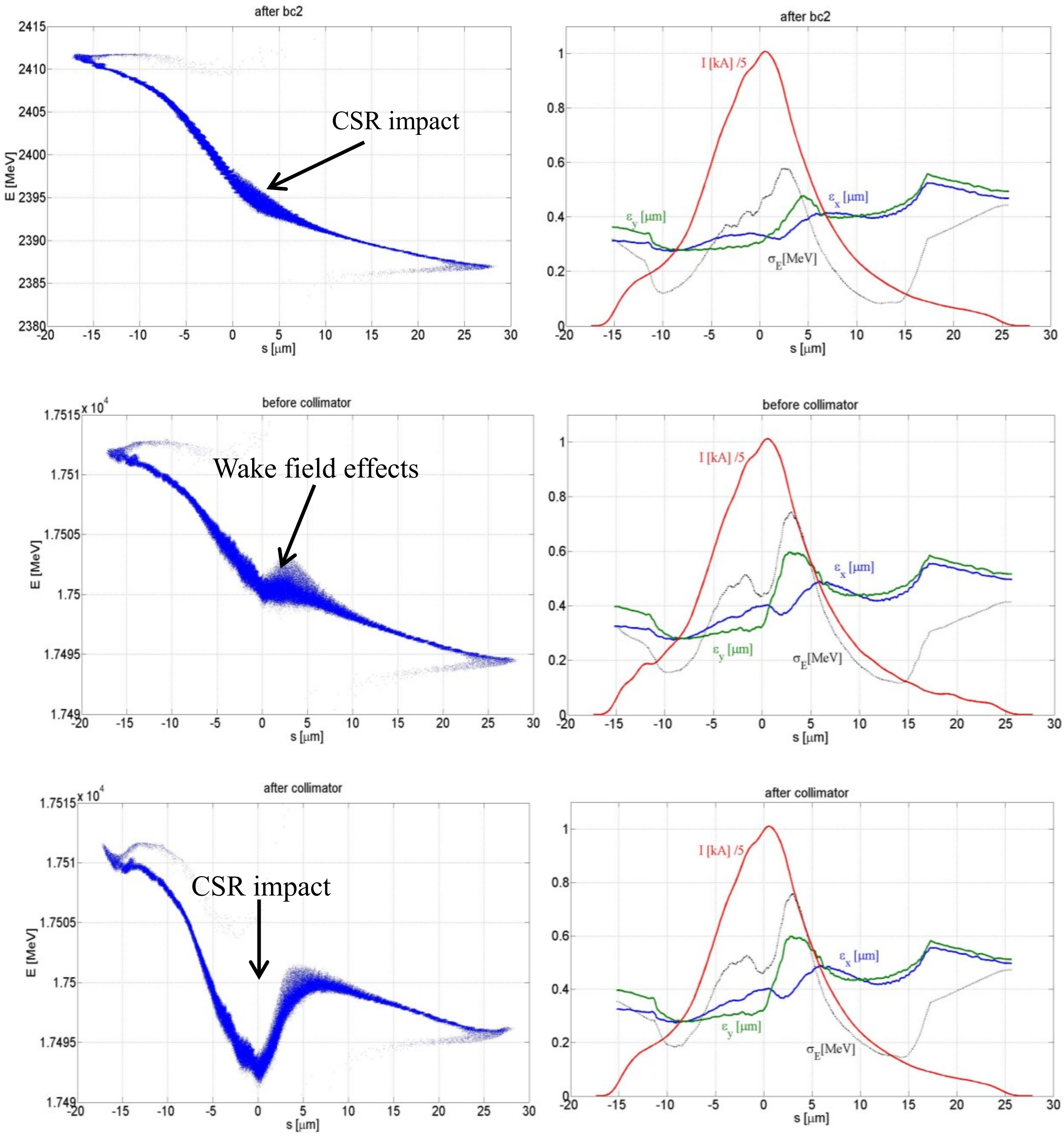


Figure 18. Longitudinal phase space, slice emittance and energy spread for 0.25nC.

3. 0.1nC bunch charge case

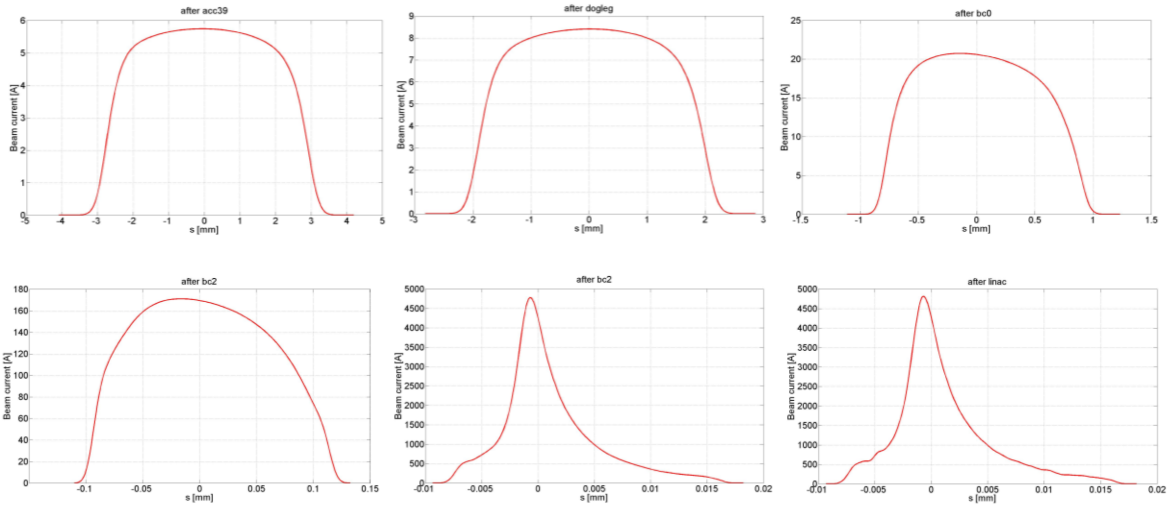
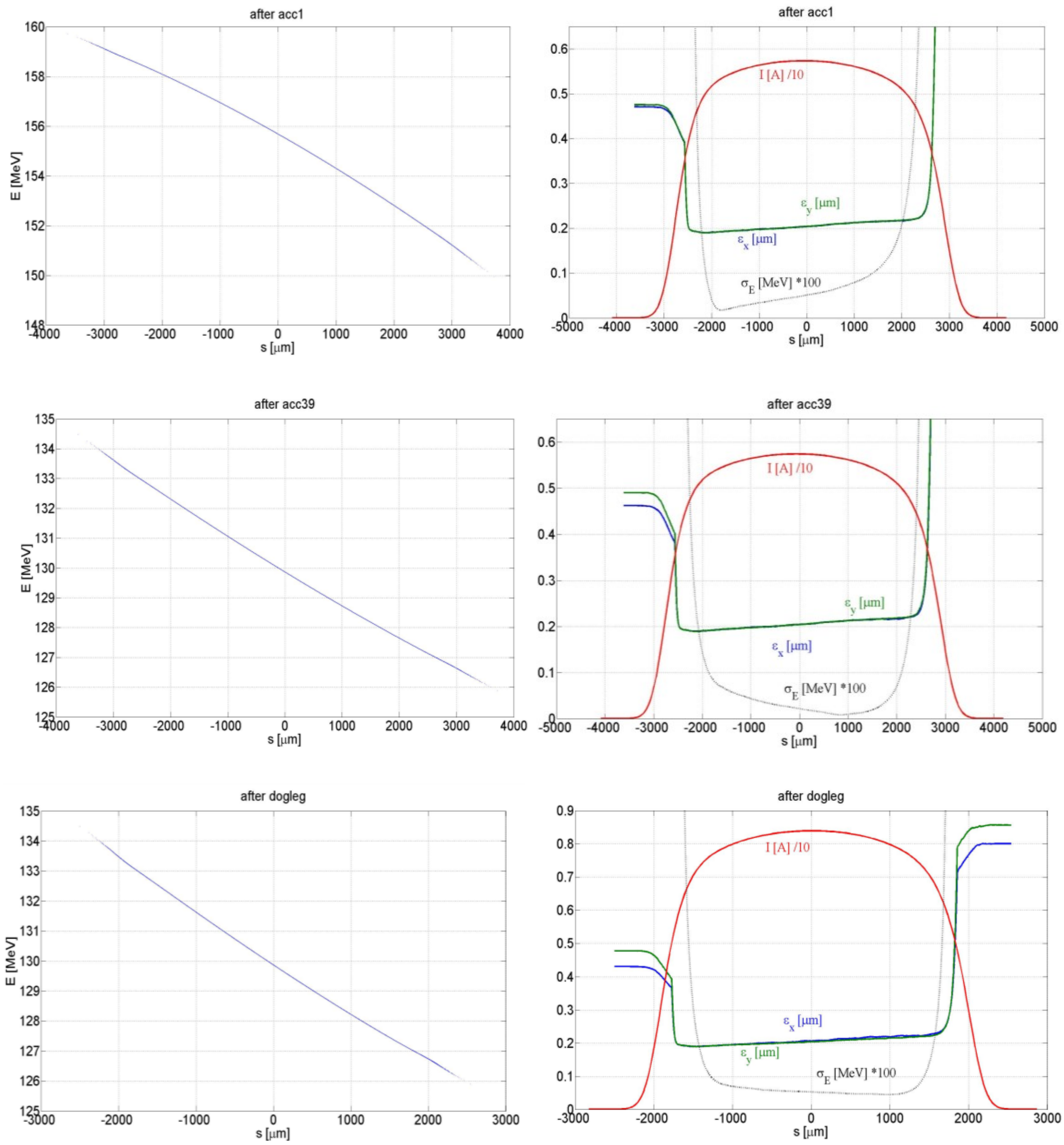
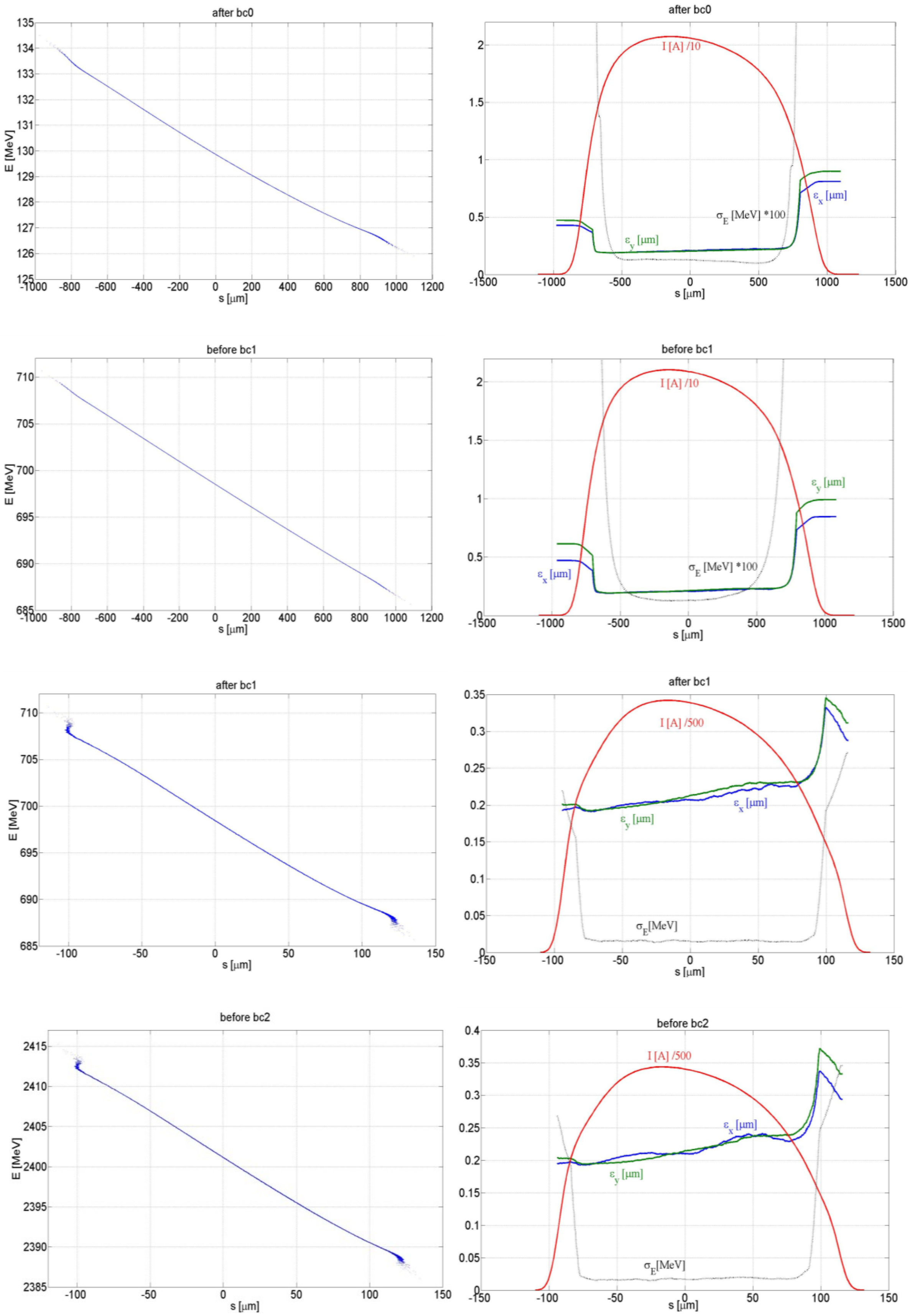


Figure 19. Current profile along the beam line for 0.1nC case





after bc0
E [MeV]
s [μm]
after bc0
I [A] /10
ε_y [μm]
ε_x [μm]
σ_E [MeV] *100
s [μm]
before bc1
E [MeV]
s [μm]
before bc1
I [A] /10
ε_y [μm]
ε_x [μm]
σ_E [MeV] *100
s [μm]
after bc1
E [MeV]
s [μm]
after bc1
I [A] /500
ε_y [μm]
ε_x [μm]
σ_E[MeV]
s [μm]
before bc2
E [MeV]
s [μm]
before bc2
I [A] /500
ε_x [μm]
ε_y [μm]
σ_E[MeV]
s [μm]

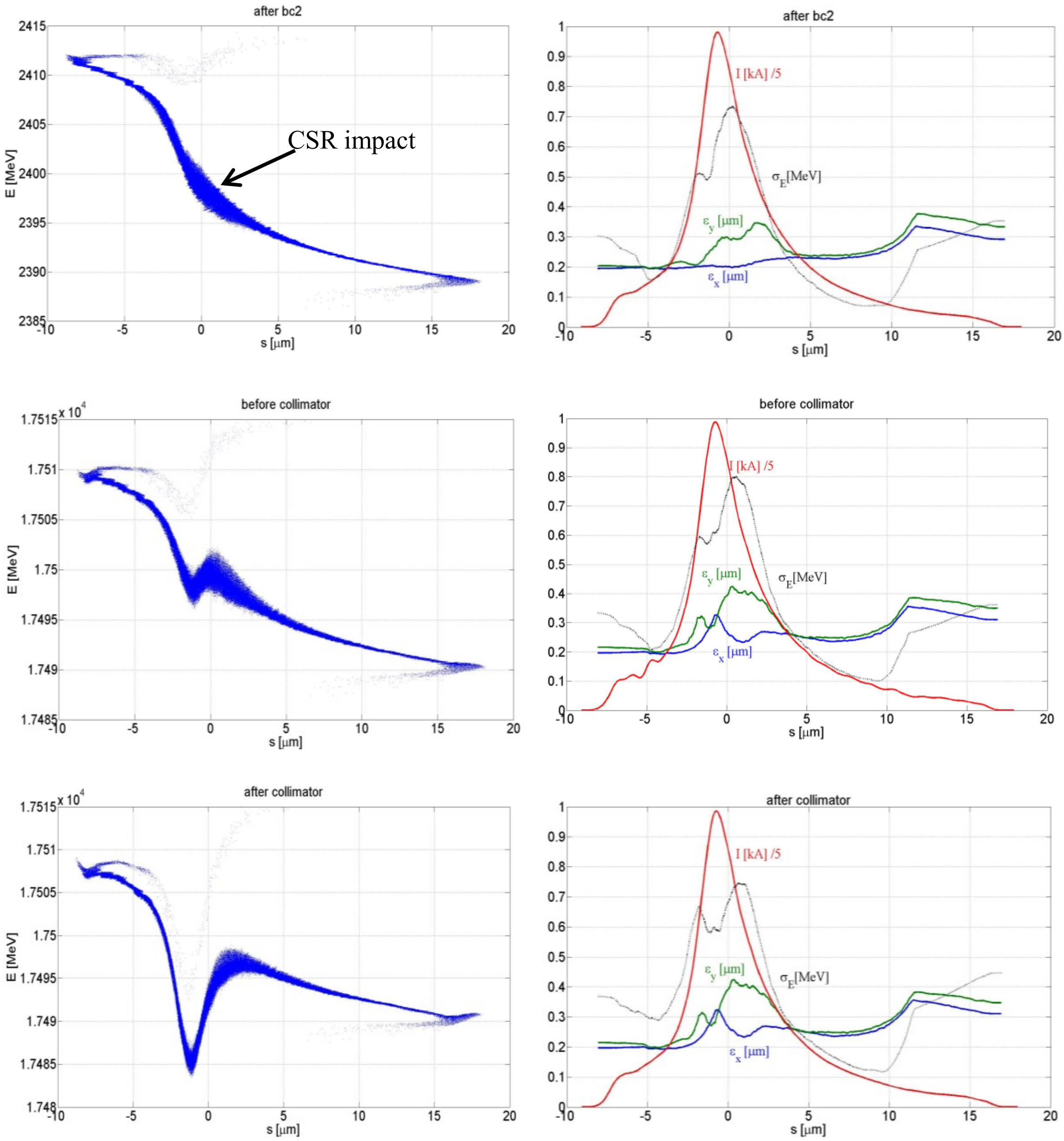


Figure 20. Longitudinal phase space, slice emittance and energy spread for 0.1nC.

4. 0.02nC bunch charge case

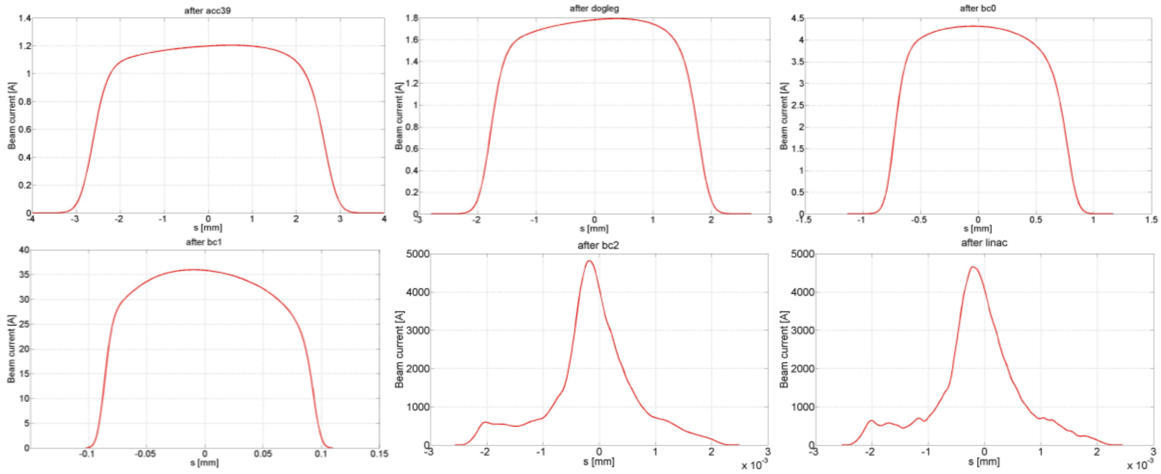
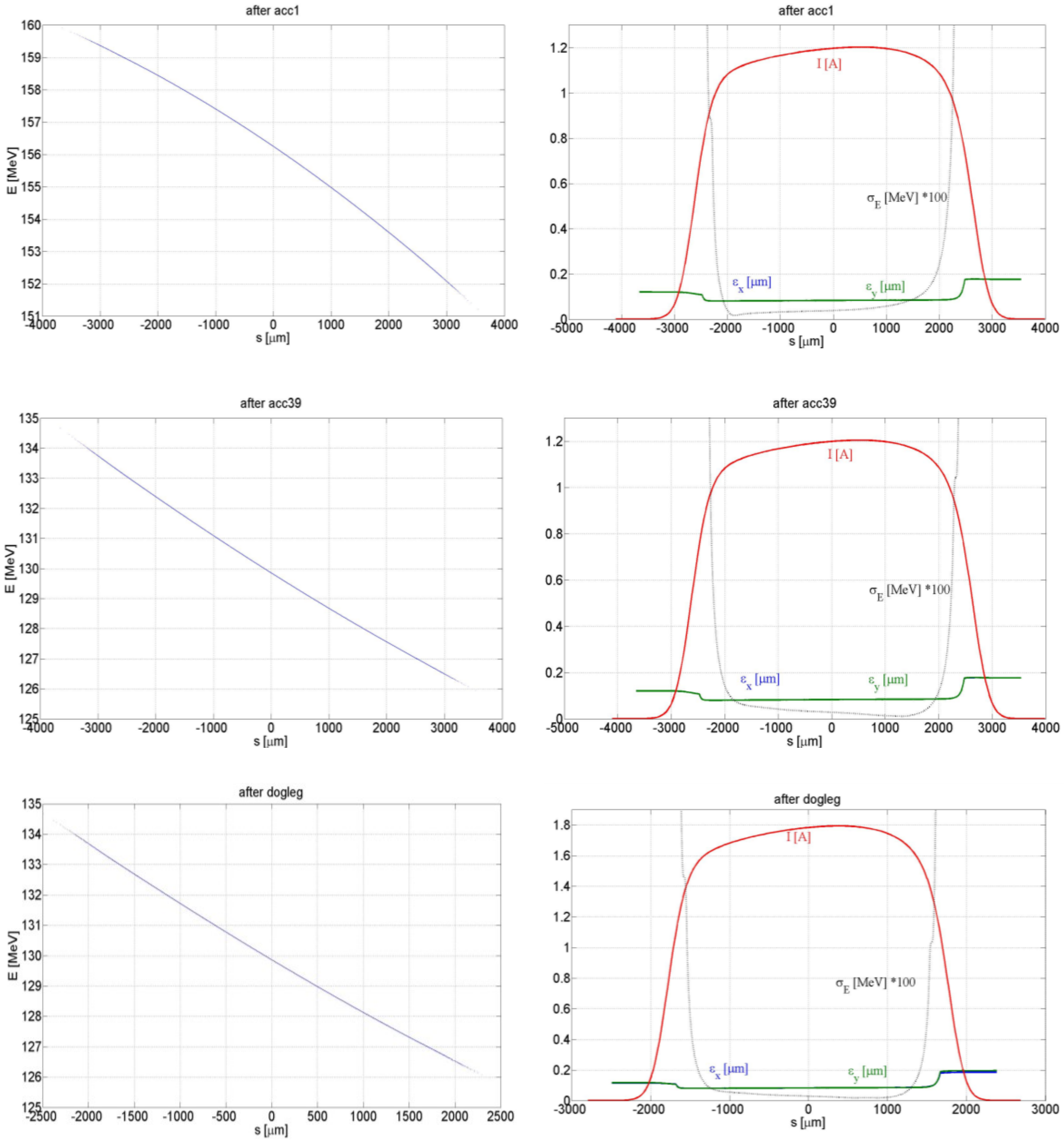
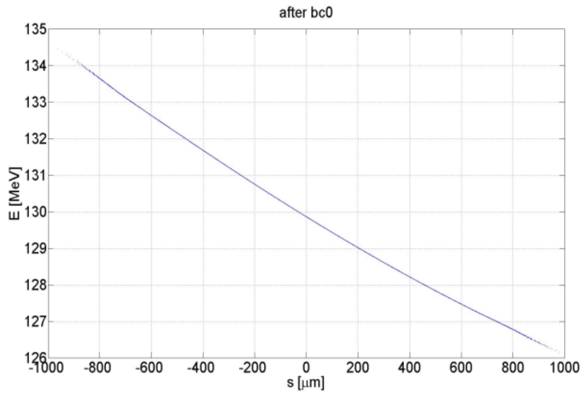
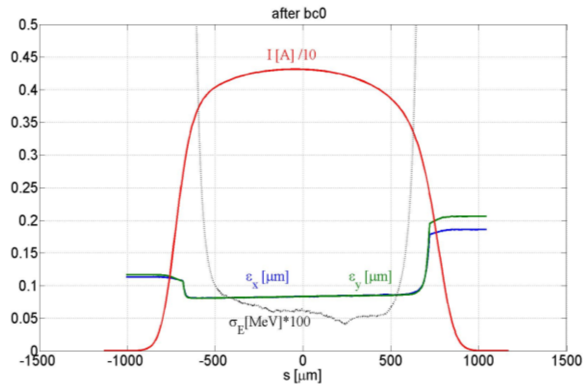


Figure 21. Current profile along the beam line for 0.02nC case




after bc0
E [MeV]
s [µm]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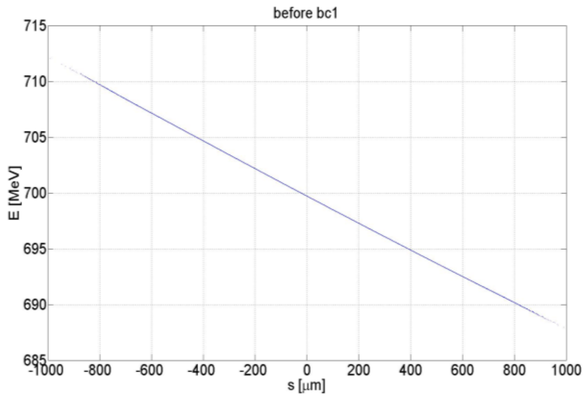
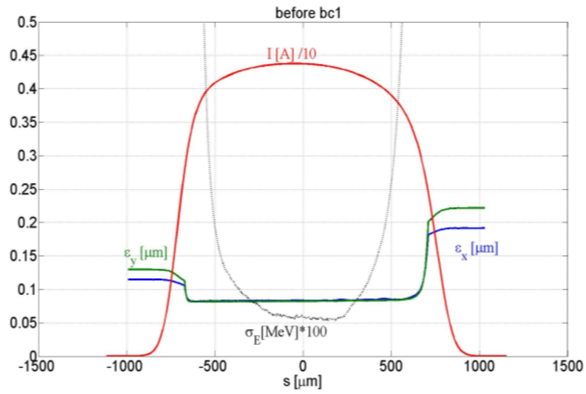
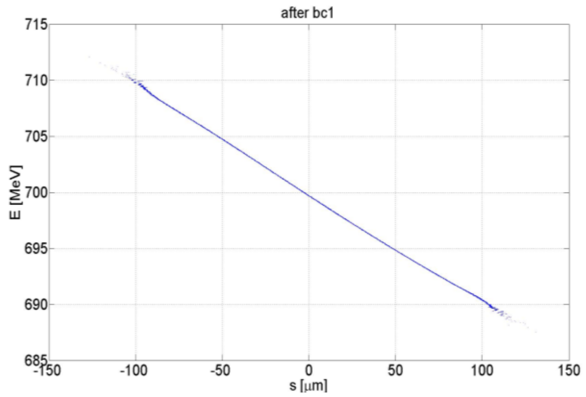
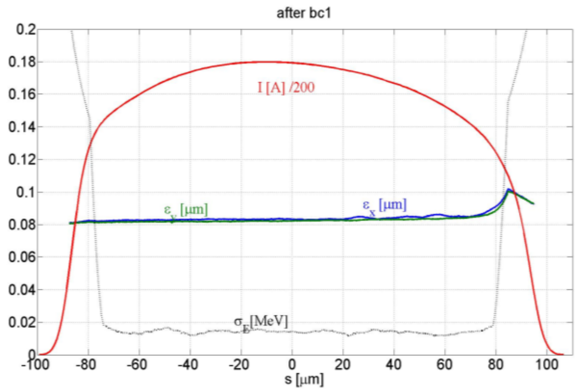
I [A] /10
ε_x [µm]
ε_y [µm]
σ_E[MeV]*100
s [µm]


before bc1
E [MeV]
s [µm]


before bc1
I [A] /10
ε_y [µm]
ε_x [µm]
σ_E[MeV]*100
s [µm]


after bc1
E [MeV]
s [µm]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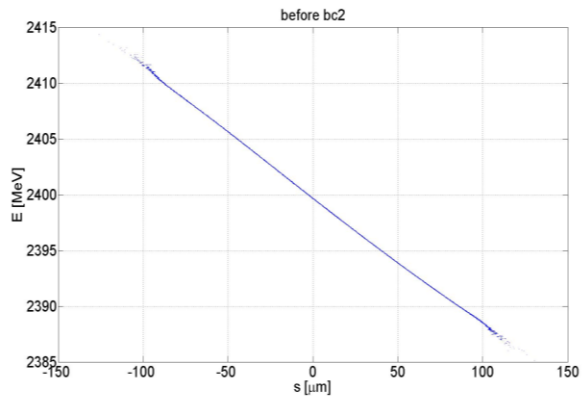
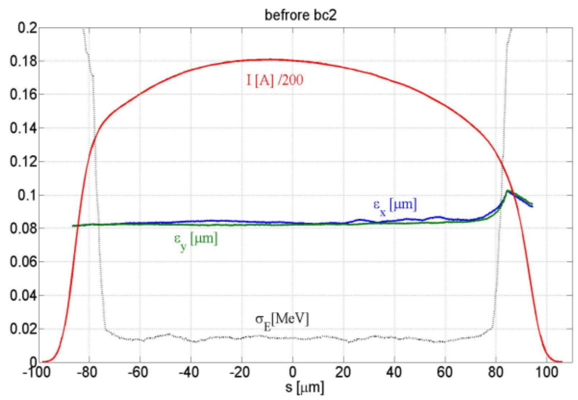
I [A] /200
ε_y [µm]
ε_x [µm]
σ_E[MeV]
s [µm]


before bc2
E [MeV]
s [µm]


befrore bc2
I [A] /200
ε_x [µm]
ε_y [µm]
σ_E[MeV]
s [µm]

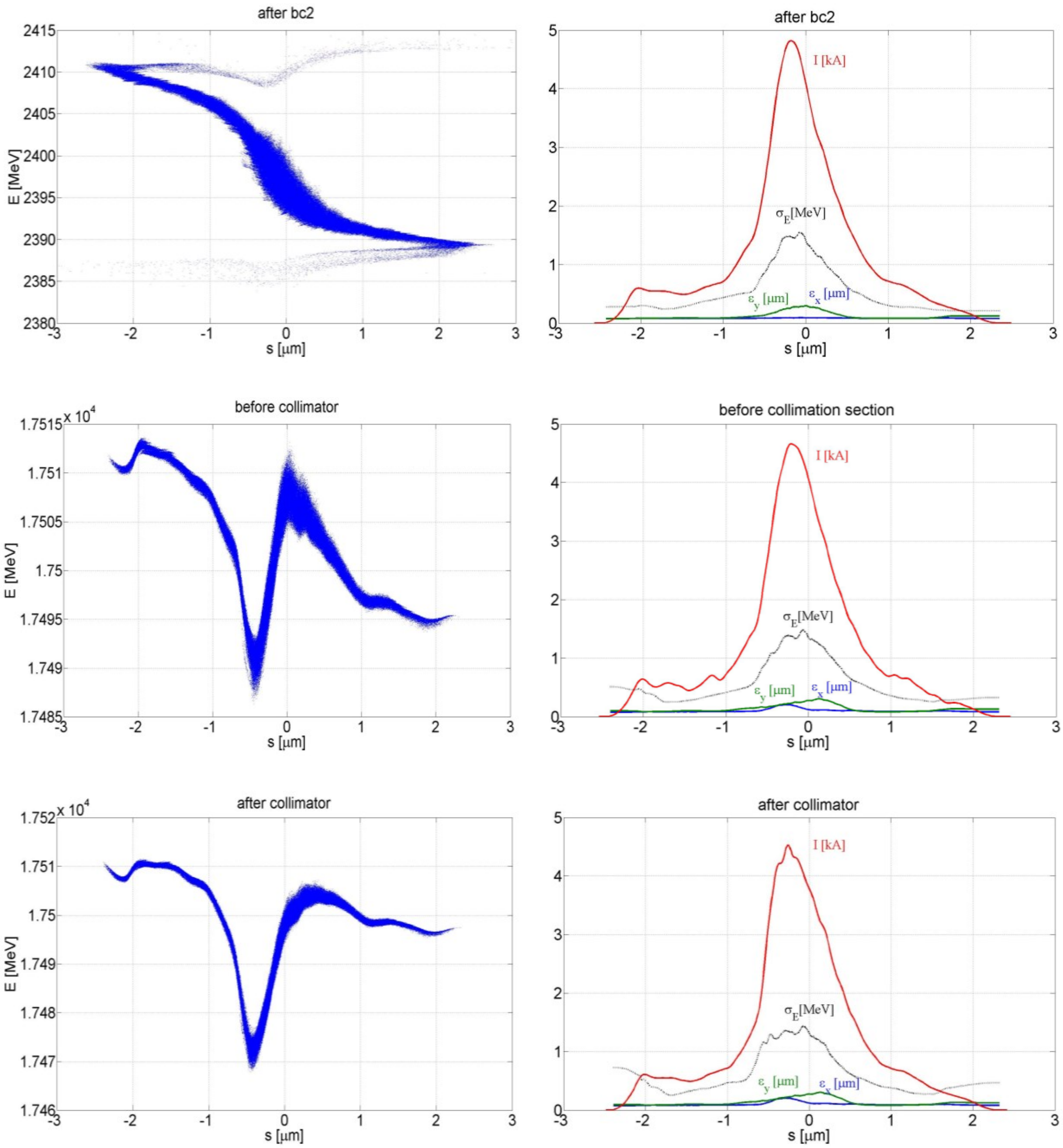


Figure 22. Longitudinal phase space, slice emittance and energy spread for 0.02nC.