uB in XFEL

one stage, rigid beam approximation → BC2 exit

- shot noise and rms current fluctuation
- induced energy spread

better models

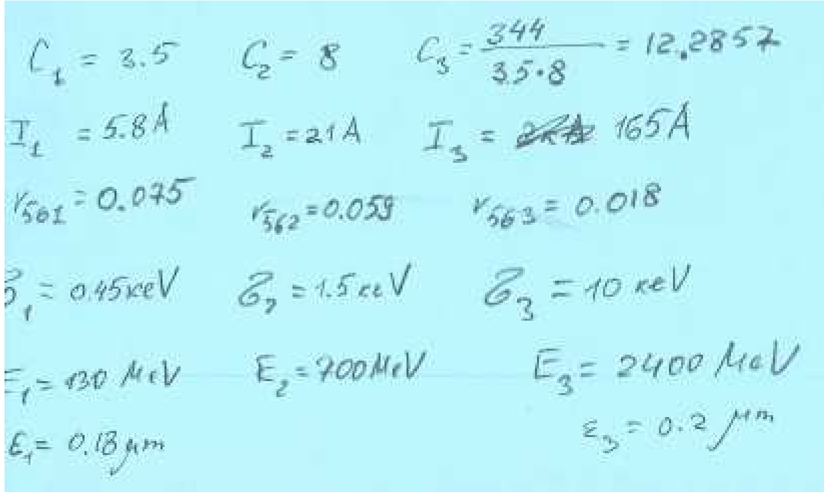
- LGM
- 1d particle model
- 3d periodic

XFEL with 1d particle model → BC0 exit

XFEL with 3d periodic

- comparison with non-periodic
- increased initial energy spread (gaussian) → BC1 exit
- increased initial energy spread (LH)

summary/conclusion



$C_1 = 3.5$ $C_2 = 8$ $C_3 = \frac{344}{3.5 \cdot 8} = 12.2857$

$I_1 = 5.8\,A$ $I_2 = 21\,A$ $I_3 = 165\,A$

$r_{561} = 0.075$ $r_{562} = 0.053$ $r_{563} = 0.018$

$\sigma_1 = 0.45\,keV$ $\sigma_2 = 1.5\,keV$ $\sigma_3 = 10\,keV$

$E_1 = 130\,MeV$ $E_2 = 700\,MeV$ $E_3 = 2400\,MeV$

$\varepsilon_1 = 0.18\,\mu m$ $\varepsilon_3 = 0.2\,\mu m$

one stage, rigid beam approximation

$$G = \left(1 - i\frac{Cr_{56}}{\mathcal{E}_{\text{ref}}/e} I_1 k_1 Z\right) \exp\left(-\frac{(Ck_1 r_{56}\sigma_\delta)^2}{2}\right)$$

beam current and wave number before compression

round beam space charge impedance:

$$Z = \int_{S_1}^{S_2} Z'(\sigma_r(S), \gamma(S))dS$$

"effective" beam size:

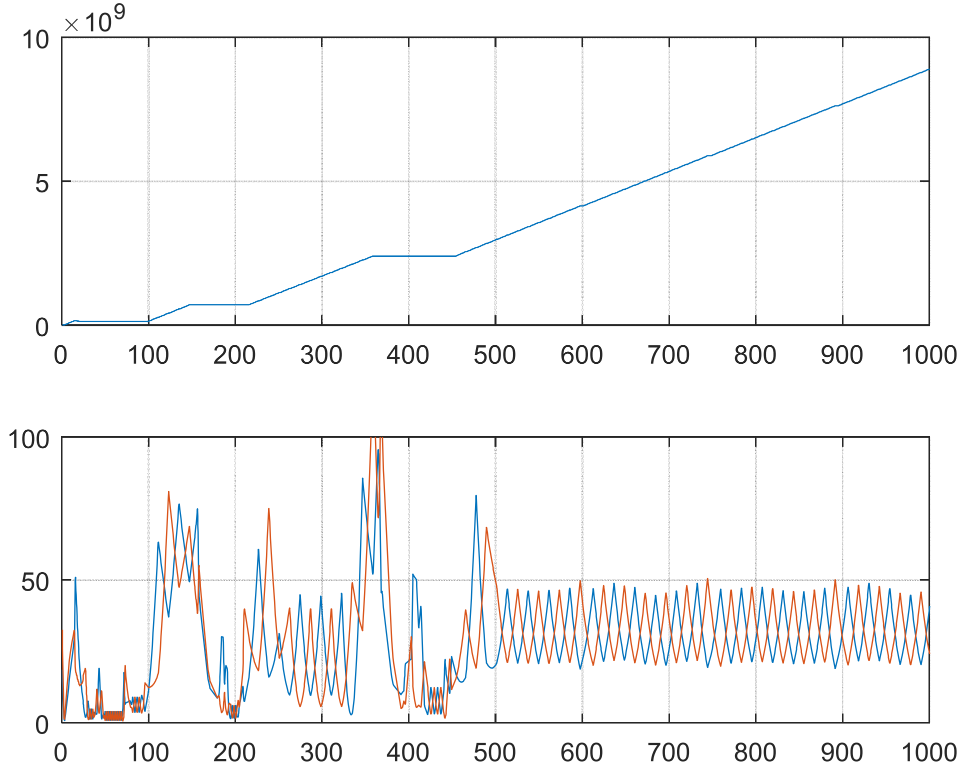
$$\sigma_r(Z) = \left(\varepsilon_x(Z)\beta_x(Z)\varepsilon_y(Z)\beta_y(Z)\right)^{1/4}$$

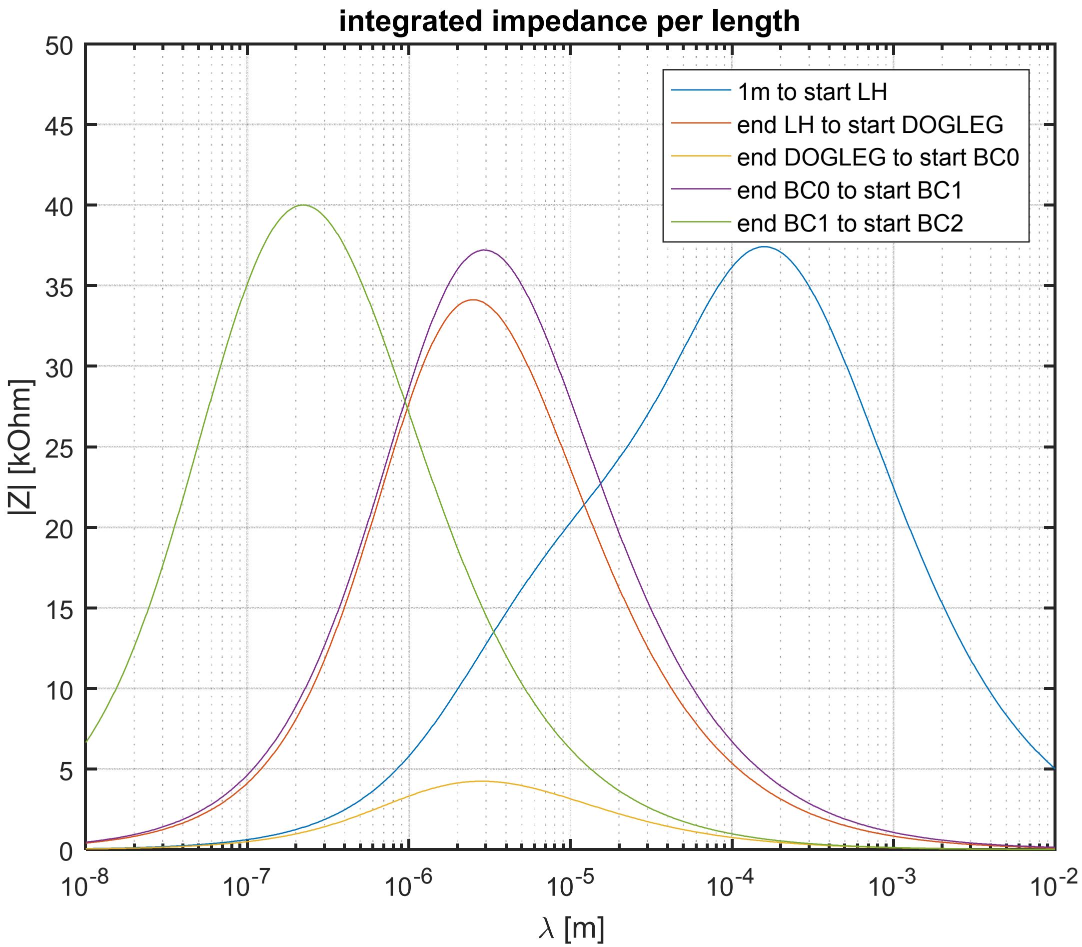
multi stage gain (pre LGM!)

$$G = G_1 G_2 G_3$$

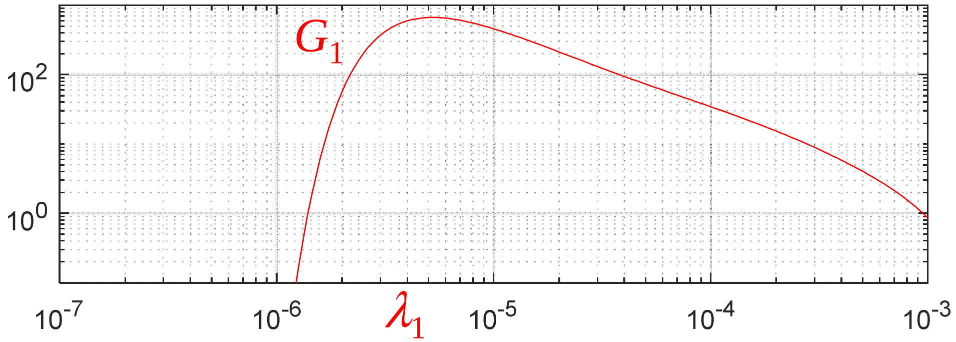
for large one stage gains

energy profile and optic (normalized emittance =0.2 um)



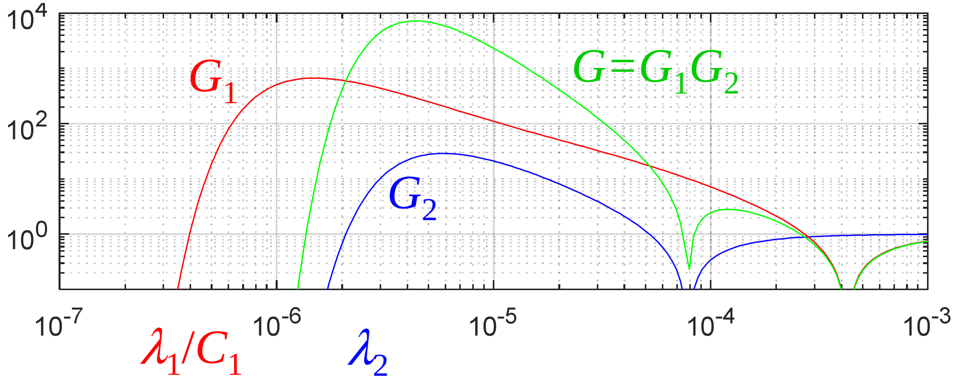

integrated impedance per length
1m to start LH
end LH to start DOGLEG
end DOGLEG to start BC0
end BC0 to start BC1
end BC1 to start BC2
|Z| [kOhm]
λ [m]
0
5
10
15
20
25
30
35
40
45
50
10-8
10-7
10-6
10-5
10-4
10-3
10-2

$\sigma_{E1} = 450\ \text{eV}$



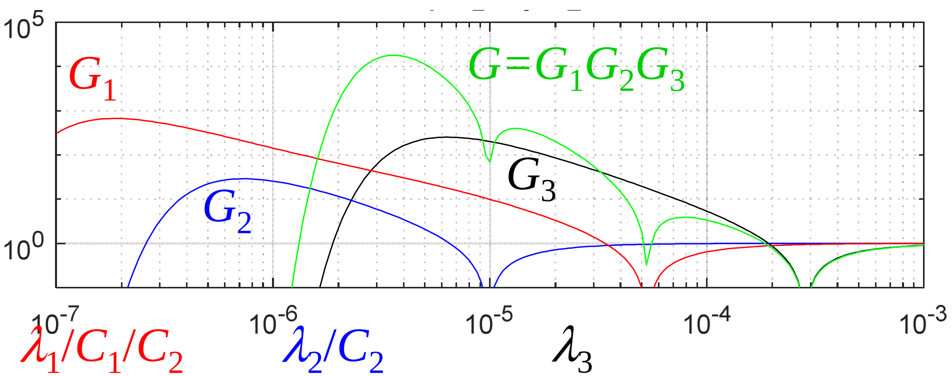
G_1 = one stage gain after BC0

wavelength before BC0 [m]



G_2 = one stage gain after BC1

wavelength before BC1 [m]

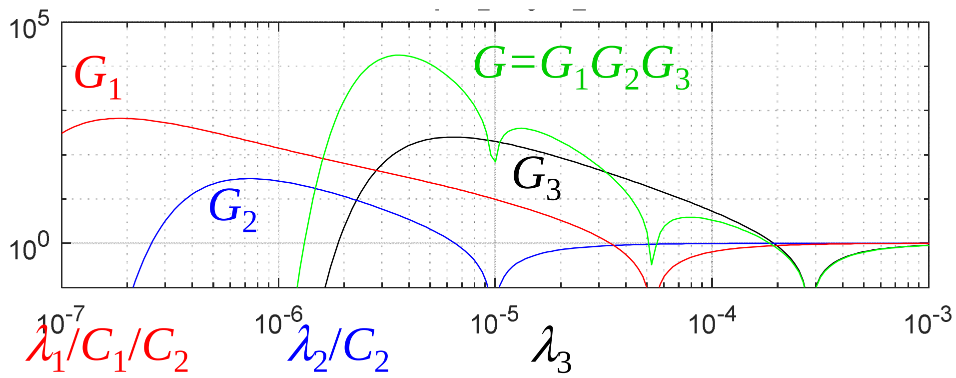


$\max\{G\} > 10^4$

G_3 = one stage gain after BC2

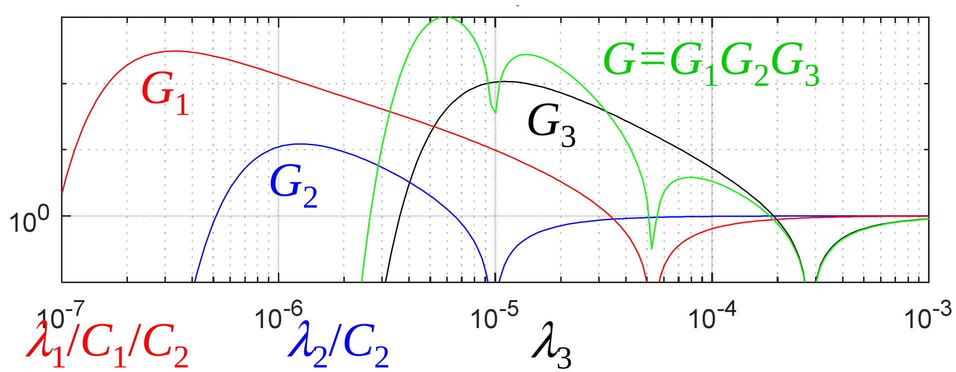
wavelength before BC3 [m]

$$\sigma_{E1} = 450 \text{ eV}$$
$$\rightarrow \sigma_{E4} = C_{tot}\sigma_{E1} = 155 \text{ keV}$$



$$\max\{G\} > 10^4$$

$$\sigma_{E1} = 850 \text{ eV}$$
$$\rightarrow \sigma_{E4} = C_{tot}\sigma_{E1} = 285 \text{ keV}$$



$$\max\{G\} \approx 10^3$$

shot noise and rms current fluctuation

I_1 initial coasting beam

$$I_{rms,in} = \sqrt{\frac{eI_1}{\pi}\left|\omega_1 - \omega_2\right|}$$

white shot noise $\rightarrow$
rms current fluctuation of initial coasting beam in frequency range between ω_1 and ω_2

$$\rightarrow I_{rms,\mathrm{out}} = C\sqrt{\frac{eI_1}{\pi}\int_{\omega_1}^{\omega_2}\left|G(\omega)\right|^2 d\omega}$$

linear amplified noise (from the initial frequency range, transformed to $C\omega_1$ and $C\omega_2$)

this does not consider the shot noise of the compressed beam nor shot noise after intermediate stages

assumption: shot noise of later stages is negligible compared to amplified initial noise

c. b. I_1	before stage 1 / after stage 1	$I_2 = C_1 I_1$	before stage 2 / after stage 2	I_3	before stage 3 / after stage 3	I_4
white shot noise particle start times are independent		amplified I_1 shot noise other noise particle times are correlated		amplified I_1 shot noise amplified other noise + further noise … correlated		amplified I_1 shot noise amplified other + further noise … correlated

induced energy spread: linear regime + rigid beam

effect of impedance after compressor, range from S_1 to S_2

$$C\left(S_1 \le S < S_2\right) = C$$

$$G\left(\omega, S_1 \le S < S_2\right) \approx G\left(\omega\right)$$

$$Z\left(\omega\right) = \int_{S_1}^{S_2} Z'\left(\omega, S\right) dS$$

$$\Delta E_{rms} \approx eC\sqrt{\frac{eI_1}{\pi}\int \left|Z\left(\omega\right)G\left(\omega\right)\right|^2 d\omega} \approx eI_{rms,\text{out}}\left|Z_{eff}\right|$$

linear regime

$$\frac{I_{rms,\mathrm{out}}}{CI_1} << 1 \rightarrow \frac{e}{\pi}\int_{\omega_1}^{\omega_2} \left|G(\omega)\right|^2 d\omega << I_1$$

$$I_1 = 5.8\ \mathrm{A}$$

multiplicative one stage rigid beam approximation:

$\sigma_{E0} = 450\ \mathrm{eV}$	$\sigma_{E0} = 830\ \mathrm{eV}$
$\downarrow$	$\downarrow$
$\frac{e}{\pi}\int_{\omega_1}^{\omega_2} \left|G_{1\to 2}(\omega)\right|^2 d\omega \approx 4.3\ \mathrm{A}$	$\frac{e}{\pi}\int_{\omega_1}^{\omega_2} \left|G_{1\to 2}(\omega)\right|^2 d\omega \approx 0.52\ \mathrm{A}$
$\frac{e}{\pi}\int_{\omega_1}^{\omega_2} \left|G_{1\to 2}(\omega)\right|^2 d\omega \approx 420\ \mathrm{A}$	$\frac{e}{\pi}\int_{\omega_1}^{\omega_2} \left|G_{1\to 2}(\omega)\right|^2 d\omega \approx 10\ \mathrm{A}$
$\frac{e}{\pi}\int_{\omega_1}^{\omega_2} \left|G_{1\to 3}(\omega)\right|^2 d\omega \approx 2.3\ \mathrm{kA}$	$\frac{e}{\pi}\int_{\omega_1}^{\omega_2} \left|G_{1\to 3}(\omega)\right|^2 d\omega \approx 3.8\ \mathrm{A}$

no!

better models

1d impedance or wake
- one stage, rigid beam
- linear gain model
- (2x)1d particle model

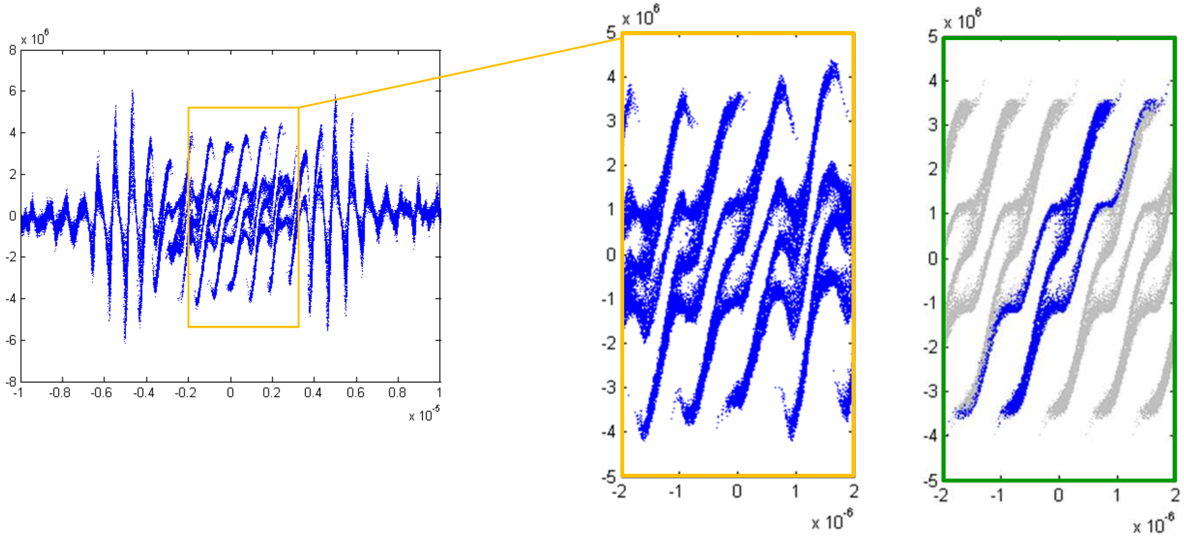
3d periodic space charge
- (2x)3d particle tracking

linear gain model, (2x)1d particle model, (2x)3d particle tracking: 3d linear optic

discrete

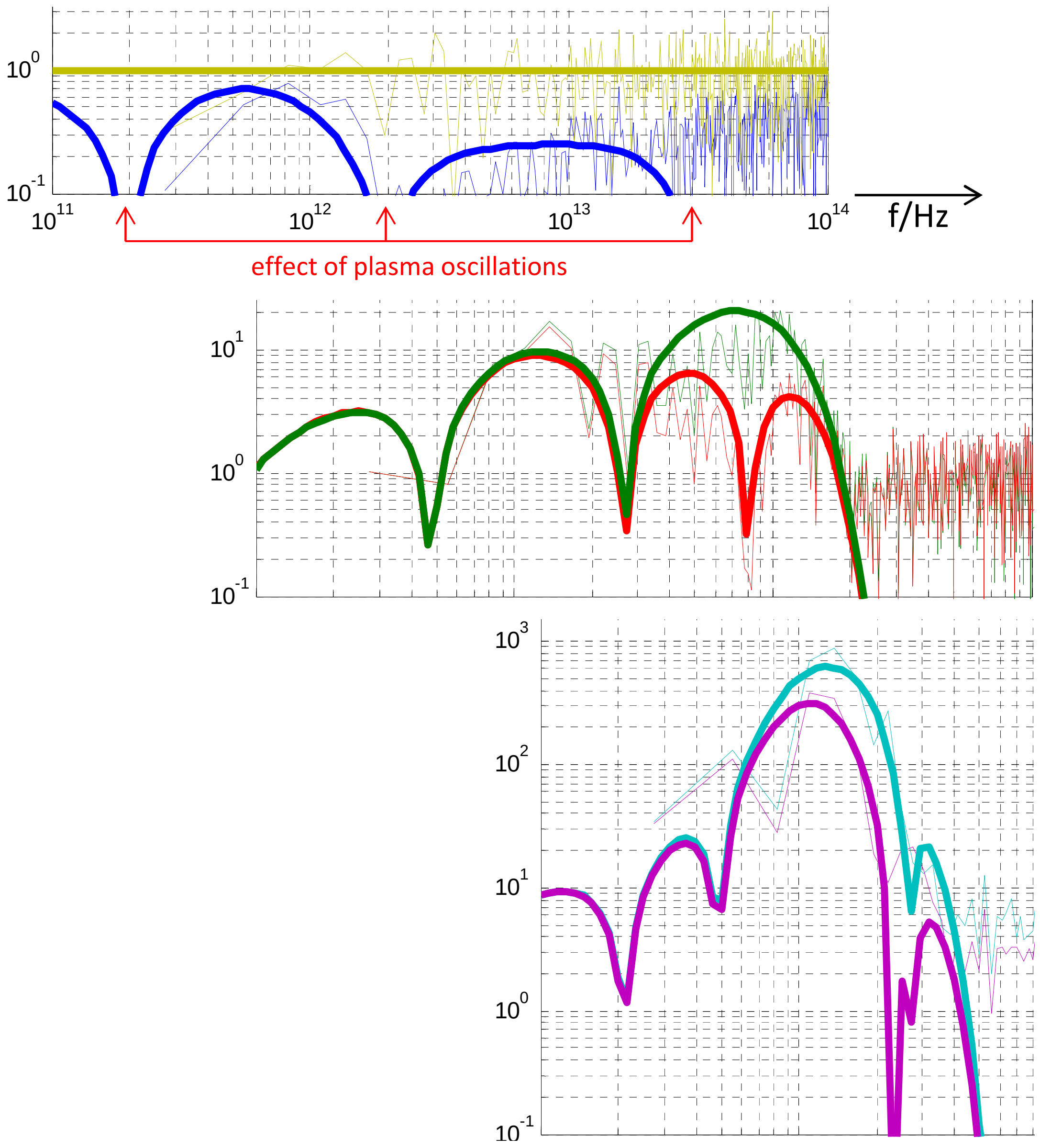
one stage, rigid beam; linear gain model: linear dynamic

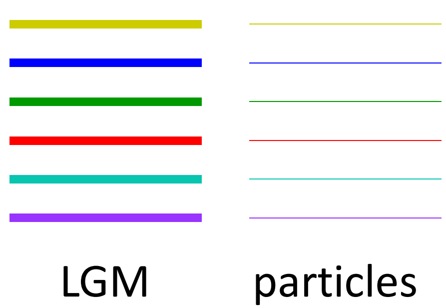
3d linear optic; (2x)3d particle tracking: non-linear dynamic



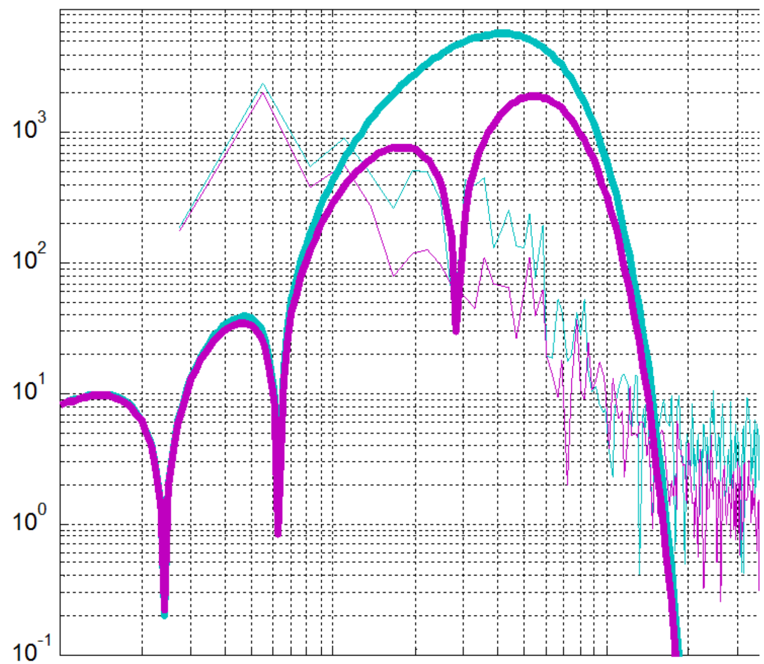
example: **LGM vs 1d particles**

DESY-FLASH





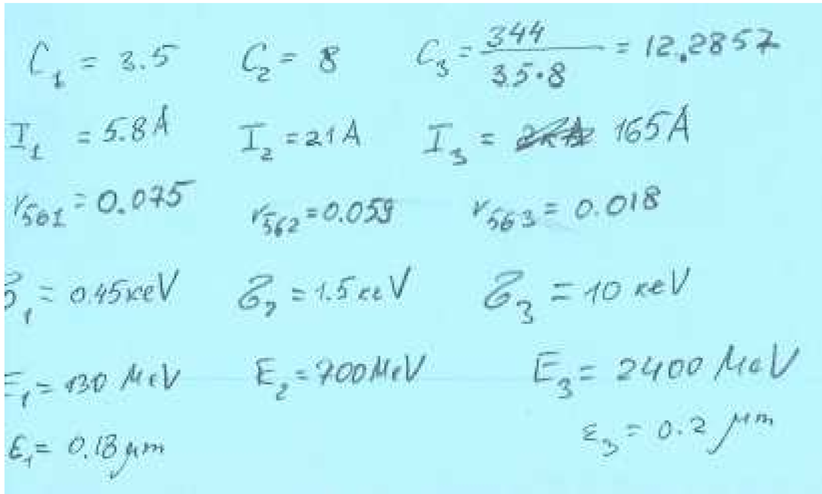
other working point → non linear effects



XFEL with 1d particle model

back to Igor's problem, only 1st stage

but with r_{56} of LH and DOGLEG



$C_1 = 3.5$	$C_2 = 8$	$C_3 = \frac{344}{3.5 \cdot 8} = 12.2857$
$I_1 = 5.8\,A$	$I_2 = 21\,A$	$I_3 = $ ~~2kA~~ $165\,A$
$r_{561} = 0.075$	$r_{562} = 0.059$	$r_{563} = 0.018$
$\sigma_1 = 0.45\,keV$	$\sigma_2 = 1.5\,keV$	$\sigma_3 = 10\,keV$
$E_1 = 130\,MeV$	$E_2 = 700\,MeV$	$E_3 = 2400\,MeV$
$\varepsilon_1 = 0.18\,\mu m$		$\varepsilon_3 = 0.2\,\mu m$

simplified 1d particle model

continuous drifts:

$$\frac{dz_\nu}{dS} = \frac{1}{\gamma^2}\delta_\nu$$

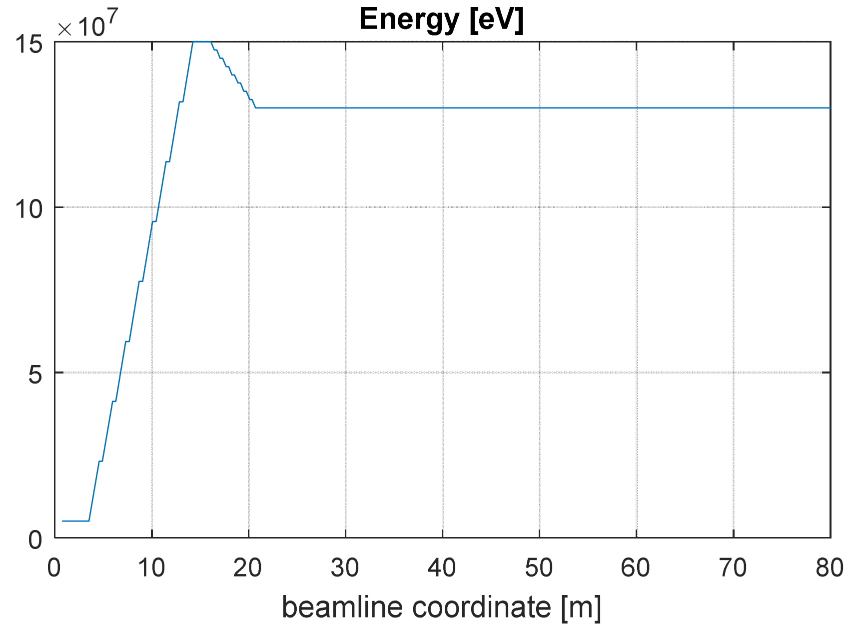
$$\frac{d\delta_\nu}{dS} \sim \mathrm{Re}\left\{\tilde{I}Z'\exp\left(-ikz_\nu\right)\right\}$$

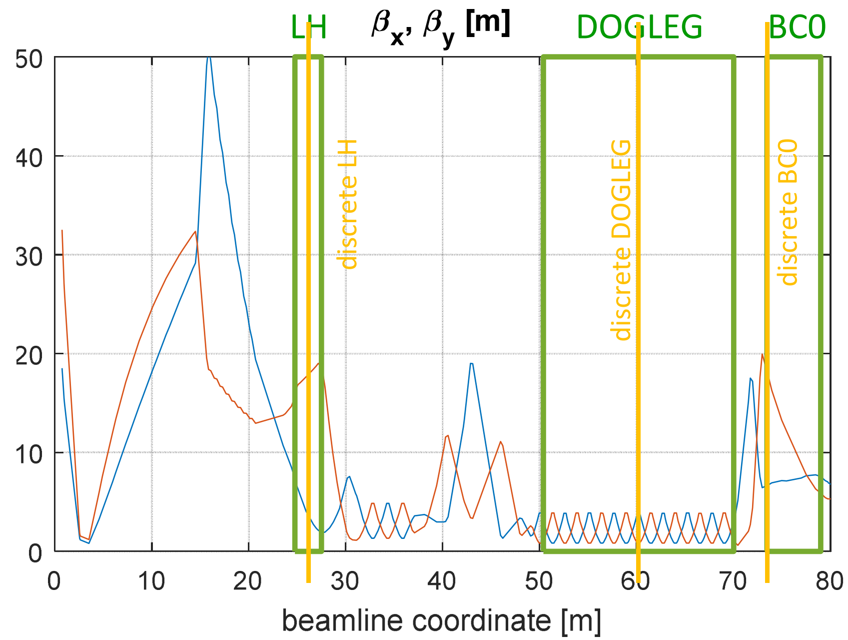
$$\tilde{I} \sim \sum_\nu \exp\left(ikz_\nu\right)$$

discrete compression stages:

$$z_\nu^{(\mathrm{out})} = z_\nu^{(\mathrm{in})} + r_{56}\delta_\nu^{(\mathrm{in})}$$

$$\delta_\nu^{(\mathrm{out})} = \delta_\nu^{(\mathrm{in})}$$



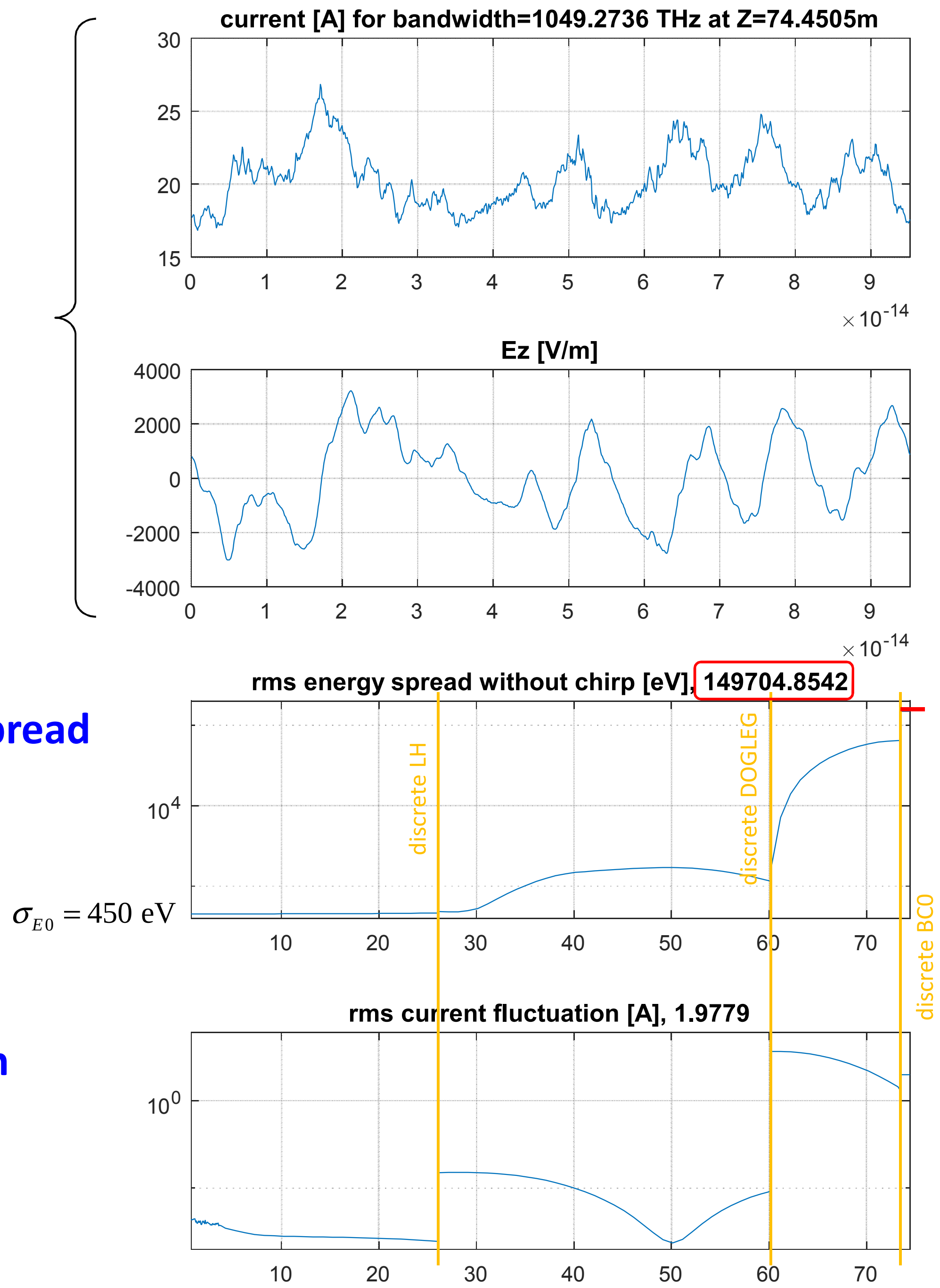


after BC0:
current and slice energy

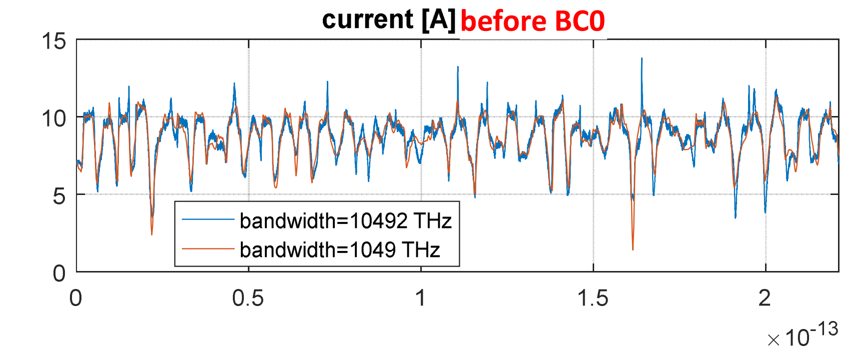
uncorrelated energy spread

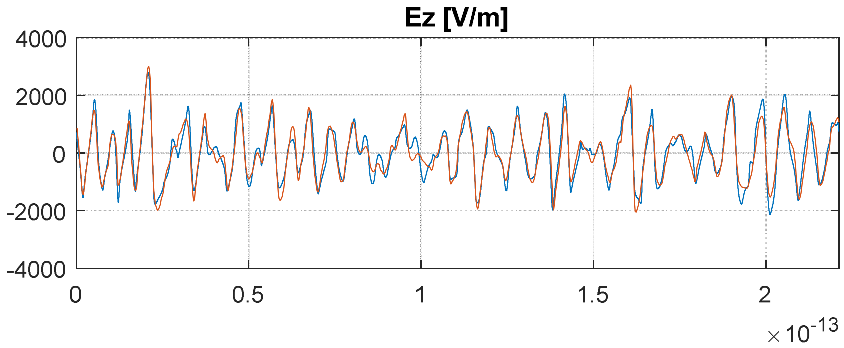
rms current fluctuation

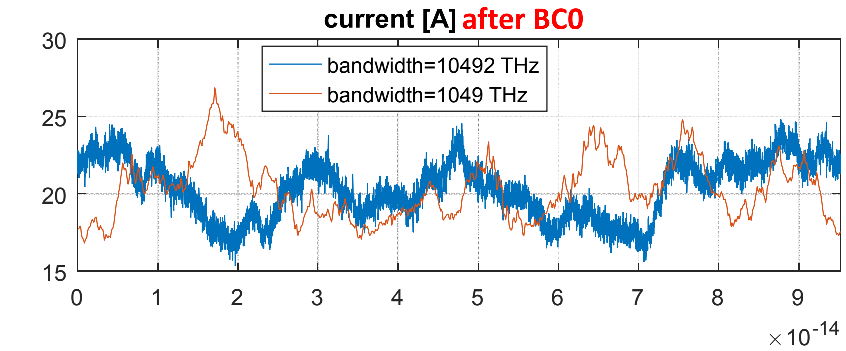
different qualitative behavior than expected for rigid beam approximation!!!

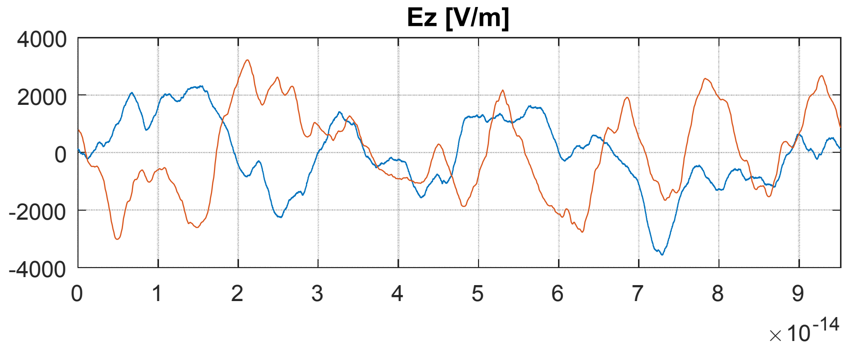


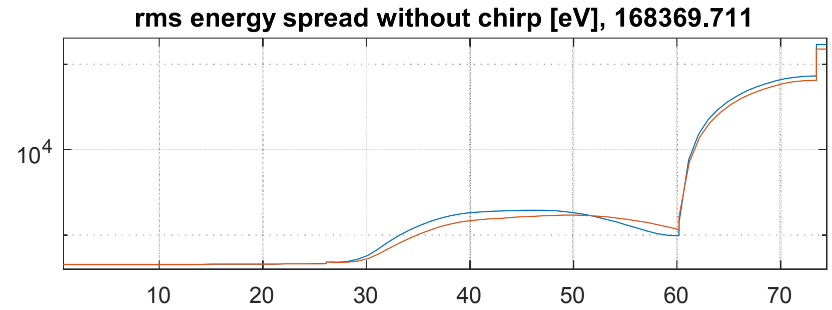
150 keV was expected after BC2 for 2kA beam!!!

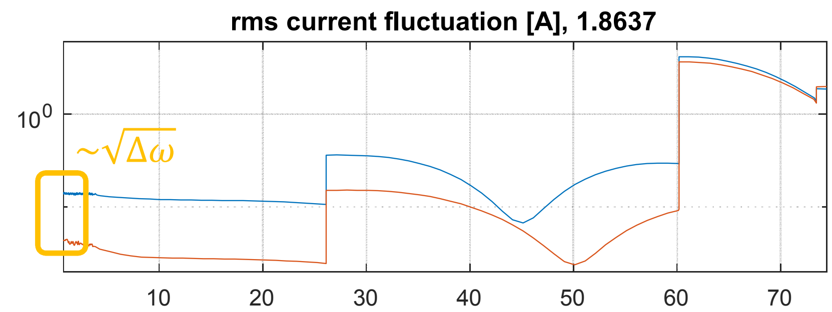












comparison for simulation with two different band widths

same initial particle distribution!

non linear mixing of phase space:

before BC0: similar time signals

after BC0: different time signals but similar rms- and similar frequency-structure

current fluctuation can be decreased

XFEL with 3d periodic

comparison with non-periodic

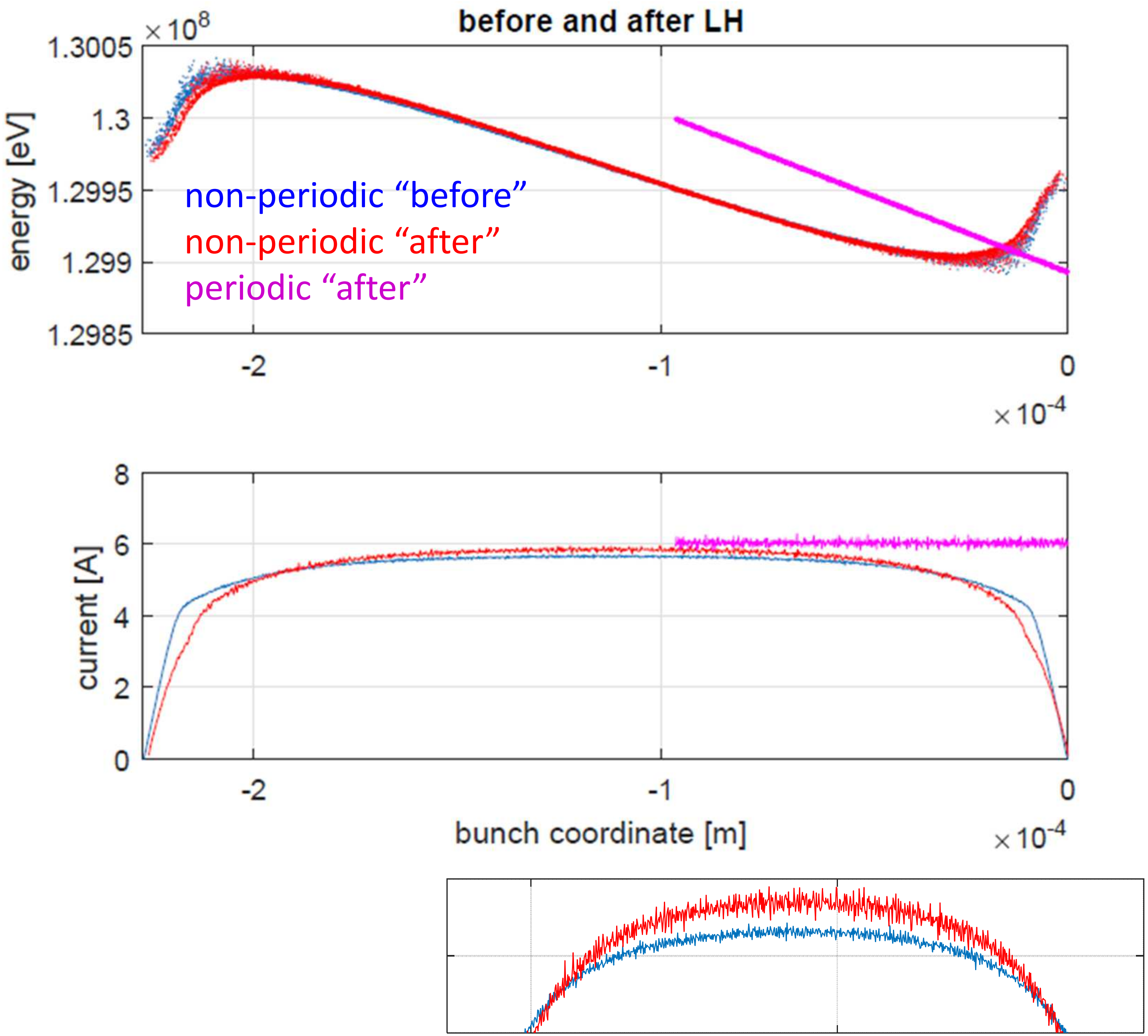
March 27, 2019

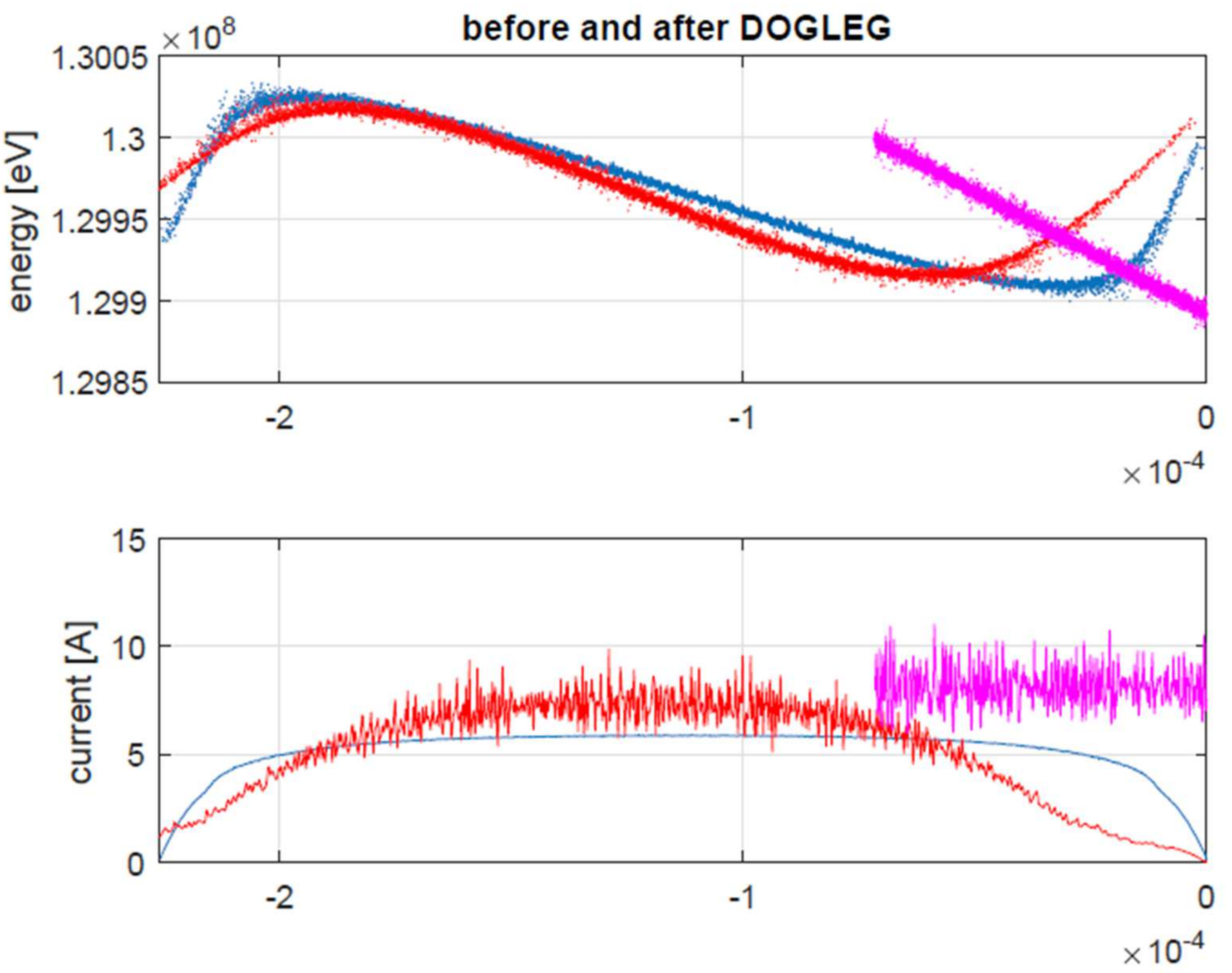
beam parameters:
inital beam current 5.8A;
normalized emittance after A1 0.188 μm (in both planes);
initial energy 6.65 MeV;
initial beamline coordinate 3.3 m;
uncorrelated energy spread 450 eV, gaussian;
bunch is generated by random generator; horizontal, vertical and longitudinal phase spaces are decoupled; the initial beam is round, all transverse density functions are gaussian; twiss parameters $\alpha_x = \alpha_y$ and $\beta_x = \beta_y$ are chosen according to a Astra simulation; the emittances are chosen $\varepsilon_x = \varepsilon_y$ to obtain a normalized emittance of about 0.2 μm after A1;
the chirp of A1 is chosen for an compression $C_0 = 3.5$ after bunch compressor BC0;

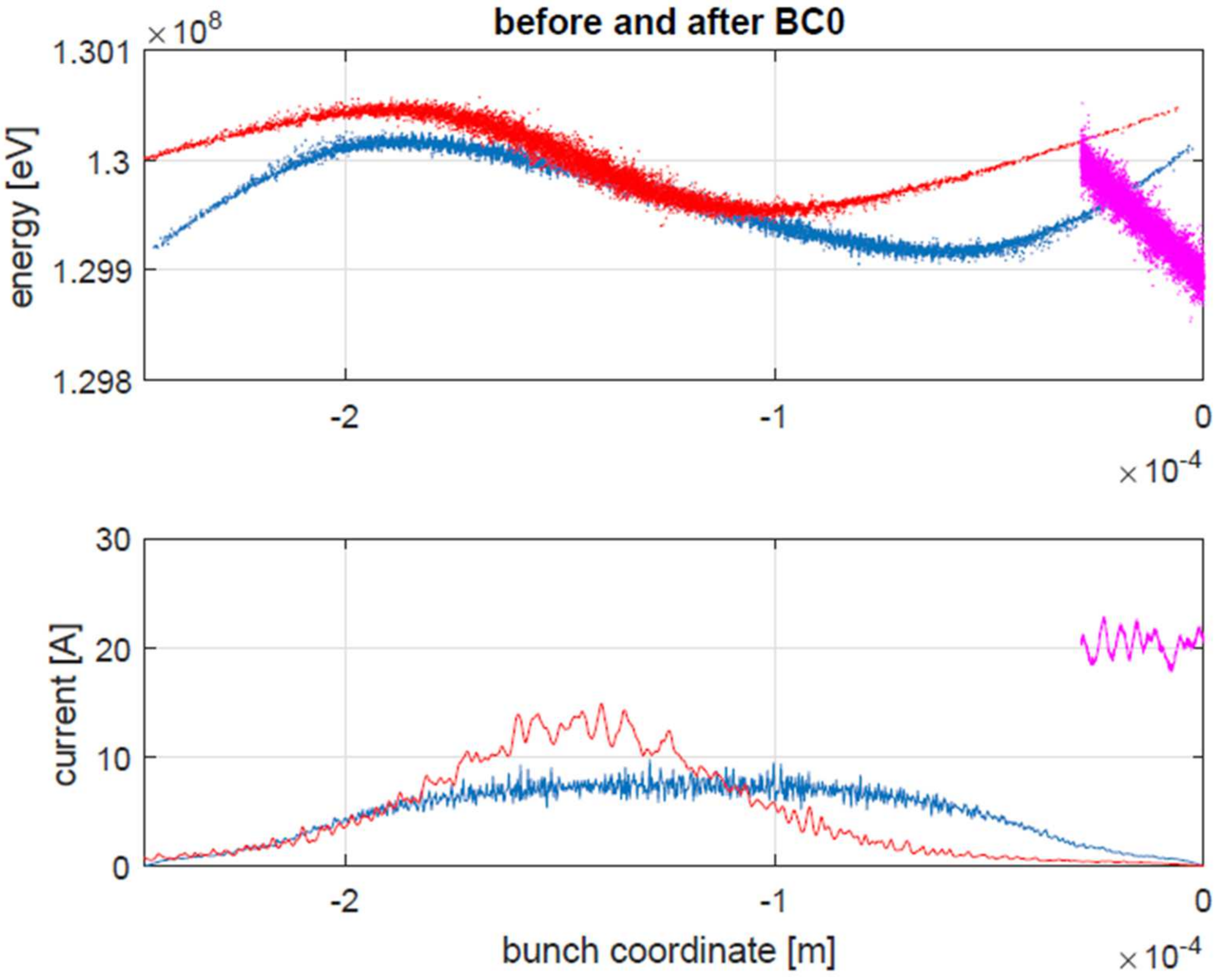
dispersive things and compression:
r56LH/mm=4.7
r56DOGLEG/mm=30.8
r56BC0/mm=54.2
r56BC1/mm=51.7;
beam current after BC0 is 20.3A;
beam current after BC1 is 162A;

resolution:
charge of macroparticles is elementary charge;
longitudinal density is uniform; length is 0.2 mm for nonperiodic or 0.1 mm for periodic simulations;

laser heater off !!!

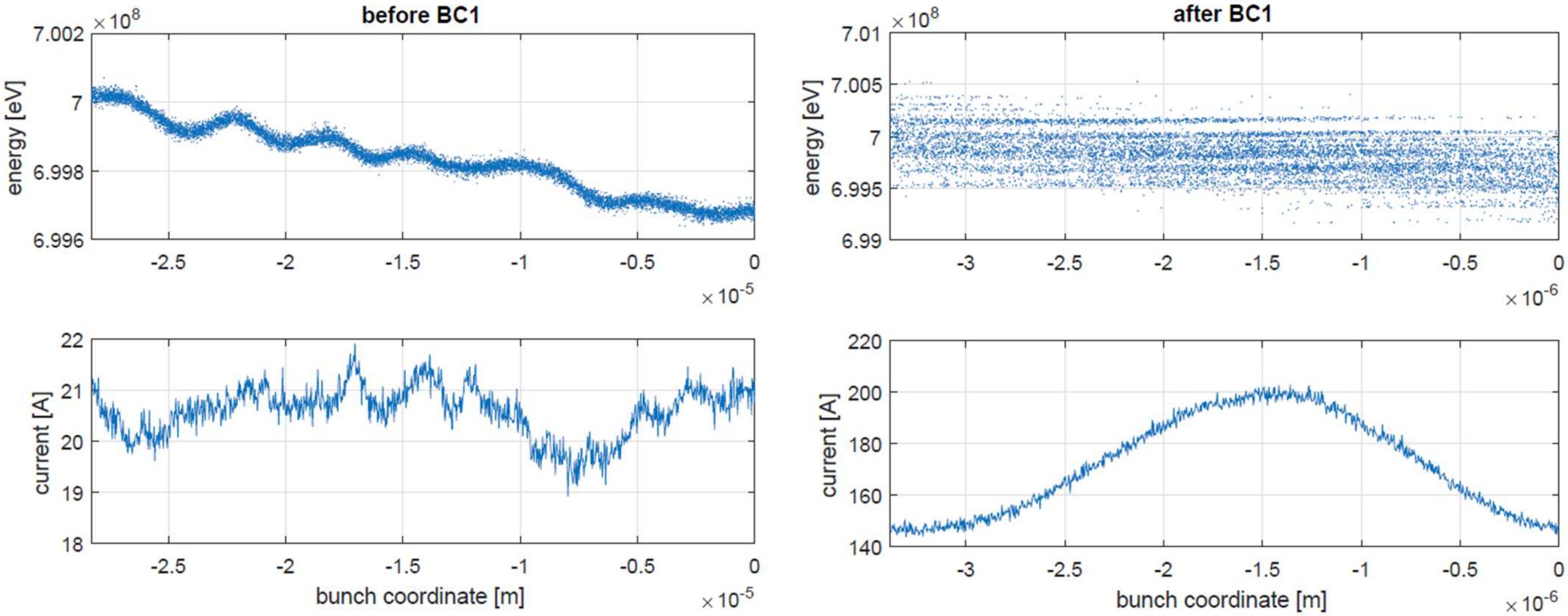

before and after LH
×10^8
1.3005
1.3
1.2995
1.299
1.2985
energy [eV]
non-periodic "before"
non-periodic "after"
periodic "after"
-2
-1
0
×10^-4
8
6
4
2
0
current [A]
bunch coordinate [m]
×10^-4


before and after DOGLEG
×10^8
1.3005
1.3
1.2995
1.299
1.2985
energy [eV]
-2
-1
0
×10^-4
15
10
5
0
current [A]
-2
-1
0
×10^-4



before and after BC0
× 10^8
1.301
1.3
1.299
1.298
energy [eV]
-2
-1
0
× 10^-4
30
20
10
0
current [A]
-2
-1
0
bunch coordinate [m]
× 10^-4

only periodic model:



only periodic model:

	current (A)	rms noise (A)	σ_E (eV)
before LH	5.8	0.030	560
after LH	6.0	0.063	580
before DOGLEG	6.0	0.024	1340
after DOGLEG	8.1	0.89	2530
before BC0	8.1	0.85	4060
after BC0	20.3	1.05	10350

before BC1	20.6	0.50	22170
after BC1	172	18.8	190E3

periodic model

1d particles, discrete stages (LH, DOGLEG, BC0), BW=1THz

	current (A)	rms noise (A)		σ_E (eV)	
before LH	5.8	0.030	0.025	560	462
after LH	6.0	0.063	0.15	580	484
before DOGLEG	6.0	0.024	0.09	1340	1150
after DOGLEG	8.1	0.89	**3.64**	2530	1640
before BC0	8.1	0.85	1.3	4060	**64k**
after BC0	20.3	1.05	2.0	10350	**150k**
before BC1	20.6	0.50		22170	
after BC1	172	18.8		190E3	

1d model severely overestimates effects

XFEL with 3d periodic

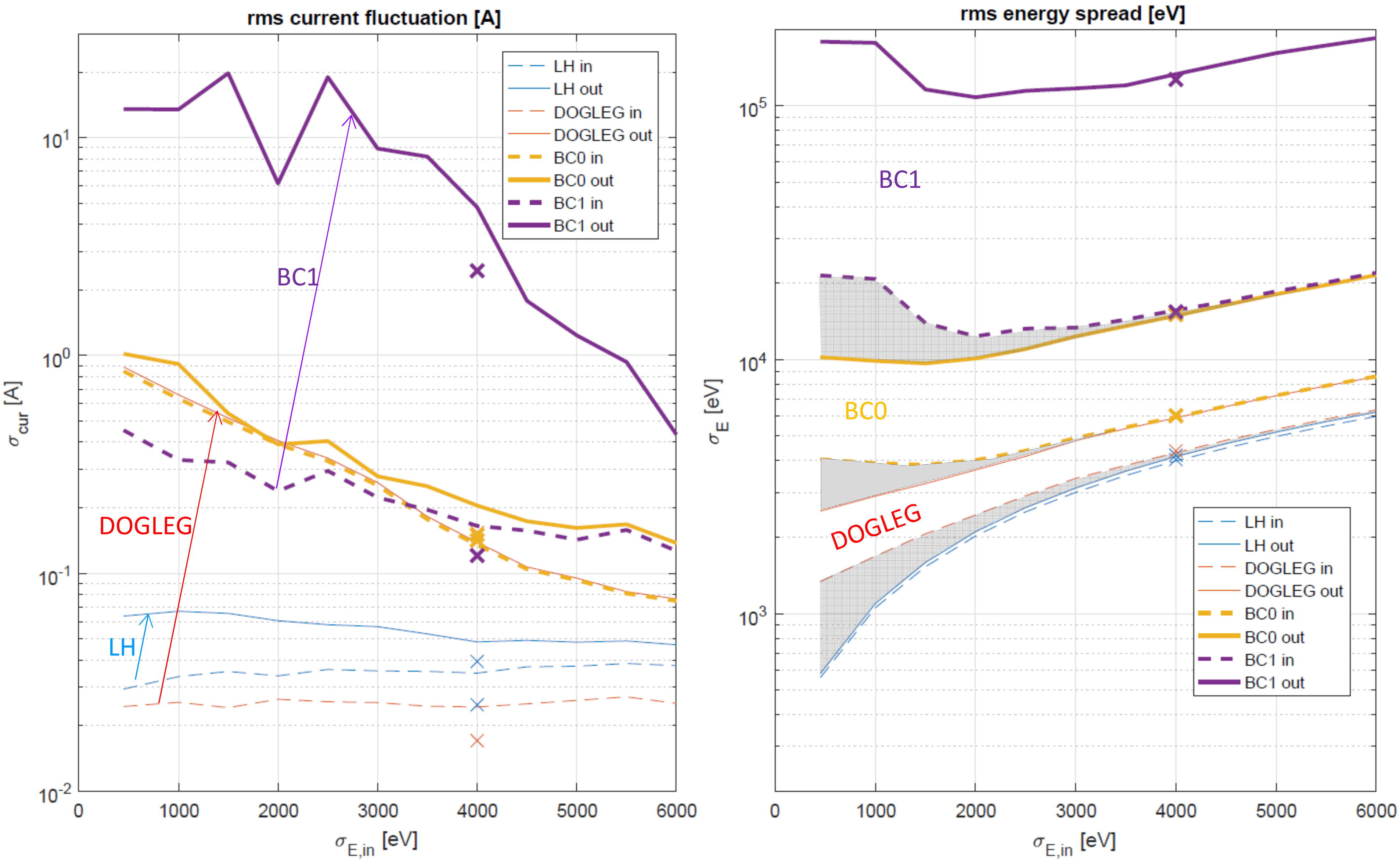
Gaussian “laser heater”:

April 9, 2019

beam parameters:
all beam parameters are as before with exception of the uncorrelated energy spread;
start distribution with an arbitrary gaussian spread of 450 eV, 1000 eV, 1500 eV ... 6000 eV;

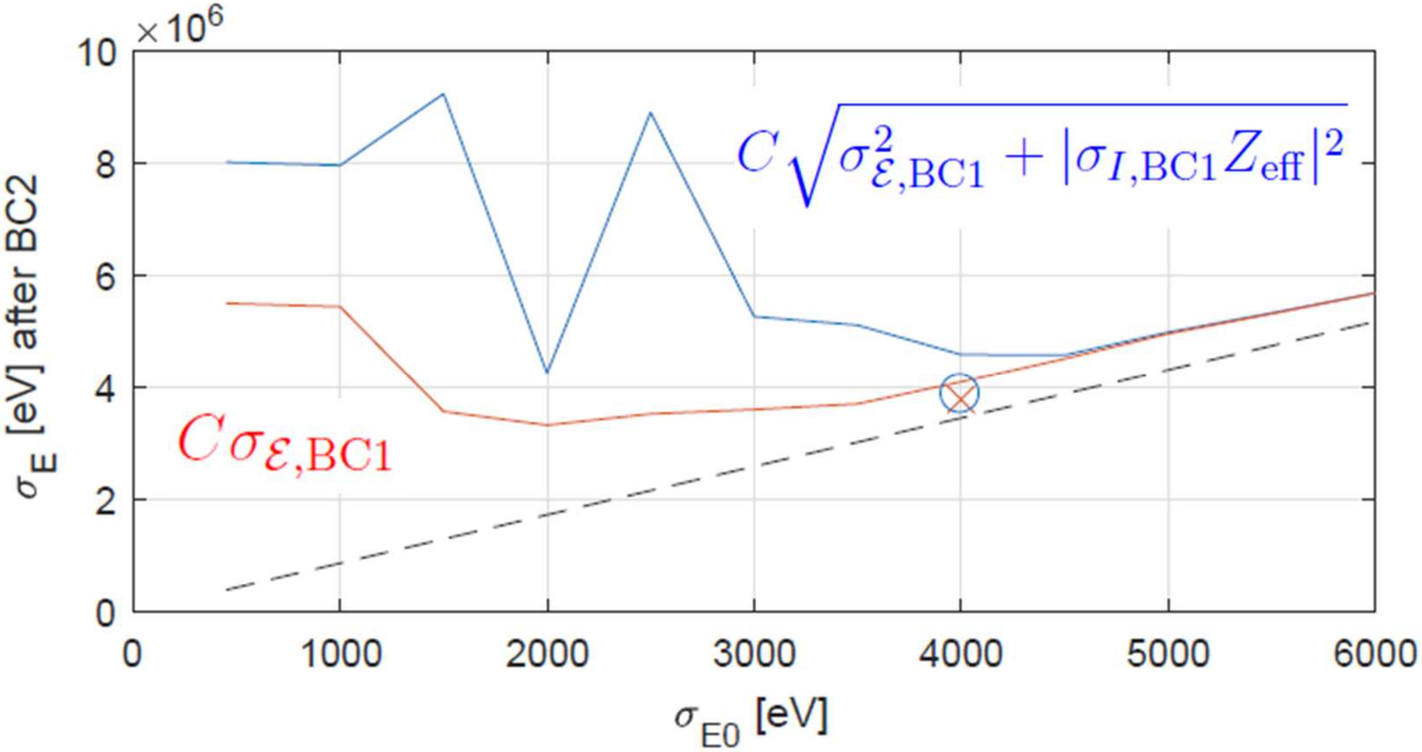
dispersive things and compression:
r56 values and compression as before;

resolution:
charge of macroparticles is elementary charge;
the resolution to the exit of BC0 is as before (0.1µm);
the longitudinal resolution from BC0 exit to BC1 exit is enhanced to 0.03µm;
initial period length 0.1 mm



the extra point (x) is calculated with a period length of 0.3 mm

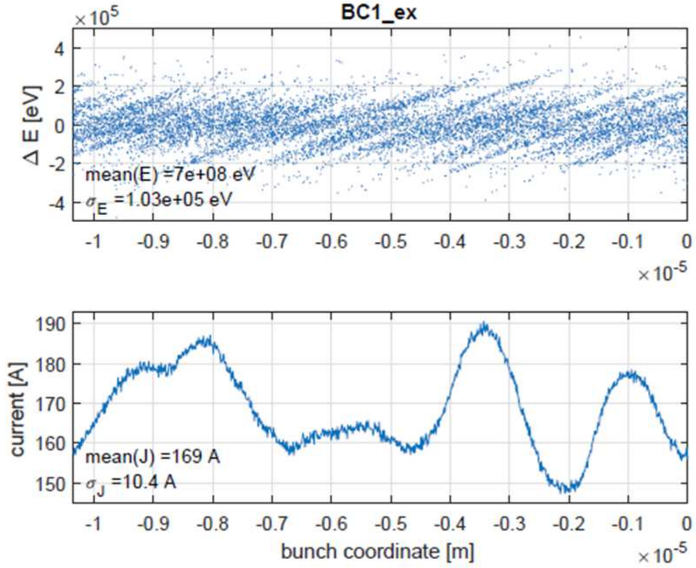
expected slice energy spread after compression in BC2 to 5 kA



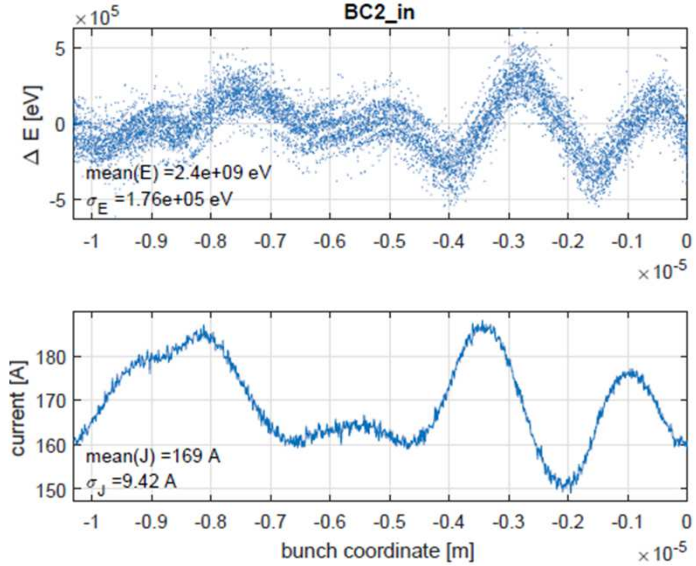
with an effective of about 14 kOhm (for the wavelength of maximal micro-bunching)

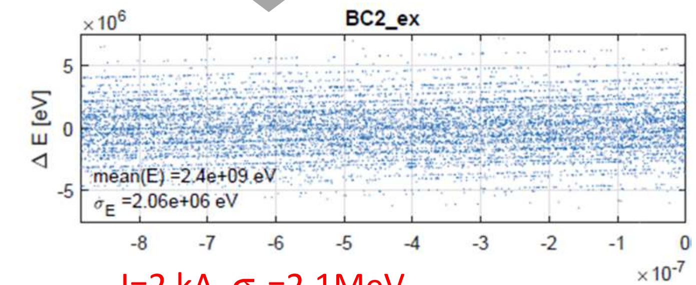
the extra point (x) is calculated with a period length of 0.3 mm

yes, I did simulations to BC2 exit: initial σ_E=4 keV (gaussian)

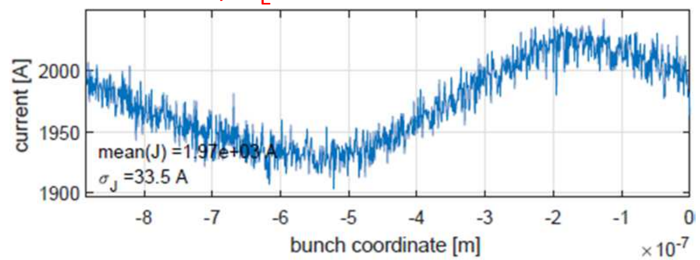


rigid beam !!!

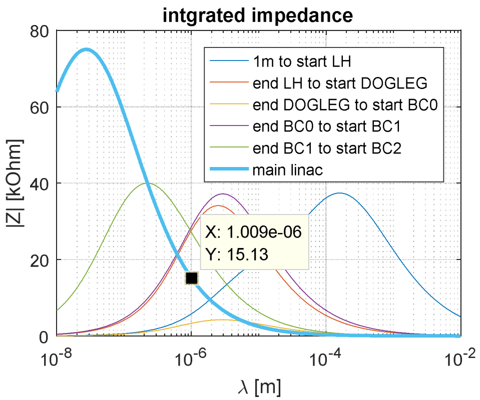




I=2 kA, σ_E=2.1MeV

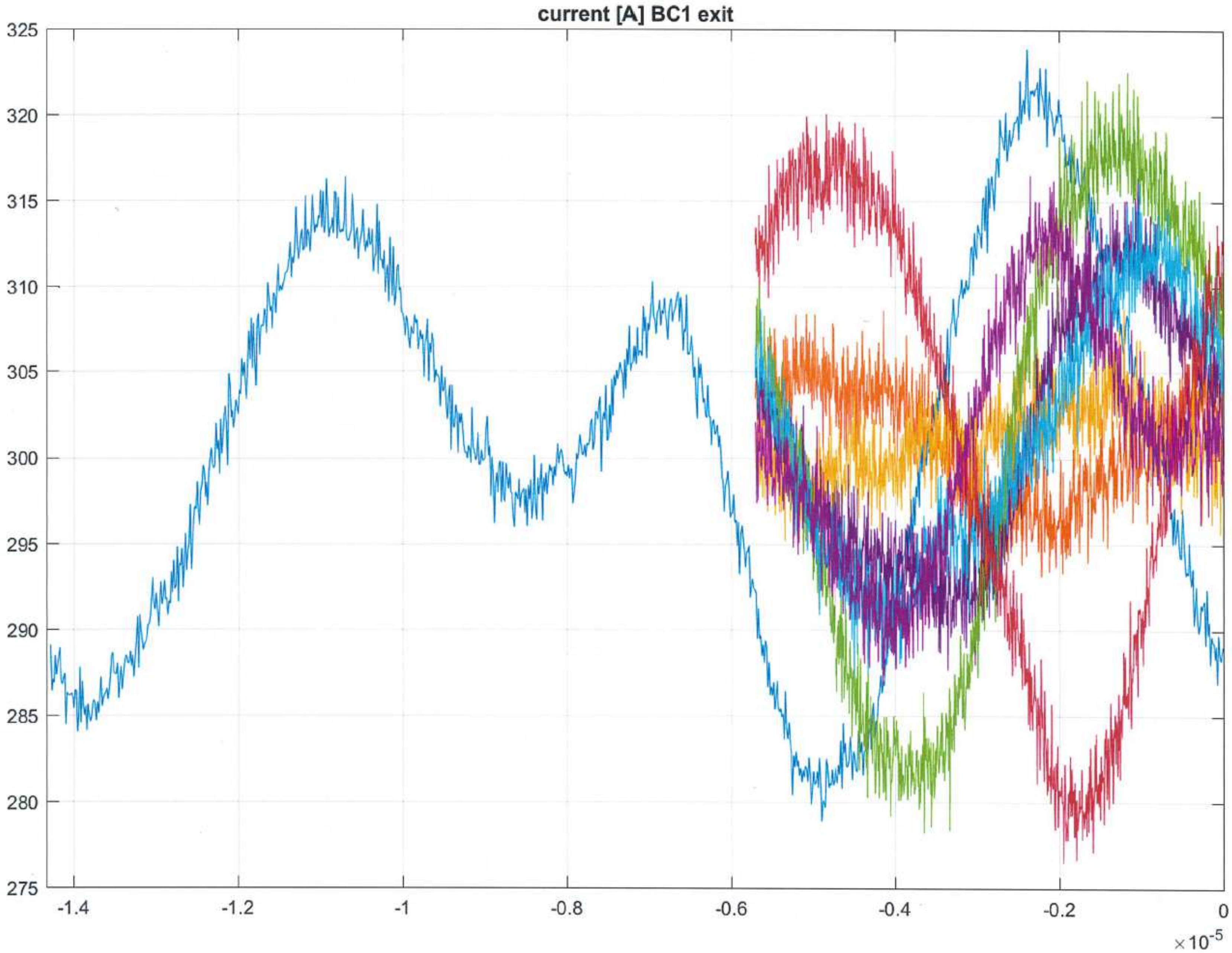


wavelength ~ 1 μm is determined by period length of simulation !!!



$$\sigma_I \approx 33.5\text{A}$$
$$* \quad Z(\text{main linac})$$
$$\approx 0.5 \text{ MeV}$$

an other case: initial period length might be too short!



XFEL with 3d periodic

real laser heater

April 17, 2019

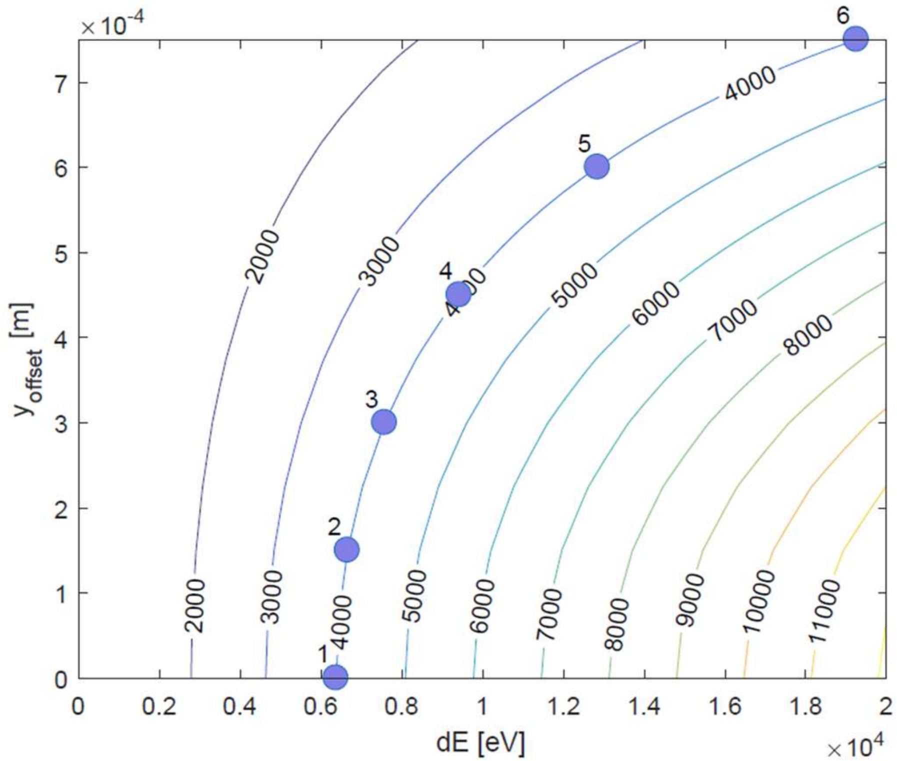
beam parameters:
all beam parameters are as before, initial gaussian spread of 450 eV;

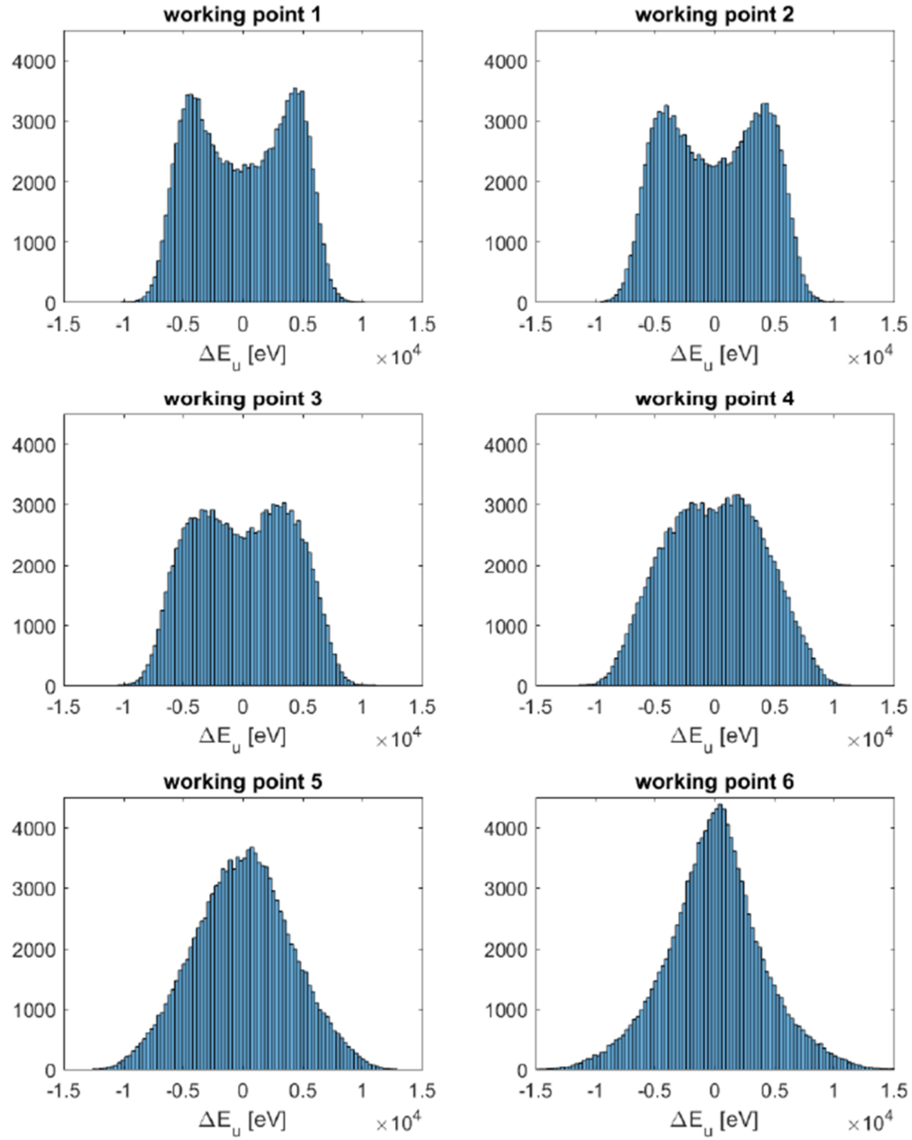
LH:
matching to design optic in LH
different LH working points → same rms spread of 7 keV

dispersive things and compression:
r56 values and compression as before;

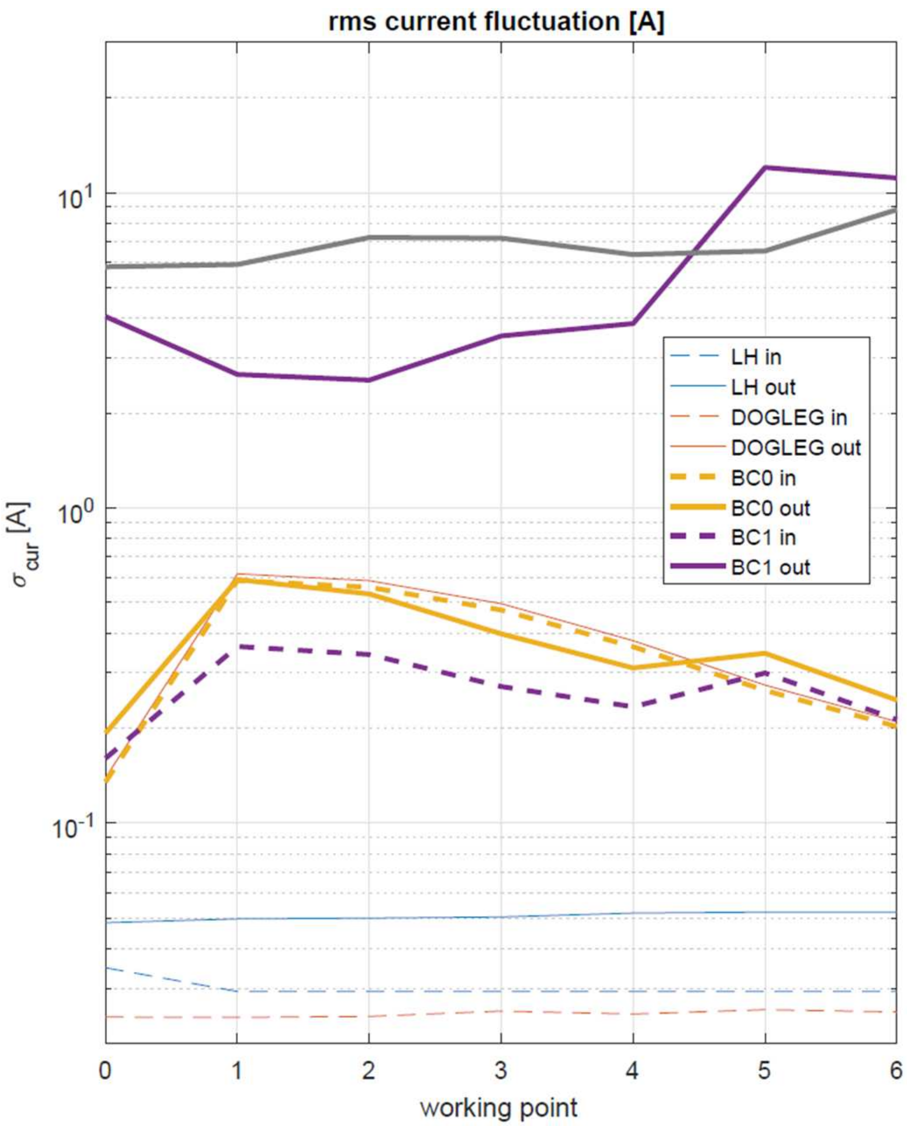
resolution:
charge of macroparticles is elementary charge;
the resolution to the exit of BC0 is as before (0.1µm);
the longitudinal resolution from BC0 exit to BC1 exit is enhanced to 0.03µm;
initial period length 0.3 mm

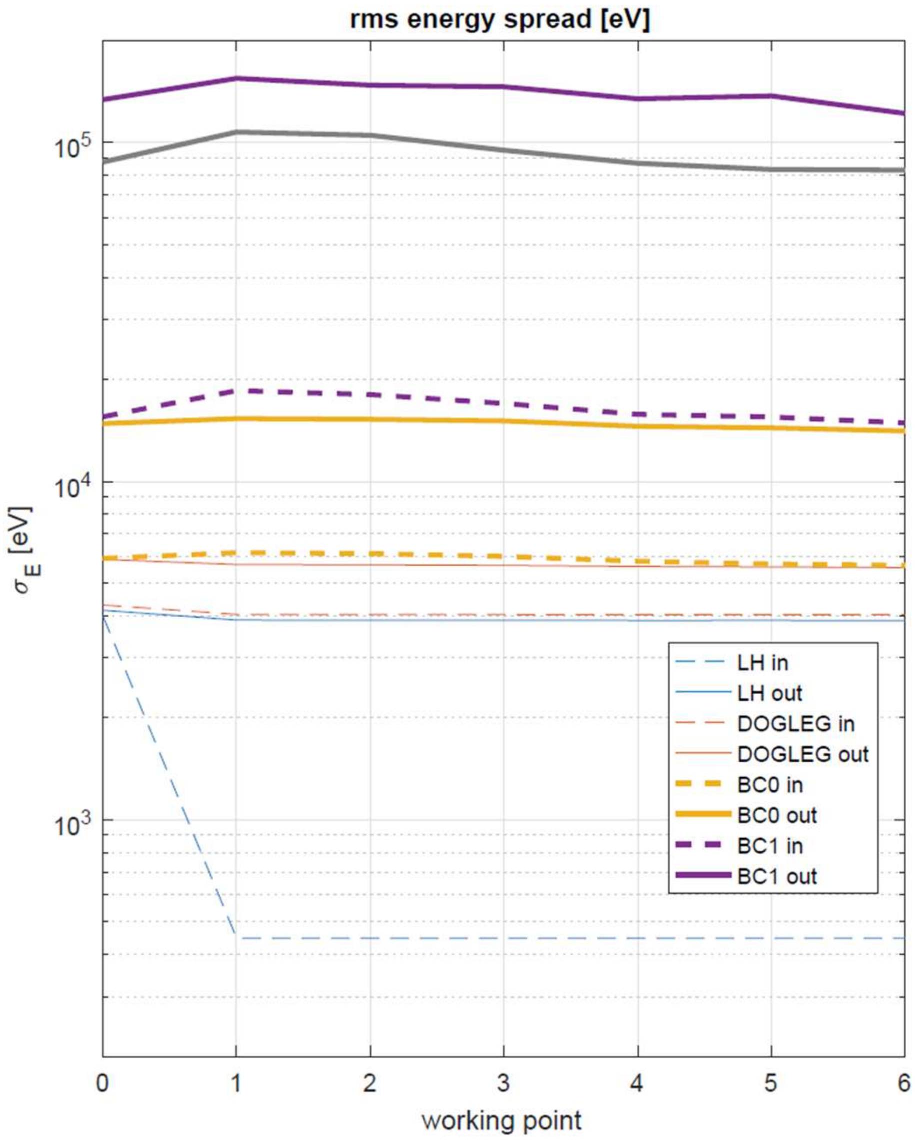
working points for “5.8 A beam” $\rightarrow$ 4 keV





Gaussian (0) and LH working points (1-6)





purple C1=8

gray C1=5.5

summary/conclusion

gain models:

one stage, rigid beam approximation

not applicable before BC0: beam is not rigid
not applicable after BC0: non linear effects

LGM useful in linear domain; needs transverse optic for dispersive sections

simulation of real particle noise:

1d particle model

with non-linear effects
without transverse optic: discrete dispersive sections
to be developed: real dispersive sections with effective optic

full 3d CPU cluster: full bunch simulation; moderate resolution
single PC: reduced bunch length; interference with macro effects

3d periodic

linear optic; very high spatial resolution
no macro effects; limited period length
problem: "non linear phase space mixing"
??? how to generate an effective new distribution
no CSR $\rightarrow$ implement simple periodic CSR model

summary/conclusion

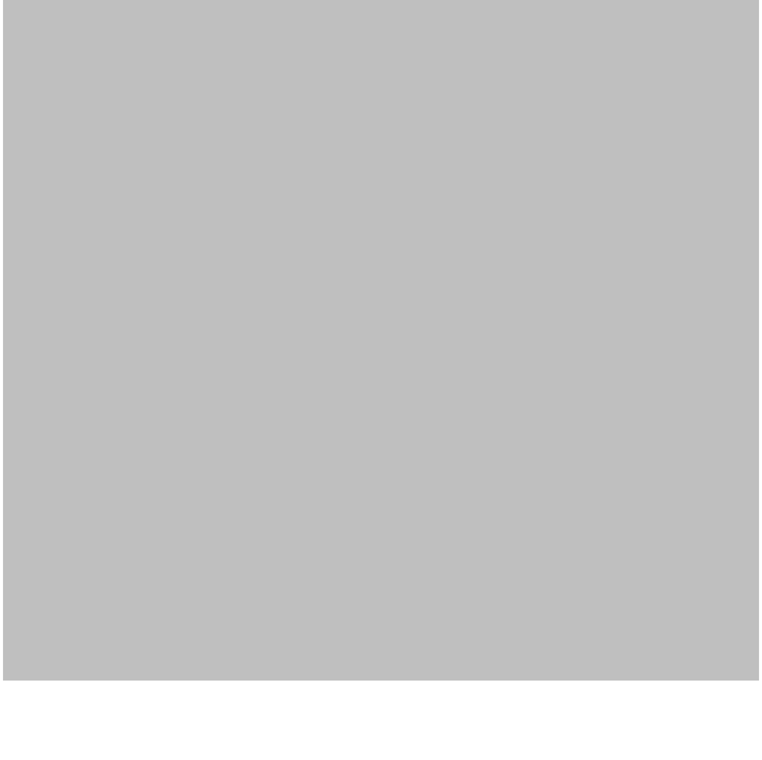
XFEL: earlier investigations did not consider LH and DOGLEG
μB effects are significantly increased

discrete model for DOGLEG is not appropriate

LH: 450 eV $\rightarrow$ 5 keV
after BC1: $\sigma_I \approx 10$ A, $I \approx 10$ A, $\sigma_E \approx 100$ keV
after BC2: $\sigma_I \approx 33$ A, $I \approx 2$ kA, $\sigma_E \approx 2.1$ MeV
5 kA $\rightarrow \sigma_E \approx 5$ MeV

need to be investigated: collimator and beam distribution system

3D periodic simulations with increased period length & more random seeds !!!



induced energy spread: linear regime + rigid beam

$$i(t,S)=\int I_0(\omega)G(\omega,S)\exp\left(j\omega tC(S)\right)d\omega$$

$$E_z(t,S)=\int Z'(\omega,S)I_0(\omega)G(\omega,S)\exp\left(j\omega tC(S)\right)d\omega$$

effect of impedance after compressor, range from S_1 to S_2

$$C(S_1\leq S<S_2)=C$$

$$G(\omega,S_1\leq S<S_2)\approx G(\omega) \qquad\qquad Z(\omega)=\int_{S_1}^{S_2}Z'(\omega,S)\,dS$$

$$\Delta E(t)=e\int I_0(\omega)\exp(j\omega tC)\int_{S_1}^{S_2}Z'(\omega,S)G(\omega,S)\,dS\,d\omega$$

$$=e\int I_0(\omega)\exp(j\omega tC)G(\omega)Z(\omega)\,d\omega$$

$$\boxed{\Delta E_{rms}=\sqrt{\frac{1}{T}\int_0^T\left(\Delta E(t)\right)^2dt}\approx eC\sqrt{\frac{eI_1}{\pi}\int\left|Z(\omega)G(\omega)\right|^2d\omega}} \qquad \approx eI_{rms,\mathrm{out}}\left|Z_{eff}\right|$$