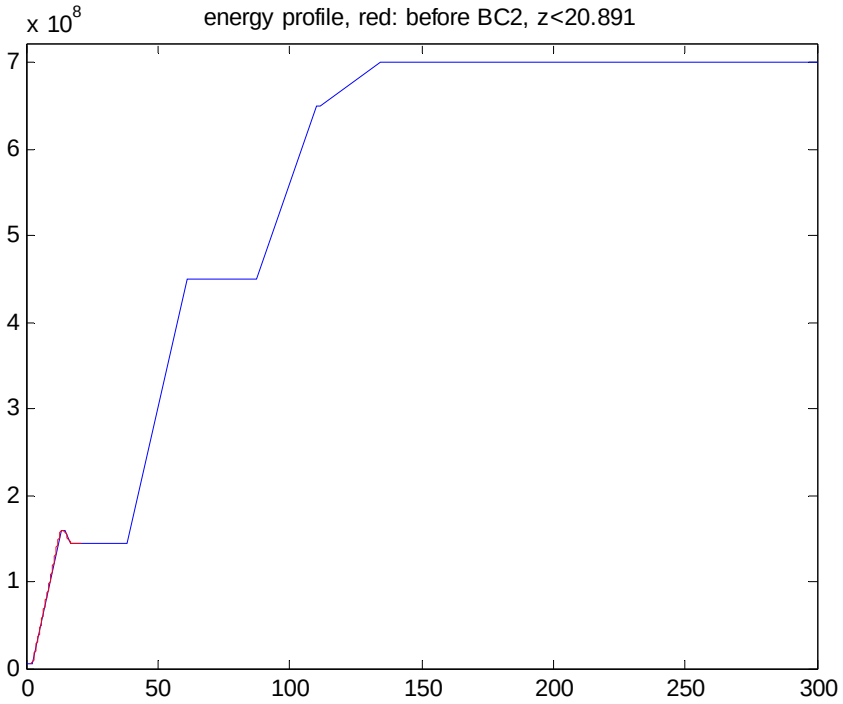
Micro-Bunching and increasing Energy Spread in Flash

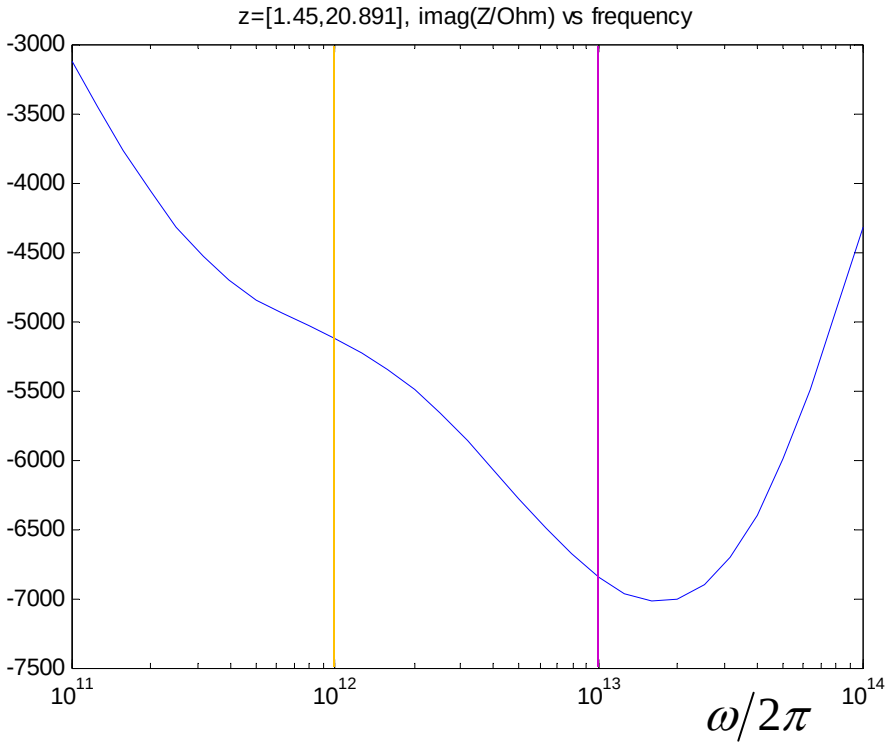
Flash SC-impedances (end-energy = 700 MeV)
Astra bunch (one particular bunch 0.4nC)
methods
before BC3: LGM
periodic tracking
LGM with higher spatial resolution (--> PO2)
what we know so far
after BC3: LGM (not applicable)
periodic tracking
1-stage LG: BC3
Flash2 seeding chicane
some numbers

FLASH SC-impedances

before BC2

SC impedance for emittance = 1um
and beta_av = 10 m



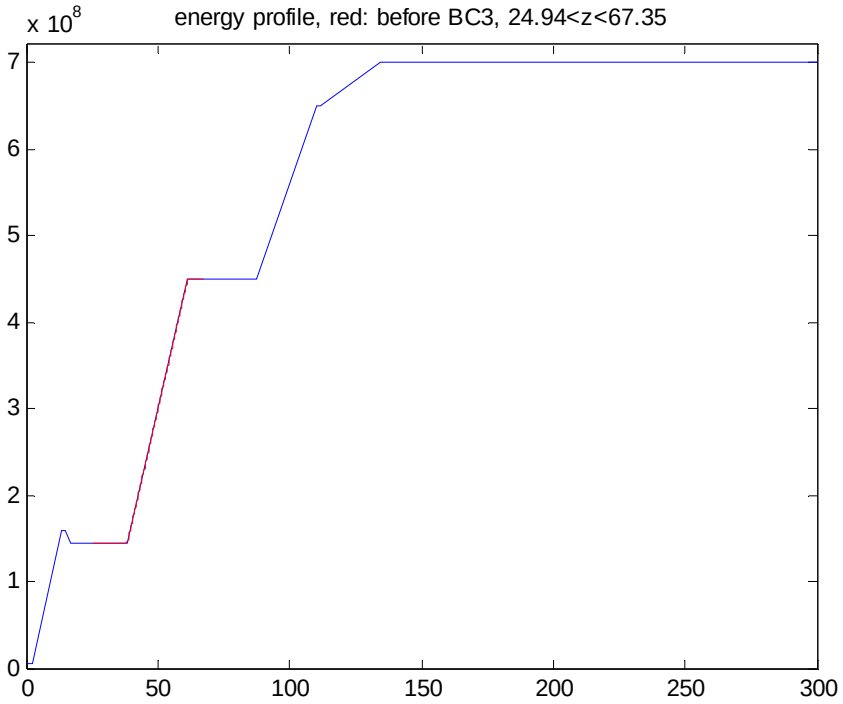


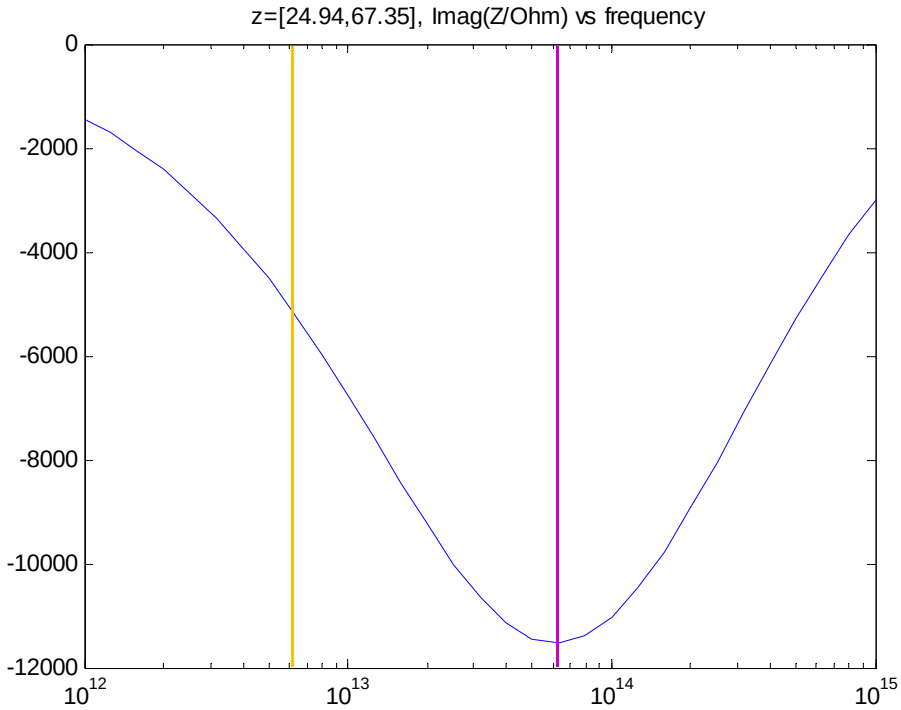
$\lambda/\mu m = 300 = C1 \cdot 48 = C1 \cdot C2 \cdot 4.4$

$\lambda/\mu m = 30 = C1 \cdot 4.8 = C1 \cdot C2 \cdot 0.44$

before BC3

SC impedance for emittance = 1um
and beta_av = 10 m

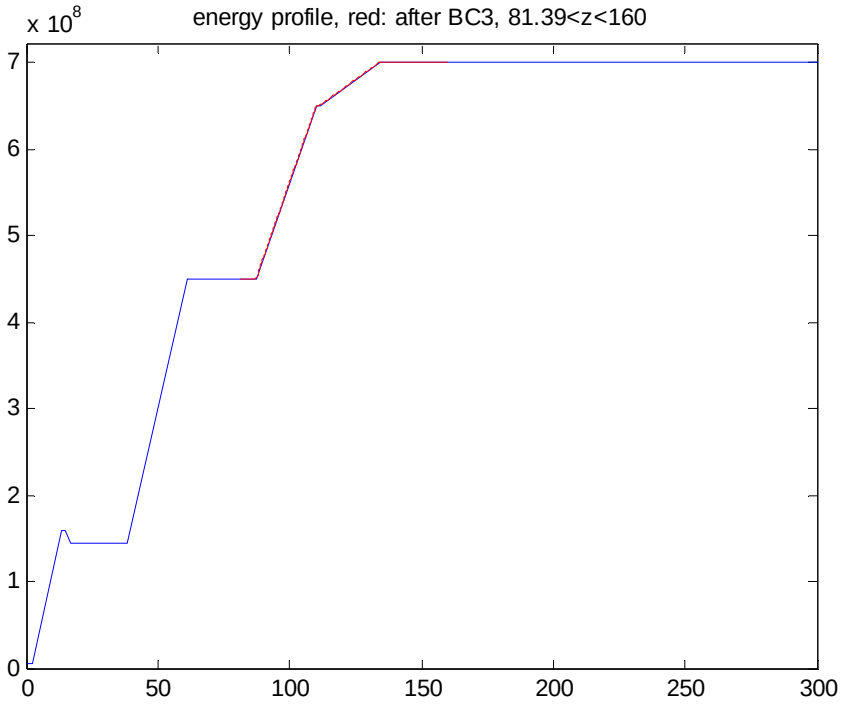


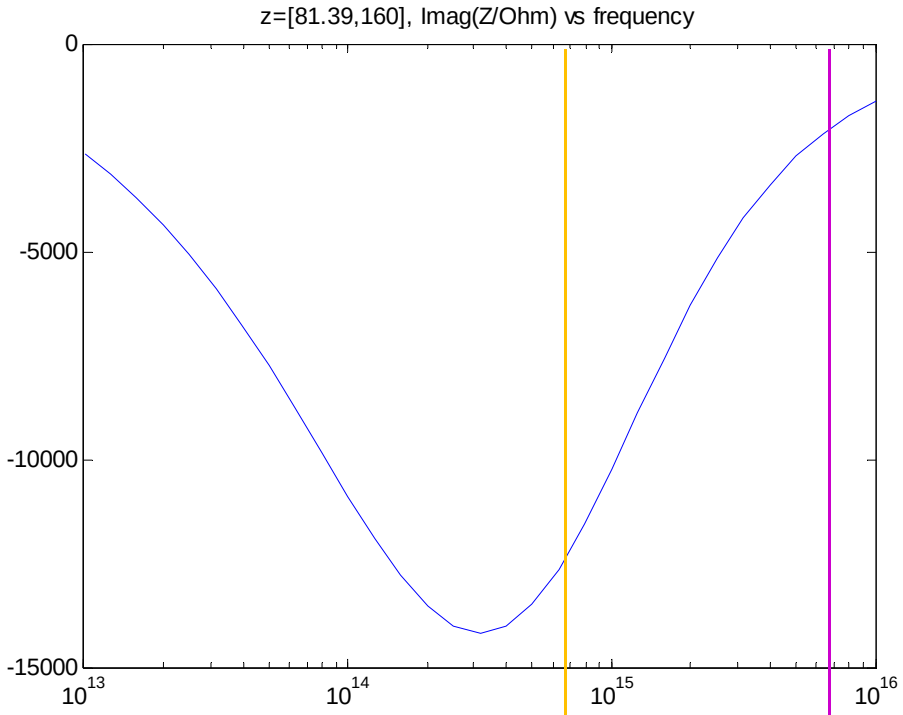


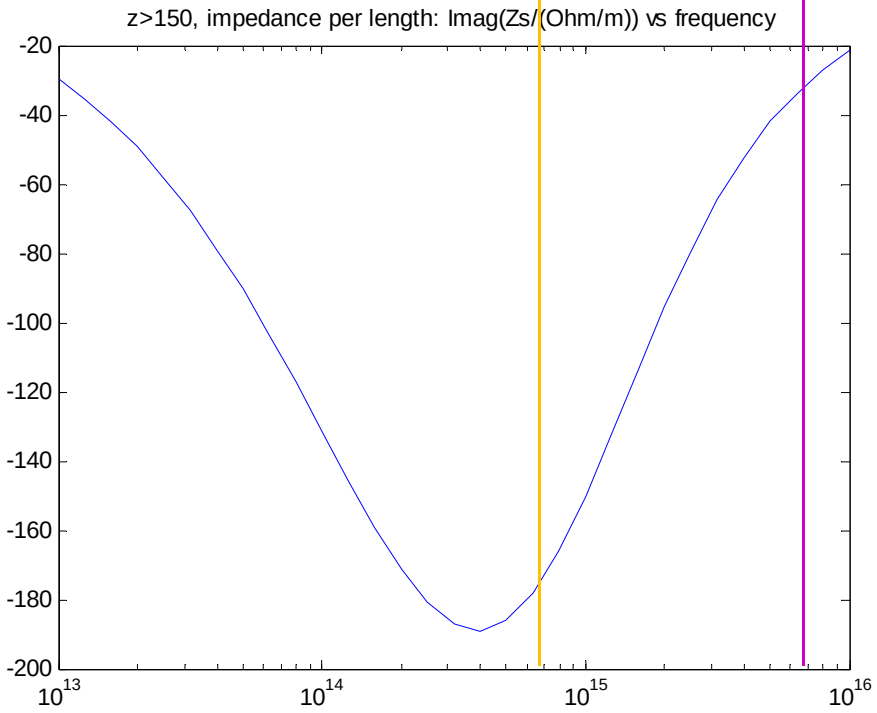
$\lambda/\mu m = 300/C1 = 48 = C2 \cdot 4.4$

$\lambda/\mu m = 30/C1 = 4.8 = C2 \cdot 0.44$

SC impedance for emittance = 1um
and beta_av = 10 m







λ/μm = 300/C1/C2 = 48/C2 = 4.4

λ/μm = 30/C1/C2 = 4.8/C1 = 0.44

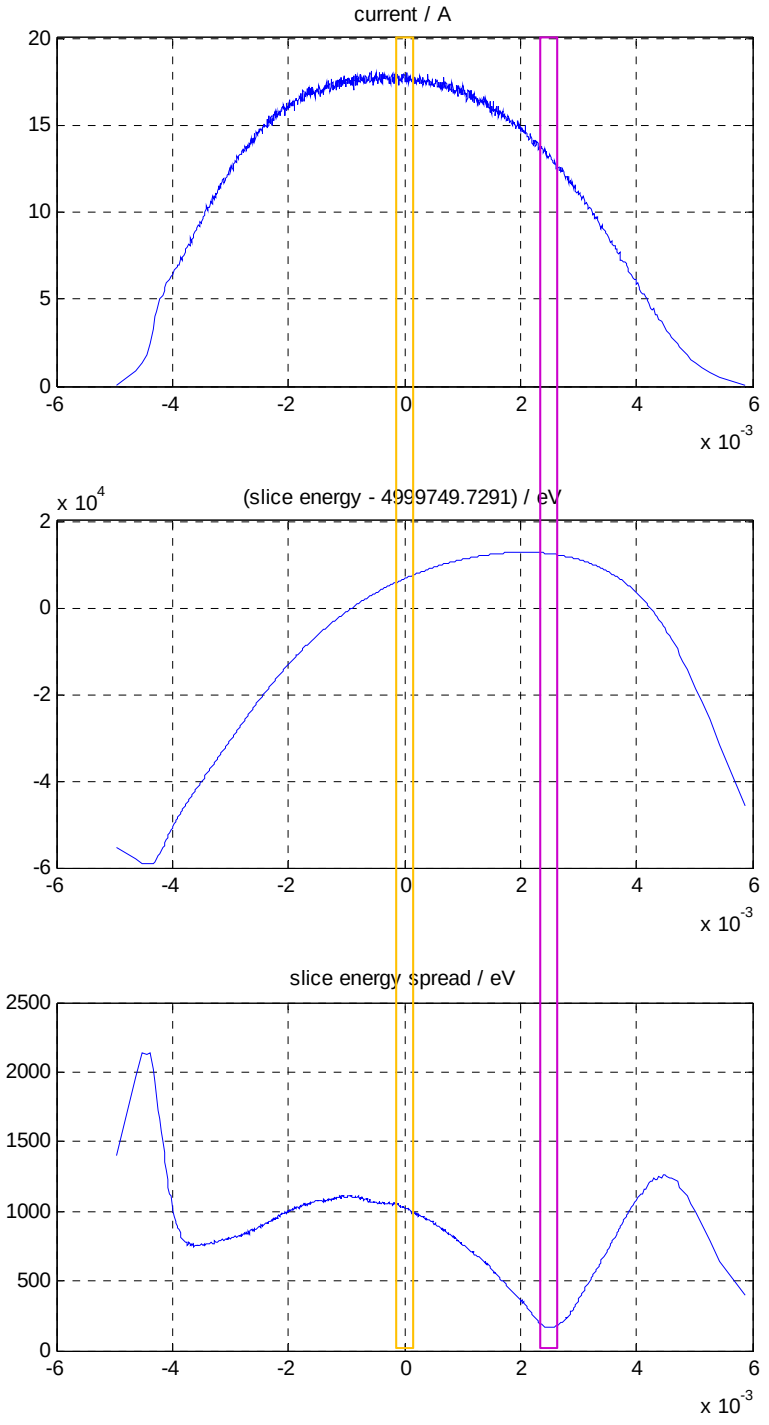
Astra bunch

Astra bunch 0.4 nC, at z=1.45 m

calculation with 10^7 particles

"slice 1"
(~1keV energy spread, I=17.6 A)

"slice 2"
(small energy spread, I=13.1 A)



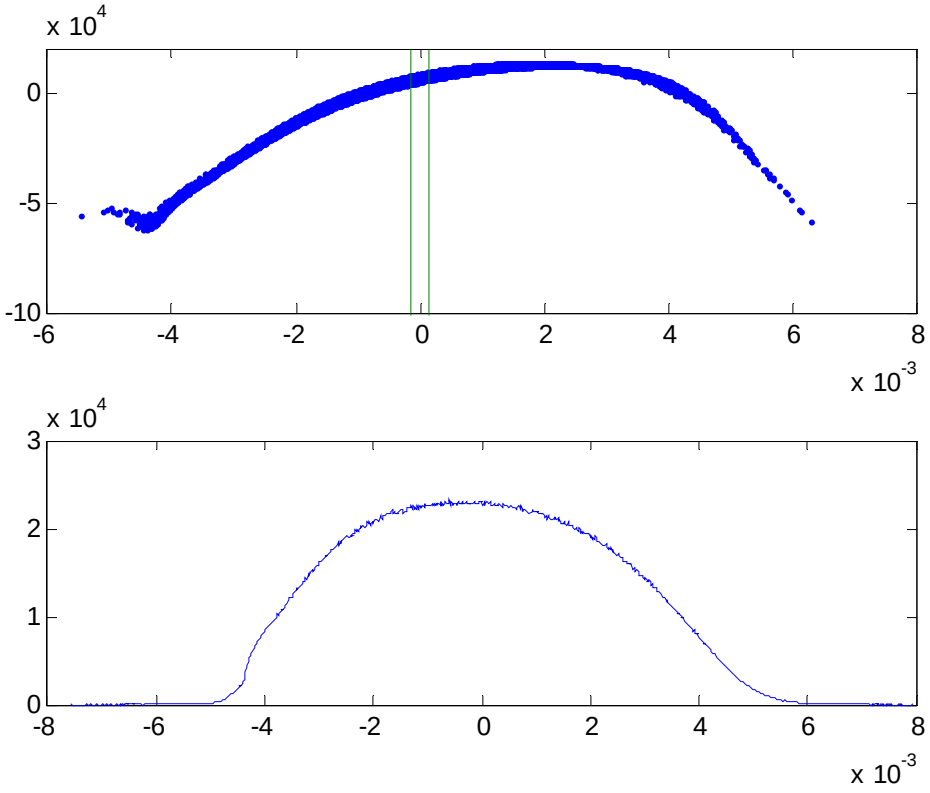
I/A
bunch current

$\left(\langle E \rangle_s - E_0\right)/eV$
slice energy

σ_E/eV
slice energy spread

"slice" 1: Astra bunch 0.4 nC, at z=1.45 m

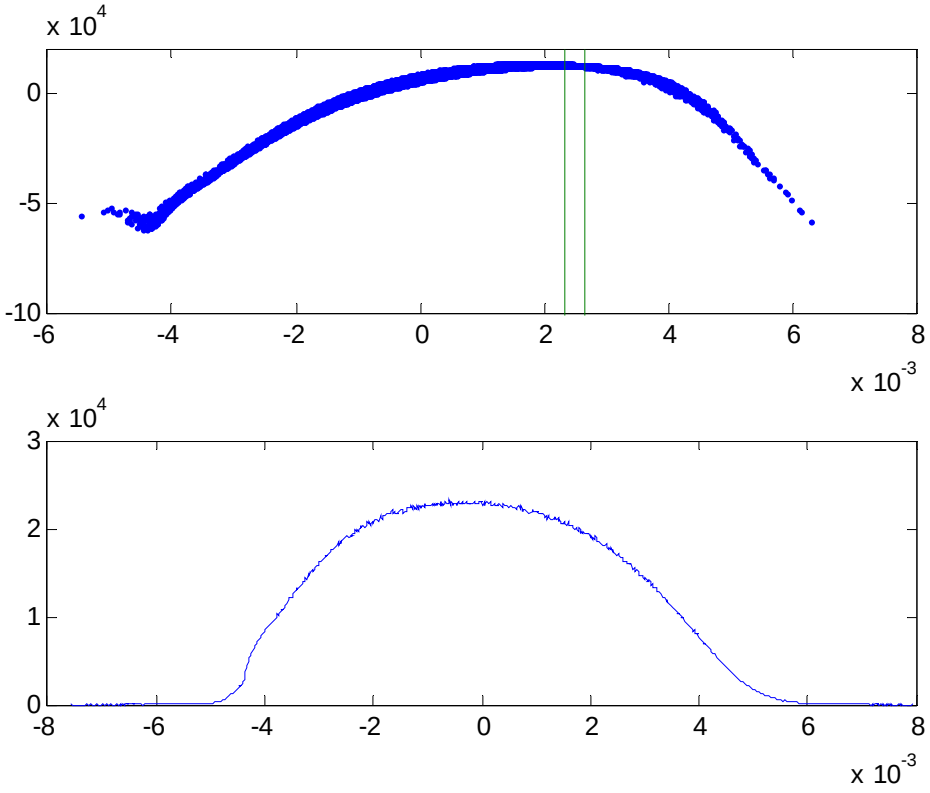
0.3mm "slice" with center at s=0mm (~1keV energy spread, I=17.6 A)
about 110E6 particles



compression: 17.7A --> 110A --> 1200A

“slice” 2: Astra bunch 0.4 nC, at z=1.45 m

0.3mm slice with center at s=2.5mm (small energy spread, I=13.1 A)
about 82E6 particles



compression: 13.1A --> 85.5A --> 944A

methods

linear gain model (LGM)

frequency of (small) initial density modulation ω

initial current (no modulation) I_0

linear gain function $G(\omega, S) = \tilde{I}(S) / \left(\tilde{I}(0) C(S)\right)$

solve integral equation: $G(S) = G_0 + \int_0^S K(B, S) G(B) dB$

kernel depends on linear optics, local impedance and (slice) energy distribution

rms amplitude of shot noise $i_{C,eff} = C \sqrt{\frac{eI_0}{\pi} \int |G(\omega)|^2 d\omega}$

rms energy spread due to shot noise (for a given impedance) $\sigma_E = eC \sqrt{\frac{eI_0}{\pi} \int |G(\omega) Z(C\omega)|^2 d\omega}$

start at z=0.40m (after Gun)

“periodic tracking”

here: tracking of a periodic distribution

real number of electrons --> real shot noise

short period (~ 0.3mm, ~ 100E6 particles)

linear external forces, but non-linear space charge forces (periodic SC solver)

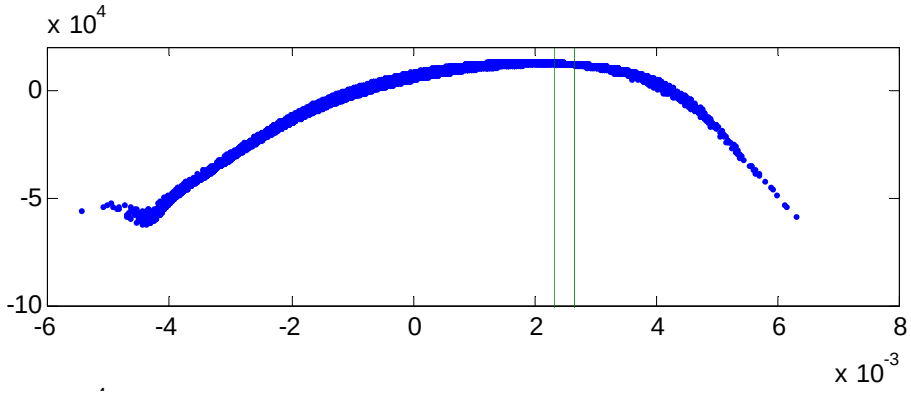
all lattice elements behave linear
rf curvature neglected (short period)
no wakes
no self-effects in chicanes

tricks: preparation of initial distribution (next slide)

reduce number of particles after BC2: ~100E6 --> 10E6 particles
density fluctuations are well above shot noise
(s2e full resolution calculation is possible!)

start at z=1.45m (after solenoid)

preparation of phase space distribution:



Astra distribution with 10E6 particles, but 0.4 nC /e = 2.5E9
we need 250 particles per Astra-particles

procedure: select all particles in the given slice,
extract correlations with z (to 3rd order)
keep information about linear z-energy correlation
throw away z-information
multiply (replicate x 250) and mix the 5D-distribution
use random generator for z-coordinates
regenerate linear z-energy correlation

LGM before BC3

0.3mm slice with center at s=0mm
(~1keV energy spread, I=17.6 A)

```
>> main_LGM
setup finished
number of frequency points = 200
integral equation finished
Ctot                      = 6.25
Ctot*current_0            = 110
rms energy spread         = 999.6854
rms energy spread @ end   = 6248.0335
maximal gain              = 41.226
integral(gain^2,domega)   = 6.642e+16
Cnoise = Ctot*sqrt(...)   = 1.525   (1.538 with CSR)
```

from initial energy spread

shot noise after BC2

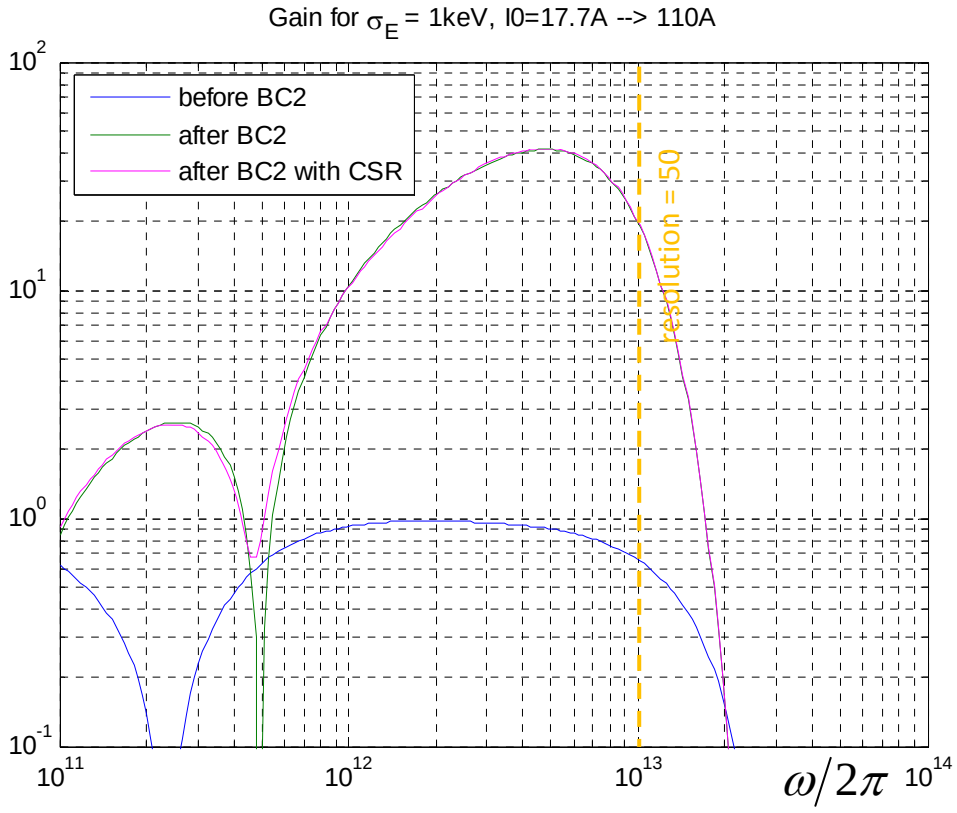
$$i_{C,eff} = C\sqrt{\frac{eI_0}{\pi}\int |G(\omega)|^2 d\omega} =$$

1.53 A

energy spread due to shot noise BC2 --> BC3

$$\sigma_E = eC\sqrt{\frac{eI_0}{\pi}\int |G(\omega)Z(C\omega)|^2 d\omega} =$$

16 keV



0.3mm slice with center at s=2.5mm
(small energy spread, I=13.1 A)

```
>> main_LGM
setup finished
number of frequency points = 200
integral equation finished
Ctot                       = 6.5267
Ctot*current_0             = 85.5
rms energy spread          = 249.9379
rms energy spread @ end    = 1631.2744
maximal gain               = 92.2164
integral(gain^2,domega)    = 1.344e+18
Cnoise = Ctot*sqrt(...)    = 6.1809   (6.277 with CSR)
```

from initial energy spread

shot noise after BC2

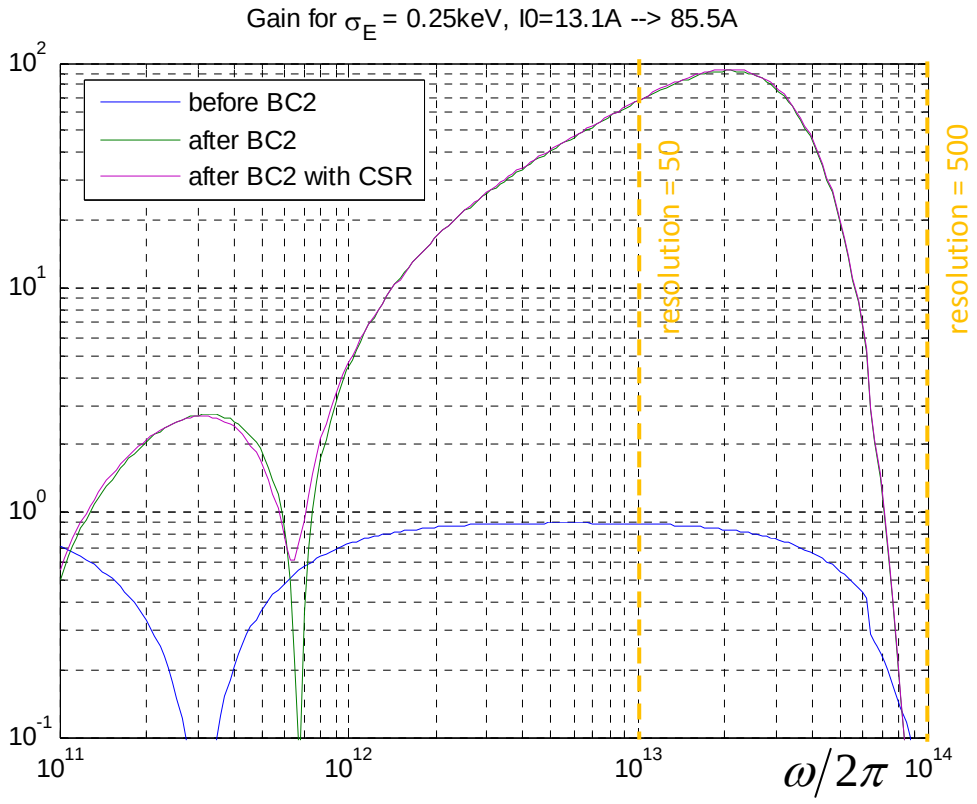
$$i_{C,eff} = C\sqrt{\frac{eI_0}{\pi}\int |G(\omega)|^2 d\omega} =$$

6.18 A

energy spread due to shot noise
BC2 --> BC3

$$\sigma_E = eC\sqrt{\frac{eI_0}{\pi}\int |G(\omega)Z(C\omega)|^2 d\omega} =$$

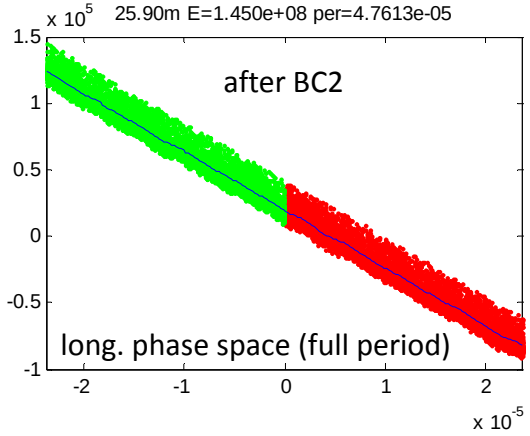
62 keV

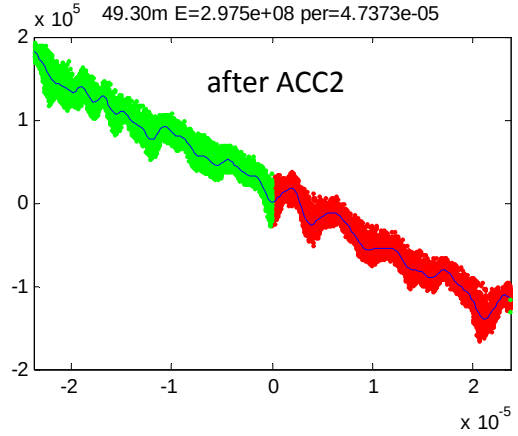


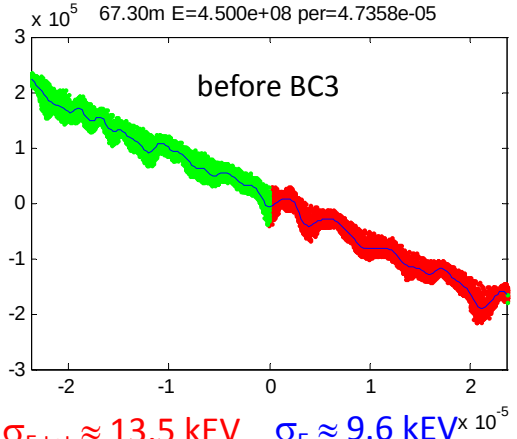
periodic tracking before BC3

```
24.90 after BC2
49.30 after ACC2
67.30 before BC3
```

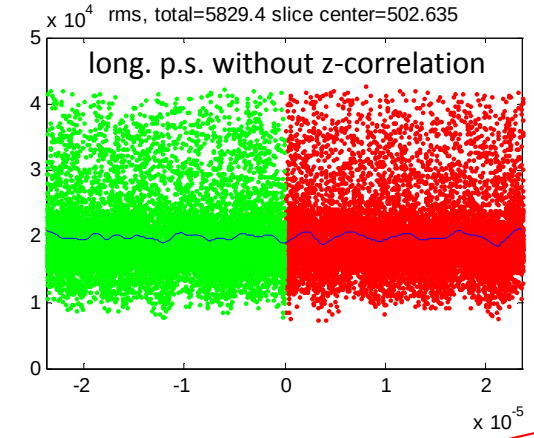
0.3mm slice with center at s=0mm (~1keV energy spread, I=17.6 A)

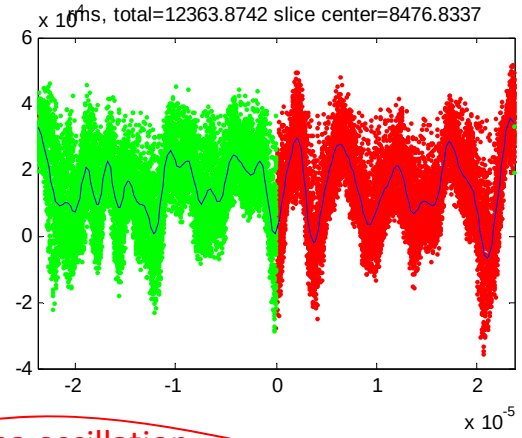


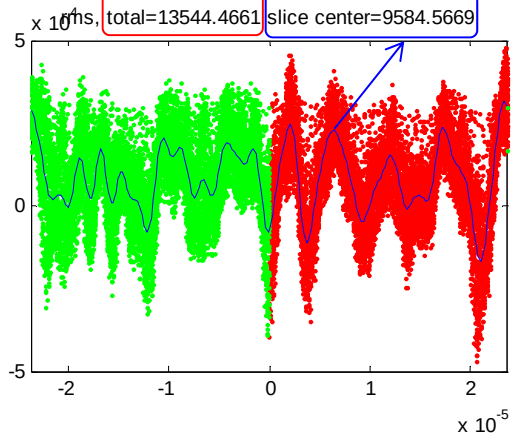




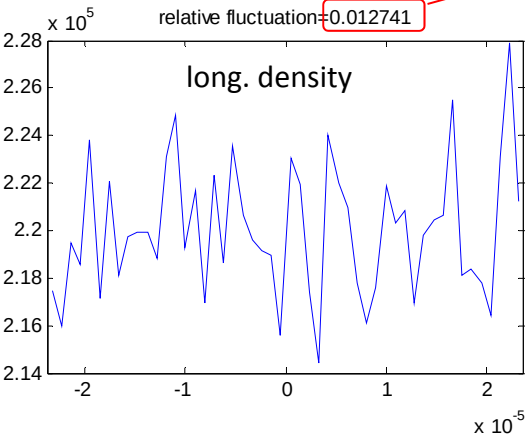
$\sigma_{E,tot} \approx 13.5$ kEV $\sigma_E \approx 9.6$ kEV

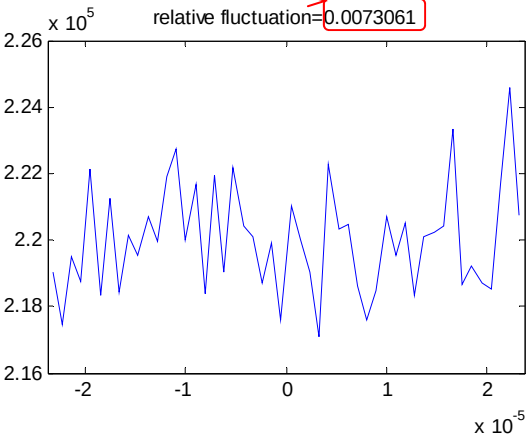


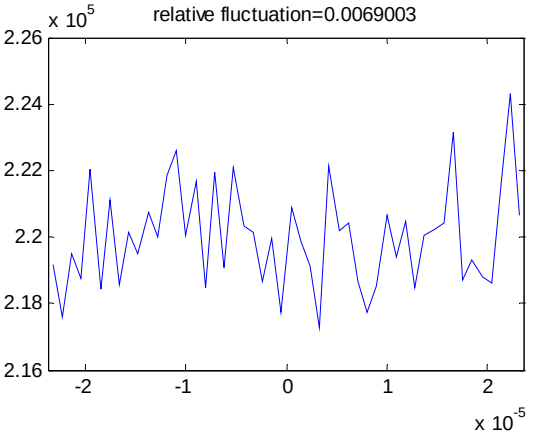




plasma oscillation

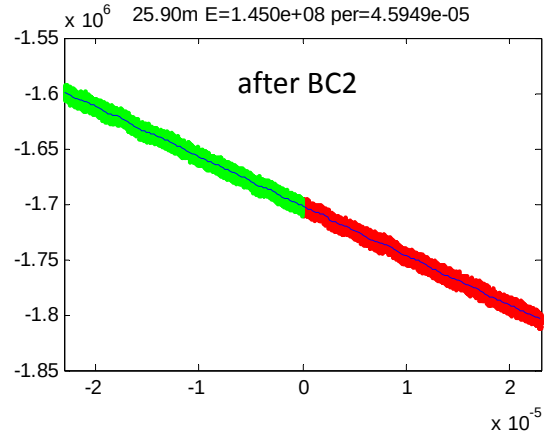


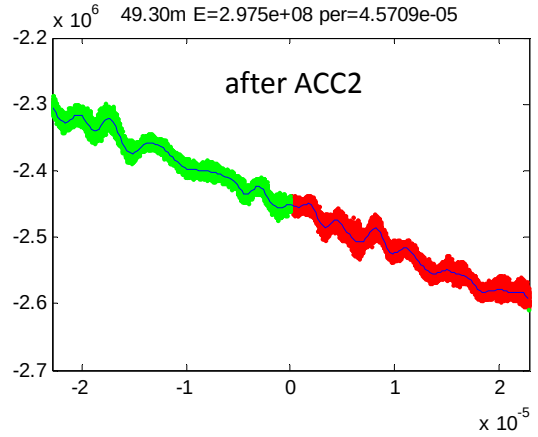


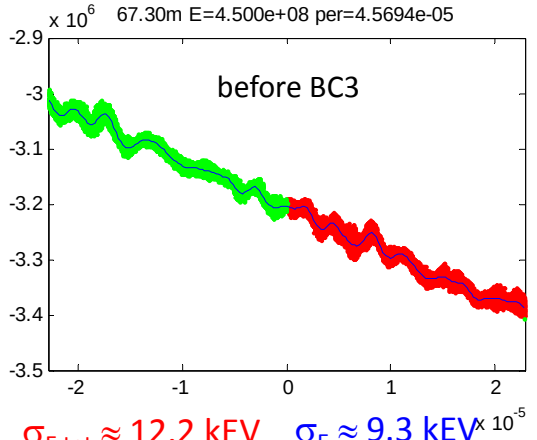


0.3mm slice with center at s=2.5mm (small energy spread, I=13.1 A)

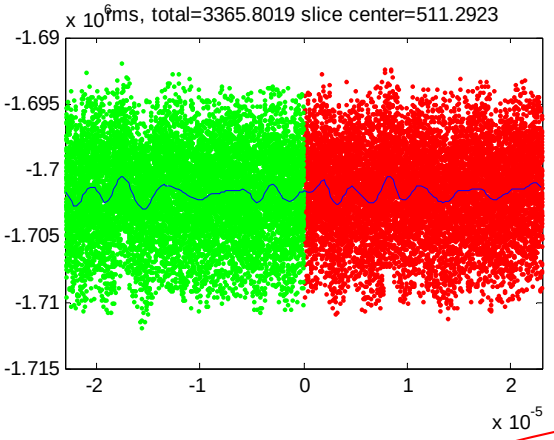
resolution = 50

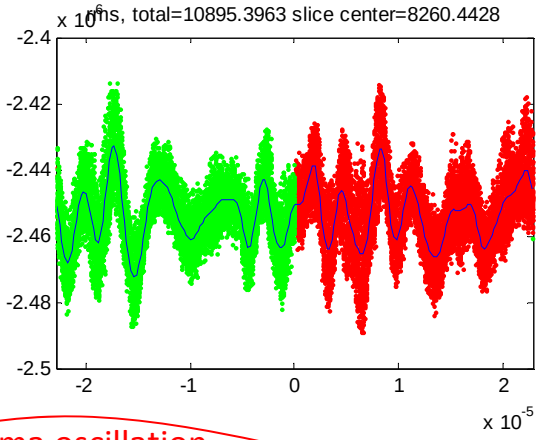


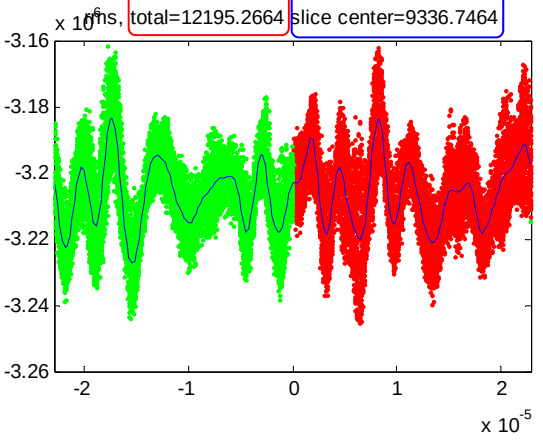




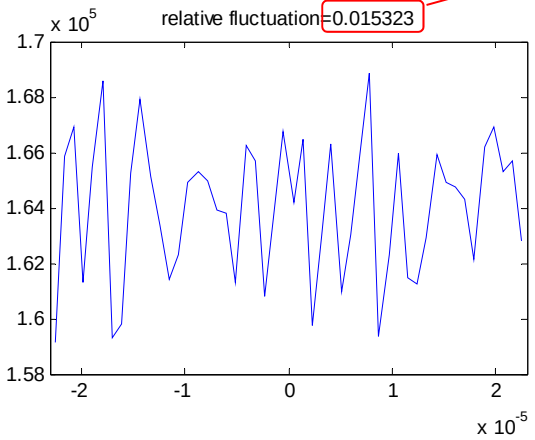
$\sigma_{E,tot} \approx 12.2$ kEV $\sigma_E \approx 9.3$ kEV

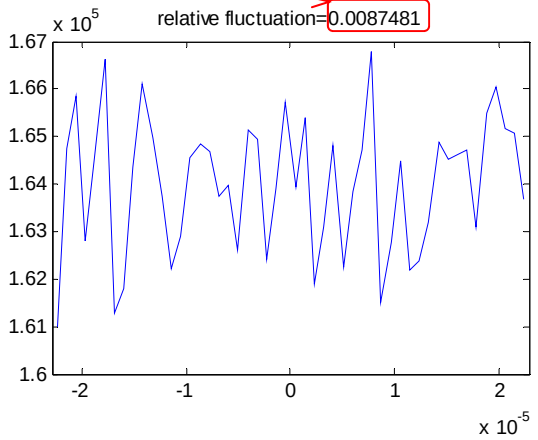


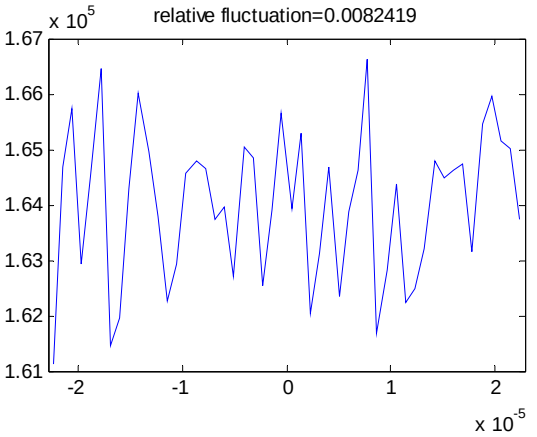




plasma oscillation

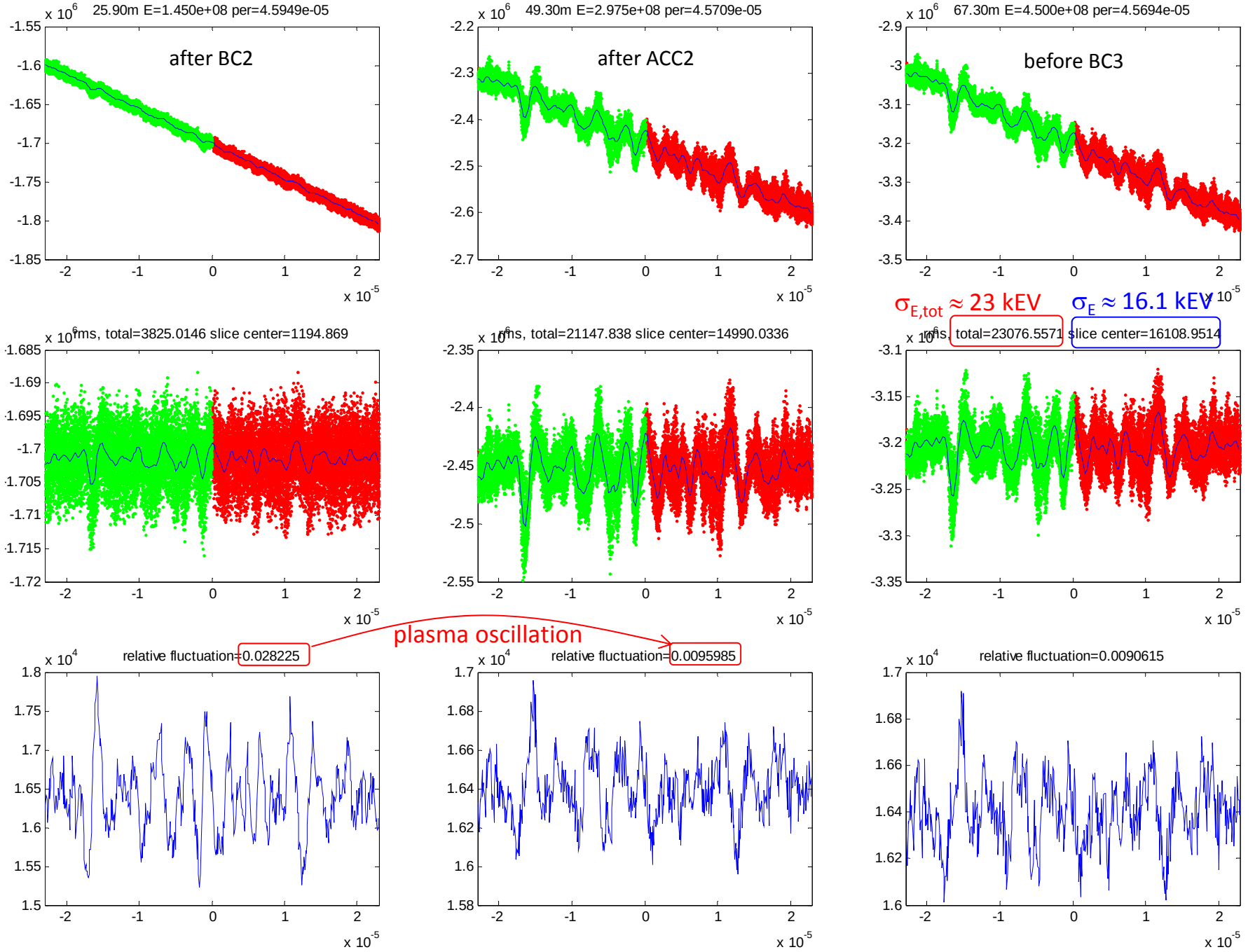






0.3mm slice with center at s=2.5mm (small energy spread, I=13.1 A)

resolution = 500



LGM before BC3 with PO2

PO1 = plasma oscillation before BC2
PO2 = plasma oscillation before BC3

0.3mm slice with center at s=0mm
(~1keV energy spread, I=17.6 A)

```
>> main_LGM
setup finished
number of frequency points = 200
integral equation finished
Ctot                       = 6.2891
Ctot*current_0             = 110.6883
rms energy spread          = 999.6854
rms energy spread @ end    = 6287.1265
maximal gain               = 41.226
integral(gain^2,domega)    = 1.77e+16
Cnoise = Ctot*sqrt(...)    = 0.79228   (0.795 with CSR)
```

from initial energy spread

shot noise before BC3

$$i_{C,eff} = C\sqrt{\frac{eI_0}{\pi}\int |G(\omega)|^2 d\omega} =$$

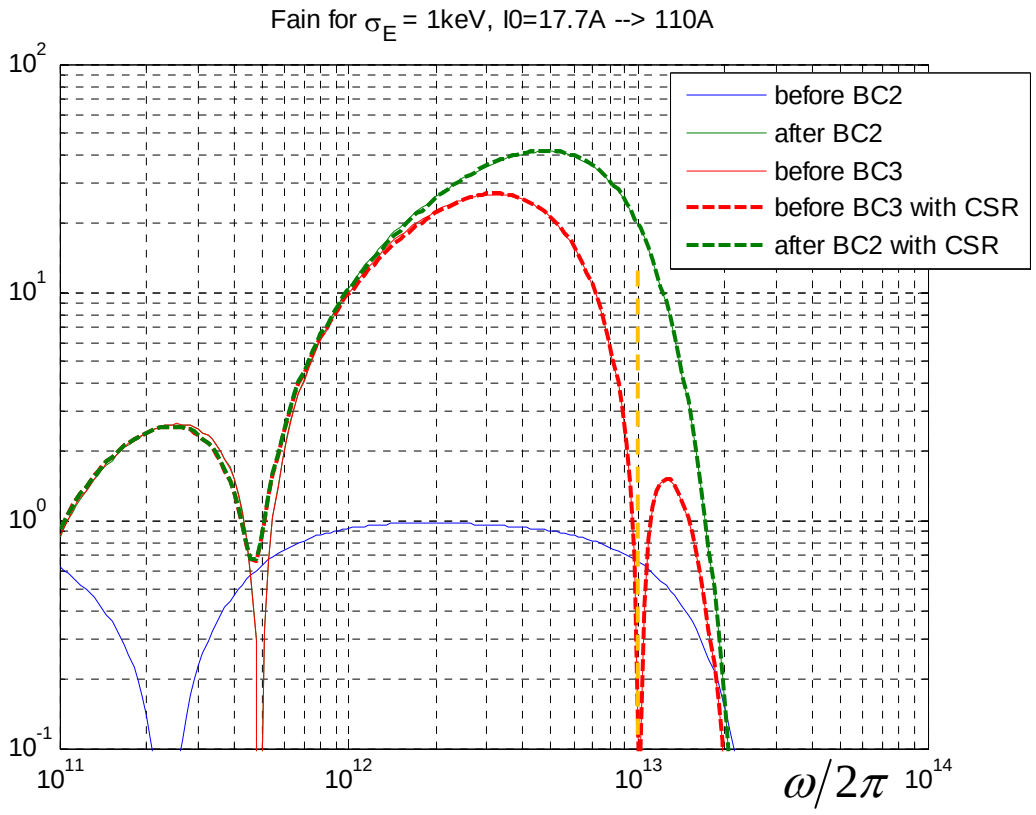
0.792 A

energy spread due to shot noise BC2 --> BC3

$$\sigma_E = eC\sqrt{\frac{eI_0}{\pi}\int |\langle G(\omega)\rangle Z(C\omega)|^2 d\omega} =$$

7.4 keV

averaged !



0.3mm slice with center at s=2.5mm
(small energy spread, I=13.1 A)

```
>>  main_LGM
setup finished
number of frequency points = 200
integral equation finished
Ctot                       = 6.5693
Ctot*current_0             = 86.0574
rms energy spread          = 249.9377
rms energy spread @ end    = 1641.9067
maximal gain               = 113.7693
integral(gain^2,domega)    = 2.589e+17
Cnoise = Ctot*sqrt(...)    = 2.7303   (6.277 with CSR)
```

from initial energy spread

shot noise before BC3

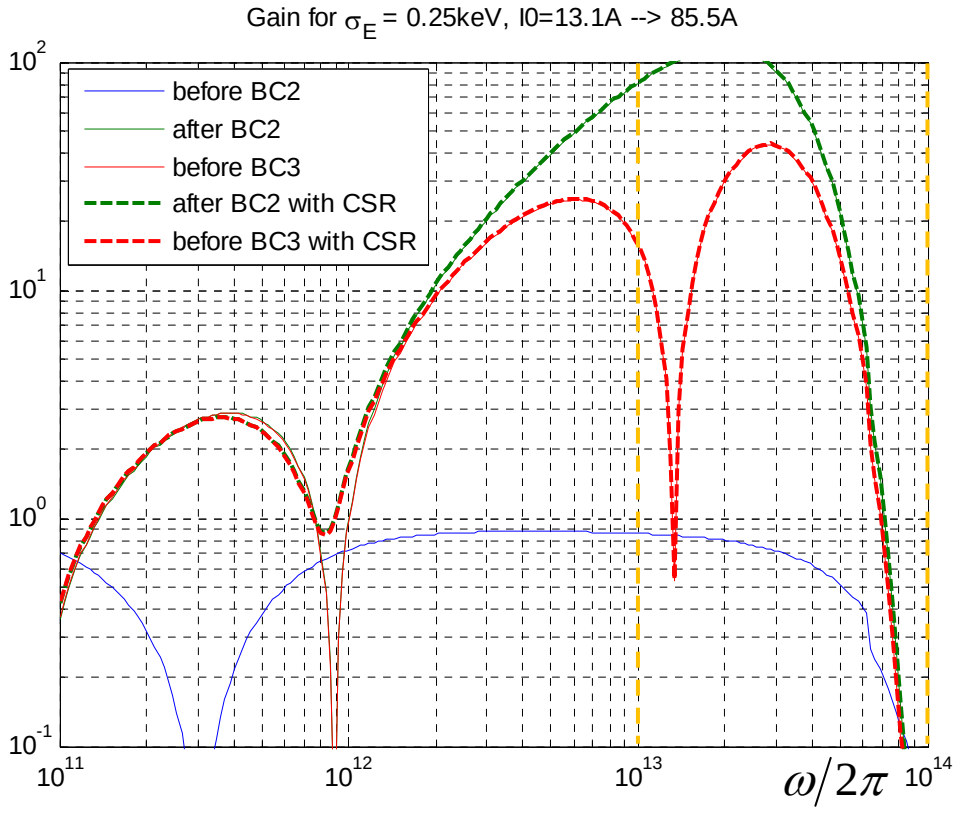
$$i_{C,eff} = C\sqrt{\frac{eI_0}{\pi}\int |G(\omega)|^2 d\omega} =$$

2.73 A

energy spread due to shot noise BC2 --> BC3

$$\sigma_E = eC\sqrt{\frac{eI_0}{\pi}\int |\langle G(\omega)\rangle Z(C\omega)|^2 d\omega} =$$

25 keV



what we know so far

total energy spread after BC3, without further effects

$$\sigma_{E,3} = C_2\sqrt{(C_1\sigma_{E,i})^2 + \sigma_{E,2}^2}$$

0.3mm slice with center at s=0mm
(~1keV energy spread, I=17.6 A)

$C_1 = 110/17.7$

$C_2 = 1200/110$

$\sigma_{E,i} = 1\,\mathrm{keV}$

$\sigma_{E,2} = 7.4\,\mathrm{keV}$

particle tracking $\rightarrow$ (9.6 keV)

$\sigma_{E,3} = 105\,\mathrm{keV}$

(127 keV)

0.3mm slice with center at s=2.5mm
(small energy spread, I=13.1 A)

$C_1 = 85.5/13.1$

$C_2 = 944/85.5$

$\sigma_{E,i} = 0.25\,\mathrm{keV}$

$\sigma_{E,2} = 25\,\mathrm{keV}$

(9.3 keV*, 23 keV)

$\sigma_{E,3} = 273\,\mathrm{keV}$

(133 keV*, 253 keV)

* too small due to limited bandwidth!

LGM after BC3

is not applicable, but look:

```
>>  main_LGM
setup finished
number of frequency points = 200
integral equation finished
Ctot                       = 70.784
Ctot*current_0             = 1245.7987
rms energy spread          = 999.6854
rms energy spread @ end = 70761.7435
maximal gain               = 622.6615
integral(gain^2,domega) = 2.635e+18
Cnoise = Ctot*sqrt(...) = 108.794
```

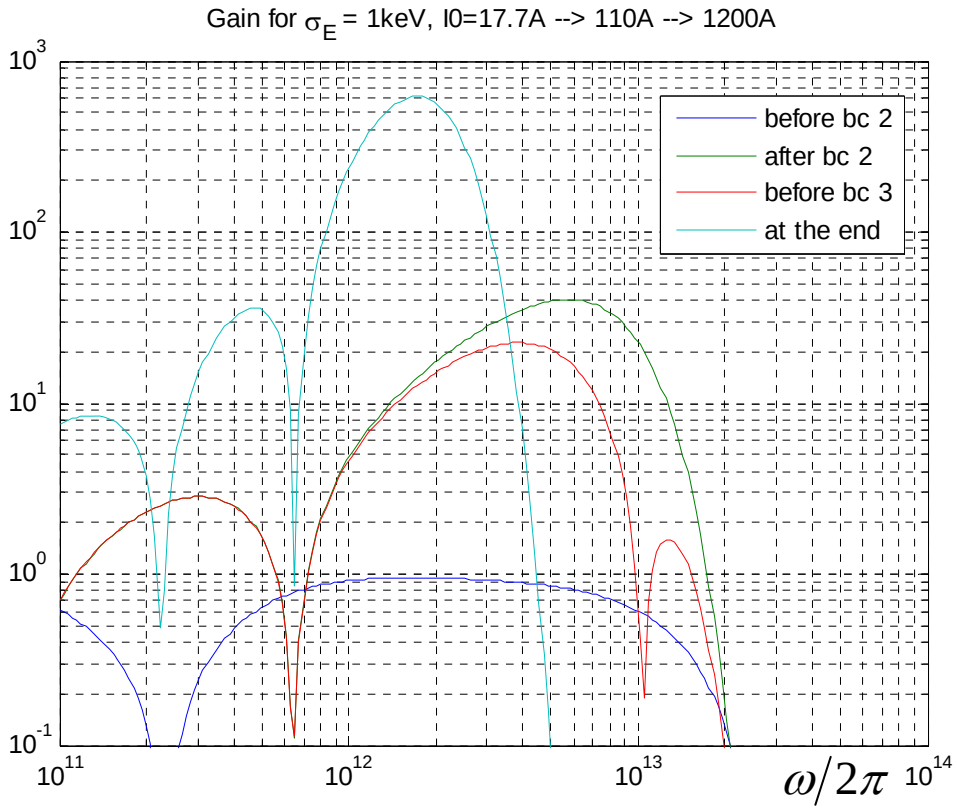
0.3mm slice with center at s=0mm
(~1keV energy spread, I=17.6 A)

from initial energy spread

shot noise after BC3

$$i_{C,eff} = C_1 C_2 \sqrt{\frac{eI_0}{\pi}\int |G(\omega)|^2 d\omega} =$$

109 A



```
>> main_LGM
setup finished
number of frequency points = 200
integral equation finished
Ctot                       = 75.1269
Ctot*current_0             = 984.1623
rms energy spread          = 249.9213
rms energy spread @ end    = 18775.8132
maximal gain               = 10085.6972
integral(gain^2,domega)    = 2.522e+21
Cnoise = Ctot*sqrt(...)    = 3081.4198
```

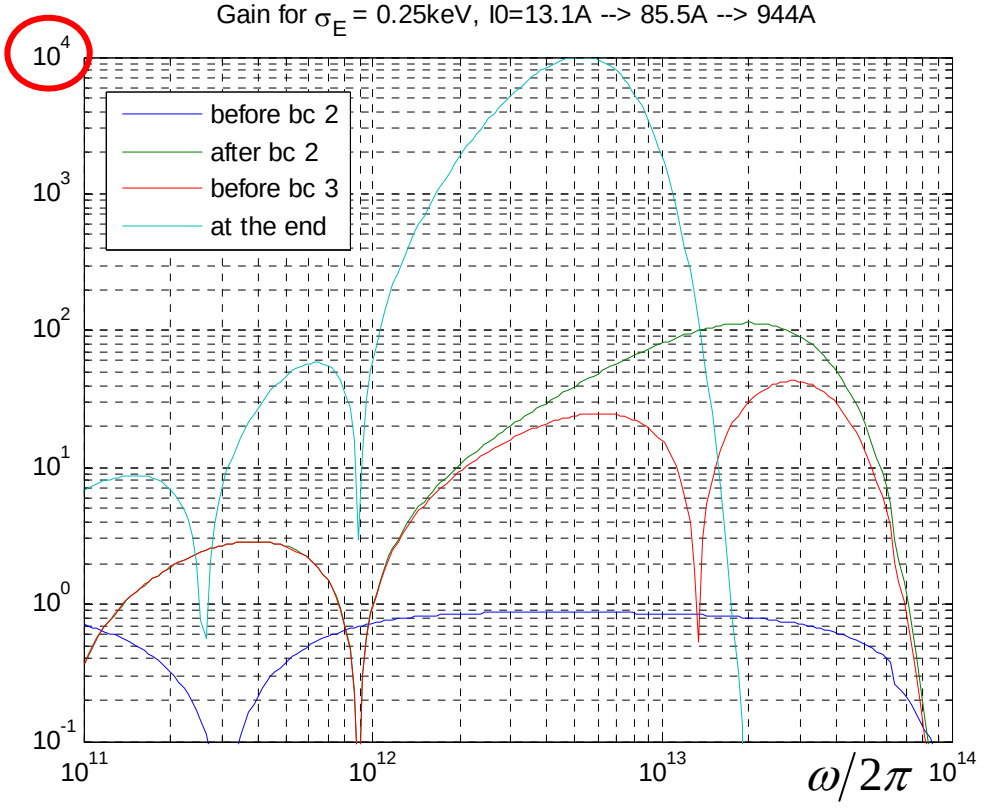
0.3mm slice with center at s=2.5mm
(small energy spread, I=13.1 A)

from initial energy spread

shot noise after BC3

$$i_{C,eff} = C_1 C_2 \sqrt{\frac{eI_0}{\pi}\int |G(\omega)|^2 d\omega} =$$

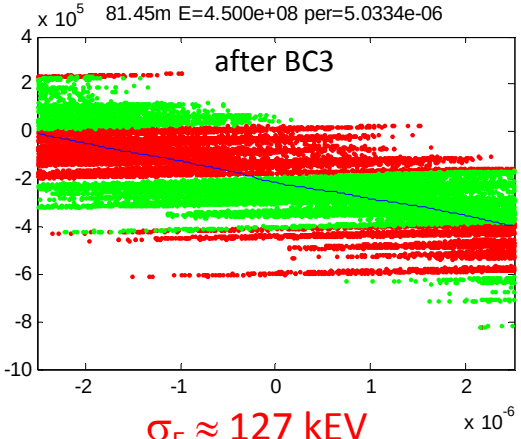
3 kA

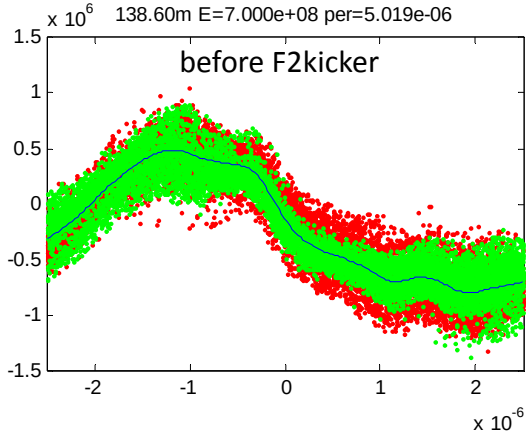


periodic tracking after BC3

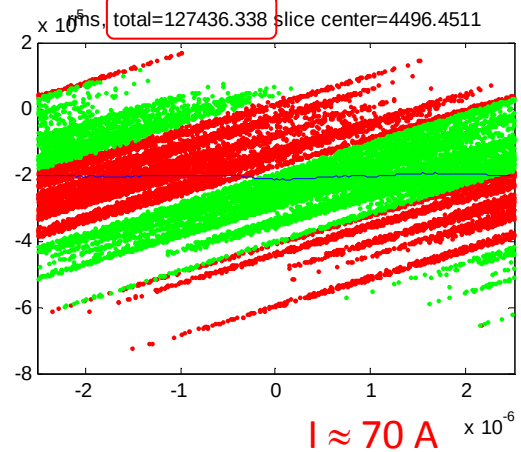
```
81.45 after BC3
138.60,'before kicker, before septum,
       Flash2 with seeding chicane, phi=20mrad, R56≈1..2mm
190.70,'after V4FL2SEED6'
```

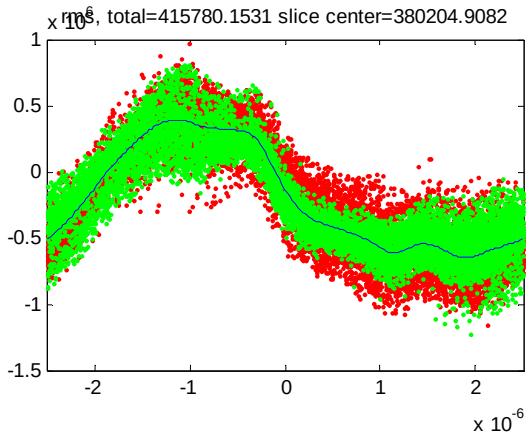
0.3mm slice with center at s=0mm (~1keV energy spread, I=17.6 A)



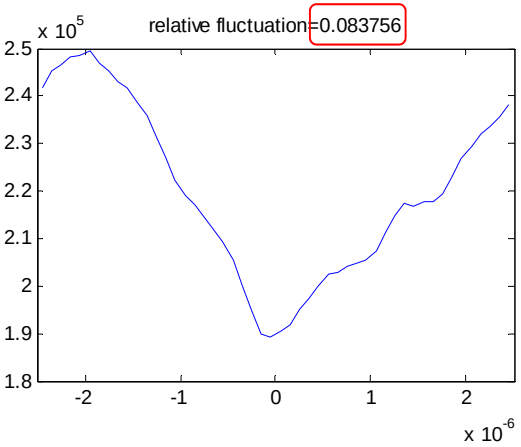


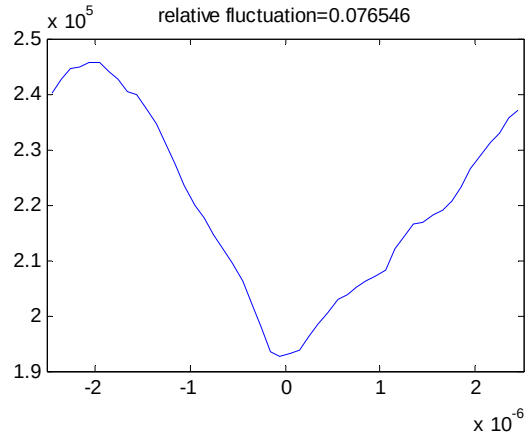
$\sigma_E \approx 127$ kEV



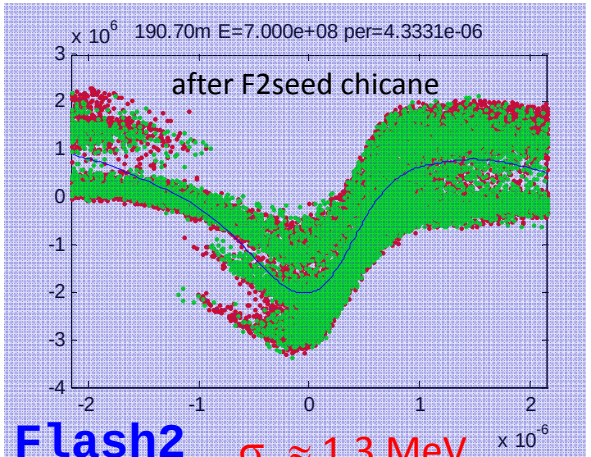


$I \approx 70$ A

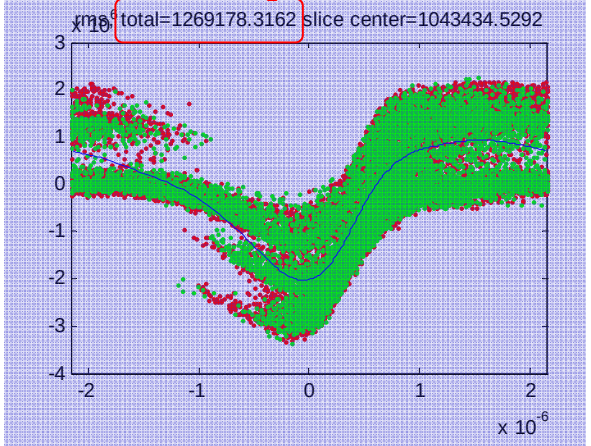


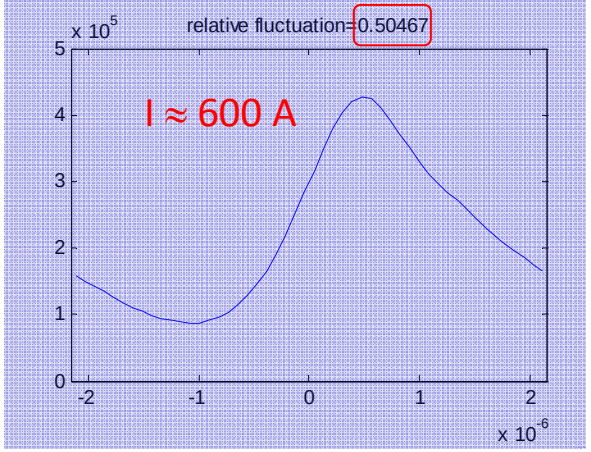


Flash2



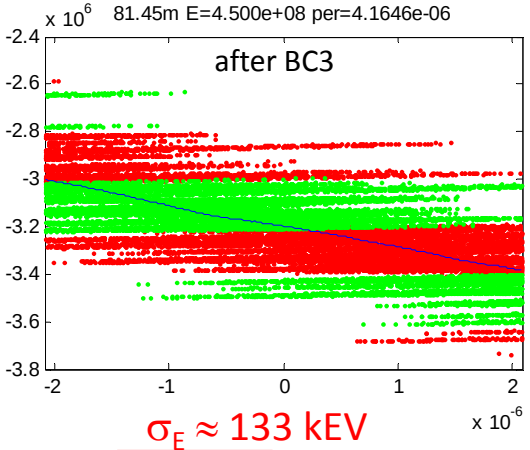
$\sigma_E \approx 1.3$ MeV



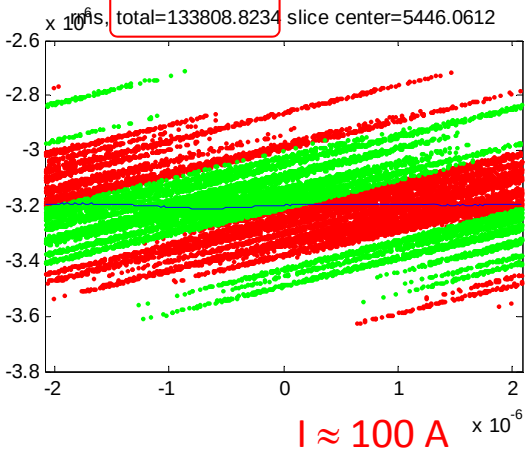


0.3mm slice with center at s=2.5mm (small energy spread, I=13.1 A)

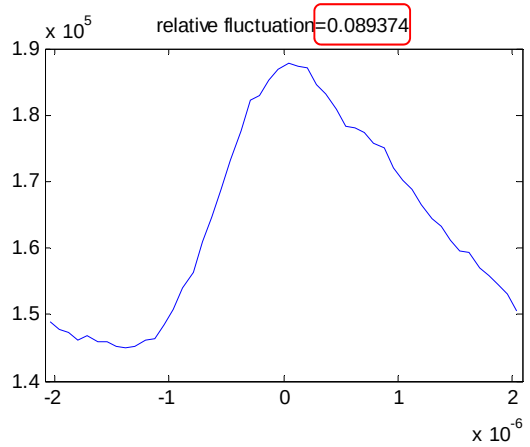
resolution = 50

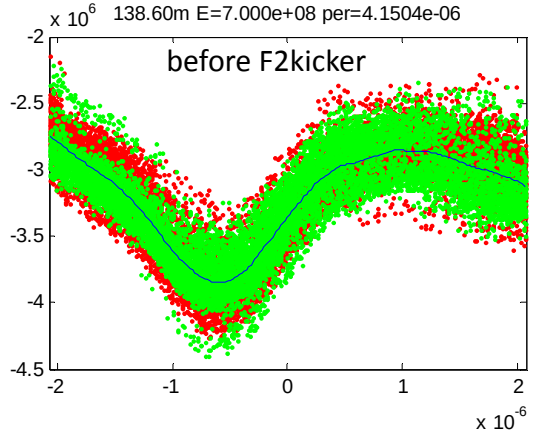


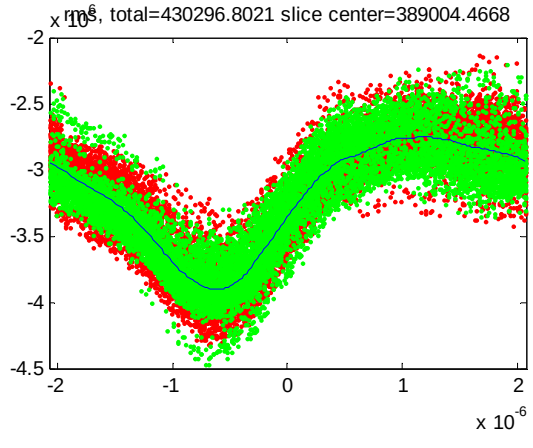
$\sigma_E \approx 133$ kEV

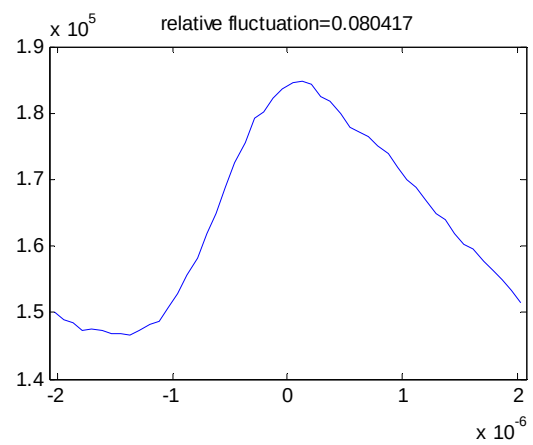


I ≈ 100 A

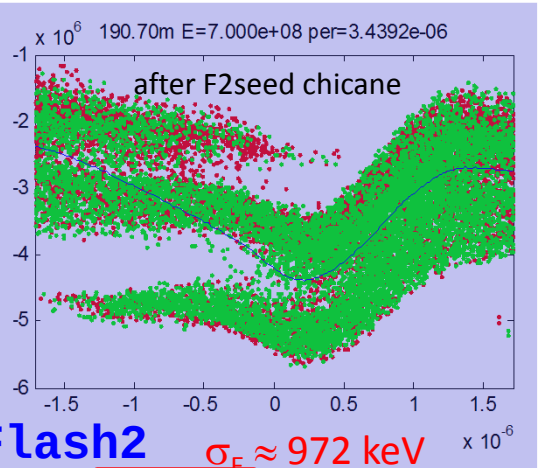




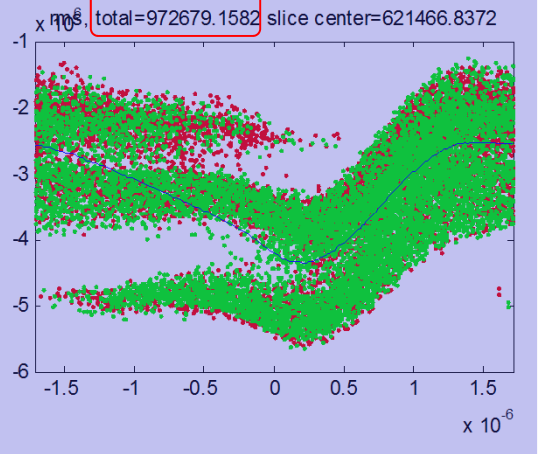


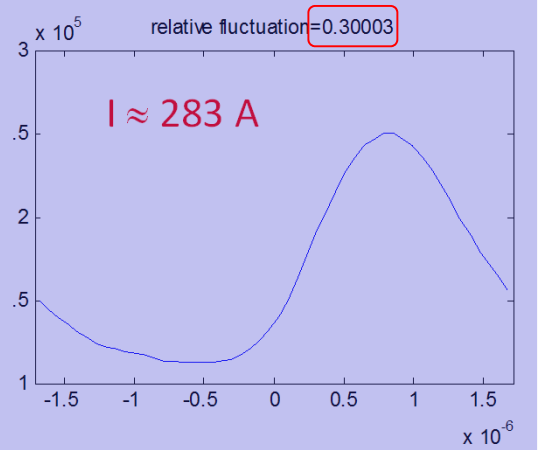


Flash2



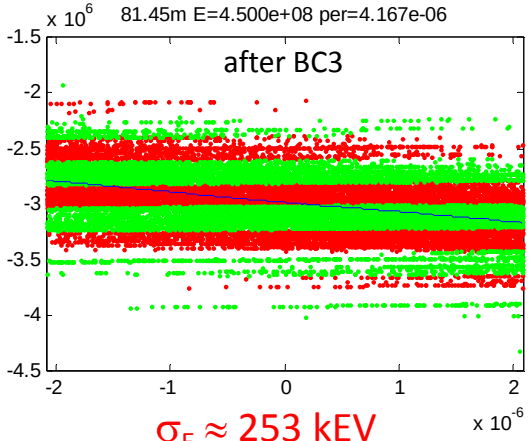
$\sigma_E \approx 972$ keV

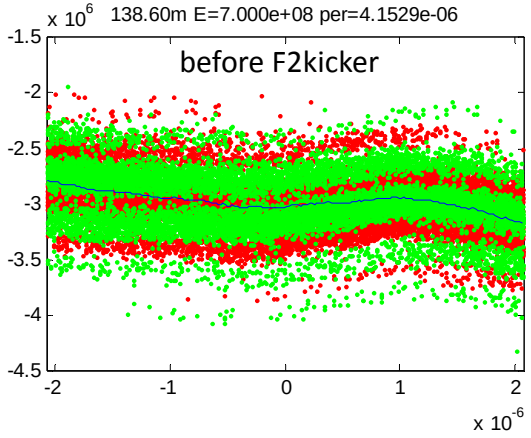


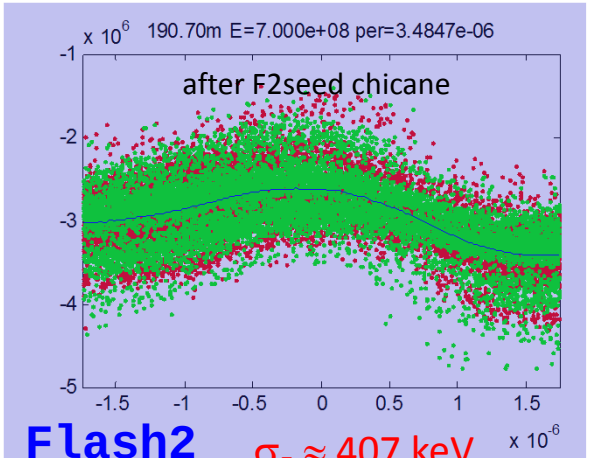


0.3mm slice with center at s=2.5mm (small energy spread, I=13.1 A)

resolution = 500



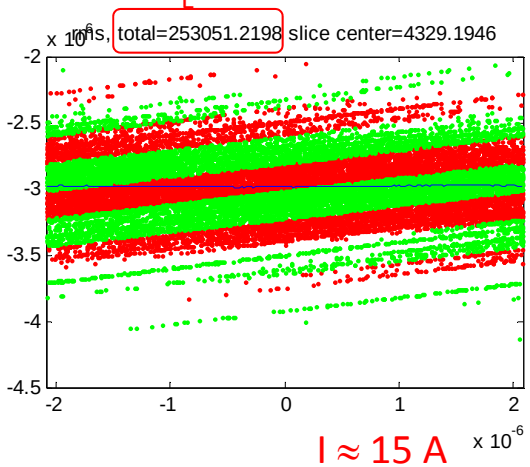


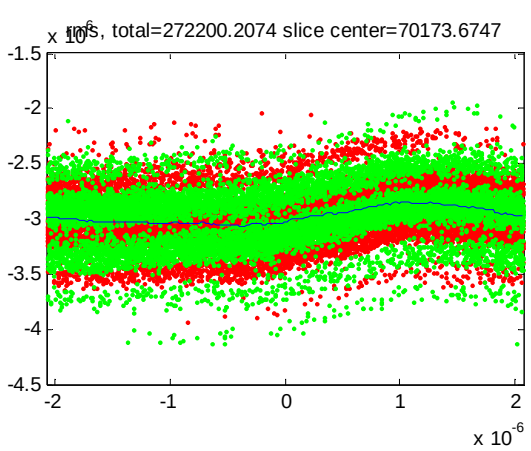


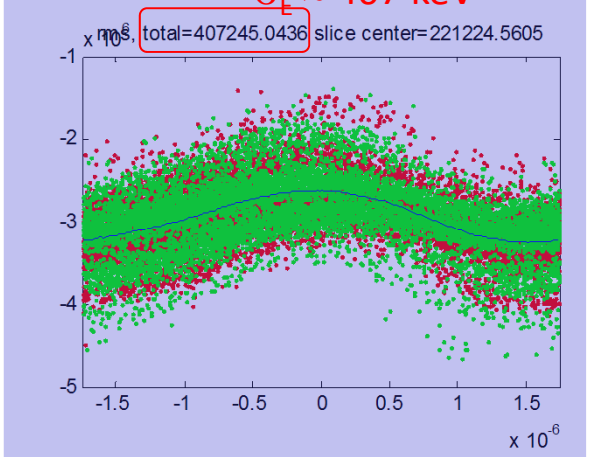
$\sigma_E \approx 253$ kEV

Flash2

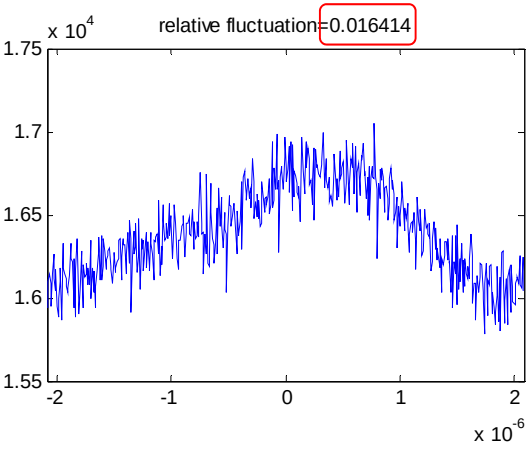
$\sigma_E \approx 407$ keV

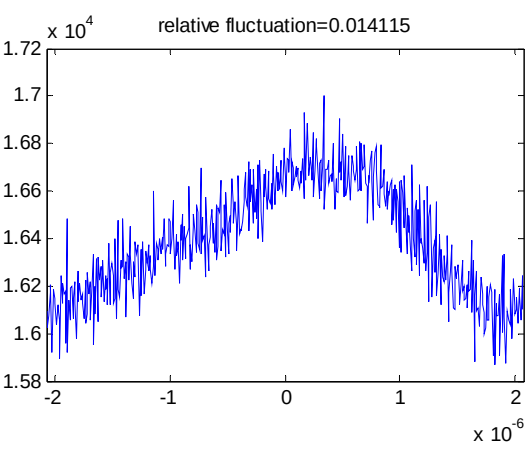


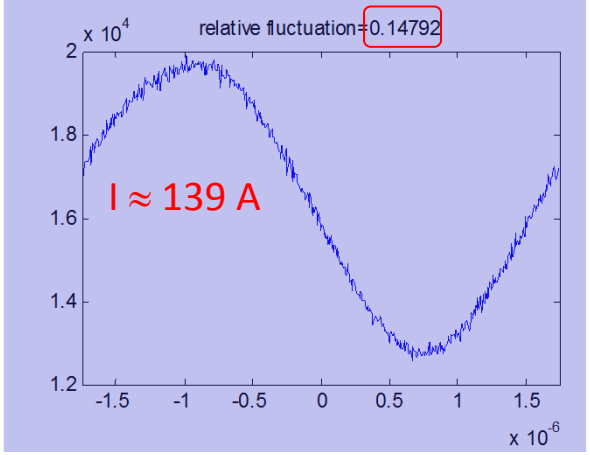




$I \approx 15$ A







$I \approx 139$ A

one stage LG

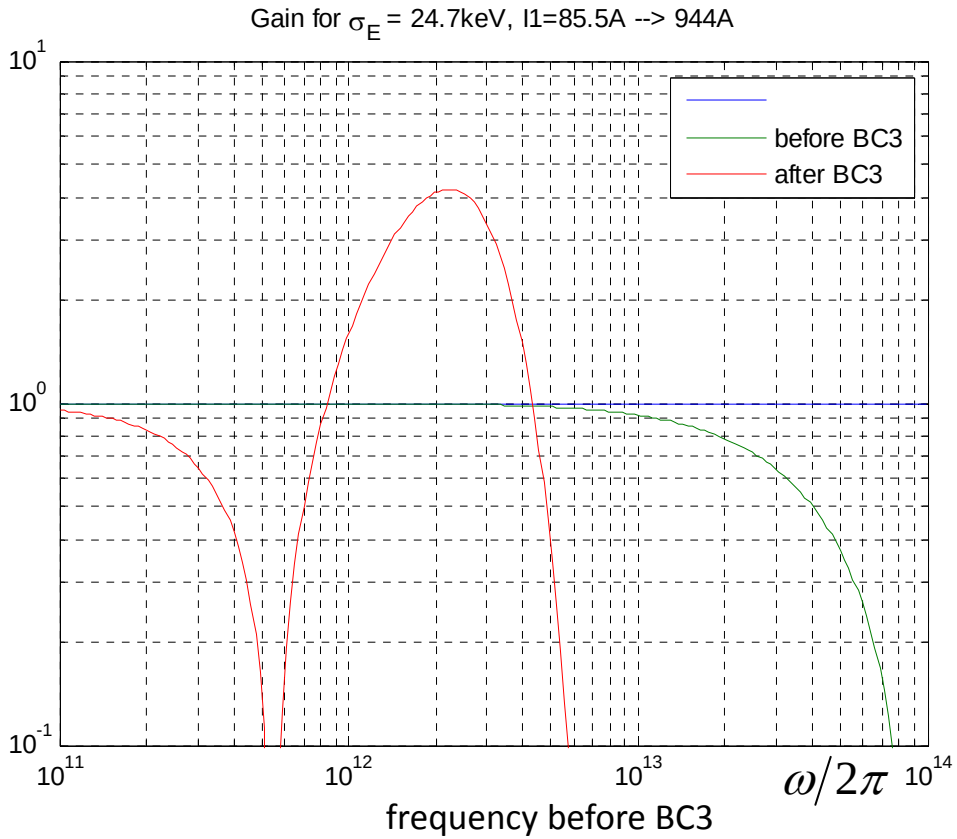
impedance (exit_BC2 --> start BC3) + R56_BC3

0.3mm slice with center at s=2.5mm
(small energy spread, I=13.1 A)

```
>> main_LGM
setup finished
number of frequency points = 200
integral equation finished
Ctot                      = 11.0409
Ctot*current_0            = 944
rms energy spread         = 24692.2283 <-- total energy spread from LGM before BC3!
rms energy spread @ end = 272625.3041
maximal gain              = 6.4391
integral(gain^2,domega) = 2.102e+14
Cnoise = Ctot*sqrt(...) = 0.33401
```

maximal gain ≈ 4.2 @ 2.5 THz
--> 11 μm after BC3
780 μm before BC2 !

this is the macroscopic scale!

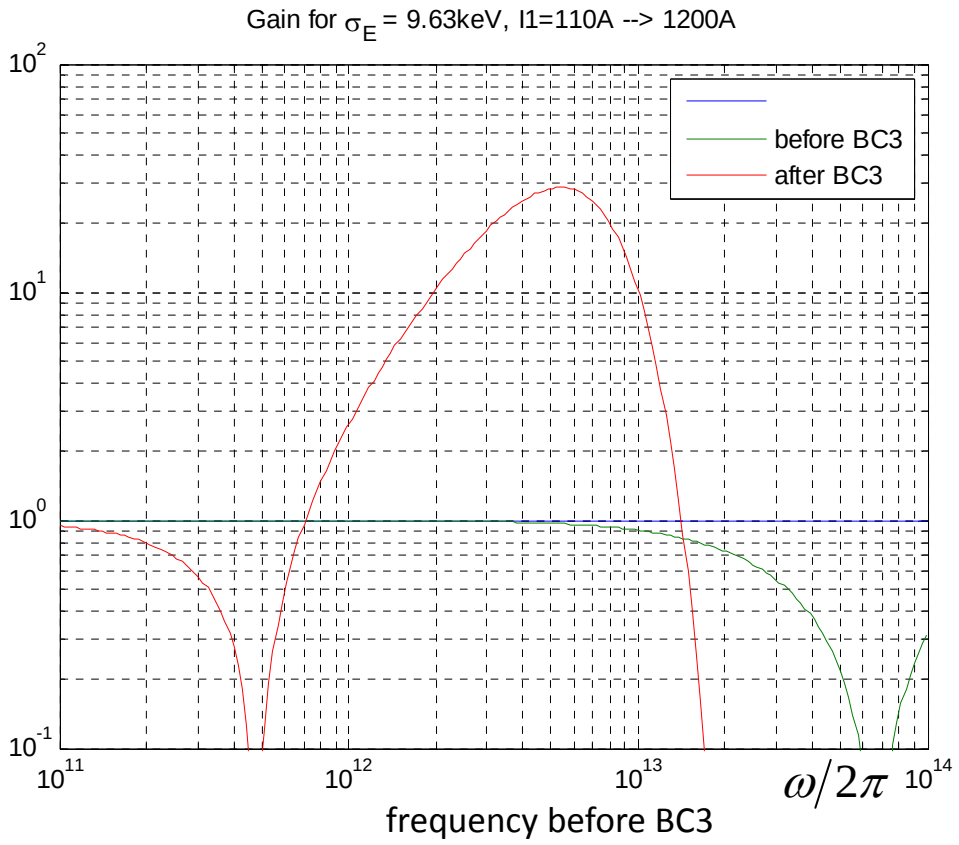


0.3mm slice with center at s=0mm
(~1keV energy spread, I=17.6 A)

```
>>  main_LGM
setup finished
number of frequency points = 200
integral equation finished
Ctot                      = 10.9091
Ctot*current_0            = 1200
rms energy spread         = 9626.9945
rms energy spread @ end = 105021.7585
maximal gain              = 28.6818
integral(gain^2,domega) = 2.572e+16
Cnoise = Ctot*sqrt(...) = 4.1412
```

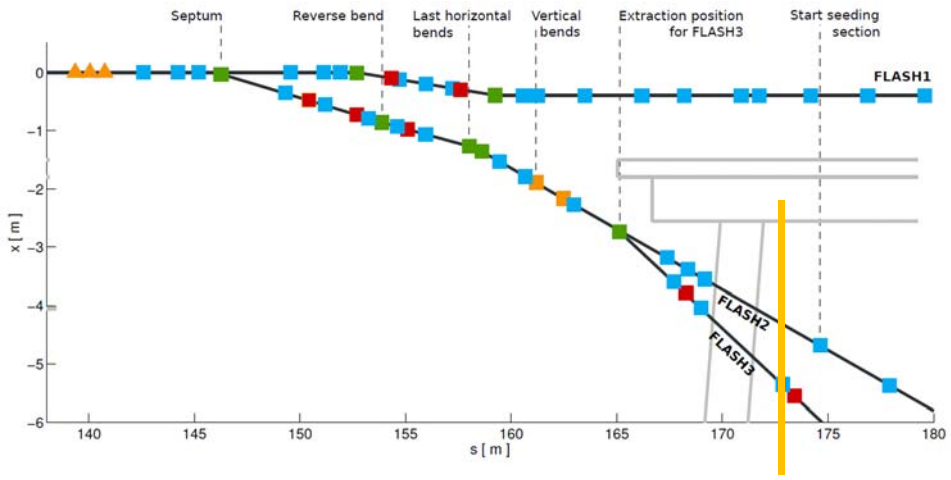
<-- total energy spread from LGM before BC3!

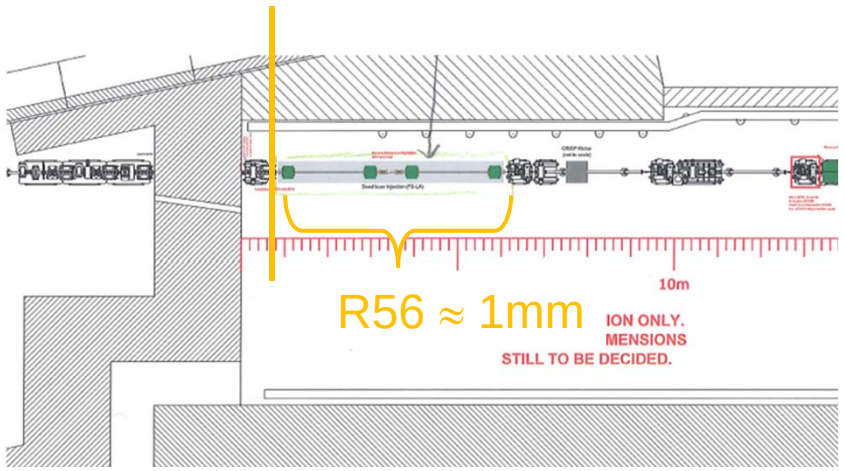
maximal gain ≈ 28 @ 5.5 THz
--> 5 μm after BC3
340 μm before BC2 !



one stage LG

impedance (exit_BC3 --> 172m) + R56_seed



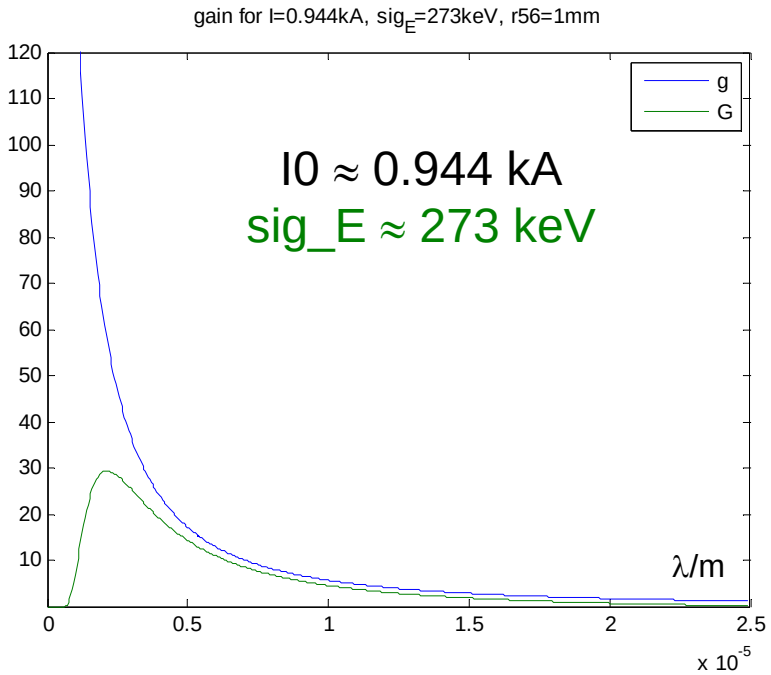


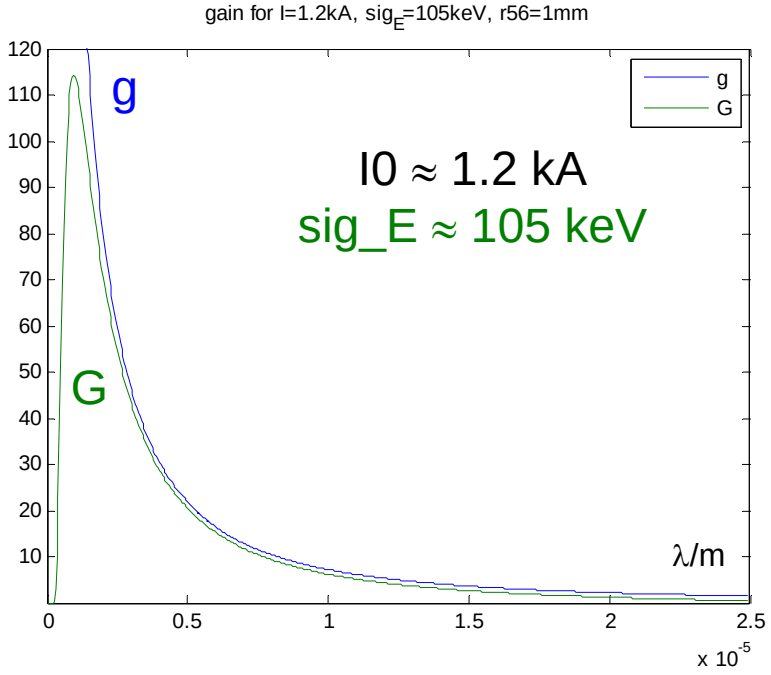
one-stage amplification

$$G = \left(1 - \boxed{i\frac{Cr_{56}}{\mathcal{E}_{\mathrm{ref}}/e} I_1 k_1 L_{sc} Z'(ck_1)}\right) \exp\left(-\frac{(Ck_1 r_{56}\sigma_\delta)^2}{2}\right)$$

g

impedance from 81m (450 MeV) --> 172.4 m (700 MeV)
r56 = 1 mm





some numbers

total energy spread after BC3, without further effects

$$\sigma_{E,3} = C_2\sqrt{(C_1\sigma_{E,i})^2 + \sigma_{E,2}^2}$$

0.3mm slice with center at s=0mm (~1keV energy spread, I=17.6 A)	0.3mm slice with center at s=2.5mm (small energy spread, I=13.1 A)
$C_1 = 110/17.7$	$C_1 = 85.5/13.1$
$C_2 = 1200/110$	$C_2 = 944/85.5$
$\sigma_{E,i} = 1\,\mathrm{keV}$	$\sigma_{E,i} = 0.25\,\mathrm{keV}$
$\sigma_{E,2} = 7.4\,\mathrm{keV}$	$\sigma_{E,2} = 25\,\mathrm{keV}$
particle tracking → 9.6 keV	23 keV
$\sigma_{E,3} = 105\,\mathrm{keV}$	$\sigma_{E,3} = 273\,\mathrm{keV}$
127 keV	253 keV

---

further effects after BC3

modulation amplitude (given by maximal period length 300μm/C_{tot} ≈ 4.3μm)

	I_{mod} = 70 A	I_{mod} = 15 A
before F2kicker	$\sigma_{E,4}$ = 420 keV	$\sigma_{E,4}$ = 270 keV
	$\lvert I_{mod}\,Z\rvert \approx 400$ keV	$\lvert I_{mod}\,Z\rvert \approx 100$ keV

& amplification in seeding chicane