Analysis of Measurements of XFEL Gun

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what does the gun phase?

wakes in our simulations

Frank's measurements (13th Juli) compared to simulations

wrong curvature

cross-check (calibration)

strange bunch shape

simulations with different cathode distributions

simulations plus artificial (inductive) wake

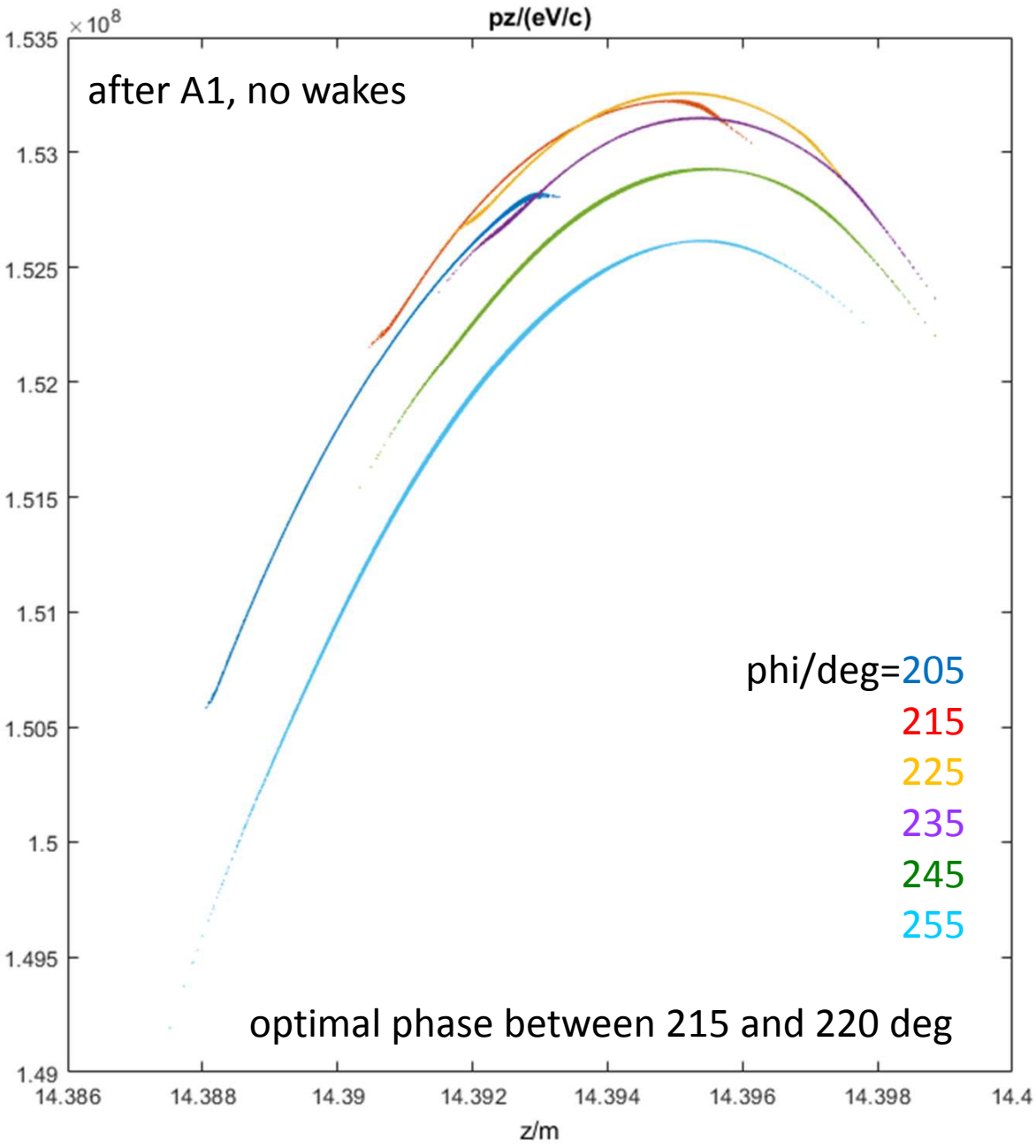
time domain simulations (real Maxwell solutions)

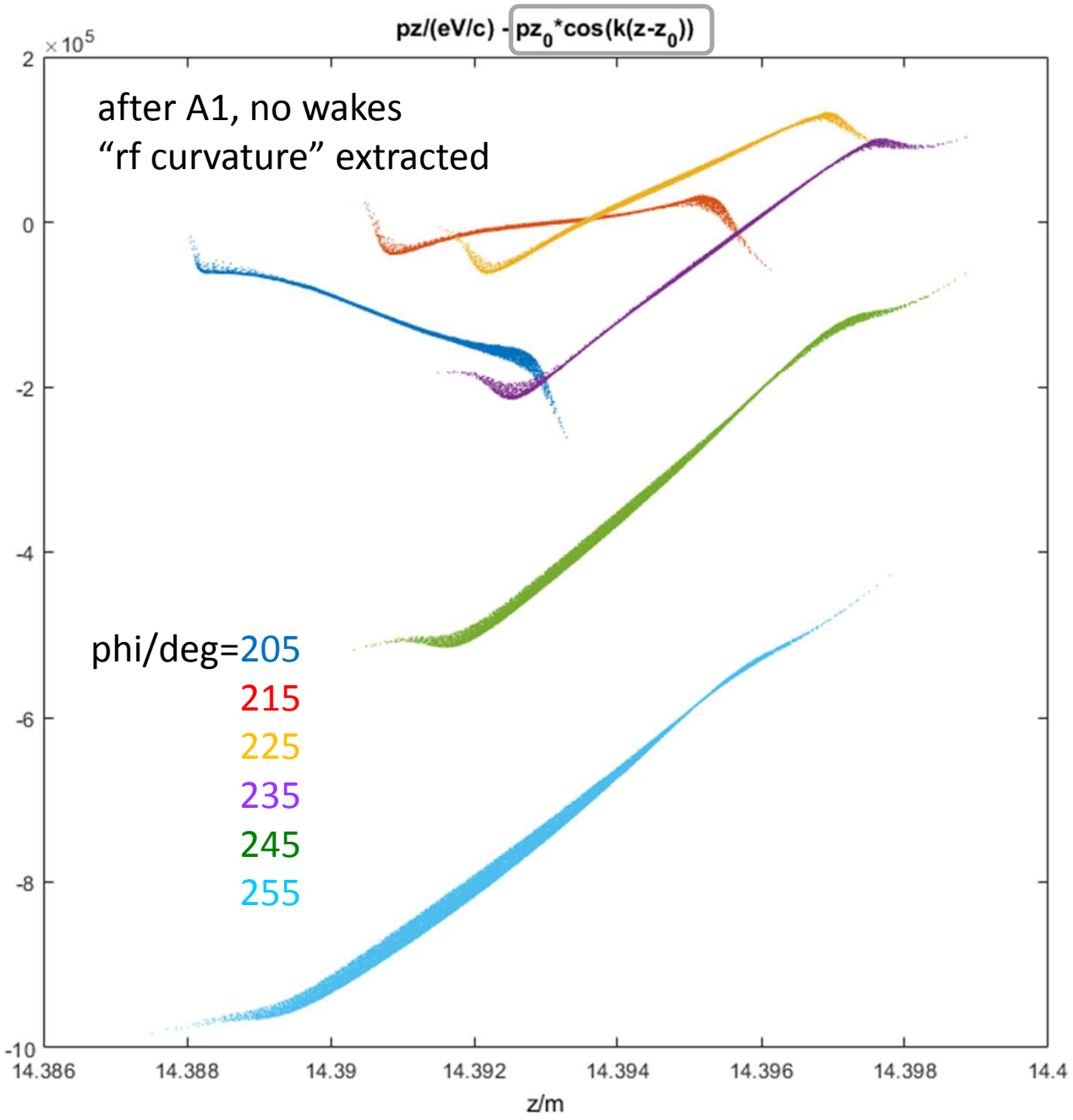
time domain simulation with simplified (1d) particle tracking

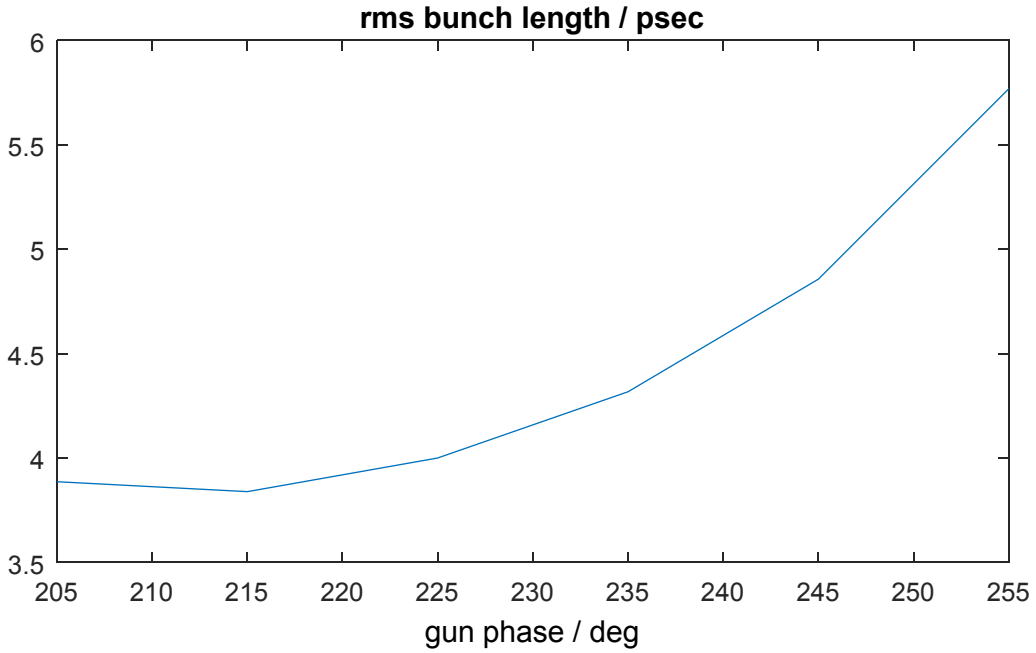
finally

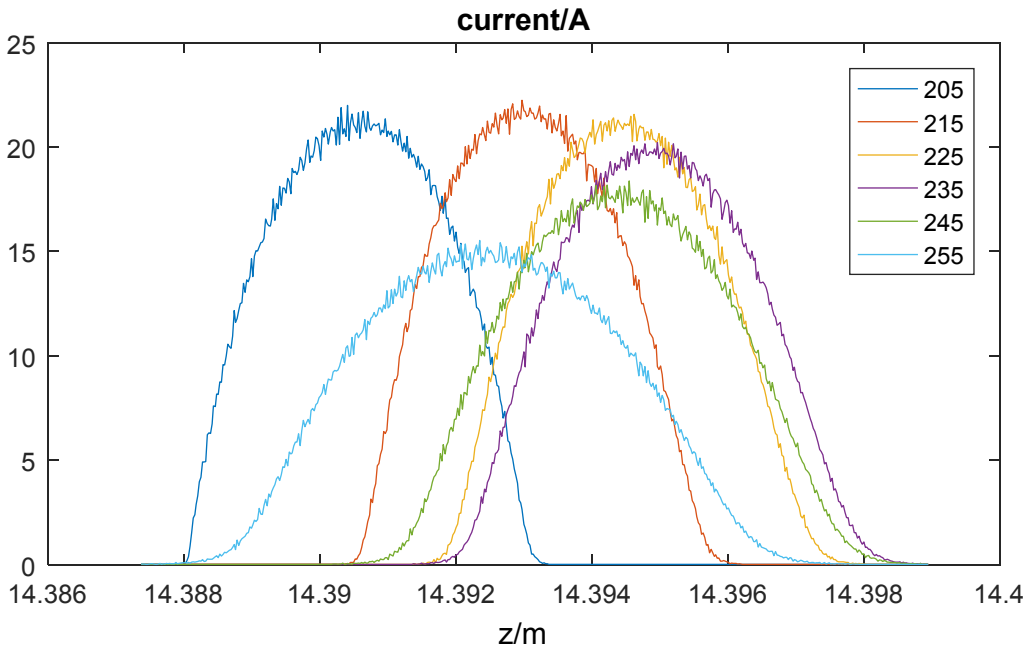
what does the gun phase?

simulated phase scan for
source = 250 pC, 3 psec
gun = 58 MV/m, phi
solenoid = 0.221 T (optimal for phi = 216.4 deg “optimal phase”)
A1 = 8 x 34.0MV/m (on crest for optimal phase)


pz/(eV/c)
×10^8
1.535
1.53
1.525
1.52
1.515
1.51
1.505
1.5
1.495
1.49
14.386
14.388
14.39
14.392
14.394
14.396
14.398
14.4
z/m
after A1, no wakes
phi/deg=205
215
225
235
245
255
optimal phase between 215 and 220 deg

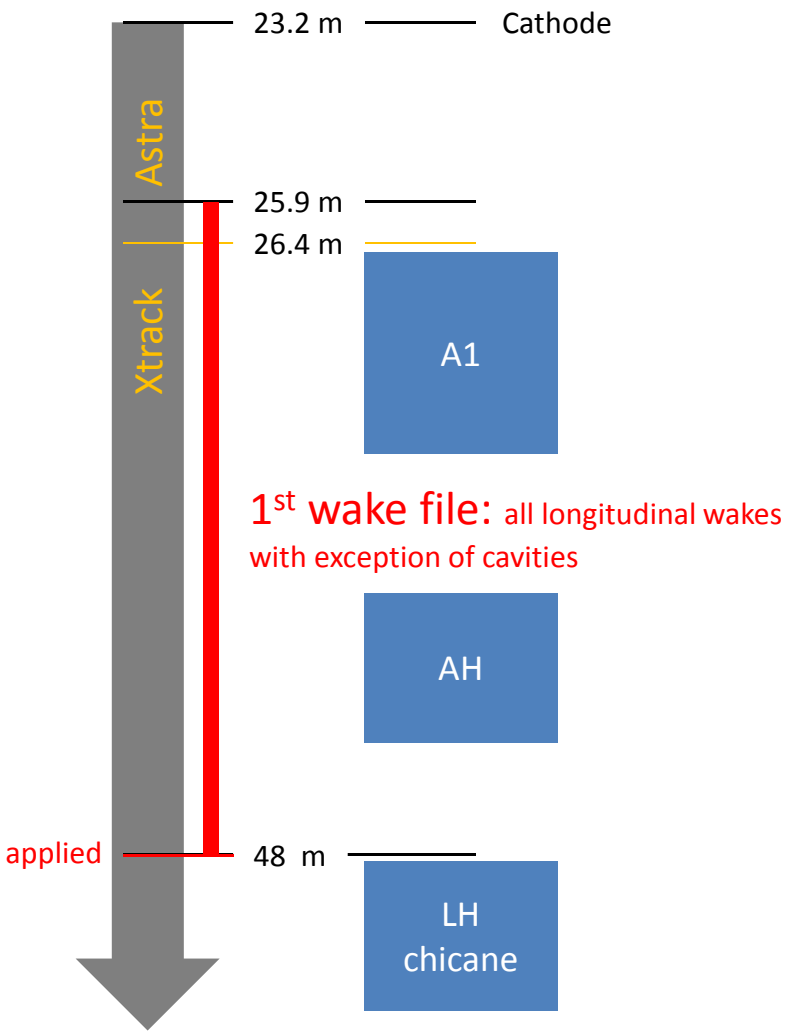

pz/(eV/c) - pz0*cos(k(z-z0))
×10^5
2
0
-2
-4
-6
-8
-10
14.386
14.388
14.39
14.392
14.394
14.396
14.398
14.4
z/m
after A1, no wakes
“rf curvature” extracted
phi/deg=205
215
225
235
245
255

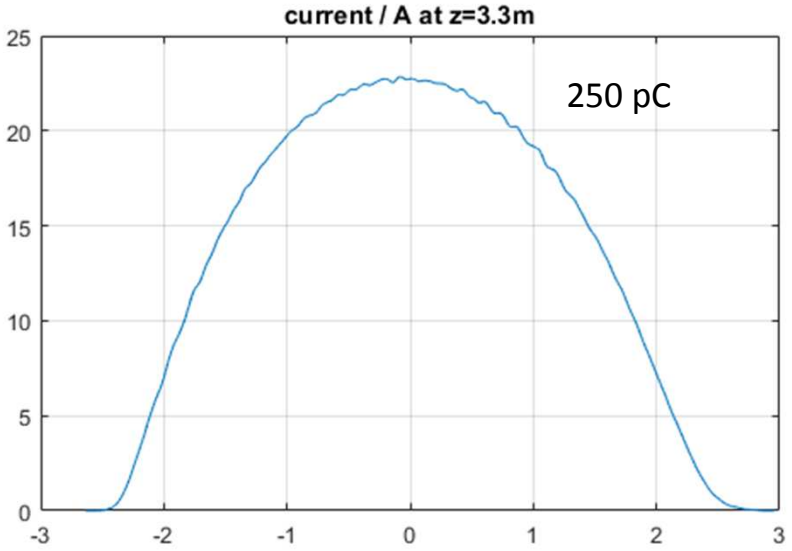

rms bunch length / psec
6
5.5
5
4.5
4
3.5
205
210
215
220
225
230
235
240
245
250
255
gun phase / deg

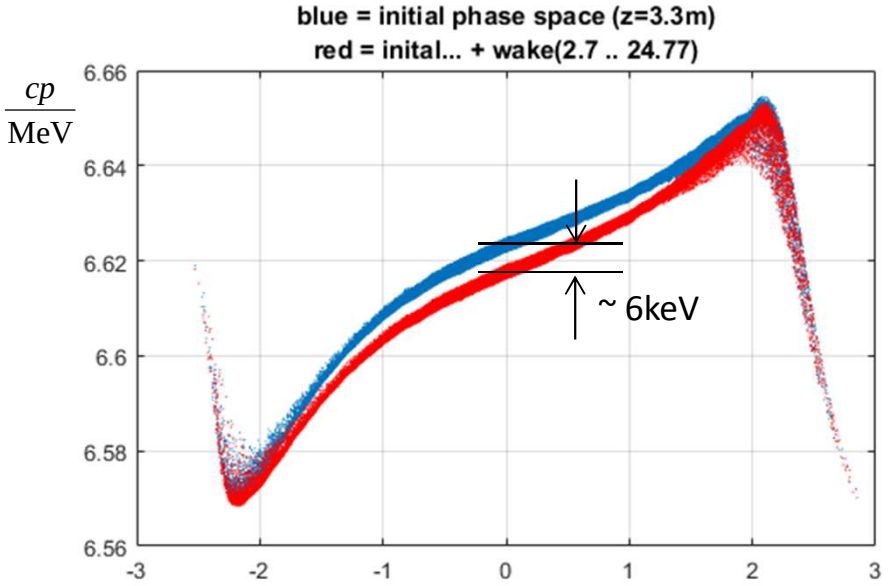

current/A
25
20
15
10
5
0
14.386
14.388
14.39
14.392
14.394
14.396
14.398
14.4
z/m
205
215
225
235
245
255

wakes in our simulations

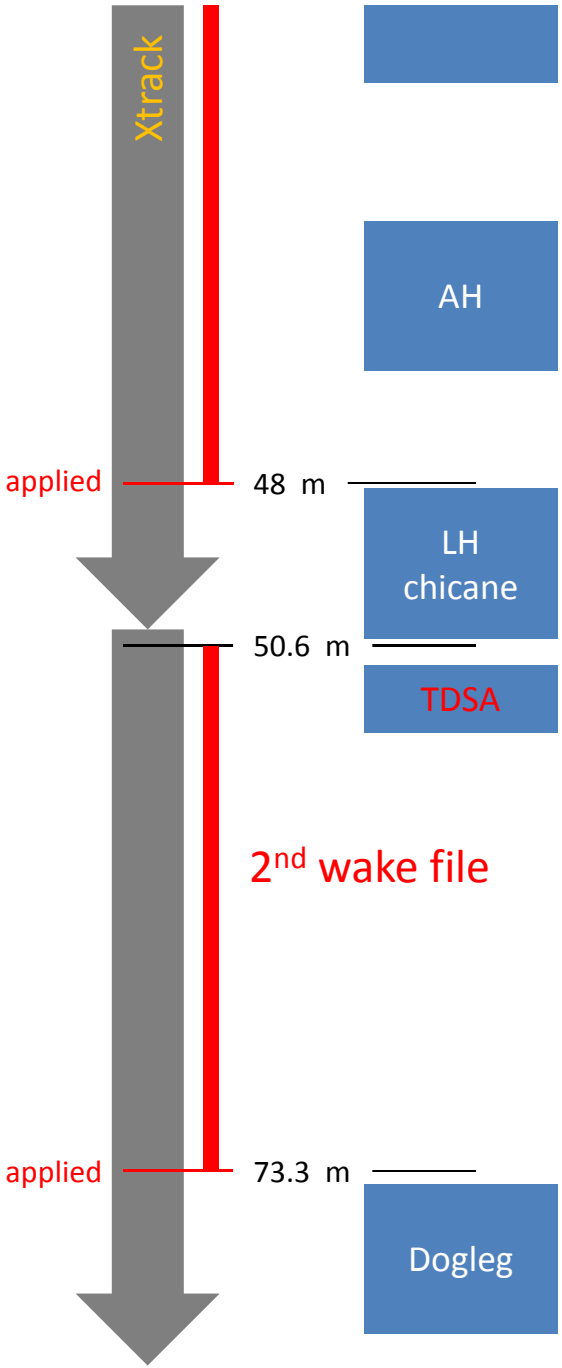
(from the XFEL impedance data base)

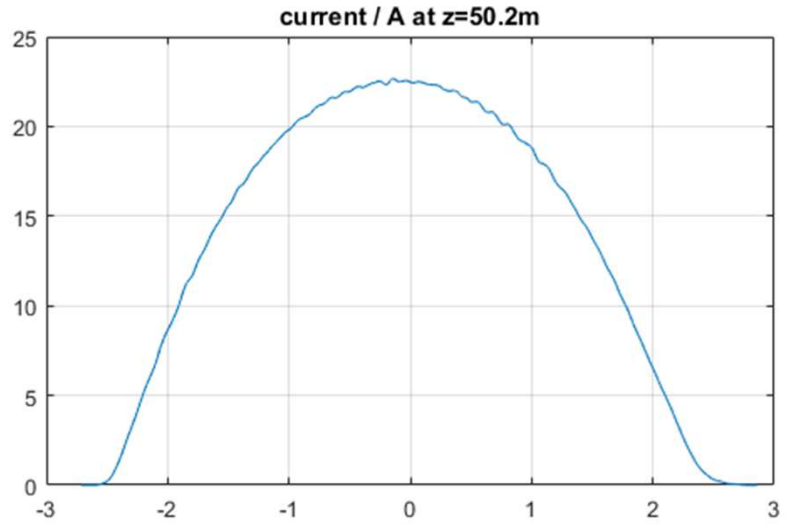


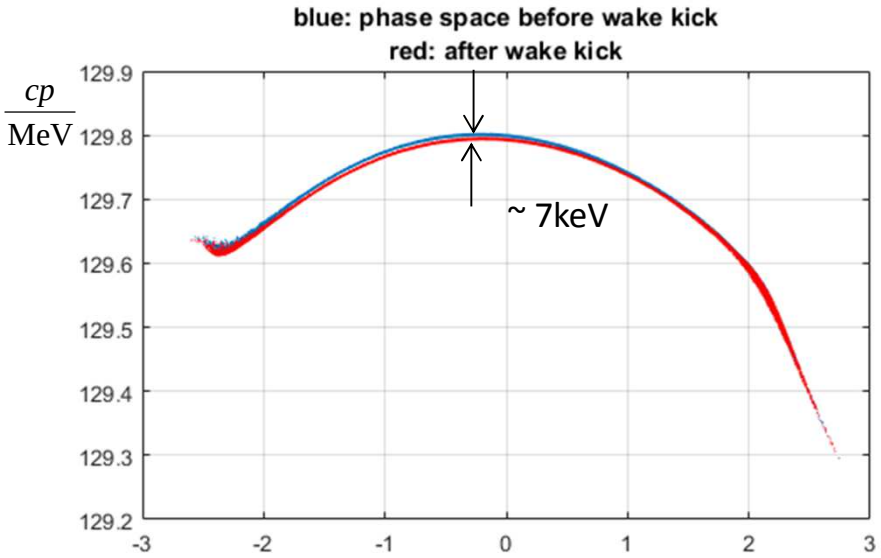




all wakes of ~22m (without cavities) !!! 6kV/23A ≈ 260Ω


Xtrack
AH
applied
48 m
LH
chicane
50.6 m
TDSA
2nd wake file
applied
73.3 m
Dogleg

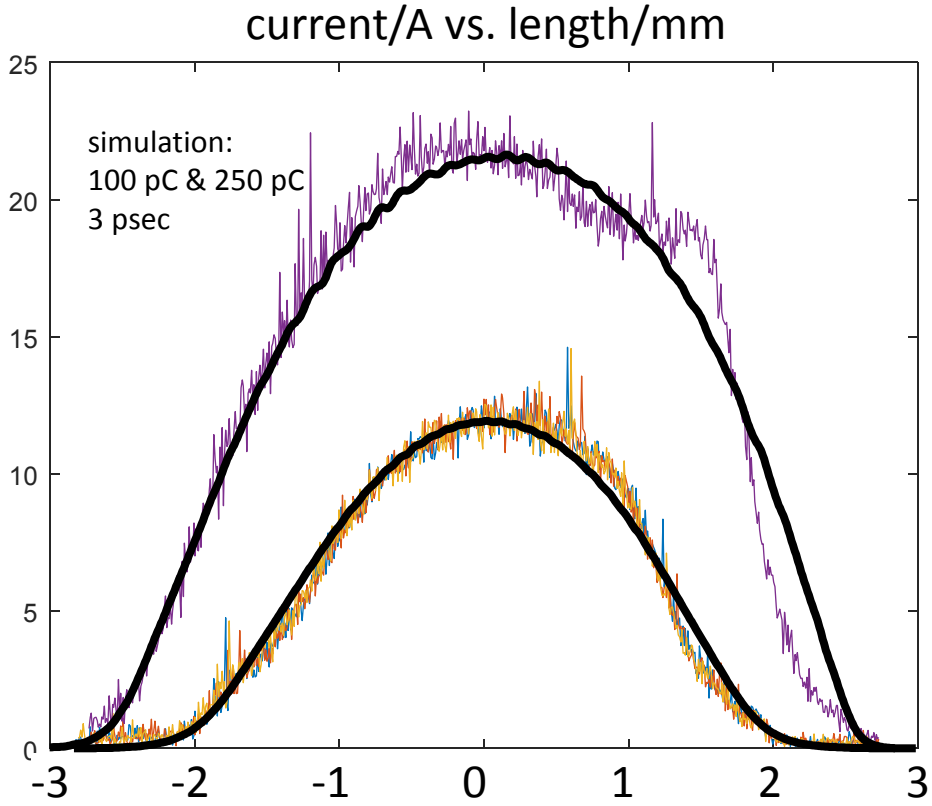

current / A at z=50.2m
25
20
15
10
5
0
-3
-2
-1
0
1
2
3


blue: phase space before wake kick
red: after wake kick
cp
MeV
129.9
129.8
129.7
129.6
129.5
129.4
129.3
129.2
~ 7keV
-3
-2
-1
0
1
2
3

Frank's measurements (13th Juli) compared to simulations

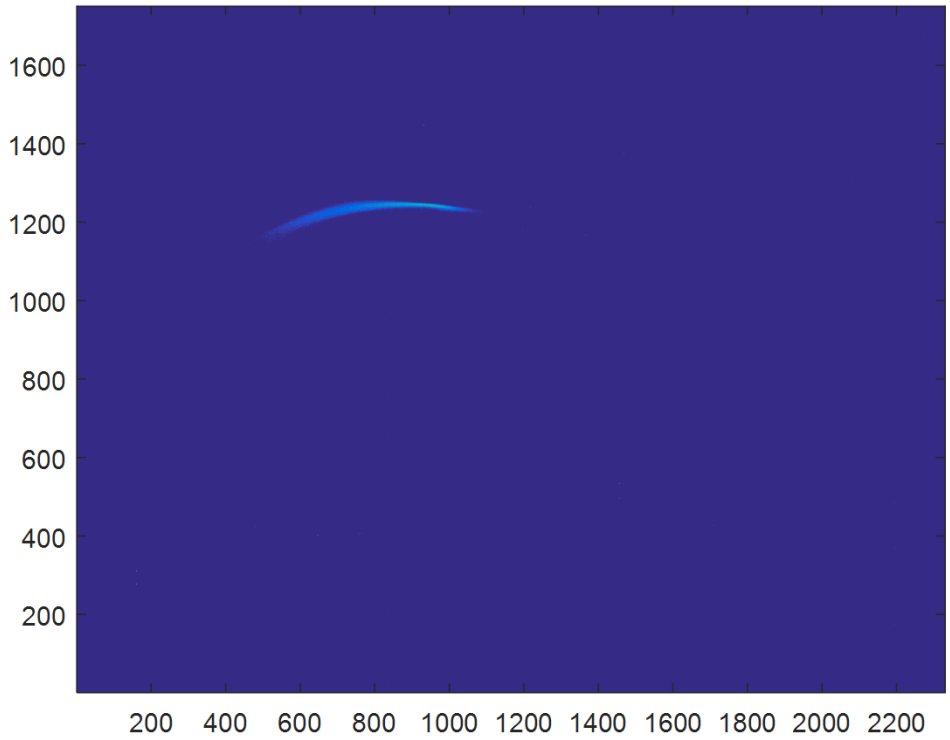
gun=58.6 MV/m -41.5 deg

19-47-27	"100-1"	q=100 pC	A1=138.66 MV	0.47 deg	AH = 15.41 MV	-179.84 deg
19-50-01	"100-2"		135.60	0.48	12.34	-179.81
19-51-30	"100-3"		134.94	0.48	11.68	-179.80
20-12-31	"250"	q=250 pC	123.25	1.00	0.01	0.0

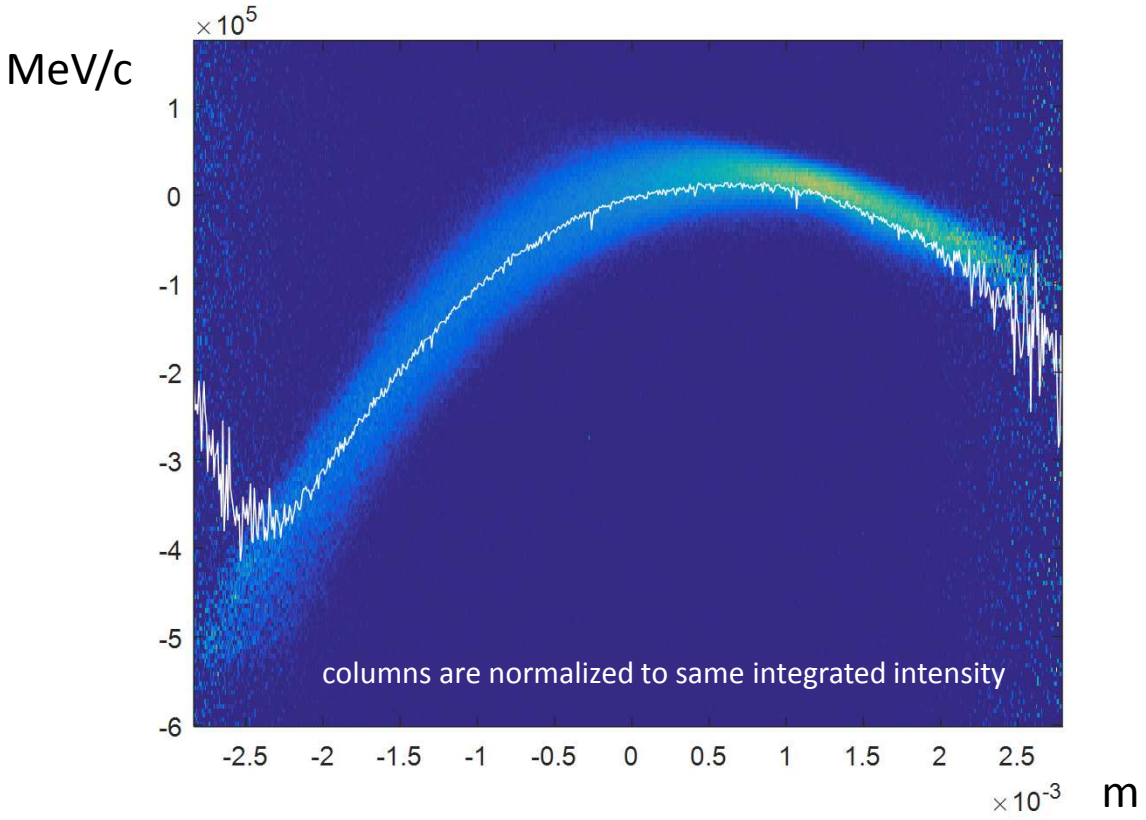


time scale is adjusted for 3 psec rms length of 100 pC bunches

“250” full screen, background subtracted

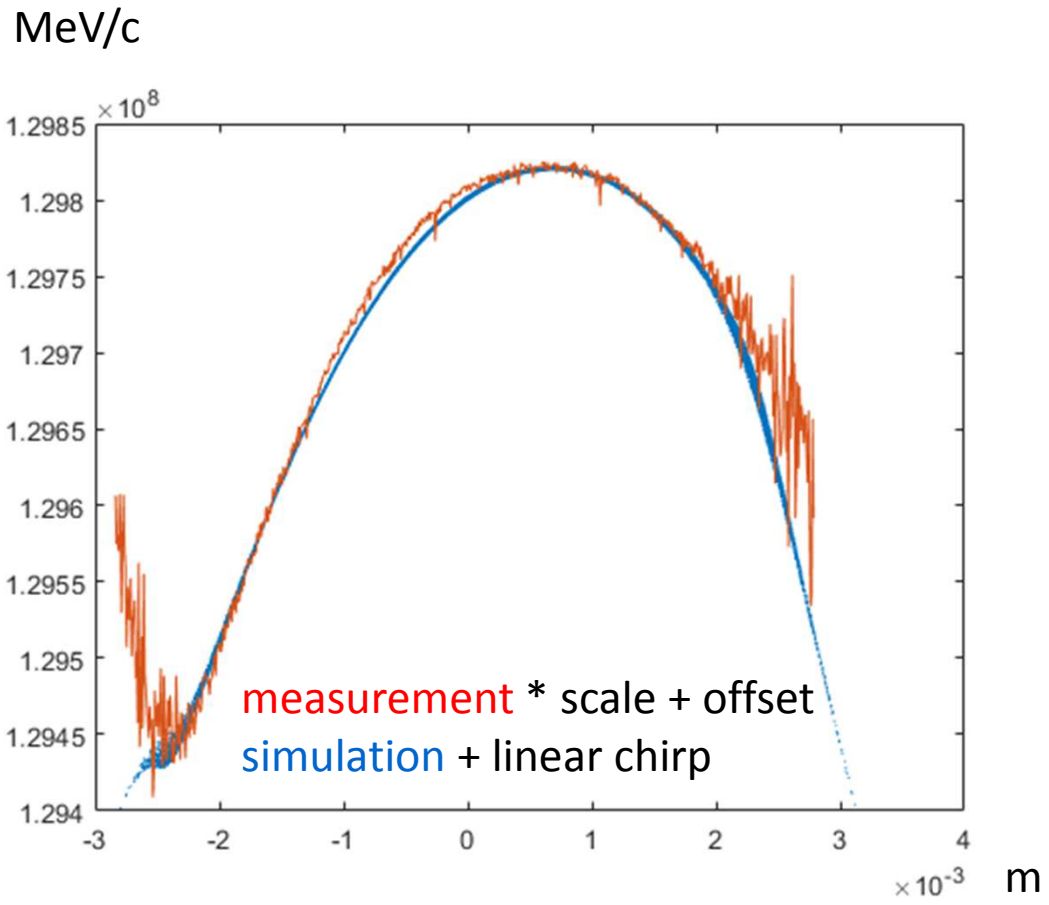


“250” relevant window
time/length scale adjusted for 3 psec @ 100 pC
energy scaling see next slide



slice energy is averaged energy per column

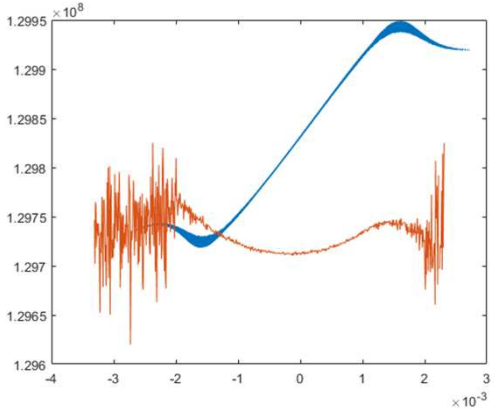
"250" adjustment of energy scale with 3 fit parameters: offset, scale and chirp



theoretical dispersion = 0.59 m

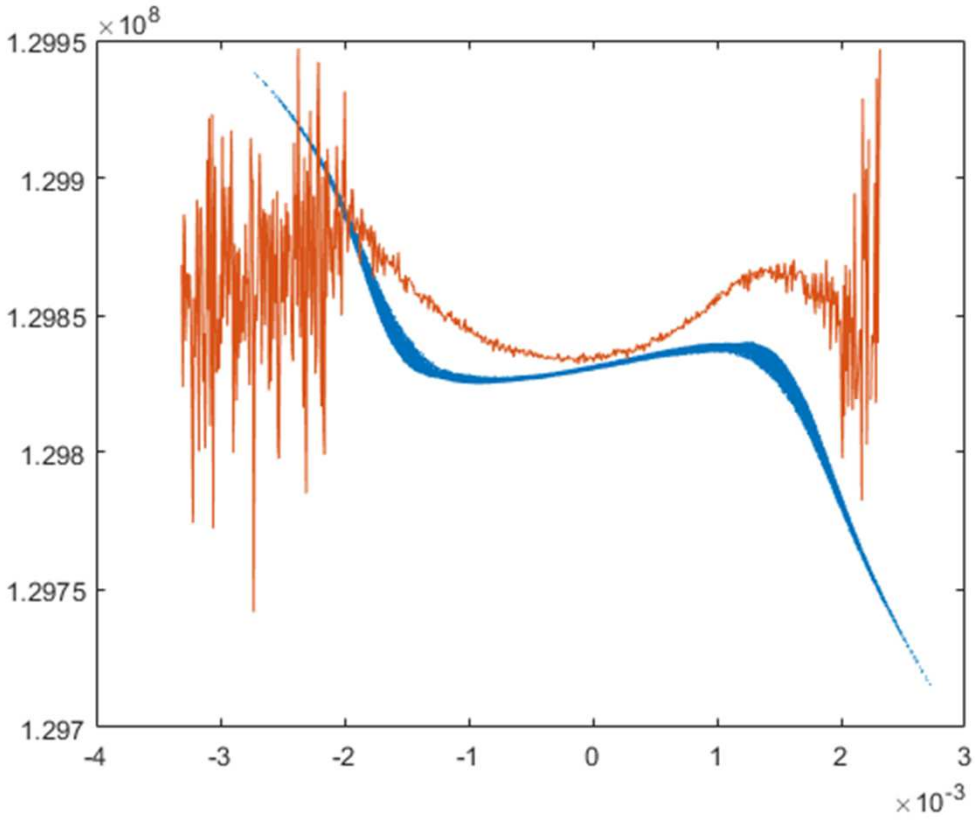
dispersion according to fit = (0.59/1.66) m !!??

the 100 pC measurements



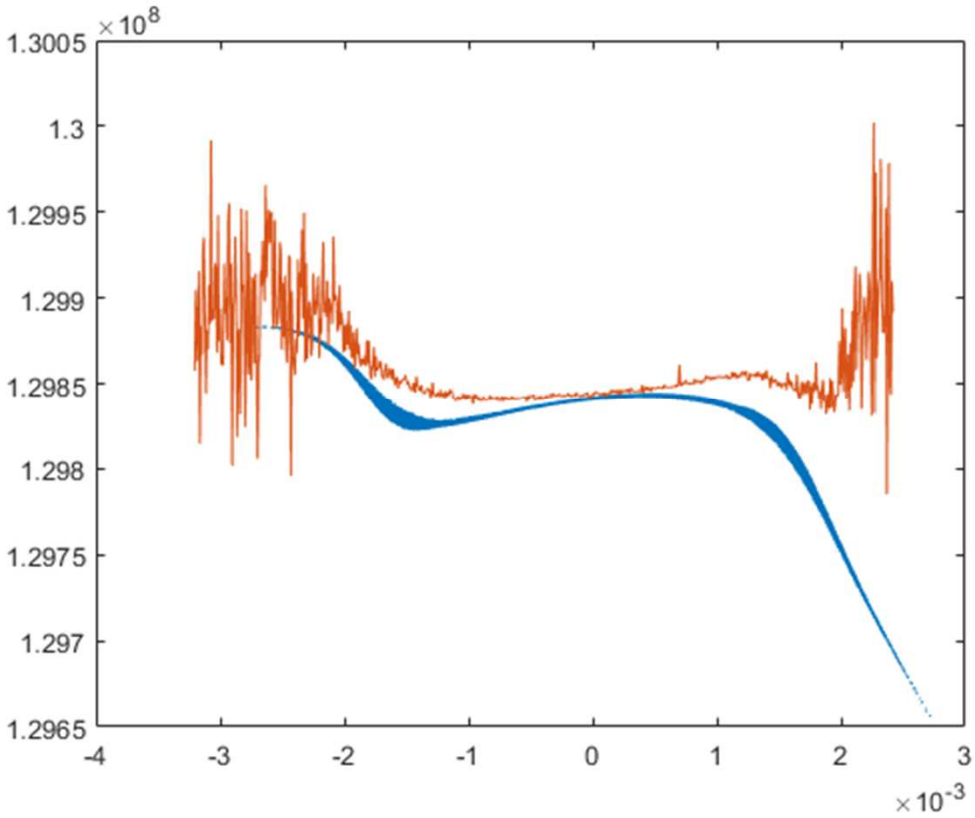
"100-1"
A1=138.66 MV 0.47 deg AH = 15.41 MV -179.84 deg

set additional chirp to zero
adjust offset



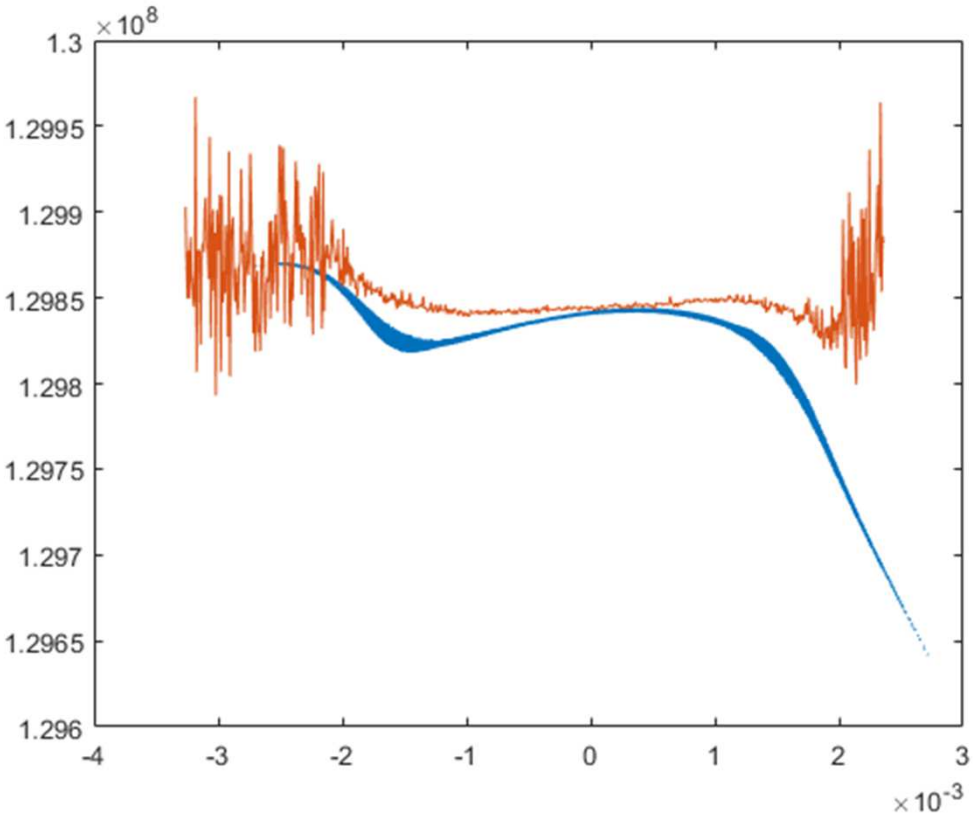
“100-2”
A1=135.60 MV 0.48 deg AH = 12.34 MV -179.81 deg

additional chirp = zero
adjust offset



“100-3”
A1=135.60 MV 0.48 deg AH = 12.34 MV -179.81 deg

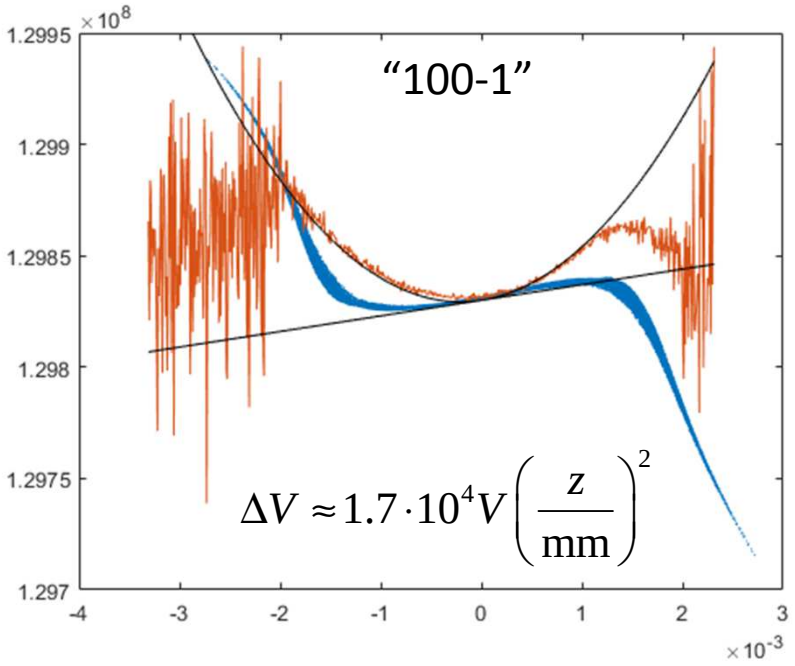
chirp = zero
adjust offset

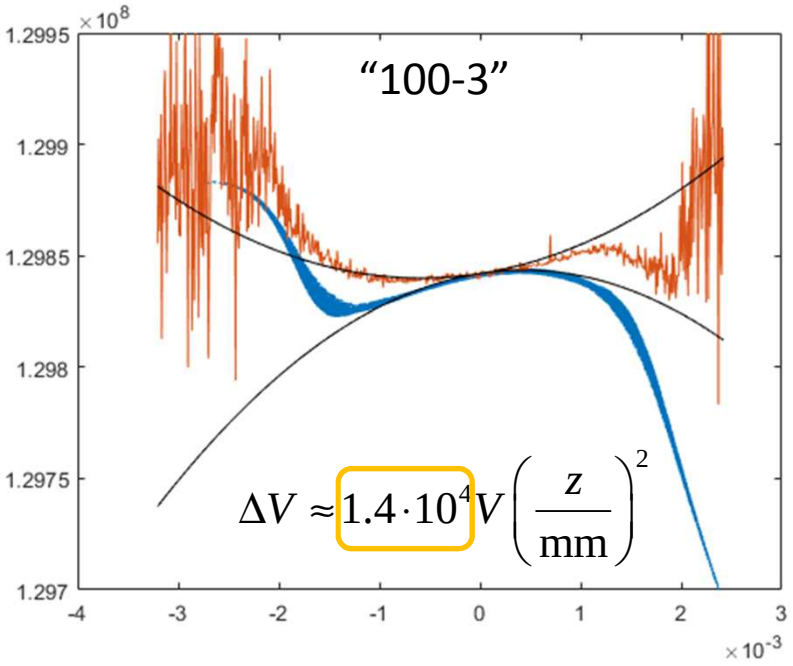


wrong curvature

either the rf curvature is too strong or some wake is missing

1) rf curvature



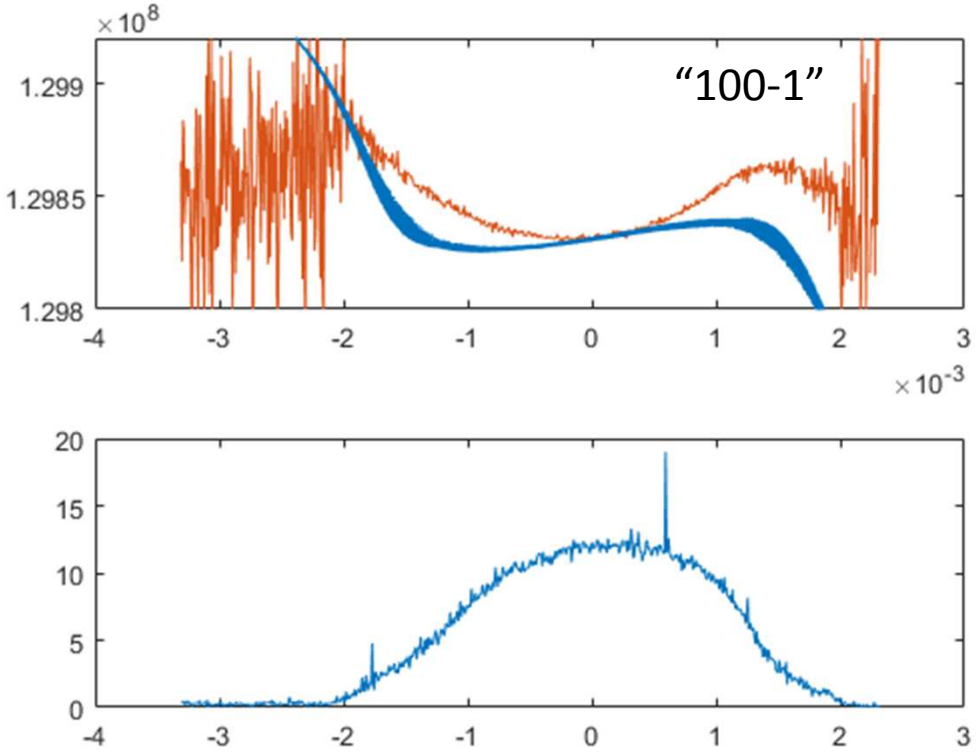


$$\Delta V \approx \Delta V_1 \left(1 - \cos kz\right)$$

1.3 GHz --> $\Delta V \approx 37$ MV

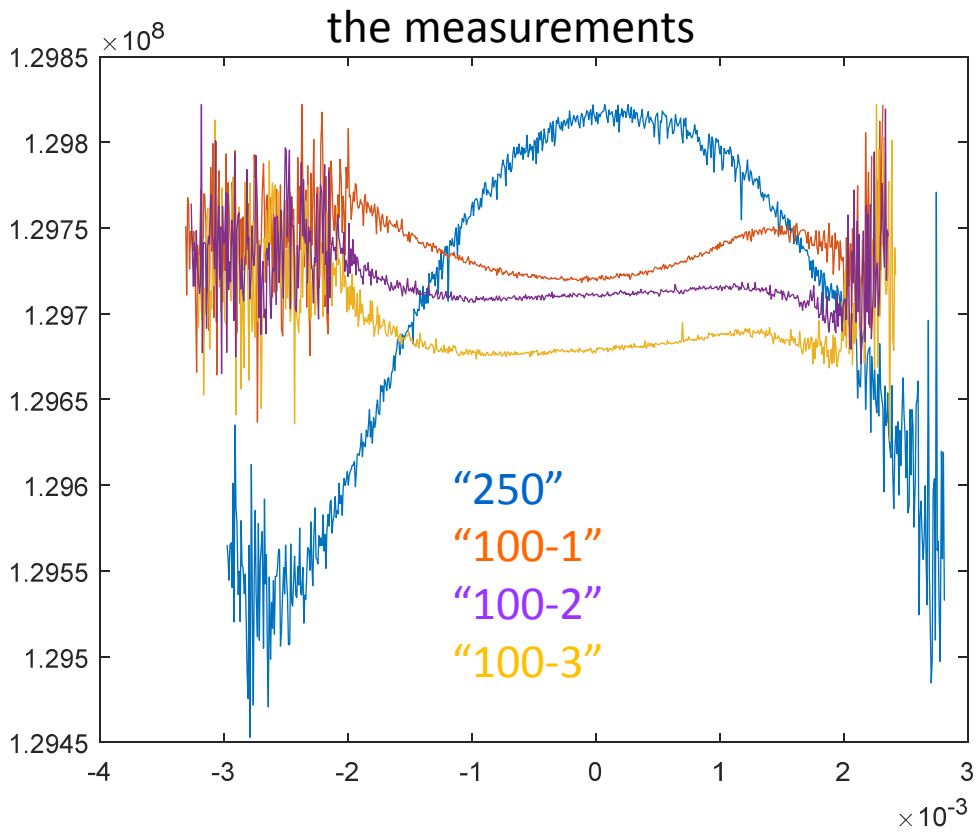
3.9 GHz 12 MV

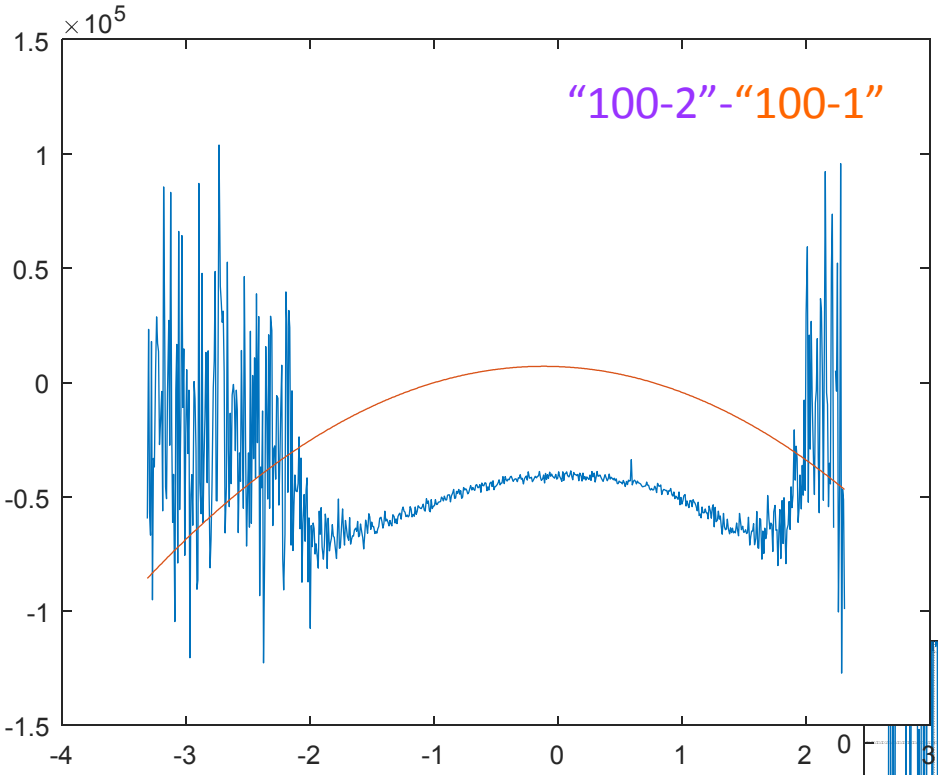
2) wake, assumption “resistive”

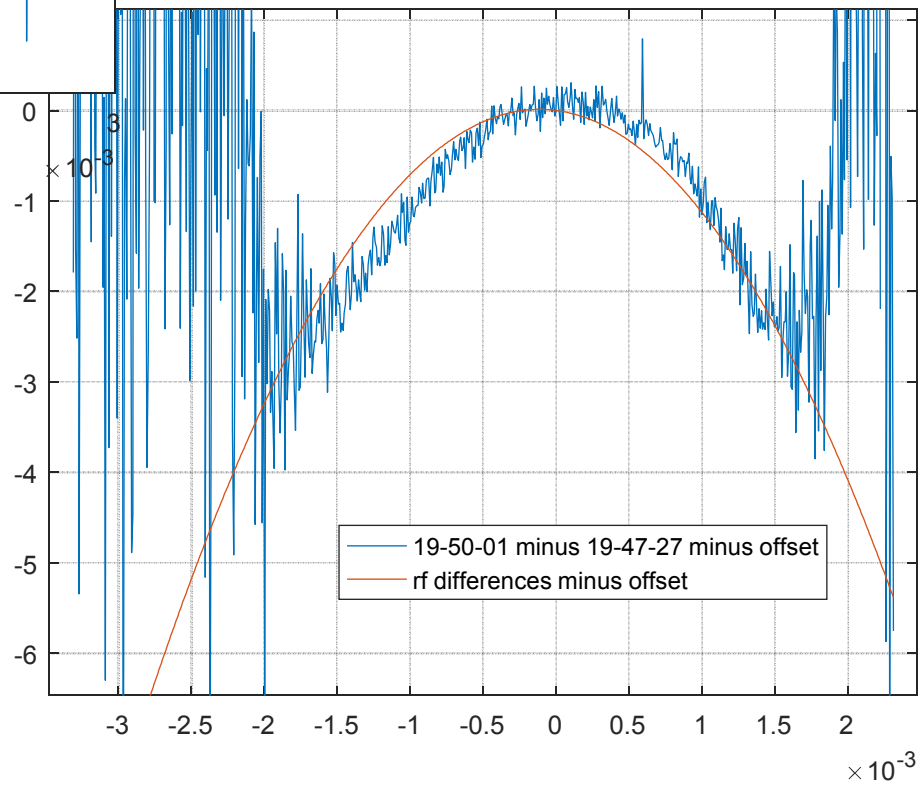


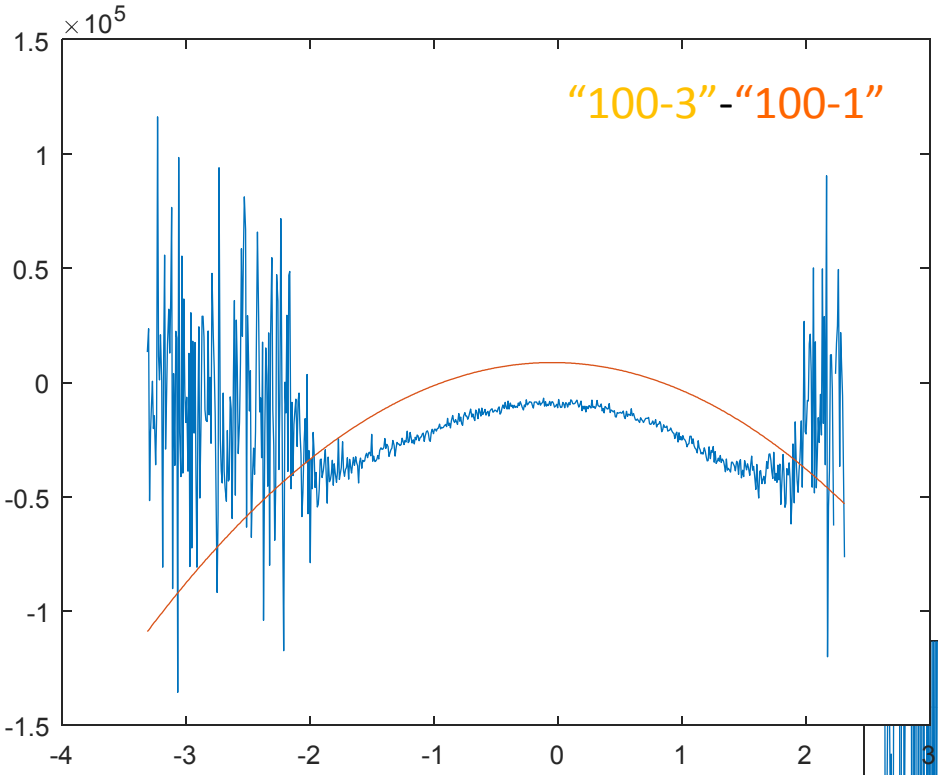
$$\Delta V \approx R \times I \rightarrow R \approx \frac{14 \cdots 20\text{kV}}{12\text{A}} \approx 1.2 \cdots 1.7\ \text{k}\Omega$$

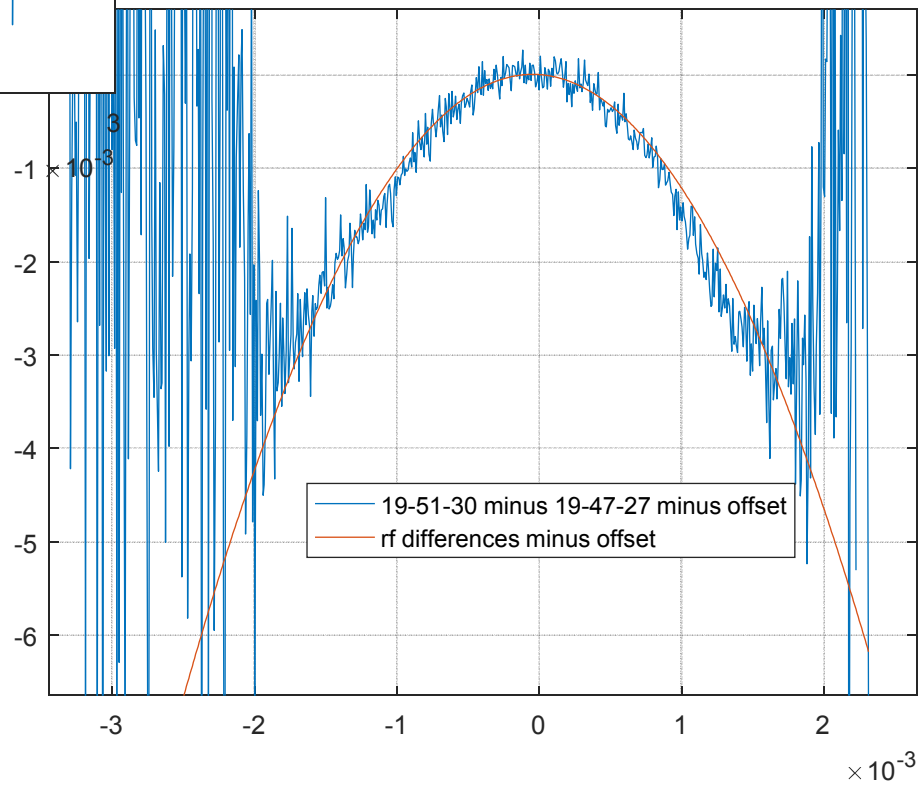
crosscheck: (measurement – measurement) vs. (rf-rf)

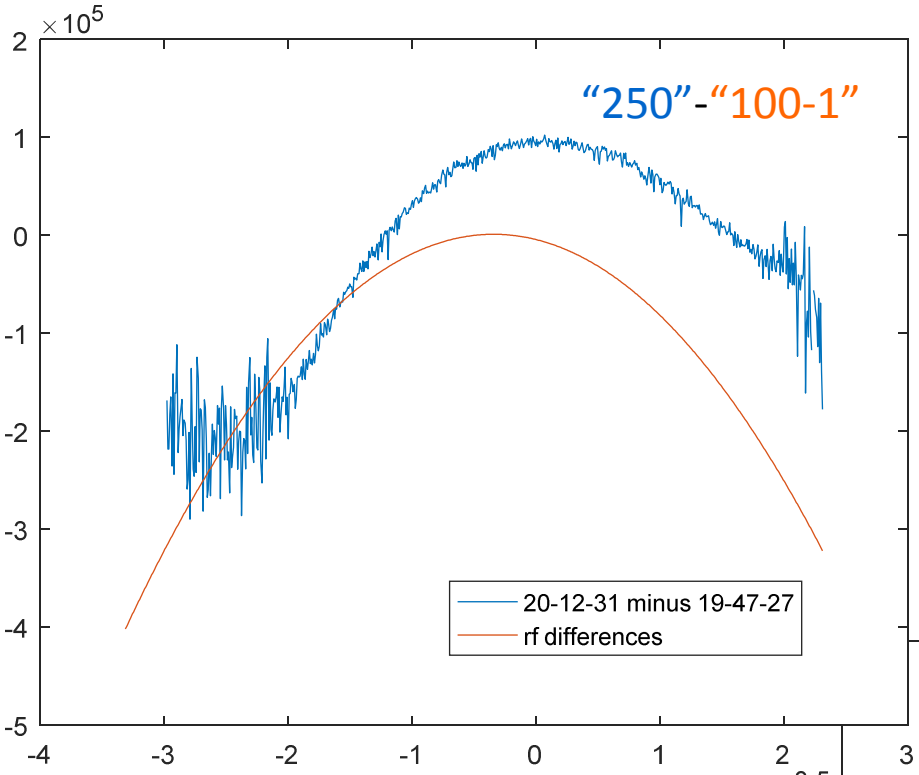


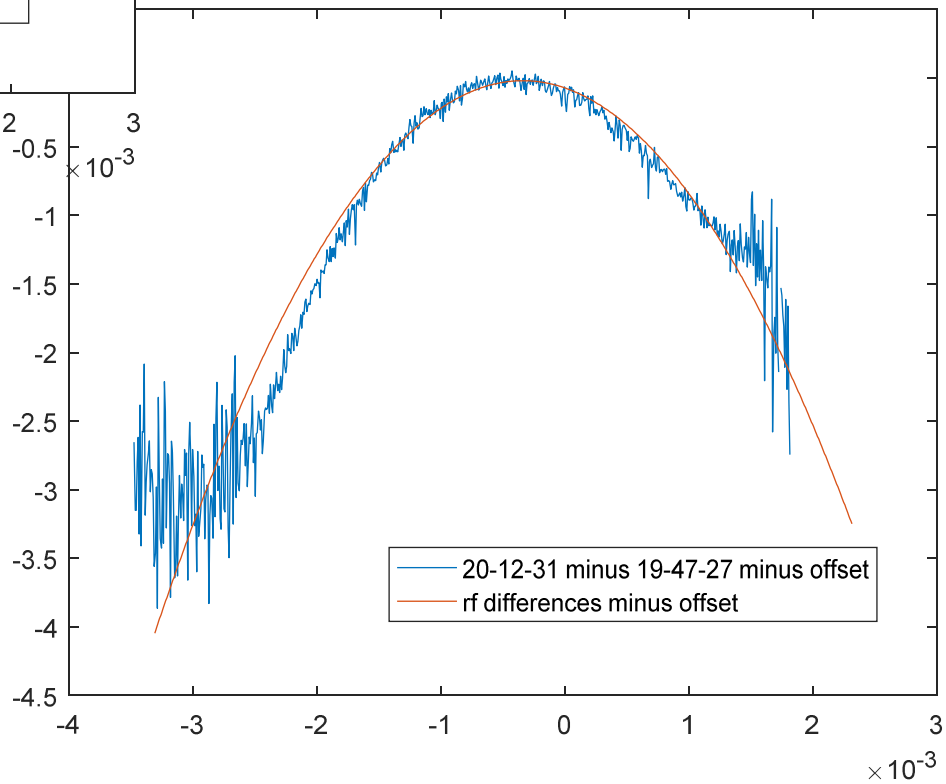

×10^5
1.5
1
0.5
0
-0.5
-1
-1.5
-4
-3
-2
-1
0
1
2
"100-2"-"100-1"


×10^-3
0
-1
-2
-3
-4
-5
-6
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
×10^-3
19-50-01 minus 19-47-27 minus offset
rf differences minus offset

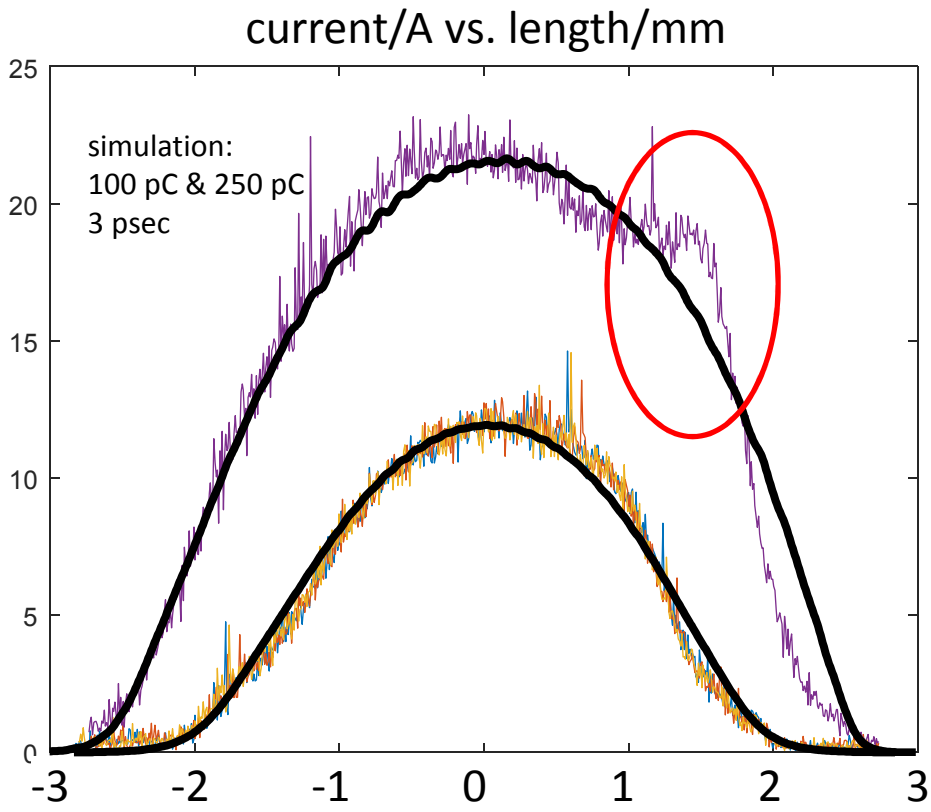

×10^5
1.5
1
0.5
0
-0.5
-1
-1.5
-4
-3
-2
-1
0
1
2
"100-3"-"100-1"

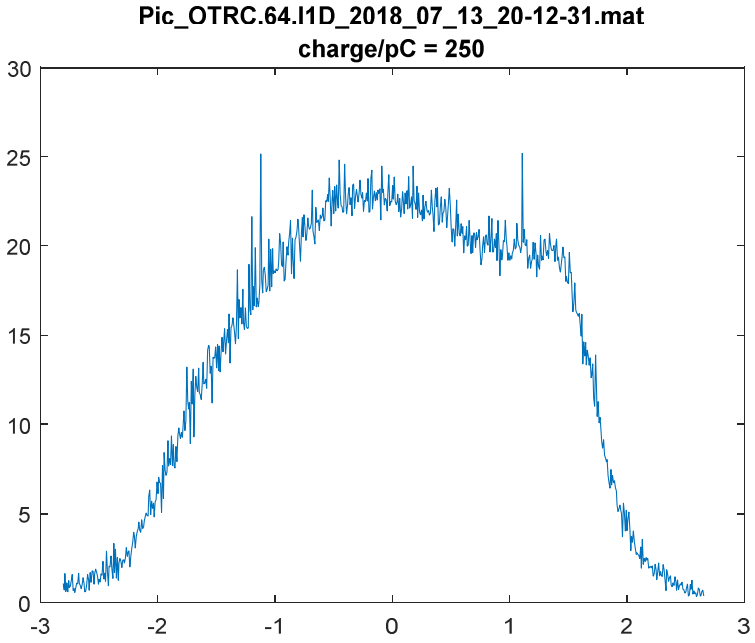

×10^-3
-1
-2
-3
-4
-5
-6
-3
-2
-1
0
1
2
×10^-3
19-51-30 minus 19-47-27 minus offset
rf differences minus offset

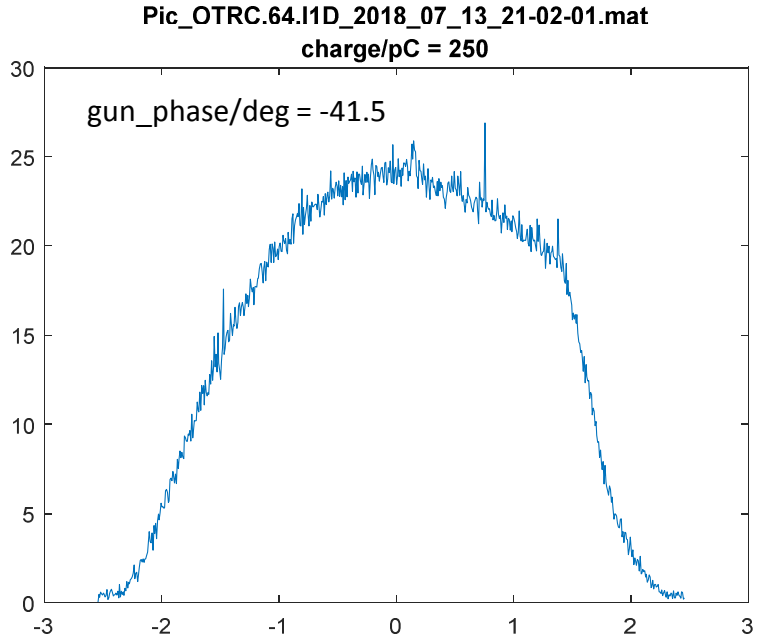

×10^5
2
1
0
-1
-2
-3
-4
-5
-4
-3
-2
-1
0
1
2
3
"250"-"100-1"
20-12-31 minus 19-47-27
rf differences

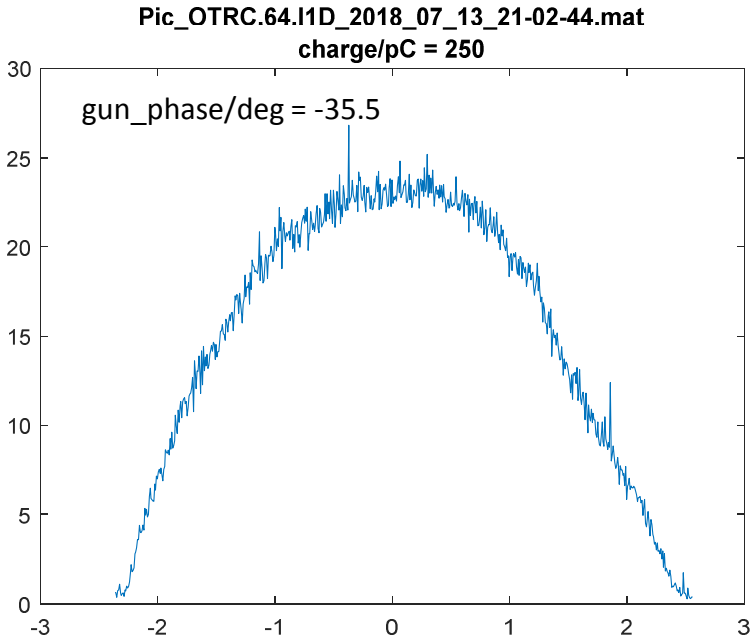

-0.5
×10^-3
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-4
-3
-2
-1
0
1
2
3
×10^-3
20-12-31 minus 19-47-27 minus offset
rf differences minus offset

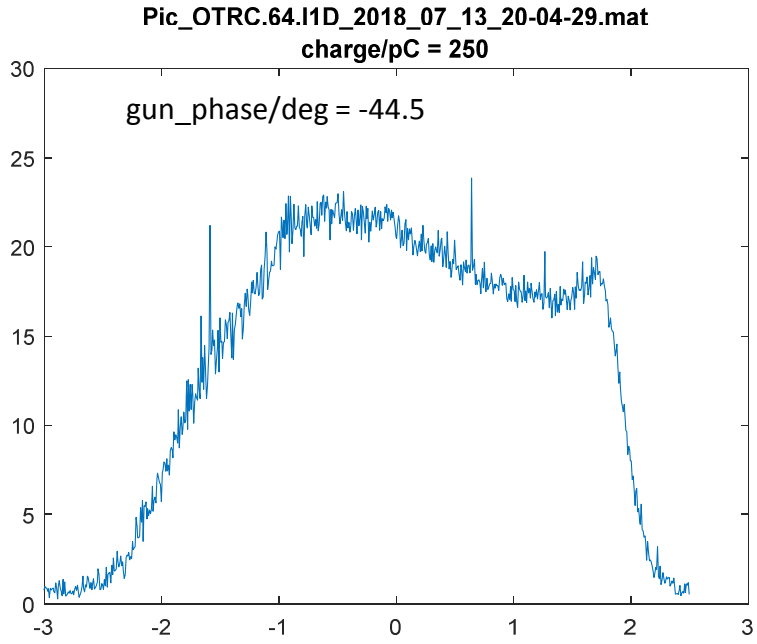
strange bunch shape

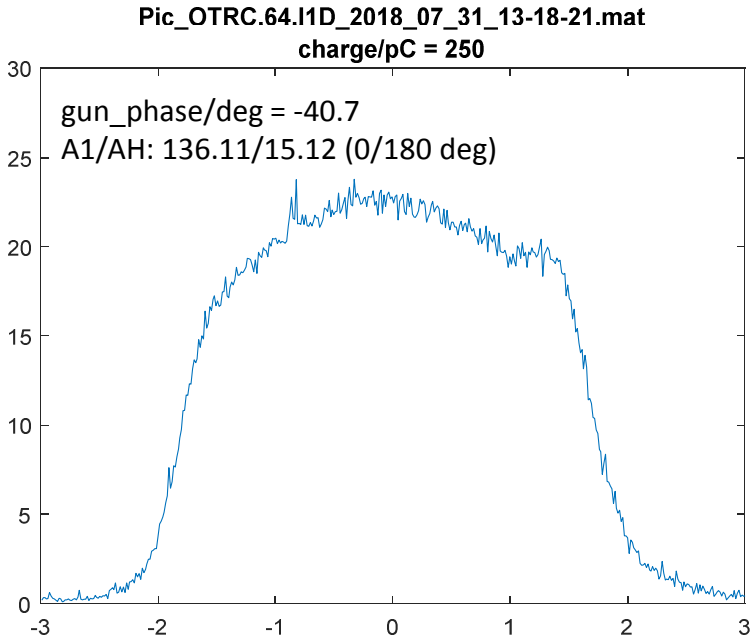


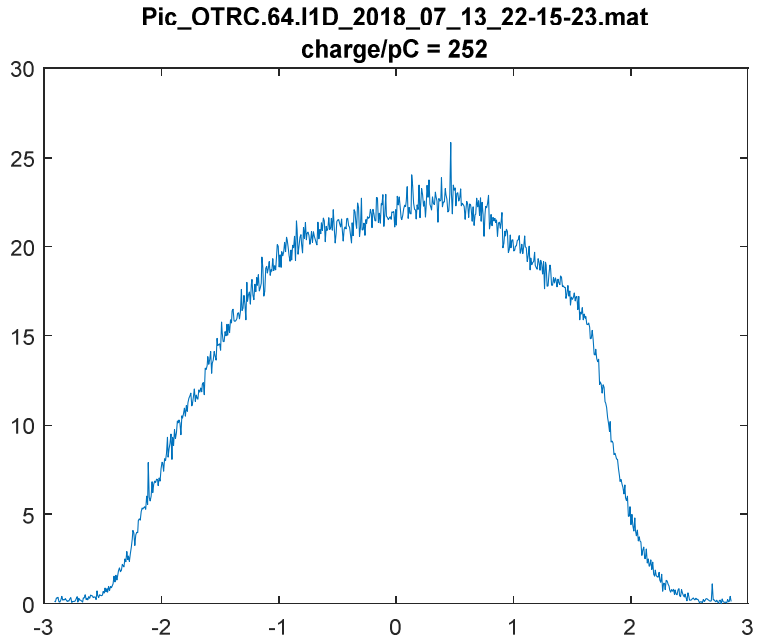

Pic_OTRC.64.I1D_2018_07_13_20-12-31.mat
charge/pC = 250

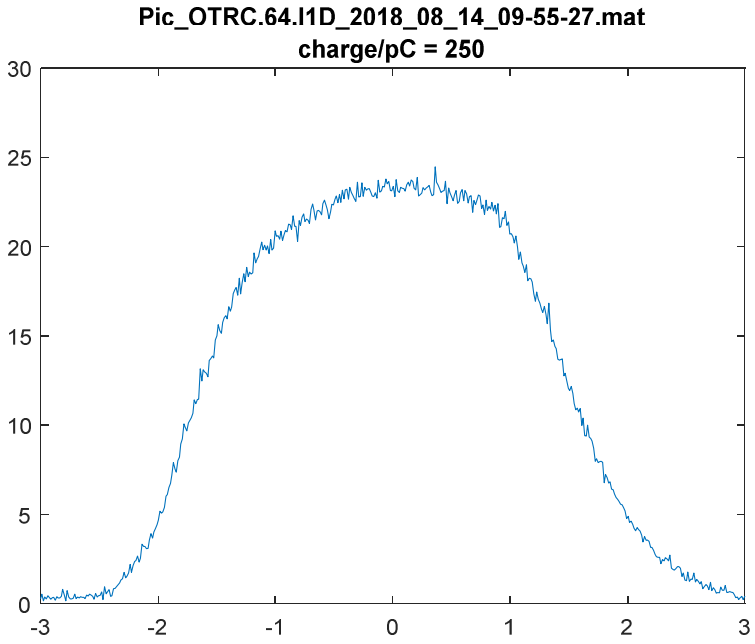

Pic_OTRC.64.I1D_2018_07_13_21-02-01.mat
charge/pC = 250
gun_phase/deg = -41.5

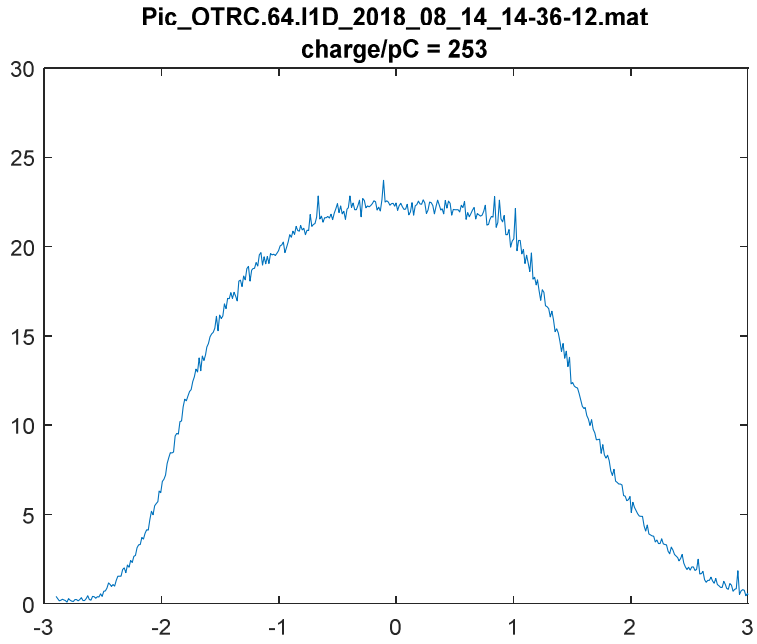

Pic_OTRC.64.I1D_2018_07_13_21-02-44.mat
charge/pC = 250
gun_phase/deg = -35.5


Pic_OTRC.64.I1D_2018_07_13_20-04-29.mat
charge/pC = 250
gun_phase/deg = -44.5

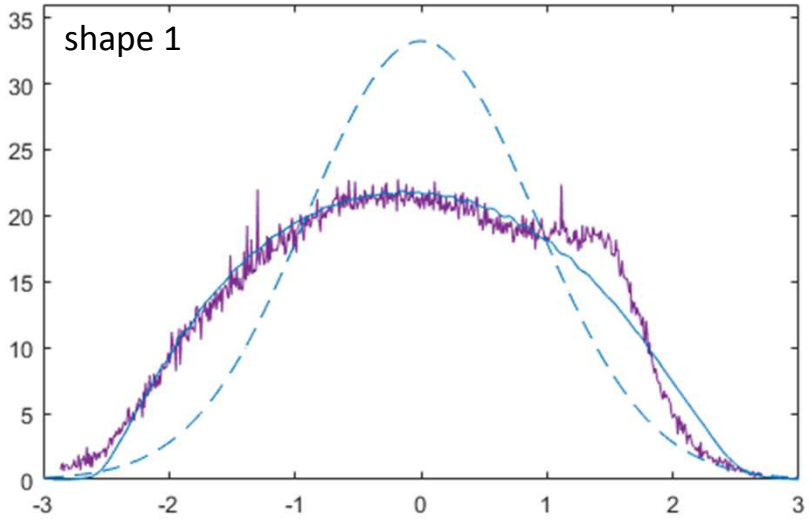

Pic_OTRC.64.I1D_2018_07_31_13-18-21.mat
charge/pC = 250
gun_phase/deg = -40.7
A1/AH: 136.11/15.12 (0/180 deg)

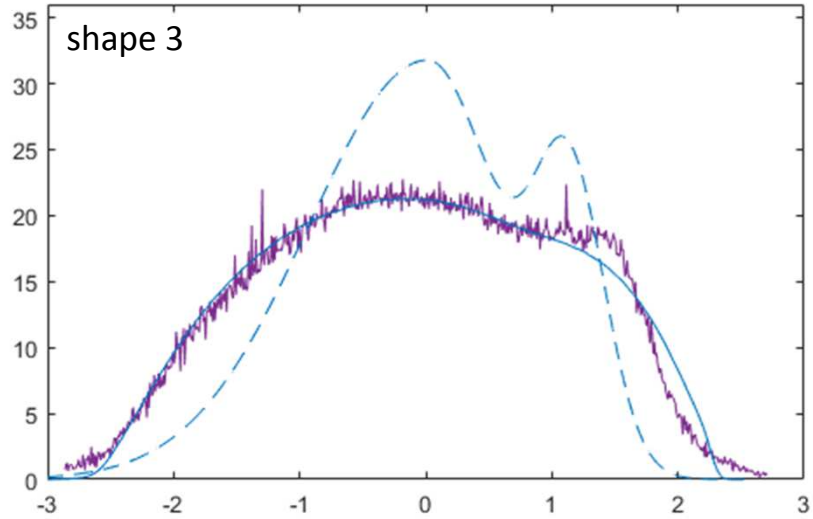

Pic_OTRC.64.I1D_2018_07_13_22-15-23.mat
charge/pC = 252

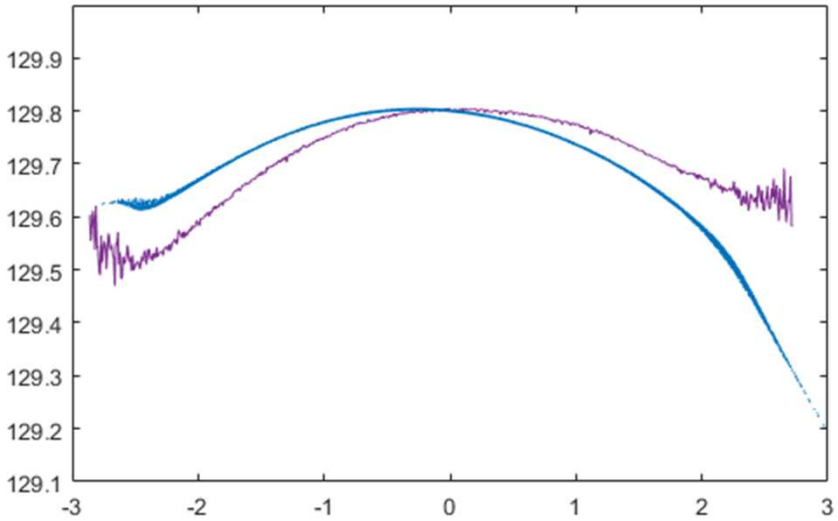

Pic_OTRC.64.I1D_2018_08_14_09-55-27.mat
charge/pC = 250

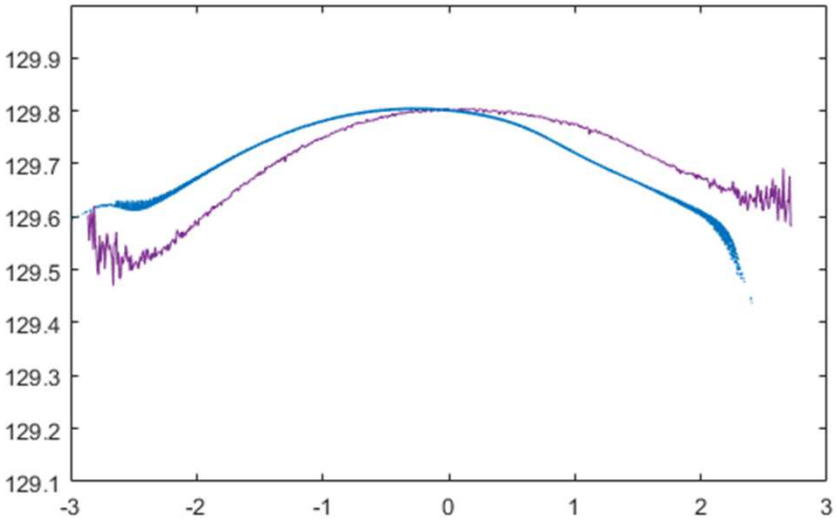

Pic_OTRC.64.I1D_2018_08_14_14-36-12.mat
charge/pC = 253

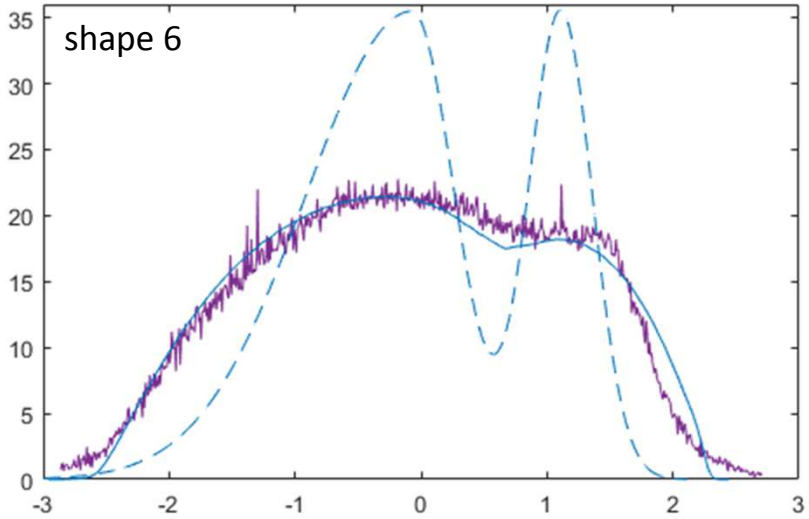
simulations with different cathode distributions

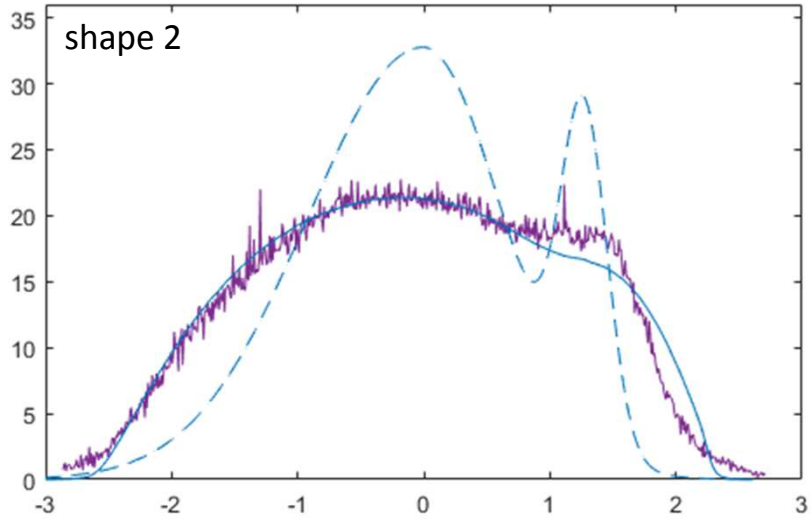


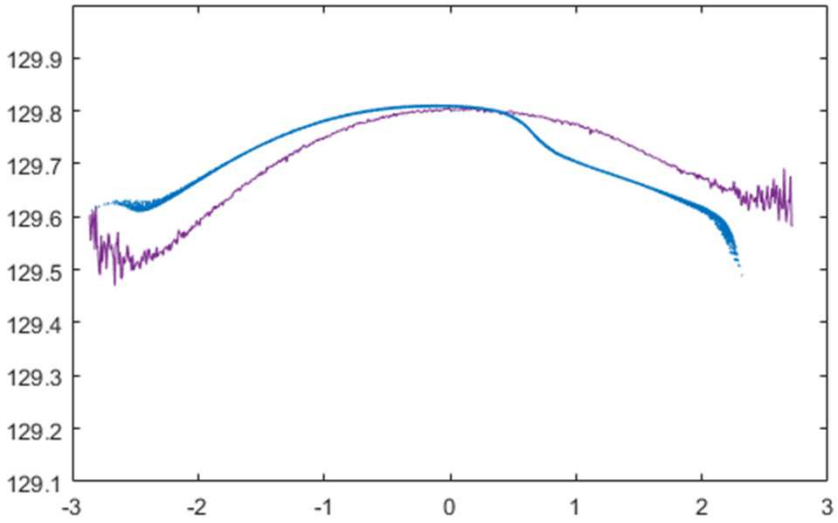


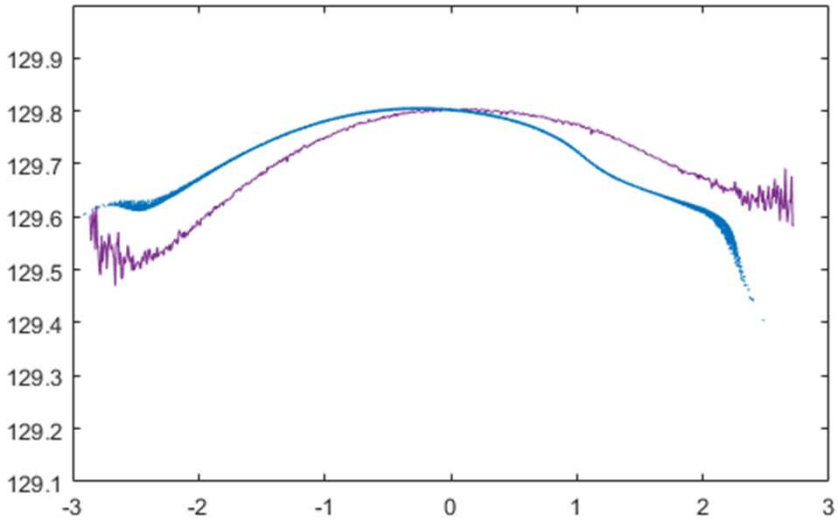


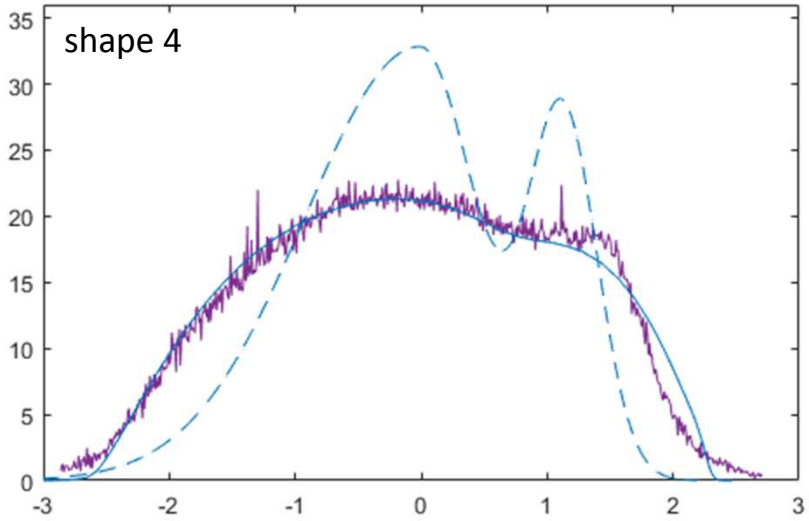


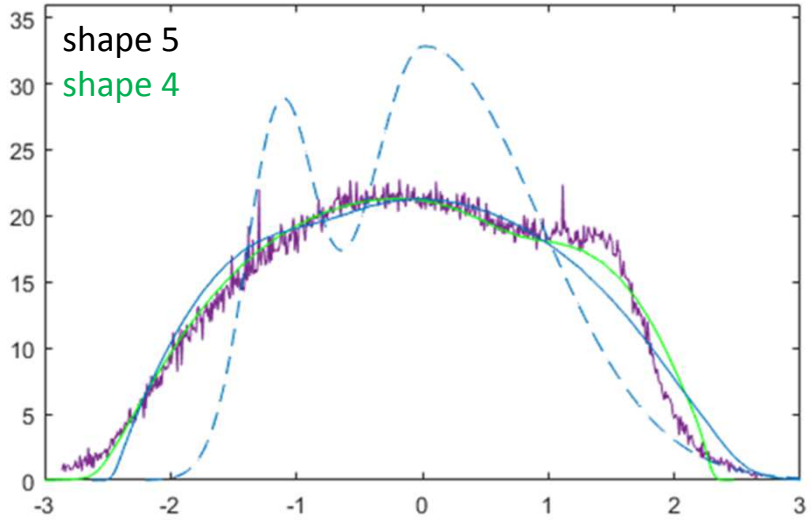

shape 6
35
30
25
20
15
10
5
0
-3
-2
-1
0
1
2
3

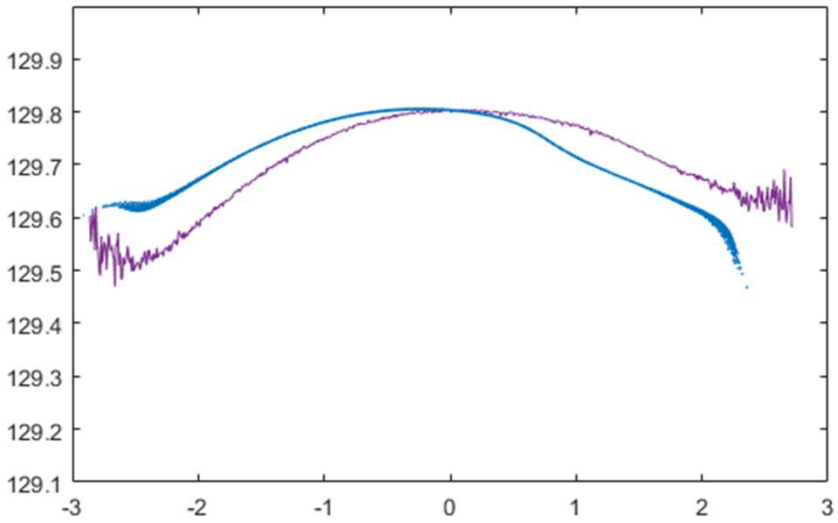

shape 2
35
30
25
20
15
10
5
0
-3
-2
-1
0
1
2
3

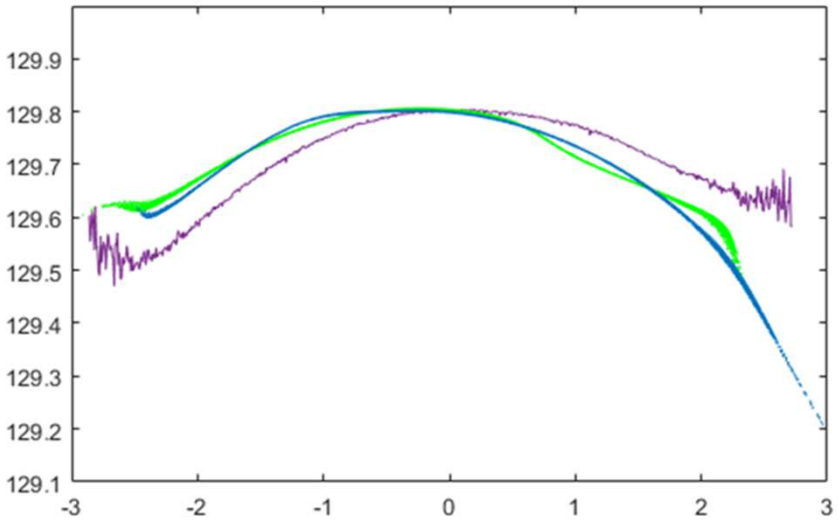

129.9
129.8
129.7
129.6
129.5
129.4
129.3
129.2
129.1
-3
-2
-1
0
1
2
3

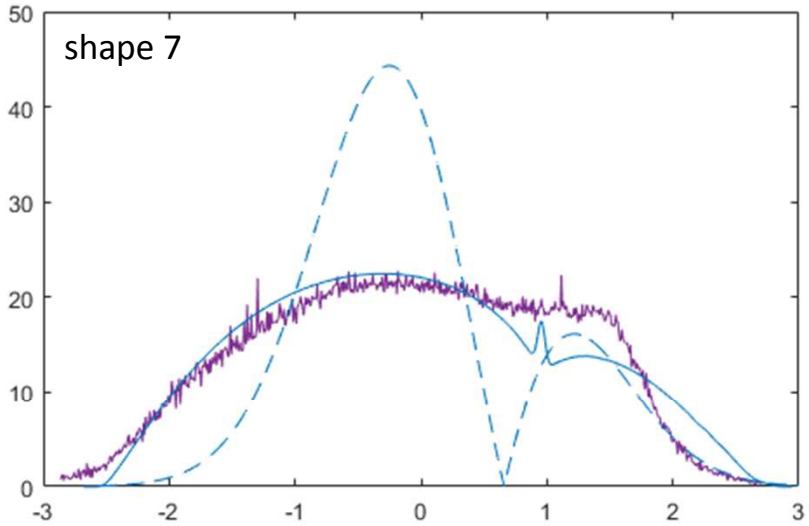

129.9
129.8
129.7
129.6
129.5
129.4
129.3
129.2
129.1
-3
-2
-1
0
1
2
3

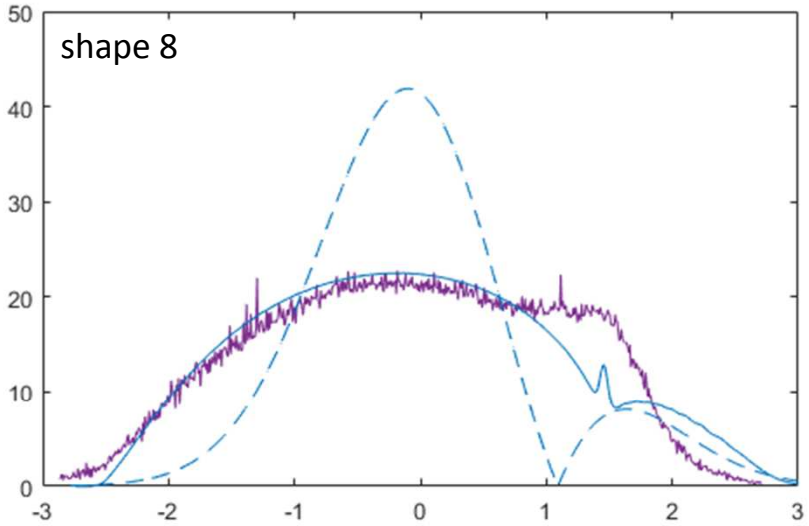

shape 4

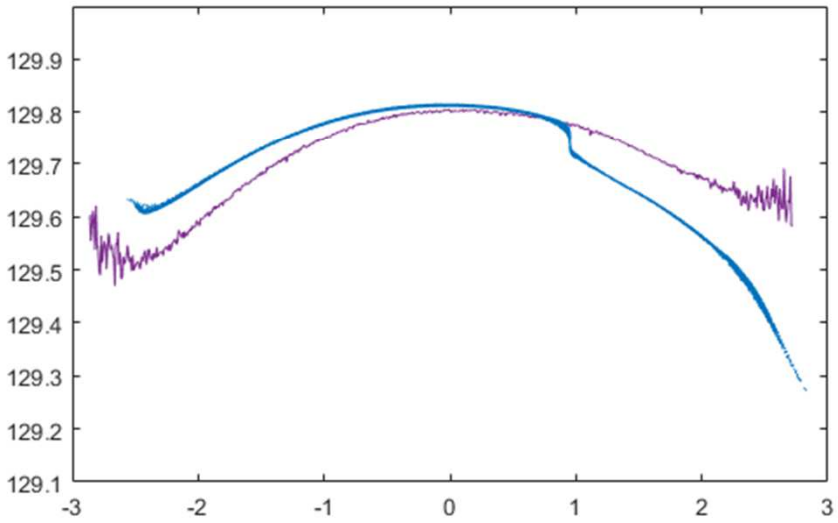

shape 5
shape 4

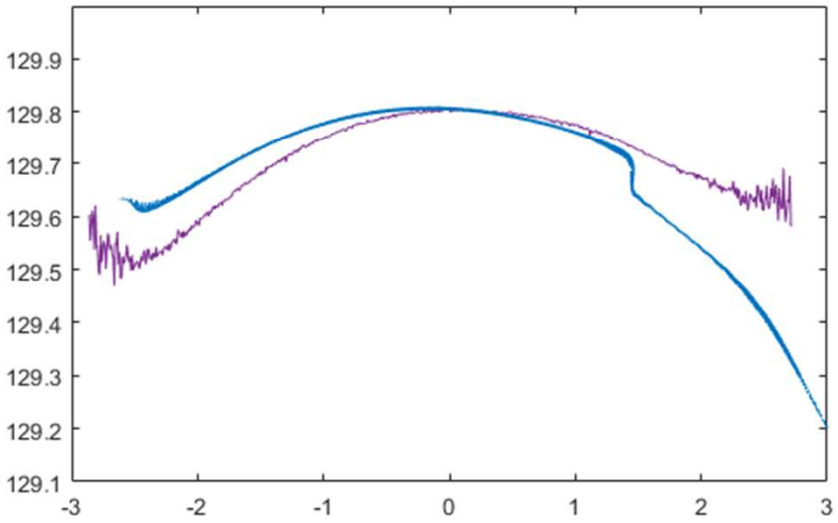





shape 7
50
40
30
20
10
0
-3
-2
-1
0
1
2
3


shape 8
50
40
30
20
10
0
-3
-2
-1
0
1
2
3


129.9
129.8
129.7
129.6
129.5
129.4
129.3
129.2
129.1
-3
-2
-1
0
1
2
3


129.9
129.8
129.7
129.6
129.5
129.4
129.3
129.2
129.1
-3
-2
-1
0
1
2
3

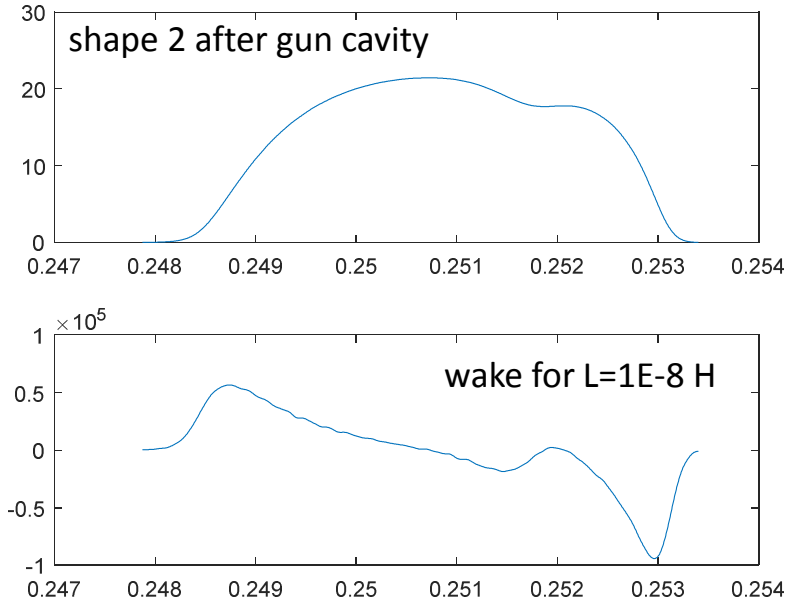
the Astra-type gun simulations have a strong low-pass characteristic

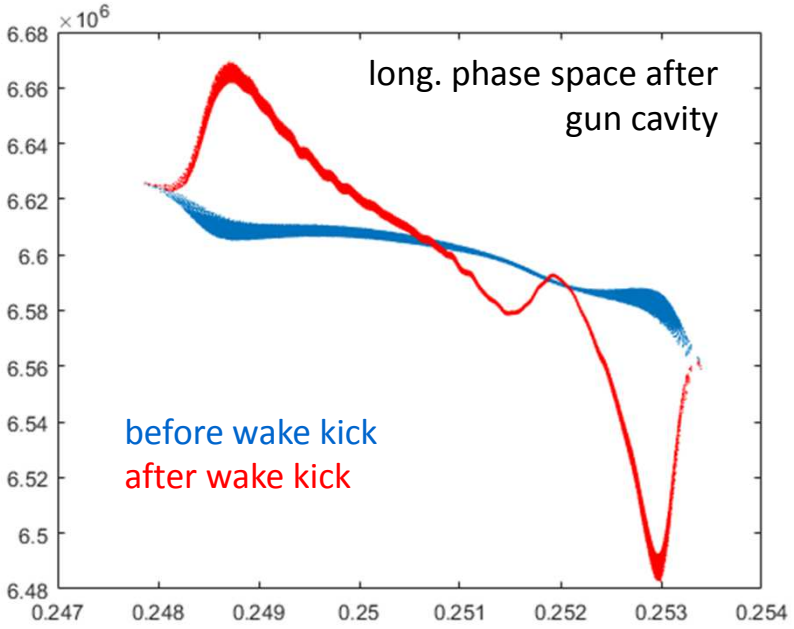
even start distribution with strong perturbation do not generate the measured profiles

???: there must be an other effect in or close to the gun; perhaps a wake that is not considered in the impedance data base

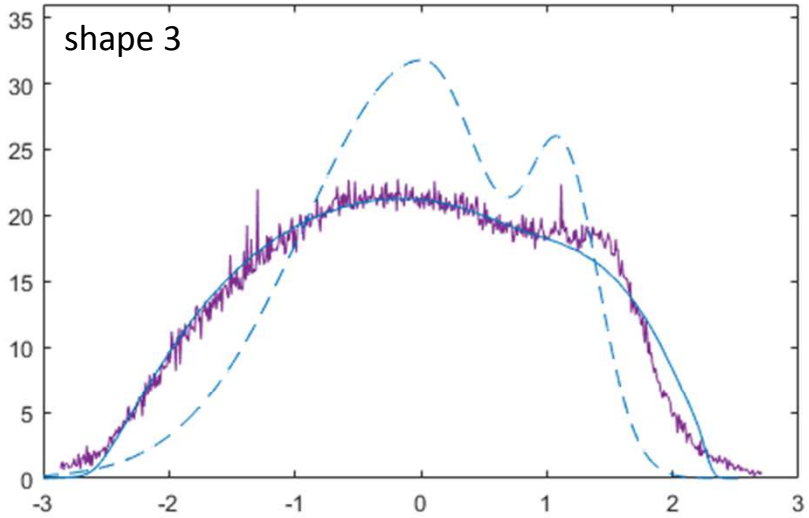
this unknown wake should enhance fast structures;

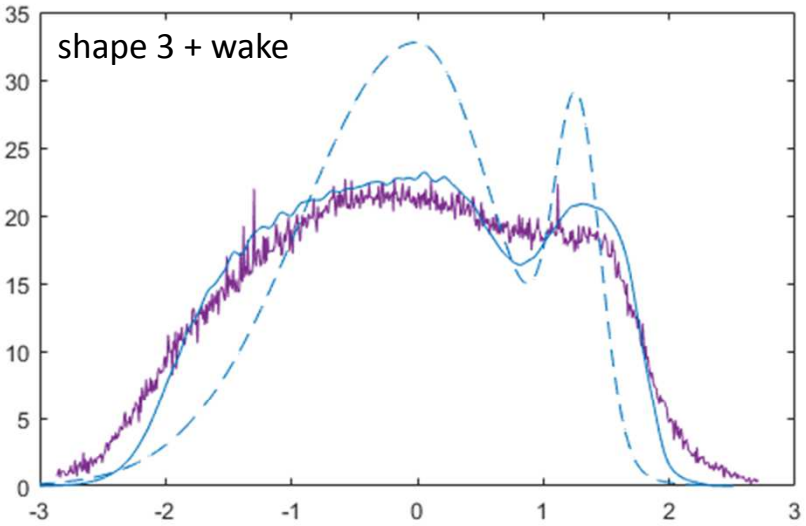
→ try inductive wake direct after the gun cavity

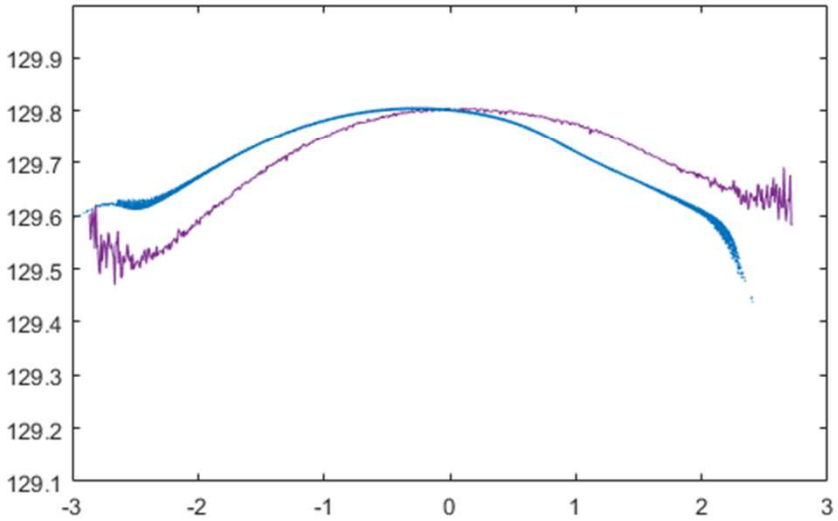


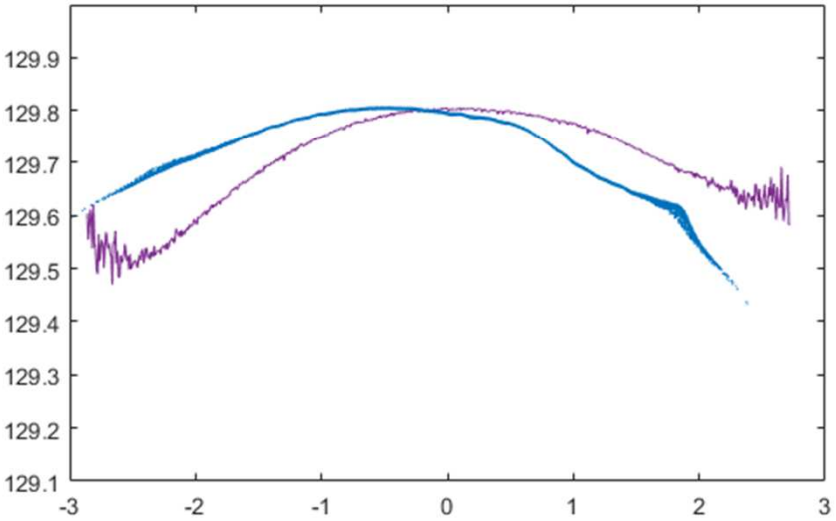


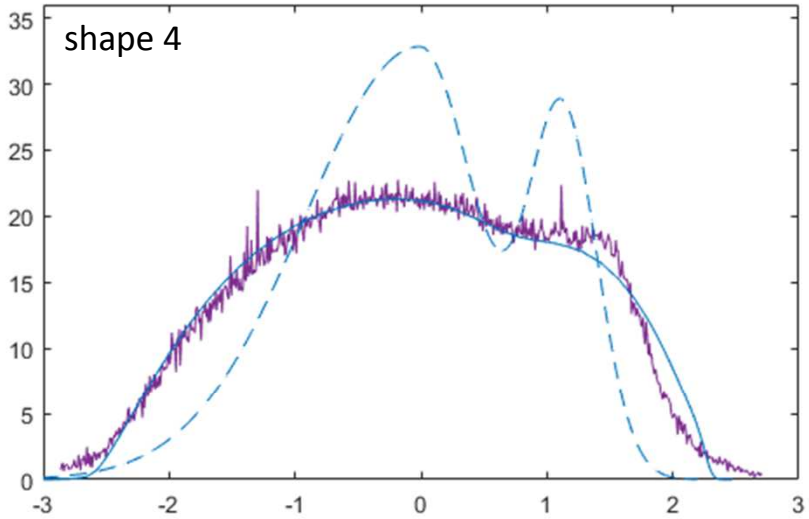
simulations plus artificial (inductive) wake

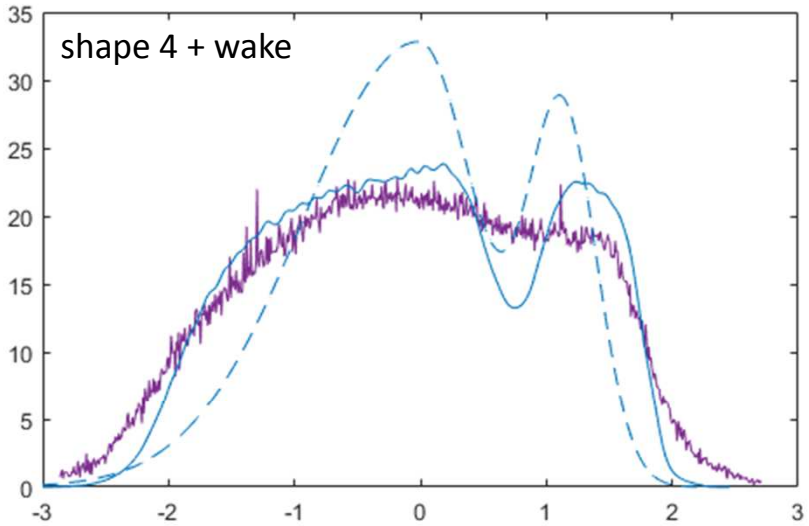


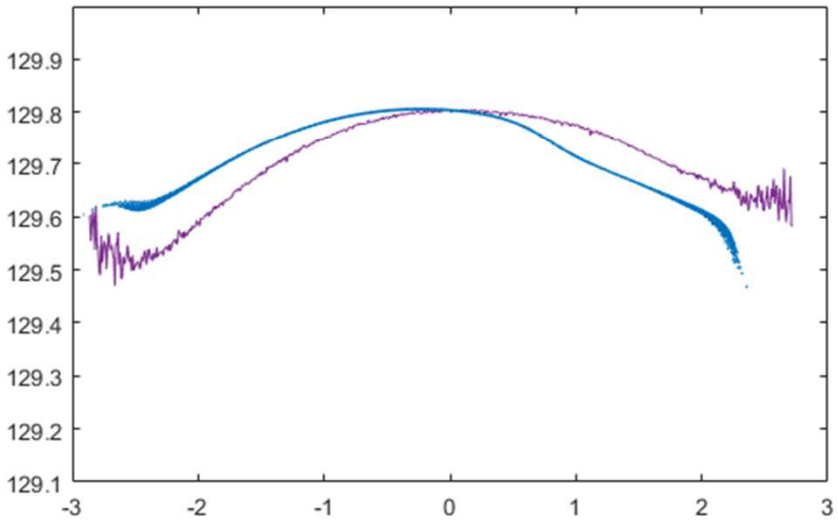


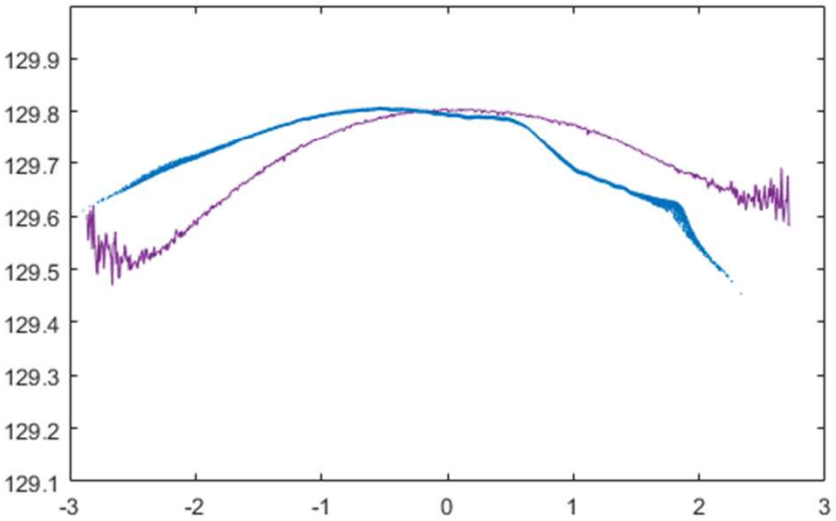





shape 4
35
30
25
20
15
10
5
0
-3
-2
-1
0
1
2
3


shape 4 + wake
35
30
25
20
15
10
5
0
-3
-2
-1
0
1
2
3


129.9
129.8
129.7
129.6
129.5
129.4
129.3
129.2
129.1
-3
-2
-1
0
1
2
3


129.9
129.8
129.7
129.6
129.5
129.4
129.3
129.2
129.1
-3
-2
-1
0
1
2
3

less wake or an initial distribution with smaller perturbation could produce the measured shape

the effect of wakefields **in** the gun might be stronger

time domain simulation of an accelerated bunch

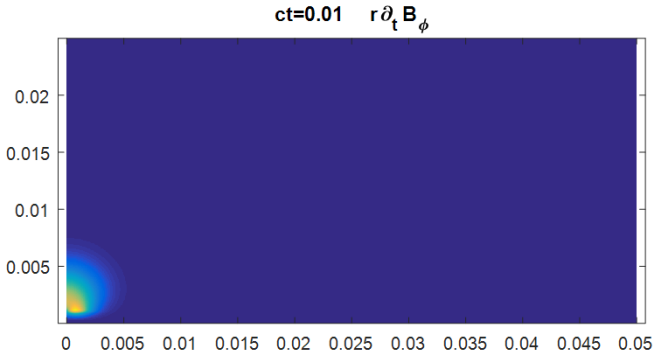
simplified stimulation: $\mathbf{J}(\mathbf{r},t) = e_z \eta(r) i\left(t - t_z(z)\right)$

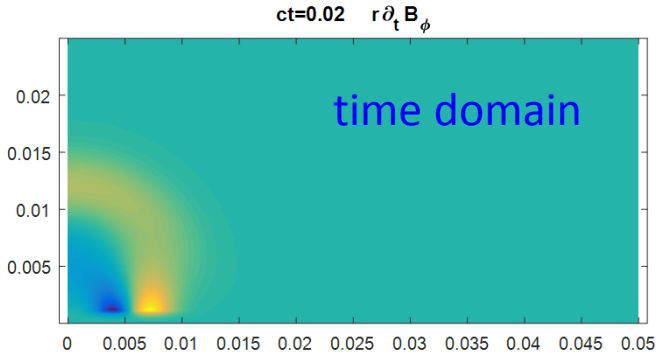
with $\gamma(z) = 1 + \frac{qE_0}{m_0 c^2} z \rightarrow v(z) \rightarrow t_z(z)$

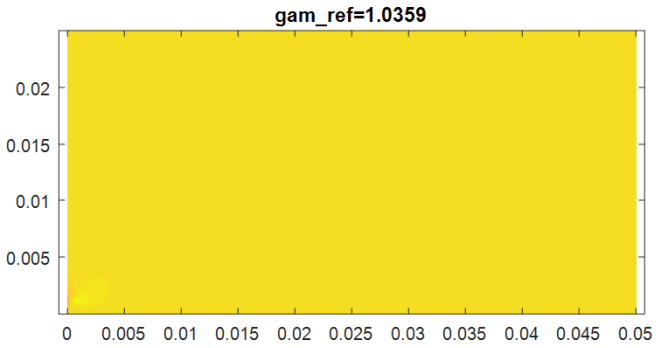
example 1: $\sigma_t = 6.7$ psec

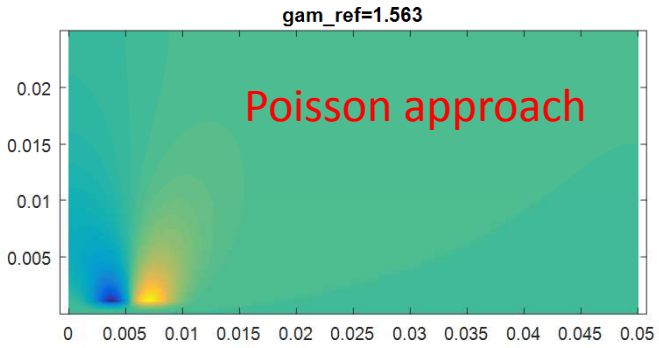
$r_b = 0.5$ mm pencil beam

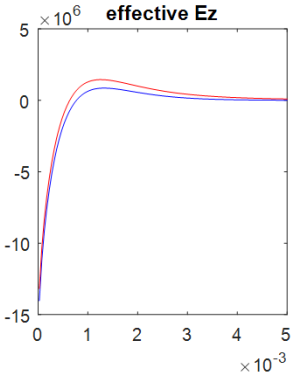
$E = 51.1$ MV/m external field is constant (in time and space)

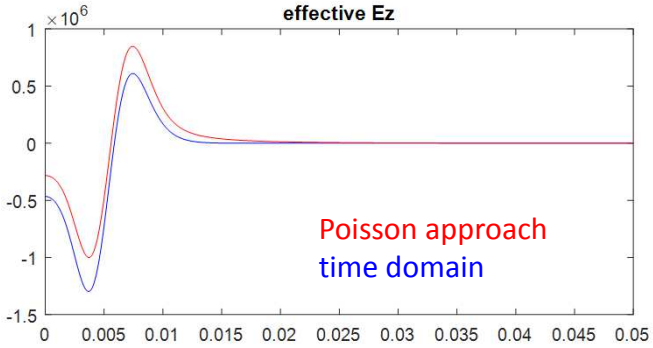

ct=0.01 r∂t Bϕ
0.02
0.015
0.01
0.005
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05

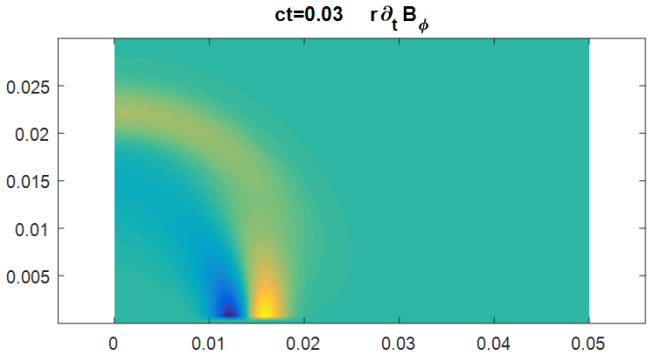

ct=0.02 r∂t Bϕ
time domain
0.02
0.015
0.01
0.005
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05

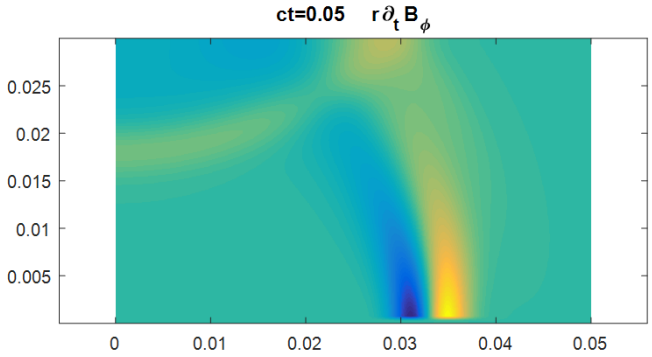

gam_ref=1.0359
0.02
0.015
0.01
0.005
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05

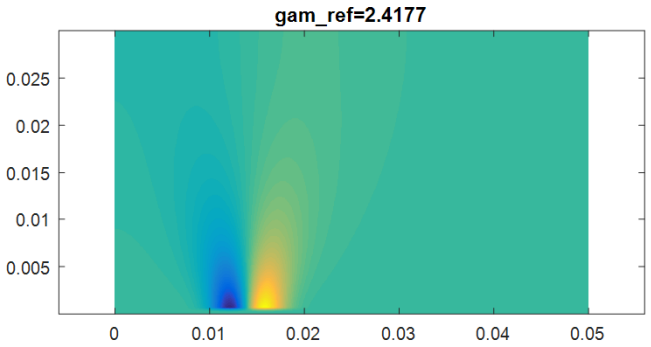

gam_ref=1.563
Poisson approach
0.02
0.015
0.01
0.005
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05


effective Ez
×10^6
5
0
-5
-10
-15
0 1 2 3 4 5
×10^-3


effective Ez
×10^6
1
0.5
0
-0.5
-1
-1.5
Poisson approach
time domain
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05


ct=0.03 r∂t Bϕ
0.025
0.02
0.015
0.01
0.005
0
0.01
0.02
0.03
0.04
0.05


ct=0.05 r∂t Bϕ
0.025
0.02
0.015
0.01
0.005
0
0.01
0.02
0.03
0.04
0.05


gam_ref=2.4177
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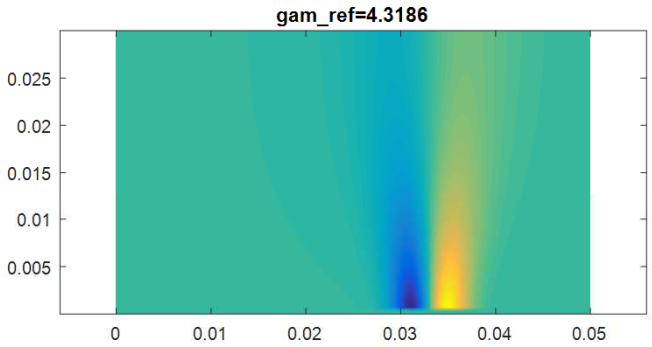
0.02
0.015
0.01
0.005
0
0.01
0.02
0.03
0.04
0.05


gam_ref=4.3186
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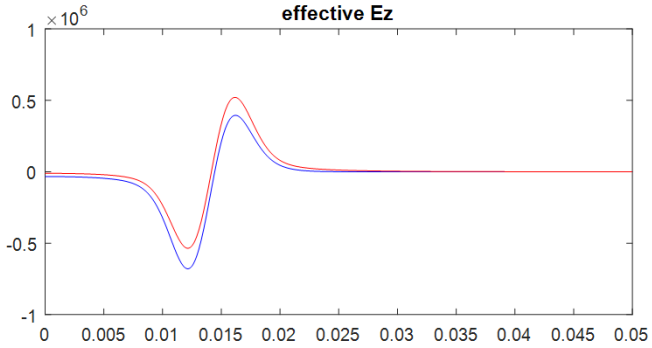
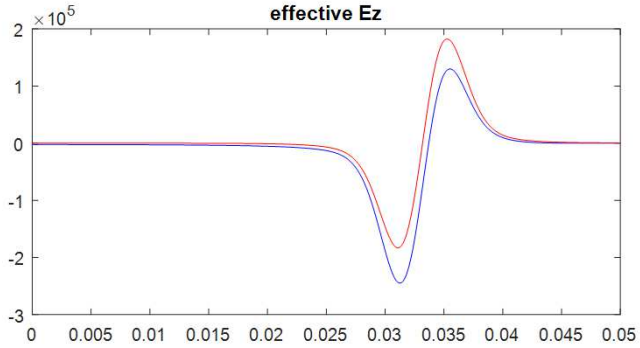
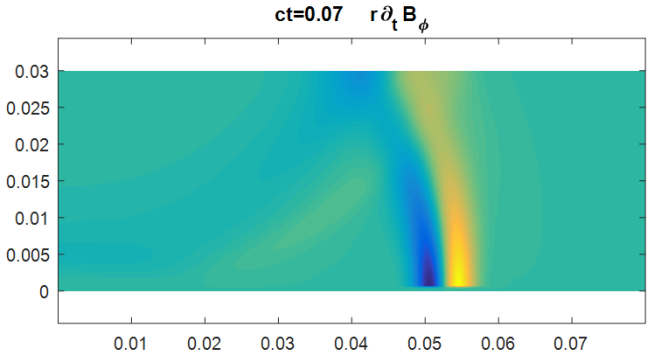
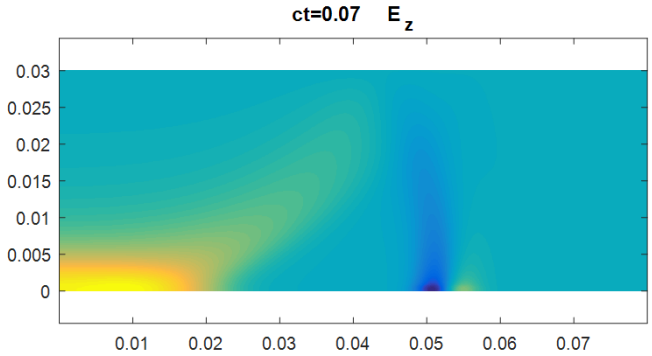
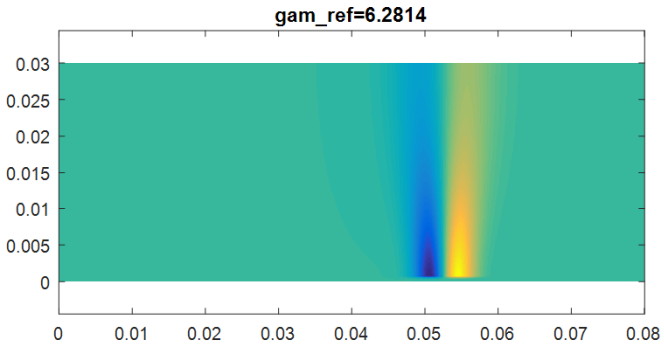
0.02
0.015
0.01
0.005
0
0.01
0.02
0.03
0.04
0.05


effective Ez
×10^6
1
0.5
0
-0.5
-1
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05


effective Ez
×10^5
2
1
0
-1
-2
-3
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05


ct=0.07 r∂t Bϕ
0.03
0.025
0.02
0.015
0.01
0.005
0
0.01 0.02 0.03 0.04 0.05 0.06 0.07


ct=0.07 Ez
0.03
0.025
0.02
0.015
0.01
0.005
0
0.01 0.02 0.03 0.04 0.05 0.06 0.07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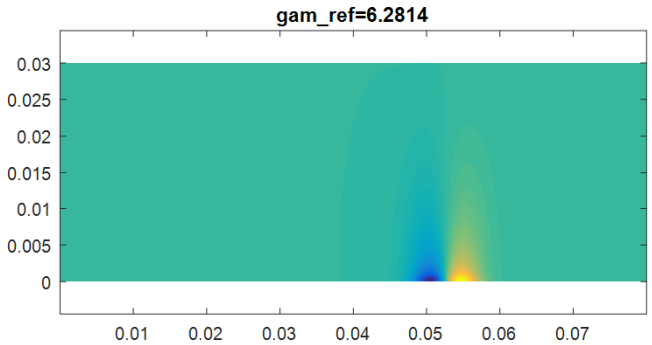
0.025
0.02
0.015
0.01
0.005
0
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08


gam_ref=6.2814
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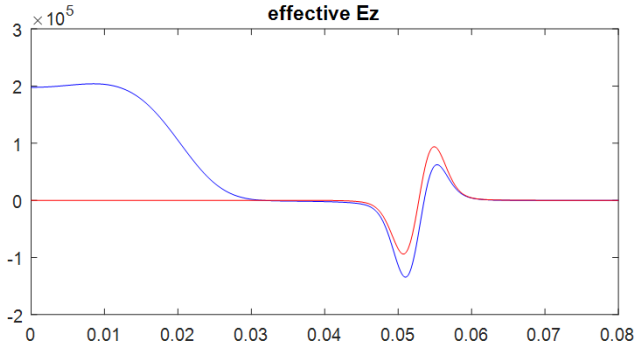
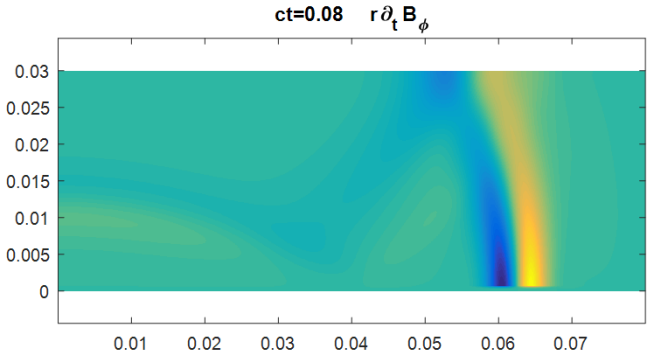
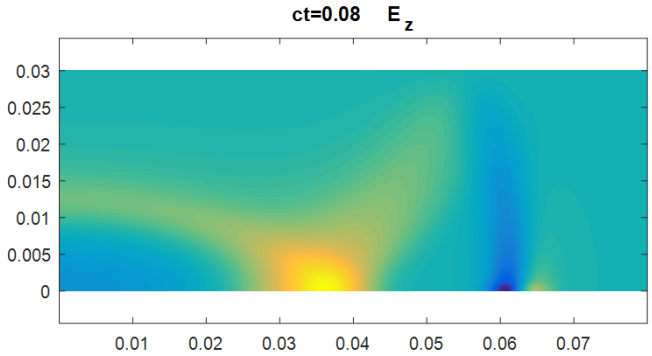
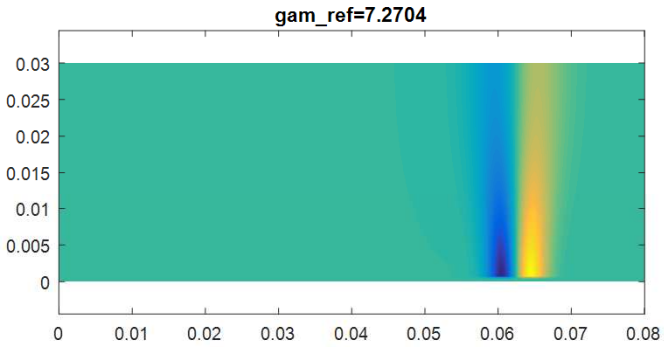
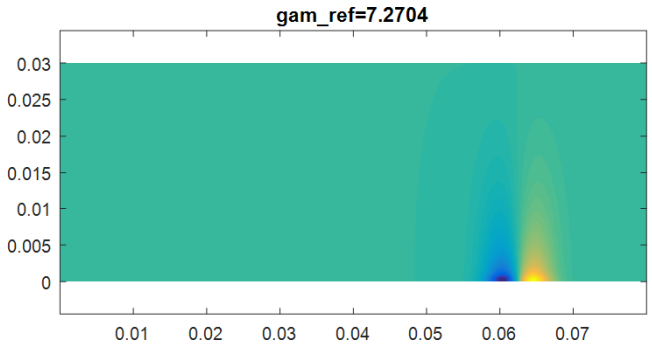
0.025
0.02
0.015
0.01
0.005
0
0.01 0.02 0.03 0.04 0.05 0.06 0.07

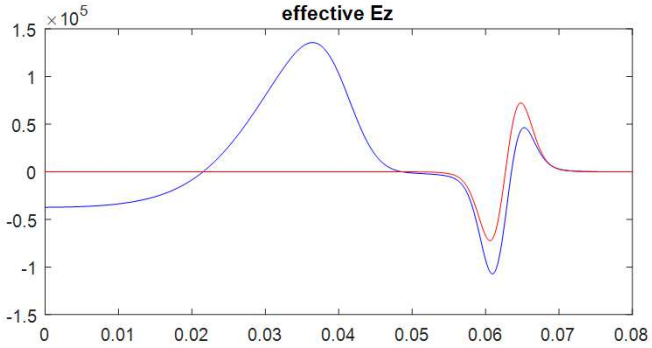

effective Ez
×10^5
3
2
1
0
-1
-2
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08


ct=0.08 r∂t Bϕ
0.03
0.025
0.02
0.015
0.01
0.005
0
0.01 0.02 0.03 0.04 0.05 0.06 0.07


ct=0.08 Ez
0.03
0.025
0.02
0.015
0.01
0.005
0
0.01 0.02 0.03 0.04 0.05 0.06 0.07


gam_ref=7.2704
0.03
0.025
0.02
0.015
0.01
0.005
0
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08


gam_ref=7.2704
0.03
0.025
0.02
0.015
0.01
0.005
0
0.01 0.02 0.03 0.04 0.05 0.06 0.07


effective Ez
×10^5
1.5
1
0.5
0
-0.5
-1
-1.5
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08

time domain simulation with simplified (1d) particle tracking

simplified stimulation: $\mathbf{J}(\mathbf{r},t) = e_z \eta(r) i(z,t)$

$\eta(r)$ pencil beam with $r_b = 0.5$ mm

$i(z,t)$ from particle tracking $\{z_v, p_{zv}\}$

$$E_z^{(\mathrm{eff})}(z,t) = \int E_z(r,z,t)\eta(r)2\pi r dr + E_z^{(\mathrm{ext})}(z,t)$$

$E_z^{(\mathrm{ext})}(z,t) = E_0 \cos(\omega t + \varphi)\cos(kz)$ in the cavity (58MV/m, 216.4 deg)

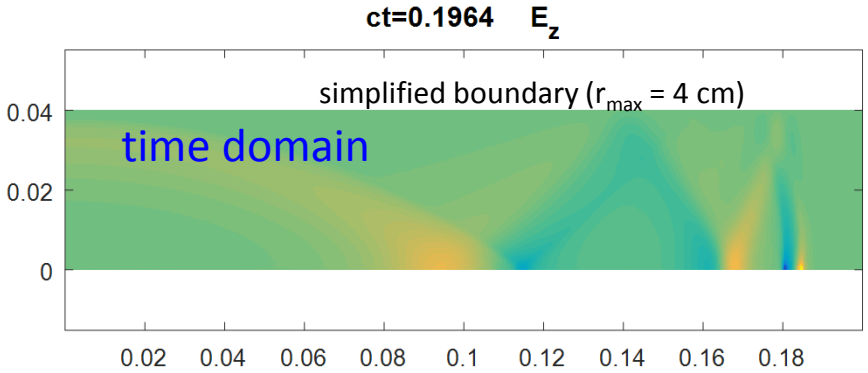
1d particle tracking: $z_v + v(p_{zv})\delta t \to z_v$

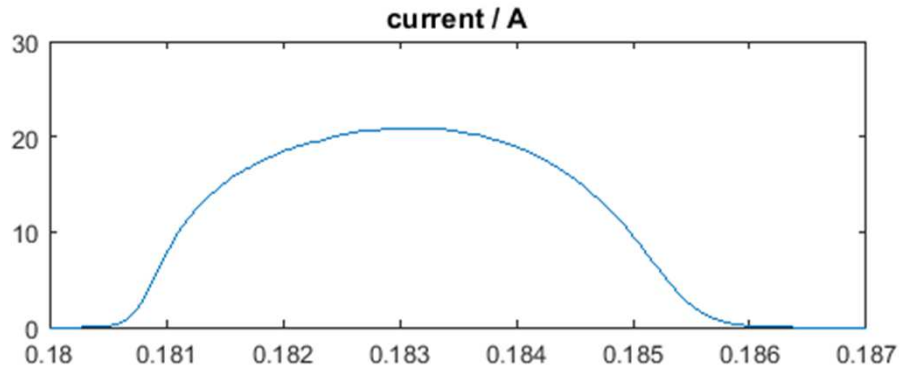
$$p_{zv} + qE_z^{(\mathrm{eff})}(z_v) \to p_{zv}$$

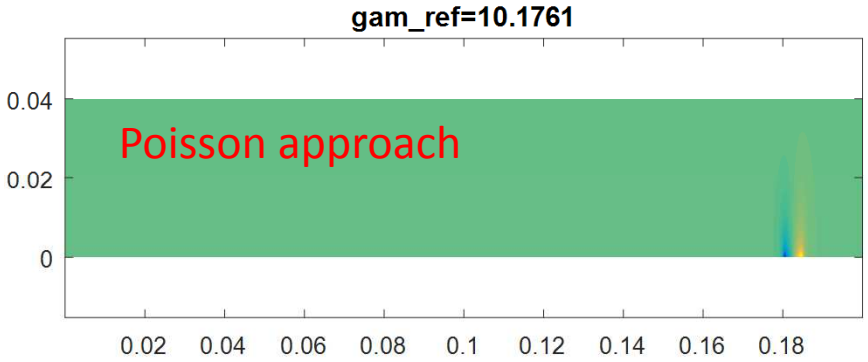
$$z_v + v(p_{zv})\delta t \to z_v$$

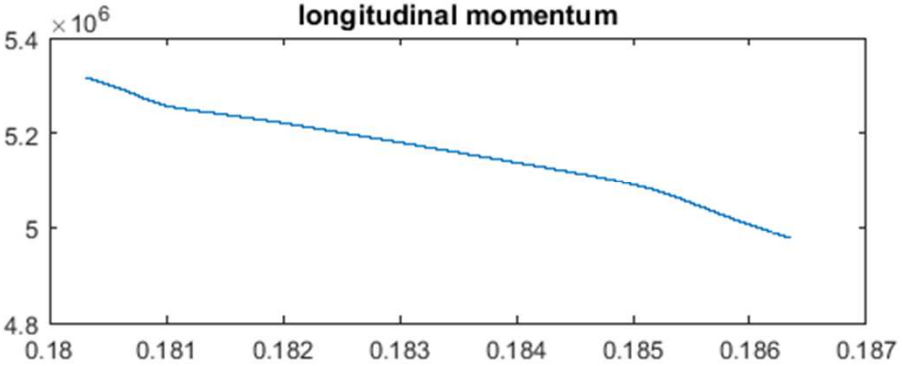
$\ldots$

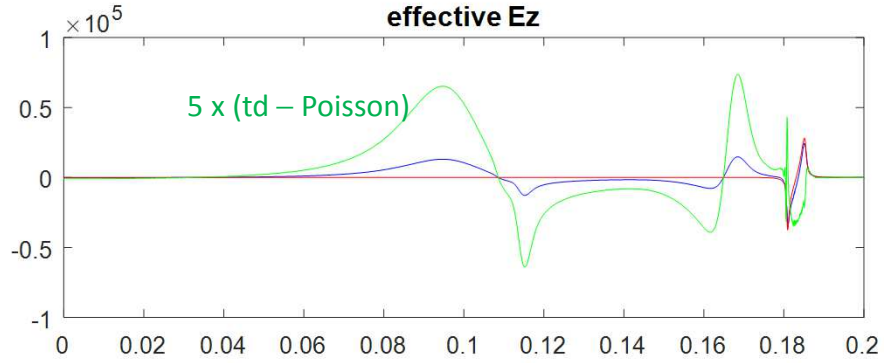
start distribution: 250 pC, 3 psec, 2E6 particles

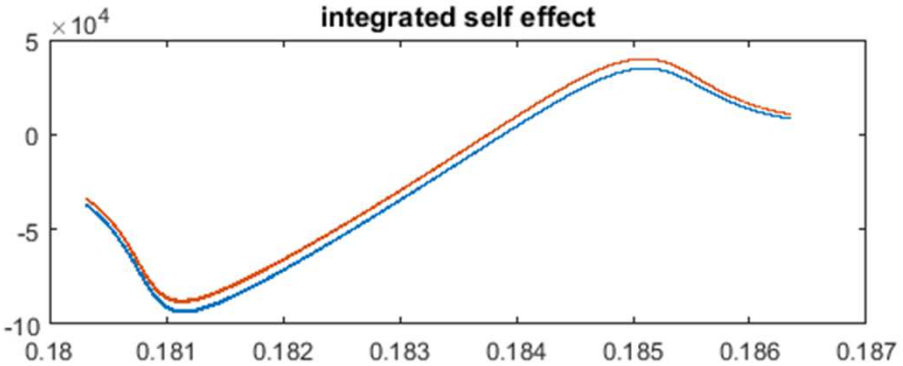

ct=0.1964 E_z
simplified boundary (r_{max} = 4 cm)
time domain
0.04
0.02
0
0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18

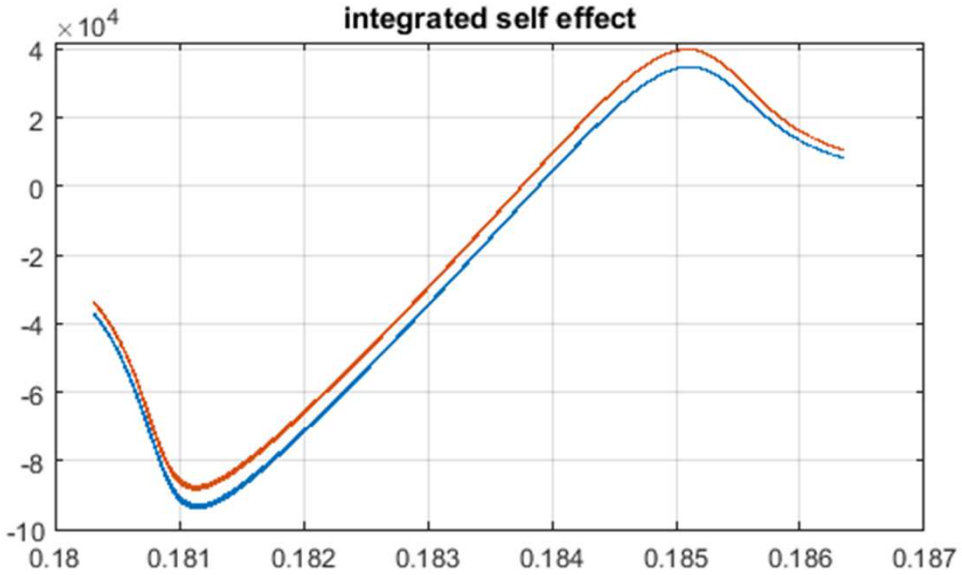

current / A
30
20
10
0
0.18 0.181 0.182 0.183 0.184 0.185 0.186 0.187

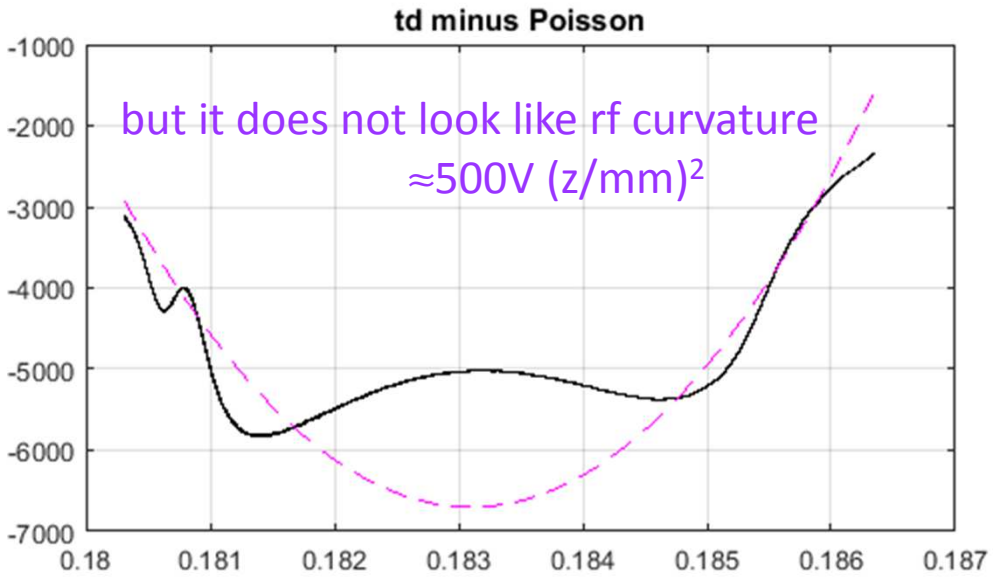

gam_ref=10.1761
Poisson approach
0.04
0.02
0
0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18


longitudinal momentum
×10^6
5.4
5.2
5
4.8
0.18 0.181 0.182 0.183 0.184 0.185 0.186 0.187


effective Ez
×10^5
5 x (td – Poisson)
1
0.5
0
-0.5
-1
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2

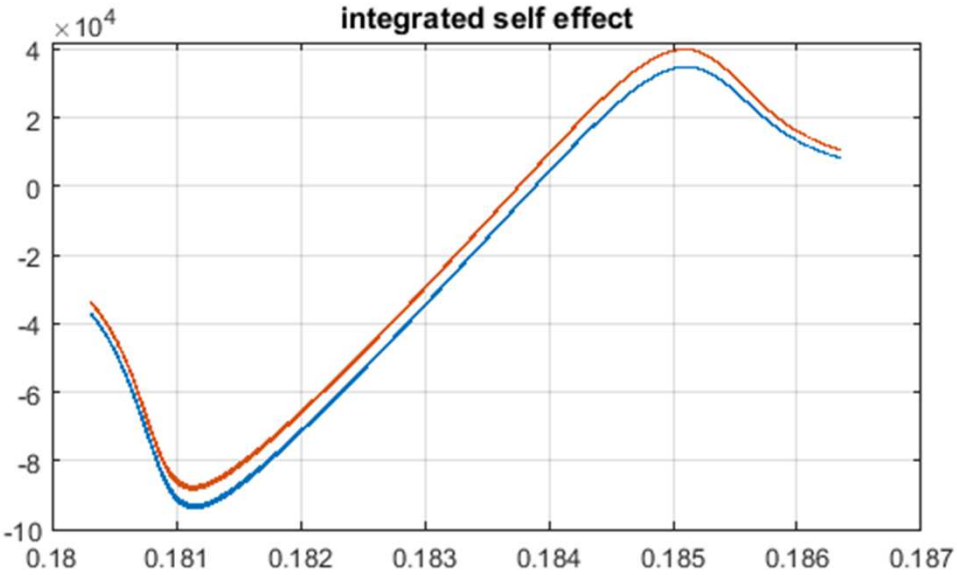

integrated self effect
×10^4
5
0
-5
-10
0.18 0.181 0.182 0.183 0.184 0.185 0.186 0.187

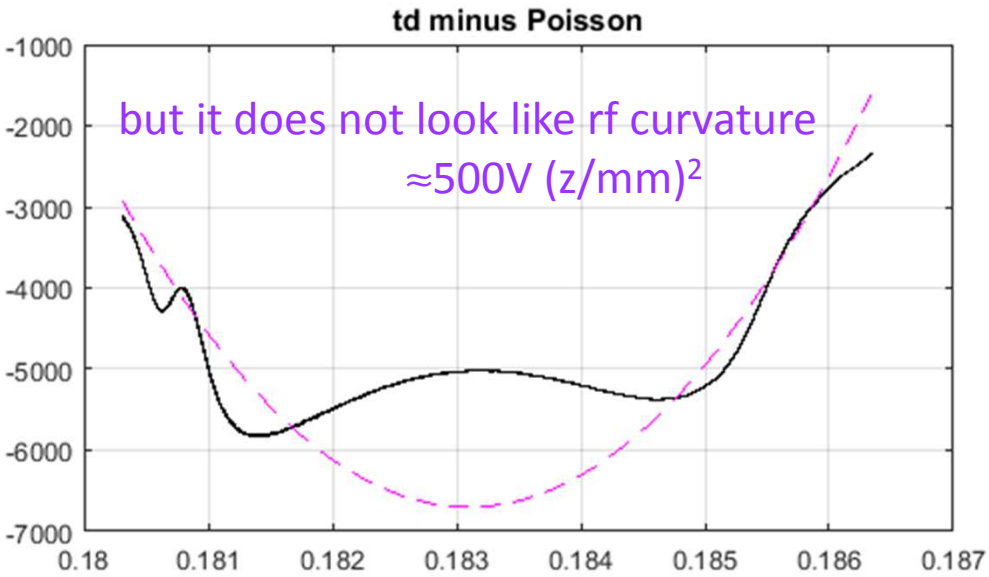




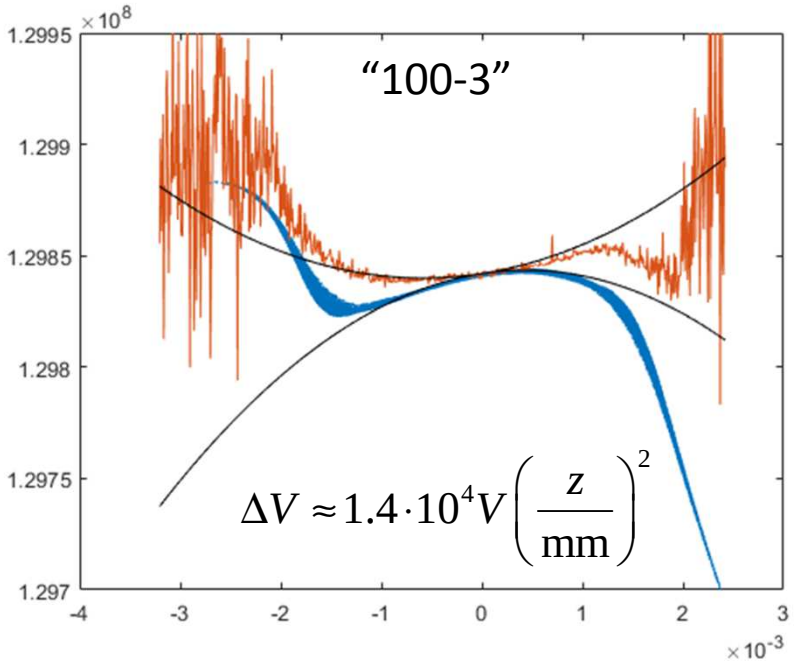
but it does not look like rf curvature

≈500V (z/mm)^2



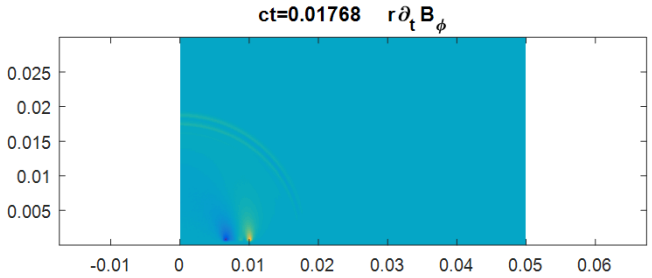


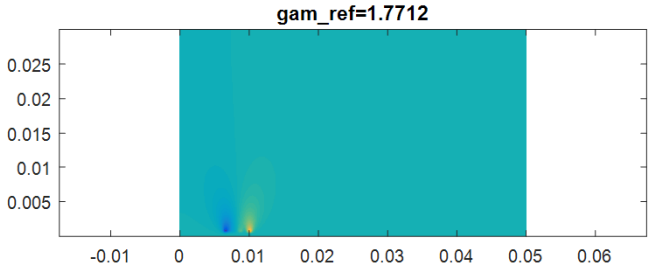
but it does not look like rf curvature
≈500V (z/mm)²

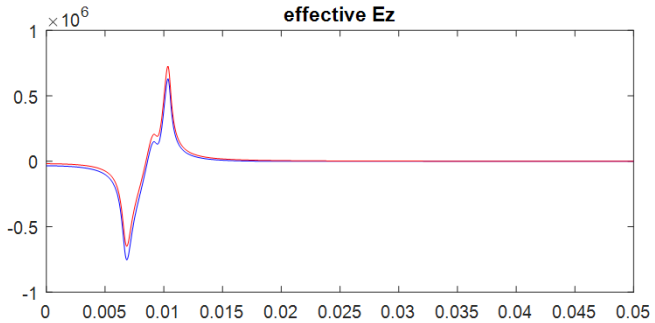


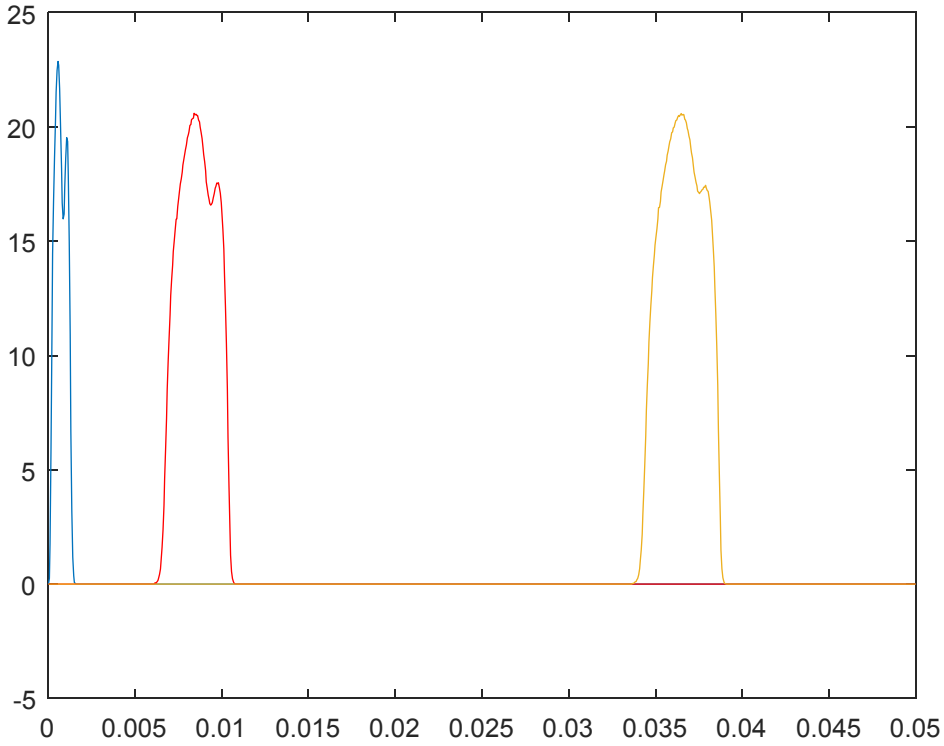
… is too weak

simulation for shape 3:

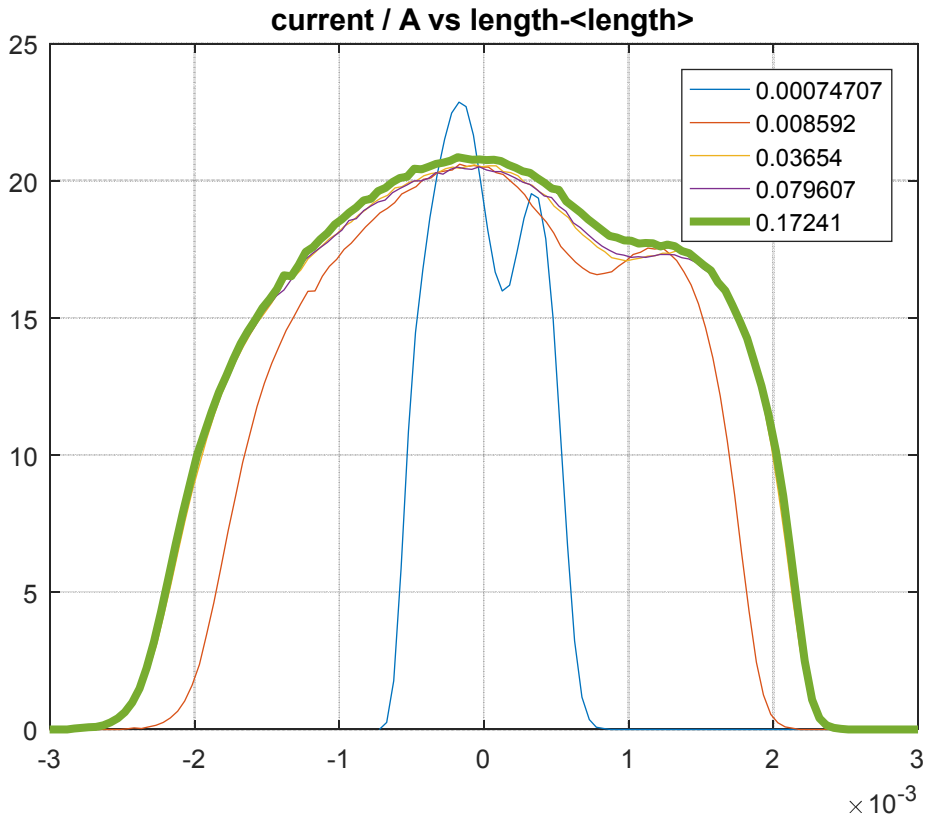








the fast structure is suppressed as before



finally

measurements after TDSA:

screen pictures → averaged slice energy
calibration of time axis: “3 psec assumption”
calibration of energy axis: fit to simulation (250pC, AH off)
→ deviation from theoretical dispersion by factor 1.7

simulations: gun with Astra or Krack3 (usually without wakes)
from ~3.2m with Xtrack , discrete wakes from impedance date base
Maxwell time-domain simulations → acceleration wake (weak)
reflections from boundary
→ “gun cavity wake”

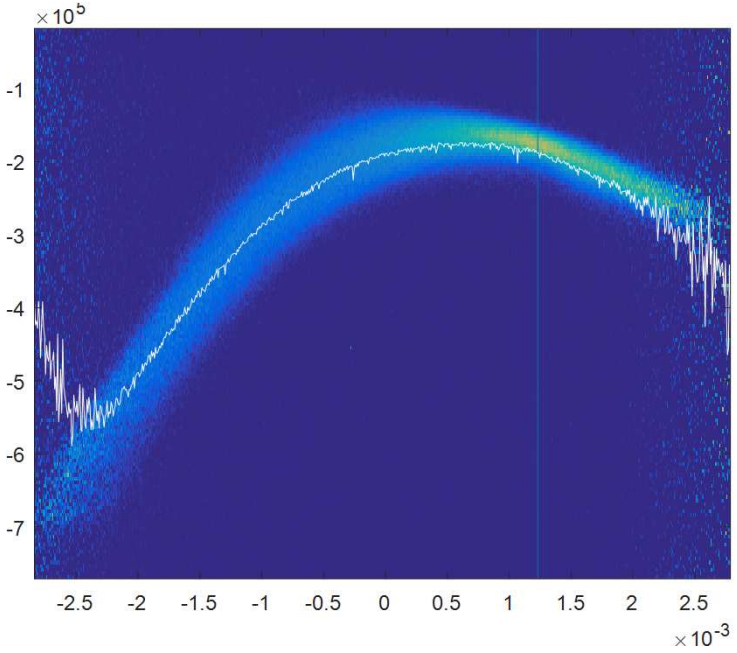
impedance data base incomplete: no elements from 0 to 3 m

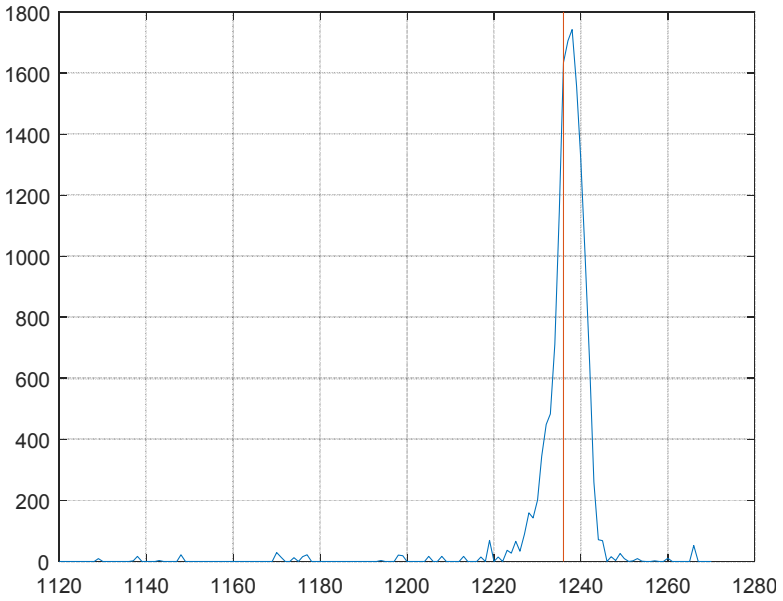
not understood: bunch shape
curvature of phase space

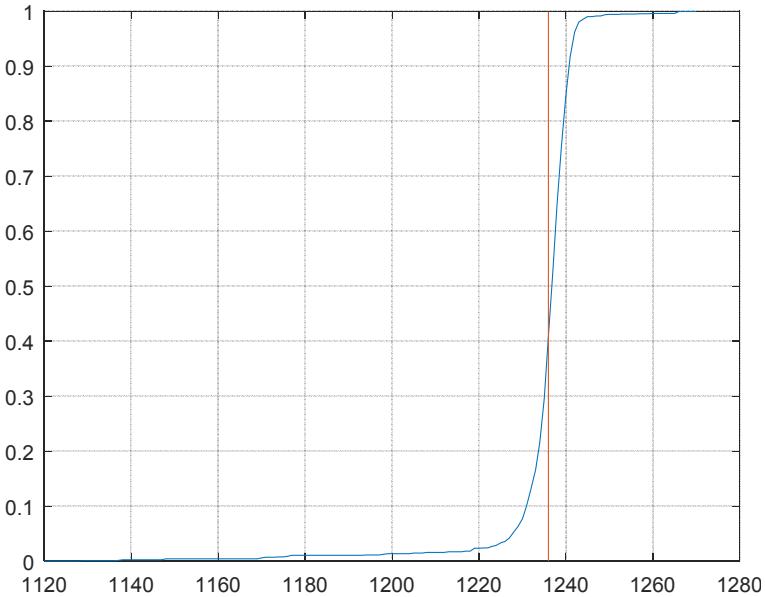
unknown cathode effects
strange longitudinal laser profile
additional wakes (strong resistive)

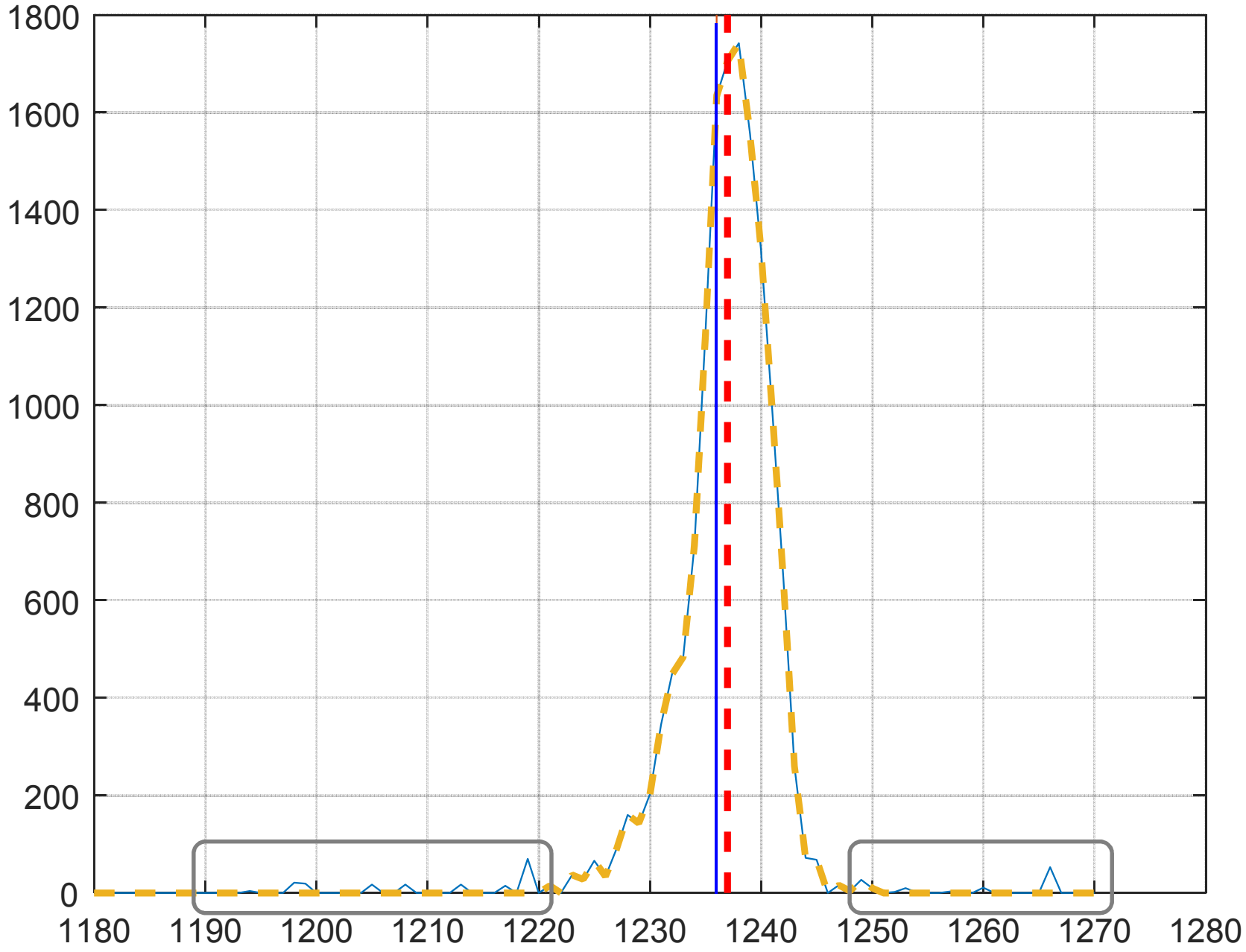
calibration error
calculation of energy per slice
rf error
unknown wake (strong inductive)

calculation of averaged slice energy:

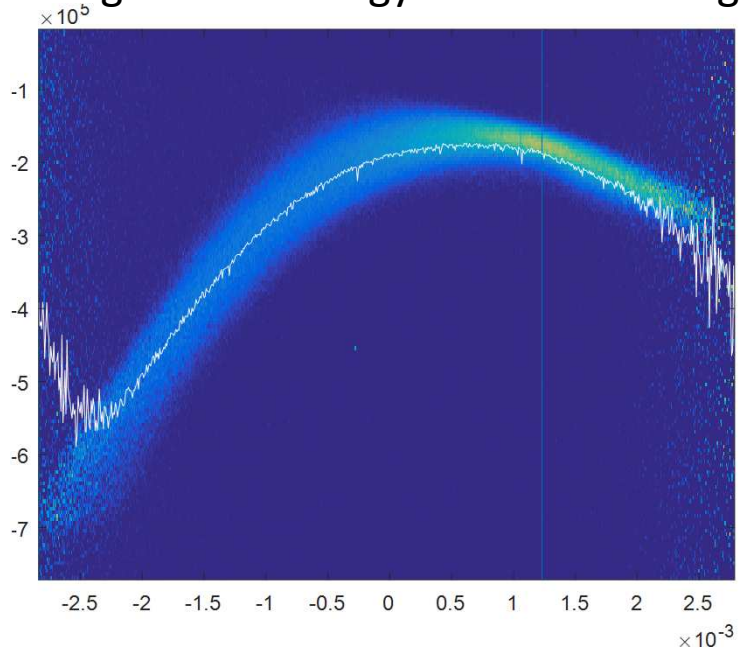


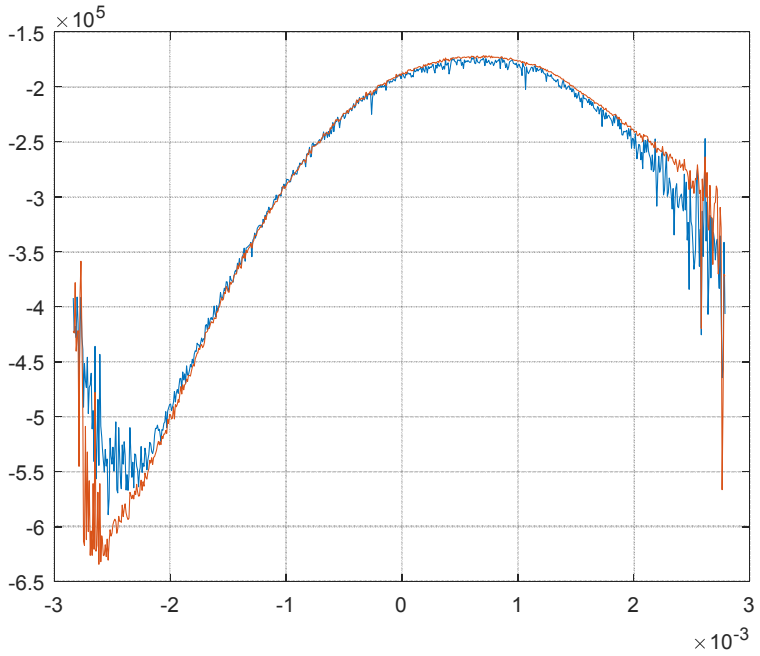


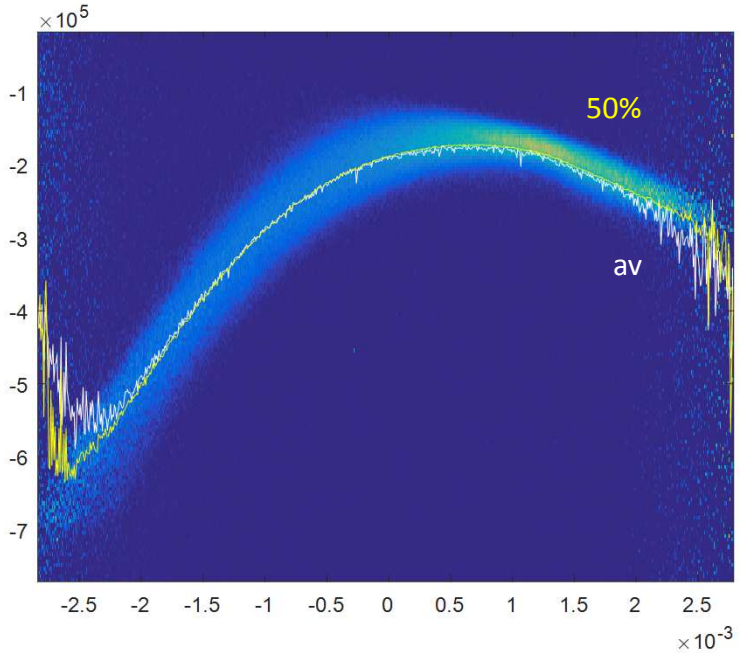


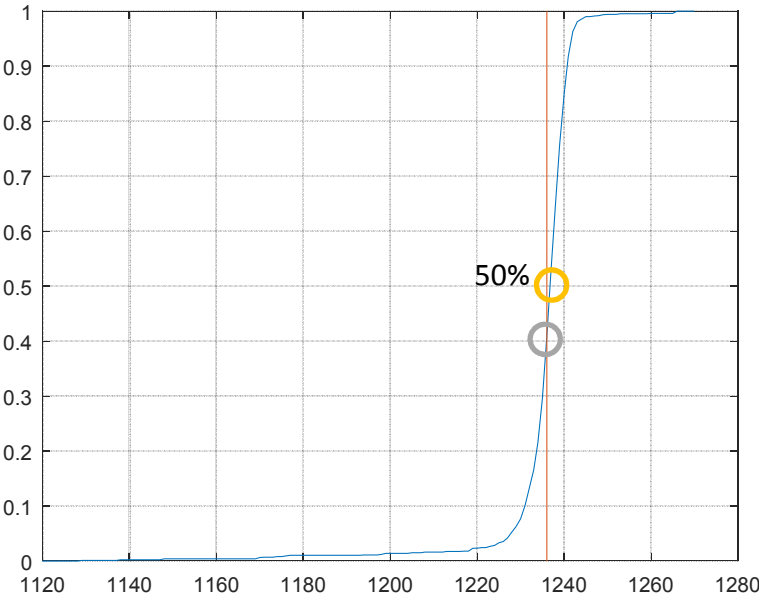

1800
1600
1400
1200
1000
800
600
400
200
0
1180
1190
1200
1210
1220
1230
1240
1250
1260
1270
1280

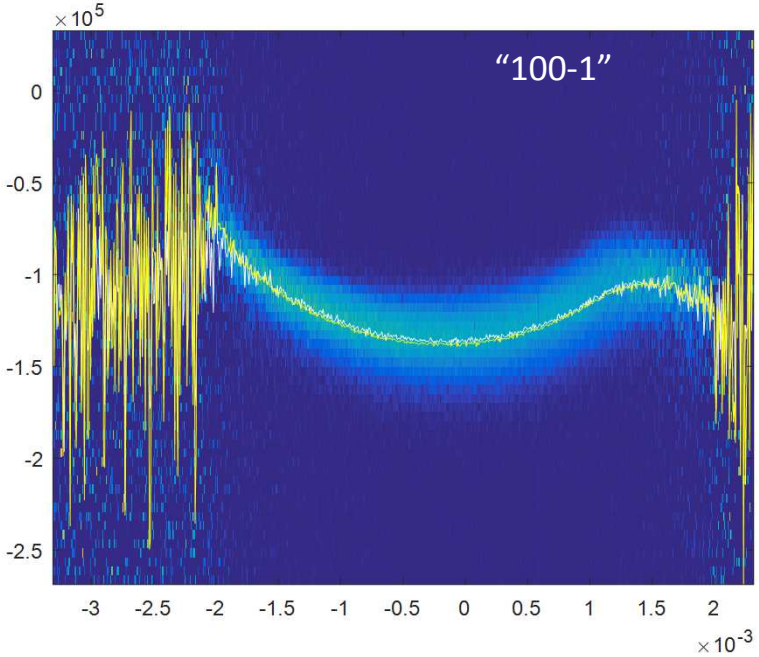
averaged slice energy → middle energy

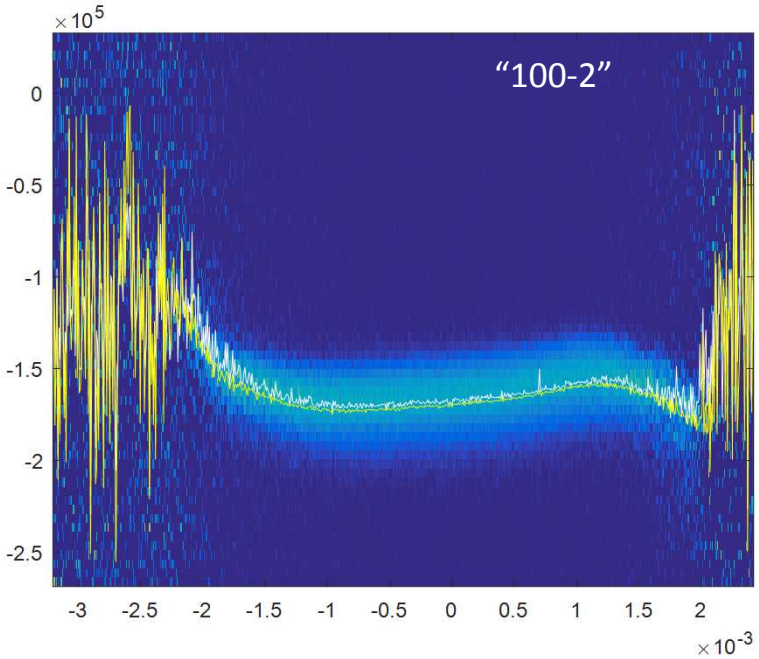


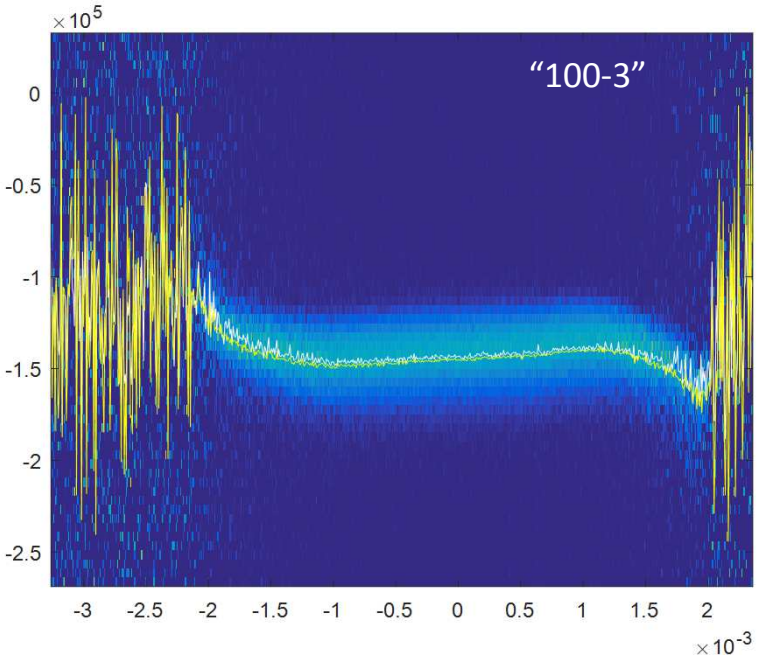







×10^5
0
-0.5
-1
-1.5
-2
-2.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
×10^-3
“100-1”


×10^5
0
-0.5
-1
-1.5
-2
-2.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
×10^-3
“100-2”


×10^5
0
-0.5
-1
-1.5
-2
-2.5
-3
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
×10^-3
“100-3”