Start2End Simulations for Micro–Bunching Experiments at FLASH

“reloaded” :-(

19.11.2007

Mathias Vogt (MPY)

- **Two Slides of Theory. . .**
- **A Revised Set Up (thanx to N.G. & V.B.)**
- **Scans & Evaluation**
- **A New Candidate . . .**
- **Double–Humps**

A Simple Purely Longitudinal Model of Micro–Bunching (1)

- long. phasespace $\mathbb{R}^2$: $v := (z, p_z)$
- ps–density $\Psi(z, p_z)$, $\int \Psi \, d^2v = 1$
- (linear!) projection operator $\hat{Q}$:
  $\Psi \mapsto \rho := \hat{Q}\Psi = \int \Psi \, dp_z$
- ultra–relativistic $\Rightarrow \rho(z)$ **=const**,
  except in **BunchCompressor**
- cavity, space charge (any long. wake) :
  KICKS
- all kicks commute $\Leftrightarrow$ cav+SC :
  $(z, p_z) \mapsto (z, p_z + \mathrm{cav}(z) + (g_{sc} * \rho)(z))$
  $g_{sc} * \rho := \int g_{sc}(z, z')\rho(z')dz'$
- collective kick : $K[\rho] = Id + \Delta[\rho]$:
  $(z, p_z) \mapsto (z, p_z + (g * \rho)(z))$
  Property: $K[\rho_1 + \rho_2] = K[\rho_1] + \Delta[\rho_2]$
  with $\boxed{K^{-1}[\rho_1 + \rho_2] = K^{-1}[\rho_1] - \Delta[\rho_2]}$

- BunchCompressor :
  (generalized) **DRIFT** with R_{56}/p_0 as "length"
- FEL w/o undulator := Cascade :
  (**ACC**$\rightarrow$**BC**$\rightarrow$)^n $\Rightarrow$
  $\mathbf{D_n} \circ \mathbf{K_n}[\rho_{\mathbf{n-1}}] \circ \ldots \mathbf{D_1} \circ \mathbf{K_1}[\rho_{\mathbf{0}}]$
  (FLASH : $n = 2$)
- $\Leftarrow$ all the former maps are measure preserving !!!
  $\Rightarrow \boxed{\Psi_k = \Psi_{k-1} \circ K_k^{-1}[\hat{Q}\Psi_{k-1}] \circ D_k^{-1}}$
- $\Leftarrow$ **linear** operator $\mathcal{M}[\rho]$:
  $\Psi \mapsto \mathcal{M}[\rho]\Psi := \Psi \circ K^{-1}[\rho] \circ D^{-1}$
  $\boxed{\Psi_k = \mathcal{M}[\hat{Q}\Psi_{k-1}]\Psi_{k-1}}$
  time–discrete Vlasov system,
  nonlinear integro-difference-eqn.

A Simple Purely Longitudinal Model of Micro–Bunching (2)

- Now assume we already now

$\boxed{\Psi_1 := \mathcal{M}[\hat{Q}\Psi_0]\,\Psi_0}$ (Ψ_0 suff. smooth)

- ...and add a tiny modulation :

$\Psi_0 \longrightarrow \Psi_0 + \epsilon\Phi_0,\ \epsilon \ll 1,\ \int \Phi_0\, d^2v = 0$

$$\Rightarrow \boxed{\tilde{\Psi}_1 := \mathcal{M}[\hat{Q}(\Psi_0 + \epsilon\Phi_0)]\,(\Psi_0 + \epsilon\Phi_0)} \qquad (*)$$

$\Leftarrow$ **NONLINEAR EVOLUTION!**

$\Leftarrow$ can lead to increasing amplitudes for certain wavelengths $\Rightarrow$**GAIN** can be $\gg 1$ $\Rightarrow$ micro–bunching

Gain Functions:

- evolution eqn. $(*)$ can in principle be **completely** studied numerically using so–called 2-D Perron–Frobenius codes (for PF see e.g. papers by Bassi, Ellison, Sobol, Venturini, Vogt, Warnock)

(Gain Functions ctd.)

- **M. Dohlus**: quasi analytic model of modulation:

$z \mapsto z/\Pi_c + \Re\{a(\delta p_z)e^{ikz}\} + c\delta p_z$

$p_z \mapsto p_0 + \chi z/\Pi_c + \Re\{b(\delta p_z)e^{ikz}\} + d\delta p_z$

with iteration procedure for all parameters for transport through **Cavity**, **BunchCompressor** and **SpaceCharge**

$\Leftarrow$ **USED IN THIS STUDY !!!**

- to linear order in ϵ, $(*)$ gives (for smooth Ψ_0 and gain$\times\epsilon \ll 1$)

$\tilde{\Psi}_1 = \Psi_1 + \epsilon\Phi_1 + O(\epsilon^2)$ with

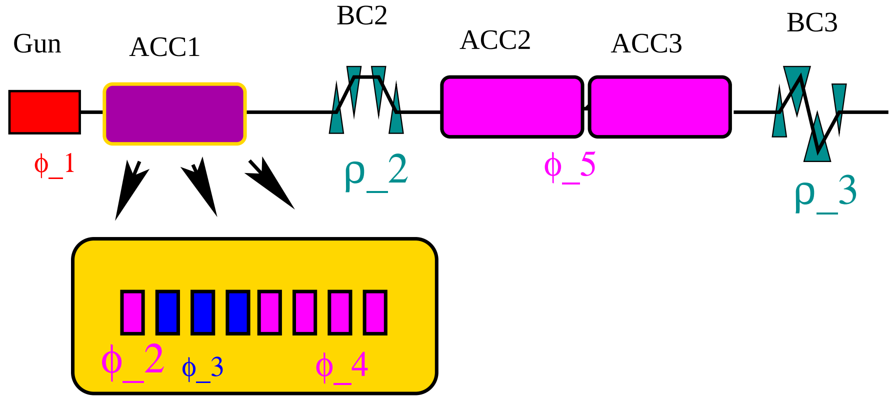
$\Phi_1 = \mathcal{M}[\hat{Q}\Psi_0]\Phi_0 - (\nabla\Psi_0 \cdot \Delta[\hat{Q}\Phi_0]) \circ D^{-1}$

spectral analysis seems at least possible.

- treatment of short–wavelength modulations is hardly possible in 6-D collective simulations. However, indications for "micro–bunching" effects exist in S2E simulations

Revised Set Up

S2E–range



- BC2 : ρ_2= $1.76, 1.82$m
  (lattice: $\rho_2 = 1.62$m)
  $R_{56}^{(2)} = -0.15, -0.14$m
  (lattice: -0.25m)
- BC3 : ρ_3= 5.7m - 7.7m
  (lattice: $\rho_3 = 7.5$m)
  $R_{56}^{(3)} = -0.09$m - -0.05m
  (lattice: -0.05m)

ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5
(gun) $-0.55°$	ACC1.1 $-90°$ - $-105°$ VB!!	ACC1.2-4 $0°$ accel.	ACC1.5-8 $-4°, -5°$ corr. chirp	ACC2&3 $0°$ - $-15°$ extra chirp
fixed	DONE $\Rightarrow -96°$	fixed	scan	scan

with long. Gaussian bunch from cathode

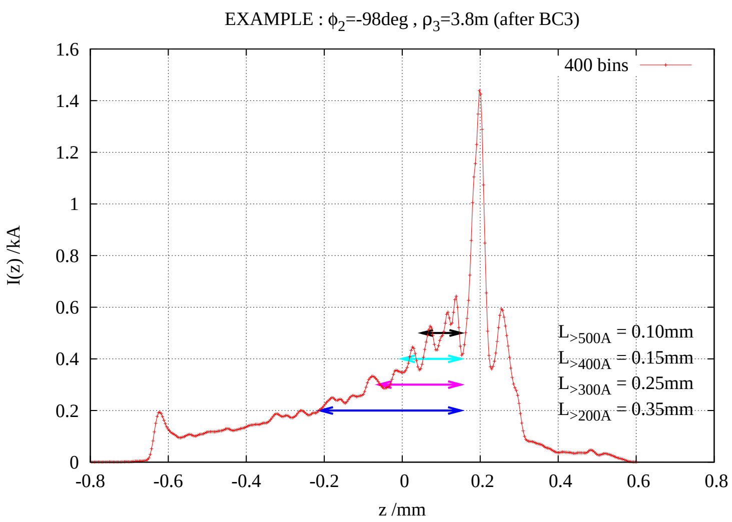
Scanning ϕ_4, ϕ_5, ρ_2 and ρ_3

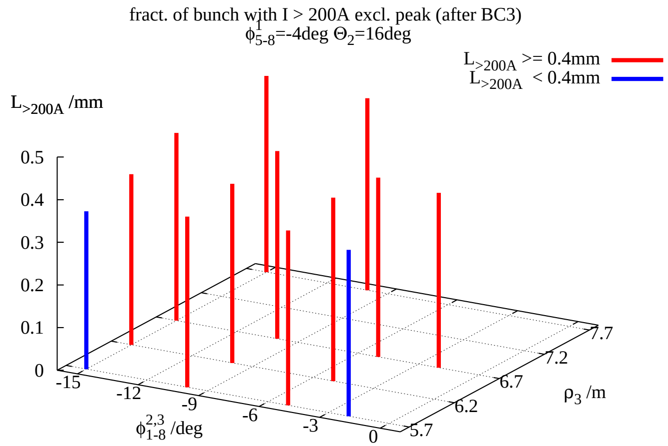
Goal of S2E Scans :

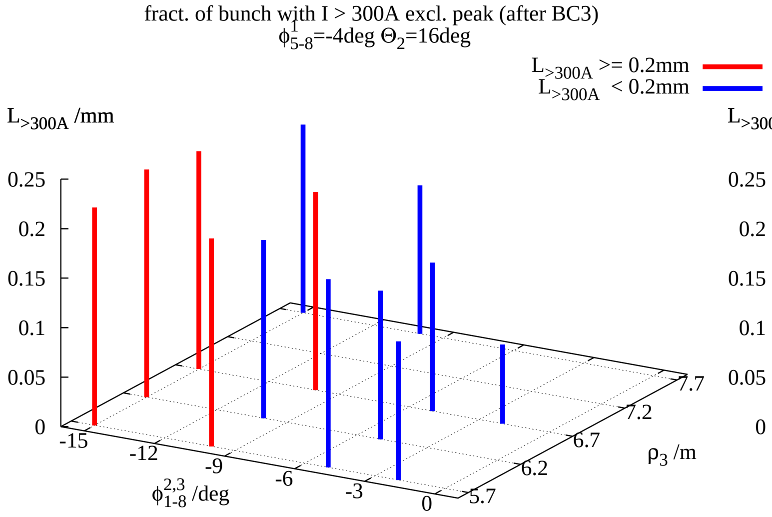
- $I(z)$ moderately large over sufficiently large length
- ...separated from spike !
- transv. ps: not first priority
- check μ–bunching gain (model & spread–sheet by M.Dohlus)

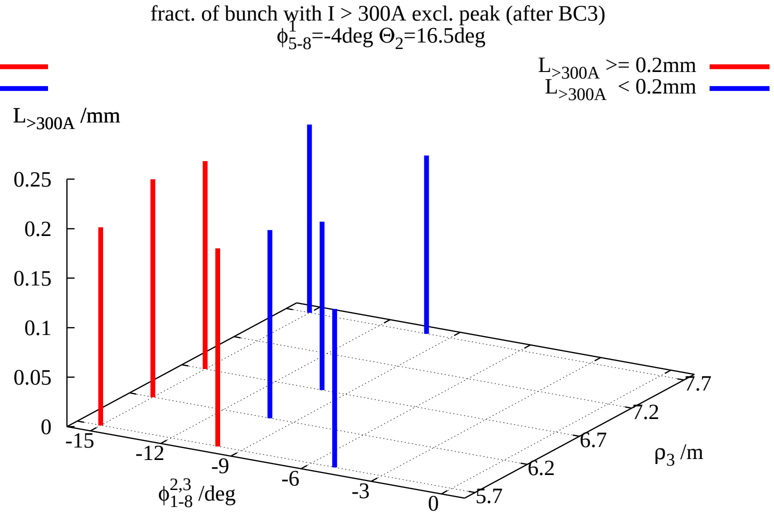
Evaluation :

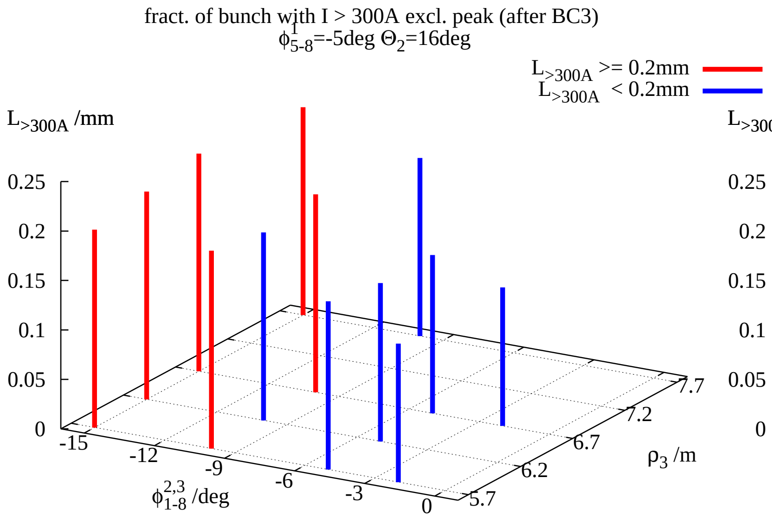
- scan of ϕ_2 (see talk from 24.09.07) **not** affected by revised setup $\Rightarrow$ $\boxed{\phi_2 = -96^\circ}$
- for different choices of ϕ_4 and ρ_2
- look at $\boxed{\text{length scales supporting various currents}}$ as function of ϕ_5 and ρ_3






fract. of bunch with I > 300A excl. peak (after BC3)
ϕ¹₅₋₈=-4deg Θ₂=16deg
L>300A >= 0.2mm
L>300A < 0.2mm
L>300A /mm
0.25
0.2
0.15
0.1
0.05
0
-15
-12
-9
-6
-3
0
ϕ²,³₁₋₈ /deg
5.7
6.2
6.7
7.2
7.7
ρ3 /m


fract. of bunch with I > 300A excl. peak (after BC3)
ϕ¹₅₋₈=-4deg Θ₂=16.5deg
L>300A >= 0.2mm
L>300A < 0.2mm
L>300A /mm
0.25
0.2
0.15
0.1
0.05
0
-15
-12
-9
-6
-3
0
ϕ²,³₁₋₈ /deg
5.7
6.2
6.7
7.2
7.7
ρ3 /m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0.05
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-15
-12
-9
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-3
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5.7
6.2
6.7
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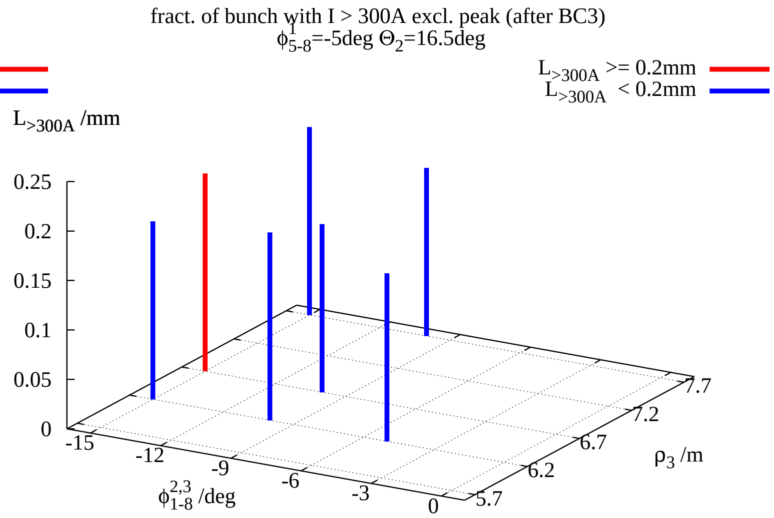
7.7
ρ3 /m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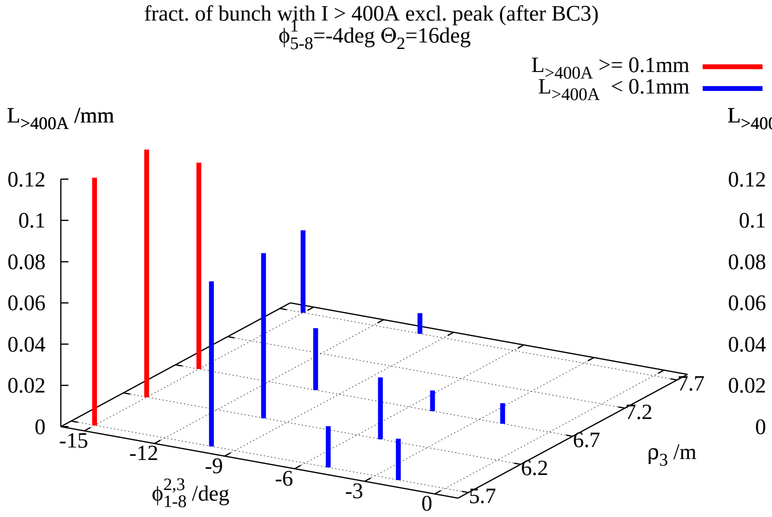
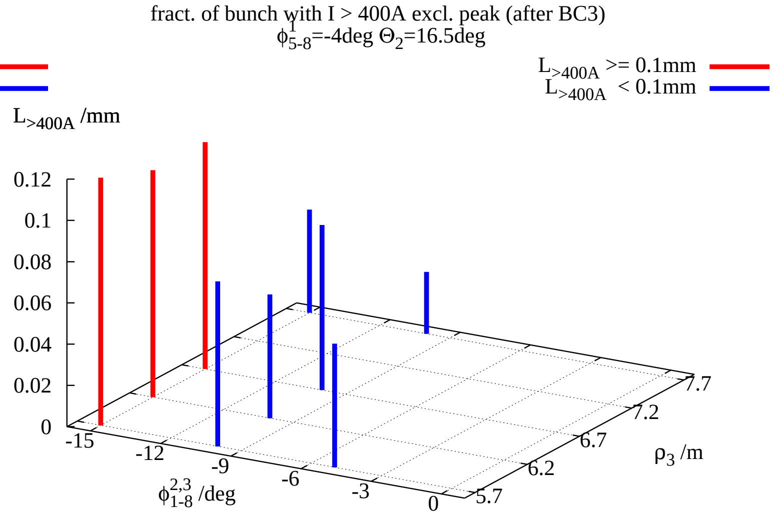
0.1
0.05
0
-15
-12
-9
-6
-3
0
ϕ²,³₁₋₈ /deg
5.7
6.2
6.7
7.2
7.7
ρ3 /m


fract. of bunch with I > 400A excl. peak (after BC3)
φ¹5-8=-4deg Θ2=16deg
L>400A >= 0.1mm
L>400A < 0.1mm
L>400A /mm
φ2,3 1-8 /deg
ρ3 /m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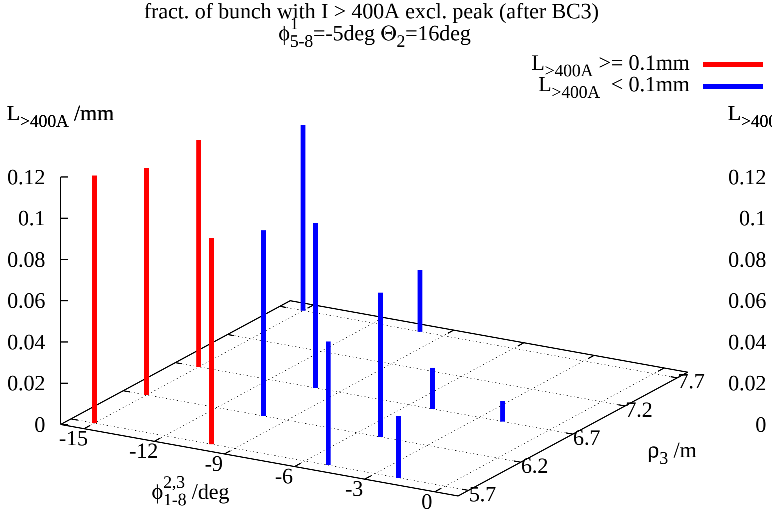
L>400A < 0.1mm
L>400A /mm
φ2,3 1-8 /deg
ρ3 /m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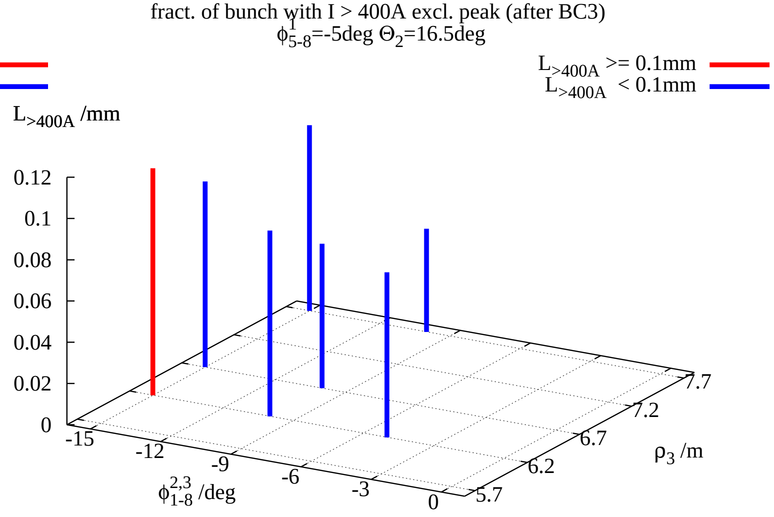
L>400A /mm
φ2,3 1-8 /deg
ρ3 /m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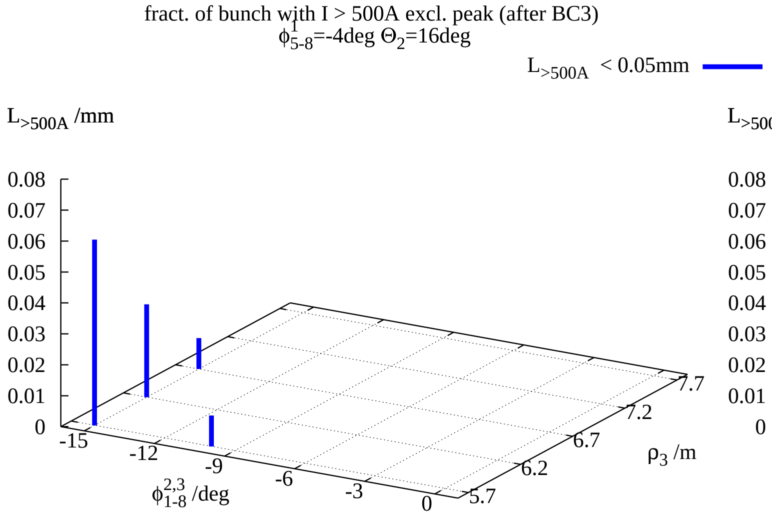
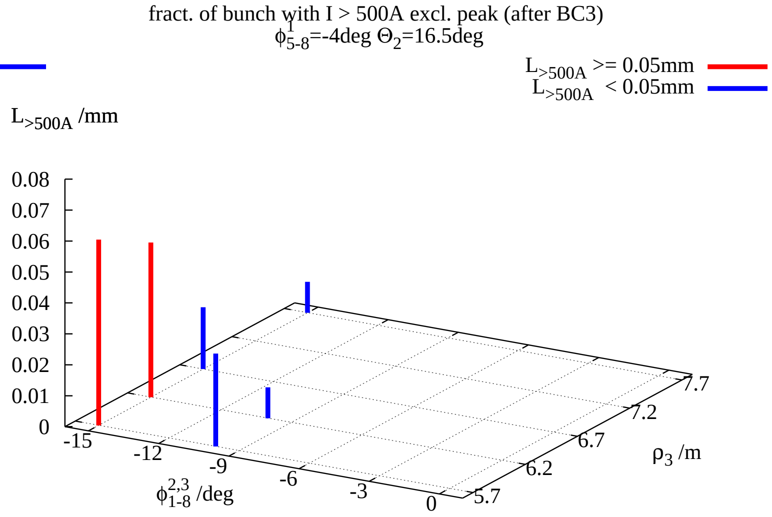
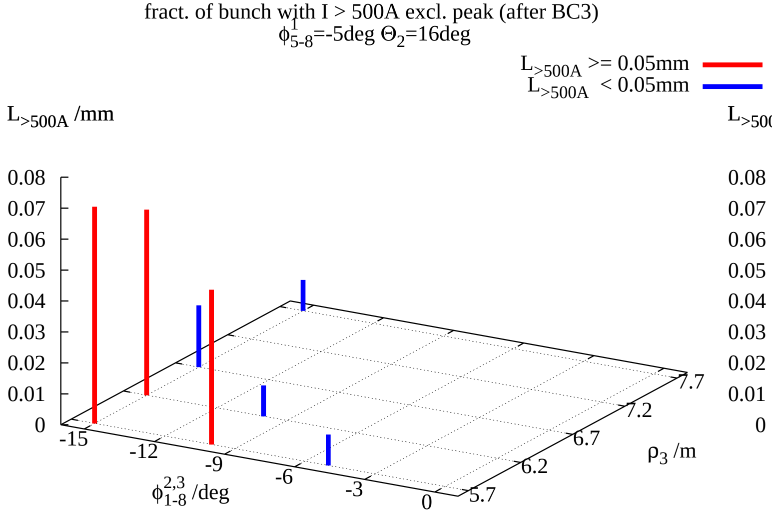
φ2,3 1-8 /deg
ρ3 /m


fract. of bunch with I > 500A excl. peak (after BC3)
$\phi^1_{5\text{-}8}$=-4deg Θ_2=16deg
$L_{>500A}$ < 0.05mm
$L_{>500A}$ /mm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m


fract. of bunch with I > 500A excl. peak (after BC3)
$\phi^1_{5\text{-}8}$=-4deg Θ_2=16.5deg
$L_{>500A}$ >= 0.05mm
$L_{>500A}$ < 0.05mm
$L_{>500A}$ /mm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m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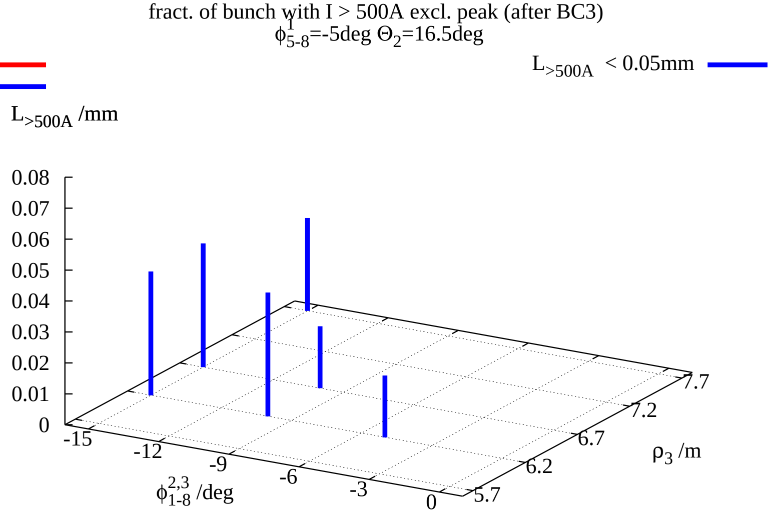
$L_{>500A}$ >= 0.05mm
$L_{>500A}$ < 0.05mm
$L_{>500A}$ /mm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m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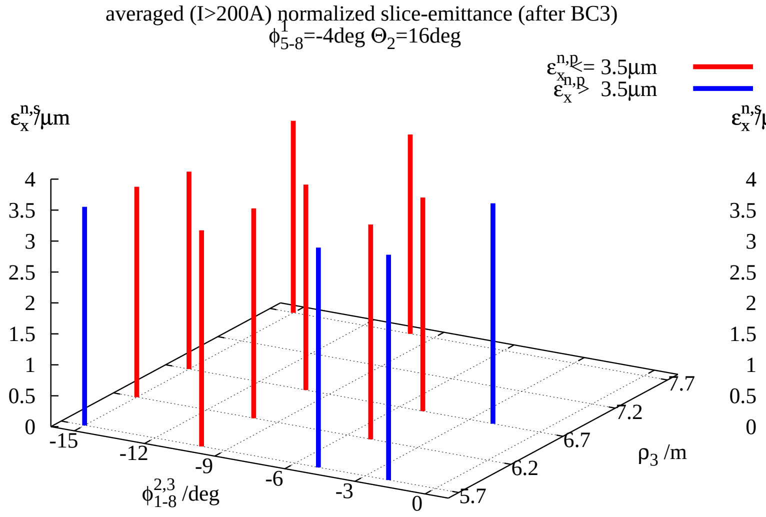
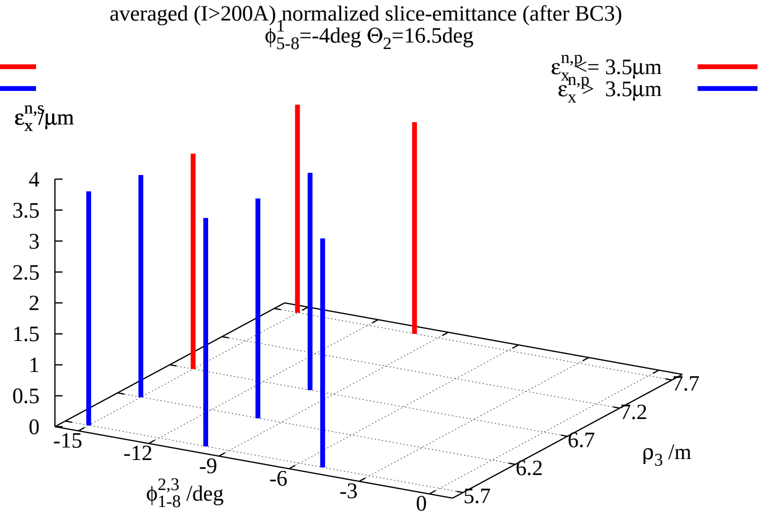
$L_{>500A}$ /mm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m


averaged (I>200A) normalized slice-emittance (after BC3)
$\phi^1_{5\text{-}8}$=-4deg Θ_2=16deg
$\epsilon_x^{n,p}$ <= 3.5μm
$\epsilon_x^{n,p}$ > 3.5μm
$\epsilon_x^{n,s}$ /μm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m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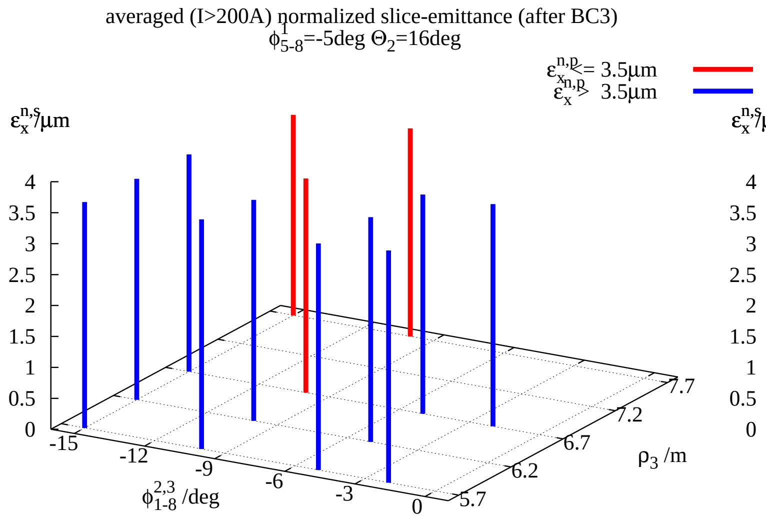
$\epsilon_x^{n,p}$ <= 3.5μm
$\epsilon_x^{n,p}$ > 3.5μm
$\epsilon_x^{n,s}$ /μm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m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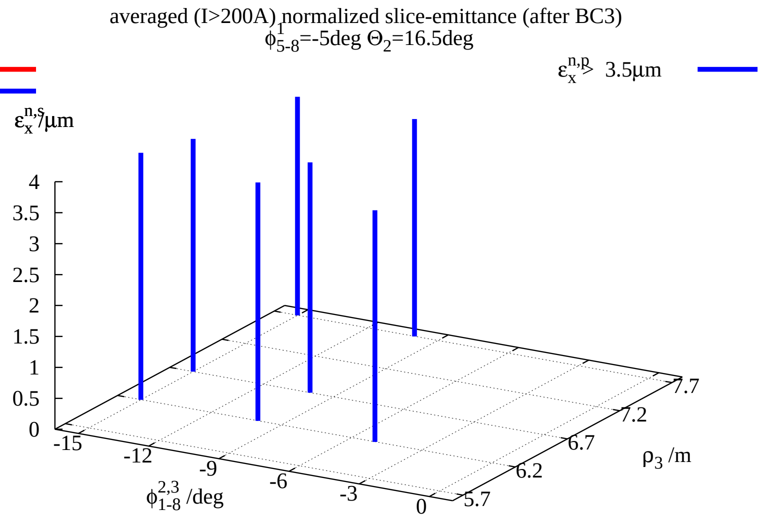
$\epsilon_x^{n,s}$ /μm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m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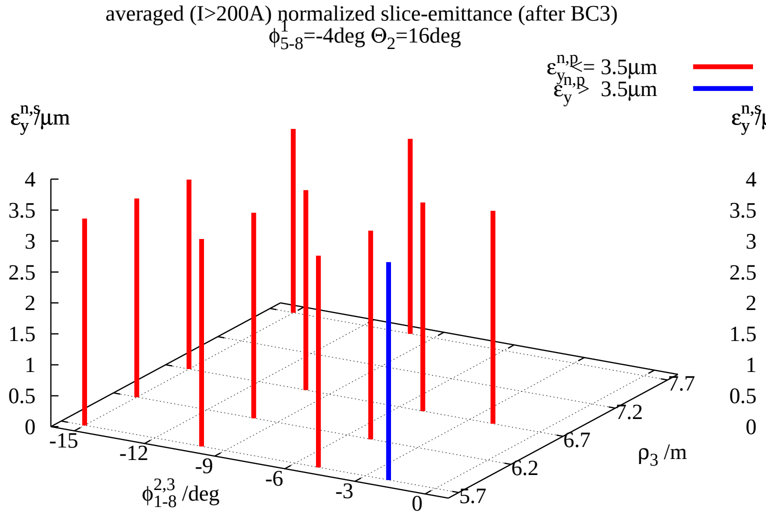
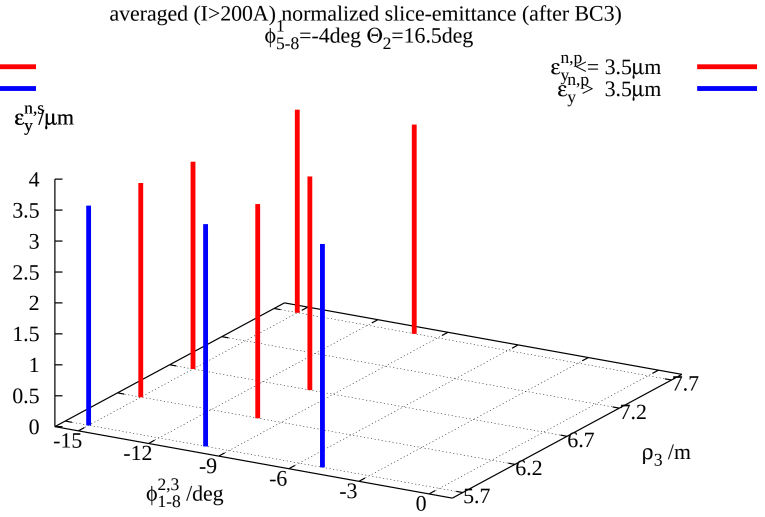
$\phi^1_{5\text{-}8}$=-5deg Θ_2=16.5deg
$\epsilon_x^{n,p}$ > 3.5μm
$\epsilon_x^{n,s}$ /μm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m


averaged (I>200A) normalized slice-emittance (after BC3)
$\phi^1_{5\text{-}8}$=-4deg Θ_2=16deg
$\epsilon^{n,p}_y$ <= 3.5µm
$\epsilon^{n,p}_y$ > 3.5µm
$\epsilon^{n,s}_y$ /µm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m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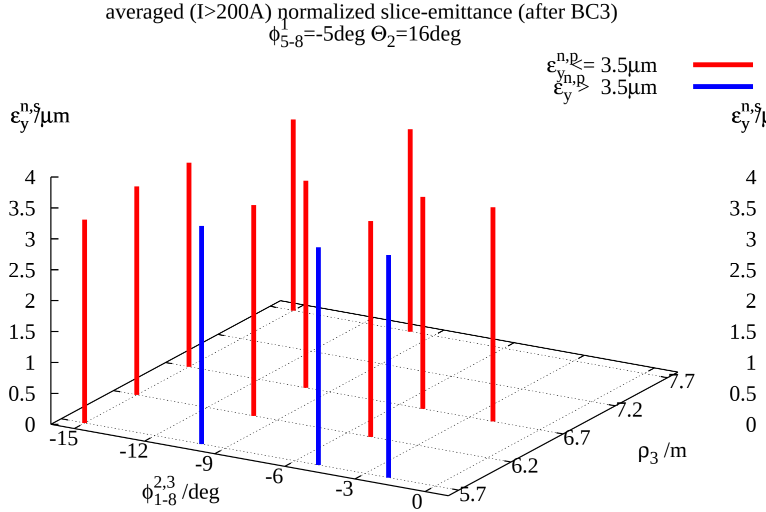
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m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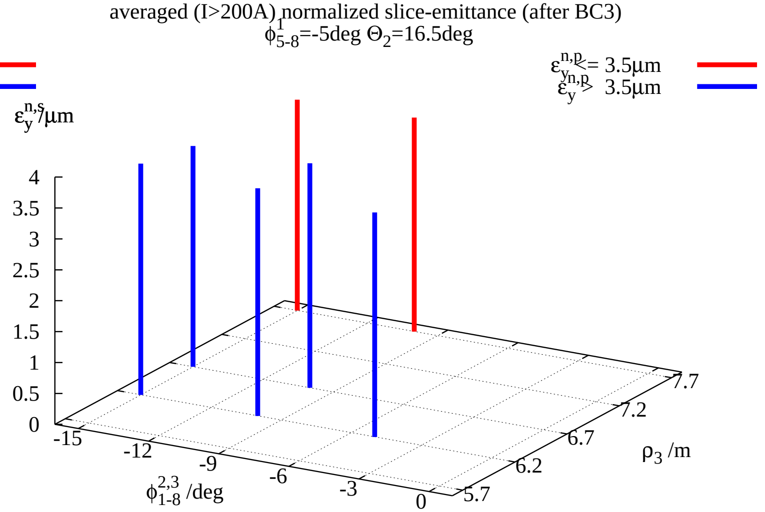
$\epsilon^{n,s}_y$ /µm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m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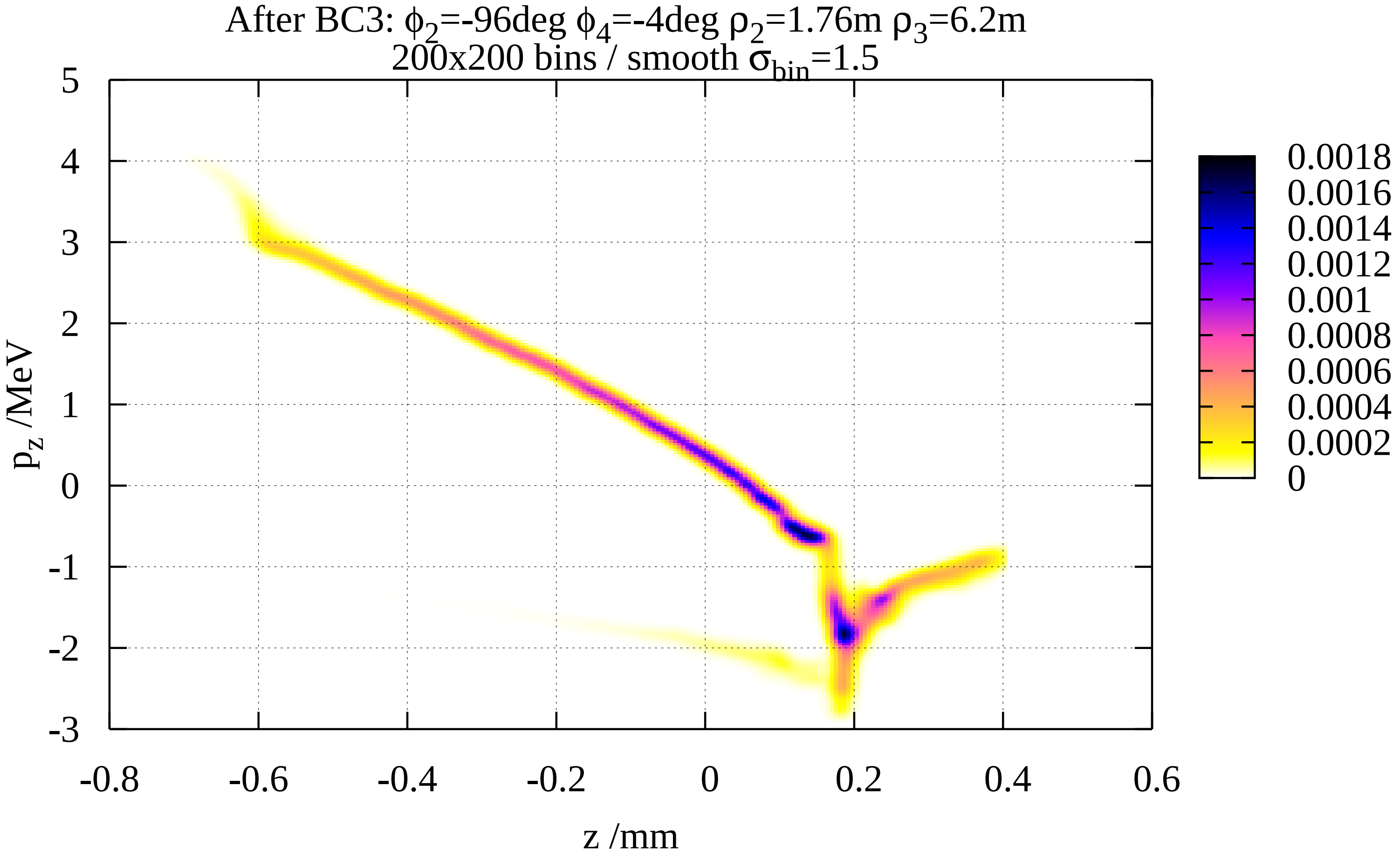
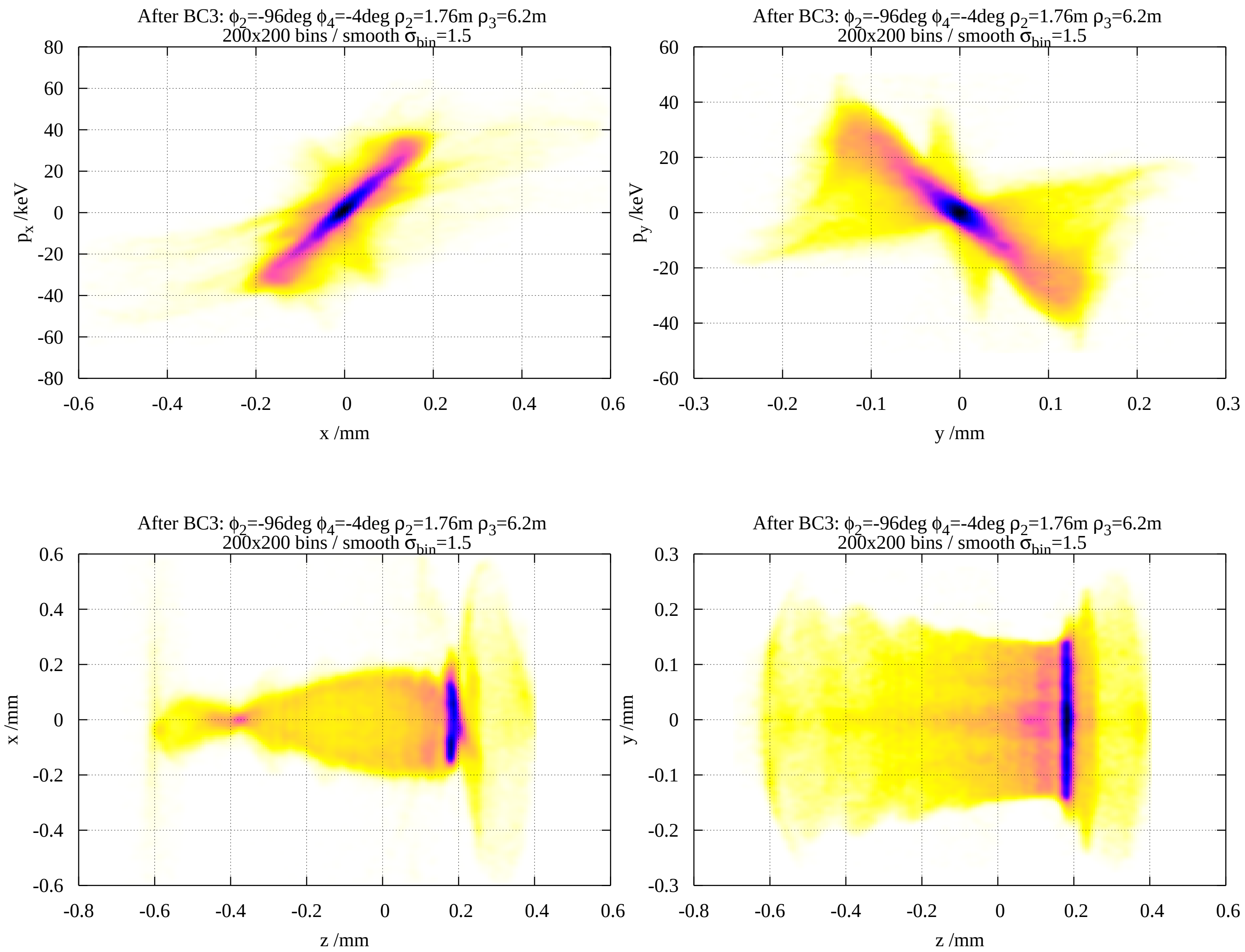
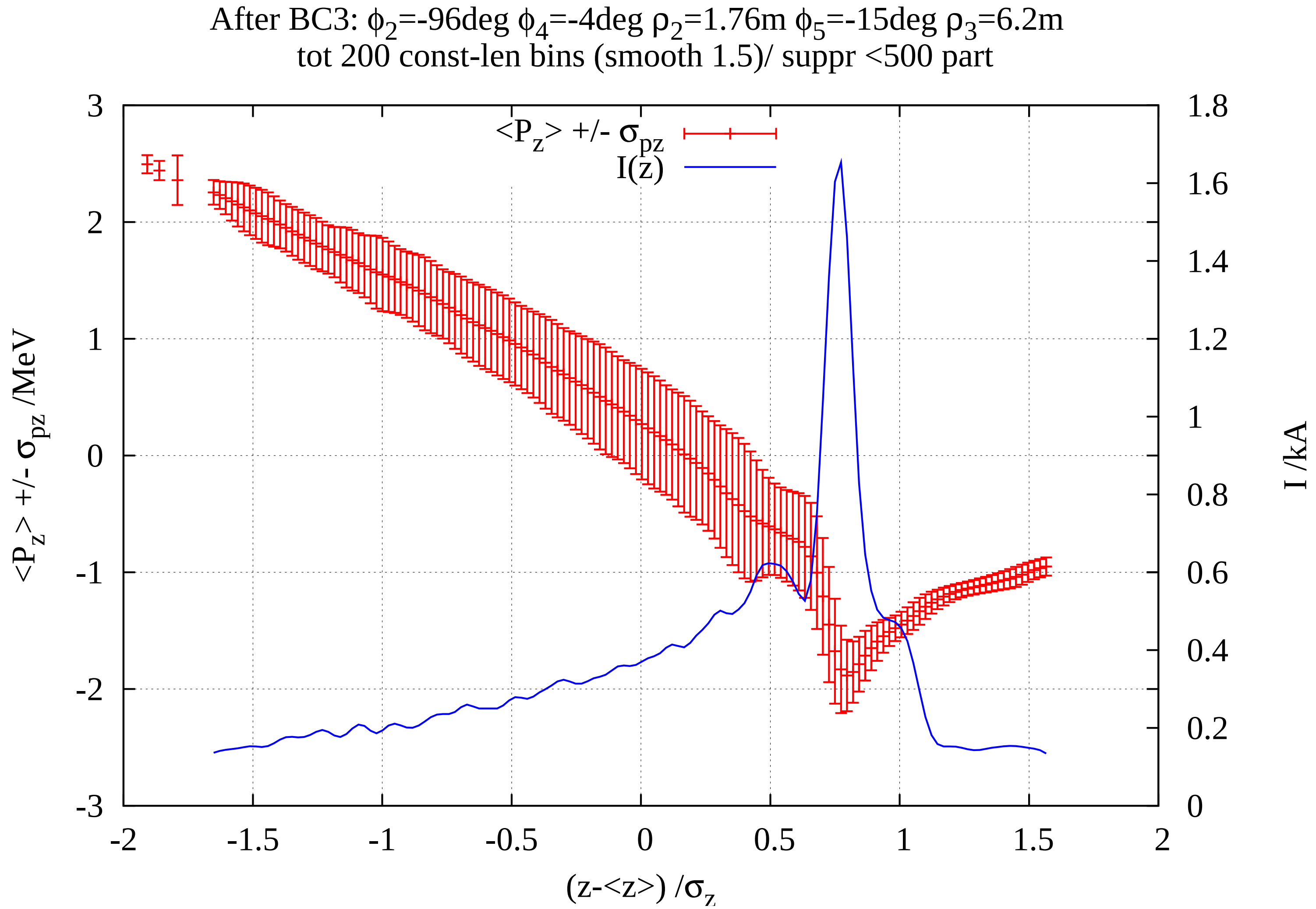
$\epsilon^{n,p}_y$ > 3.5µm
$\epsilon^{n,s}_y$ /µm
$\phi^{2,3}_{1\text{-}8}$ /deg
ρ_3 /m

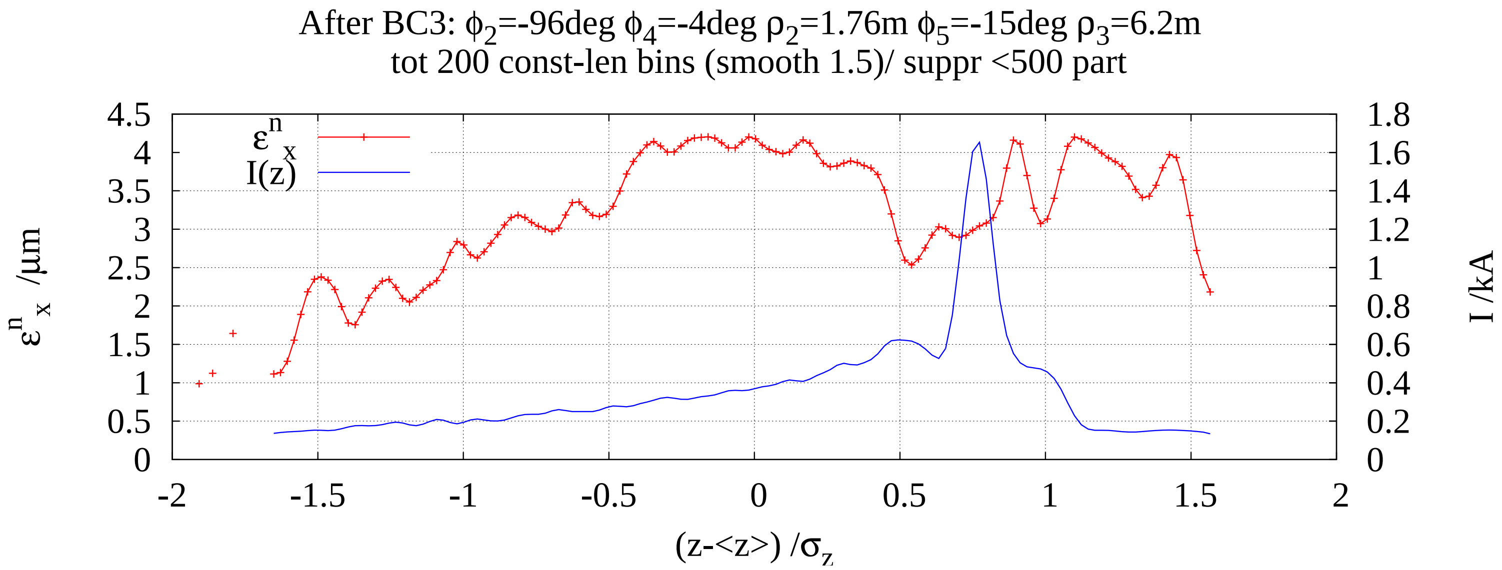
A New Candidate . . .

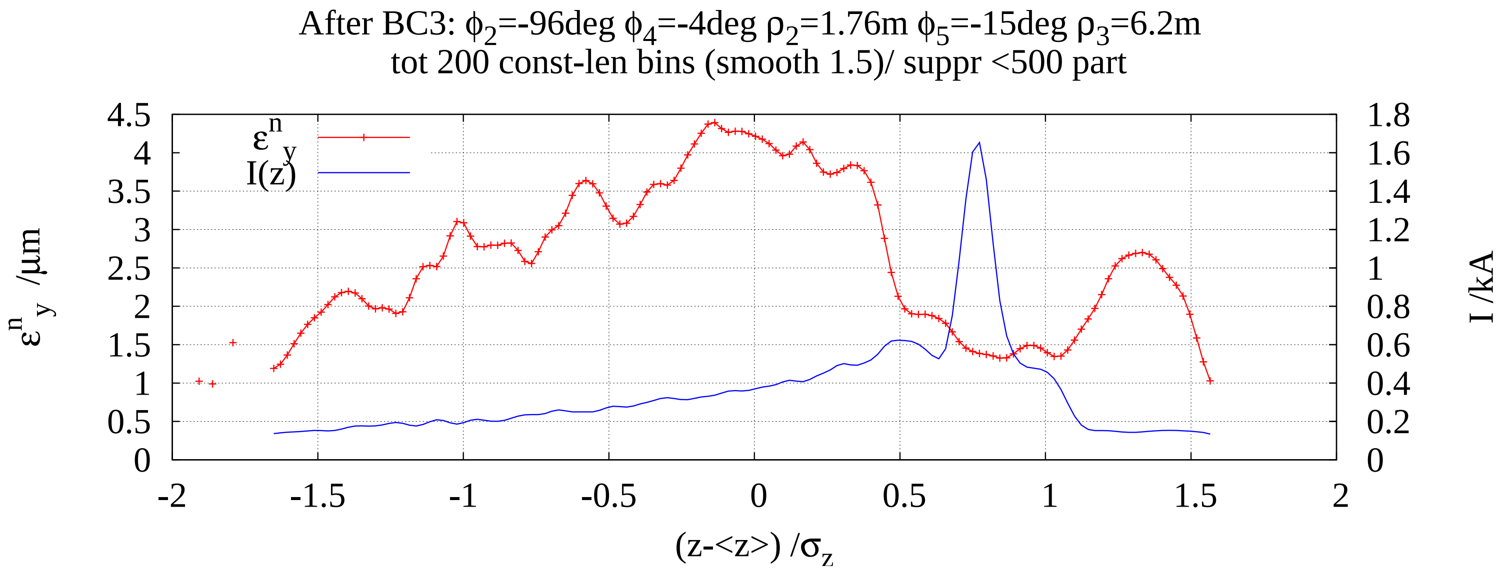


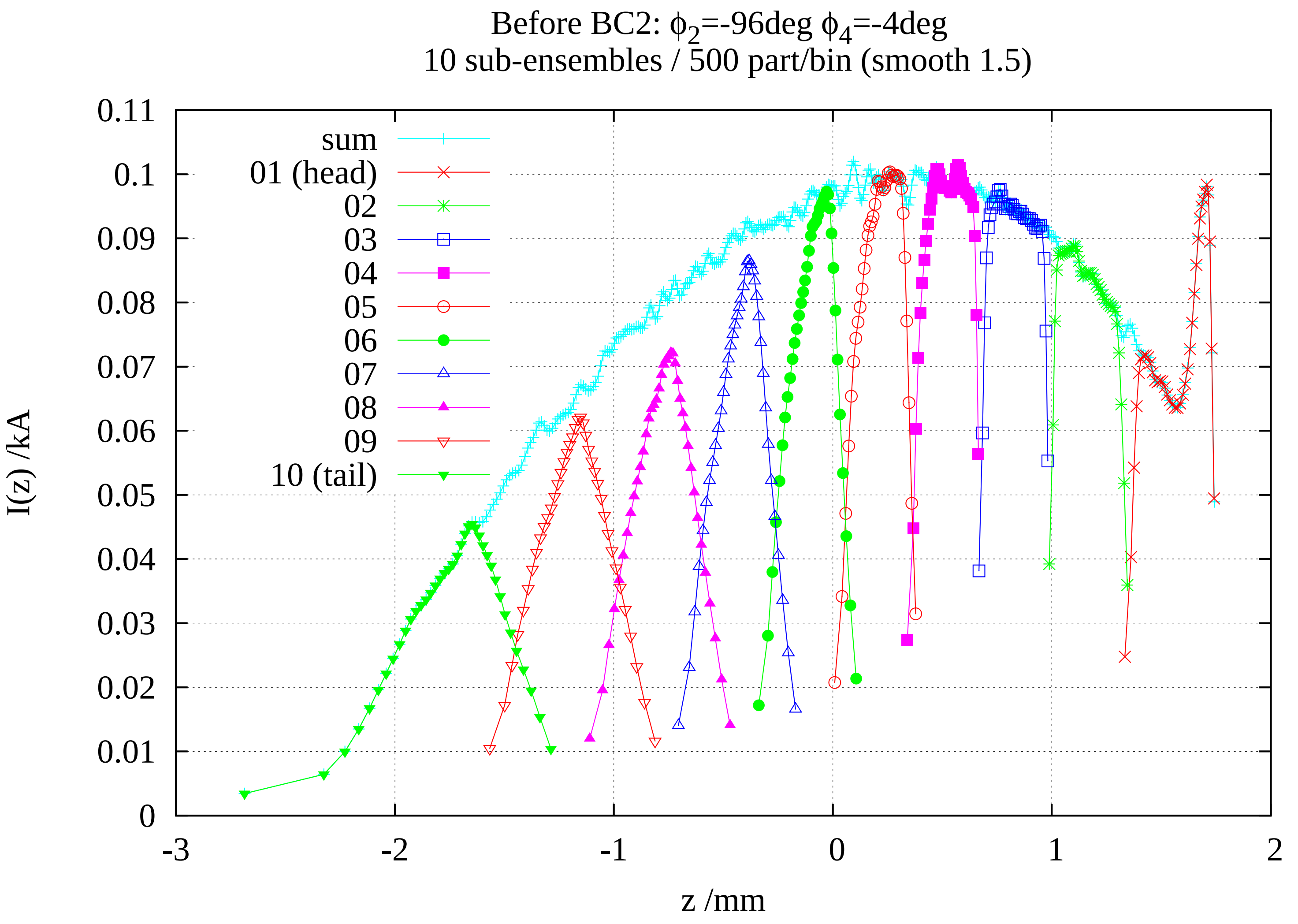

After BC3: ϕ2=-96deg ϕ4=-4deg ρ2=1.76m ρ3=6.2m
200x200 bins / smooth σbin=1.5
px /keV
x /mm
py /keV
y /mm
x /mm
z /mm
y /mm
z /mm

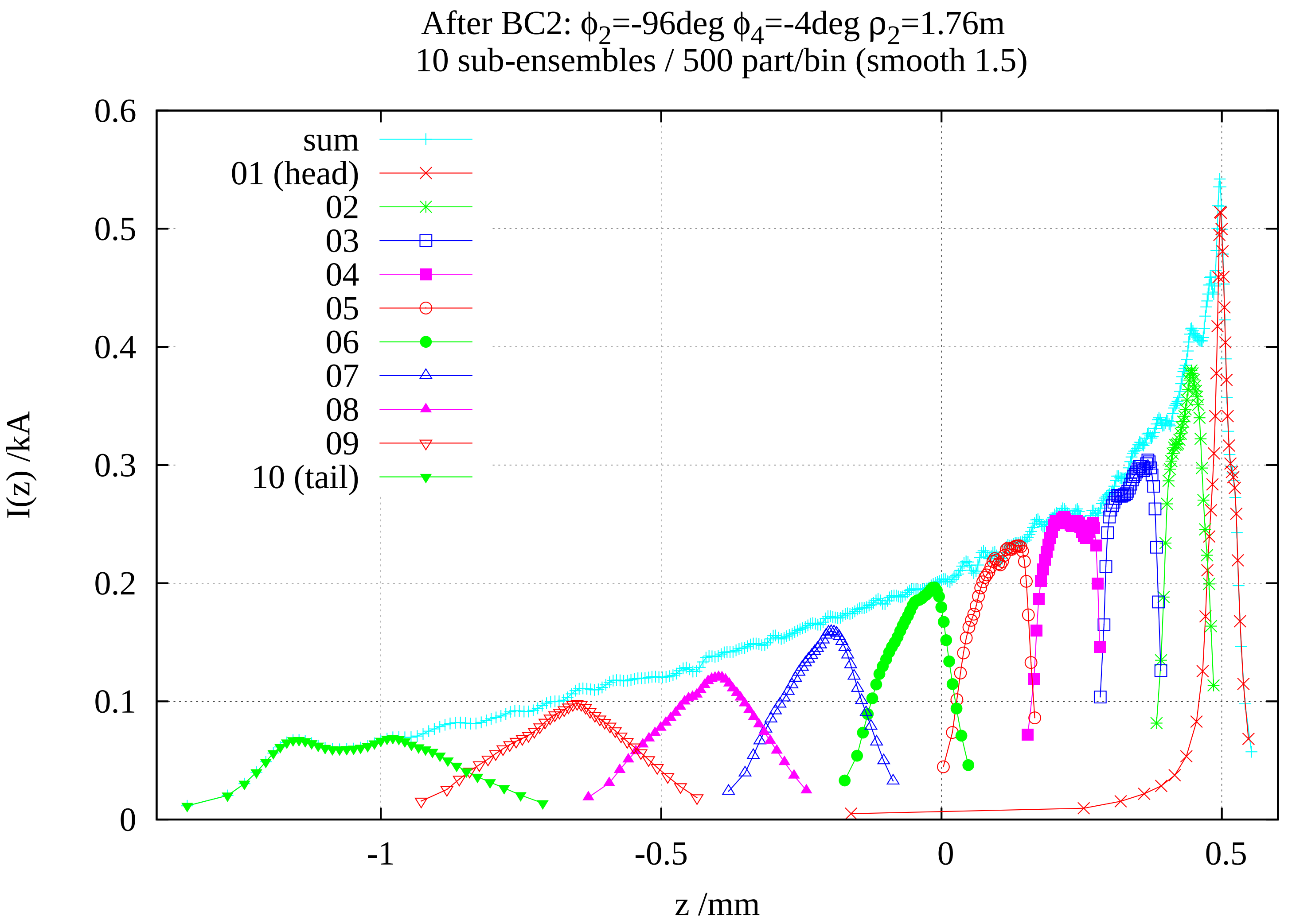


After BC3: ϕ2=-96deg ϕ4=-4deg ρ2=1.76m ϕ5=-15deg ρ3=6.2m
tot 200 const-len bins (smooth 1.5)/ suppr <500 part
<Pz> +/- σpz
I(z)
<Pz> +/- σpz /MeV
I /kA
(z-<z>) /σz
3
2
1
0
-1
-2
-3
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2


After BC3: ϕ_2=-96deg ϕ_4=-4deg ρ_2=1.76m ϕ_5=-15deg ρ_3=6.2m
tot 200 const-len bins (smooth 1.5)/ suppr <500 part
ε^n_x
I(z)
ε^n_x /µm
I /kA
(z-<z>) /σ_z


After BC3: ϕ_2=-96deg ϕ_4=-4deg ρ_2=1.76m ϕ_5=-15deg ρ_3=6.2m
tot 200 const-len bins (smooth 1.5)/ suppr <500 part
ε^n_y
I(z)
ε^n_y /µm
I /kA
(z-<z>) /σ_z


Before BC2: ϕ2=-96deg ϕ4=-4deg
10 sub-ensembles / 500 part/bin (smooth 1.5)
I(z) /kA
z /mm
sum
01 (head)
02
03
04
05
06
07
08
09
10 (tail)
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-3
-2
-1
0
1
2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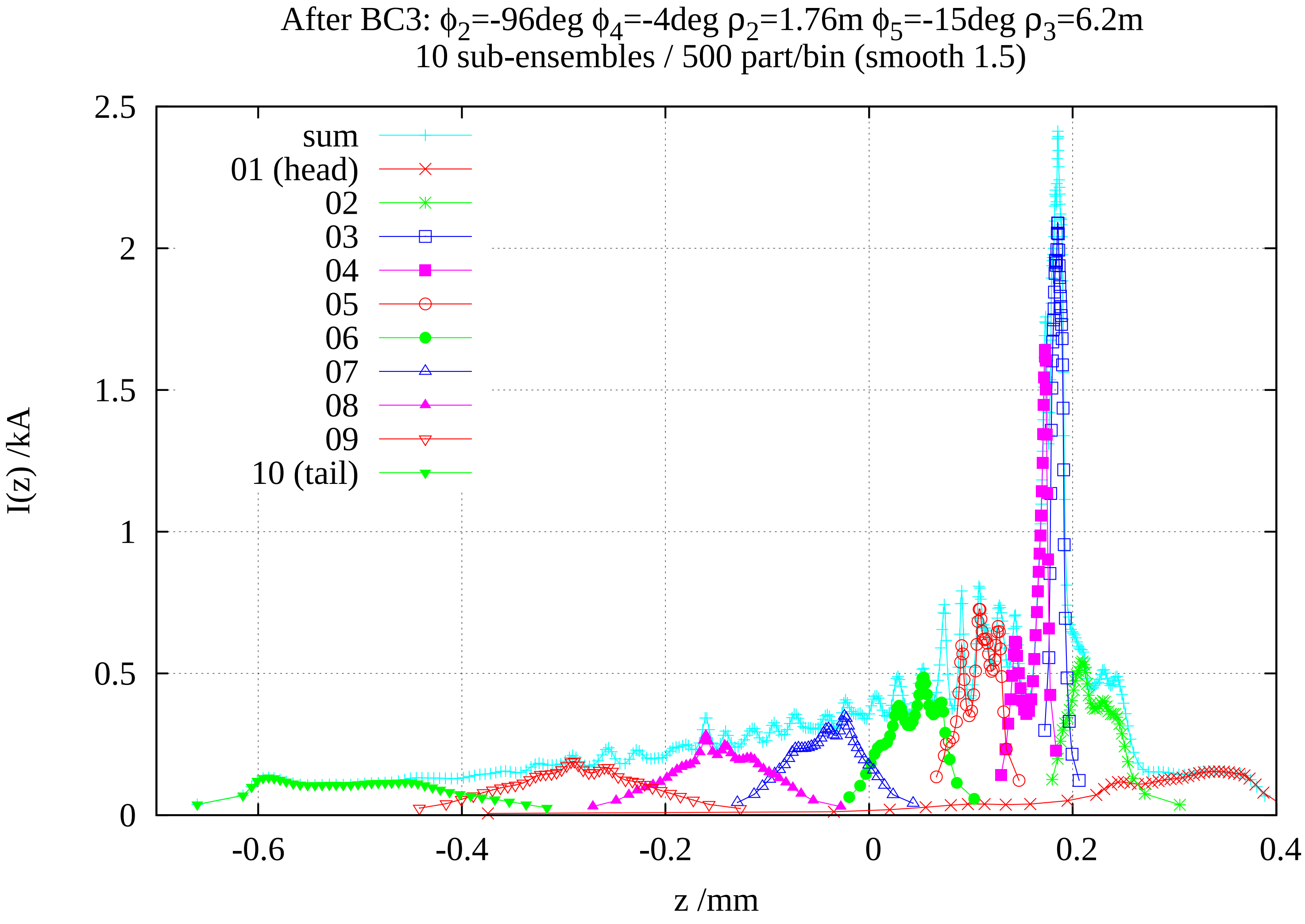
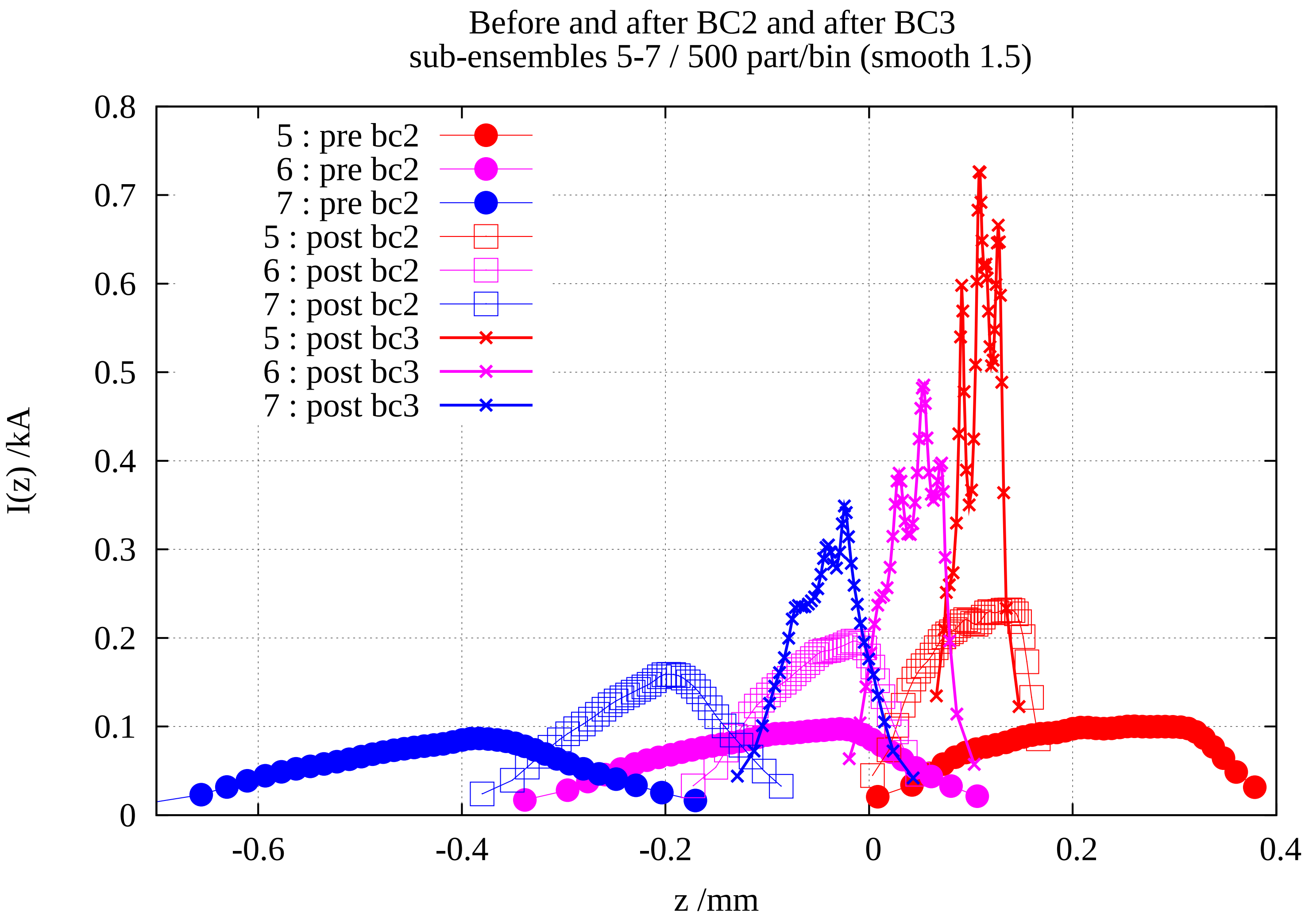
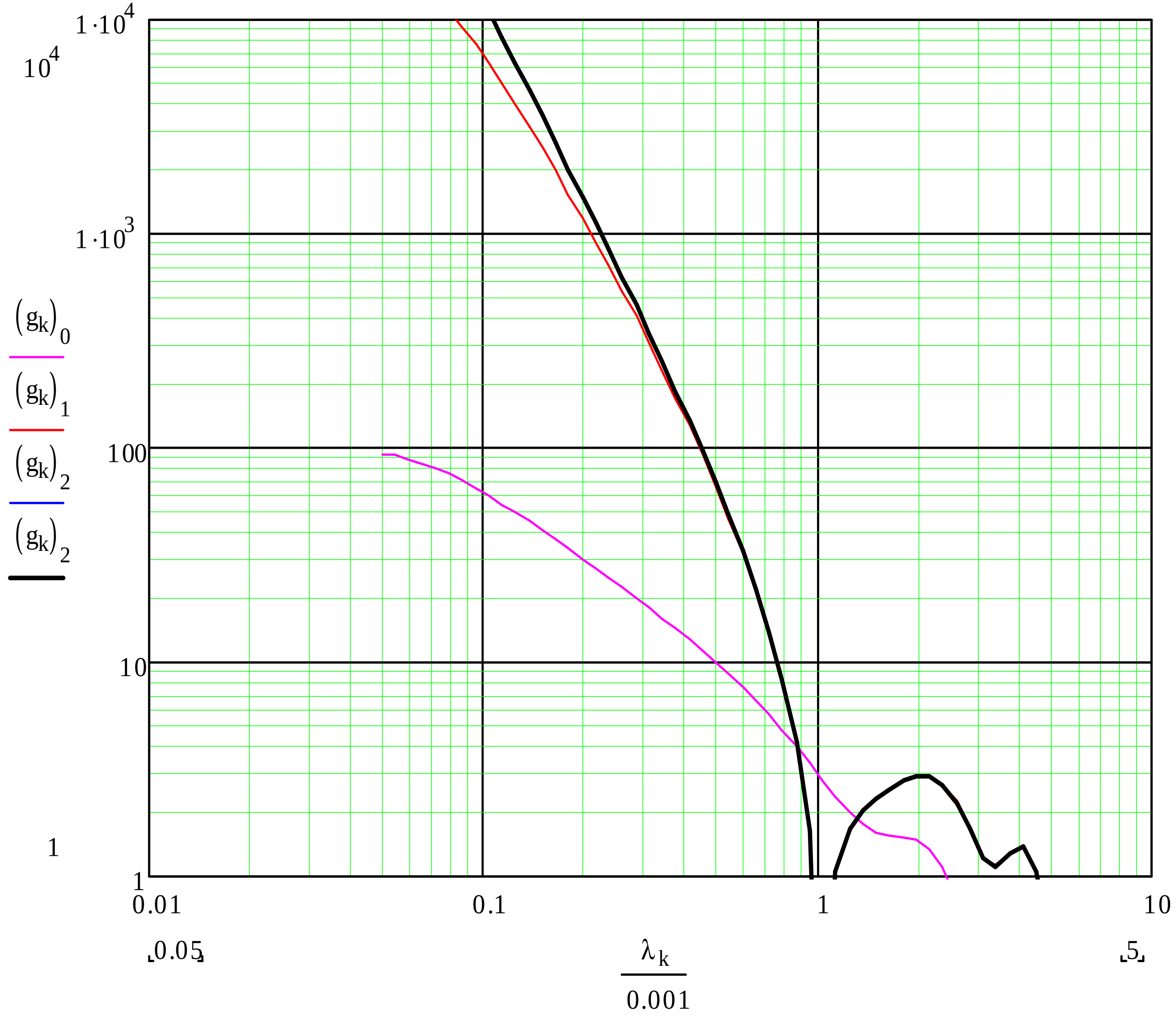
10 sub-ensembles / 500 part/bin (smooth 1.5)
I(z) /kA
z /mm
sum
01 (head)
02
03
04
05
06
07
08
09
10 (tail)
0.6
0.5
0.4
0.3
0.2
0.1
0
-1
-0.5
0
0.5

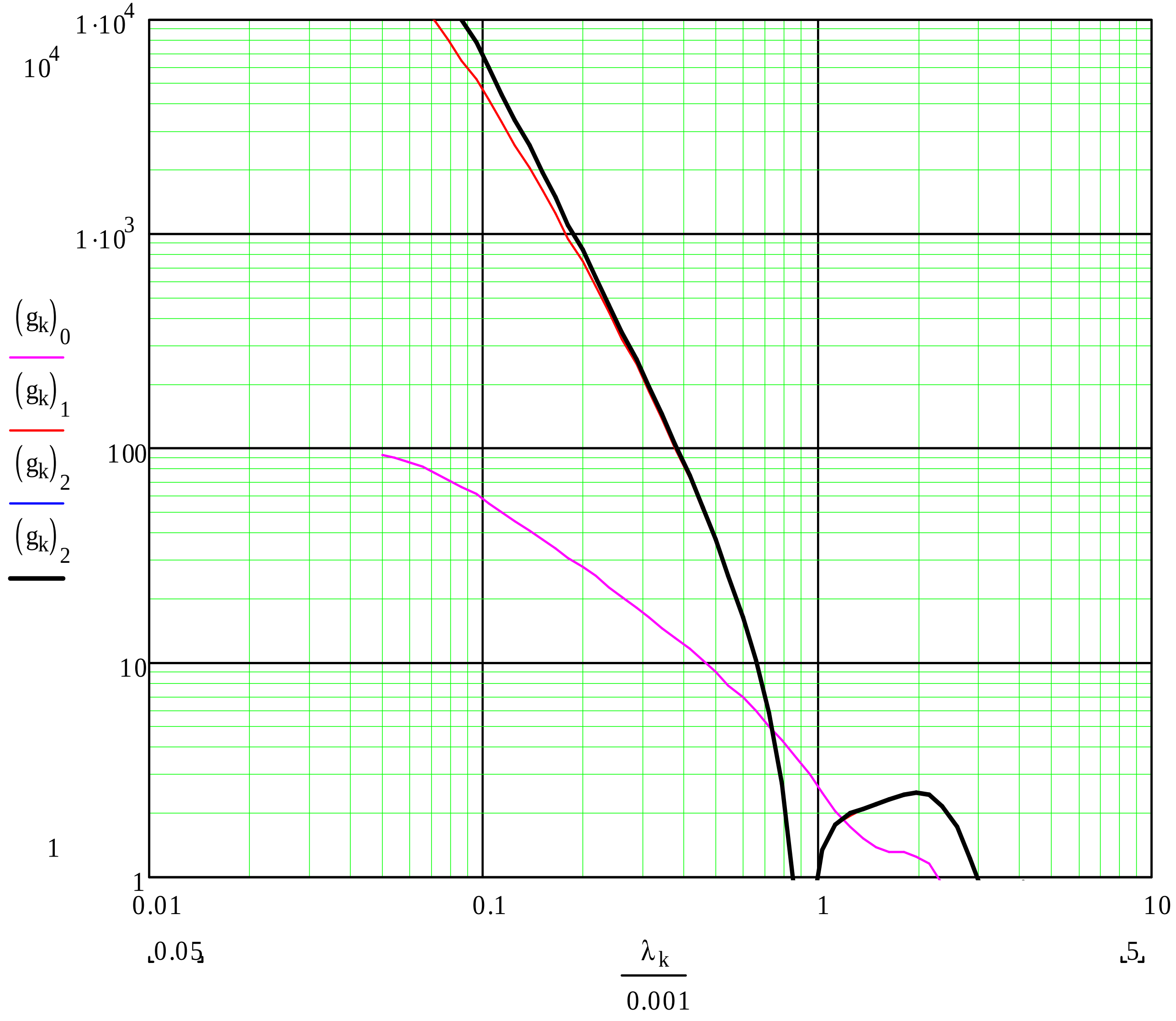

After BC3: ϕ2=-96deg ϕ4=-4deg ρ2=1.76m ϕ5=-15deg ρ3=6.2m
10 sub-ensembles / 500 part/bin (smooth 1.5)
sum
01 (head)
02
03
04
05
06
07
08
09
10 (tail)
I(z) /kA
z /mm
2.5
2
1.5
1
0.5
0
-0.6
-0.4
-0.2
0
0.2
0.4


Before and after BC2 and after BC3
sub-ensembles 5-7 / 500 part/bin (smooth 1.5)
5 : pre bc2
6 : pre bc2
7 : pre bc2
5 : post bc2
6 : post bc2
7 : post bc2
5 : post bc3
6 : post bc3
7 : post bc3
I(z) /kA
z /mm
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
-0.6
-0.4
-0.2
0
0.2
0.4

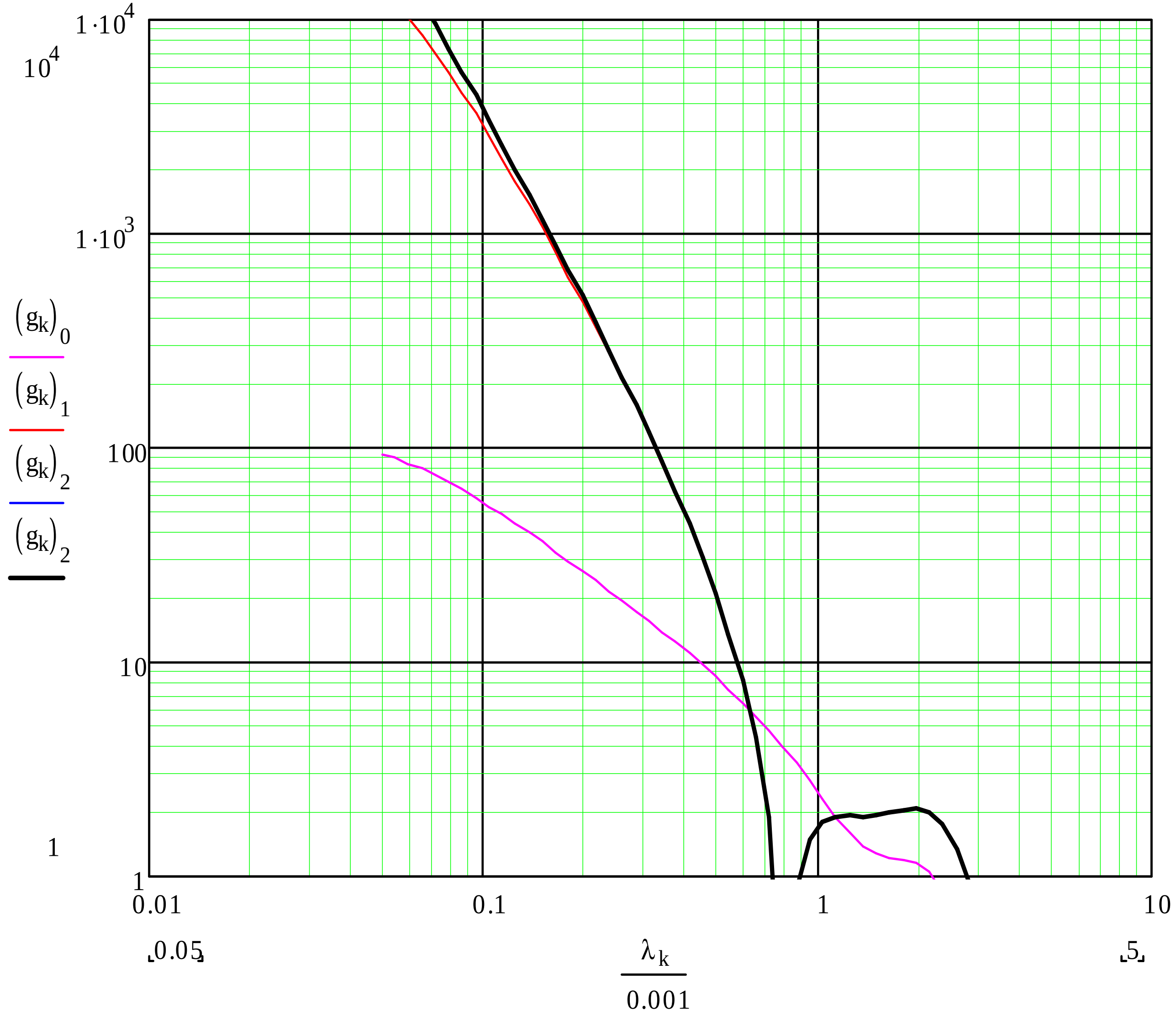
Gain Curve : $\Phi_{1-8}^{2-3} = -15°$ / SubEnsemble= 5 $\Rightarrow C^{\mathrm{bc2}} = 2.3$, $C^{\mathrm{bc3}} = 2.6$



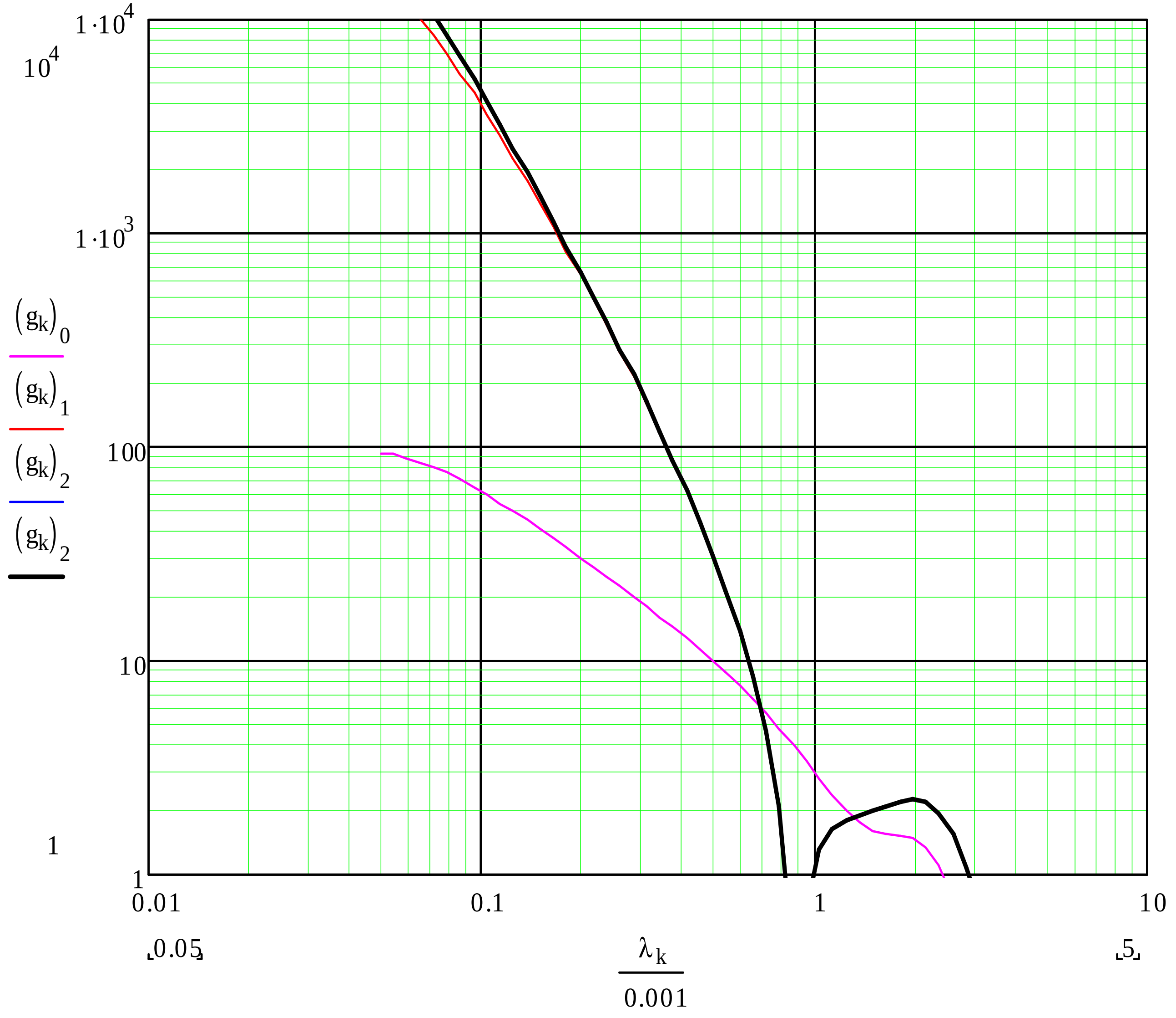
Gain Curve : $\Phi_{1-8}^{2-3} = -15°$ / SubEnsemble$=6$ $\Rightarrow C^{\mathrm{bc2}} = 2.1$, $C^{\mathrm{bc3}} = 2.25$



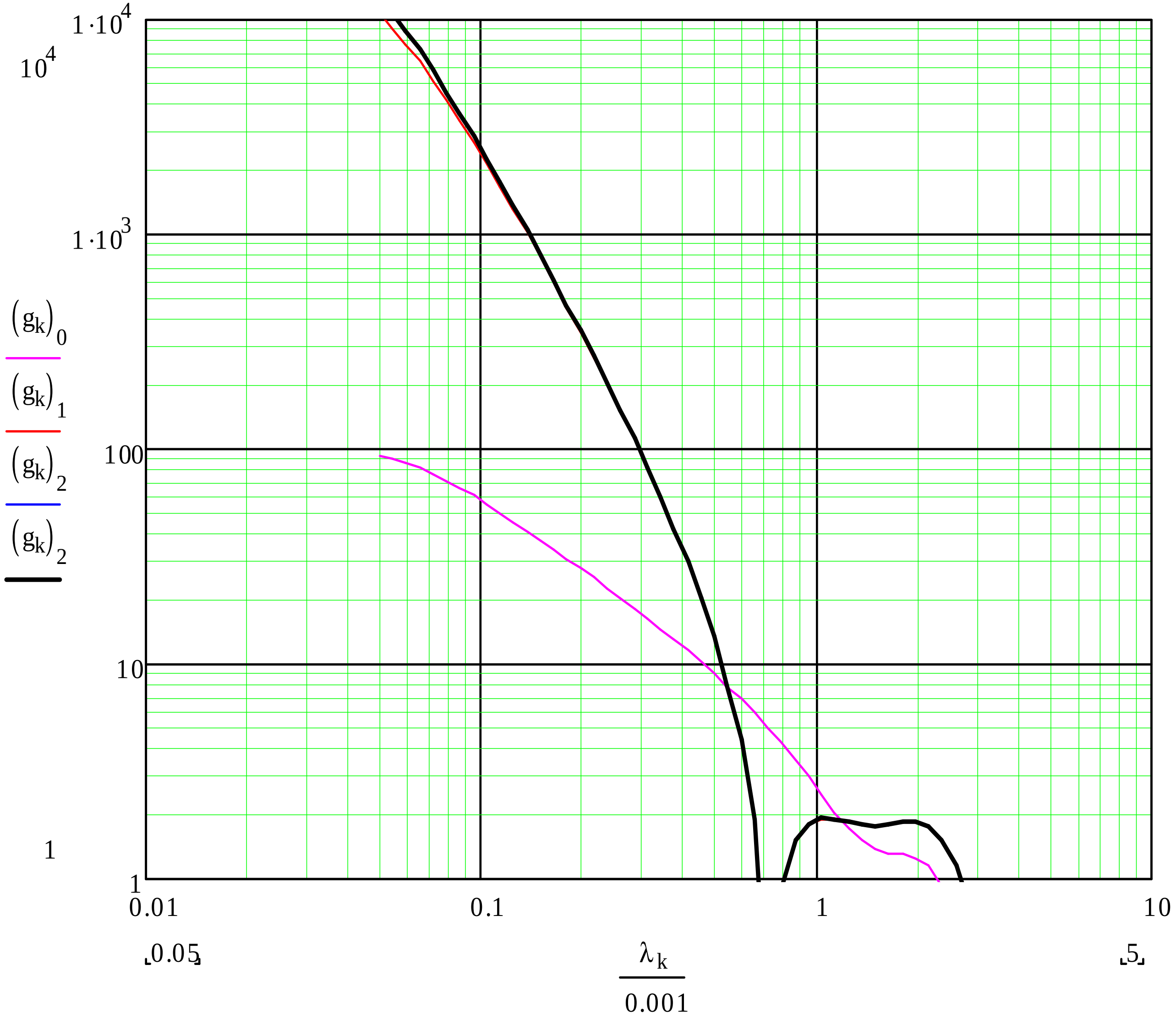
Gain Curve : $\Phi_{1-8}^{2-3} = -15°$ / SubEnsemble= 7 $\Rightarrow C^{\mathrm{bc2}} = 2.0$, $C^{\mathrm{bc3}} = 1.77$



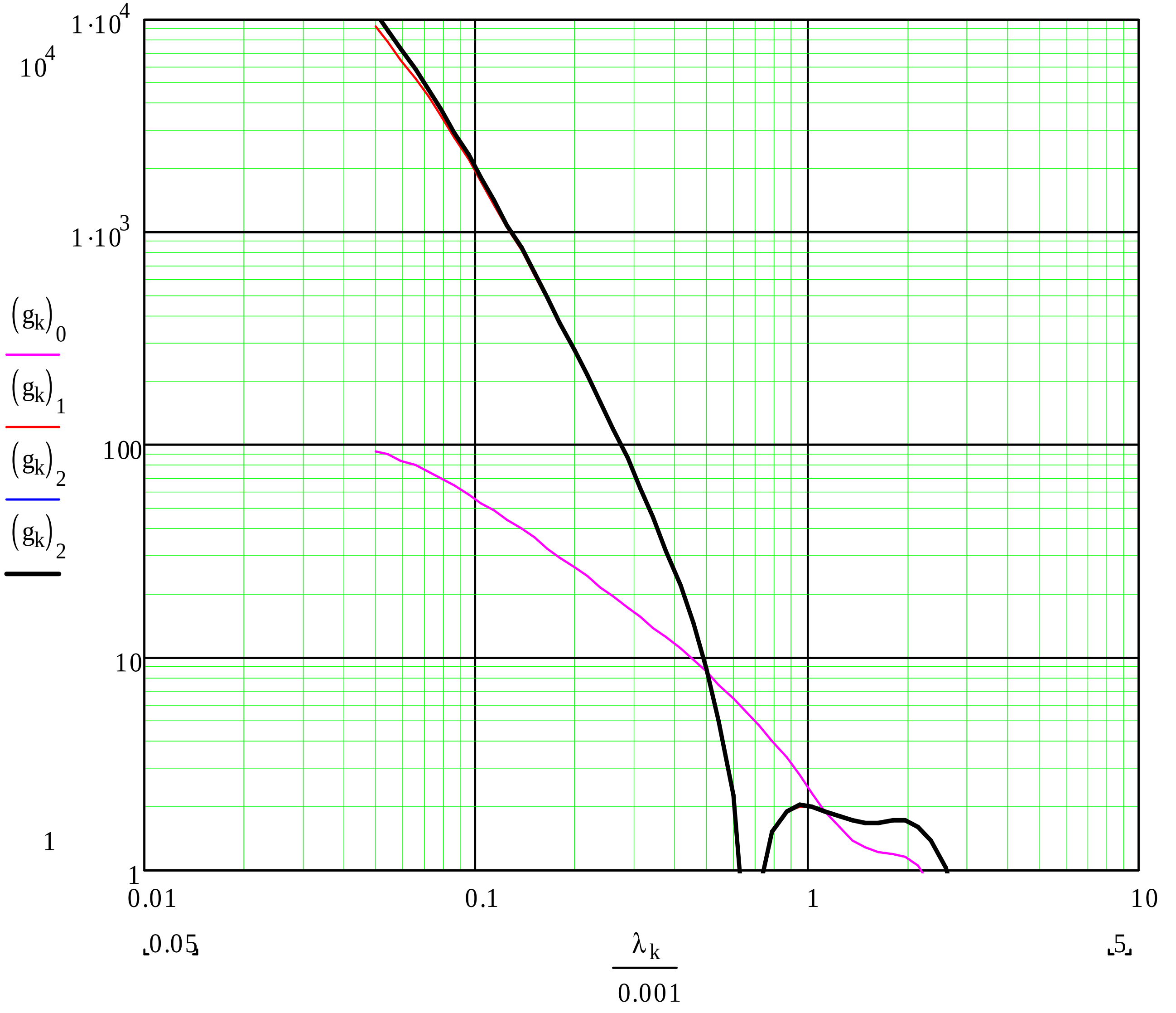
Gain Curve : $\Phi_{1-8}^{2-3} = 0°$ / SubEnsemble= 5 $\Rightarrow C^{\mathrm{bc2}} = 2.3$, $C^{\mathrm{bc3}} = 1.39$



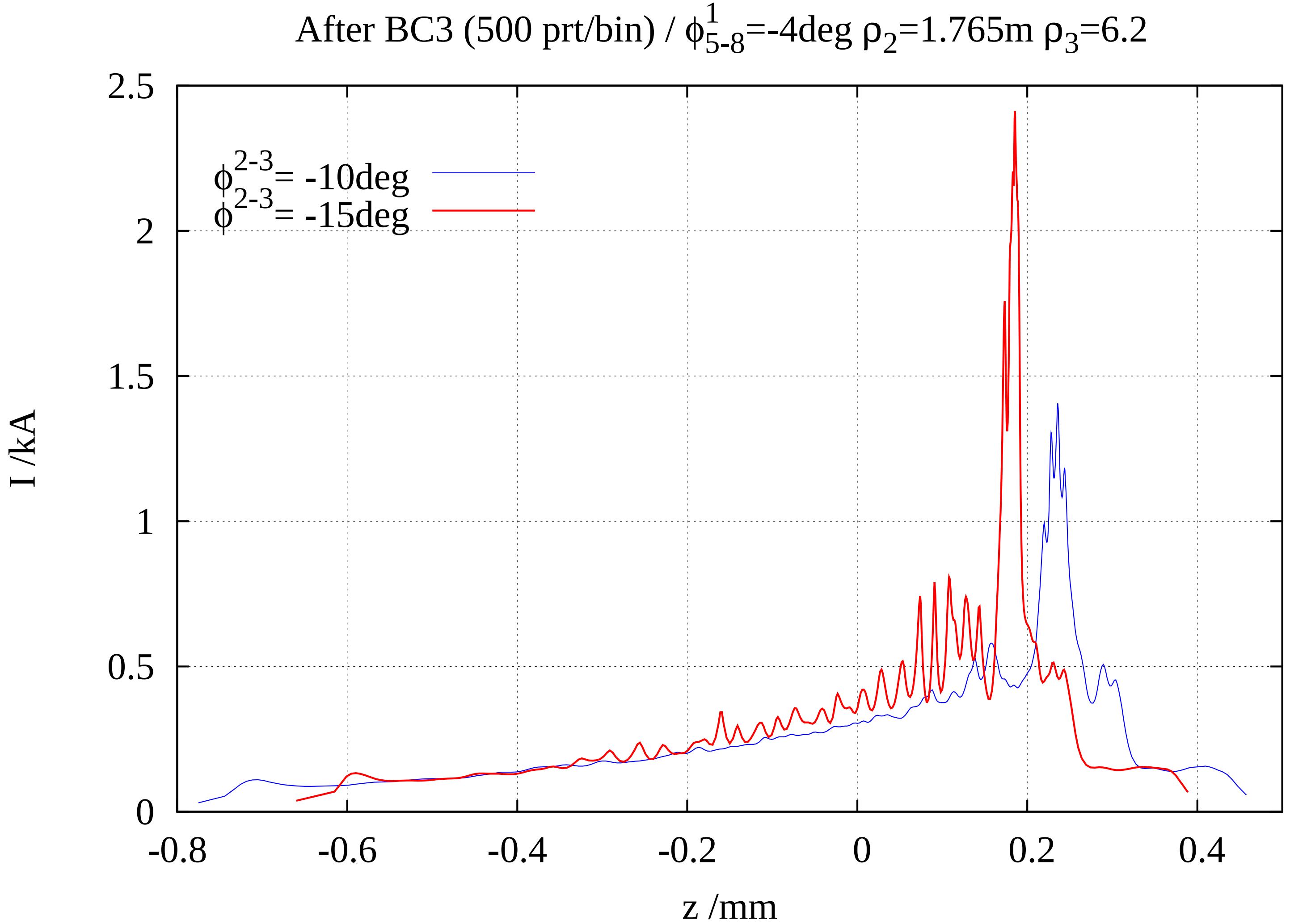
Gain Curve : $\Phi_{1-8}^{2-3} = 0°$ / SubEnsemble= 6 $\Rightarrow C^{\mathrm{bc2}} = 2.1$, $C^{\mathrm{bc3}} = 1.10$



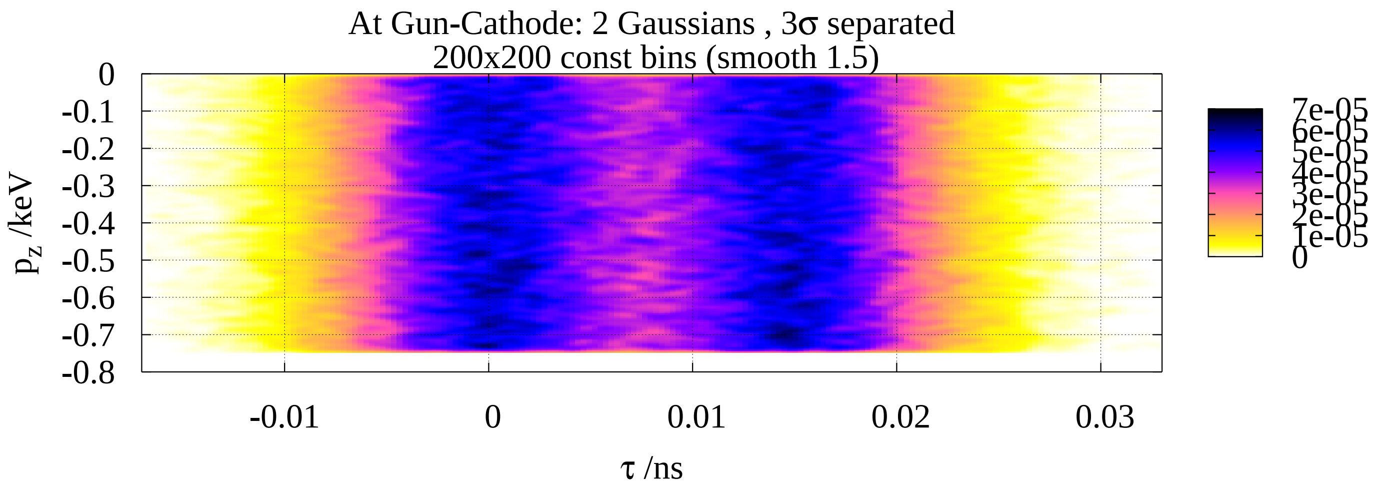
Gain Curve : $\Phi_{1-8}^{2-3} = 0^\circ$ / SubEnsemble= 7 $\Rightarrow C^{\mathrm{bc2}} = 2.0$, $C^{\mathrm{bc3}} = 1.06$

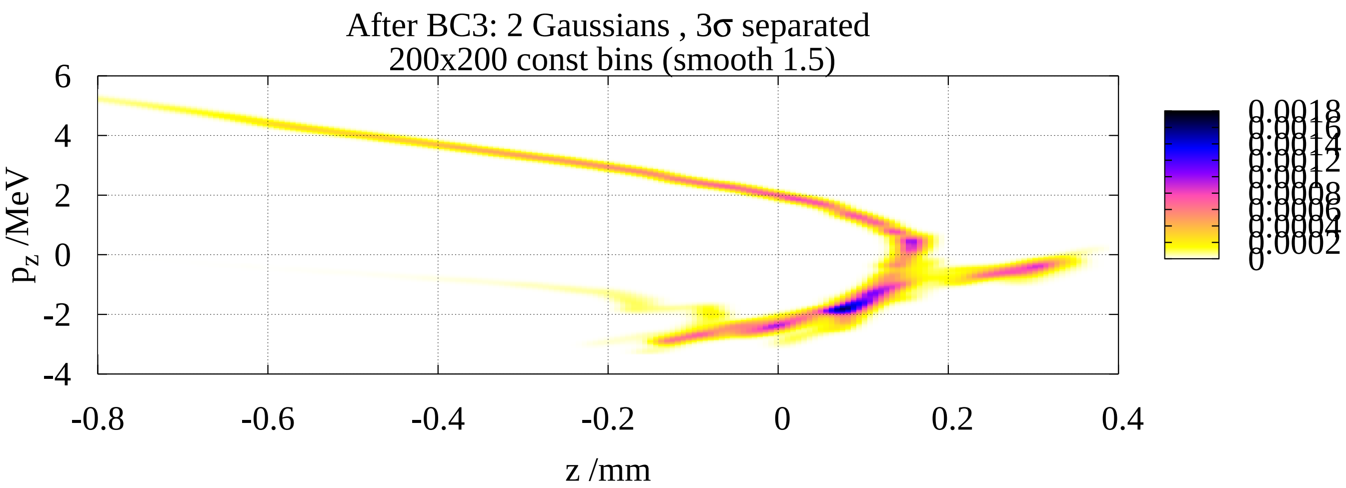


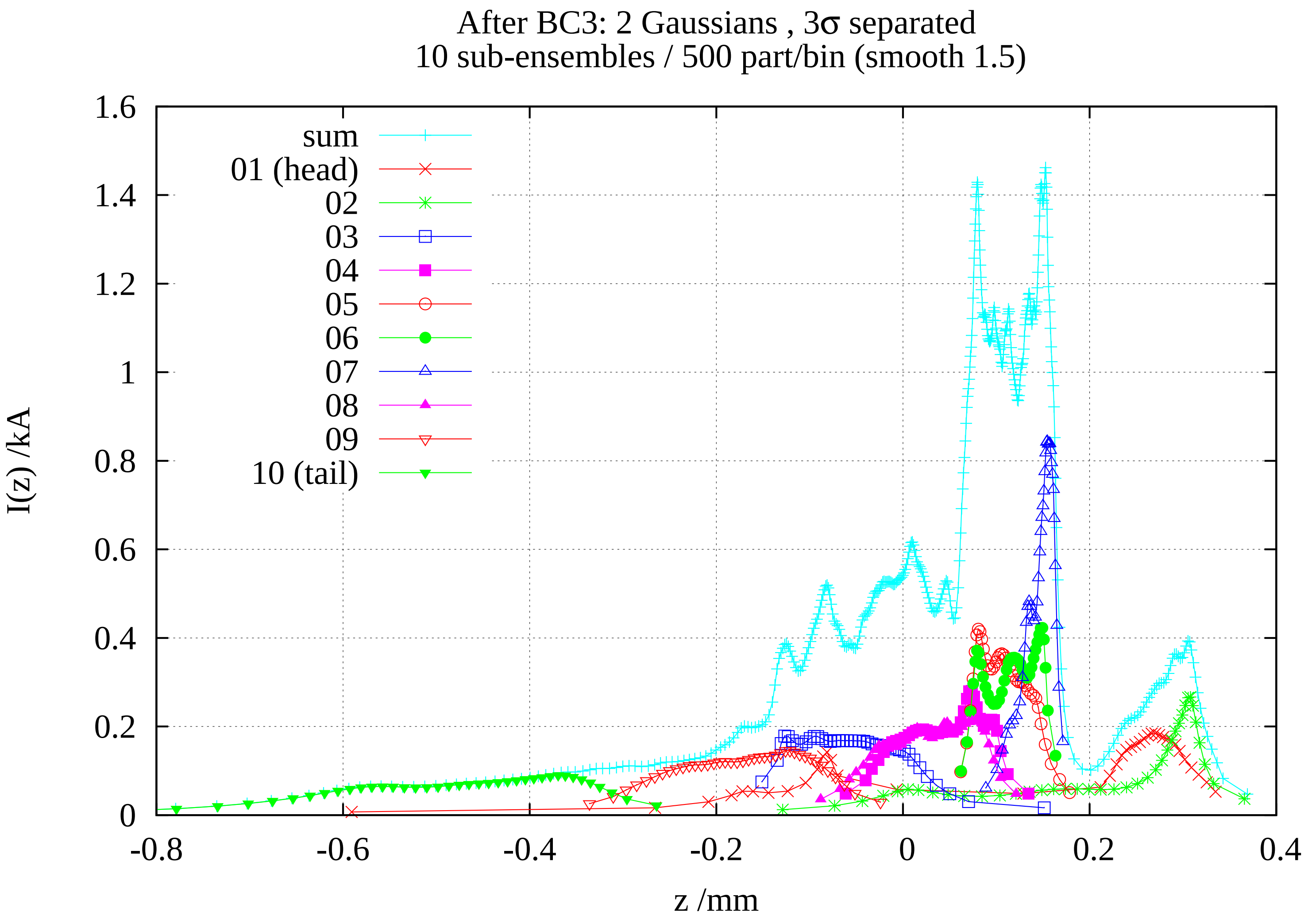
Is This Micro–Bunching in S2E-Simulations ?



Double–Humped Densities






After BC3: 2 Gaussians , 3σ separated
10 sub-ensembles / 500 part/bin (smooth 1.5)
sum
01 (head)
02
03
04
05
06
07
08
09
10 (tail)
I(z) /kA
z /mm
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4

Summary

- Proposed set of parameters

ϕ_1	ϕ_2	ϕ_3	ϕ_4	ρ_2	ϕ_5	ρ_3
(gun)	ACC1.1	ACC1.2-4	ACC1.5-8	BC2	ACC2&3	BC3
$-0.55°$	$-96°$	$0°$	$-4°$	1.765m	$-15°$	6.2m
	VB	accel.	corr. chirp		extra chirp	

⇒ decent z–region with high current outside spike
50μm with $I > 500$A, 220μm with $I > 300$A

⇒ decent transcerse phase space

⇒ no strong mixing in high–I region

⇒ estimated gain $> 1 \cdot 10^{+4}$ for 10μm $< \lambda <$ 100μm, $> 1 \cdot 10^{+3}$ for $\lambda <$ 200μm

- proposed μ–bunching “switch” : vary ϕ_5 from $0°$ to $-15°$
- possibly try double–humped initial densities from cathode