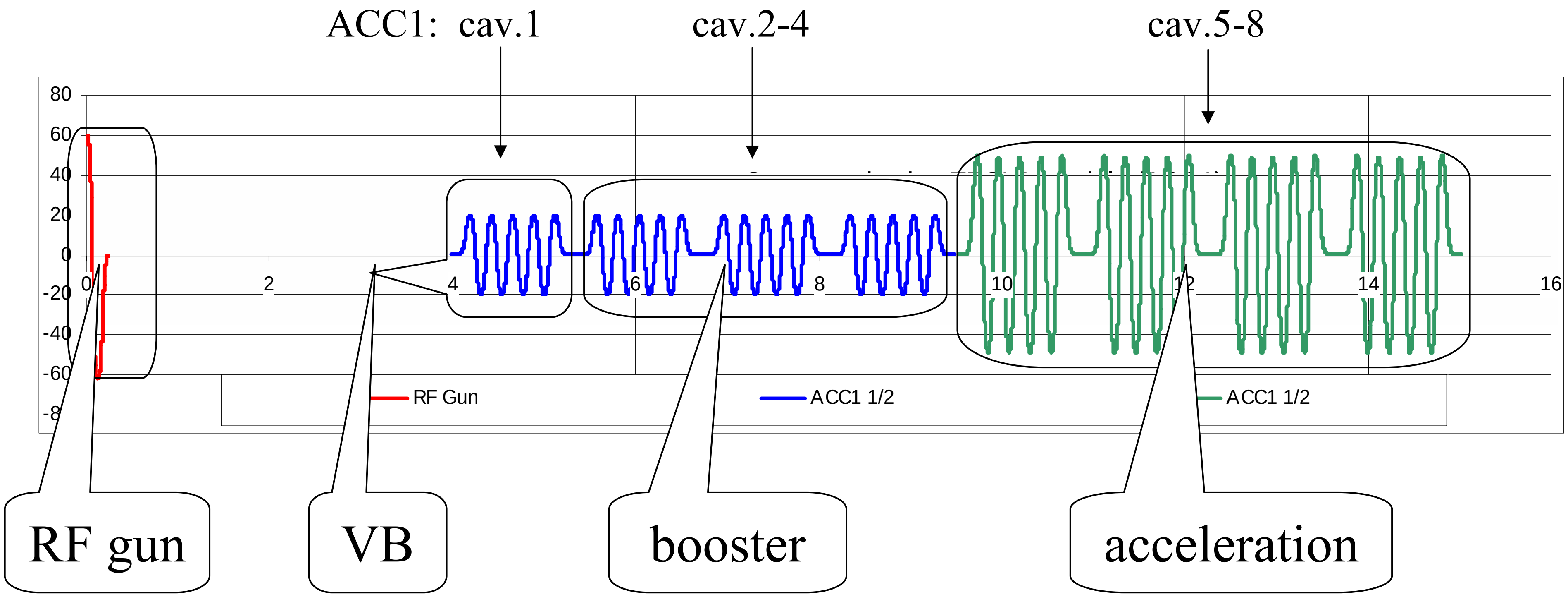
Velocity bunching simulations for XFEL photo injector

M.Krasilnikov, PITZ

FEL Beam Dynamics Meeting, 4.6.2007

Velocity bunching at XFEL photo injector

Main idea: use XFEL photo injector setup, tune machine parameters in order to increase the beam peak current



Optimization setup 1

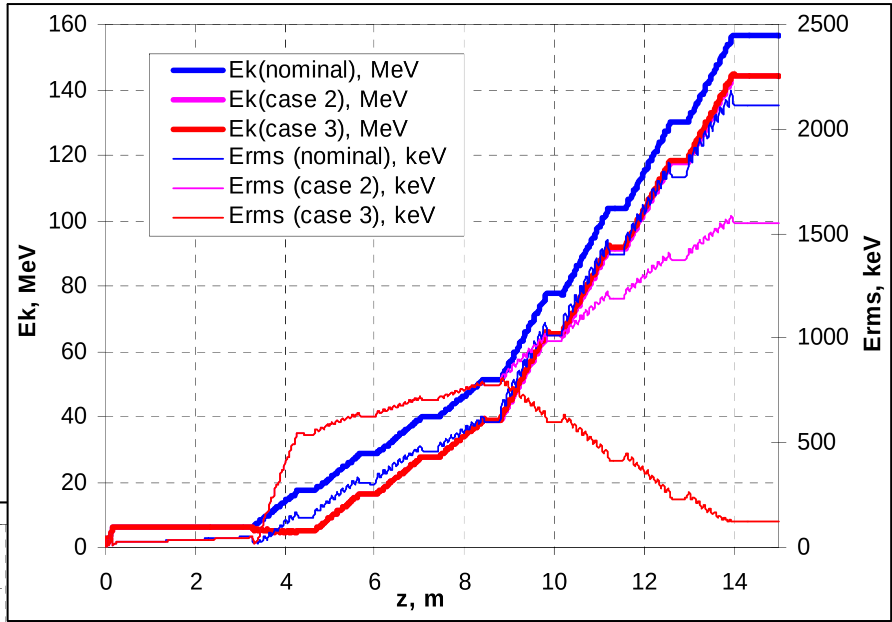
	case->			1	2	3
	Parameter		Unit	nominal	without ACC1 phase tunning	with ACC1 phase tunning
cath.laser	transverse	XYrms	mm	0.438	0.438	0.438
	longit.	Lt	ps	20	20	20
	flat-top	rt	ps	2	2	2
	thermal	Ek	eV	0.55	0.55	0.55
RF-Gun	cavity	Ecath	MV/m	60	60	60
		RF phase	deg	-0.55	-0.55	-0.55
	Solenoid	z_peak	m	0.276	0.276	0.276
		Bmax	T	-0.22466	-0.2183	-0.2183
ACC1	1st* iris	z_pos	m	3.34	3.34	3.34
	cav1	Emax	MV/m	21.53	21.53	21.53
		RF phase	deg	-15.72	-98	-98
	cav.2-4	Emax	MV/m	21.53	21.53	21.53
		RF phase	deg	-15.72	-15.72	-15.72
	cav.5-8	Emax	MV/m	50	50	50
		RF phase	deg	-15.72	-15.72	14
ASTRA		Npart		200k	200k	200k
	Space charge	Nrad		30	30	30
		Nlong		40	40	40
	Noice reduction			+	+	+

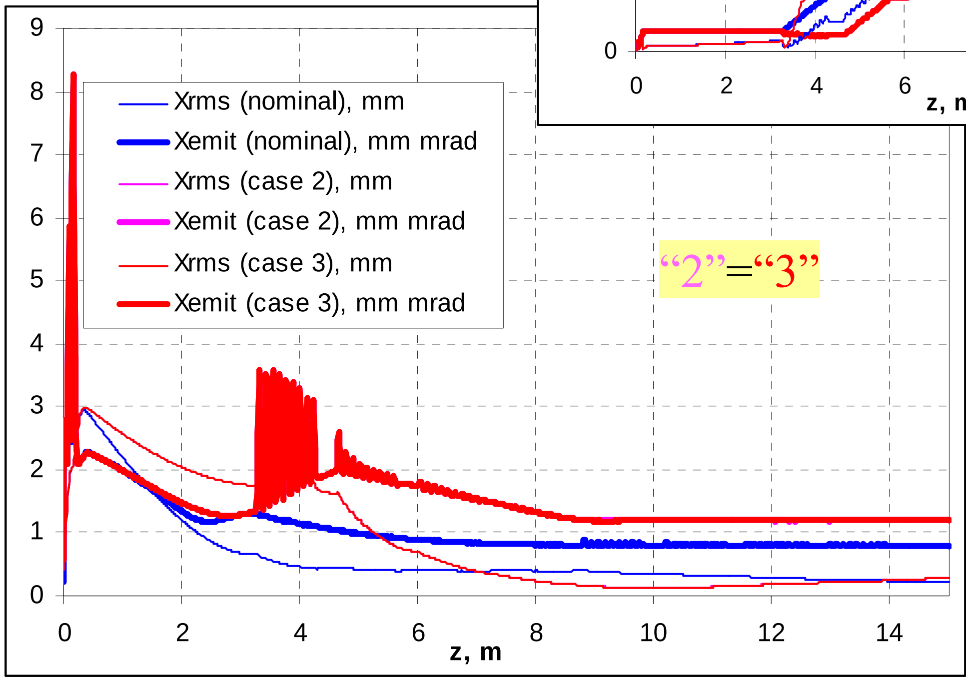
case 1: nominal= XFEL, **no** velocity bunching (VB)

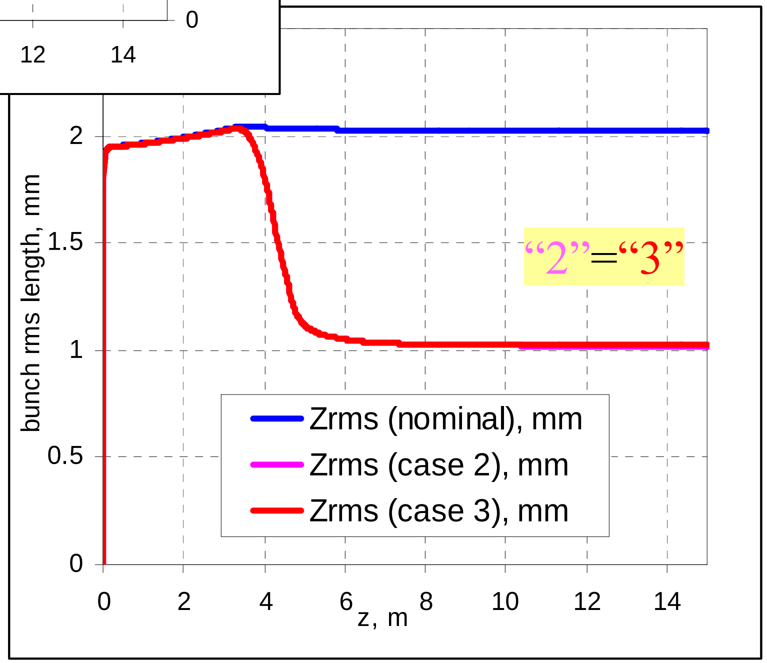
case 2: without ACC1 phase tuning= XFEL, **with VB**, the phase of last 4 cavities in ACC1 **not** tuned

case 3: with ACC1 phase tuning= XFEL, **with VB**, the phase of last 4 cavities in ACC1 **tuned for minimum energy spread**

Cases 1, 2 and 3

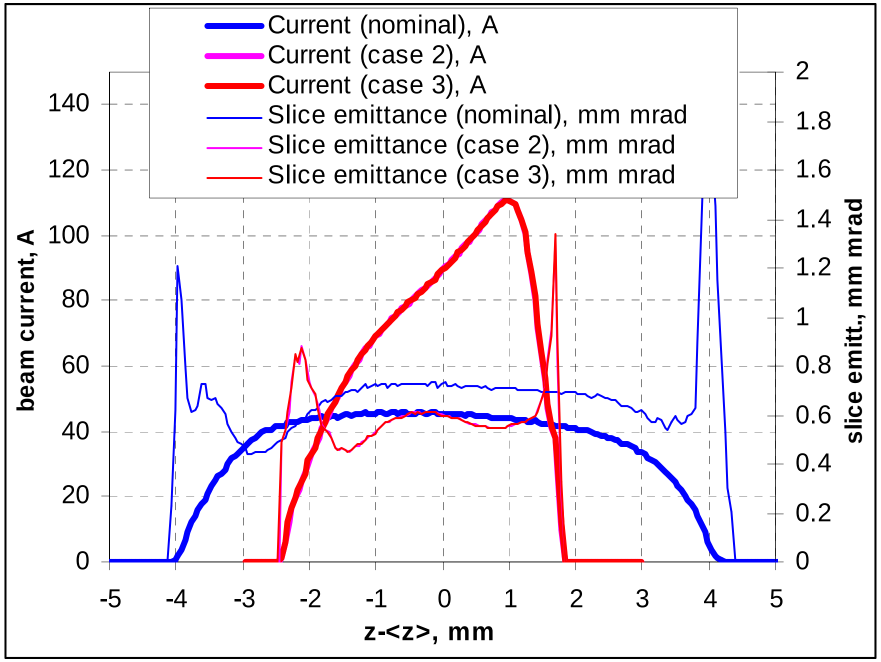


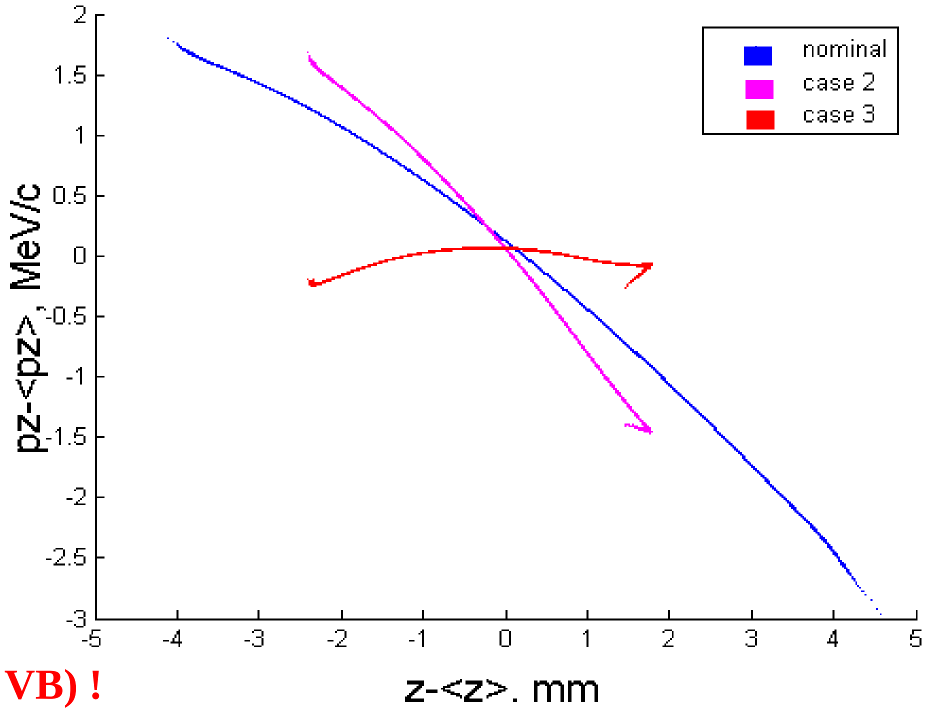




Electron bunch at z=15m

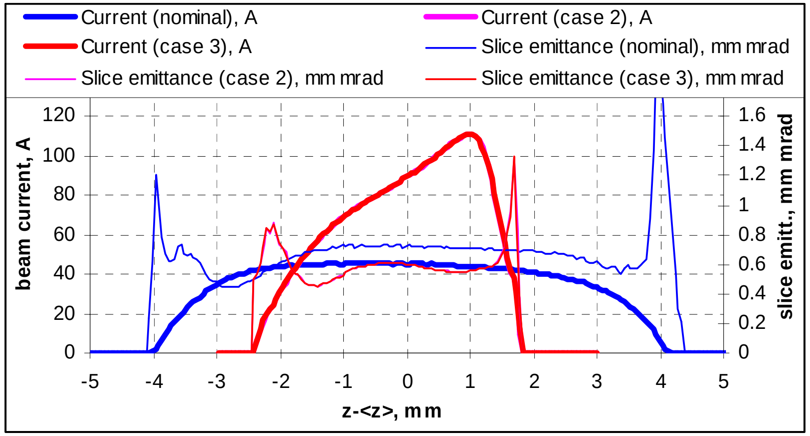
case->			1	2	3
Parameter		Unit	nominal	without ACC1 phase tunning	with ACC1 phase tunning
transverse	XYrms	mm	0.23	0.29	0.29
	norm.emit	mm mrad	0.8	1.20	1.21
long	Zrms	mm	2.0	1.02	1.02
energy	Ek	MeV	157	144	144
	Erms	keV	2111	1548	122
	Erms/Ek	-	0.013	0.011	0.001

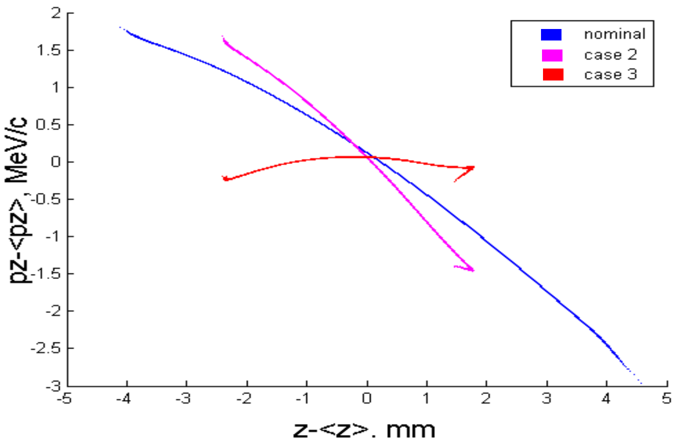


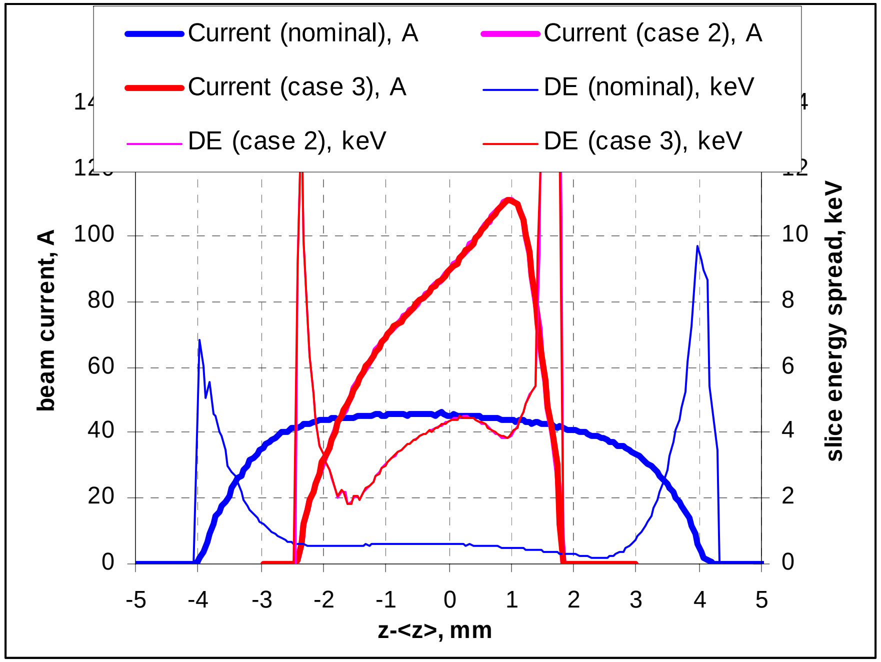


!? Slice emittance in cases 2,3 < nominal case (no VB) !

Electron bunch at z=15m

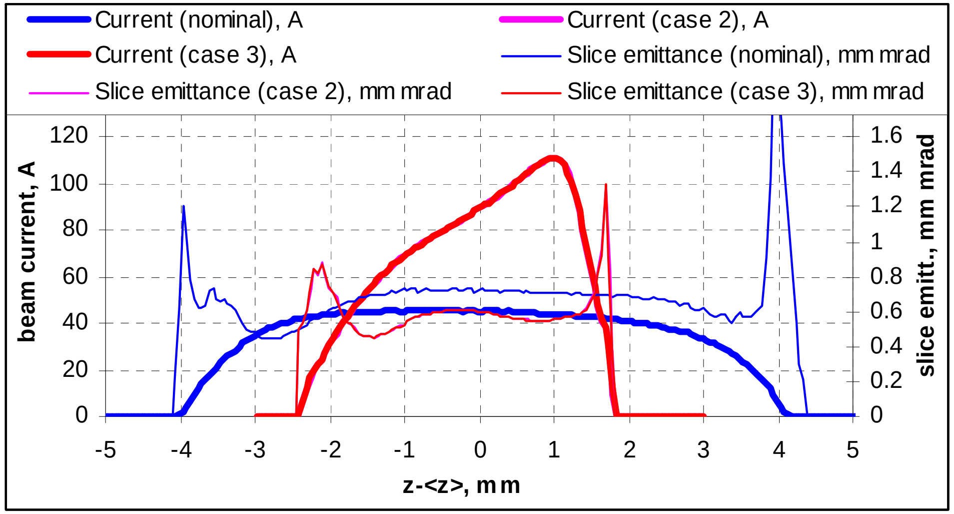


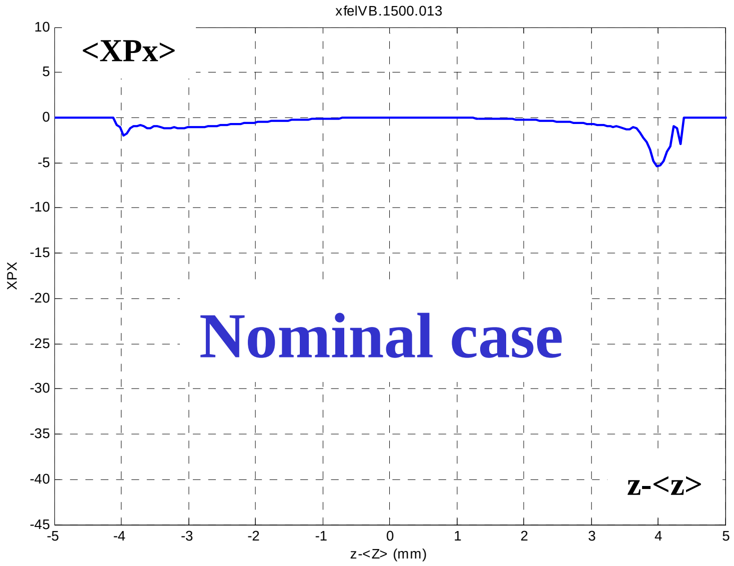


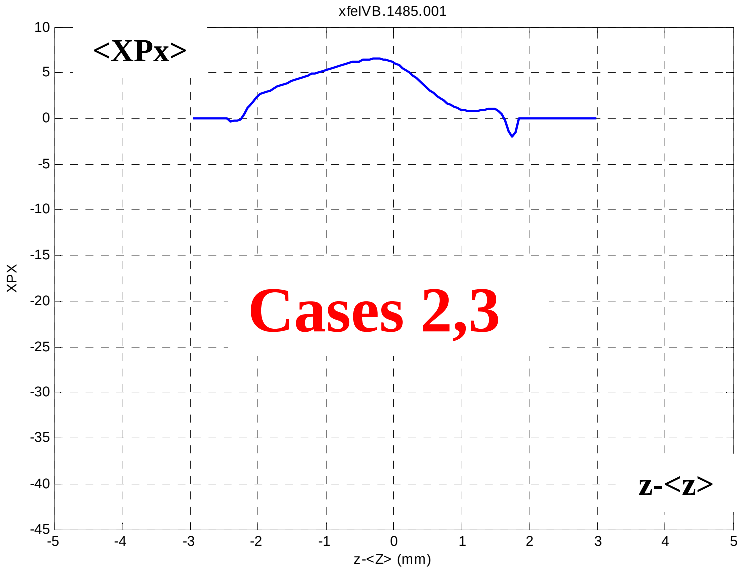


!!? Slice energy spread in cases 2,3 > nominal case (no VB) in a factor of ~7!

Electron bunch at z=15m. XPx correlation along the bunch

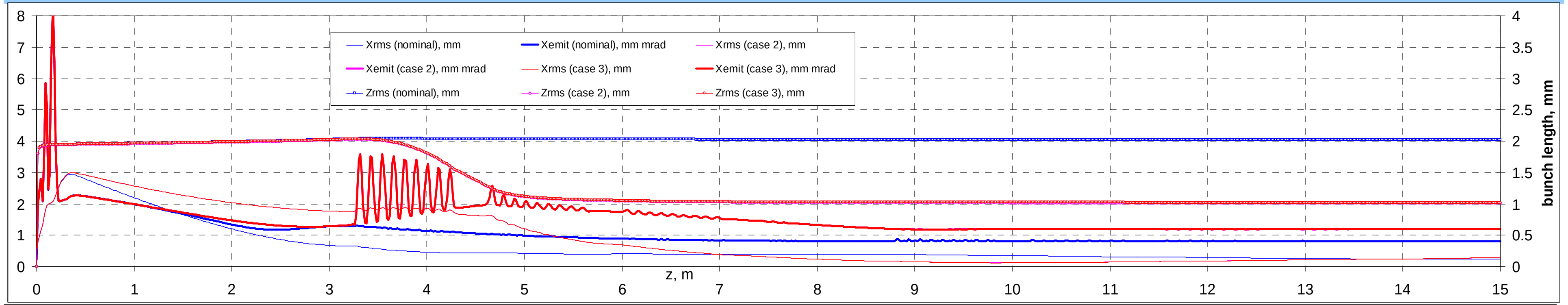


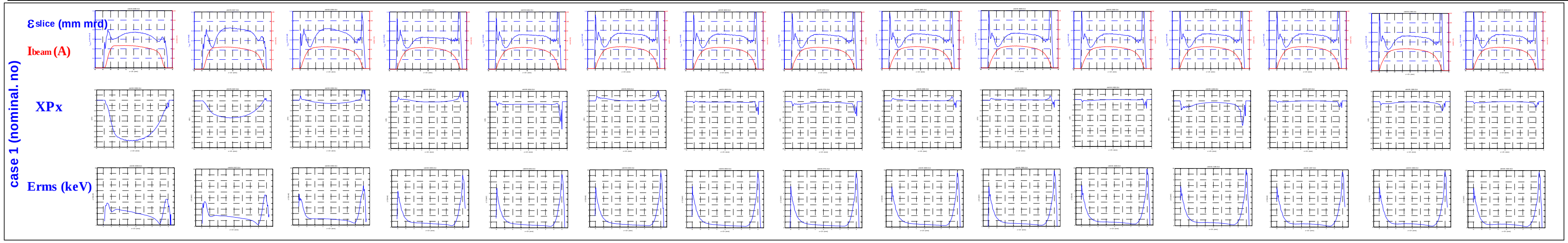


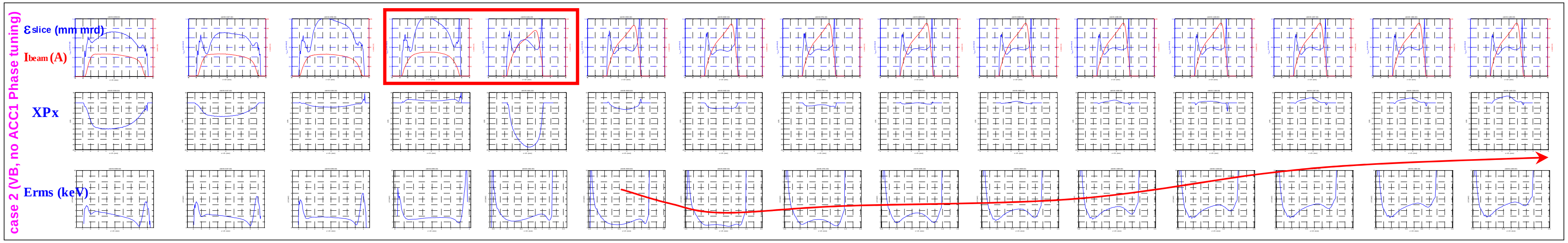


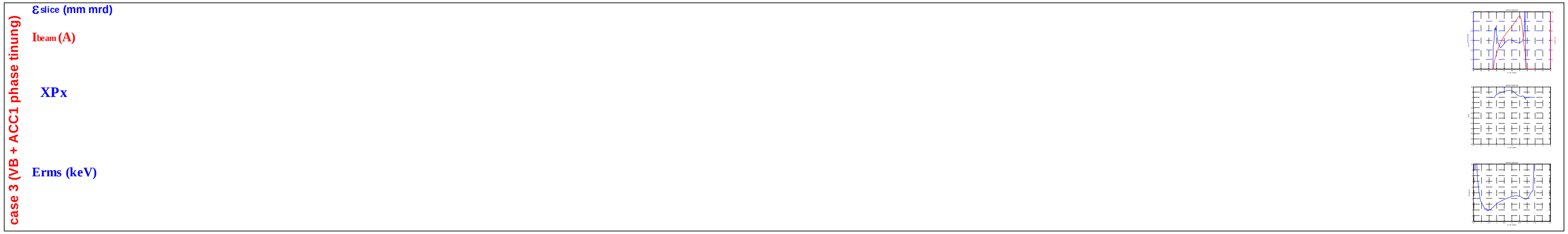
Plots of XPx(z) shows that in VB cases the correlation is positive and has stronger nonlinearity than in the nominal case. This explain increasing of the projected emittance from nominal 0.8 mm mrad to 1.2 mm mrad (VB cases)

Slice emittance, XPX correlation and uncorrelated energy spread along beam line

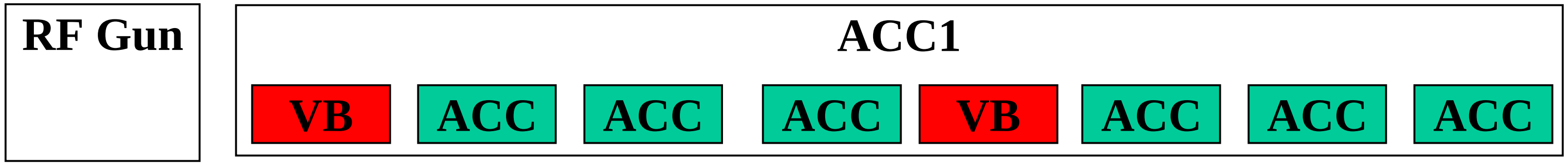








Optimization setup 2 (Ipeak=200A?)



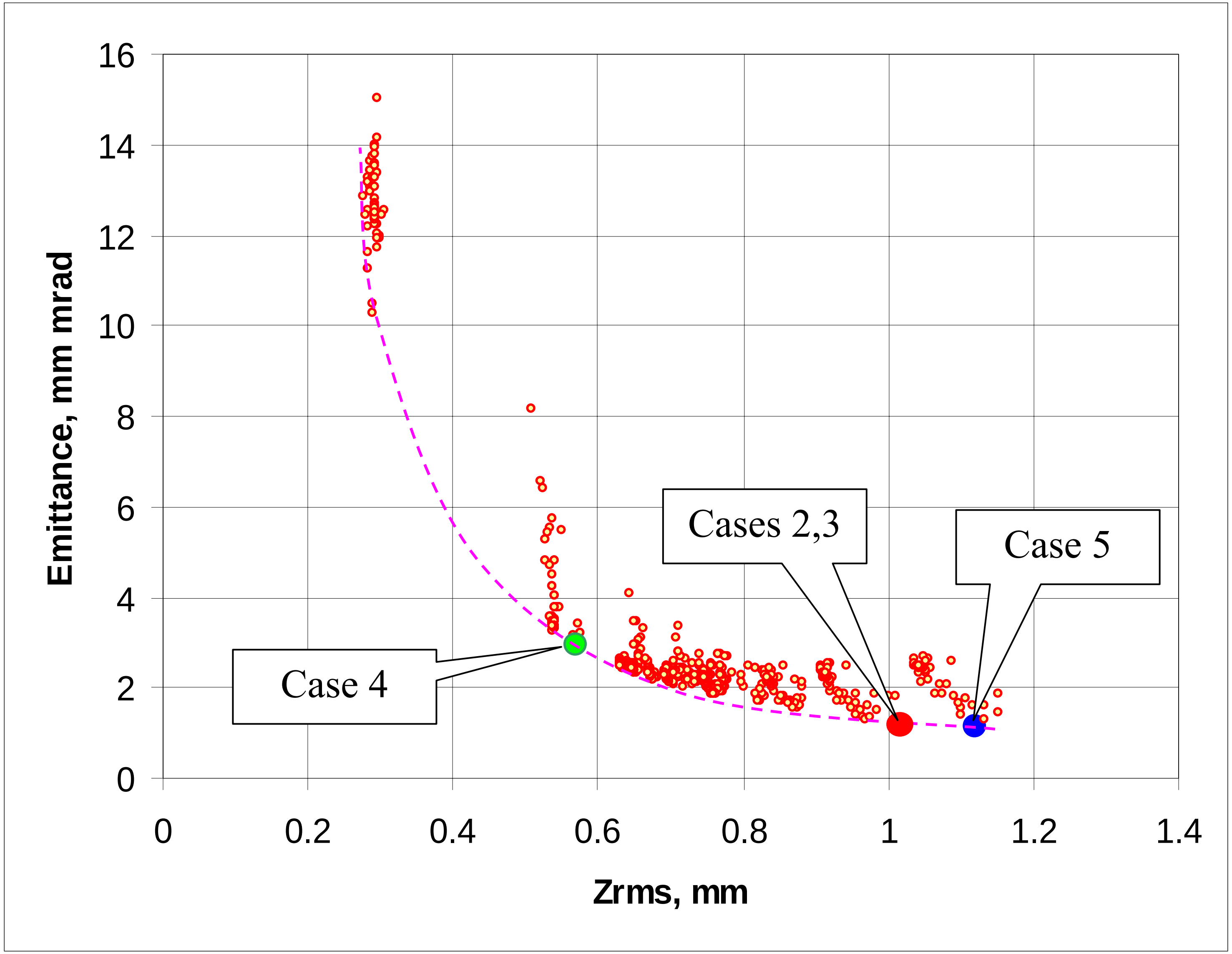
- Photo injector layout is chosen to be the nominal XFEL one (position of the gun solenoid, ACC1 z-position are fixed)
- Gun gradient (60MV/m at the photo cathode), gradients of TESLA cavities in the ACC1 are "frozen" to reduce the number of varied parameters (Emax_cav1-4=21.5MV/m, Emax_cav5-8=50MV/m)
- Laser temporal profile – a flat-top with 20ps FWHM, 2ps rise/fall time

Velocity bunching option of the nominal XFEL photo injector

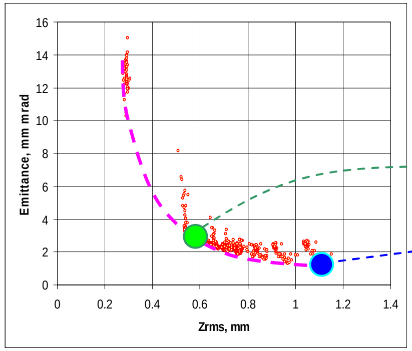
- Machine parameters being optimized:
  - RF gun (main solenoid current and rms transverse size of the cathode laser at the cathode) → 2
  - RF phases in ACC1 (phi_cav1, phi_cav2-4, phi_cav5, phi_cav6-8)→ 4
- The goal function: simultaneous minimization rms bunch length and transverse projected emittance

$$F(z_{rms},\varepsilon_{xy}) = \begin{cases} z_{rms}, \text{if } \varepsilon_{xy} < 2.5 \\ z_{rms}\cdot e^{\varepsilon_{xy}-2.5}, \text{if } \varepsilon_{xy} > 2.5 \end{cases}$$

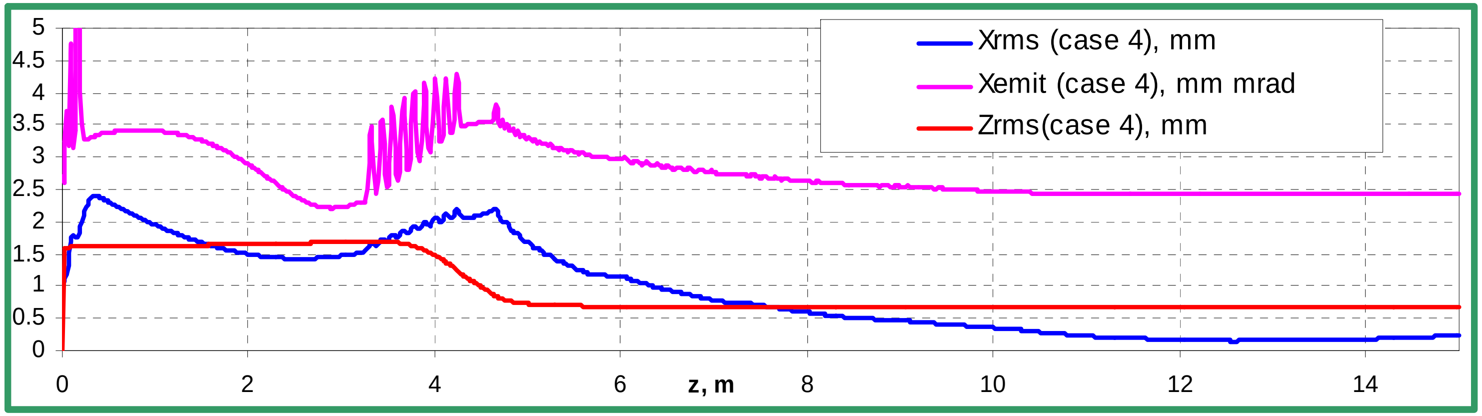
Emittance-RMS bunch length chart

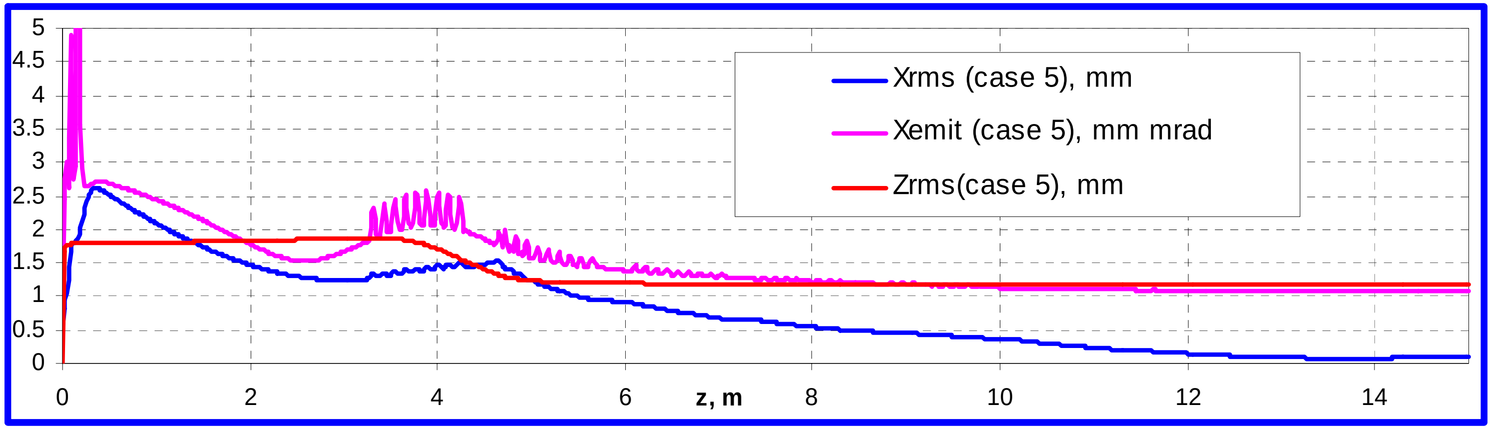


2 “optimized” cases

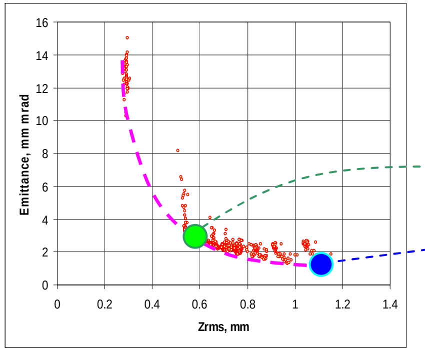


case	cath. laser XYrms, mm	main sol. peak field, T	Phi(1), deg	Phi(2-4), deg	Phi(5), deg	Phi(6-8), deg	Zrms, mm	Xemit, mm mrad
4	0.567	-0.2186	-102.2	14.2	-79.8	14.2	0.67	2.43
5	1.10	-0.2076	-102.2	14.2	-79.8	14.2	1.09	1.18





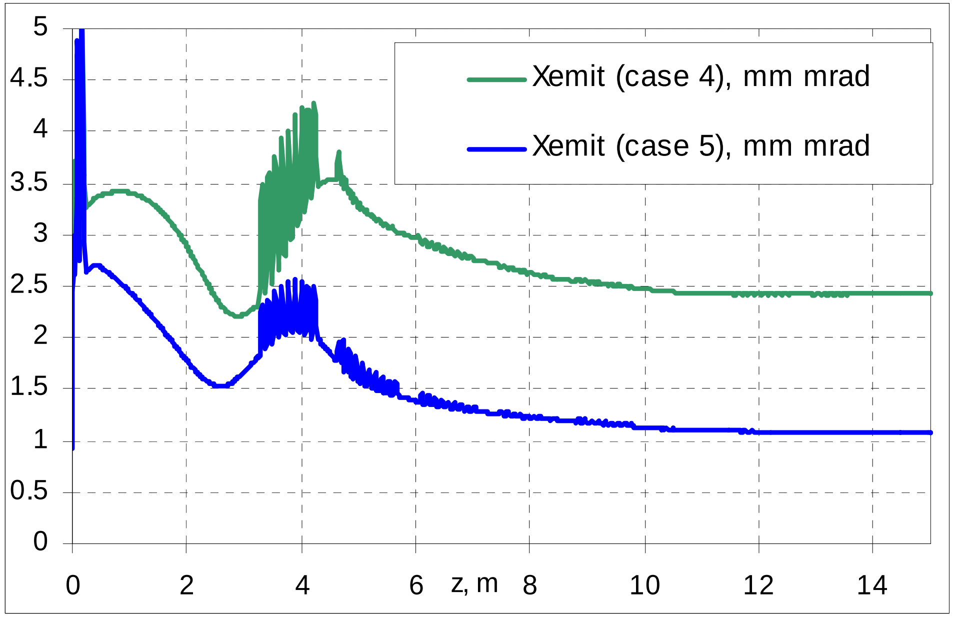
Case 4 vs. case 5



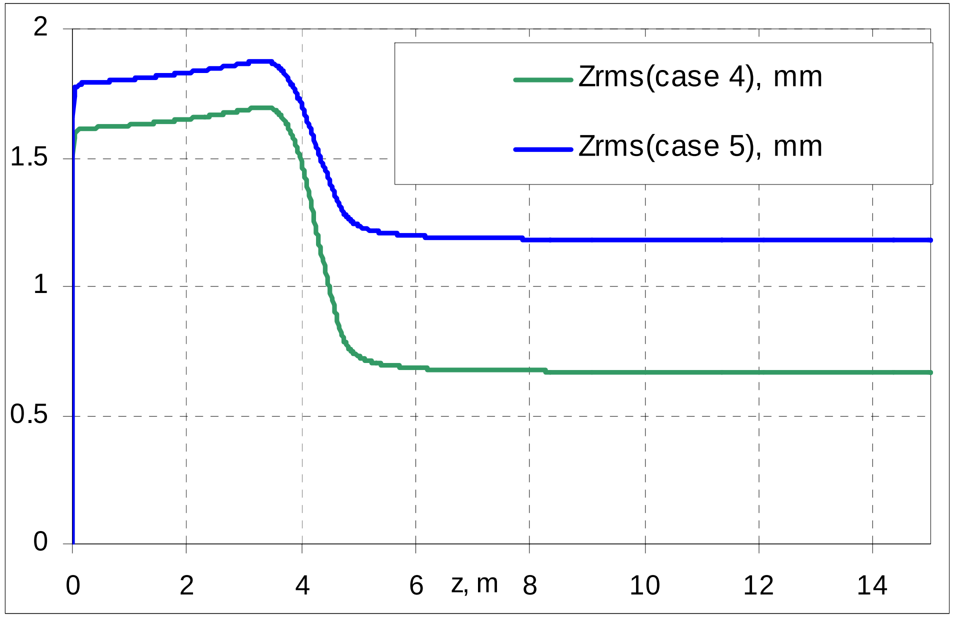
case	cath. laser XYrms, mm	main sol. peak field, T	Phi(1), deg	Phi(2-4), deg	Phi(5), deg	Phi(6-8), deg	Zrms, mm	Xemit, mm mrad
4	0.567	-0.2186	-102.2	14.2	-79.8	14.2	0.67	2.43
5	1.10	-0.2076	-102.2	14.2	-79.8	14.2	1.09	1.18

Despite an optimization of ACC1phases were (almost) independent, they resulted in the same set of RF phases.

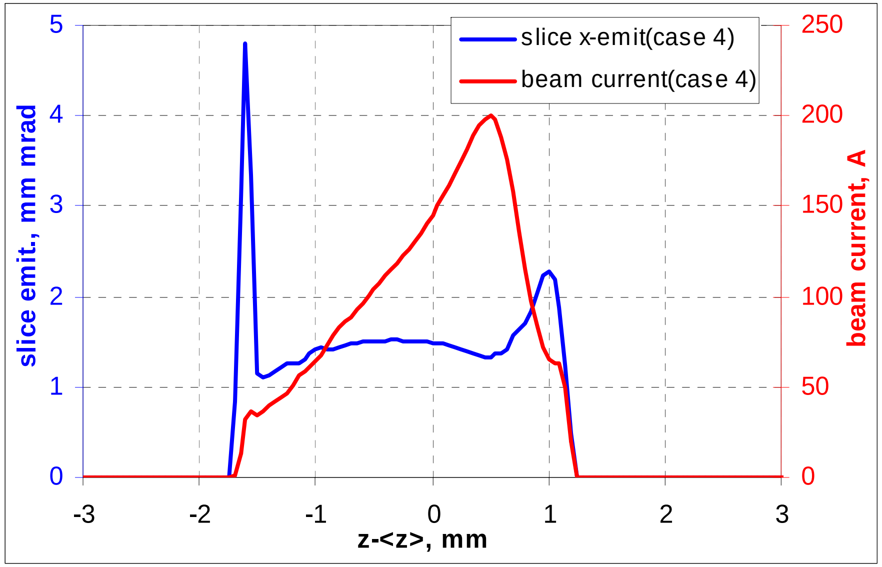
Projected Transverse Emittance

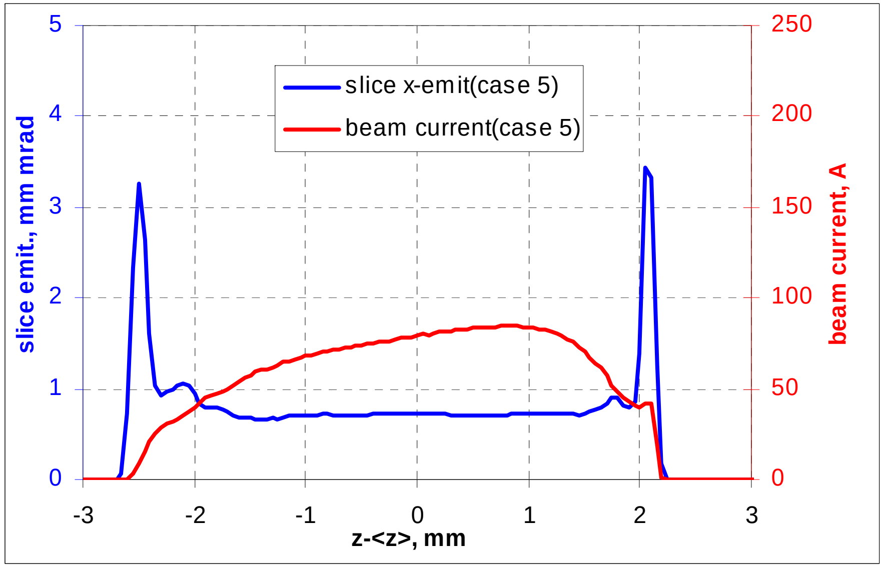


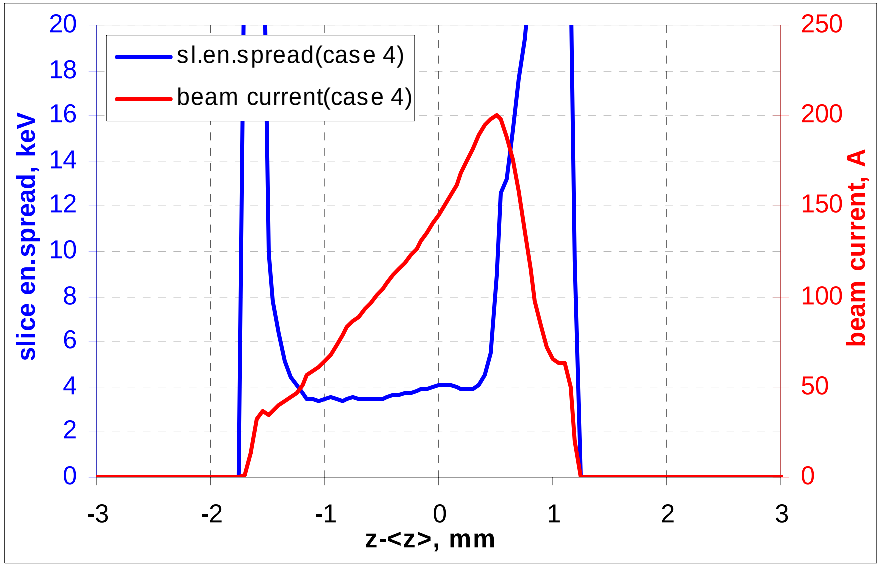
RMS bunch length

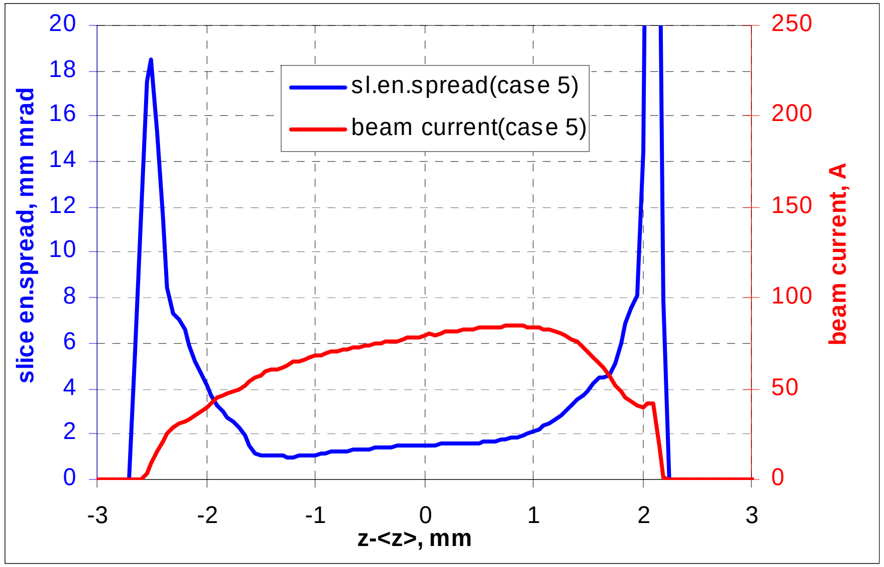


Cases 4, 5: slice parameters

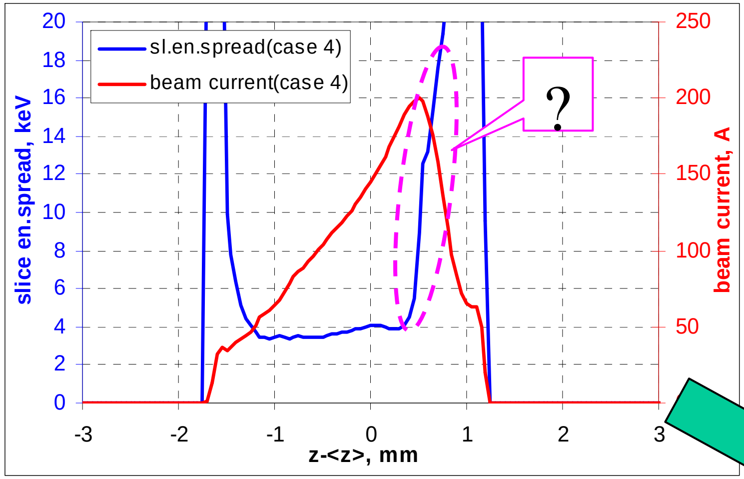


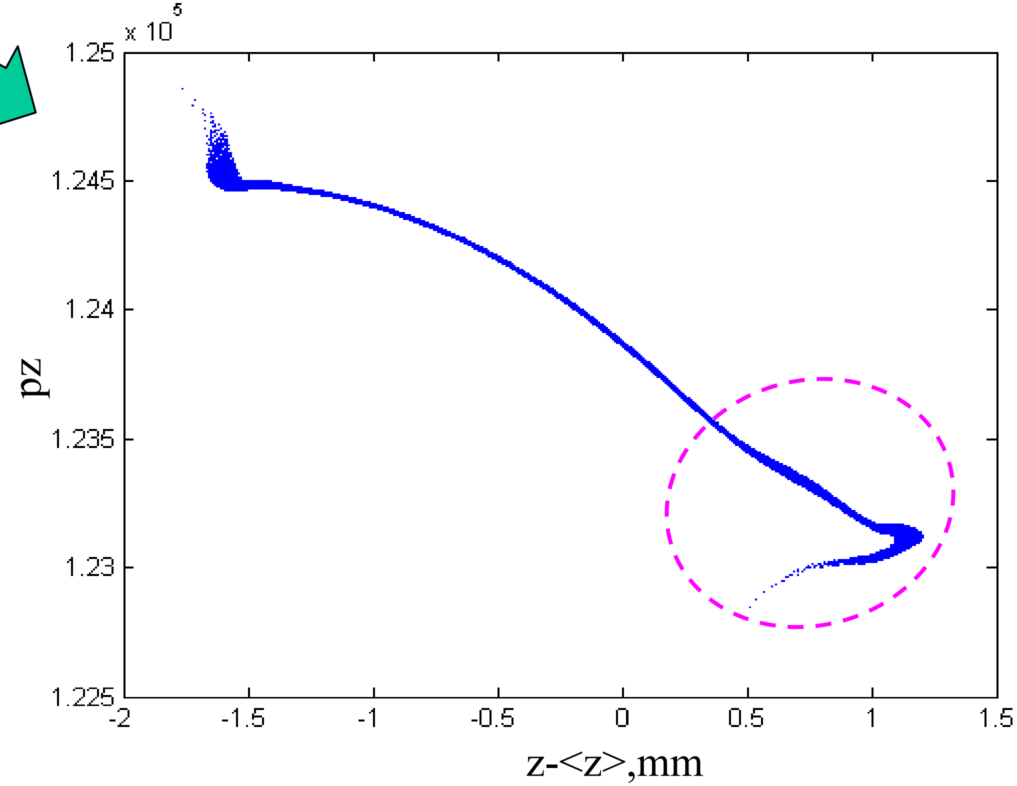




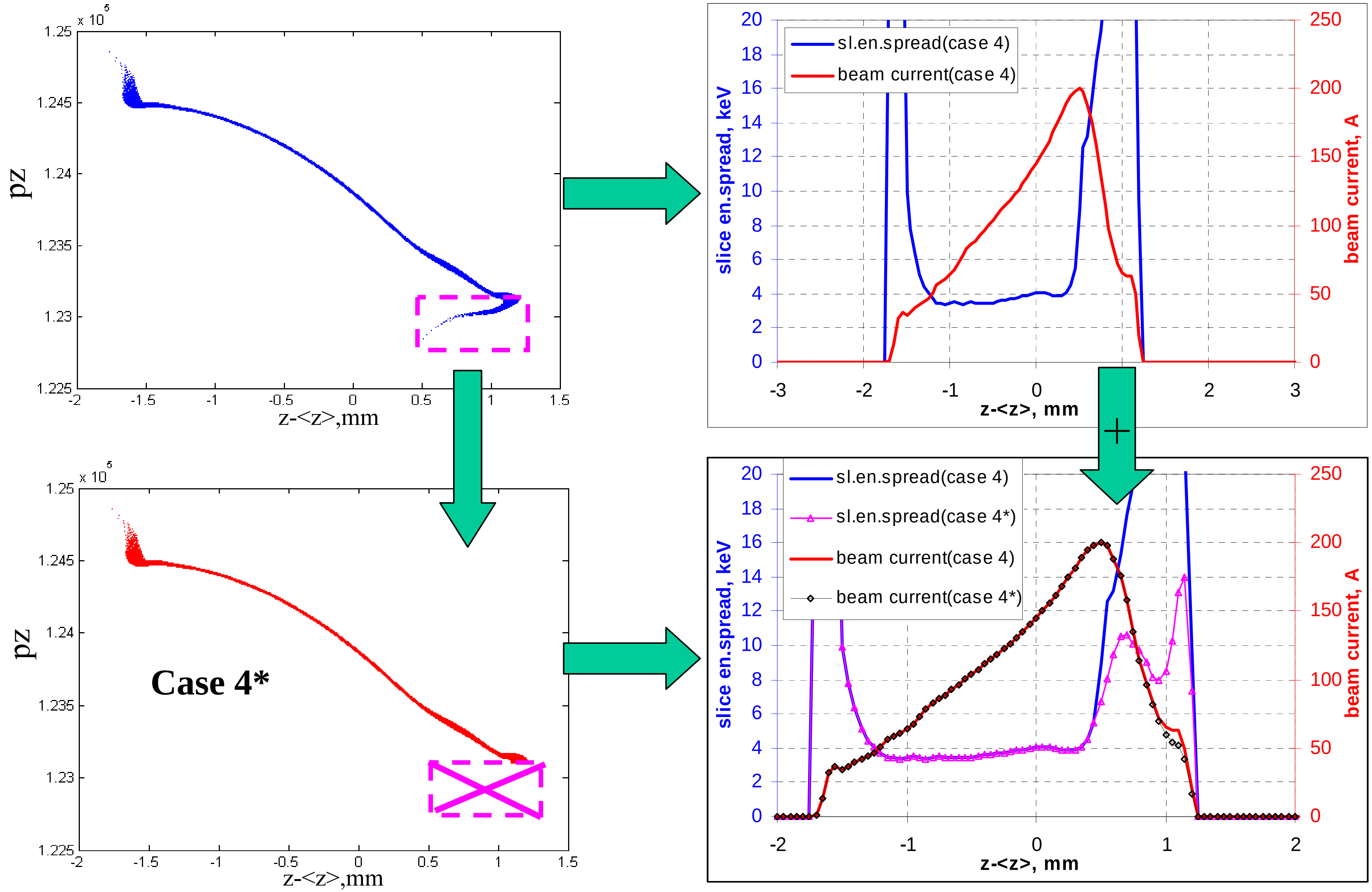


Case 4: longitudinal phase space

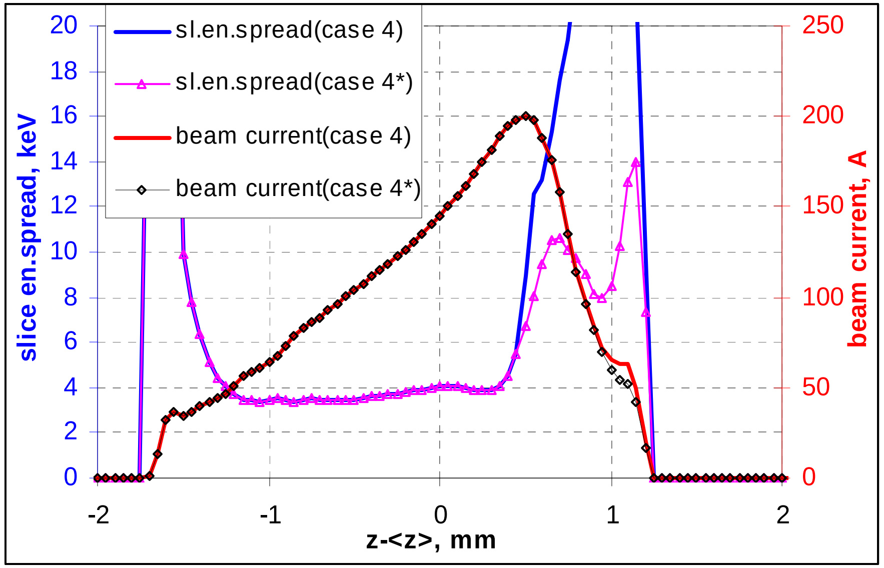


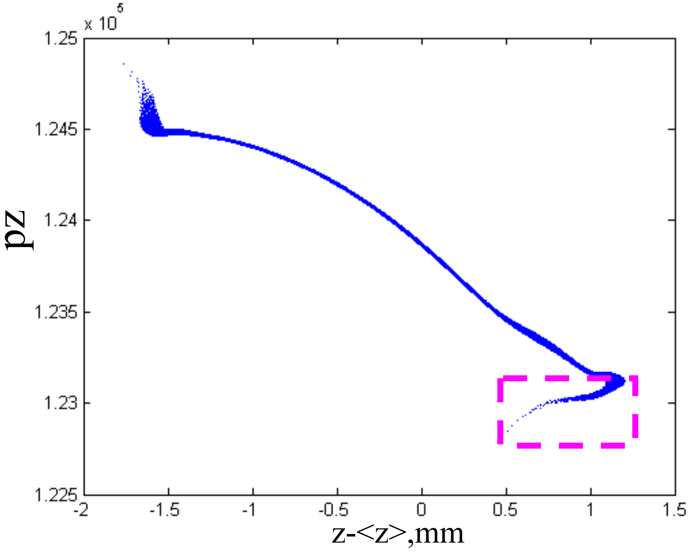


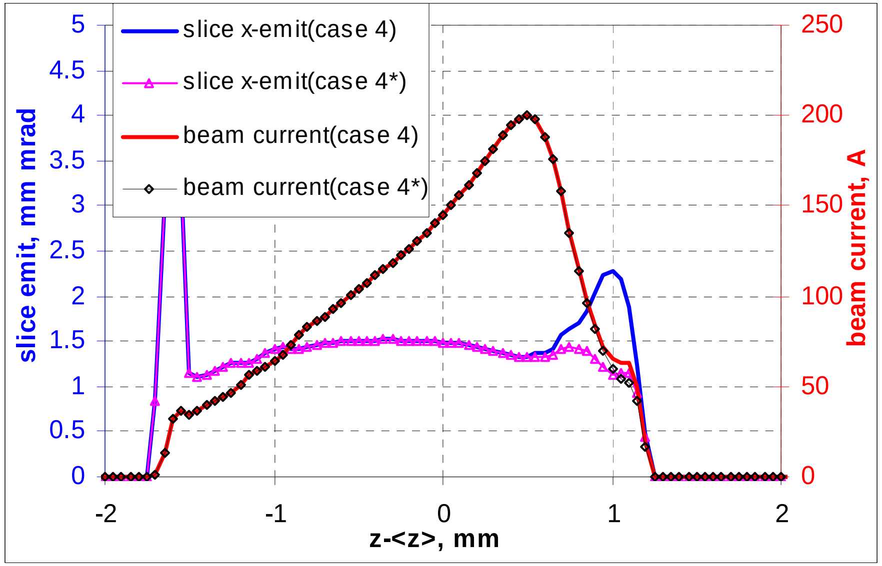
Case 4: longitudinal phase space, effect of the tail



Case 4 vs. case 4*







The main effect of the tail is the increase of the slice emittance and slice energy spread, but not the beam current

Conclusions and outlook

- ASTRA simulations of the velocity bunching (VB) options with tuned main solenoid yields (compared to the nominal case) at z=15m:
  - Peak current of ~**110A** (instead nominal 45A)
  - Slice emittance in the middle of the bunch ~**0.6 mm mrad** (nominal 0.73)
  - Slice emittance in the current peak location ~0.55 mm mrad
  - Slice energy spread in the middle of the bunch ~**4.4 keV** (nominal 0.6 keV)
  - Slice energy spread in the current peak location ~3.9 keV

- More flexible optimization of the velocity bunching option of the XFEL photo injector (including tuning the main solenoid current, laser spot size at the cathode and ACC1 separate phasing) results in better compression of the bunch after the photo injector:
  - Peak current of ~**200A** for the bunch with 0.67 mm rms bunch length
  - The projected transverse emittance of ~2.4 mm mrad
  - The slice emittance in the bunch core ~1.3-1.5 mm mrad
  - Slice energy spread increased (especially in the bunch head)

- The tail of the longitudinal phase space of the electron bunch affects corresponding slice emittance and slice energy spread but almost has no influence on the beam current profile

- Further sources of possible improvement:
  - Variation of the RF gradient along the ACC1 (VB × Emittance matching)
  - Goal function ~> peak current + slice emittance