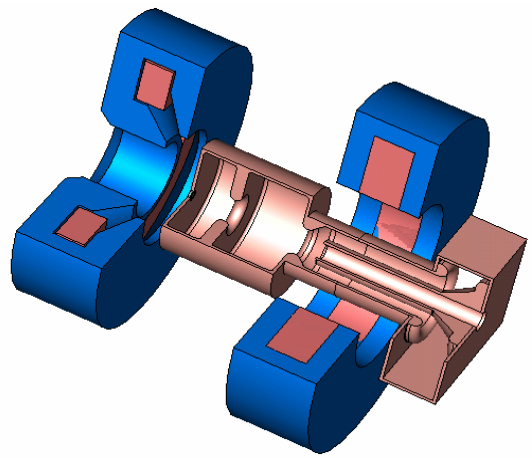
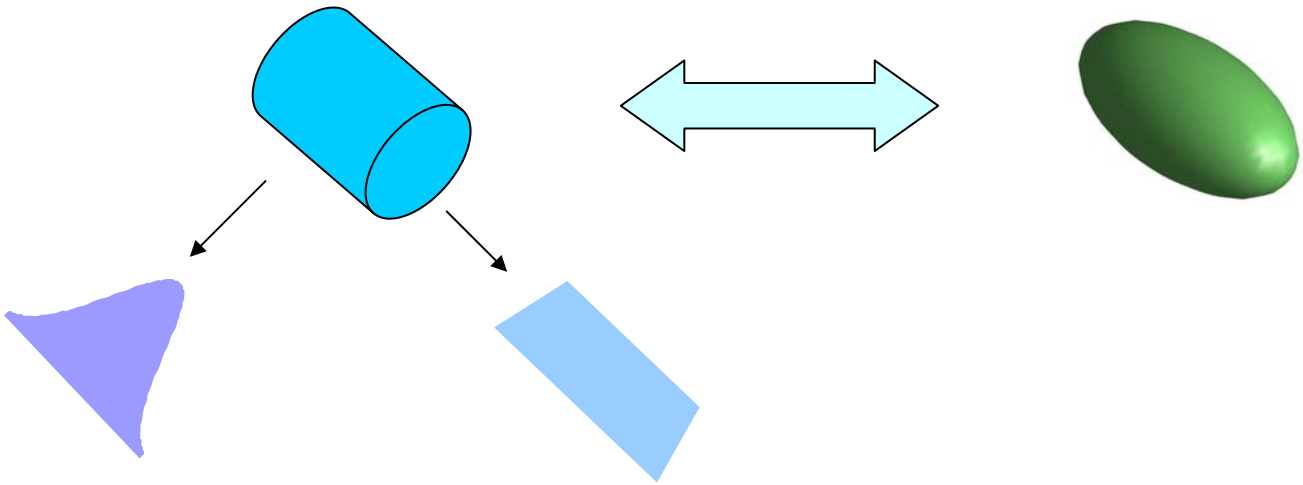
Beam dynamics simulations for various shapes of the cathode laser pulse

M.Krasilnikov, DESY, Zeuthen





Introduction

- **Motivation:** further improvement of the electron beam quality - reduction of the transverse beam emittance from the photo injector

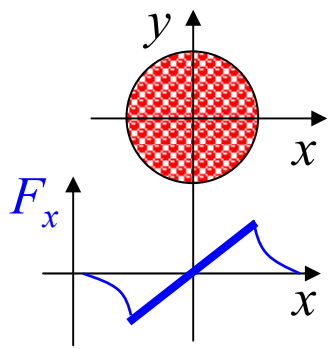
$$Goal:\ \varepsilon \le 0.9\ \ mm\ mrad\ \ (for\ nominal\ 1nC)$$

- **Main idea:** optimization of the cathode laser pulse shape in order to minimize an impact of the space charge onto the transverse phase space

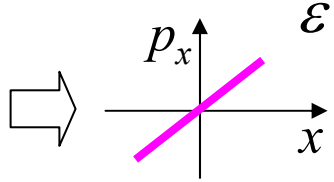
Contributions to emittance $\varepsilon = \sqrt{\varepsilon_{cath}^2 + \varepsilon_{RF}^2 + \varepsilon_{SpCh}^2}$ $\varepsilon_{SpCh} \to \min$ ε_{cath}

1959: *I.M. Kapchinsky and V.V. Vladimirsky*

transverse beam dynamics of this distribution in linacs ➔ **K-V distribution**

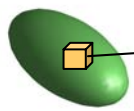


2D X-Y distribution



$\varepsilon = inv$

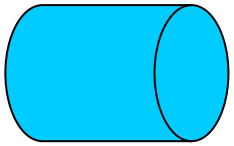
?Produce electrons uniformly distributed in 3D ellipsoid volume ➔



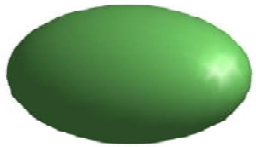
$$\frac{N}{dx\,dy\,dz} = const.$$

Photocathode laser pulse shape

cylindrical

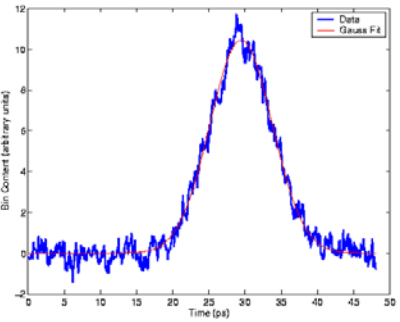


3D ellipsoidal

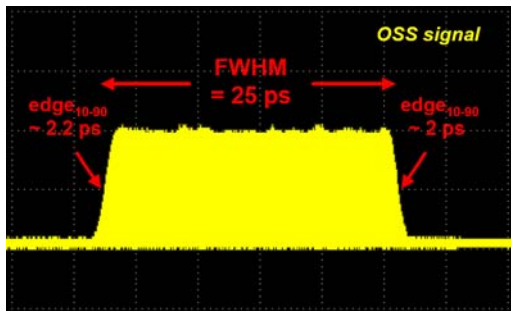


temporally

Gaussian
(e.g. FLASH)
Trms=4.4ps

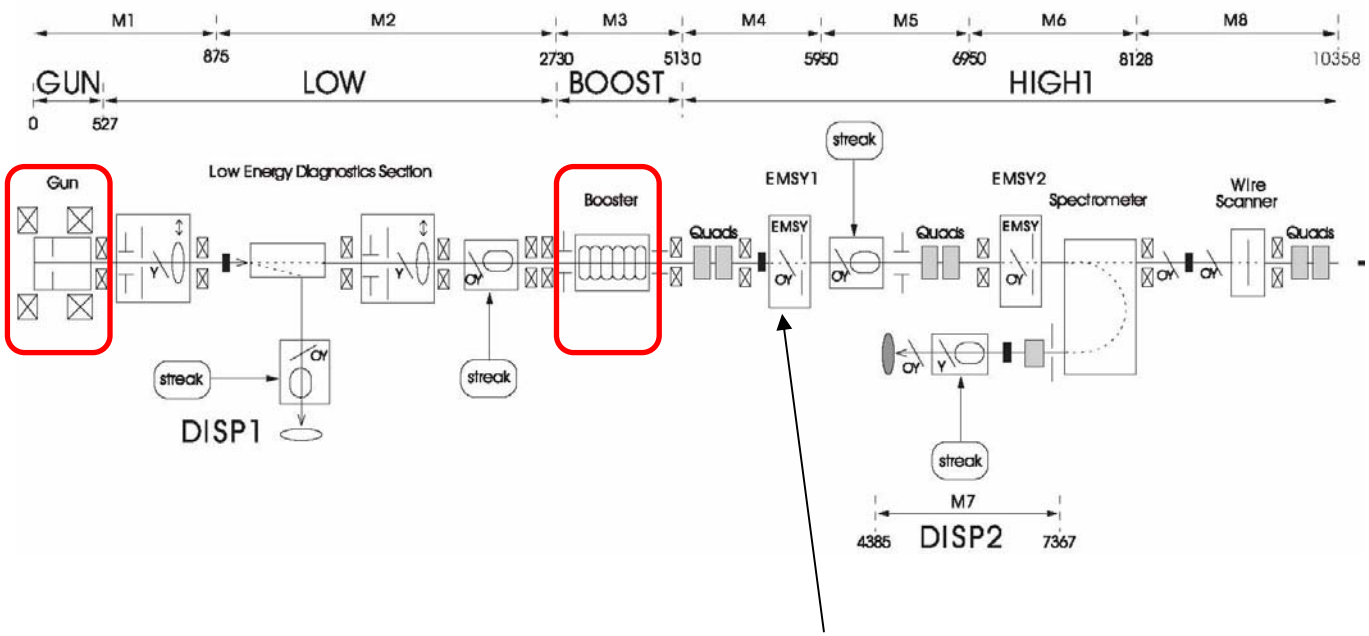


Flat-top
(e.g PITZ)
FWHM~20ps, rt~2ps



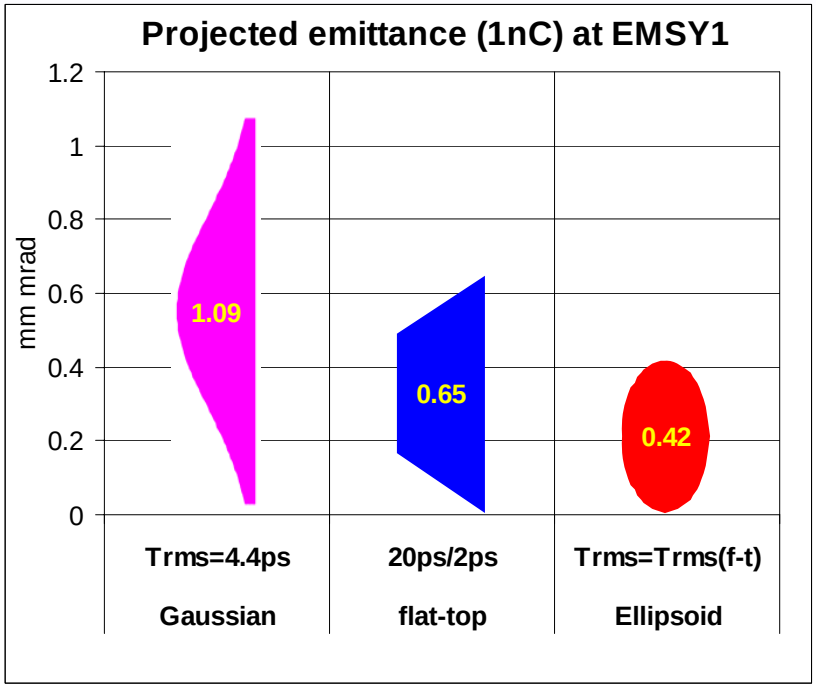
Beam dynamics (BD) simulations

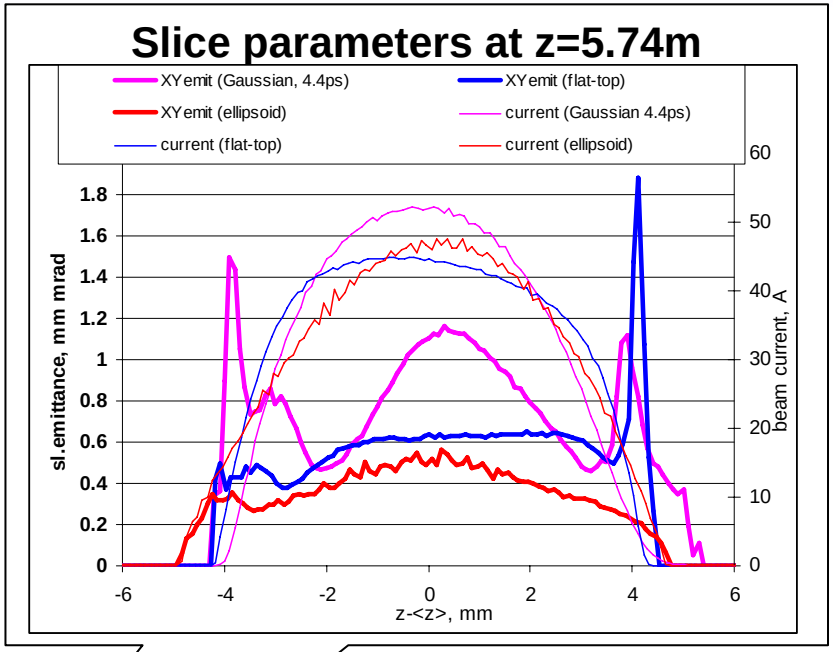
- PITZ setup:
  - Layout fixed (solenoid and booster positions)
  - Ecathode=60MV/m
  - 2 bunch charges: 1nC and 100pC

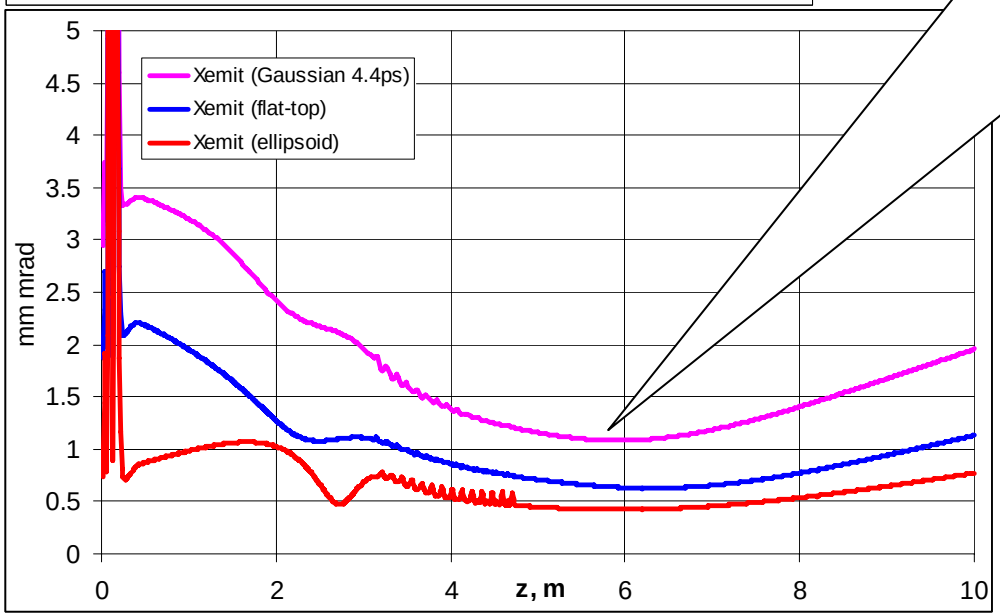


- Goal: minimum projected emittance at EMSY1 (z=5.74m)
- Tuning parameters:
  - Cathode laser (temporal and transverse), but Ek=0.55eV-fixed
  - Main solenoid peak field
  - RF-gun launch phase
  - Booster gradient

BD simulations for bunch charge 1 nC



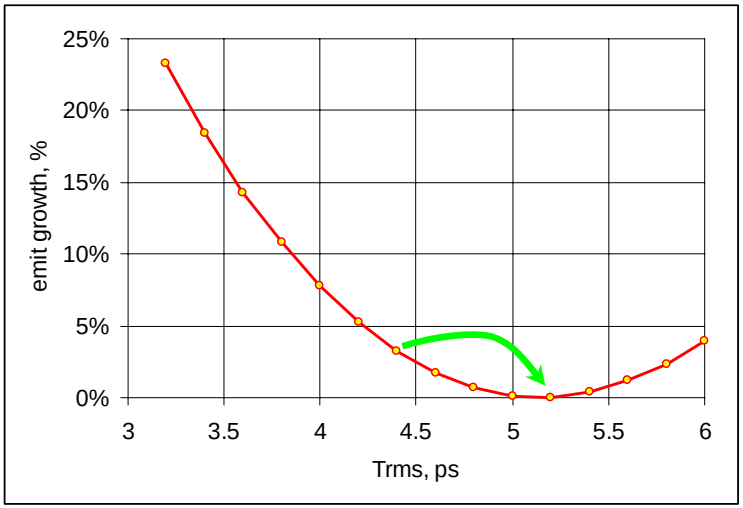


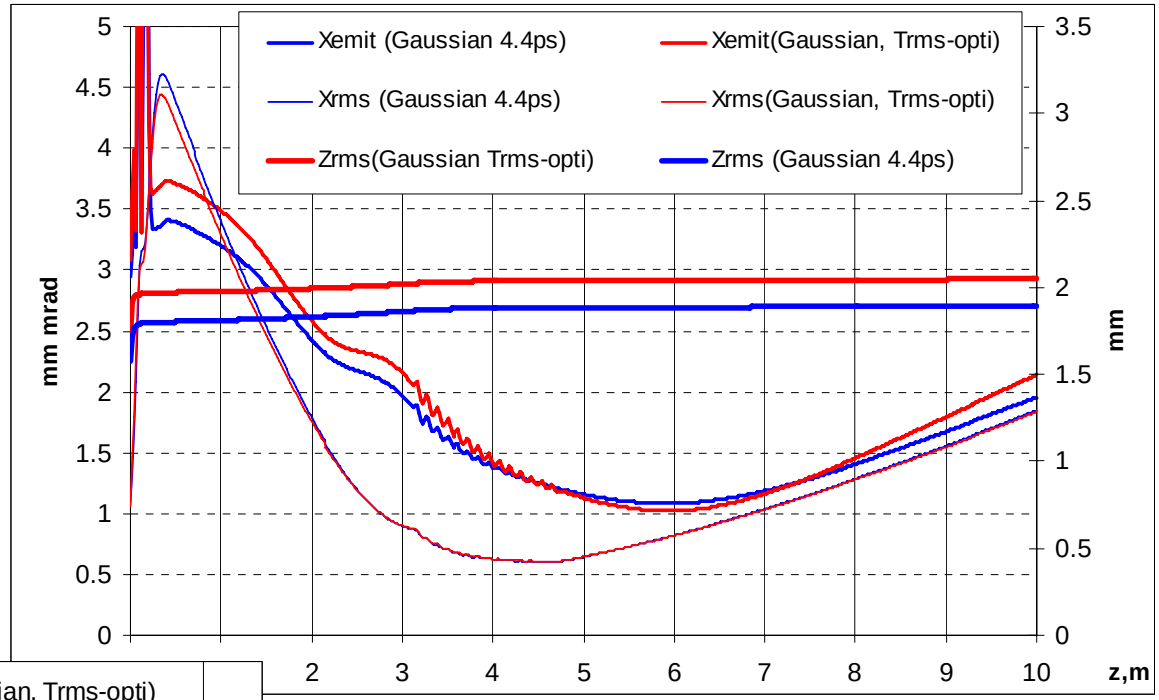


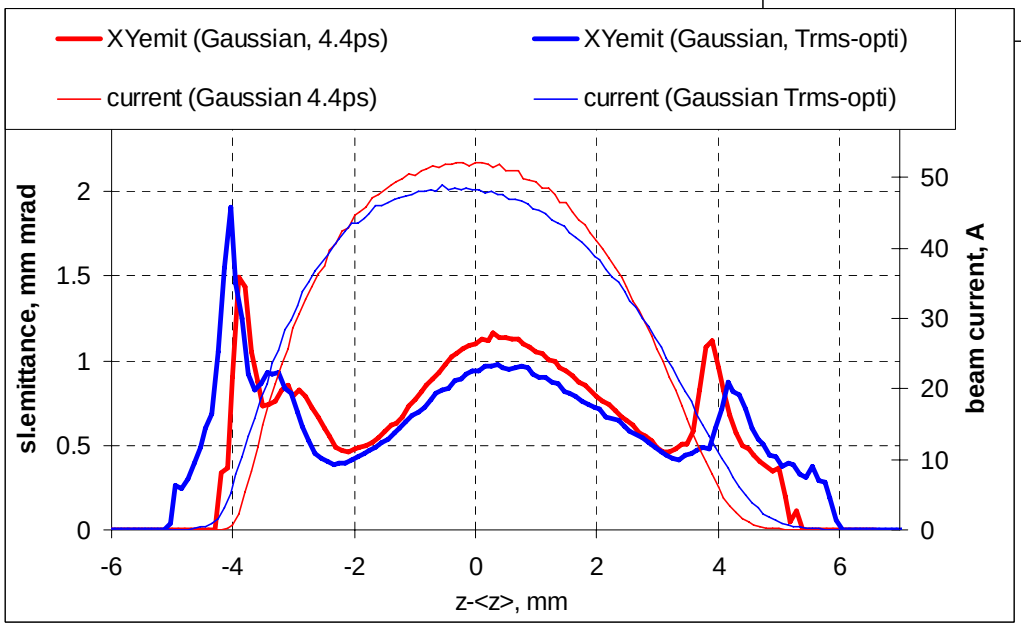
	parameter	unit	laser shape type		
			cylindrical		3D ellipsoidal
cathode laser	temporal	profile	Gaussian	Flat-top	3D ellipsoidal
	transverse	distribution	radial homogen.		
	Trms	ps	4.4	5.8	5.8
	XYrms	mm	0.427	0.415	0.389
	Ek	eV	0.55		
	th.emit.	mm mrad	0.36	0.35	0.33
RF-gun	Ecath	MV/m	60		
	phase	deg	-3.1	-1.9	-2.8
	maxBz	T	-0.2253	-0.2258	-0.2277
CDS boost	maxE		18.5	19.1	19.1
	phase	deg	0		
e-beam @EMSY1	charge	nC	1		
	energy	MeV	22.3	22.7	22.8
	proj.emit.	mm mrad	**1.09**	**0.65**	**0.42**
	th./proj.em.	%	**33%**	**54%**	**78%**
	<sl.emit.>	mm mrad	0.82	0.58	0.41

BD simulations for bunch charge 1 nC

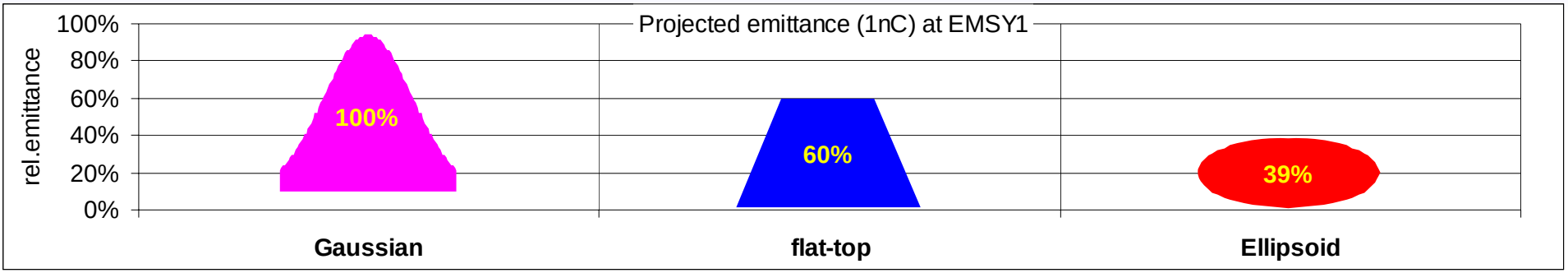
- Gaussian pulse length optimization
- 1.09→1.03 mm mrad only



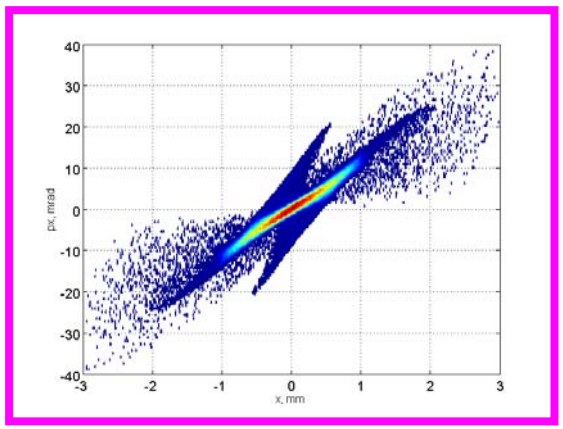


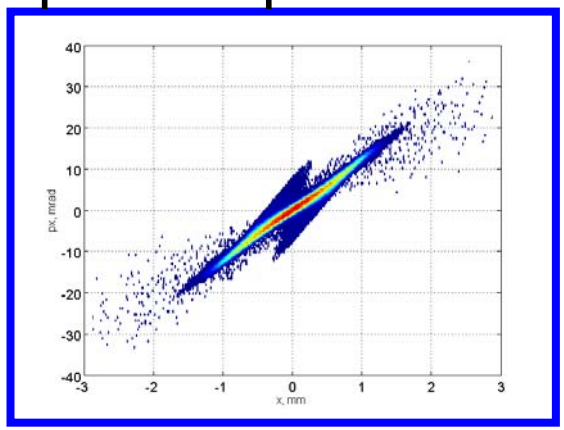


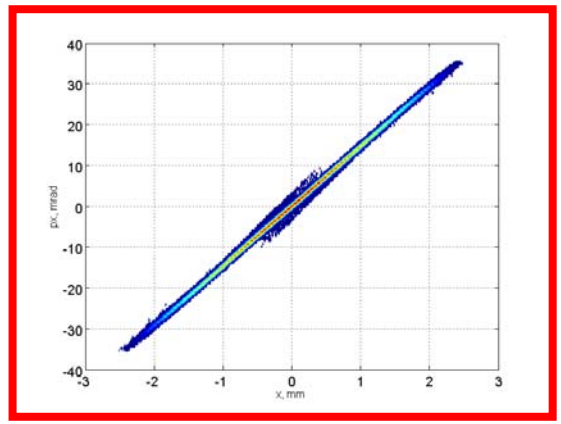
BD simulations for bunch charge 1 nC



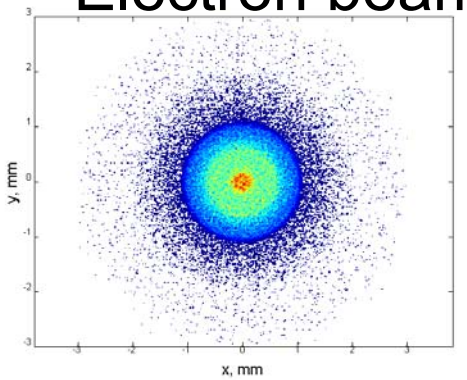
Transverse phase space at z=5.74m

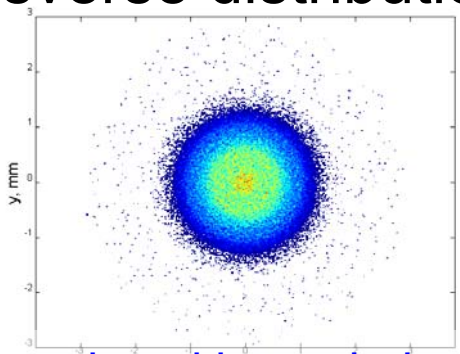




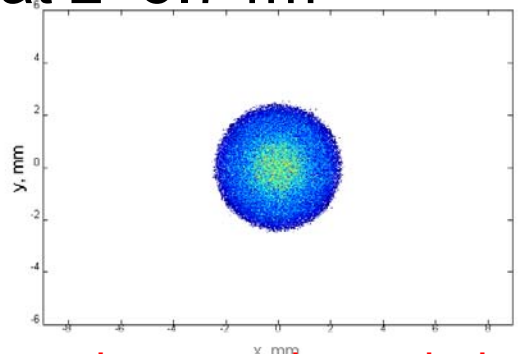


Electron beam transverse distribution at z=5.74m



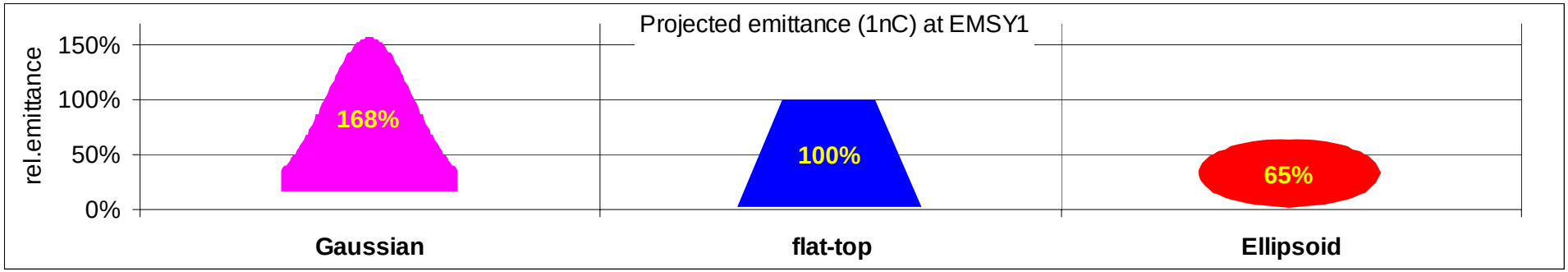


reduced beam halo

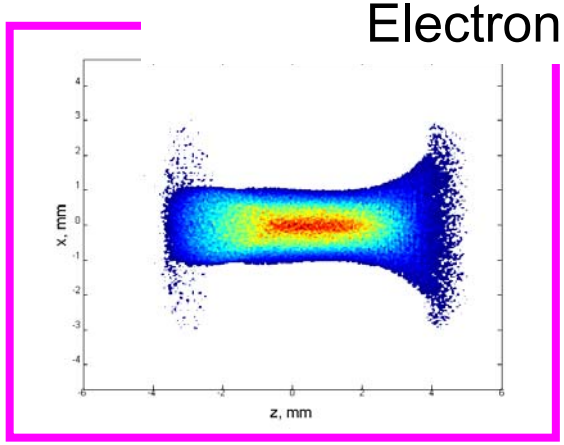


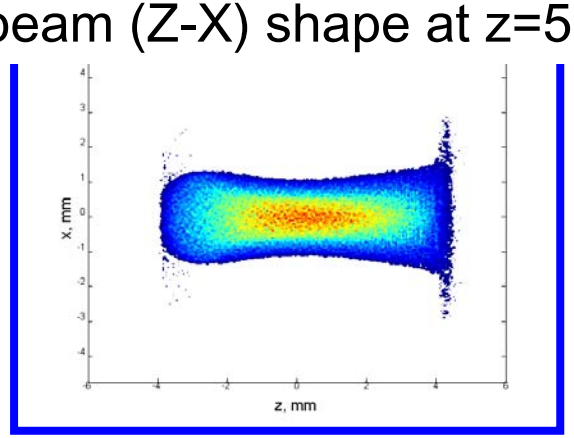
almost no beam halo

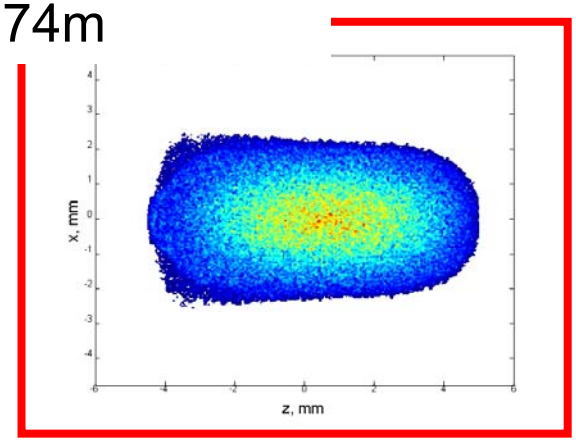
BD simulations for bunch charge 1 nC



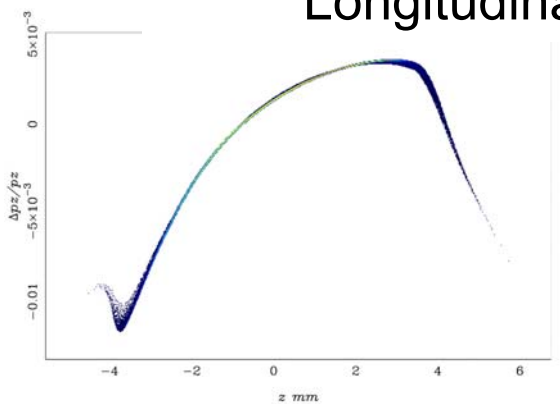
Electron beam (Z-X) shape at z=5.74m

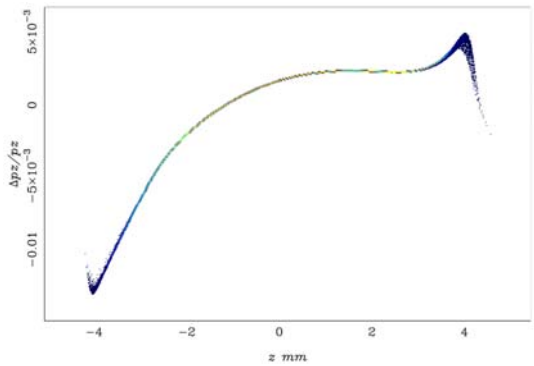


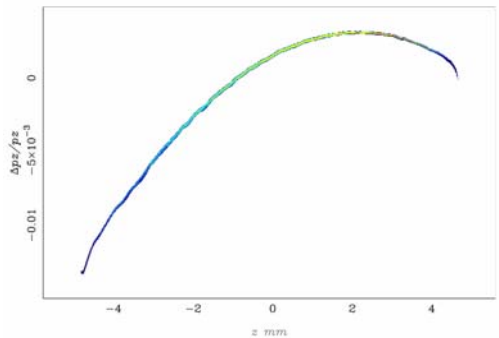




Longitudinal phase space (Z-Pz) at z=5.74m



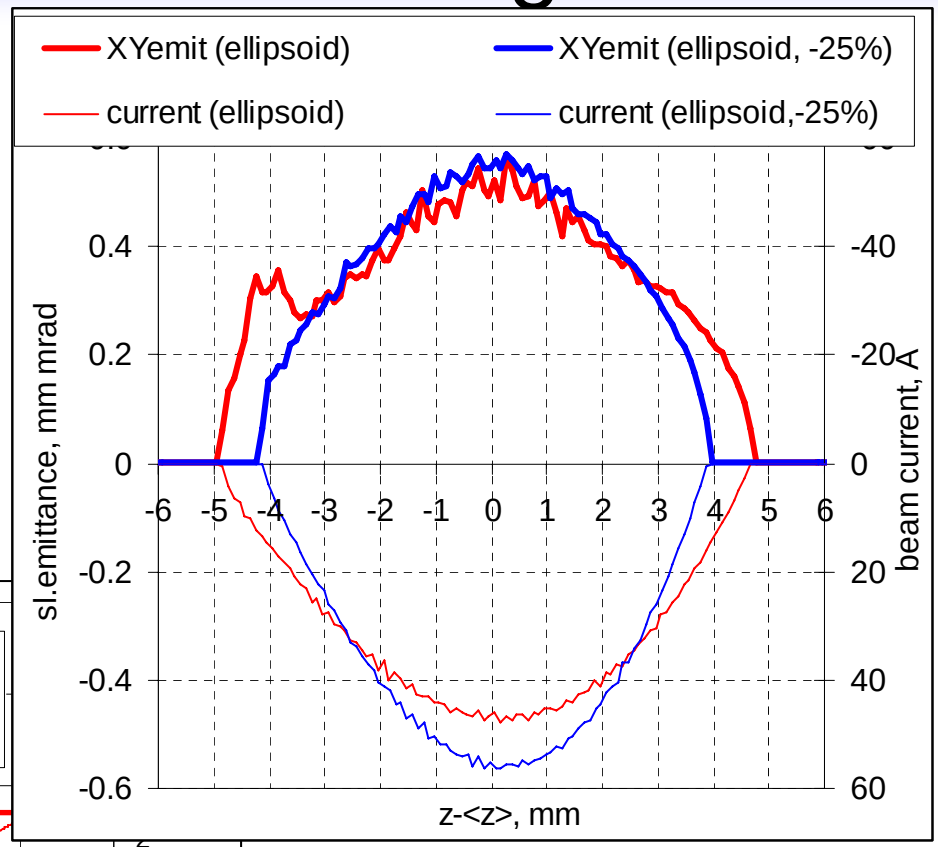


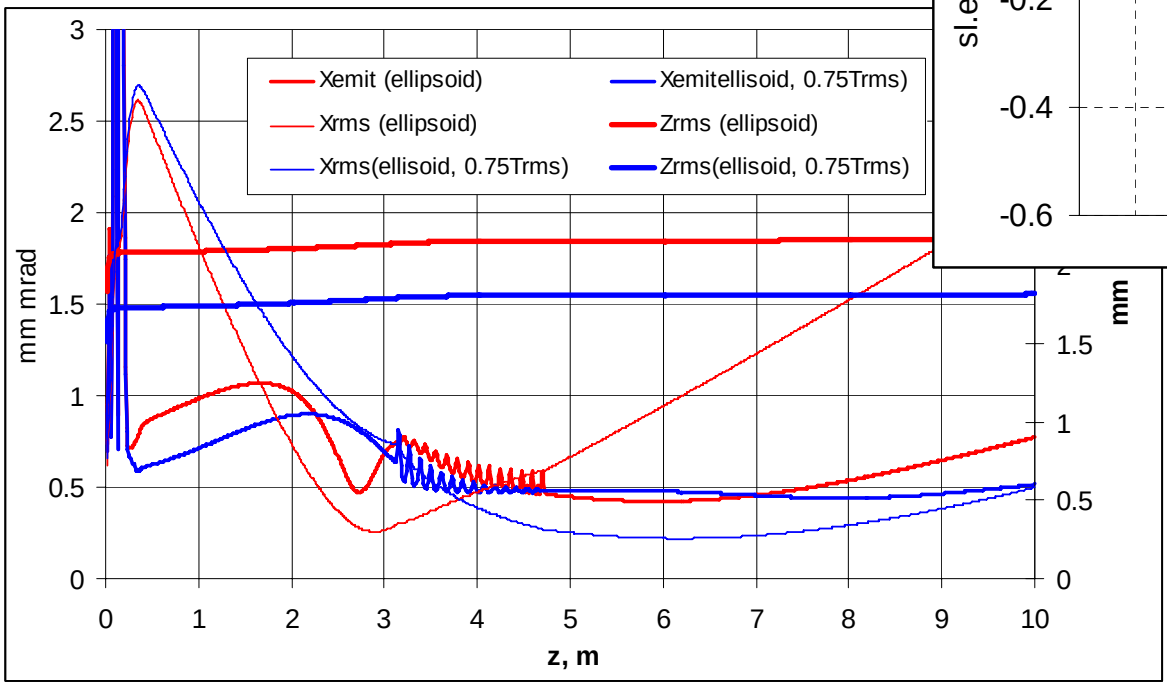


less nonlinearity

BD simulations for bunch charge 1 nC

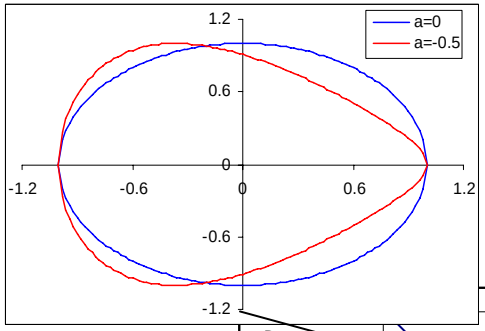
- Ellipsoidal with -25% Trms?
- 0.42 mm mrad → 0.48 mm mrad
- Not so much optimized + another minimum?

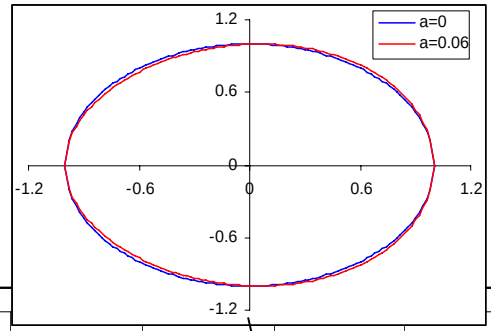


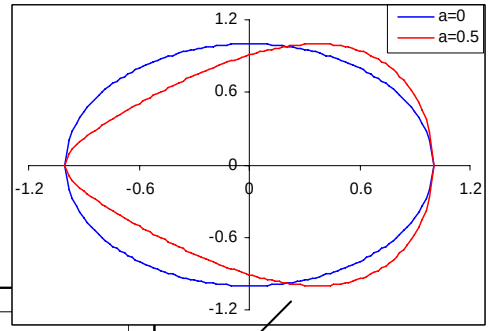


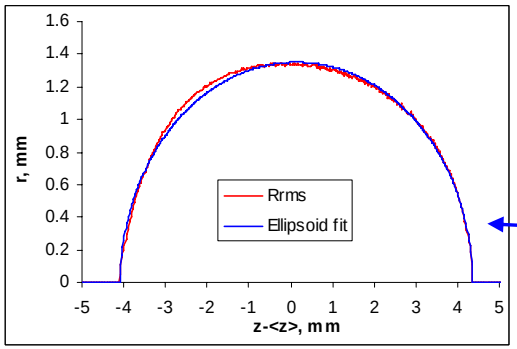
Laser 3D shape fine adjustment

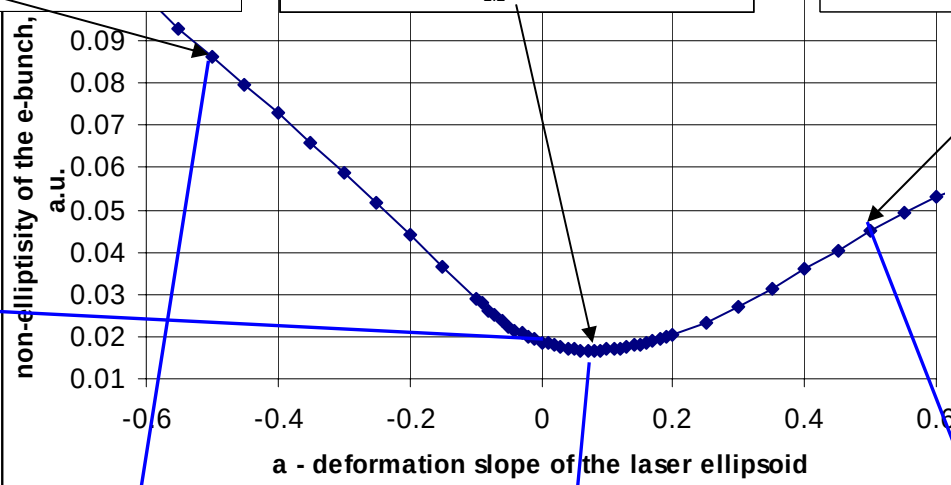
cathode laser shape

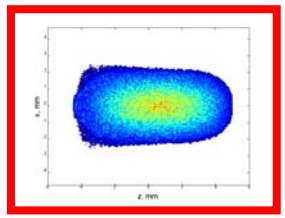




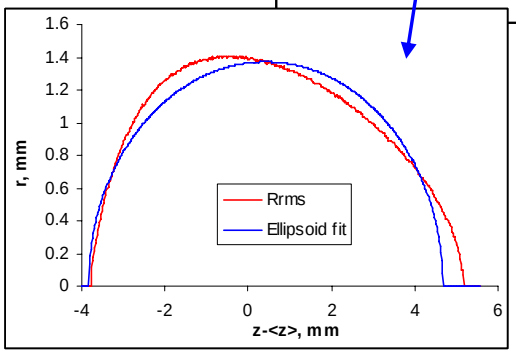


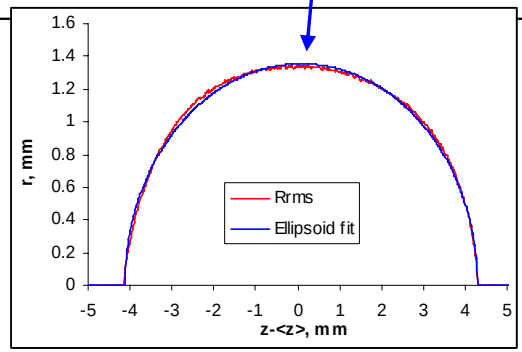


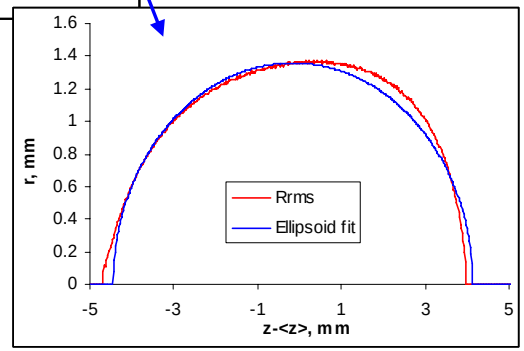




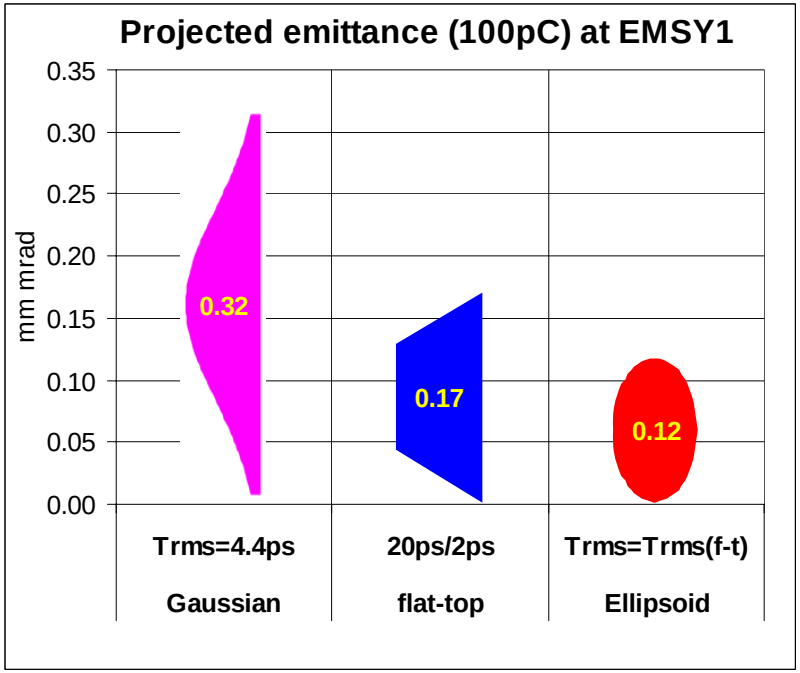
electron bunch @z=1cm

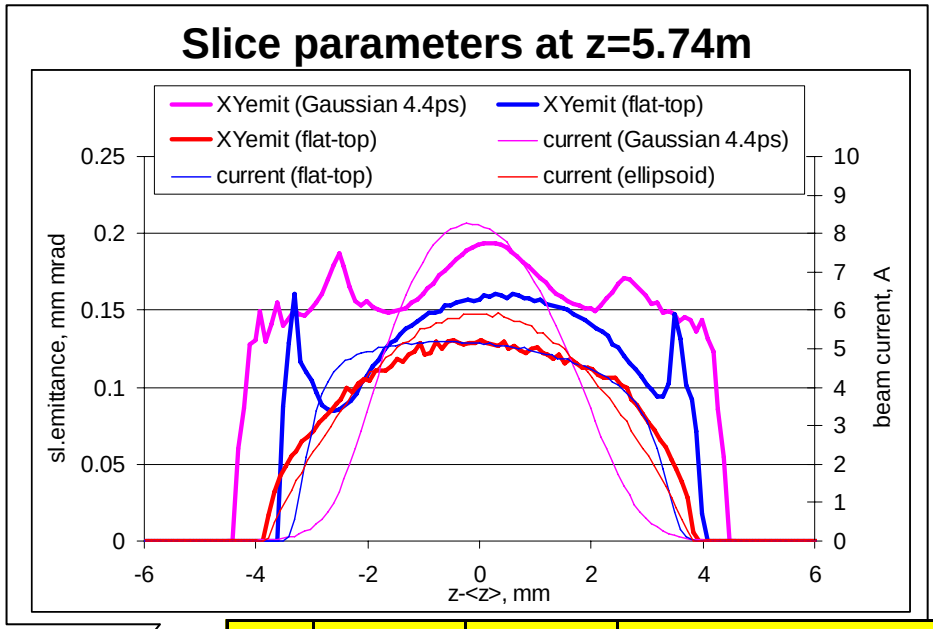


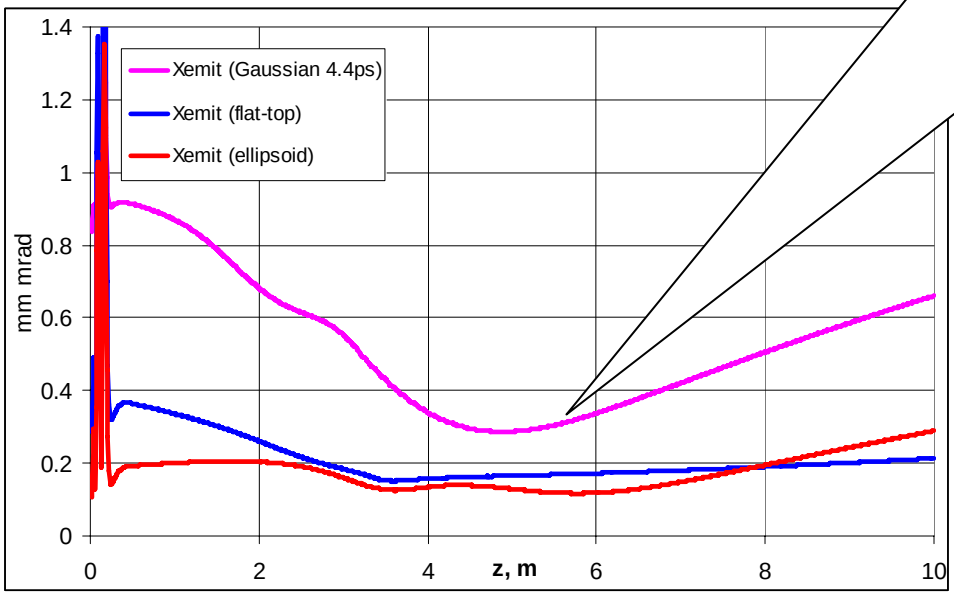




BD simulations for bunch charge 100 pC

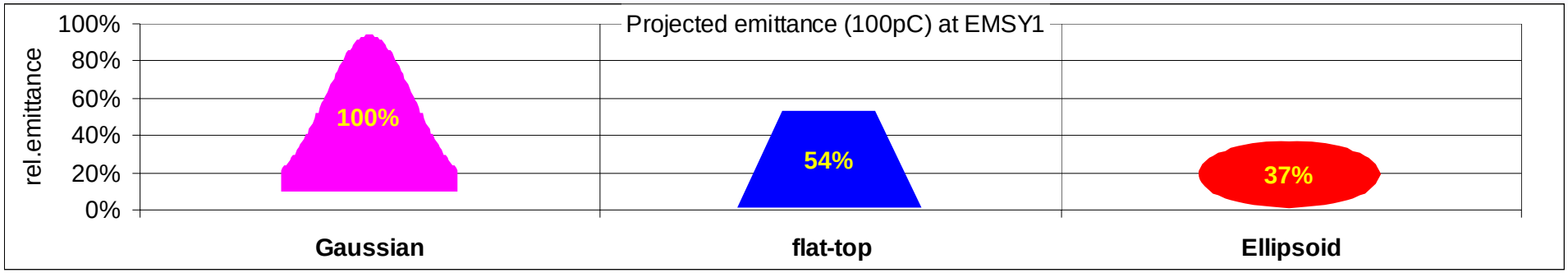




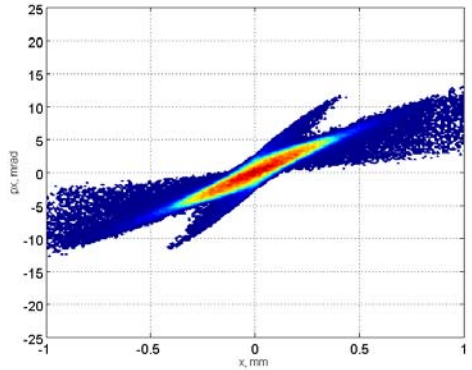


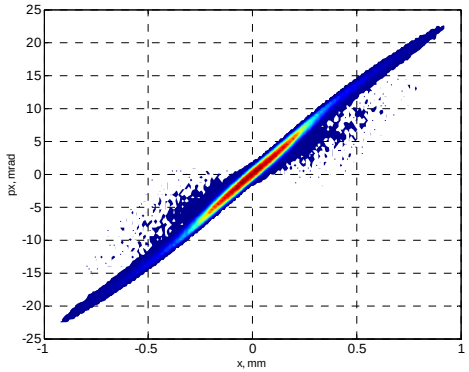
	parameter	unit	laser shape type		
			cylindrical		3D ellipsoidal
cathode laser	temporal	profile	Gaussian	Flat-top	3D ellipsoidal
	transverse	distribution	radial homogen.		
	Trms	ps	4.4	5.8	5.8
	XYrms	mm	0.175	0.102	0.125
	Ek	eV	0.55		
	th.emit.	mm mrad	0.15	0.09	0.11
RF-gun	Ecath	MV/m	60		
	phase	deg	-1.5	1.0	1.0
	maxBz	T	-0.2245	-0.2251	-0.2235
CDS boost	maxE		16.7	25.7	4.9
	phase	deg	0		
e-beam @EMSY1	charge	nC	0.1		
	energy	MeV	20.7	28.5	10.4
	proj.emit.	mm mrad	**0.32**	**0.17**	**0.12**
	th./proj.em.	%	**46%**	**51%**	**88%**
	<sl.emit.>	mm mrad	0.17	0.13	0.11

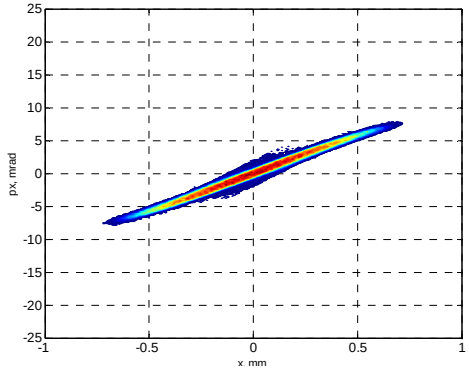
BD simulations for bunch charge 100 pC

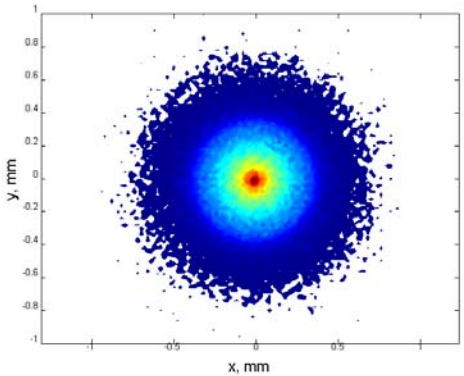


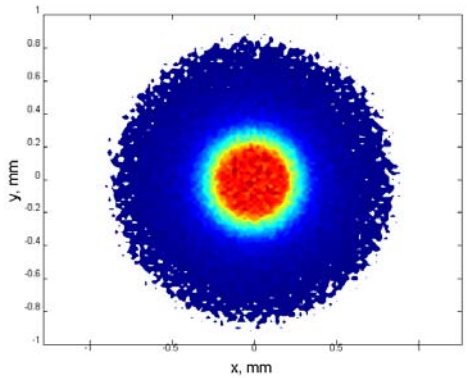
Transverse phase space at z=5.74m

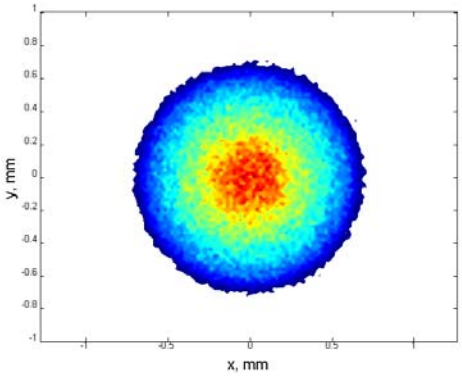






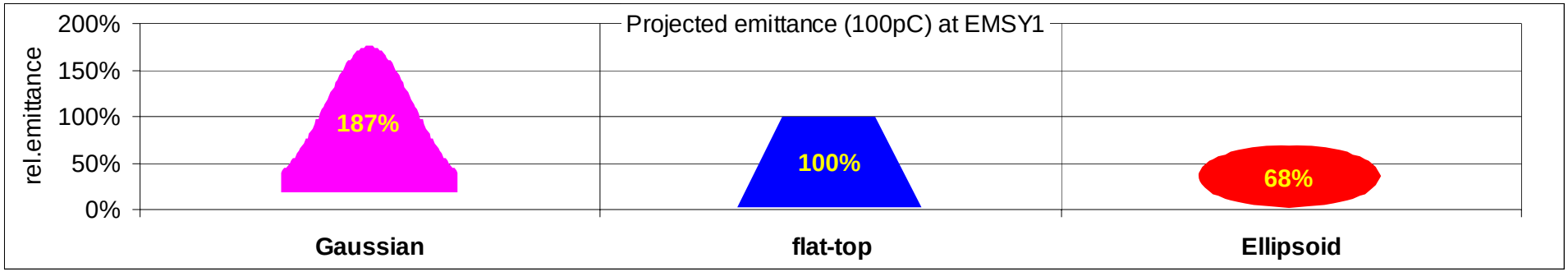




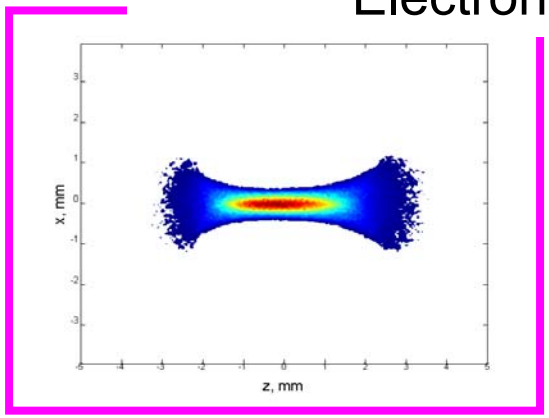


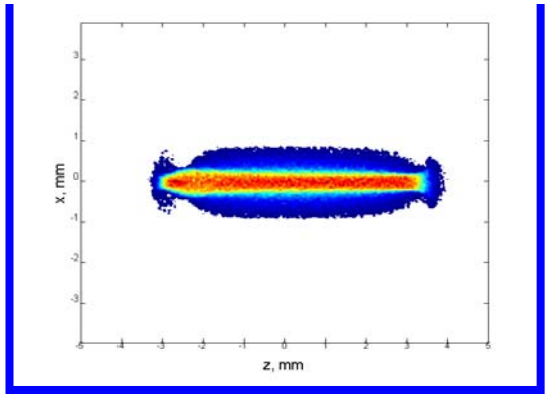
almost no beam halo

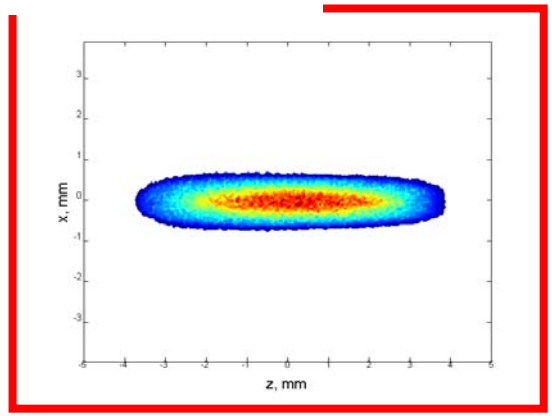
BD simulations for bunch charge 100 pC



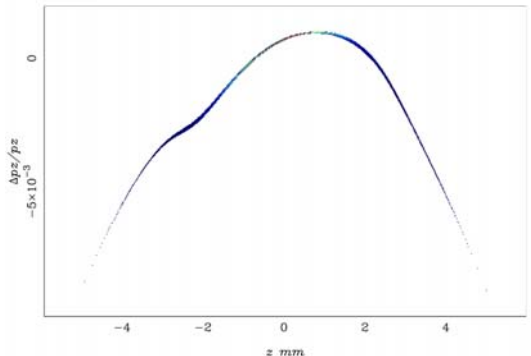
Electron beam (Z-X) shape at z=5.74m

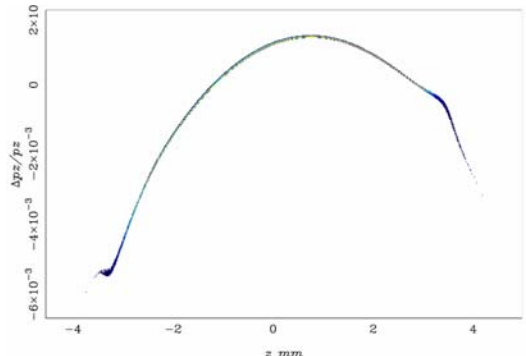


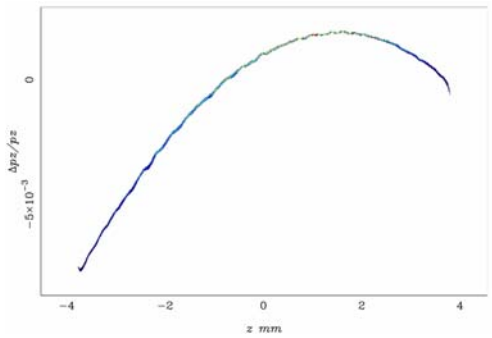




Longitudinal phase space (Z-Pz) at z=5.74m

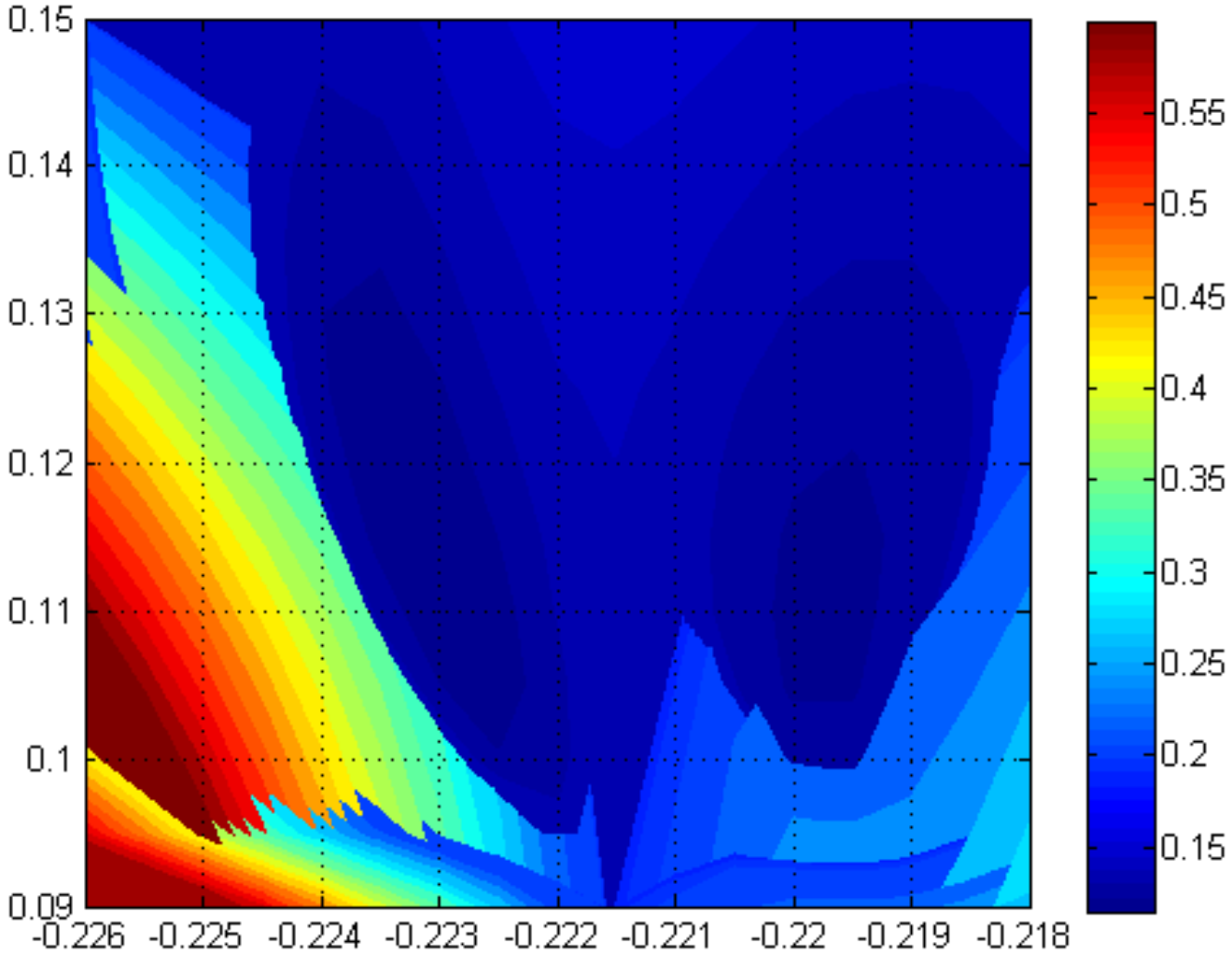






BD simulations for bunch charge 100 pC

- Ellipsoidal 2D plot with 2 minima!



BD simulations for bunch charge 100 pC

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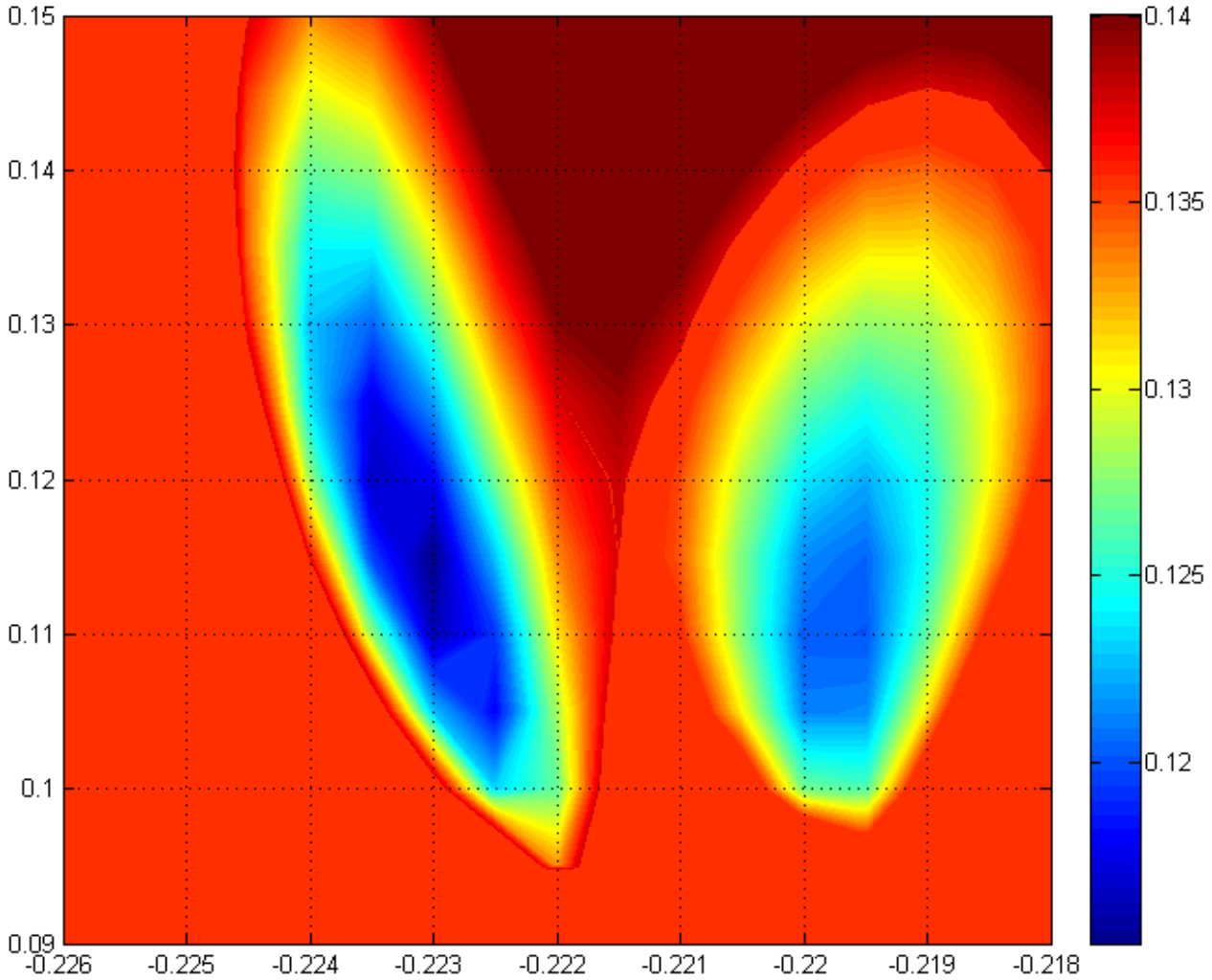

BD simulations for bunch charge 100 pC

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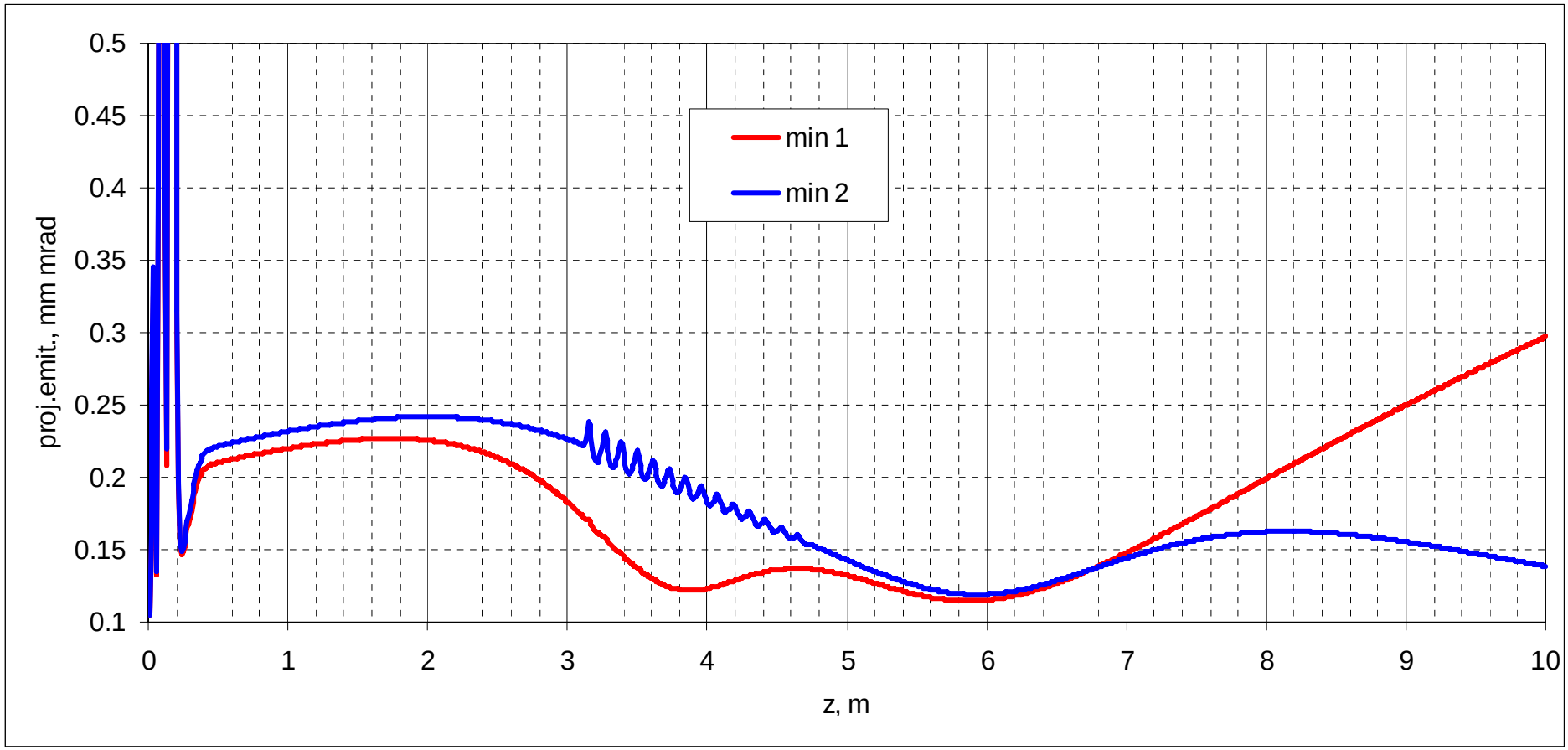
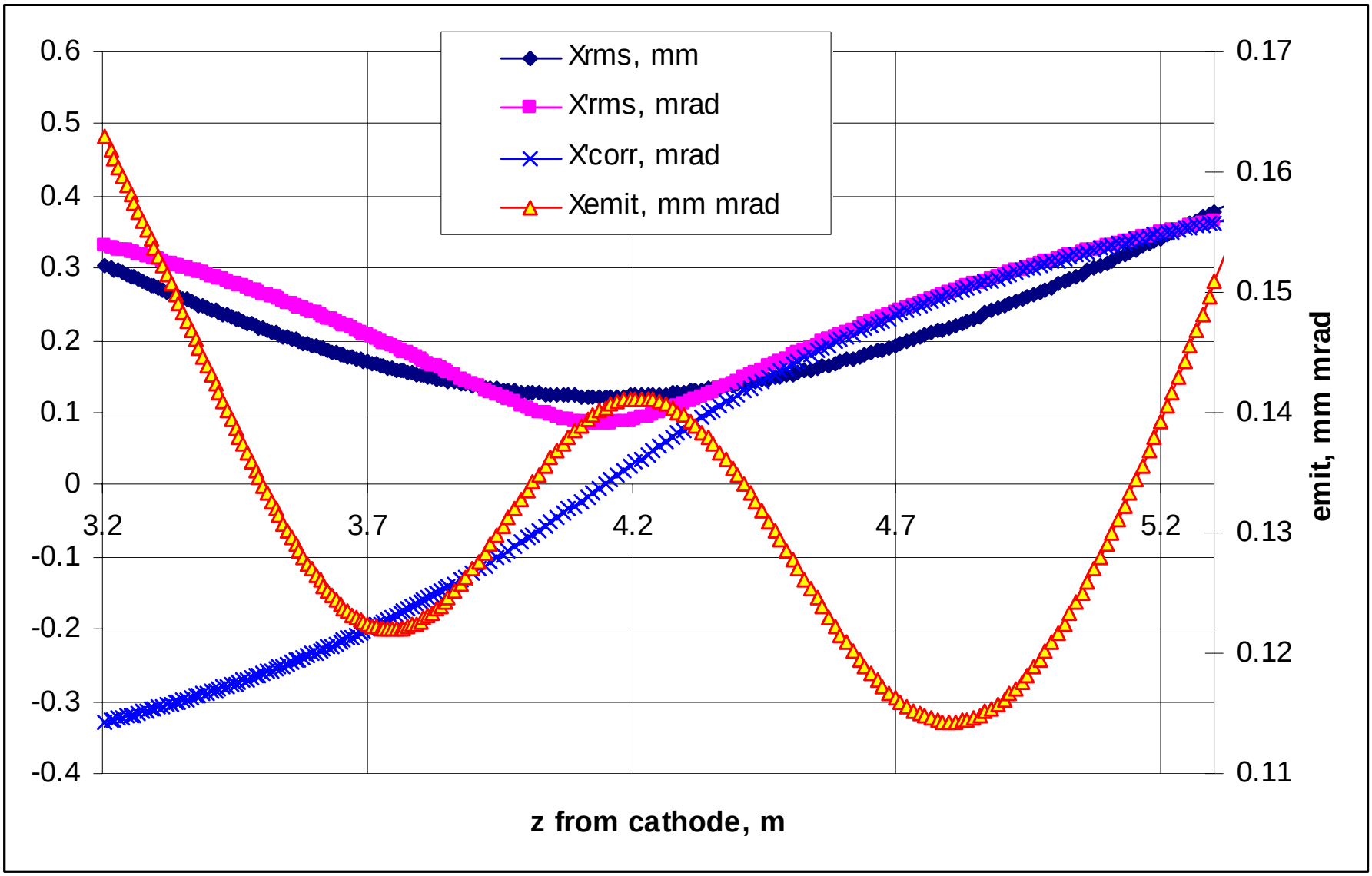


2 emittance minima

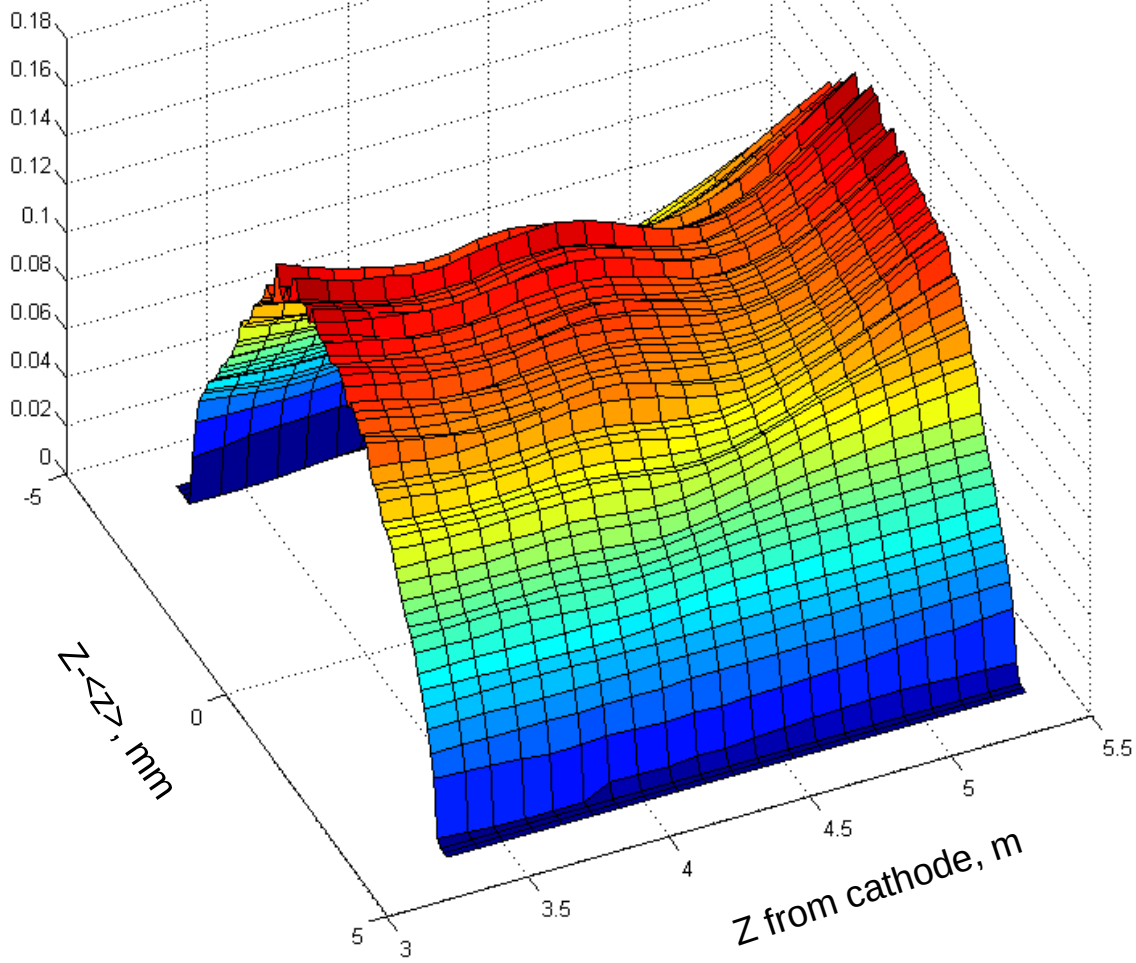
No booster applied!



2 emittance minima

- Slice emittance has also 2 minima!

No booster applied!



Conclusions

- Cathode laser pulse shaping is one of the key issues for the photo injector optimization
- Beam dynamics simulations applying a **3D** pulse shaping (ellipsoid) yield:
  - significant reduction in beam projected emittance: more than -60% compared to the Gaussian and more than -35% compared to the flat-top laser profile
  - reduction in average slice emittance: -50-35% compared to the Gaussian and -30-15% compared to the flat-top laser profile
  - projected emittance budget is strongly dominated by the thermal emittance contribution (78-88%)
  - reduced beam halo
  - less nonlinear longitudinal phase space
- PITZ is capable for experimental proof
- 3D-Ellispoid feasibility is under tests at various labs
- Start-to-End simulations remain to be done

- Emittance optimization strategy has to be refined to resolve the multi minima emittance parameter space
- Emittance compensation (2 emittance minima) has to be studied in more details

Proposals for the optimization strategy

1. Initial guess
2. 2D scan for the emittance emit (XYrms,MaxB1)
3. For all local minima – further booster optimization (gradient and position), booster phase → on crest
4. Optimization refinement in small area (XYrms,MaxB1,Phi1,Phi2)
5. Tolerances studies (1D scans)

BD simulations for bunch charge 1 nC

- Ellipsoidal with -25% Trms?
- Long.phase space plots!!!