3D ellipsoid beams for a better performance of a high brightness photoinjector

- Introduction
- Beam dynamics studies comparing different cathode laser shapes
- Booster position optimization for 3D ellipsoidal laser profile at 1nC charge
- Beam tolerance studies comparing different cathode laser shapes
- Influence of cathode laser shape imperfections on electron beam transverse emittance (3D ellipsoid)
- Booster position optimization for flat-top laser profile at 1nC charge
- Summary

Martin Khojoyan
PITZ Physics Seminar
10.10. 2013

HELMHOLTZ ASSOCIATION

PITZ Photo Injector Test Facility Zeuthen

DESY

- Introduction
- Beam dynamics studies comparing different cathode laser shapes
- Booster position optimization for 3D ellipsoidal laser profile at 1nC charge
- Beam tolerances: comparison of different laser shapes
- Influence of cathode laser shape imperfections on electron beam transverse emittance (3D ellipsoid)
- Booster position optimization for flat-top laser profile at 1nC charge
- Summary

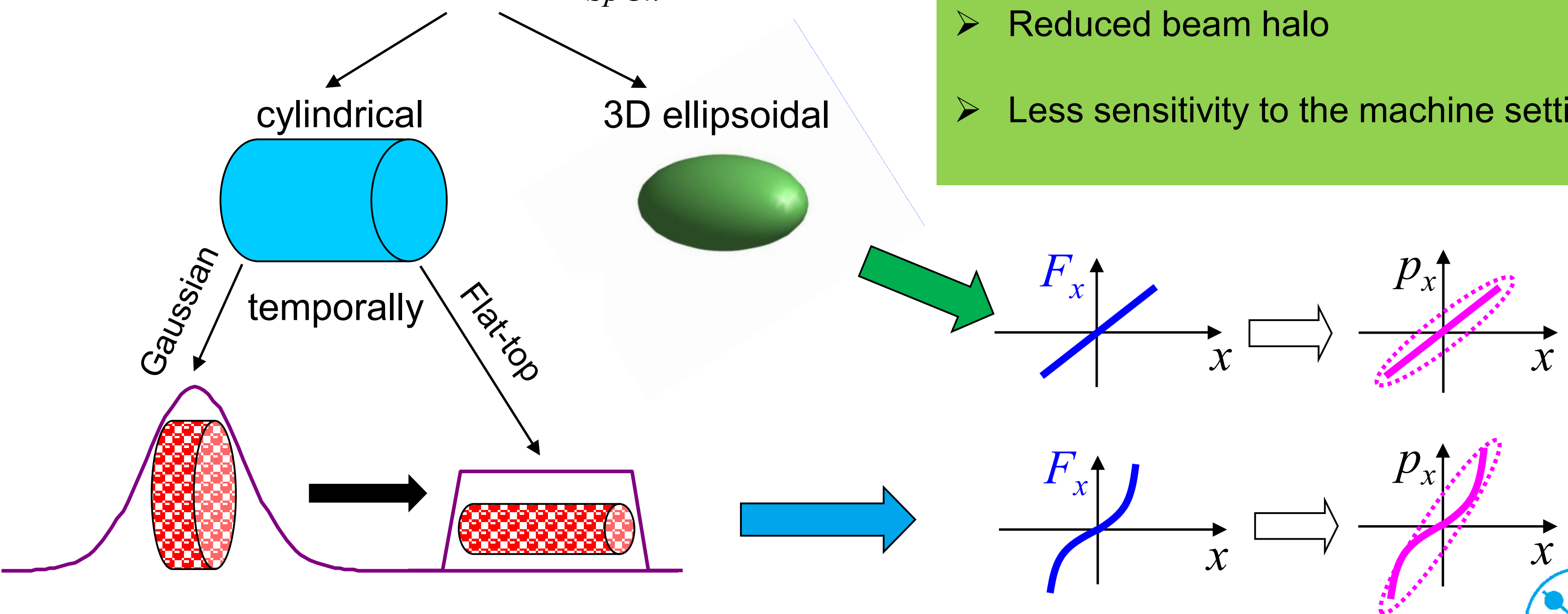
> **Motivation:** Further improvement of the electron beam quality by reduction of the transverse projected beam emittance.

> **Main idea:** Optimization of the cathode laser pulse shape in order to minimize the impact of the space charge on the transverse emittance.

$$\varepsilon = \sqrt{\varepsilon_{cath}^2 + \varepsilon_{RF}^2 + \varepsilon_{SpCh}^2}$$

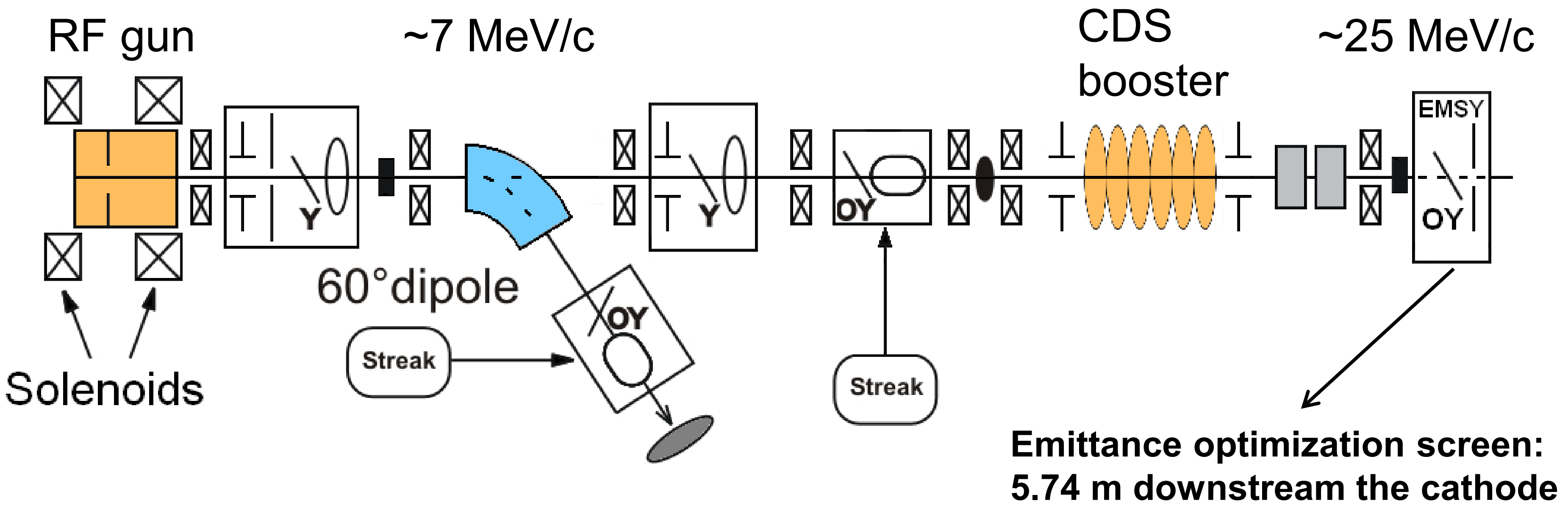
$$\text{cathode laser shape: } \varepsilon_{SpCh} \rightarrow \min$$

- Minimum SC influence on beam emittance
- Better longitudinal compression
- Reduced beam halo
- Less sensitivity to the machine settings



- Introduction
- Beam dynamics studies comparing different cathode laser shapes
- Booster position optimization for 3D ellipsoidal laser profile at 1nC charge
- Beam tolerances: comparison of different laser shapes
- Influence of cathode laser shape imperfections on electron beam transverse emittance (3D ellipsoid)
- Booster position optimization for flat-top laser profile at 1nC charge
- Summary

PITZ setup used in ASTRA simulations



Simulation setup

Three different photo cathode laser shapes have been considered in beam simulations:

- Longitudinal distribution: Gaussian. Transverse distribution: radial homogeneous
- Longitudinal distribution: Flat-top. Transverse distribution: radial homogeneous
- Uniformly filled 3D ellipsoidal distribution

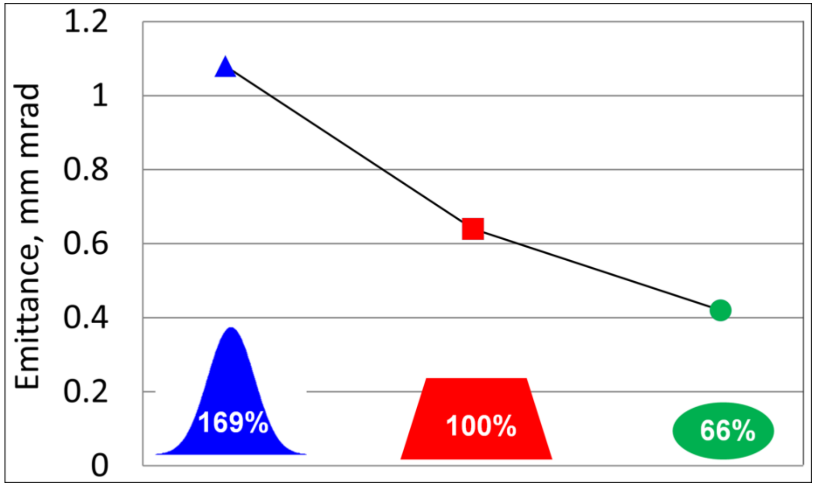
- Bunch charge: 1 nC
- Gun gradient: 60.58 MV/m corresponding to Pz~6.7 MeV/c beam momentum after the gun
- CDS booster gradient: 19.76 MV/m corresponding to Pz~24 MeV/c final beam momentum
- The reference point: EMSY1 (Z=5.74 m)

Summary of electron beam parameters for 3 cases

> Goal: "Optimizing" transverse emittance for the **same rms bunch length at EMSY1**

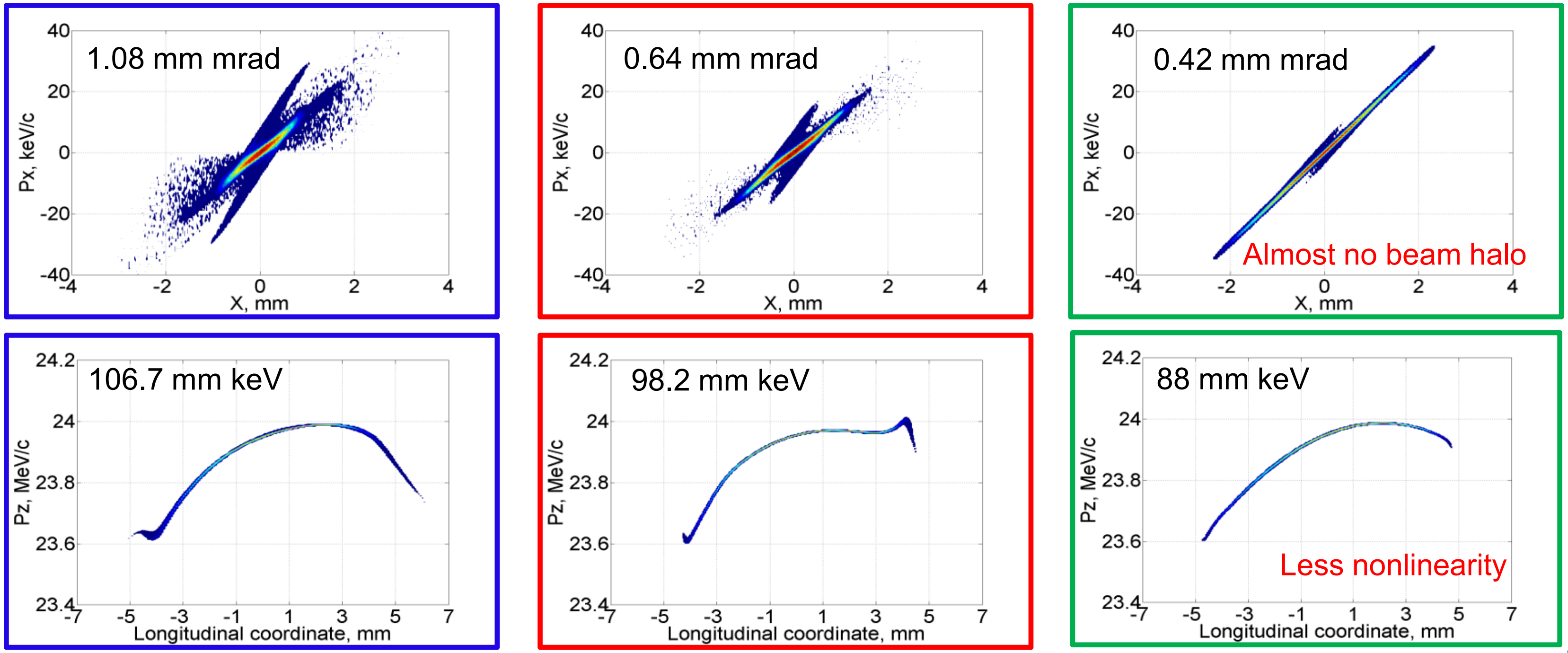
Section	Temporal	profile	cylindrical		3D ellipsoidal	Note
			Gaussian	Flat-top [**fixed** to MK paper]	3D homogeneous	
Cathode laser	Transverse	distribution	radial homogeneous		3D homogeneous	
Cathode laser	Trms	ps	5.4	6.272	6.1	varied parameters
Cathode laser	XYrms	mm	0.385	0.401	0.39	varied parameters
Cathode laser	Th. emit.	mm mrad	0.326	0.339	0.33	
RF gun	Ecath.	MV/m	60.58			
RF gun	Phase	deg	on-crest			
RF gun	MaxBz	T	0.2275	0.2279	0.2297	min emittance at EMSY1
CDS	CDS starting point	m	3.07			
CDS	MaxE	MV/m	19.76			
E-beam @ EMSY1	Charge	nC	1			
E-beam @ EMSY1	Momentum	MeV/c	23.96			
E-beam @ EMSY1	Proj. emittance	mm mrad	1.08	0.639	0.419	
E-beam @ EMSY1	Th. / proj.	%	30	53	79	
E-beam @ EMSY1	<Sl. emit.>	mm mrad	0.778	0.572	0.392	
E-beam @ EMSY1	Rms bunch length	mm	2.163	2.163	2.162	← same
E-beam @ EMSY1	Peak current	A	45.4	43.2	46.8	
E-beam @ EMSY1	Long. emittance	pi keV mm	106.7	98.2	88	

Transverse emittance at EMSY1 for 3 laser profiles



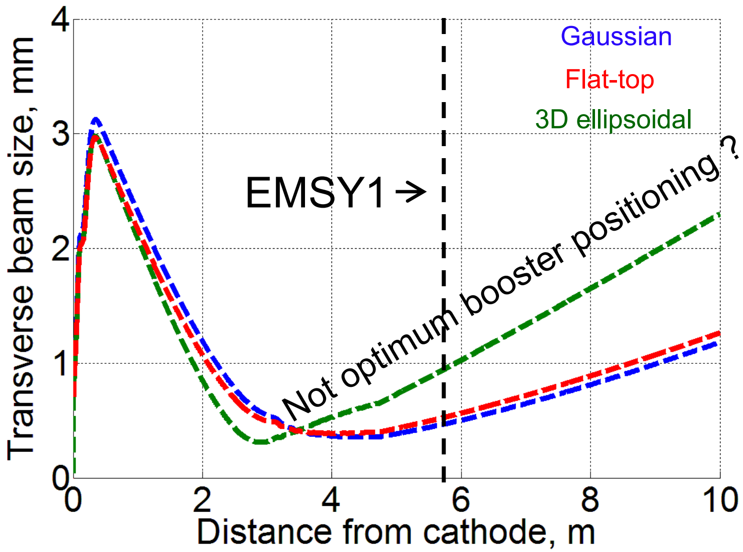
Using 3D ellipsoidal laser profile leads to:

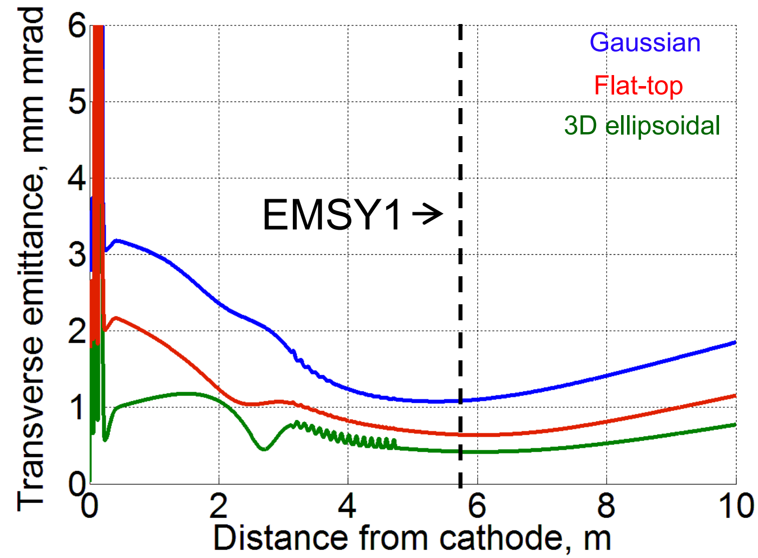
a. More than **30% reduction** in slice emittance compared to the flat-top case
b. ~ **80%** contribution from the cathode emittance



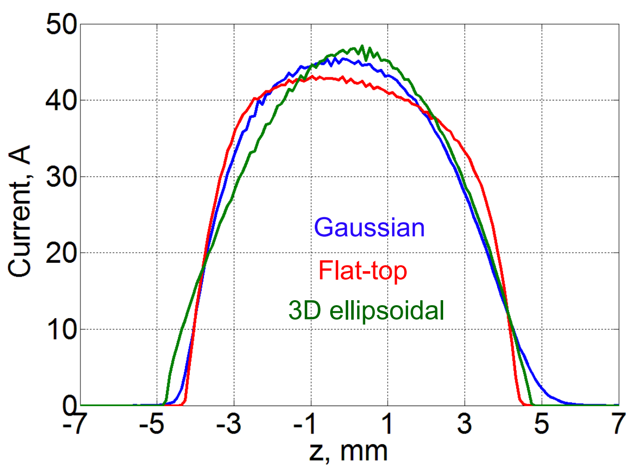
DESY

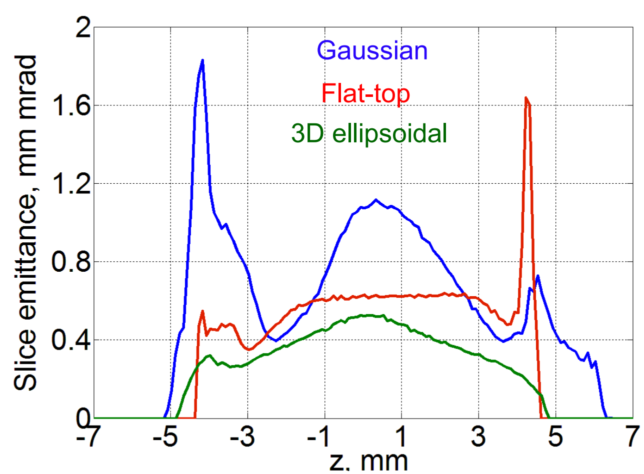
E-beam properties for 3 different temporal laser shapes

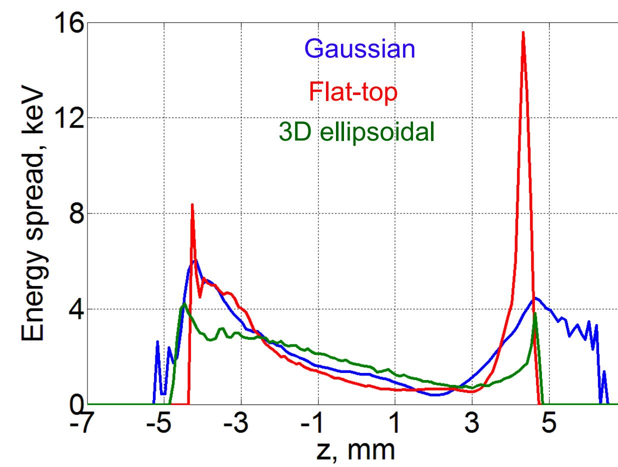




Slice parameters at EMSY1 (Z=5.74m)







- Introduction
- Beam dynamics studies comparing different cathode laser shapes
- Booster position optimization for 3D ellipsoidal laser profile at 1nC charge
- Beam tolerances: comparison of different laser shapes
- Influence of cathode laser shape imperfections on electron beam transverse emittance (3D ellipsoid)
- Booster position optimization for flat-top laser profile at 1nC charge
- Summary

Optimization of the booster position (3D ellipsoid)

ASTRA simulation setup: fixed parameters

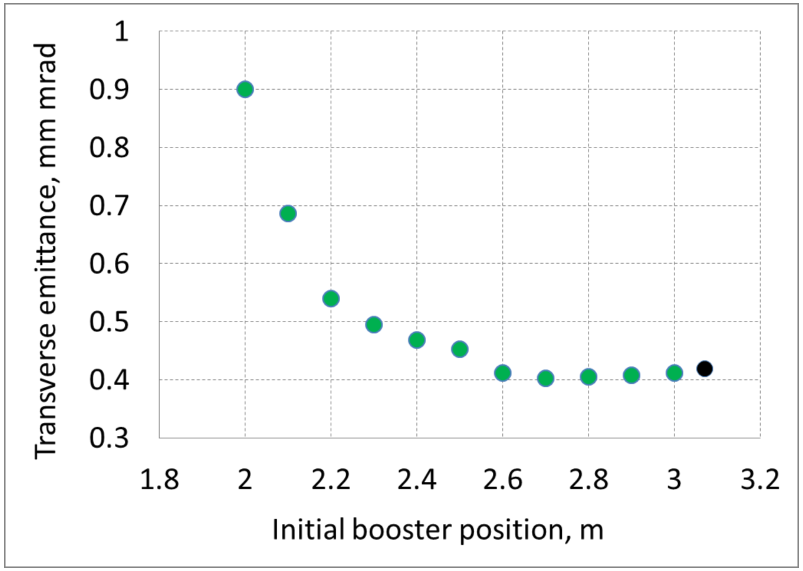
- Perfect 3D ellipsoidal cathode laser pulse with 6.1 ps rms emission time (initial bunch length)
- 0.55 eV average kinetic energy of the photoelectrons
- Gun gradient: 60.58 MV/m corresponding to Pz~6.7 MeV/c beam momentum after the gun
- CDS booster gradient: 19.76 MV/m corresponding to Pz~24 MeV/c final beam momentum
- Bunch charge: 1 nC
- Searching for the best transverse emittance at **EMSY1** (Z=5.74 m)

ASTRA simulation setup: varied parameters

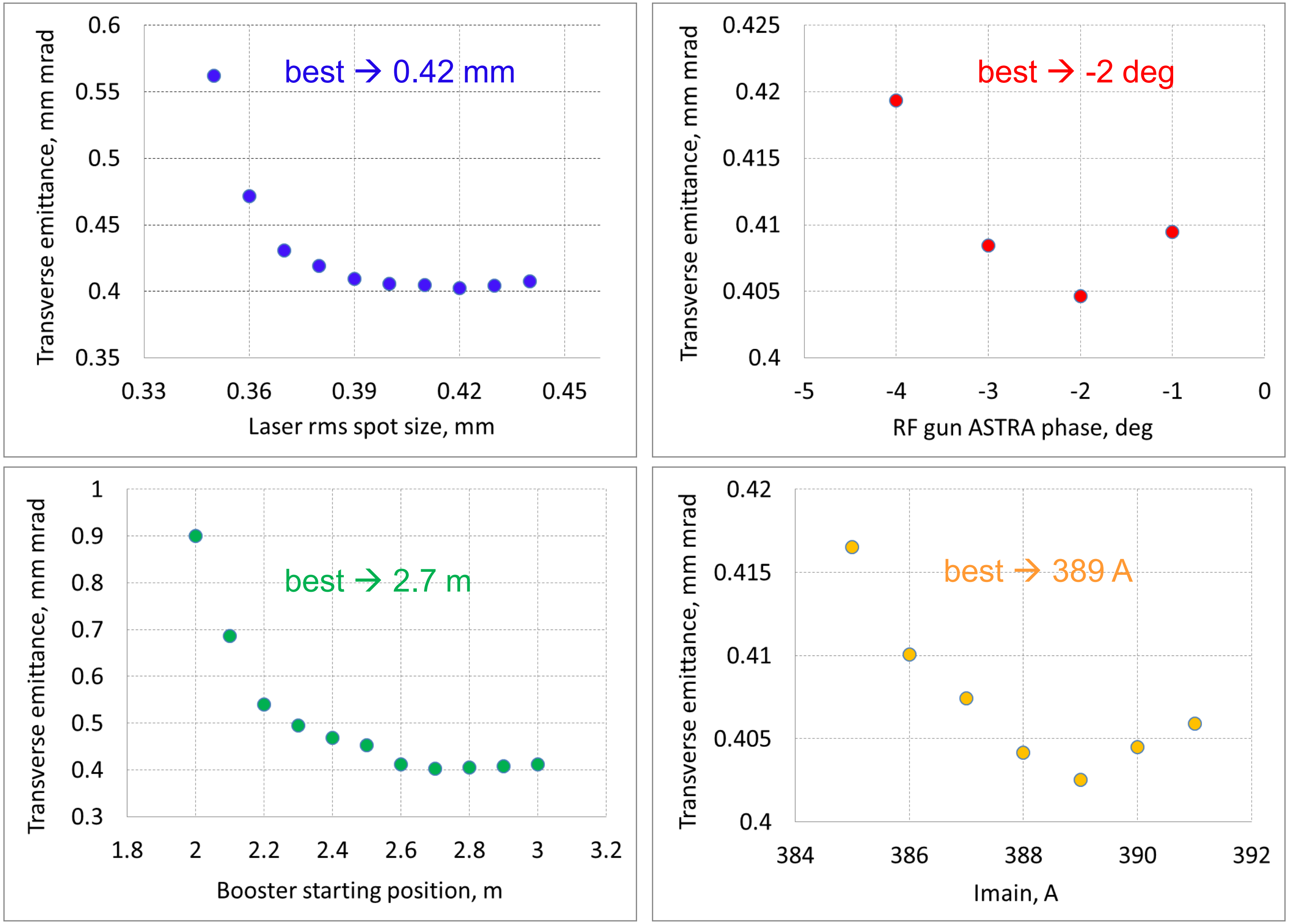
- Laser transverse rms spot size on the cathode → [0.35:0.01:0.44] mm
- Gun phase → [-4:1:-1] deg
- Initial Z position of CDS booster → [2:0.1:3] m
- Main solenoid current → [385:1:391] A

Z=2.7 m was found to be an optimum
(currently Z=3.07 m)

Best laser rms spot size → 0.42 mm
Best gun phase → phase of max acceleration
Best solenoid current → 389A

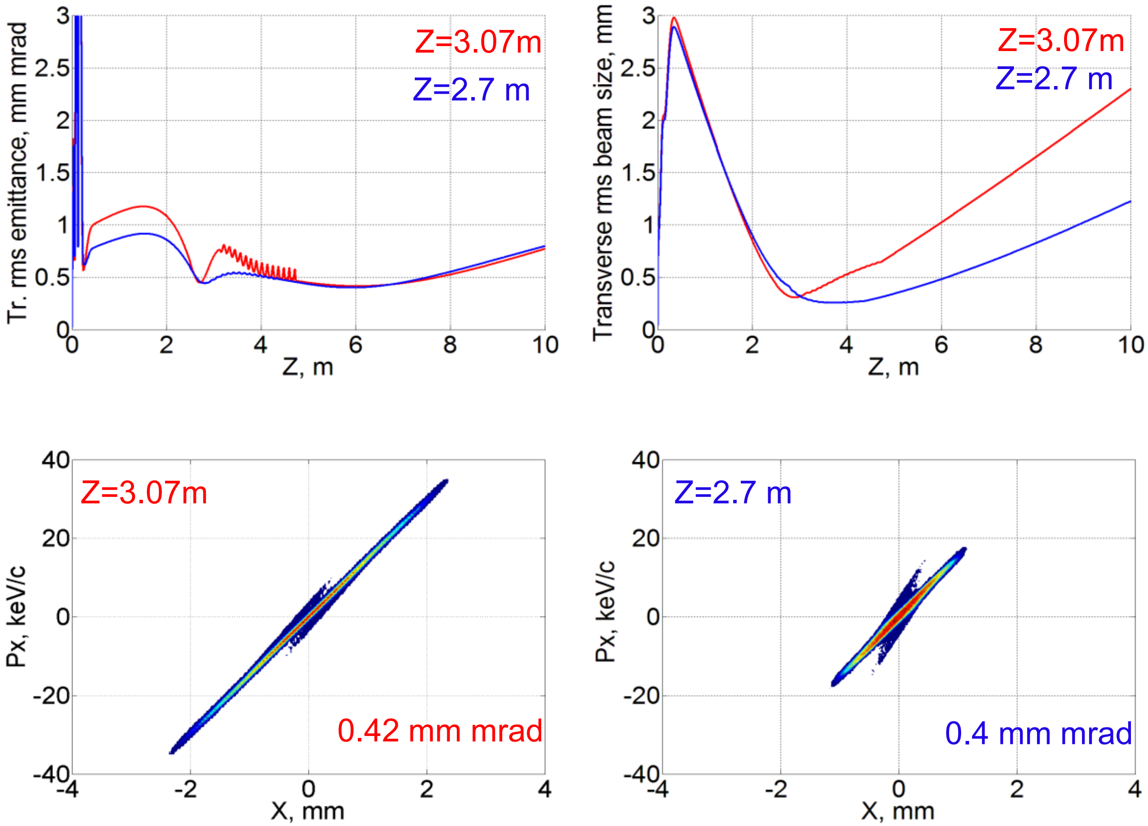


Optimization of the booster position II



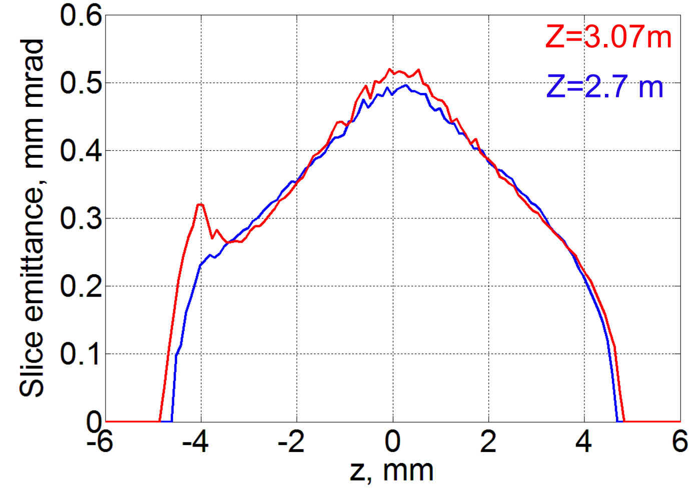
Transverse emittance as a function of machine parameters after multi parameter scan.

Optimization of the booster position III



Transverse beam properties for two different initial booster positions.

Slice emittances at EMSY1 for two cases.



Better injector performance is observed when the position of the booster is shifted by ~40 cm towards the cathode !!

Comparing 3D ellipsoidal beams at different booster positions

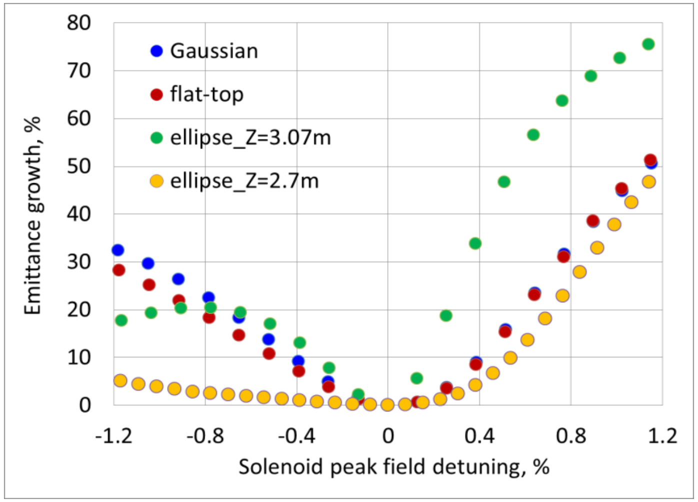
Initial booster position	m	**3.07**	**2.7**
Rms emission time (Trms)	ps	6.1	6.75
Rms laser spot size (XYrms)	mm	0.39	0.42
Thermal emittance	mm mrad	0.33	0.356
Gun gradient	MV/m	60.58	
Gun phase	deg	on-crest	
Peak field of main solenoid	T	0.2297	0.2289
Gun gradient	MV/m	60.58	
Bunch charge	nC	1	
Booster gradient	MV/m	19.76	
Final beam momentum	MeV/c	23.96	
Projected emittance	mm mrad	**0.42**	**0.4**
Thermal / projected	%	**79**	**89.5**
Average slice emittance	mm mrad	0.39	0.383
Rms bunch length	mm	2.162	2.163
Peak current	A	46.8	46.8
Longitudinal emittance	pi keV mm	88	92

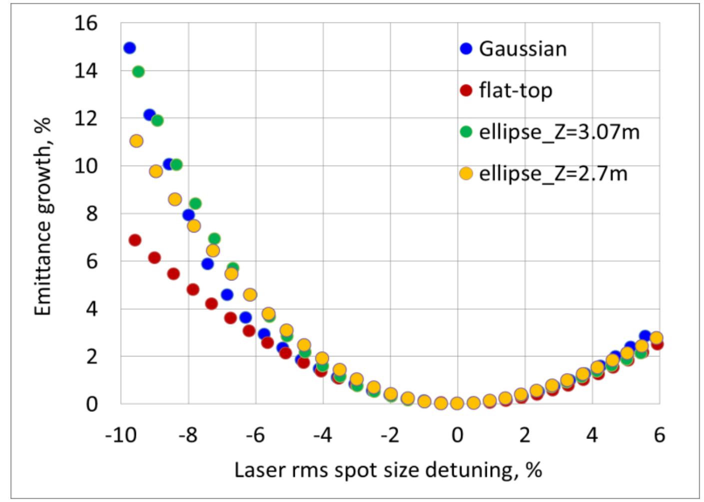
~90 % contribution from thermal emittance to the final one with shifted booster position !!

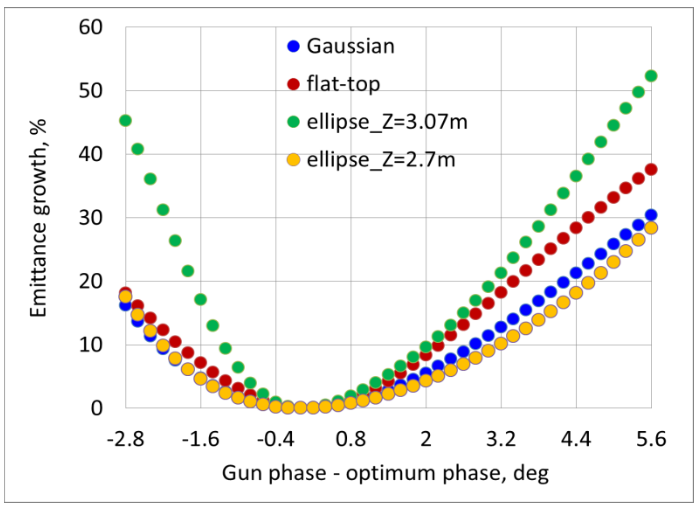
- Introduction
- Beam dynamics studies comparing different cathode laser shapes
- Booster position optimization for 3D ellipsoidal laser profile at 1nC charge
- Beam tolerances: comparison of different laser shapes
- Influence of cathode laser shape imperfections on electron beam transverse emittance (3D ellipsoid)
- Booster position optimization for flat-top laser profile at 1nC charge
- Summary

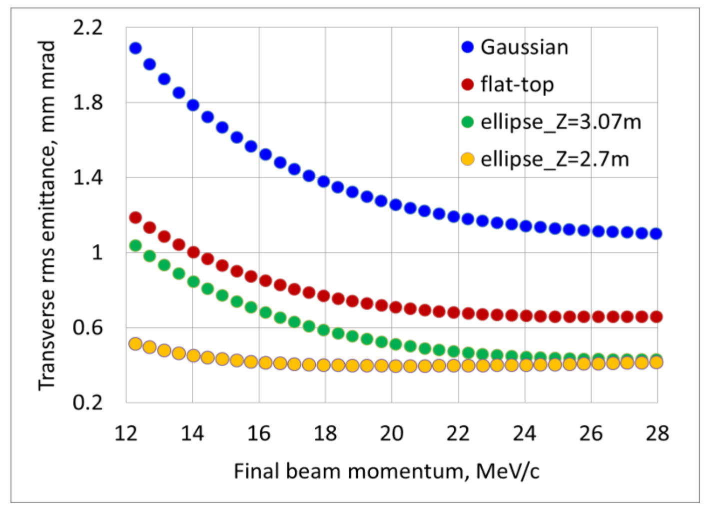
E-beam tolerances for 3 different temporal laser profiles

Emittance growth due to the deviation of machine parameters from their optimal values.







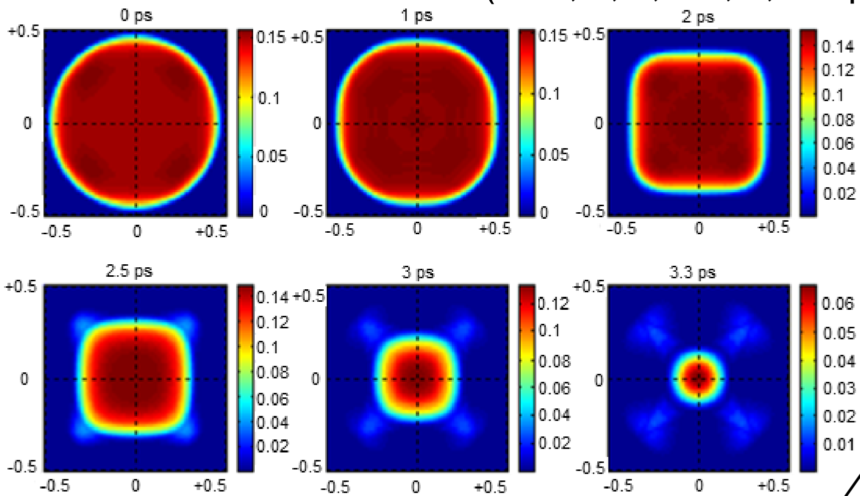


In all cases ~ same rms bunch length at EMSY1 !

- Introduction
- Beam dynamics studies comparing different cathode laser shapes
- Booster position optimization for 3D ellipsoidal laser profile at 1nC charge
- Beam tolerances: comparison of different laser shapes
- Influence of cathode laser shape imperfections on electron beam transverse emittance (3D ellipsoid)
- Booster position optimization for flat-top laser profile at 1nC charge
- Summary

Border sharpness modeling for beam simulations (MK)

Transverse distribution of the 3D ellipsoidal laser at different time cross sections (t = 0; 1; 2; 2.5; 3; 3.3 ps).



$$\rho_0 = \sqrt{\left(\frac{r}{R}\right)^2 + \left(\frac{t}{T}\right)^2}, \quad 0 \le r \le R, \quad 0 \le t \le T$$

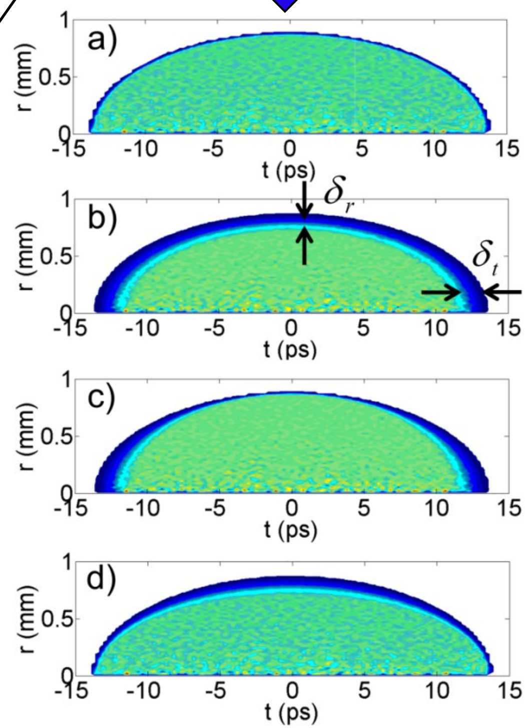
$$\rho = \sqrt{\frac{\left(\frac{r}{R}\right)^2}{(1-\delta_r)^2} + \frac{\left(\frac{t}{T}\right)^2}{(1-\delta_t)^2}}, \quad 0 \le r \le R, \quad 0 \le t \le T$$

δ_r → Border radial sharpness parameter

δ_t → Border temporal sharpness parameter

Modification of initial photon distribution by applying laser shape imperfections

$$\rho = \rho_0 \begin{cases} \frac{1}{2} - \frac{1}{2}\sin\left[\pi\left(\frac{\vartheta - 1}{\delta(r,t)} + \frac{1}{2}\right)\right], & 1-\delta(r,t) \le \vartheta \le 1 \\ 1, & if\ \vartheta < 1-\delta(r,t) \end{cases}$$



Perfect 3D shape

20% distortions over pulse

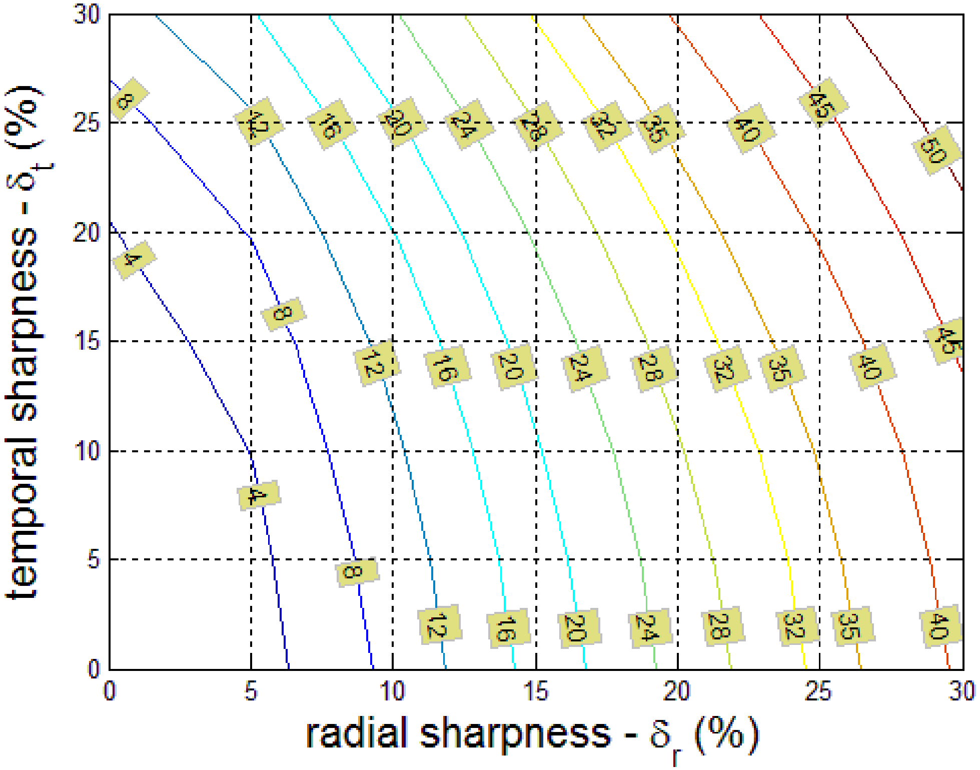
20% distortion temporally

20% distortion spatially

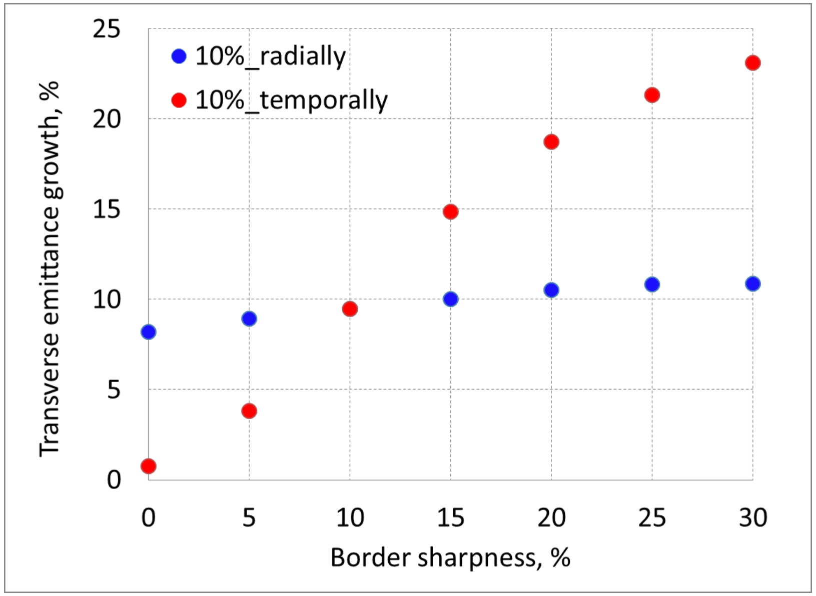
Laser beam radial vs. temporal distribution at the cathode:

Emittance growth due to non perfect border width

- Modified intensity distribution for each border width (temporal and radial) has been put into ASTRA simulations for electron beam tracking up to EMSY1
- Parameters responsible for bunch rms emission time (Trms or initial bunch length) and laser beam transverse projection onto the z axis (XYrms) were kept unchanged during the studies



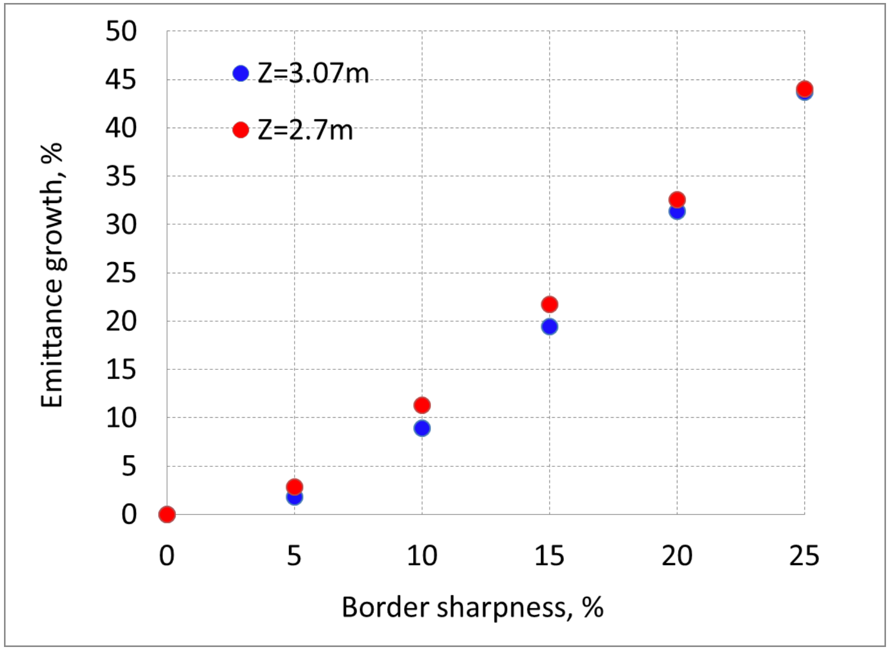
Transverse emittance growth (in %) vs. temporal (δ_t) and radial (δ_r) border sharpness parameters.



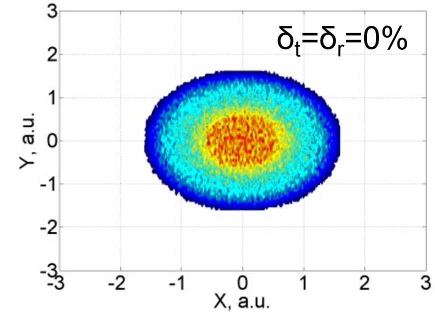
Stronger effect on transverse emittance due to imperfections in radial direction !

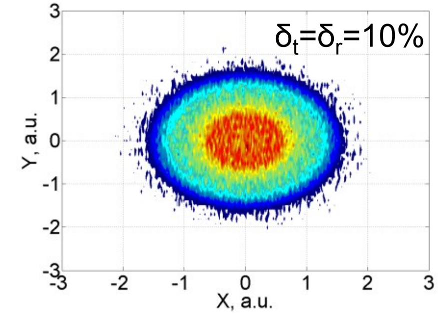
Emittance growth due to non perfect border width II

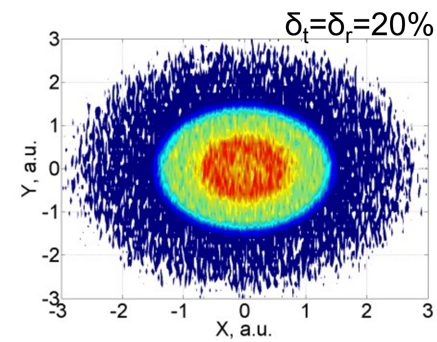
Relative emittance growth for different $\delta_t=\delta_r=\delta$.



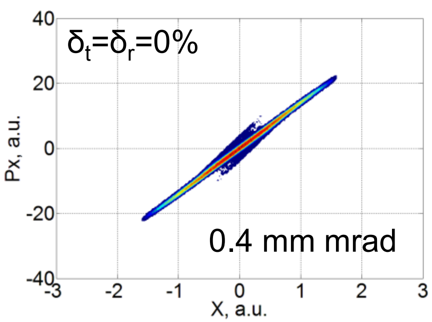
E-beam transverse distributions.

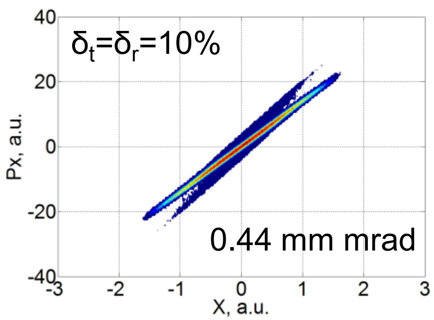


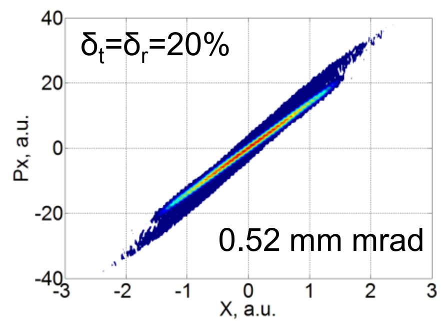




E-beam transverse phase spaces for 3 cases.

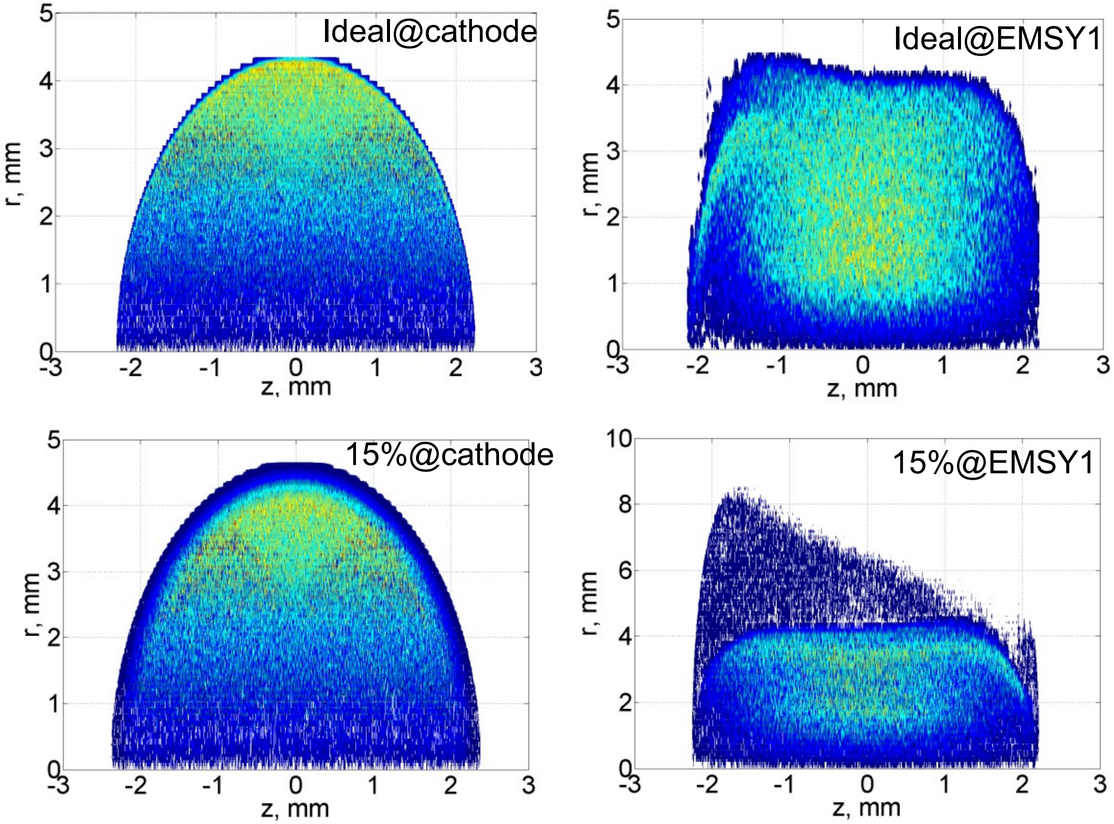




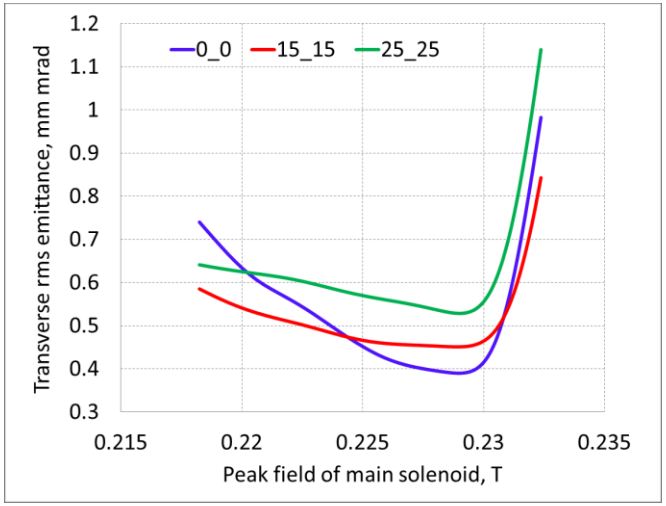


Beam parameters for different border widths

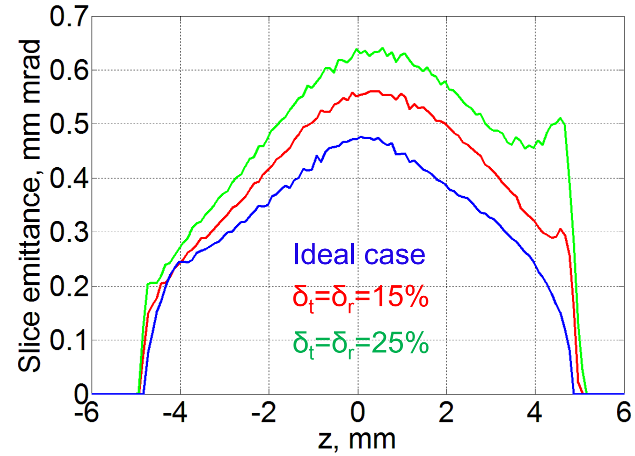
R vs. Z distributions for ideal case and $\delta_t=\delta_r=20\%$ border width



Solenoid scan for different border widths



Slice emittances for different border widths



Temporal and radial sharpness parameters	Average slice emittance (EMSY1), mm mrad
$\delta_t=\delta_r=0\%$	0.38
$\delta_t=\delta_r=15\%$	0.457
$\delta_t=\delta_r=25\%$	0.529

- Introduction
- Beam dynamics studies comparing different cathode laser shapes
- Booster position optimization for 3D ellipsoidal laser profile at 1nC charge
- Beam tolerances: comparison of different laser shapes
- Influence of cathode laser shape imperfections on electron beam transverse emittance (3D ellipsoid)
- Booster position optimization for flat-top laser profile at 1nC charge
- Summary

Optimization of the booster position (flat-top profile)

ASTRA simulation setup: fixed parameters

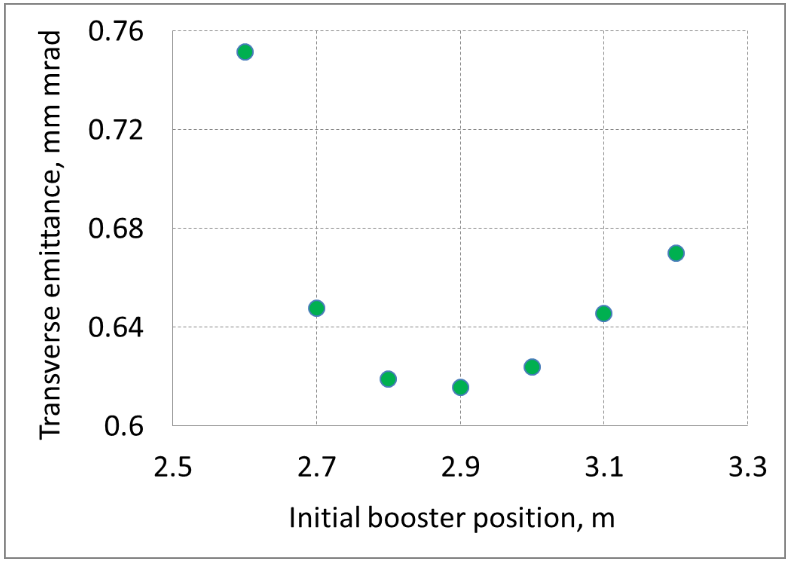
- Laser temporal profile: flat-top with 21.5ps FWHM length and 2ps rise and fall times
- 0.55 eV average kinetic energy of the photoelectrons
- Gun gradient: 60.58 MV/m corresponding to Pz~6.7 MeV/c beam momentum after the gun
- CDS booster gradient: 19.76 MV/m corresponding to Pz~24 MeV/c final beam momentum
- Bunch charge: 1 nC
- Searching for the best transverse emittance at **EMSY1** (z=5.74 m)

ASTRA simulation setup: varied parameters

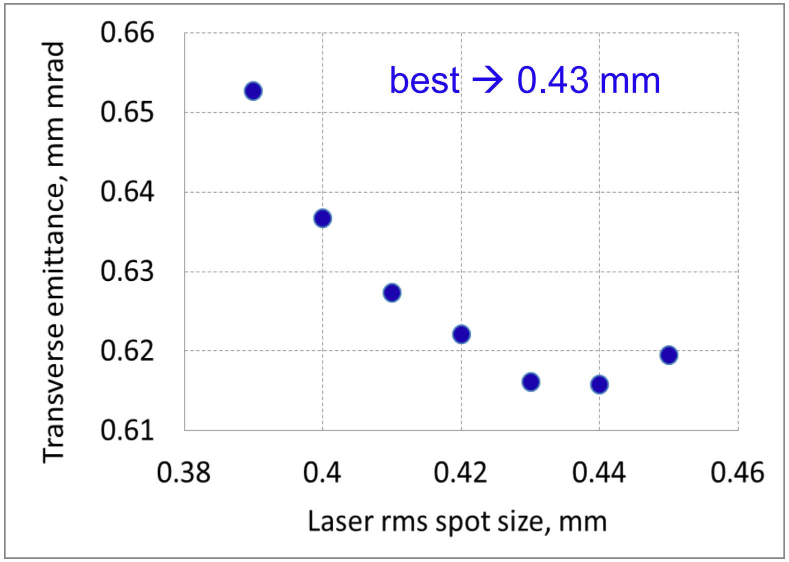
- Laser transverse rms spot size on the cathode → [0.39:0.01:0.45] mm
- Gun phase → [-3:1:1] deg
- Initial z position of CDS booster → [2.6:0.1:3.2] m
- Main solenoid current → [384:1:390] A

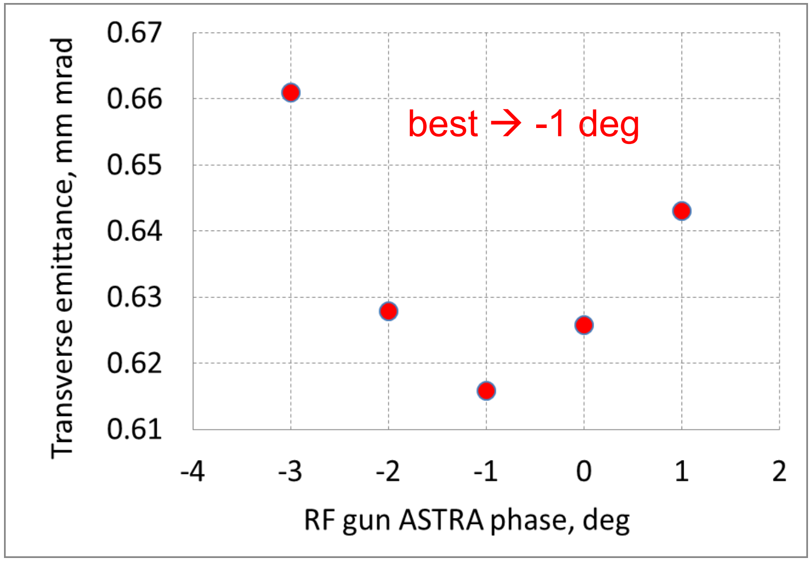
z=2.9 m was found to be an optimum
(currently z=3.07 m)

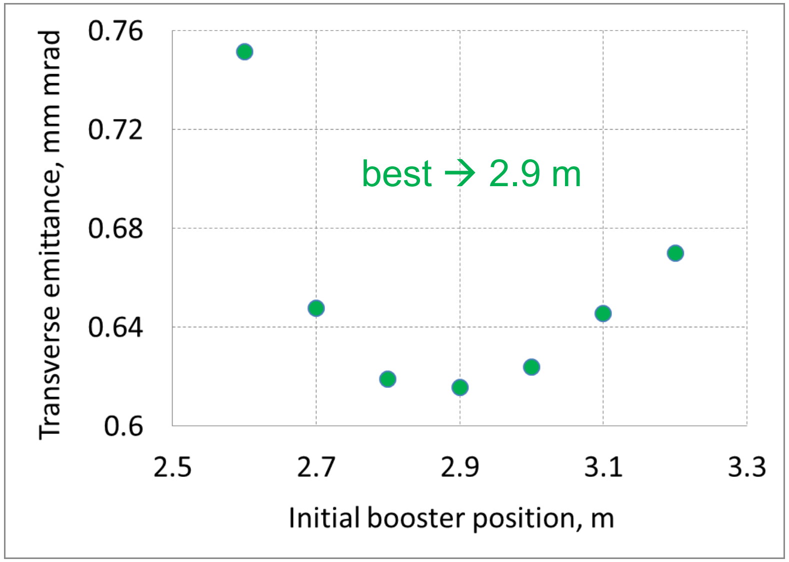
Best laser rms spot size → 0.435 mm
Best gun phase → phase of max acceleration
Best solenoid current → 387A

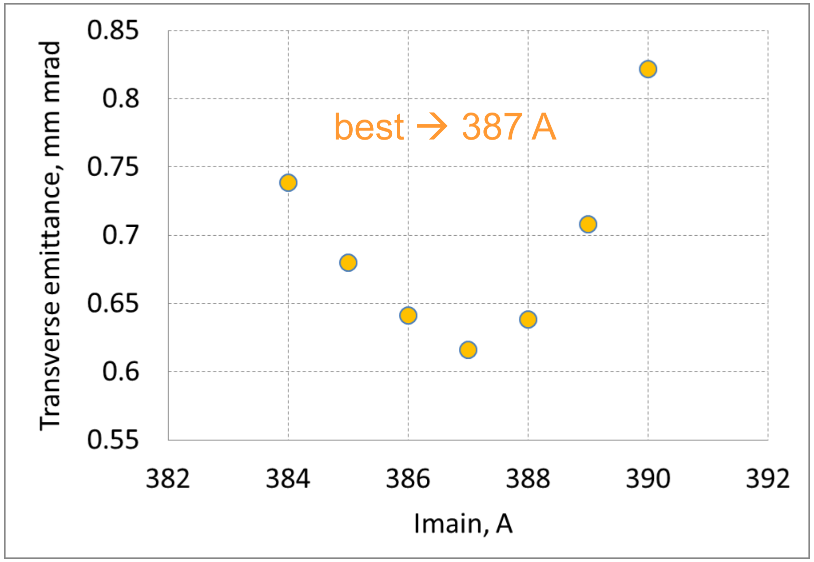


Optimization of the booster position II (flat-top)

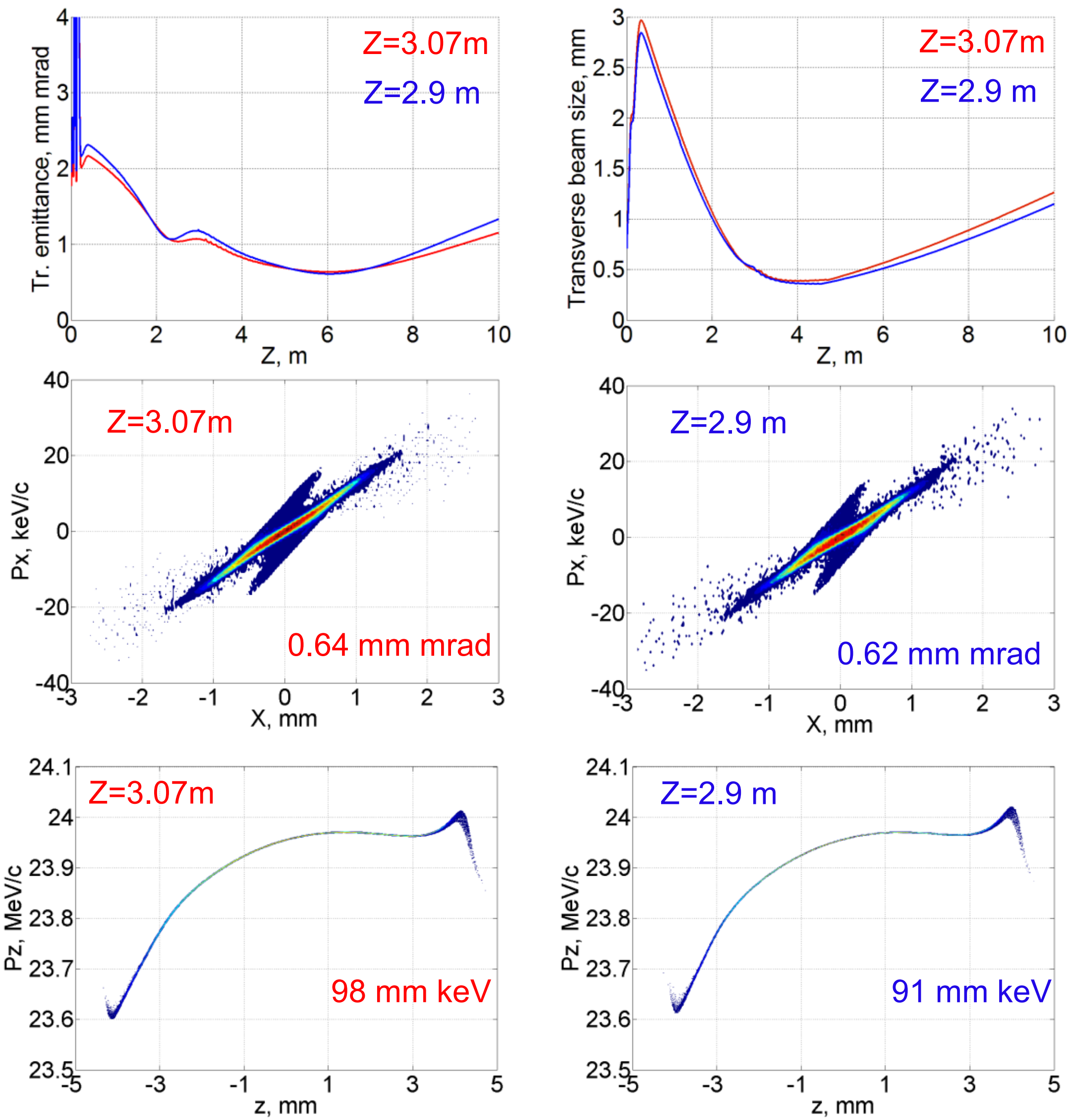






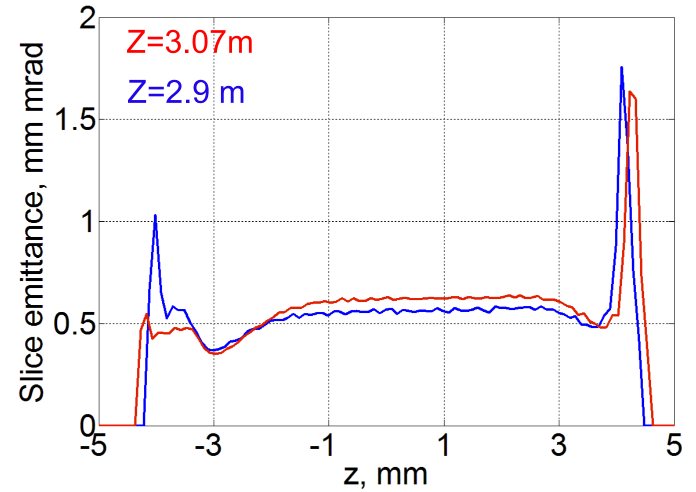


Optimization of the booster position III (flat-top)



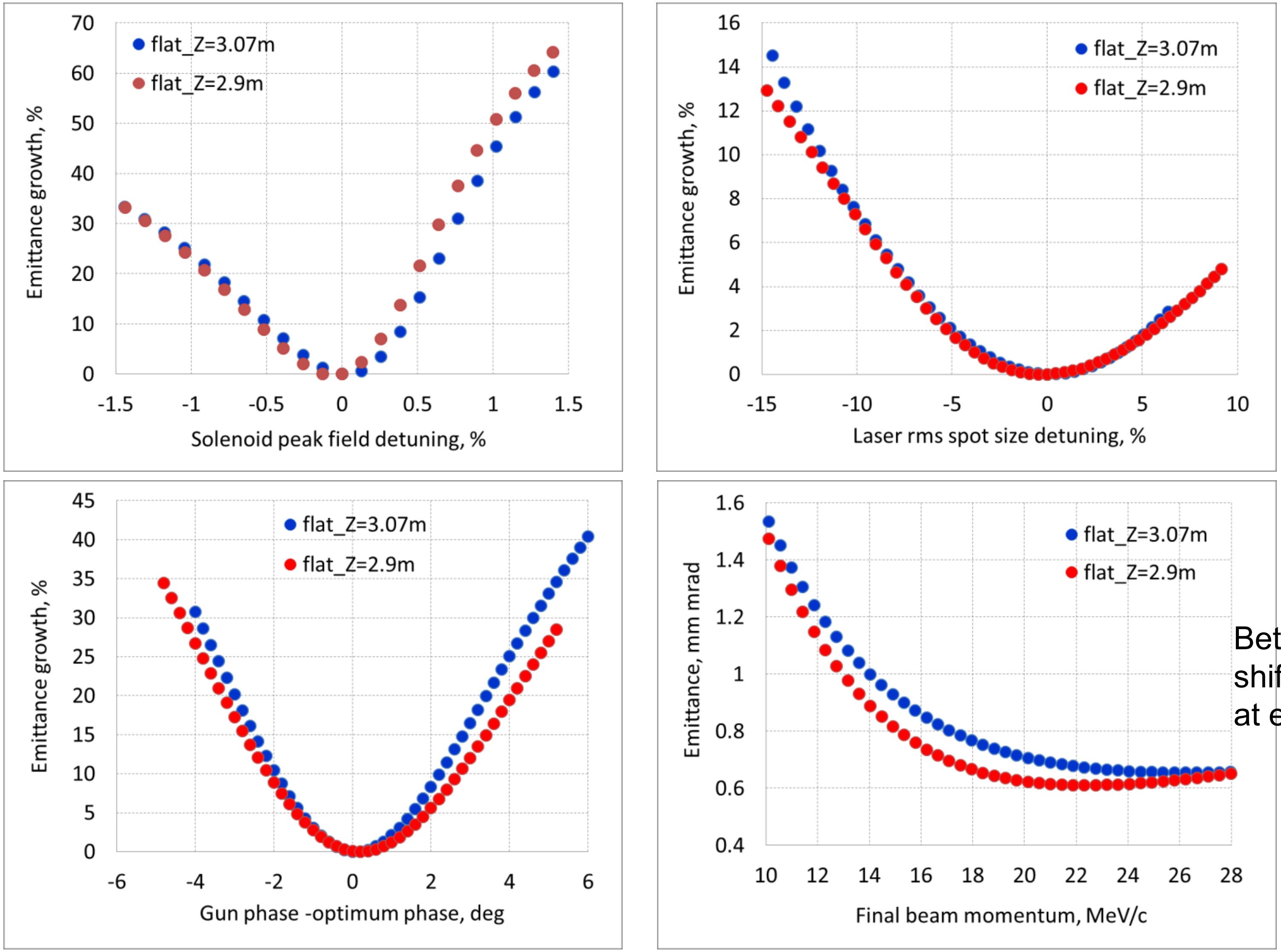
E-beam properties for two different initial booster positions.

Slice emittances at EMSY1 for two cases.



0.06 mm mrad reduction in slice emittance at “flat” part with shifted booster position.

E-beam tolerances for different booster positions



Better emittance with shifted booster position at energies < 25 MeV

Summary

- 3 different laser shapes have been compared in beam dynamics simulations:

  ~30 % reduction in slice emittance for the 3D ellipsoidal laser case compared to flat-top one was obtained (the same rms bunch length at EMSY1)

- Shifting the booster position by ~40 cm towards the cathode for 3D ellipsoidal laser profile yields to much better injector performance (90 % contribution from thermal emittance) compared to the other laser shapes
- Imperfections on 3D laser shape (temporally as well as spatially) have been modeled and included in beam simulations
- Stronger effect on the transverse emittance was observed due to radial imperfections in 3D ellipsoidal laser pulse
- Overall, from 10-15 % imperfections in 3D laser shape are still acceptable in terms of transverse emittance
- Multi parameter scan suggests Z=2.9 m as a best initial position for CDS booster in case of flat-top laser profile but there are no major improvements compared to the current case

Thank you for your attention !