Optimization of CDS booster position for the PITZ photoinjector

- Booster position optimization comparing flat-top and 3D ellipsoidal laser profiles (current position of EMSY1)
- Transverse emittance optimization comparing flat-top and 3D ellipsoidal laser profiles (various booster positions, current position of EMSY1)
- Transverse emittance optimization comparing flat-top and 3D ellipsoidal laser profiles (shifted (and fixed) booster position, various positions of EMSY1)
- Summary

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PITZ collaboration meeting
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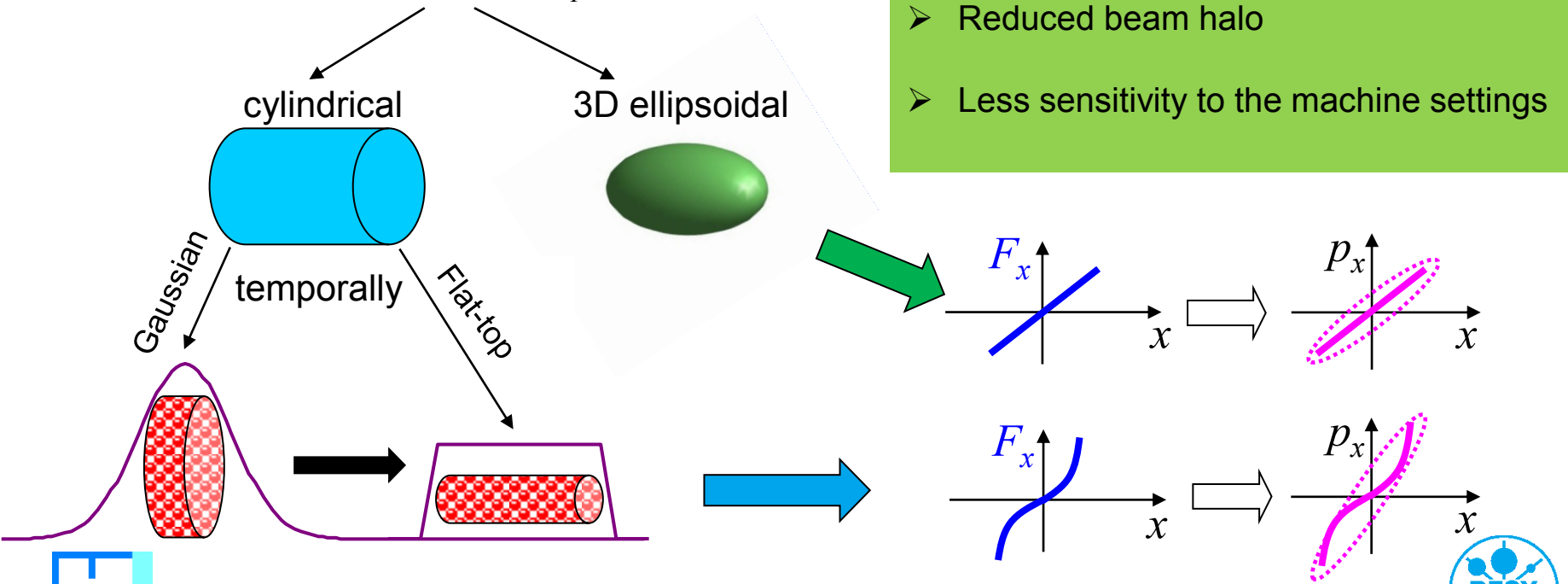
DESY

Introduction

- **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 for to minimize the impact of the space charge on the transverse emittance.

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

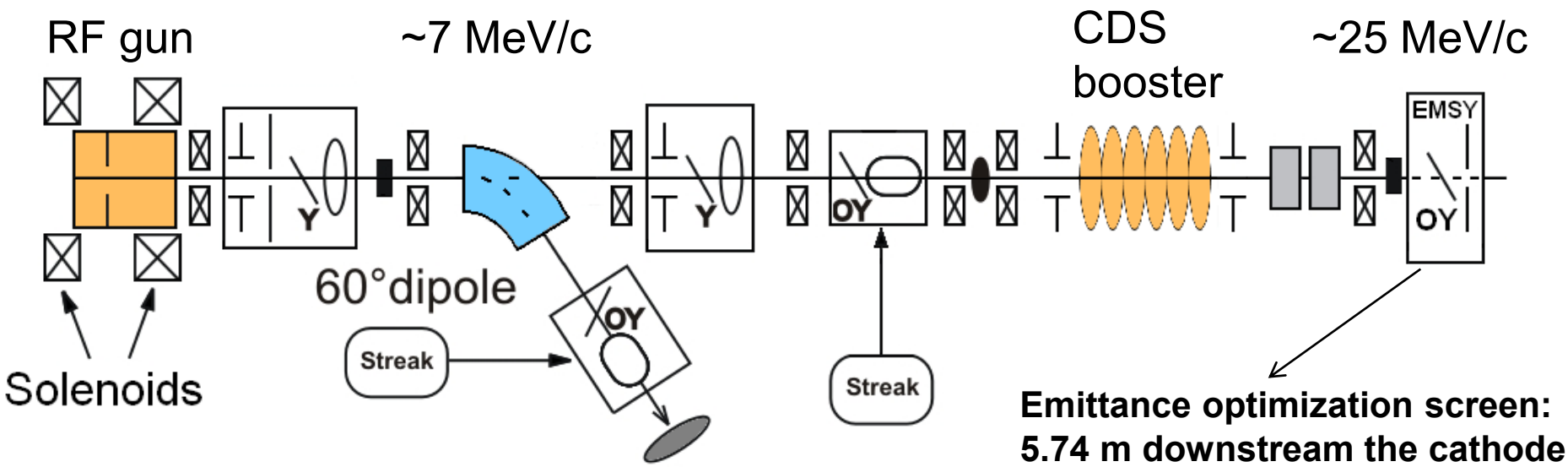
$$\text{cathode laser shape}: \varepsilon_{SpCh} \rightarrow \min$$



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

PITZ setup used for ASTRA simulations

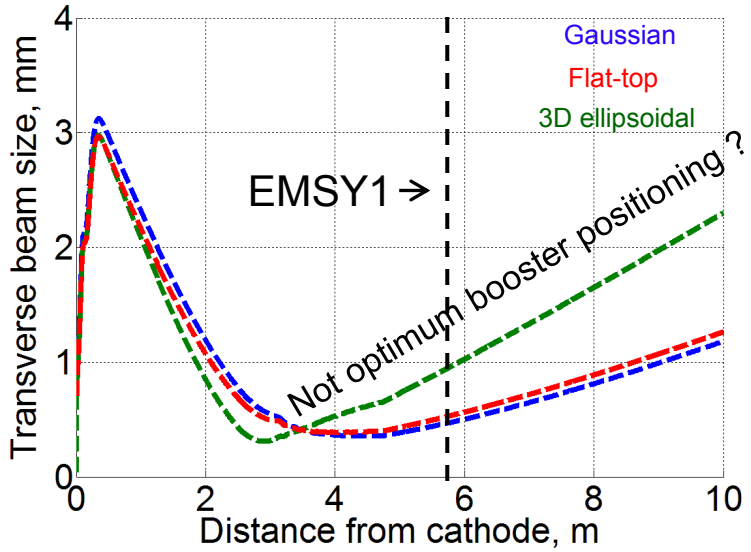
Setup used in ASTRA simulations

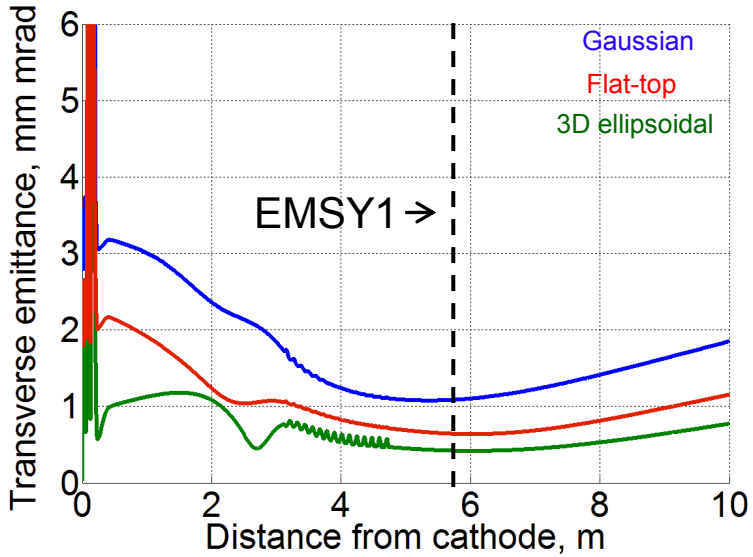


Fixed parameters in ASTRA simulations

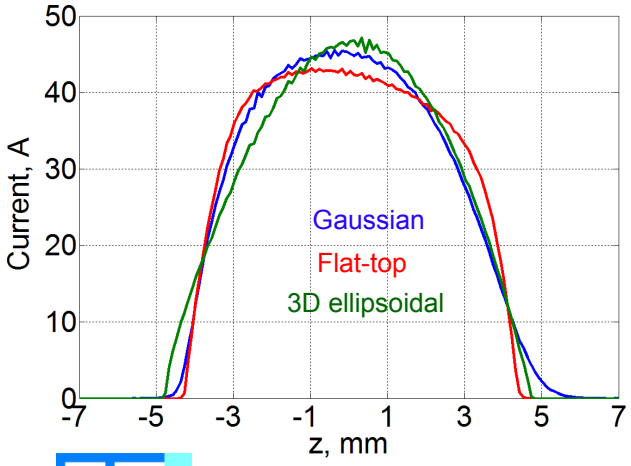
- 0.55 eV average kinetic energy of the photoelectrons
- Gun gradient: 60.58 MV/m (Pz~6.7 MeV/c beam momentum after the gun at max acceleration phase)
- 200 000 macroparticles
- Bunch charge: 1 nC
- Optimization of transverse emittance

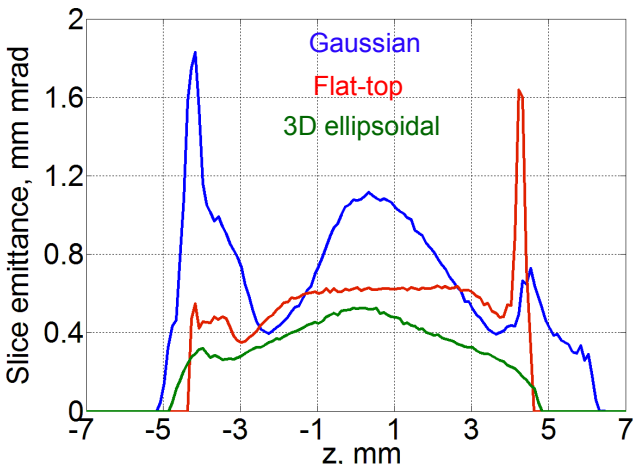
E-beam properties for 3 different temporal laser shapes

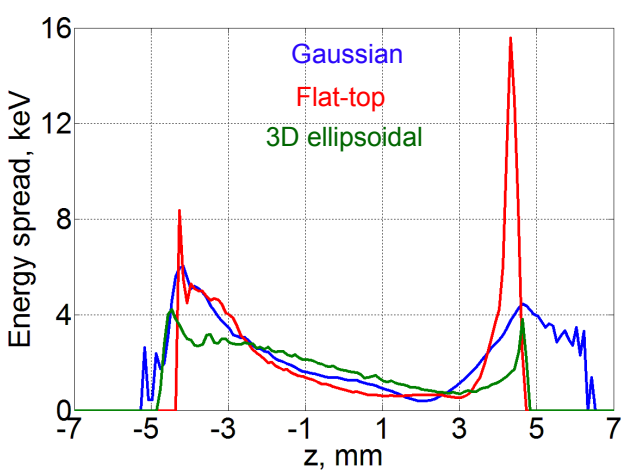




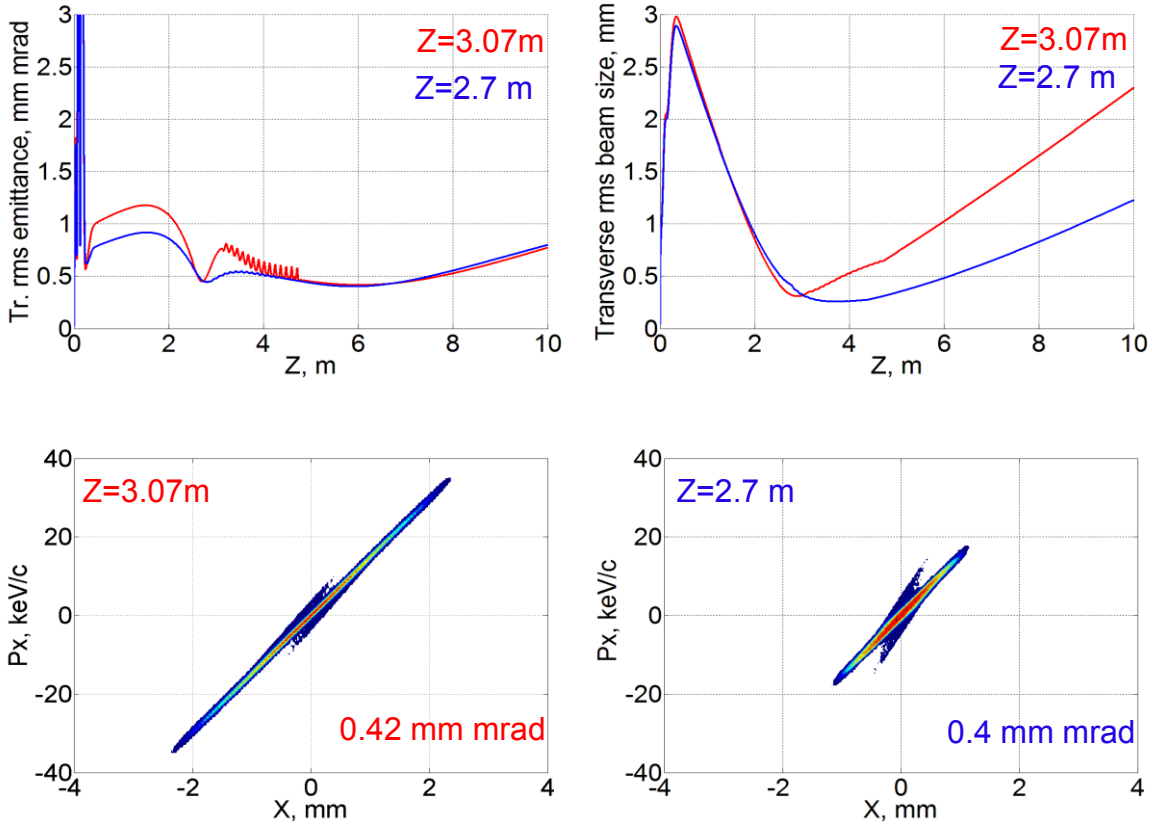
Slice parameters at EMSY1 (Z=5.74m)





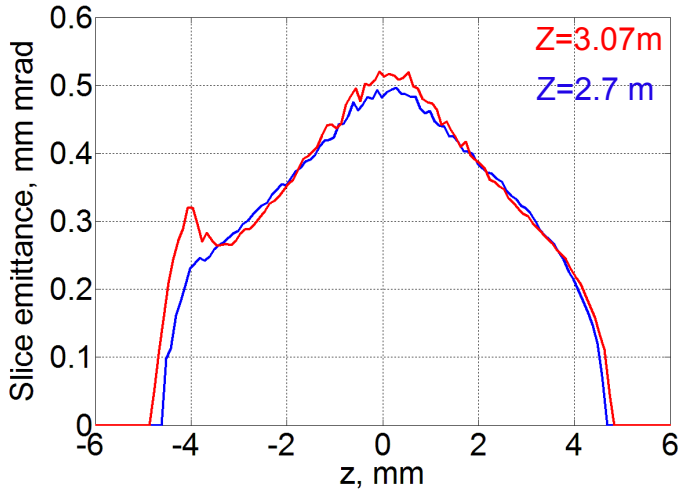


Optimization of the booster position (3D ellipsoidal laser)



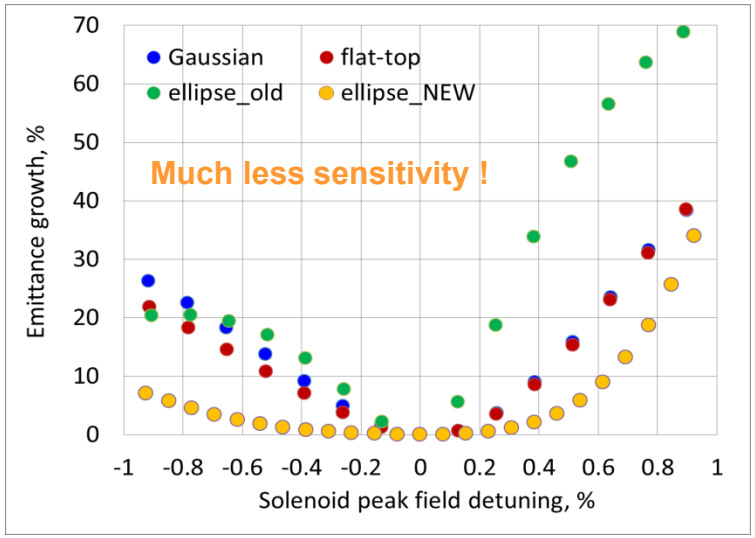
Transverse beam properties for two different initial booster positions.

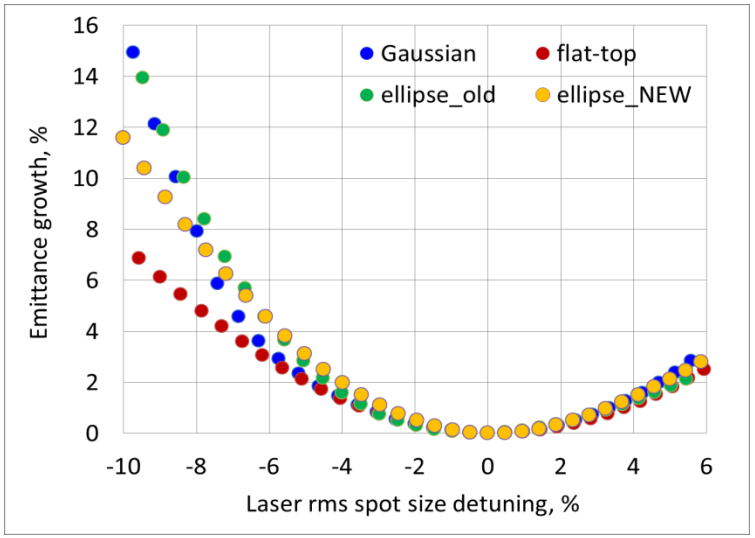
Slice emittances at EMSY1 for two cases.

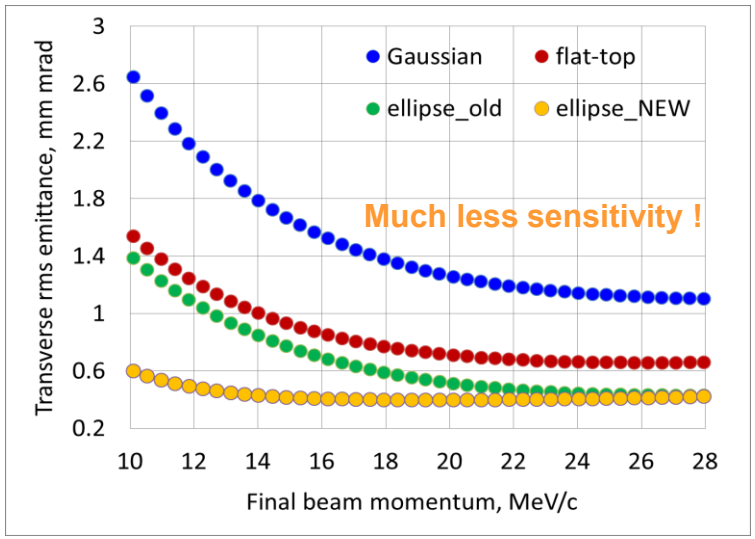


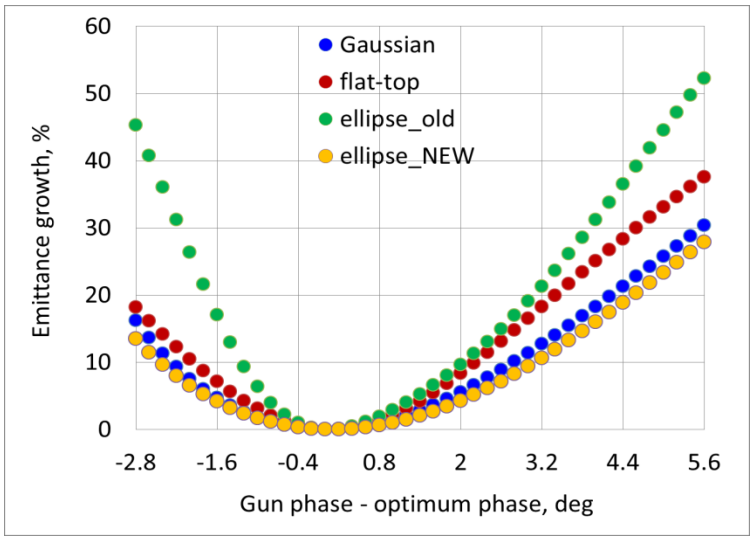
Much better injector performance is observed when the position of the booster is shifted by ~40 cm towards the cathode !!

E-beam tolerances for 3 different temporal laser profiles









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

- Booster position optimization comparing flat-top and ellipsoidal laser profiles (current position of EMSY1)
- Transverse emittance optimization comparing flat-top and 3D ellipsoidal laser profiles (various booster positions, current position of EMSY1)
- Transverse emittance optimization comparing flat-top and 3D ellipsoidal laser profiles (shifted (and fixed) booster position, various positions of EMSY1)
- Summary

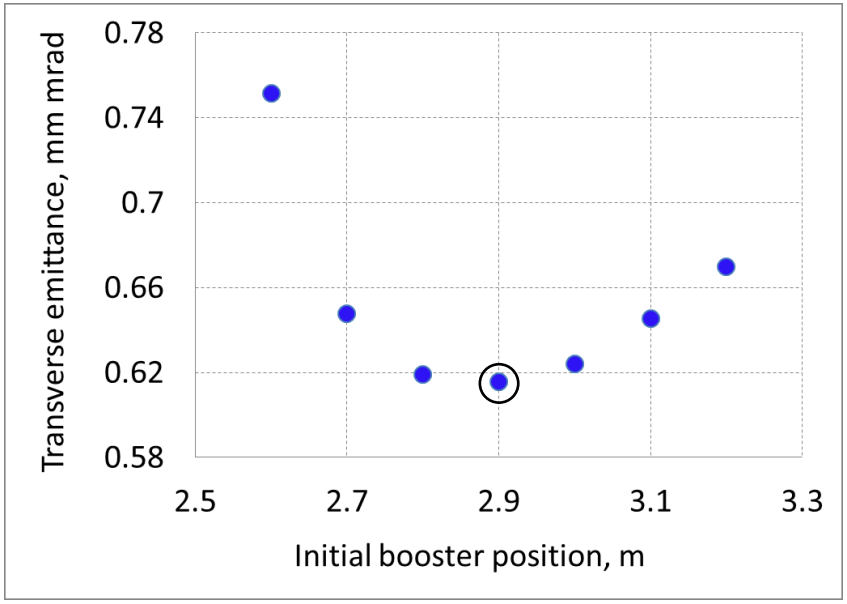
Booster position optimization for flat-top and 3D ellipsoid

Simulation setup with fixed booster gradient

Flat-top

- ❑ Trms=6.273 ps (21.5 ps FWHM, 2 ps rise/fall times)
- ❑ Booster gradient: 19.76 MV/m (Pz~24 MeV/c)
- ❑ Emittance optimization at EMSY1 (Z=5.74m)

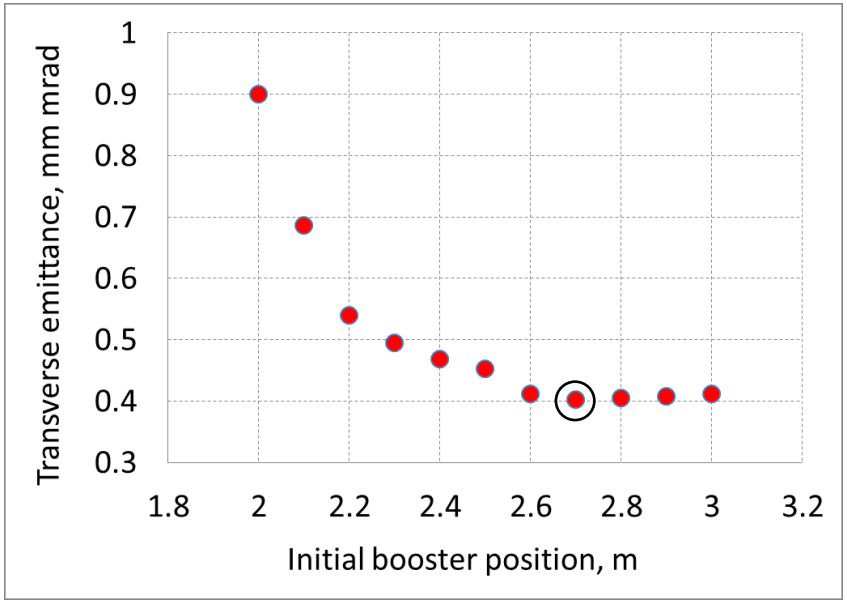
- ➢ Laser spot size at cathode → [0.39:0.01:0.45] mm
- ➢ Gun ASTRA phase → [-3:1:1] deg
- ➢ Initial z position of CDS booster → [2.6:0.1:3.2] m
- ➢ Main solenoid current → [384:1:390] A



3D ellipsoidal

- ❑ Trms=6.1 ps (~ same bunch length at EMSY1)
- ❑ Booster gradient: 19.76 MV/m (Pz~24 MeV/c)
- ❑ Emittance optimization at EMSY1 (Z=5.74m)

- ➢ Laser spot size at cathode → [0.35:0.01:0.44] mm
- ➢ Gun ASTRA phase → [-4:1:-1] deg
- ➢ Initial z position of CDS booster → [2:0.1:3] m
- ➢ Main solenoid current → [385:1:391] A



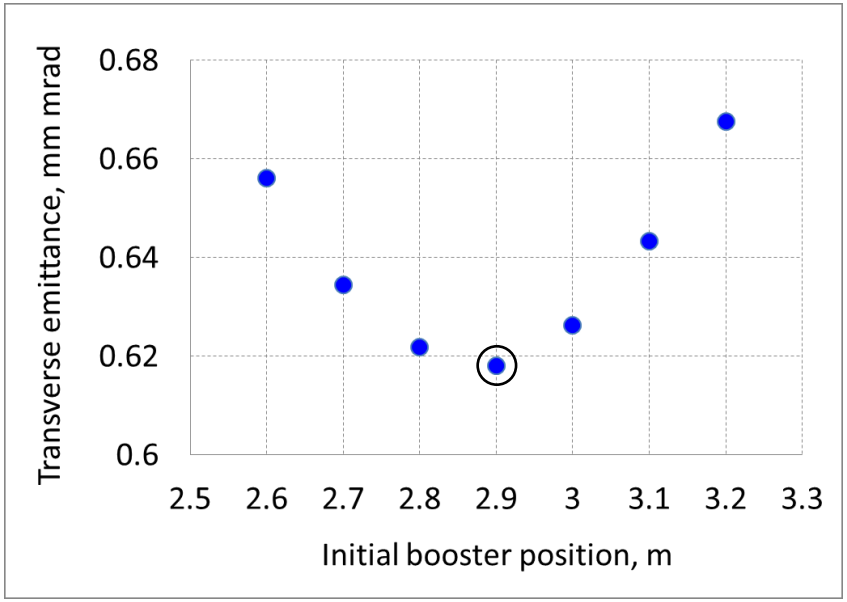
Booster position optimization for flat-top and 3D ellipsoid

Simulation setup with varied booster gradient

Flat-top

- ❑ Trms=6.273 ps (21.5 ps FWHM, 2 ps rise/fall times)
- ❑ Gun ASTRA phase: phase of max acceleration
- ❑ Emittance optimization at EMSY1 (Z=5.74m)

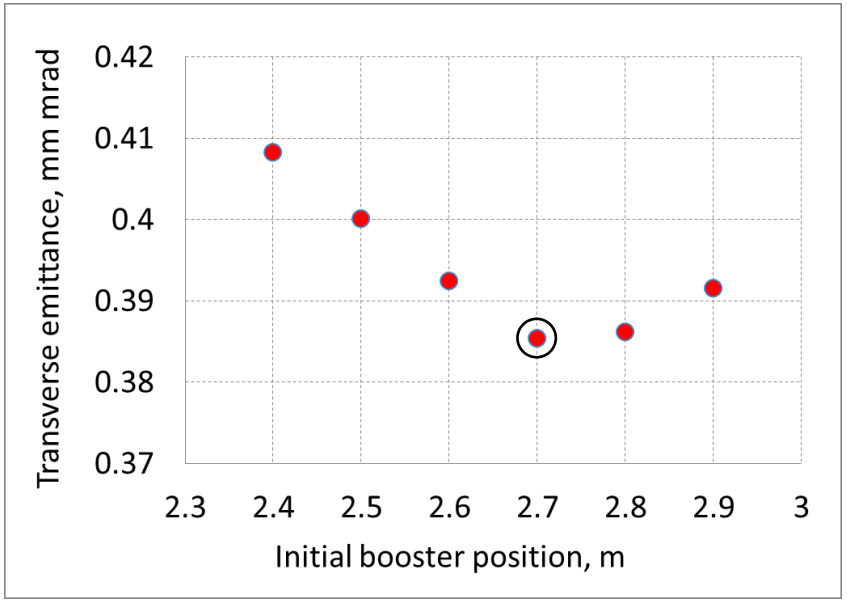
- ➢ Laser spot size at cathode → [0.36:0.02:0.5] mm
- ➢ Booster gradient → [6:2:22] MV/m
- ➢ Initial z position of CDS booster → [2.6:0.1:3.2] m
- ➢ Main solenoid current → [380:2:390] A



3D ellipsoidal

- ❑ Trms=6.1 ps
- ❑ Gun ASTRA phase: phase of max acceleration
- ❑ Emittance optimization at EMSY1 (Z=5.74m)

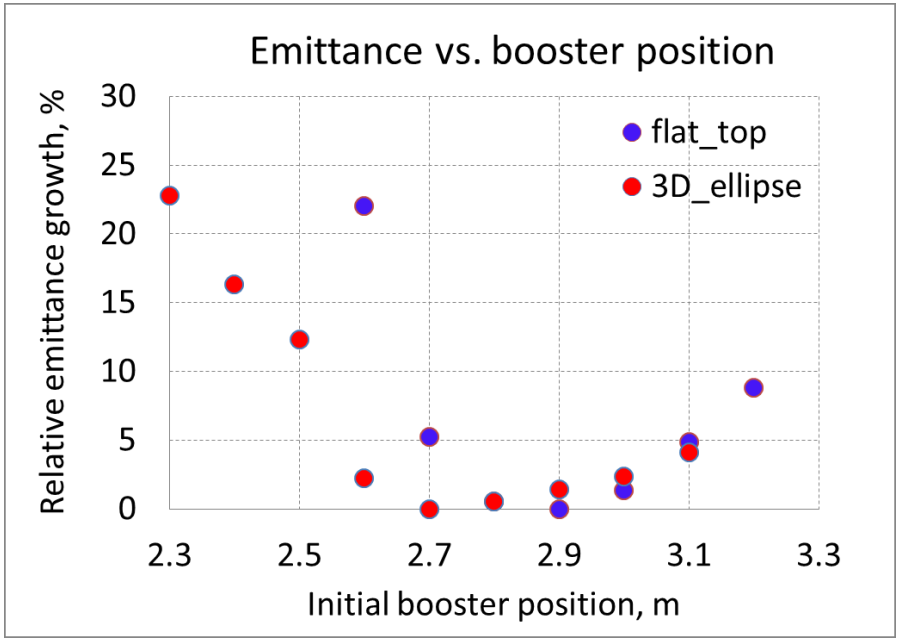
- ➢ Laser spot size at cathode → [0.34:0.02:0.5] mm
- ➢ Booster gradient → [8:2:22] MV/m
- ➢ Initial z position of CDS booster → [2.4:0.1:2.9] m
- ➢ Main solenoid current → [380:2:394] A



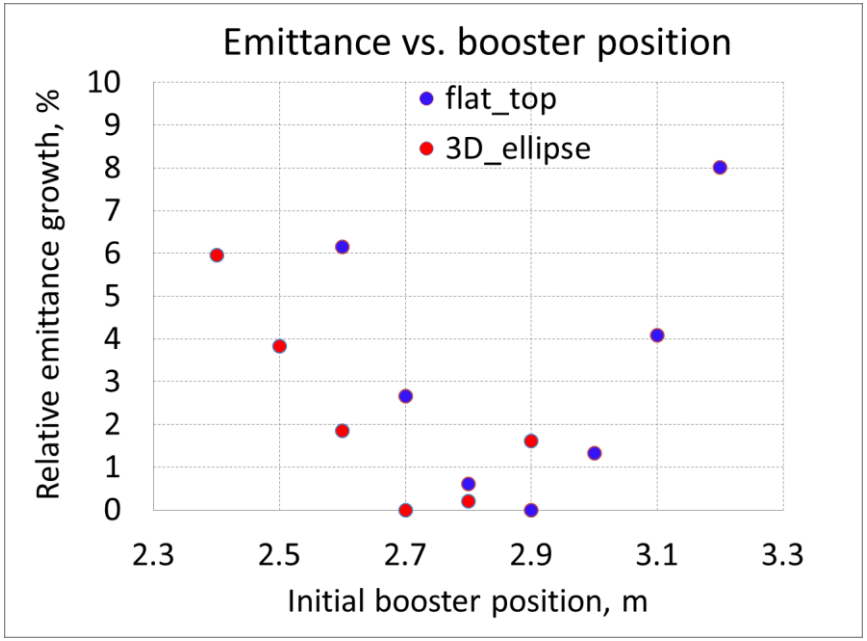
Booster position optimization for flat-top and 3D ellipsoid

Relative growth of transverse emittance (EMSY1) for different initial booster positions

Emittance optimization by fixing the booster gradient



Emittance optimization for varied booster gradient



- ~5% better transverse emittance for flat-top case when booster is shifted from 3.1m to 2.9m
- ~5% better transverse emittance for 3D ellipsoidal case when booster is shifted from 3.1m to 2.7m
- Comparable emittance values for flat-top case while booster is shifted from 3.1m to Z=2.7m

Conclusion

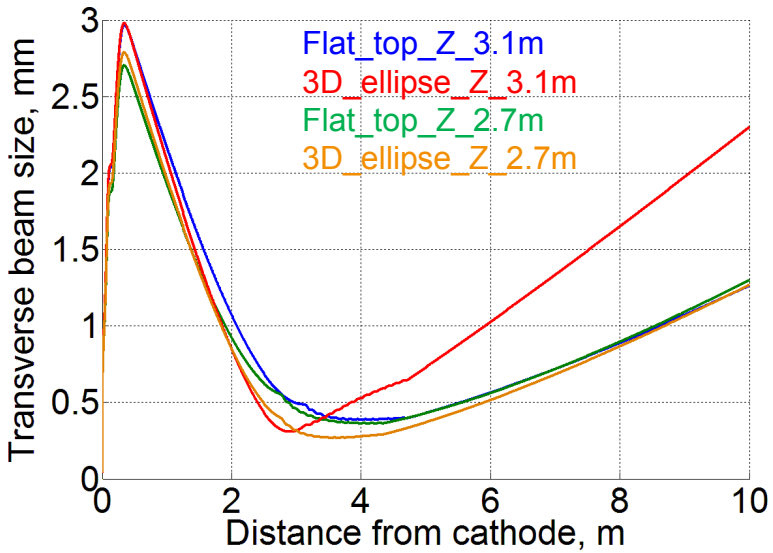
- Optimum initial booster position for 3D ellipsoidal laser profile is Z=2.7m (consistent)
- Optimum initial booster position for flat-top temporal laser profile is Z=2.9m (consistent)
- Bigger laser spot size at cathode is required if the booster is shifted towards the cathode
- Comparable emittance values for flat-top case while booster is shifted from 3.1m to Z=2.7m

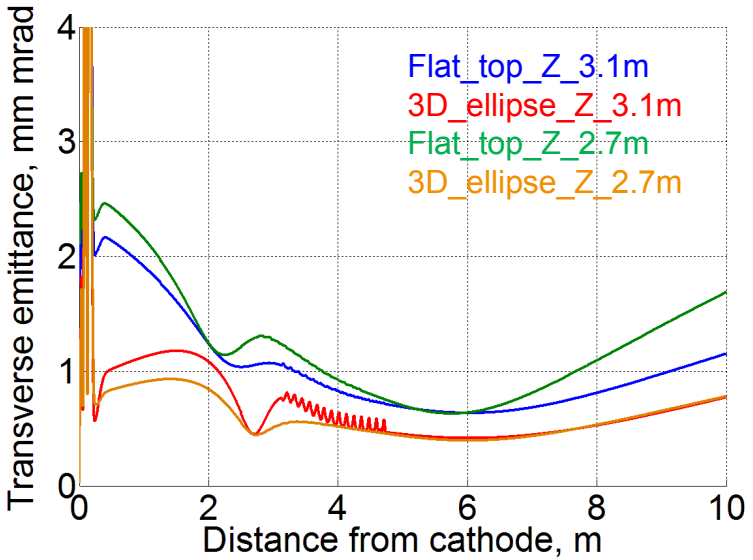
- Next step: beam studies considering various combinations of laser profiles (flat-top + 3D ellipsoidal) and initial booster positions

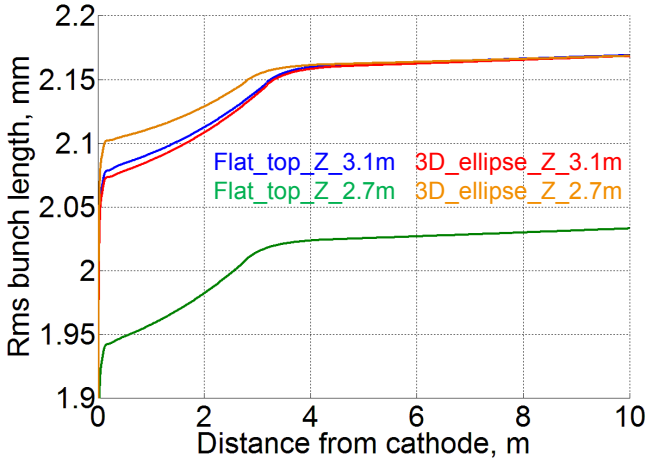
- Booster position optimization comparing flat-top and ellipsoidal laser profiles (current position of EMSY1)
- Transverse emittance optimization comparing flat-top and 3D ellipsoidal laser profiles (various booster positions, current position of EMSY1)
- Transverse emittance optimization comparing flat-top and 3D ellipsoidal laser profiles (shifted (and fixed) booster position, various positions of EMSY1)
- Summary

Beam dynamics comparing Z=2.7m and current position

Transverse beam properties along beamline: 4 different cases



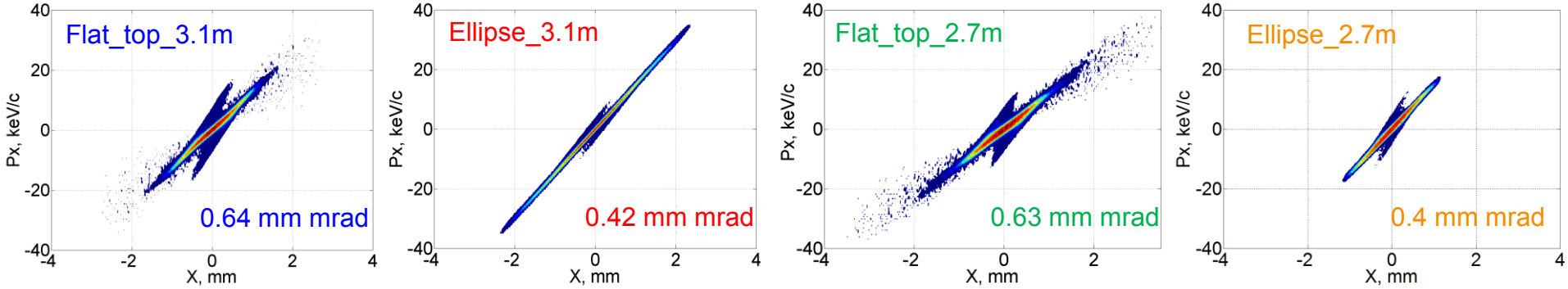




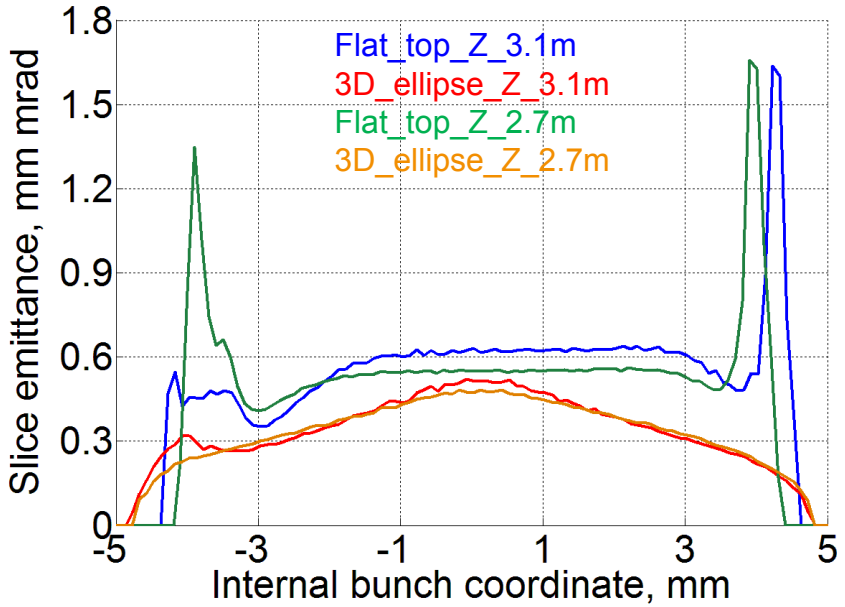
- Initial bunch length for Z=2.7m and 3D ellipsoidal laser case was tuned to get the same rms bunch length at EMSY1 as Z=3.1m
- 7% difference in bunch rms length at EMSY1 for flat-top laser case
- ~same final beam energy in all cases

Beam dynamics comparing Z=2.7 m and current position

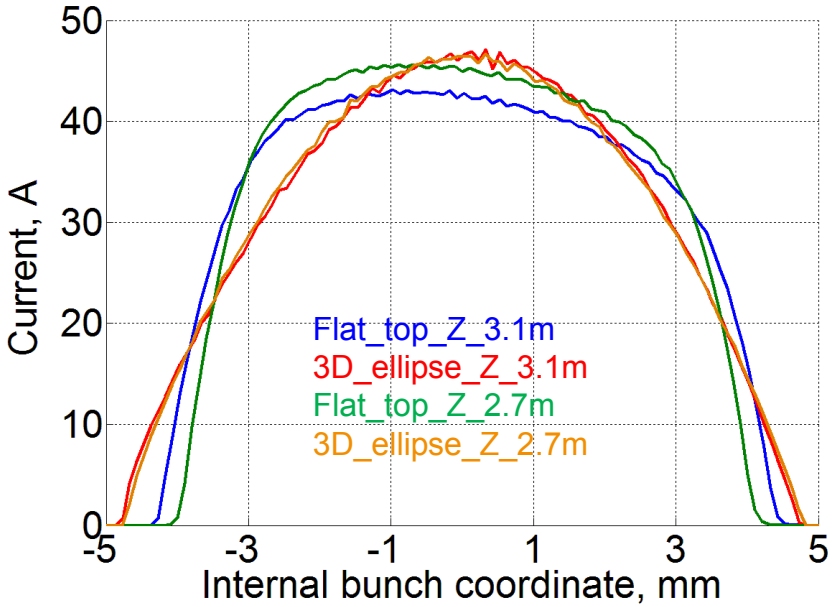
Transverse phase spaces at EMSY1: 4 different cases



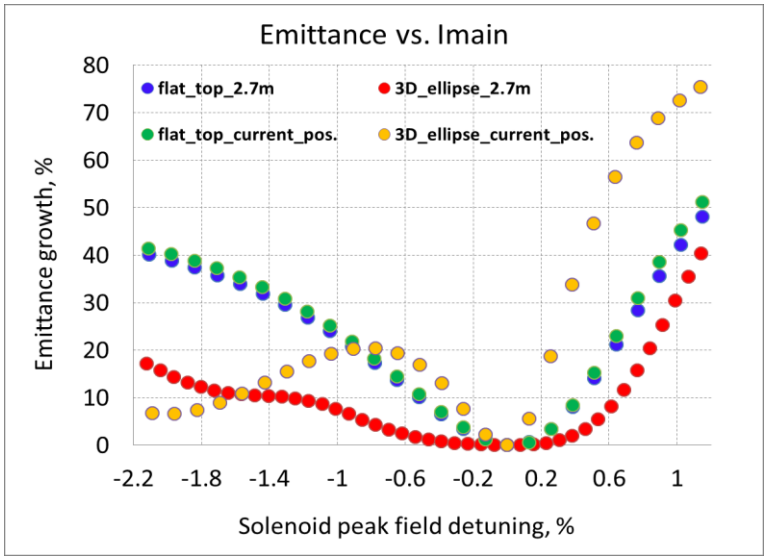
Slice emittances: EMSY1

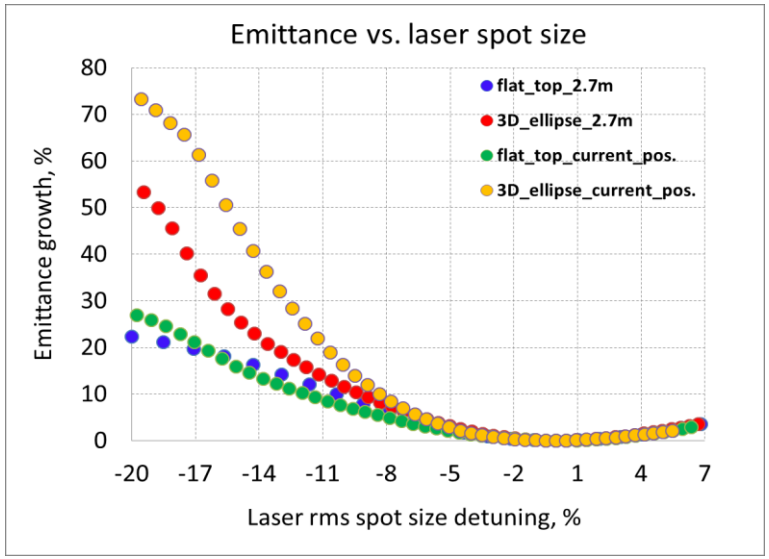


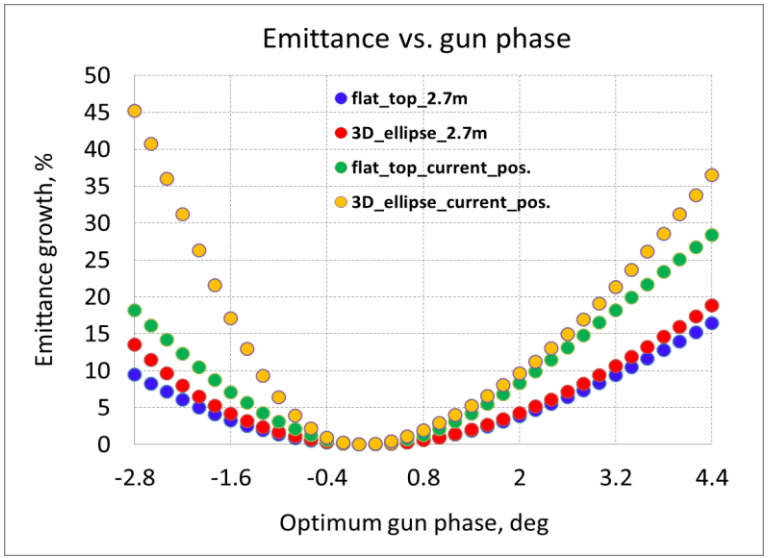
Slice currents: EMSY1

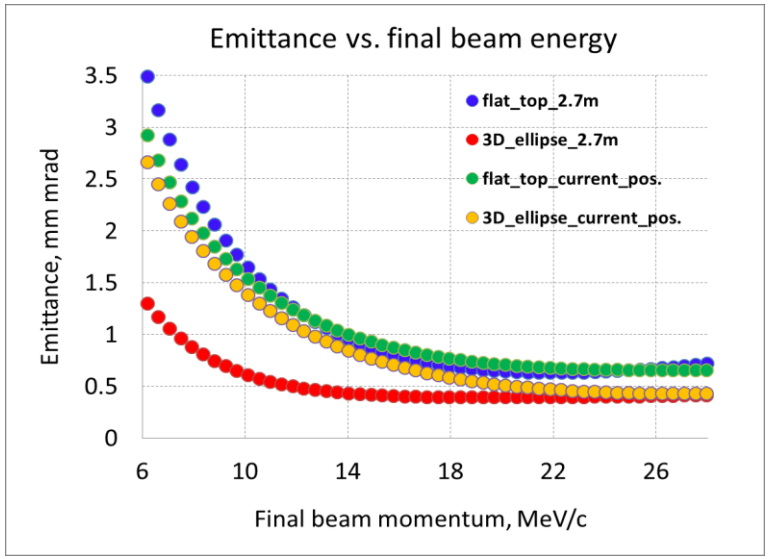


Beam tolerances comparing Z=2.7m and Z=3.1m









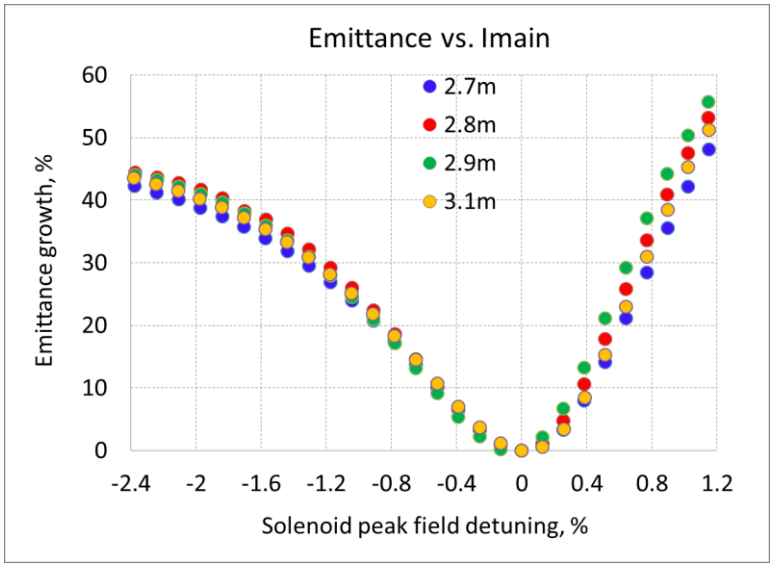
Different rms bunch lengths at EMSY1 !

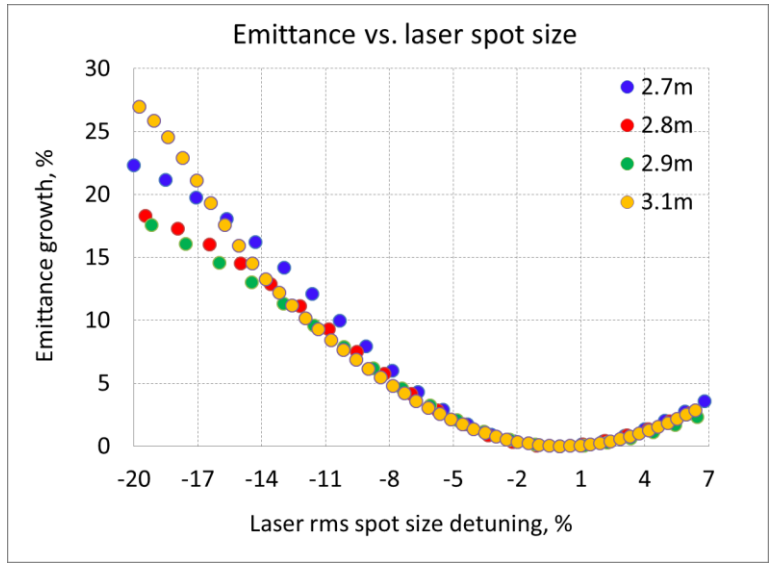
Summary of beam studies: flat-top + 3D ellipsoidal laser profiles

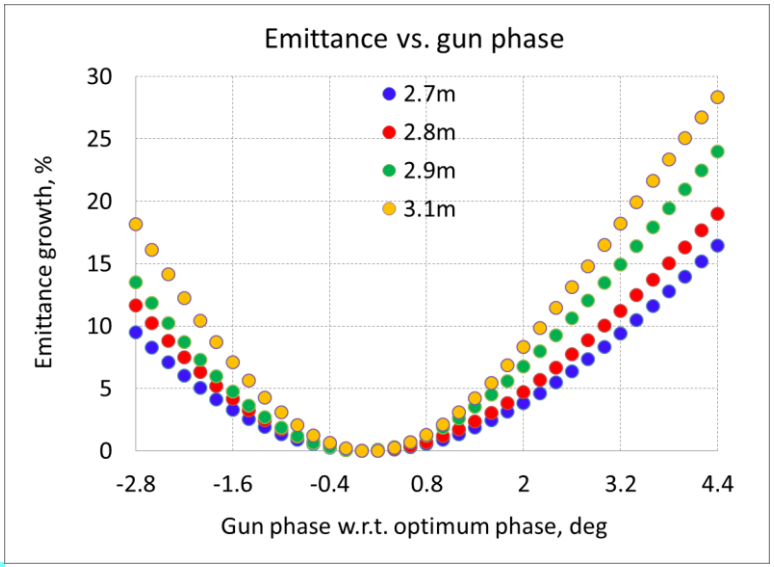
Beam studies comparing different booster positions for 2 laser profiles (position of EMSY1 is fixed)

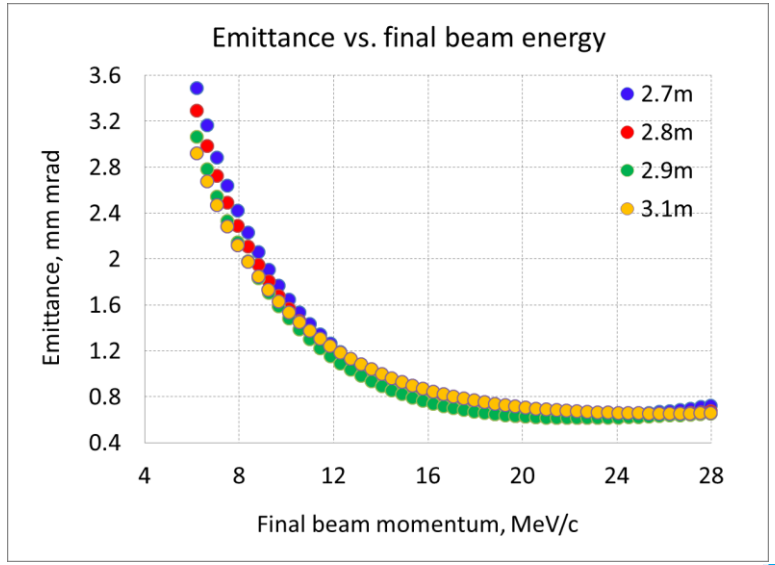
Temporal	profile	Flat-top	3D homogeneous	Flat-top	3D homogeneous	Flat-top	3D homogeneous	Flat-top	3D homogeneous
Transverse	distribution	radial homogeneous	3D homogeneous	radial homogeneous	3D homogeneous	radial homogeneous	3D homogeneous	radial homogeneous	3D homogeneous
Trms	ps	6.272	6.1	6.272	6.75	6.272	5.5	6.272	6.1
XYrms	mm	0.401	0.39	0.42	0.42	0.46	0.4	0.48	0.4
Th. emit.	mm mrad	0.339	0.33	0.356	0.356	0.39	0.339	0.407	0.339
Ecath.	MV/m	60.58							
RF gun phase	deg	-1.5	-1.5	-1	-2	-1	-2	-0.5	-2
MaxBz	T	0.2279	0.2297	0.2277	0.2289	0.228	0.2292	0.2279	0.2284
CDS starting position	**m**	**3.07**	**3.07**	**2.9**	**2.7**	**2.8**	**2.8**	**2.7**	**2.9**
MaxE	MV/m	19.76	19.76	16	19.76	20	20	18	13
Charge	nC	1							
Momentum	MeV/c	23.96	23.96	20.68	23.96	24.2	24.2	22.4	18
Projected emittance	**mm mrad**	**0.639 0.635 (6.03m)**	**0.419 0.416 (6.05m)**	**0.62 0.616 (5.78m)**	**0.4 0.394 (6m)**	**0.62 0.617 (5.9m)**	**0.423 0.419 (6m)**	**0.63 0.63 (5.76m)**	**0.408 0.393 (6.2m)**
Th. / proj.	**%**	**53**	**79**	**58**	**89**	**63**	**80**	**65**	**83**
<Sl. emit.>	mm mrad	0.572	0.392	0.558	0.383	0.54	0.395	0.543	0.389
Rms bunch length	**mm**	**2.163**	**2.162**	**2.12**	**2.163**	**2.05**	**2.05**	**2.02**	**2.13**
Peak current	**A**	**43.2**	**46.8**	**43.9**	**46.8**	**45.4**	**49.8**	**45.7**	**47.3**
Longitudinal emittance	pi keV mm	98.2	88	84	91.7	86.7	72.3	79.9	61.9

Summary of beam tolerance studies: flat-top profile



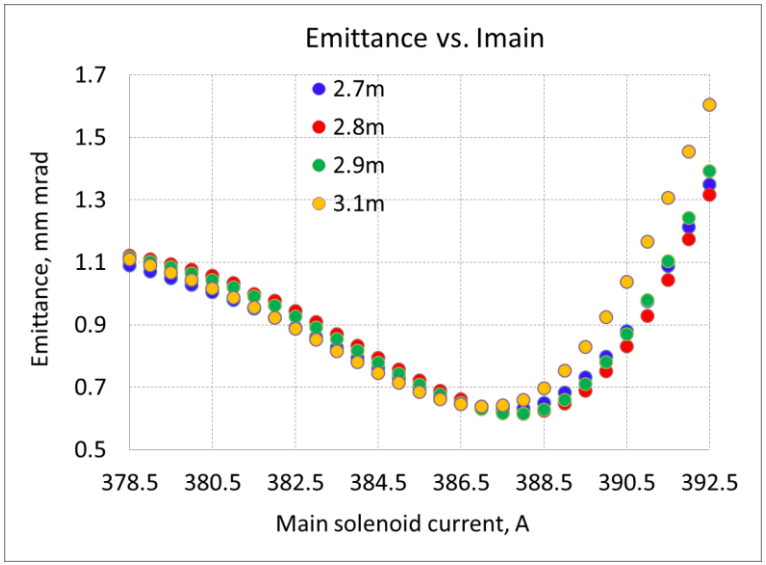


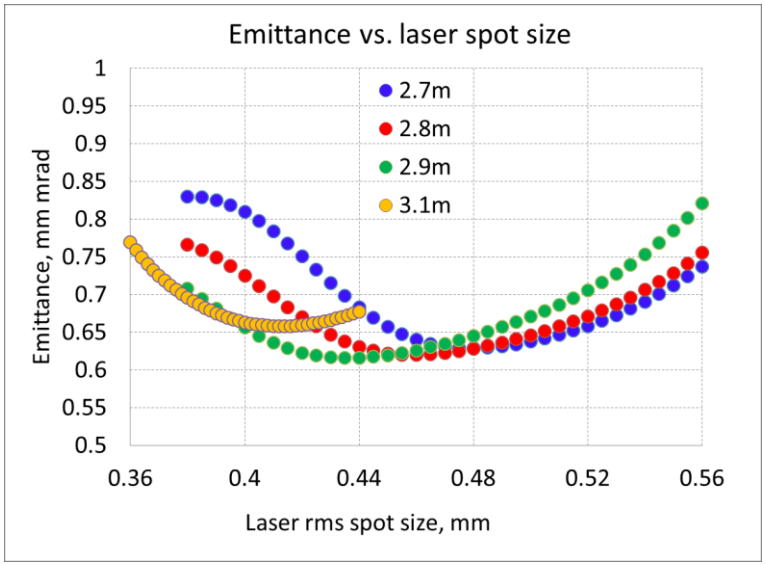


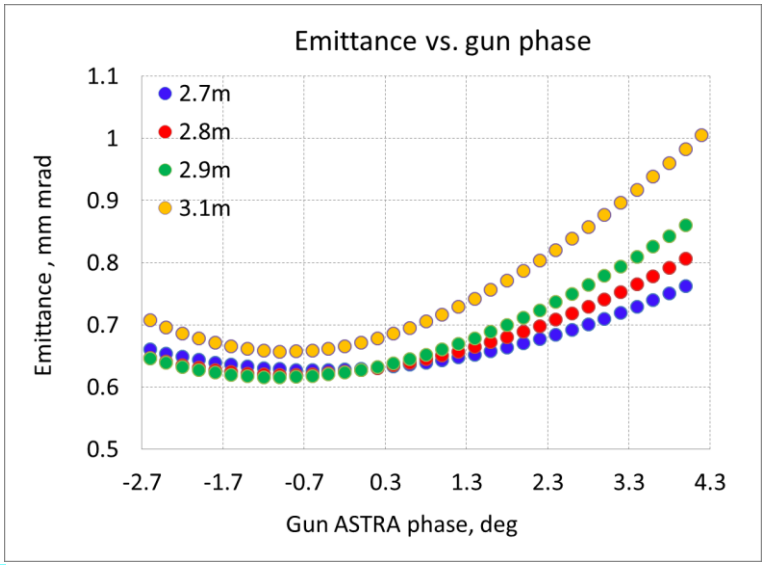


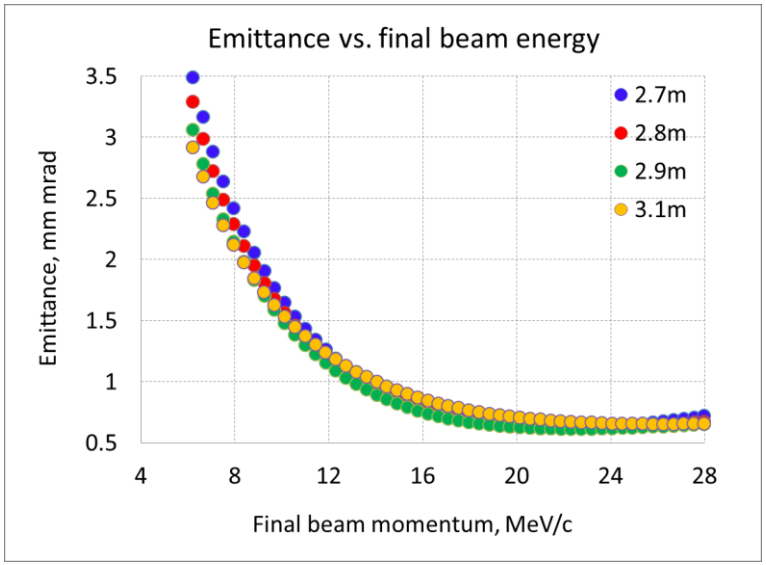
Different rms bunch lengths at EMSY1 !

Summary of beam tolerance studies: flat-top profile



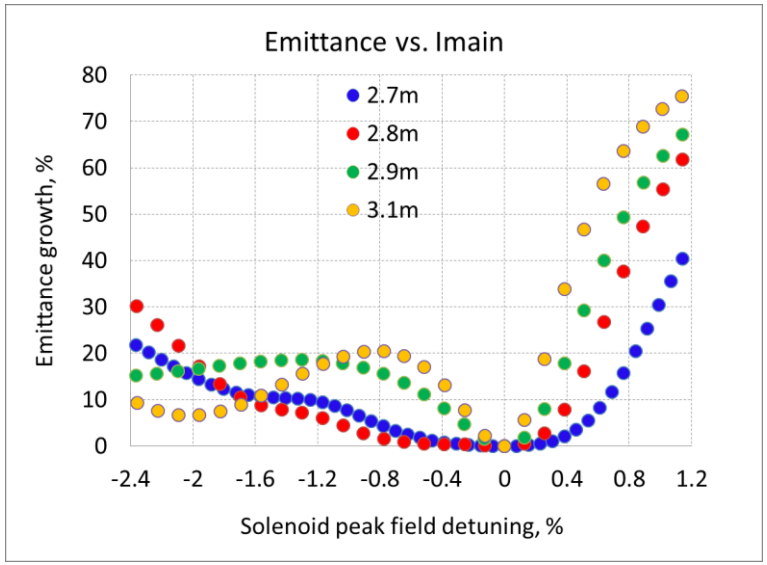


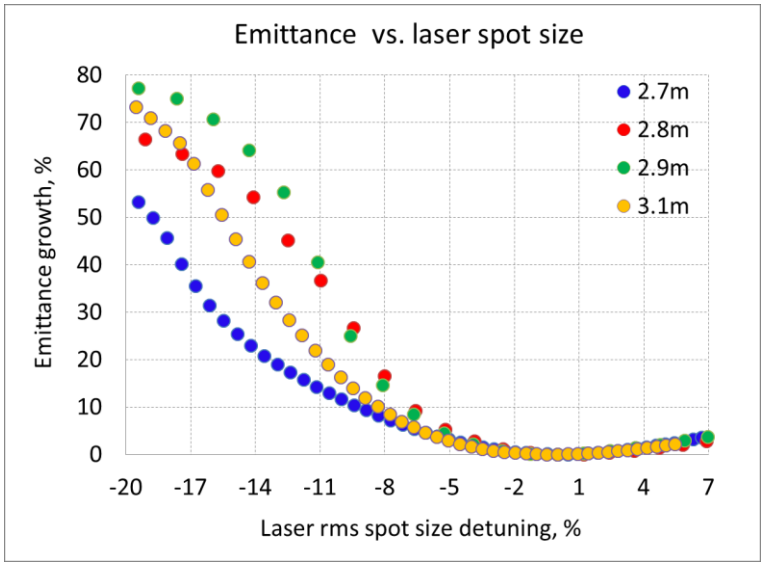


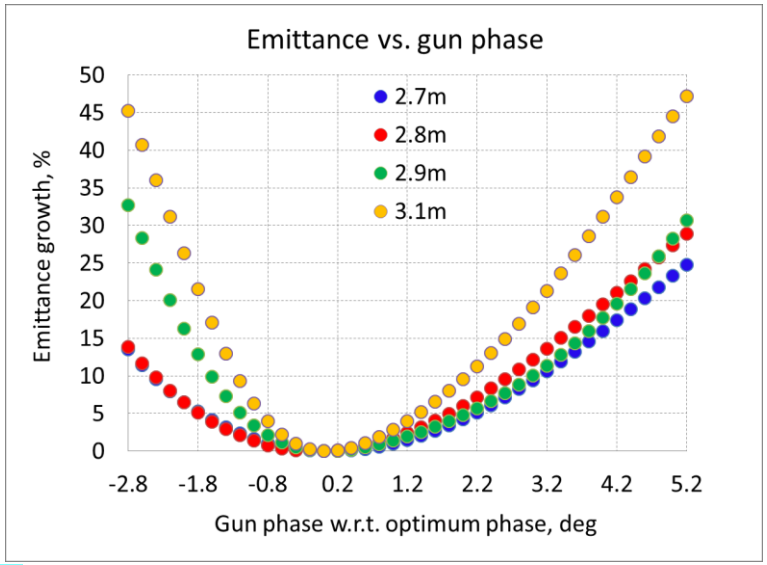


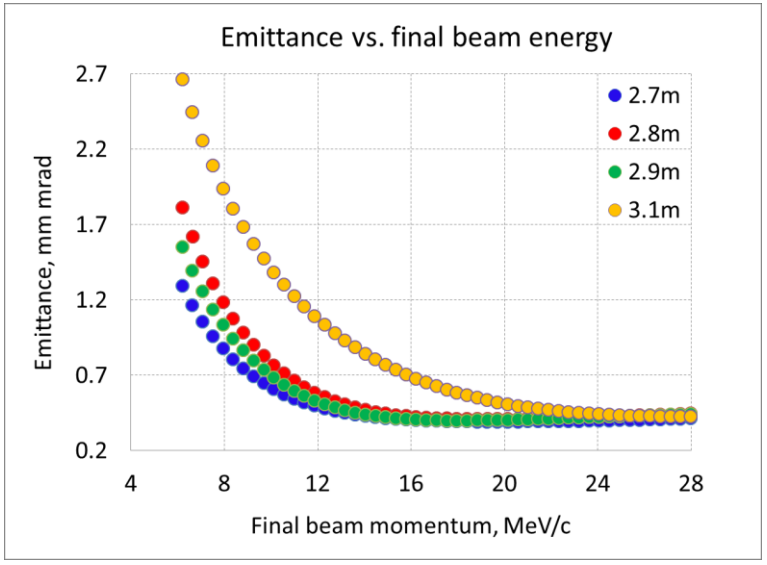
Different rms bunch lengths at EMSY1 !

Summary of beam tolerance studies: 3D ellipsoidal laser



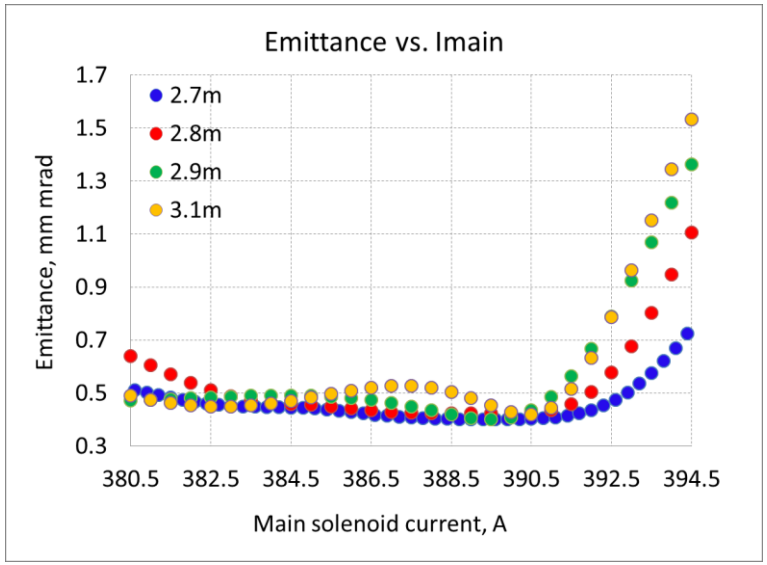


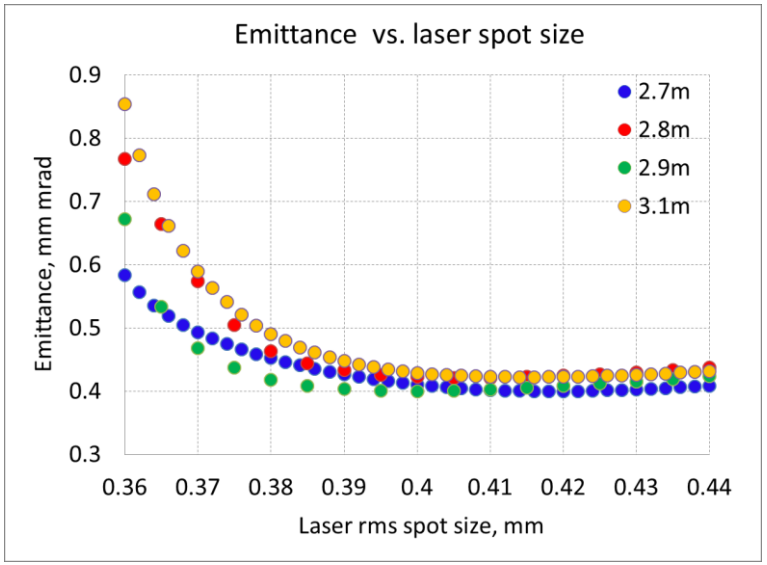


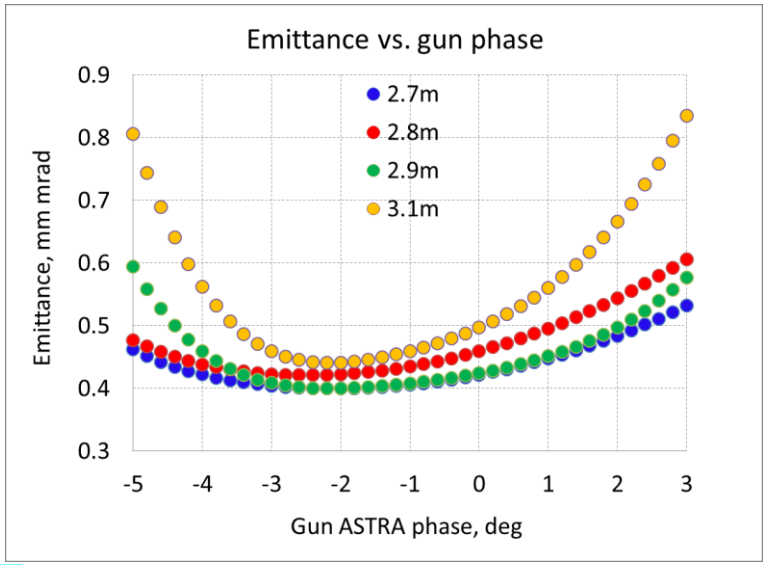


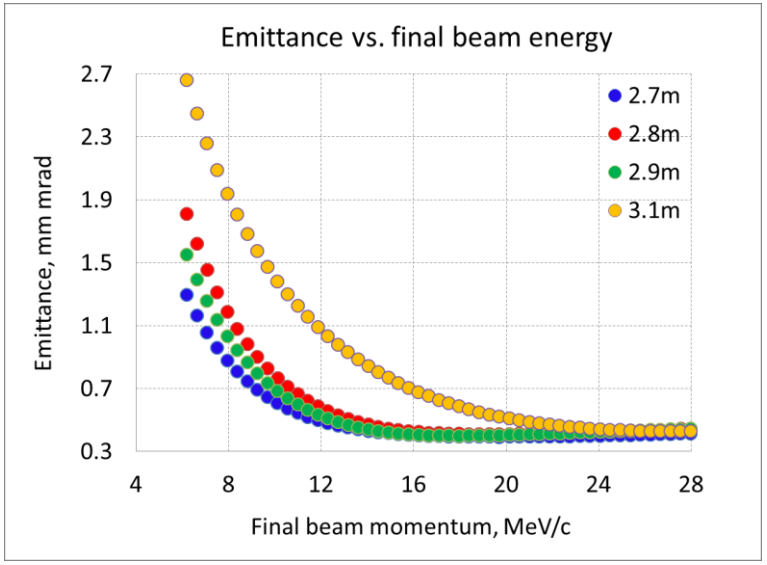
Different rms bunch lengths at EMSY1 !

Summary of beam tolerance studies: 3D ellipsoidal laser









Different rms bunch lengths at EMSY1 !

Conclusion (flat-top)

Flat-top temporal laser profile:

- Optimum booster position was found to be at Z=2.9m
- Bigger laser spot size required if booster is shifted upstream the cathode
- Tolerances comparable for all the cases (Z=2.7m and Z=2.9m preferable)
- Z=2.7m → shorter bunch length (higher peak current) as compared to Z=2.9m due to bigger initial laser spot size at the cathode, transverse (slice) emittance comparable
- Z=2.8m → smaller transverse (slice) emittance and higher peak current as compared to the current position
- Z=2.9m → Slightly lower emittance compared to Z=3.1m. Smaller emittance values at lower energies compared to other 3 cases
- Z=3.1m → Slightly higher emittance and smaller peak current compared to Z=2.9m

Conclusion (3D ellipsoidal)

3D ellipsoidal laser profile:

- Optimum booster position was found to be at Z=2.7m
- Machine stability (tolerances) strongly dependent on booster position
- Z=2.7m → Best machine performance !
- Z=2.8m → ~5% higher transverse (slice) emittances compared to Z=2.7m, better tolerances w.r.t. Z=3.1m but worse compared to Z=2.7m
- Z=2.9m → Worse beam tolerances as compared to Z=2.8 m
- Z=3.1m → The worst beam tolerances

- Next step: fix the initial booster position to Z=2.7m and vary the position of EMSY1

- Booster position optimization comparing flat-top and ellipsoidal laser profiles (current position of EMSY1)
- Transverse emittance optimization comparing flat-top and 3D ellipsoidal laser profiles (various booster positions, current position of EMSY1)
- Transverse emittance optimization comparing flat-top and 3D ellipsoidal laser profiles (shifted (and fixed) booster position, various positions of EMSY1)
- Summary

Optimization of the EMSY1 position (fixed booster position)

ASTRA simulation setup: fixed parameters

- Laser temporal profile: **flat-top** with 21.5ps FWHM length and 2ps rise and fall times
- Laser profile: **3D ellipsoidal** with tuned length to get **the same** bunch rms length at EMSY1 as for flat-top
- 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
- Gun phase fixed to on-crest
- Initial Z position of CDS booster: **2.7m**
- Bunch charge: 1 nC
- Searching for the best transverse emittance at **EMSY1**

ASTRA simulation setup: varied parameters

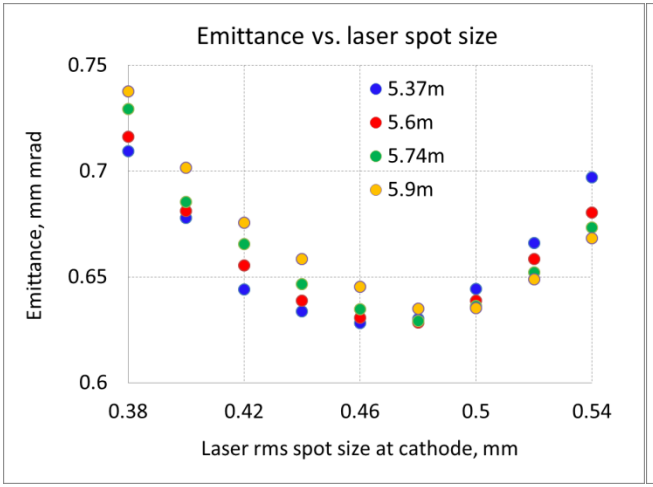
- Laser transverse rms spot size on the cathode
- CDS booster gradient
- Main solenoid current

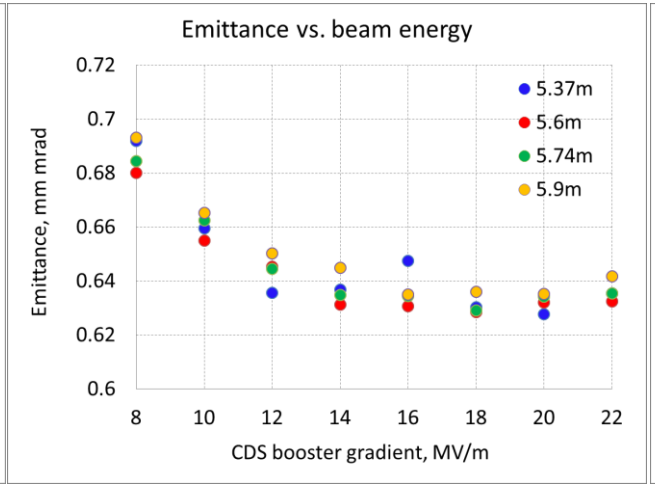
Emittance has been optimized at EMSY1 with the following positions:

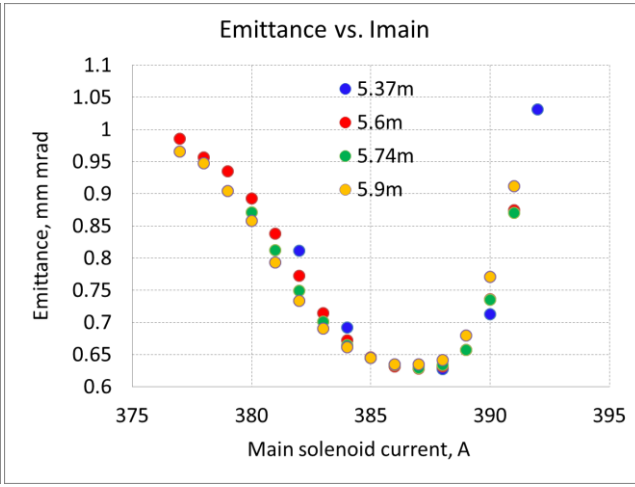
- Z=5.37m (shifted towards the cathode by the same distance as CDS booster)
- Z=5.74m (current position)
- Z=5.6m (shifted ~15cm upstream from the current position)
- Z=5.9m (shifted ~15cm downstream from the current position)

Optimization of transverse emittance comparing different EMSY1 positions (flat-top + 3D ellipsoidal laser profiles)

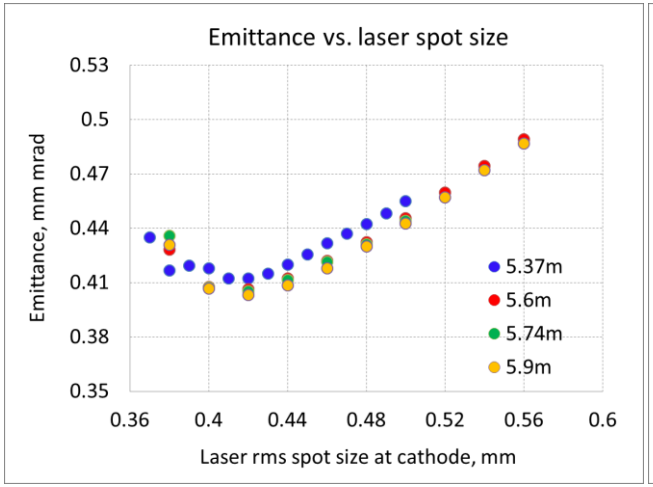
Flat-top

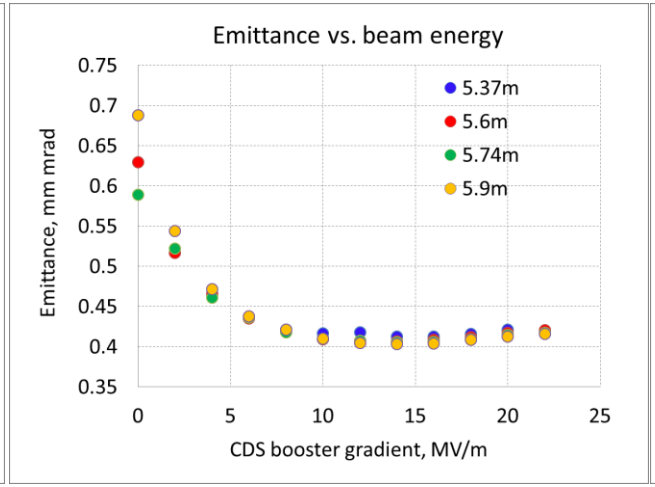


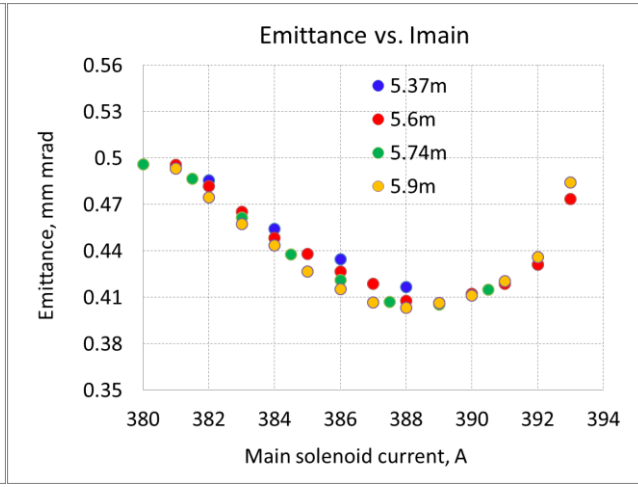




3D ellipsoidal







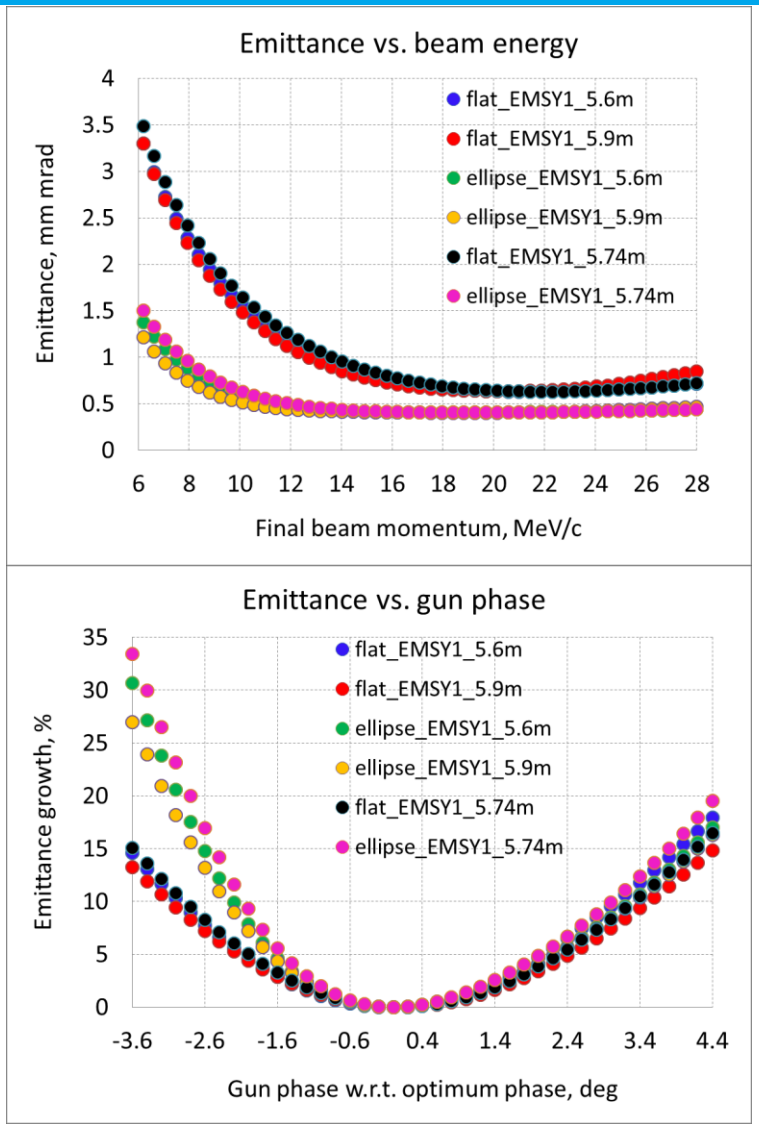
Summary of beam studies: flat-top + 3D ellipsoidal laser profiles

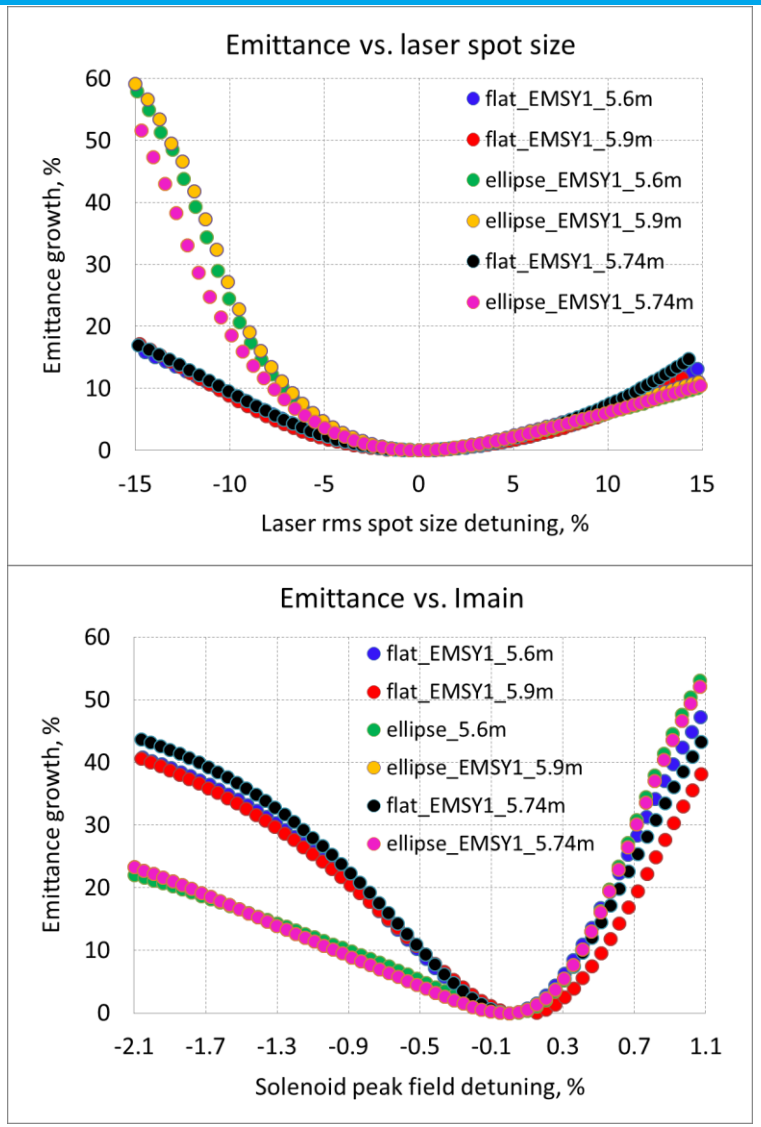
Beam studies comparing different positions of EMSY1 for 2 laser profiles (booster position fixed !)

Temporal	profile	Flat-top	3D homogeneous	Flat-top	3D homogeneous	Flat-top	3D homogeneous	Flat-top	3D homogeneous
Transverse	distribution	radial homogeneous	3D homogeneous	radial homogeneous	3D homogeneous	radial homogeneous	3D homogeneous	radial homogeneous	3D homogeneous
Trms	ps	6.272	5.5	6.272	5.5	6.272	5.5	6.272	5.5
XYrms	mm	0.46	0.42	0.48	0.42	0.48	0.42	0.48	0.42
Th. emit.	mm mrad	0.39	0.356	0.407	0.356	0.407	0.356	0.407	0.356
Ecath.	MV/m	60.58							
RF gun phase	deg	-1.0	-2.0	-1.0	-2.0	-1.0	-2.0	-1.0	-2.0
MaxBz	T	0.2277	0.22888	0.2277	0.22888	0.2277	0.22888	0.2271	0.2283
EMSY1 position	**m**	**5.37**	**5.37**	**5.6**	**5.6**	**5.74**	**5.74**	**5.9**	**5.9**
MaxE	MV/m	16	12	18	14	18	14	16	14
Charge	nC	1							
Momentum	MeV/c	20.6	17.2	22.4	18.9	22.4	18.9	20.6	18.9
Projected emittance	**mm mrad**	**0.638 0.63 (5.6m)**	**0.425 0.405 (5.88m)**	**0.642 0.635 (5.81m)**	**0.41 0.402 (5.95m)**	**0.636 0.635 (5.8m)**	**0.405 0.402 (5.95m)**	**0.645 0.643 (5.96m)**	**0.408 0.4 (6.23m)**
Th. / proj.	%	**61**	**84**	**63**	**87**	**64**	**88**	**63**	**87**
<Sl. emit.>	mm mrad	0.555	0.403	0.55	0.396	0.546	0.394	0.558	0.395
Rms bunch length	**mm**	**2.05**	**1.99**	**2.02**	**1.99**	**2.02**	**1.99**	**2.02**	**1.99**
Peak current	**A**	**45.5**	**50.9**	**45.9**	**50.9**	**45.9**	**50.9**	**45.9**	**50.9**
Longitudinal emittance	pi keV mm	76.9	46.2	79.1	51.5	79.2	51.5	75	51.4

← same

Summary of beam tolerance studies: different positions of EMSY1





The same rms bunch lengths at EMSY1 !

Summary

Overall, when the booster is shifted from 3.07m to 2.7m:

- Initially bigger laser spot size at the cathode yields to more relaxed space charge conditions for flat-top temporal laser profile
- Very good injector performance for the case of 3D ellipsoidal laser profile
- It is preferable to keep the position of EMSY1 unchanged

- Optimization of transverse emittance for different initial laser lengths and for different bunch charges (flat-top + 3D ellipsoidal)

Thank you for your attention !