

Beam Dynamics Simulations for the current setup of the EXFEL Photo Injector

Based on setup for the gun quad tests performed on 19-22.10.2017 (I. Isaev, “Gun quadrupole tests at European XFEL “, PPS, 02.11.2017)

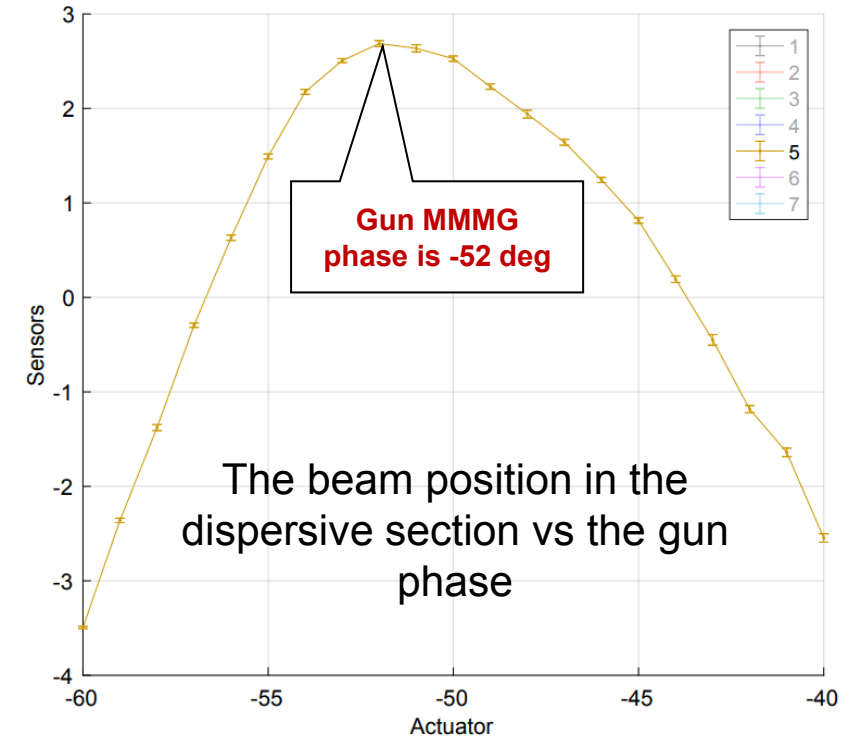
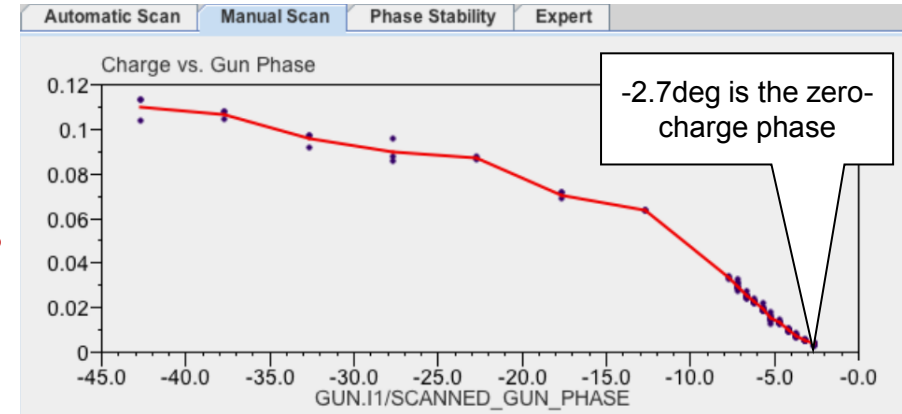
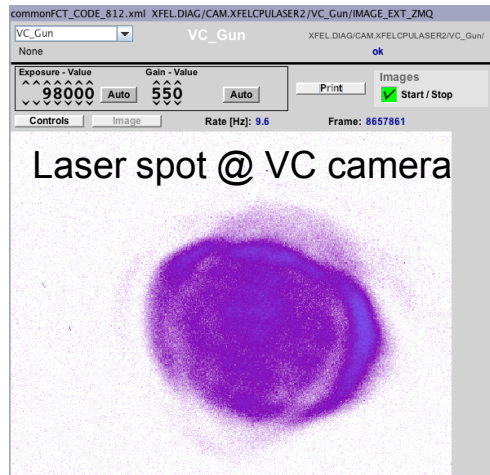
Mikhail Krasilnikov
DESY-TEMF meeting
Zeuthen, 14.11.2017

Injector settings → ASTRA input

- Gun power: 5.13MW (53MV/m)
- Beam momentum after the gun: **unknown**
- Gun RF phase: -43deg (w.r.t. **zero-charge phase**) it is not MMMG phase

Gun phase estimation: ($[-52^\circ - (-2.7^\circ)] = 49.3^\circ$; $49.3^\circ - 43^\circ = 6.3^\circ$ → $\phi_{ASTRA} = \text{MMM}G - 6^\circ$

- Beam momentum after AH1: 130 MeV/c (after A1 → ~150MeV)
- A1 adjusted for MMMG phase
- Gun main solenoid current **329.5 A**
- Gun bucking solenoid current 17.7 A
- Bunch charge: 500 pC
- Laser BSA: 1.2 mm



The beam position in the dispersive section vs the gun phase

ASTRA input

Gun:

- Field: gun43cavity.txt (FB=1.048)
- Ecath=53MV/m
- Gun RF phase: **MMMG-6°**, MMMG

A1:

- Field: 2 x tesla4cav.dat (1st cavity centered at z=4.0401m → 1st iris at z=3.637m)
- MaxE=34.42MV/m

Bunch charge: 500 pC, 200000 macroparticles

Laser BSA: 1.2 mm

- Temporal → Gaussian 6 ps rms (14.1 fwhm)
- Radial homogeneous: 1.2 mm → 0.3 mm rms (→ core+halo, 2D asymmetric)

Solenoid:

- Field: gunsolenoidsPITZ.txt (bucking → compensation)
- ?Calibration: $\text{MaxB} = -(0.0000372 + 0.000588 \cdot I_{\text{main}})$

Output:

- Beam at 14.44m (1st quadrupole position)

Main solenoid peak field scan

Gun phase=MMMG-6°

Emittance:

- Min (at -0.20265T) → 1.0 mm mrad
- Another min (at -0.19107T) → 1.6 mm mrad

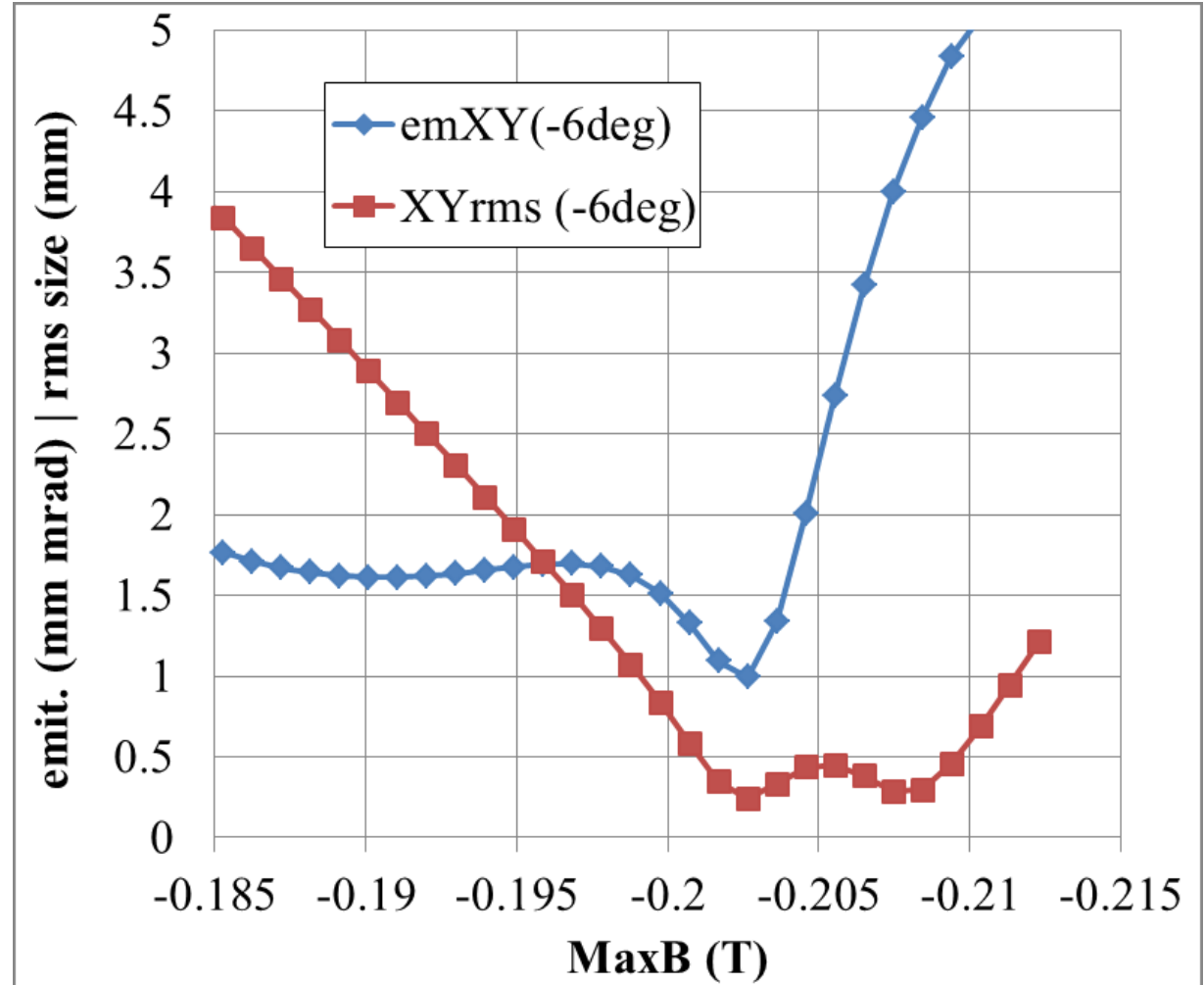
? Main solenoid calibration:

$$\text{MaxB[mT]} = 0.4 + 0.6 * \text{Imain[A]}$$

I. Bohnet, K. Flöttmann, Q. Zhao "Magnetic Field Investigations of the Solenoid Arrangement for PITZ", PITZ Note October 8, 2002

Another Danfysik main solenoid calibration (L. Staykov, 2002):

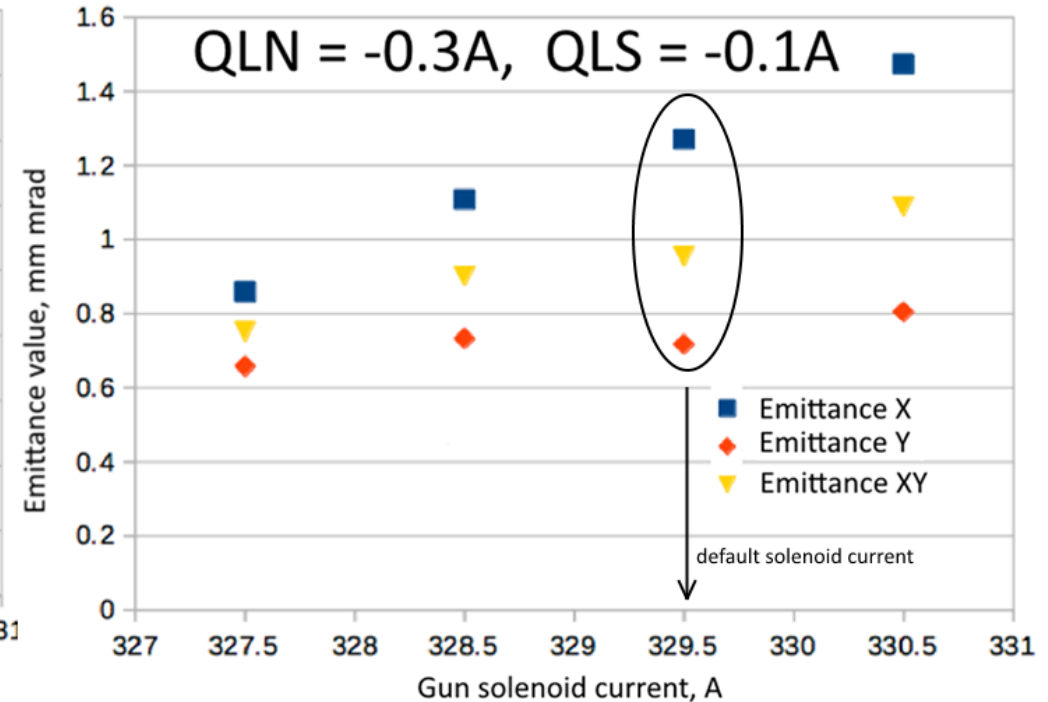
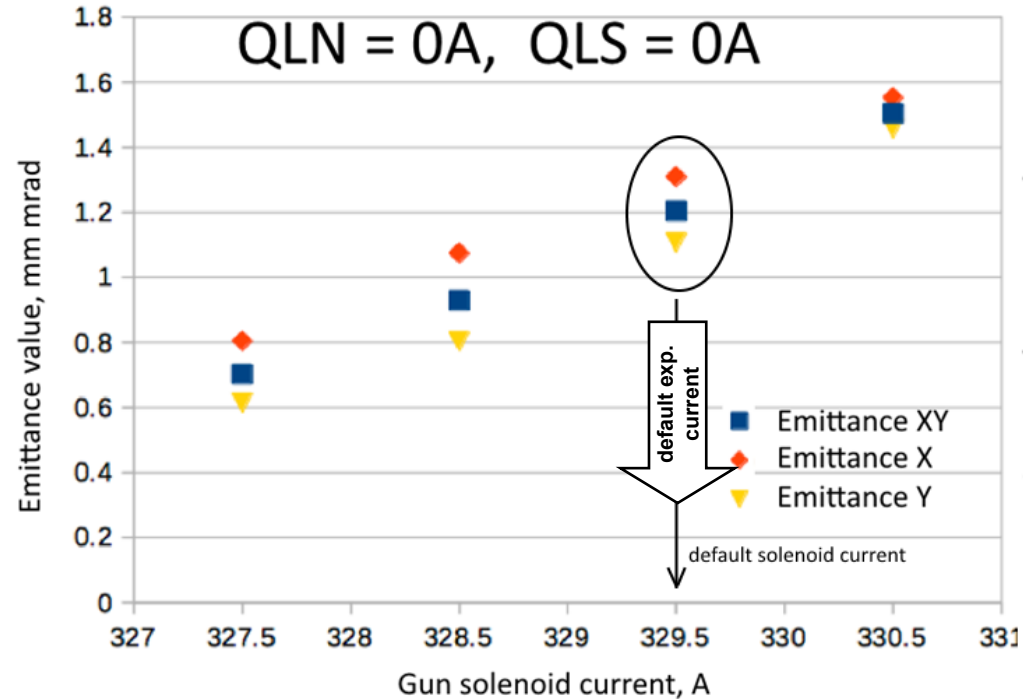
$$\text{MaxB[T]} = -(0.0000372 + 0.000588 * \text{Imain[A]})$$



NB: $Q(0.5\text{nC}, \text{MMMG-6}^\circ) = 0.4996\text{nC}$

Some results of the gun quadrupole adjustments (I. Isaev)

2nd experiment: emittance vs solenoid current



- The experiment shows that **the tuning the gun solenoid current can decrease emittance value at least by ~40%**. But in that case the gun quadrupoles must be readjusted for obtaining the smallest emittance.
- The emittance measurements were not done for the solenoid current **lower than 327A** because at these current a **beam loss in the injector section** was observed (non-optimal beam trajectories and collision with the collimator).

Main solenoid current scan

Case1: Gun phase=MMMG-6°

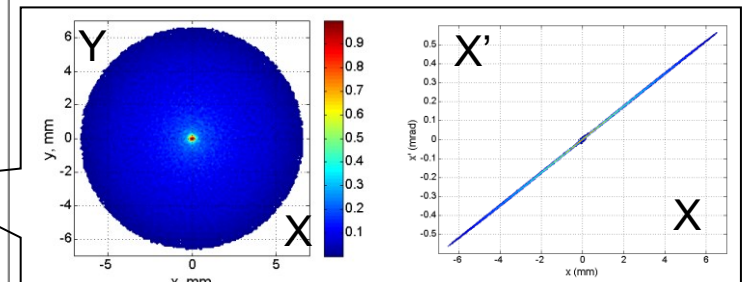
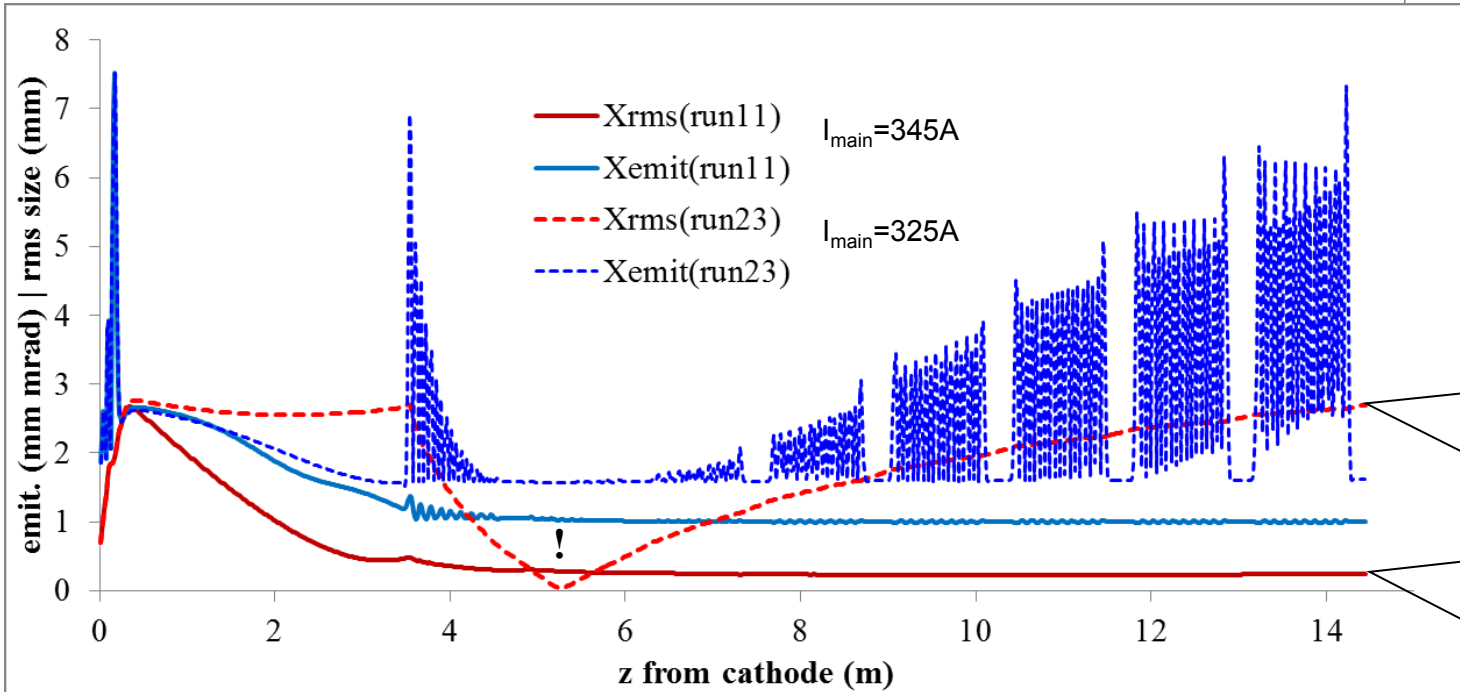
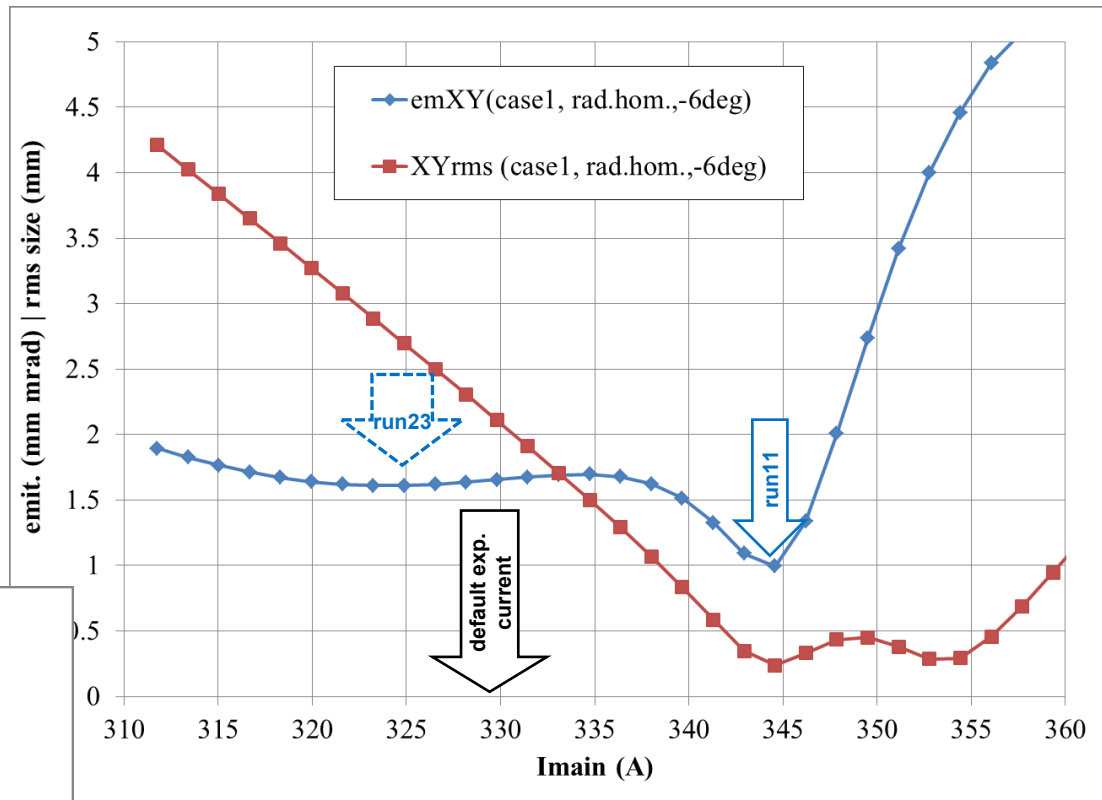
$$\text{MaxB[T]} = -(0.0000372 + 0.000588 \cdot \text{CF} \cdot \text{I}_{\text{main}}[\text{A}])$$

“Correction factor (CF) of the calibration coefficient”:

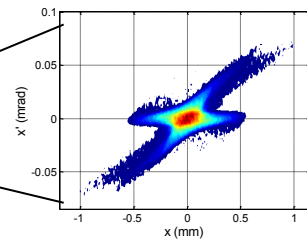
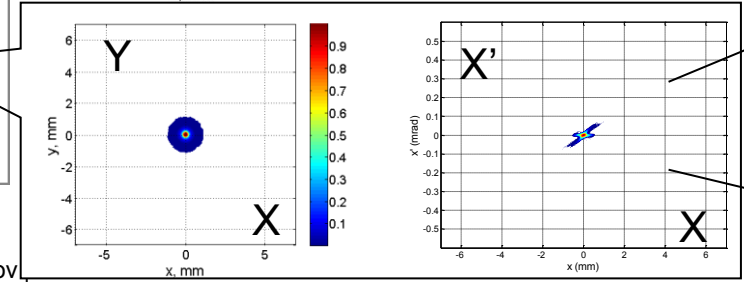
- PITZ (e-beam rms size based) → 0.982
- EXFEL (emittance min based*) → 1.05!

Emittance (CF=1):

- Min (at 345A) → 1.0 mm mrad → run11
- Another min (at 325A) → 1.6 mm mrad → run23

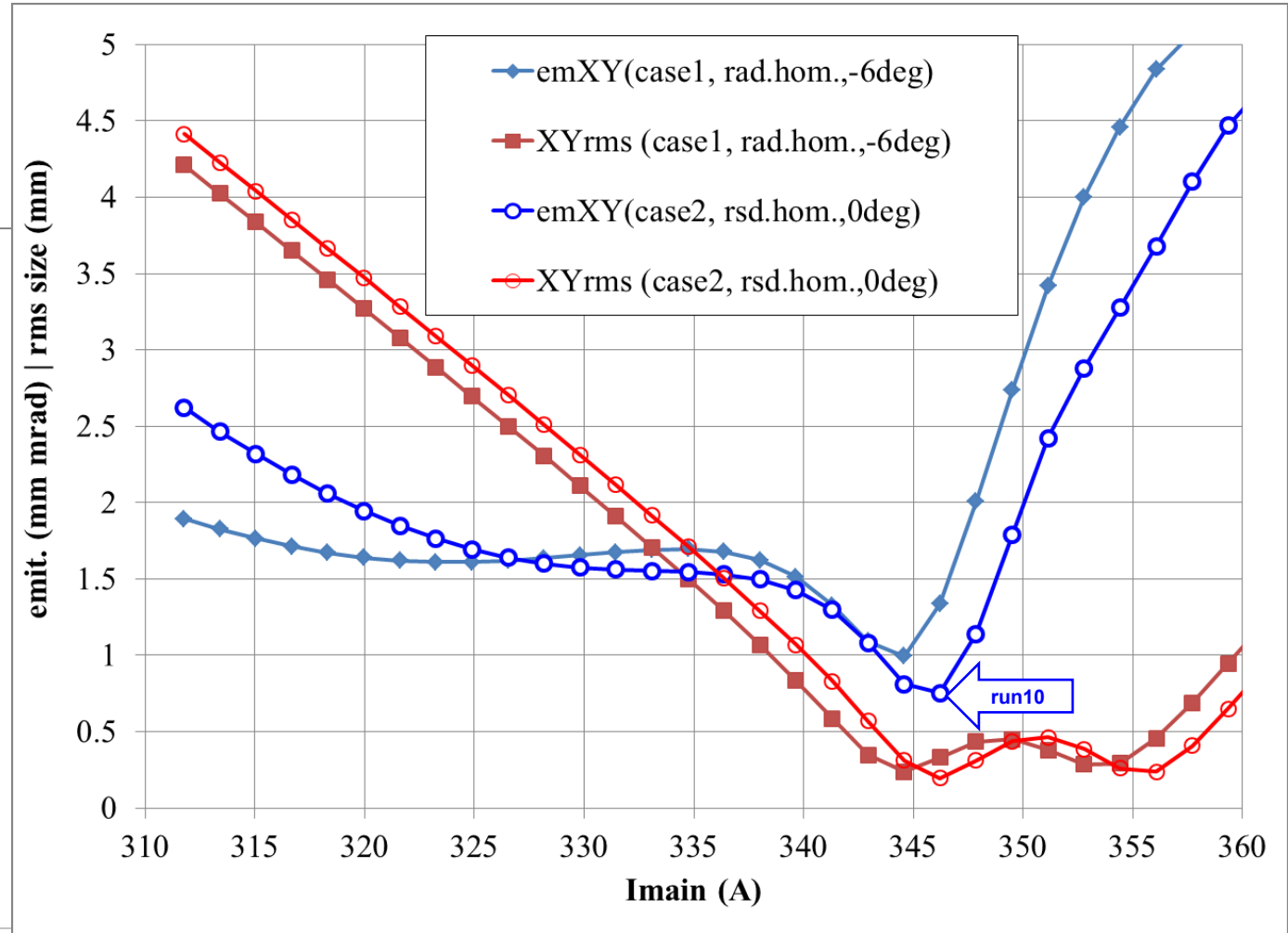
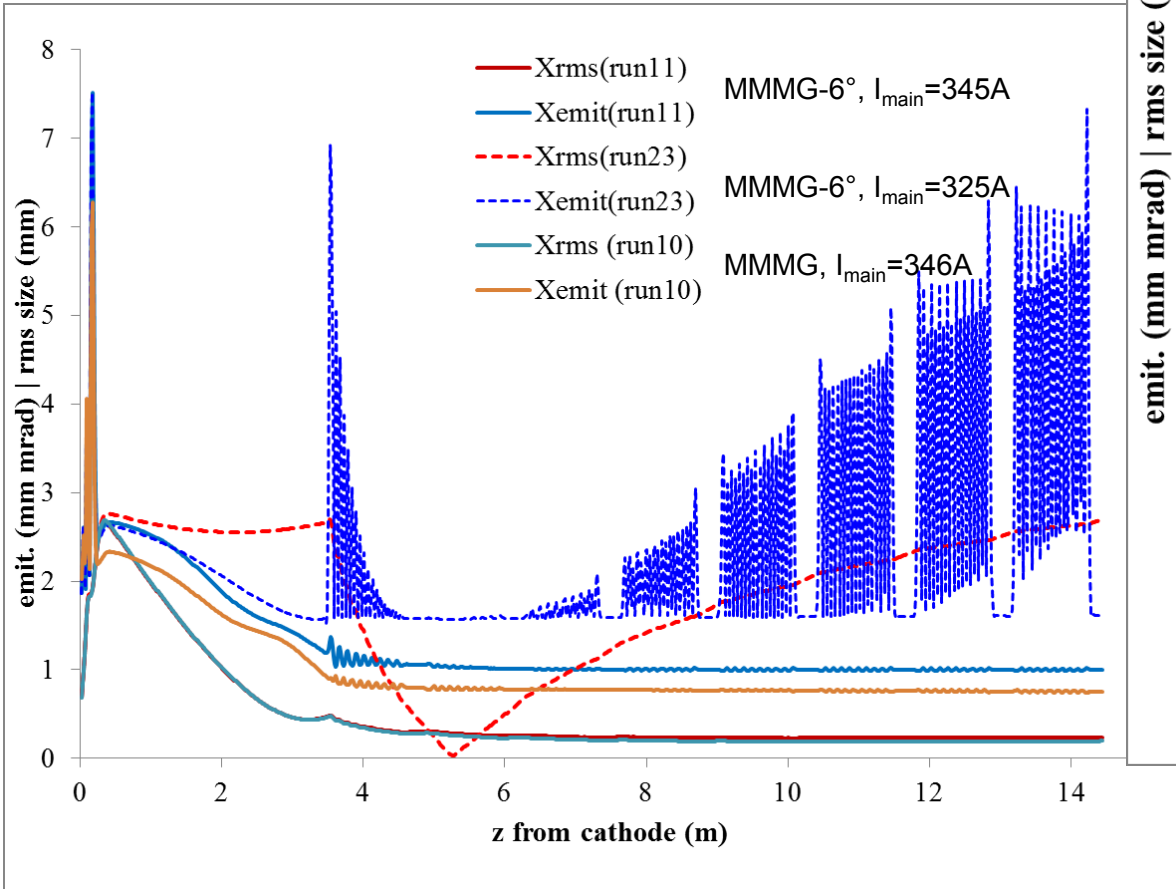


large transverse halo of electron beam → cut during emittance measurements?



Main solenoid current scan

Gun phase=MMMG-6° (case 1) vs. MMMG (case 2)



Emittance (case2):

- Min (at 346A) → 0.75 mm mrad → run10

$Q(0.5\text{nC}, \text{MMMG-6}^\circ)=0.4996\text{nC}$

$Q(0.5\text{nC}, \text{MMMG})=0.5\text{nC}$

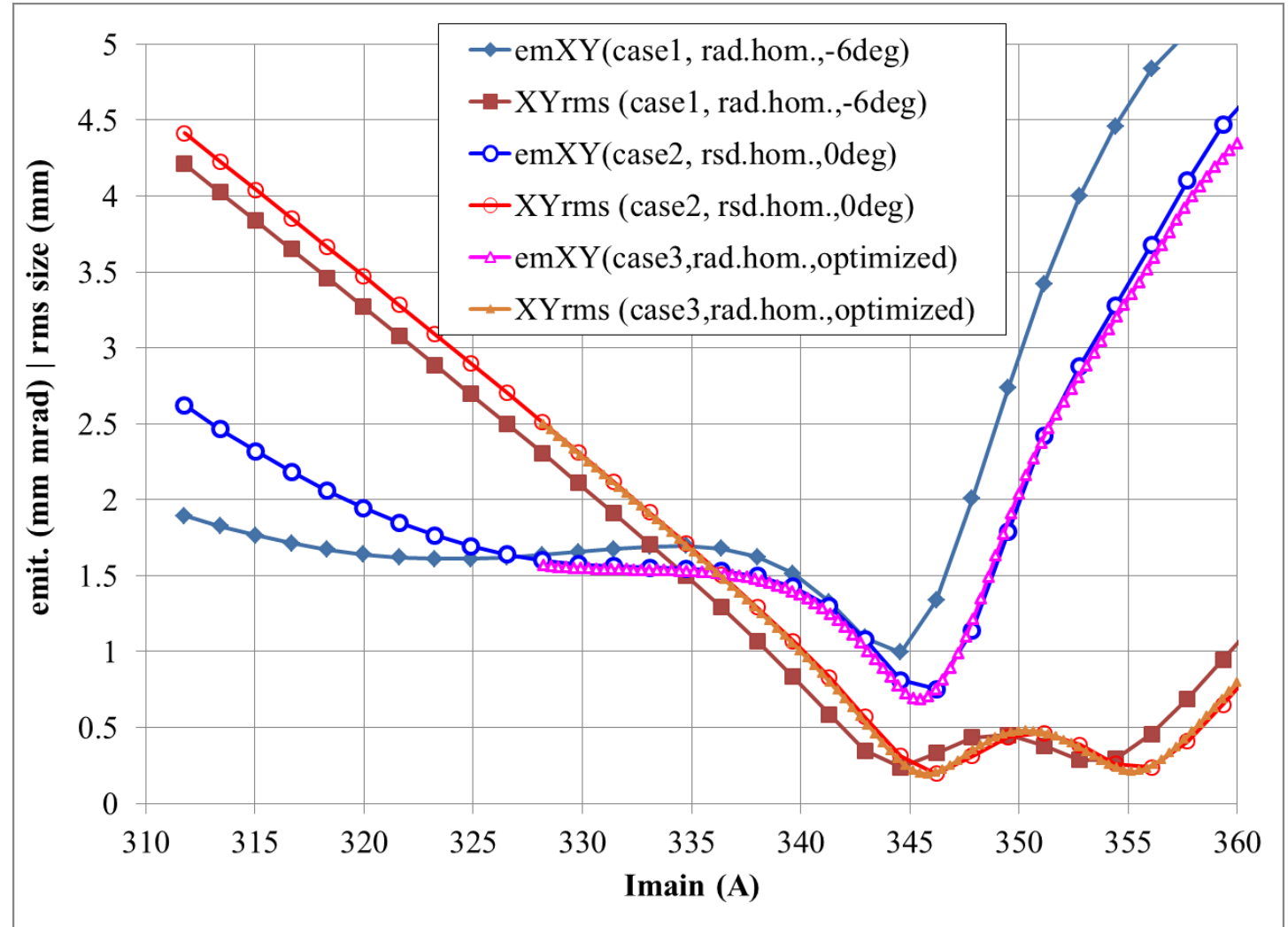
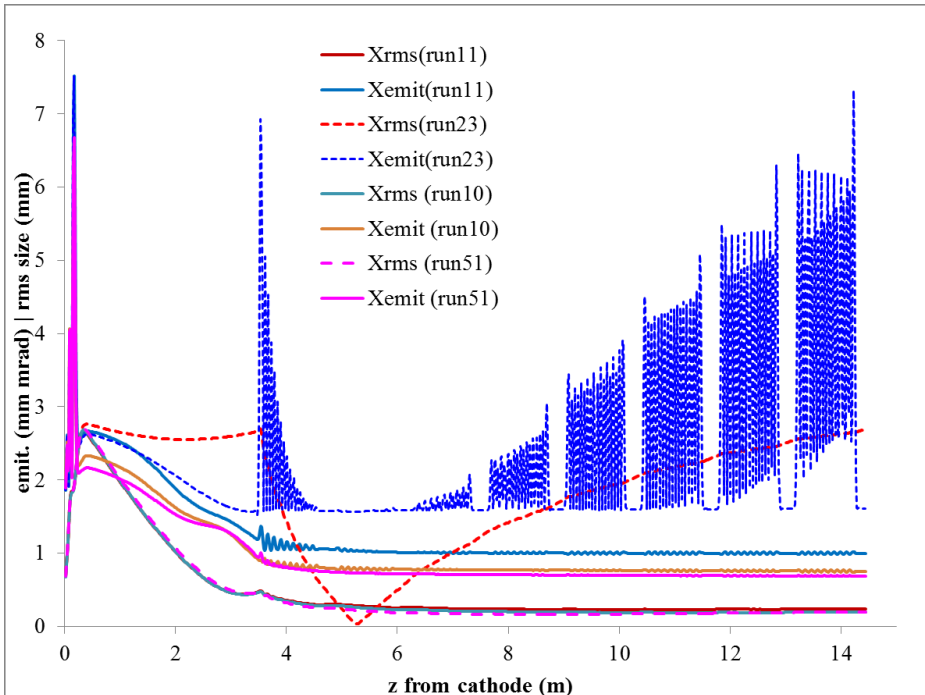
Fine emittance optimization for current setup

Case 3: Optimized parameters: { main solenoid current x laser XYrms x Gun phase }

- Optimized setup:
 - Laser XYrms=0.295mm
 - Gun phase = -1.48°
 - MaxB=-0.20318T

Emittance (case 3):

- Min (at 345.5A) → **0.687 mm mrad** → run51

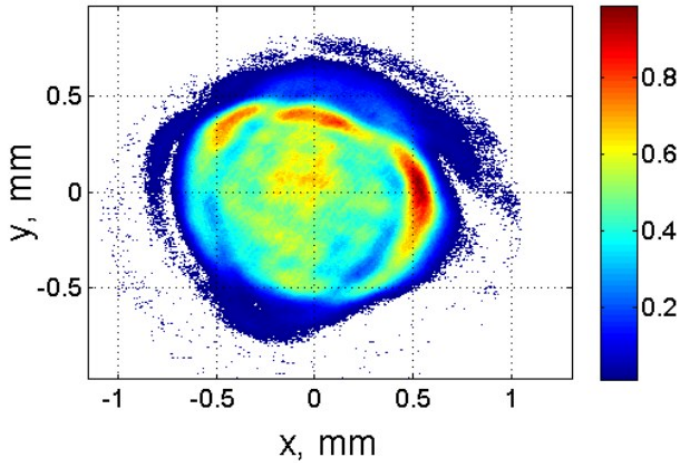


NB: $Q(0.5\text{nC}, \text{MMMG}-1.48^\circ) = 0.5\text{nC}$

More realistic laser transverse distributions

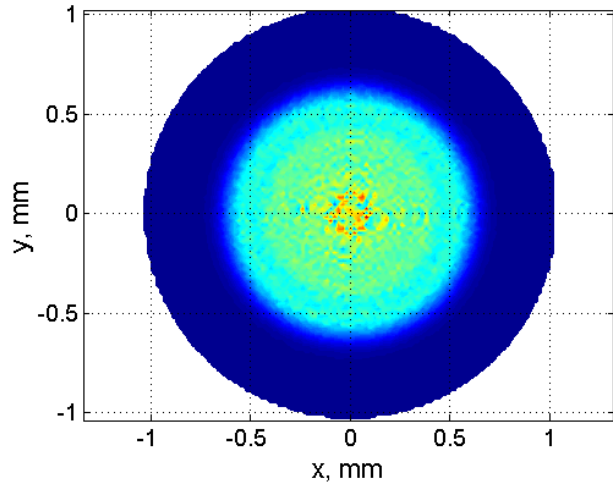
Core+halo = rings and 2D asymmetric distribution

VC measured

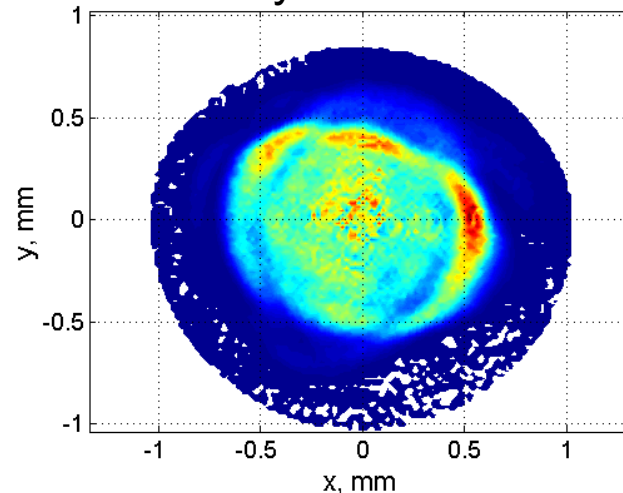


Distribution	σ_x , mm	σ_y , mm	σ_{xy} , mm
VC measured	0.34	0.29	0.31
Rad.homog	0.3	0.3	0.3
Rings	0.31	0.31	0.31
2D asym.	0.34	0.29	0.31

Core+Halo=Rings



2D asymmetric



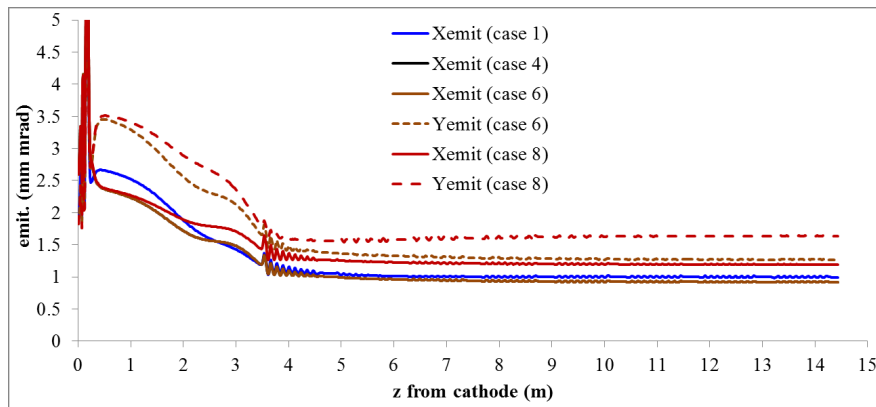
Case	PC laser transverse	ASTRA SC	Gun phase w.r.t. MMMG
1	Rad.homogen.	2D	-6°
2	Rad.homogen	2D	0°
3	Rad.homogen	2D	optimized
4	Core+Halo=Rings	2D	-6°
5	Core+Halo=Rings	2D	0°
6	2D asymmetric	2D	-6°
7	2D asymmetric	2D	0°
8	2D asymmetric	2D→3D	-6°
9	2D asymmetric	2D→3D	0°

SC: 2D→3D

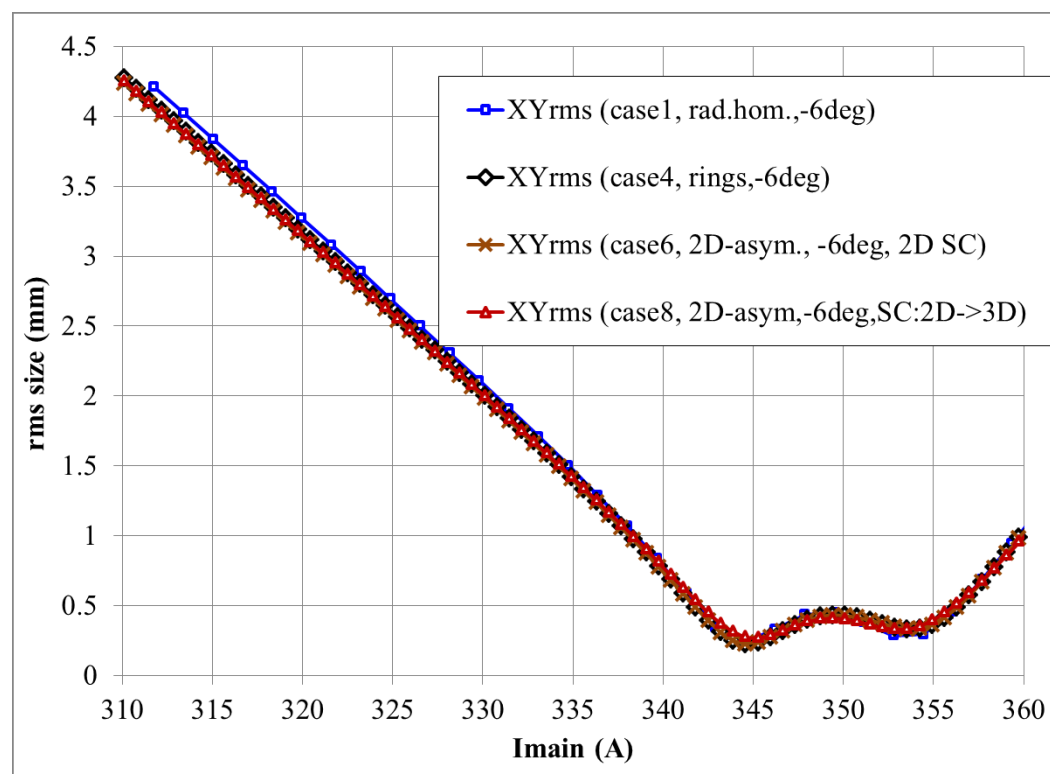
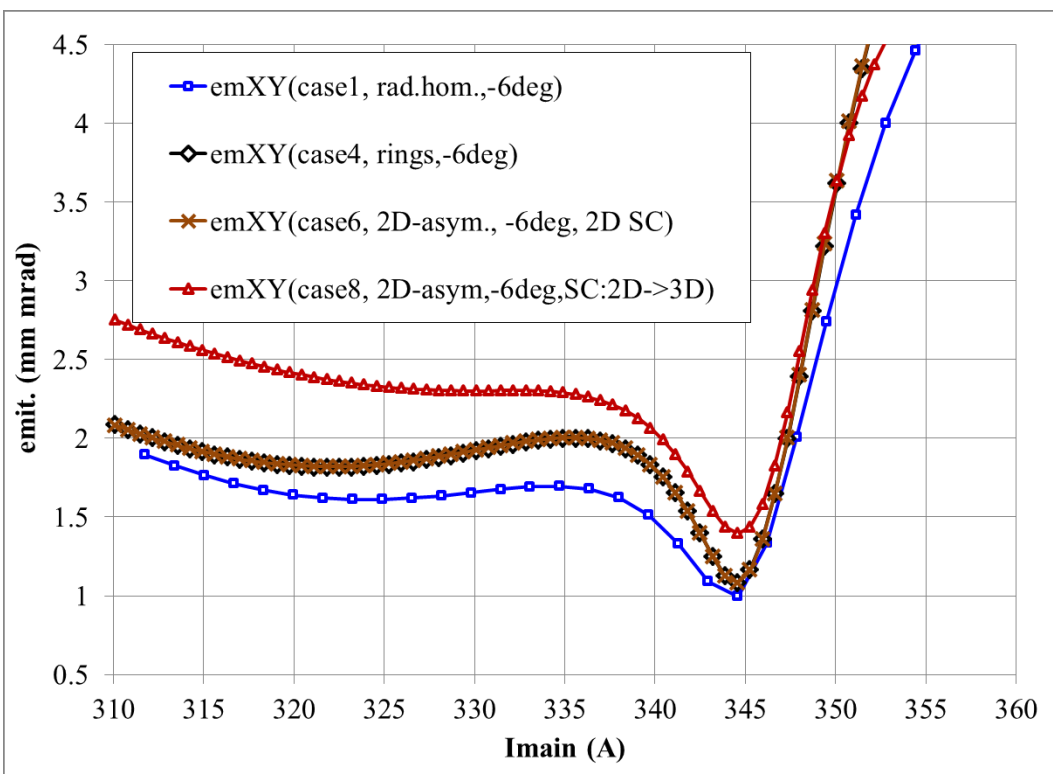
- Nrad = 50,
- Nlong_in = 100
- L2D_3D=.T
- z_trans=0.1
- Nxf=32, Nyf=32, Nzf=32

Different cased for the gun phase -6°

Cases 1,4,6,8

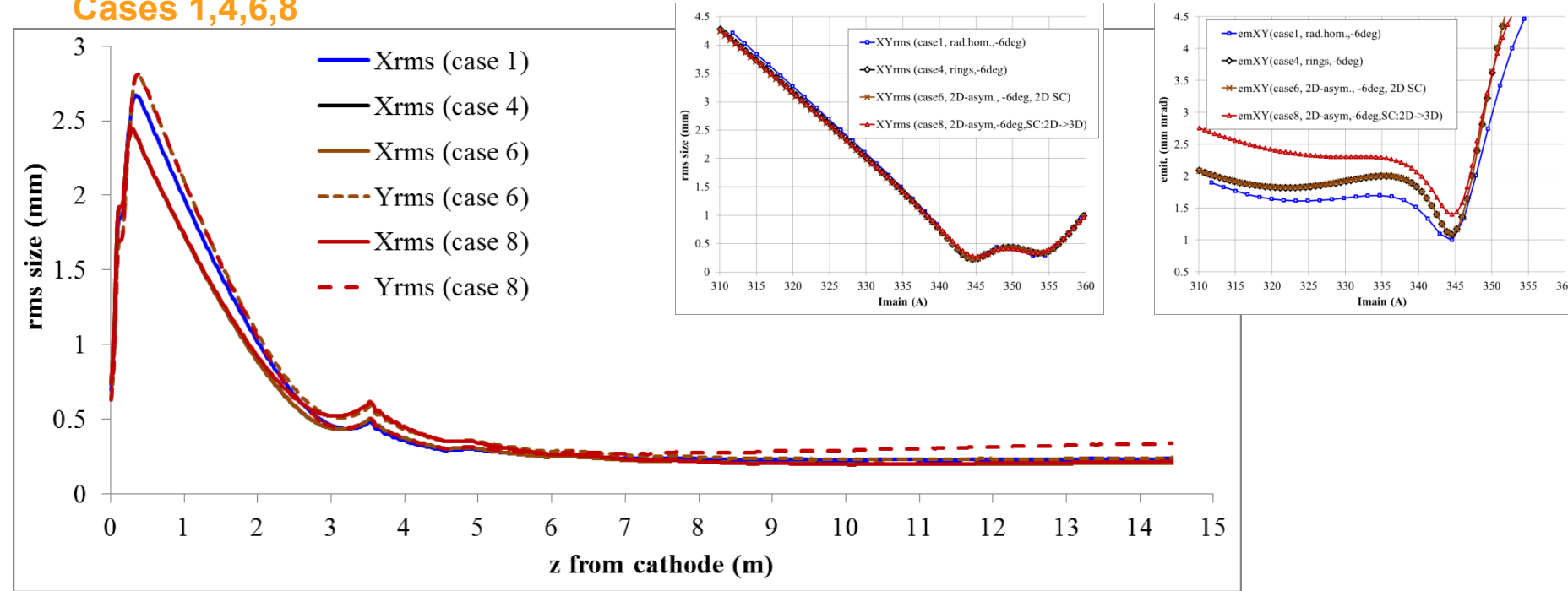


Case	PC laser transverse	ASTRA SC	Gun phase w.r.t. MMMG
1	Rad.homogen.	2D	-6°
2	Rad.homogen	2D	0°
3	Rad.homogen	2D	optimized
4	Core+Halo=Rings	2D	-6°
5	Core+Halo=Rings	2D	0°
6	2D asymmetric	2D	-6°
7	2D asymmetric	2D	0°
8	2D asymmetric	2D→3D	-6°
9	2D asymmetric	2D→3D	0°

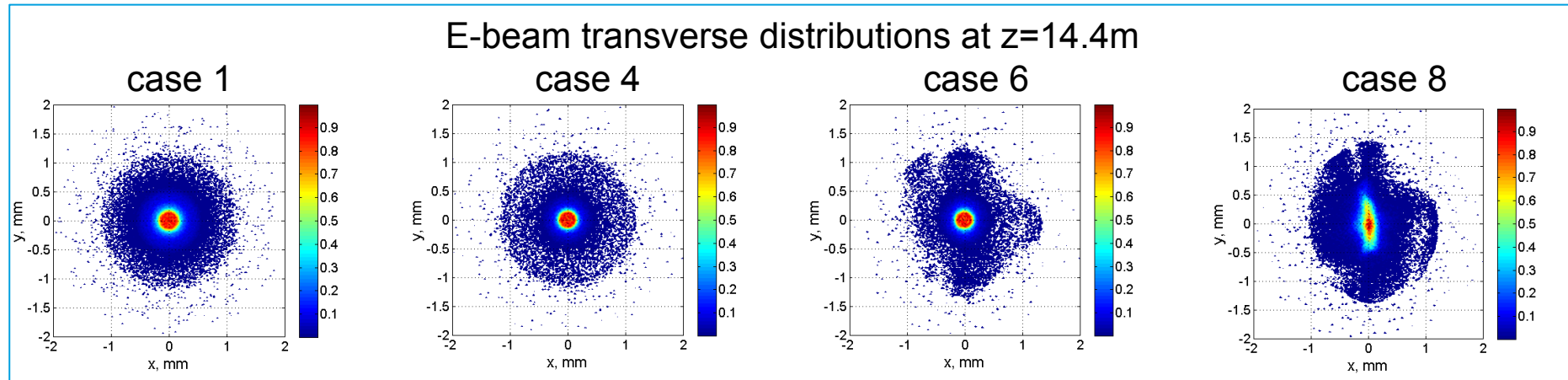


Different cased for the gun phase -6°

Cases 1,4,6,8



Case	PC laser transverse	ASTRA SC	Gun phase w.r.t. MMMG
1	Rad.homogen.	2D	-6°
2	Rad.homogen	2D	0°
3	Rad.homogen	2D	optimized
4	Core+Halo=Rings	2D	-6°
5	Core+Halo=Rings	2D	0°
6	2D asymmetric	2D	-6°
7	2D asymmetric	2D	0°
8	2D asymmetric	2D→3D	-6°
9	2D asymmetric	2D→3D	0°



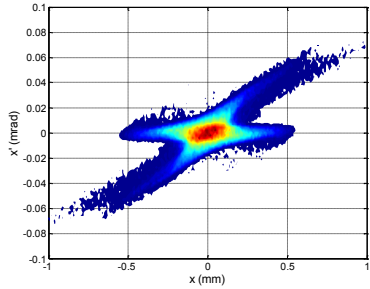
Different cased for the gun phase -6°

Cases 1,4,6,8

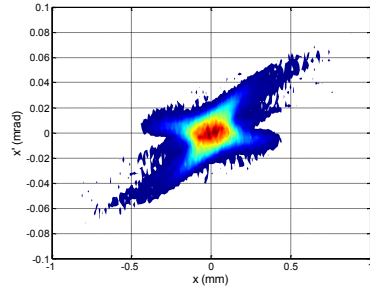
Case	PC laser transverse	ASTRA SC	Gun phase w.r.t. MMMG
1	Rad.homogen.	2D	-6°
2	Rad.homogen	2D	0°
3	Rad.homogen	2D	optimized
4	Core+Halo=Rings	2D	-6°
5	Core+Halo=Rings	2D	0°
6	2D asymmetric	2D	-6°
7	2D asymmetric	2D	0°
8	2D asymmetric	2D→3D	-6°
9	2D asymmetric	2D→3D	0°

Phase spaces at $z=14.4\text{m}$

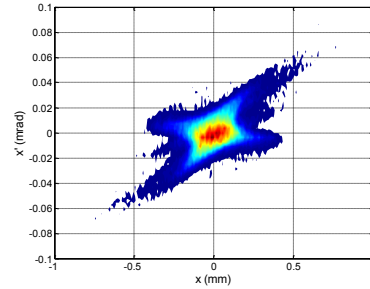
case 1



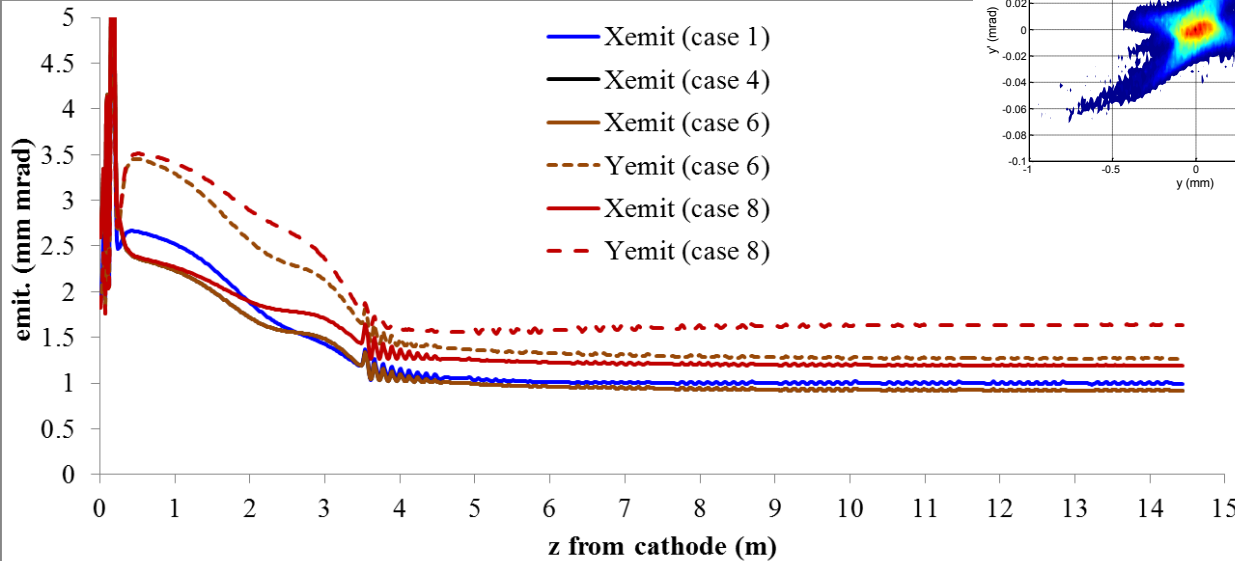
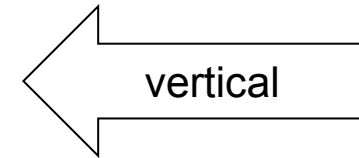
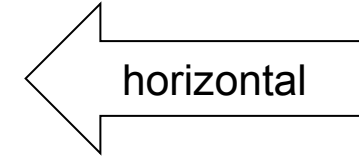
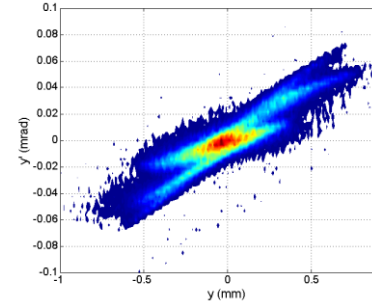
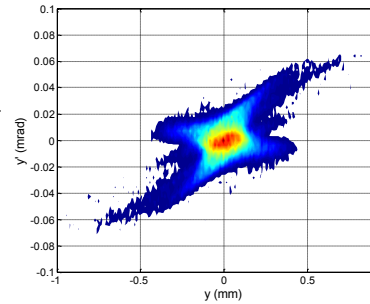
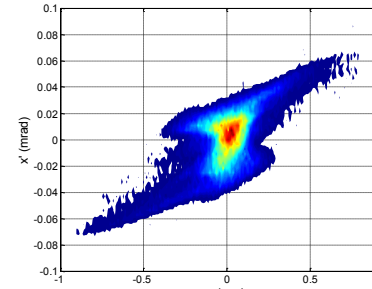
case 4



case 6



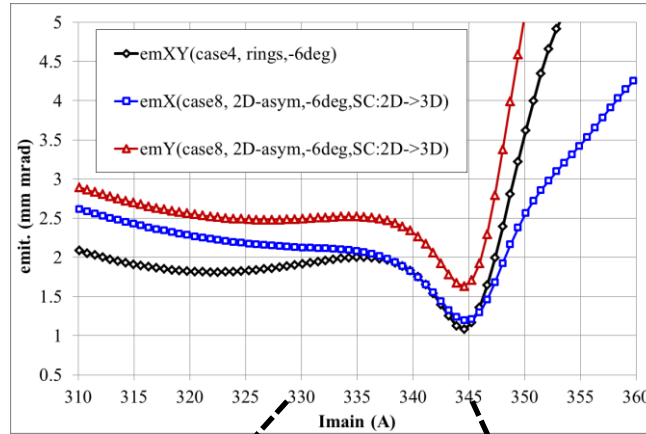
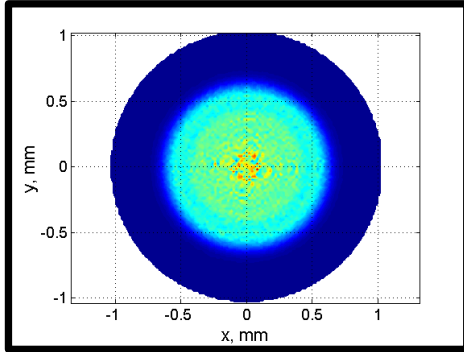
case 8



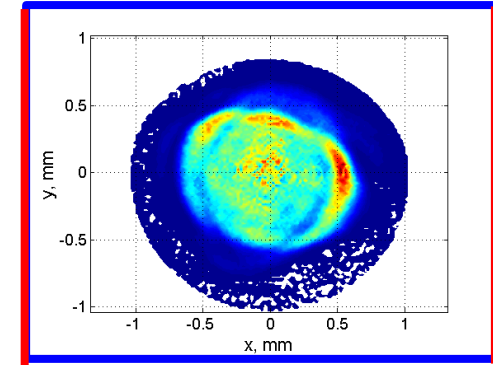
Slice emittance

Cases 4 and 8: Gun phase=MMMG-6°

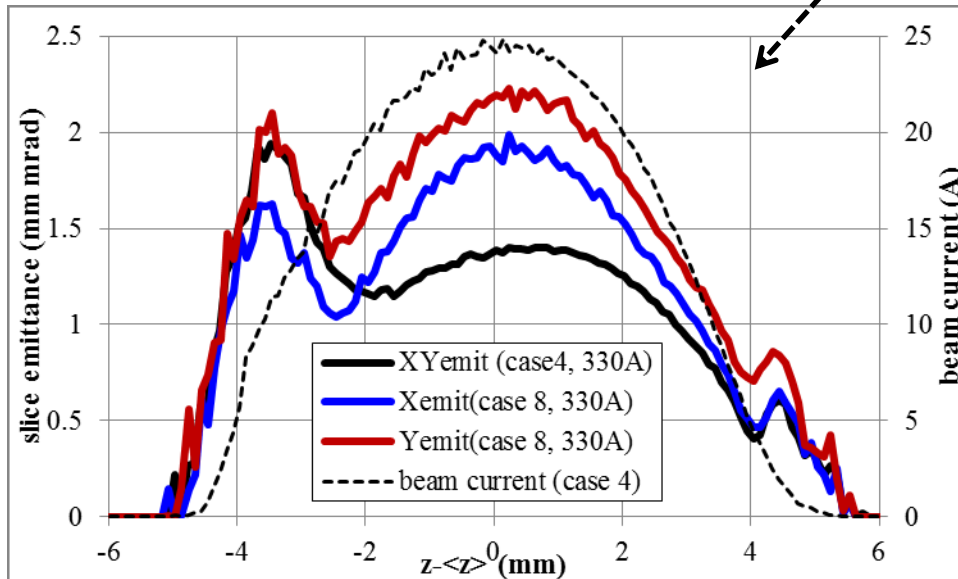
PC laser: Core+Halo=Rings



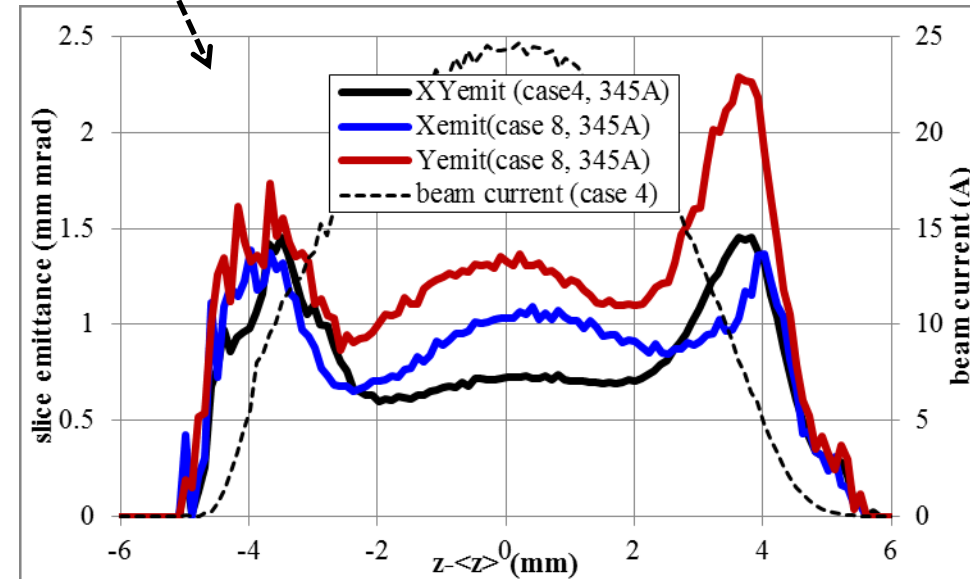
PC laser: 2D asymmetric



$I_{\text{main}} = 330\text{A}$



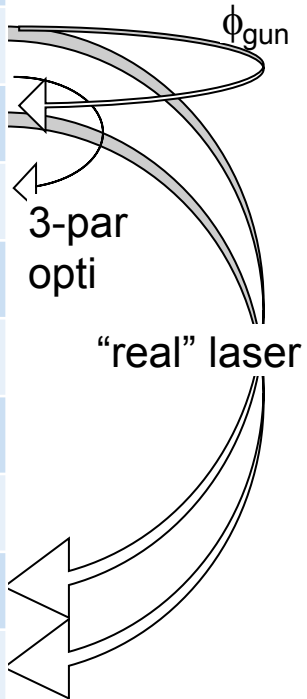
$I_{\text{main}} = 345\text{A}$



Simulation cases summary

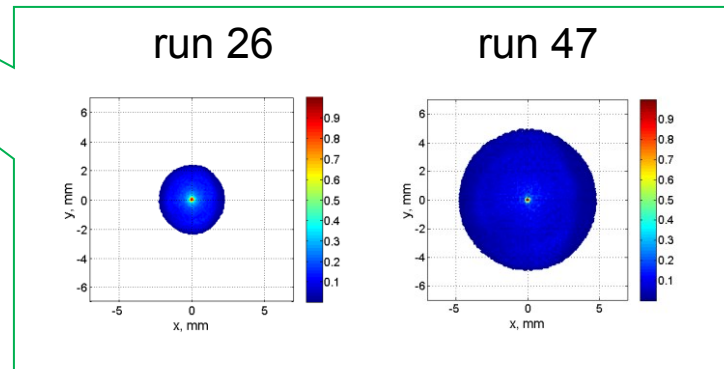
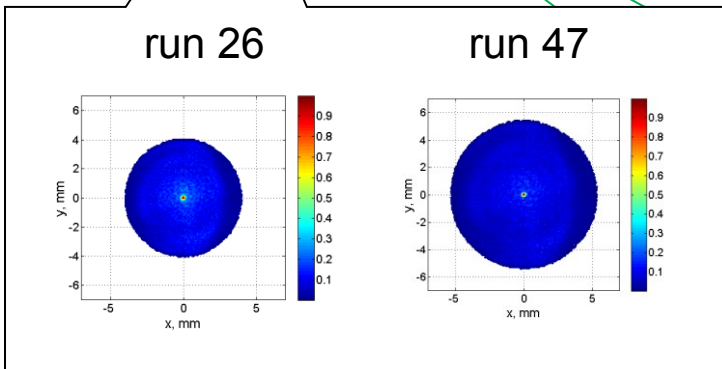
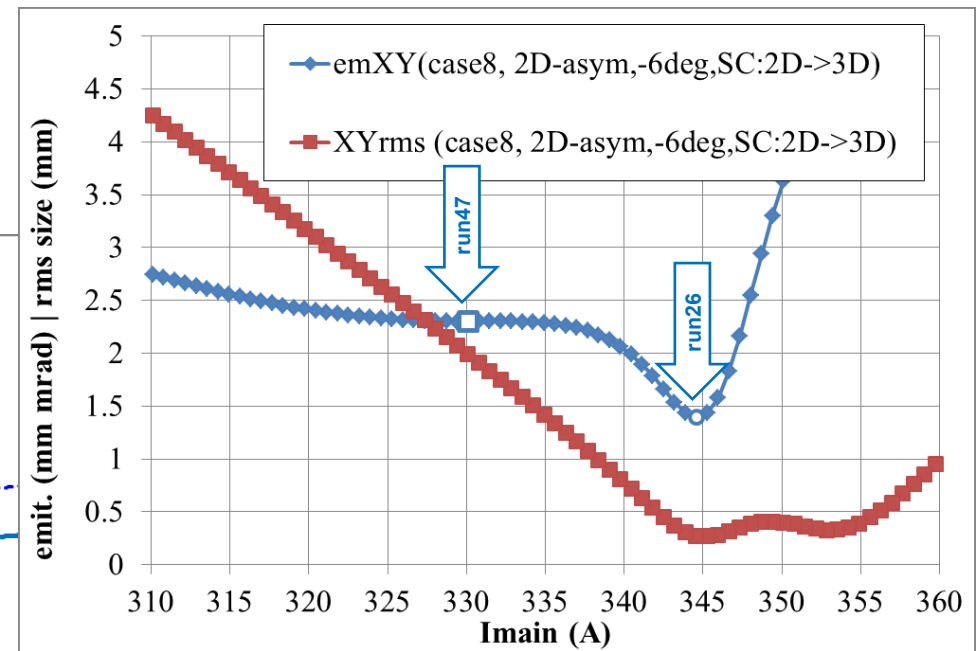
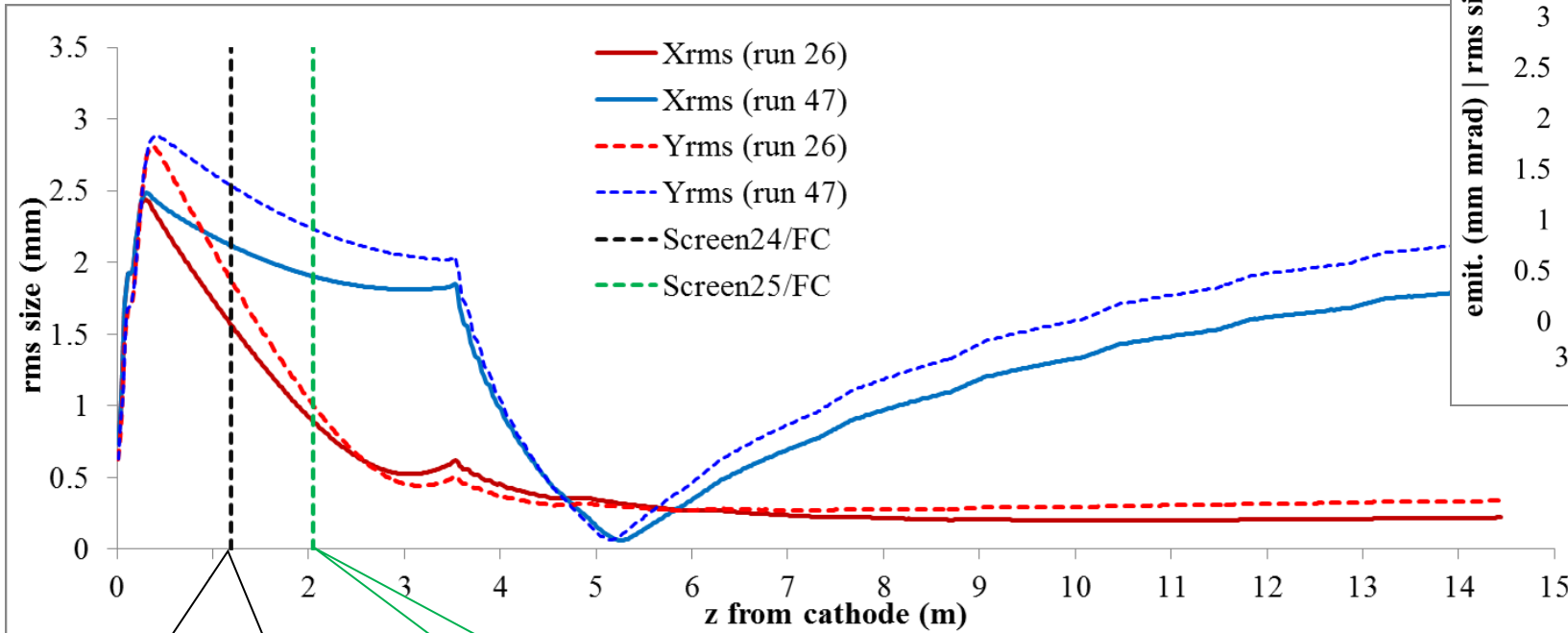
Impact of laser transverse distribution and gun phase onto beam emittance

Case	PC laser transverse	ASTRA SC	Gun phase w.r.t. MMMG	Projected normalized emittance at 14.44m [mm mrad]			
				I _{main} * [A]	X-emittance	Y-emittance	XY-emittance → min*
1	Rad.homogen.	2D	-6°	344.6	1.00	1.00	1.00
2	Rad.homogen	2D	0°	346.2	0.75	0.75	0.75
3	Rad.homogen	2D	-1.48° (opti)	345.5	0.69	0.69	0.69
4	Core+Halo=Rings	2D	-6°	344.6	1.08	1.08	1.08
5	Core+Halo=Rings	2D	0°	346.6	0.95	0.95	0.95
6	2D asymmetric	2D	-6°	344.6	0.92	1.27	1.08
7	2D asymmetric	2D	0°	346.0	0.77	1.11	0.92
8	2D asymmetric	2D→3D	-6°	344.6	1.19	1.63	1.39
9	2D asymmetric	2D→3D	0°	346.0	1.00	1.48	1.22



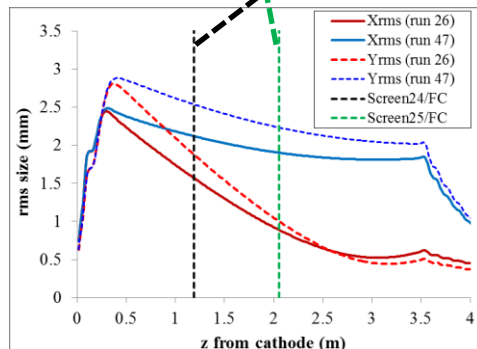
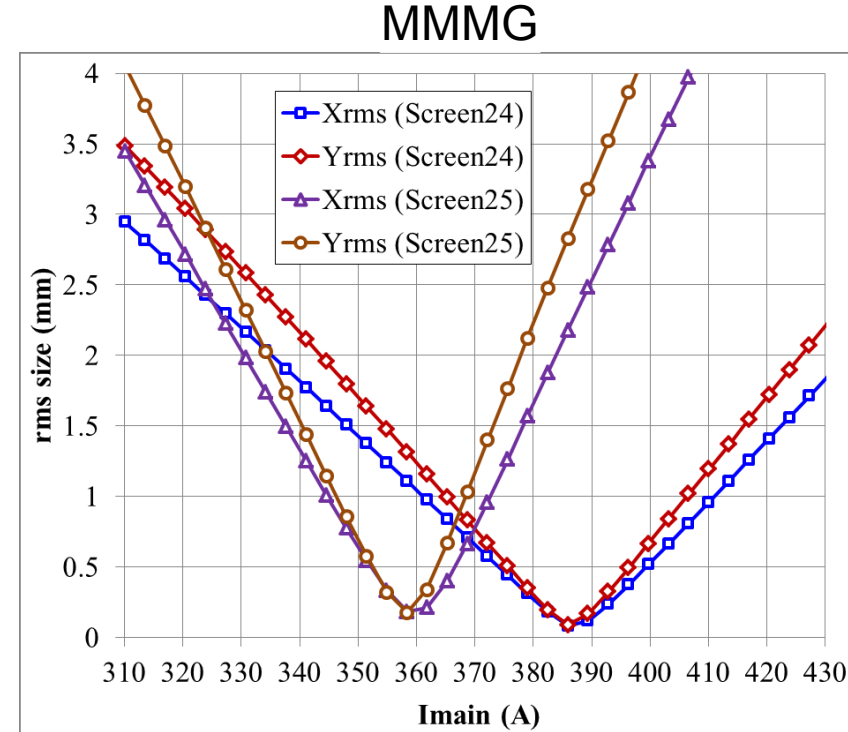
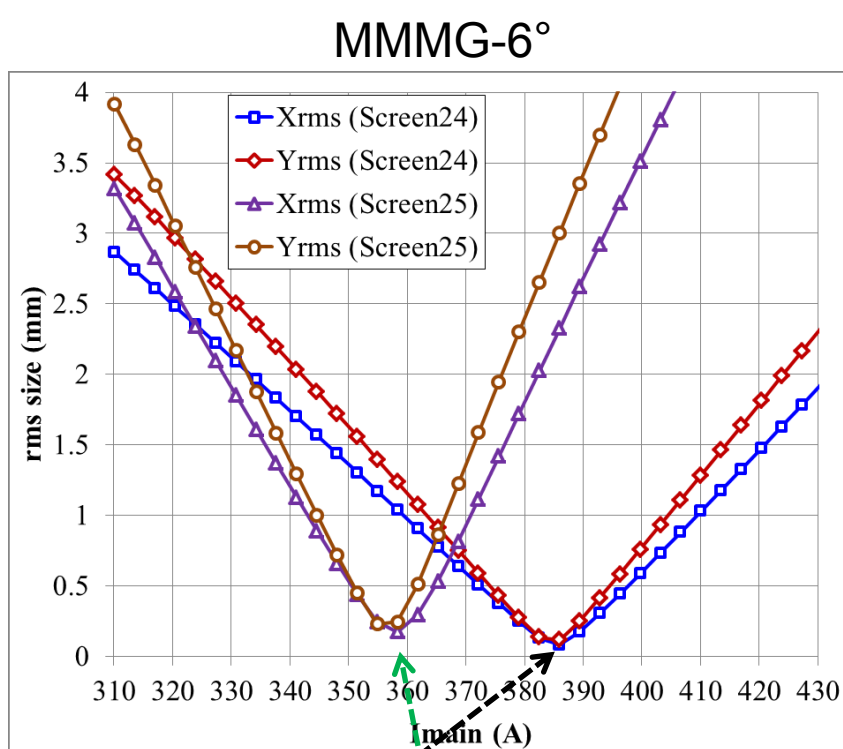
E-beam size along photo injector

Including first two screens in front of A1



Main solenoid scans at Screen24 and Screen25

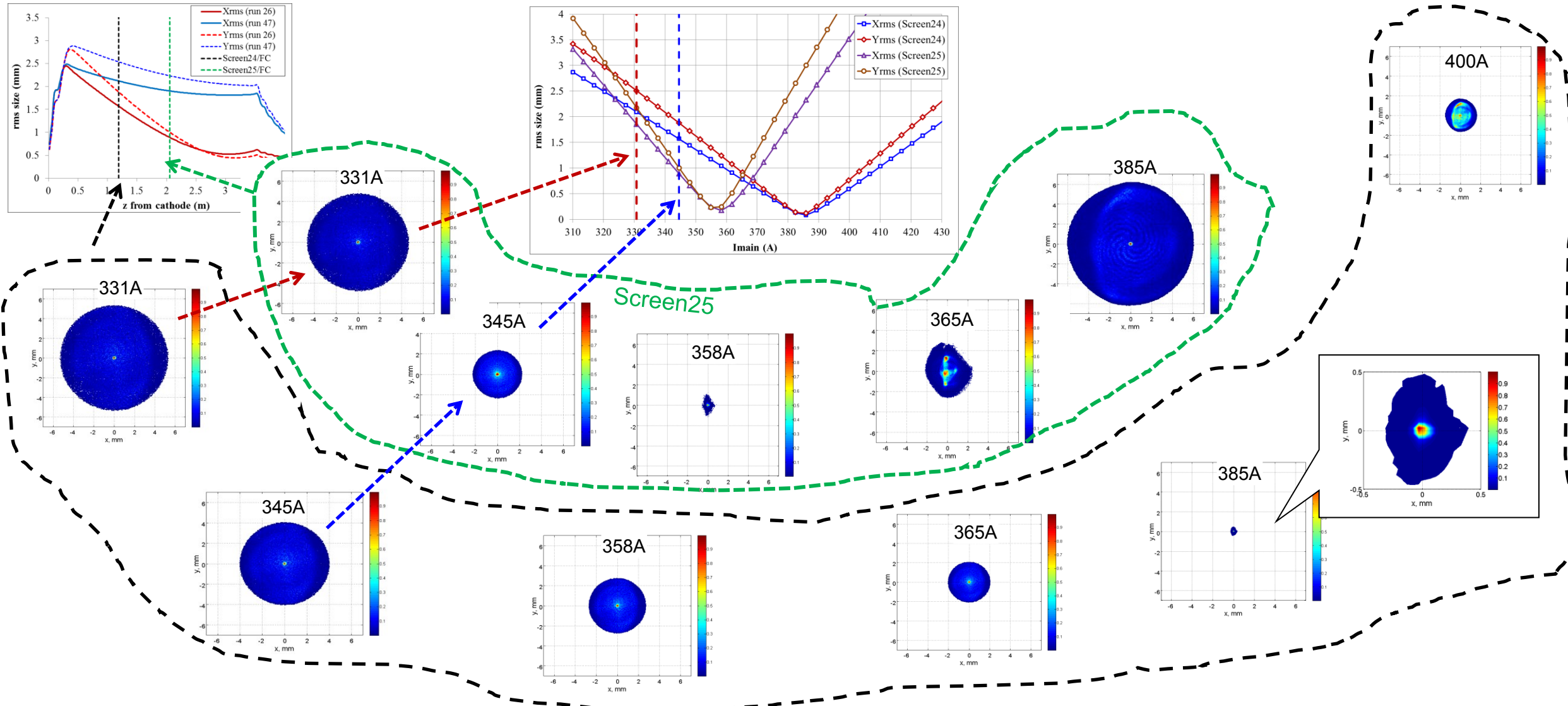
ASTRA simulations with 2D asymmetric laser and gun phases = MMMG-6° and MMMG (cases 8 and 9)



Screen24: $z=1.189\text{m}$
 Screen25: $z=2.0522\text{m}$

X-Y distributions at Screen24 and Screen25

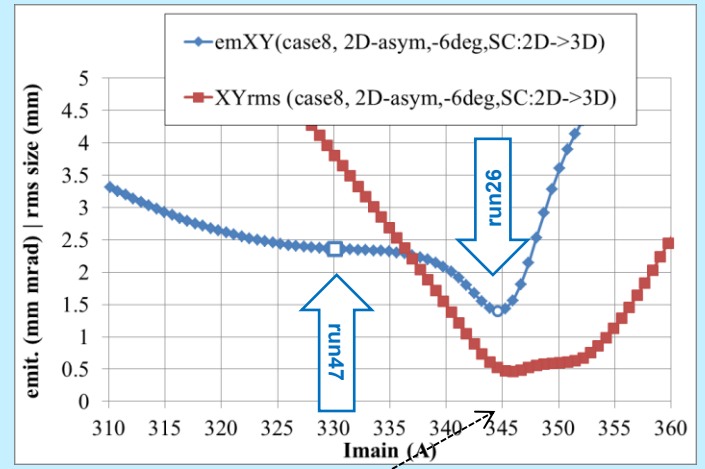
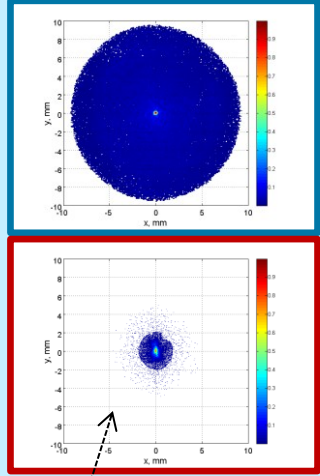
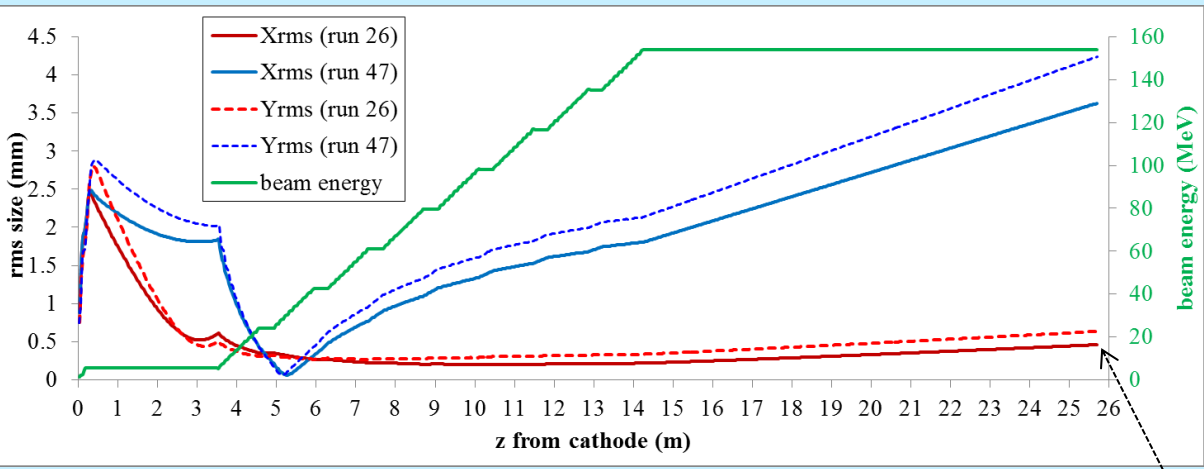
ASTRA simulations with 2D asymmetric laser and gun phases = MMMG-6° (case 8)



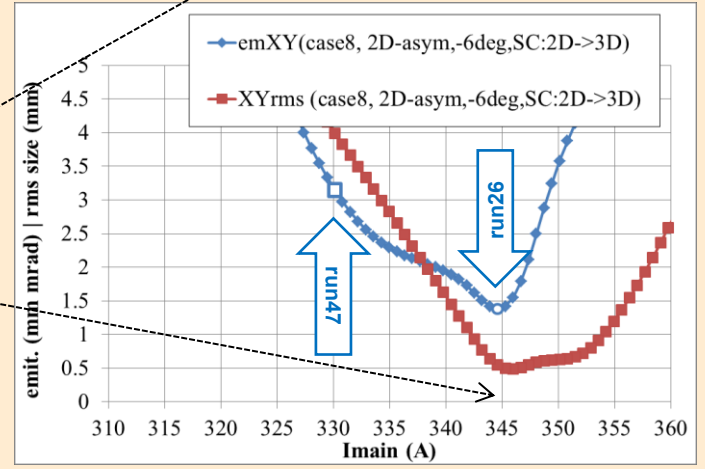
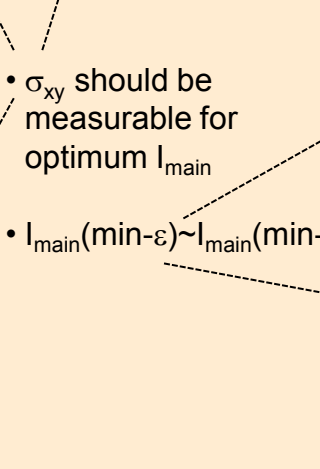
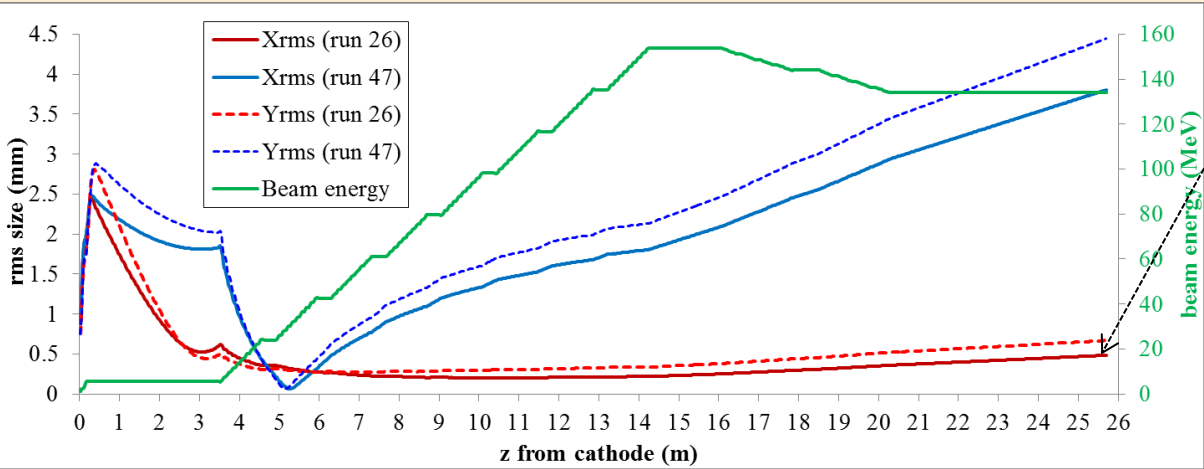
Simulated beam sizes until Screen OTRL.48.I1 (z=25.7m)

Case 8: w/o and w/ AH1 (ACC39), no quads applied

w/o 3rd harmonic module



with 3rd harmonic module



- σ_{xy} should be measurable for optimum I_{main}
- $I_{main}(\min-\epsilon) \sim I_{main}(\min-\sigma)$

Conclusions (preliminary)

- Beam dynamics simulations (ASTRA) have been performed for the EXFEL photo injector setup (19-22.10.2017):
 - Ecath=53MV/m
 - Gun phase = MMMG, MMMG-6° ($\langle Pz \rangle \sim 6.0 \text{ MeV}/c$)
 - Photocathode laser: temporal – Gaussian 6 ps rms, BSA=1.2mm (ideal radial homogeneous with 0.3 mm rms, core+halo=rings, 2D asymmetric distribution)
 - A1: Emax=34.42MV/m \rightarrow final $\langle Pz \rangle \sim 154 \text{ MeV}/c$
 - Various space charge options (2D, 2D \rightarrow 3D)
- Applying main solenoid calibration: $\text{MaxB}[\text{T}] = -(0.0000372 + 0.000588 \cdot I_{\text{main}}[\text{A}])$:
 - **Two emittance minima** for the gun phase=MMMG-6° found: 325A and 345A, the first $\epsilon_{n,xy}(325\text{A}) = 1.6 \text{ mm mrad}$ is improper (strong over focusing in the A1), but it seems to be closer to the default operation conditions (329.5A)
 - Beta functions are rather different for these solenoid currents: $\beta(325\text{A}) = 1360\text{m}$, $\beta(345\text{A}) = 17\text{m}$
 - The second (proper) minimum $\epsilon_{n,xy}(345\text{A}) = 1.0 \text{ mm mrad}$ can be improved by additional tuning (Laser XYrms=0.295mm, Gun phase = -1.48°, MaxB=-0.20318T) to $\epsilon_{n,xy}(345\text{A}) = 0.7 \text{ mm mrad} \rightarrow$ best expected (“ideal” laser)
 - Applying current laser distribution \rightarrow **min “realistic” emittance $\sim 1.0\text{-}1.2 \text{ mm mrad}$**
 - Results of measurements using quadrupoles could be explained by rather large halo of electron beam while the core is rather compact...
- From PITZ experience a mismatch of 2-6A in the solenoid values are not unusual, but 15-20A is too much!
 - PITZ experience (rms size) \rightarrow correction factor 0.982; current EXFEL needs 1.05!
- Next steps (proposals):
 - Measure beam distributions at screens in front of A1 as a function of the main solenoid current, (vs. corresponding simulations)
 - If it works, new beam matching (quadrupoles) has to be found, beam transport etc...

Gun reference phase determination!

Laser transverse profile needs to be improved!

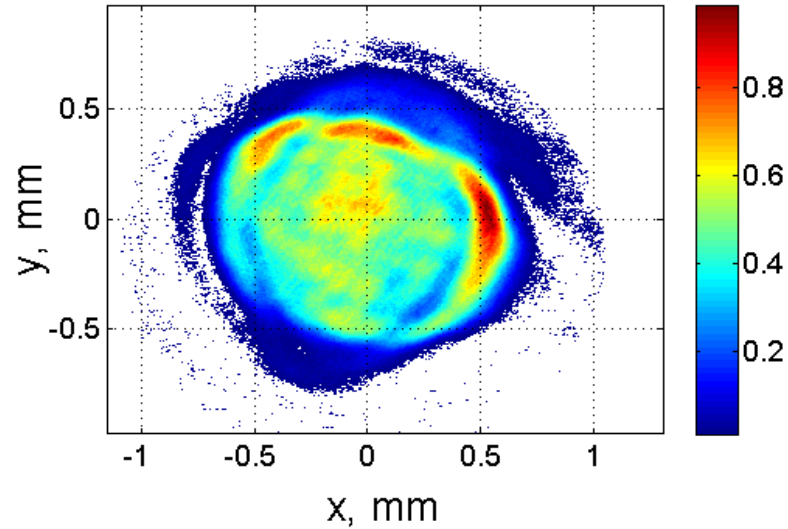
PC laser: Check 2D asymmetry impact

Solenoid calibration cross-check with e-beam!

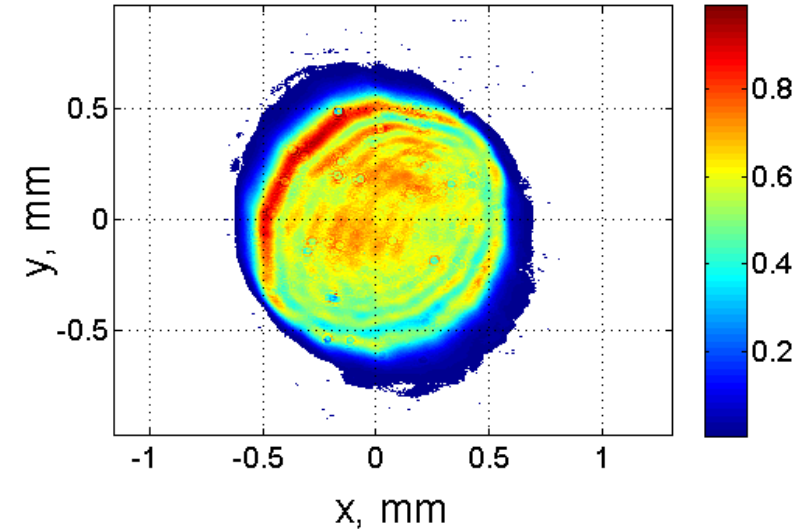
Backup slides

PC Laser BSA=1.2mm

EXFEL 20.10.2017



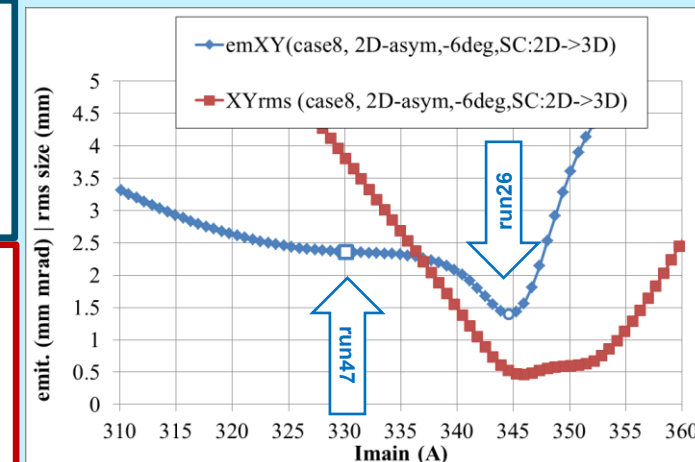
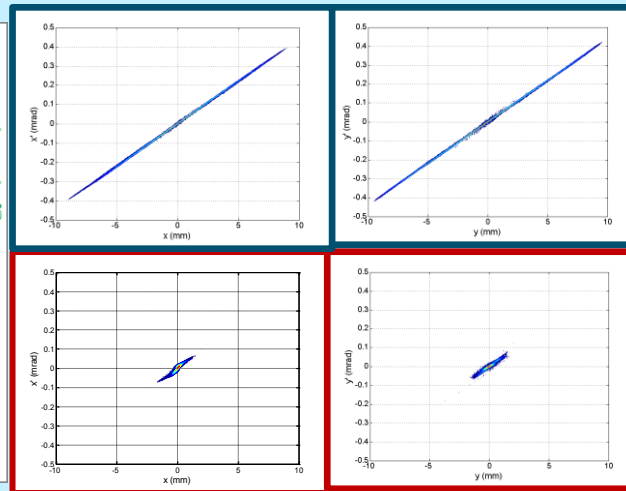
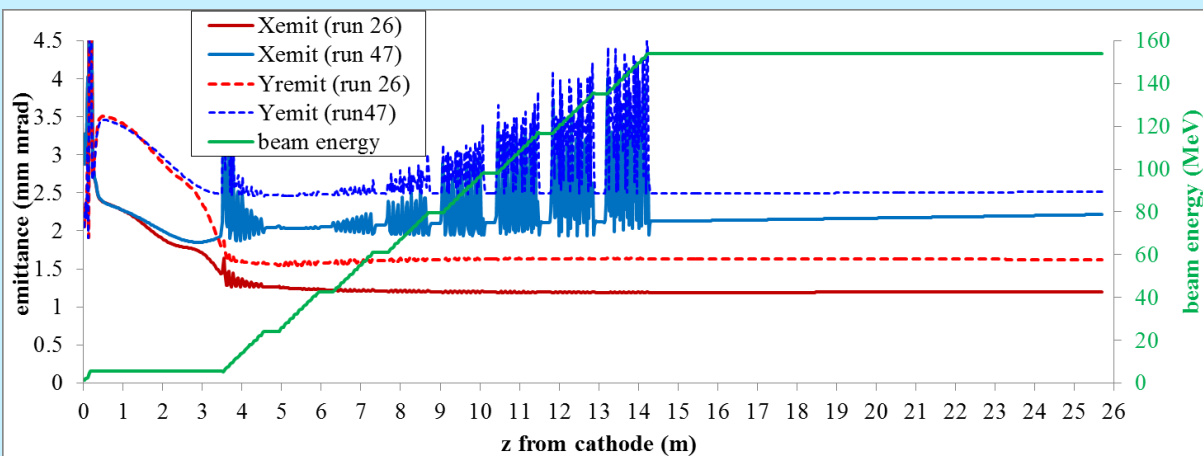
PITZ 15.09.2017



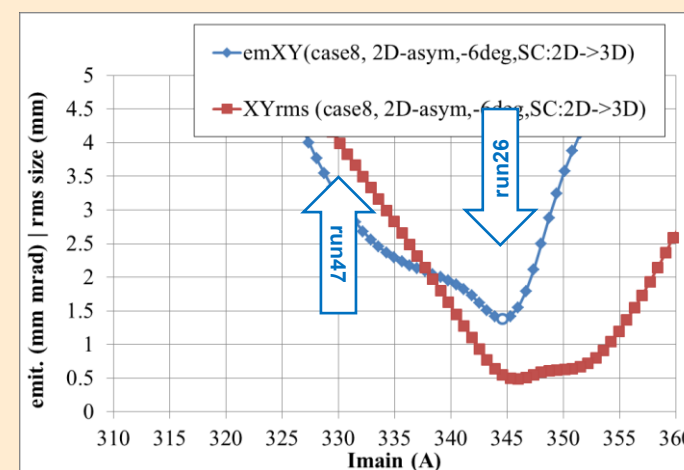
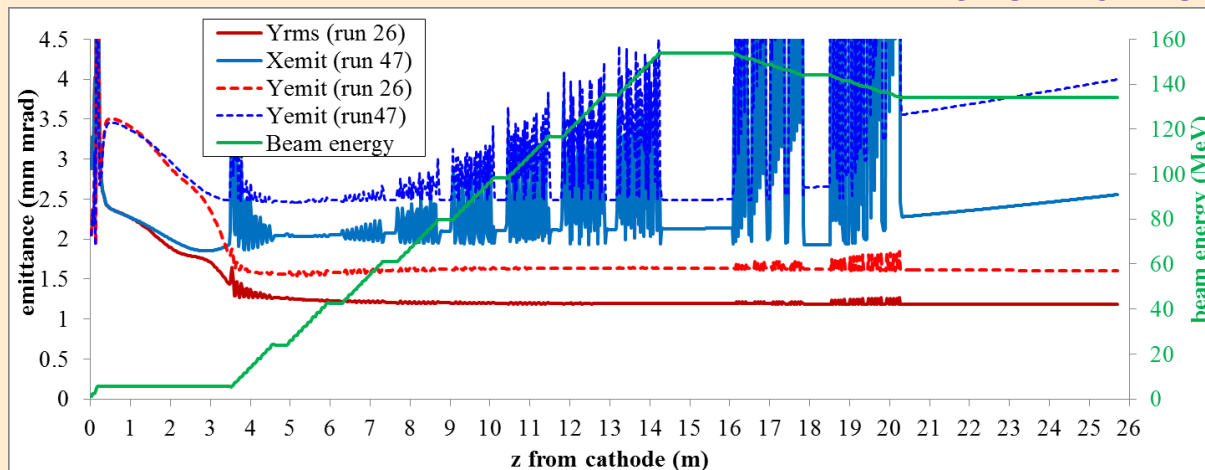
Simulated emittances until Screen OTRL.48.I1 (z=25.7m)

Case 8: w/o and w/ AH1 (ACC39), no quads applied

w/o 3rd harmonic module

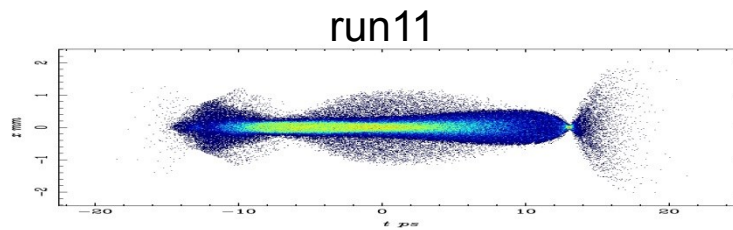
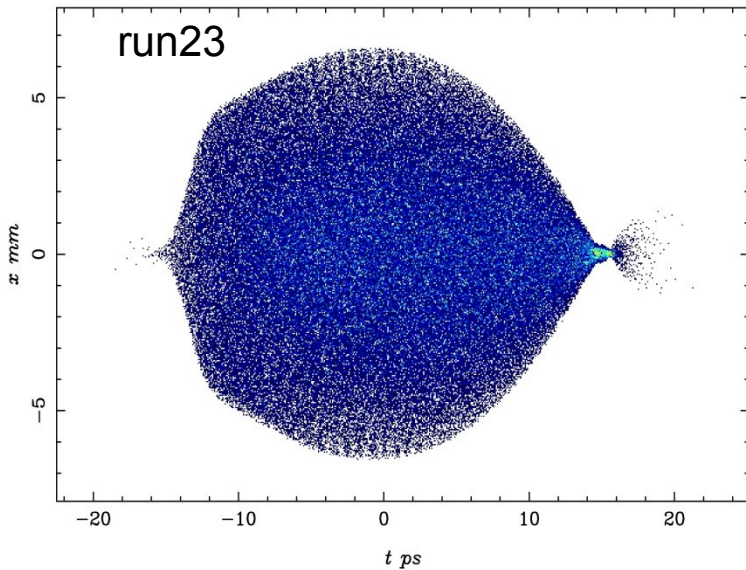
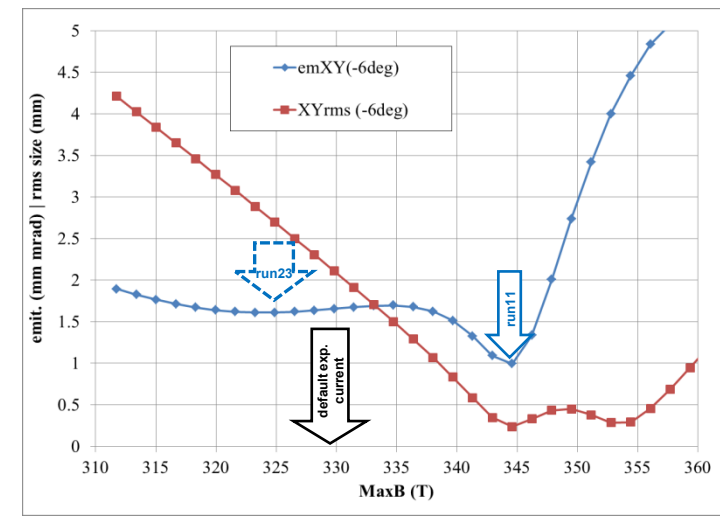
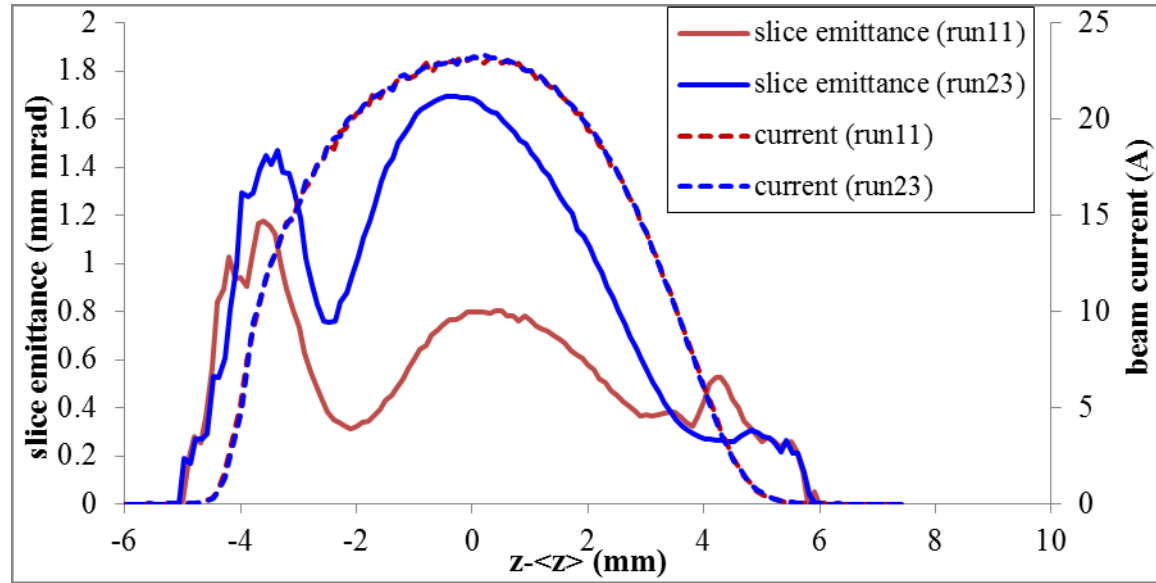


with 3rd harmonic module



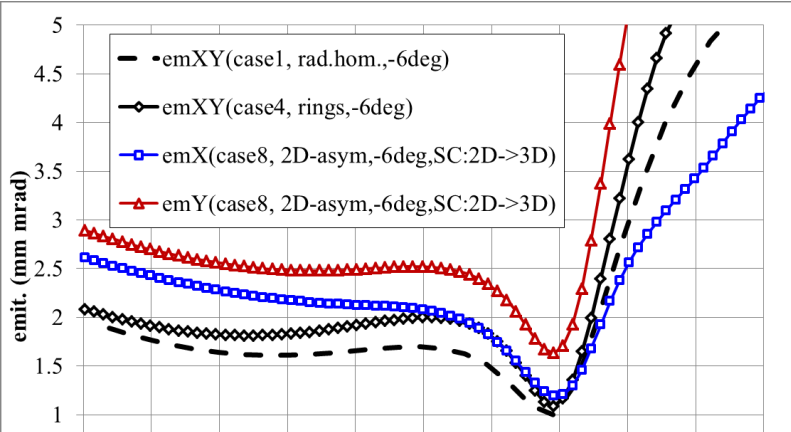
Beam monitors: Runs 11 vs 23

Case 1: Gun phase=MMMG-6°

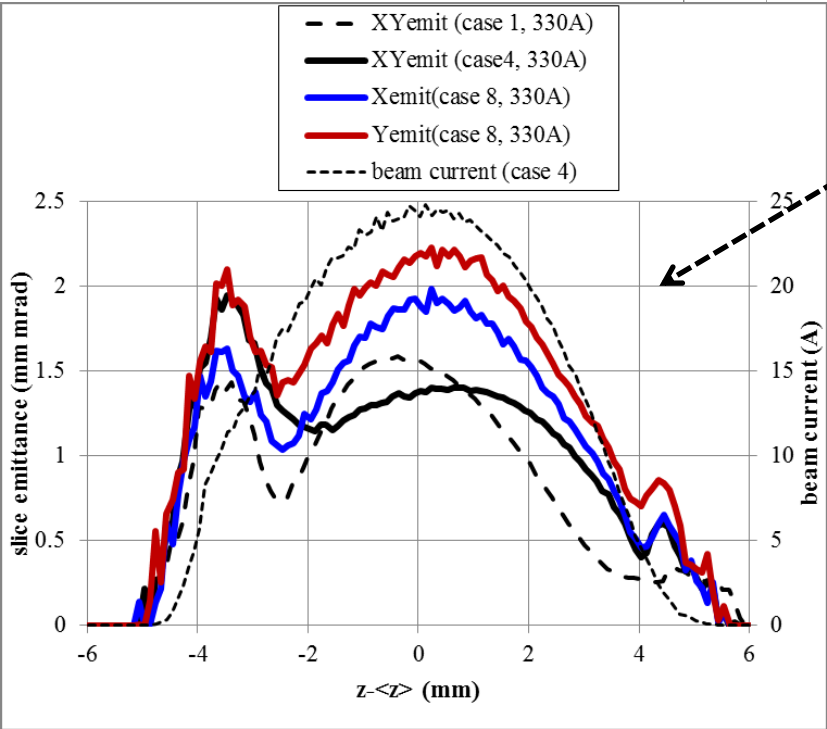


Slice emittance

Cases 4 and 8: Gun phase=MMMG-6°



$I_{main}=330A$



$I_{main}=345A$

