

4D Transverse phase space characterization using VPP

Review of VPP

Gun quad angle scans

4D TPS

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PPS

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4D TPS

Motivation

- PITZ → space-charge dominated beams
- Slit scan methodology → 2D phase space
- Virtual Pepper Pot (VPP) → 4D phase space
- What is VPP Technique?
 - Crossing of horizontal and vertical beamlets → PP-like beamlet
 - Corresponding horizontal and vertical slit positions → PP-like mask
 - Eliminates mechanical design considerations
 - Multi-shot method relying on stable machine operation

$$\sigma^{4D} = \begin{pmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle xy \rangle & \langle xy' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle x'y \rangle & \langle x'y' \rangle & \langle yy' \rangle & \langle y'^2 \rangle \end{pmatrix}$$

$$\epsilon_x = \sqrt{\langle xx \rangle \langle x'x' \rangle - \langle xx' \rangle^2}$$

$$\epsilon_y = \sqrt{\langle yy \rangle \langle y'y' \rangle - \langle yy' \rangle^2}$$

$$\epsilon_{xy} = \sqrt{\epsilon_x \epsilon_y}$$

$$C_{xy} = \sqrt{\langle xy \rangle \langle x'y' \rangle - \langle xy' \rangle \langle x'y \rangle}$$

$$\epsilon_{4D}^2 = \det(\sigma^{4D}) = \epsilon_x^2 \epsilon_y^2 - C_{xy}^4$$

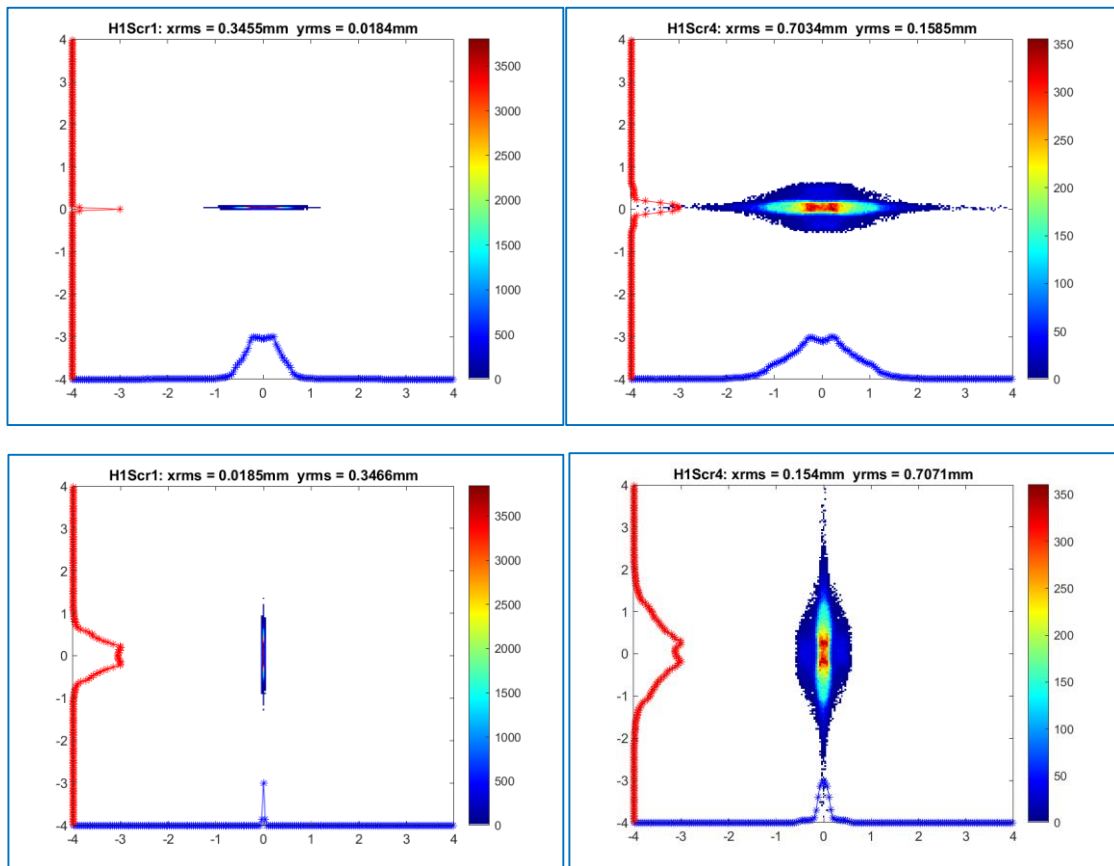
$$I_2 = \epsilon_x^2 + \epsilon_y^2 + 2C_{xy}^2$$

$$C = \frac{\sqrt{\epsilon_x \epsilon_y}}{\epsilon_{4D}} - 1$$

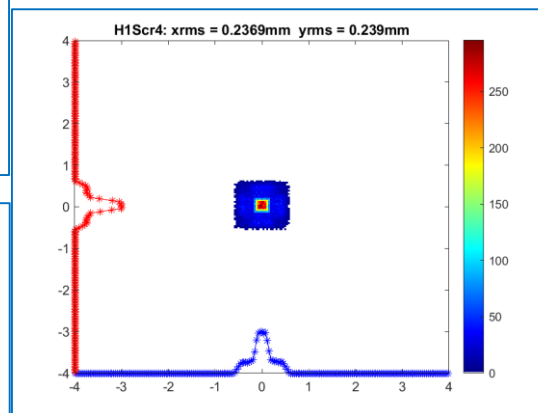
Virtual Pepper Pot Technique

Crossing of beamlets and EMSY mask

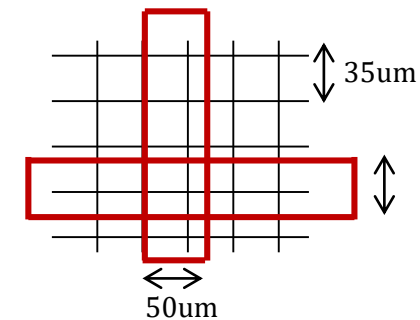
Result of crossing horizontal and vertical beamlets



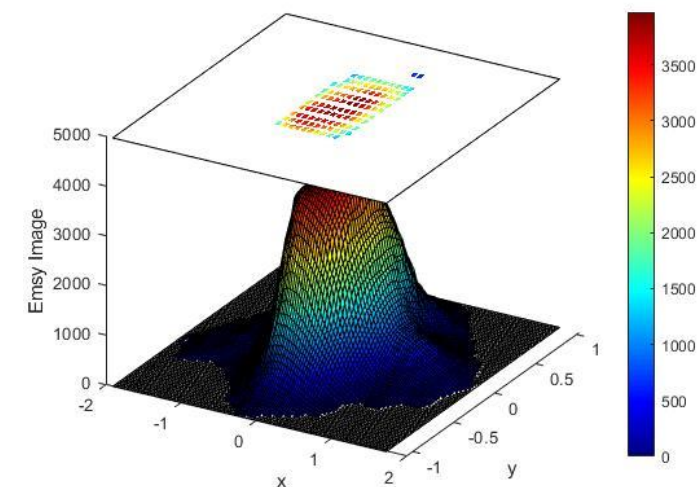
Pixel-wise minimum
of crossed beamlets



Crossed Slit positions

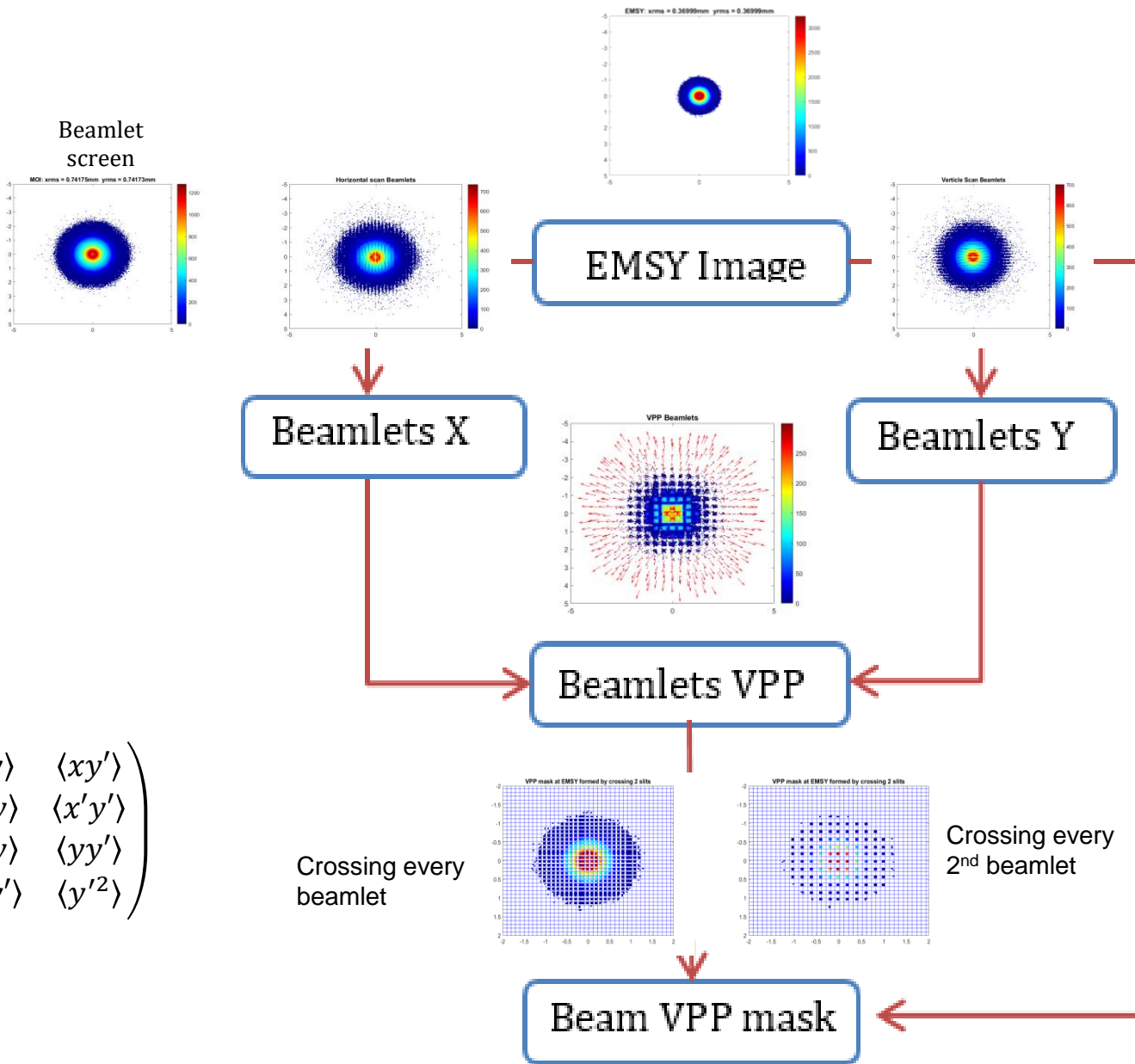


EMSY mask



VPP

Algorithm

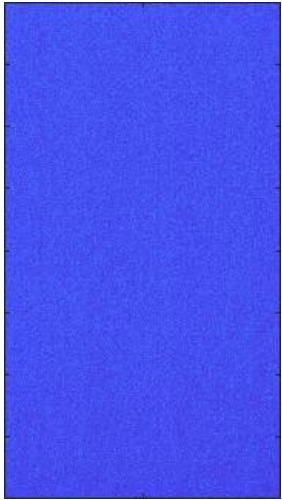


$$\sigma^{4D} = \begin{pmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle xy \rangle & \langle xy' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle x'y \rangle & \langle x'y' \rangle & \langle yy' \rangle & \langle y'^2 \rangle \end{pmatrix}$$

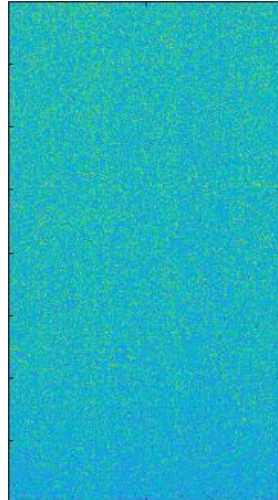
VPP

Charge Cut (simulated beam + noise from experiment)

Horizontal scan



Vertical Scan



1D charge cut → 2D charge cut

- **thresholding (u)**

$$\text{cutEmsy} = \text{Emsy} > u$$

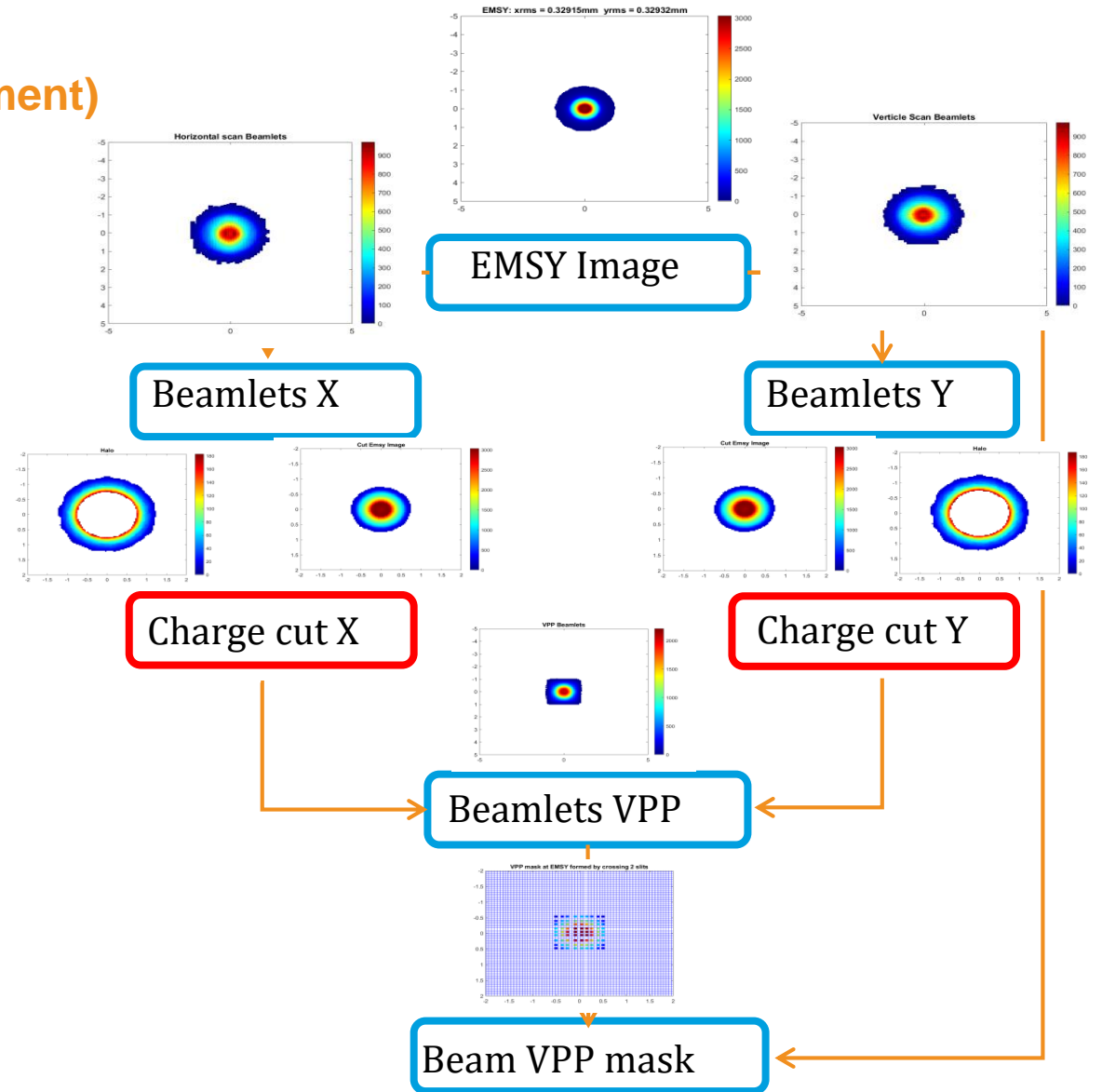
- **Position shifting (Δ)**

$$\text{ProjcutEmsyPos} = \text{ProjcutEmsy} + \Delta$$

- **Scaling (A)**

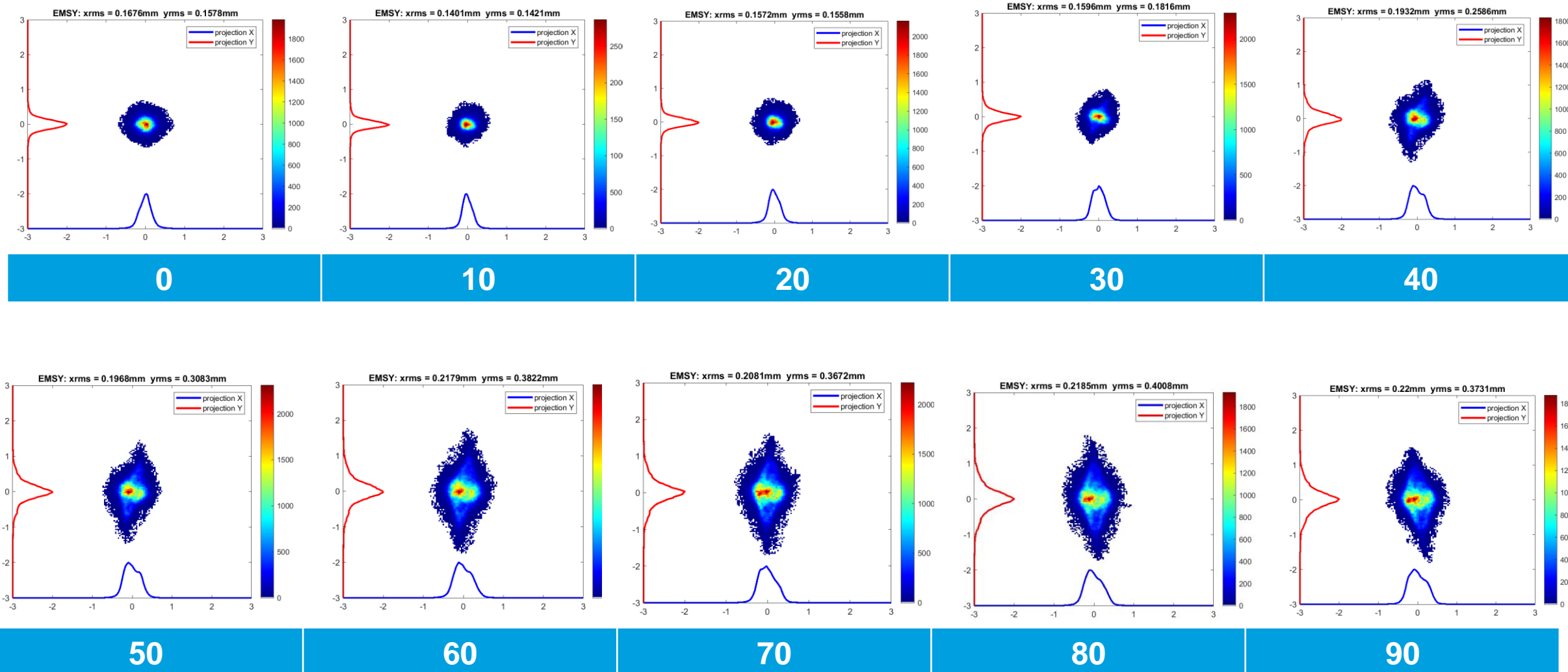
$$\varphi(\Delta, A) = \sqrt{\sum(|\text{ProjcutEmsyPos} - A \cdot \text{SoP}|^2)}$$

- **Charge cut** = $\sum(\text{cutEmsy} < u) / \sum(\text{Emsy})$



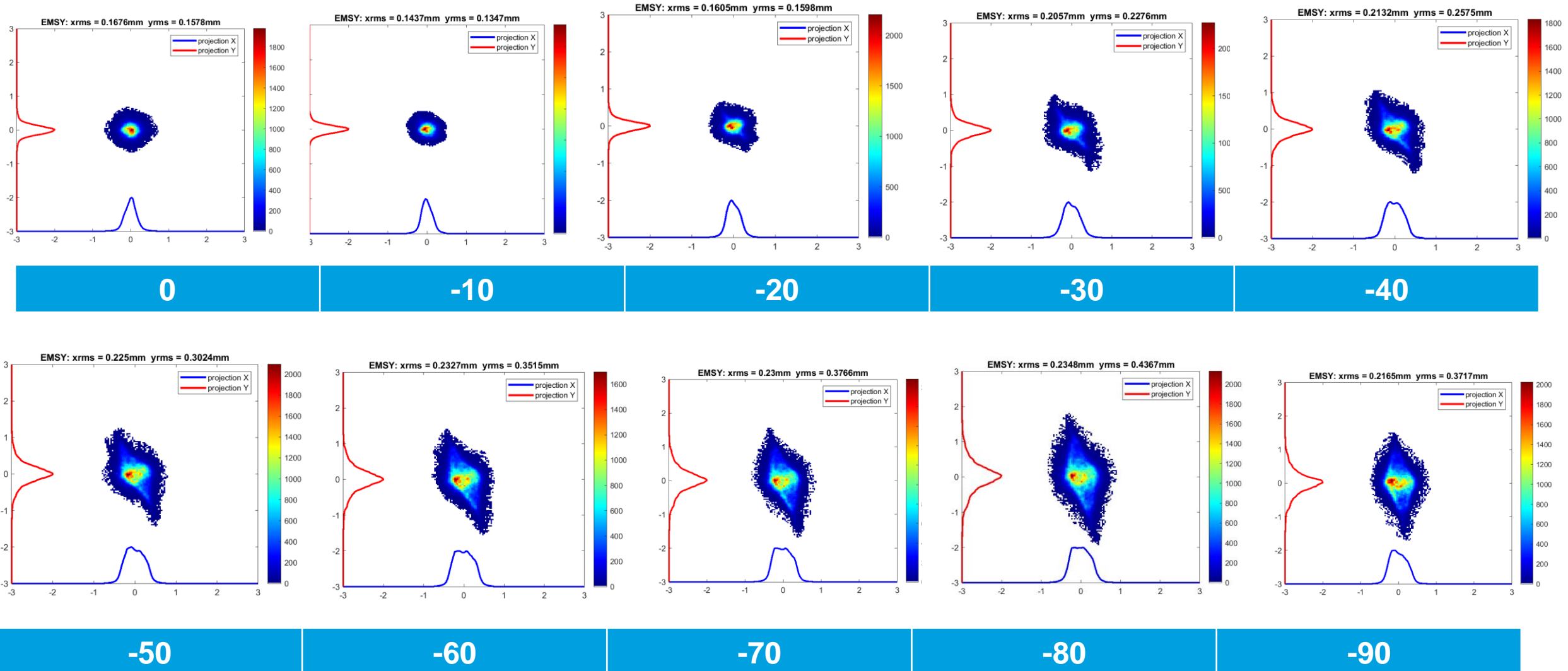
Gun quadrupole angle scan Q1 Q2

EMSY images 0 to 90 degrees



Gun quadrupole angle scan

EMSY images 0 to -90 degrees



TPS

Fast scan vs VPP results

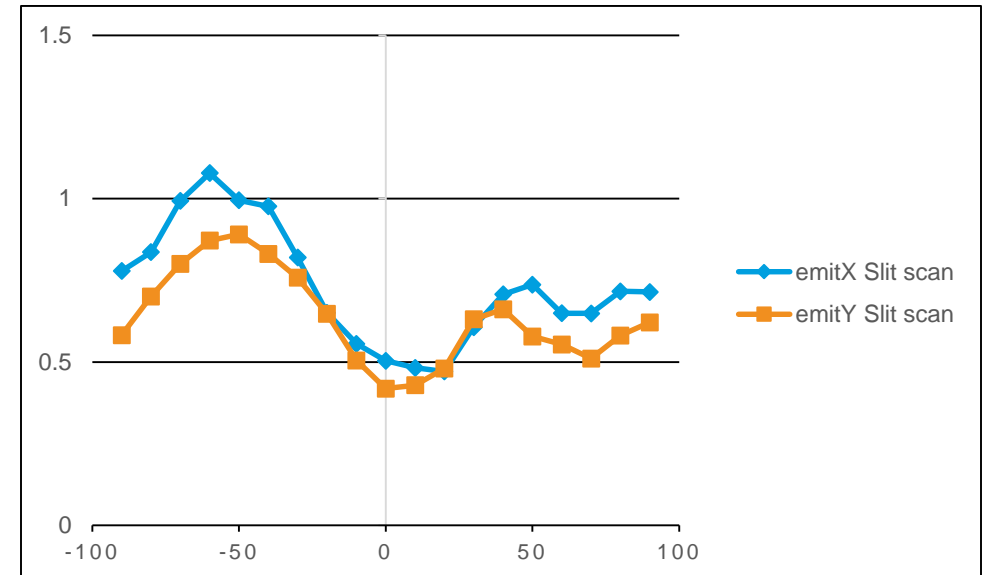
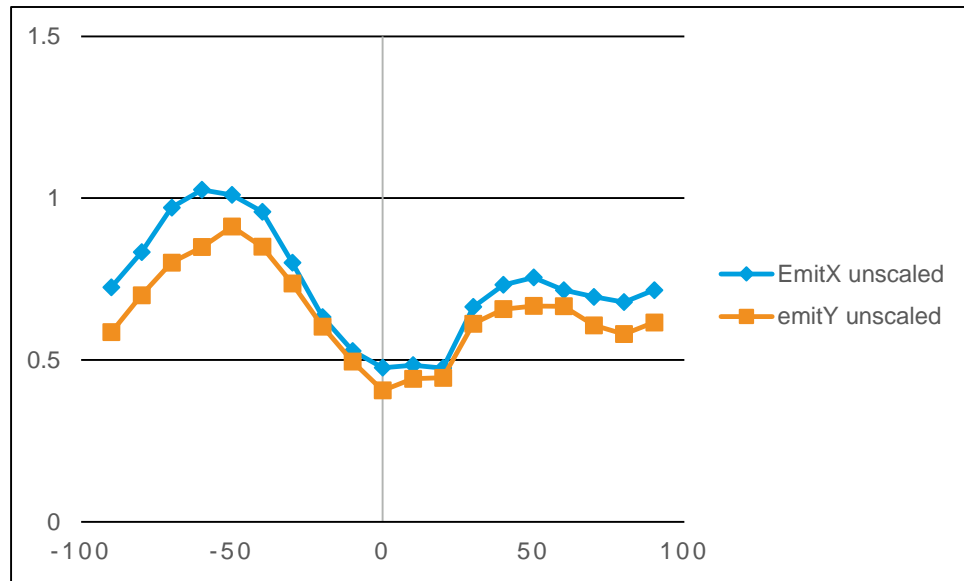


Using SVD filter



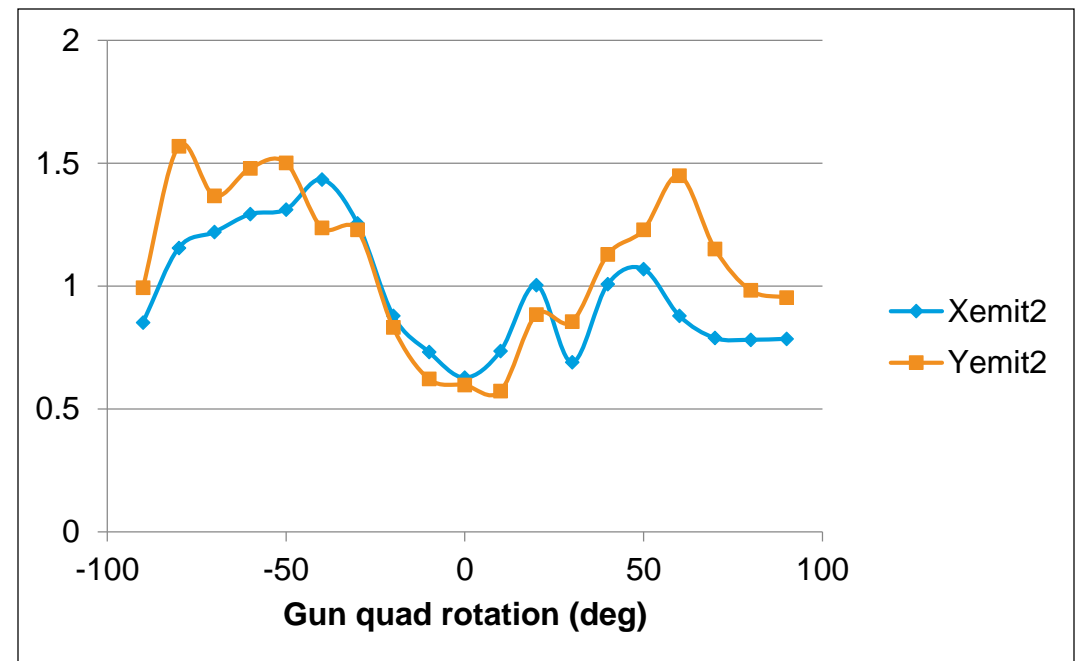
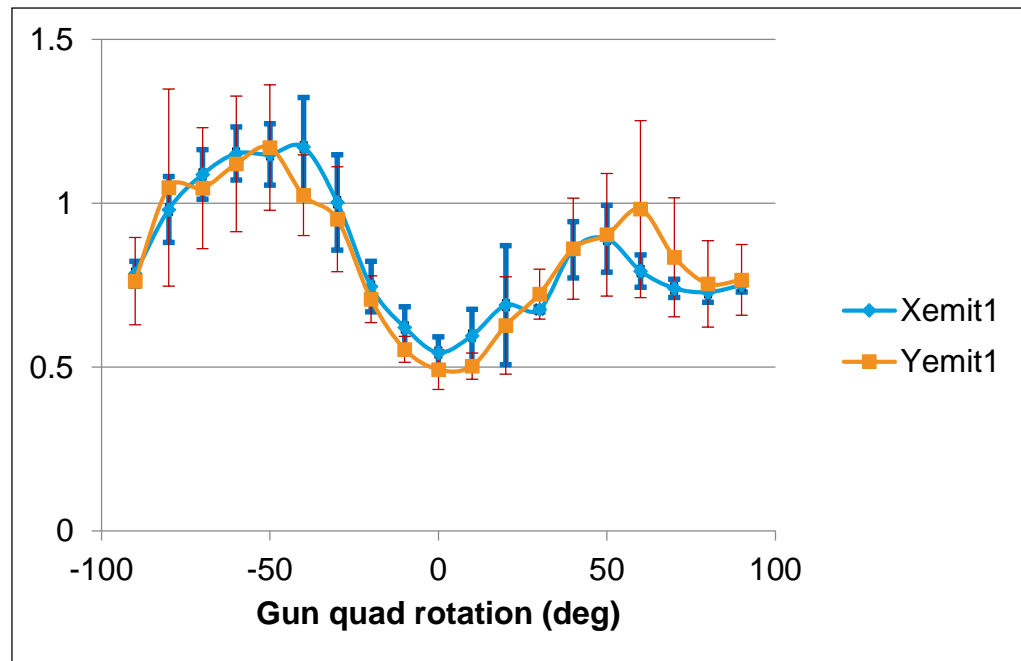
TPS

Fast scan vs VPP results



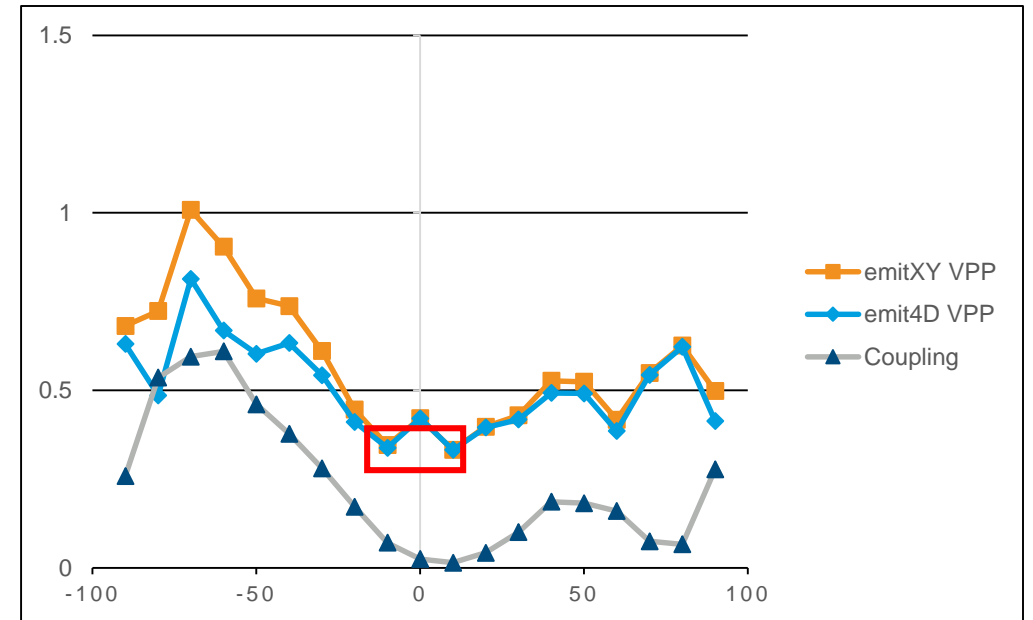
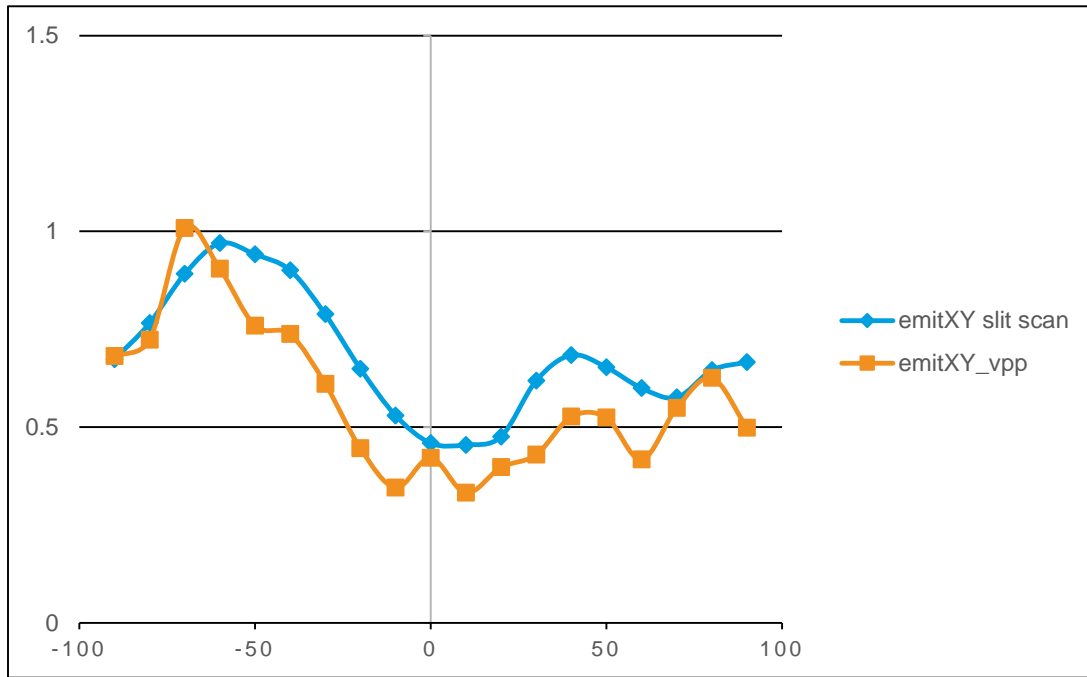
TPS

Fast scan -> scaled emittances



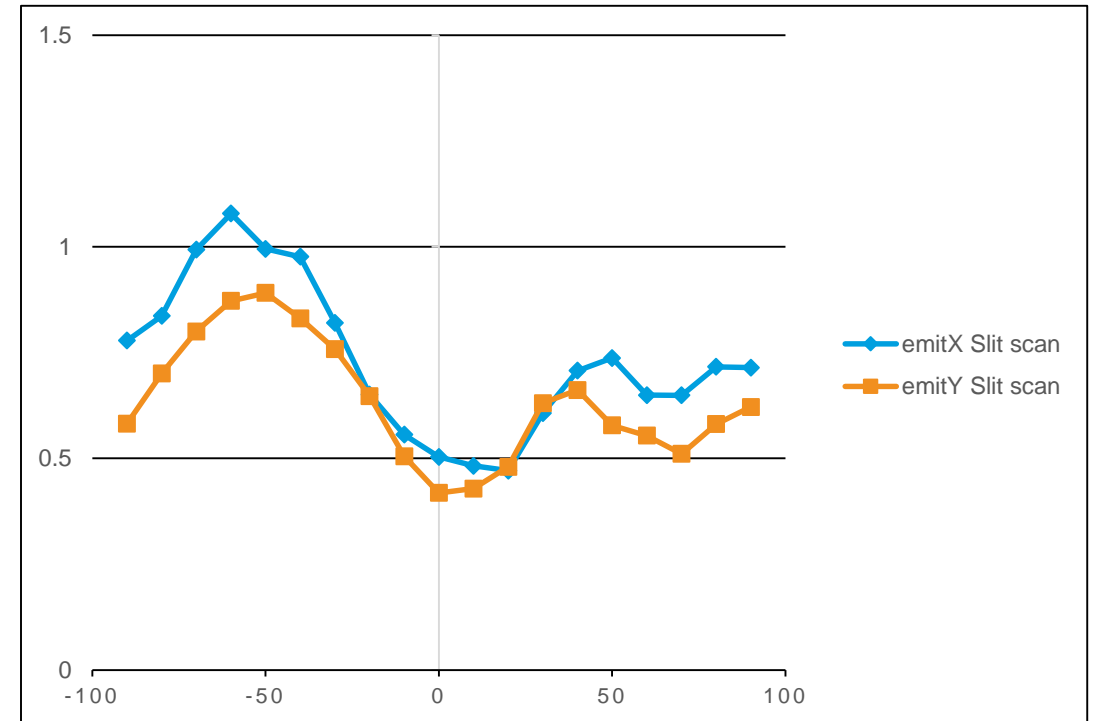
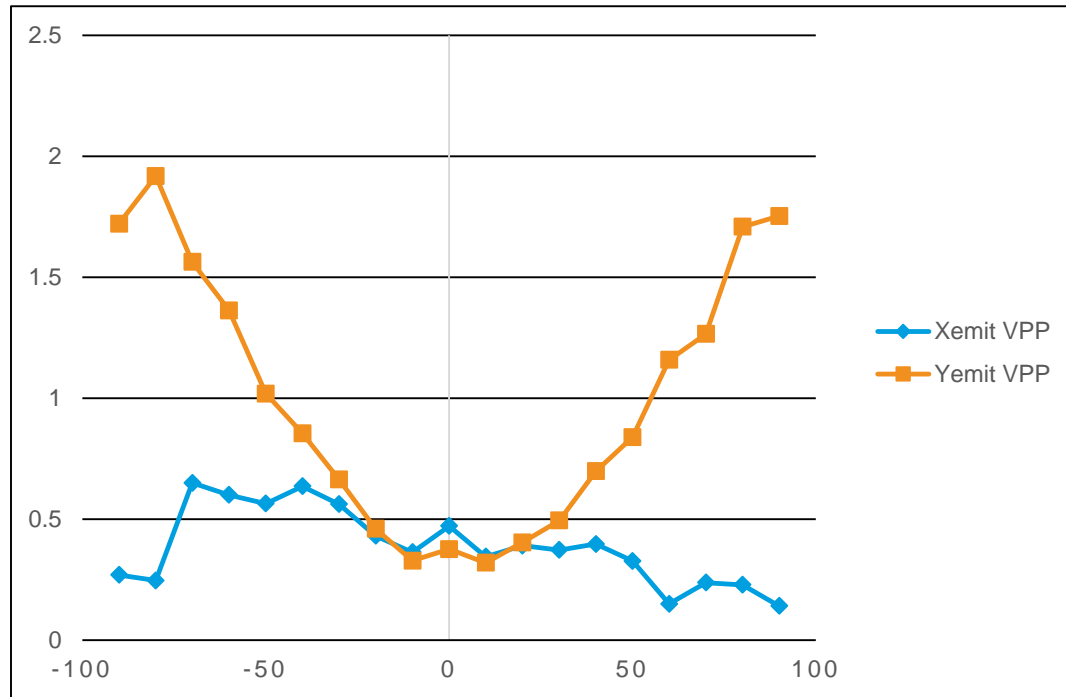
TPS

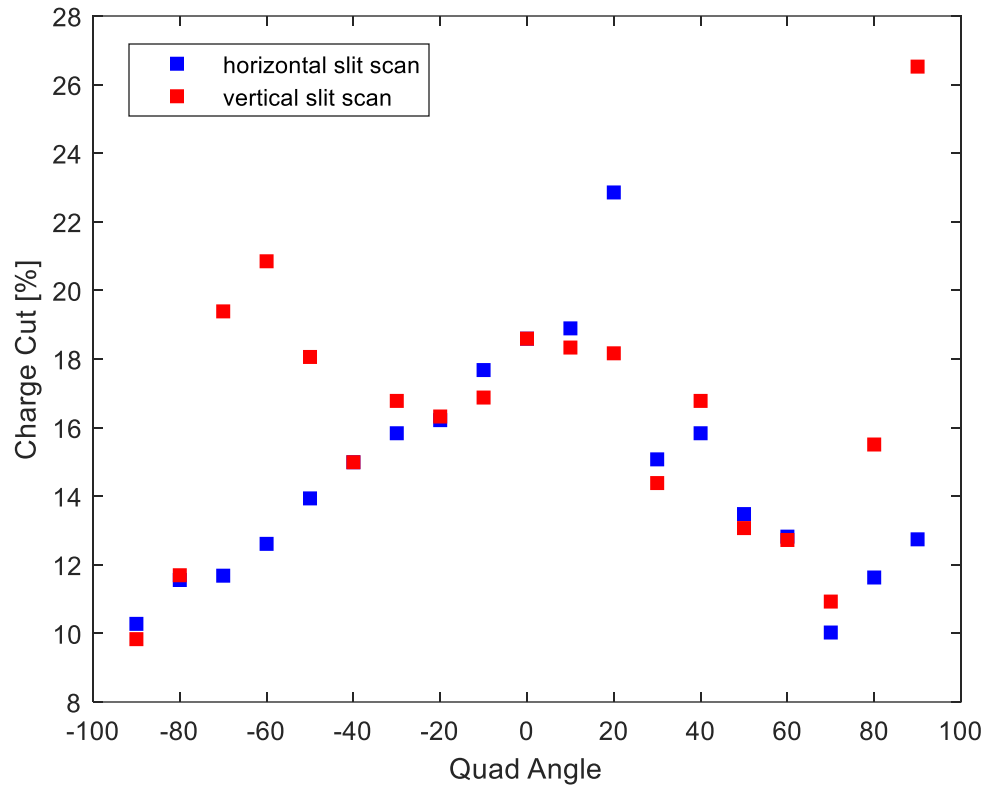
VPP with 2D charge cut



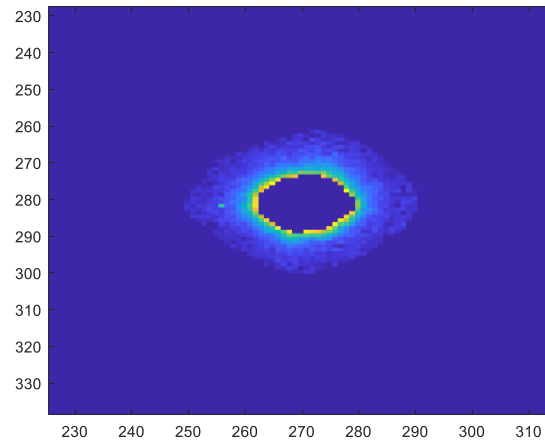
TPS

VPP with 2D charge cut

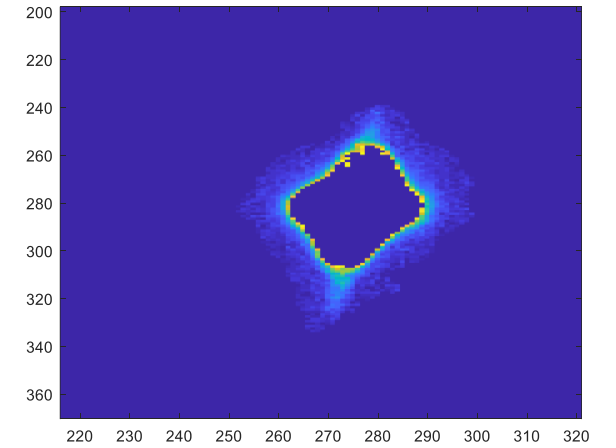




Core EMSY 0 deg

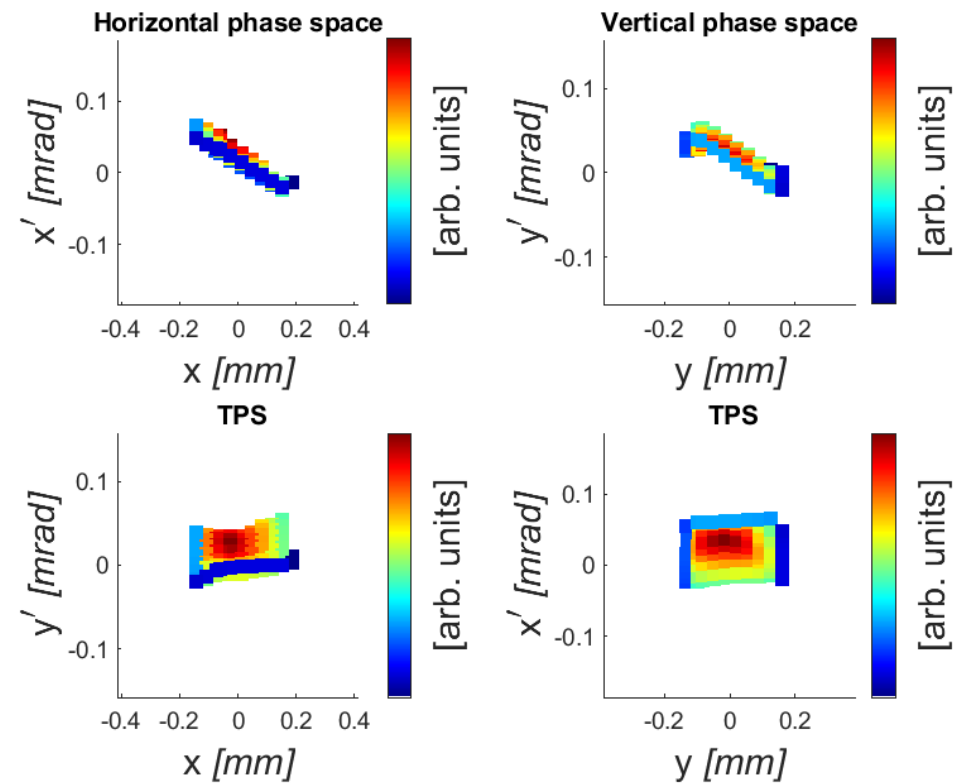
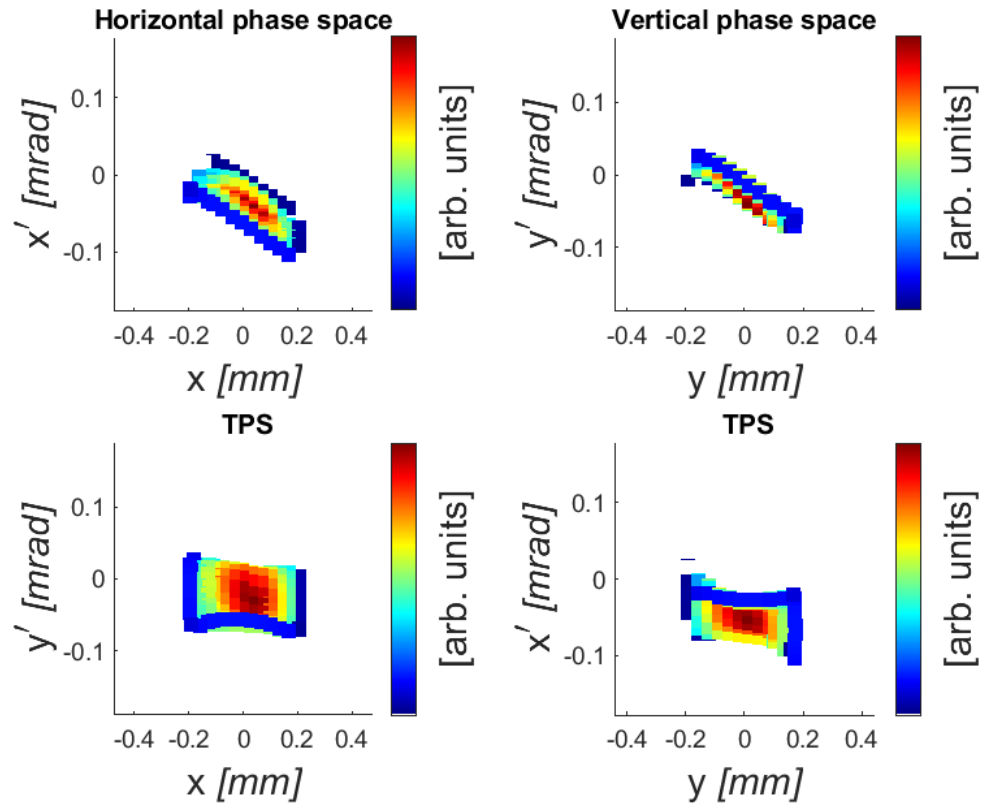


Core EMSY 90 deg

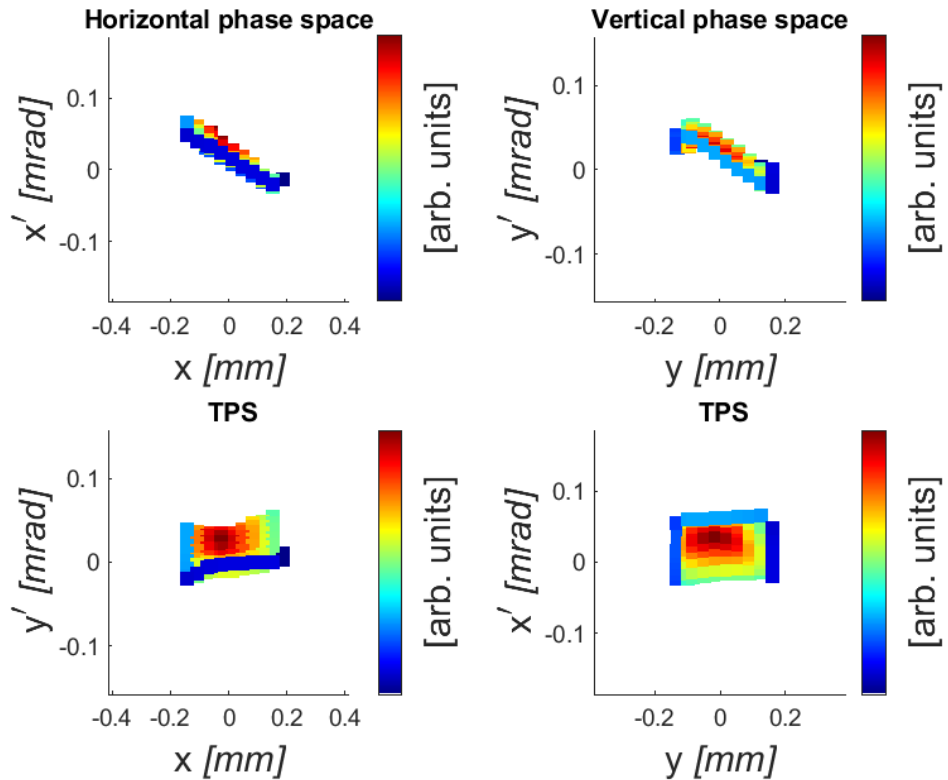


0 deg

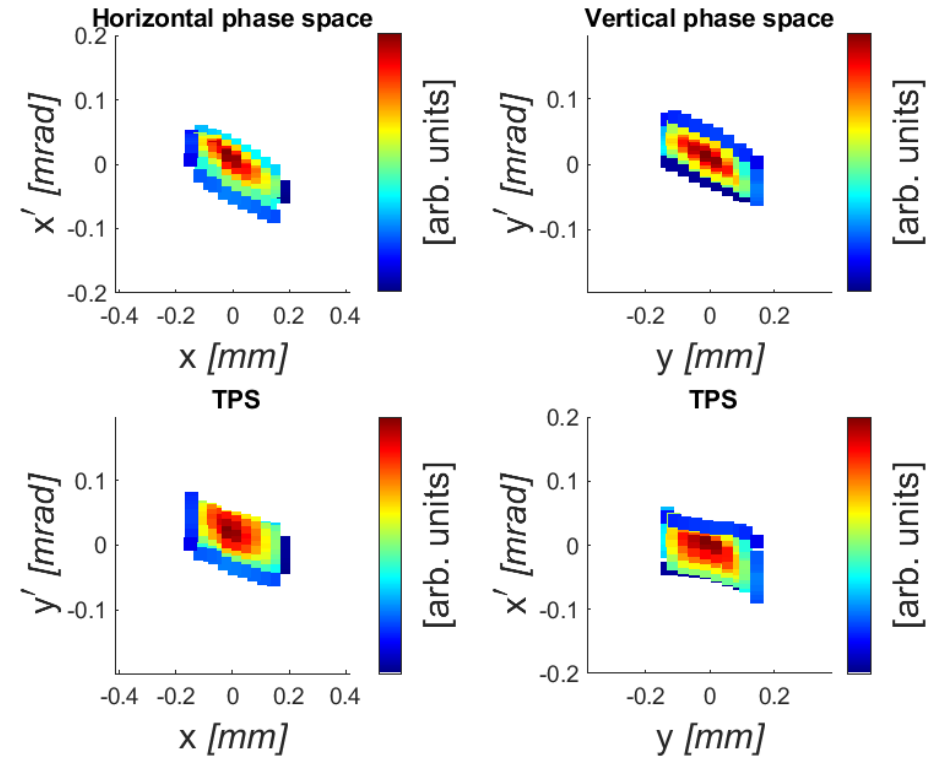
10 deg



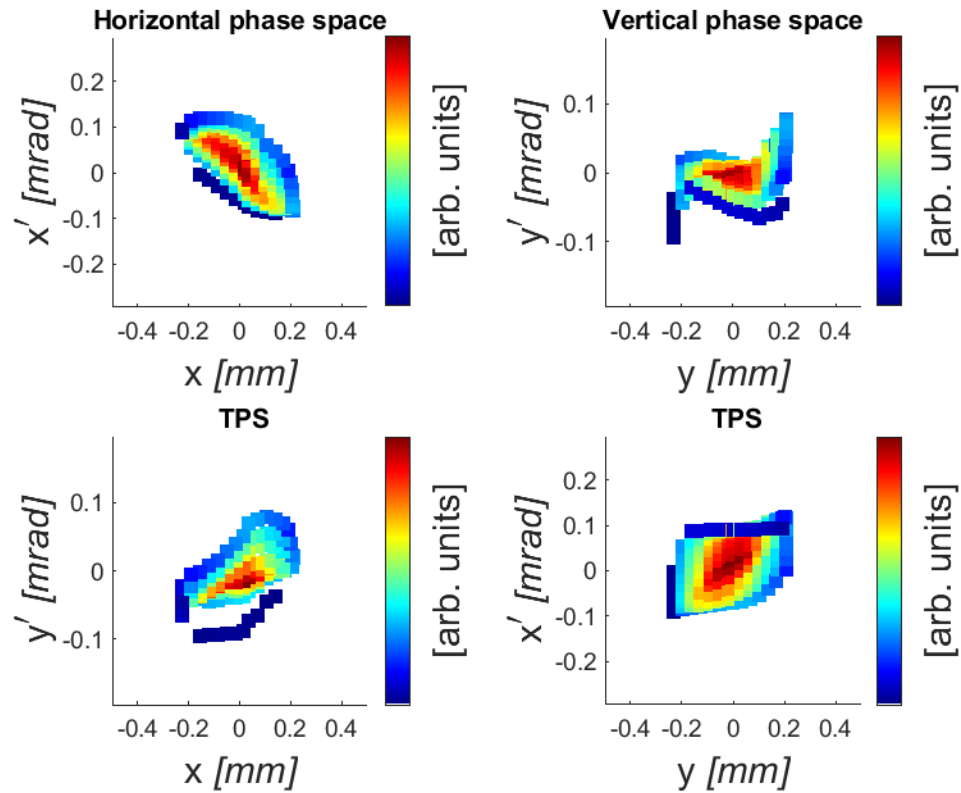
10 deg



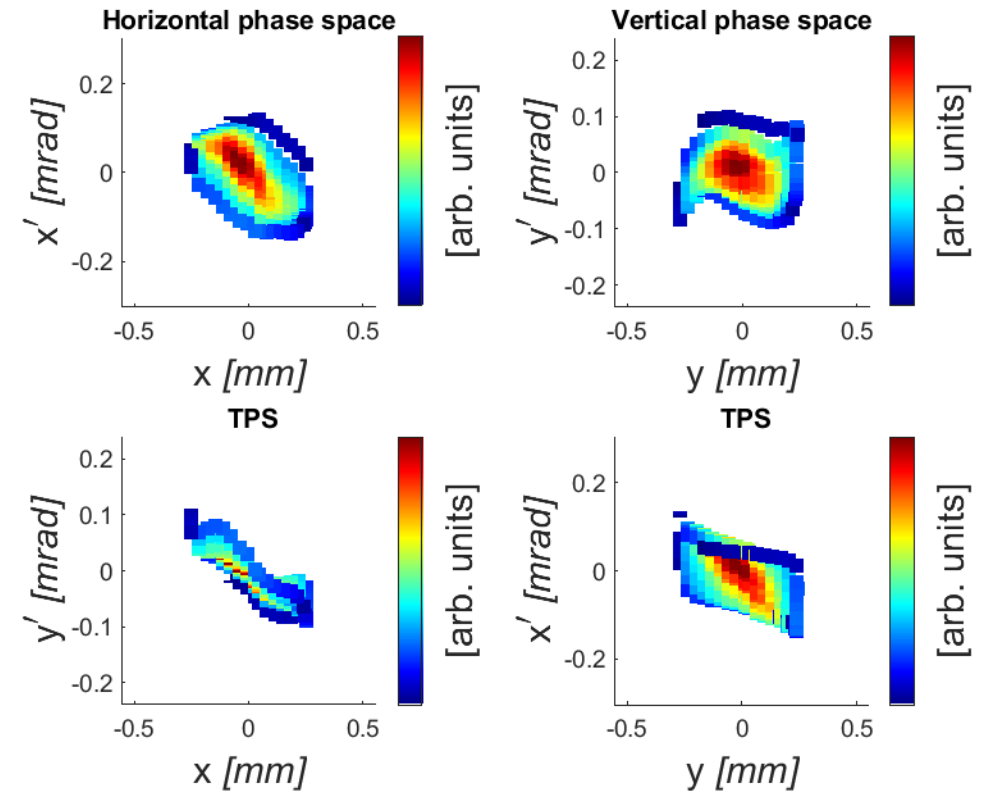
-10 deg



30 deg

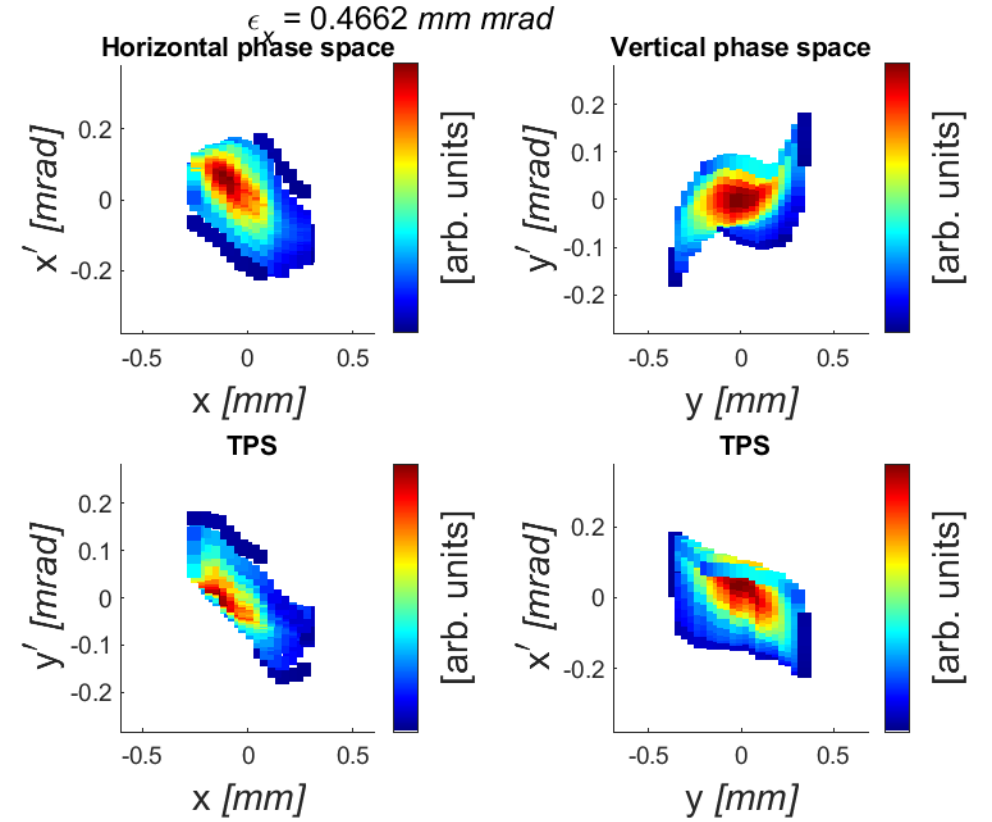
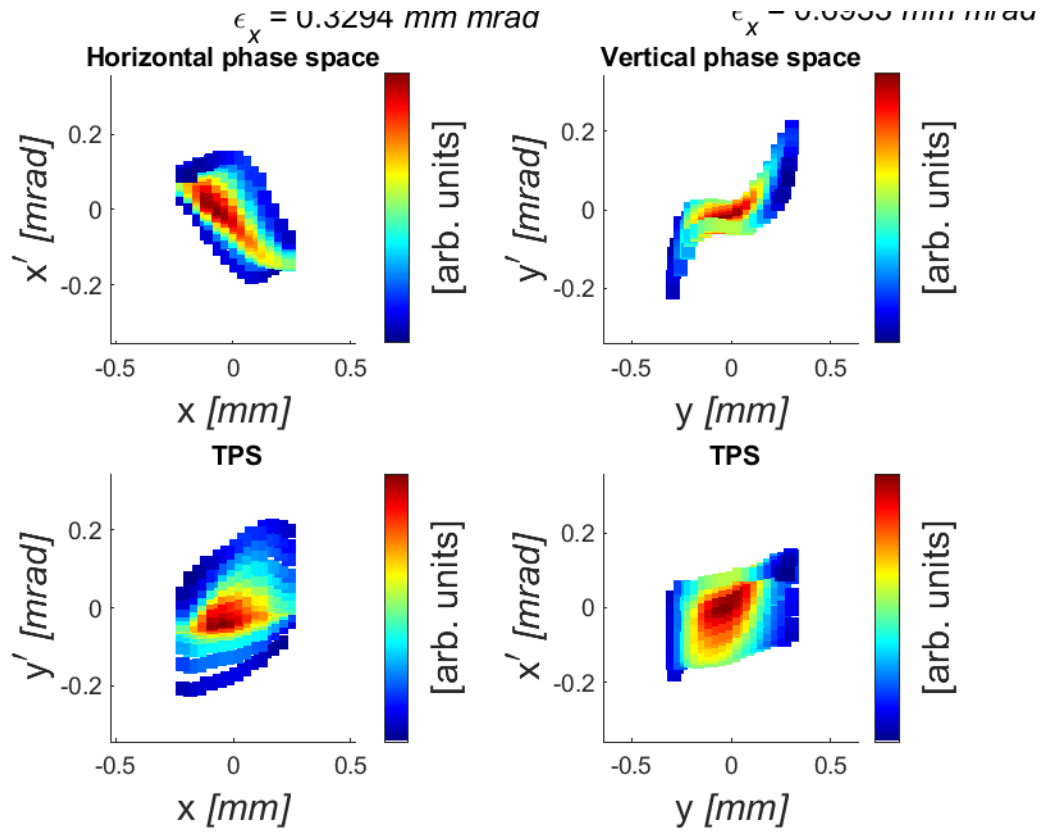


-30 deg



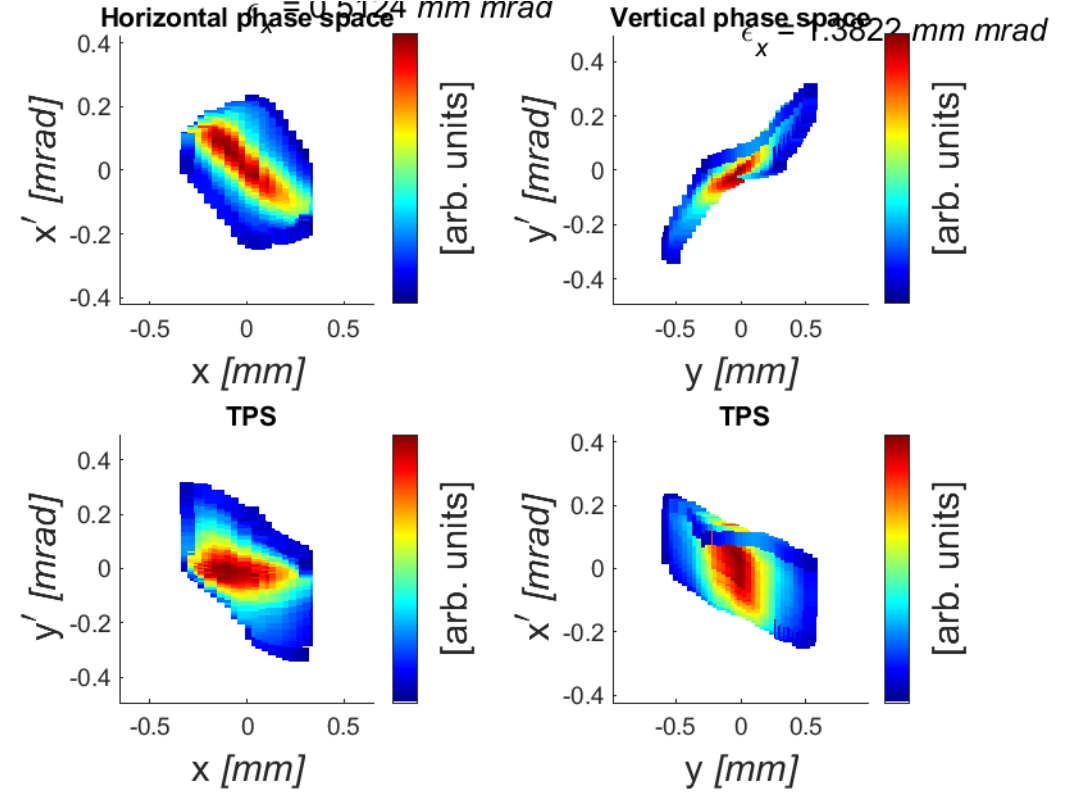
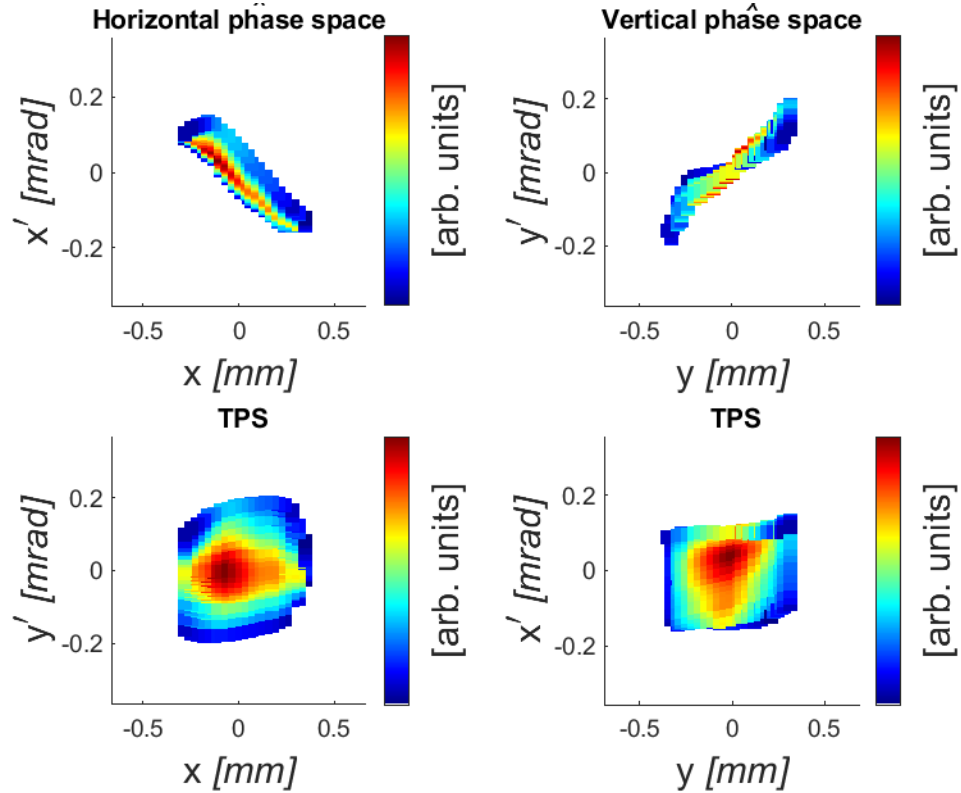
40 deg

-40 deg



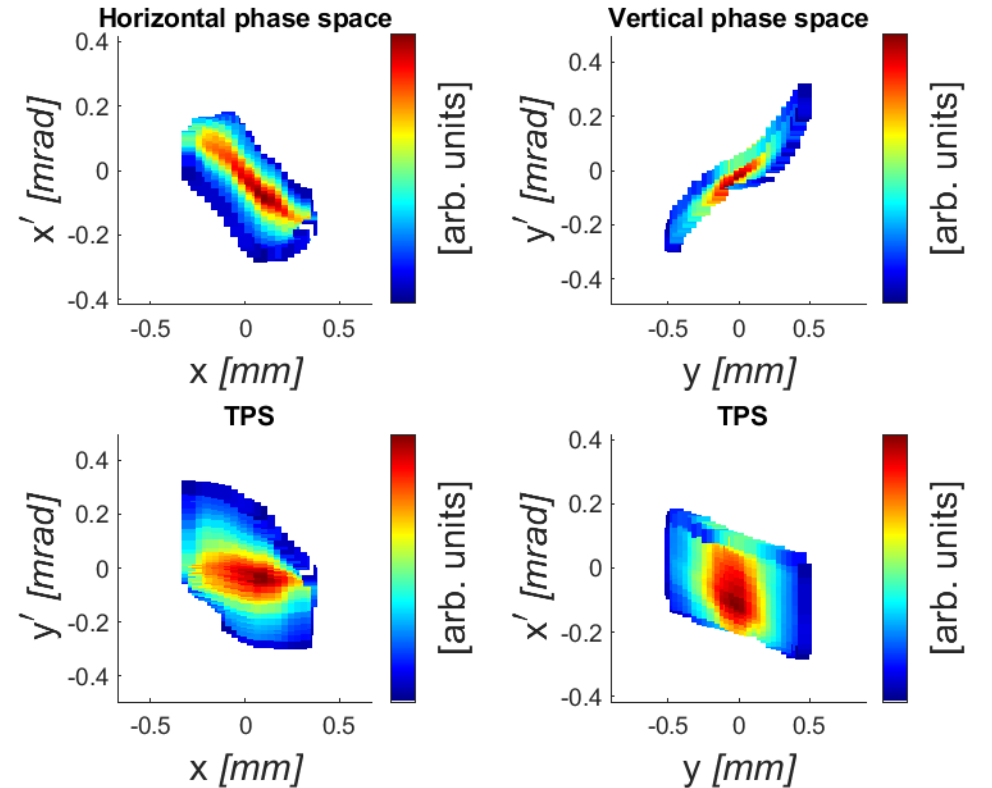
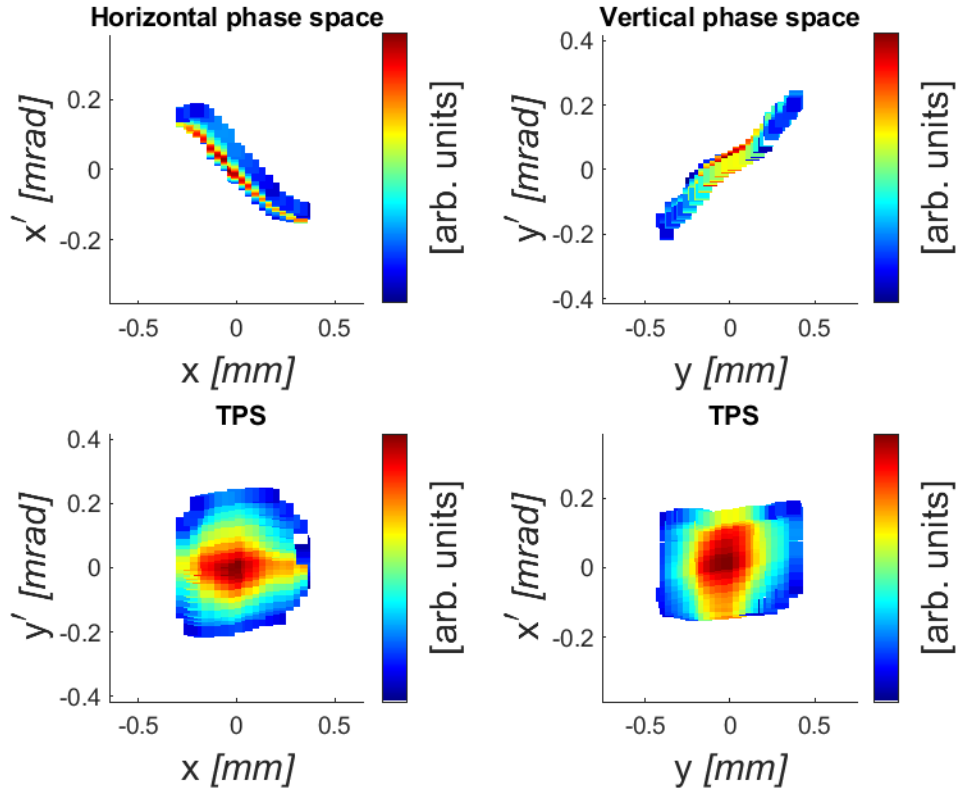
60 deg

-60 deg

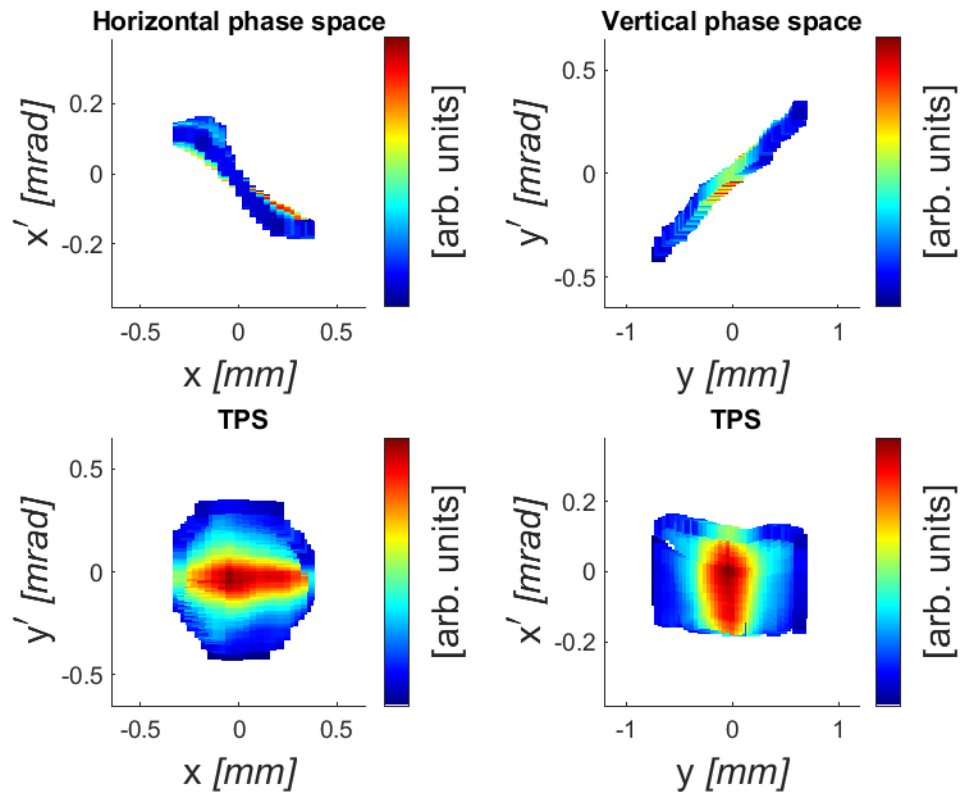


70 deg

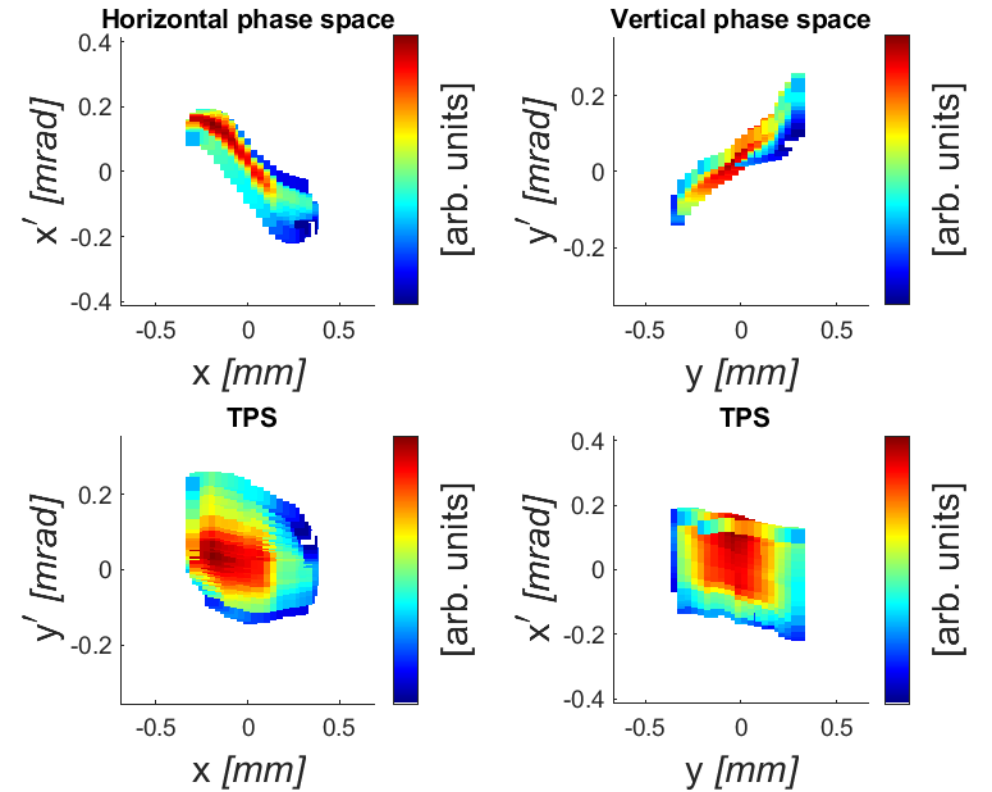
-70 deg



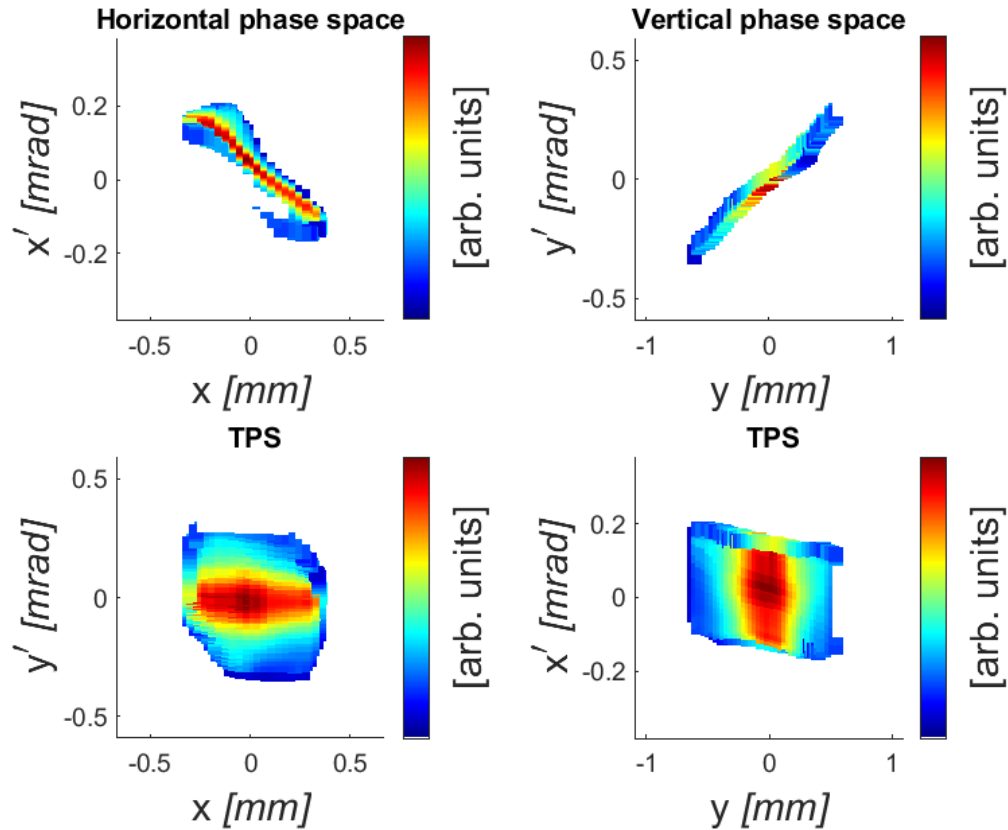
80 deg



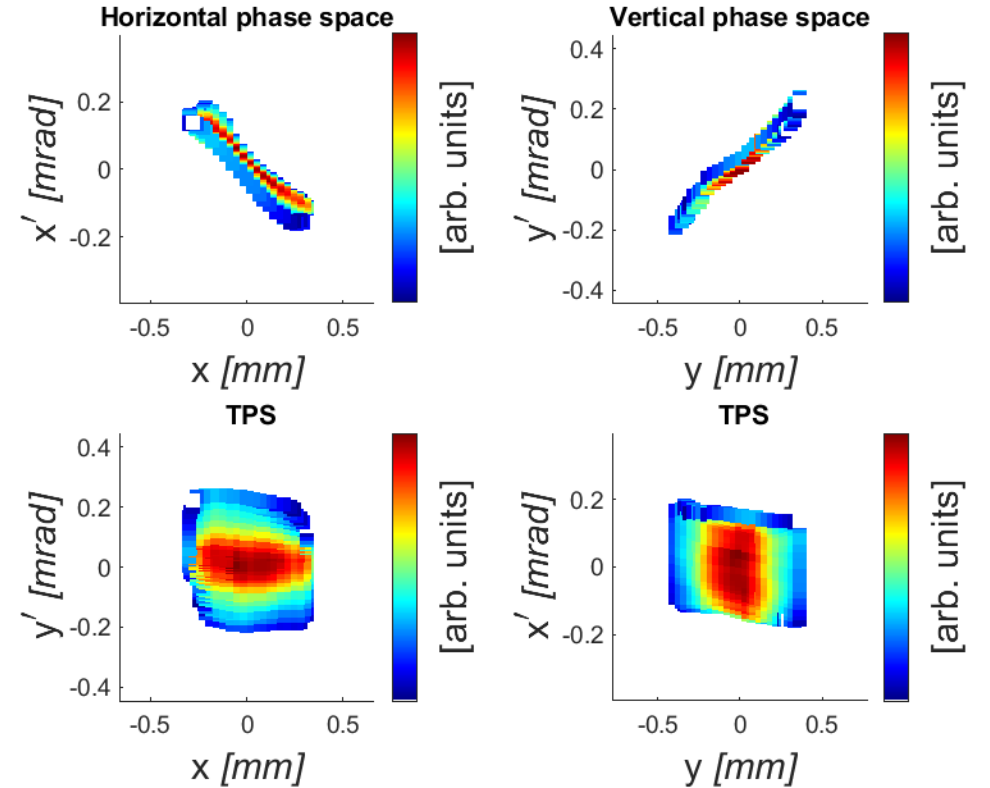
-80 deg



90 deg

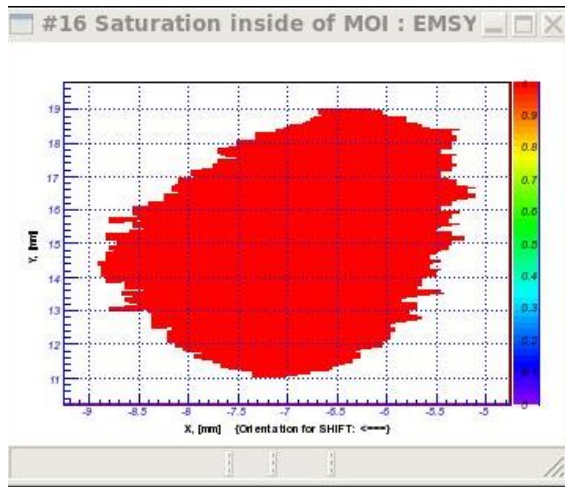
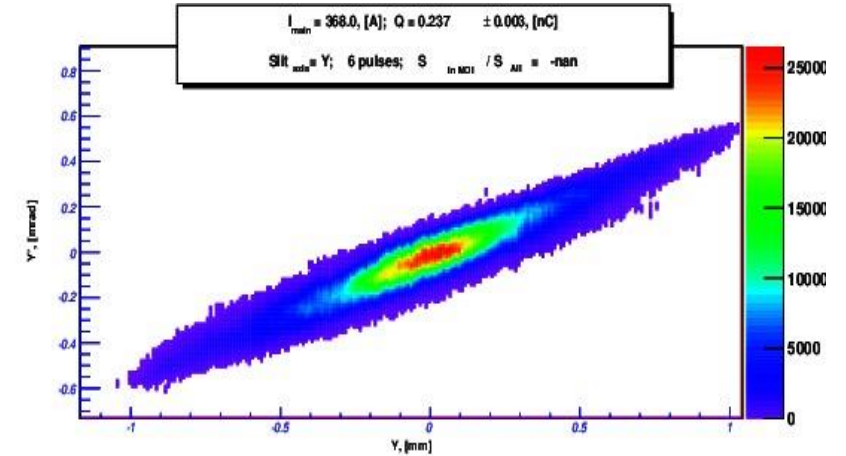
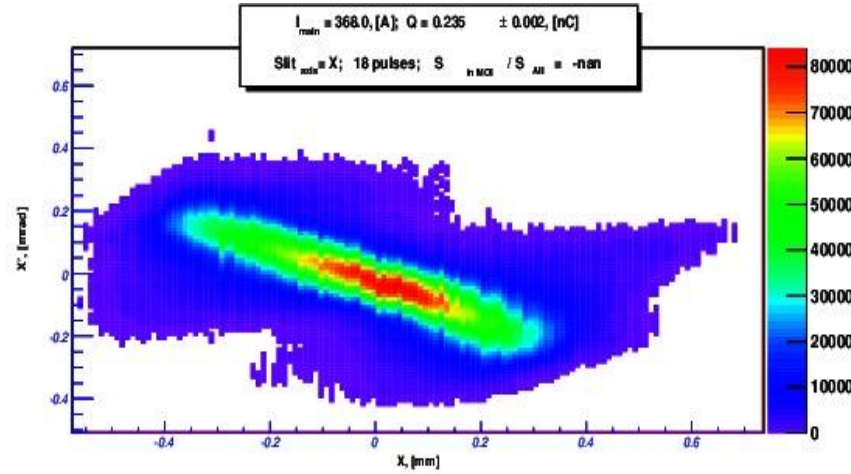
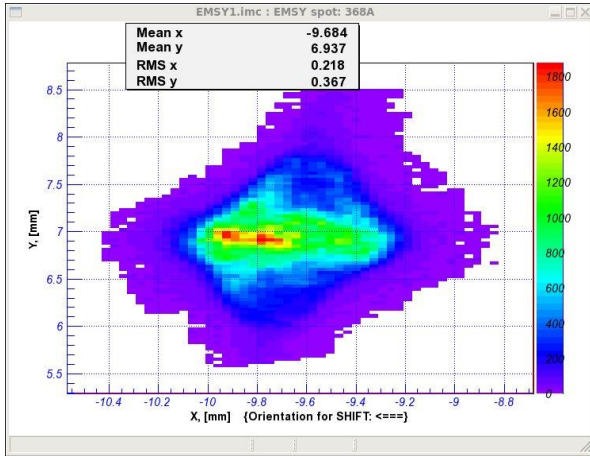


-90 deg



Fast scan

phase space of beam with $\theta=90^\circ$



Results
Plot system ver. Sep 20 2019 18:23:44

Parameter	Value	Unit
Laser:		
ms size	$\langle x \rangle = 0.25100$	[mm]
	$\langle y \rangle = 0.28300$	[mm]
Electron beam:		
Momentum gun	6.30650	[MeV/c]
Momentum booster	19.42600	[MeV/c]
σ_x	0.21640	[mm]
σ_y	0.20530	[mm]
divergence	0.12628	[mrad]
covariance	-0.01649	[mm mrad]
sheared div	0.01620	[mrad]
LDiff	3.13300	[m]
β	2.31537	[mm]
γ	0.87731	[mrad]
α	1.01553	[mm mrad]
$\beta\gamma\alpha^2$	1.00000	
σ_{scaled}	0.674	[mm mrad]
σ_{sheared}	0.692	[mm mrad]
$\sigma_{\text{scaled 2D}}$	0.736	[mm mrad]

Comments: no corr

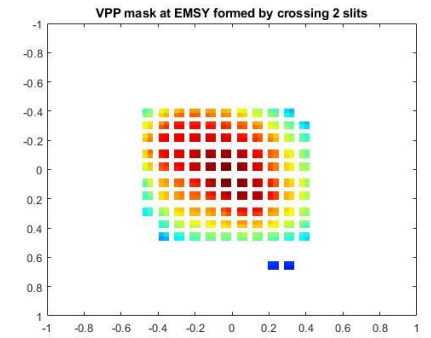
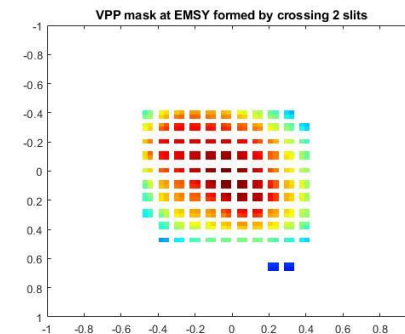
Results
Plot system ver. Sep 20 2019 18:23:44

Parameter	Value	Unit
Laser:		
ms size	$\langle x \rangle = 0.25100$	[mm]
	$\langle y \rangle = 0.28300$	[mm]
Electron beam:		
Momentum gun	6.30650	[MeV/c]
Momentum booster	19.42600	[MeV/c]
σ_x	0.36600	[mm]
σ_y	0.29504	[mm]
divergence	0.16436	[mrad]
covariance	0.04977	[mm mrad]
sheared div	0.01601	[mrad]
LDiff	3.13300	[m]
β	5.43611	[mm]
γ	1.88705	[mrad]
α	-2.85649	[mm mrad]
$\beta\gamma\alpha^2$	1.00000	
σ_{scaled}	0.739	[mm mrad]
σ_{sheared}	0.609	[mm mrad]
$\sigma_{\text{scaled 2D}}$	0.757	[mm mrad]

Comments: no corr

Conclusion

- VPP ability to do 4D TPS diagnostics
- insight to transverse beam phase space coupling
- Core emittance and phase space with charge cut
- Systematic error sources
 - crossing of slits (how many and which)
 - Weight of VPP beamlet from EMSY mask (very sensitive to pixel)
 - Extrapolation of pixels in EMSY mask



Thank you