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

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

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

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

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

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

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

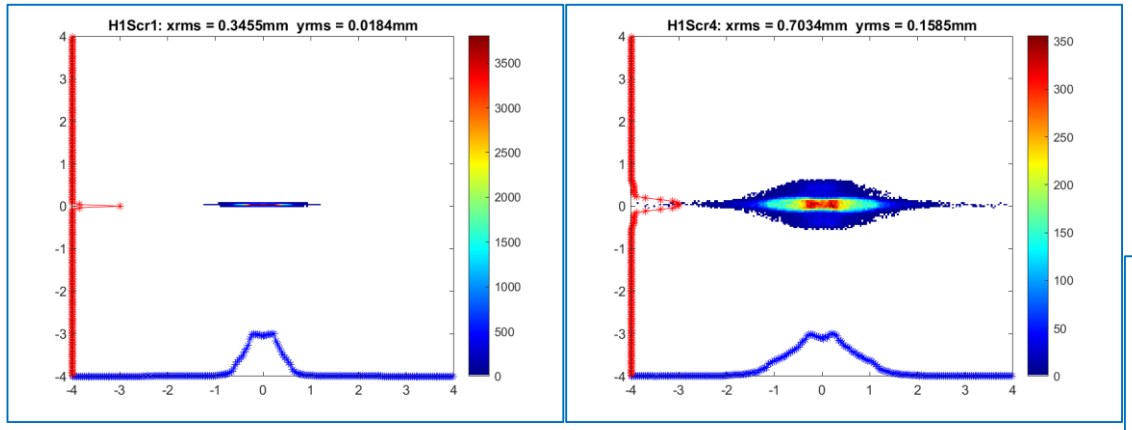
$$I_2 = \epsilon_x^2 + \epsilon_y^2 + 2C_{xy}^2$$

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

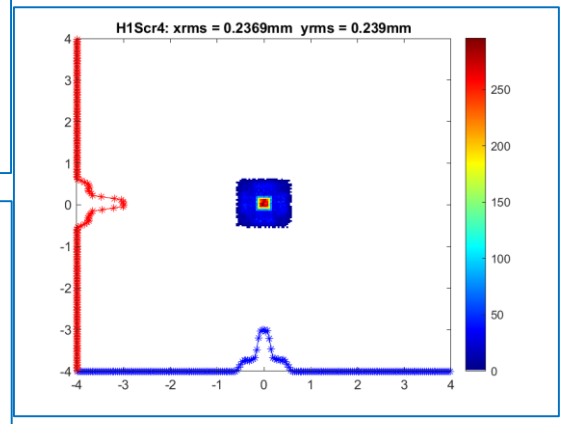
Virtual Pepper Pot Technique

Crossing of beamlets and EMSY mask

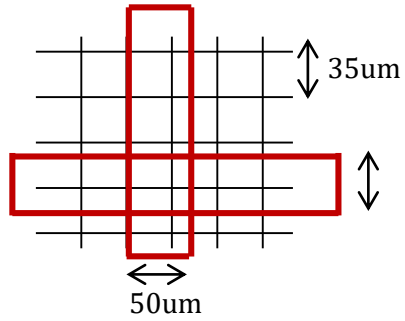
Result of crossing horizontal and vertical beamlets



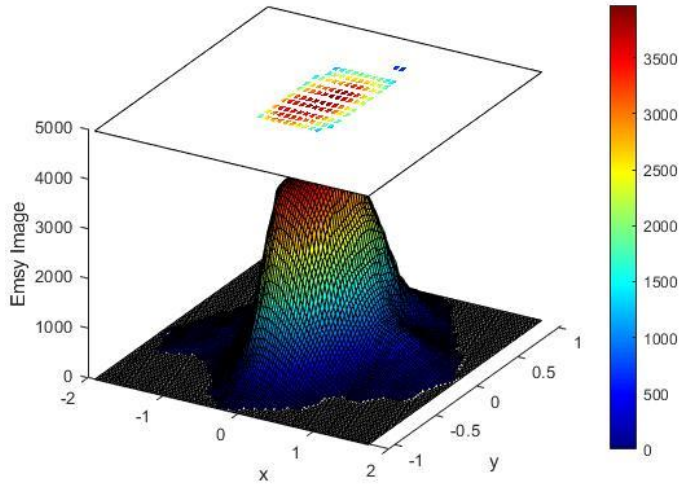
Pixel-wise minimum of crossed beamlets



Crossed Slit positions

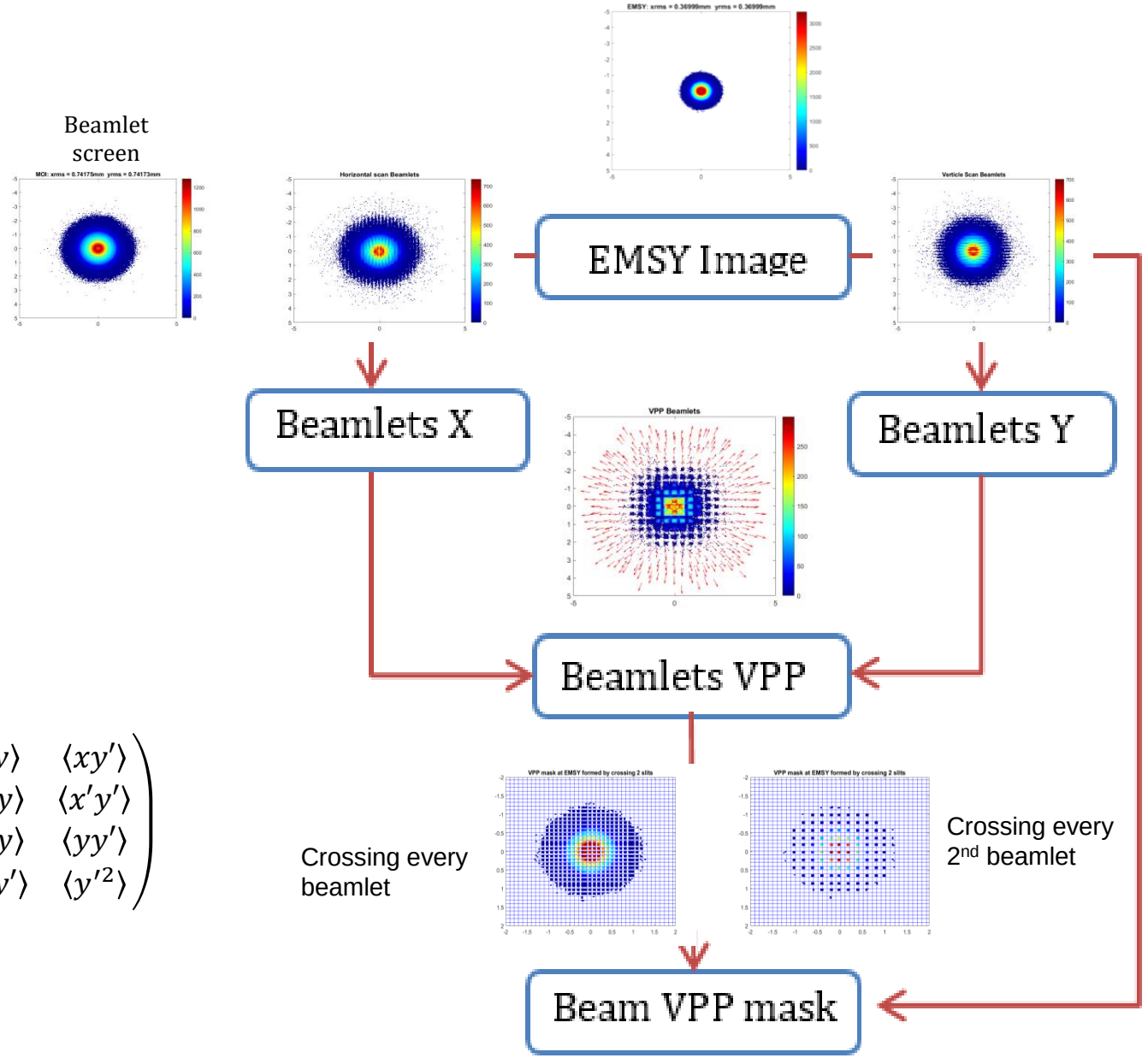


EMSY mask



VPP

Algorithm

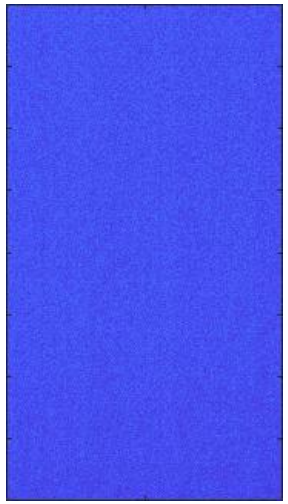


$$\sigma^{4D} = \begin{pmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle xy \rangle & \langle xy' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle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

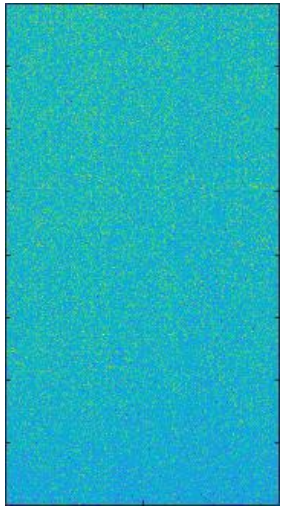
VPP

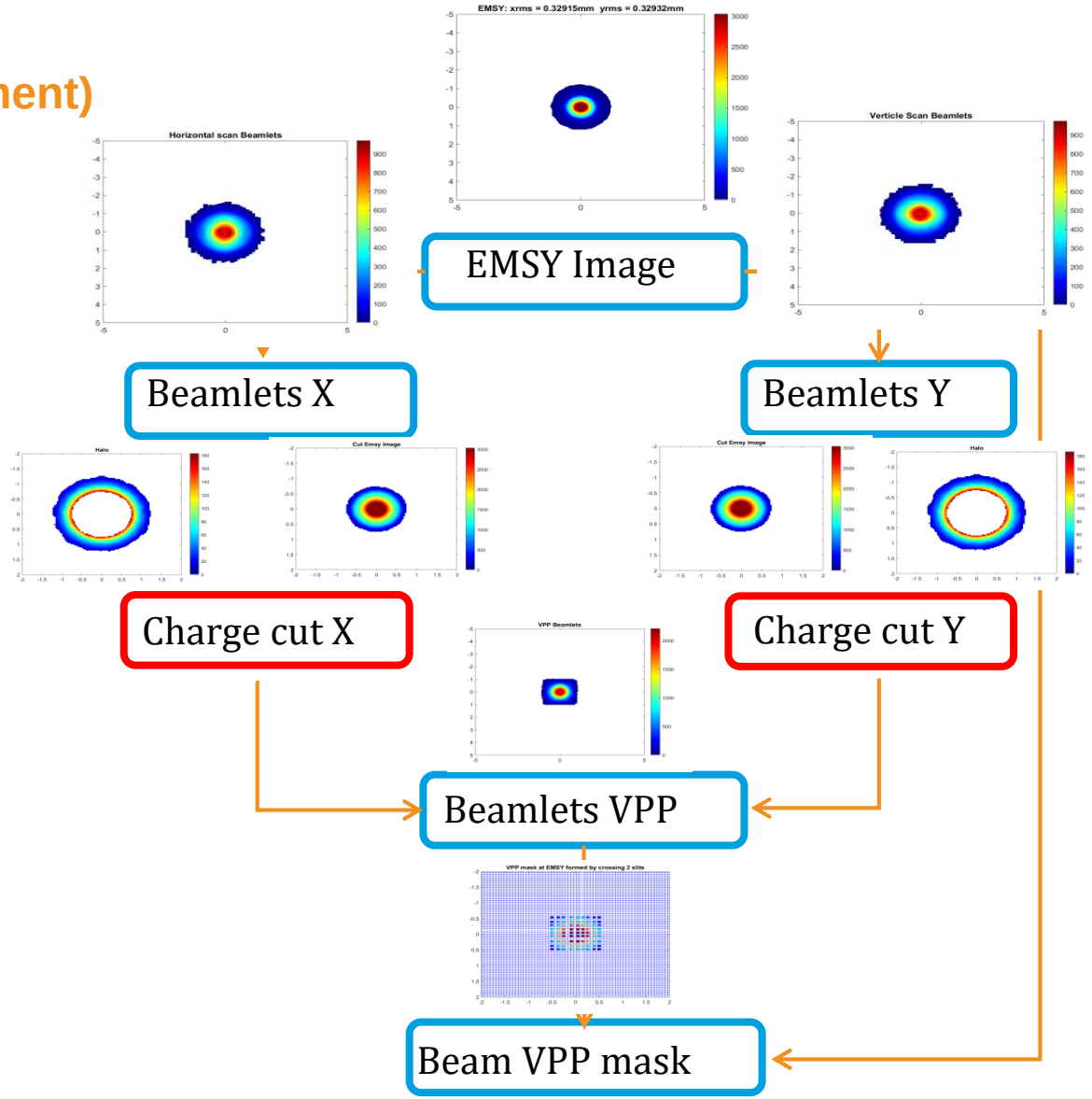
Charge Cut (simulated beam + noise from experiment)

Horizontal scan



Vertical Scan





1D charge cut → 2D charge cut

- **thresholding (u)**

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

- **Position shifting (Δ)**

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

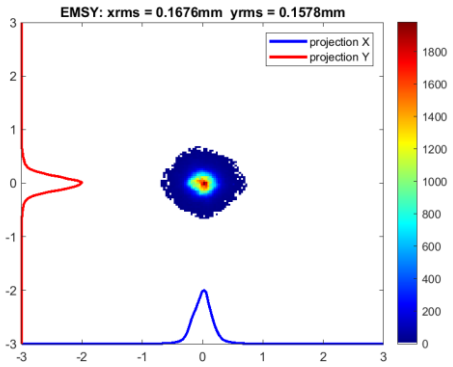
- **Scaling (A)**

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

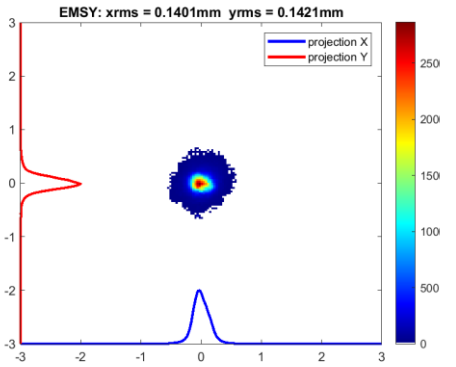
- **Charge cut** = sum(cutEmsy < u) / sum(Emsy)

Gun quadrupole angle scan Q1 Q2

EMSY images 0 to 90 degrees



0



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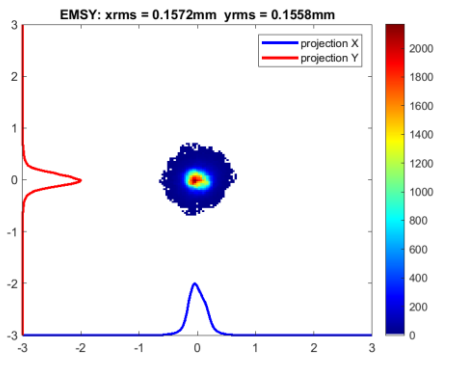

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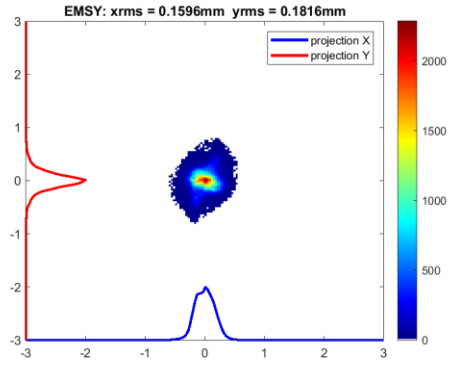

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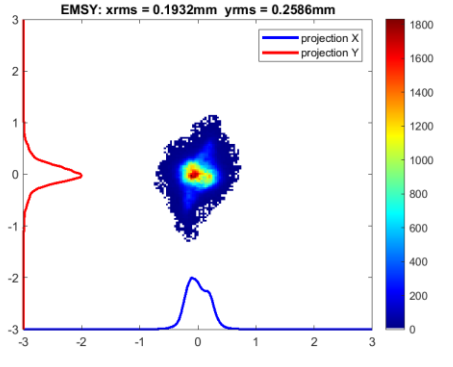

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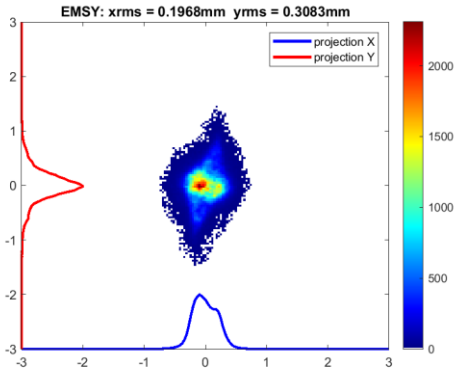

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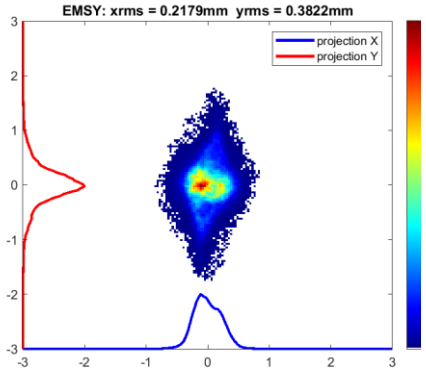

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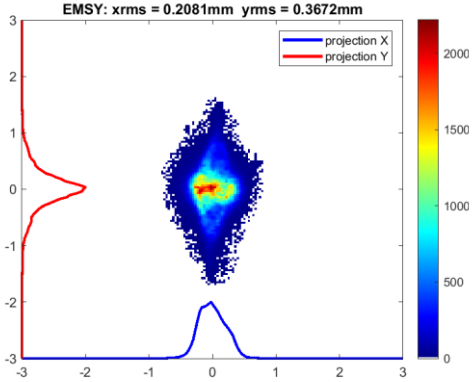

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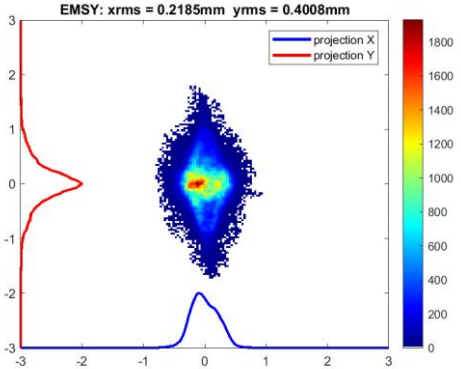

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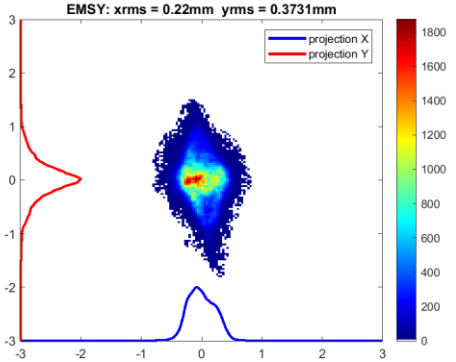
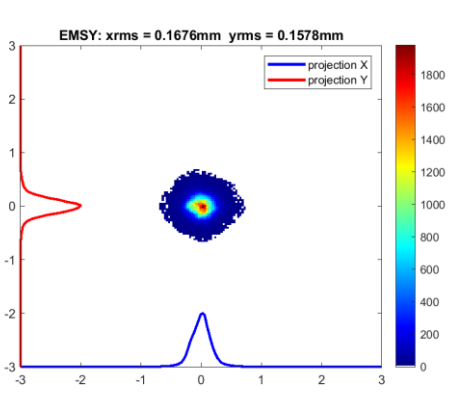
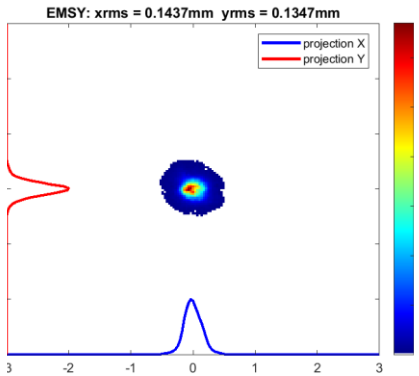


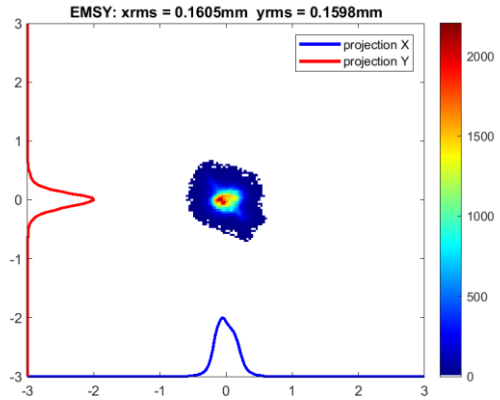
90

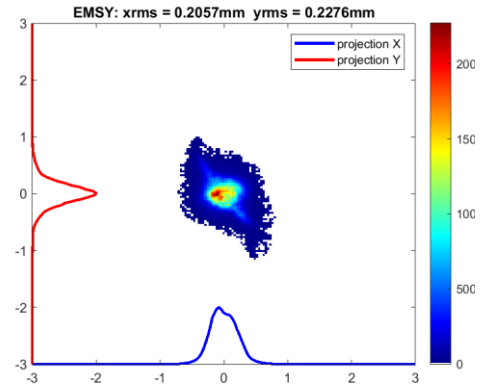
Gun quadrupole angle scan

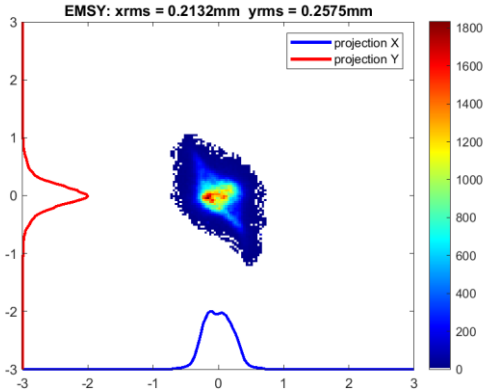
EMSY images 0 to -90 degrees



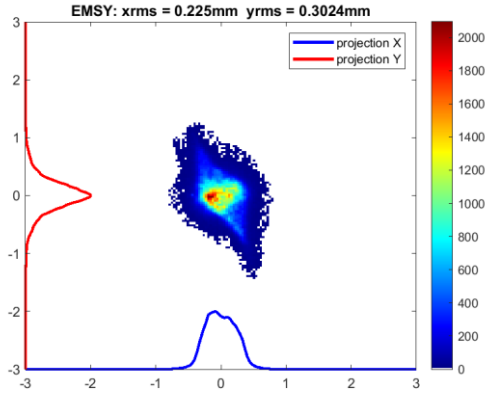


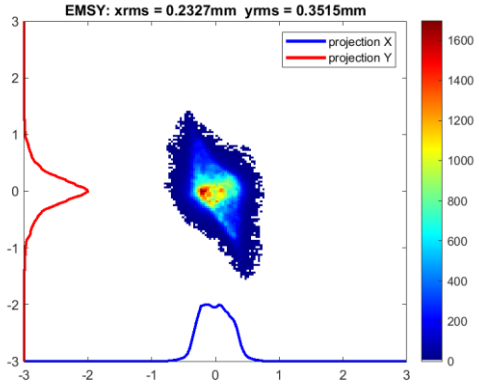


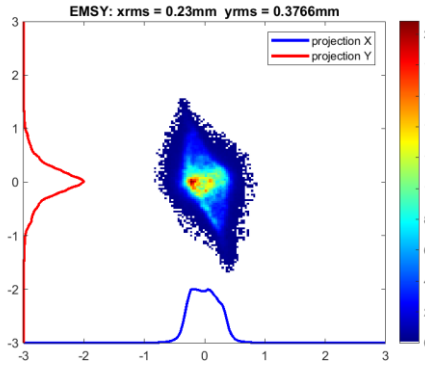


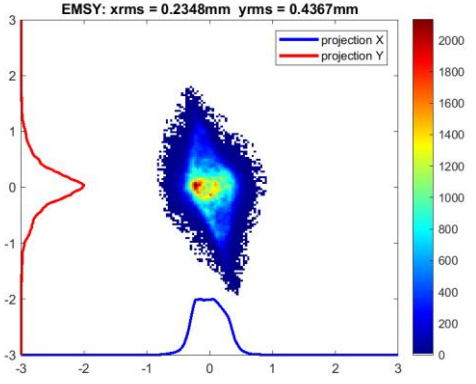


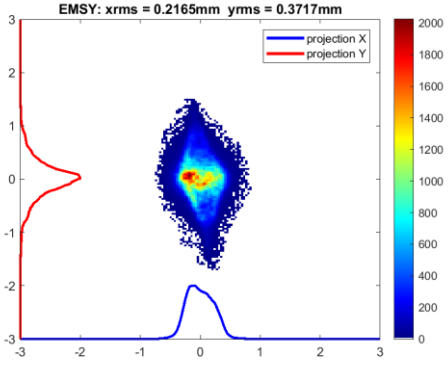
0	-10	-20	-30	-40









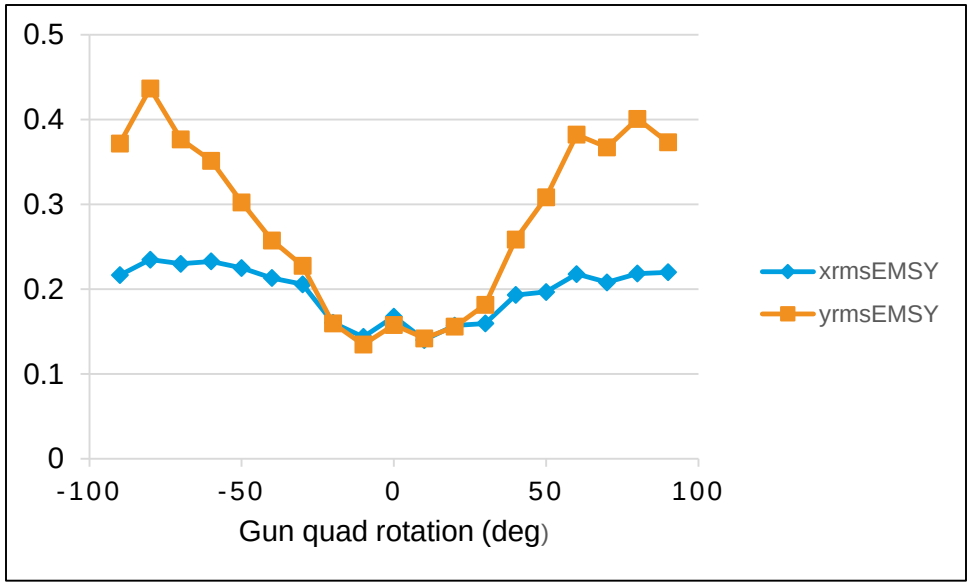


-50	-60	-70	-80	-90

TPS

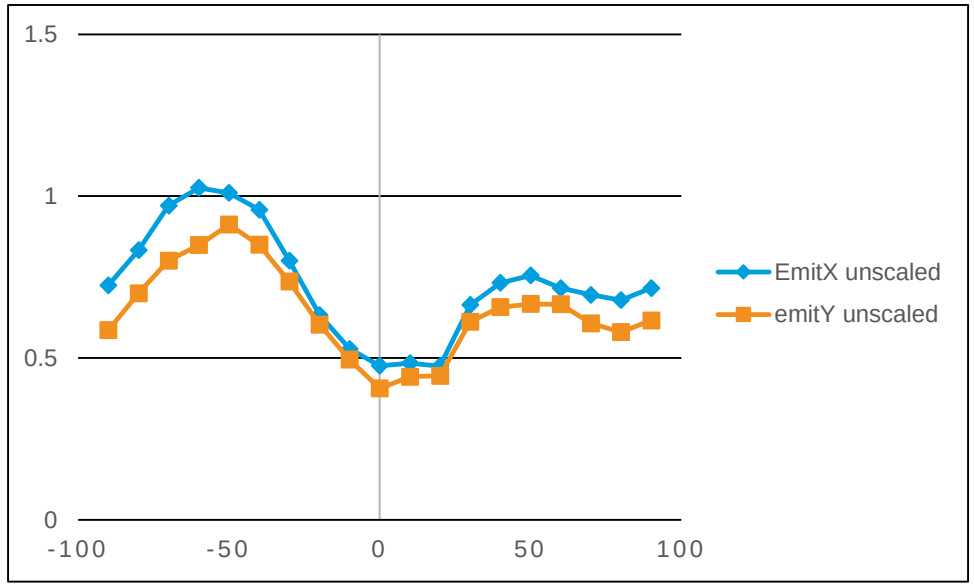
Fast scan vs VPP results

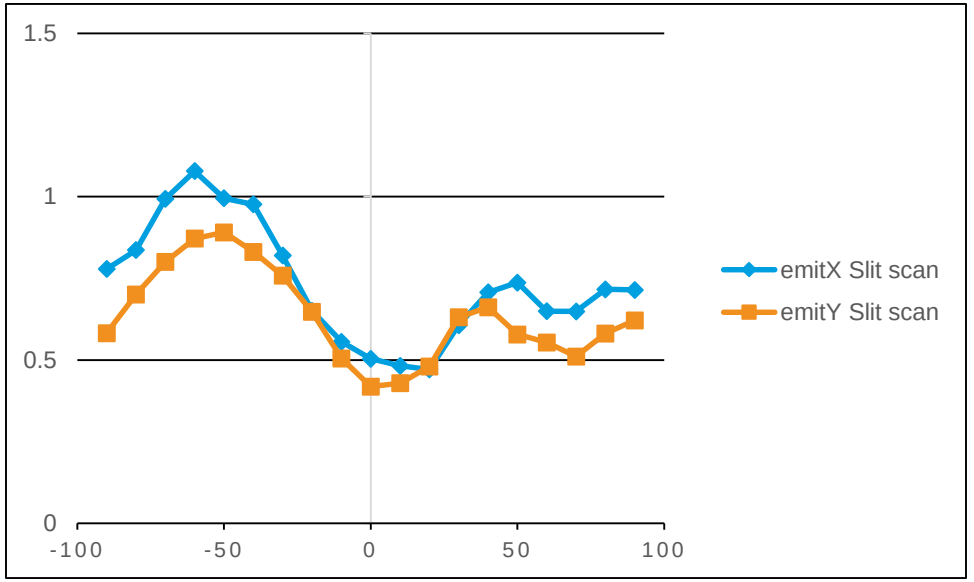
Using SVD filter



TPS

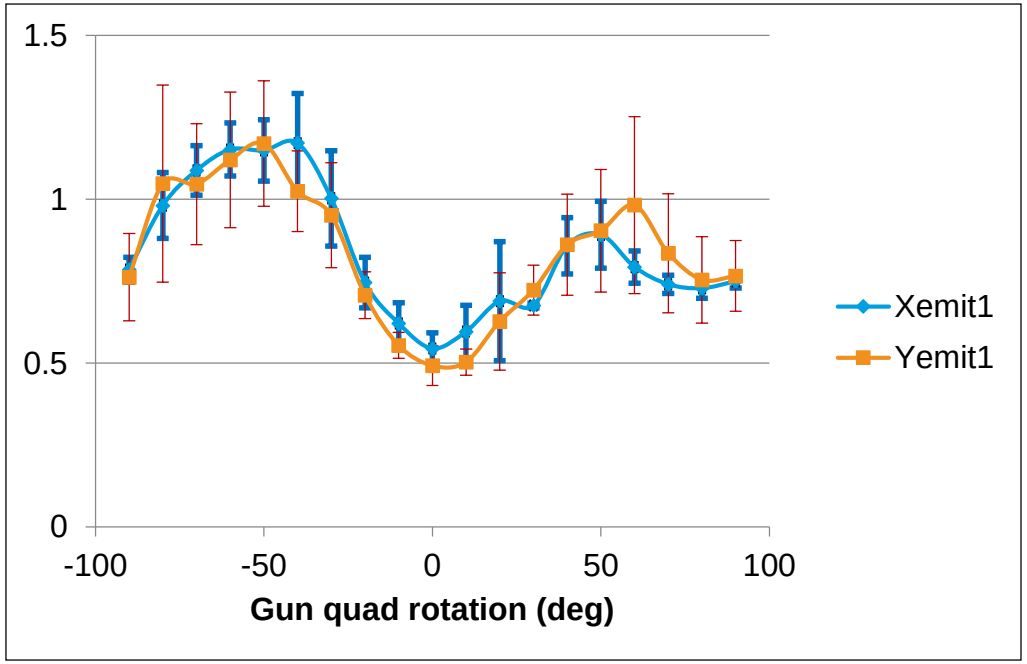
Fast scan vs VPP results

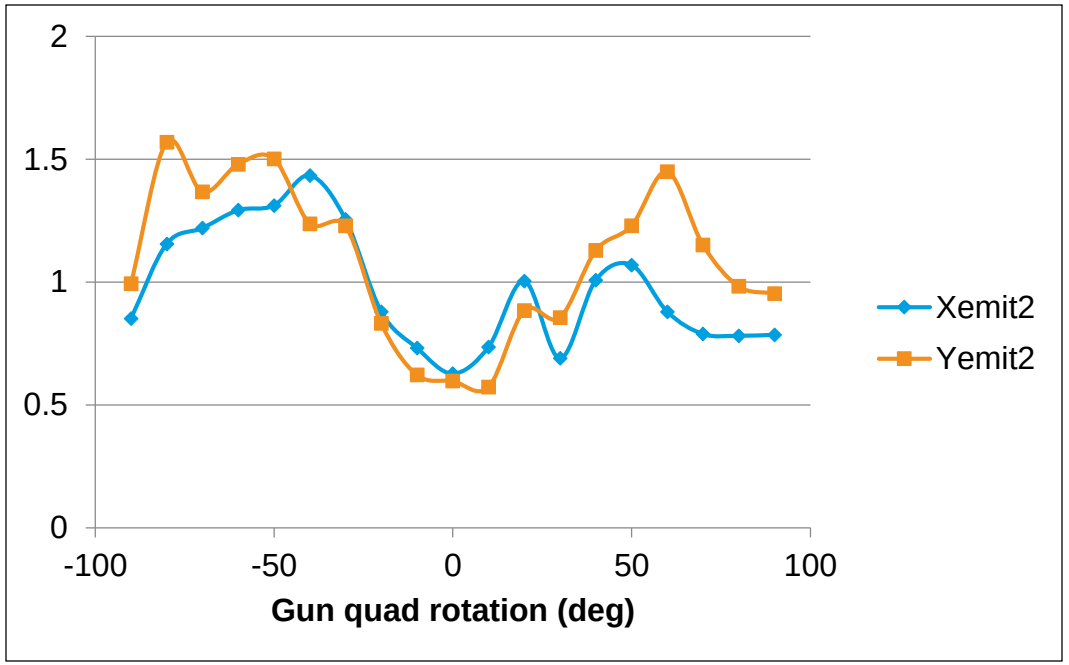




TPS

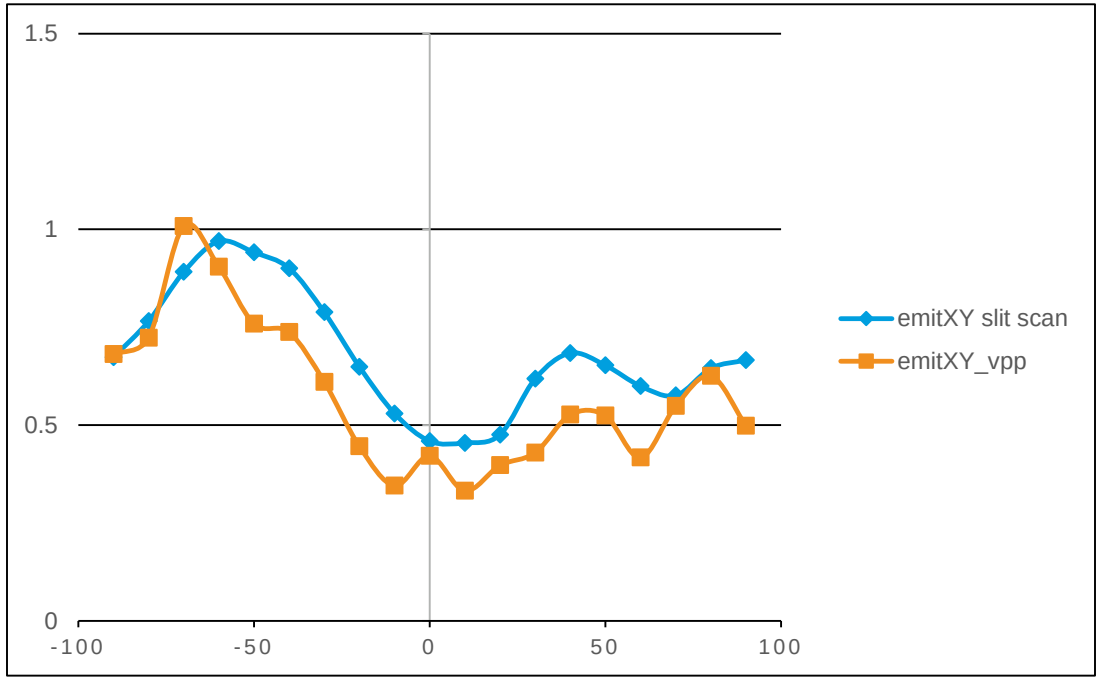
Fast scan -> scaled emittances

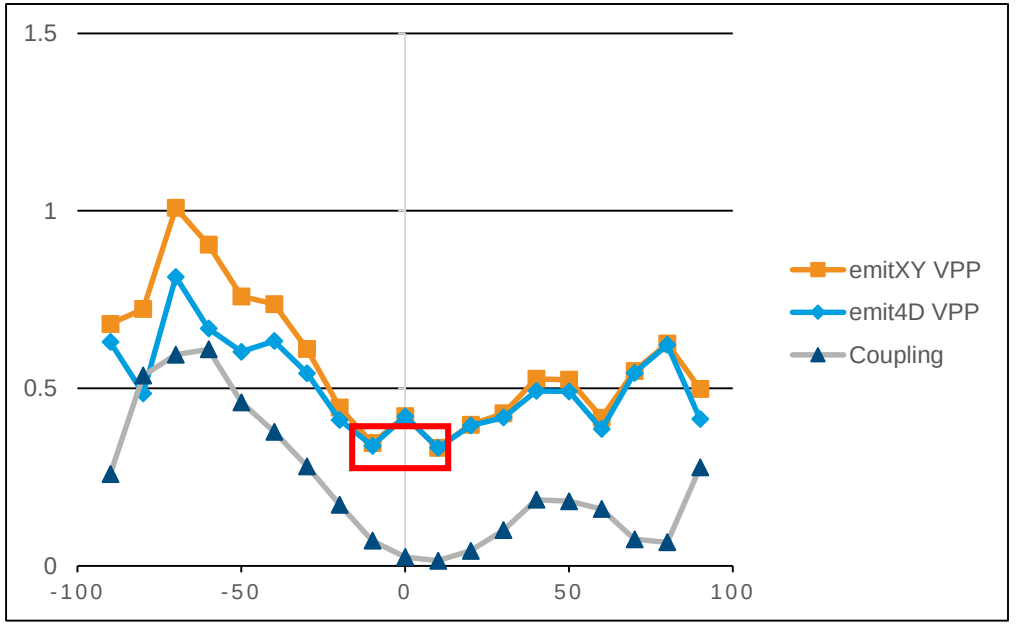




TPS

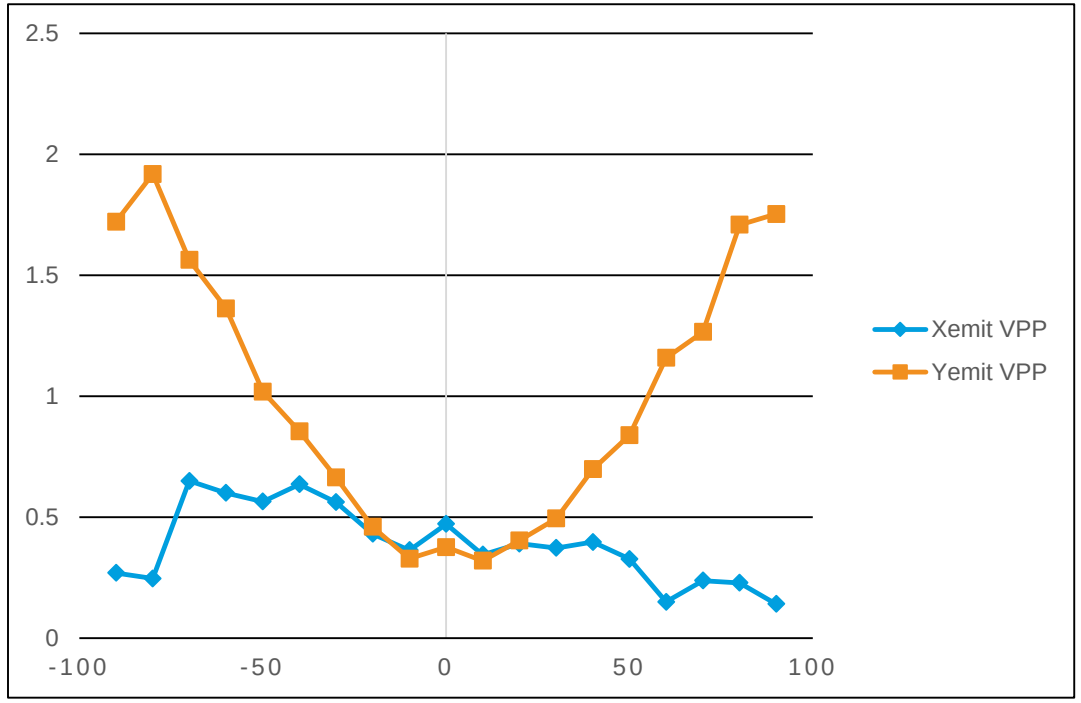
VPP with 2D charge cut

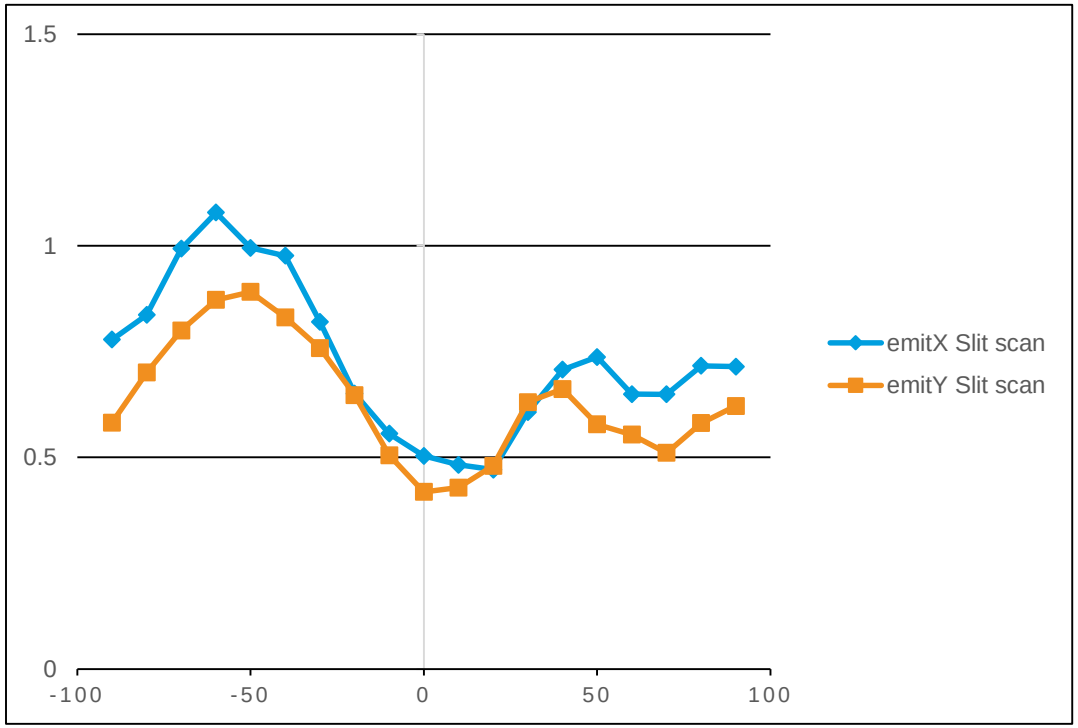




TPS

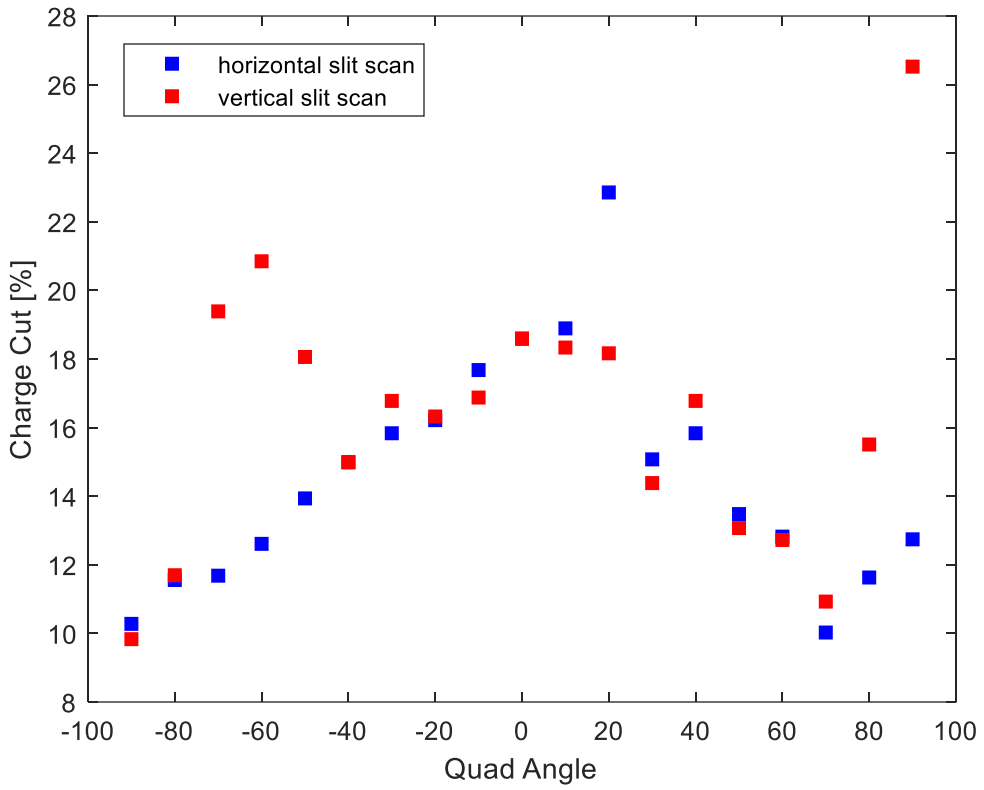
VPP with 2D charge cut



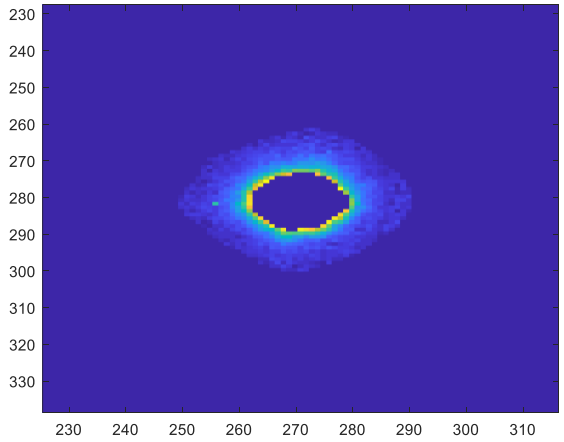


VPP

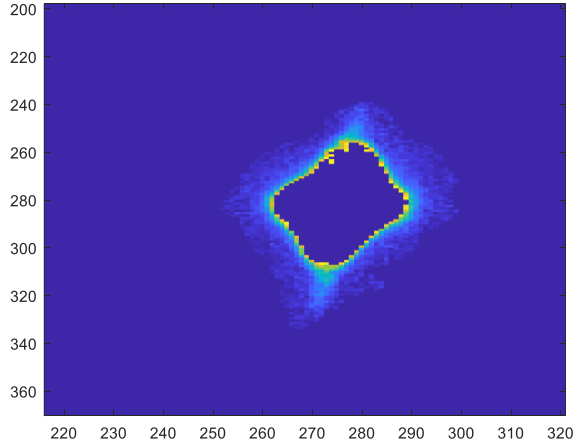
Charge cut



Core EMSY 0 deg



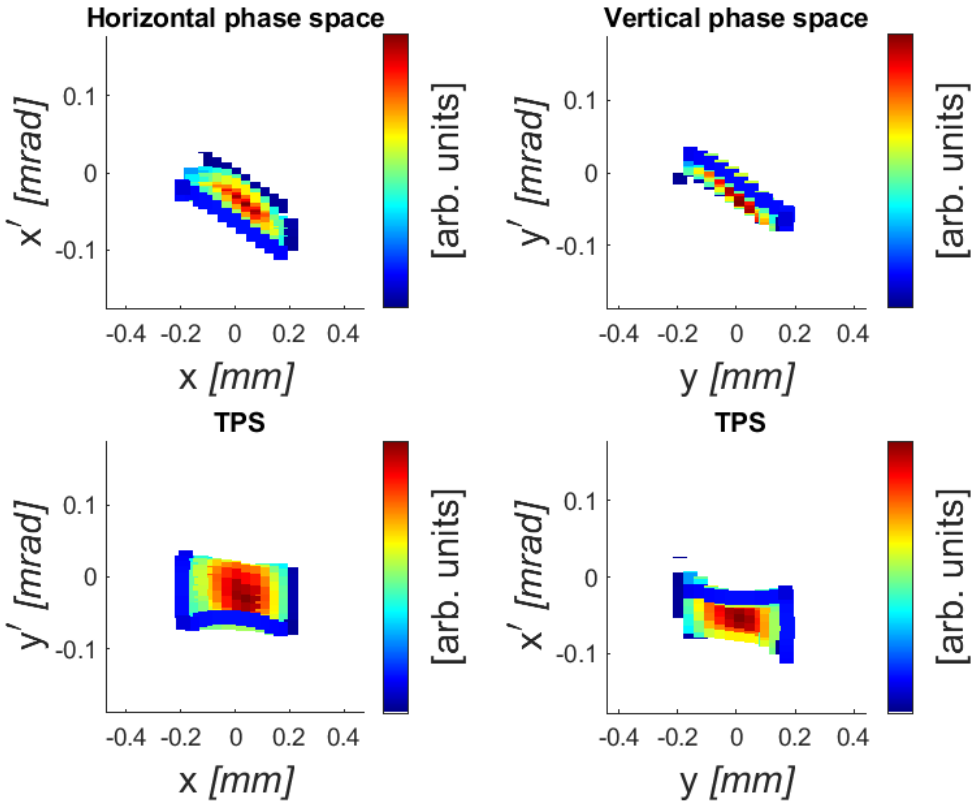
Core EMSY 90 deg



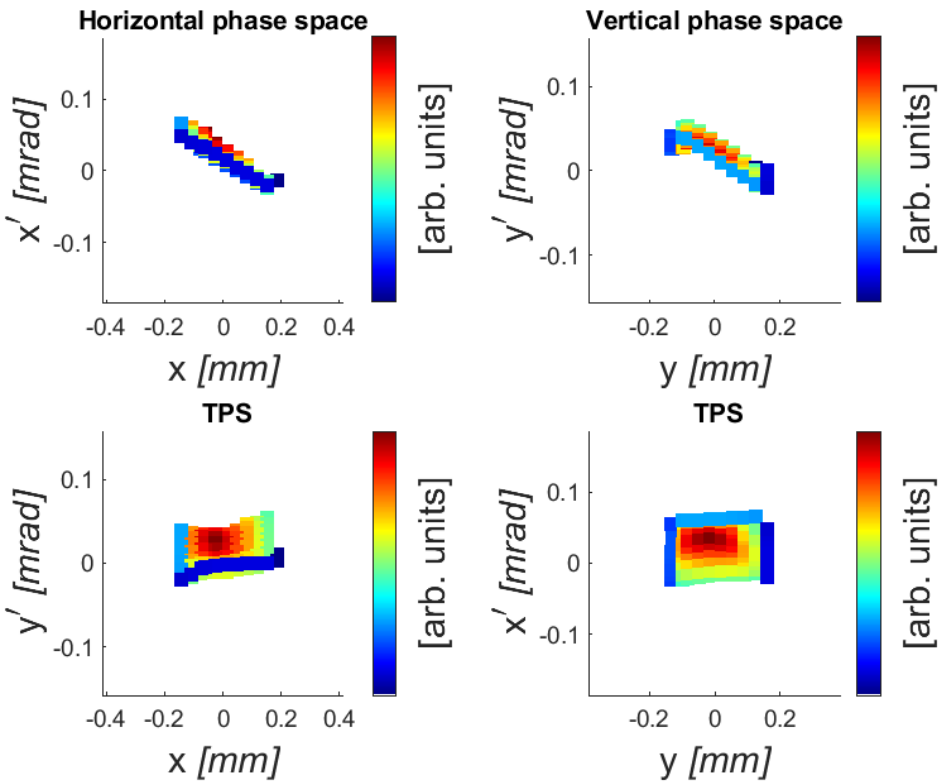
VPP

Gun quad scan

0 deg



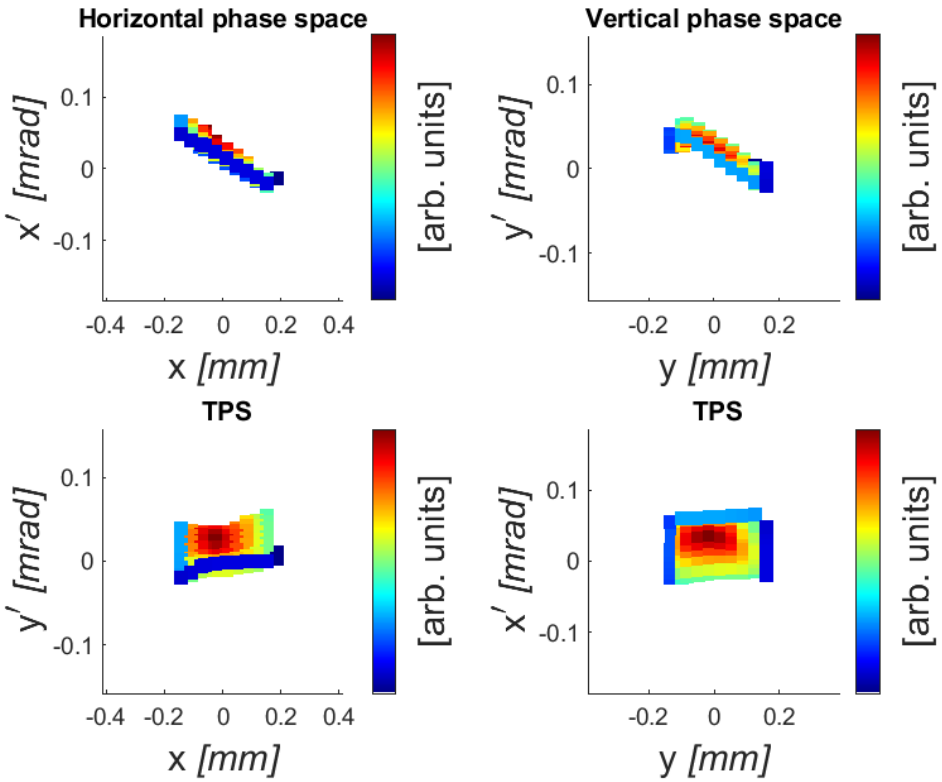
10 deg



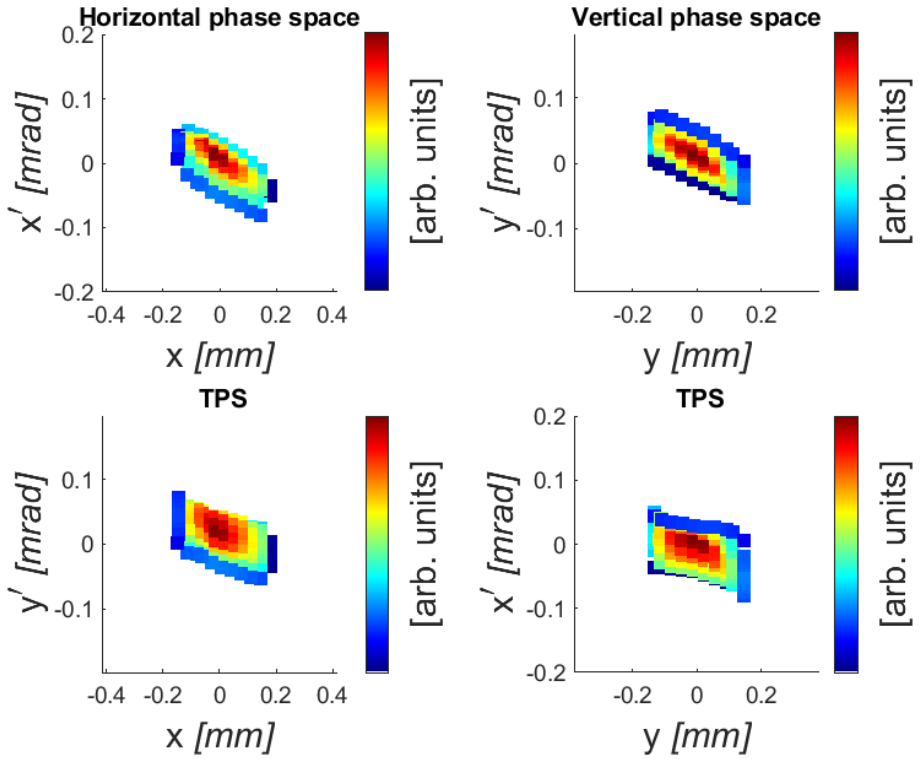
VPP

Gun quad scan

10 deg



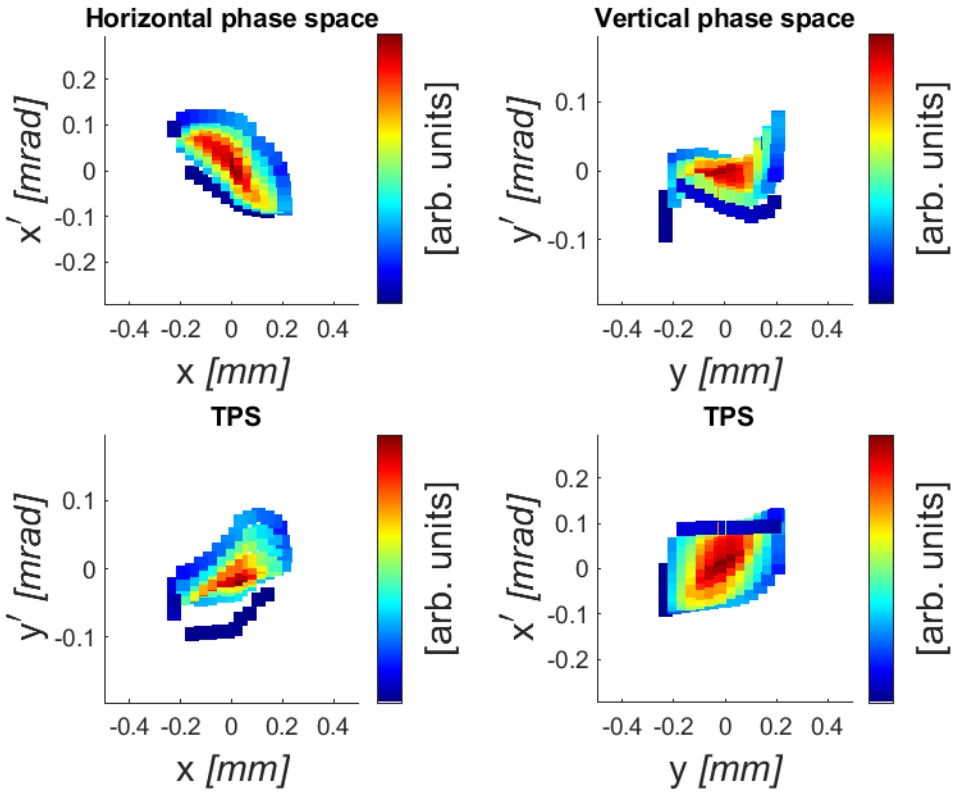
-10 deg



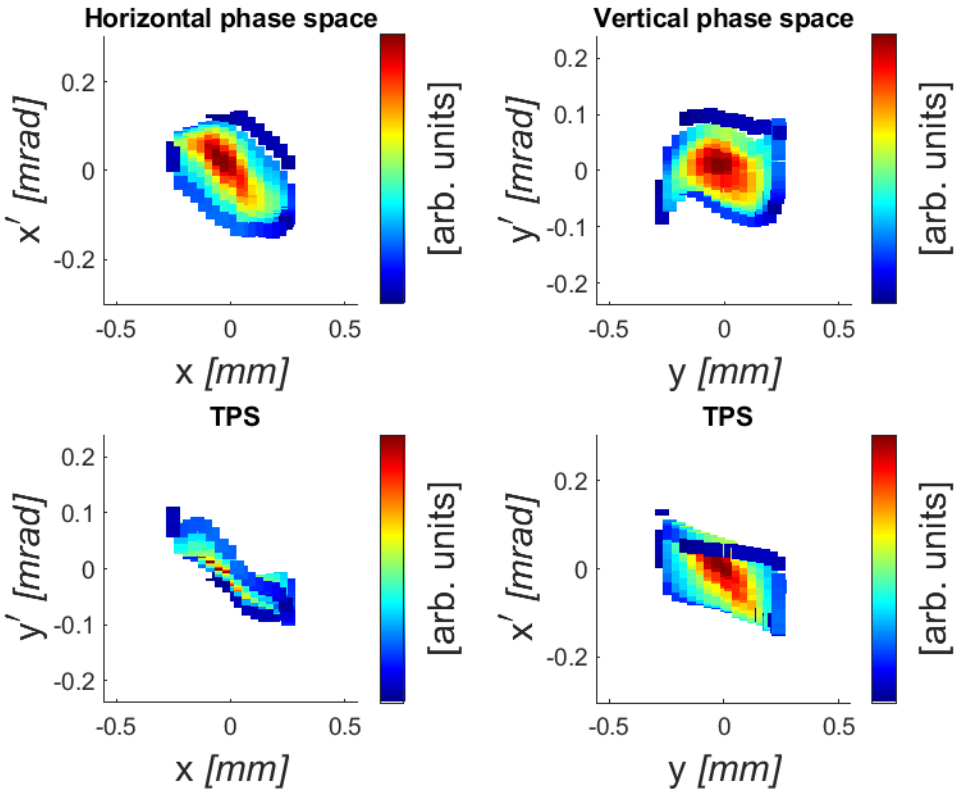
VPP

Gun quad scan

30 deg



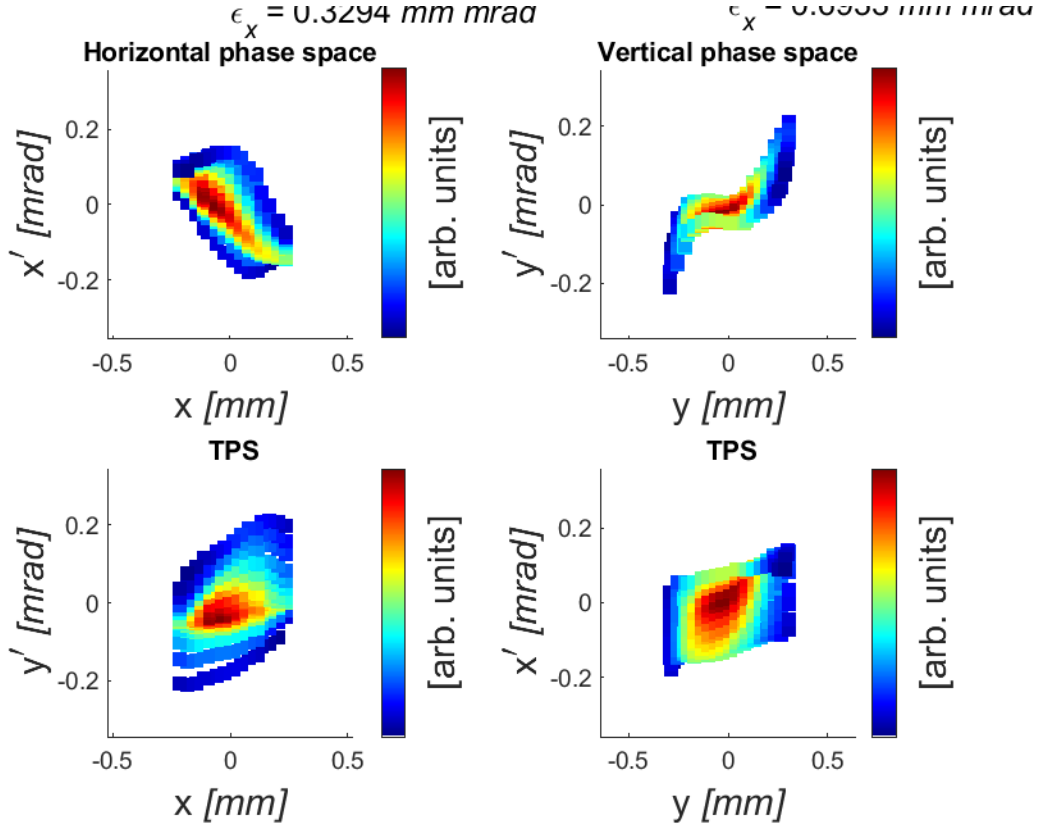
-30 deg



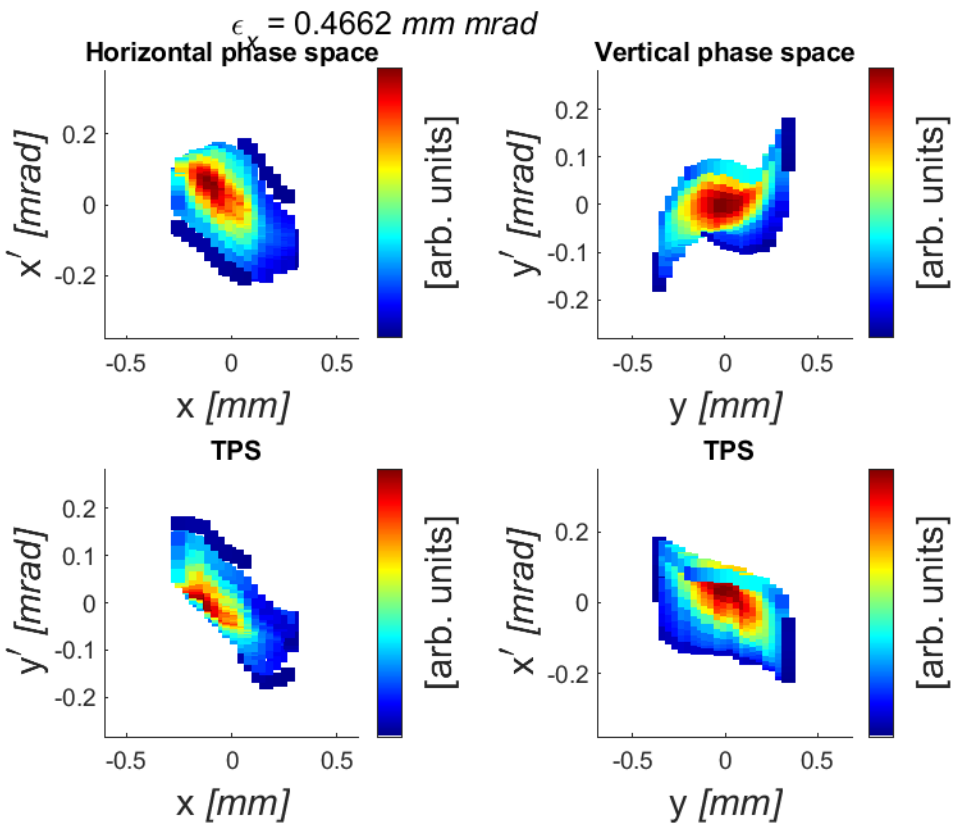
VPP

Gun quad scan

40 deg



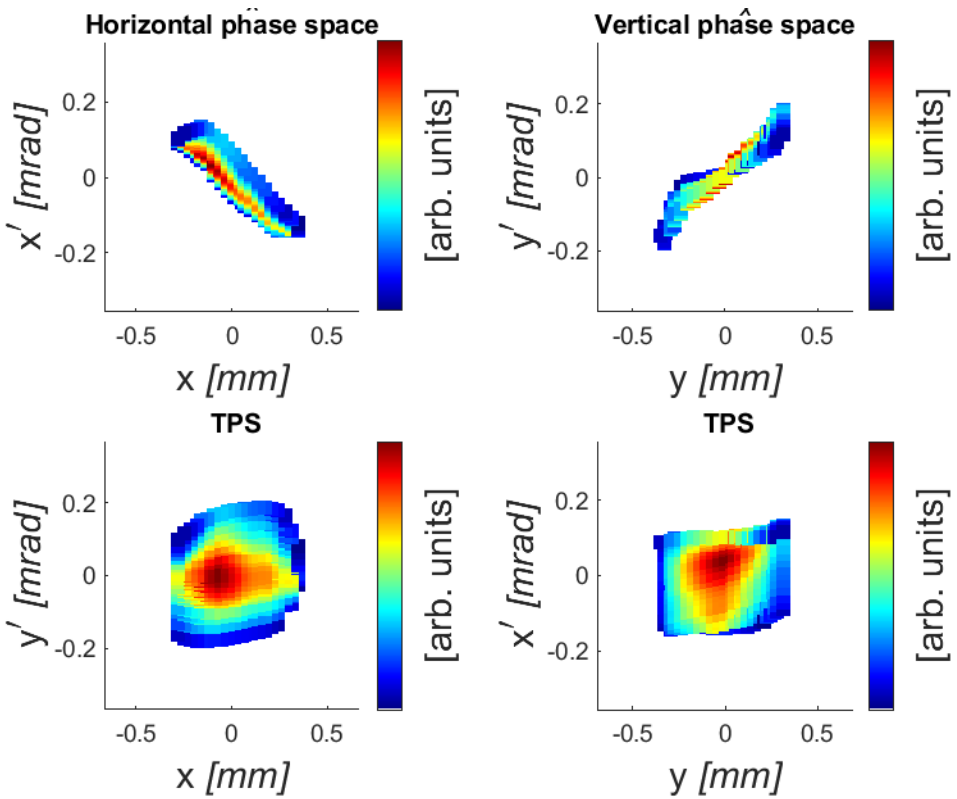
-40 deg



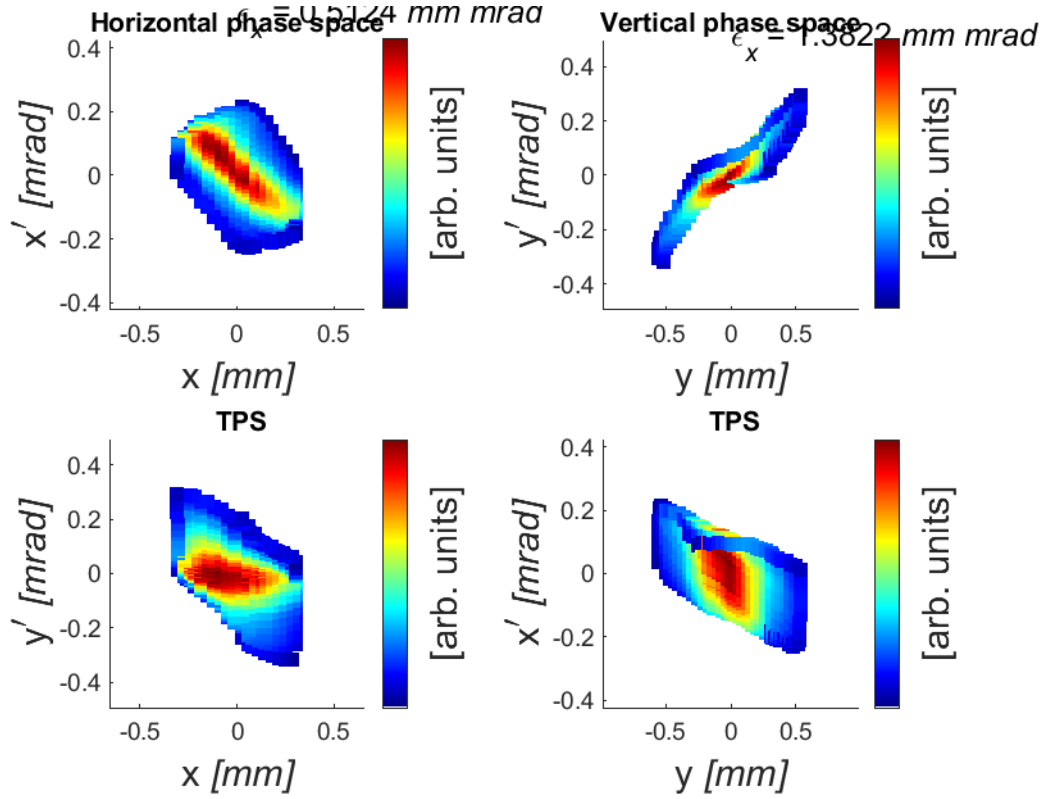
VPP

Gun quad scan

60 deg



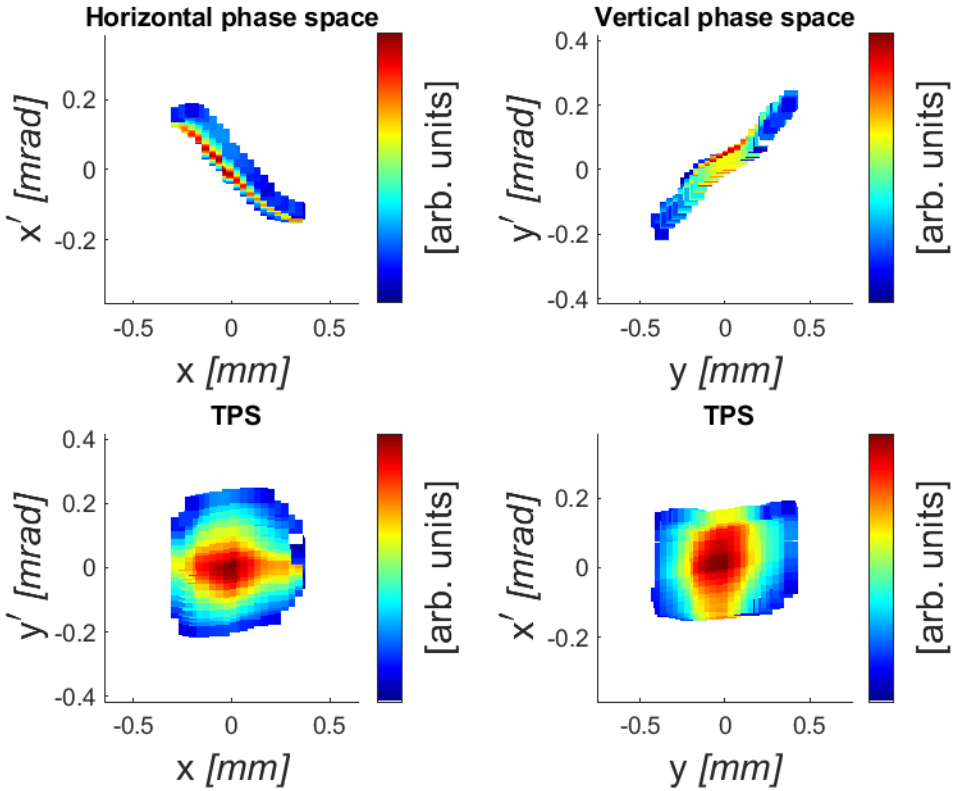
-60 deg



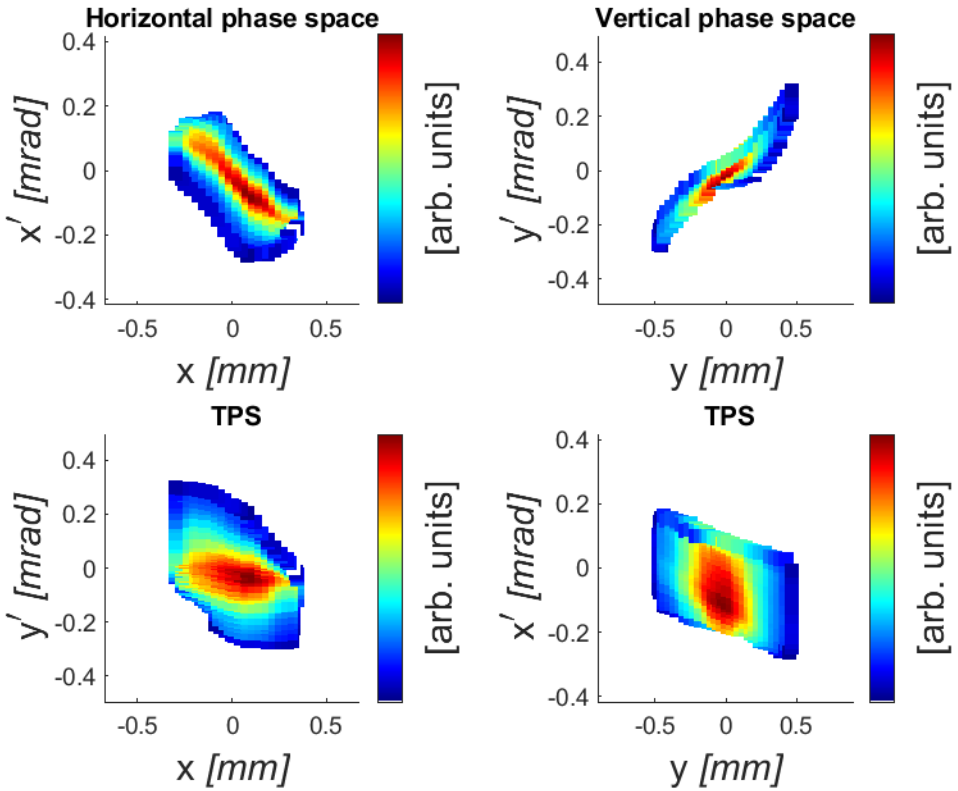
VPP

Gun quad scan

70 deg



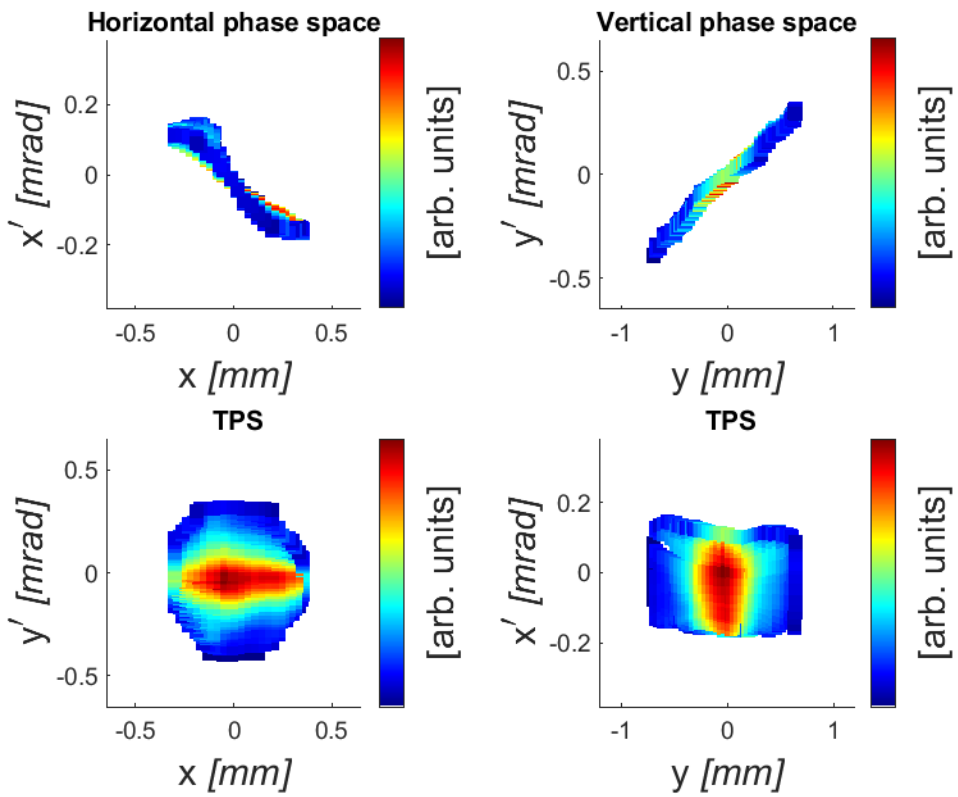
-70 deg



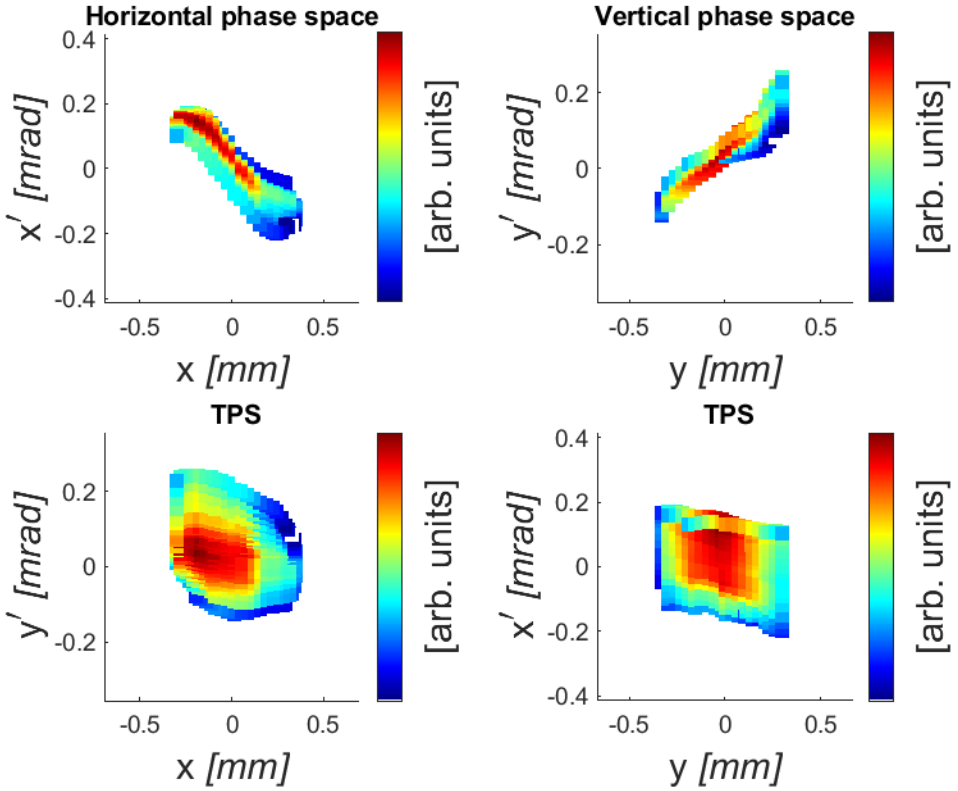
VPP

Gun quad scan

80 deg



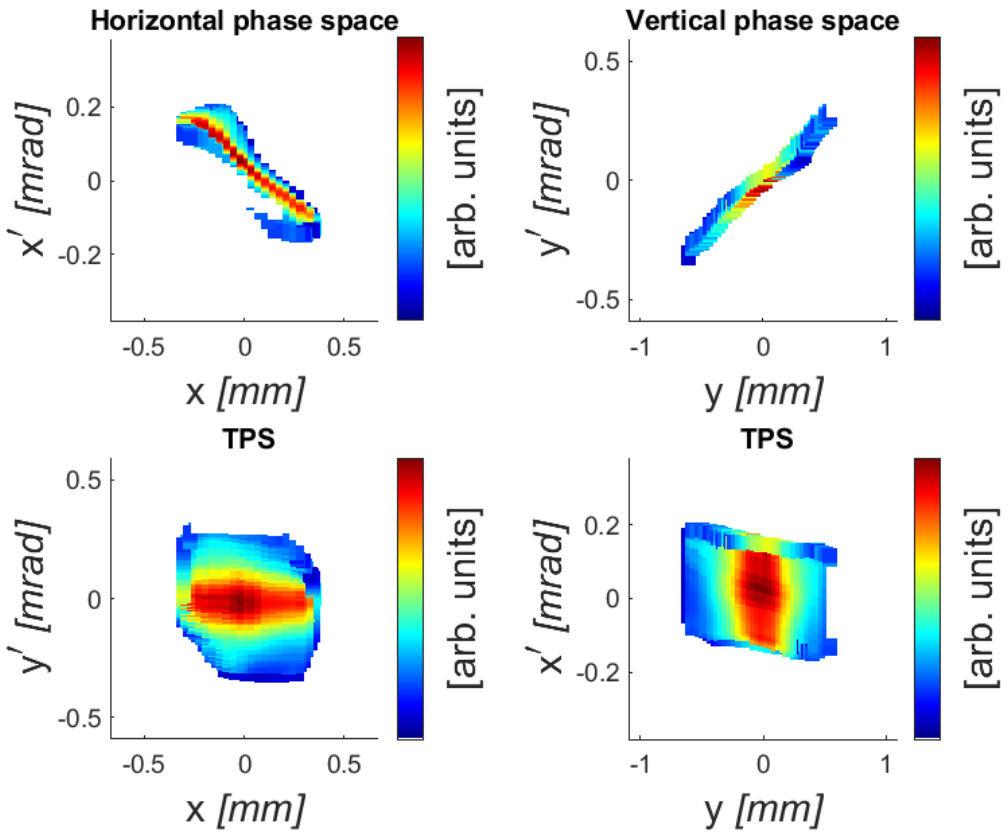
-80 deg



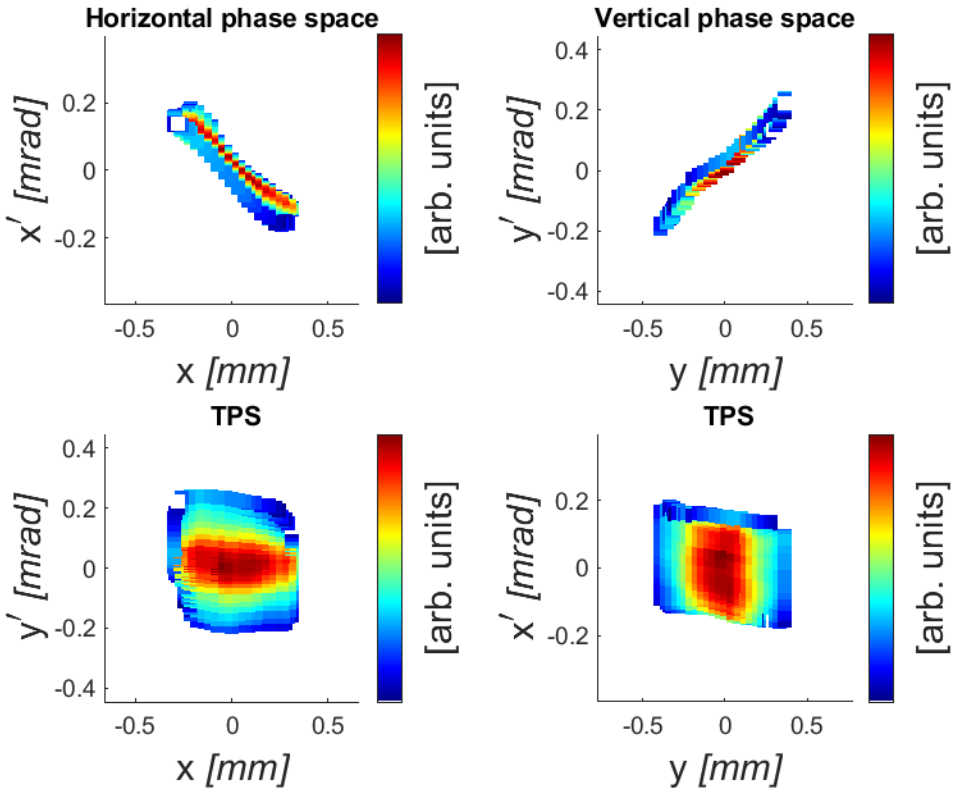
VPP

Gun quad scan

90 deg

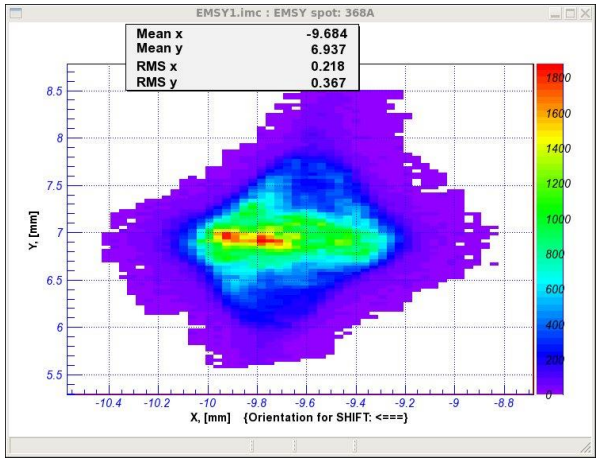


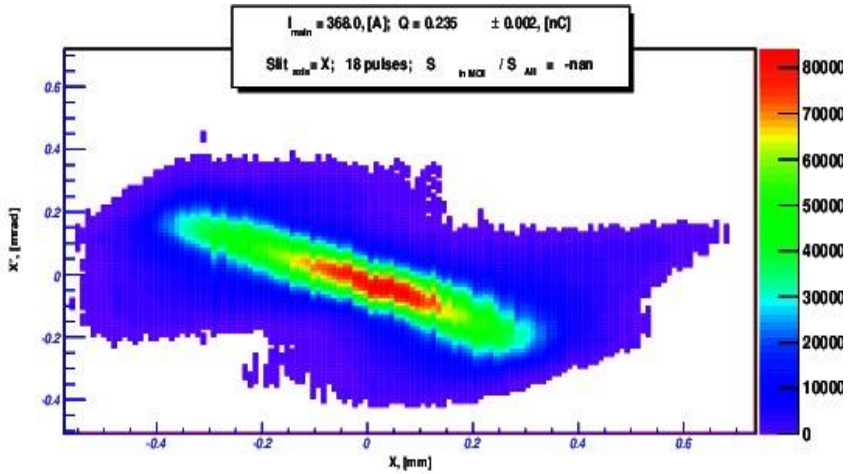
-90 deg

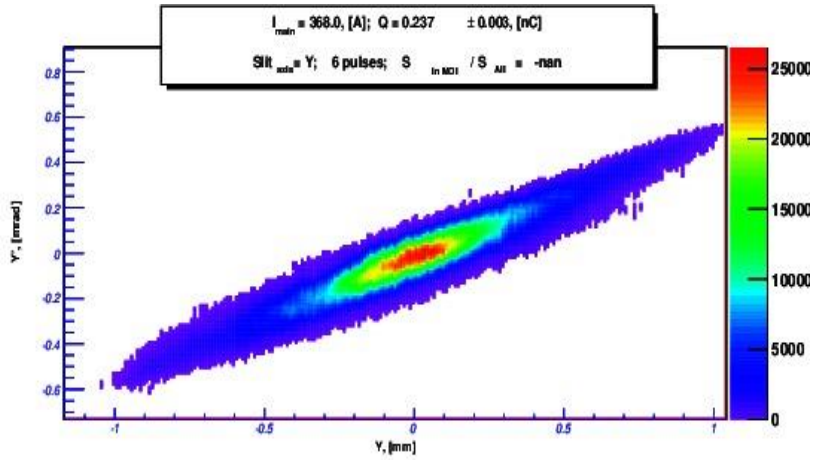


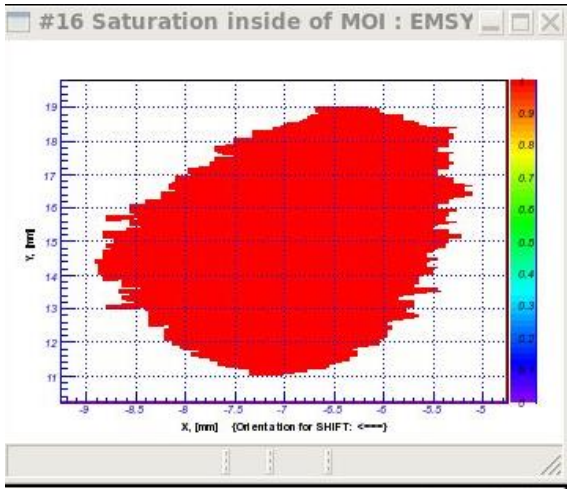
Fast scan

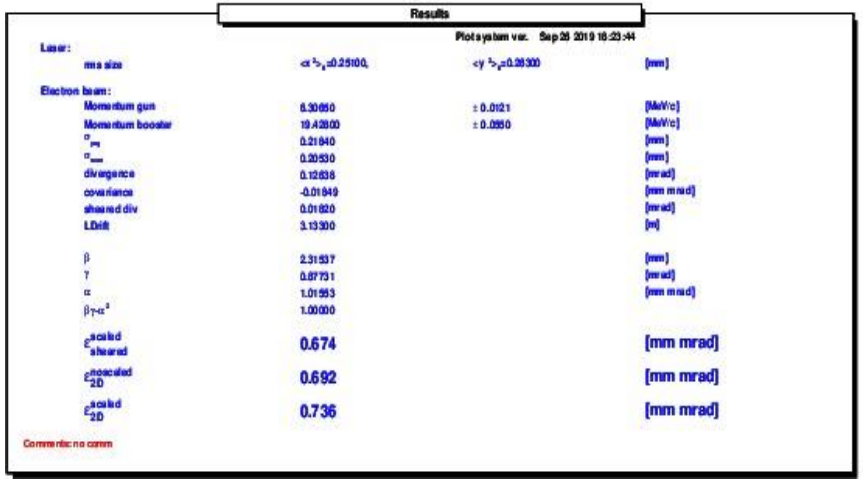
phase space of beam with θ=90°

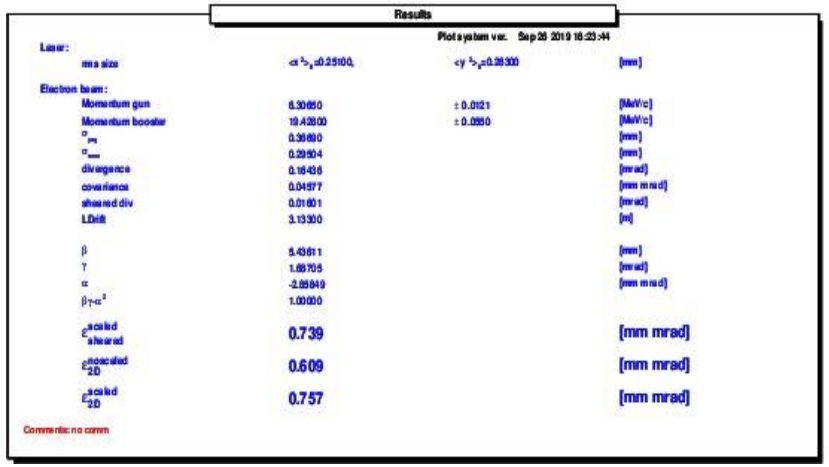










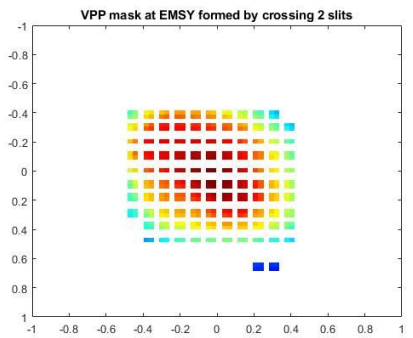


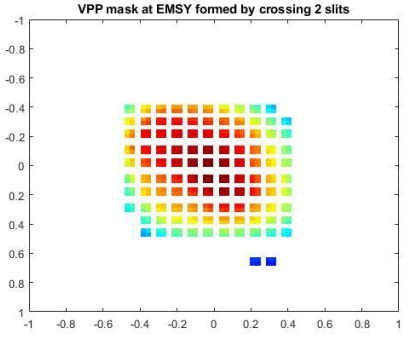
VPP

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