# Virtual Pepper-Pot technique: procedure and results

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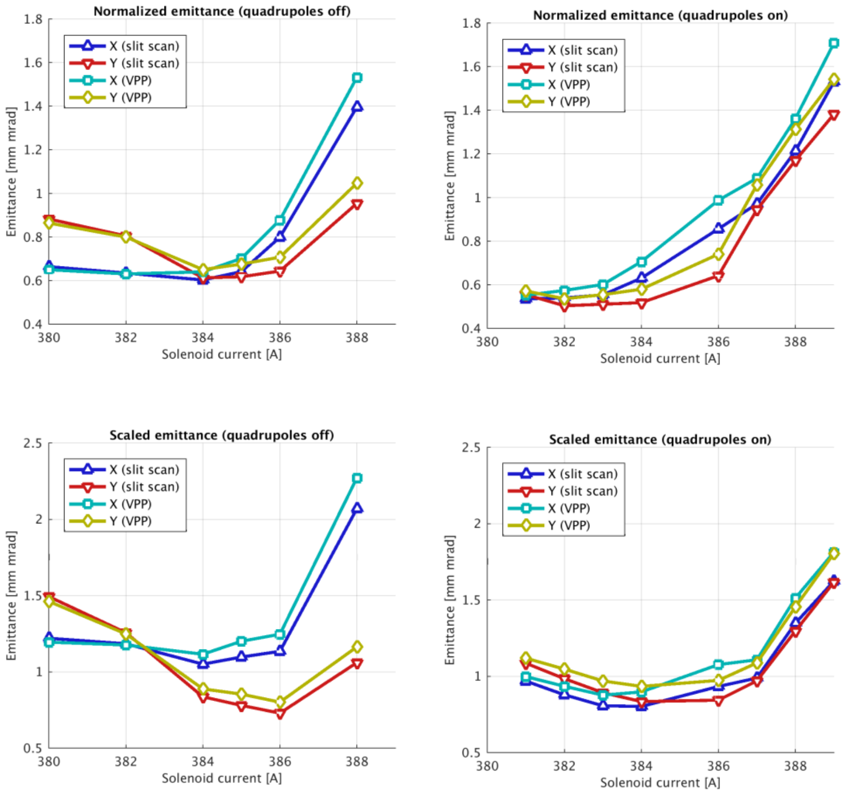
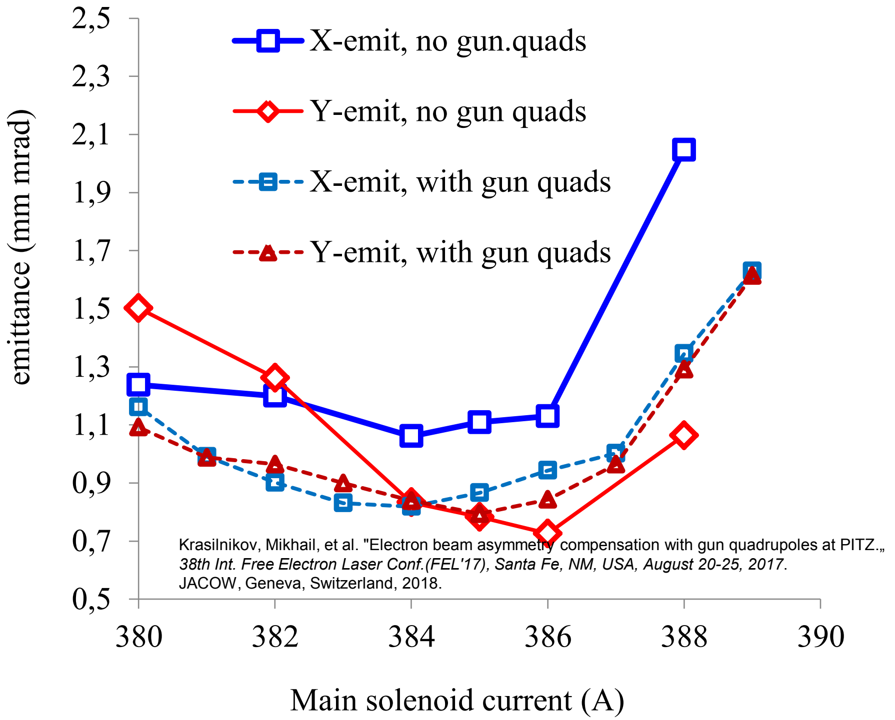
PPS 08.03.2019



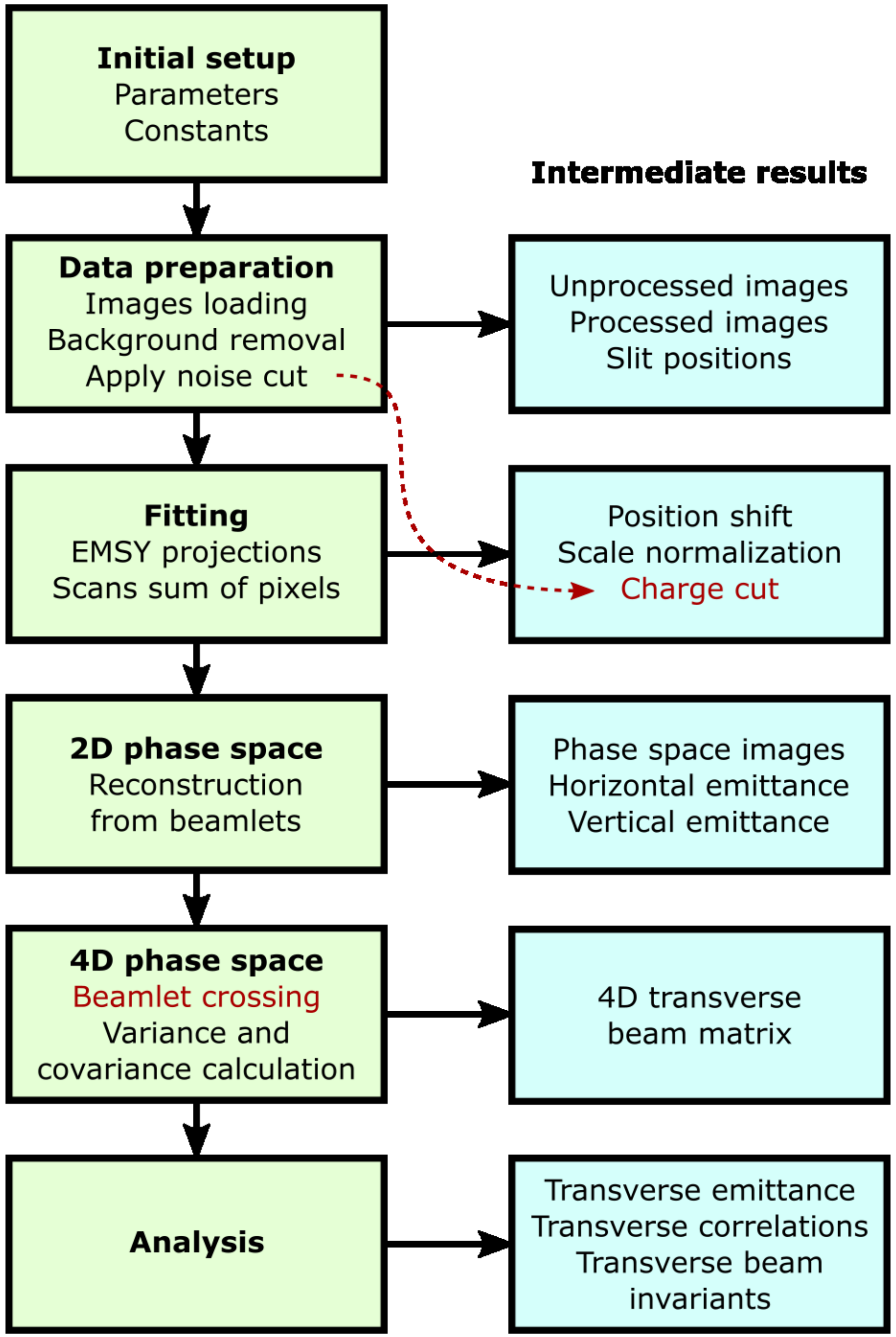

Krasilnikov, Mikhail, et al. "Electron beam asymmetry compensation with gun quadrupoles at PITZ.„ *38th Int. Free Electron Laser Conf.(FEL'17), Santa Fe, NM, USA, August 20-25, 2017.* JACOW, Geneva, Switzerland, 2018.

# Virtual Pepper-Pot

## Reintroduction

- Measurement of 4D transverse phase space
- Virtual pepper-pot (VPP) technique
  - **Novel** technique
  - Data analysis
  - Extending slit scans to **4D measurements**
- Slit scan
  - Only 2D phase spaces restored
- Pepper-pot mask experiment
  - 4D phase space restored
  - Difficulties
    - Mask hole size and spacing, intensity
- VPP procedure overview - diagram

No noise cut discussion in this talk



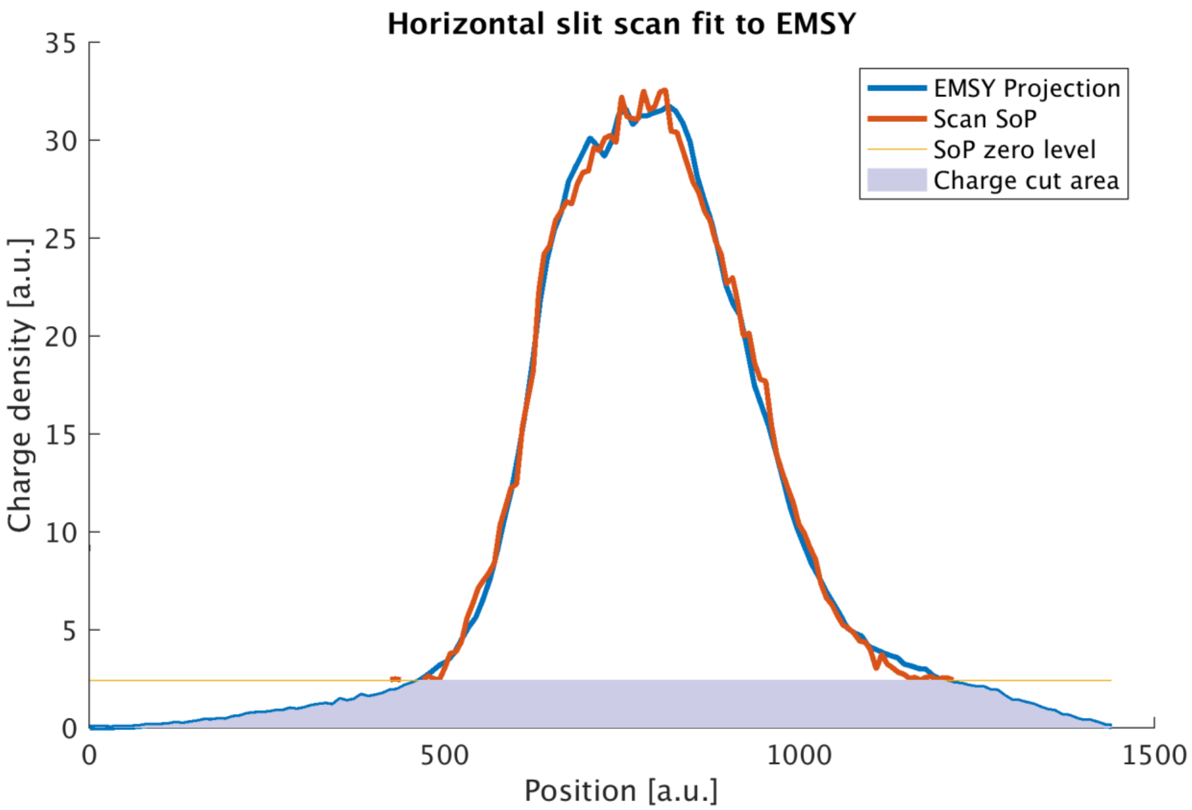
# Fitting slit scan and EMSY

## Offset, normalization, charge cut

- Same beam – same curves
  - EMSY projection along an axis
  - Sum of pixels (SoP) of beamlets along an axis
- Fitting parameters
  - Position shift
  - Scale normalization
  - Zero level difference
- Charge cut
  - Fraction of the beam **not** measured

Scale normalization to common point (EMSY) of X and Y slit scan images.

Part of the beam (halo and tail) **excluded** from further analysis.

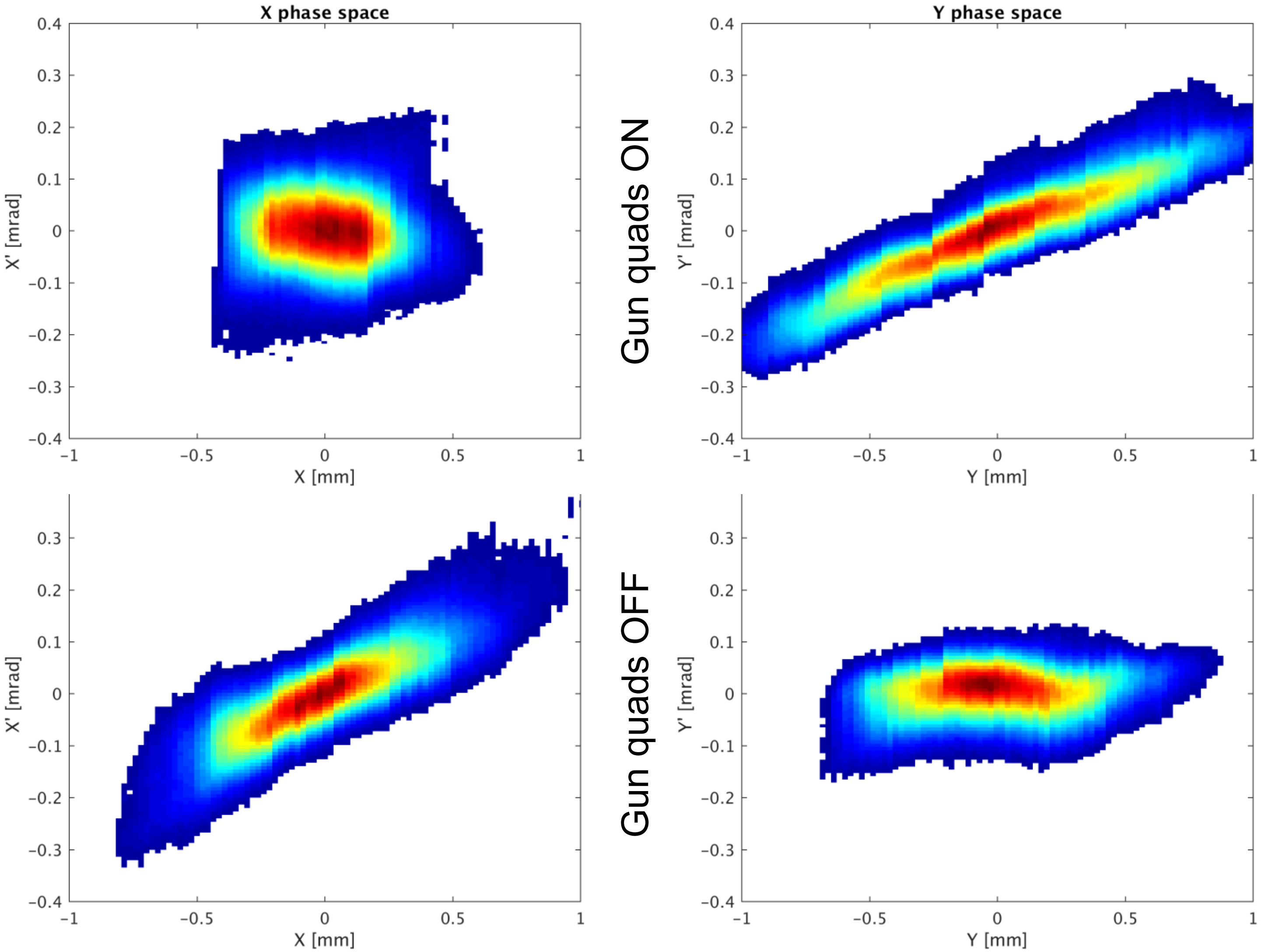



$$SF = \frac{\sigma_{EMSY}}{\sigma_{SoP}}$$

# 2D phase space

## Phase space images and 2D emittance

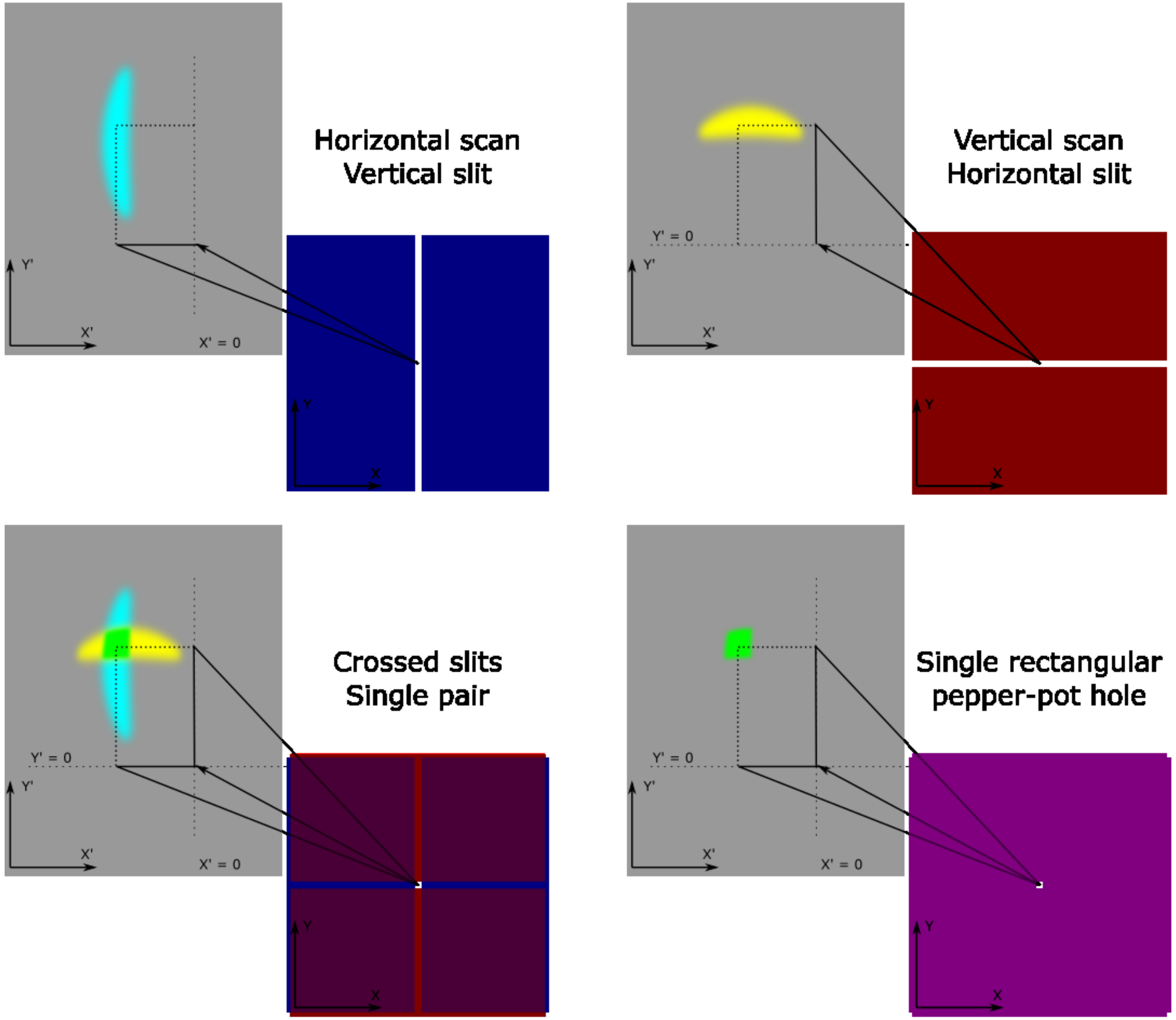
- Reconstructed phase spaces
- Matched with EMcalc3
  - Reproduced noise-cut filter
  - Good emittance agreement
- Reference in further analysis



# Beamlet crossing (1)

## Basic principle and methods

- Reconstruction
  - Two crossed slits → small opening
  - Multiple crossed pairs → PP mask
  - Beamlet crossing to slit crossing
    - **Ideally** shall be equivalent
- Crossing methods
  - Must preserve units
  - Must give 0 if any beamlet pixel is 0
  - **Pixel-wise geometric mean**
  - **Pixel-wise minimum value**
    - Normalization dependent



# Beamlet crossing (2)

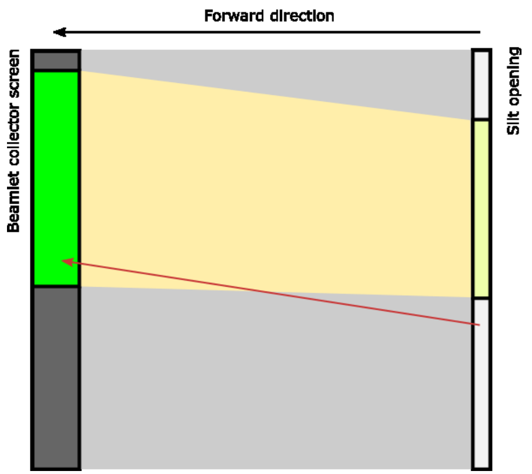
## Foreign charge and crossing performance

- Challenges
  - X scan, Y scan conditions
  - Image noise
  - **Foreign charge**
- Pixel-wise geometric mean
  - Systematic error ∝ $\sqrt{Q_{fx}}, \sqrt{Q_{fx}}$
- Pixel-wise minimum value
  - Minimizes foreign portions
  - Better choice with foreign charge

Data sample without gun quadrupoles and Imain = 386 A

### Foreign charge model

$$Q_x = Q_0 + Q_{fx}$$
$$Q_y = Q_0 + Q_{fy}$$




$$Q_{cross} = \sqrt{Q_x Q_y} = \sqrt{Q_0(Q_0 + Q_{fx} + Q_{fy}) + Q_{fx}Q_{fy}}$$

$$Q_{cross} = \min(Q_x, Q_y) = Q_0 + \min(Q_{fx}, Q_{fy})$$

| Case | $\epsilon_x$ (norm.) | $\epsilon_y$ (norm.) | Ratio $\epsilon_x/\epsilon_y$ | $\epsilon_x\epsilon_y$ |
|---|---|---|---|---|
| Slit scan (not VPP) | 0,799 | 0,643 | 1,24 | 0,514 |
| Min. val., EMSY normalized | 0,922 | 0,685 | 1,35 | 0,632 |
| Min. val., ratio optimized normalization | 0,878 | 0,707 | **1,24** | 0,620 |
| Geometrical mean | 0,933 | 0,748 | **1,25** | 0,699 |
| Min. val., incorrect normalization A | 1,17 | 0,618 | 1,88 | 0,720 |
| Min. val., incorrect normalization B | 0,742 | 0,887 | 0,84 | 0,659 |

# 4D transverse beam matrix

## Definitions and calculation

- Covariance matrix of the transverse phase space
- 4D transverse emittance with correlations
- Element calculation in VPP

$$\begin{pmatrix} \langle xx\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'x'\rangle & \langle yx'\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle yx'\rangle & \langle yy\rangle & \langle yy'\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'y'\rangle \end{pmatrix}$$

$$\epsilon_{4D}^4 = \begin{vmatrix} \langle xx\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'x'\rangle & \langle yx'\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle yx'\rangle & \langle yy\rangle & \langle yy'\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'y'\rangle \end{vmatrix} = \epsilon_x^2\ \epsilon_y^2 - \underline{C_{xy}^4}$$

$$\epsilon_x^2 = \begin{vmatrix} \langle xx\rangle & \langle xx'\rangle \\ \langle xx'\rangle & \langle x'x'\rangle \end{vmatrix} = \langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2$$

$$Corr = \sqrt[4]{\frac{\epsilon_x^2\epsilon_y^2}{\epsilon_{4D}^4}} - 1$$

$$\langle f(x, x', y, y')\rangle = \frac{\sum_i \sum_j \sum_k \sum_l f(x_i, x'_j, y_k, y'_l)\ w_{ik}(x'_j, y'_l)}{\sum_i \sum_j \sum_k \sum_l w_{ik}(x'_j, y'_l)}$$

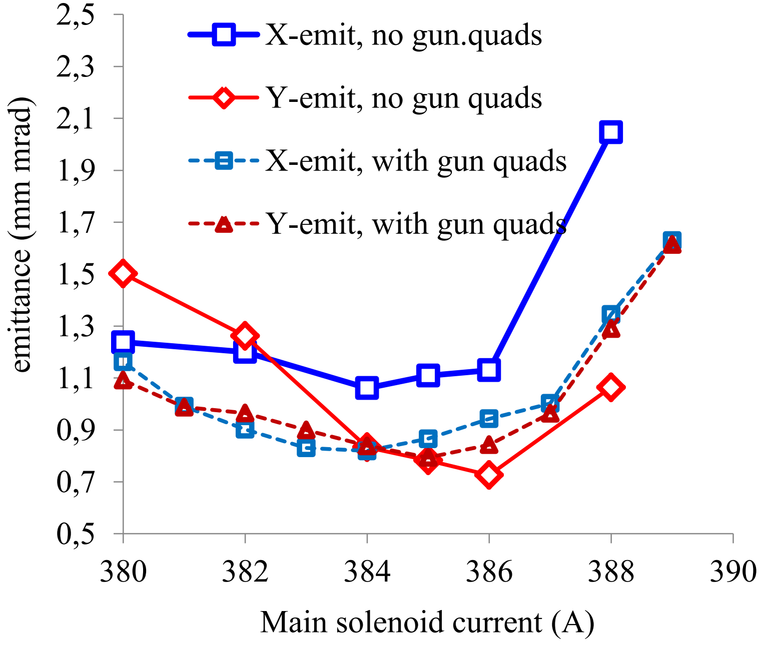
$w_{ik}$ - crossed beamlets image for i-th horizontal and k-th vertical slit positions

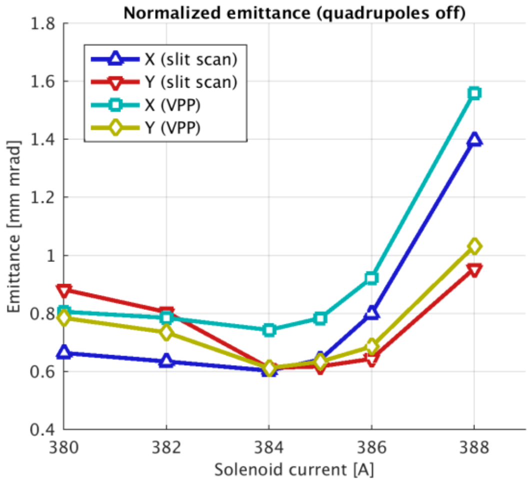
$x'_j$ - x‘ of j-th pixel column
$y'_l$ - y‘ of l-th pixel row

# Results: 2D emittance

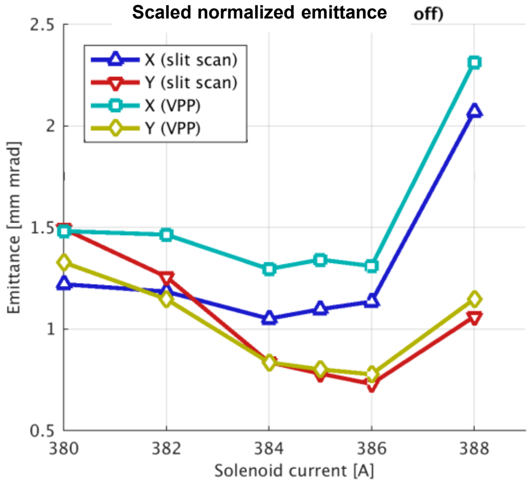
## Method comparison

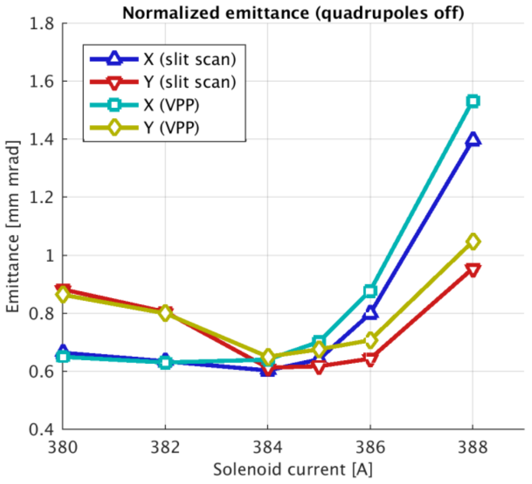
- Min. val. with EMSY norm
  - Horizontal is higher
- Min. val. with norm for ratio
  - **Best agreement**
- Geometrical mean
  - Both are higher



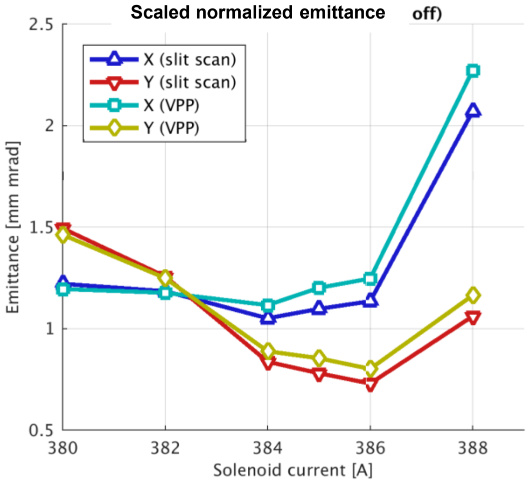



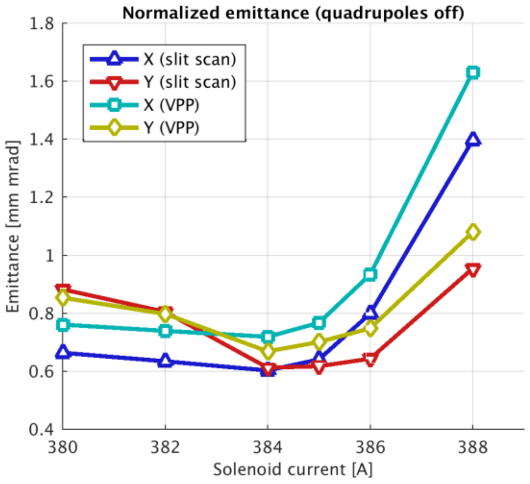

Minimum value, EMSY norm



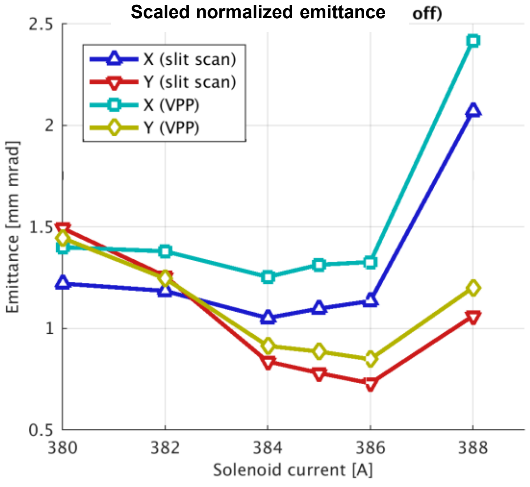




Minimum value, Ratio norm



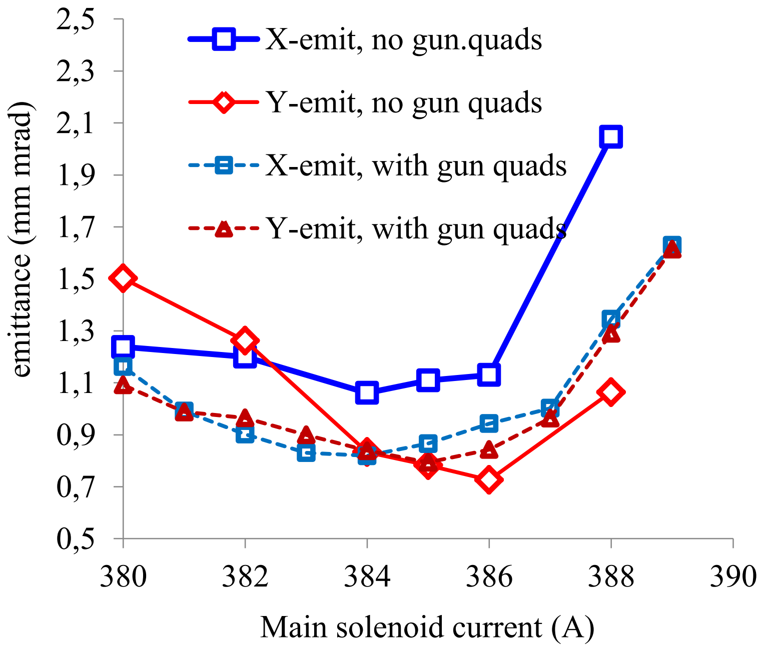

Minimum value, Geom. mean

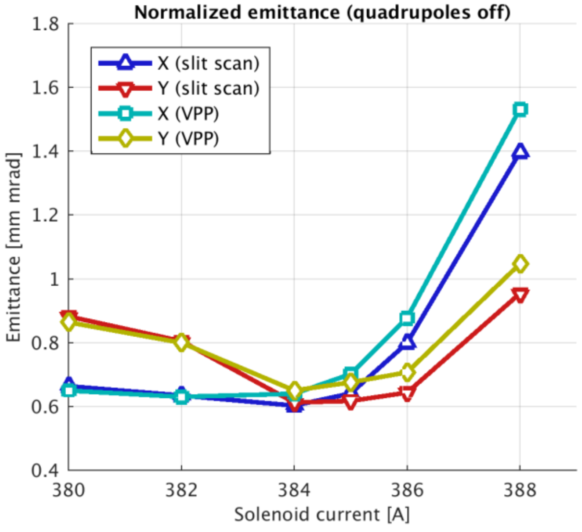


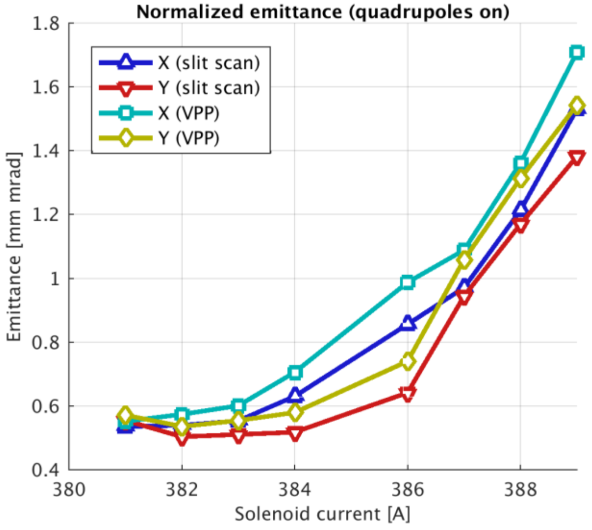
# Results: 2D emittance

## Gun quads ON and OFF

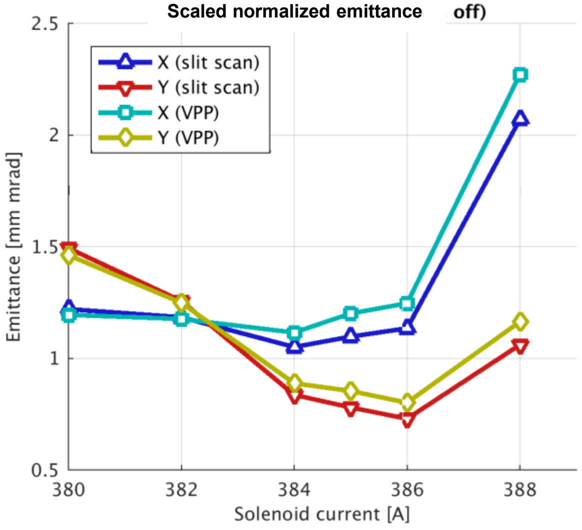
- Using min. val. crossing for best ratio
- Agreement with slit scan and previous studies
  - Higher at larger $I_{main}$

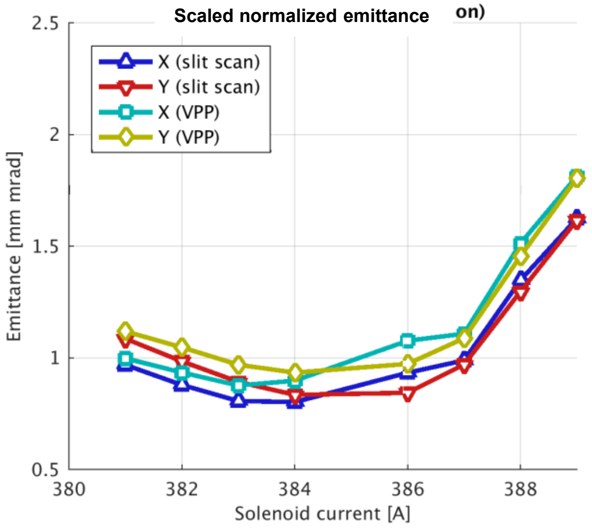



Minimum value cross, Ratio optimized norm



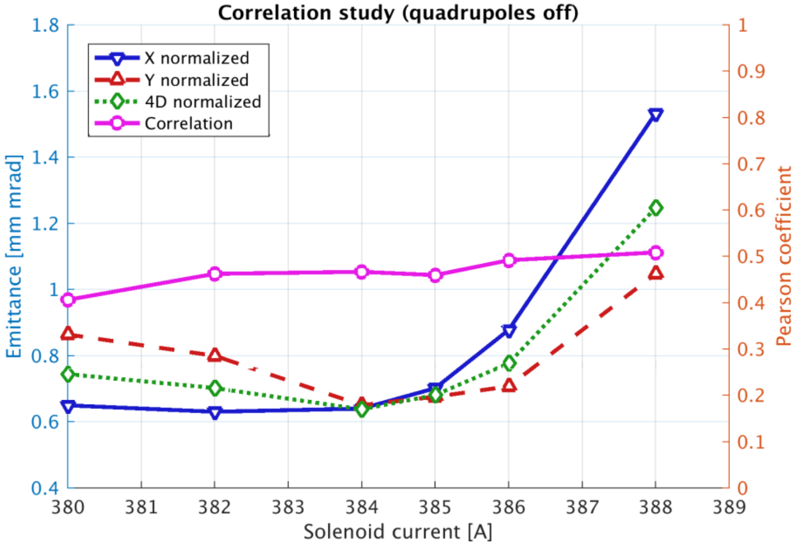
# Results: 4D emittance

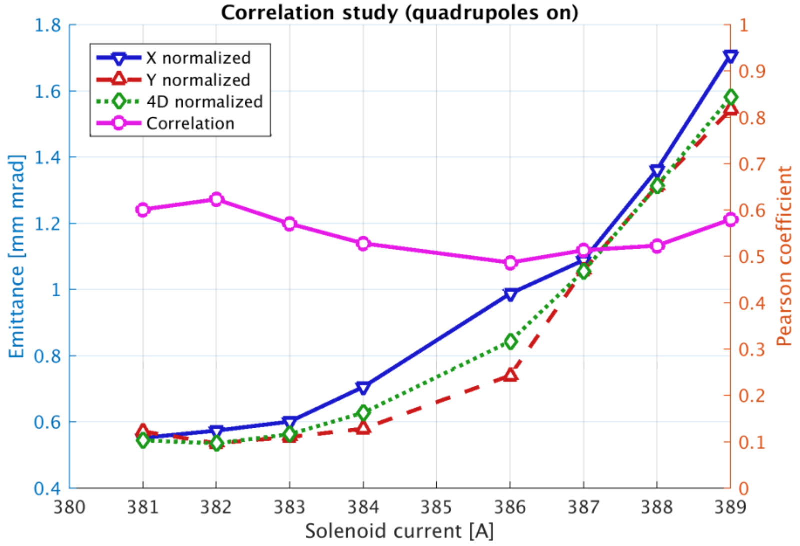
## Correlations

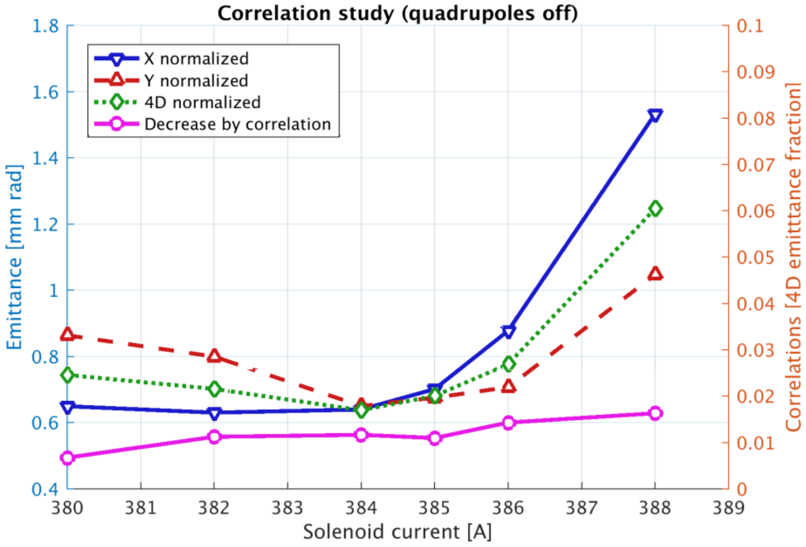
- Pearson coefficient ~ 0.5
  - Coupling between X and Y
  - Small effect on 4D emittance
- Quadrupoles introduce correlations

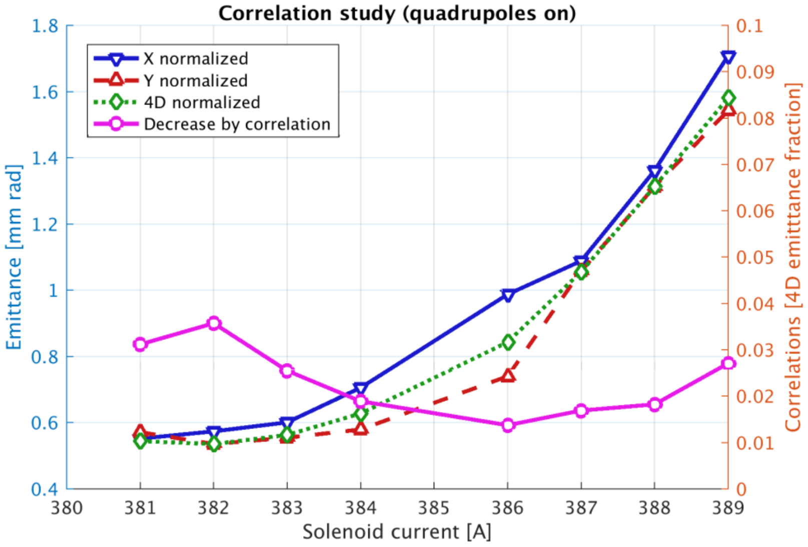
$$Corr = \sqrt[4]{\frac{\epsilon_x^2\epsilon_y^2}{\epsilon_{4D}^4} - 1}$$

$$\Delta_{coupling} = \sqrt[4]{\frac{\epsilon_x^2\epsilon_y^2}{\epsilon_{4D}^4}} - 1$$



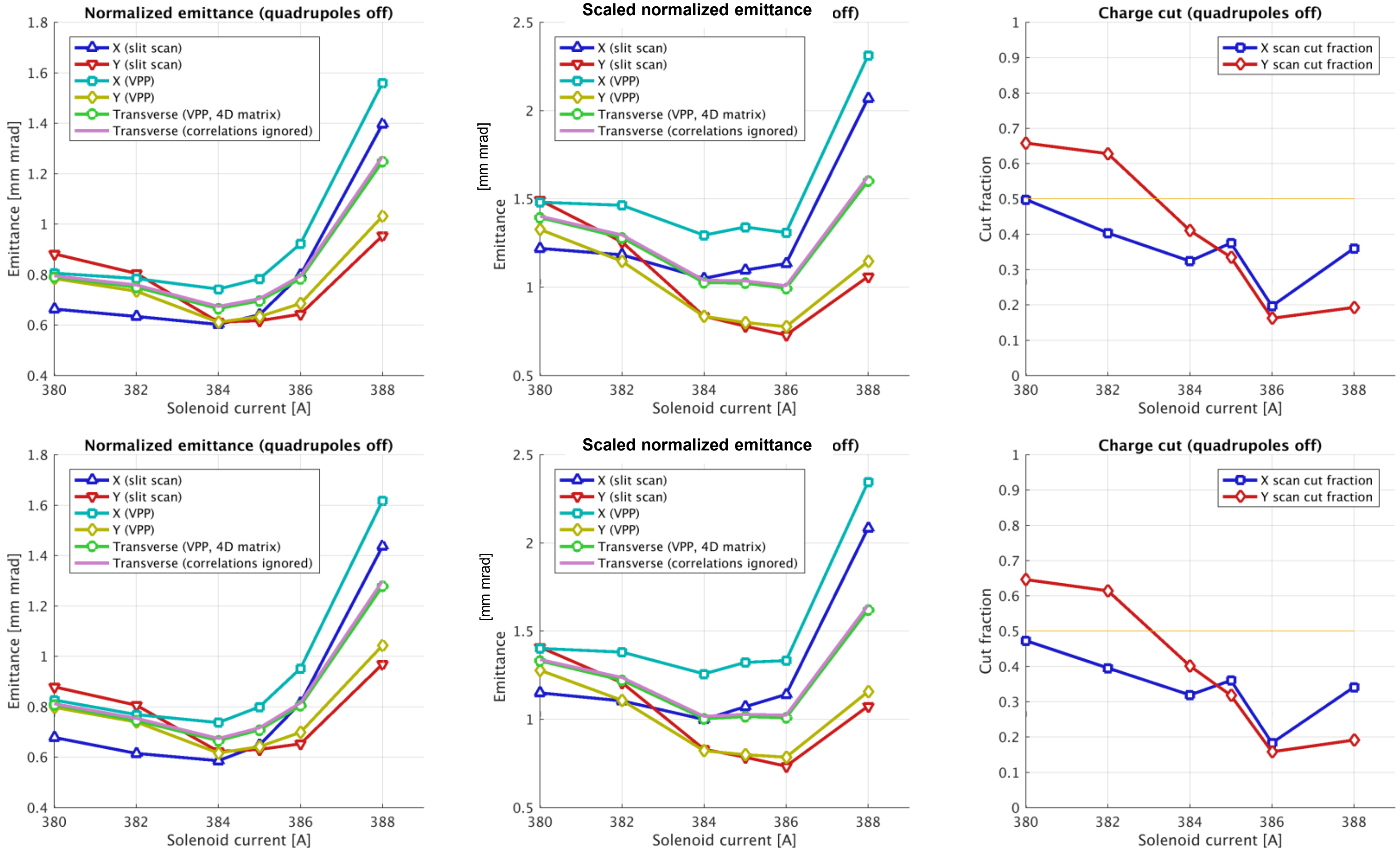



# Charge cut

## Charge cut and noise cut

- **Significant** charge cut
    - Above 25% on many points
- SNR and median filtering
    - Small charge cut descrease
    - Negligible difference in emittance

Part of the beam (halo and tail) **excluded** from further analysis.



# Conclusions

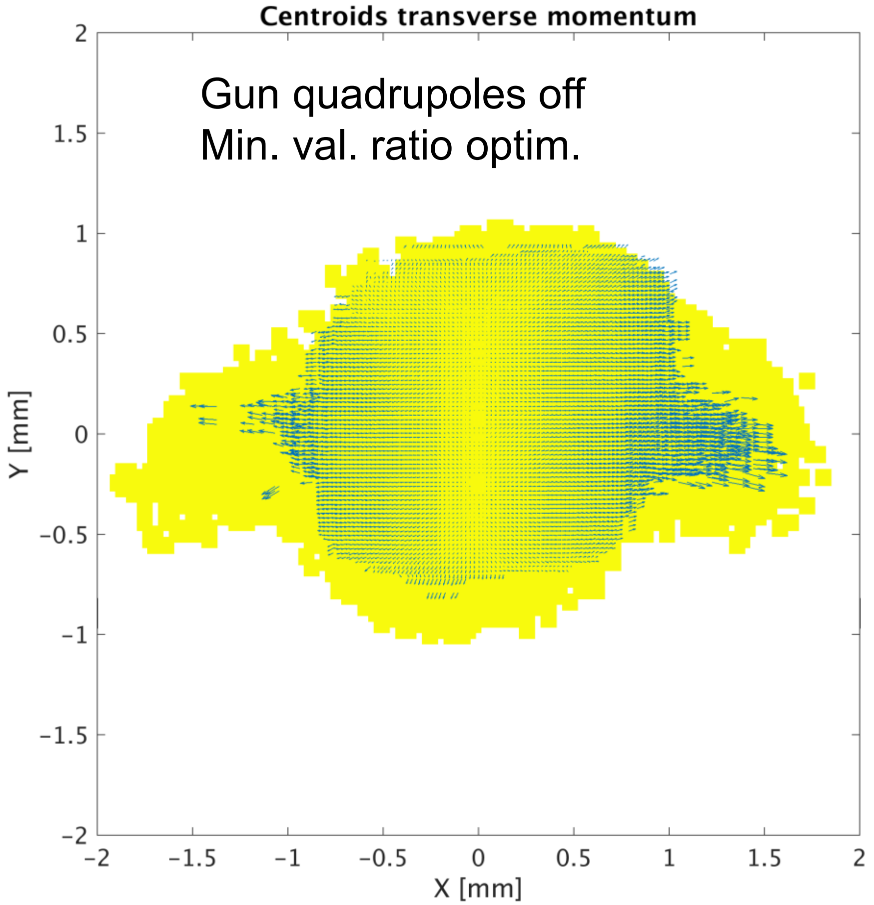
- Virtual Pepper-Pot results agree with Emcalc3
  - Minimum value crossing with normalization optimized for emittance ratio
- Correlations discovered
  - Gun quadrupoles increase coupling
- Significant charge cut
- Outlook
  - 4D transverse beam matrix eigenvalues – eigenemittances
  - Charge cut extrapolation to 0
    - Scaling factor studies
  - Full beamlet reconstruction

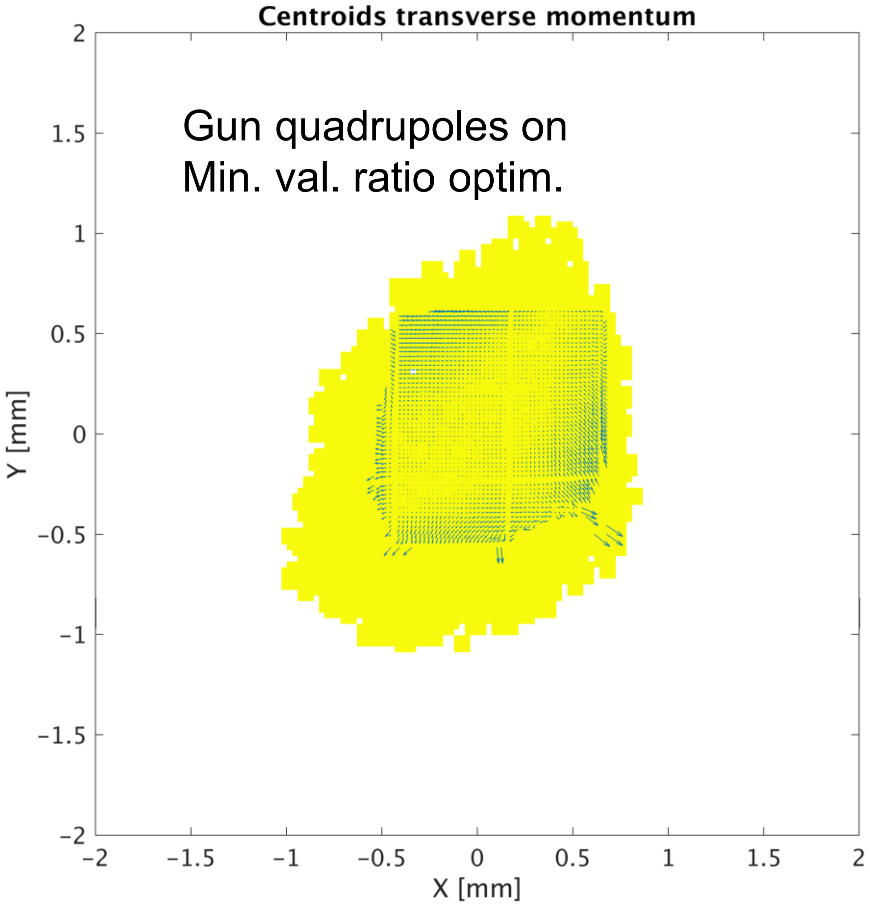
# THANK YOU!

# Centroid velocities

(Bonus slide)

- Centroid particle assigned for each crossed image of the VPP



# Emittance invariant

## 4D kinematic invariant (Bonus slide)

- Transverse emittance invariant (for linear optics)
- Increase at stronger Imain

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