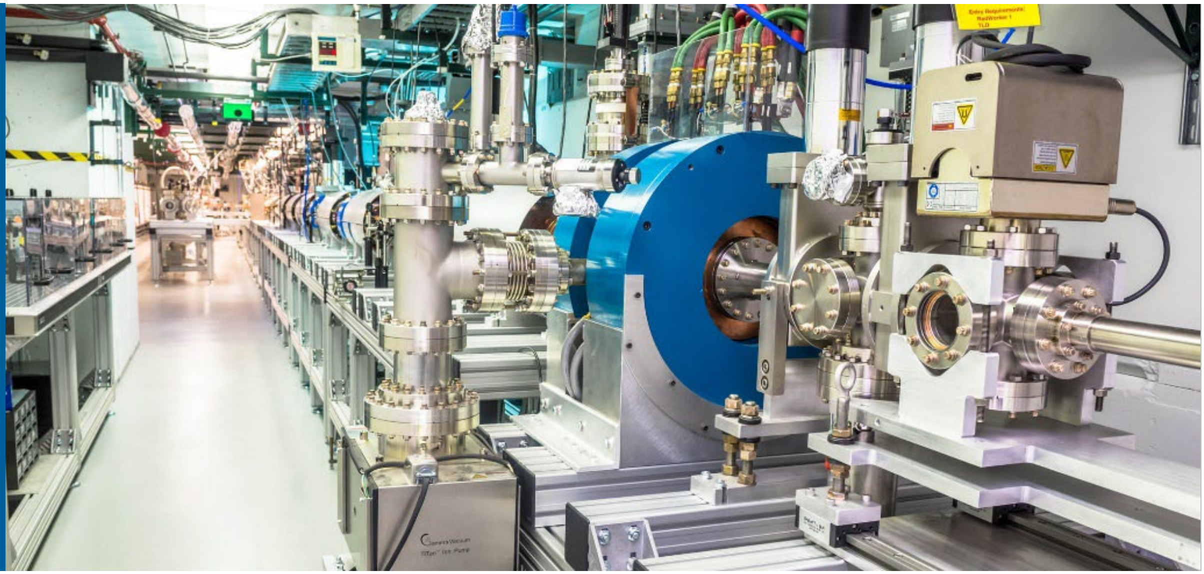
MARCH 7, 2024

SLAC NATIONAL ACCELERATOR LABORATORY | THE UNIVERSITY OF CHICAGO | Northern Illinois University | Argonne NATIONAL LABORATORY

DETAILED 4D PHASE SPACE RECONSTRUCTION OF FLAT AND MAGNETIZED BEAMS USING DIFFERENTIABLE SIMULATIONS AND NEURAL NETWORKS*



SEONGYEOL KIM (FORMER AWA MEMBER FOR BEAM DYNAMICS)**
On behalf of Argonne Wakefield Accelerator Group

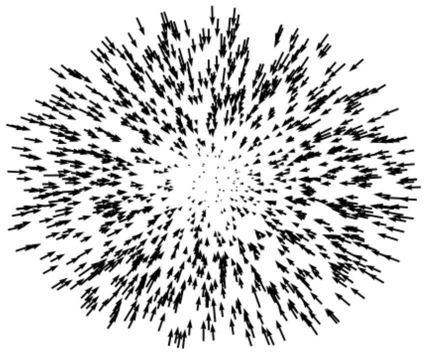
*Based on submitted paper: Seongyeol Kim, Juan Pablo Gonzalez-Aguilera *et al.*, arXiv:2402.18244, 2024.
**Currently at Pohang Accelerator Laboratory, Republic of Korea.

Contents

- ❖ **Brief introduction and motivation**
  - ➢ Flat and magnetized beams
- ❖ **Generative phase space reconstruction (GPSR) algorithm**
  - ➢ Brief introduction to the algorithm
- ❖ **Demonstrations at Argonne Wakefield Accelerator (AWA)**
- ❖ **Summary**

Introduction: what are flat and magnetized beams?

Round beam



Typical beam we use (does not rotate)

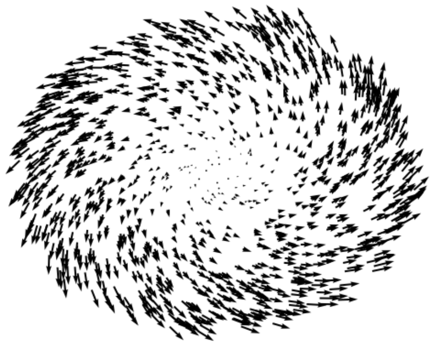
Solenoid field at the cathode

$\mathbf{P} = \mathbf{p} + e\mathbf{A} = \mathbf{p} + \frac{B_c}{2}(-y\hat{x} + x\hat{y})$

$\mathbf{L} = \mathbf{r} \times \mathbf{P}$

Canonical Angular momentum

Round, magnetized beam



Angular-momentum-dominated beam

$$\Sigma_0 = \begin{bmatrix} \epsilon_{eff} T_0 & \mathcal{L} J \\ -\mathcal{L} J & \epsilon_{eff} T_0 \end{bmatrix}$$

Magnetization

$$\mathcal{L} = \frac{\langle L \rangle}{2 m_e c}$$

where $T_0 = \begin{bmatrix} \beta & -\alpha \\ \alpha & \gamma \end{bmatrix}$ $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

Transformation using skew triplet

$$\Sigma_1 = M \Sigma_0 M^{\intercal}$$

$$\Sigma_1 = \begin{bmatrix} \epsilon_+ T_+ & 0 \\ 0 & \epsilon_- T_- \end{bmatrix}$$

Flat beam

Eigenemittance

$$\epsilon_+ \approx 2\mathcal{L} \quad \epsilon_- \approx \frac{\epsilon_{th}^2}{2\mathcal{L}}$$

ϵ_{th} Uncorrelated emittance

For magnetization = 50 um, and ϵ_{th} = 5.0 um,

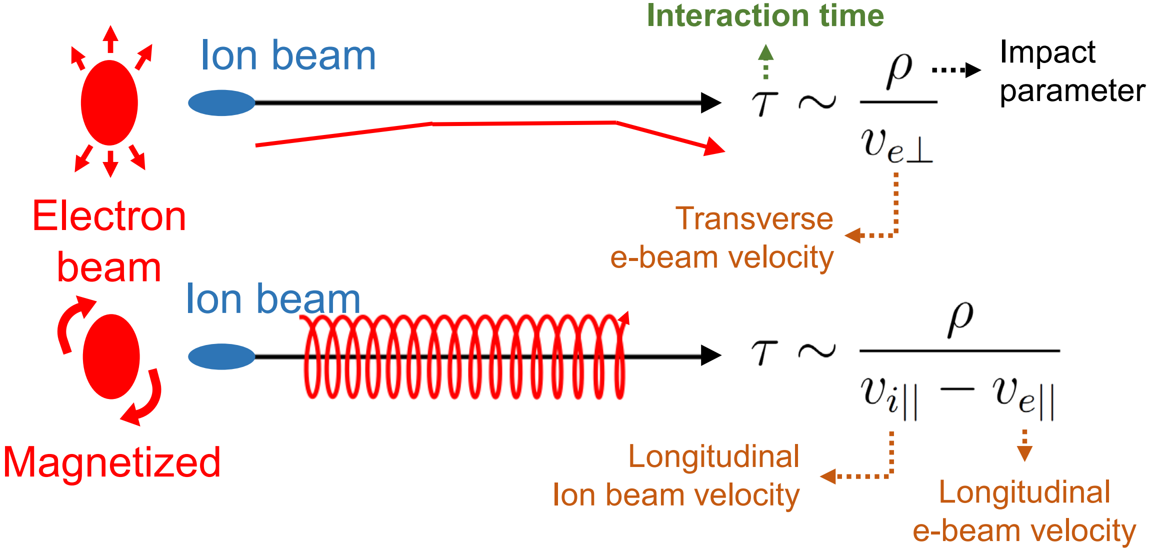
ϵ_+ (Emit_nx) (mm mrad)	ϵ_- (Emit_ny) (mm mrad)
100	0.25

Introduction: why flat and magnetized beams?

Ways to increase luminosity in colliders

Hadron cooling:

Reduction of hadron beam emittance



$$\tau \sim \frac{\rho}{v_{e\perp}}$$

$$\tau \sim \frac{\rho}{v_{i||} - v_{e||}}$$

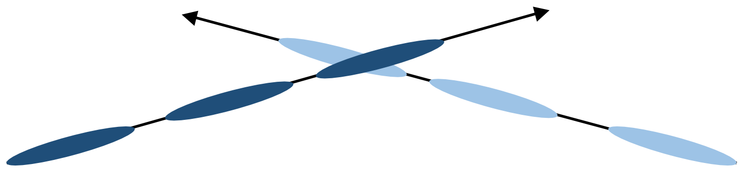
Use of magnetized beam[1), 2)] :

➡ Increases cooling efficiency

1) Y. Sun, Angular-Momentum-Dominated Electron Beams and Flat-Beam Generation, 2005.
2) Y. Derbenev and A. Skrinsky, *Part. Accel.* **8**, 235, 1978.

Use of flat beam[3)]:

Direct increases of luminosity



Luminosity[4)] $L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS}\sigma_z}}{\sigma_y}$

Small vertical beam size:

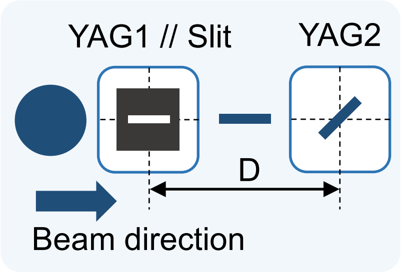
by flat beam with large magnetization $\epsilon_- \approx \frac{\epsilon_{th}^2}{2\mathcal{L}}$

3) K. Yokoya, P. Chen, Beam-beam phenomena in linear colliders, 2005.
4) K. Buesser, Electron-Positron Linear Collider, 2009.

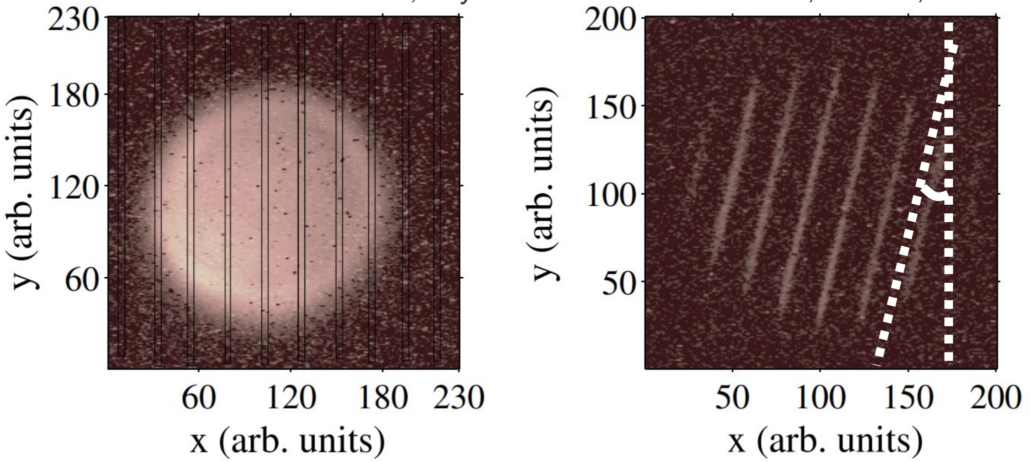
Motivation of beam diagnostics using AI/ML methods

Magnetization: conventional slit*

$$\mathcal{L} = \gamma \frac{\sigma_1 \sigma_2 \sin\theta}{D}$$



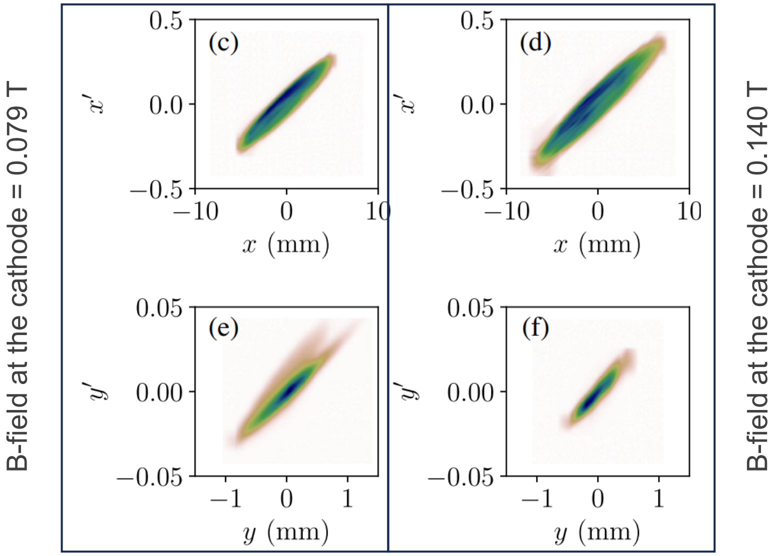
*Y. Sun *et al.*, *Phys. Rev. ST Accel. Beams* **7**, 123501, 2004.



Requires additional slit, sensitive

Flat beam transverse emittance: Quadrupole scan, slit-scan**

T. Xu *et al.*, *Phys. Rev. Accel. Beams* **25, 044001, 2022.



Quadrupole scan: cannot get correlations
Slit-scan: uncertainties due to finite slit width

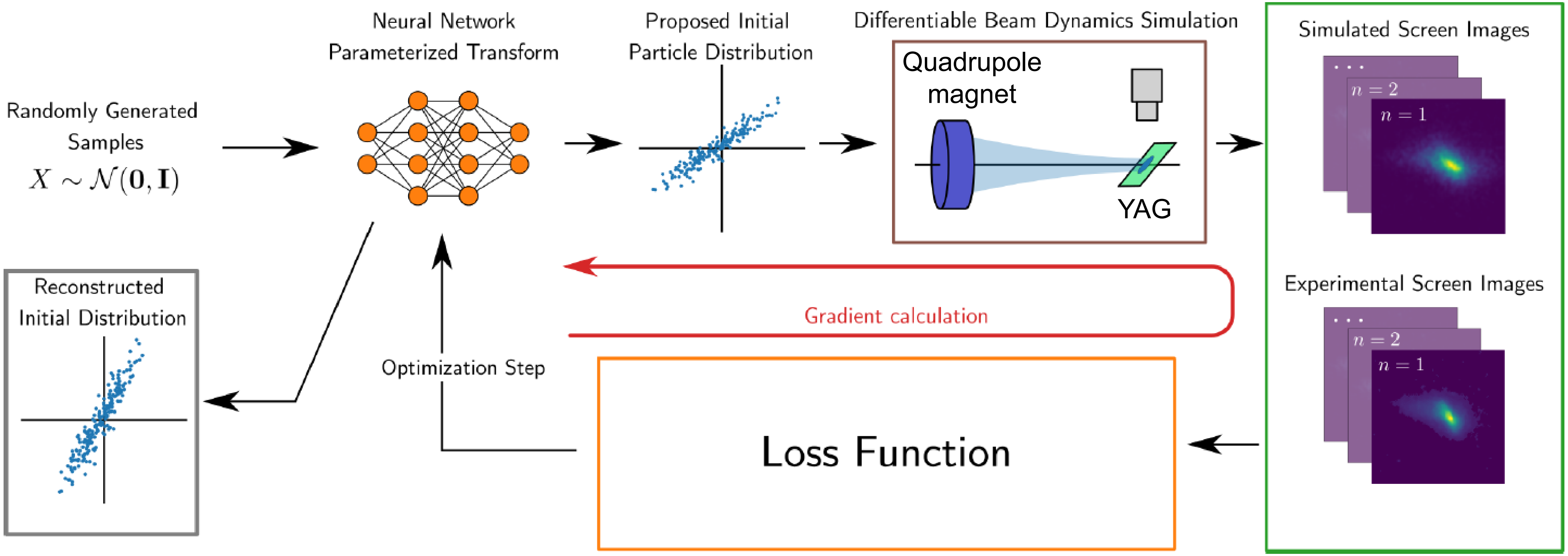
Robust way to characterize those special beams:
Generative Phase Space Reconstruction based on AI/ML method

Generative phase space reconstruction

Solving for the initial distribution using gradient-based optimization

R. Roussel *et al.*, *Phys. Rev. Lett.* **130**, 145001, 2023.

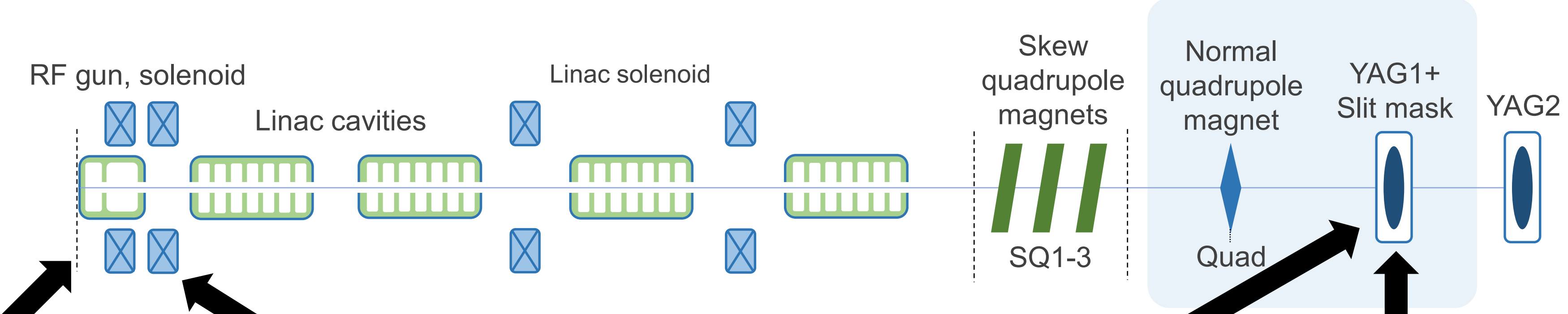
R. Roussel, AWANOW workshop, August 2023.



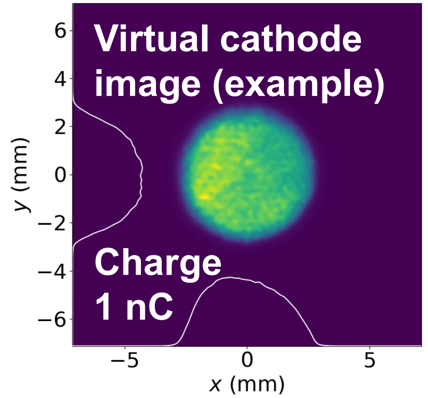
Experimental setup @ AWA

Experimental setup @ Argonne Wakefield Accelerator*

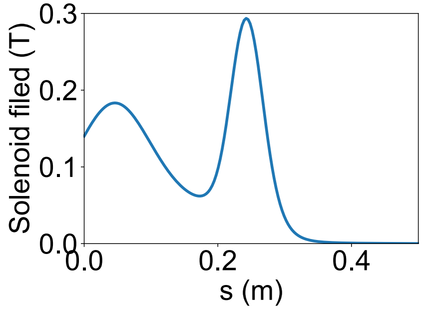
Conventional quadrupole scan: Samples GPSR dataset

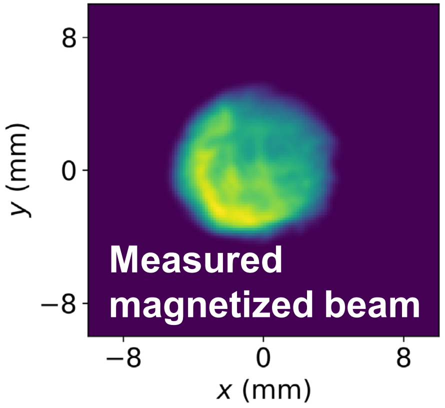


Use of multi-lens array (MLA)

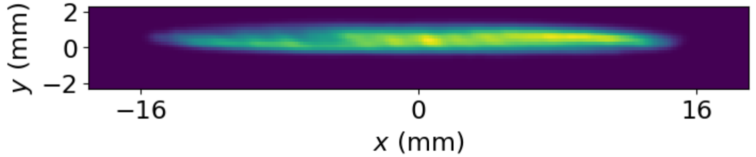


No bucking solenoid: Non-zero B-field at cathode





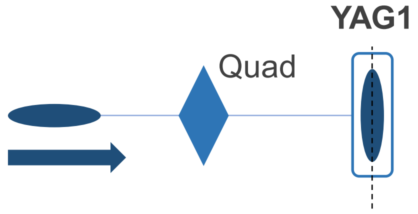
Measured flat beam



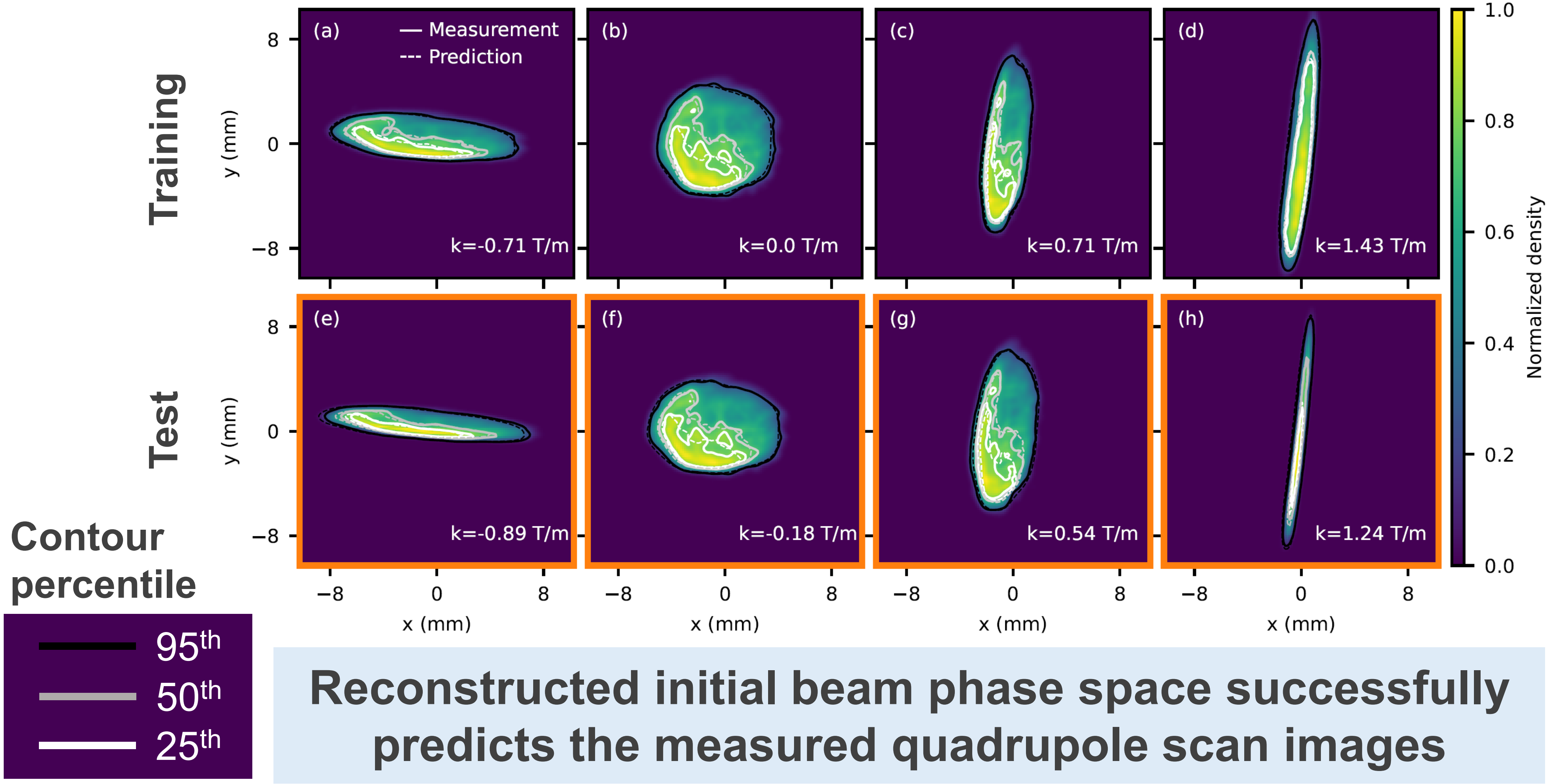
- **Dataset: YAG1 image with 21-22 different quad strengths**
- **Half/half: training/test**

Case 1: magnetized beam reconstruction

Prediction using reconstructed phase space

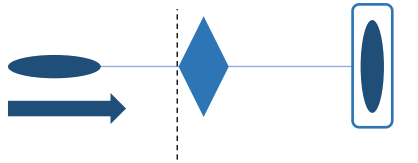


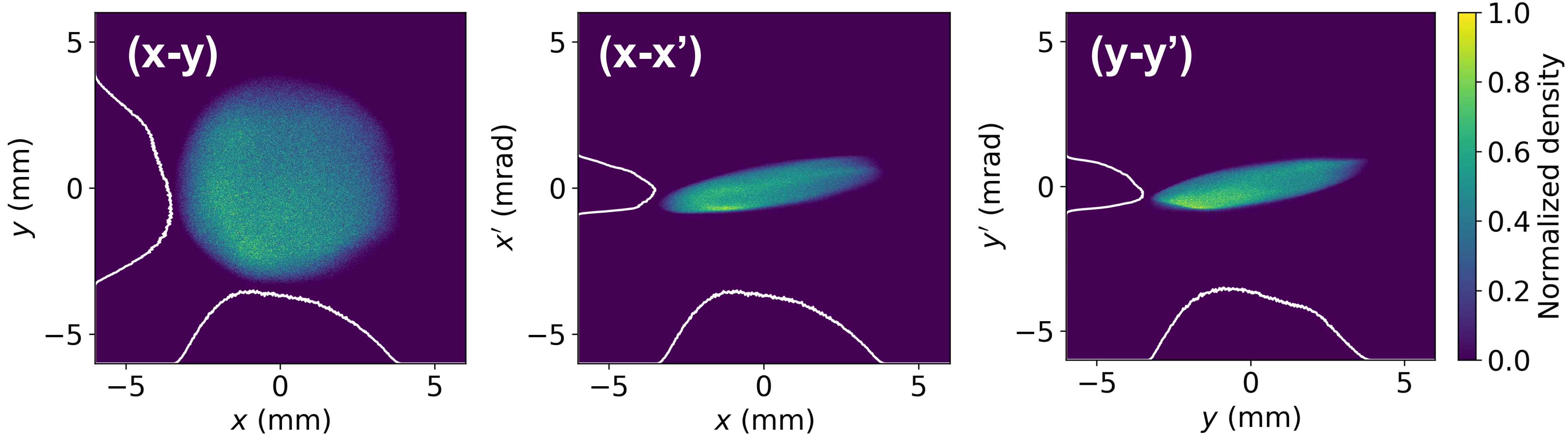
Background image: measured beam distribution @ YAG1



Reconstructed initial beam phase space successfully predicts the measured quadrupole scan images

Reconstructed initial beam phase space



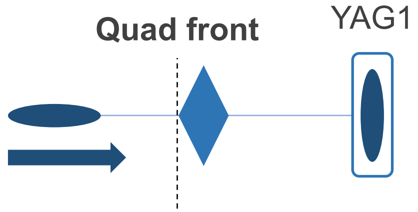


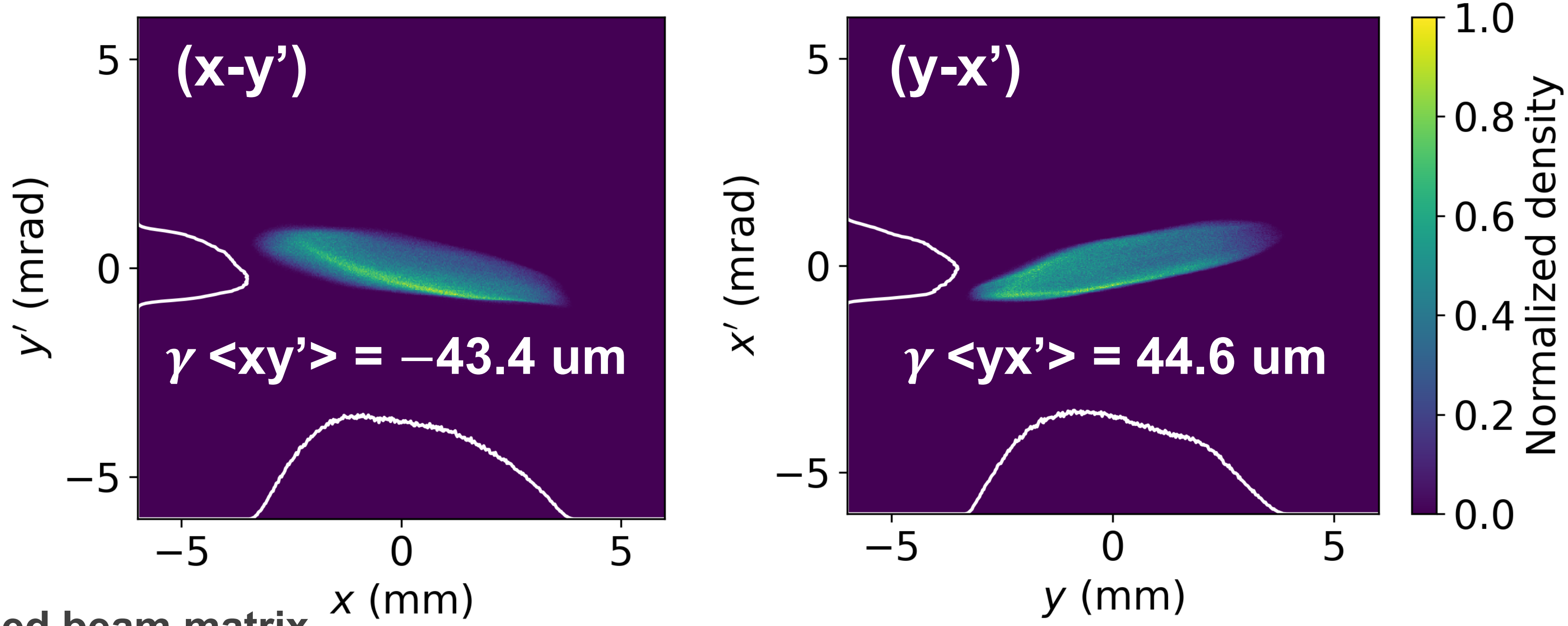
- **RMSX = 1.62 mm**
- **RMSY = 1.58 mm**

<xx'> = 0.476 um

<yy'> = 0.466 um

Reconstructed initial beam phase space





Magnetized beam matrix

$$\begin{bmatrix} \epsilon_{eff}\beta_x & -\epsilon_{eff}\alpha_x & 0 & \mathcal{L} \\ -\epsilon_{eff}\alpha_x & \epsilon_{eff}\gamma_x & -\mathcal{L} & 0 \\ 0 & -\mathcal{L} & \epsilon_{eff}\beta_y & -\epsilon_{eff}\alpha_y \\ \mathcal{L} & 0 & -\epsilon_{eff}\alpha_y & \epsilon_{eff}\gamma_y \end{bmatrix}$$

$\epsilon_{eff} = \sqrt{\epsilon_{th}^2 + \mathcal{L}^2}$ β, α, γ Twiss parameters

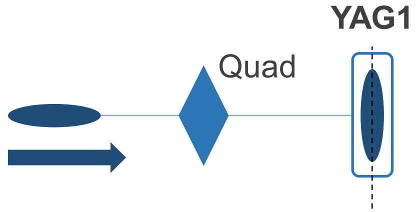
Magnetization, case	Value (um)
Reconstruction	**44.0**
Slit measurement	**48.4±0.9**

Successful estimation of the magnetization using GPSR technique

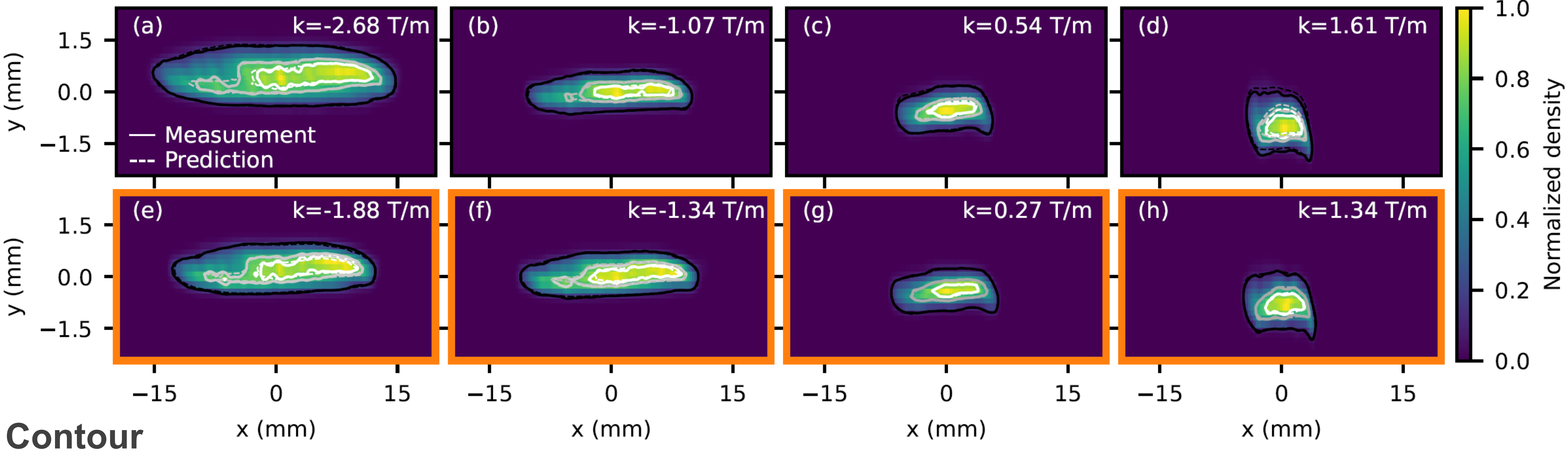
Case 2: flat beam reconstruction

- Applied solenoid field at the cathode is different from magnetized beam reconstruction

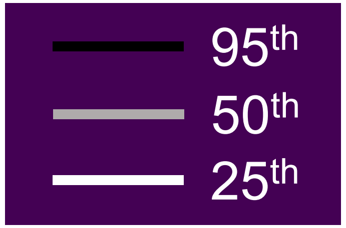
Prediction using reconstructed phase space



Background image: measured beam distribution @ YAG1



Contour percentile



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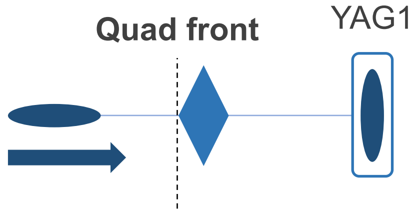
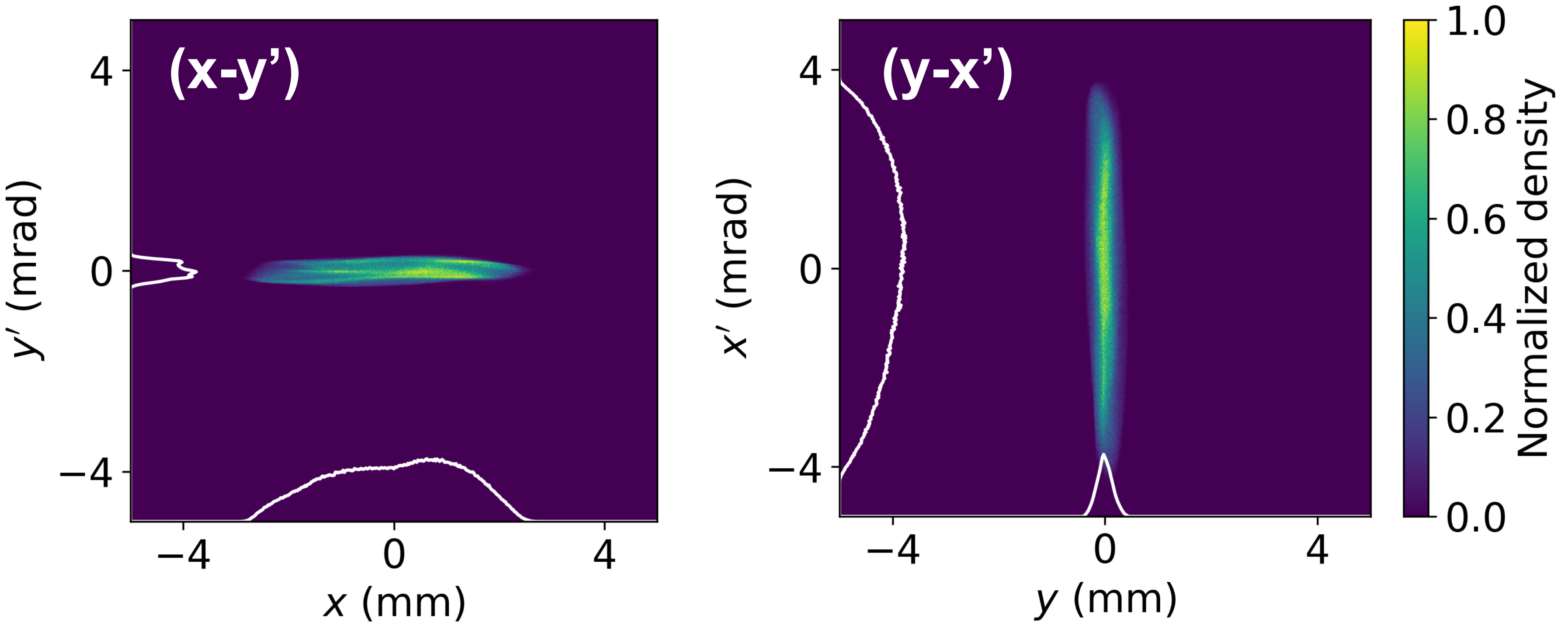
Reconstructed initial beam phase space

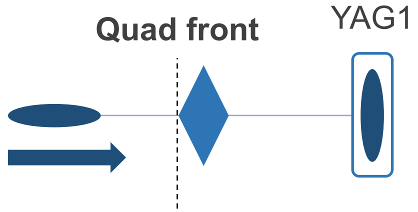


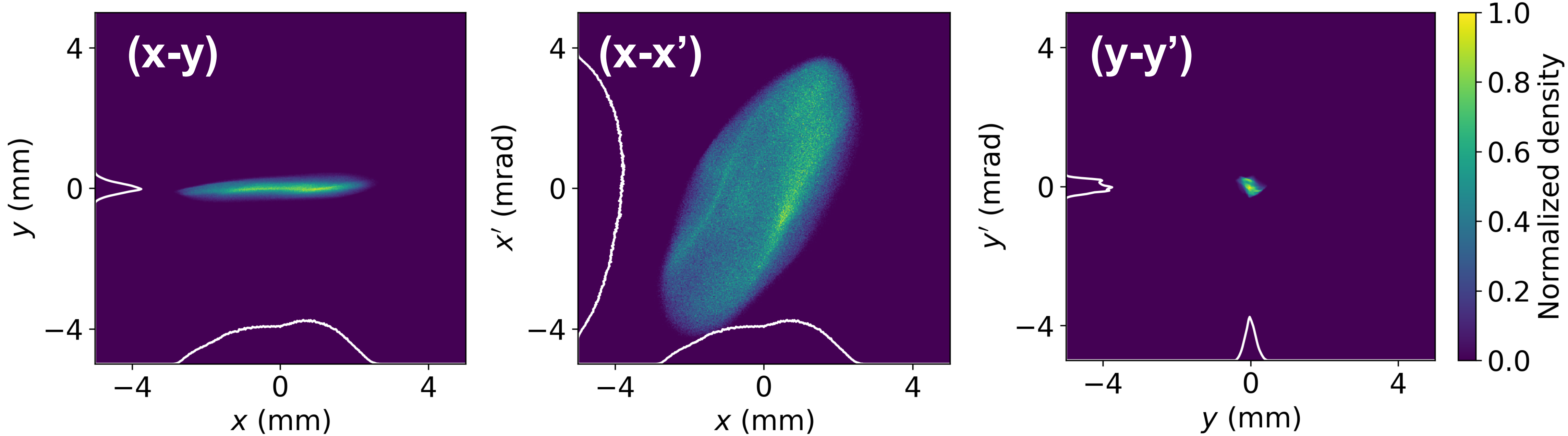


$$\Sigma_1 = \begin{bmatrix} \epsilon_+ T_+ & 0 \\ 0 & \epsilon_- T_- \end{bmatrix}$$

Reconstructed flat beam follows the transformed beam matrix: <u>no major correlations</u>

Reconstructed initial beam phase space





Case	Emit_nx (mm mrad)	Emit_ny (mm mrad)
Reconstruction	**140.14**	**1.53**
Measurement (Quadrupole scan)	**144.64±1.36**	**1.47±0.10**

R. Ryan, Fast 6-Dimensional Phase Space Reconstructions using Generative Beam Distribution Models and Differentiable Beam Dynamics, March 7, 2024

** **JP Gonzalez-Aguilera**, High-dimensional characterization of coherent synchrotron radiation effects using generative-model-based phase space reconstruction methods , March 7, 2024

Summary

- **Successful characterization of the flat and magnetized beams are performed using generative phase space reconstruction method**
  - **Magnetization was successfully estimated using simple quadrupole scan method + GPSR, without use of slit**
  - **It was verified through the GPSR method that transverse correlations on the flat beam is minimized // emittance ratio is large (>90)**
- **As shown in Ryan and Juan-Pablo's talk**, complete six-dimensional phase space reconstruction is available together with deflecting cavity + spectrometer**
  - **It is the robust diagnostic method for characterizing the transverse-longitudinal correlations for the beam manipulations (e.g., EEX, DEEX*)**

*Emittance Exchange beamline, Double EEX beamline

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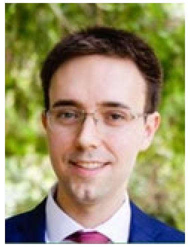

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