17th International Particle Accelerator Conference, Deauville, France

Manipulating and diagnosing electron beam with cross-plane coupling in transverse and longitudinal phase spaces

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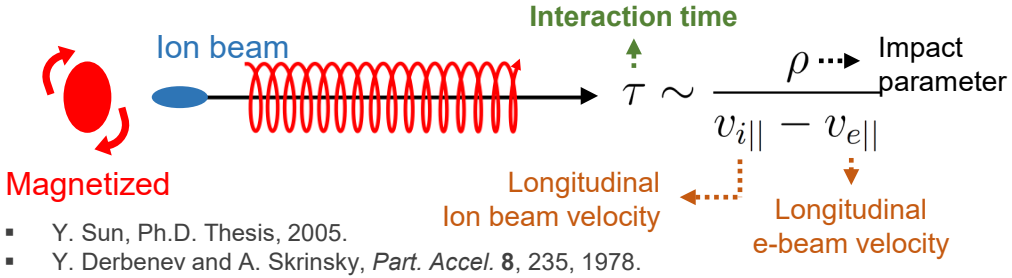
- **Motivation of beam manipulation and precise beam diagnostics**
  - For HEP applications and high-bright light sources
  - Generative Phase Space Reconstruction technique (GPSR)
- **4D and 6D beam manipulation + GPSR–based diagnostics**
  - Flat and magnetized beam transformations @ AWA facility
  - Detailed 6D phase space reconstruction @ PAL-XFEL facility
- **Summary and future work**

*e.g., double horn-suppressed, flat slice emittance

Motivation of beam manipulation

Use of magnetized beam:

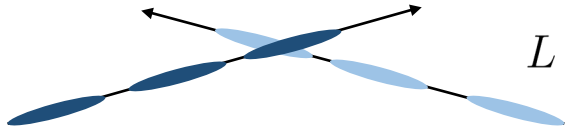
Reduction of hadron beam emittance: cooling



- Y. Sun, Ph.D. Thesis, 2005.
- Y. Derbenev and A. Skrinsky, *Part. Accel.* **8**, 235, 1978.

Use of flat beam:

Direct increases of luminosity



Luminosity

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

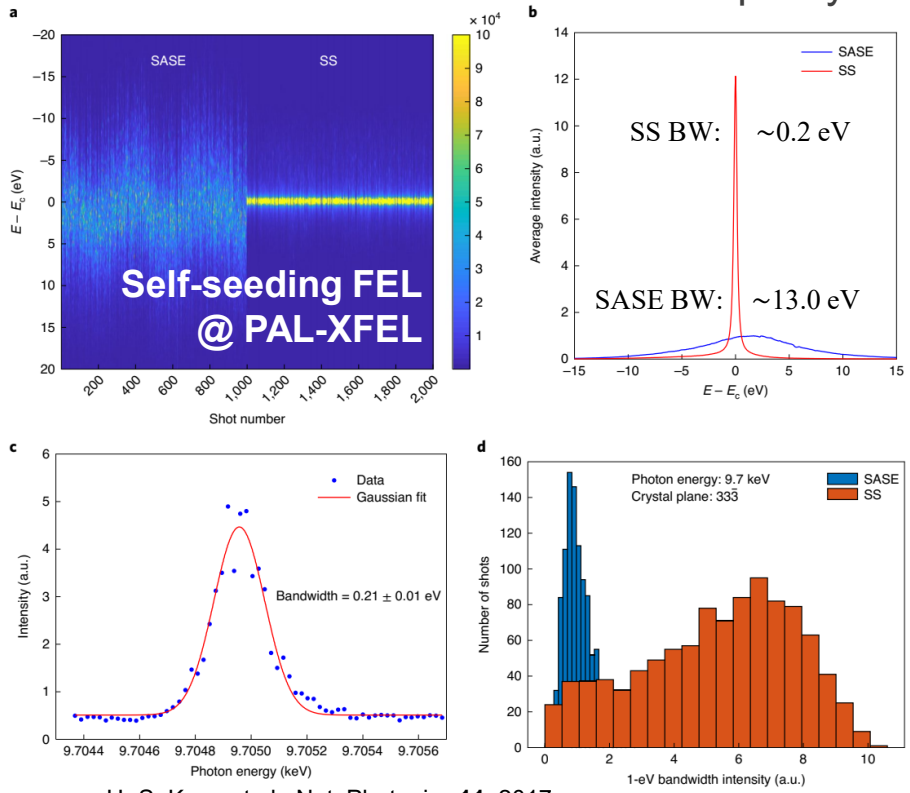
Small vertical beam size:
by flat beam with large magnetization

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

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

Use of refined electron beam*:

Enhancement of Free Electron Laser quality



- H.-S. Kang et al., Nat. Photonics **11**, 2017.
- I. Nam *et al., Nat. Photonics* **15**, 2021.

For high-energy physics applications and high-brightness X-ray light:

Proper and accurate beam phase space manipulation is essential

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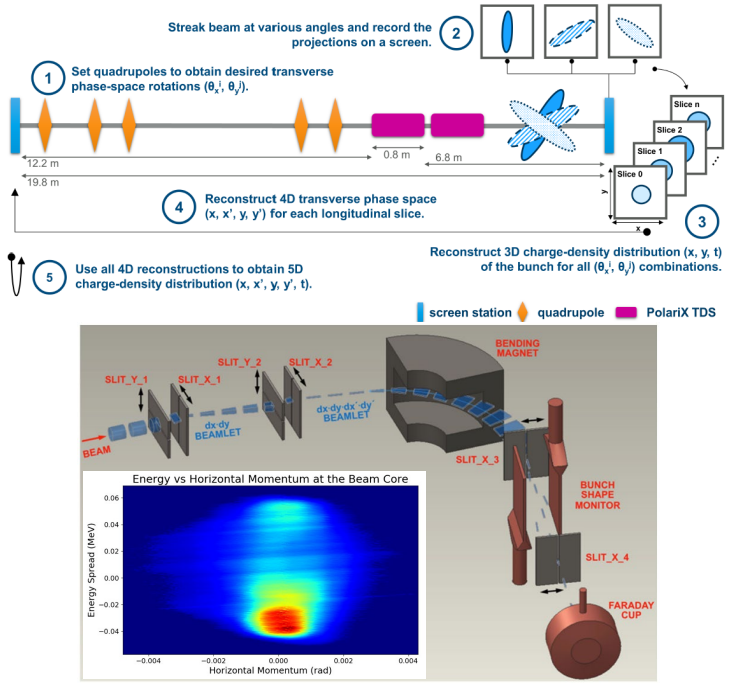
* Accuracy, efficiency, and required time for diagnostics

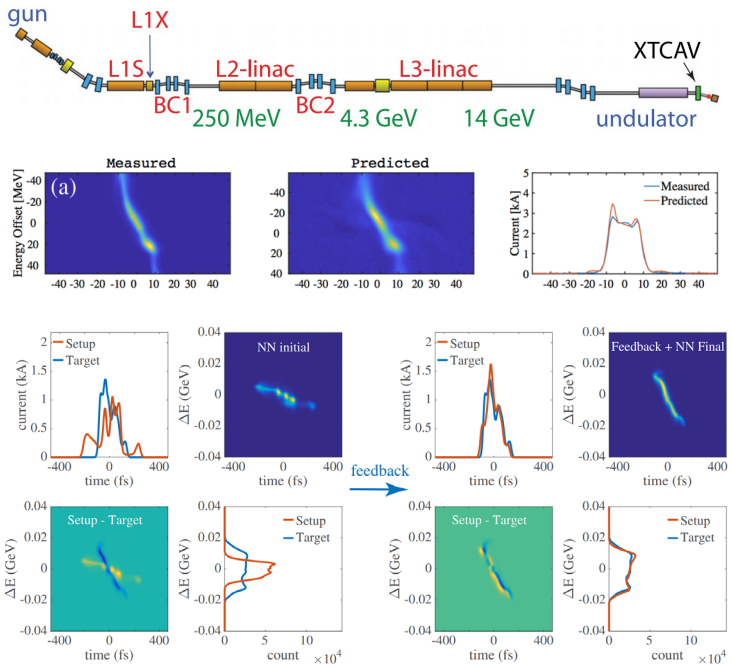
Beam diagnostics for characterizing manipulated beams

Conventional diagnostics



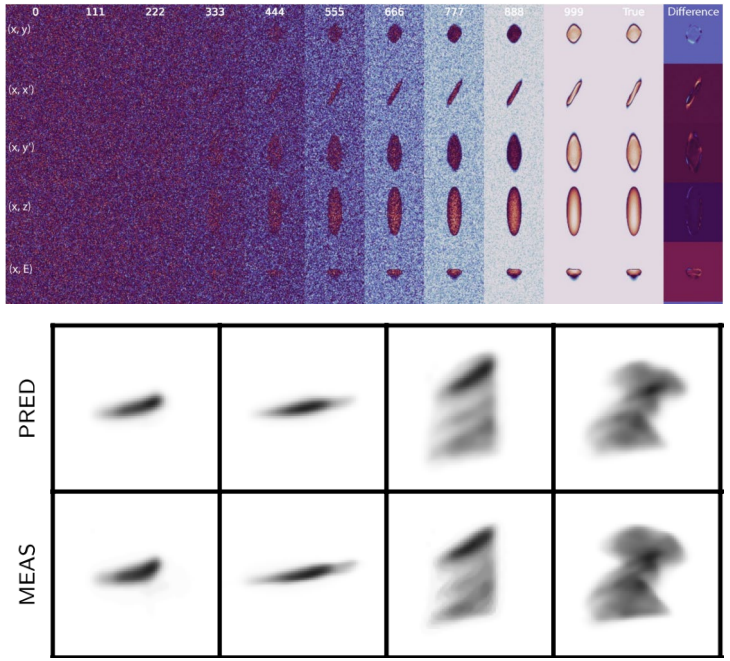
S. Jaster-Merz *et al.*, *PRAB* **27**, 072801, 2024.
B. Cathey *et al.*, *PRL* **121**, 064804, 2018.

Virtual diagnostics



C. Emma *et al.*, *PRAB* **21**, 112802, 2018.
A. Scheinker *et al.*, *PRL* **121**, 044801, 2018.

Generative learnings



A. Scheinker, *Sci. Rep.* **14**, 29303, 2024.
A. Hoover, *PRAB* **28**, L084601, 2025.

Beam diagnostics from conventional approach to AI/ML technique-incorporated:

allows us to investigate phase space characterization in a robust way*

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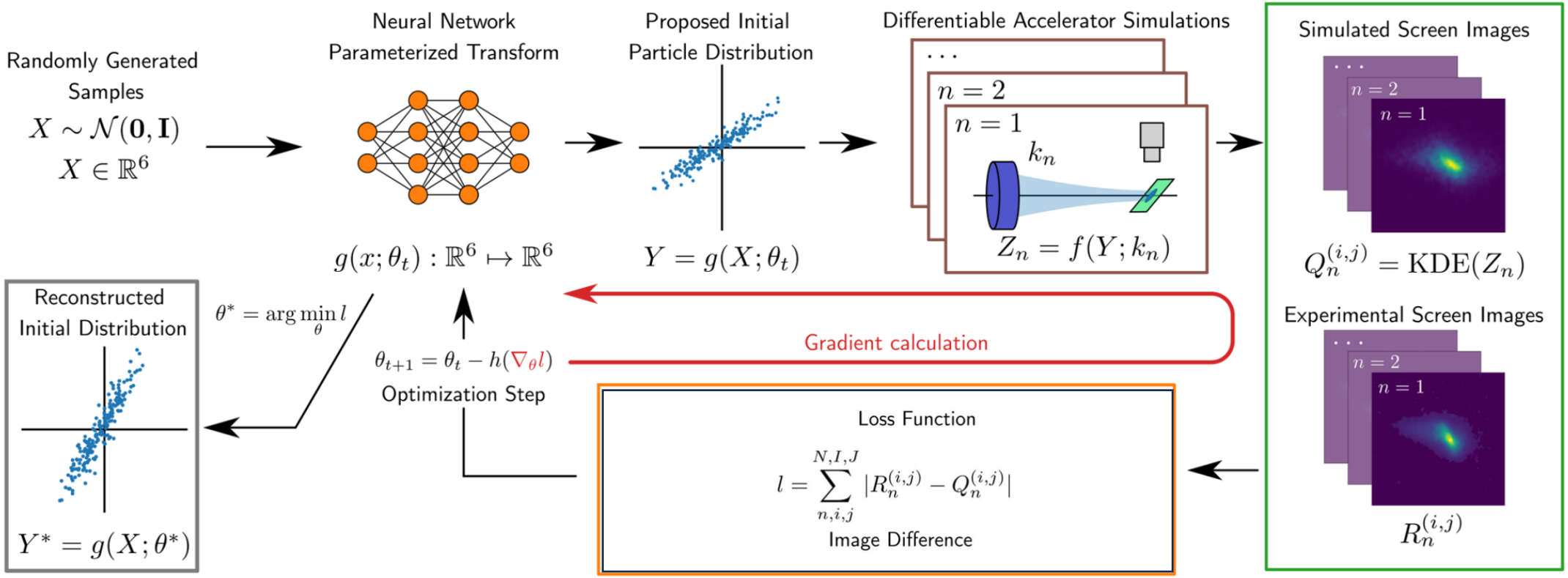
- R. Roussel *et al.*, *PRL* **130**, 145001, 2023.
- S. Kim *et al.*, *PRAB* **27**, 074601, 2024.
- R. Roussel *et al.*, *PRAB* **27**, 094601, 2024.
- J.P. Gonzalez-Aguilera *et al.*, *IPAC'24*, 2024.

Generative phase space reconstruction (GPSR)

Based on neural networks and differentiable simulations



Iteration process to update weights of neural networks:

To reconstruct beam phase space that successfully predicts experimental measurements

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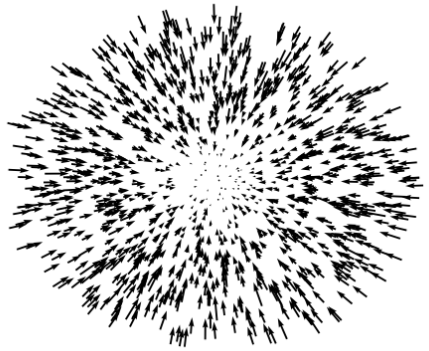
4D phase space manipulation and reconstruction

Based on:

- Seongyeol Kim *et al., Phys. Rev. Accel. Beams* **27**, 074601, 2024.
- Seongyeol Kim *et al., Nucl. Inst. Meth. Phys. Res. A* **1072**, 170206, 2025.

What are flat and magnetized beams?

Round beam



Typical beam we use (does not rotate)

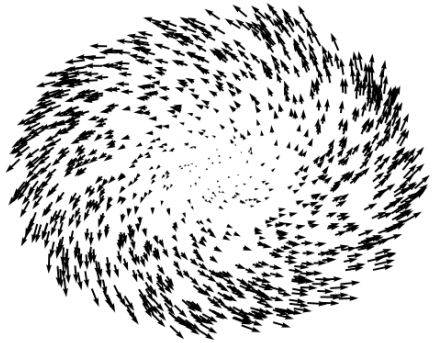
Solenoid field at the cathode

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

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

Canonical Angular momentum

Round, magnetized beam



Angular-momentum-dominated beam

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

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

Magnetization

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

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

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*Relativistic factor larger than 50

Back-to-back beam transformations @ AWA facility

Back-to-back(B2B): Round-to-flat and flat-to-round(magnetized) beam transformations*

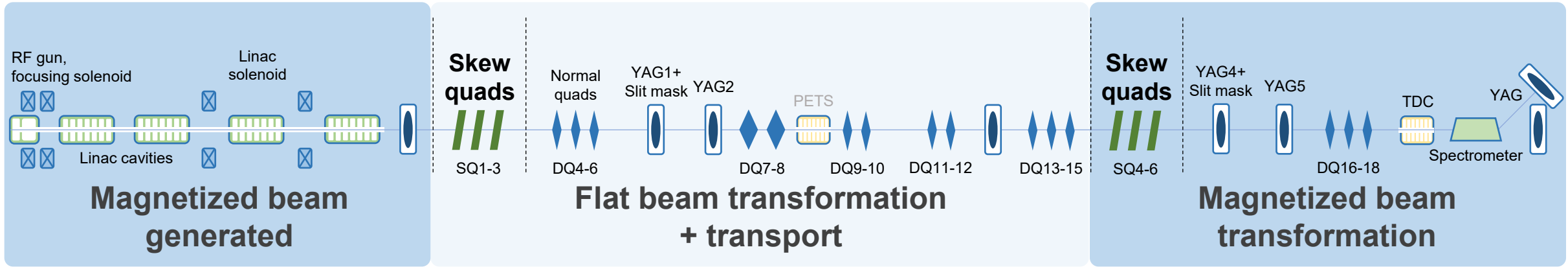
Motivation of beam transformations:

- Difficulty of high-energy* magnetized beam transport: make it easy by decoupling
- Then, transformation back to magnetized condition at the application section (e.g., cooling)

High-energy magnetized beam generation using photoinjector → Flat beam transformation + beam transport → Magnetized beam transformation + application

Goal of demonstration:

- Experimental demo of back-to-back transformations at Argonne Wakefield Accelerator (AWA) Facility



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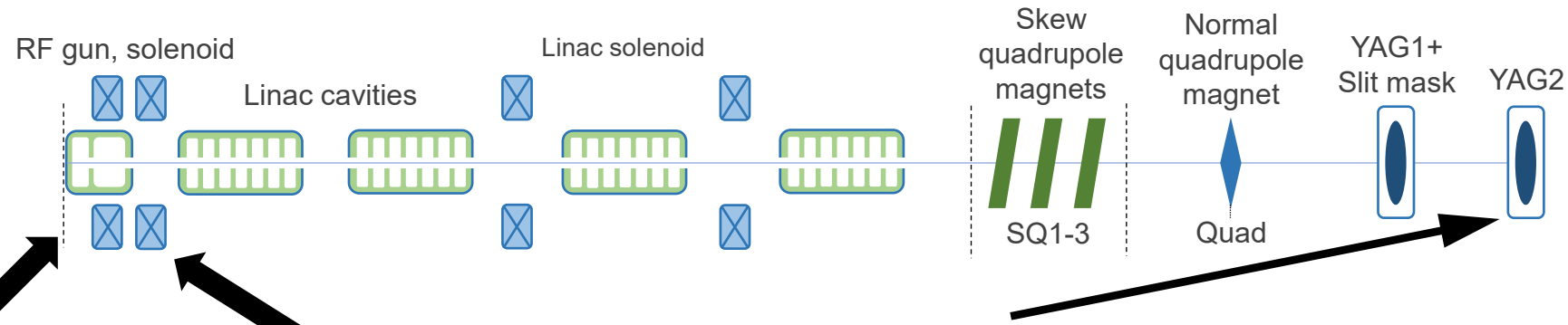
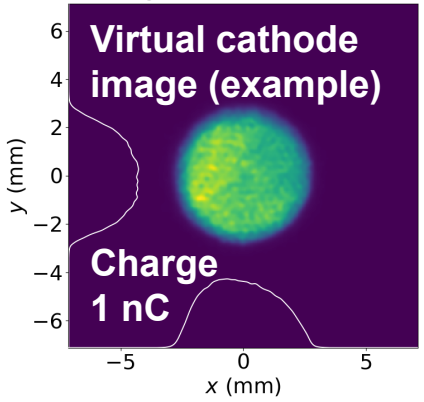
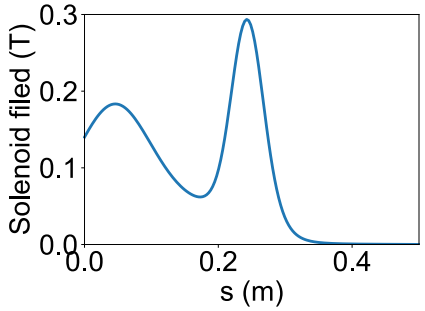
Experimental demonstration of beam transformations

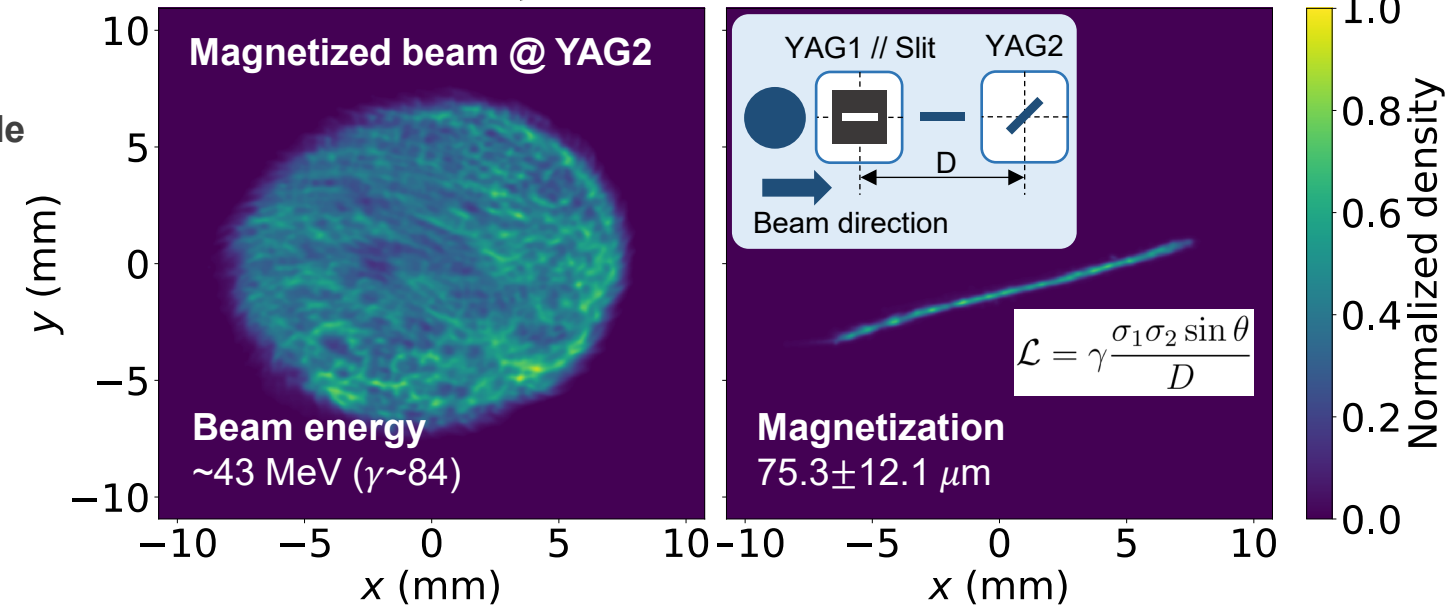


Use of multi-lens array (MLA)



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





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*E. Thrane Proc. LINAC 2002, 2002.
*A. Wolski, *Phys. Rev. Accel. Beams et al.*, **9**, 204001, 2006.

Experimental demonstration of beam transformations

For magnetized beam: $\mathbf{Y} = C\mathbf{X}$

$\mathbf{X} = (x, p_x), \mathbf{Y} = (y, p_y)$

$$C = \frac{\mathcal{L}}{\epsilon_{eff}} \begin{bmatrix} \alpha & \beta \\ -\frac{1+\alpha^2}{\beta^2} & -\alpha \end{bmatrix}$$

Twiss Parameters

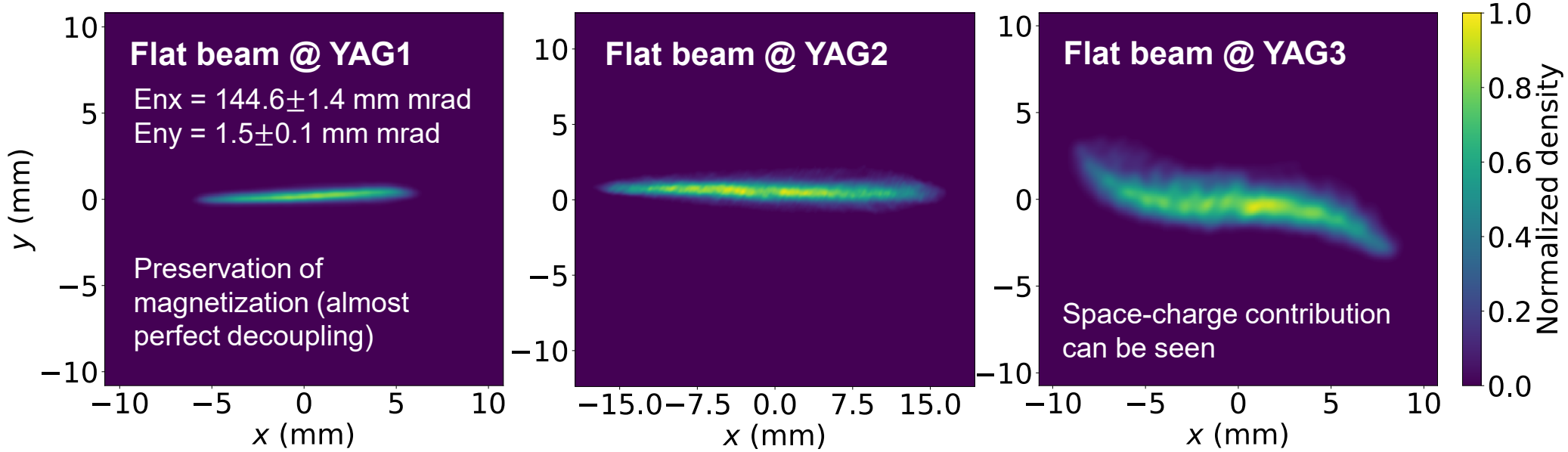
where $\epsilon_{eff} = \sqrt{\epsilon_{th}^2 + \mathcal{L}^2}$

RFBT matrix calculation

$$\begin{pmatrix} \mathbf{X} \\ \mathbf{Y} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} [A + B + (A - B)C]\mathbf{X} \\ [A - B + (A + B)C]\mathbf{X} \end{pmatrix}$$

where skew triplet matrix, $M_{SQ} = \begin{pmatrix} A+B & A-B \\ A-B & A+B \end{pmatrix}$

RFBT goal: find skew quad settings that vanishes $\mathbf{Y}$



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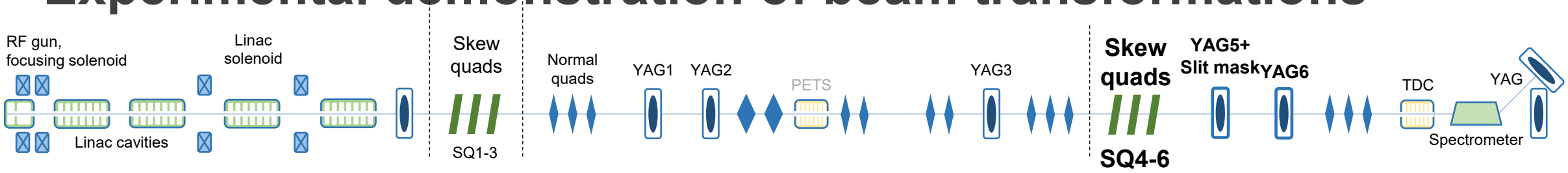
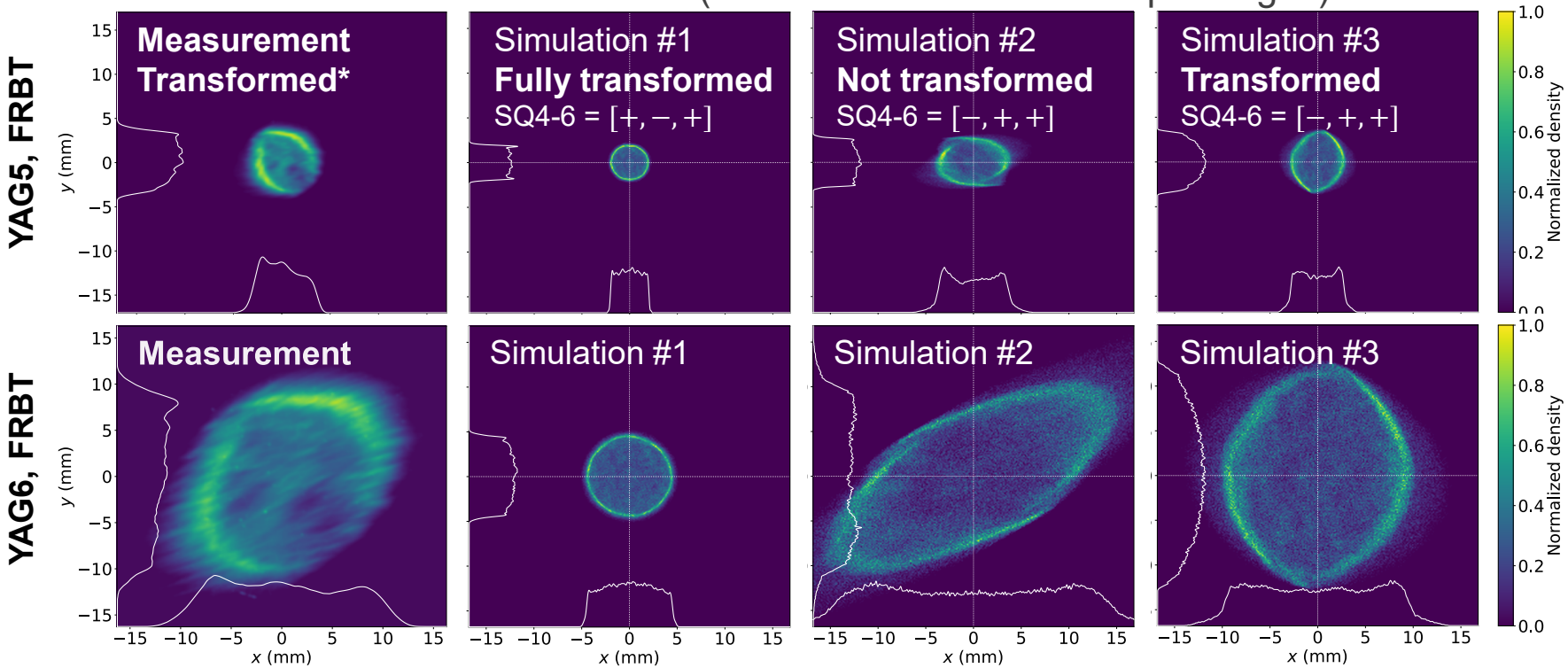
*E. Thrane Proc. LINAC 2002, 2002.
*A. Wolski, *Phys. Rev. Accel. Beams et al.*, **9**, 204001, 2006.

Experimental demonstration of beam transformations



Flat to round beam transformation (simulations with different quad signs)



Magnetization
(slit-measurement)
74.3±17.7 μm

Magnetization
74.1 μm

Magnetization
68.8 μm

Magnetization
71.9 μm

*For simulation #2,

$$|\gamma\langle xy'\rangle| \neq |\gamma\langle x'y\rangle|$$

Thus, not transformed

precise beam diagnostic method is required for accurate validation of transversely coupled beam!

GPSR technique

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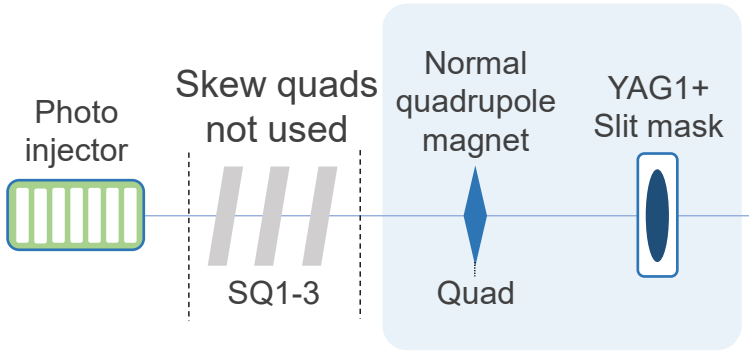
Characterization of magnetized beam using GPSR

Different UV distribution and solenoid field were applied in this case

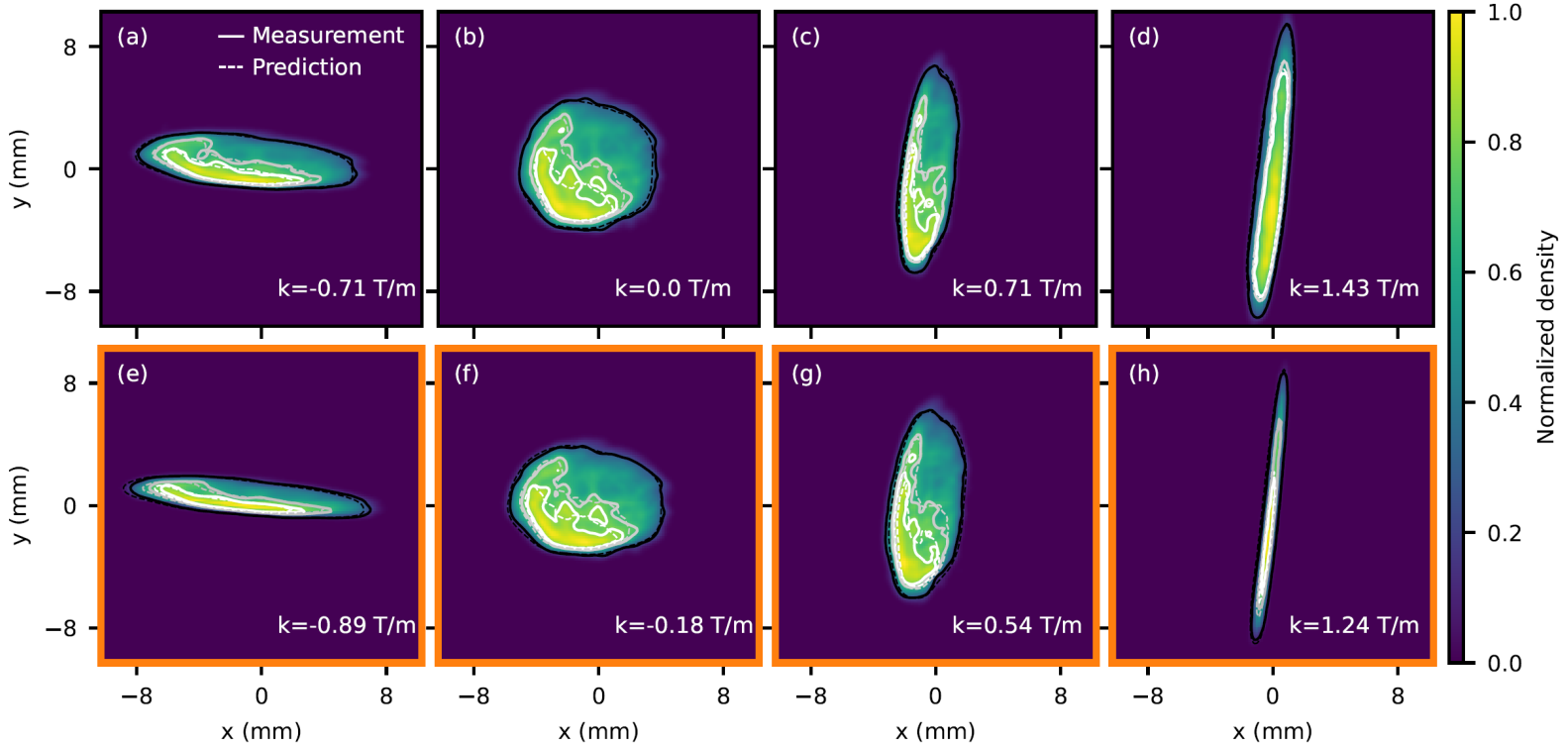


GPSR setup:

- 21 quadscan samples (half for train)
- 250x250 image bins
- 100k particles, 4000 epochs

measurement Test dataset

Comparison of training / test dataset (images @ YAG1)



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Characterization of magnetized beam using GPSR

Different UV distribution and solenoid field were applied in this case

Magnetized beam matrix

$$\begin{bmatrix} \epsilon_{eff}\beta_x & -\epsilon_{eff}\alpha_x & 0 & \mathcal{L} \\ -\epsilon_{eff}\alpha_x & \epsilon_{eff}\gamma_x & -\mathcal{L} & 0 \\ 0 & -\mathcal{L} & \epsilon_{eff}\beta_y & -\epsilon_{eff}\alpha_y \\ \mathcal{L} & 0 & -\epsilon_{eff}\alpha_y & \epsilon_{eff}\gamma_y \end{bmatrix} \Rightarrow \left|\gamma\left(\langle xy'\rangle - \langle yx'\rangle\right)\right|/2$$

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

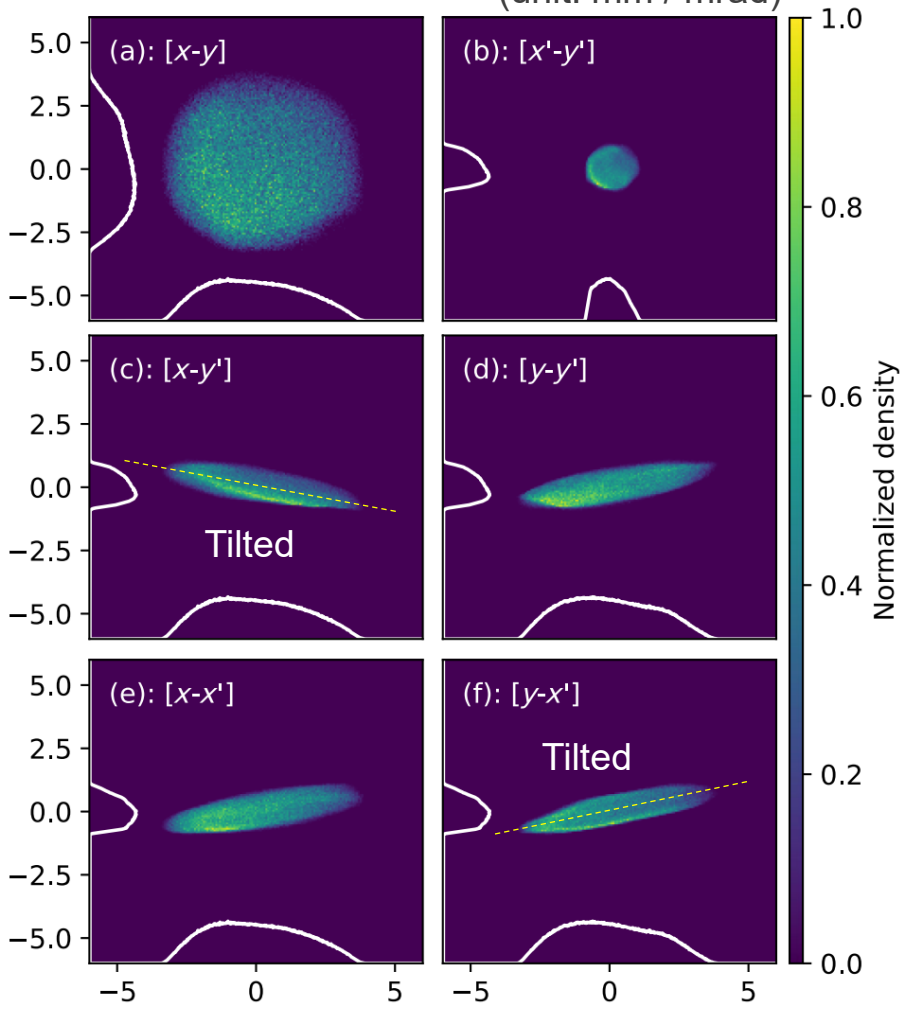
Magnetization, case	Value (um)
Reconstruction	**44.0**
Slit measurement	**47.2±0.9**

GPSR for magnetized beams:

Successful to obtain detailed phase space information including couplings

Reconstructed phase space

(unit: mm / mrad)



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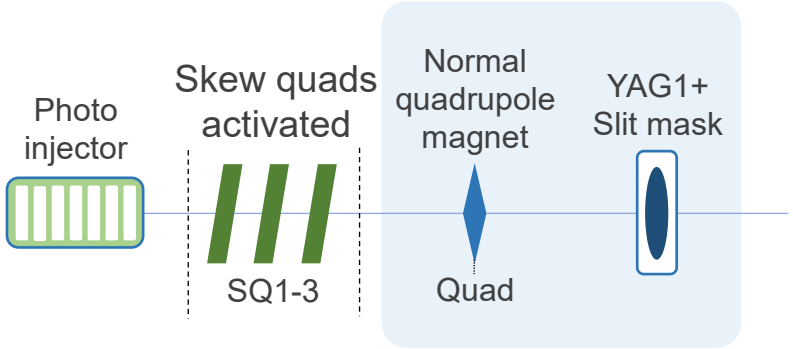
Characterization of flat beam using GPSR

Different UV distribution and solenoid field were applied (also compared to magnetized beam GPSR)



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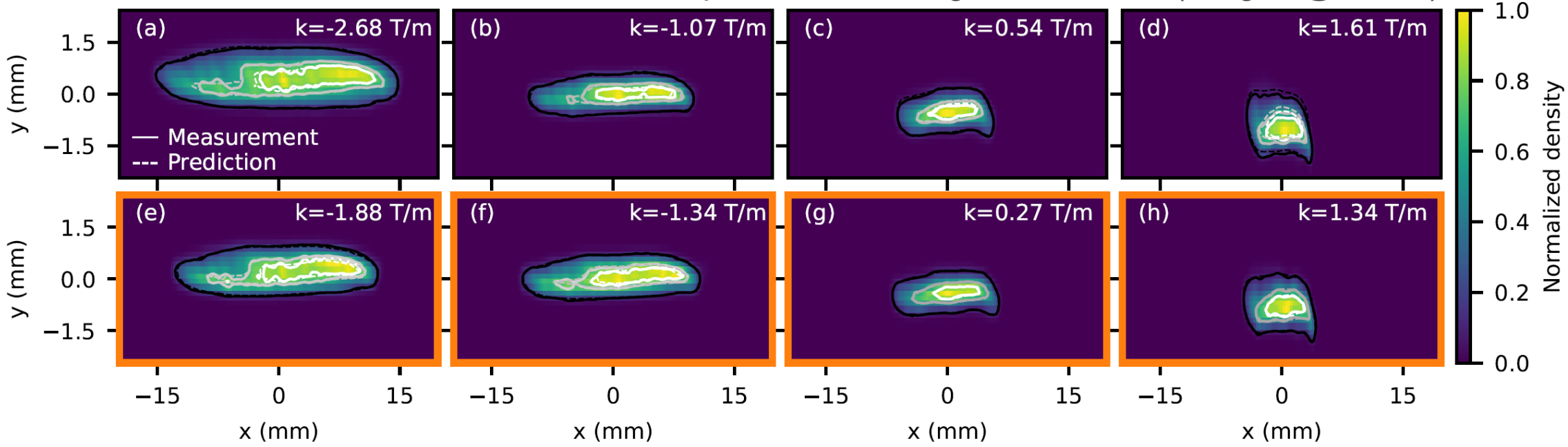

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Characterization of flat beam using GPSR

Different UV distribution and solenoid field were applied (also compared to magnetized beam GPSR)

After beam transformation, beam covariance becomes:

$$\begin{bmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle yx'\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle xy'\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle yx'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'^2\rangle \end{bmatrix} = \begin{bmatrix} \epsilon_+\beta_+ & -\epsilon_+\alpha_+ & 0 & 0 \\ \epsilon_+\alpha_+ & \epsilon_+\gamma_+ & 0 & 0 \\ 0 & 0 & \epsilon_-\beta_- & -\epsilon_-\alpha_- \\ 0 & 0 & \epsilon_-\alpha_- & \epsilon_-\gamma_- \end{bmatrix}$$

Where eigen-emittances:

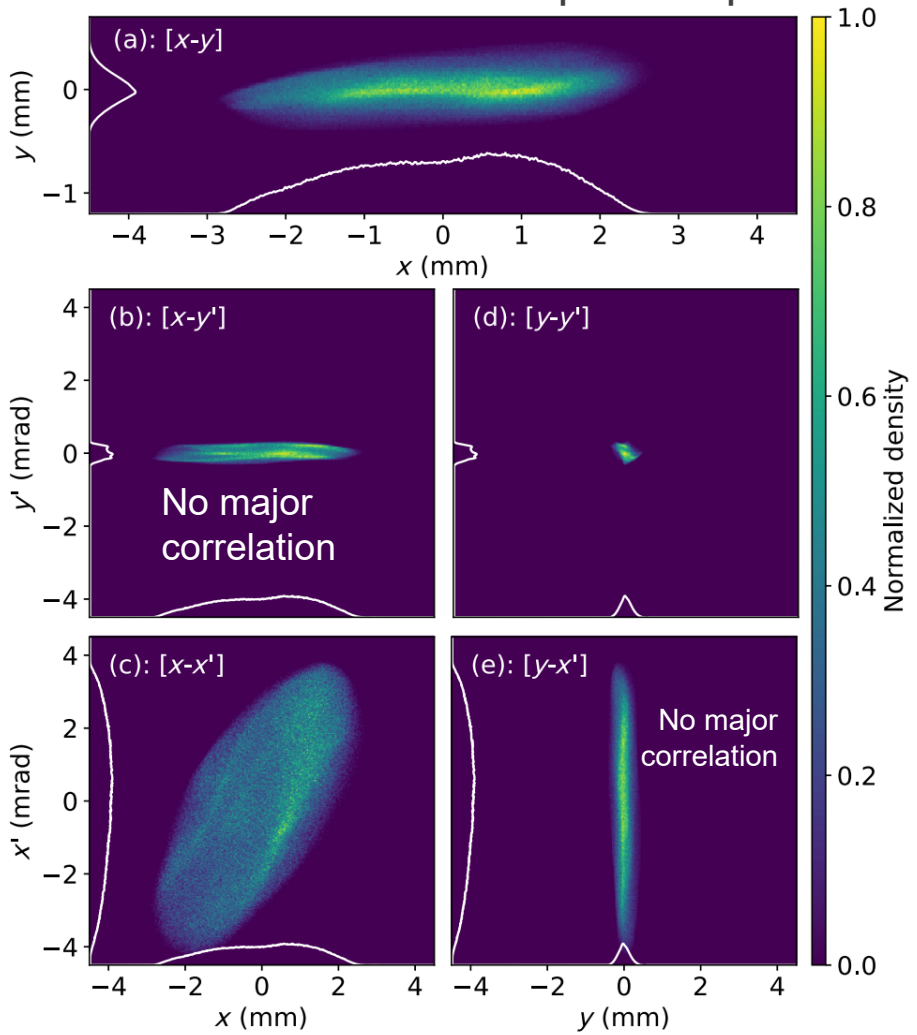
$$\epsilon_+ \approx 2\mathcal{L} \quad \epsilon_- \approx \frac{\epsilon_{th}^2}{2\mathcal{L}}$$

ϵ_{th} Uncorrelated emittance

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

Also, GPSR technique successfully reconstructed flat beams!

Reconstructed phase space



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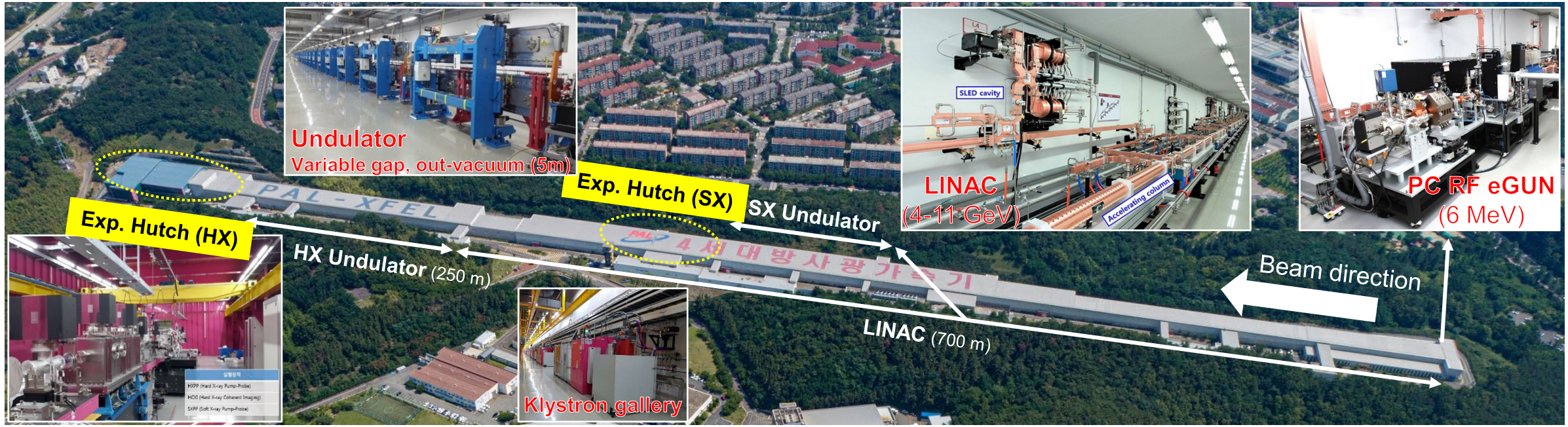
6D phase space manipulation and reconstruction

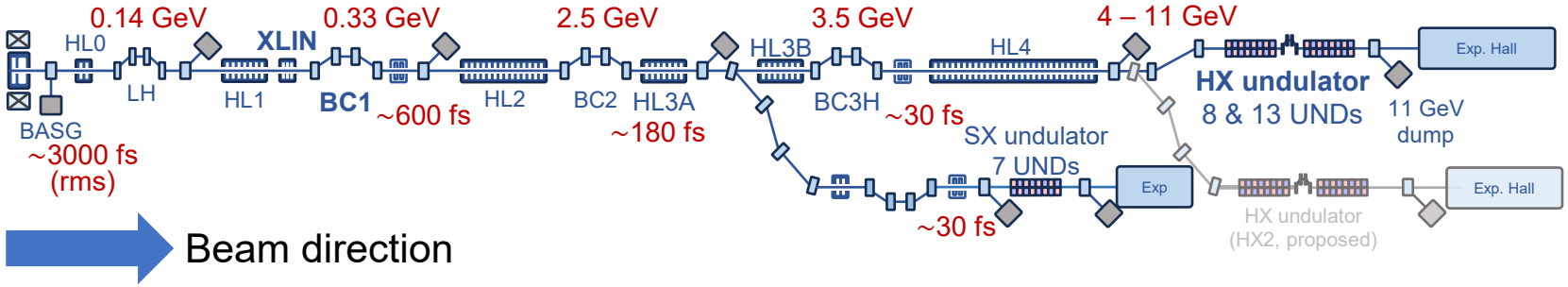
Based on:

- Seongyeol Kim *et al., Sci. Rep.* **15**, 43049, 2025.

Pohang Accelerator Laboratory, X-ray Free Electron Laser



PAL-XFEL Layout



Undulator Line	HX	SX
Photon energy (keV)	2.0~20.0	0.25~1.25
Beam energy (GeV)	4~11	3.0
Beam charge (pC)	190/250	160/250
Peak current (kA)	~3	~2.5
E_{ph} tuning	Energy/Gap	Gap
Repetition rate (Hz)	60	60
FEL intensity	> 1 mJ	> 250 μJ

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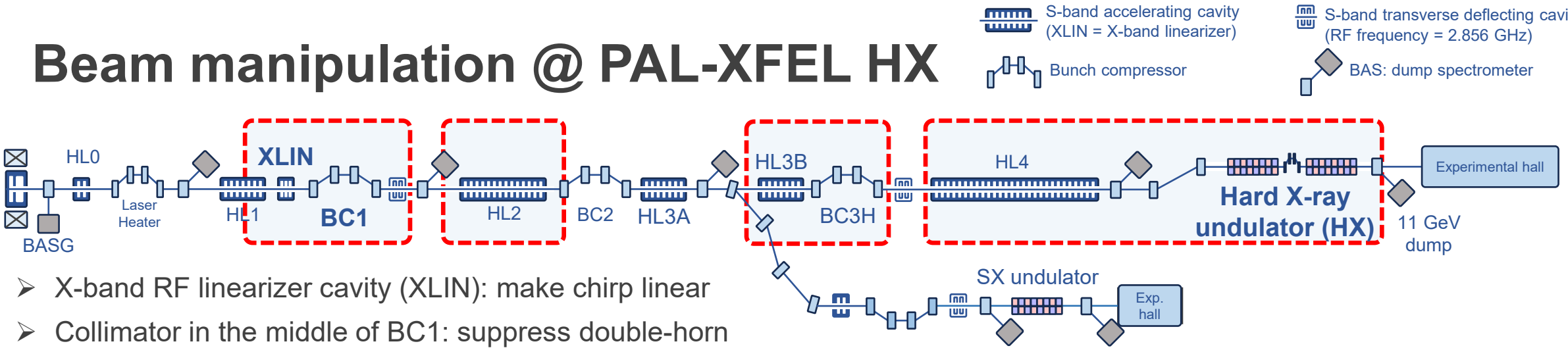
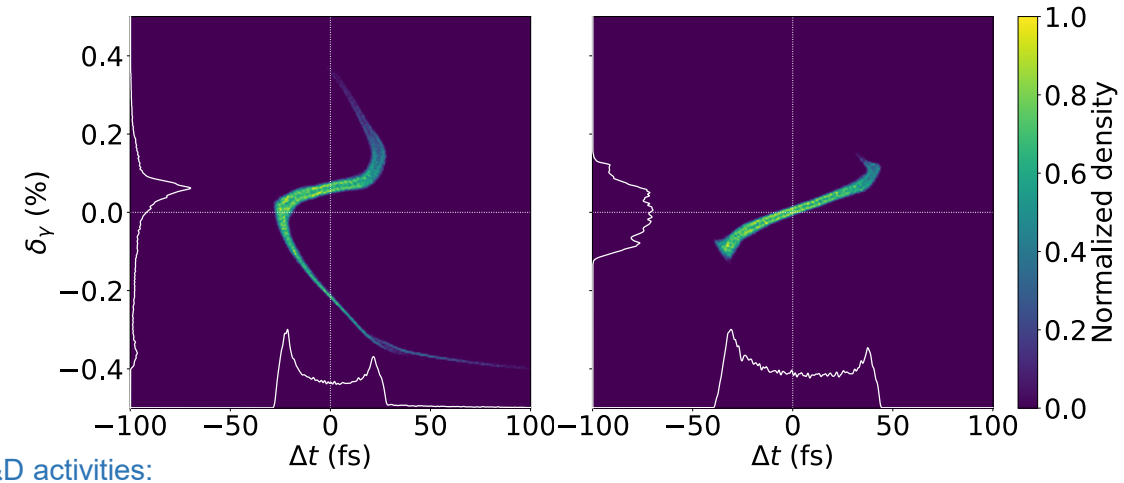
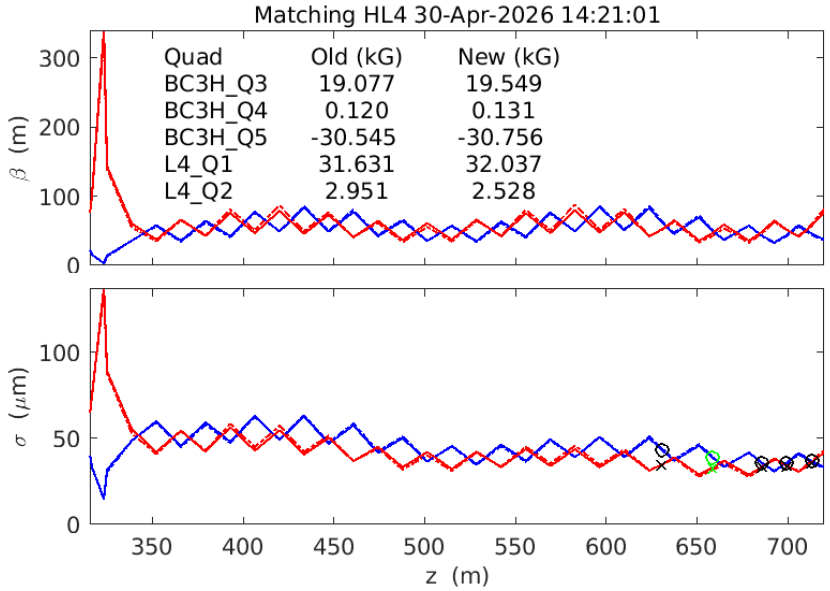
Beam manipulation @ PAL-XFEL HX



- X-band RF linearizer cavity (XLIN): make chirp linear
- Collimator in the middle of BC1: suppress double-horn
- BC3H: emittance optimization against CSR
- HL2, HL4, HX sections: FODO lattice matching





Other R&D activities:

- UV laser control: **Seong-Hoon Kwon *et al.*, TUP7721 (Tuesday poster)**
- FEL mode development: **Chi Hyun Shim *et al.*, TUP2662 (Tuesday poster)**
- Beam phase space diagnostics: **Myunghoon Cho *et al.*, MOP6656 (Monday poster)**

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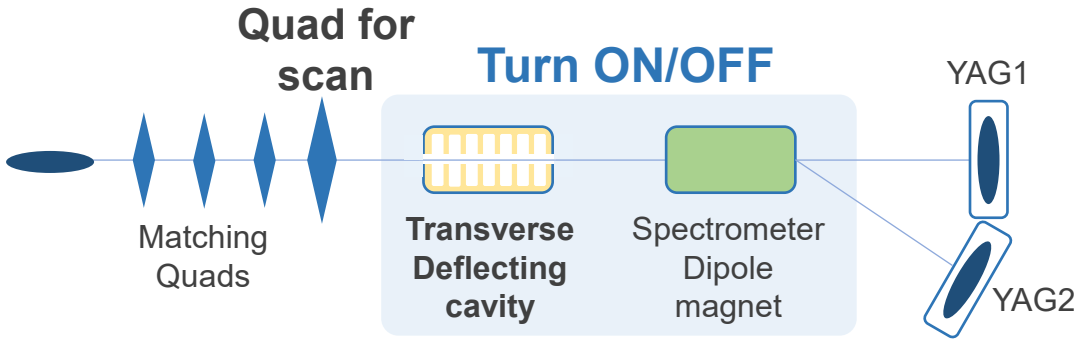
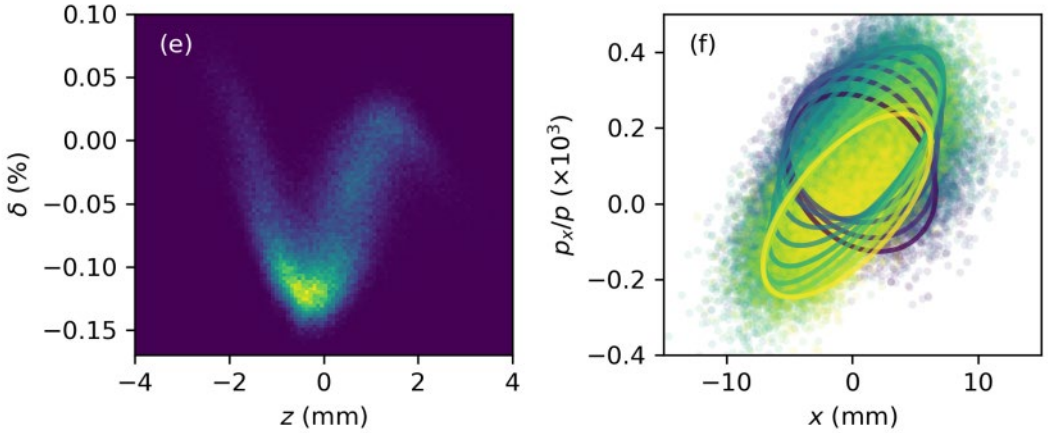
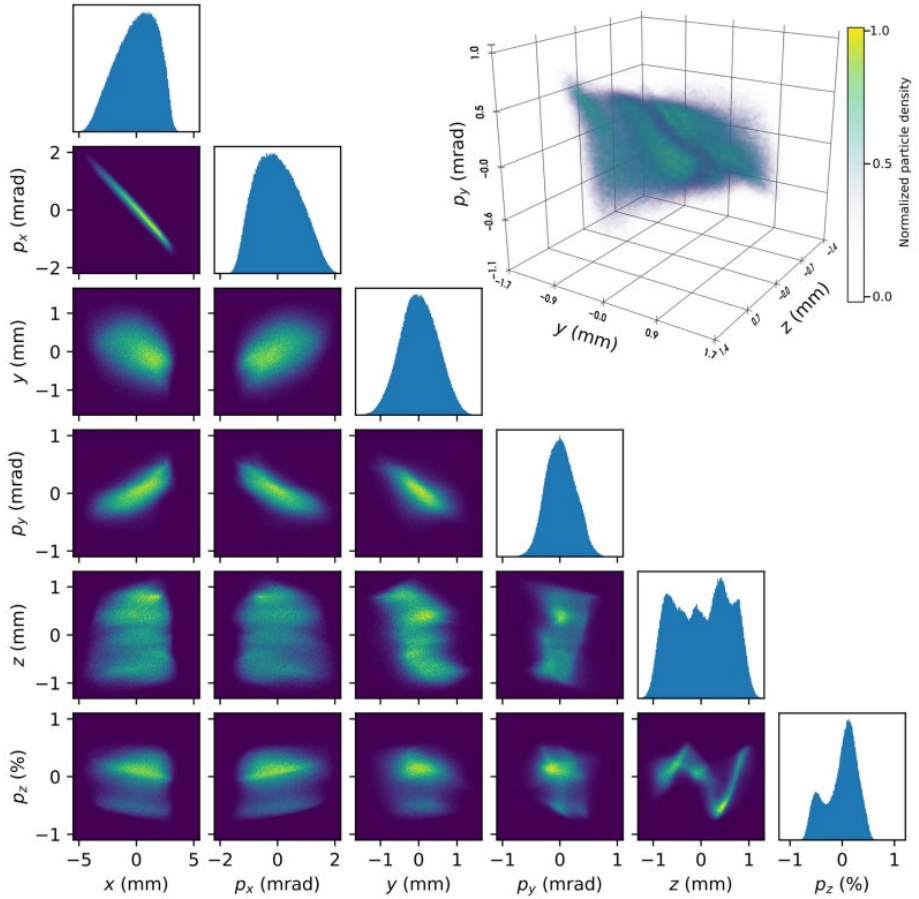
- R. Roussel *et al.*, *PRAB* **27**, 094601, 2024.
- J.P. Gonzalez-Aguilera *et al.*, *IPAC'24*, 2024.
- *R. Roussel *et al.*, arXiv:2604.20125, 2026.

6D GPSR using transverse deflecting cavity



CSR characterization





➡ **6-dimensional phase space reconstruction is also successfully performed and currently deployed @ LCLS-II, SLAC***

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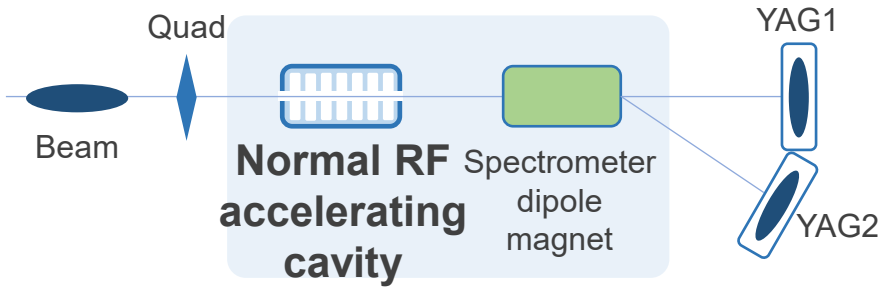
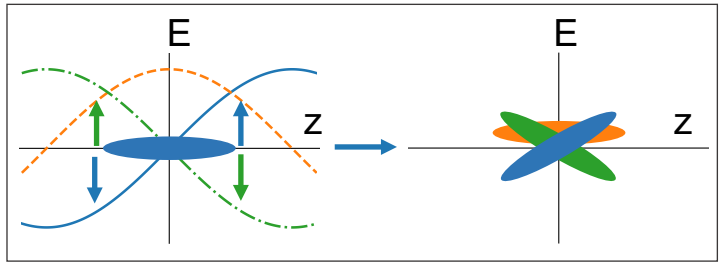
6D GPSR using RF accelerating cavity

Inspired by conventional longitudinal emittance measurement*

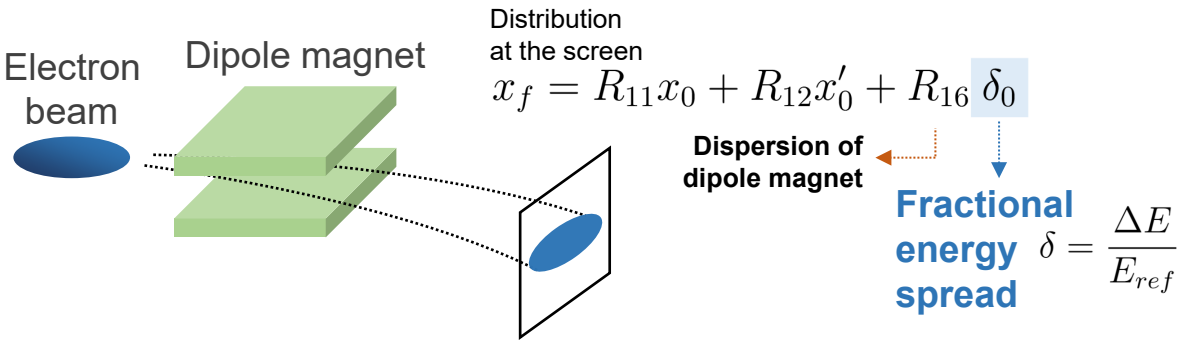


$$\Delta E(z) = eV\cos\left(k_{RF}z + \phi_{RF}\right)$$

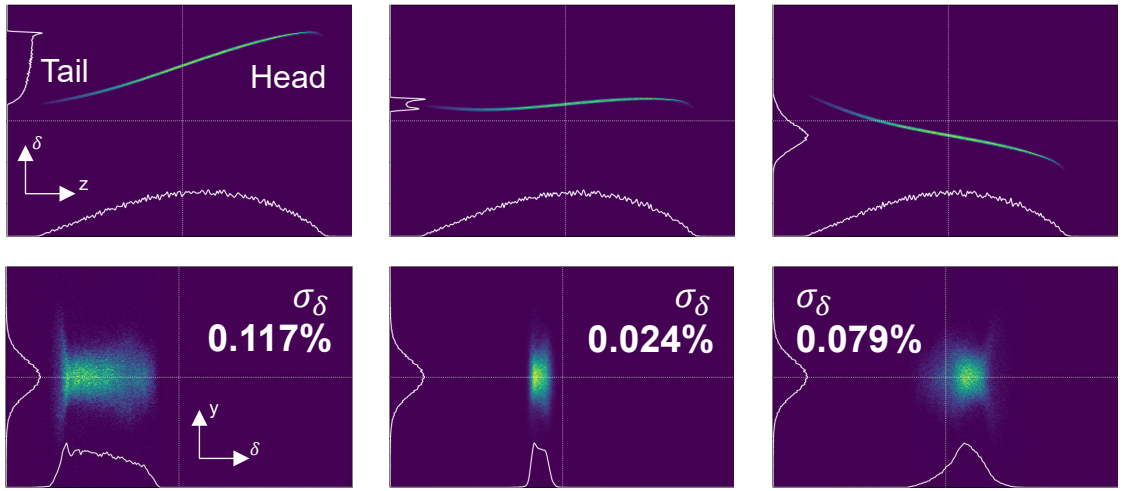


For a given longitudinal distribution:

➡ **Energy changes induced by the cavity can be captured at the spectrometer screen**



Top: longitudinal phase space **Bottom: beam at spectrometer screen**



***Longitudinal emittance:**

- D. Dowell *et al., In. Proc. PAC'03,* 2003.
- D. Dowell *et al., Nucl. Inst. Meth. Phys. Res. A* **507**, 331, 2003.

Longitudinal phase space tomography:

- H. Loos *et al., Nucl. Inst. Meth. Phys. Res. A* **528**, 189-193, 2004.

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6D GPSR using RF accelerating cavity

Inspired by conventional longitudinal emittance measurement*

*Longitudinal emittance:
- D. Dowell *et al., In. Proc. PAC'03,* 2003.
- D. Dowell *et al., Nucl. Inst. Meth. Phys. Res. A* **507**, 331, 2003.

Longitudinal phase space tomography:
- H. Loos *et al., Nucl. Inst. Meth. Phys. Res. A* **528**, 189-193, 2004.

Transfer matrix for cavity and drift

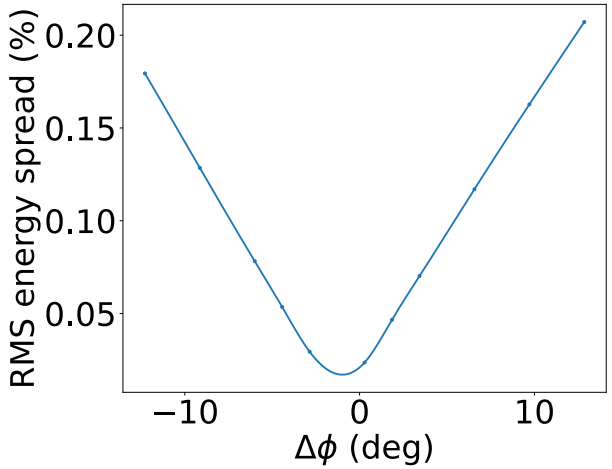
$$M = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -V\sin(\phi_{RF}) & 1 \end{pmatrix} \quad \text{where} \quad \Sigma_i = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} < z^2 > & < z\delta > \\ < z\delta > & < \delta^2 > \end{pmatrix}$$

$$\sigma_{22}^{YAG} = \sigma_\delta^2 = V^2\sigma_{11}\,\phi^2 - 2V\sigma_{12}\,\phi + \sigma_{22}$$

RMS energy spread at the screen $= A\phi^2 + B\phi + C$ ➡ Similar to normal quadscan: Estimation of second-order moments

$$\epsilon_z = \sqrt{\sigma_{11}\sigma_{12} - \sigma_{12}^2}$$ ➡ **Emittance**

Example: Quadratic behavior of energy spread



By combining quadrupole field and cavity phase scans, **and GPSR**:

We can obtain complete 6-dimensional coupled phase space of the beam

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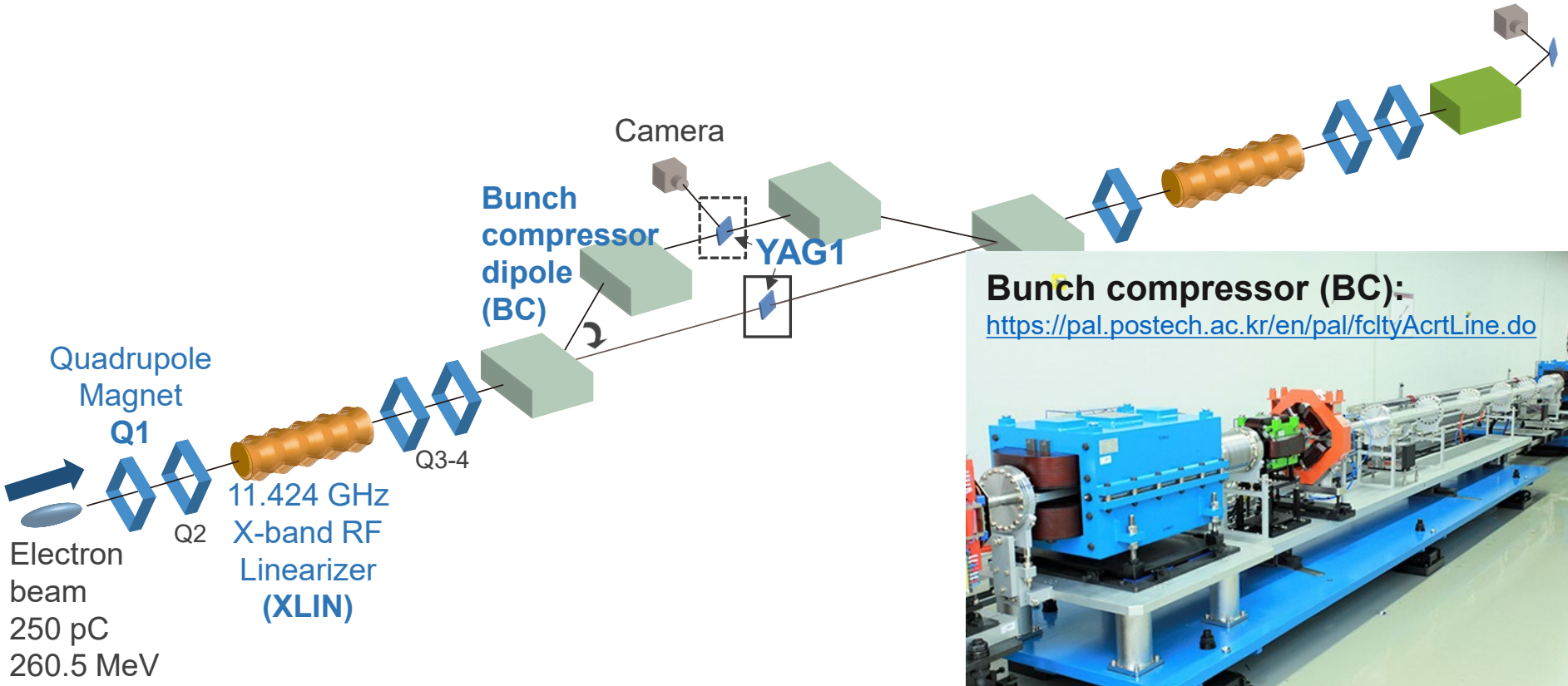
Experimental setup for the GPSR @ PAL-XFEL



Bunch compressor (BC):
https://pal.postech.ac.kr/en/pal/fcltyAcrtLine.do

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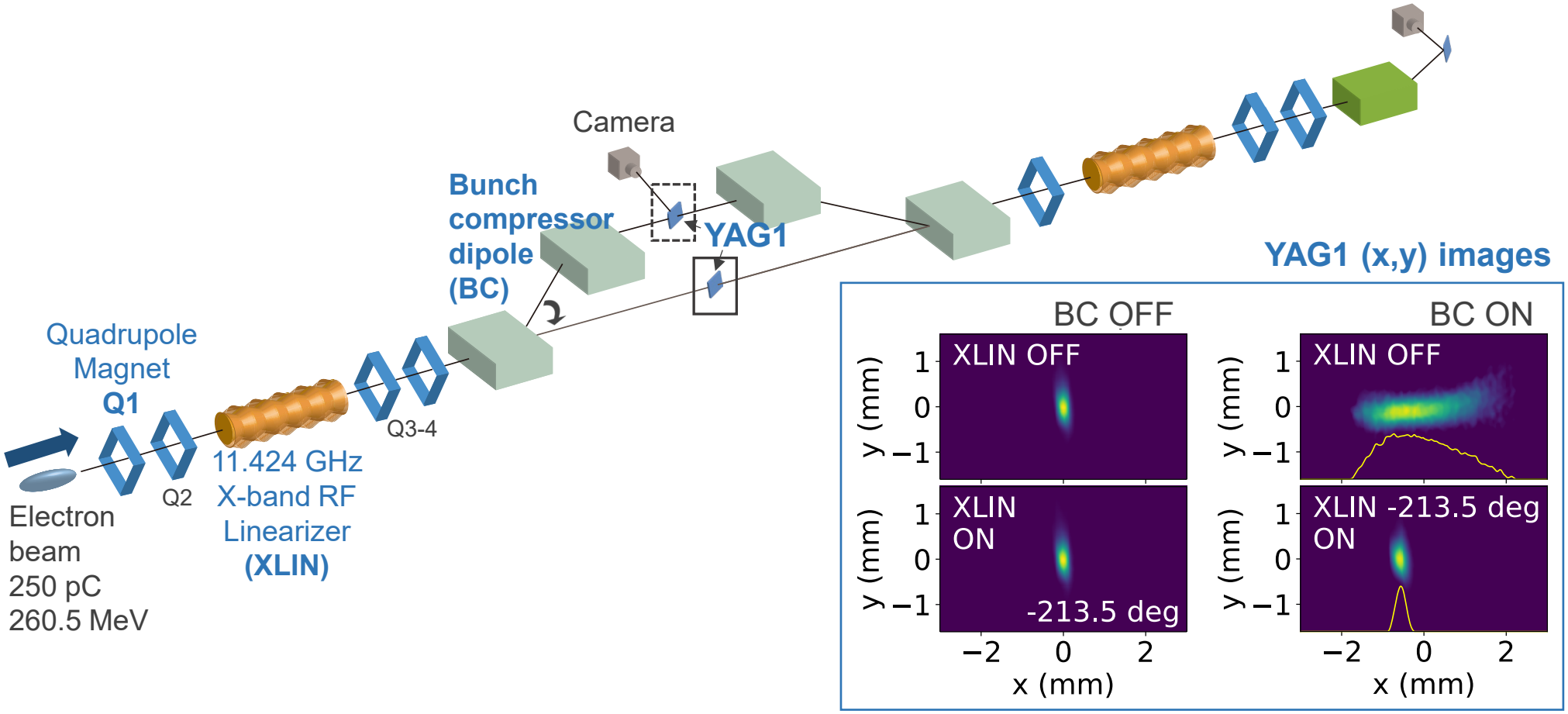
Experimental setup for the GPSR @ PAL-XFEL



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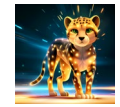
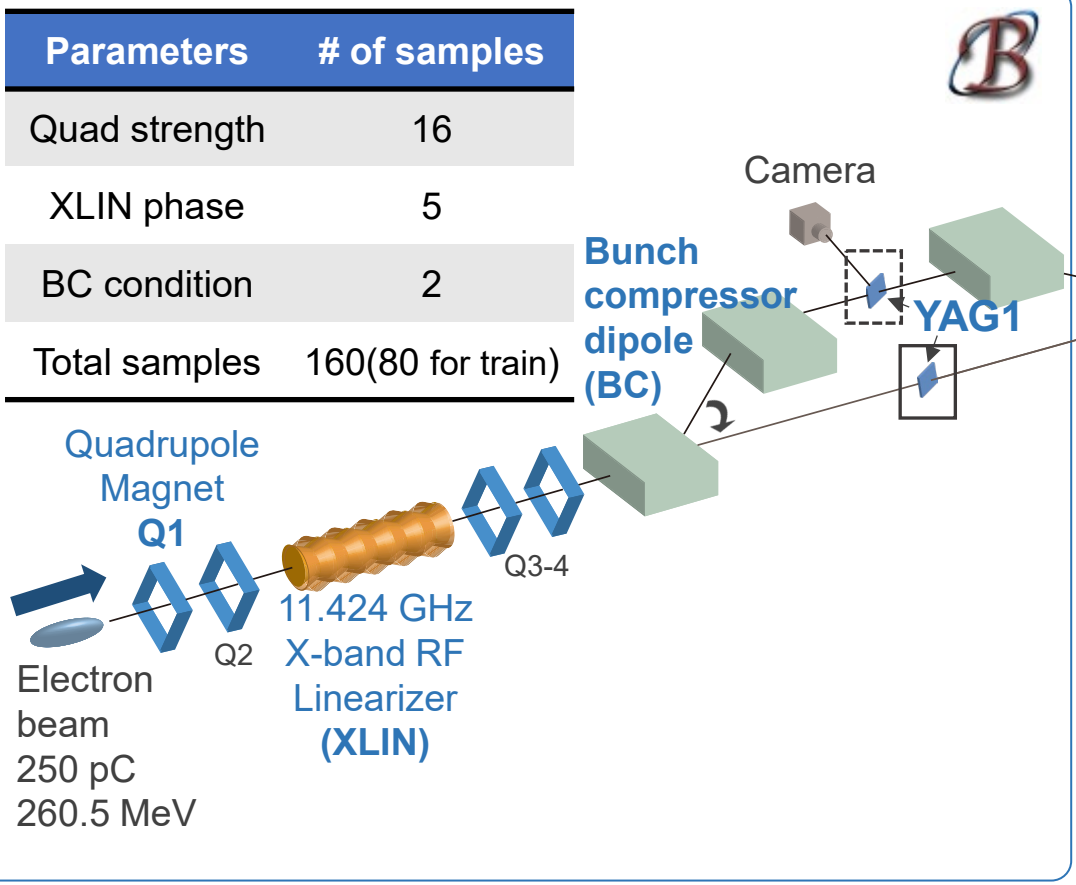
- Bmad-X: https://github.com/bmad-sim/Bmad-X
- Transition in progress from Bmad-X to Cheetah simulation @ PAL-XFEL: https://github.com/desy-ml/cheetah

Experimental setup for the GPSR @ PAL-XFEL

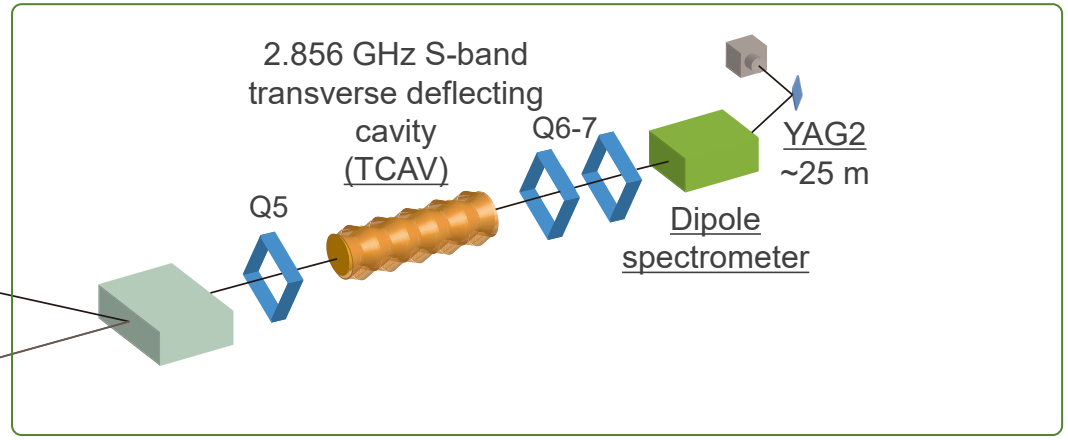


GPSR demo section

Parameters	# of samples
Quad strength	16
XLIN phase	5
BC condition	2
Total samples	160(80 for train)



GPSR validation section



GPSR setup	Values
# of particles	100,000
# of iterations	1,000
Training time	~30 mins (Nvidia A100)

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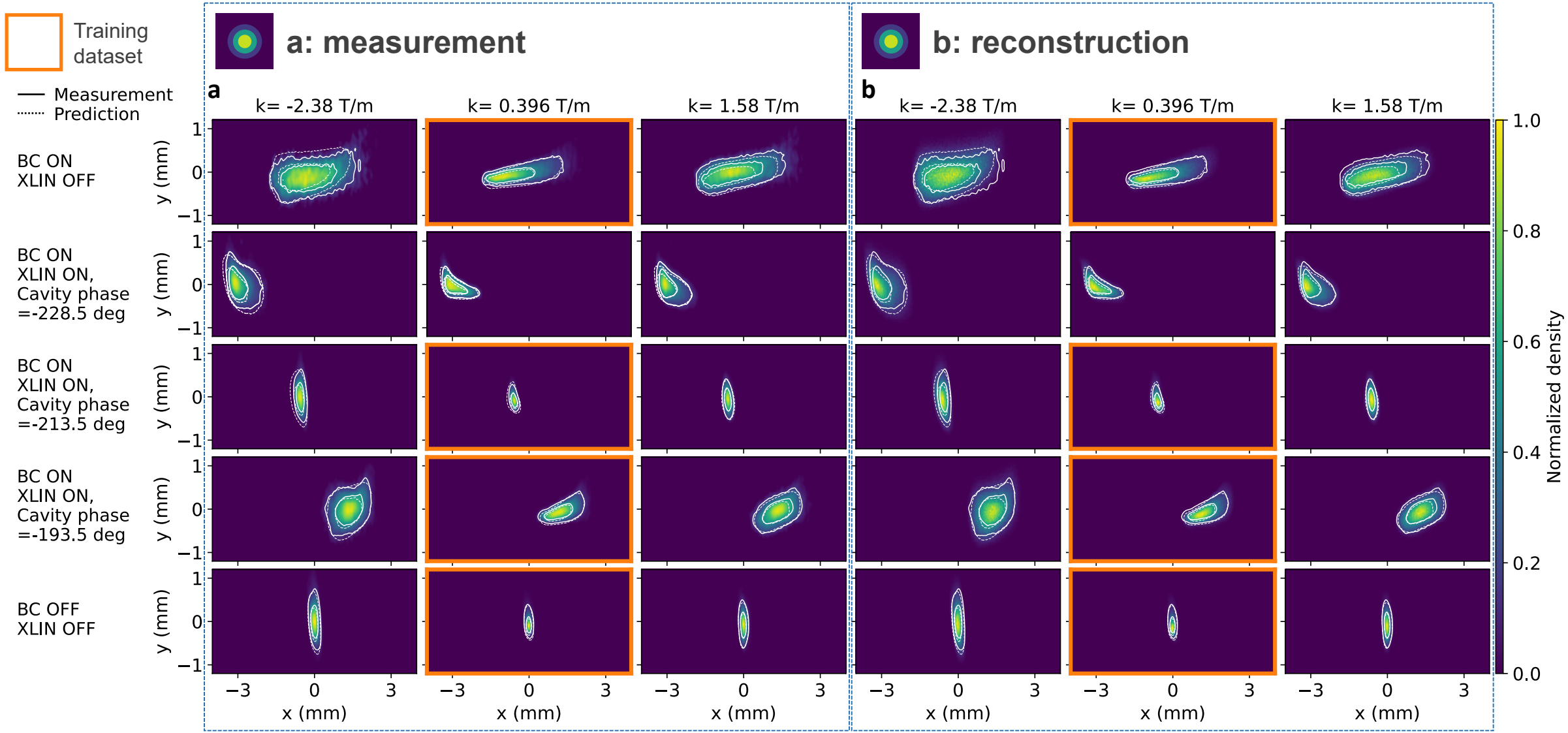
Comparison of training and test datasets @ YAG1



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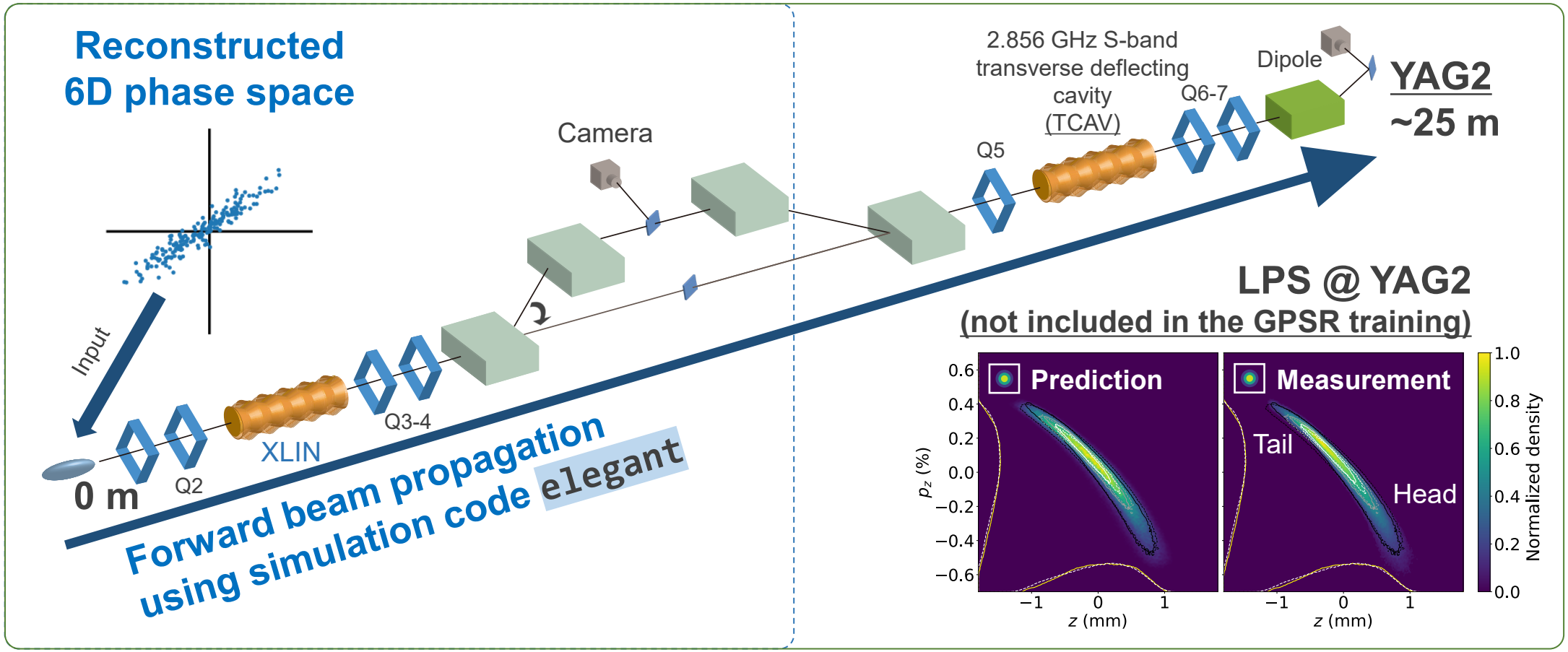
GPSR validation using downstream measurements



6D reconstructed phase space of the beam:

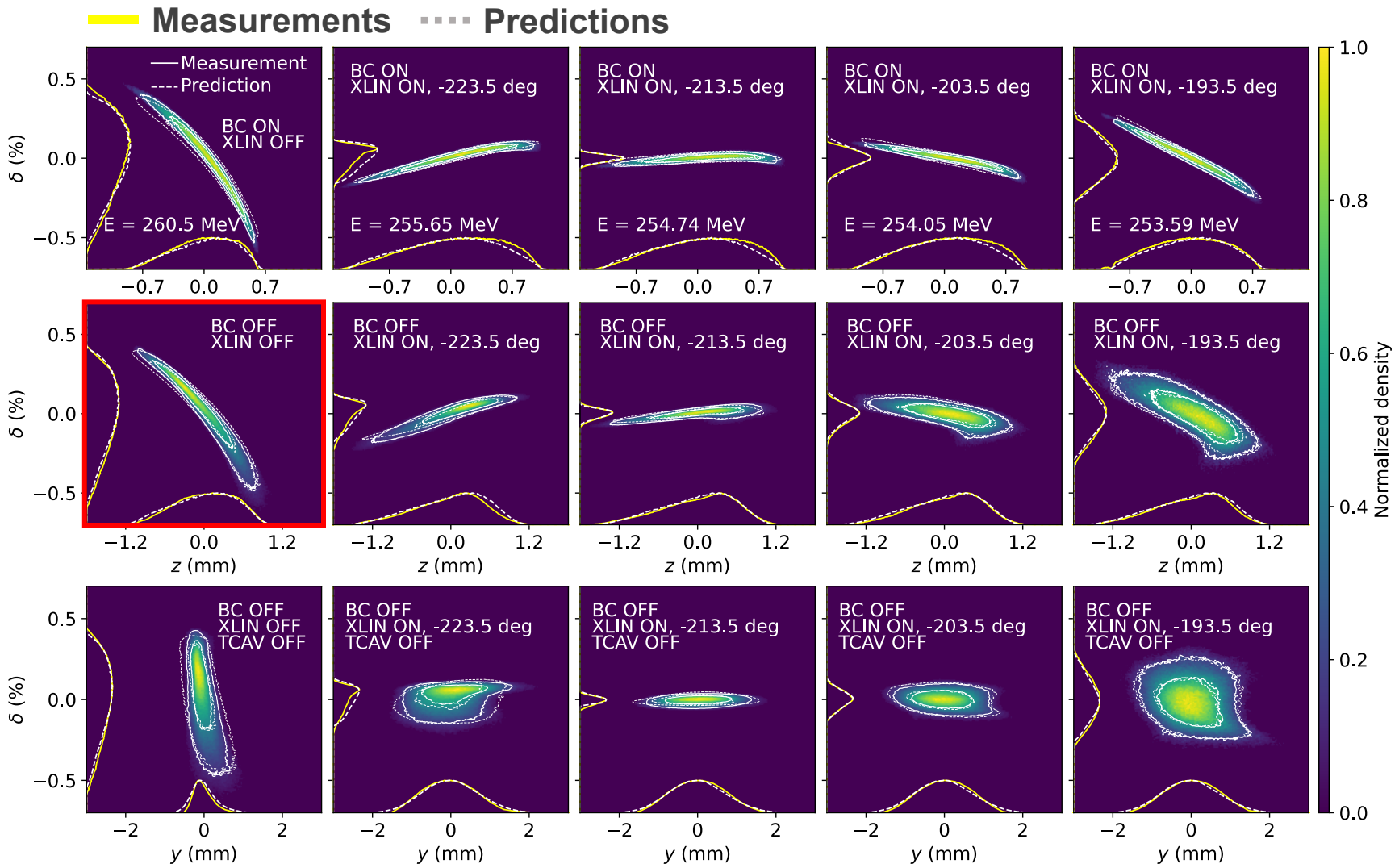
➡ **Can be used to predict the phase space at downstream beamline**

Predictions using reconstructed phase space @ YAG2

Beam image:
Measurement

Measurements
Predictions

GPSR also successfully predicts independent downstream measurements!



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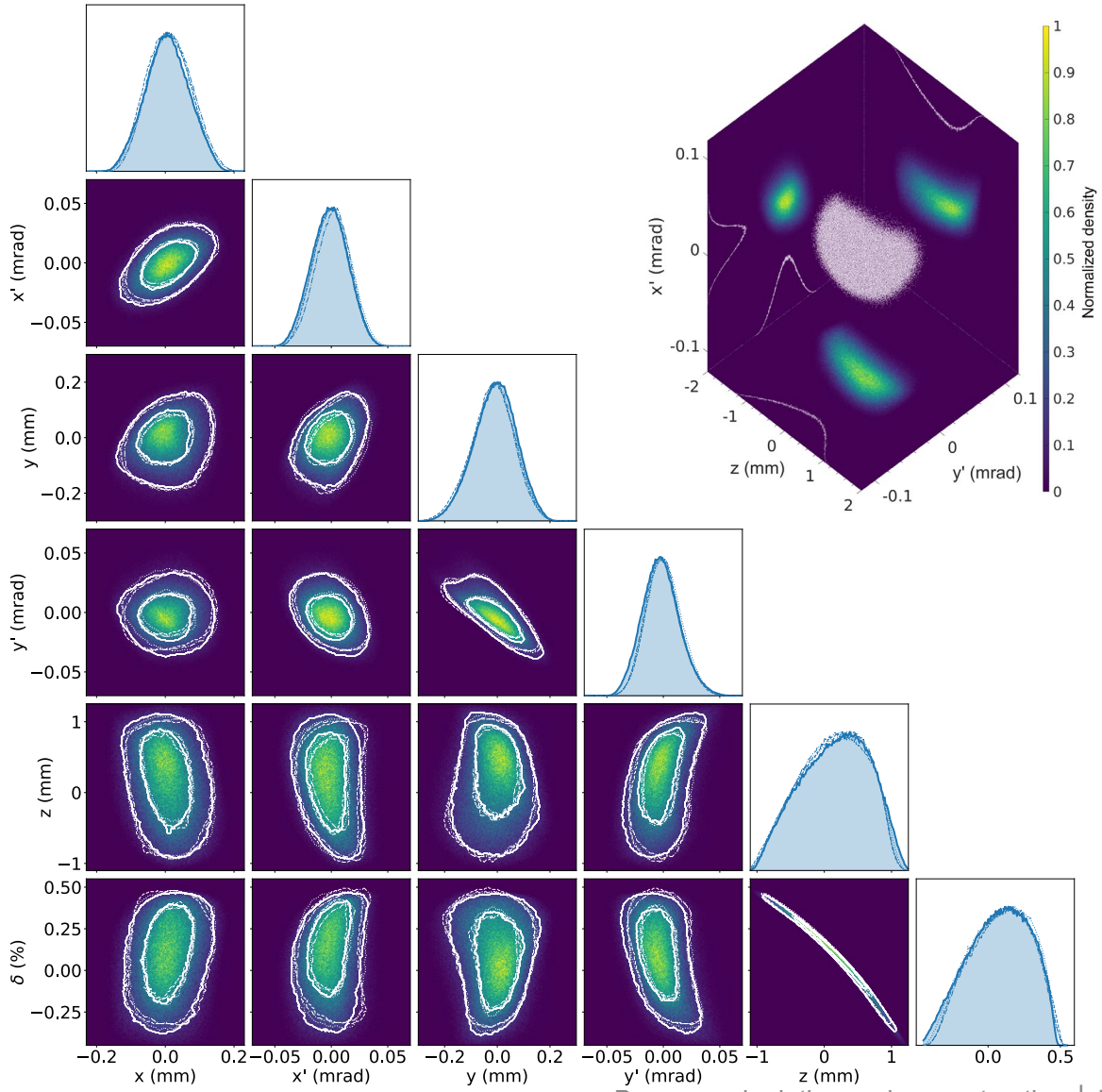
Reconstructed phase space @ Q1 entrance



Parameters	4D Reconstruction	6D reconstruction
β_x (m)	4.59±0.08	4.51±0.07
β_y (m)	7.65±0.11	7.81±0.10
α_x (rad)	−0.55±0.02	−0.52±0.05
α_y (rad)	1.18±0.02	1.15±0.06
ε_{nx} (mm mrad)	0.43±0.01	0.43±0.01
ε_{ny} (mm mrad)	0.41±0.01	0.41±0.02

Parameters	Measurement	6D reconstruction
ε_{nz} (mm mrad)	137.34±17.240	143.36±3.87
σ_z (mm)	0.45±0.01	0.46±0.00
σ_δ (%)	0.24±0.01	0.22±0.00
Slice σ_δ(%)		0.01 (typical)

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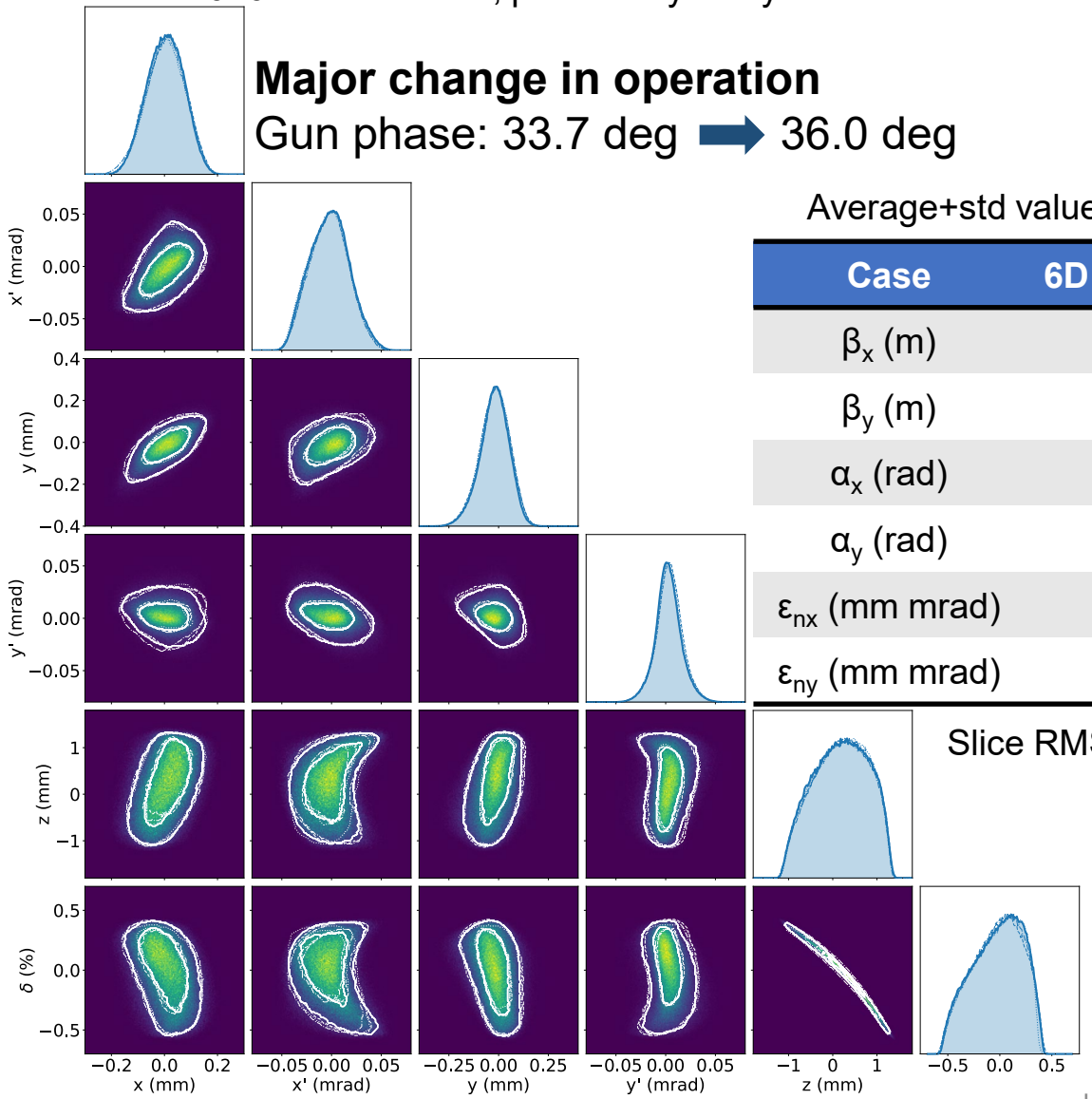
More information from 6D GPSR

- March 2026 measurement, preliminary analysis



Major change in operation

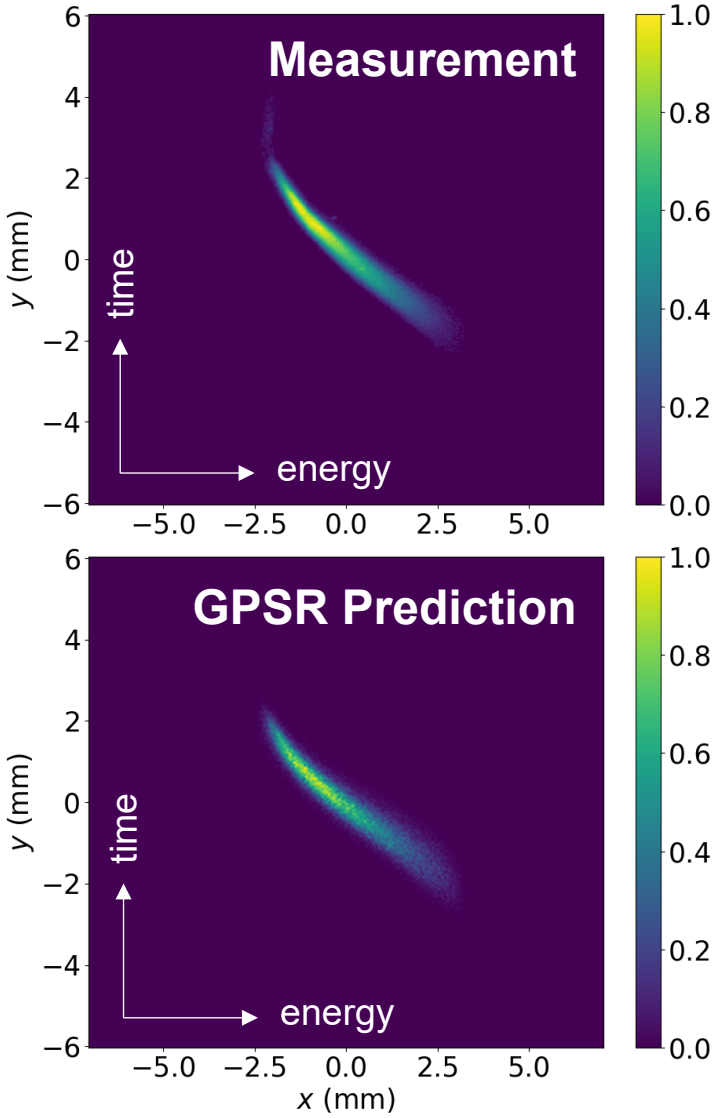
Gun phase: 33.7 deg ➡ 36.0 deg

Average+std value from 15 iterations

Case	6D reconstruction
β_x (m)	4.28±0.19
β_y (m)	5.96±0.18
α_x (rad)	-0.60±0.03
α_y (rad)	0.37±0.03
ε_{nx} (mm mrad)	0.57±0.011
ε_{ny} (mm mrad)	0.45±0.013

Slice RMS energy spread: 0.01%

Longitudinal phase space: **(x,y) projection**



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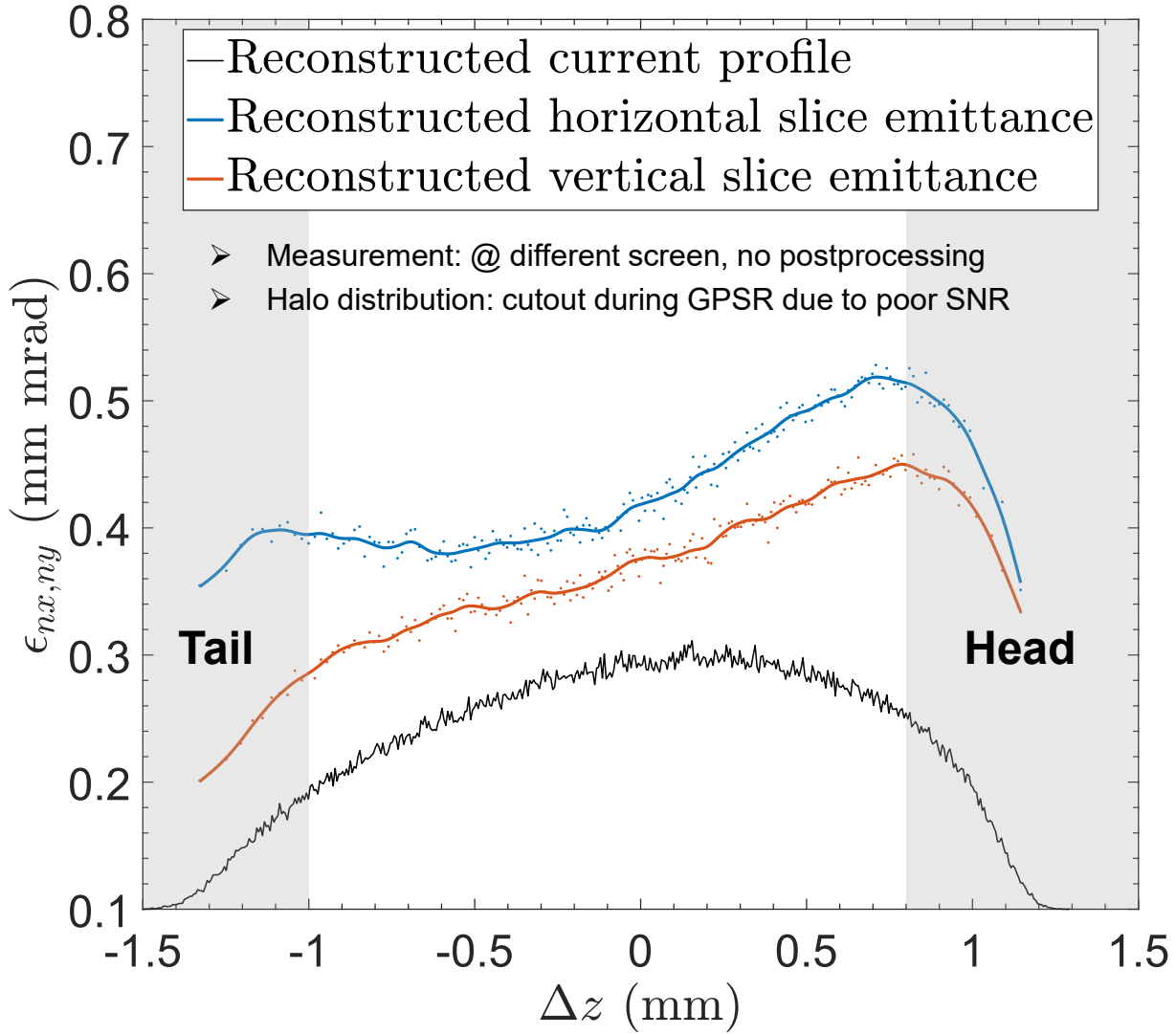
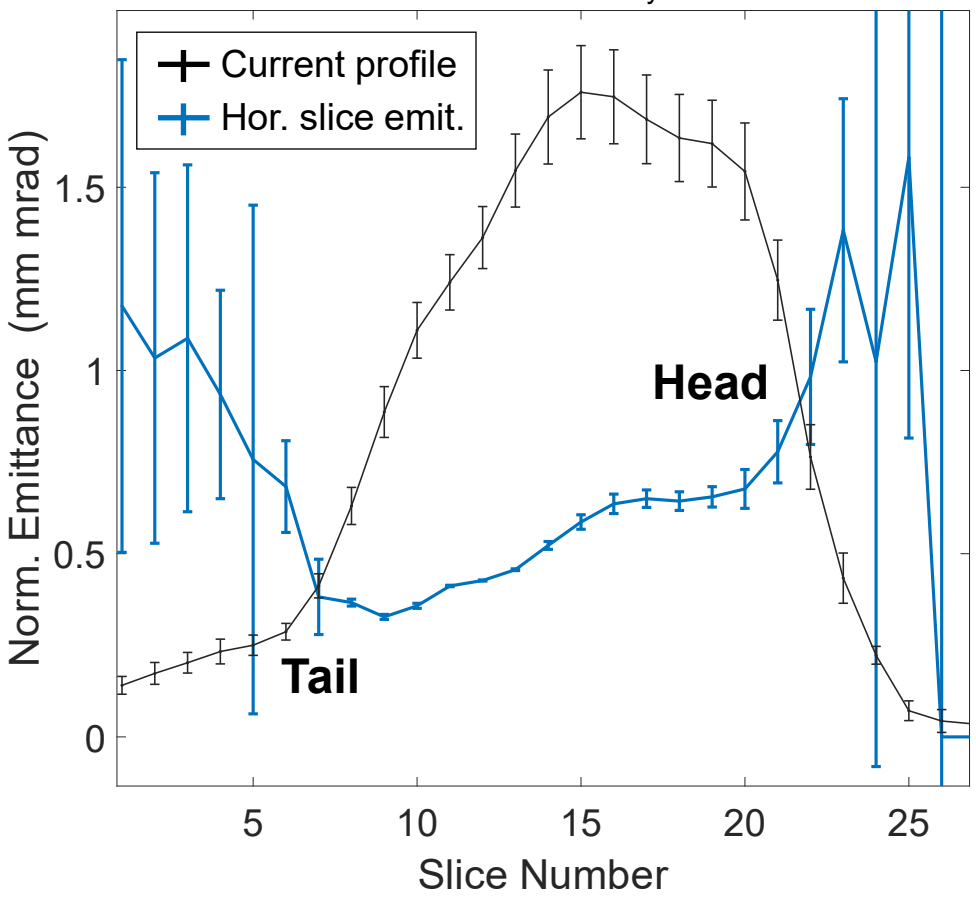
More information from 6D GPSR: x/y slice emittances

- March 2026 measurement, preliminary analysis



Conventional slice emittance measurement @ different screen (using TCAV)



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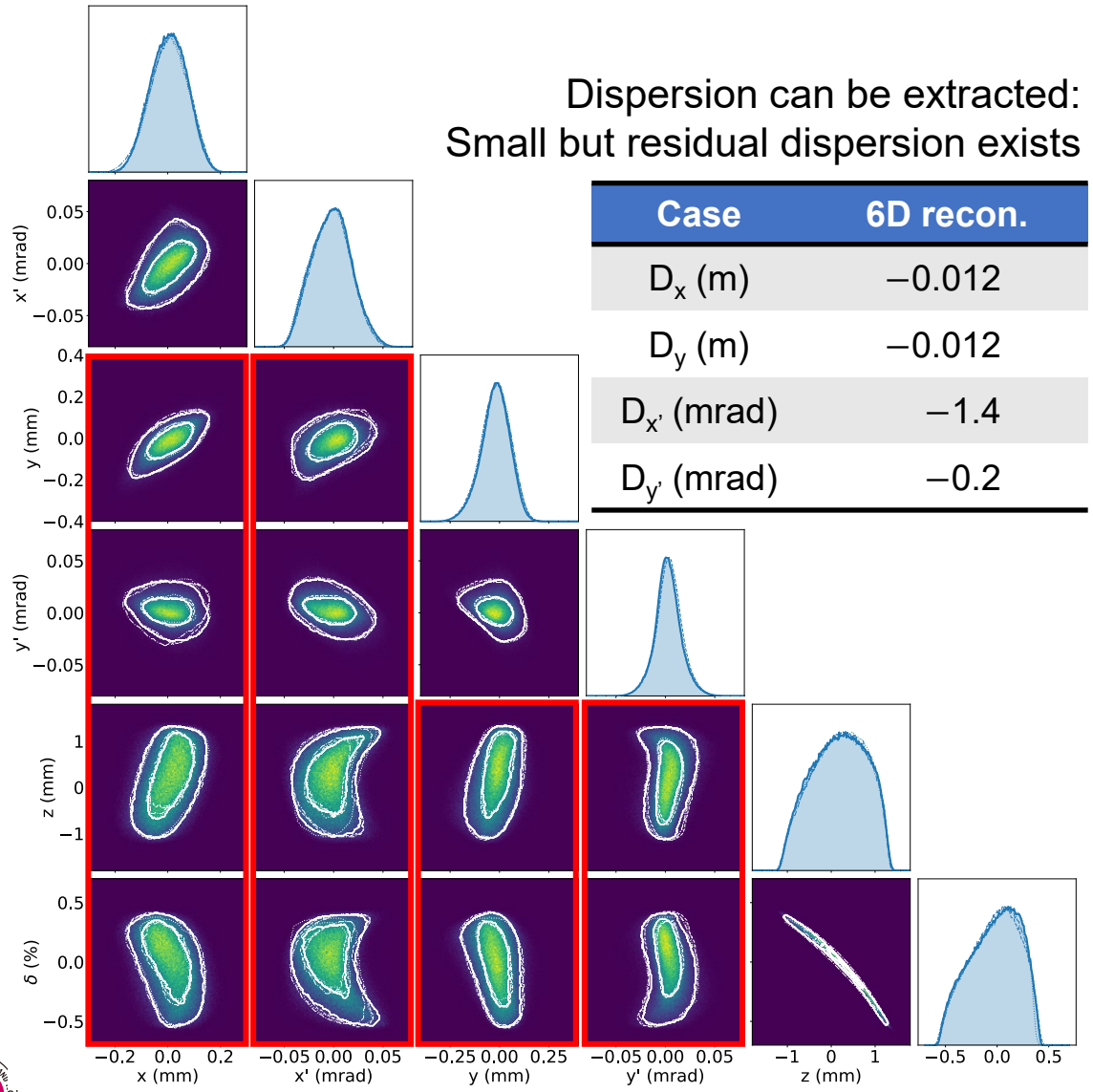
*Diagonal terms are naturally 1.0

More information from 6D GPSR: dispersion, correlations

- March 2026 measurement, preliminary analysis



Dispersion can be extracted:
Small but residual dispersion exists

Case	6D recon.
D_x (m)	−0.012
D_y (m)	−0.012
$D_{x'}$ (mrad)	−1.4
$D_{y'}$ (mrad)	−0.2

For $\mathbf{X} = (x, x', y, y', z, \delta)$,

Pearson correlation coefficient: $\rho(i,j) = \frac{< X_i X_j >}{\sqrt{< X_i^2 >< X_j^2 >}}$

Coefficient close to ± 1: strongly correlated*

Coefficient for reconstructed phase space

$$\rho_{\mathbf{X}} = \begin{bmatrix} 1.000 & 0.516 & 0.673 & -0.089 & 0.425 & -0.400 \\ 0.516 & 1.000 & 0.455 & -0.430 & 0.152 & -0.174 \\ 0.673 & 0.455 & 1.000 & -0.351 & 0.378 & -0.365 \\ -0.089 & -0.430 & -0.351 & 1.000 & 0.061 & -0.029 \\ 0.425 & 0.152 & 0.378 & 0.061 & 1.000 & -0.988 \\ -0.400 & -0.174 & -0.365 & -0.029 & -0.988 & 1.000 \end{bmatrix}$$

For ideal impact+elegant simulations, correlations are typically in the order of 0.001

This information from the GPSR can be used for the optimization of beam correlations

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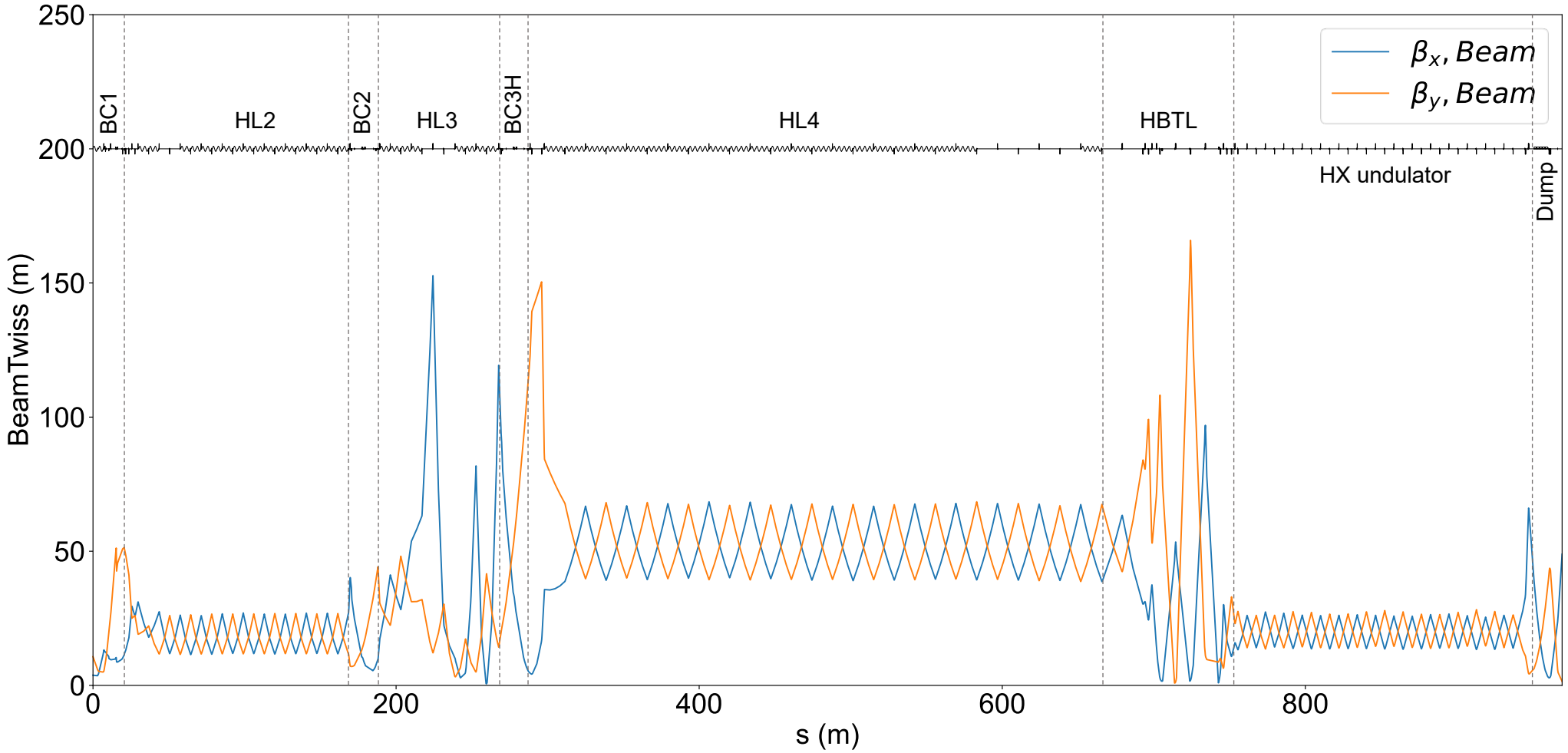
*Model calibration: currently under investigation at the PAL-XFEL

For more information on the optimization: S. Kim *et al., In. Proc. ICALEPCS 2025*, Chicago, IL, USA, **MOCG004 (2025)

Applications using 6D GPSR: beamline optimizations

- elegant simulation used



GPSR-based beam diagnostics → optimization → calibrated model-based digital twin*

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Summary and future works

- **Beam manipulation becomes gradually important**
  - Manipulation of cross-plane correlation, nonlinear chirp and double horn, final focus with certain shape, for high-energy physics applications and high-brightness X-ray light

- **GPSR-based phase space reconstruction was successfully demonstrated both at test and user facilities**
  - All the coupled phase spaces can be successfully predicted also for special beams
  - readily applicable using common elements such as RF cavity, quad, dipole, and screen
  - Near unique solution: can represent the physical ground truth
  - Optimization of the beamline using 6D GPSR results, incorporated into physics simulations

- **PAL-XFEL enhancement will be carried out**
  - Beam diagnostics using the GPSR technique will be performed @ PAL-XFEL to investigate the machine condition: measurement-based model calibration can be performed
  - Therefore, measurement-based optimization using calibrated model can be performed to maximize the FEL quality and on-line virtual diagnostics

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