SLAC NATIONAL ACCELERATOR LABORATORY | THE UNIVERSITY OF CHICAGO

PAL 포항가속기연구소 POHANG ACCELERATOR LABORATORY

POSTECH

5th ICFA ML workshop, Geneva, Switzerland, April 2025

A path to efficient machine learning-based beam diagnostics: 6-dimensional phase space reconstruction along bunch compressors at PAL-XFEL*

Seongyeol Kim

PAL-XFEL Beam Physics Group

April 10, 2025

*Original title: Complete six-dimensional generative phase space reconstruction without RF deflecting cavity

*Pohang Accelerator Laboratory, X-ray Free Electron Laser, Pohang, Republic of Korea

*Presentation based on: Seongyeol Kim *et al.,* https://arxiv.org/abs/2502.20654, 2025.

Contents

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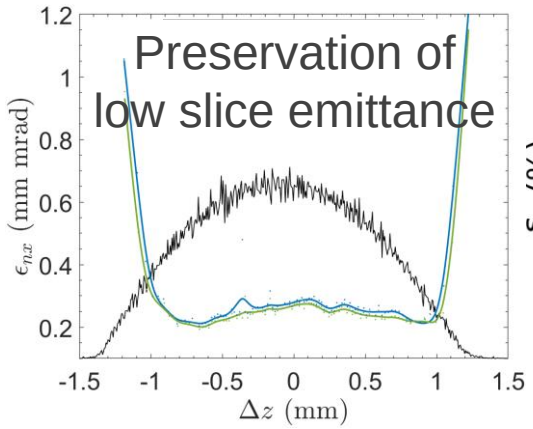
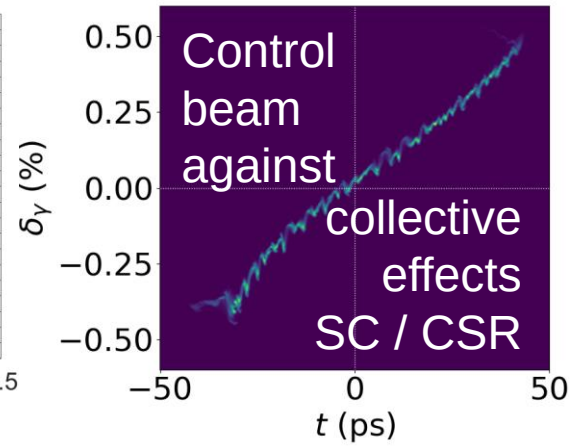
- C. A. Lindstrom *et al., Phys. Rev. Lett.* **126**, 014001, 2021.
- C. Emma *et al., Phys. Rev. Lett.* **134**, 085001, 2025.

Introduction: 6-dimensional phase space diagnostics

X-ray Free Electron Laser (XFEL)

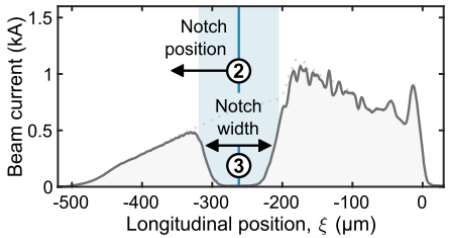
For ultra-short, high-brightness XFEL:



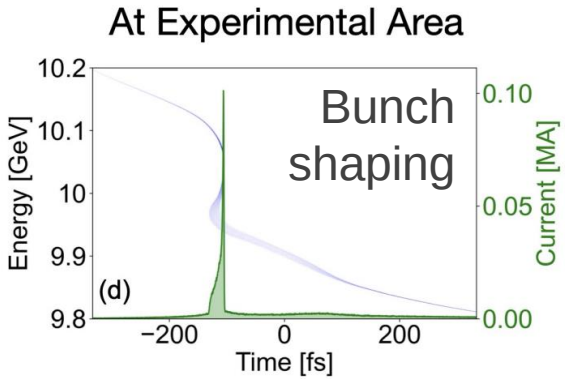


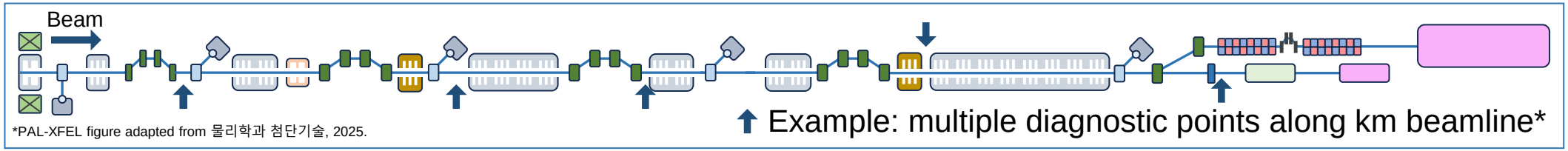
Advanced Accelerator Concepts

For high-efficiency wakefield accelerations:



Preservation of
energy spread





*PAL-XFEL figure adapted from 물리학과 첨단기술, 2025.

For ultra short, high-brightness XFEL and high-efficiency advanced accelerators:

Precise 6D beam diagnostics at multiple beamline locations are essential

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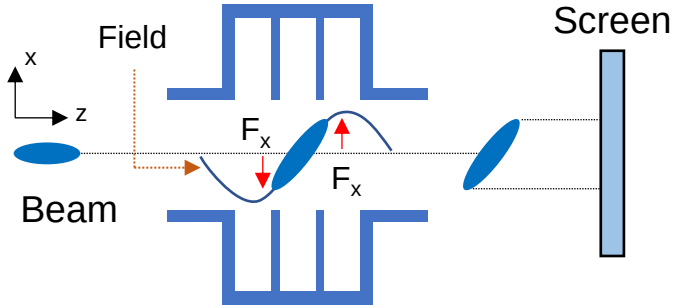
Conventional diagnostic methods

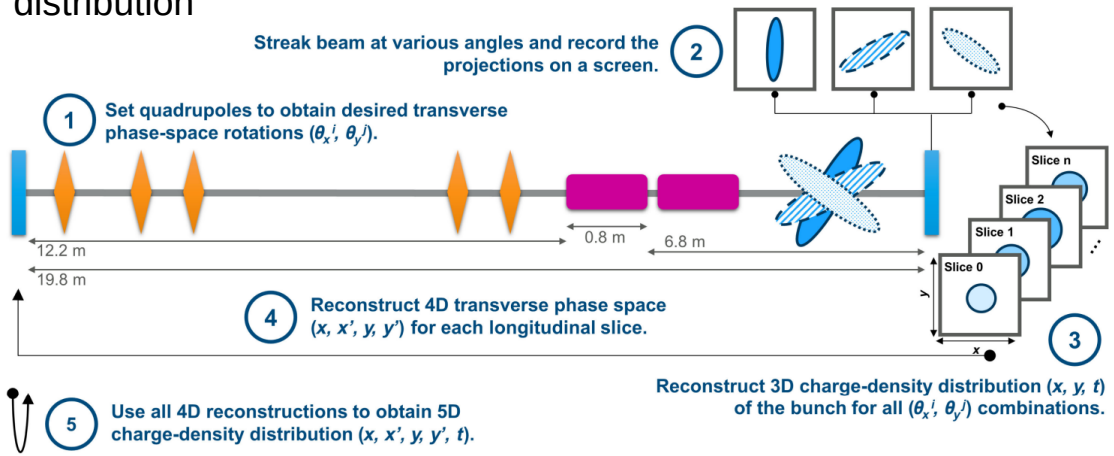
Based on tomography method

- S. Andersen and A. Kak, SART, *Ultrasonic Imaging* **6**, 81, 1984.
- Hock K. and Ibison M., *J. Instrumentation* **8**, 2013.
- B. Marchetti *et al., Sci. Rep.* **11**, 3560, 2021.
- S. Jaster-Merz *et al., Phys. Rev. Accel. Beams* **27**, 072801, 2024.
- Brandon Cathey *et al., Phys. Rev. Lett.* **121**, 064804, 2018.

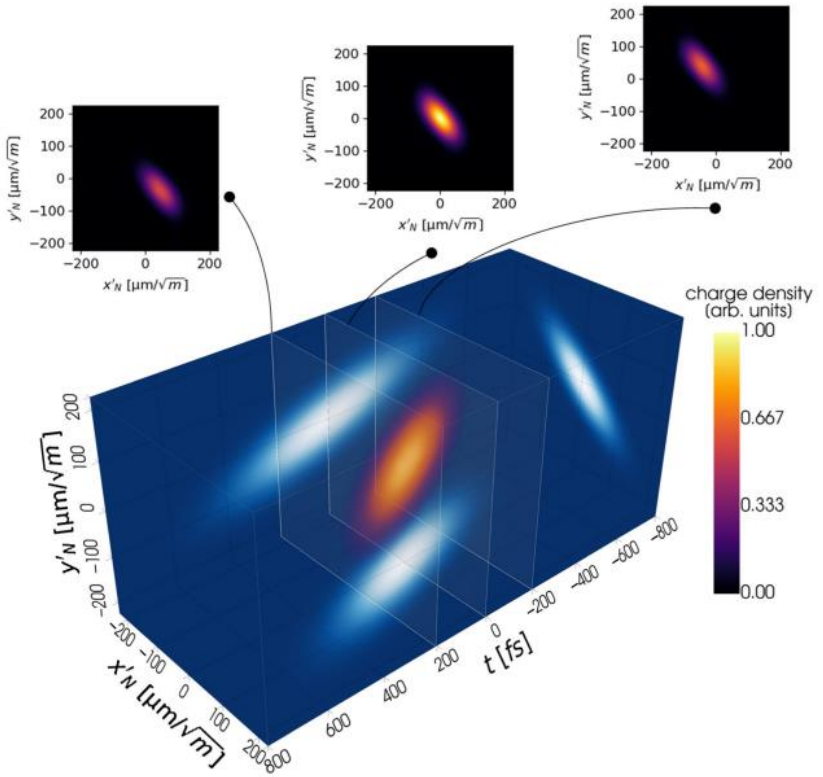
RF Transverse deflecting cavity (TDS or TCAV)



➢ kick the bunch to induce x-z correlation: can obtain the longitudinal distribution



5D tomography using PolariX TDS



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- B. Marchetti *et al., Sci. Rep.* **11**, 3560, 2021.
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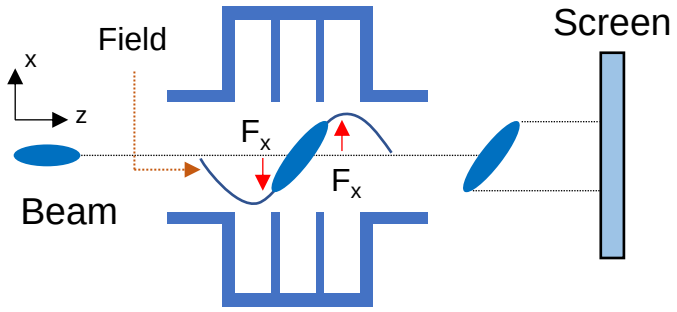
RF Transverse deflecting cavity (TDS or TCAV)



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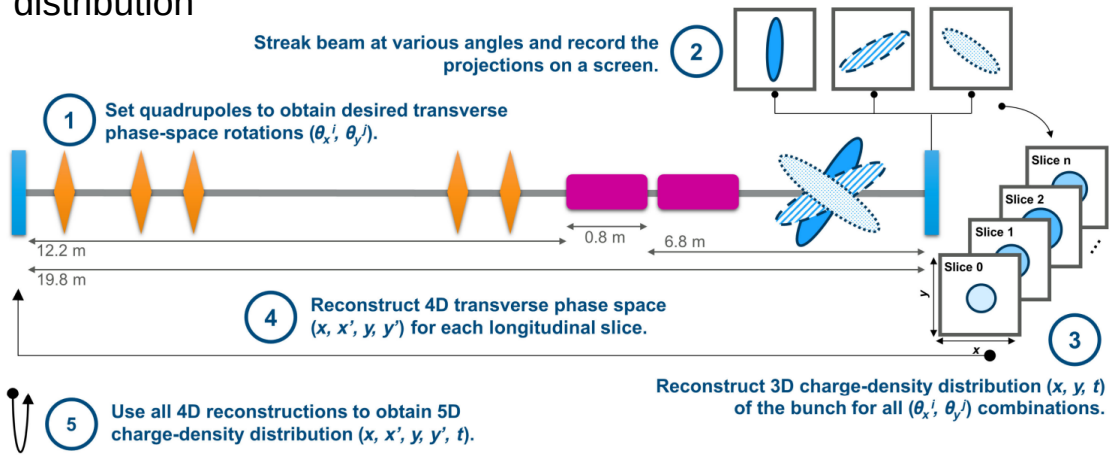
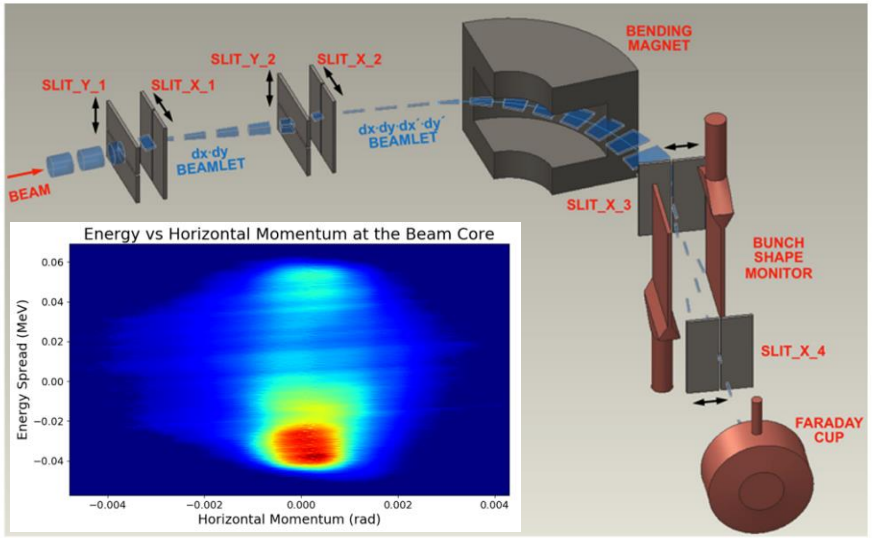


5D tomography using PolariX TDS

First 6D phase space diagnostics @ SNS, ORNL



Cases	# of data samples
5D	6,000 (Tracking sim., 60 trans. rotation + 100 streaking angles)
6D	5,675,740 grids (32 hours to take)

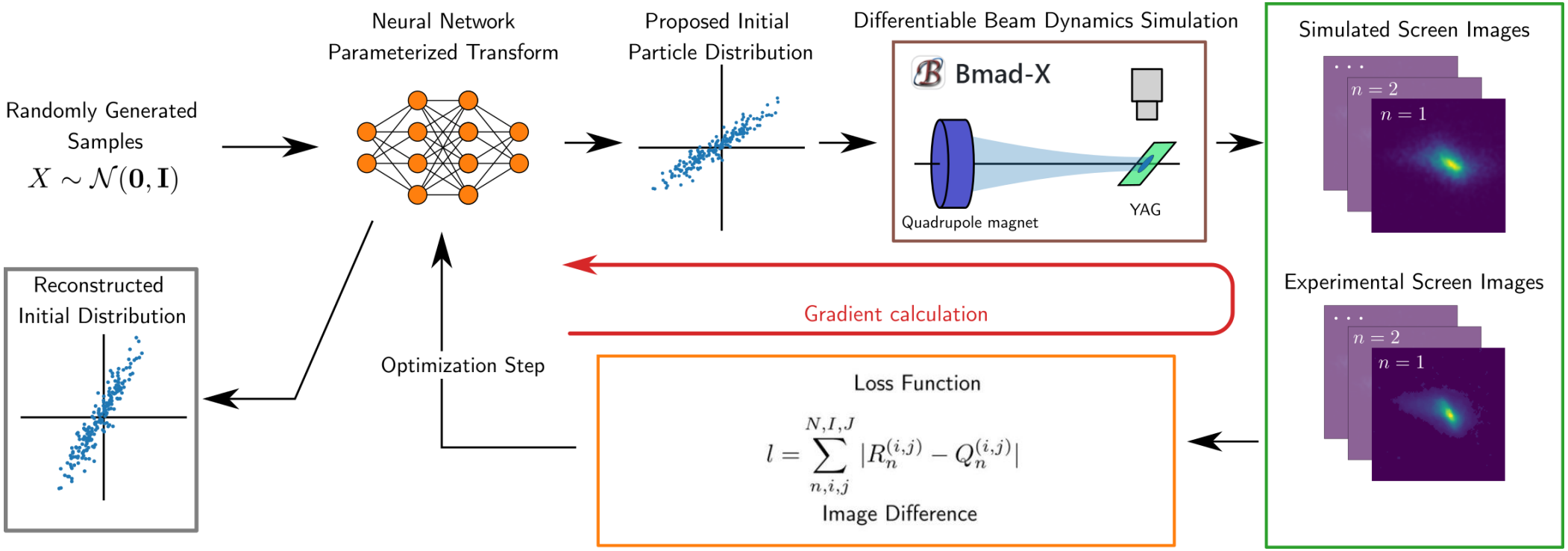
Conventional diagnostics requires specialized elements and dedicated beam time

Robust diagnostic technique is needed for simple / fast / accurate measurements

- 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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Generative phase space reconstruction (GPSR)

- R. Roussel *et al., PRL* **130**, 145001, 2023.
- S. Kim *et al., PRAB* **27**, 074601, 2024.
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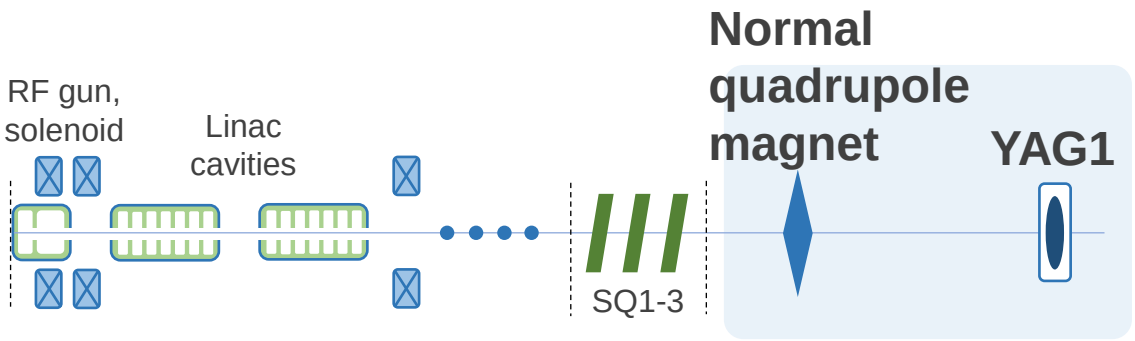
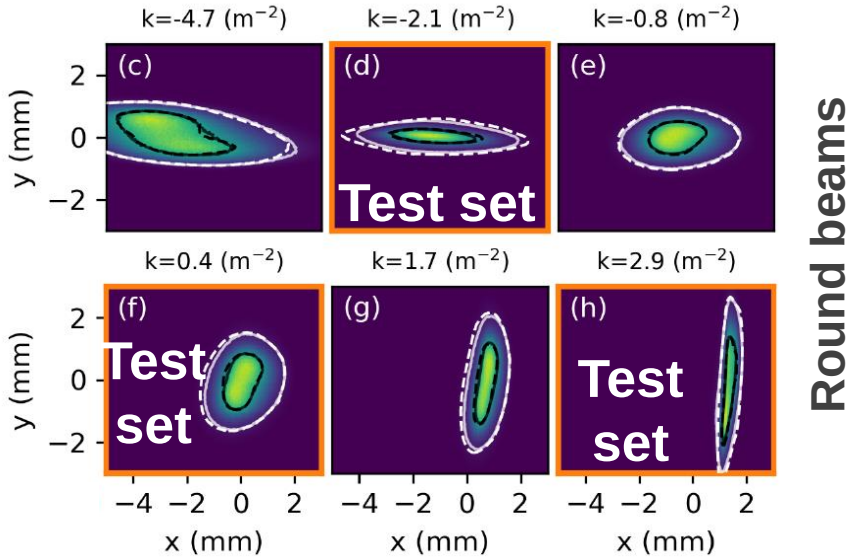
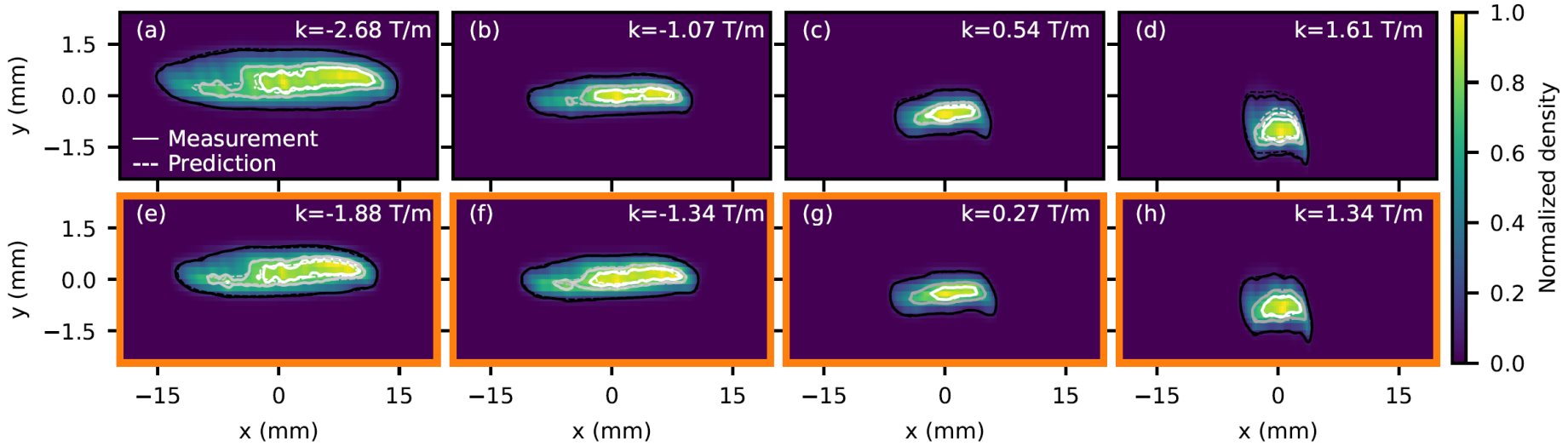


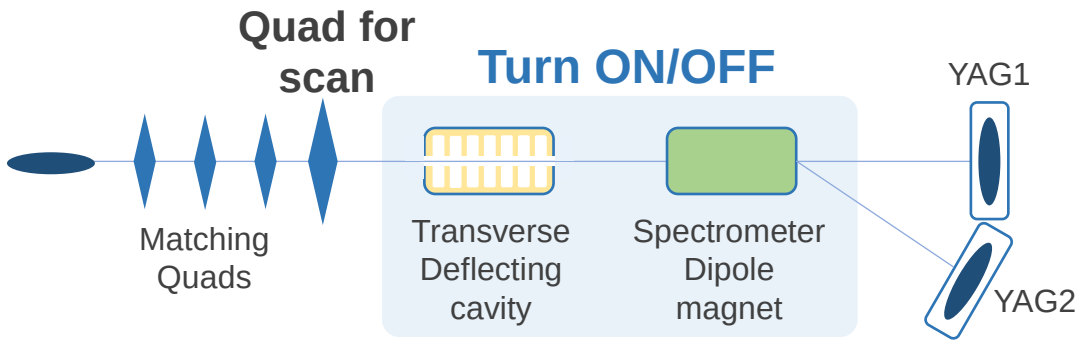


Flat / magnetized beams

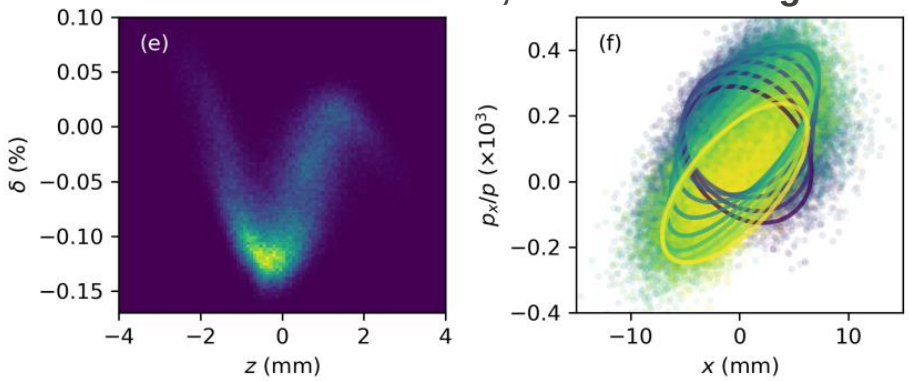


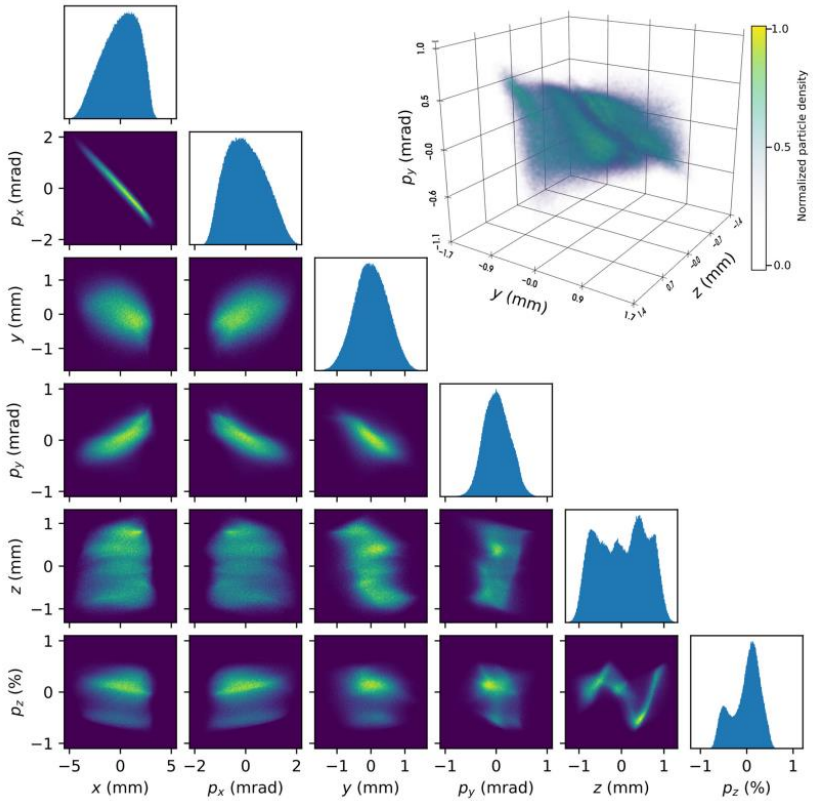
- R. Roussel *et al., PRL* **130**, 145001, 2023.
- S. Kim *et al., PRAB* **27**, 074601, 2024.
- R. Roussel *et al., PRAB* **27**, 094601, 2024.
- J.P. Gonzalez-Aguilera *et al., IPAC'24*, 2024.

Generative phase space reconstruction (GPSR)



CSR characterization, JP Gonzalez-Aguilera





➡ Need a breakthrough for GPSR-based efficient beam diagnostics without specialized diagnostic equipment

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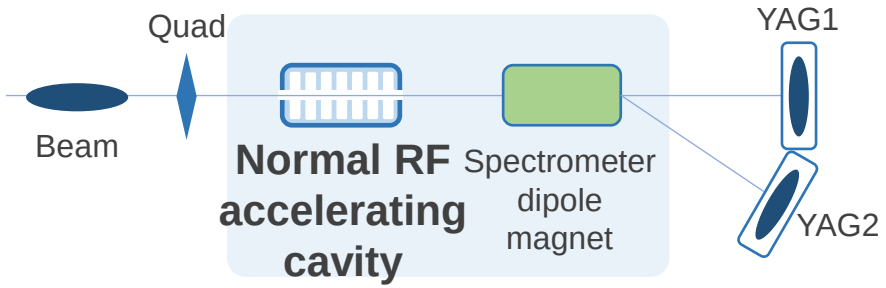
6D GPSR using RF accelerating cavity

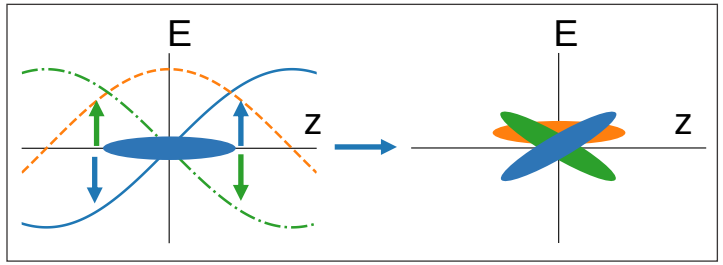
Inspired by conventional longitudinal emittance measurement*

***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.

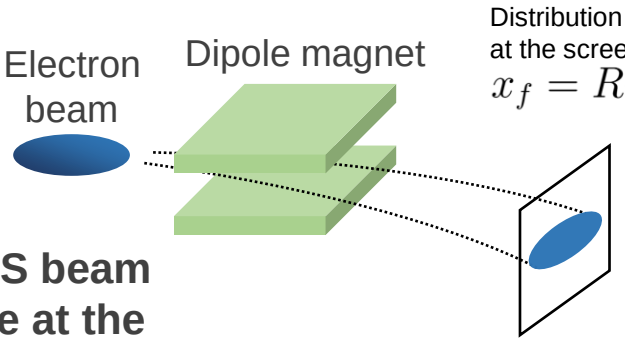


$$\Delta E(z) = eV\cos\left(k_{RF}z + \phi_{RF}\right)$$



For a given longitudinal distribution:

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



Distribution at the screen

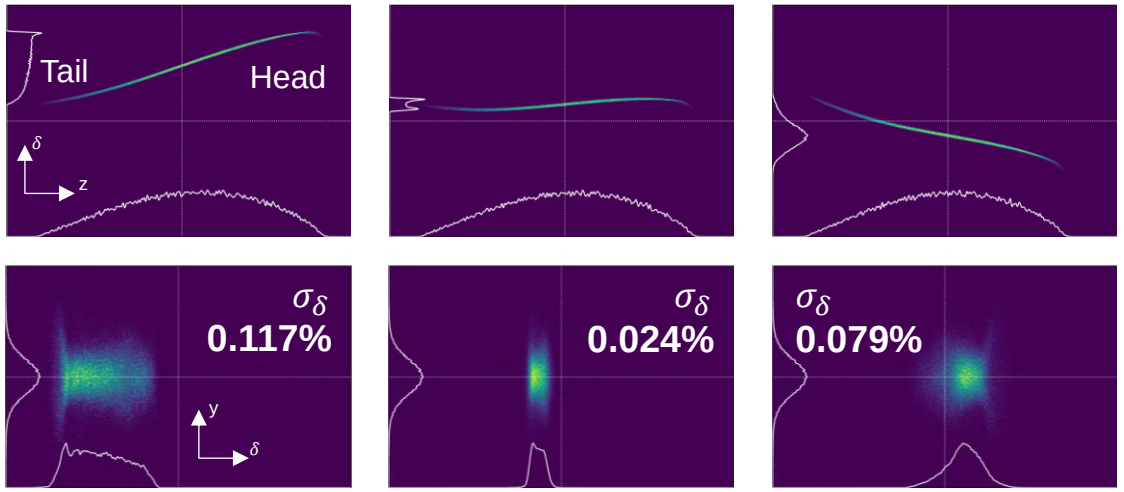
$$x_f = R_{11}x_0 + R_{12}x_0' + R_{16}\,\delta_0$$

Dispersion of dipole magnet — **Fractional energy spread**

RMS beam size at the screen

$$\sigma_x = \sqrt{\beta_x\epsilon_x + \left(D_x\,\sigma_\delta\right)^2}$$ → **RMS energy spread**

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



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

Transfer matrix for cavity and drift

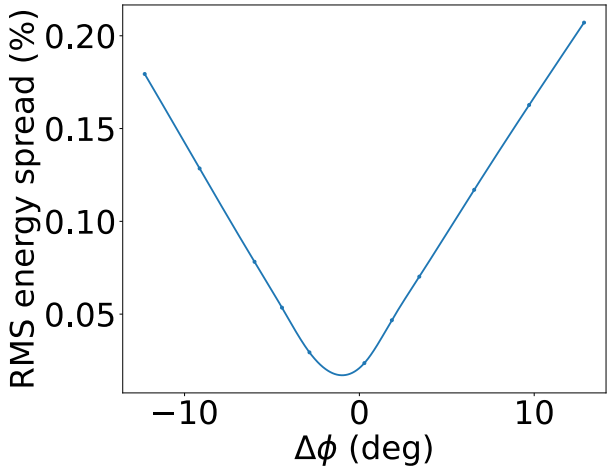
$$M = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -V\sin(\phi_{RF}) & 1 \end{pmatrix} \quad \text{where} \quad \Sigma_i = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} < z^2 > & < z\delta > \\ < z\delta > & < \delta^2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

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

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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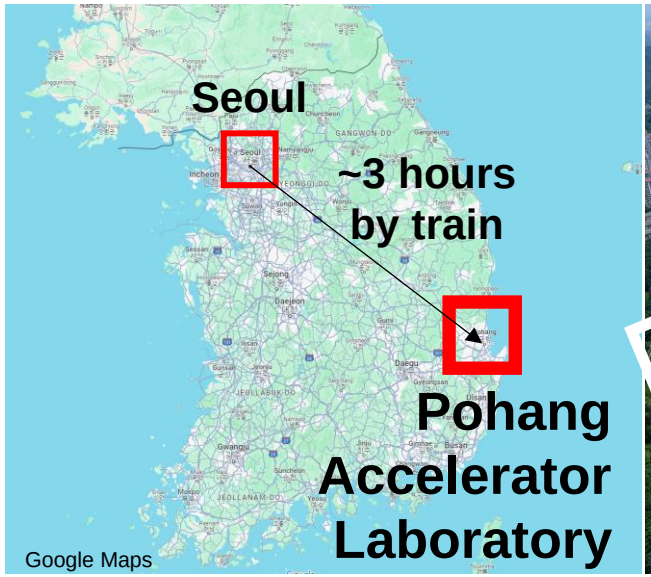
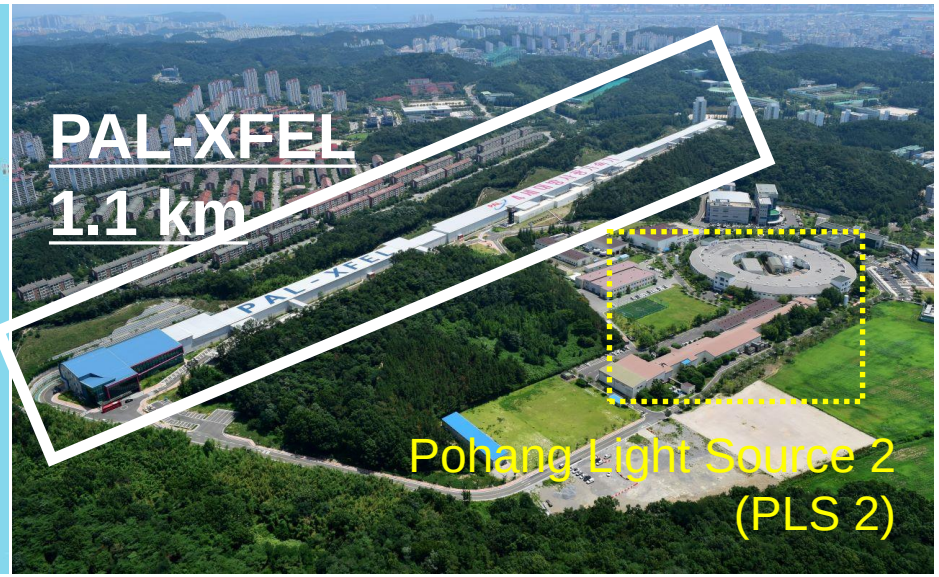
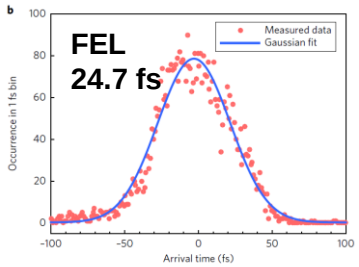
- H.-S. Kang *et al., Nat. Photonics* **11**, 2017.
- I. Nam *et al., Nat. Photonics* **15**, 2021.
- PAL-XFEL figure adapted from 물리학과 첨단기술, 2025.

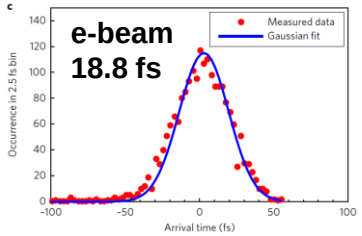
Introduction to PAL-XFEL, Korea



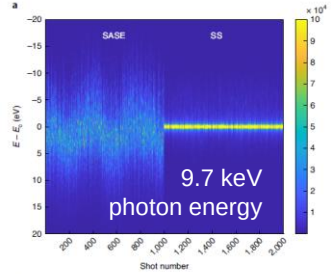


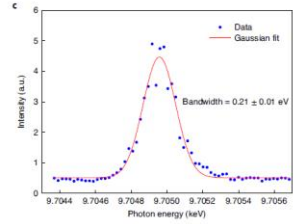
Femtosecond timing jitter[1)]

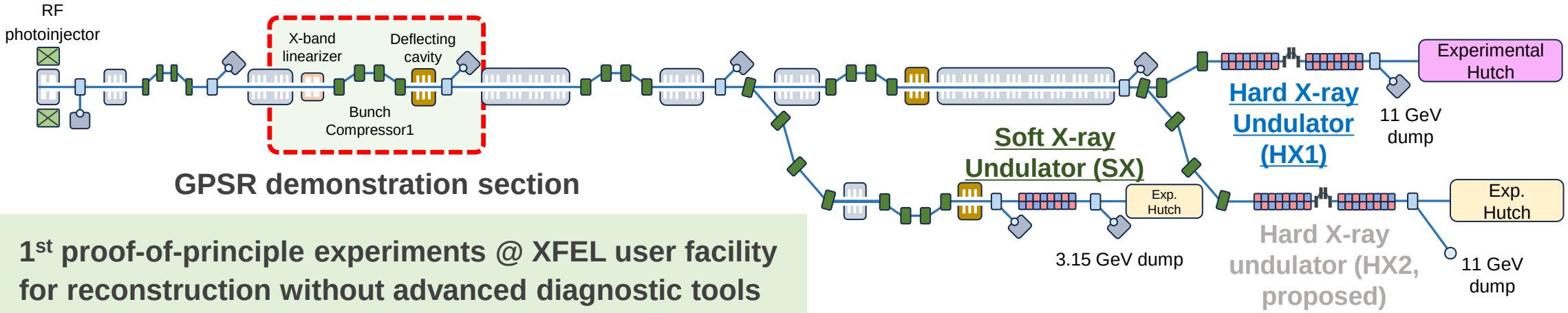




High-brightness self-seeded FEL[2)]







GPSR demonstration section

1st proof-of-principle experiments @ XFEL user facility for reconstruction without advanced diagnostic tools

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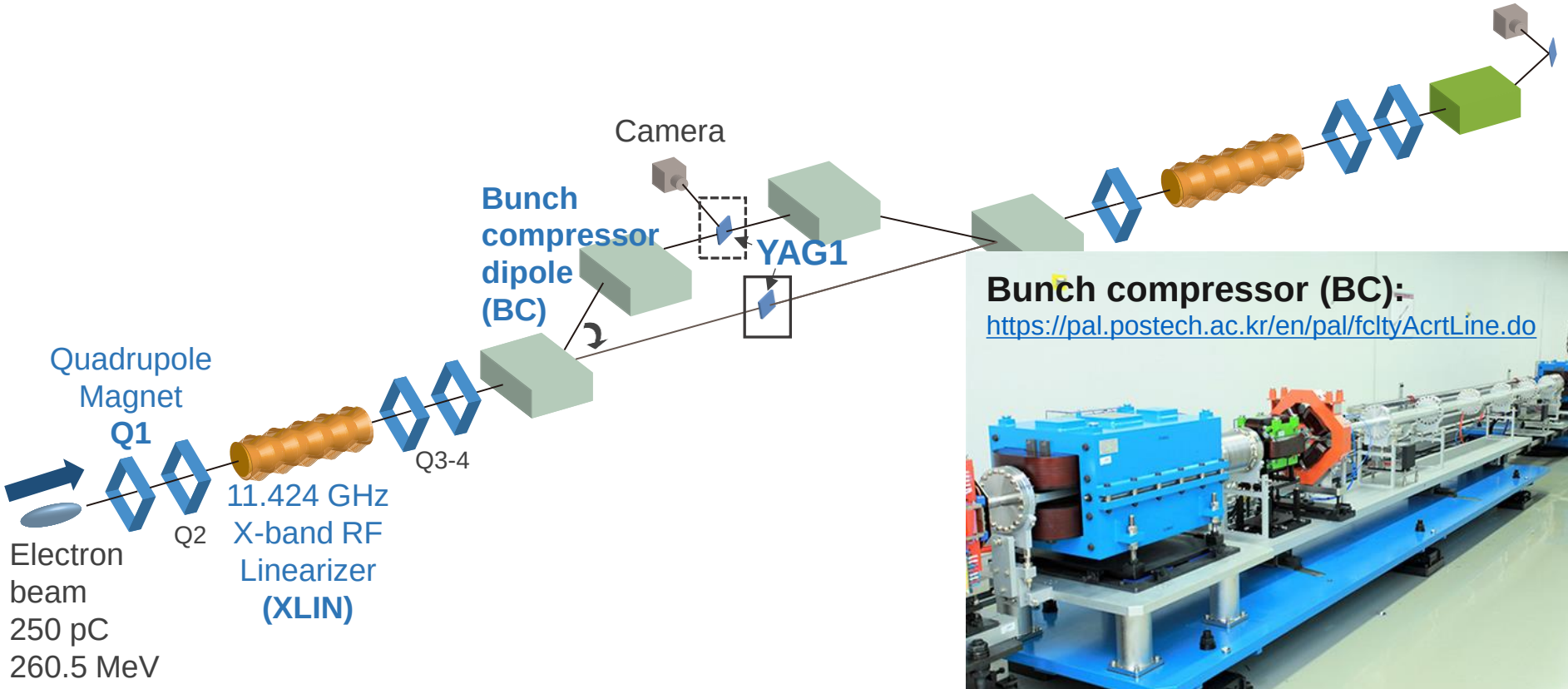
Experimental setup for the GPSR



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

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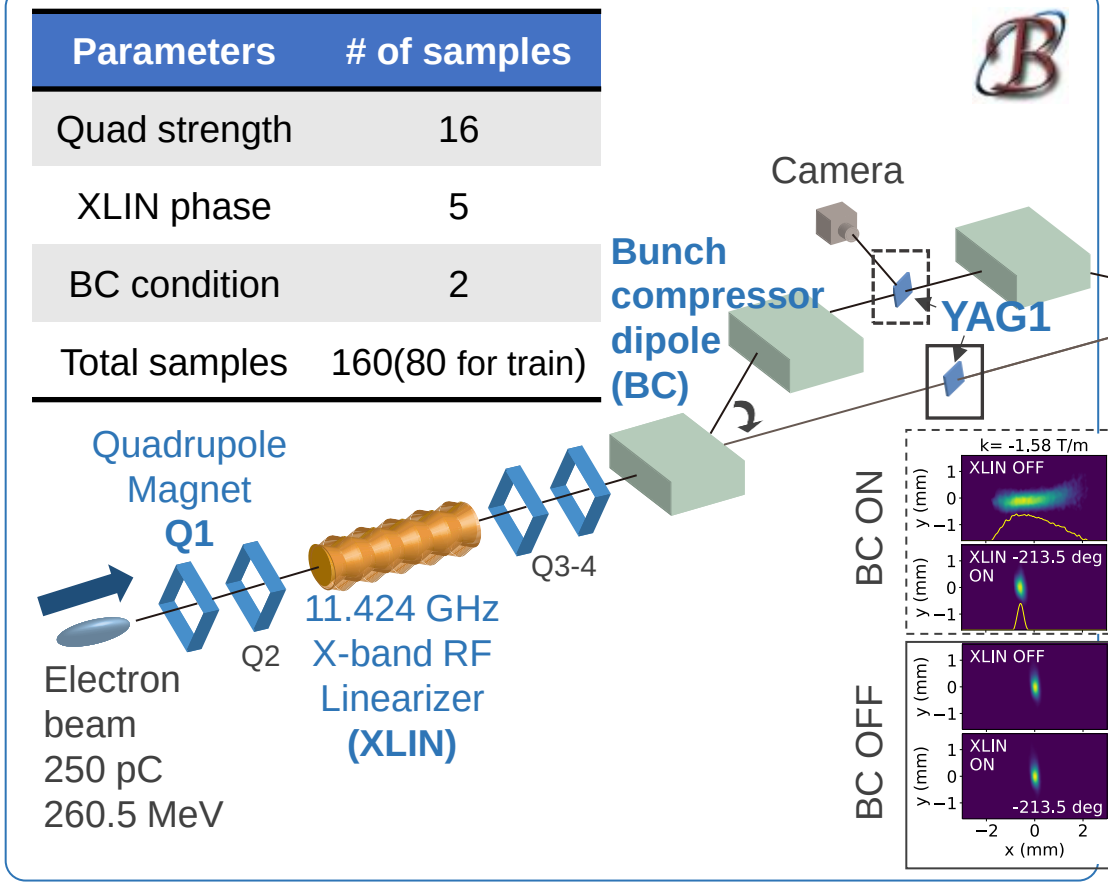
- Bmad-X: https://github.com/bmad-sim/Bmad-X

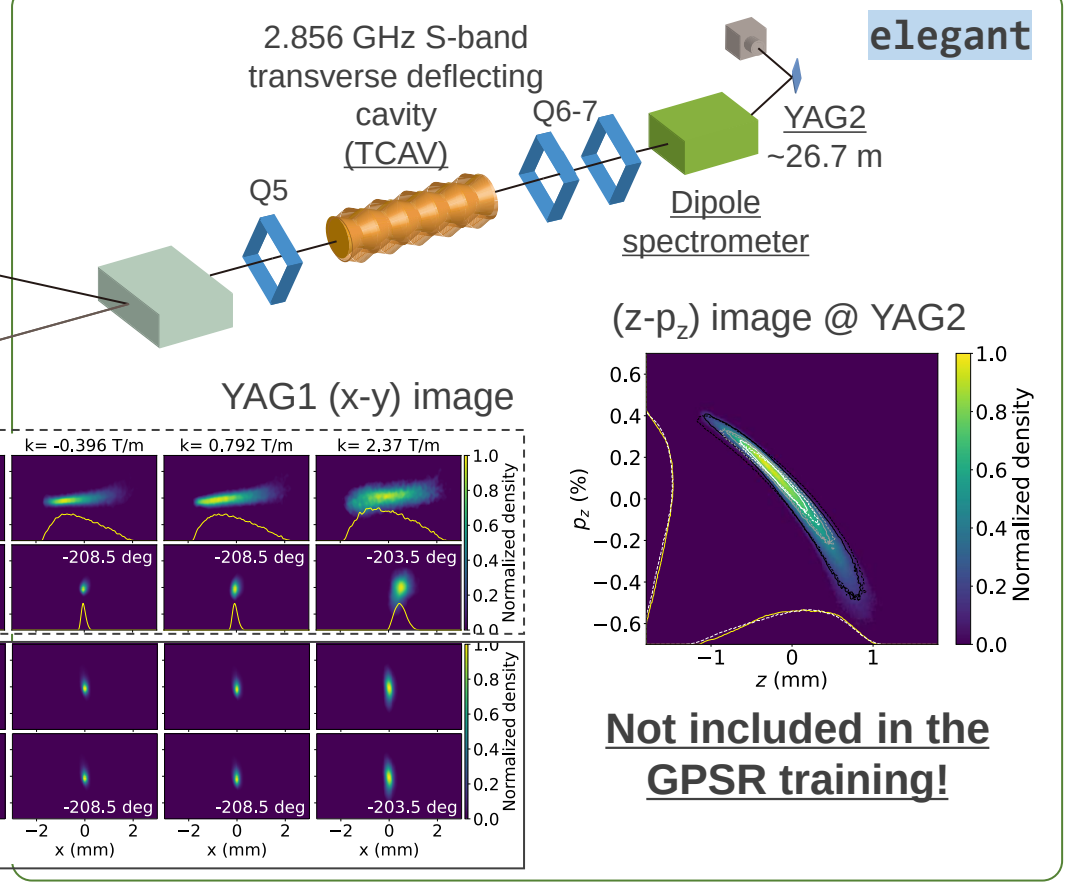
Experimental setup for the GPSR

GPSR demo section

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



GPSR validation section



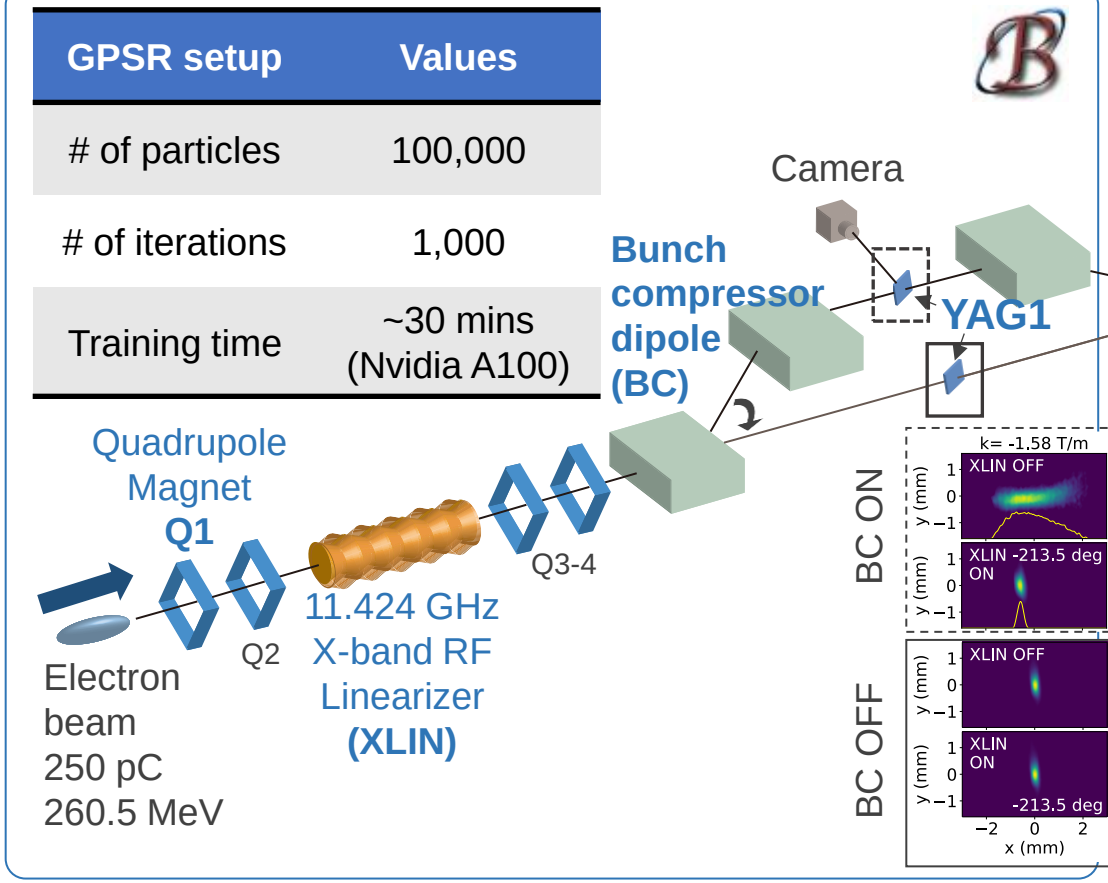
Not included in the GPSR training!

- Bmad-X: https://github.com/bmad-sim/Bmad-X

Experimental setup for the GPSR

GPSR demo section

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



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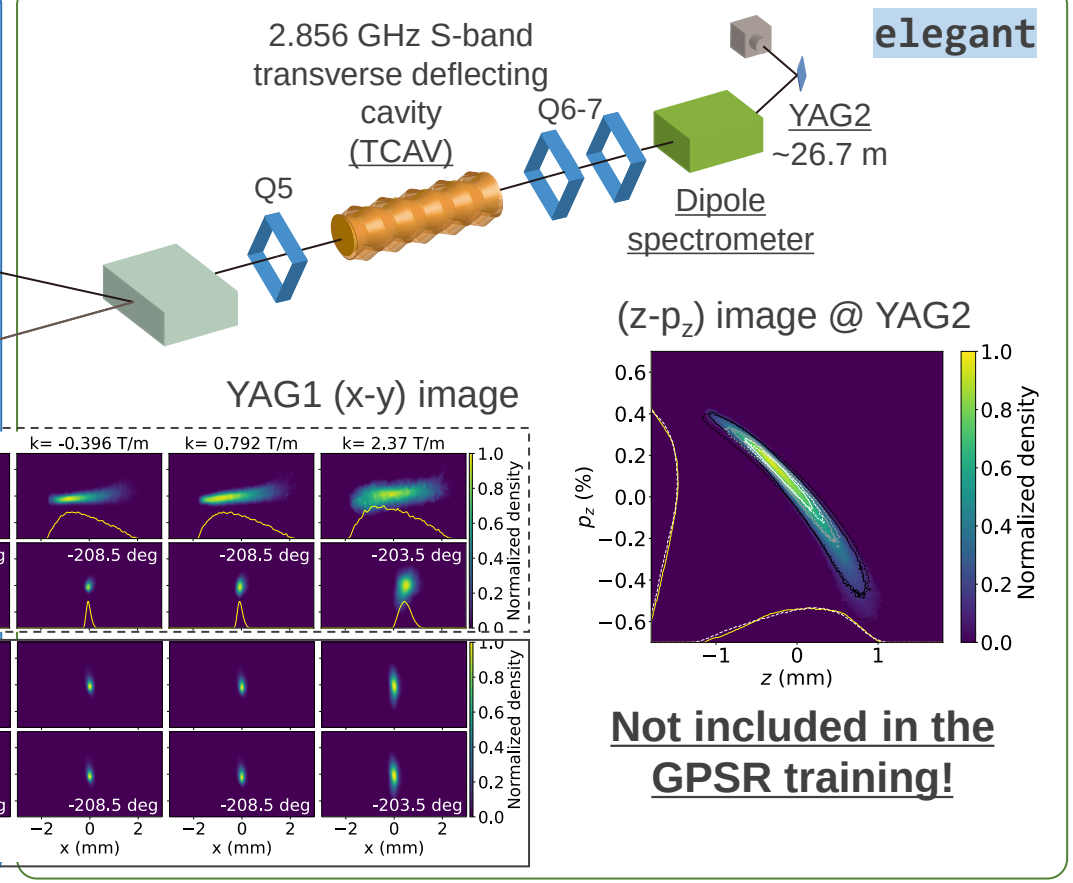


Not included in the GPSR training!

Predictions using reconstructed phase space: YAG1

Test dataset

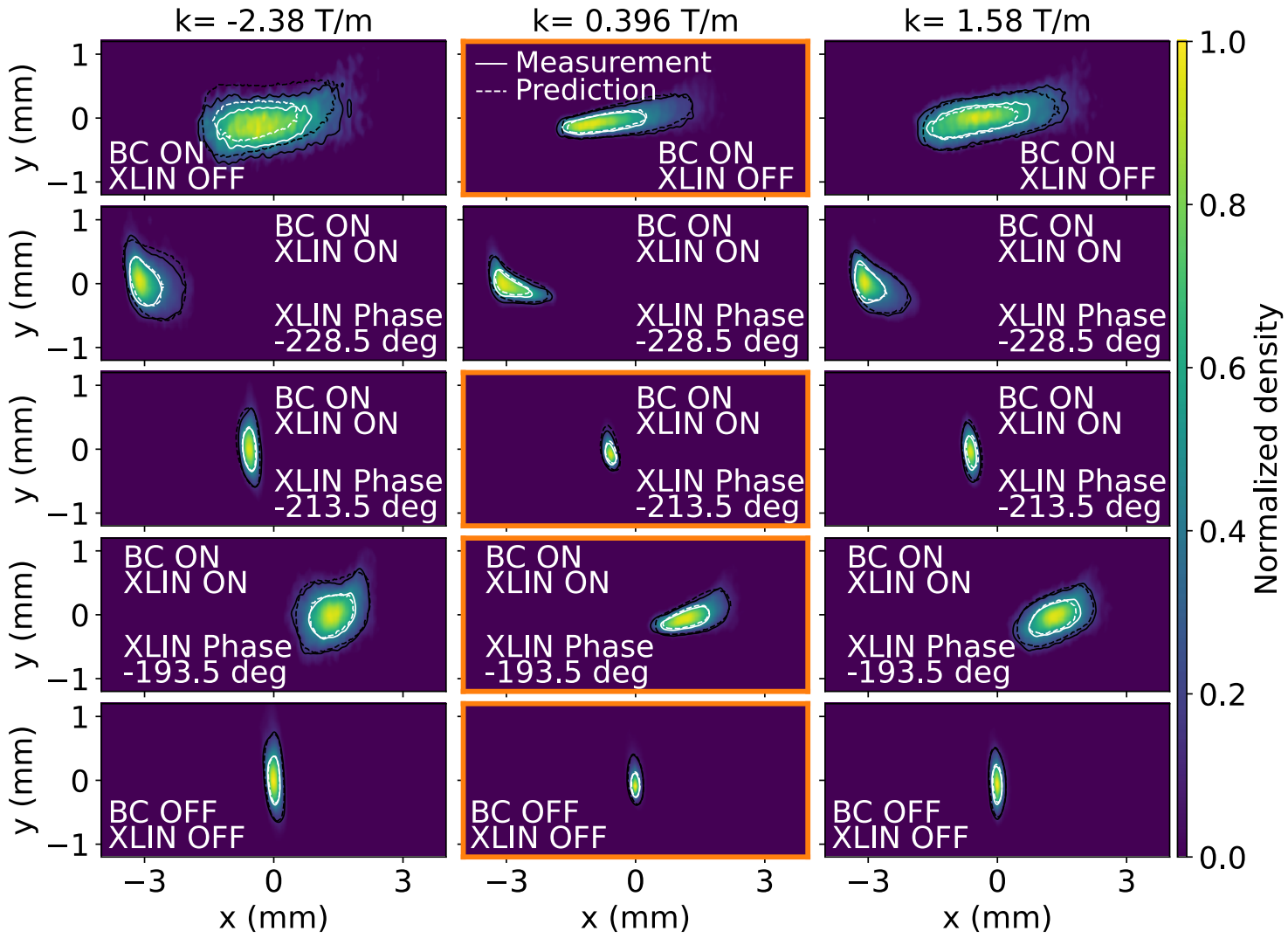
Training dataset

Background:
Measurement

90th
50th
Contour percentile

Measurements
Predictions

Reconstructed initial beam phase space successfully predicts YAG1 images



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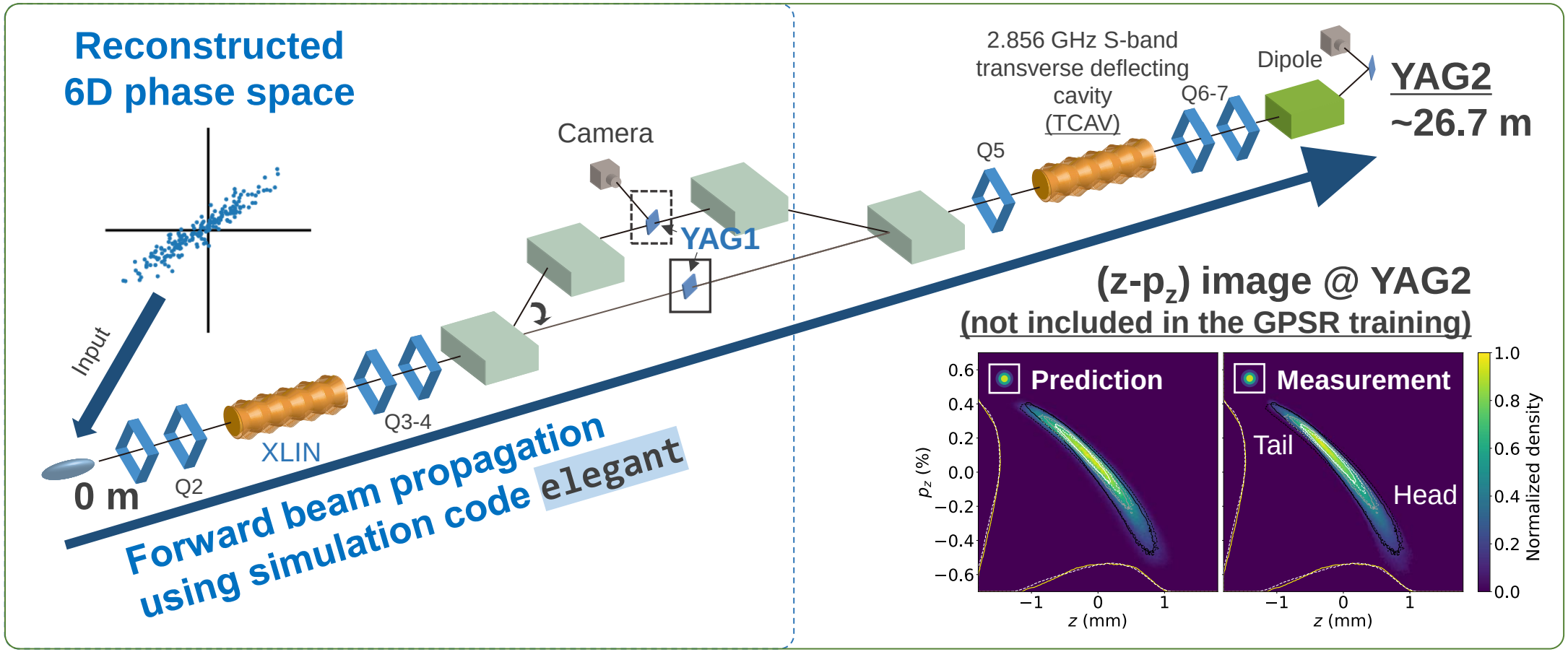
GPSR validation using downstream measurements



6D reconstructed phase space of the beam:

➡ **Can be used to predict the phase space at multiple locations**

Predictions using reconstructed phase space: YAG2

Independent downstream measurements

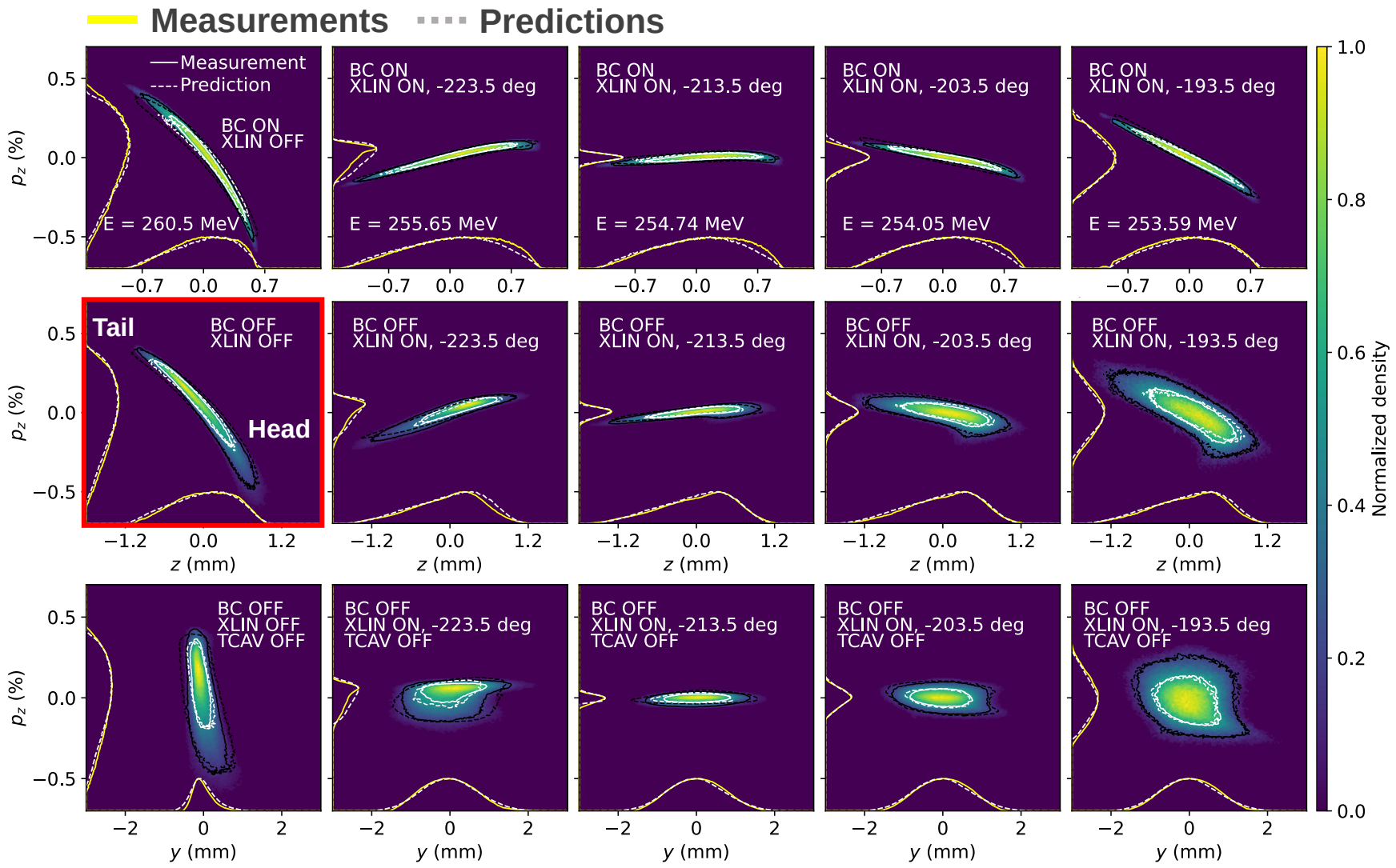
Background: Measurement

90th 50th Contour percentile

Measurements

Predictions

GPSR also successfully predicts independent downstream measurements!



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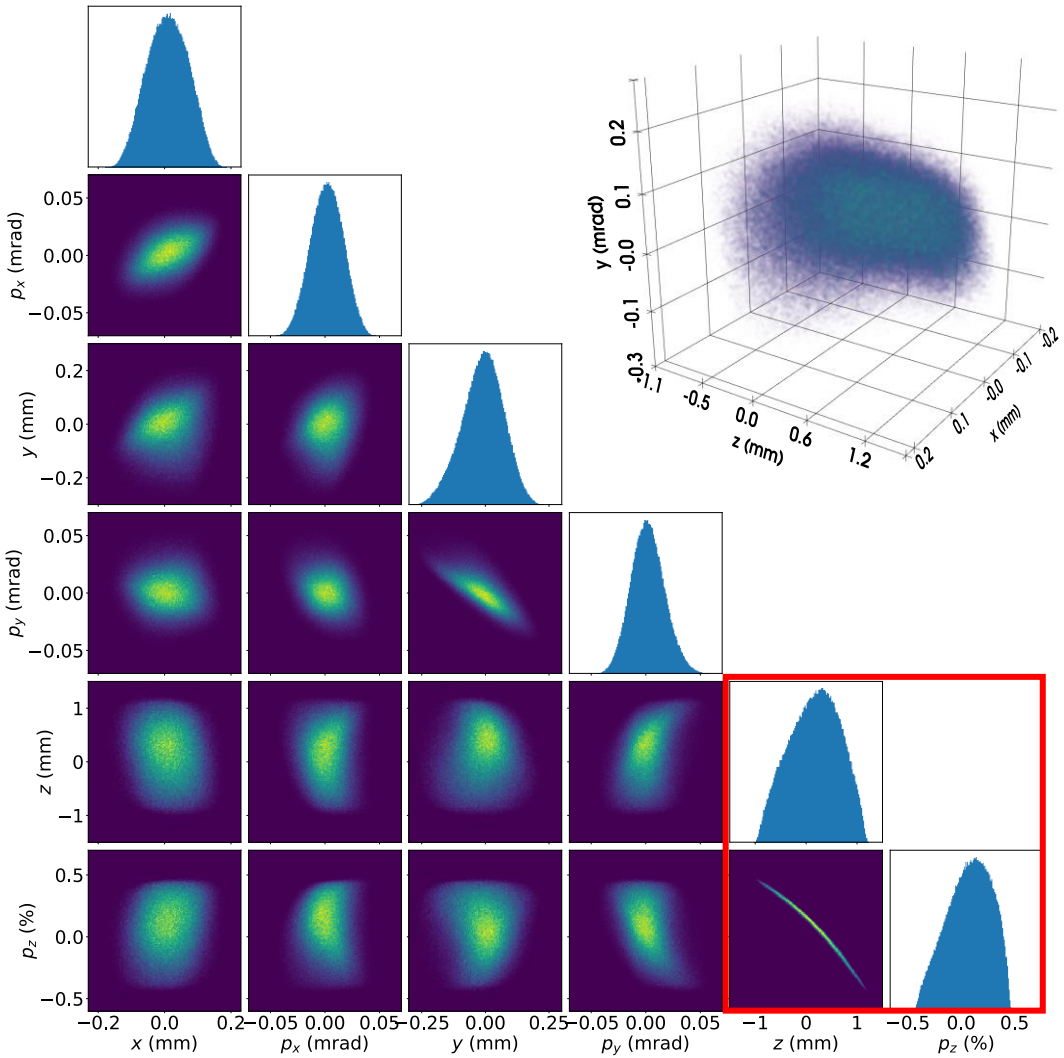
Reconstructed phase space @ Q1 entrance



Parameters	4D Reconstruction	6D reconstruction
β_x (m)	4.53	4.67
β_y (m)	7.78	8.12
α_x (rad)	–0.56	–0.50
α_y (rad)	1.25	1.17
ε_{nx} (mm mrad)	0.42	0.40
ε_{ny} (mm mrad)	0.39	0.40

Parameters	Measurement	6D reconstruction
ε_{nz} (mm mrad)	137.34±17.240	140.05
σ_z (mm)	0.45±0.01	0.49
σ_{pz} (%)	0.24±0.01	0.22
Slice σ_{pz} (%)		0.01 (typical)

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Summary and future works

- **6-dimensional phase space reconstruction using accelerating cavity was successfully demonstrated at the user facility**
  - All the coupled phase spaces can be successfully predicted
  - Specialized diagnostic elements are no longer required > readily applicable using common elements such as accelerating cavity, quad, dipole, and screen

- **Uncertainty quantification will be studied further**
  - Current demonstration also shows accurate predictions >> establish a standard for condition to get minimized uncertainty
  - Establish the 6D-GPSR standard for typical diagnostic techniques in accelerator facilities

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Acknowledgements

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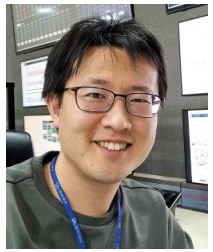
THE UNIVERSITY OF CHICAGO

Haeryong Yang

Myung-Hoon Cho

Chi Hyun Shim



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