High-dimensional phase space reconstruction using generative modeling of beam distributions

AAC - July 2026

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SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT of ENERGY

Outline

Introduction

- phase space measurements

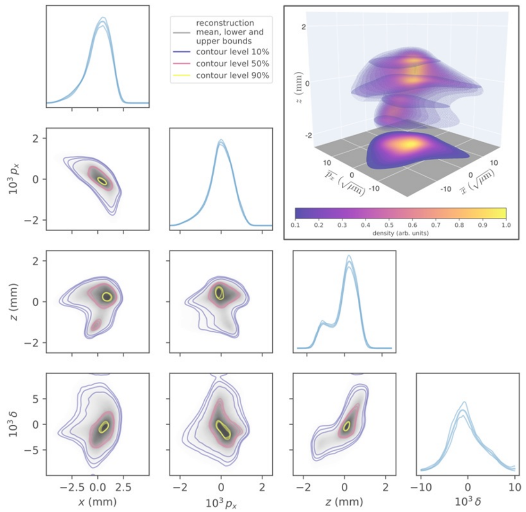
Generative phase space reconstruction (GPSR)

- generative modeling of beam distributions
- differentiable particle tracking simulations
- 4D GPSR pipeline
- extension to 6D

Implementations

- Argonne Wakefield Accelerator (AWA)
  - 4D GPSR flat/magnetized beams
  - 6D GPSR beams affected by CSR
- PAL-XFEL
  - 6D GPSR without TDC
- SLAC LCLS-II: automatic measurements
- SLAC FACET-II: two-bunch

Conclusions and Future Work

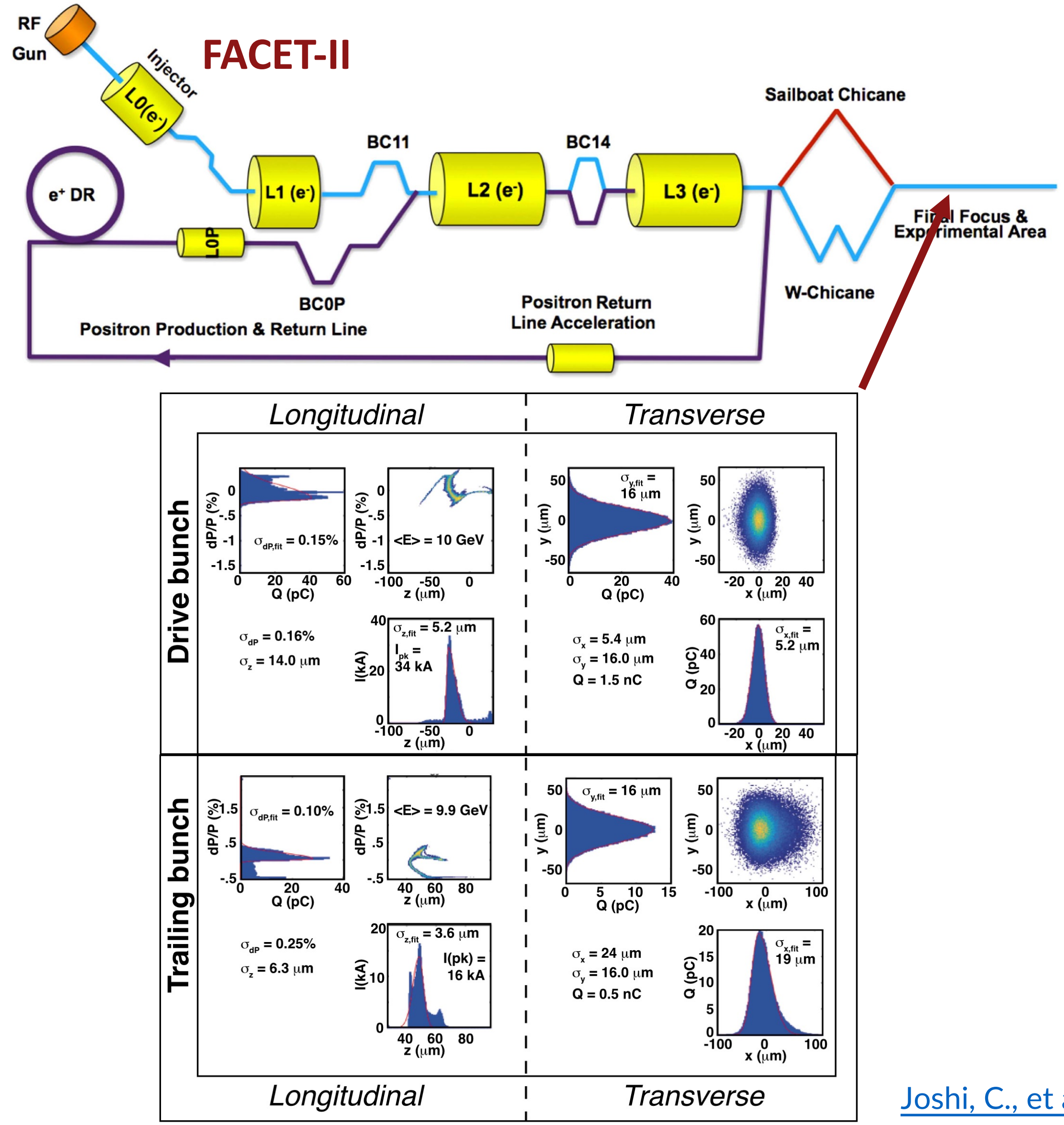


Argonne NATIONAL LABORATORY

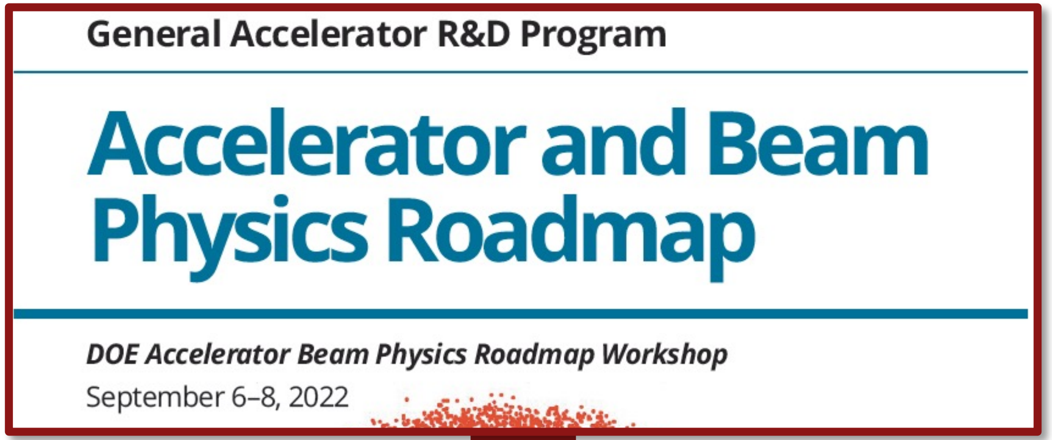
PAL POHANG ACCELERATOR LABORATORY

Manipulating beams in phase space

FACET-II



Joshi, C., et al (2018)



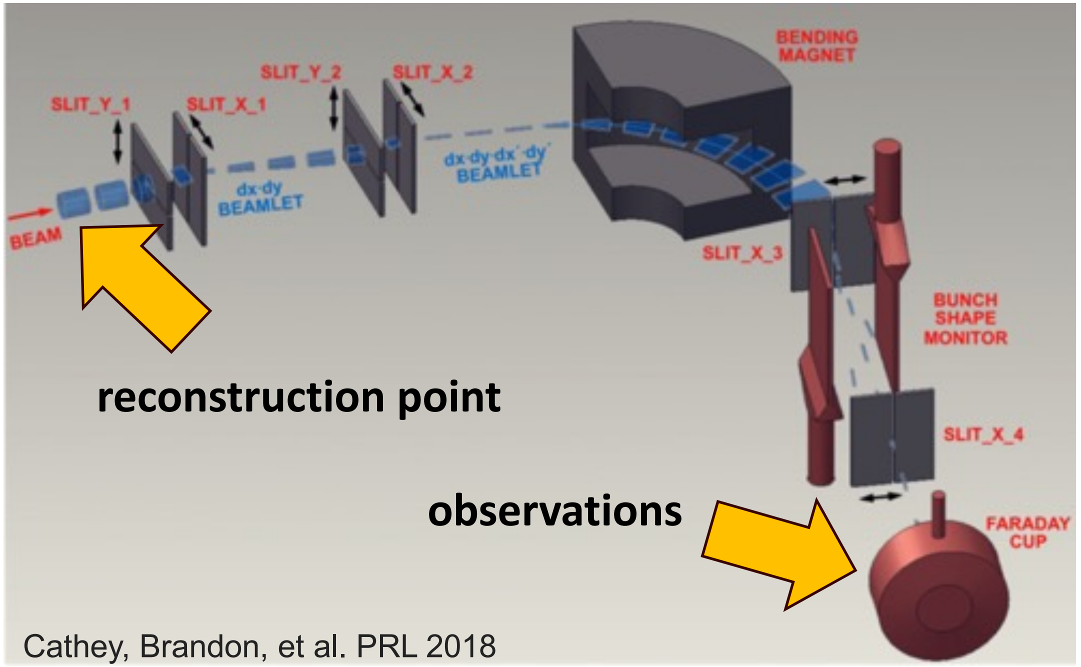
5 Grand Challenge Three

Beam Control: How do we control and diagnose the beam distribution at all scales—from its macroscopic properties down to the level of individual particles?

Detailed measurement of beam phase space distribution is important for Accelerator R&D!

Measuring phase space distributions

6D phase space measurement at SNS (ORNL)



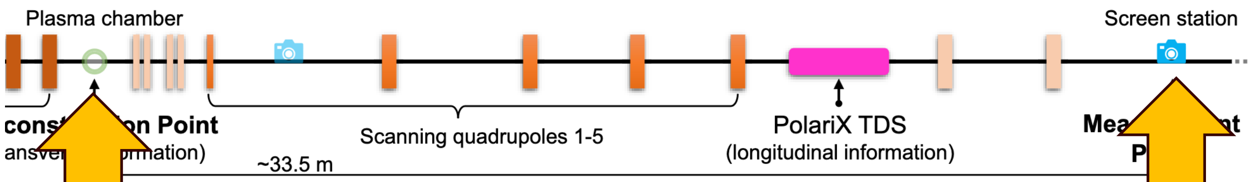
reconstruction point

observations

Cathey, Brandon, et al. PRL 2018

~5 million measurements -> ~36h

5D tomography at FLASHForward (DESY)



Jaster-Merz, S., et al PRR 2025

reconstruction point

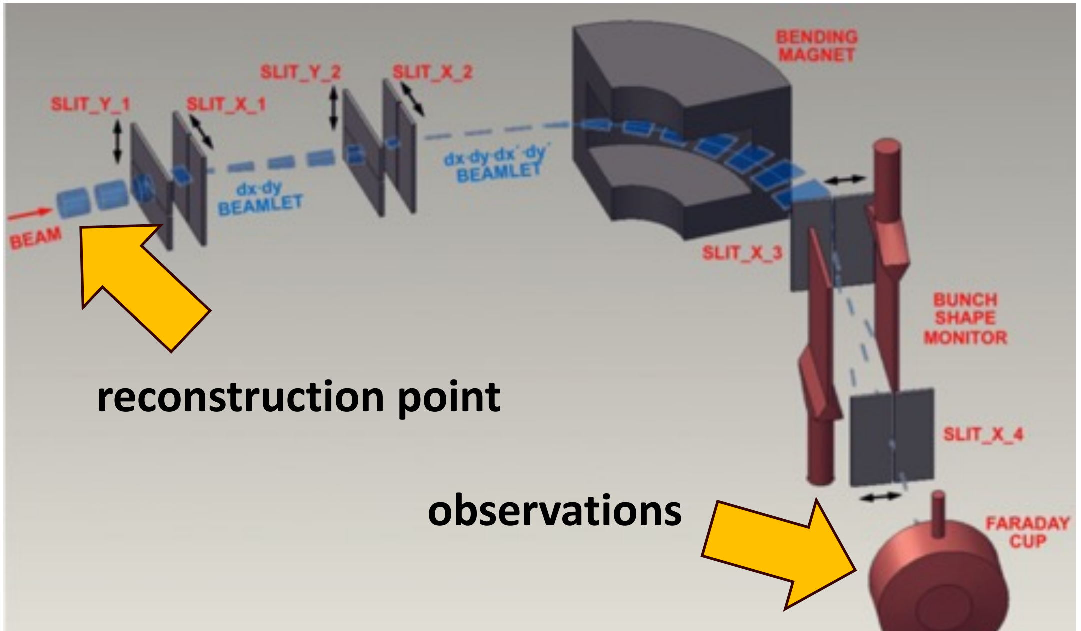
observations

~1000 measurements-> ~28h

Tens of hours of beamtime for measurements!

Measuring phase space distributions

6D phase space measurement at SNS (ORNL)

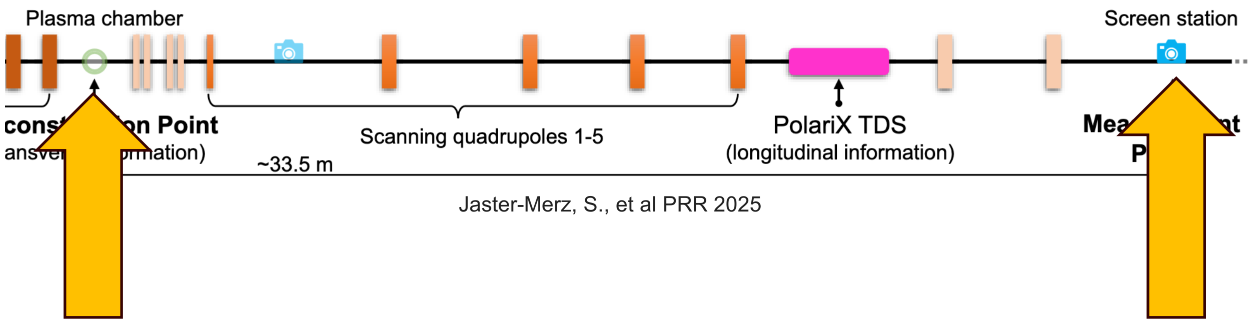


reconstruction point

observations

Cathey, Brandon, et al. PRL 2018

5D tomography at FLASHForward (DESY)



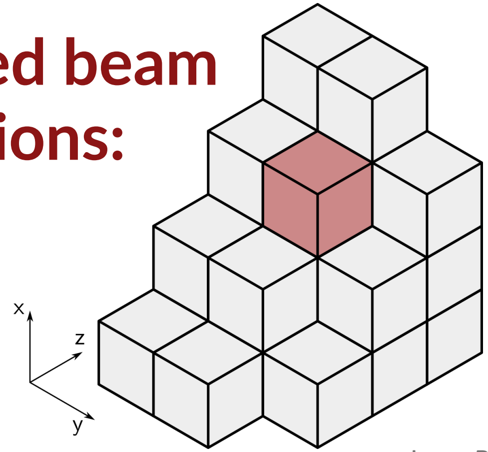
Jaster-Merz, S., et al PRR 2025

reconstruction point

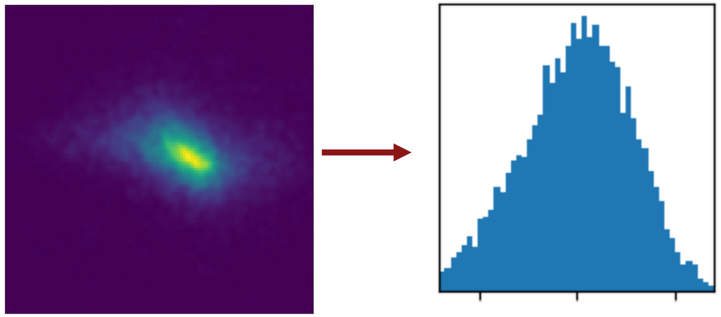
observations

Costs of detailed beam representations:

$$N_{bins} \propto n^D$$



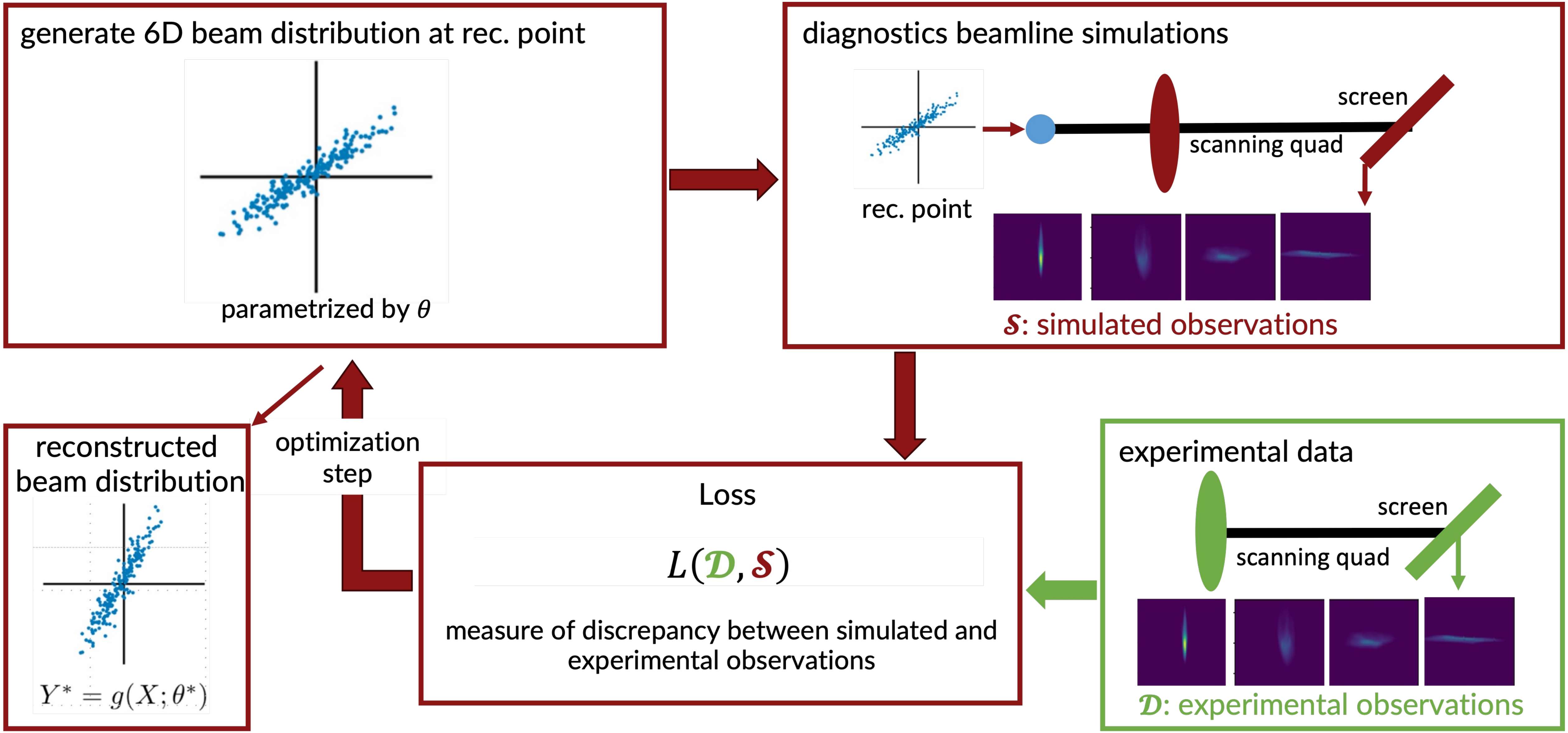
Information compression



2D image

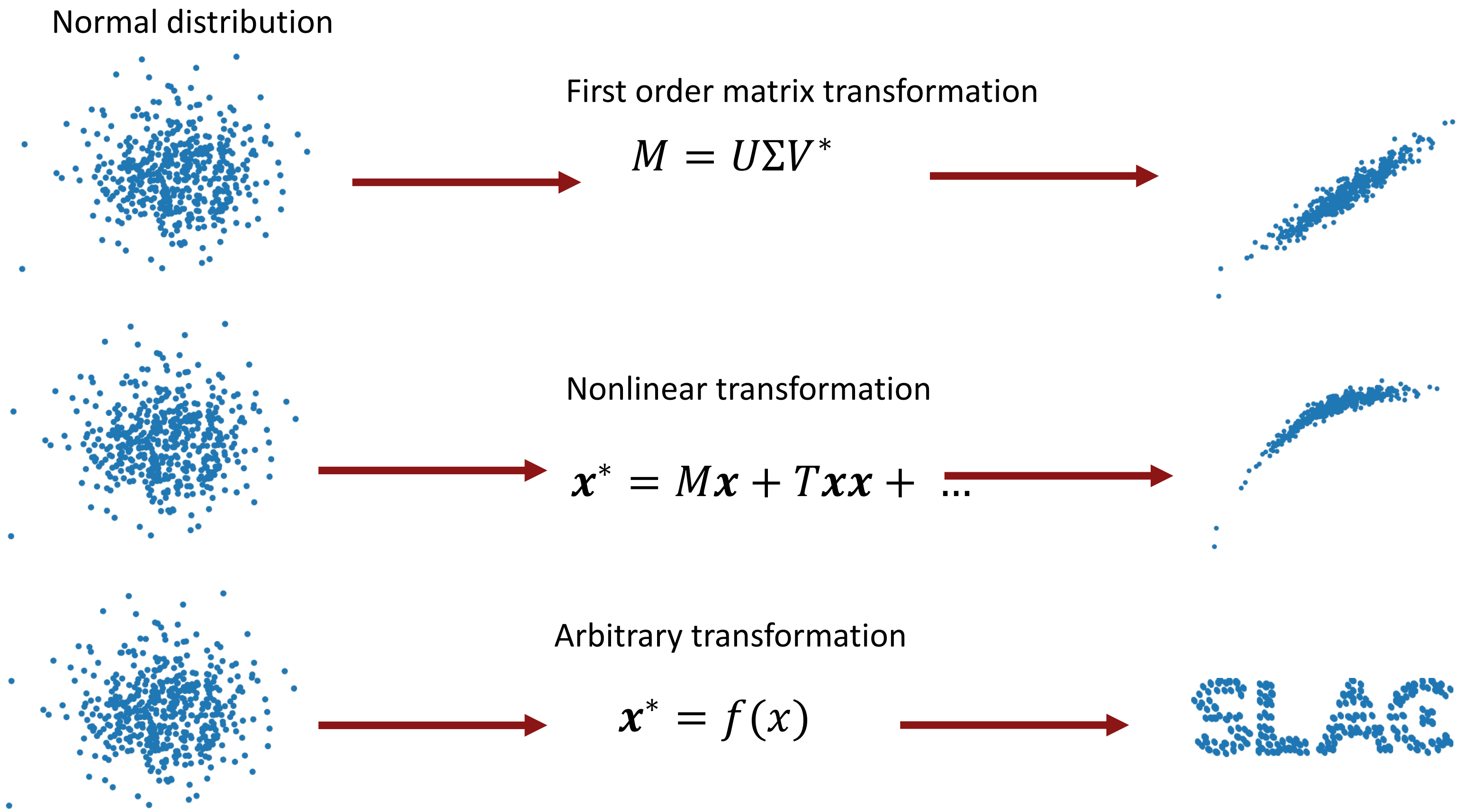
1D projection

Phase space fitting as an inverse problem



Beam generator

How do we **generate** arbitrary 6D phase-space distributions in a **flexible** and **learnable** way?



Beam generator

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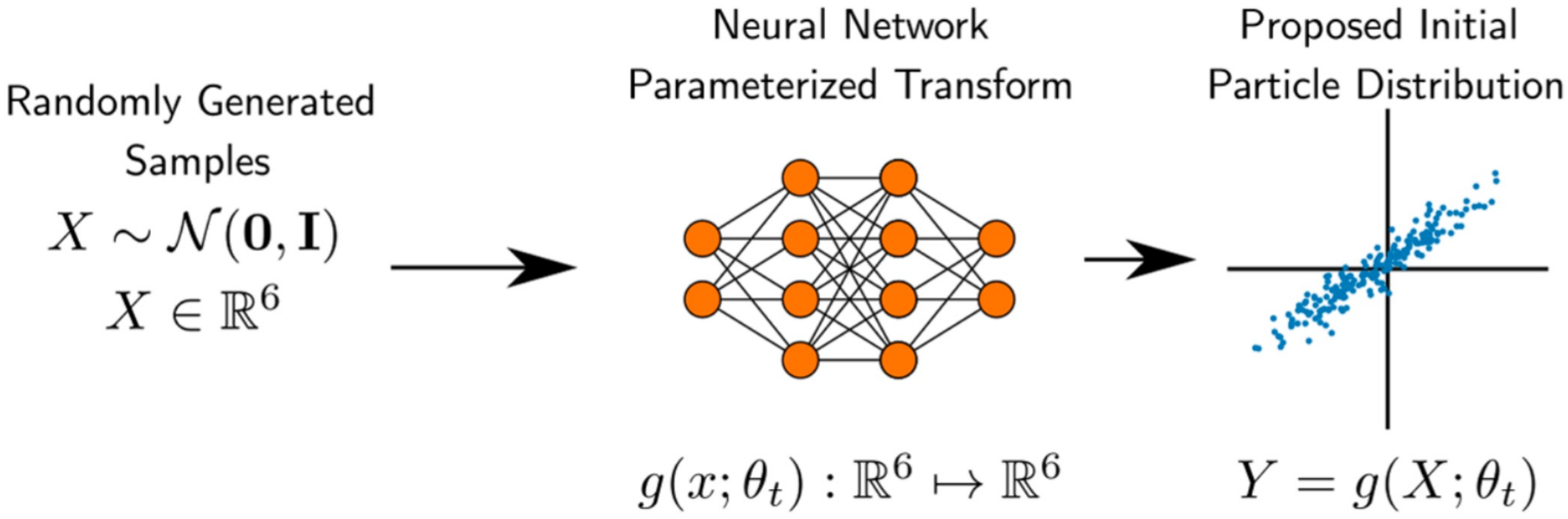
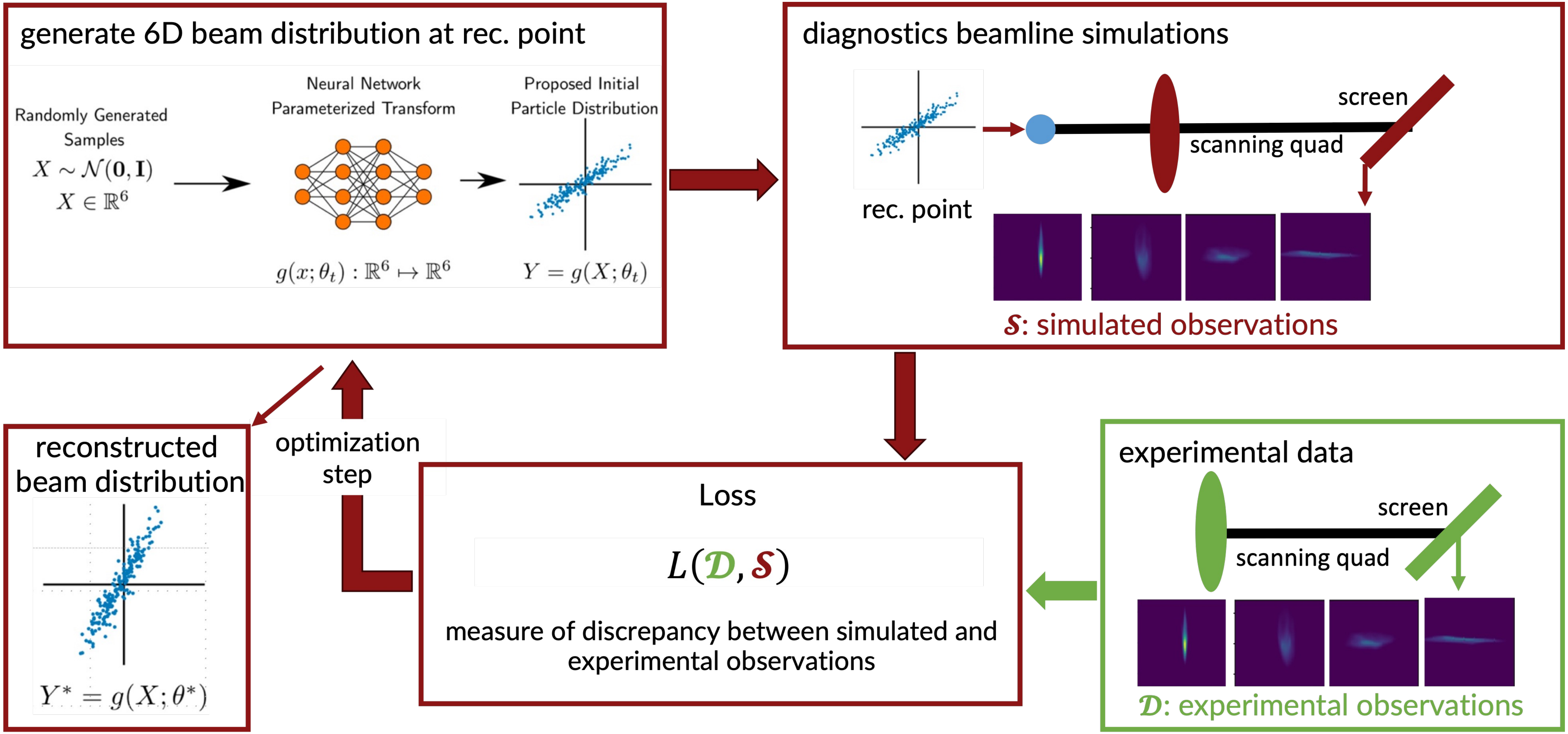


Fully connected NN with **~ 1k parameters**

Phase space fitting as an inverse problem

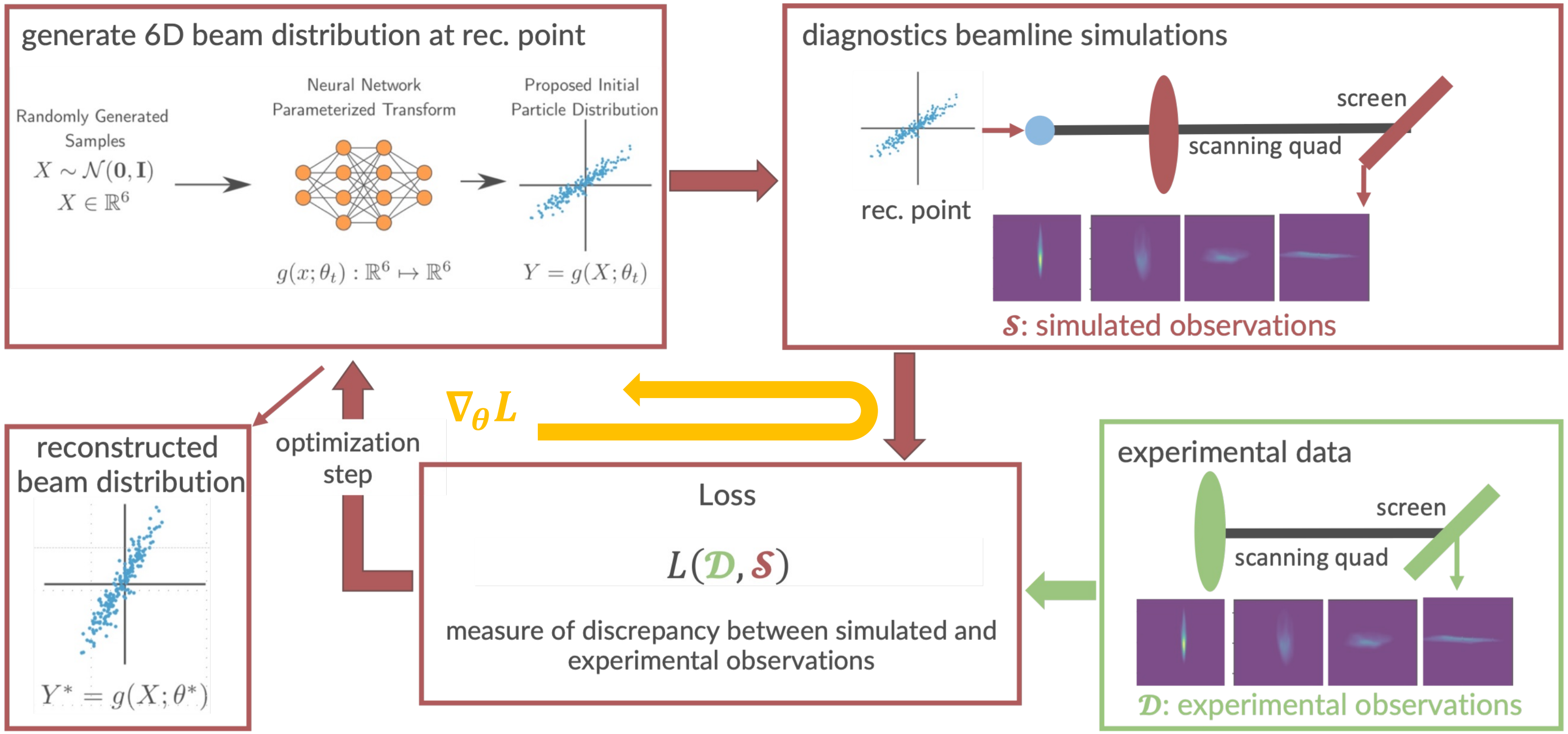


Challenge: curse of dimensionality

challenge:
need to learn ~1K parameters of the beam generator θ

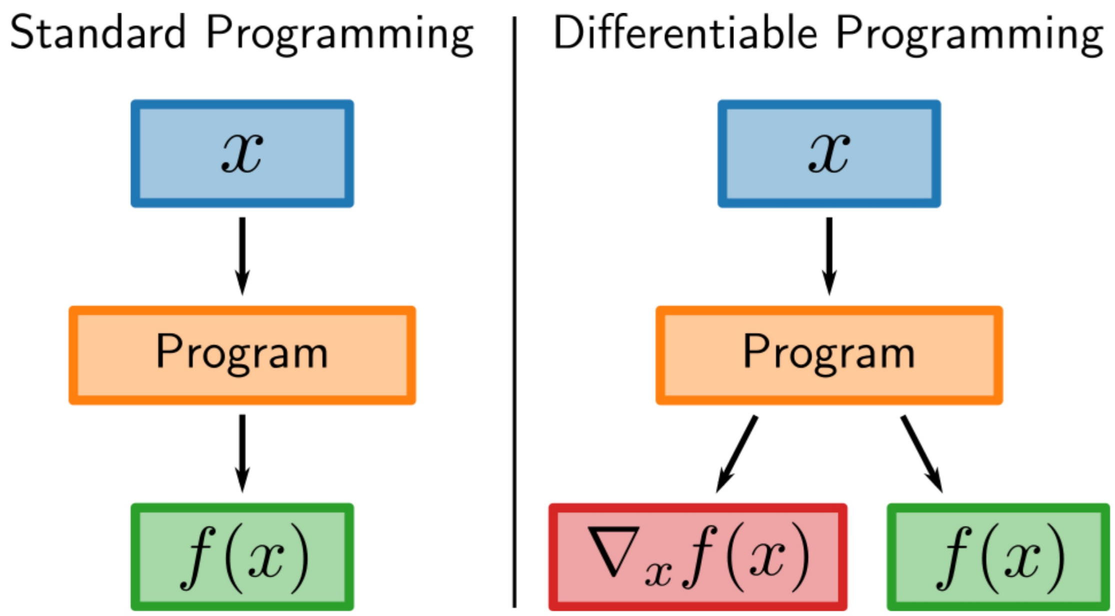
solution:
gradient based optimization

new challenge:
compute high-dimensional gradients $\nabla_\theta L$



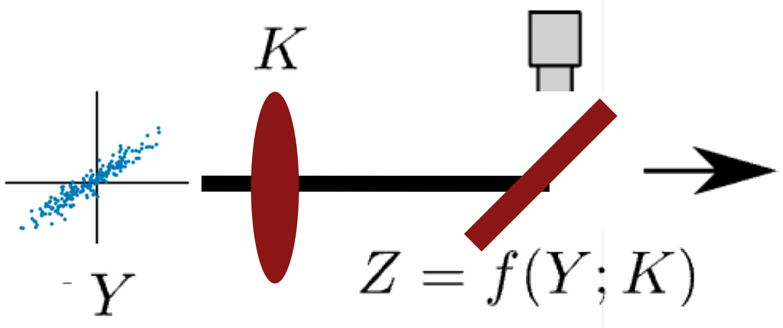
Differentiable simulations

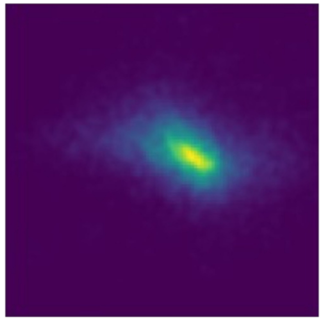
Automatic differentiation



Automatic differentiation enables cheap gradient evaluation

Differentiable particle tracking simulations





Bmad-X

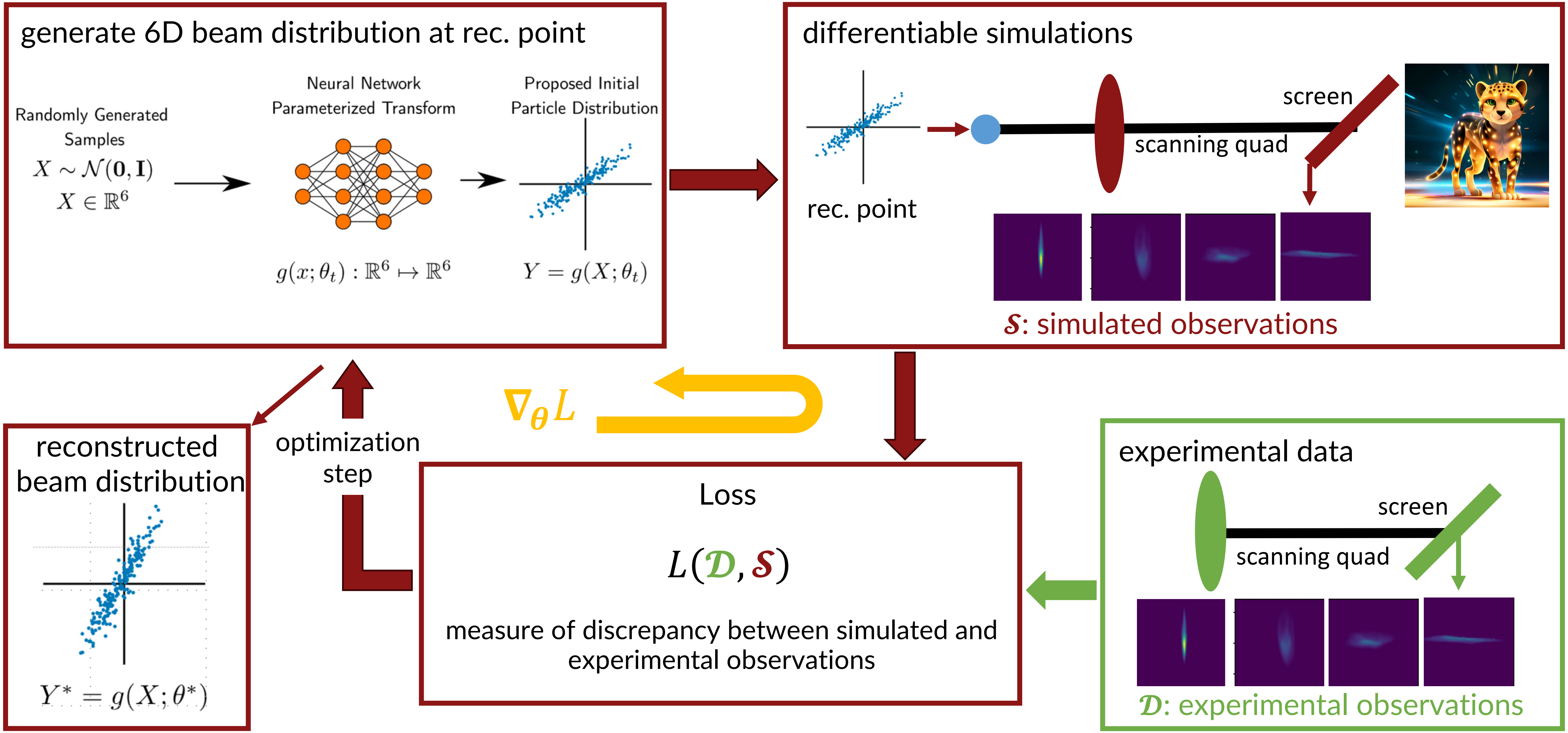
$$Q^{(i,j)} = \mathrm{KDE}(Z)$$

$$\frac{\partial Q^{(i,j)}}{\partial Y}$$

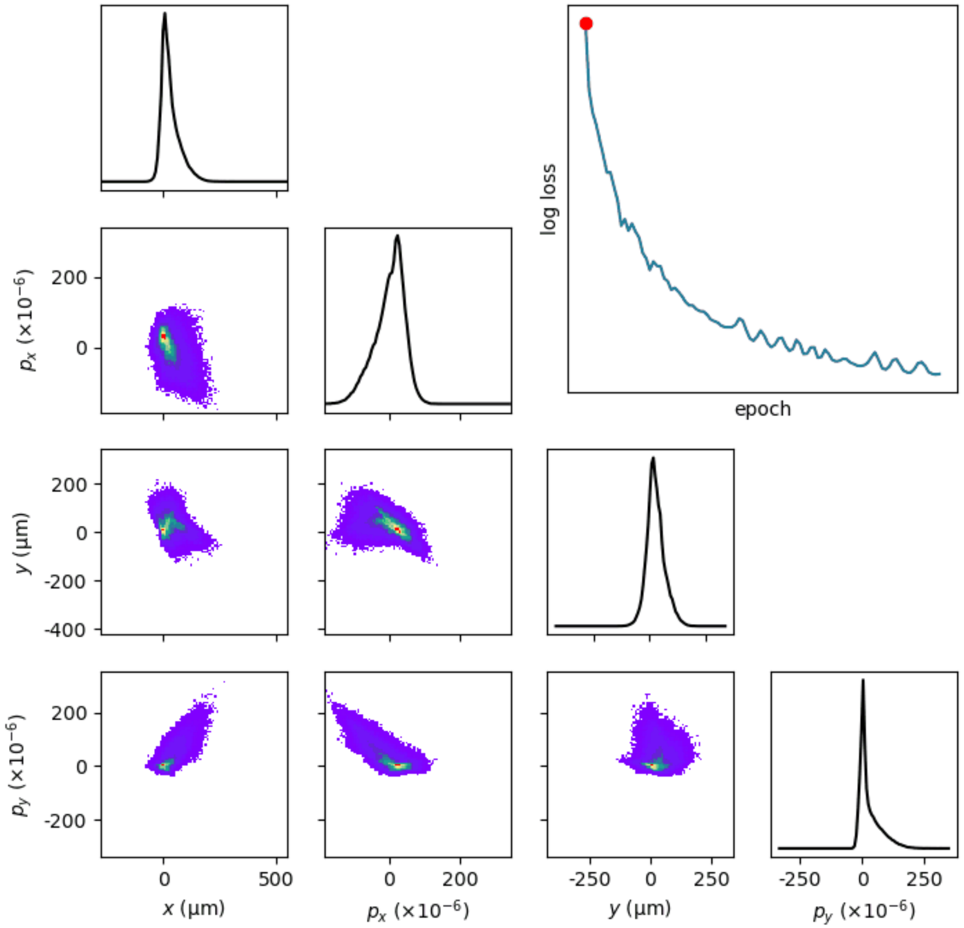
Enables gradients from screen pixels *wrt* beam distribution parameters

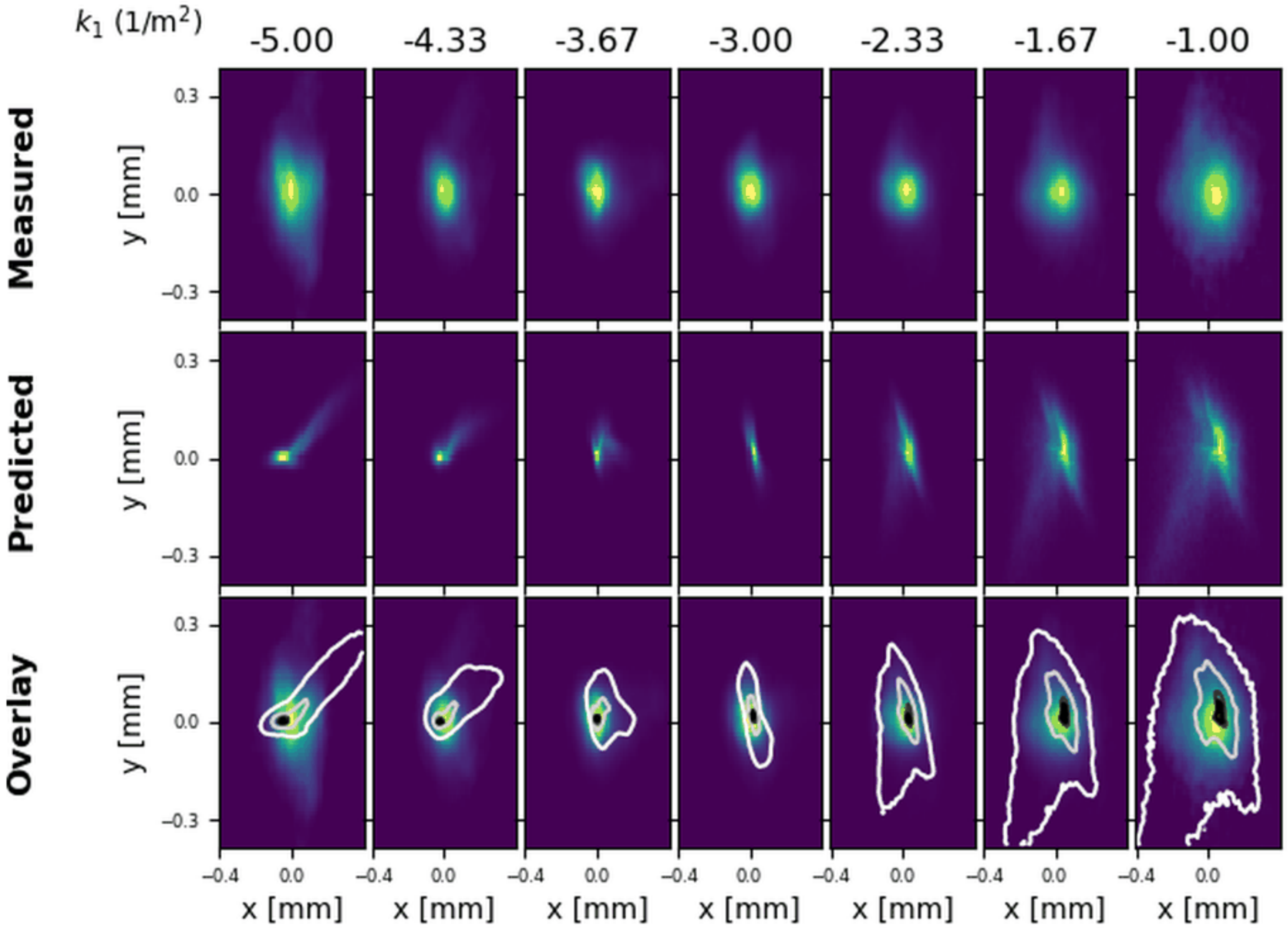
R. Roussel, *et al.* LINAC`24 J.P. Gonzalez-Aguilera, *et al.* IPAC'23 J. Kaiser, *et al.* PRAB 2024

Generative phase space reconstruction (GPSR)



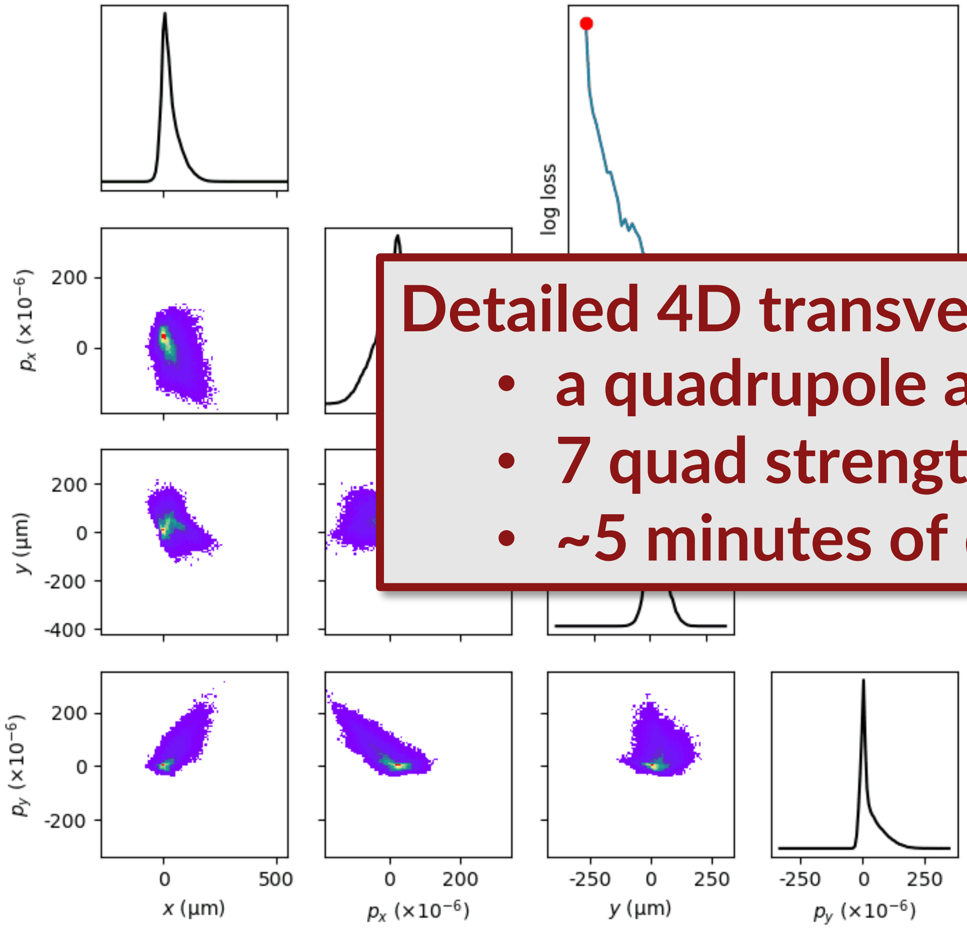
4D transverse phase space GPSR

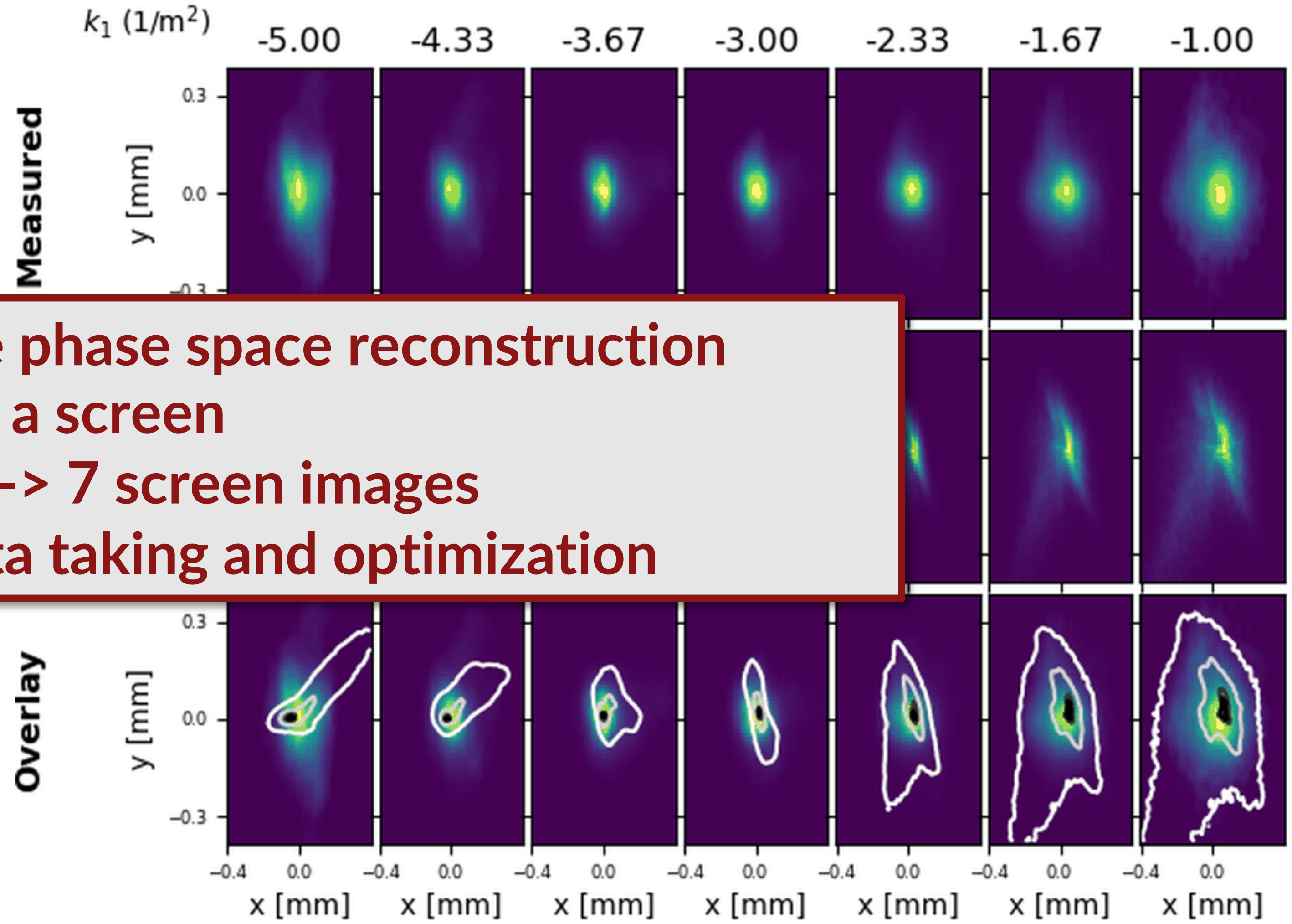




Animation by An Le

4D transverse phase space GPSR

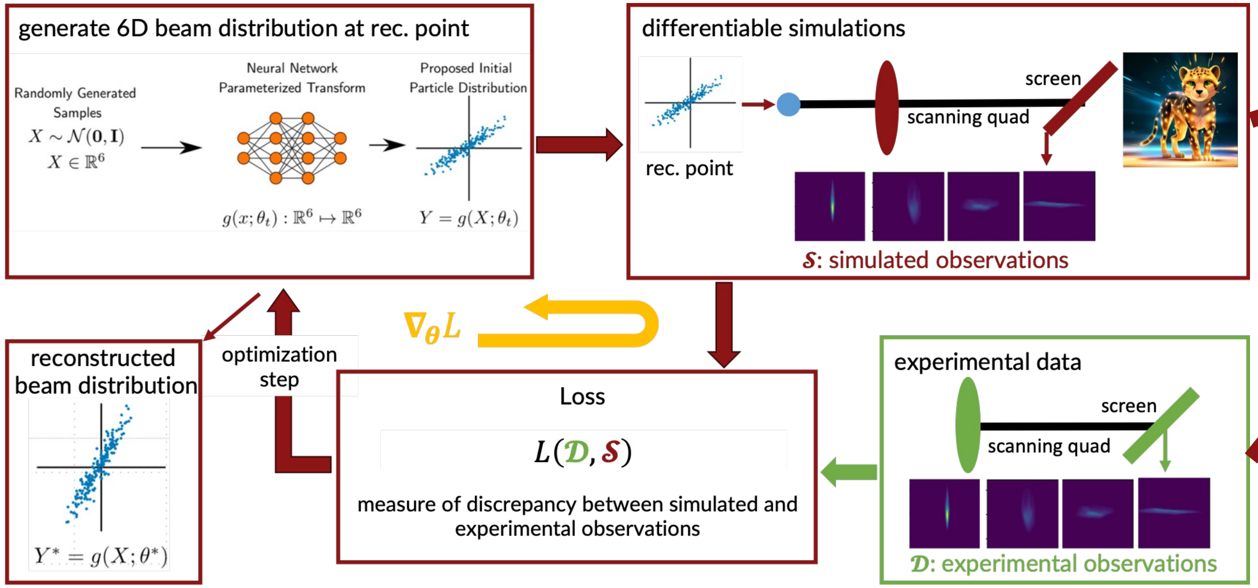


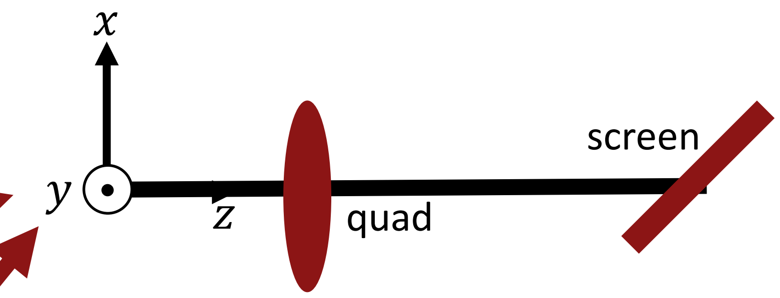


Detailed 4D transverse phase space reconstruction
- a quadrupole and a screen
- 7 quad strengths -> 7 screen images
- ~5 minutes of data taking and optimization

Animation by An Le

Extension to 6D





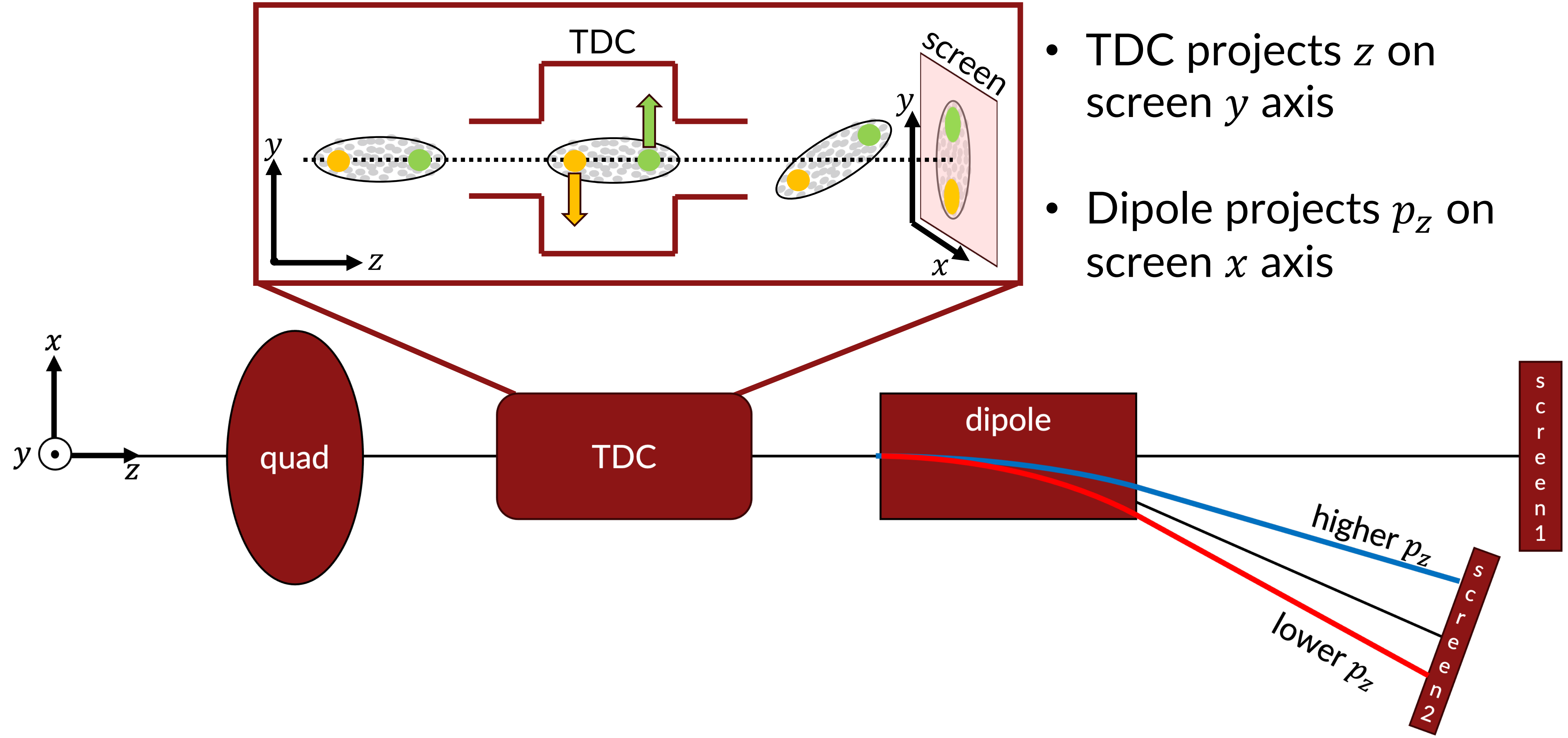
Limitation:

- Quadrupoles mostly project x, p_x, y, p_y coordinates on x-y screen

$$H = \frac{p_x^2 + p_y^2}{2(1+p_z)} + \frac{k_1}{2}(x^2 - y^2)$$

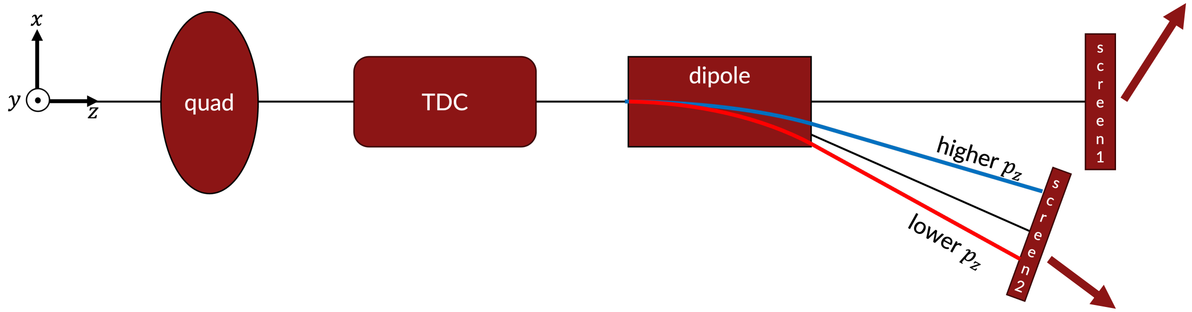
- No (z, p_z) information at screens

Longitudinal diagnostics

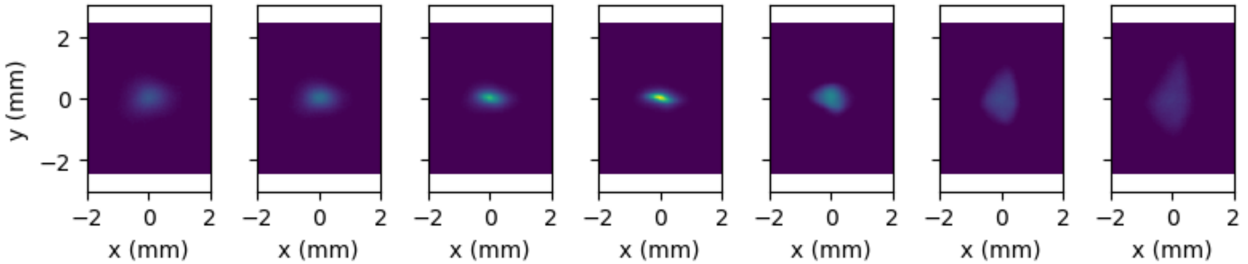


- TDC projects z on screen y axis
- Dipole projects p_z on screen x axis

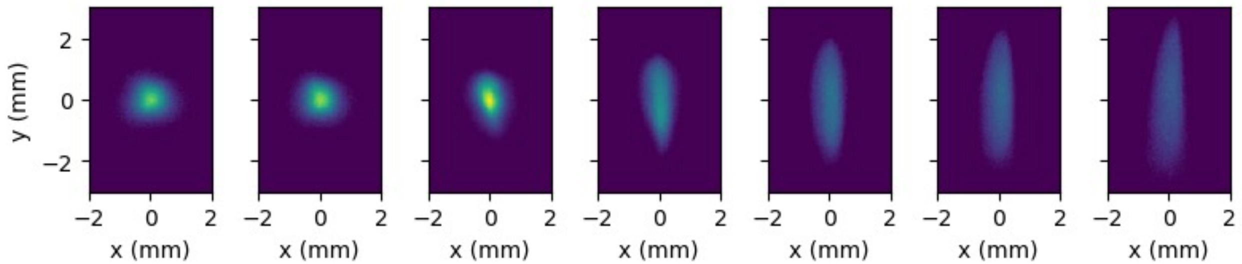
6D GPSR data



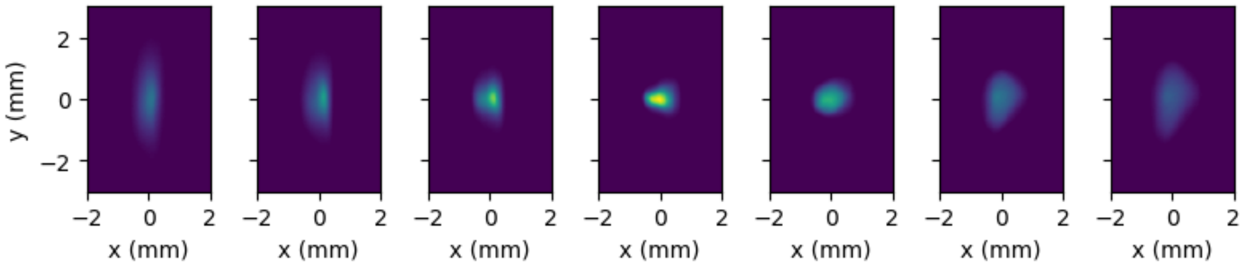
screen 1, TDC off



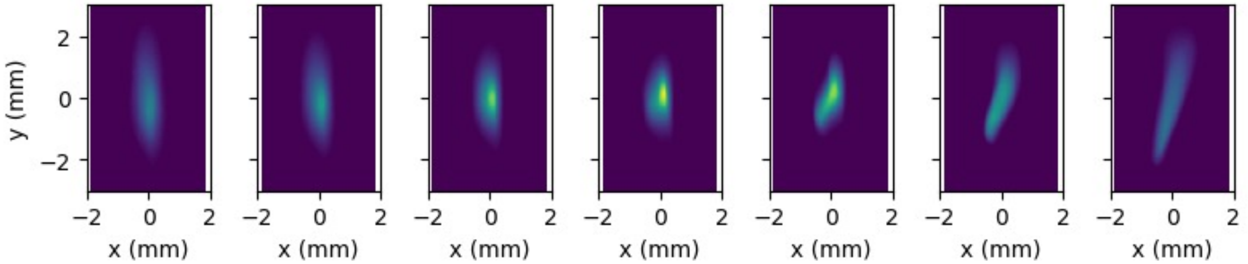
screen 1, TDC on



screen 2, TDC off

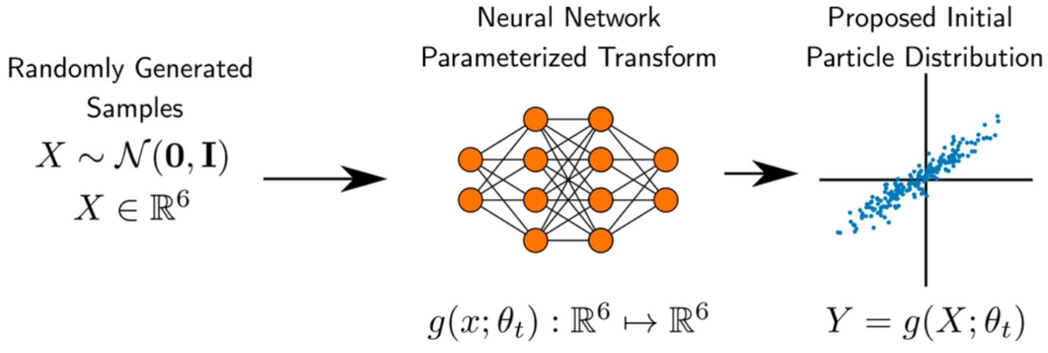


screen 2, TDC on

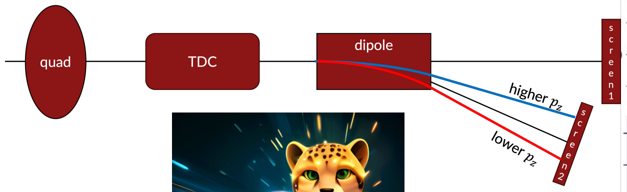


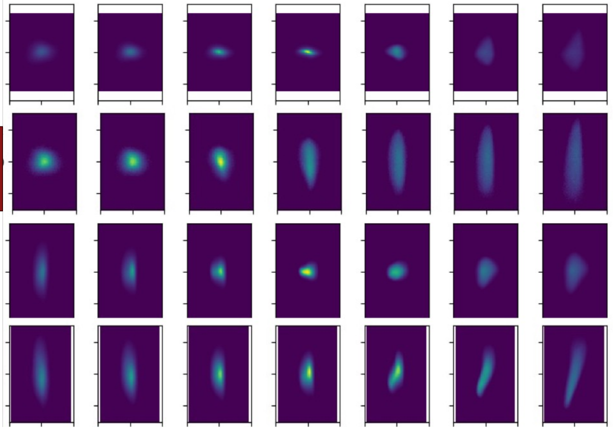
6D GPSR pipeline: same pipeline, more diagnostics

generate 6D beam distribution at rec. point



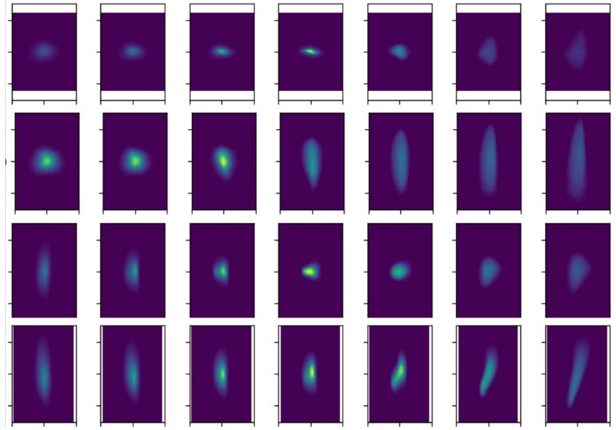
differentiable simulations





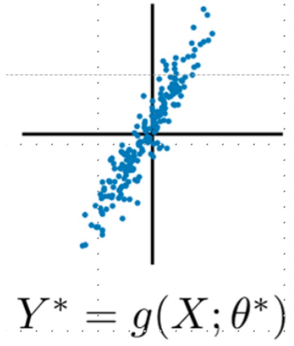
$\mathcal{S}$: simulated observations

experimental data



$\mathcal{D}$: experimental observations

reconstructed beam distribution



optimization step

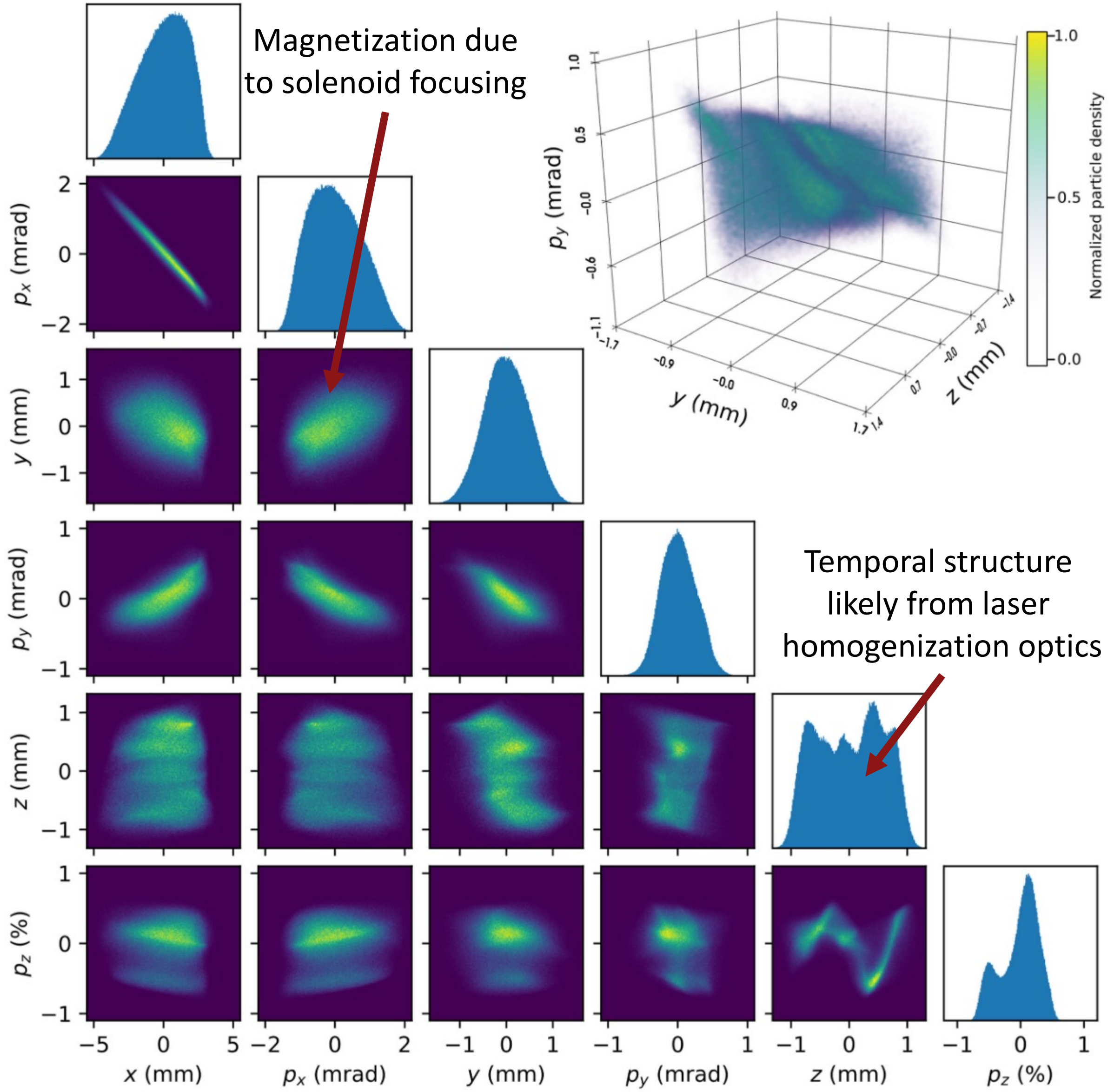
$\nabla_\theta L$

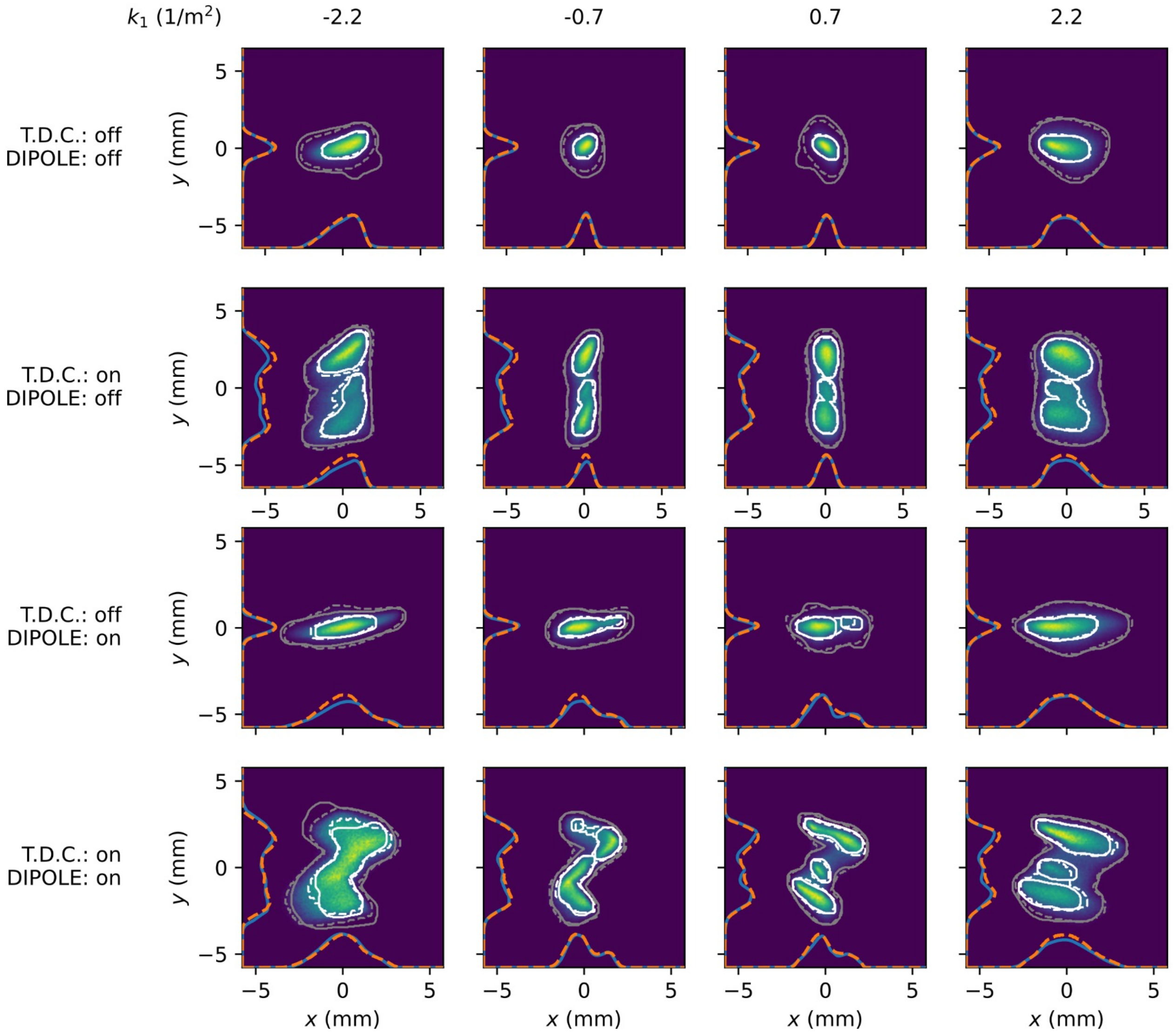
Loss

$$L(\mathcal{D}, \mathcal{S})$$

measure of discrepancy between simulated and experimental observations

6D GPSR at the Argonne Wakefield Accelerator

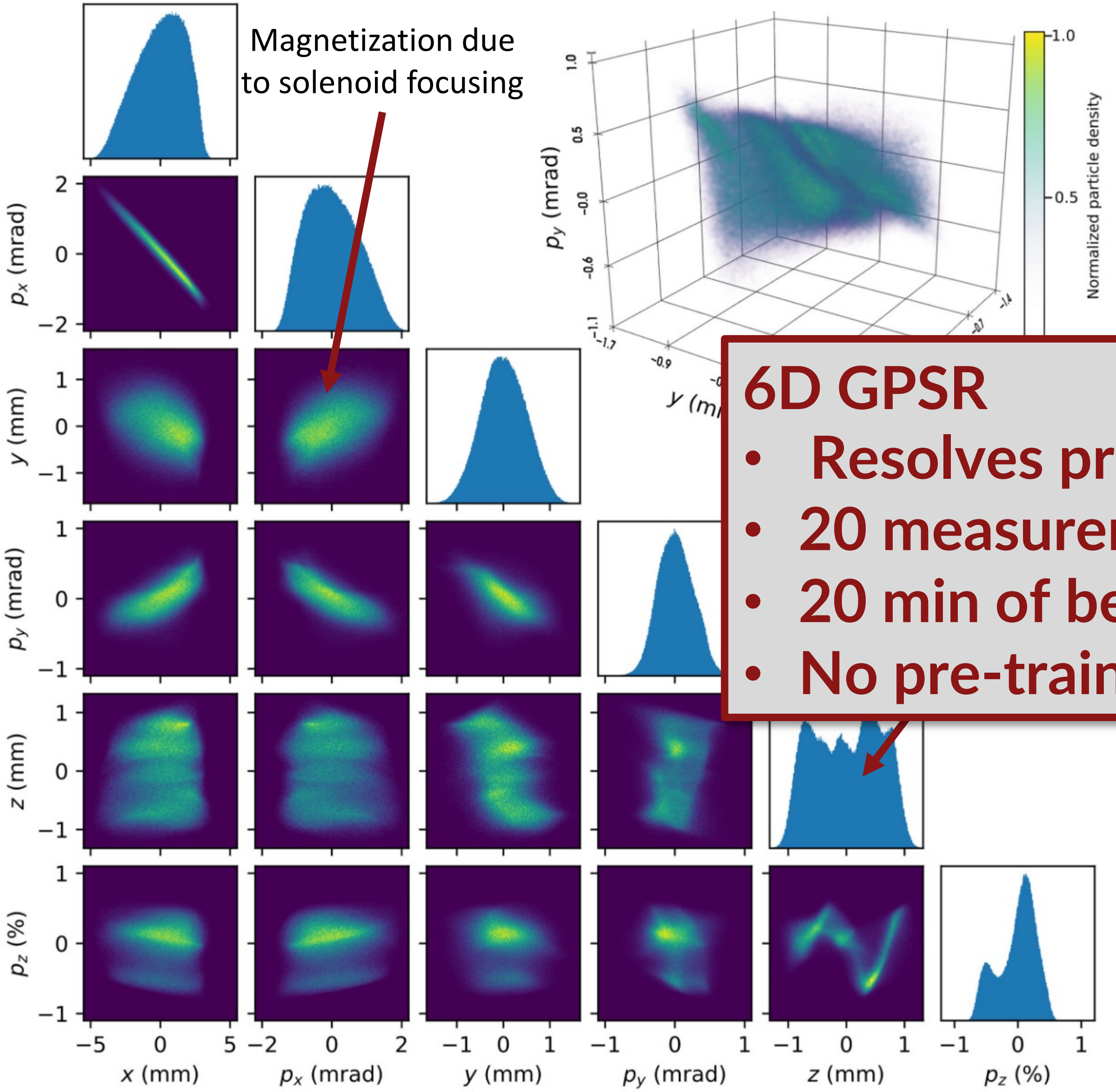


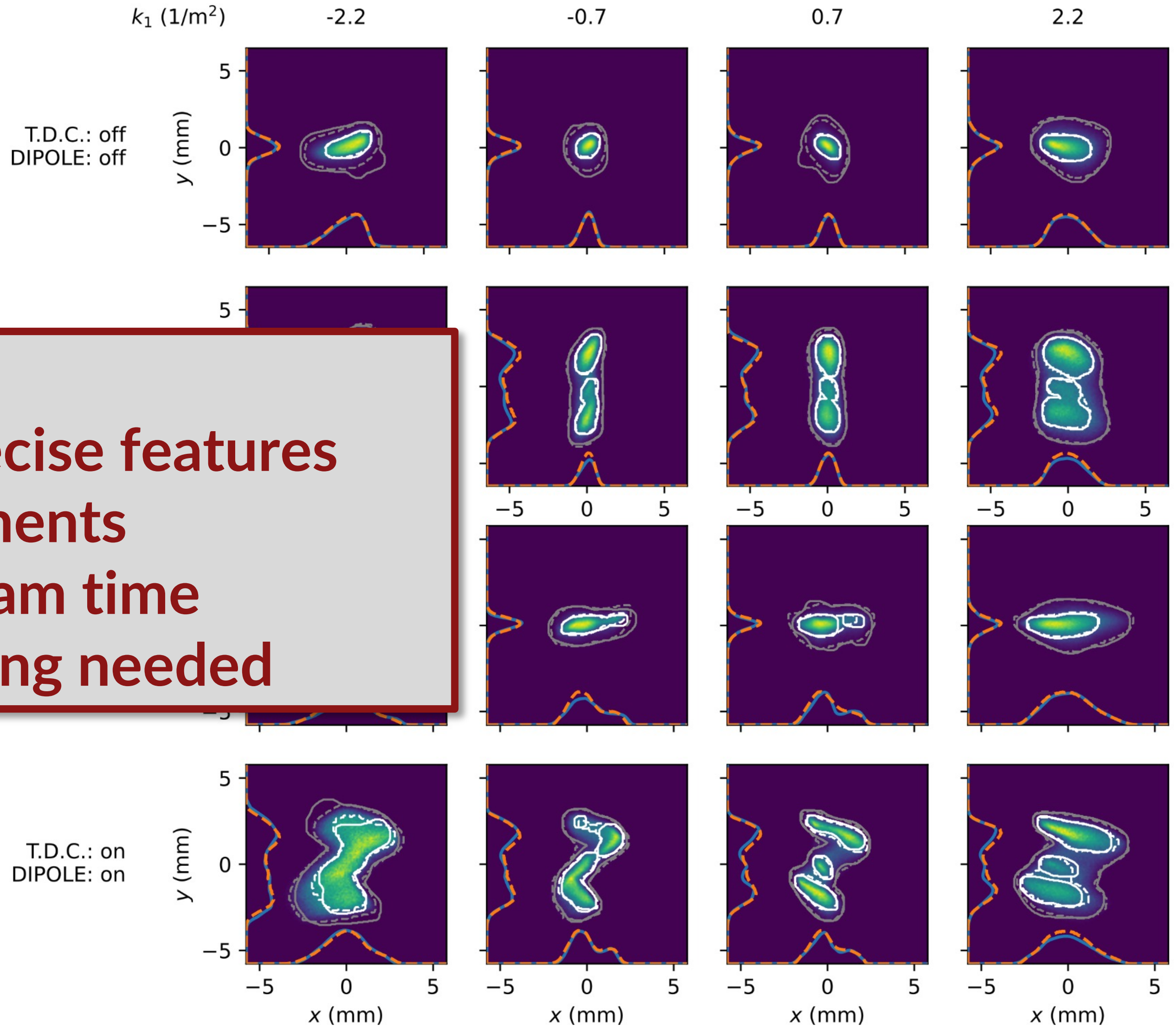


R. Roussel, JP. Gonzalez-Aguilera, *et al.* PRAB (2024)

6D GPSR at the Argonne Wakefield Accelerator

Magnetization due to solenoid focusing





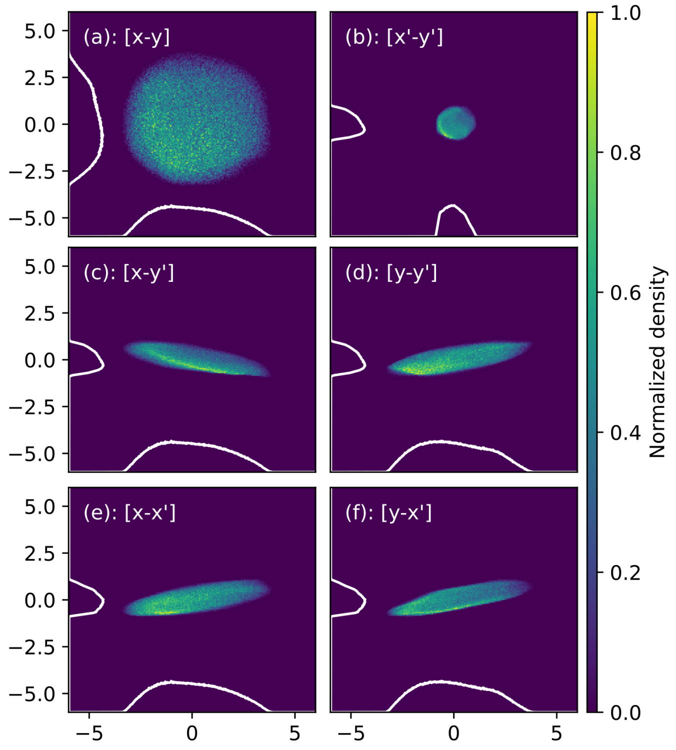
6D GPSR

- Resolves precise features
- 20 measurements
- 20 min of beam time
- No pre-training needed

[R. Roussel, JP. Gonzalez-Aguilera, *et al.* PRAB (2024)]

Previous implementations and applications

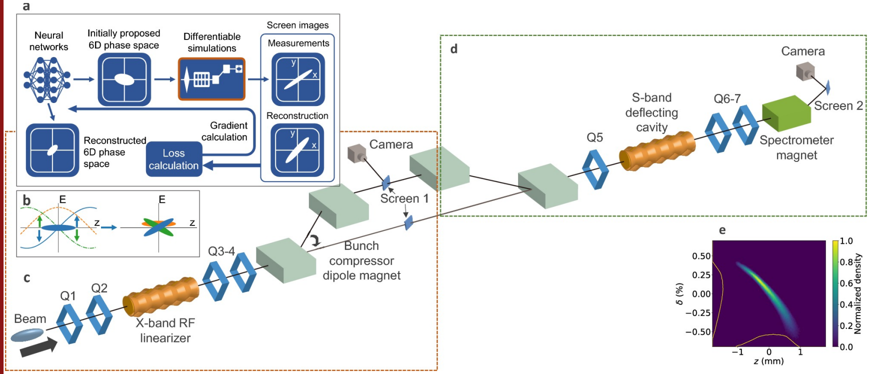
4D TPS GPSR of flat and magnetized beams at AWA

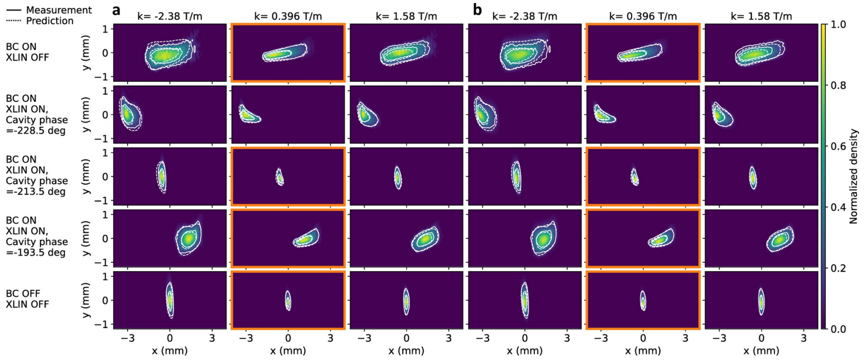


Seongyeol Kim, et al PRAB 2024

6D GPSR implementation and validation at PAL-XFEL

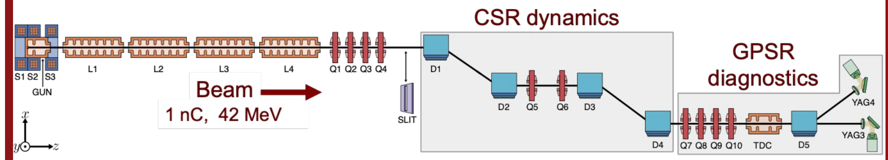
POHANG ACCELERATOR LABORATORY

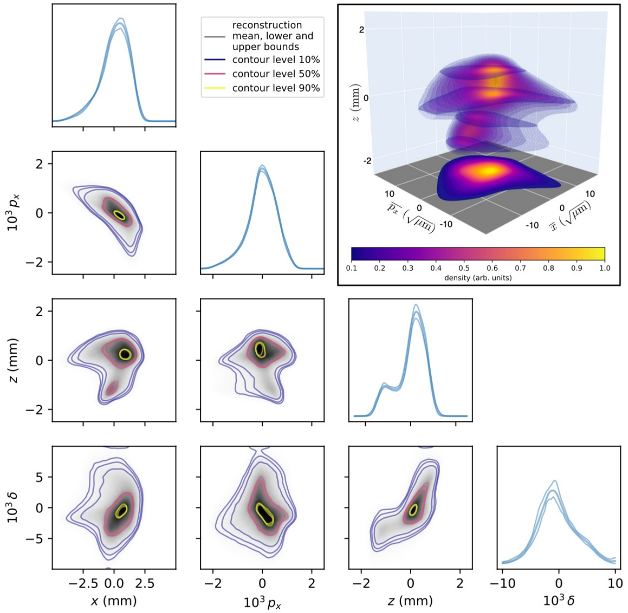




Seongyeol Kim, et al Sci. Rep 2025

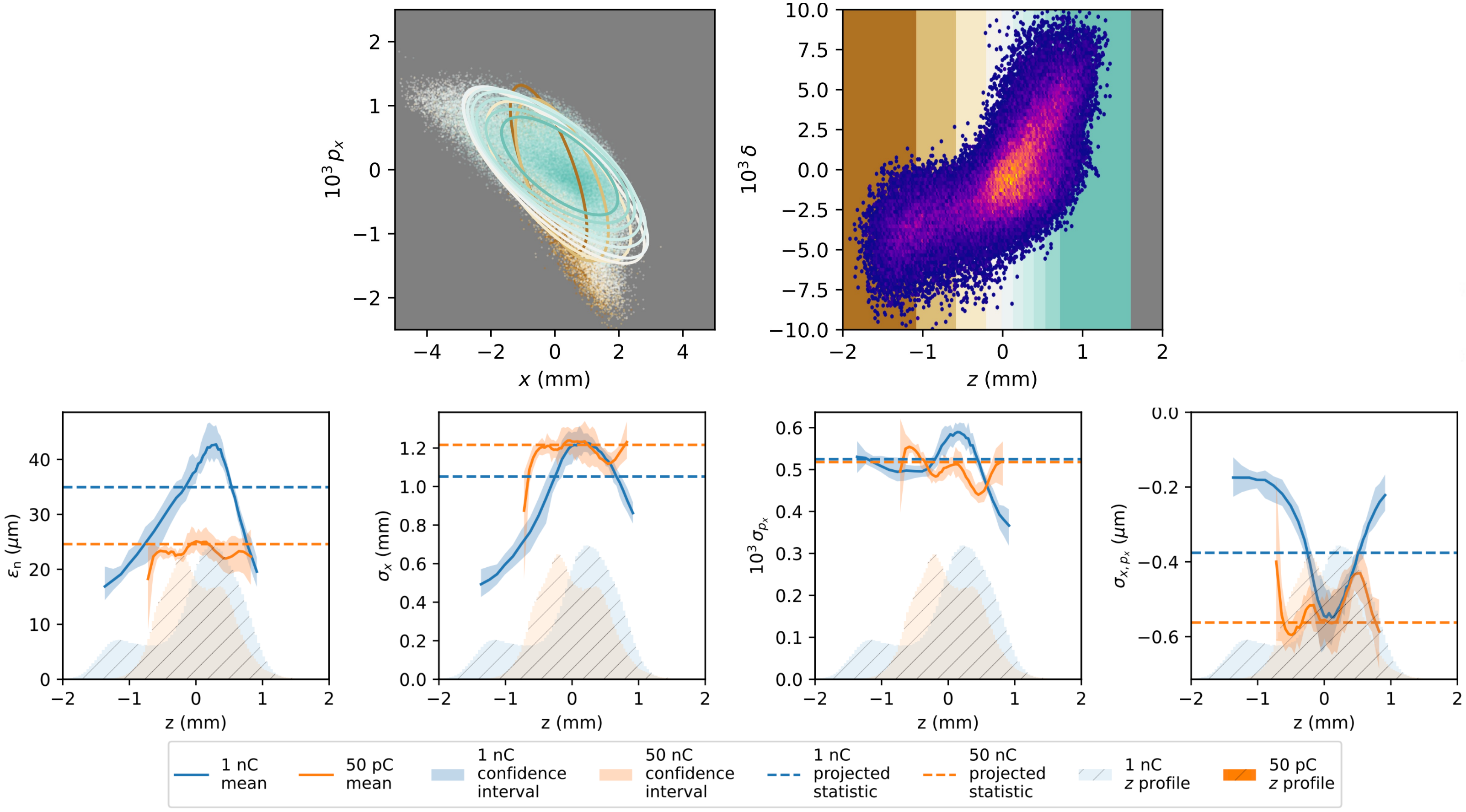
6D GPSR of beams affected by CSR at AWA

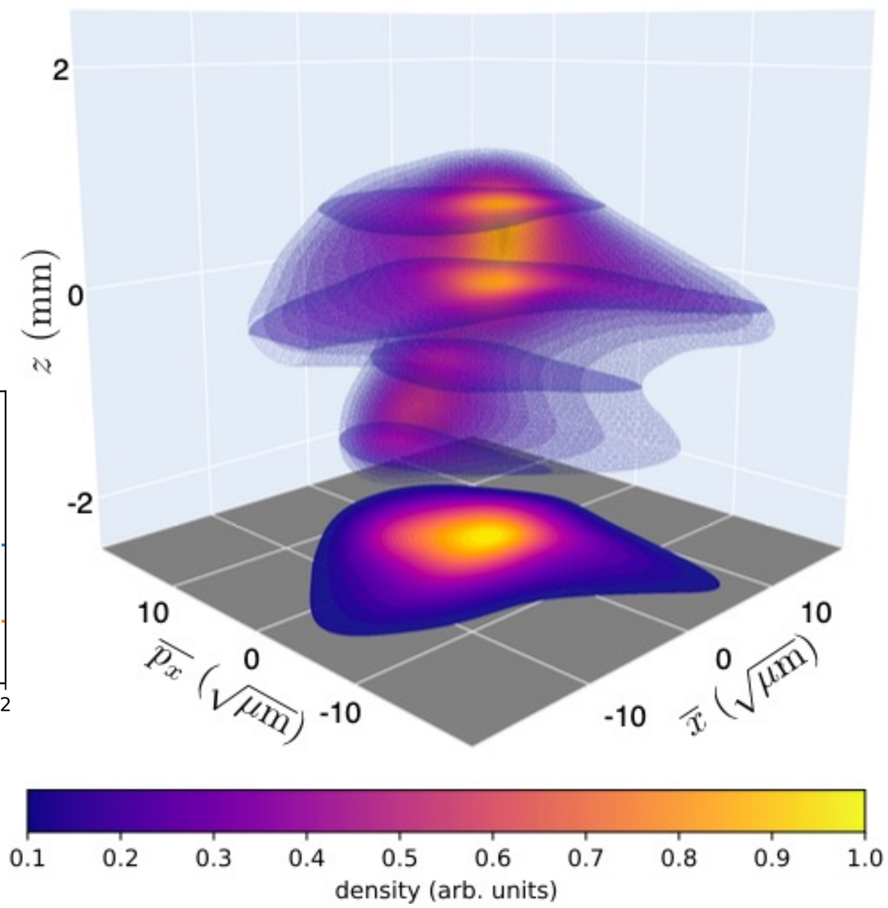




J.P. Gonzalez Aguilera. Doctoral Dissertation 2026

6D GPSR of beam affected by CSR (AWA)



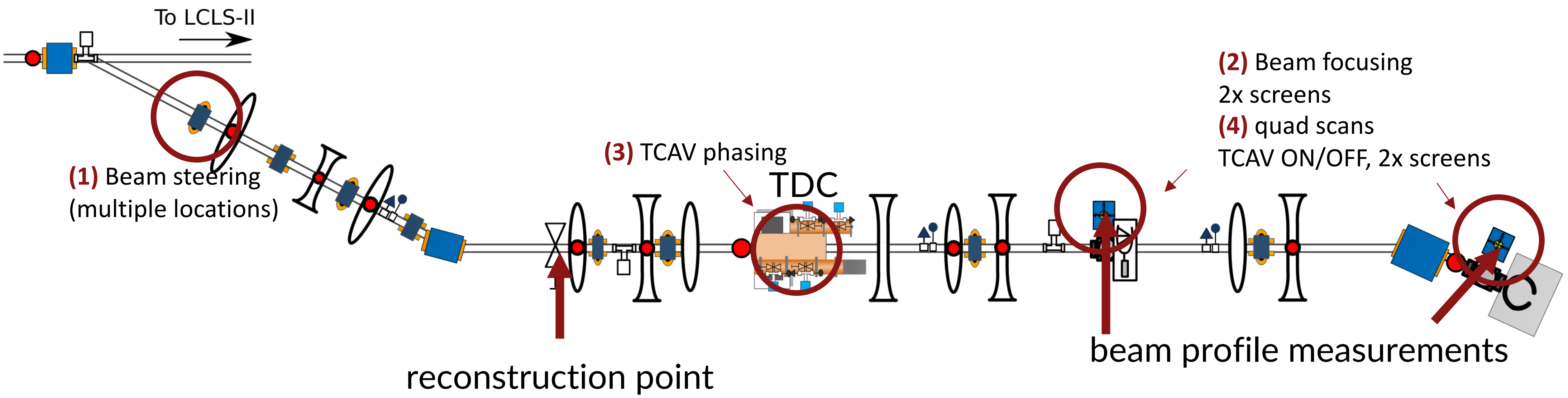


Detailed structure and metrics of PS slices with only 36 screen measurements

J.P. Gonzalez Aguilera. Doctoral Dissertation 2026

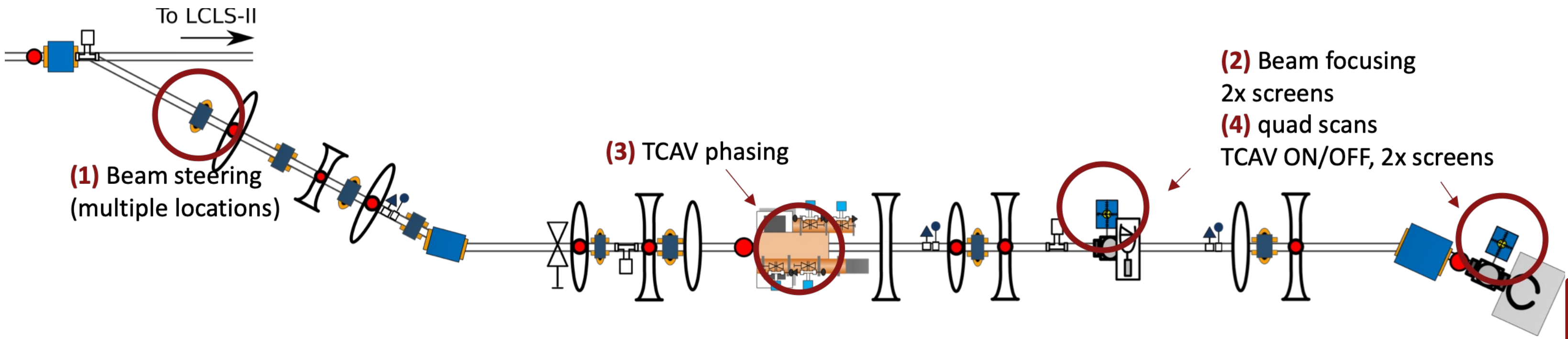
Automated GPSR at LCLS-II

Goal: Develop a workflow that autonomously operates DIAG0 to monitor the 6D phase space distribution over the span of multiple hours (~5 min. per measurement)



R. Roussel *et. al.* 2026 arXiv:2604.20125

Automated GPSR at LCLS-II

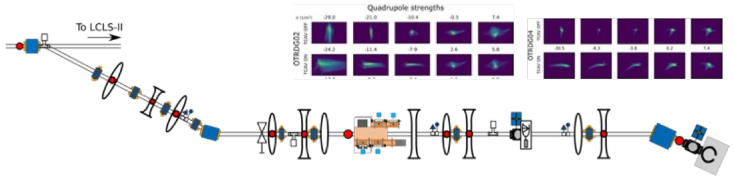


Automated tuning and 6D phase space reconstruction → ~5 minutes online

Continuous estimate of 6D phase space

Started exploring tuning directly on reconstruction

Tomographic measurements from DIAG0



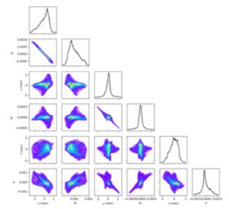
Streaming data transfer

SLAC S3DF SLAC SHARED SCIENCE DATA FACILITY

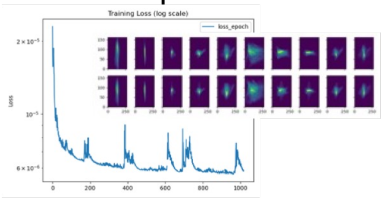
Triggers analysis workflow

Generative Phase Space Reconstruction (GPSR)

Reconstructed 6D distribution



Validation plots

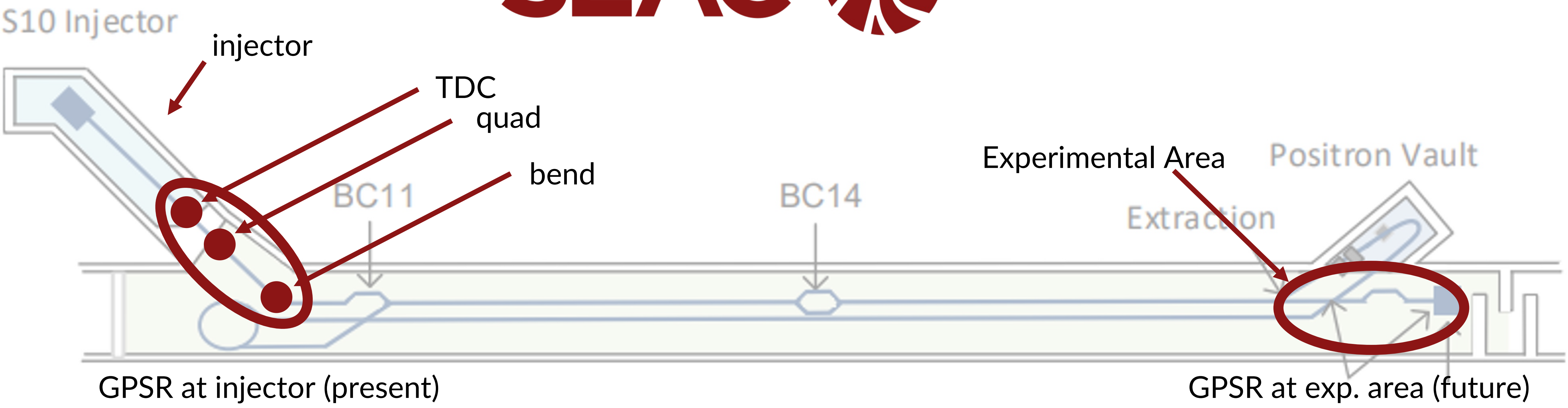


Injector tuning (future)

Control room visualization (future)

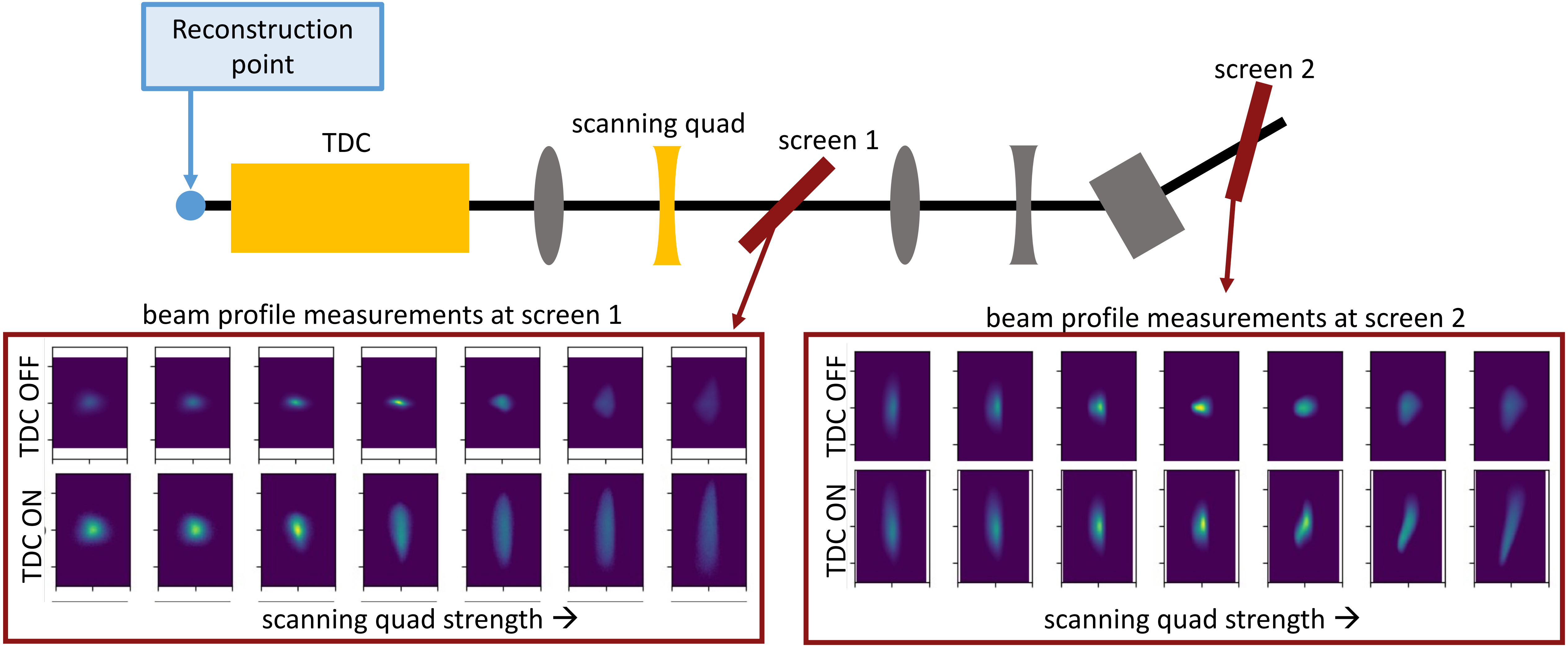
R. Roussel *et. al.* 2026 [arXiv:2604.20125](https://arxiv.org/abs/2604.20125)

GPSR at FACET-II

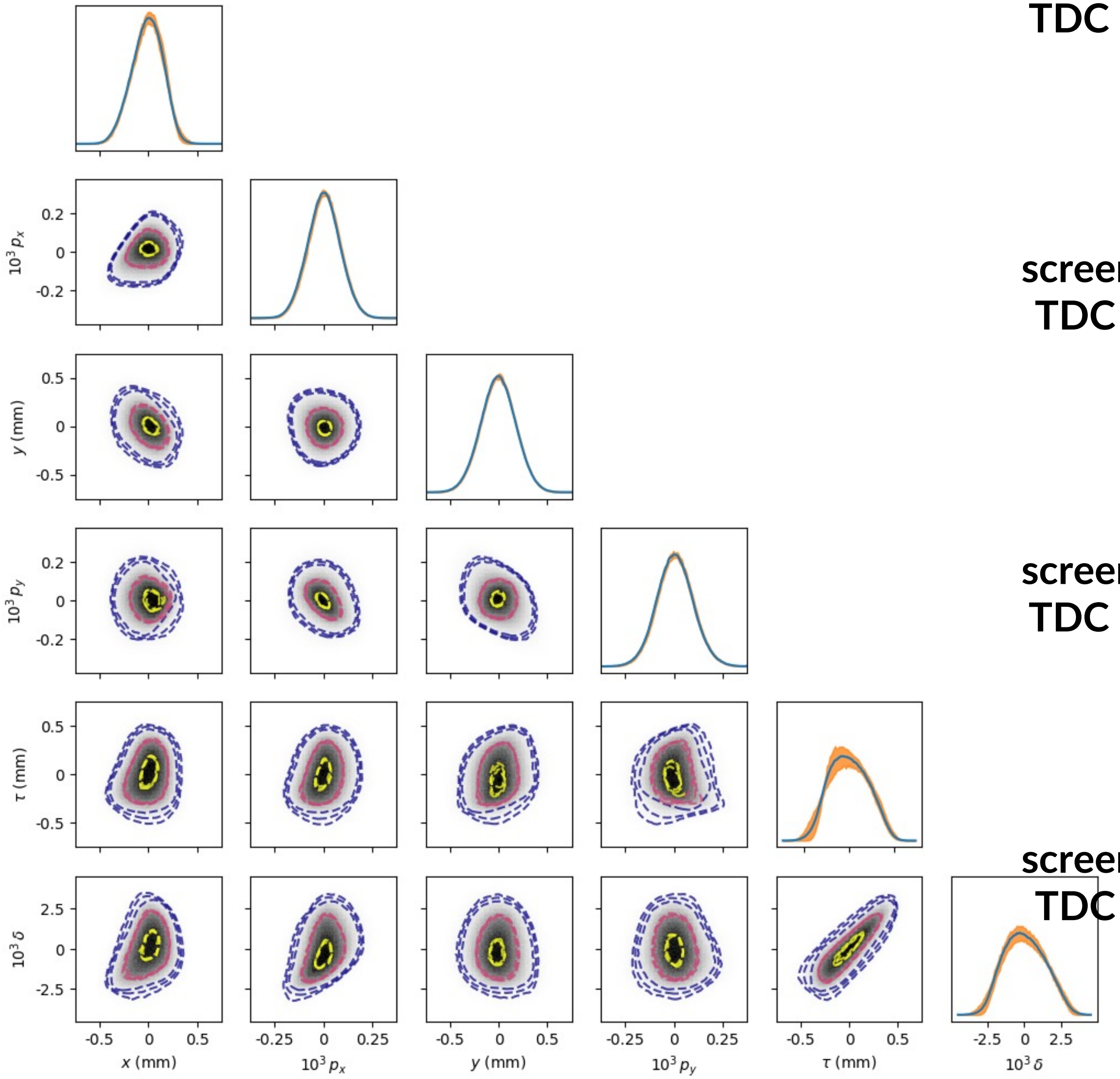


challenges:
- single and two-bunch operation
- beam dynamics at experimental area

GPSR at FACET-II injector



FACET-II single bunch

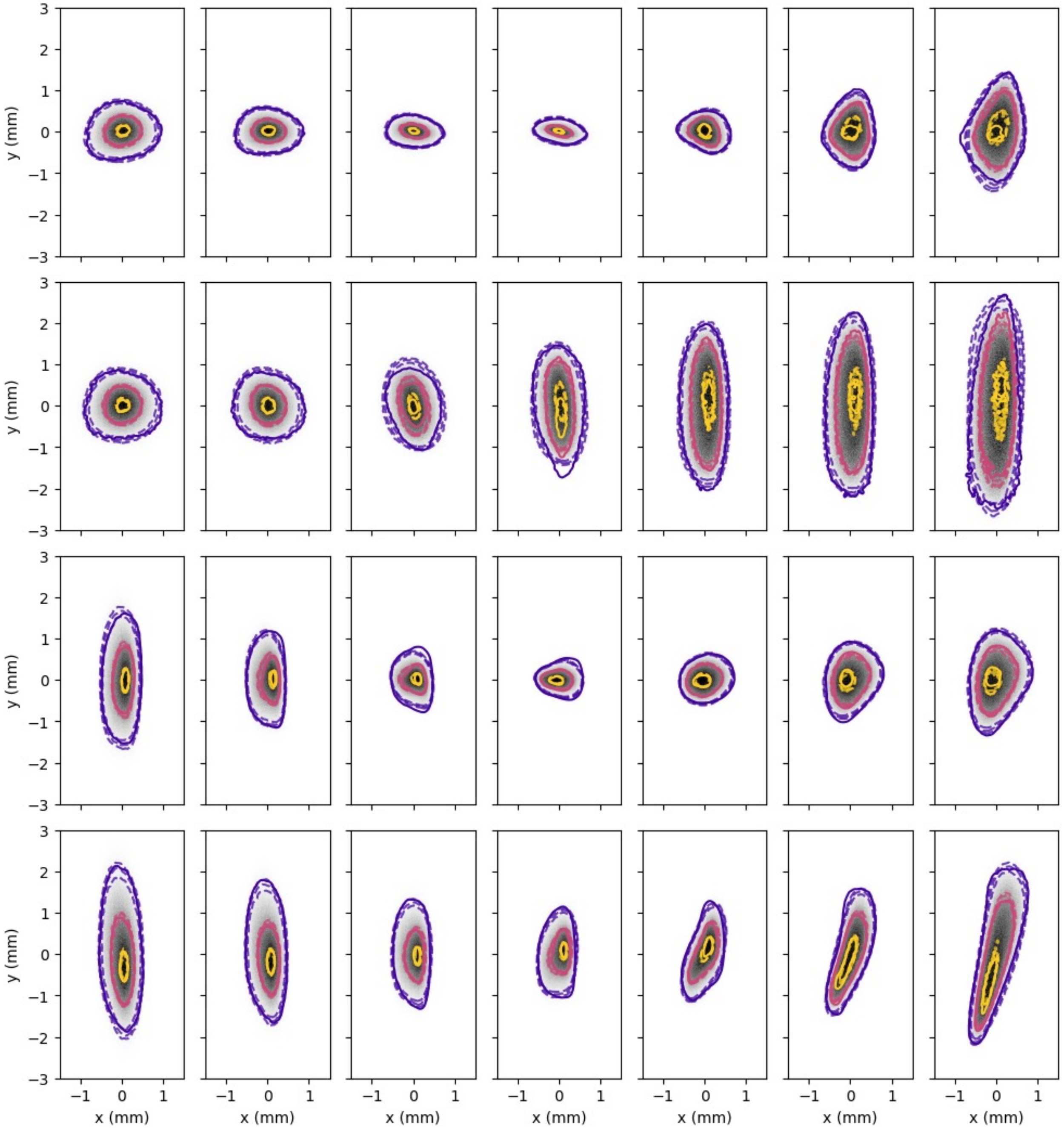


screen 1
TDC off

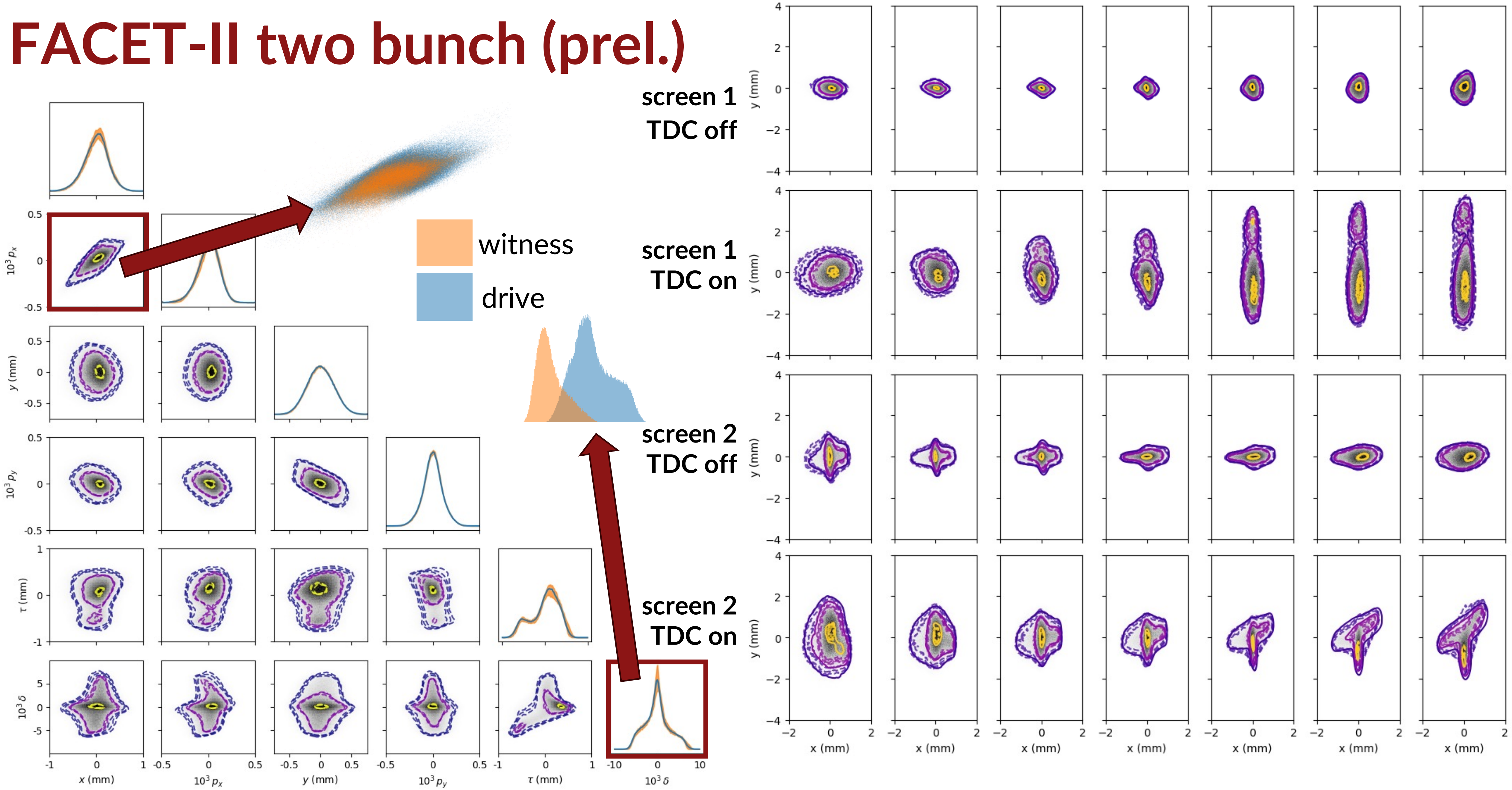
screen 1
TDC on

screen 2
TDC off

screen 2
TDC on



FACET-II two bunch (prel.)



Summary

GPSR is precise and fast:

- 4D ~5 min
- 6D ~ 20 min
- no pre-training
- not a virtual diagnostic

Efficiency relies on:

- beam generator
- differentiable simulations (only for diagnostic beamline)

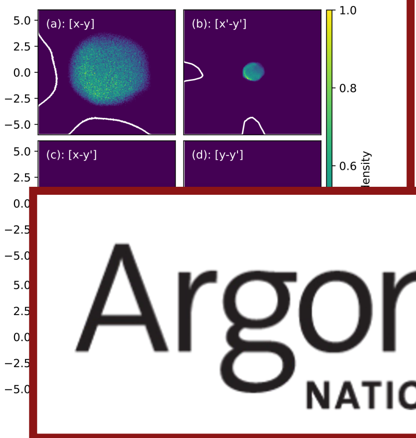
Flexible framework for implementation in different facilities:

- different available diagnostics (with/without TDC, screen placements)
- various applications (flat/magnetized beams, CSR, two-bunch)

Present/future:

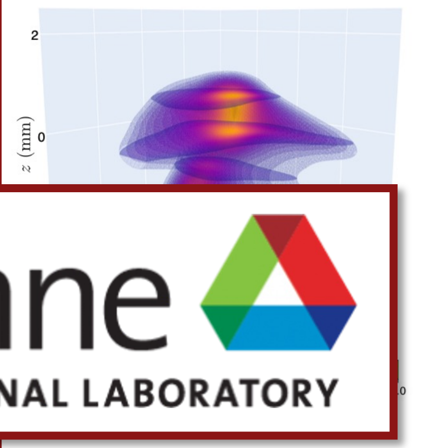
- integration with automatic workflows at FACET-II and LCLS-II
- online 6D phase space tuning

Flat/magnetized beams at **AWA**



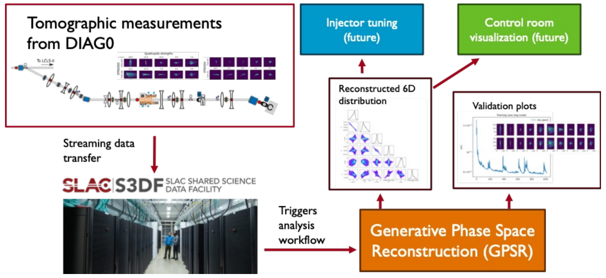
Seongyeol Kim, et al PRAB 2024

CSR-affected beams at **AWA**



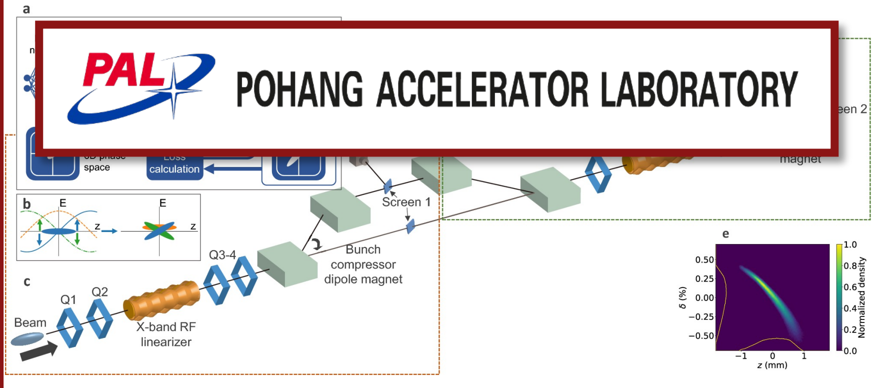
JP Gonzalez-Aguilera, Dissertation 2026

Automated online GPSR at **LCLS-II**



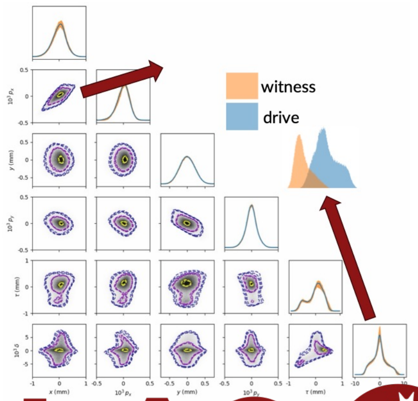
R. Roussel, *et. al.* 2026 arXiv:2604.20125

6D GPSR *w/o* TDC at **PAL-XFEL**



Seongyeol Kim, et al Sci. Rep 2025

Two-bunch GPSR at **FACET-II**



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FACET-II Facility for Advanced Accelerator Experimental Tests

LCLS Linac Coherent Light Source

Argonne NATIONAL LABORATORY

PAL POHANG ACCELERATOR LABORATORY

DESY.