Efficient 6-dimensional phase space reconstructions from experimental measurements using generative machine learning

Ryan Roussel

rroussel@slac.stanford.edu

U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

Modern Challenges in Beam Control

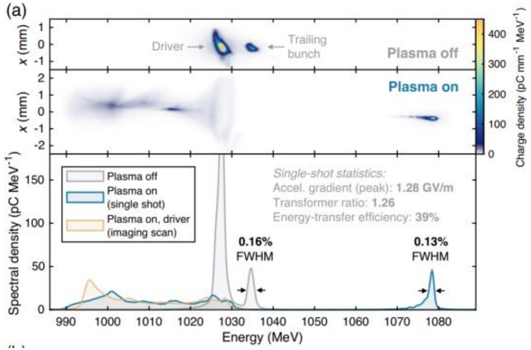
Modern accelerator developments require **precise control** over **high dimensional** beam structure

$$\boldsymbol{x} = (x, p_x, y, p_y, z, p_z)^T$$

RMS quantities → Exact beam structure

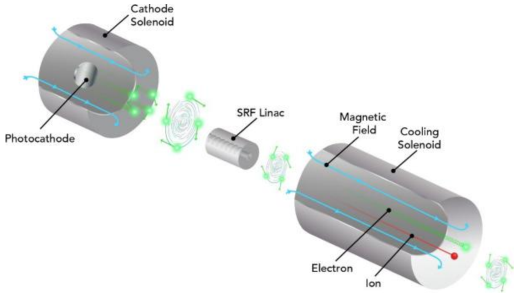
Macroscopic scale *Mesoscopic scale* *Microscopic scale*

Beam shaping for high efficiency PWFA



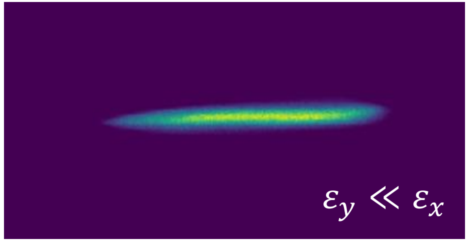
C. A. Lindstrøm, et al. Phys. Rev. Lett. **126**, 014801

Magnetized beams for hadron cooling @ EIC



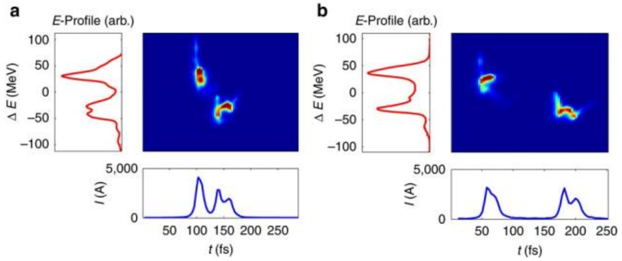
Wijethunga, S. A. K., et al. NIMA 1051 (2023): 168194.

Flat beams for colliders



Chen, P., and K. Yokoya. (1991): 91-2.

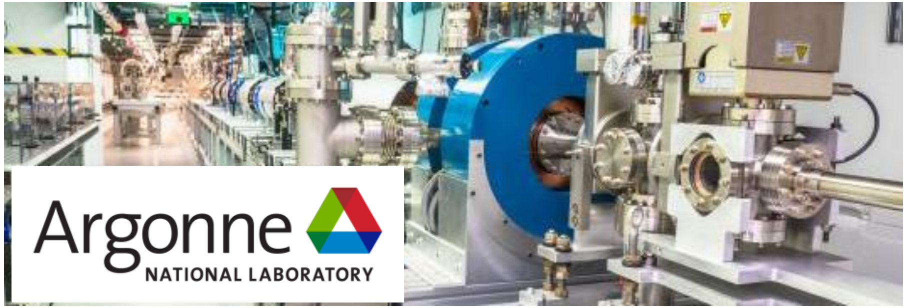
Free electron lasers



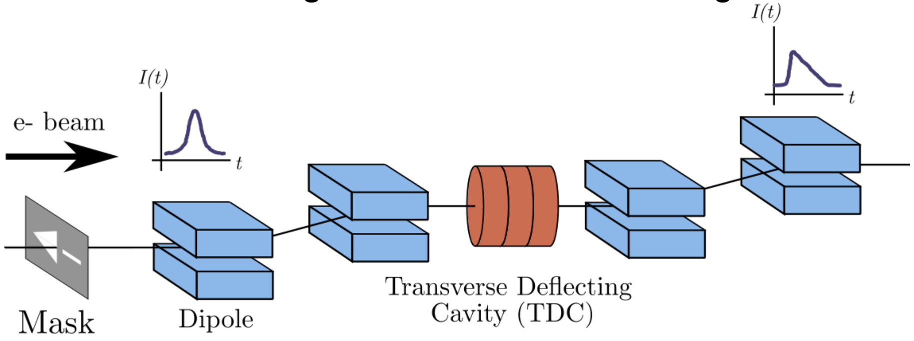
Marinelli, A., et al. *Nature communications* 6.1 (2015): 6369.

Methods for 6D Beam Shaping

Argonne Wakefield Accelerator (AWA)

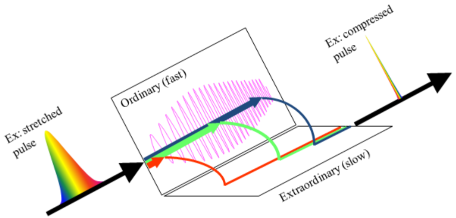


Transverse-to-longitudinal emittance exchange

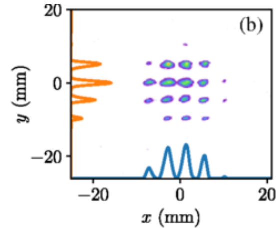


Emma, P., et al. PRAB 9.10 (2006): 100702.

Temporal laser pulse shaping

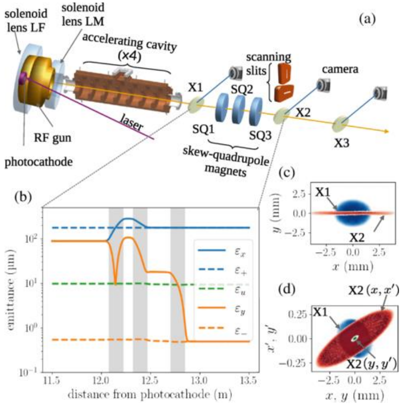


Transverse laser pulse shaping



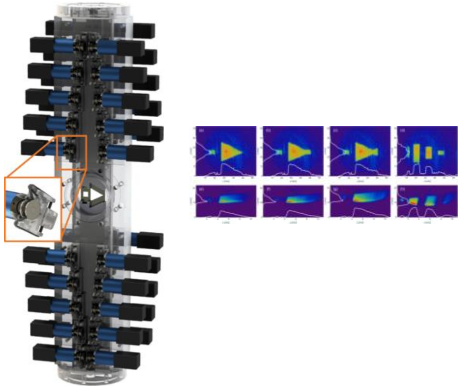
Halavanau, A., et al. PRAB 22.11 (2019): 114401.

Round-to-flat beam transformation



Xu, T., et al. PRAB 25.4 (2022): 044001.

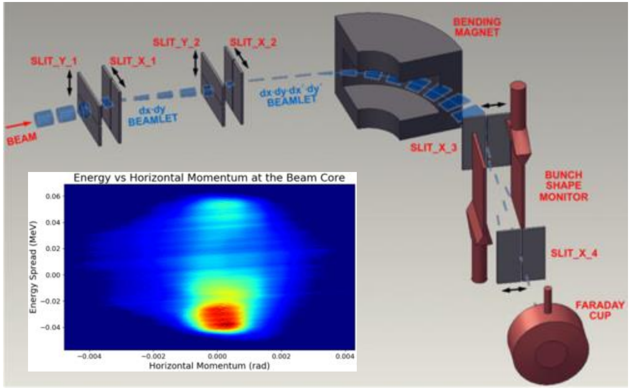
Adjustable transverse beam masking



Majernik, N., et al. PRAB 26.2 (2023): 022801.

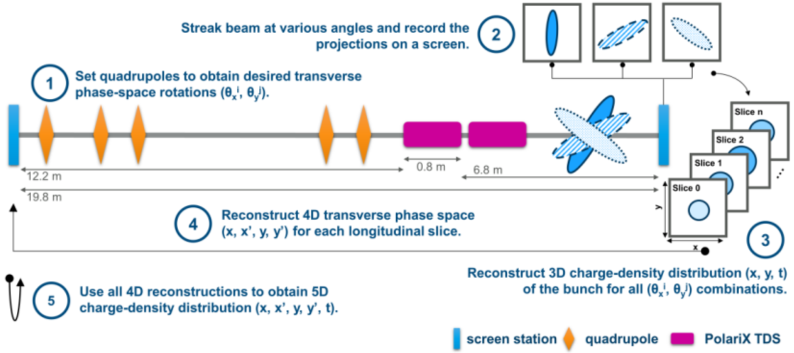
Measuring 6D Beam Distributions

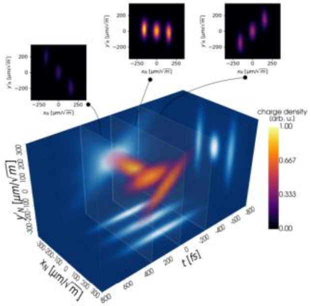
Multiple scanning slits with dipole and bunch shape monitor @ SNS (ORNL)



Cathey, Brandon, et al. PRL 121.6 (2018): 064804.

5D tomography with polarizable X-band TDC @ ARES (DESY)

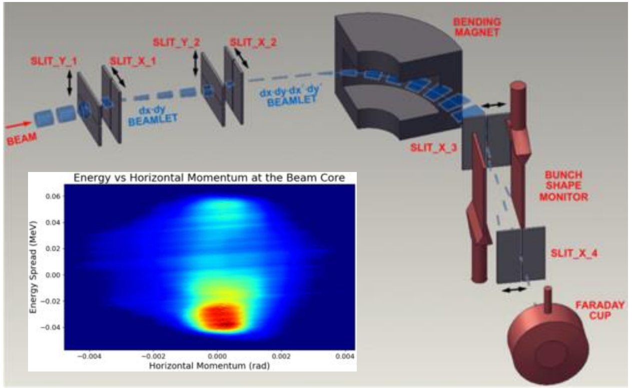




Jaster-Merz, S., et al *Proc. IPAC'22* (2022): 279-283.

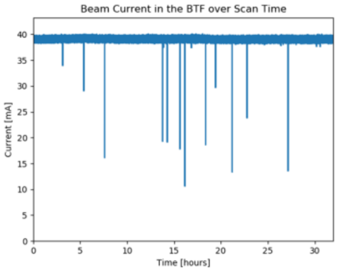
Progress on Measuring 6D Beam Distributions

Multiple scanning slits with dipole and bunch shape monitor @ SNS (ORNL)

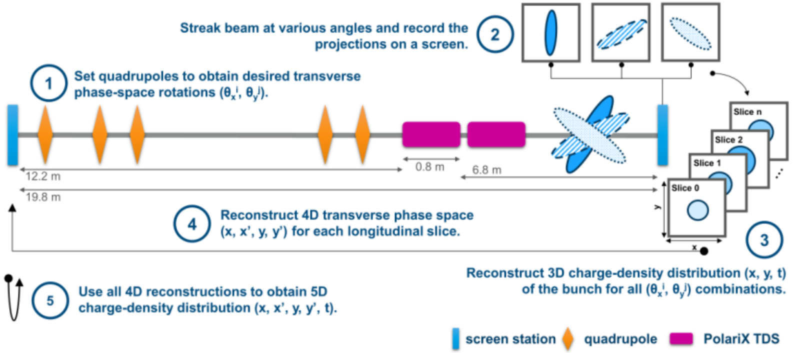


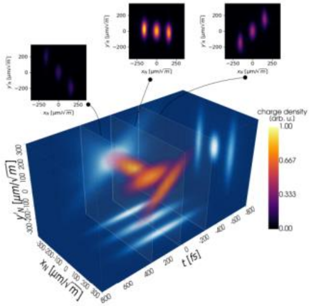
Cathey, Brandon, et al. PRL 121.6 (2018): 064804.

5 million (!) measurements **~ 32 hrs**



5D tomography with polarizable X-band TDC @ ARES (DESY)



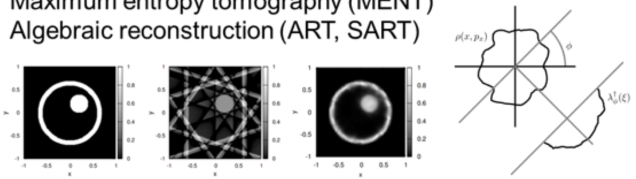


Jaster-Merz, S., et al *Proc. IPAC'22* (2022): 279-283.

960 measurements **~ 28 hrs**

Tomographic reconstruction **~ 24 hrs**

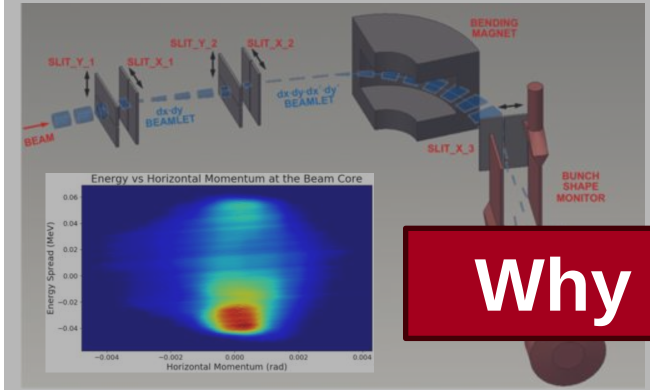
- Maximum entropy tomography (MENT)
- Algebraic reconstruction (ART, SART)



Hock K. and Ibison M., JINST, 2013

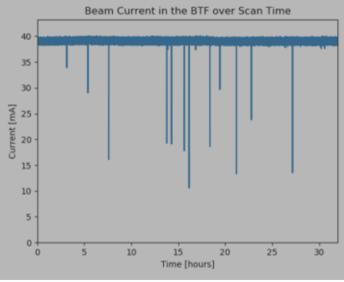
Progress on Measuring 6D Beam Distributions

Multiple scanning slits with dipole and bunch shape monitor @ SNS (ORNL)

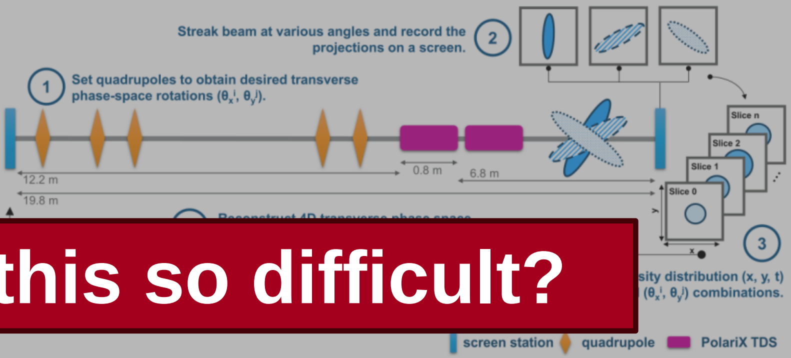


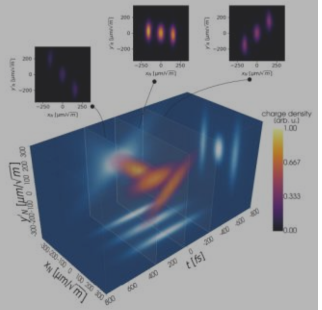
Cathey, Brandon, et al. PRL 121.6 (2018): 064804.

5 million (!) measurements **~ 32 hrs**



5D tomography with polarizable X-band TDC @ ARES (DESY)





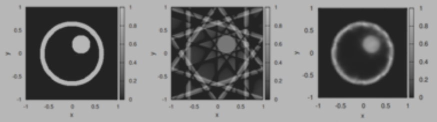
Why is this so difficult?

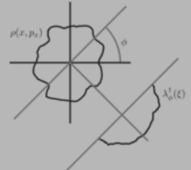
Jaster-Merz, S., et al *Proc. IPAC'22* (2022): 279-283.

960 measurements **~ 28 hrs**

Tomographic reconstruction **~ 24 hrs**

- Maximum entropy tomography (MENT)
- Algebraic reconstruction (ART, SART)

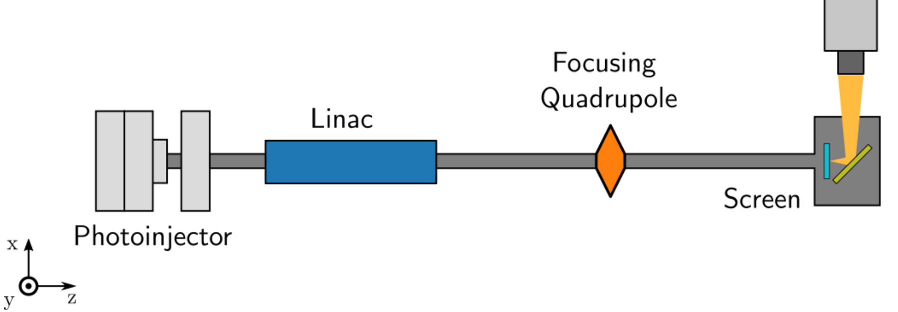


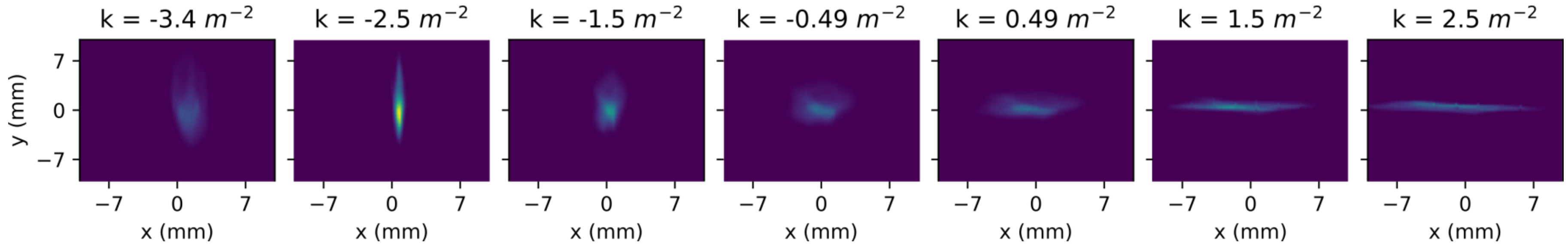


Hock K. and Ibison M., JINST, 2013

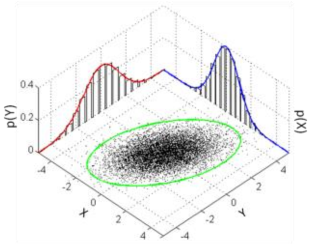
Example: Quadrupole Scan @ AWA

Drive beamline





Using Optimization to Reconstruct Distributions

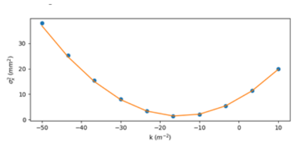


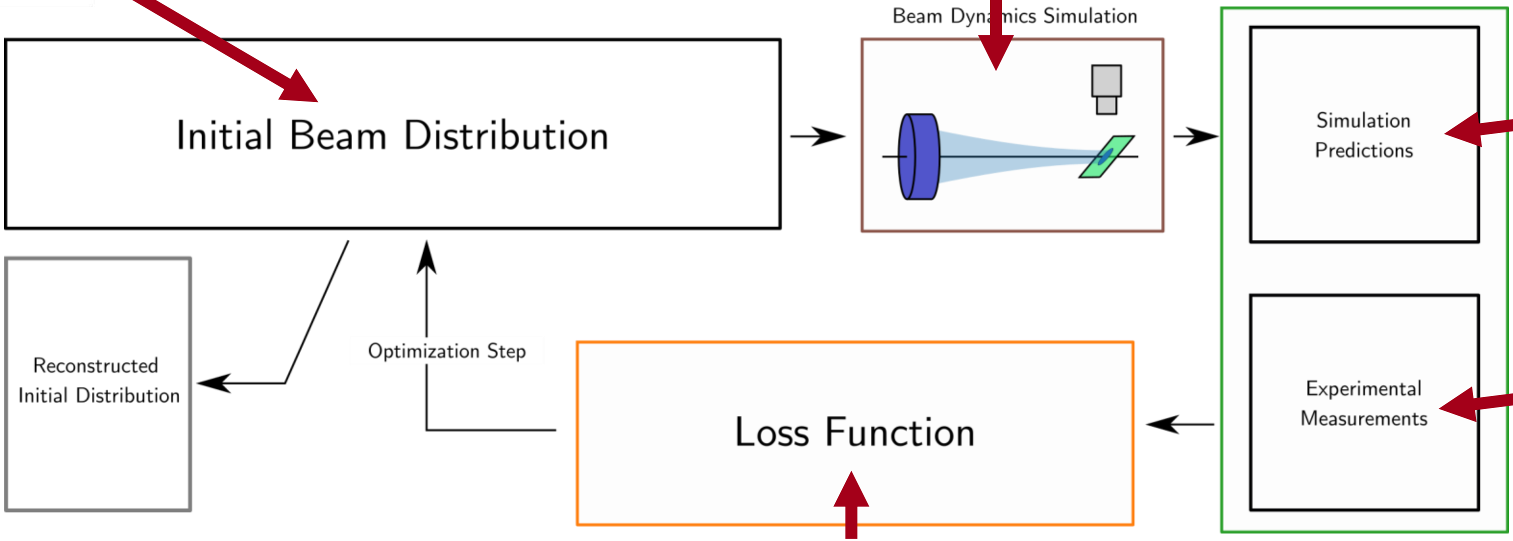
Second order beam moments

$\sigma_x, \sigma_{xx'}, \sigma_{x'}$

Analytical beam dynamics model

$$\sigma_{x,p}^2 = (1 + dlk)^2\sigma_x^2 + 2(1 + dlk)\sigma_{xx'} + d^2\sigma_{x'}^2$$



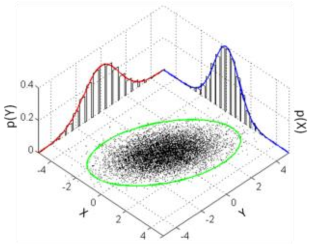


$\sigma_{x,p}$

$\sigma_{x,m}$

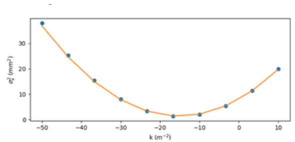
$$l = \sum\left(\sigma_{x,p} - \sigma_{x,meas}\right)^2$$

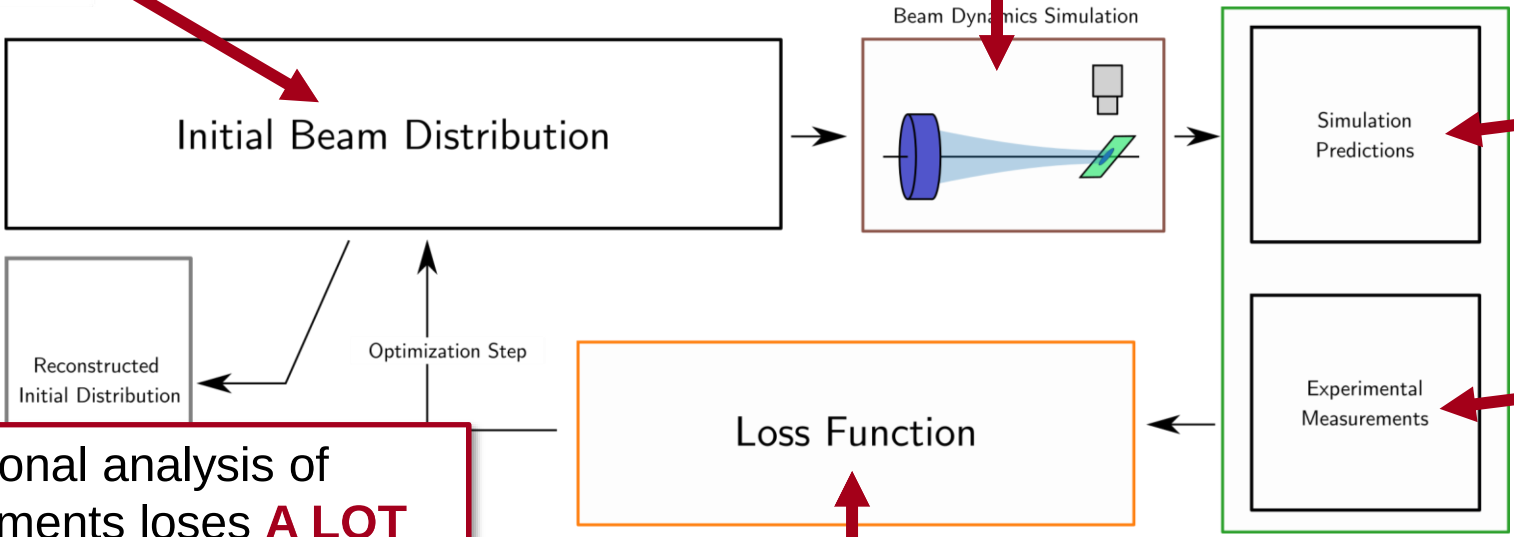
Using Optimization to Reconstruct Distributions



Second order beam moments
$\sigma_x, \sigma_{xx'}, \sigma_{x'}$

Analytical beam dynamics model
$$\sigma_{x,p}^2 = (1 + dlk)^2\sigma_x^2 + 2(1 + dlk)\sigma_{xx'} + d^2\sigma_{x'}^2$$





$\sigma_{x,p}$

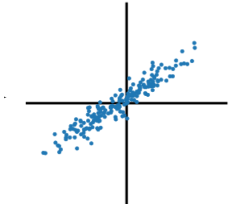
$\sigma_{x,m}$

Conventional analysis of measurements loses **A LOT** of beam information

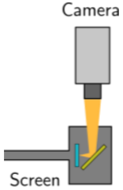
$$l = \sum(\sigma_{x,p} - \sigma_{x,meas})^2$$

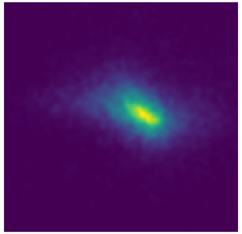
Why Is This So Difficult?

Information compression

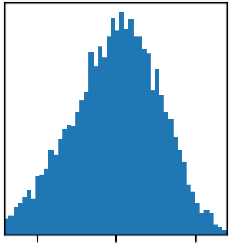


6D distribution





2D image



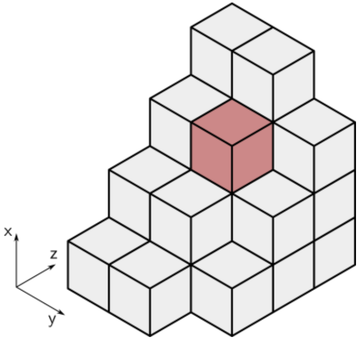
1D projection(s)

$\{< x >, \sigma_x\}$

Scalar values

Often required by analysis constraints (analytical tractability, optimization simplicity, etc.)

Costs of detailed beam representations



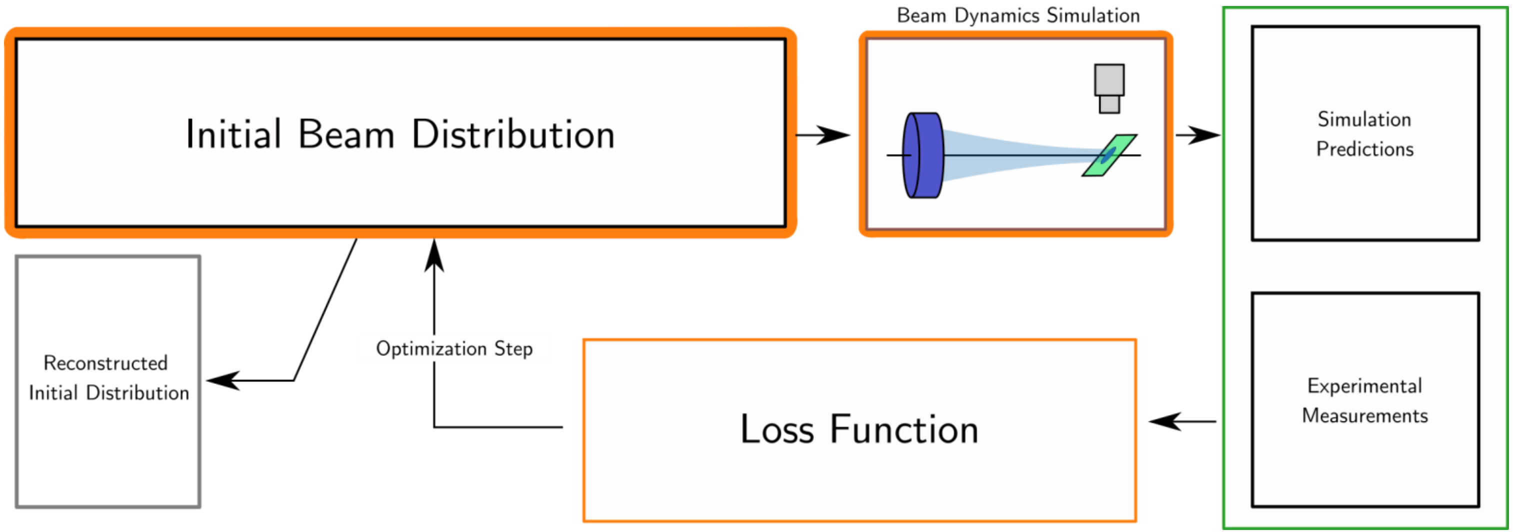
Histogramming scales poorly with number of dimensions, $N_{bins} \propto n^D$

Reasonable resolution, $n = 100$
For a 6D distribution, $N_{bins} = 10^{12}$!

The Road to Efficient 6D Reconstructions

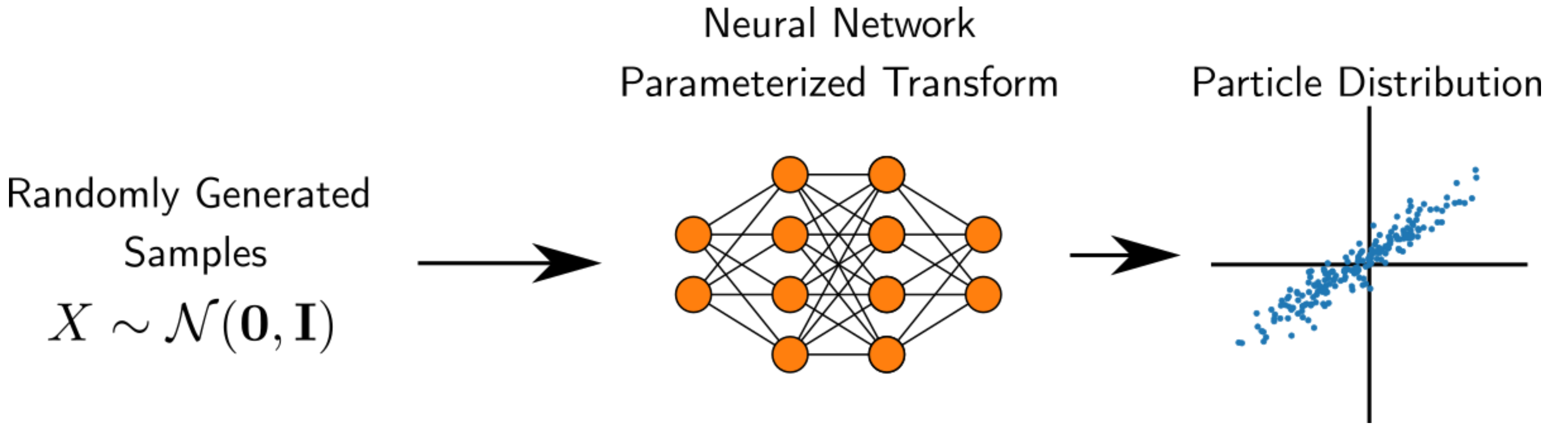
(1) Use **generative machine learning** to represent complex 6D beam distributions.

(2) Implement **differentiable** beam dynamics simulations to enable learning



Machine Learning Based Beam Representations

Use a **generative** machine learning model to create **arbitrary beam distributions**

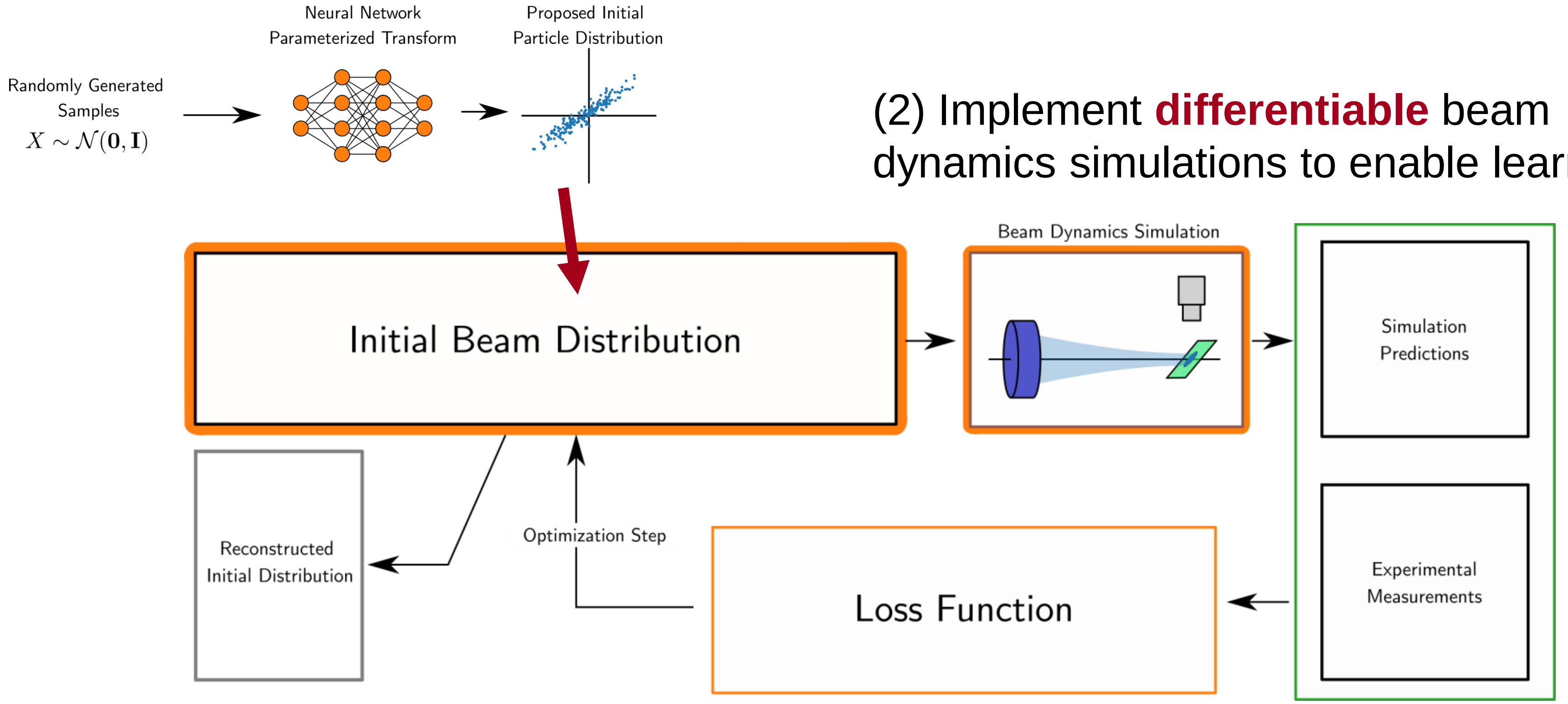


O(~1000) parameters of the neural network control the distribution of particles in 6D phase space

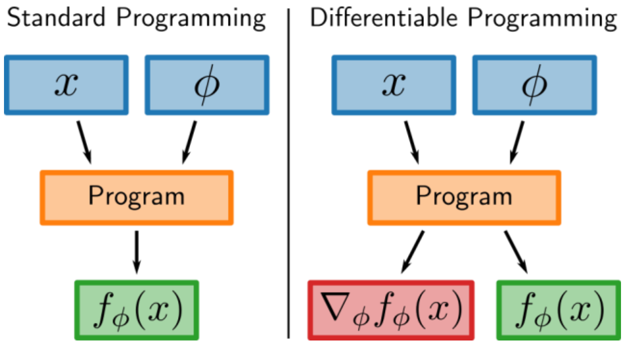
Learn the NN parameters → learn the beam distribution

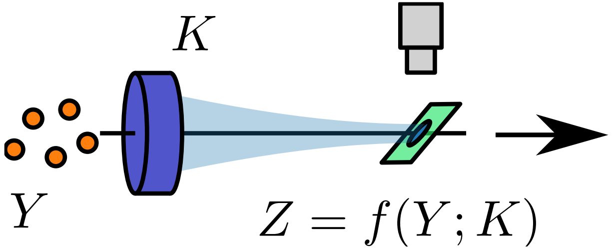
The Road to Efficient 6D Reconstructions

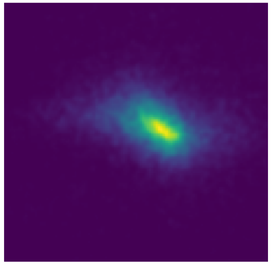
(2) Implement **differentiable** beam dynamics simulations to enable learning



Differentiable Beam Physics Simulations







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

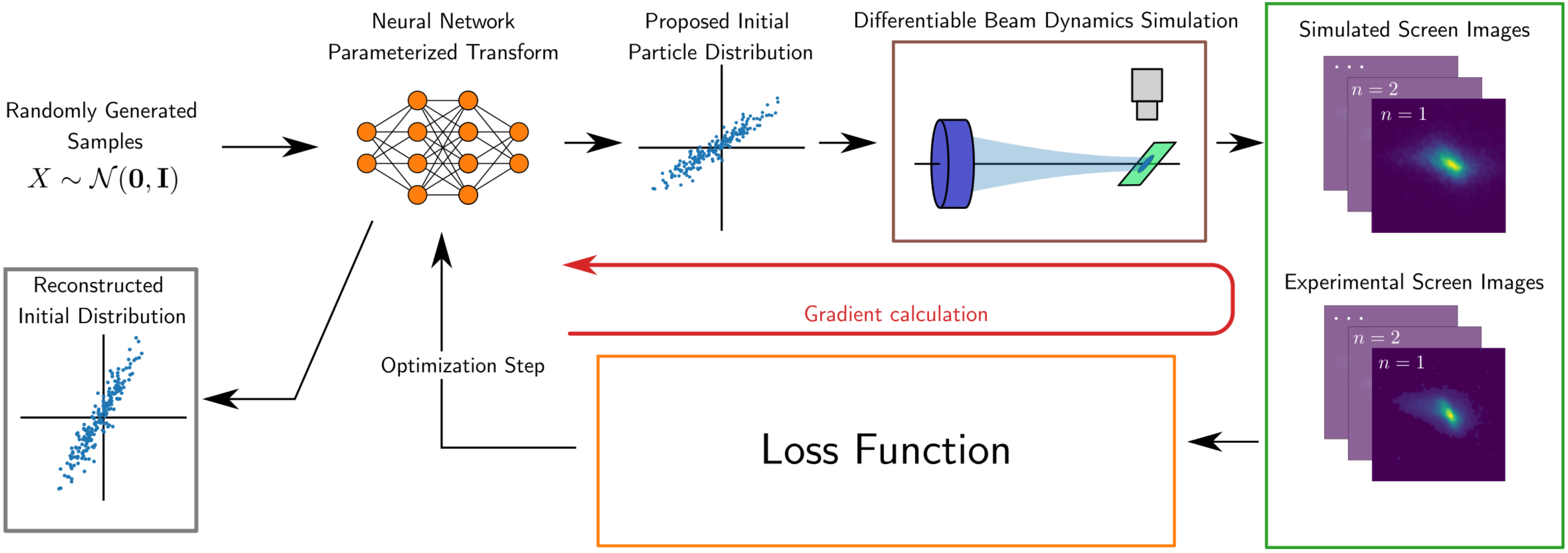
Differentiable sims keep track of derivative information during **every** calculation step.

$$\frac{\partial Z}{\partial Y}, \frac{\partial Z}{\partial K}, \frac{\partial \sigma_Z}{\partial K}, \ldots \qquad \frac{\partial Q^{(i,j)}}{\partial Y}, \frac{\partial Q^{(i,j)}}{\partial K}$$

Enables **cheap gradient evaluations** which enable optimization of >10k free parameters.

Allows us to extract information from the **individual pixels** of an image.

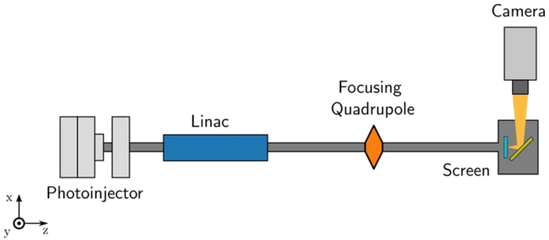
Generative Phase Space Reconstruction (GPSR)

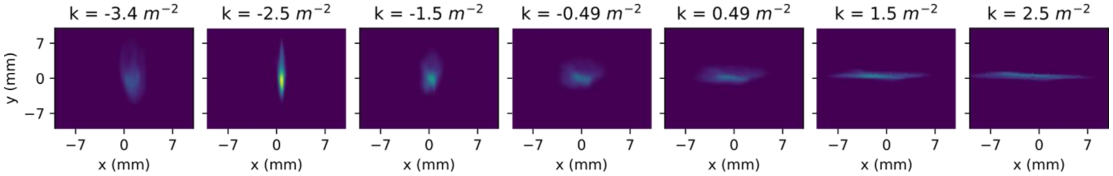


Now we can use **gradient descent** to optimize (train) beam parameters → **necessary** for learning O(~1000) parameters

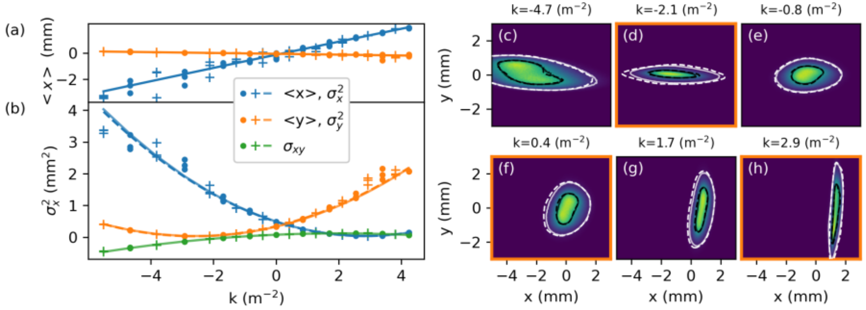
Roussel, Ryan, et al. PRL (2023)

Four-dimensional reconstructions using GPSR



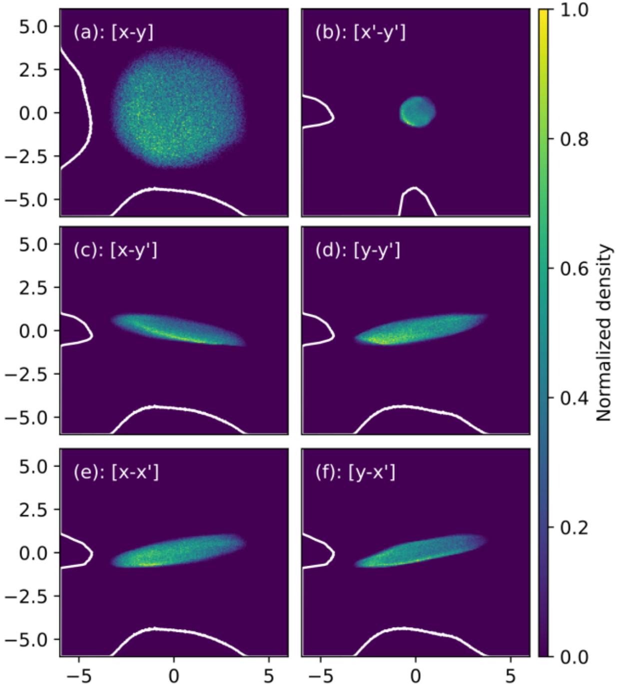


Proof of concept reconstruction from quadrupole scan



Roussel, R, et al. PRL (2023)

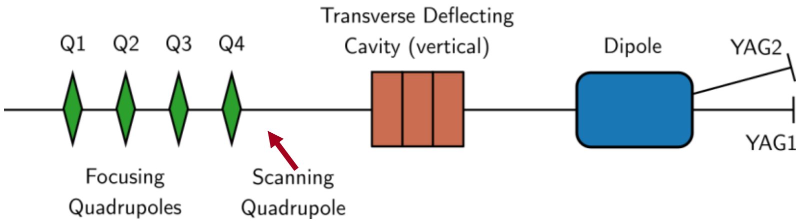
Application to magnetized / flat beams

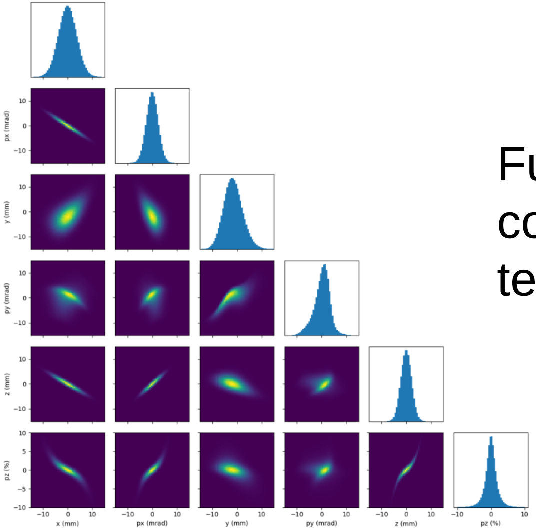


Kim, S., et al. PRAB (2024)

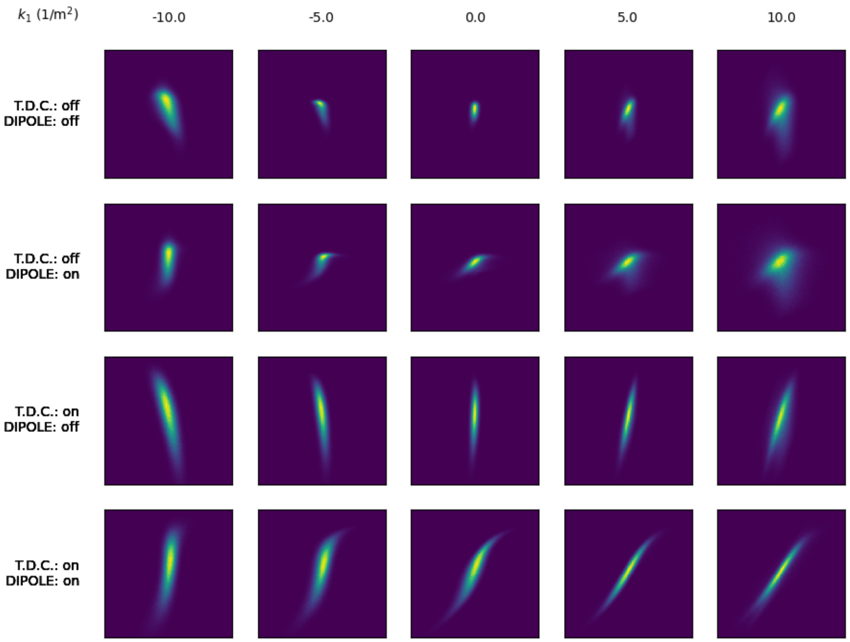
6D Phase Space Reconstruction (Simulation)

Logical next step, combine 4D reconstructions from quad scans with single shot longitudinal phase space diagnostics





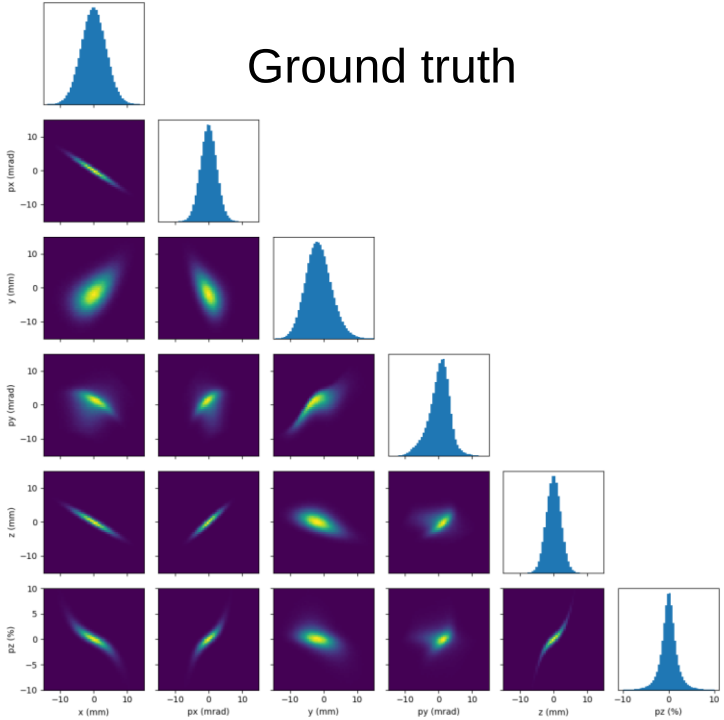
Fully correlated test beam

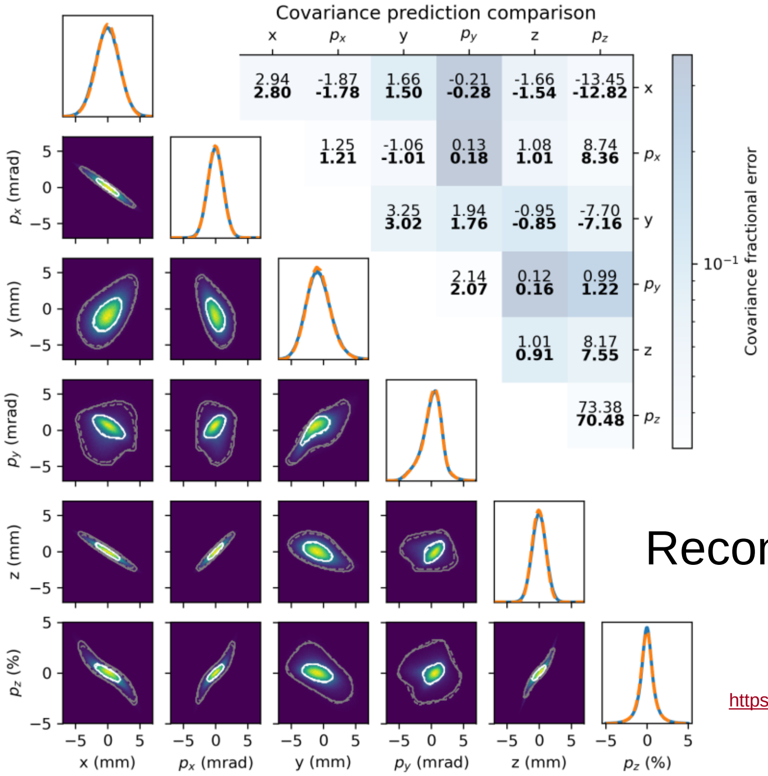


20 simulated measurements

Reconstruction Results (Simulation)

Ground truth



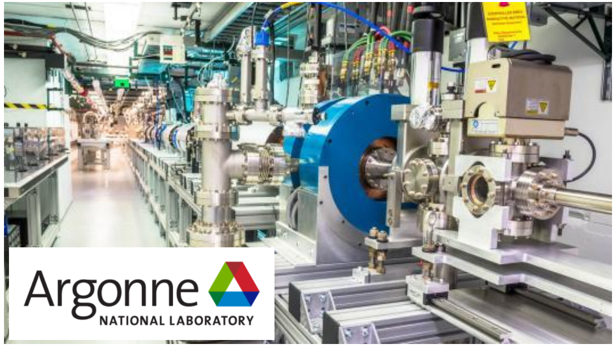


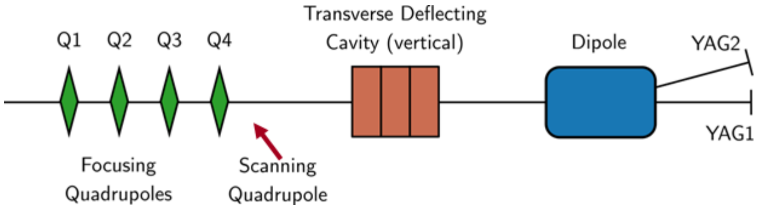
Reconstruction

Roussel, R, et al.
https://arxiv.org/abs/2404.10853
(Submitted to PRAB)

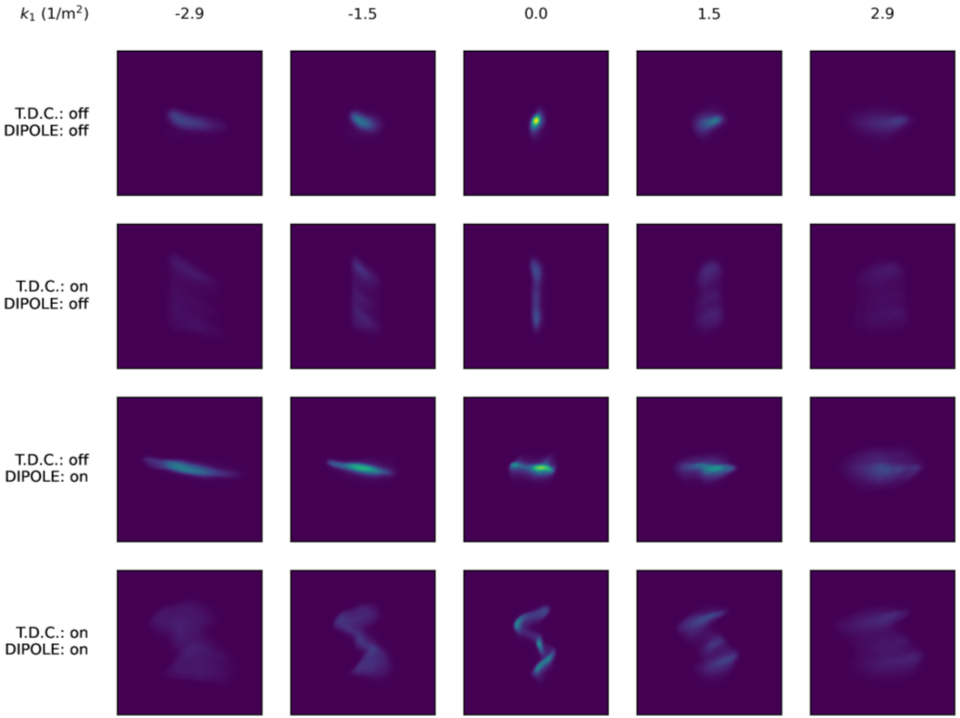
Successful reconstruction with 20 measurements, ~8 min computation time

Experimental Results from AWA





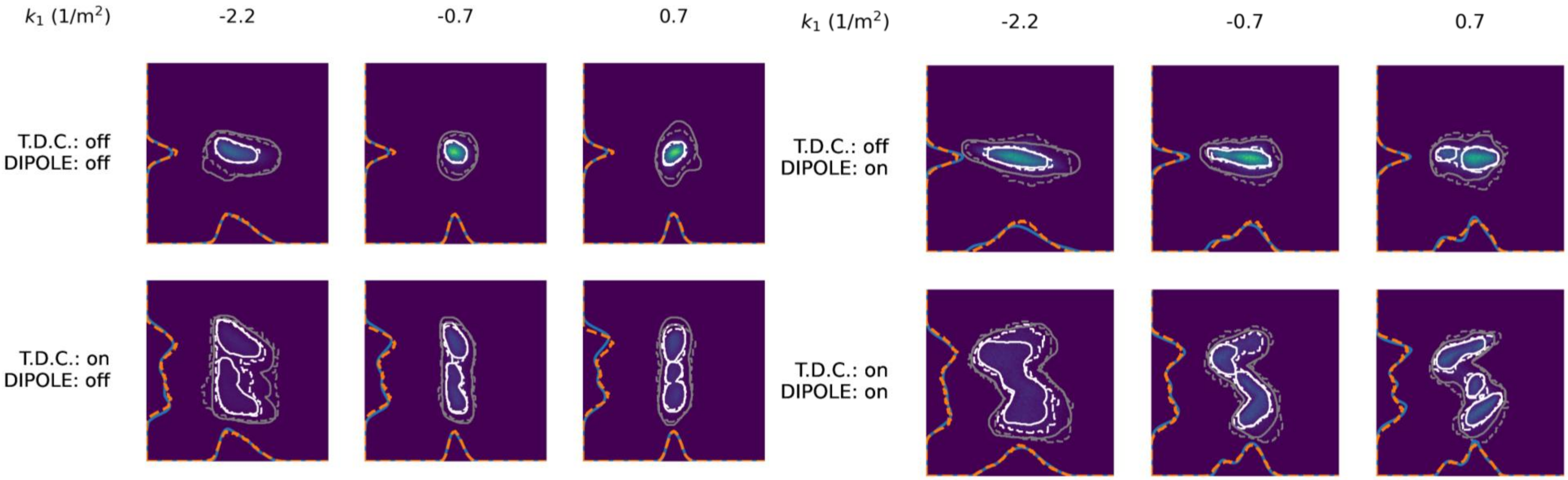
Measurement data



Roussel, R, et al. https://arxiv.org/abs/2404.10853
(Submitted to PRAB)

Experimental Results from AWA

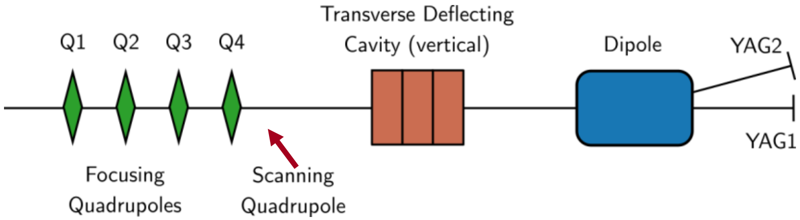
Reconstruction predictions on test data



— Measured - - Predicted

Roussel, R, et al. https://arxiv.org/abs/2404.10853
(Submitted to PRAB)

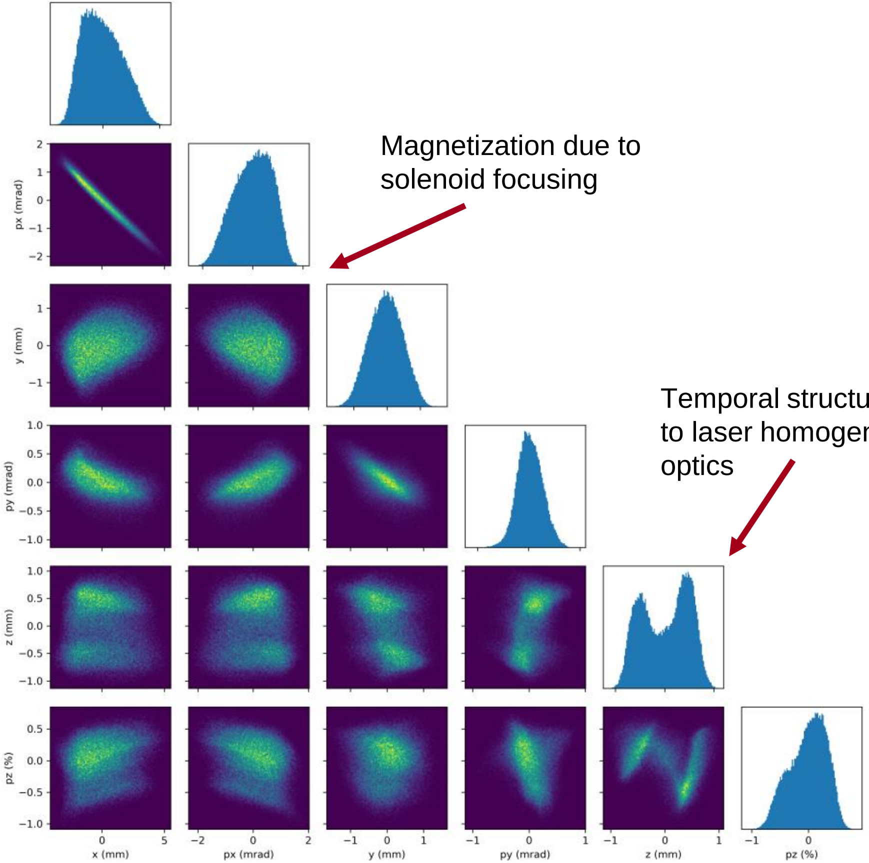
Experimental Results from AWA



Reconstructed 6D distribution
Measurement: ~8 mins
Training: ~17 mins

Roughly **75x faster** than previous demonstrations

Roussel, R, et al. https://arxiv.org/abs/2404.10853
(Submitted to PRAB)



Magnetization due to solenoid focusing

Temporal structure likely to laser homogenization optics

Conclusion

SLAC

- **Generative modeling** + **differentiable physics simulations (GPSR)** → substantial improvements in analysis capabilities
- Experimental demonstration at AWA → reconstructions + analysis **in ~ 17 mins →** can be further improved
- **Enables better understanding of beam distributions in experiment** → better wakefield accelerators, beams for colliders/cooling, better understanding of beam physics (CSR)

Questions?

SLAC

- Auralee Edelen
- Chris Mayes
- Daniel Ratner

U. Chicago

- Juan Pablo Gonzalez-Aguilera

Argonne Wakefield Accelerator

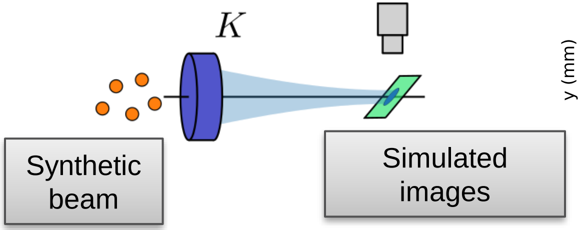
- Seongyeol Kim
- John Power
- Eric Wisniewski
- Wanming Liu
- Alexander Ody

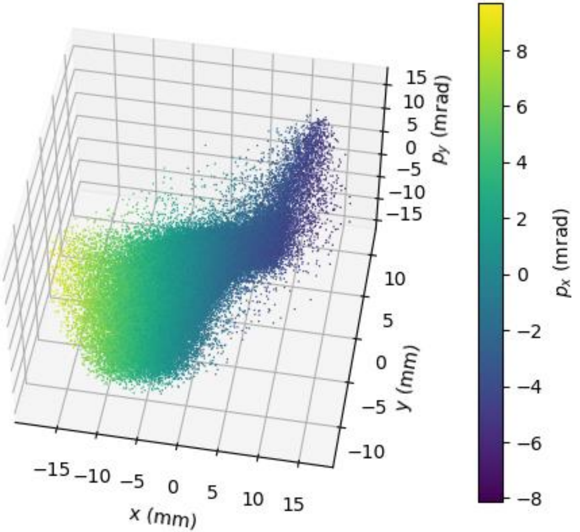
Thanks to the team!

Backup

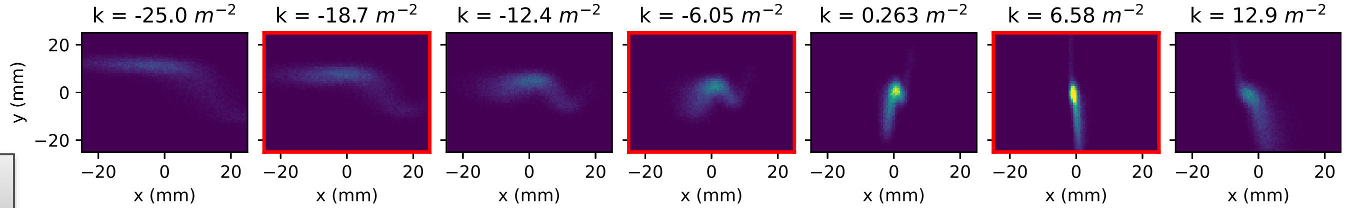
GPSR Synthetic Example

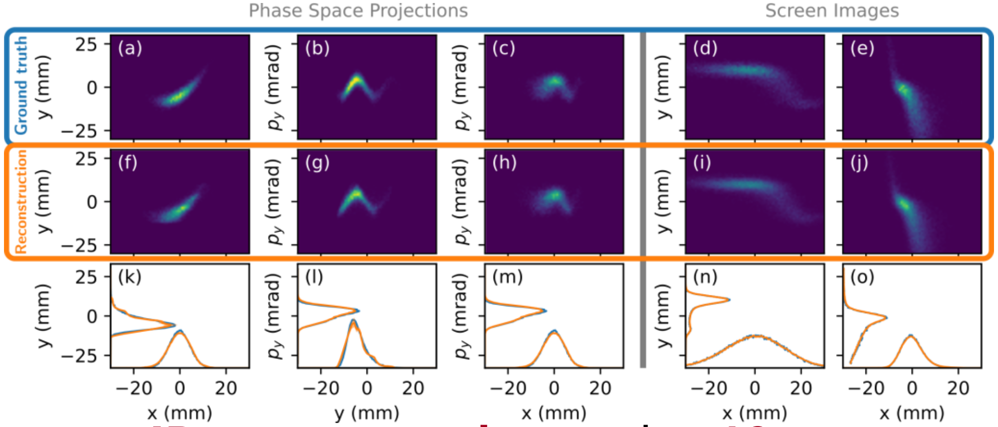
Beamline





Screen images





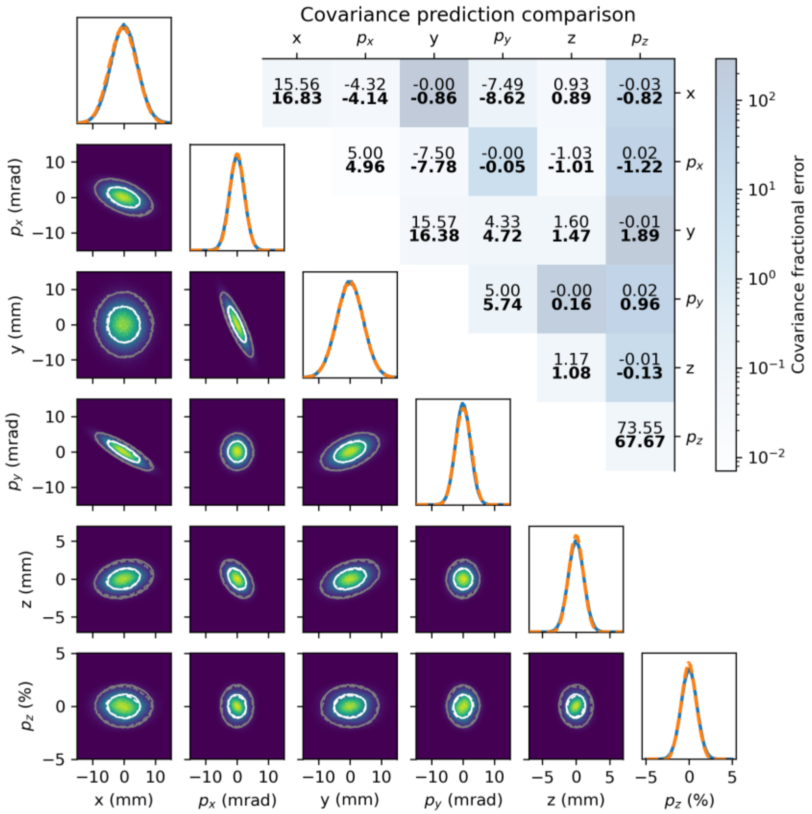
Accurate **4D reconstructions** using **10 measurements**

Reconstruction (training) time **< 5 mins**

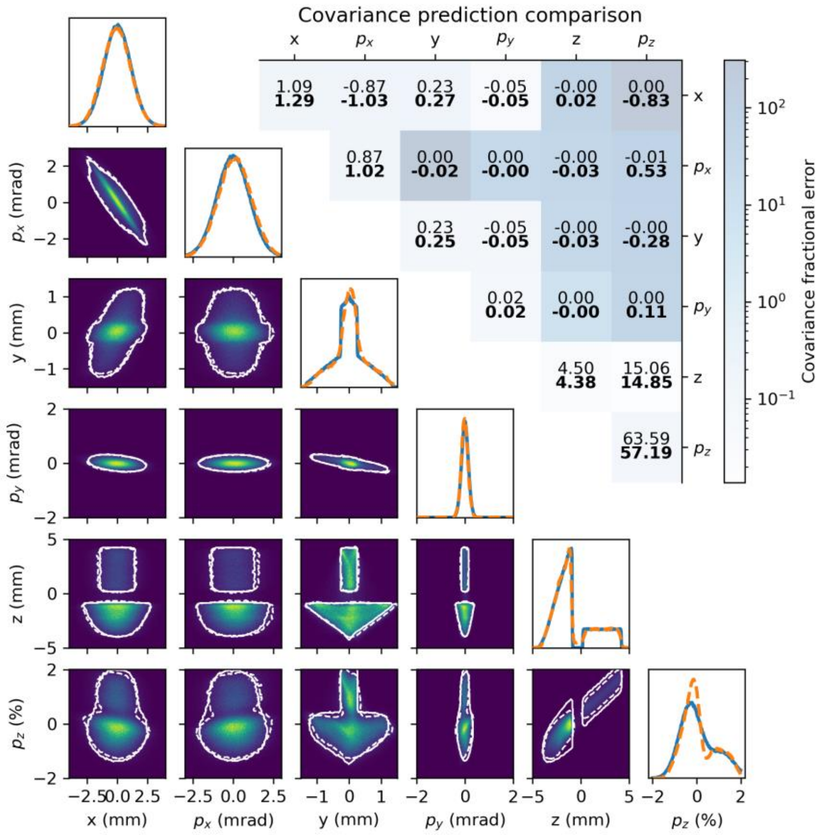
No prior training data needed

Roussel, R, et al. PRL (2023)

Reconstruction Results (Gaussian Beam)

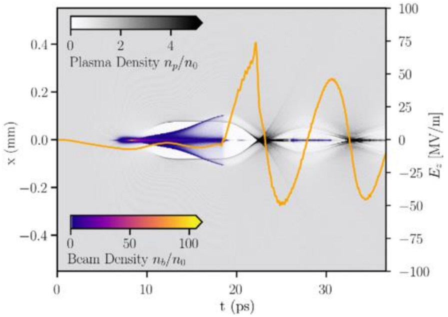


Reconstruction Results (EEX Beam)



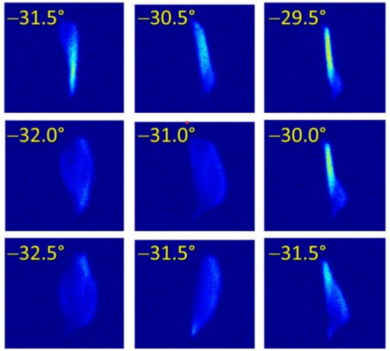
Needs From the Accelerator Community

- There is a need for **fast, sample efficient** methods to reconstruct **detailed 6D beam distributions**
- This would enable:
  - **Practical optimization of complex beam distributions** for wakefield acceleration, magnetized beams, collective effect mitigation, free electron accelerators
  - **Improvements in understanding complex physical phenomena** (plasma wakes, coherent synchrotron radiation (CSR) on beam distributions)



High transformer ratio wakefield acceleration using triangular beams

Roussel, R, et al. PRL 124.4 (2020): 044802.



CSR measurements @ LCLS

Emma, P., et al. FEL2012 (2012).