

# Phase Space Reconstruction of CSR- affected Beams

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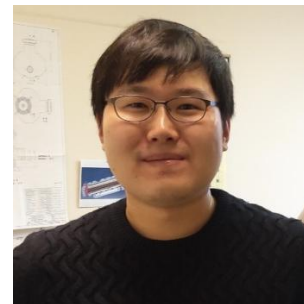
# Team



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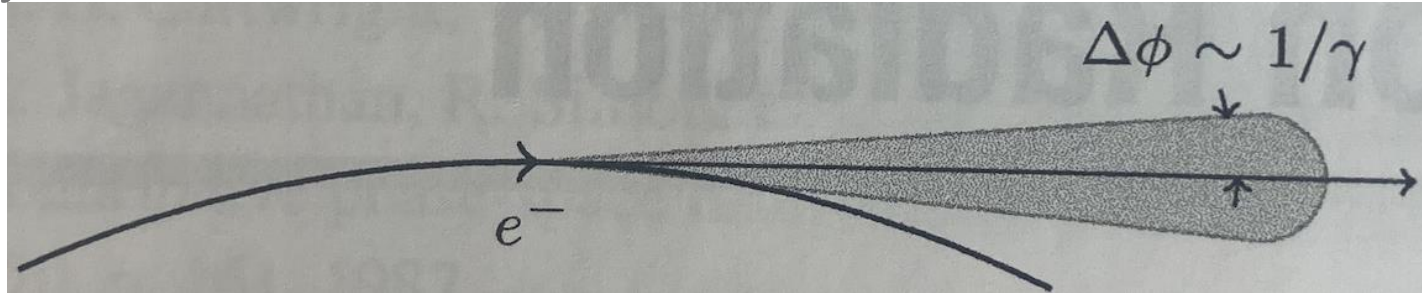
This work was supported by:

- NSF award PHY-1549132, the Center for Bright Beams
- DoE contract No. DE-AC02-05CH11231, NERSC award BES-ERCAP0023724



# Synchrotron Radiation

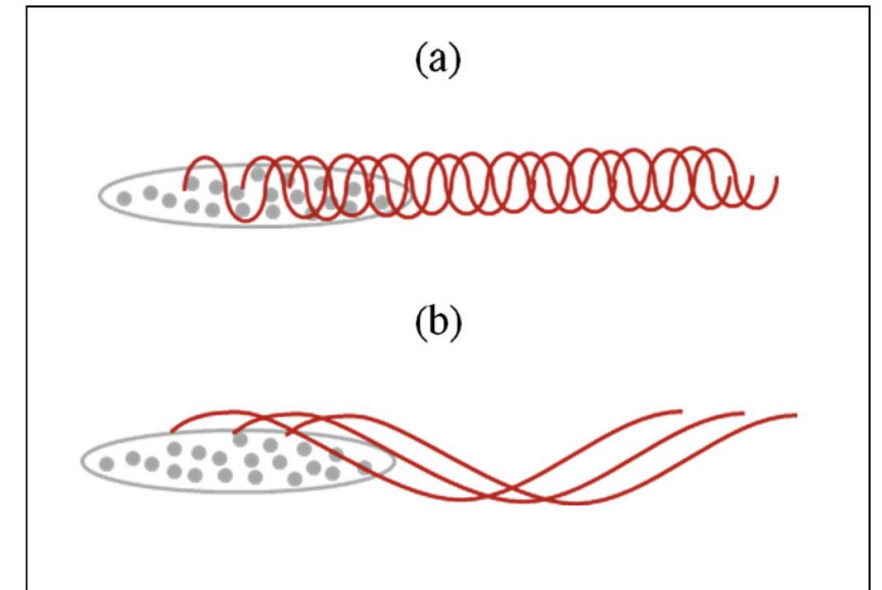
- Radiation produced by relativistic charged particles moving along curved trajectory



K.-J. Kim *et al.*, 2017

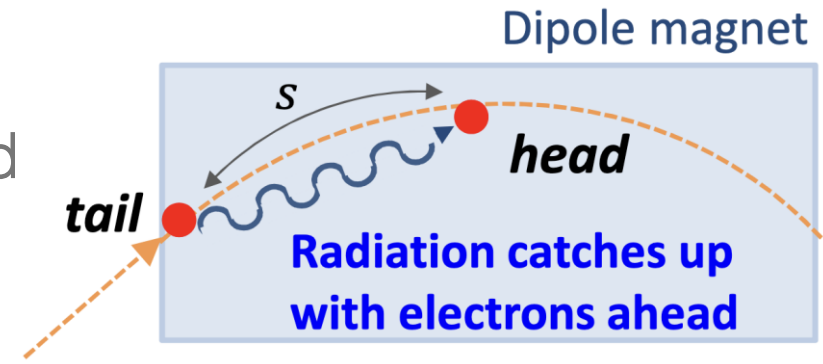
$$\frac{dP^{(N)}}{d\omega}(\omega) \approx \underbrace{N \frac{dP^{(1)}}{d\omega}}_{\text{incoherent}} + \underbrace{N(N-1) \left| \int \lambda(s) \exp\left(i \frac{\omega s}{\beta c}\right) ds \right|^2}_{\text{coherent}} \frac{dP^{(1)}}{d\omega},$$

$$P_{CSR} \propto \frac{1}{\sigma_z^{4/3}}$$



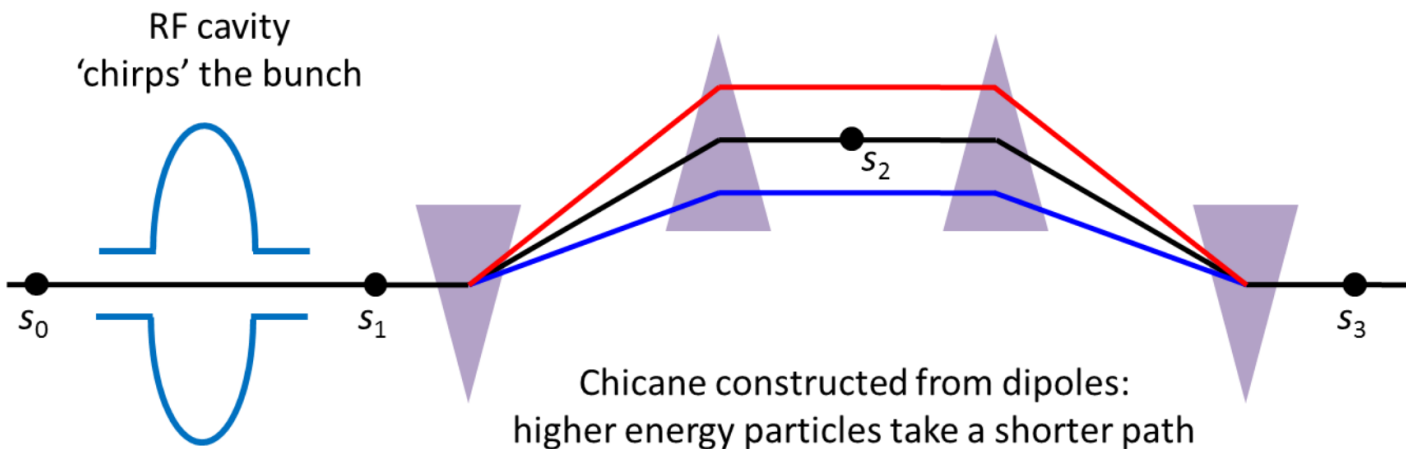
# Coherent synchrotron radiation in compressed beams

- CSR is produced when bending beam trajectory
- Radiation emitted by tail of beam kick particles ahead



S. Di Mitri, USPAS 2015

- FEL applications need highly compressed beams longitudinally
- Dispersive lattices are used to compress the beams (e.g., chicanes)

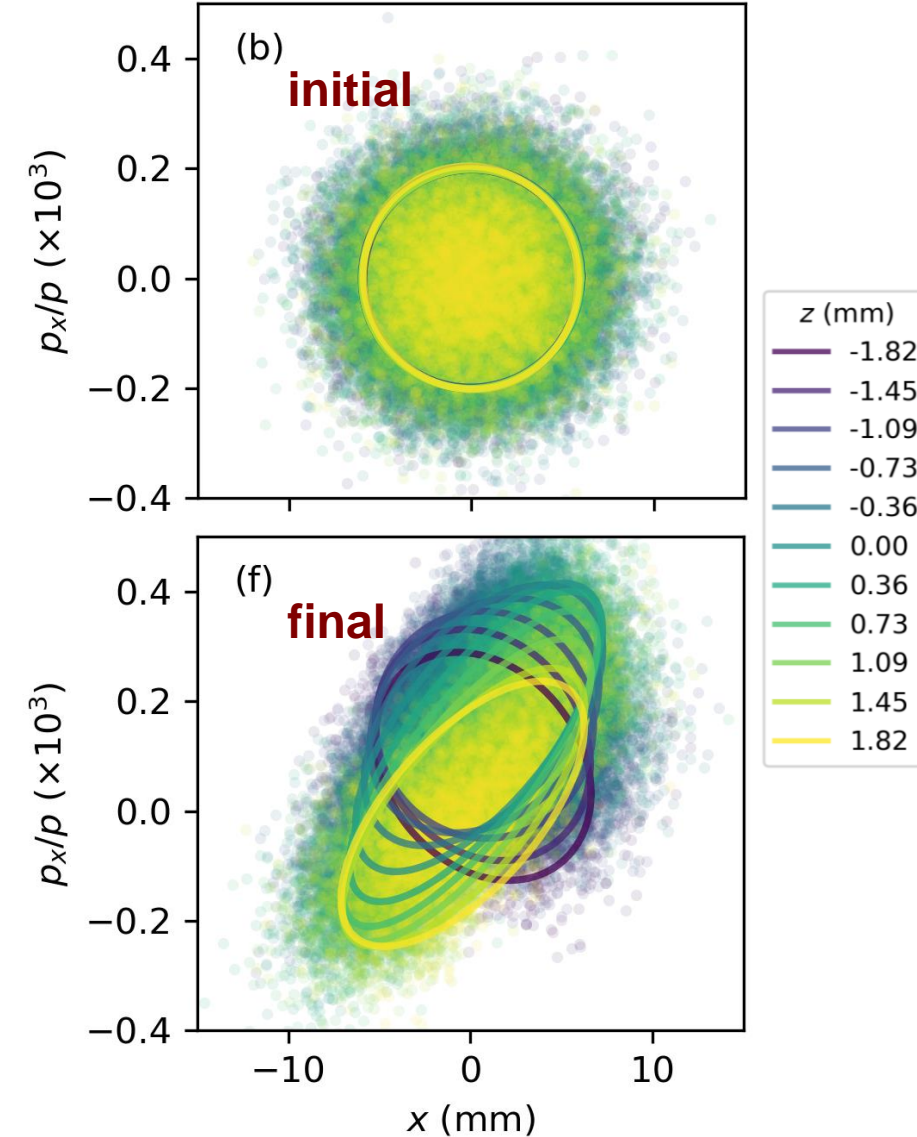
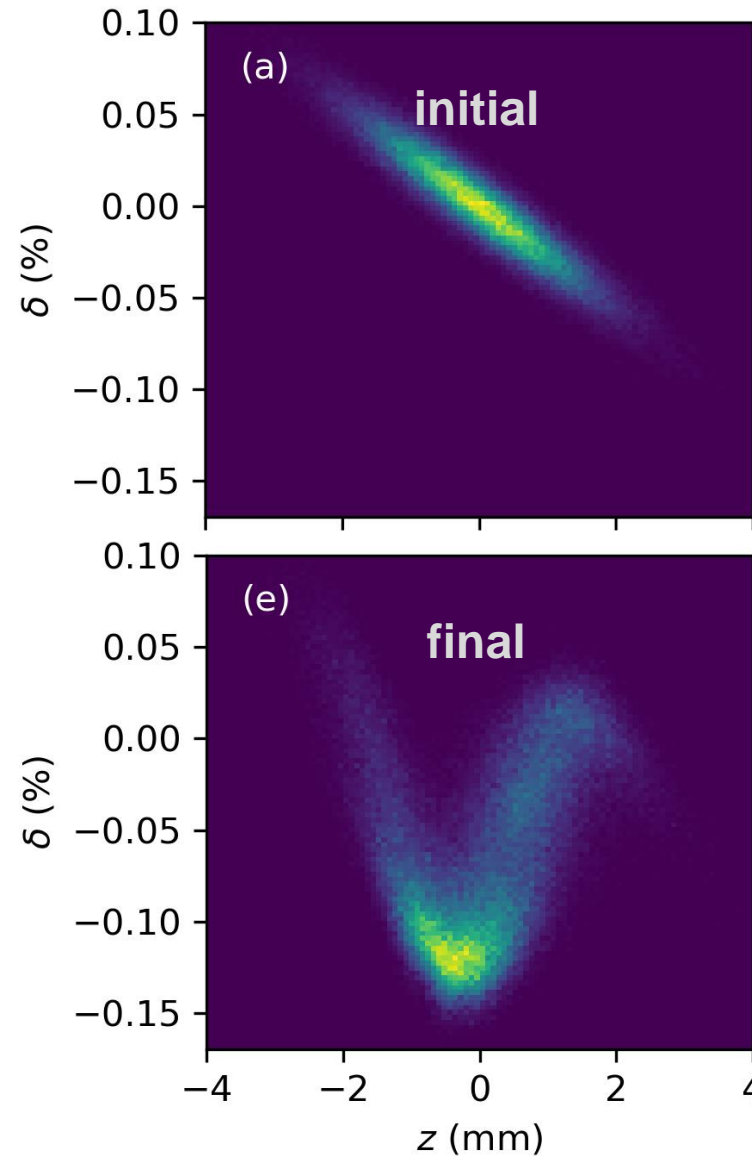


$$P_{CSR} \propto \frac{1}{\sigma_z^{4/3}}$$

H. Bartosik, 2022. arXiv:2201.01532

# CSR Degrades Beam Quality

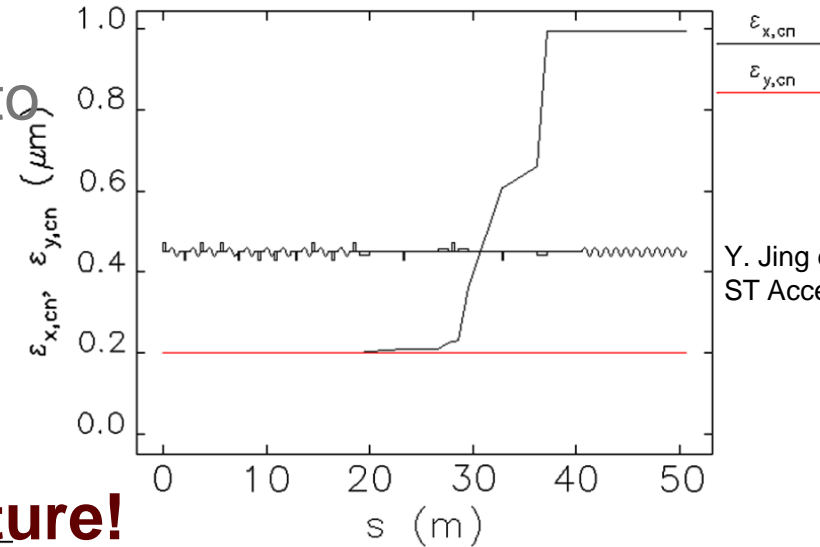
- CSR wakefield induces nonlinear kick in  $E$  vs  $z$
- Dipoles also introduce  $x, p_x$  correlations with  $E$
- **Result: rotation and centroid shift of  $x, p_x$  longitudinal slices, increasing the projected  $\varepsilon_x$**



# Measurement of CSR Effects

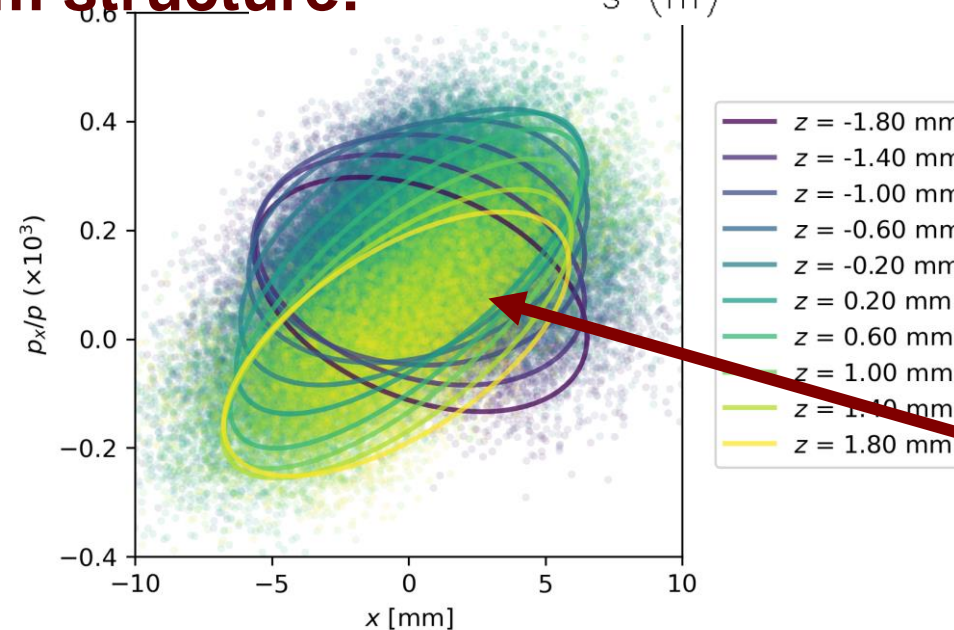
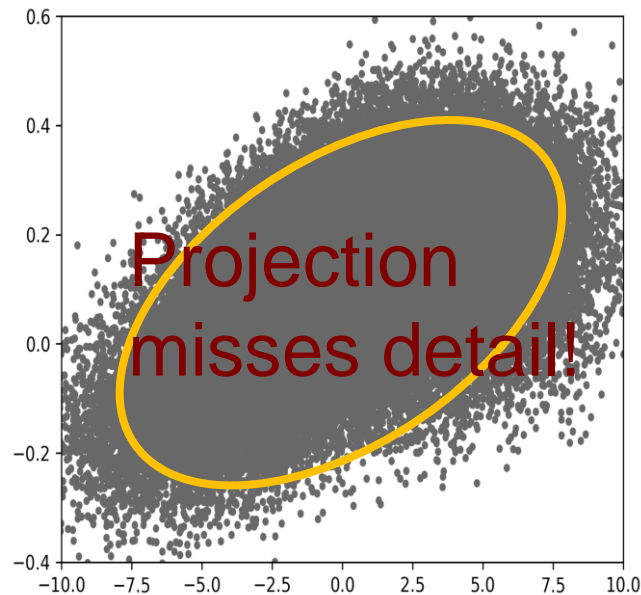
Studies of CSR effects are limited to **macro-scale** description of beam distribution:

- Projected  $\varepsilon_x$  growth



Y. Jing et al., Phys. Rev. ST Accel. Beams. 2013

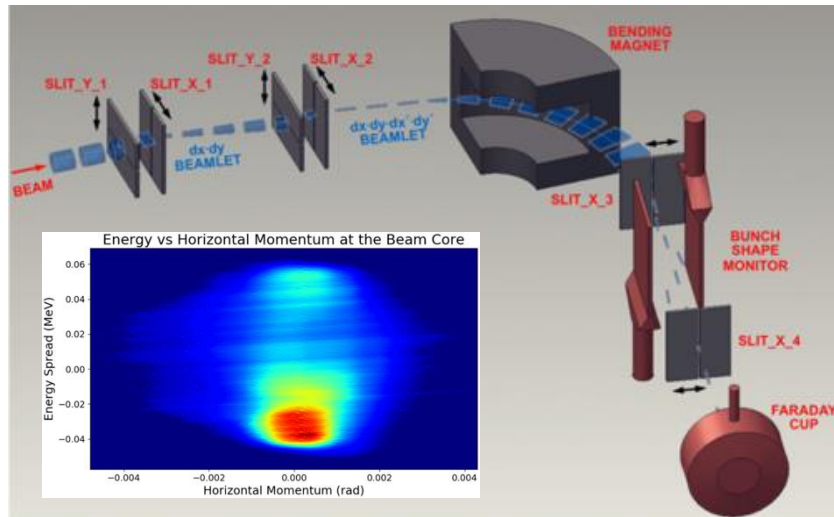
**Does not resolve detailed beam structure!**



**Full picture.  
We want this!**

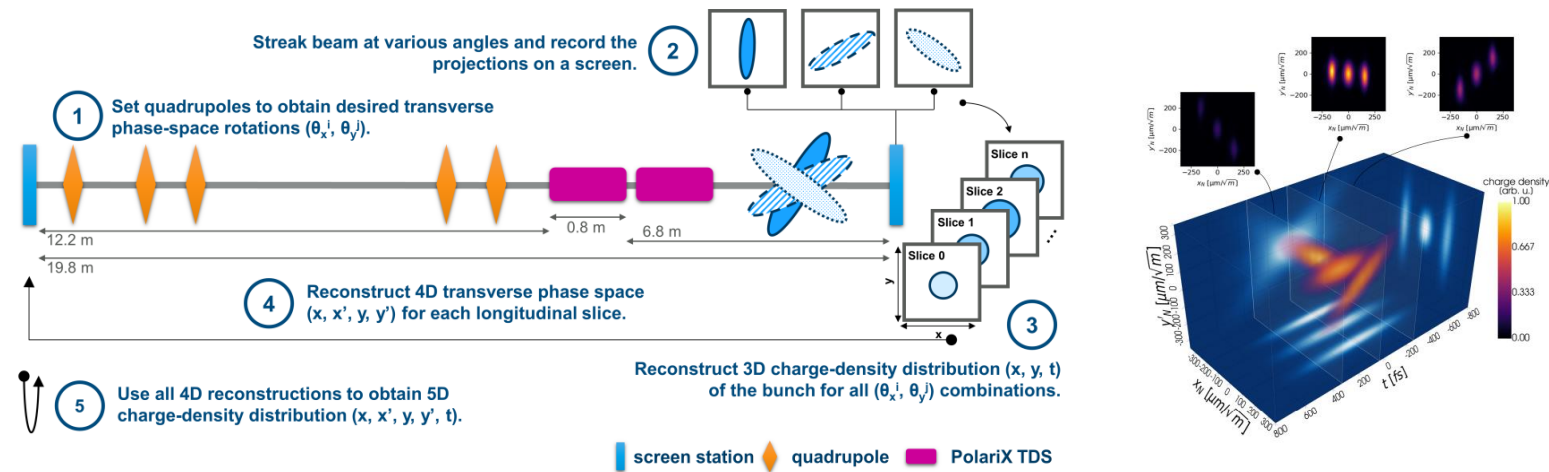
# Measuring high-dimensional beam distributions

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)

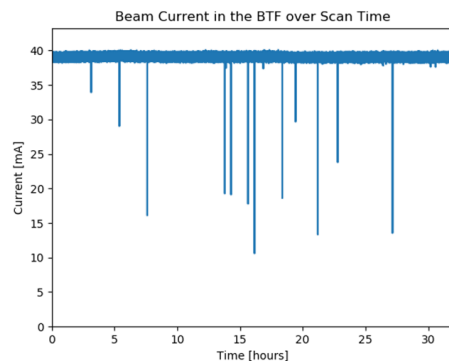


Jaster-Merz, S., et al Proc. IPAC'22 (2022): 279-283.

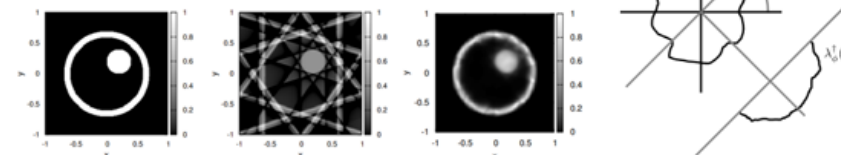
5 million (!) measurements ~ 32 hrs

960 measurements ~ 28 hrs

Tomographic reconstruction ~ 24 hrs

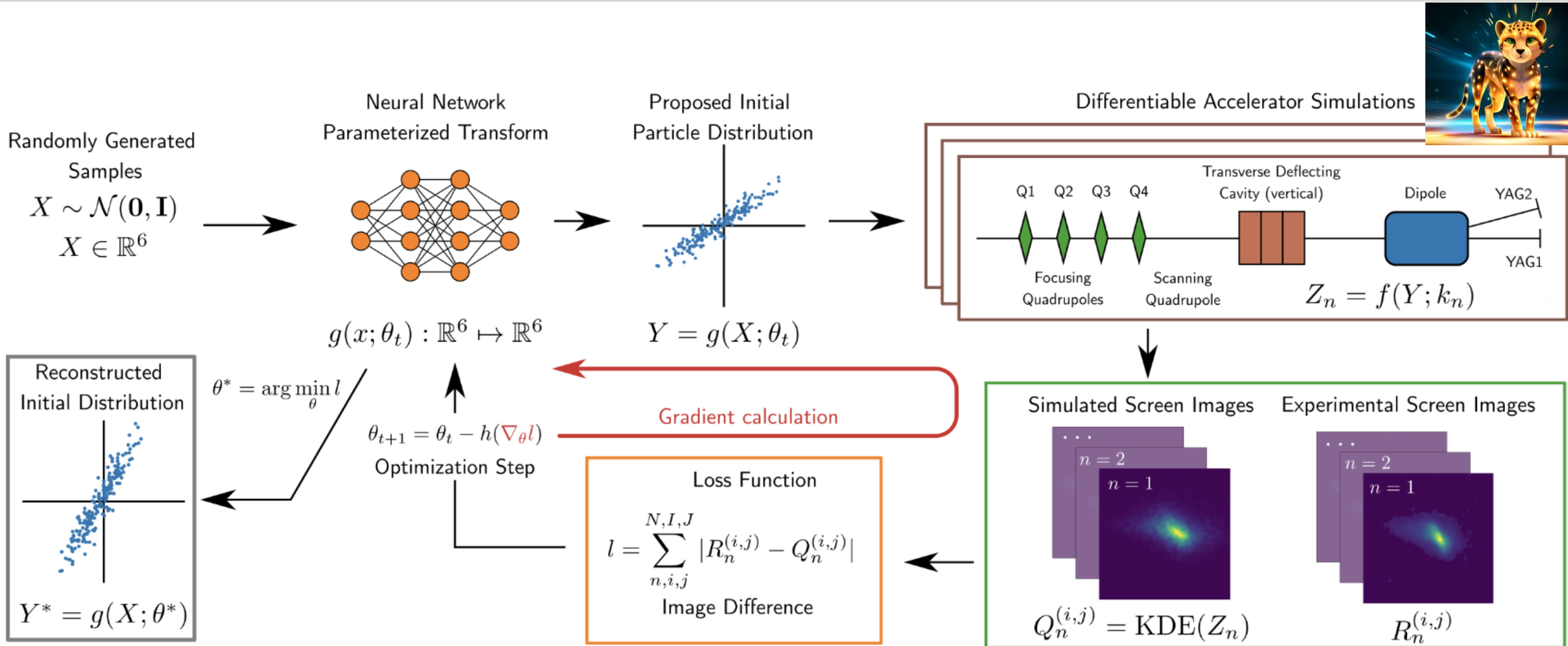


- Maximum entropy tomography (MENT)
- Algebraic reconstruction (ART, SART)



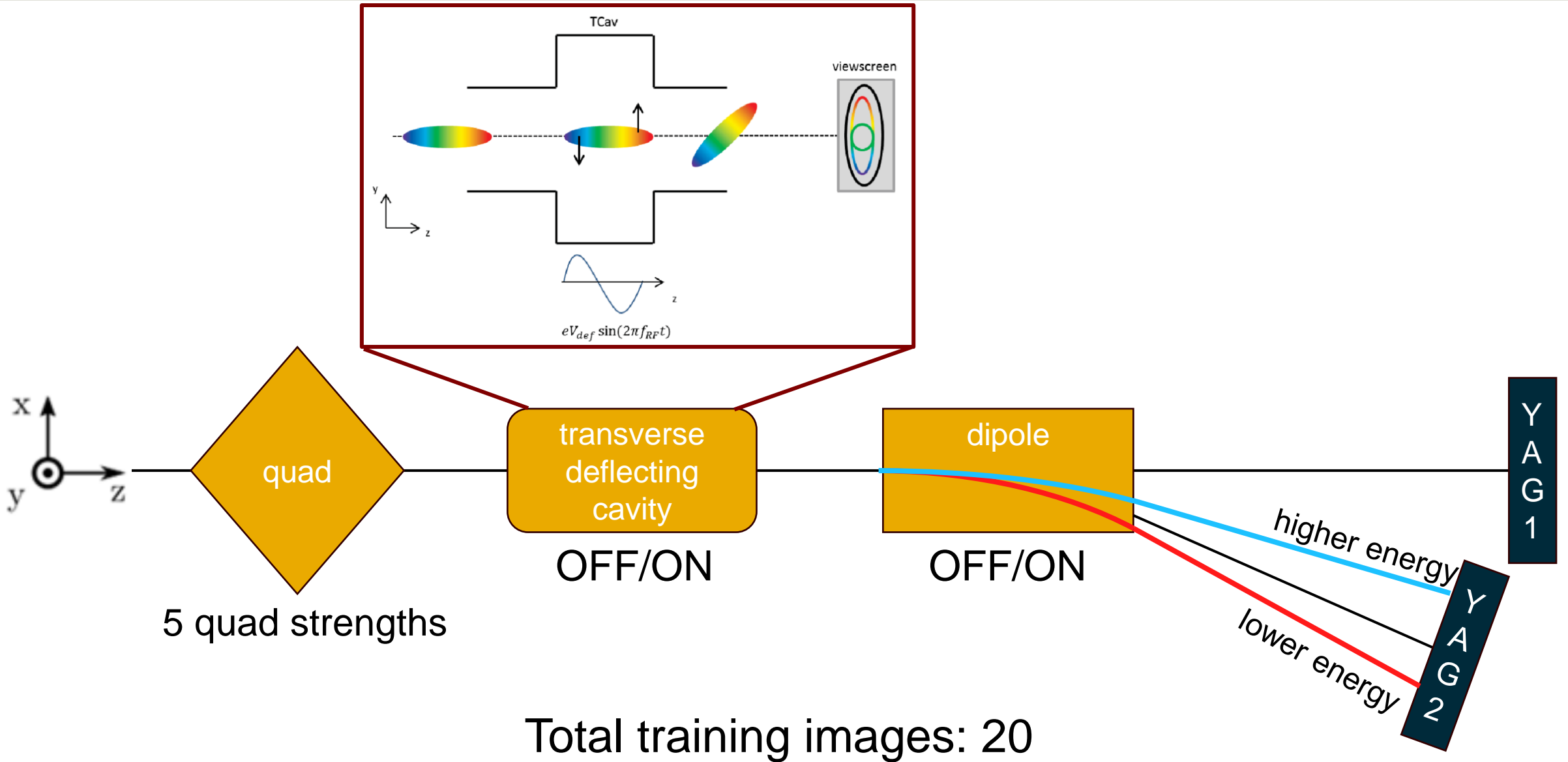
Hock K. and Ibison M., JINST, 2013

# Generative Phase Space Reconstruction (GPSR)

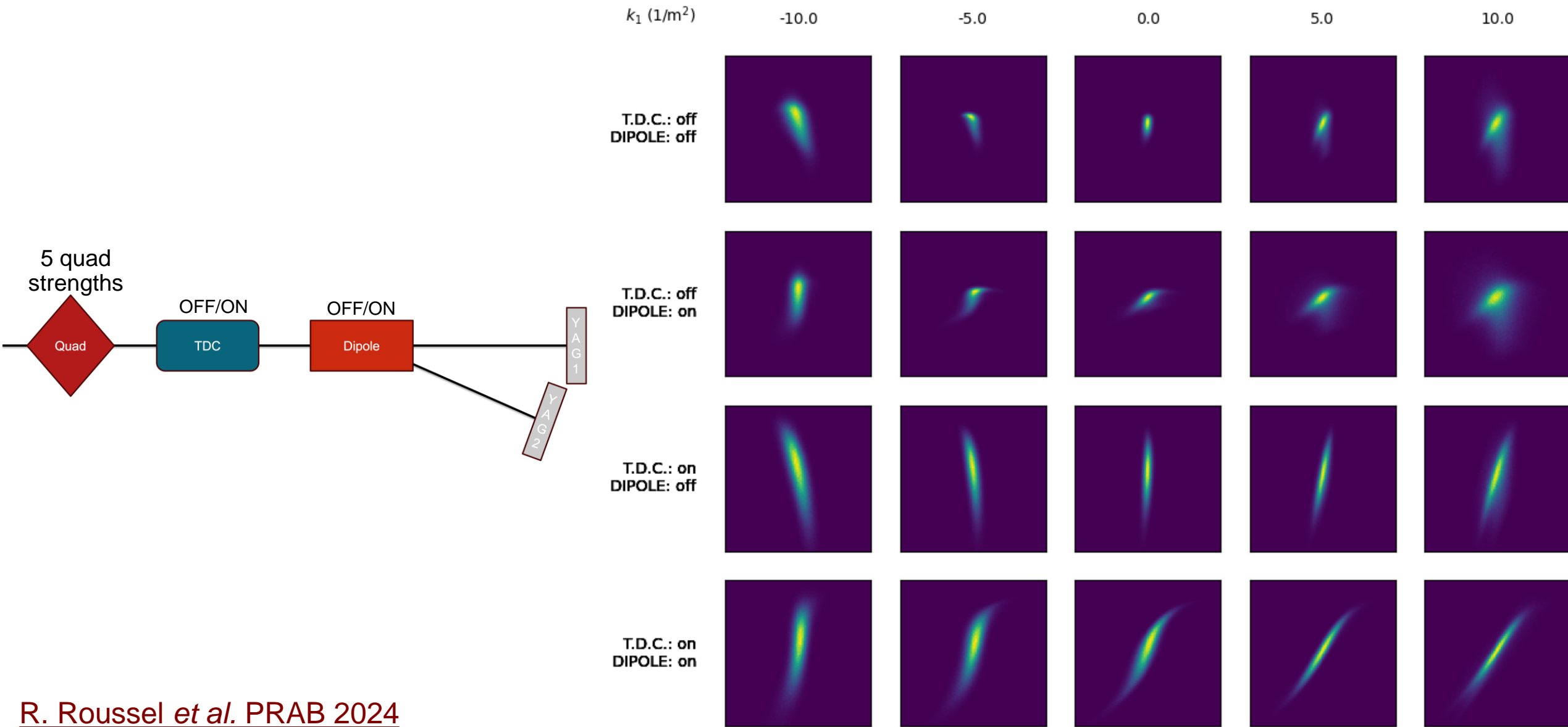


R. Roussel *et al.* PRAB 2024

# GPSR Scan

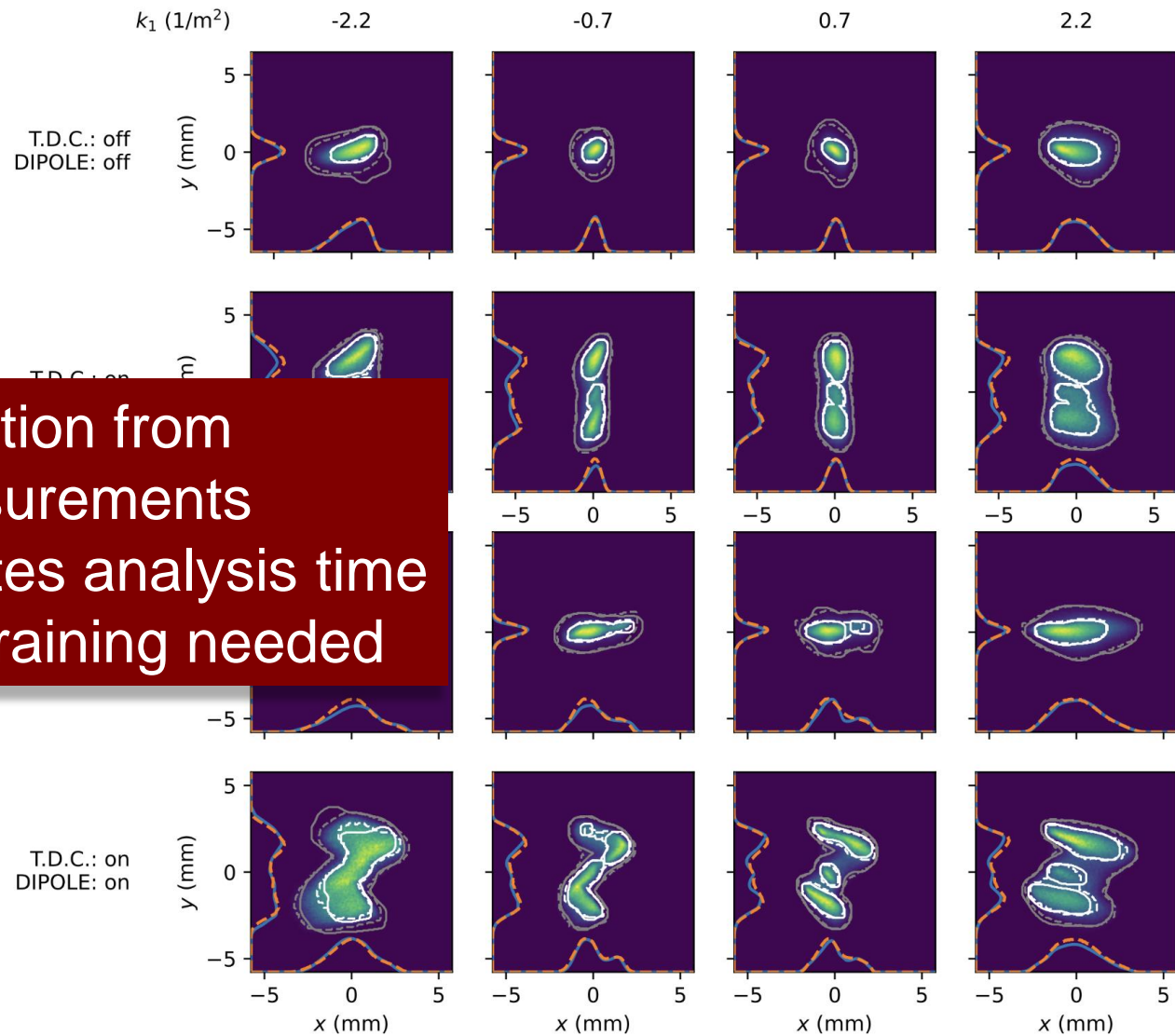
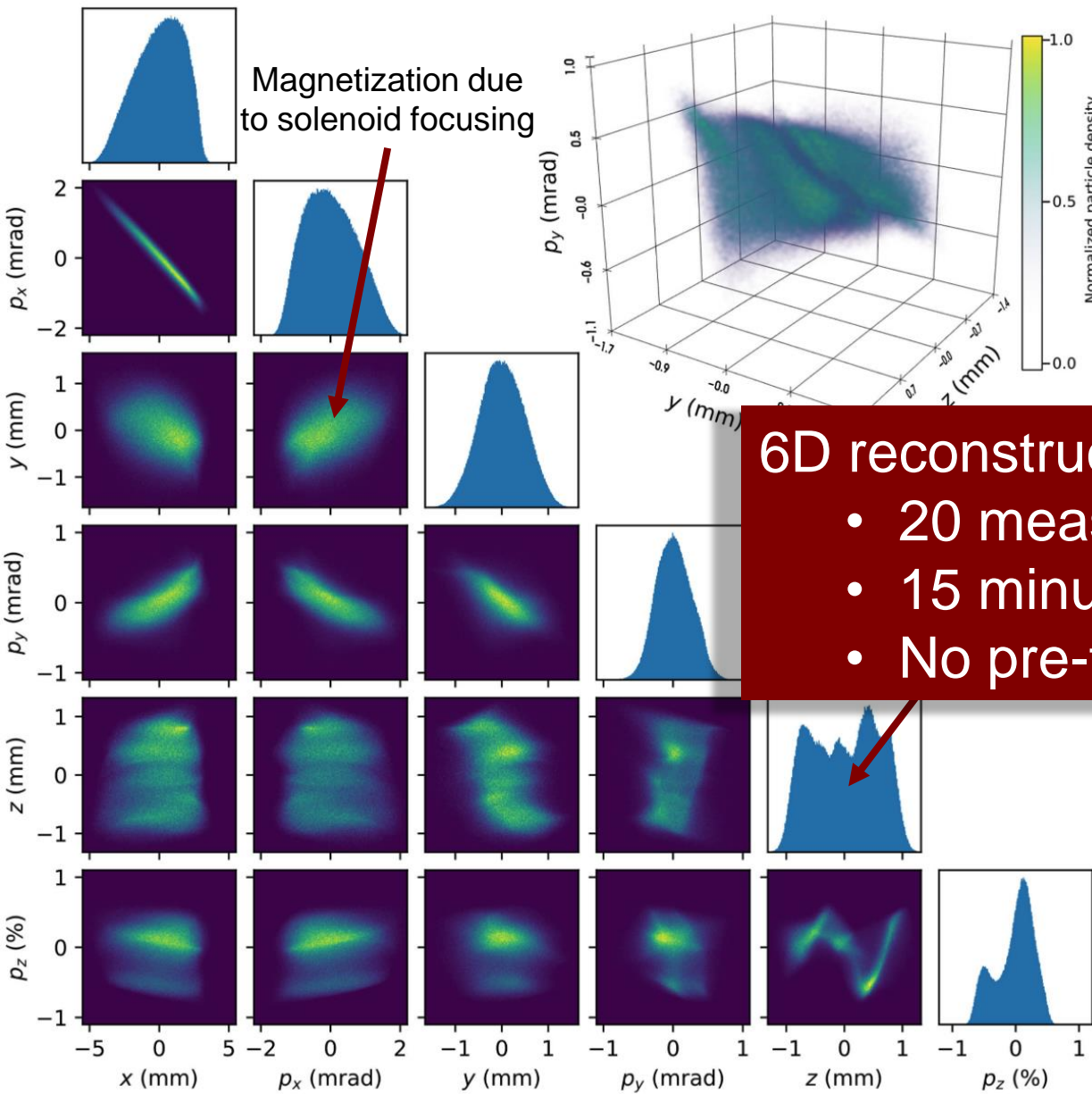


# GPSR Scan



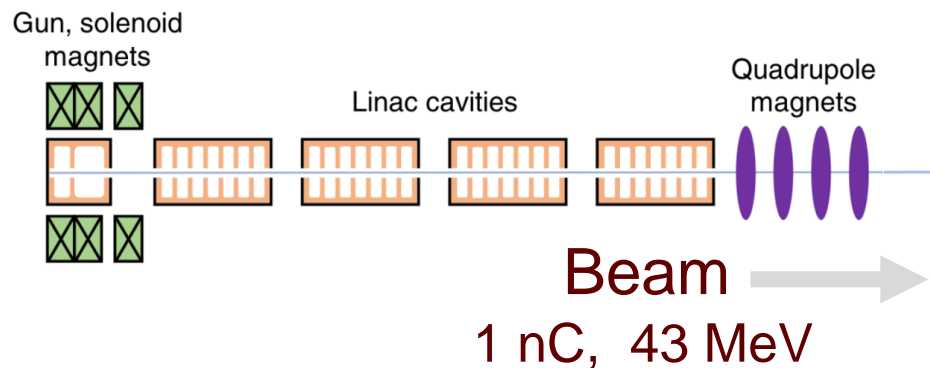
R. Roussel et al. PRAB 2024

# Experimental 6D GPSR at AWA

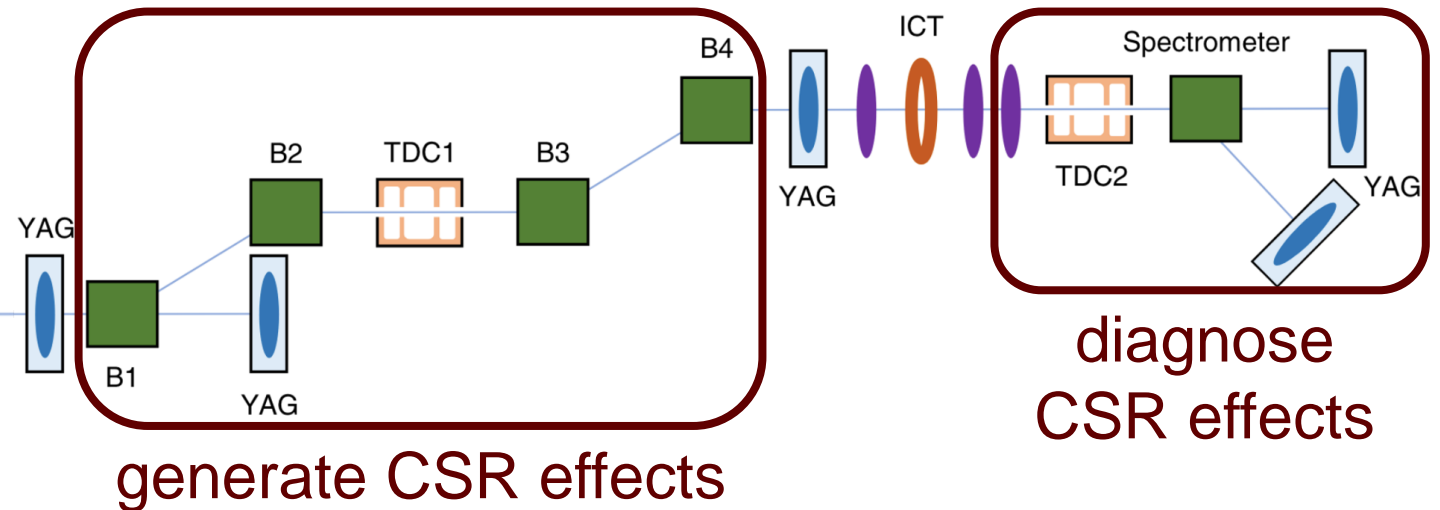


R. Roussel et al. PRAB 2024

# CSR at the Argonne Wakefield Accelerator

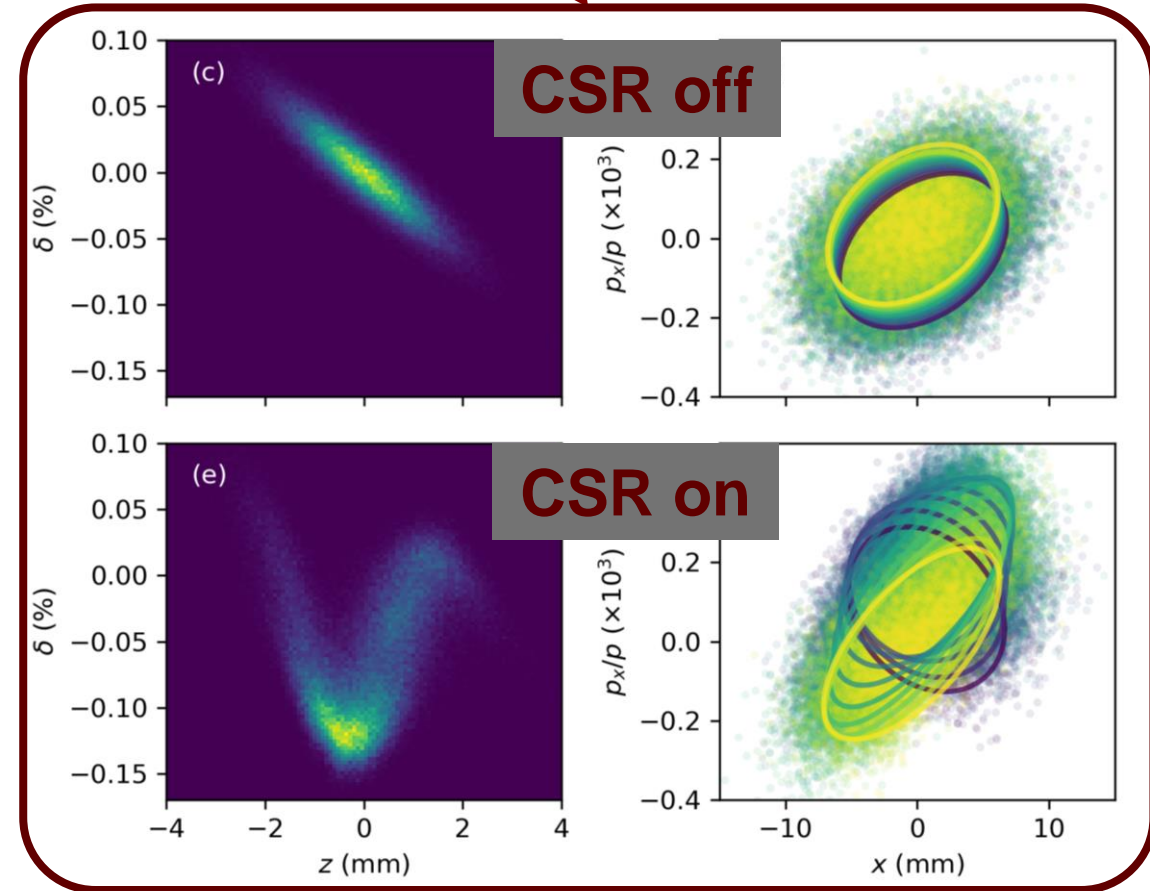
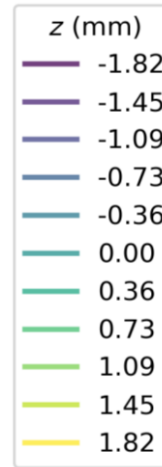
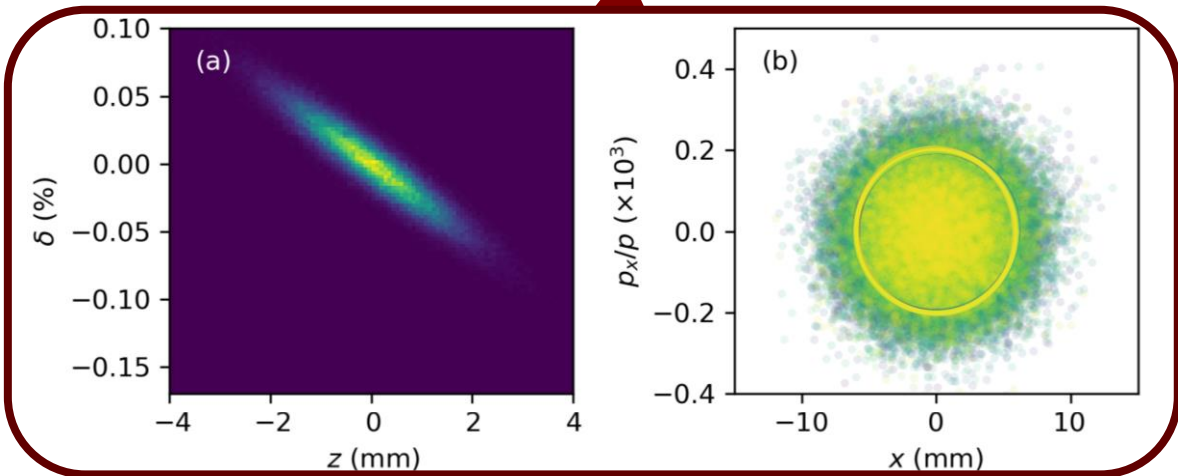
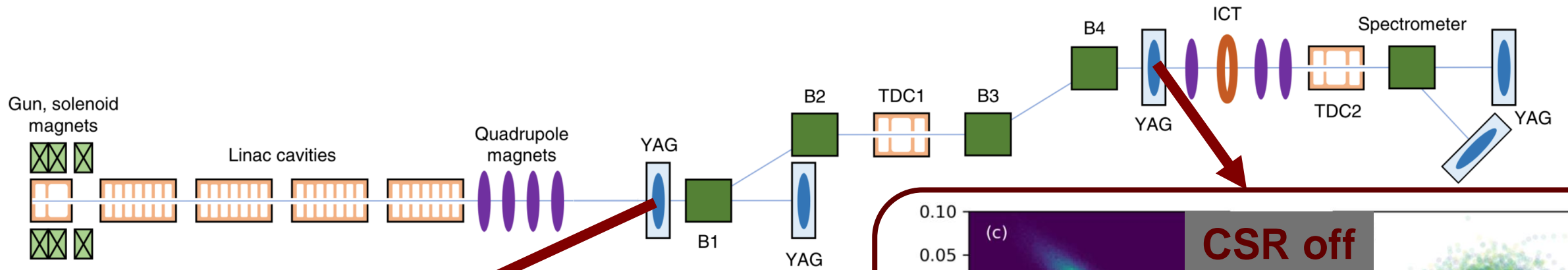


- Generate a beam influenced by CSR in double dogleg
- Measure phase space after 4<sup>th</sup> dipole with beam diagnostics

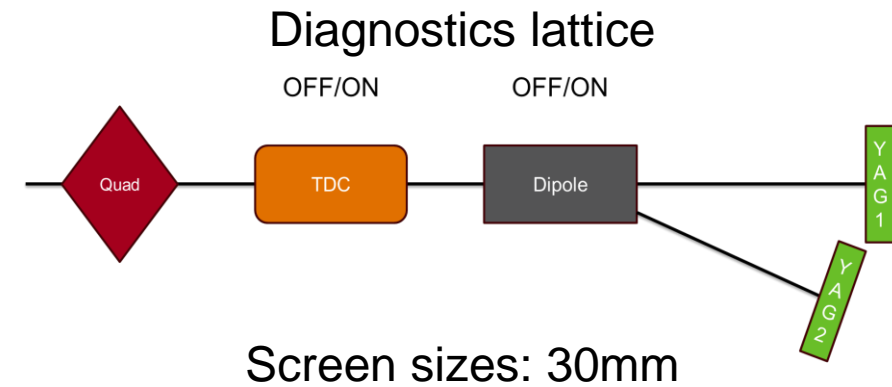
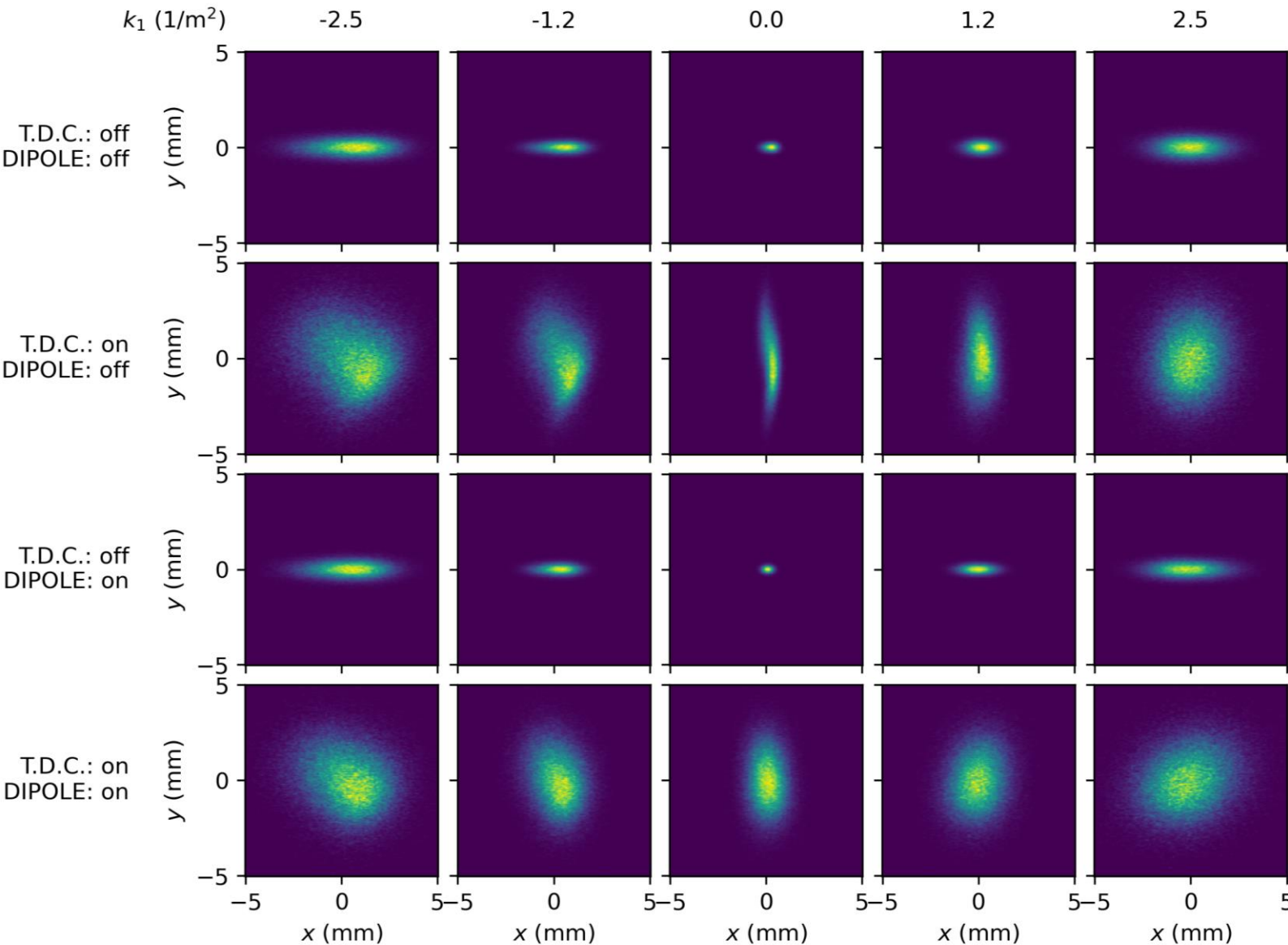


Adapted from N. Majernik et al., PRAB, 2023.

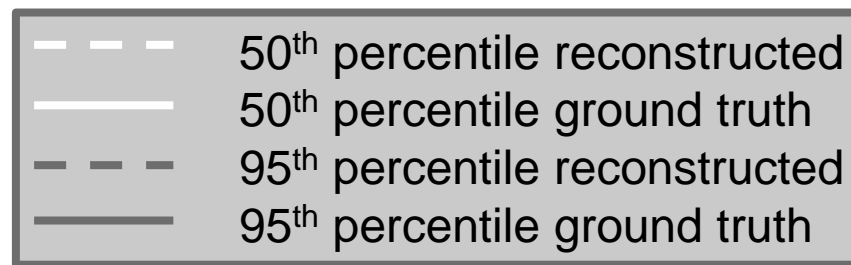
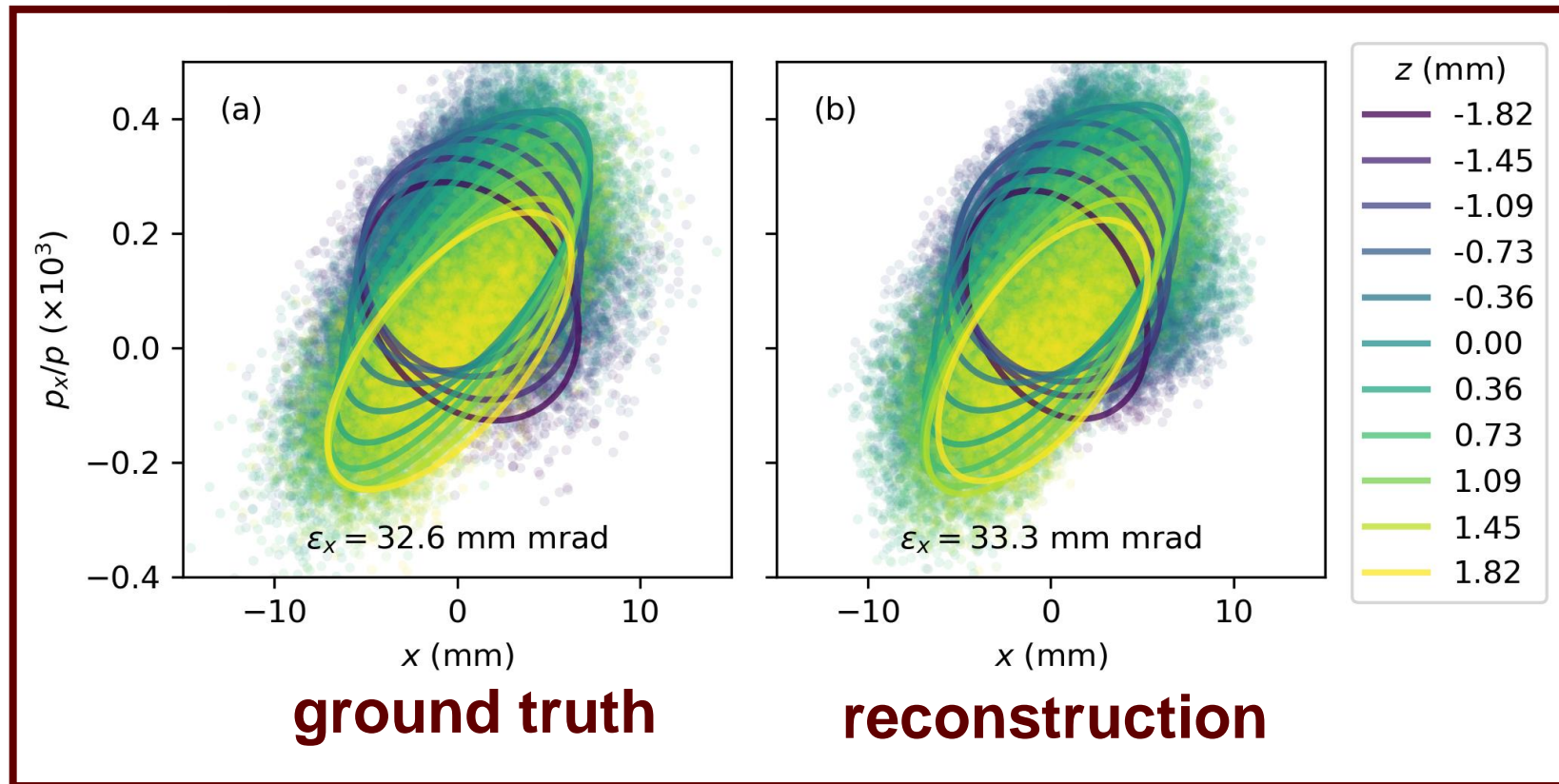
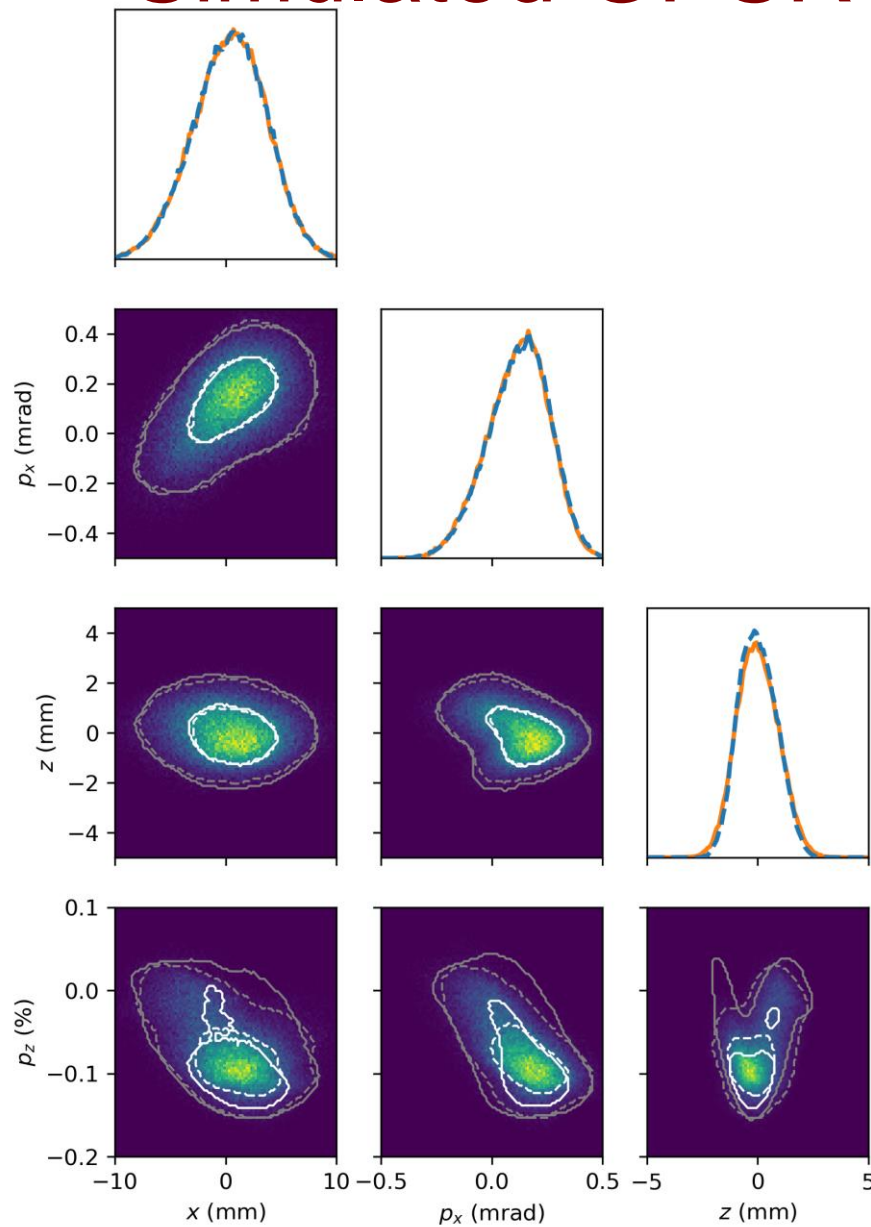
# Simulated CSR Effects: $E - z$ and $x - p_x$



# Simulated GPSR Training Data



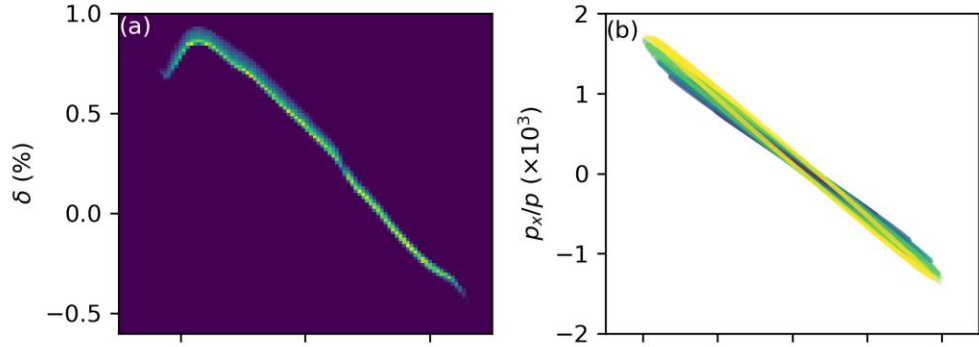
# Simulated GPSR Results



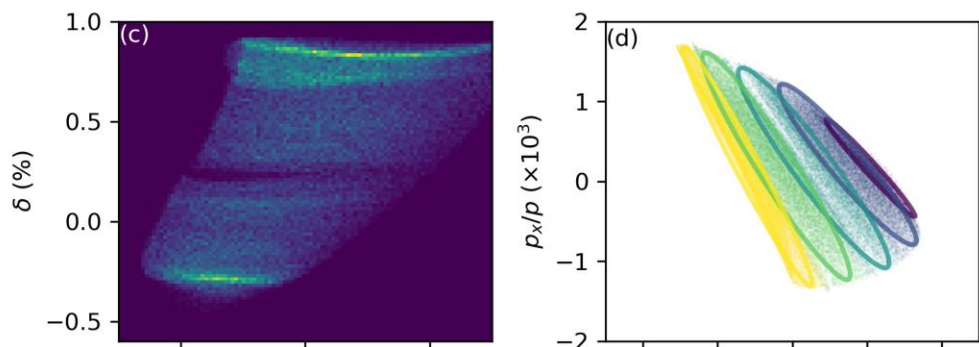
Gonzalez-Aguilera et. al., Proc. IPAC'24

# Dispersion dominates for larger energy spread

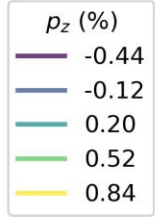
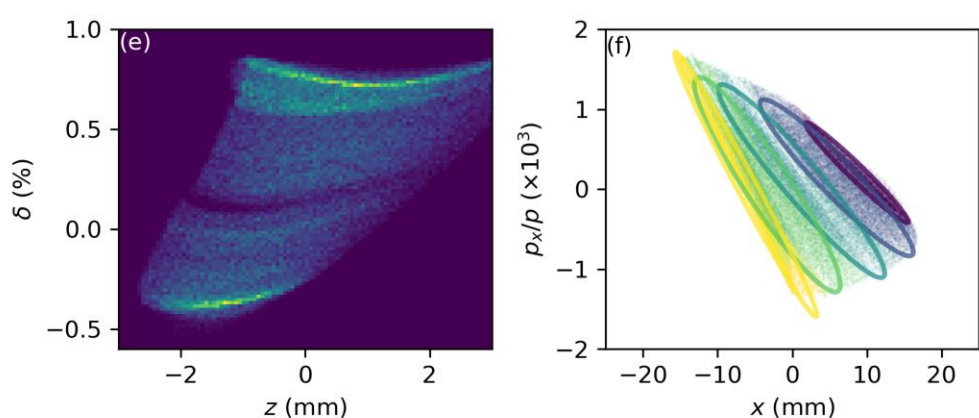
initial



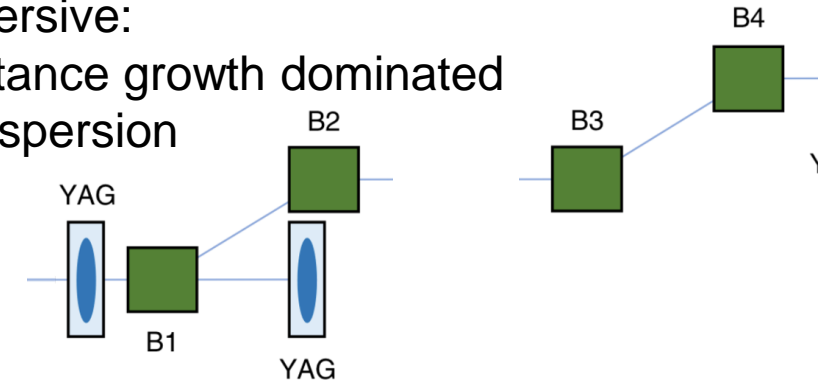
CSR off



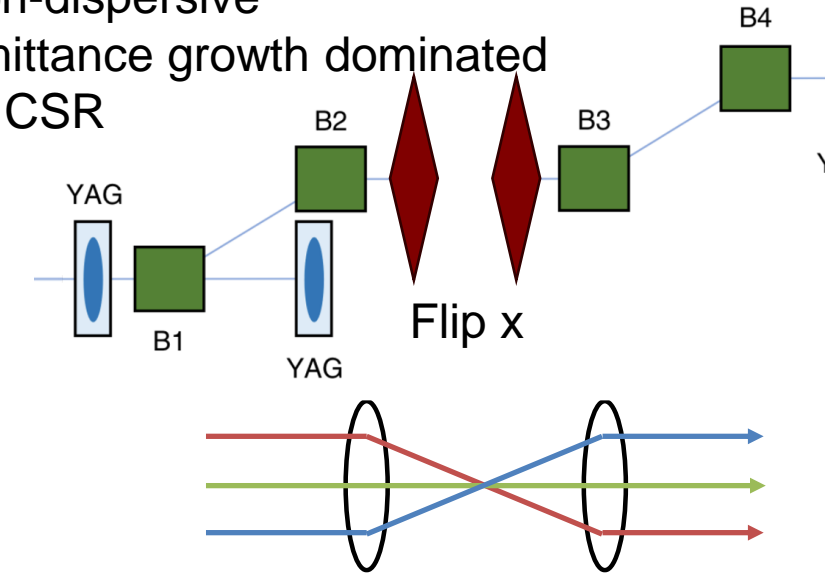
CSR on



Dispersive:  
Emittance growth dominated by dispersion



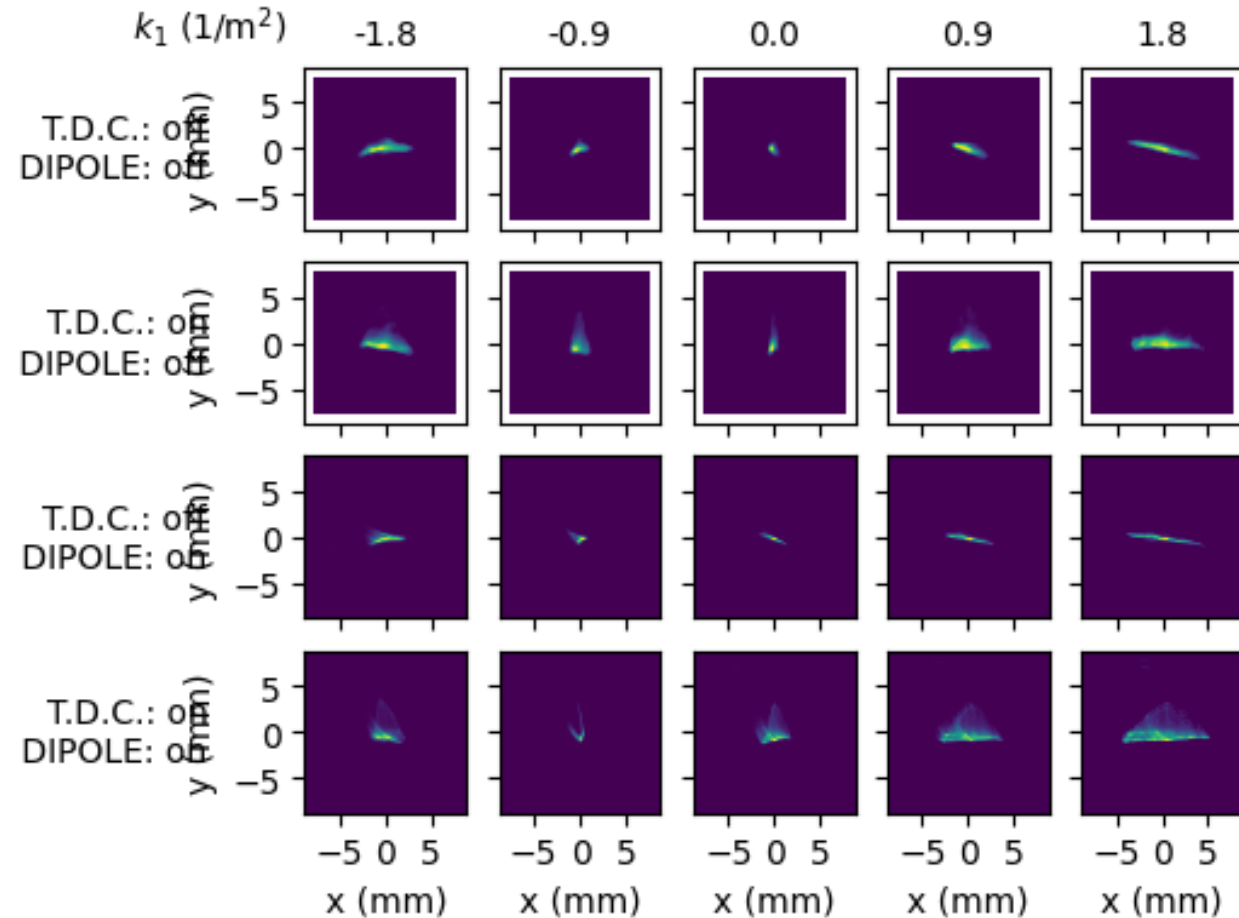
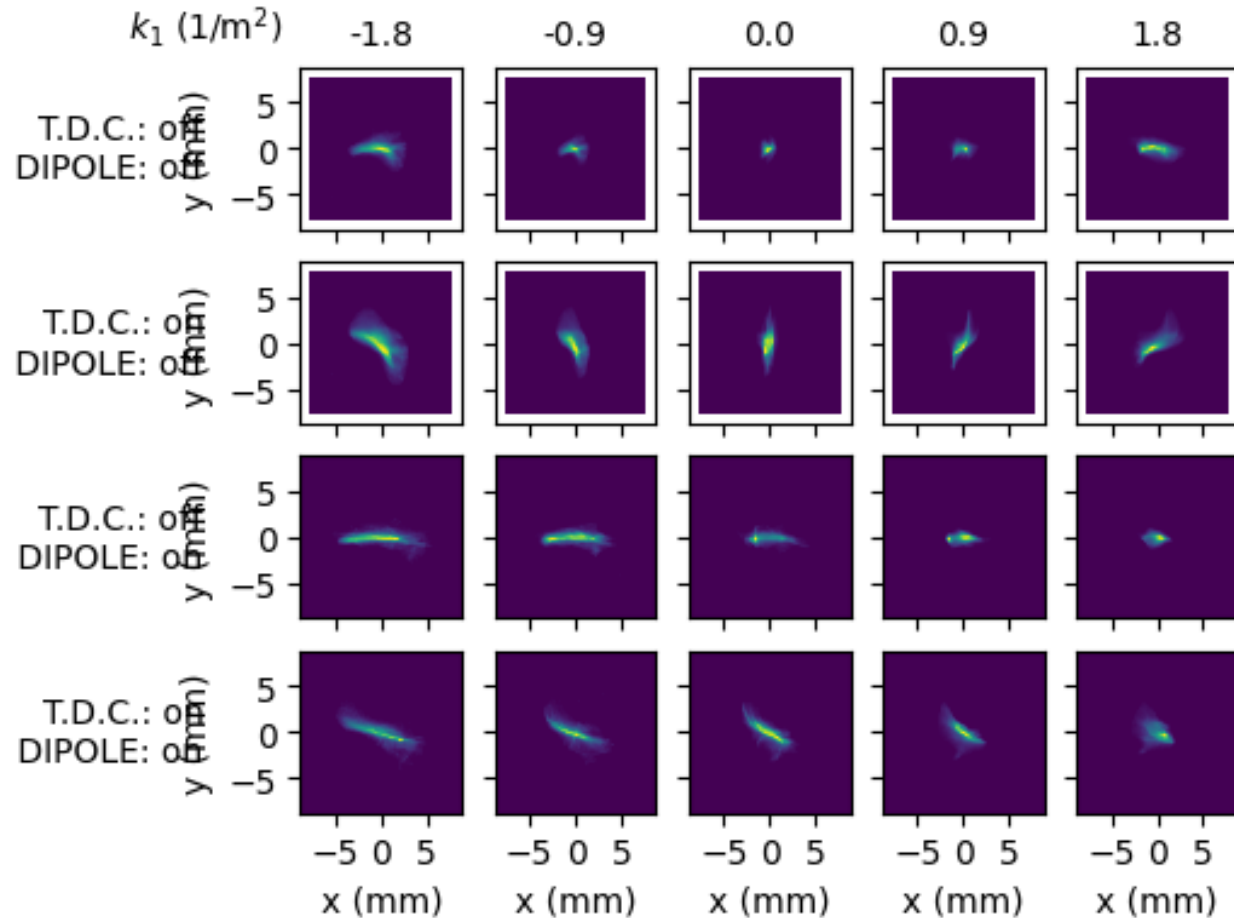
Non-dispersive  
Emittance growth dominated by CSR



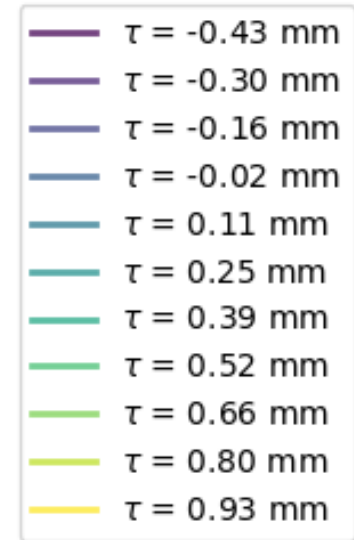
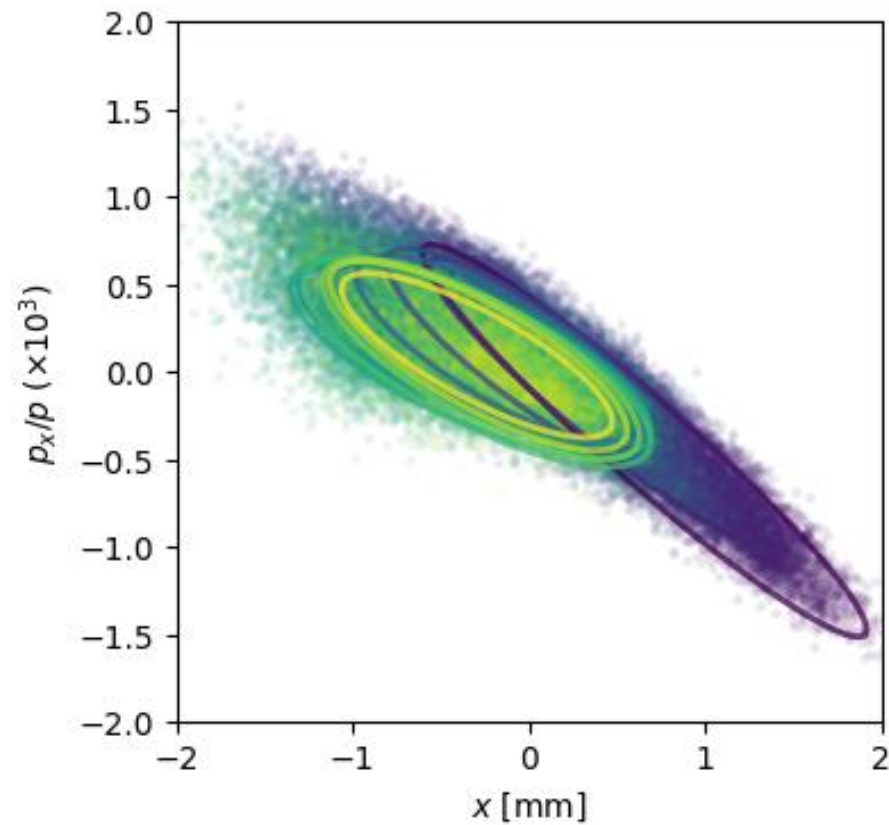
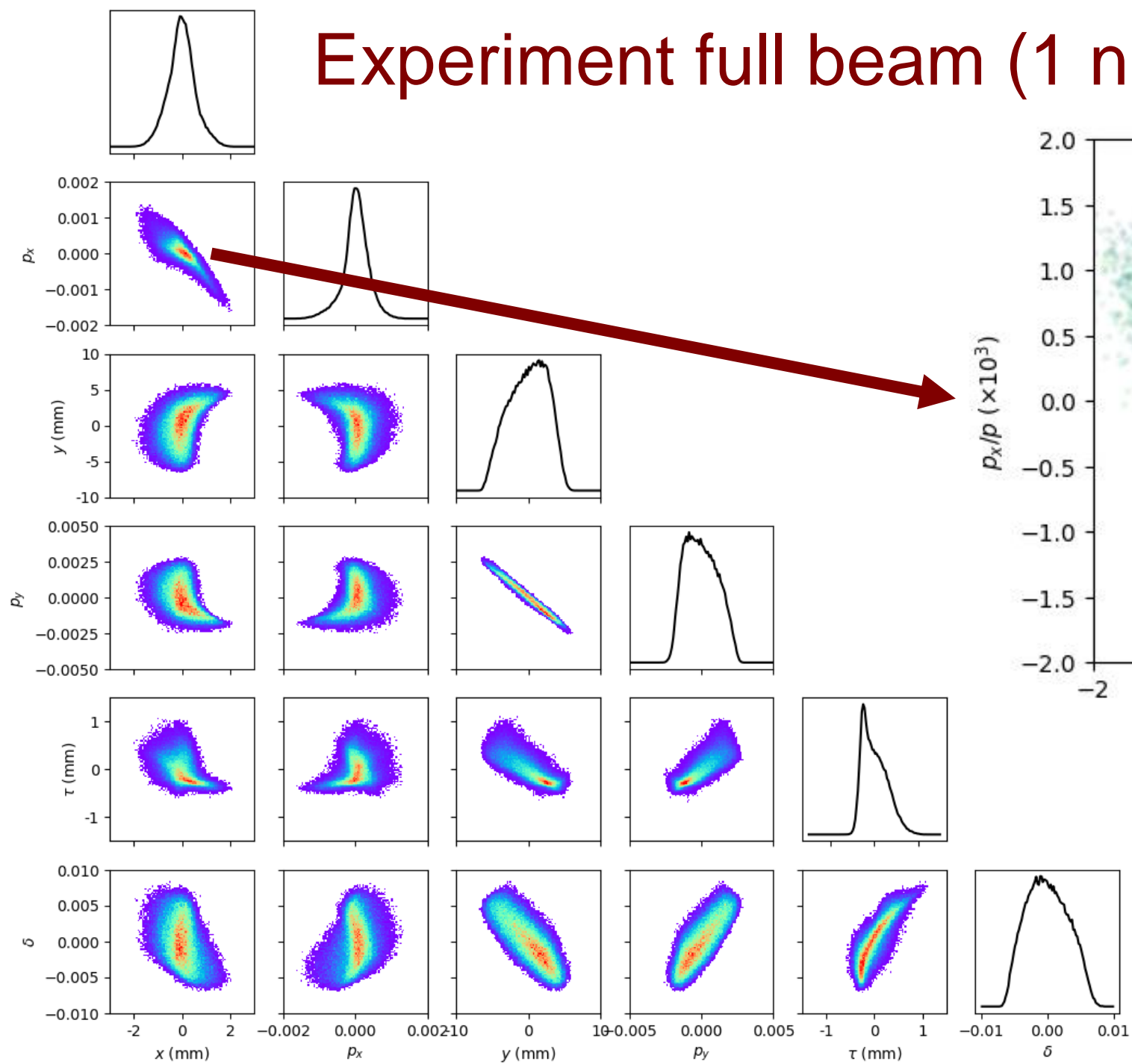
# Experiment data

Full beam (1nC)  
Expect: significant CSR effects

Masked beam (0.05 nC)  
Masked along x before first dipole  
Expect: less CSR effects

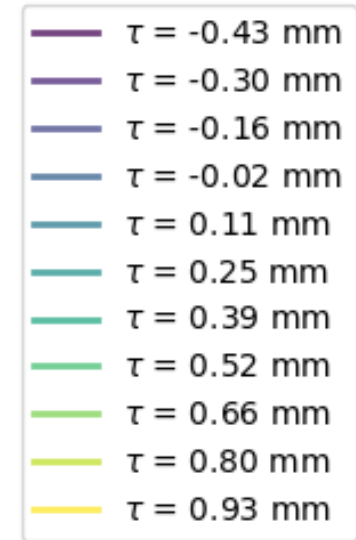
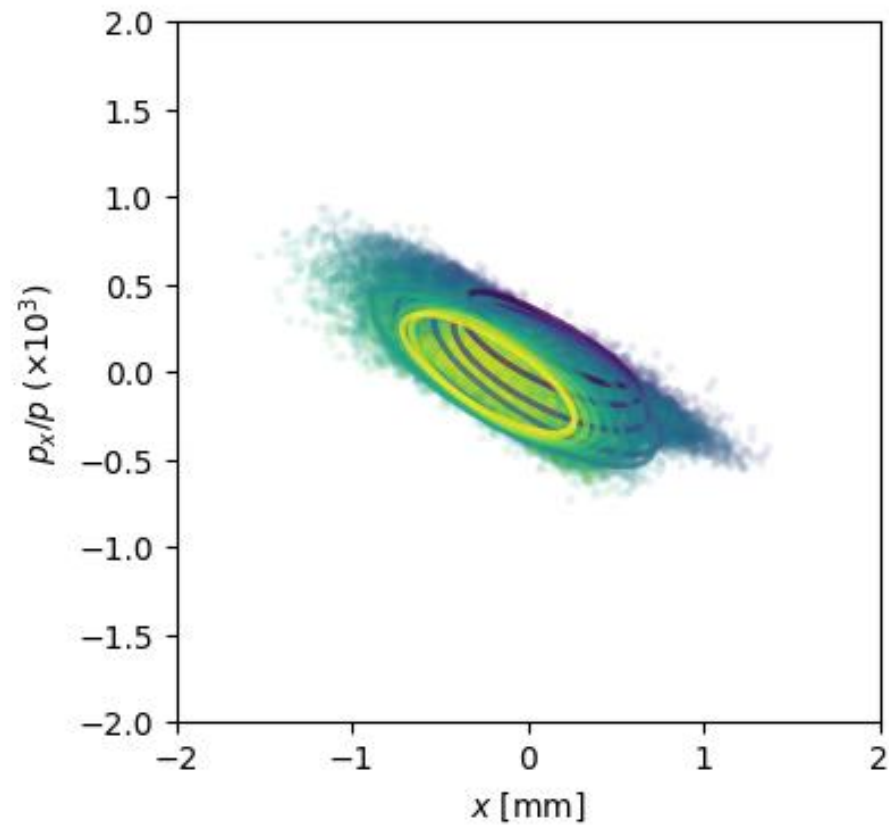
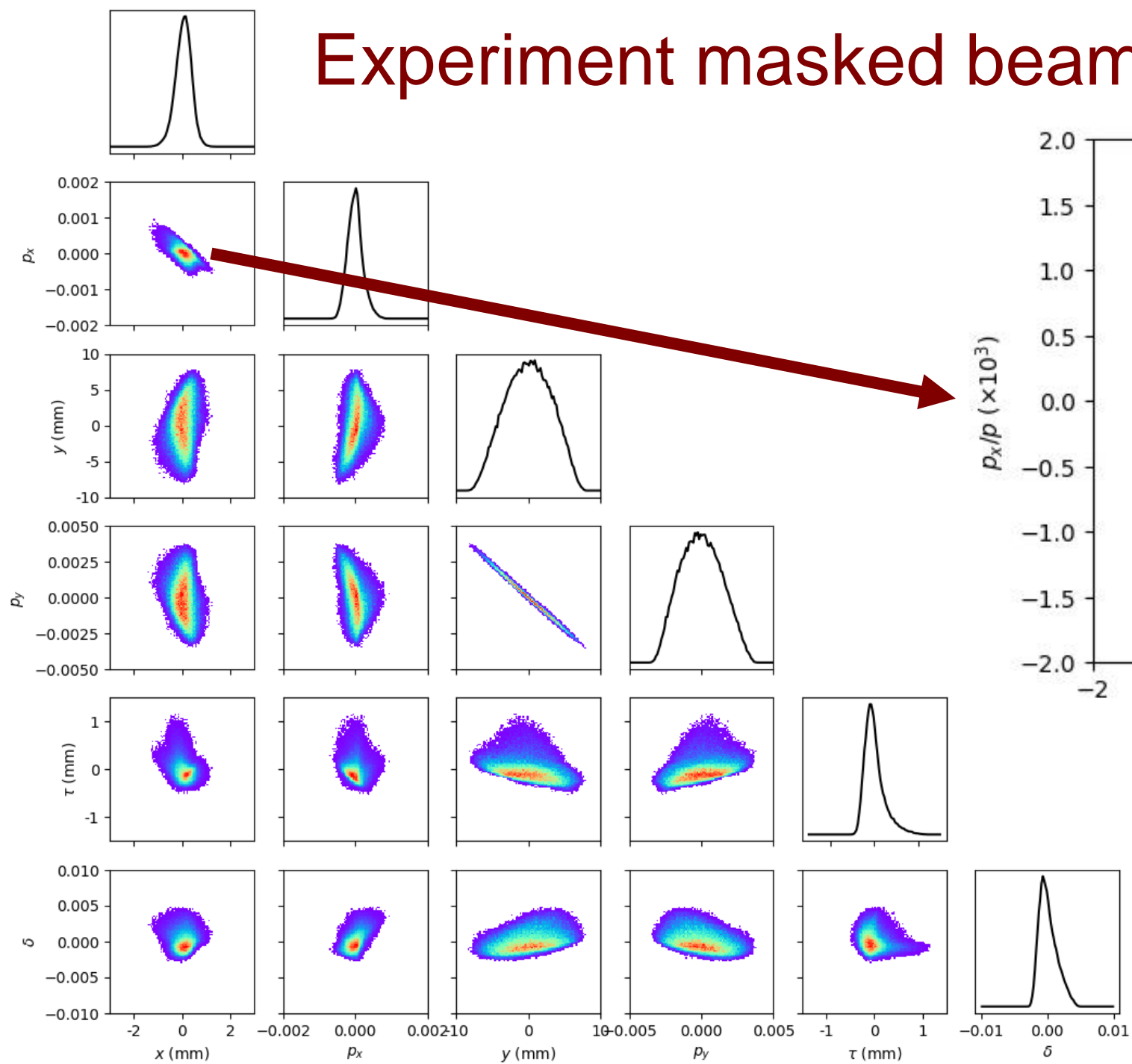


# Experiment full beam (1 nC)



$$\epsilon_x = 9.5 \mu\text{m}$$

# Experiment masked beam (0.05 nC)



$$\epsilon_x = 4.6 \mu\text{m}$$

# Conclusions

- Experiments at AWA look promising
  - Reconstructed beam show indication of CSR effects at 1nC
  - Must compare with more accurate simulations
- GPSR can reconstruct structure of CSR-affected beams
  - Fast
  - Accurate
  - Detailed
- GPSR is a very powerful tool
  - 6D phase space information gives the full physical picture

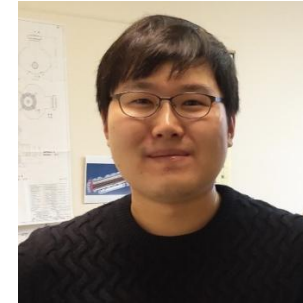
# Thanks! Questions?



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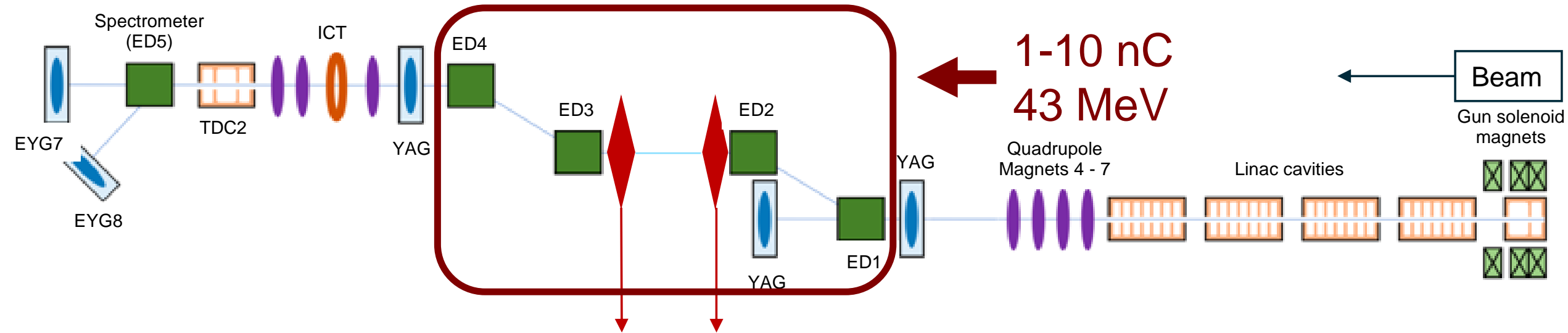
Alexander Ody

This work was supported by:

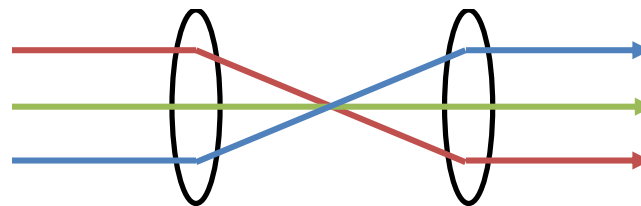
- NSF award PHY-1549132, the Center for Bright Beams
- DoE contract No. DE-AC02-05CH11231, NERSC award BES-ERCAP0023724



# Bckp, reversing quads



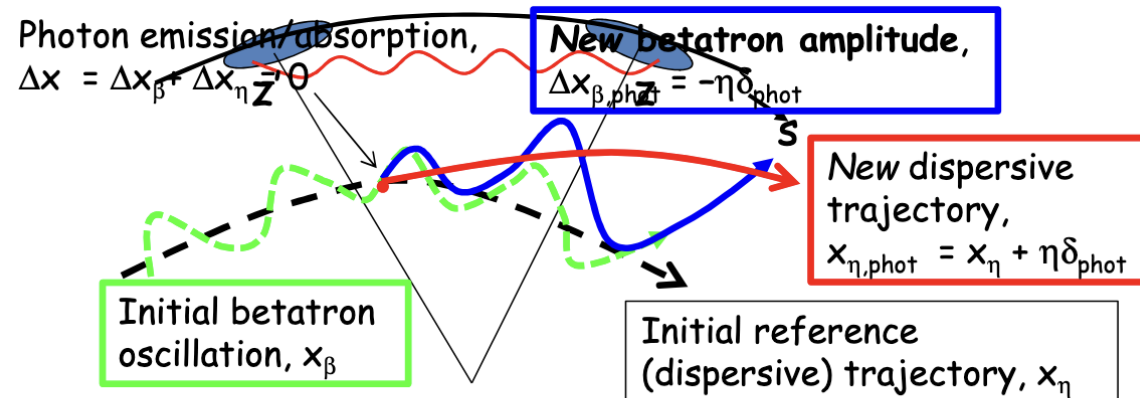
Reversing quadrupoles: now behaves as a compressor, removing most of dispersion



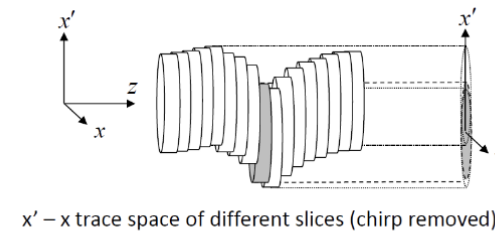
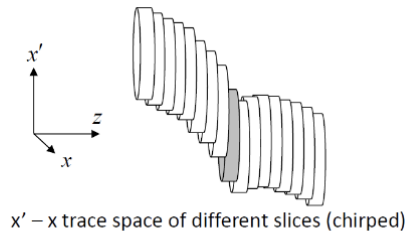
# Bckp, CSR-induced emittance growth

## CSR-Induced Emittance Growth: Naïve Picture

- At any point of emission/absorption, particle's *transverse coordinates do not change*:  $\Delta x=0, \Delta x'=0$ . Since the emission happens in an energy-dispersive region, it implies  $\Delta x_\beta = -\Delta x_\eta$ . That is, the particle starts  **$\beta$ -oscillating** ( $\Delta x_\beta$ ) around a **new dispersive trajectory** ( $-\Delta x_\eta$ ).



- Once  $\eta_x$  is zeroed, e.g. At the exit of a symmetric chicane, the CSR-induced  $\beta$ -oscillation remains: the beam as «gained» a non-zero C-S amplitude which sums up to its initial emittance.



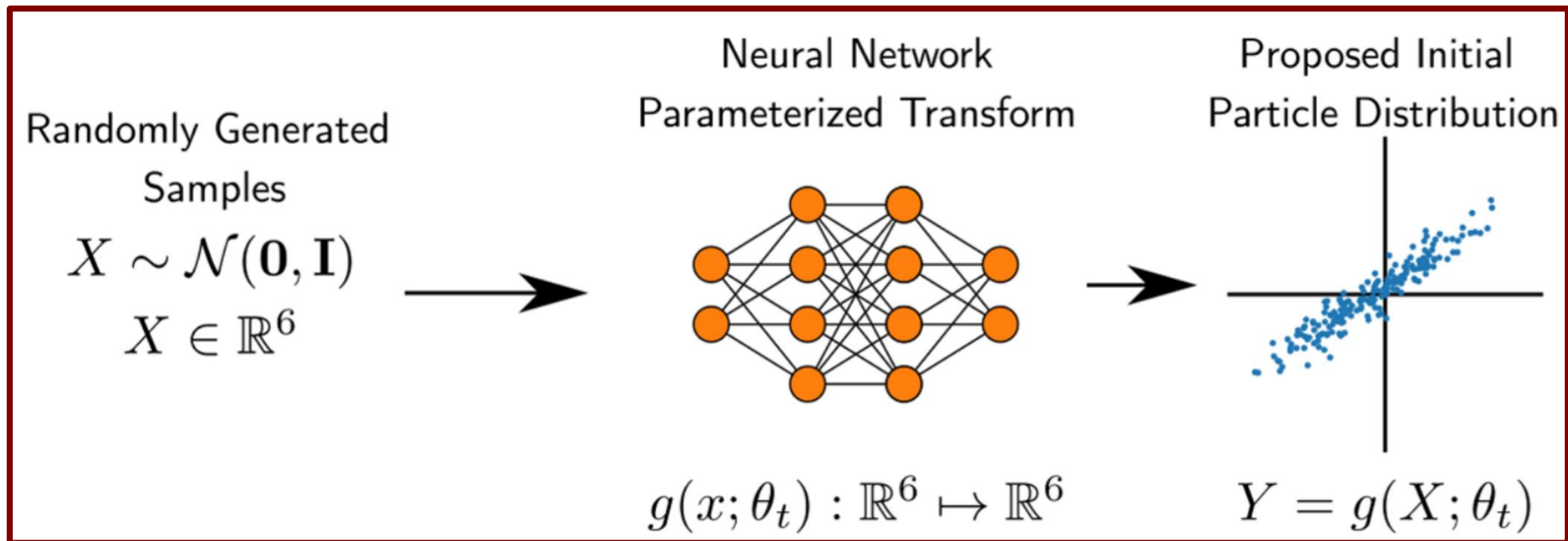
USPAS June 2015

S. Di Mitri - Lecture\_We9

4

# Bckp, NN Generator

- 6D phase space distribution parametrization that is
  - flexible
  - learnable



Fully connected NN with  $\sim \mathbf{O(1k)}$  parameters