Detailed Characterization of Coherent Synchrotron Radiation Effects using Generative Phase Space Reconstruction

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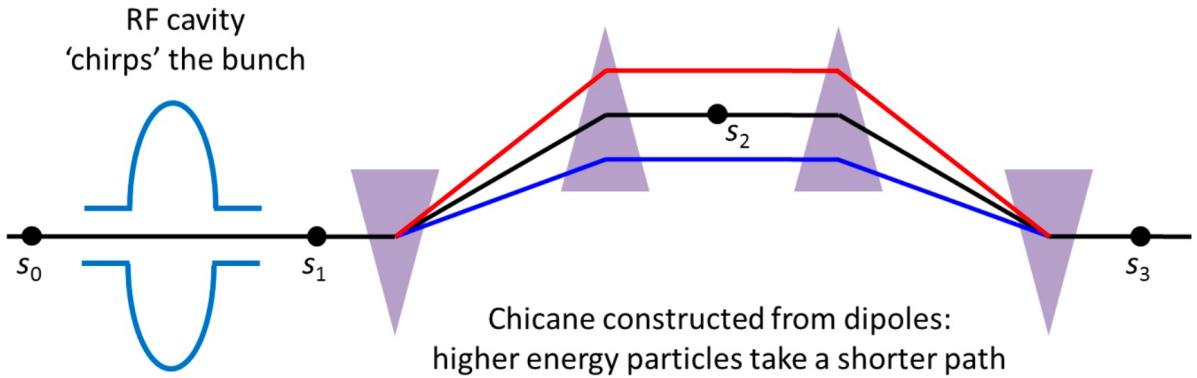
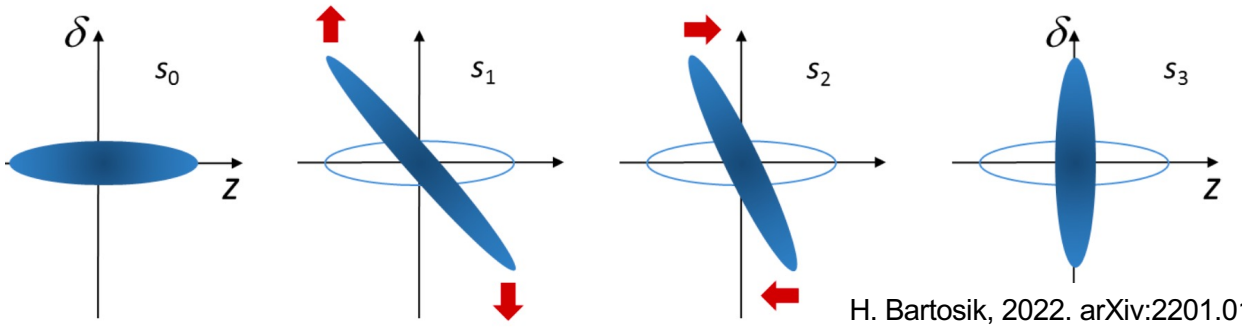
Outline

- Introduction
  - Coherent Synchrotron Radiation (CSR)
    - Importance
    - Measurement
  - 6D generative phase space reconstruction (GPSR – R. Roussel's talk)
- Simulation studies of CSR at the Argonne Wakefield Accelerator (AWA)
- Detailed characterization of CSR using GPSR
- Discussion
- Summary and Conclusions

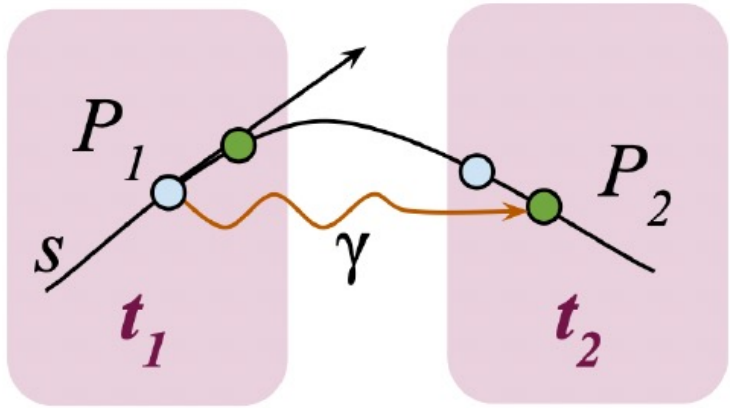
Coherent Synchrotron Radiation (CSR)

- FELs, need highly compressed beams longitudinally
- Dispersive lattices are used to compress the beams (e.g., chicanes)
- Coherent synchrotron radiation (CSR) is produced when bending beam trajectory
- CSR degrades beam quality





H. Bartosik, 2022. arXiv:2201.01532

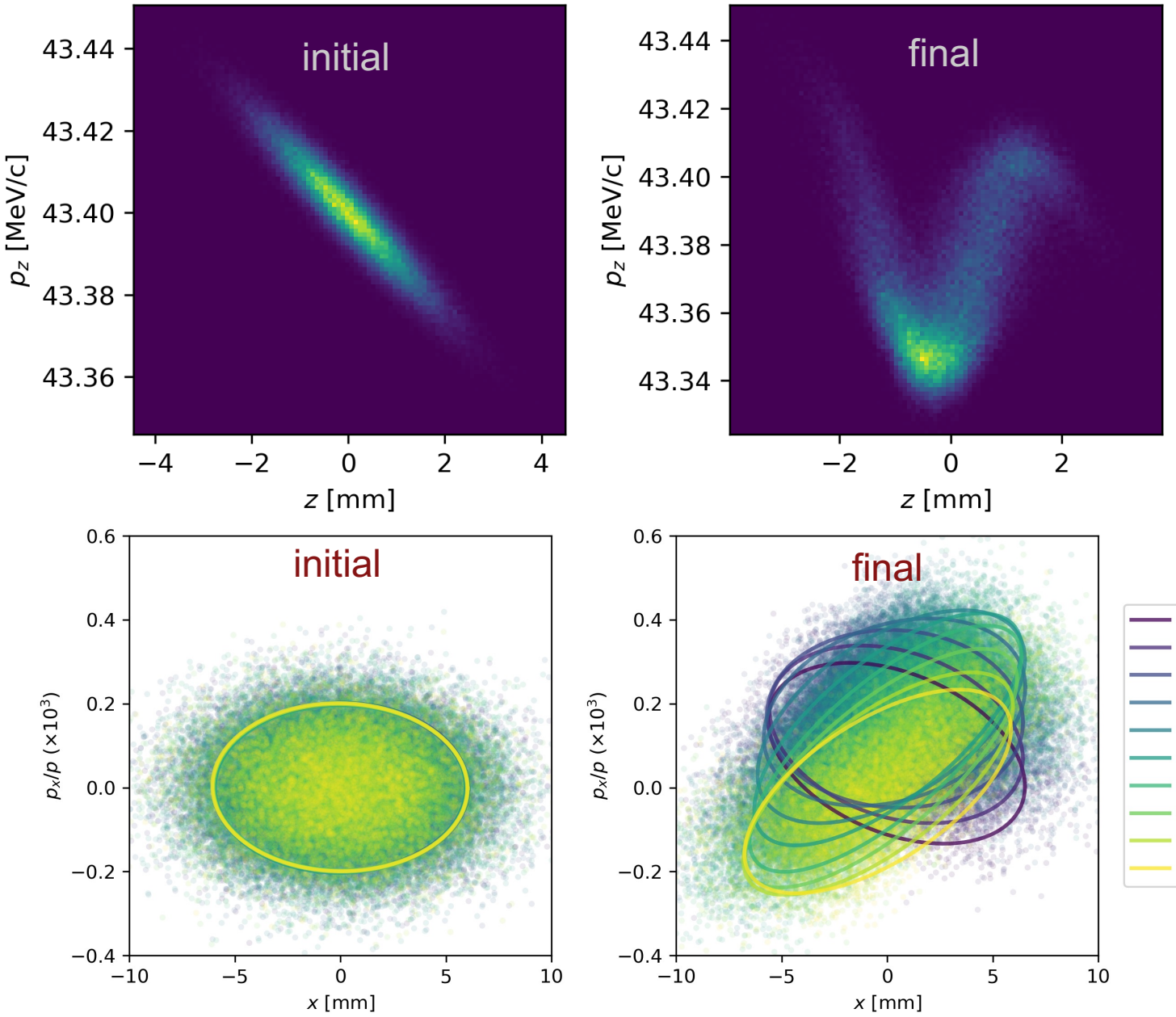


A. Edelen et al., IPAC 2022

CSR is a complex phenomenon that degrades beam quality

CSR Degrades Beam Quality

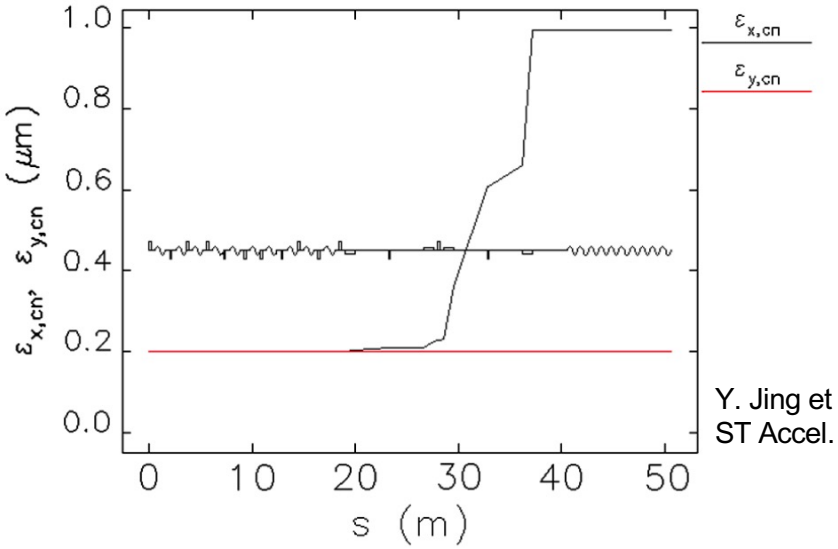
- Short-range CSR wakefield induces nonlinear kick in E vs z
- Dipoles also introduce x, p_x correlations with E
- **Result: rotation and centroid shift of x, p_x longitudinal slices, increasing the projected ε_x**



Measurement of CSR Effects

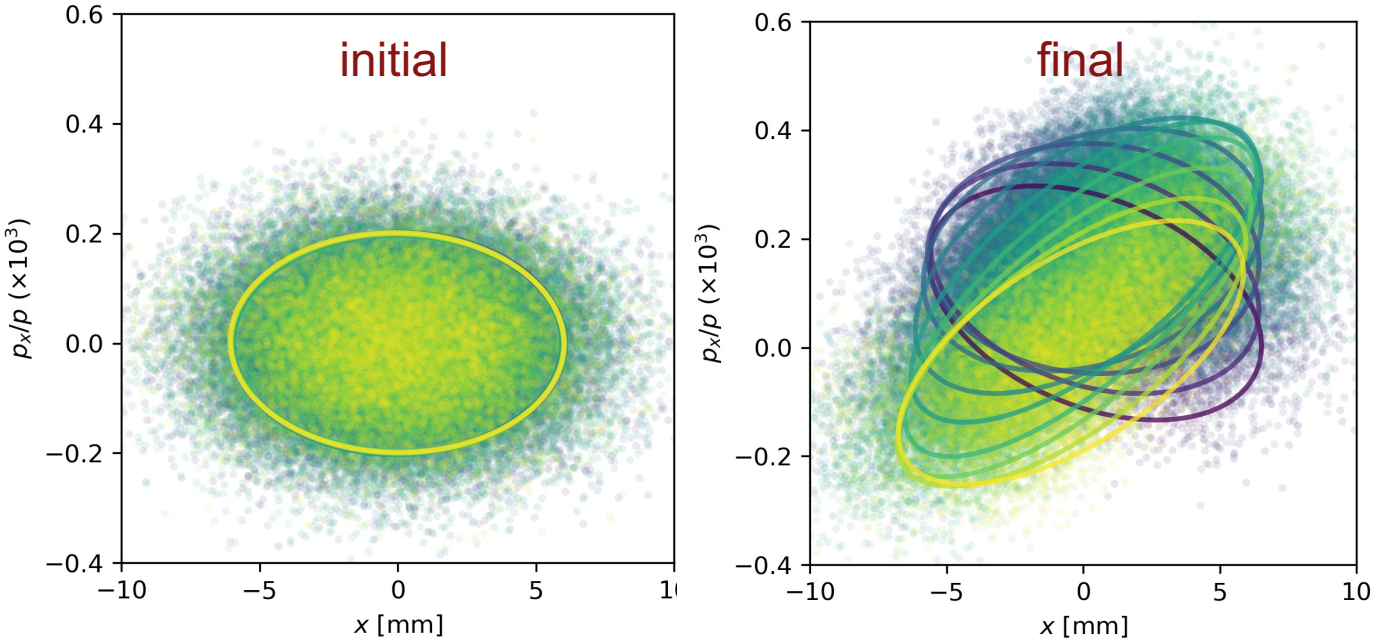
Studies of CSR effects are limited to **macro-scale** description of beam distribution:

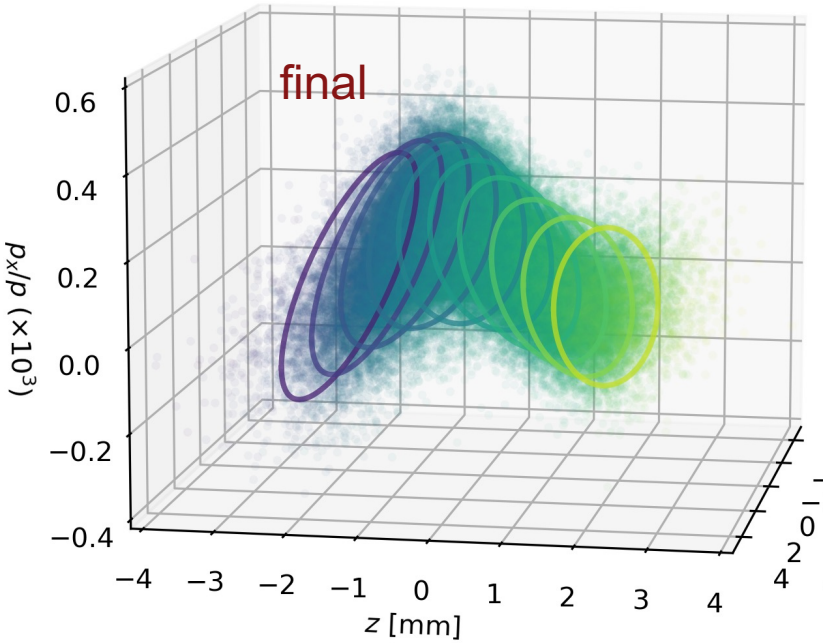
- Projected ε_x growth



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

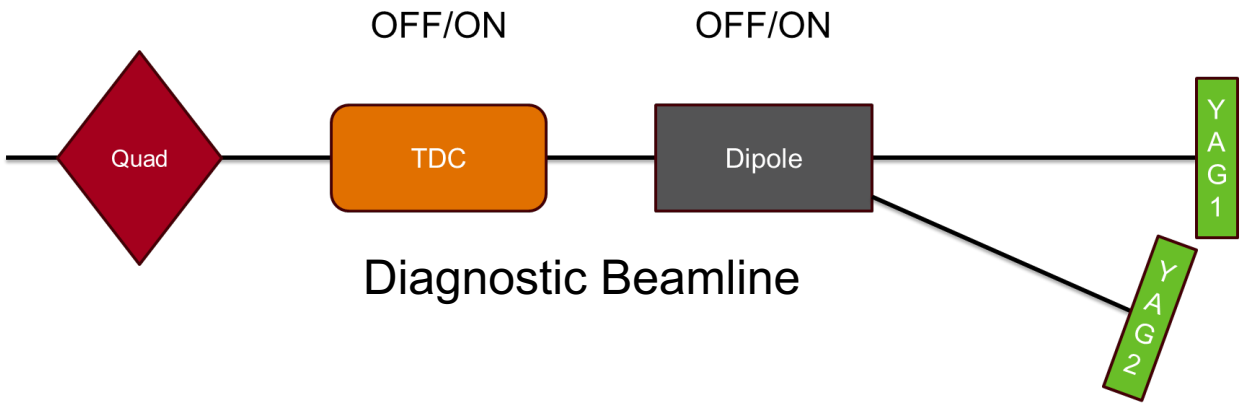
Does not resolve detailed beam structure!

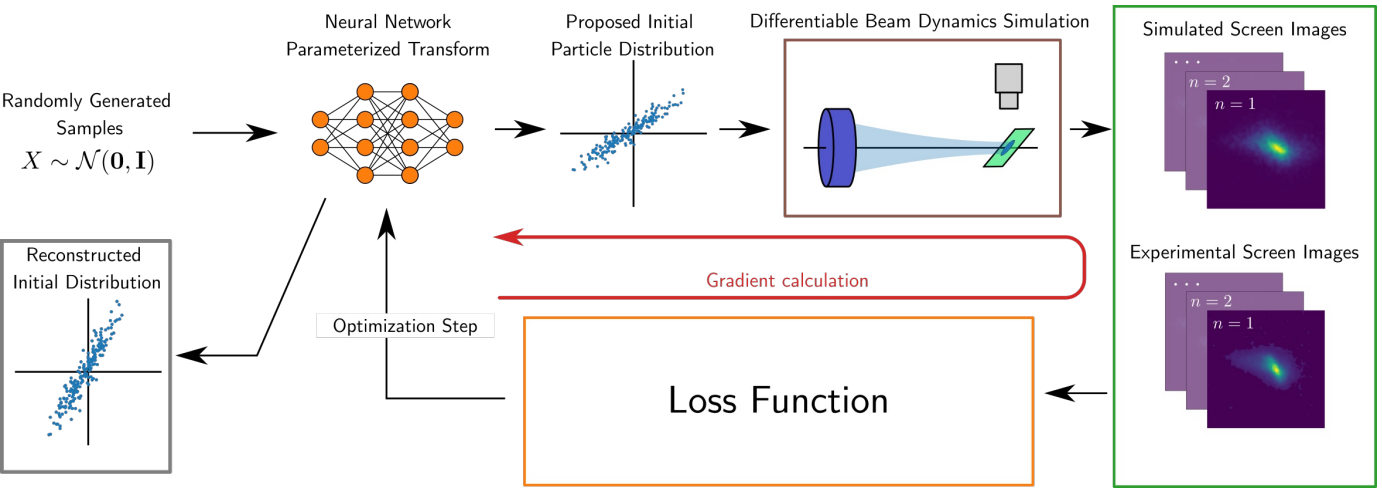




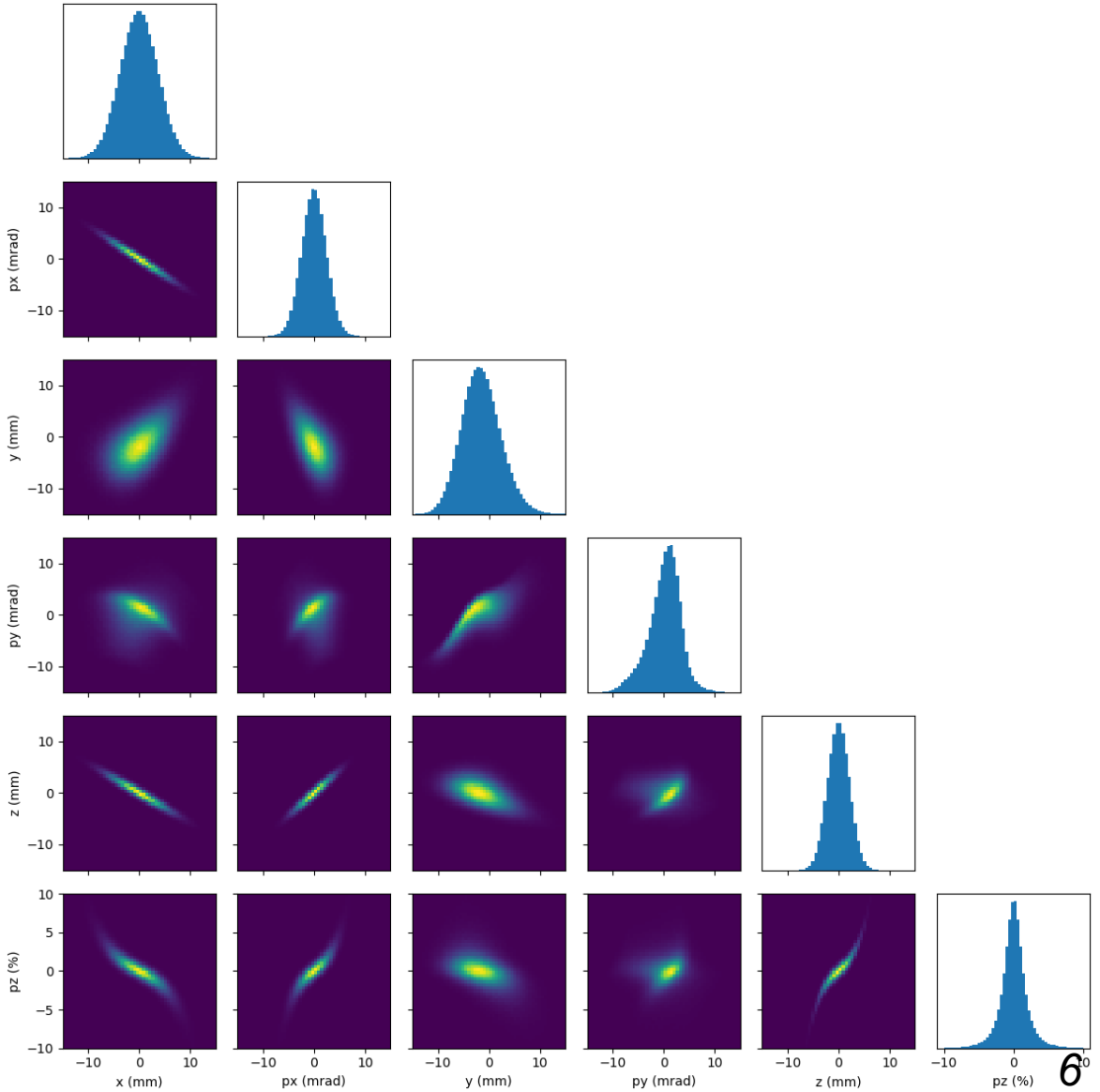
Six-Dimensional Phase Space Reconstruction

- Generative phase space reconstruction (GPSR) can provide detailed structure of the beam distribution



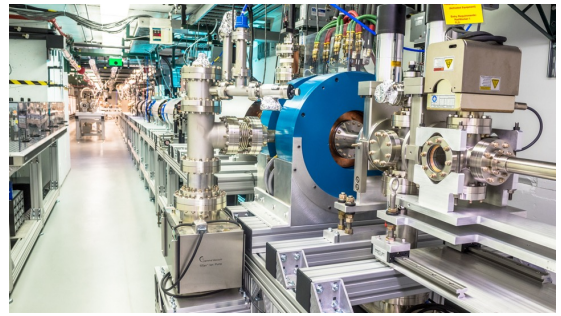


R. Roussel's talk



Characterization of CSR at AWA

- Generate a beam influenced by CSR
- Resolve CSR effects on beam distribution using GPSR
- Argonne Wakefield Accelerator (AWA)



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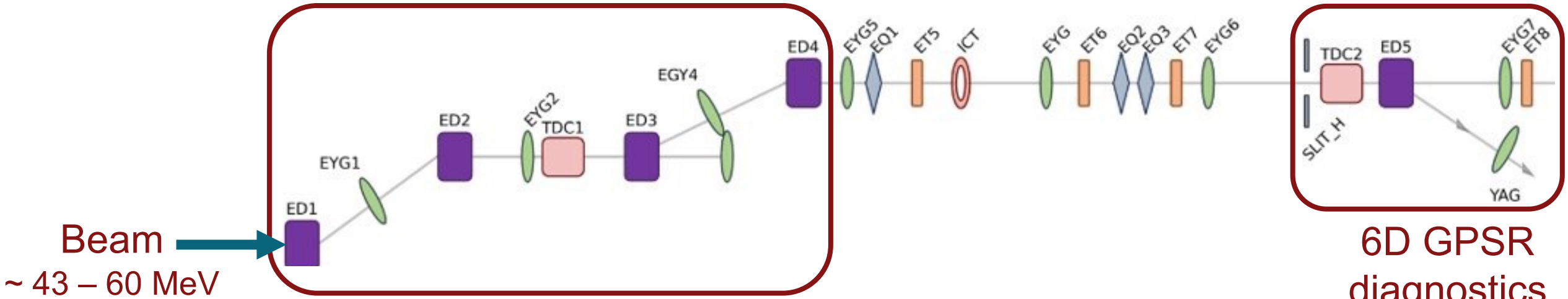
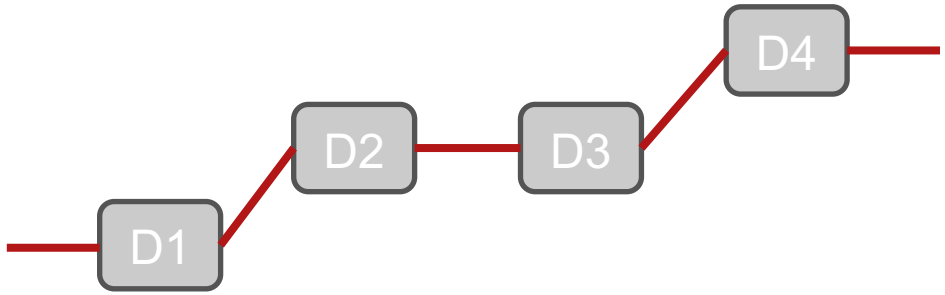


First double dogleg:
4 dipoles

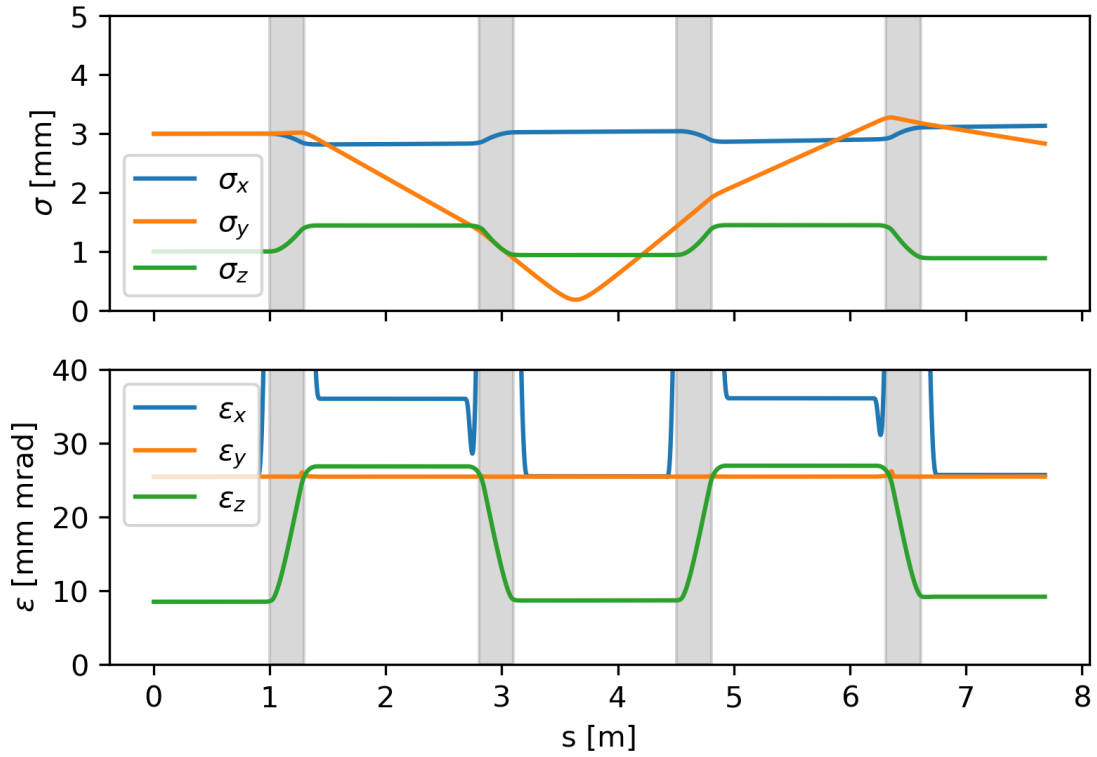
6D GPSR
diagnostics

Beam Dynamics at AWA Double Dogleg

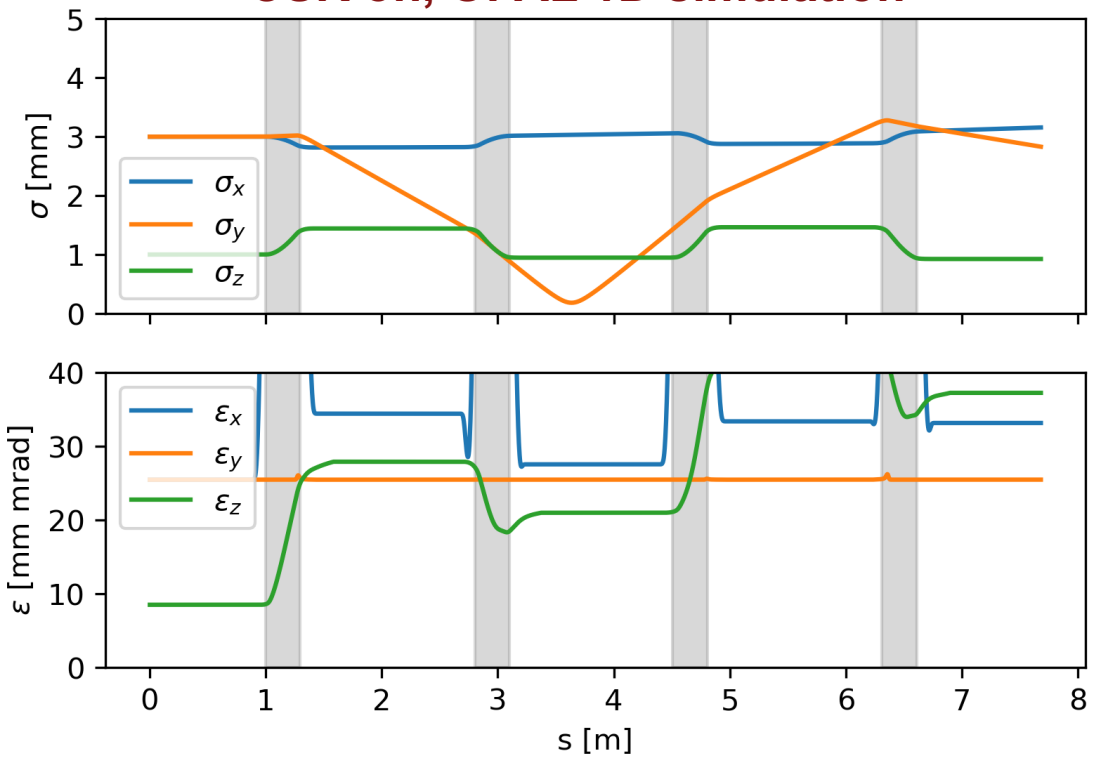
- Can we see CSR effects after double dogleg?
- Initial beam (ideal):
  - 1 nC, 43.4 MeV
  - $\varepsilon_x = 25$ mm mrad
  - 3 mm beam size, 1mm bunch length



CSR off



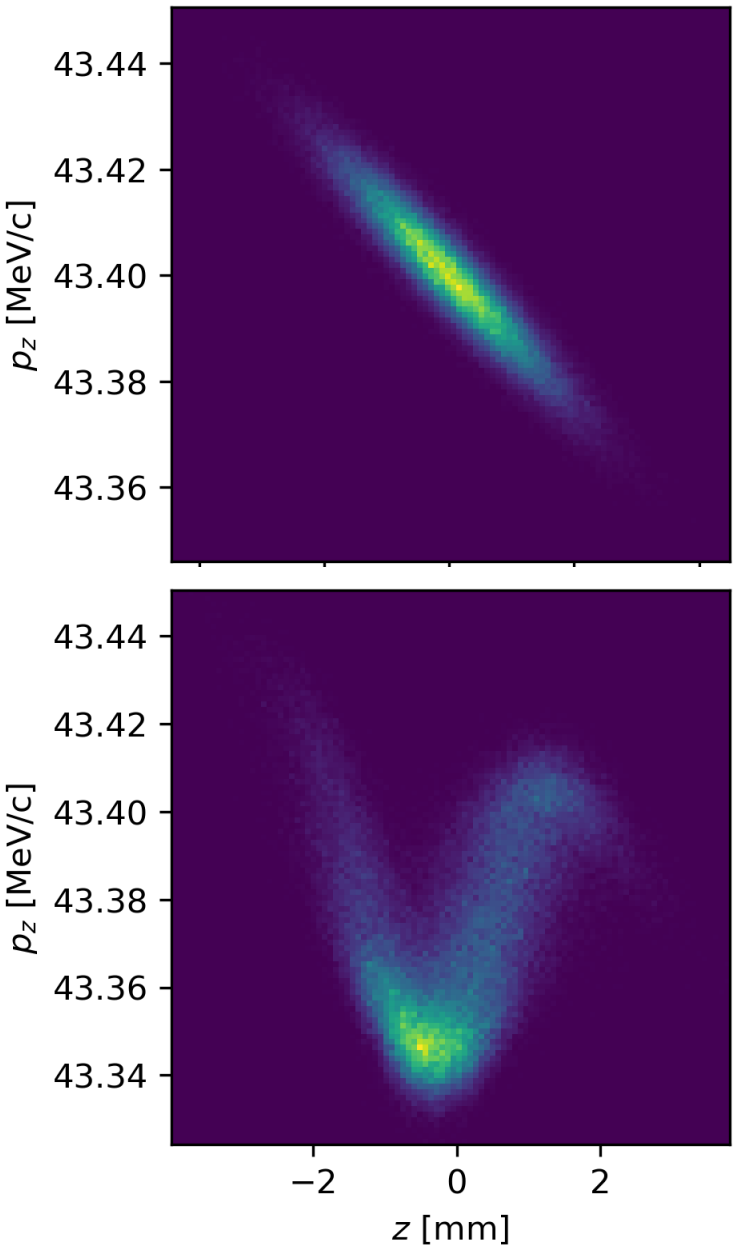
CSR on, OPAL 1D simulation

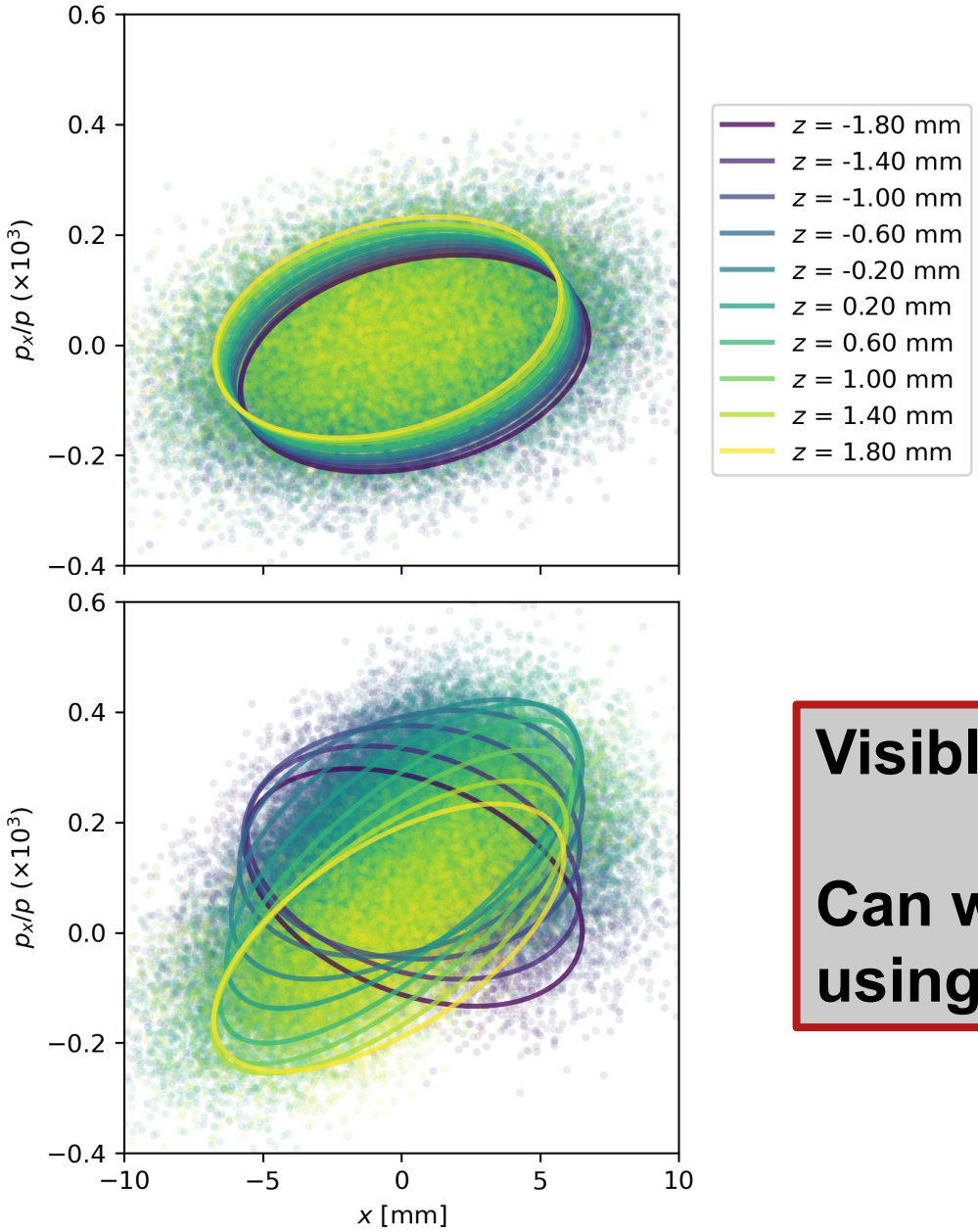


Simulated CSR Effects: $E - z$ and $x - p_x$

CSR off

CSR on

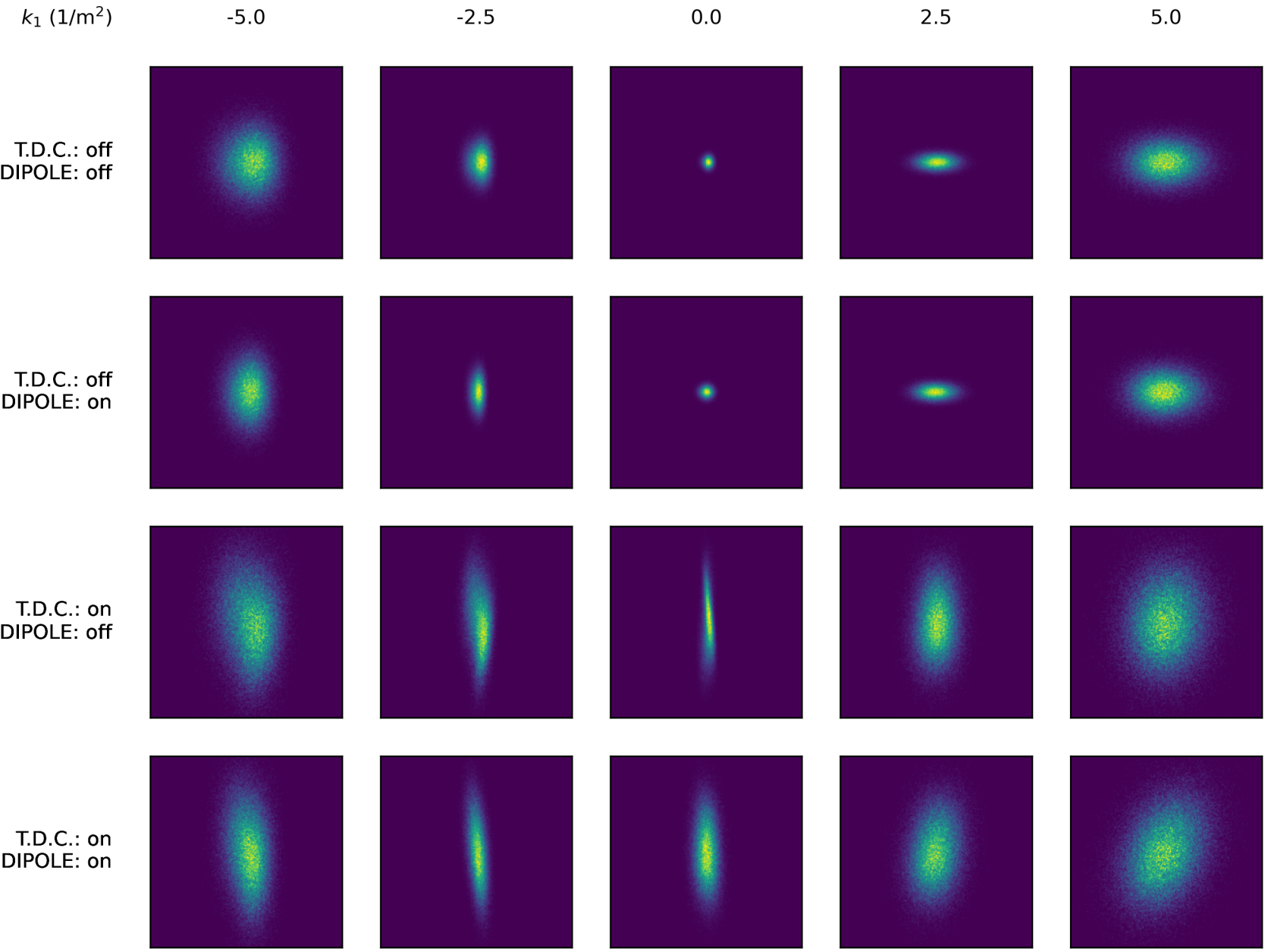


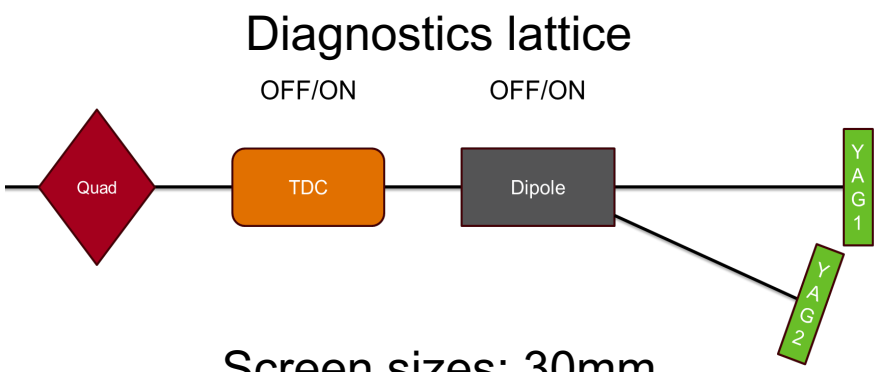


Visible CSR effects.

Can we resolve using GPSR?

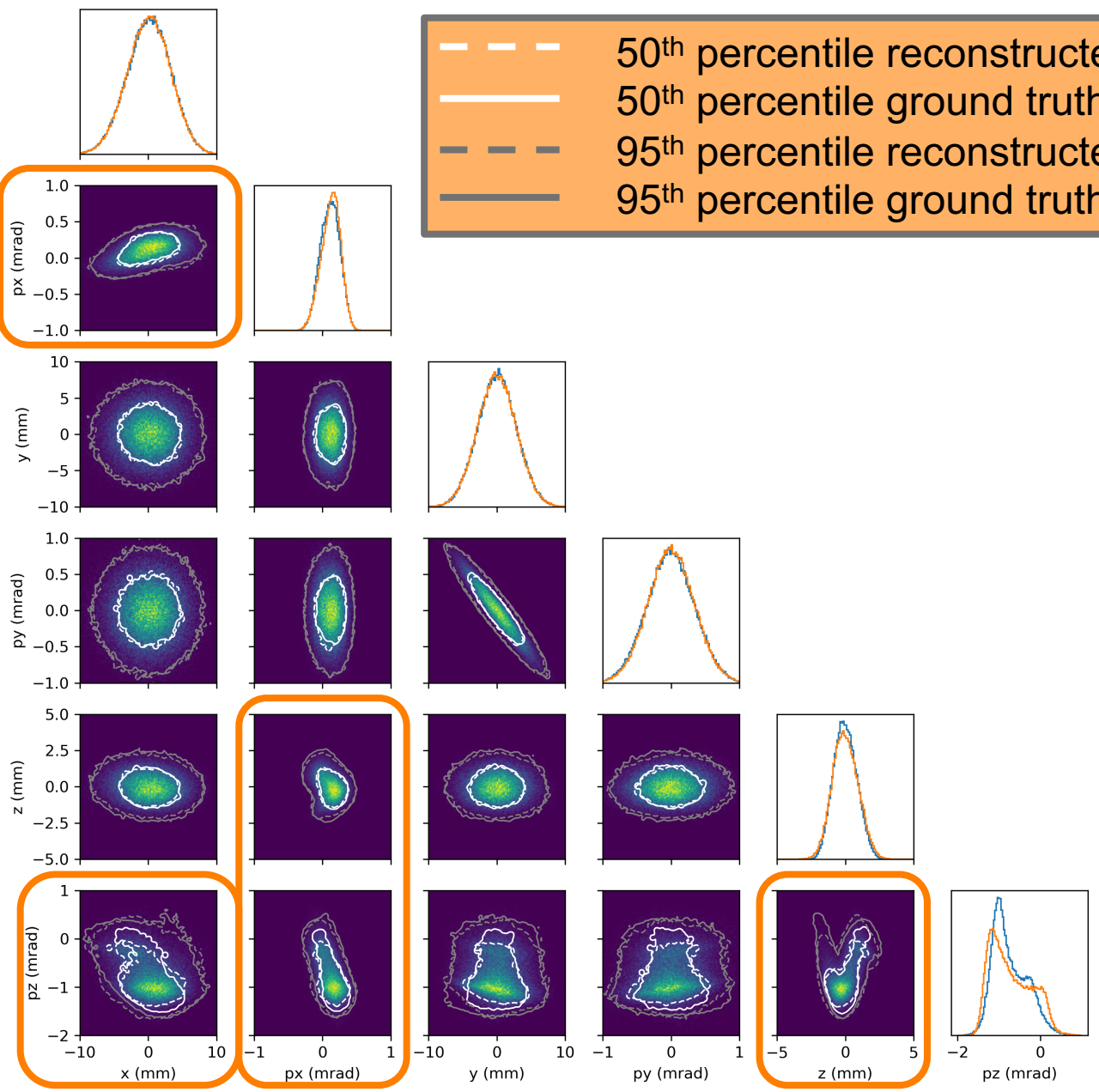
GPSR Training Data

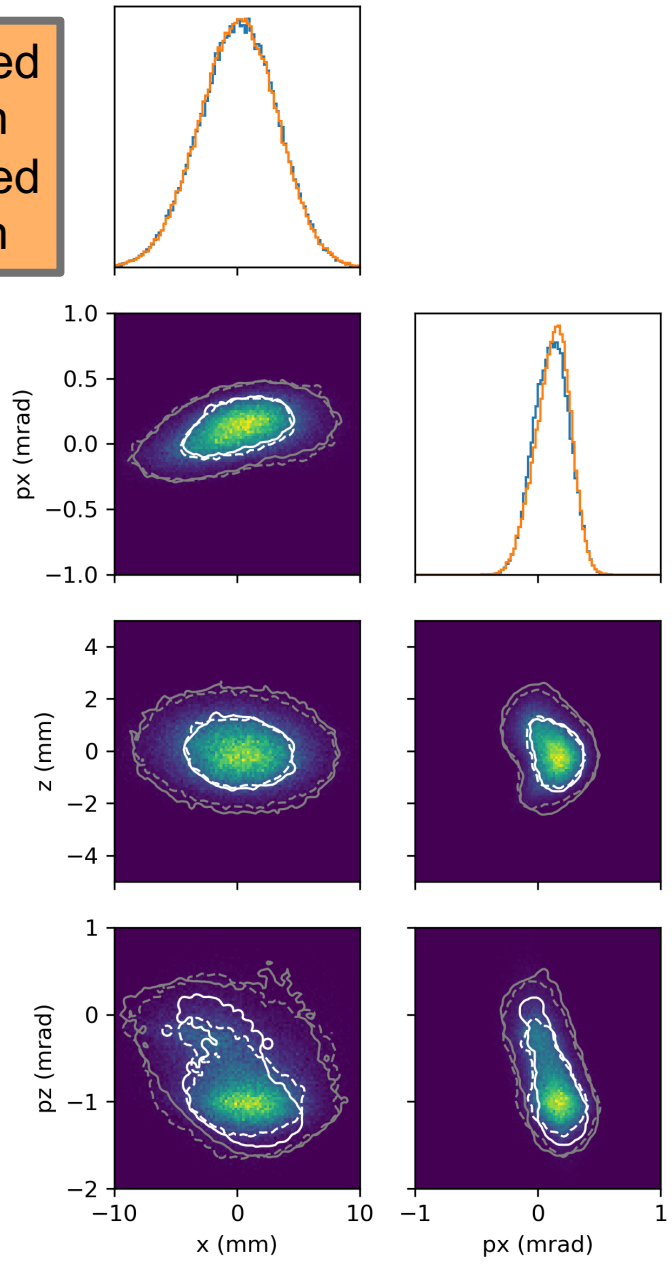




Screen sizes: 30mm

GPSR Results: 2D Projections





Horizontal-Longitudinal phase space detail

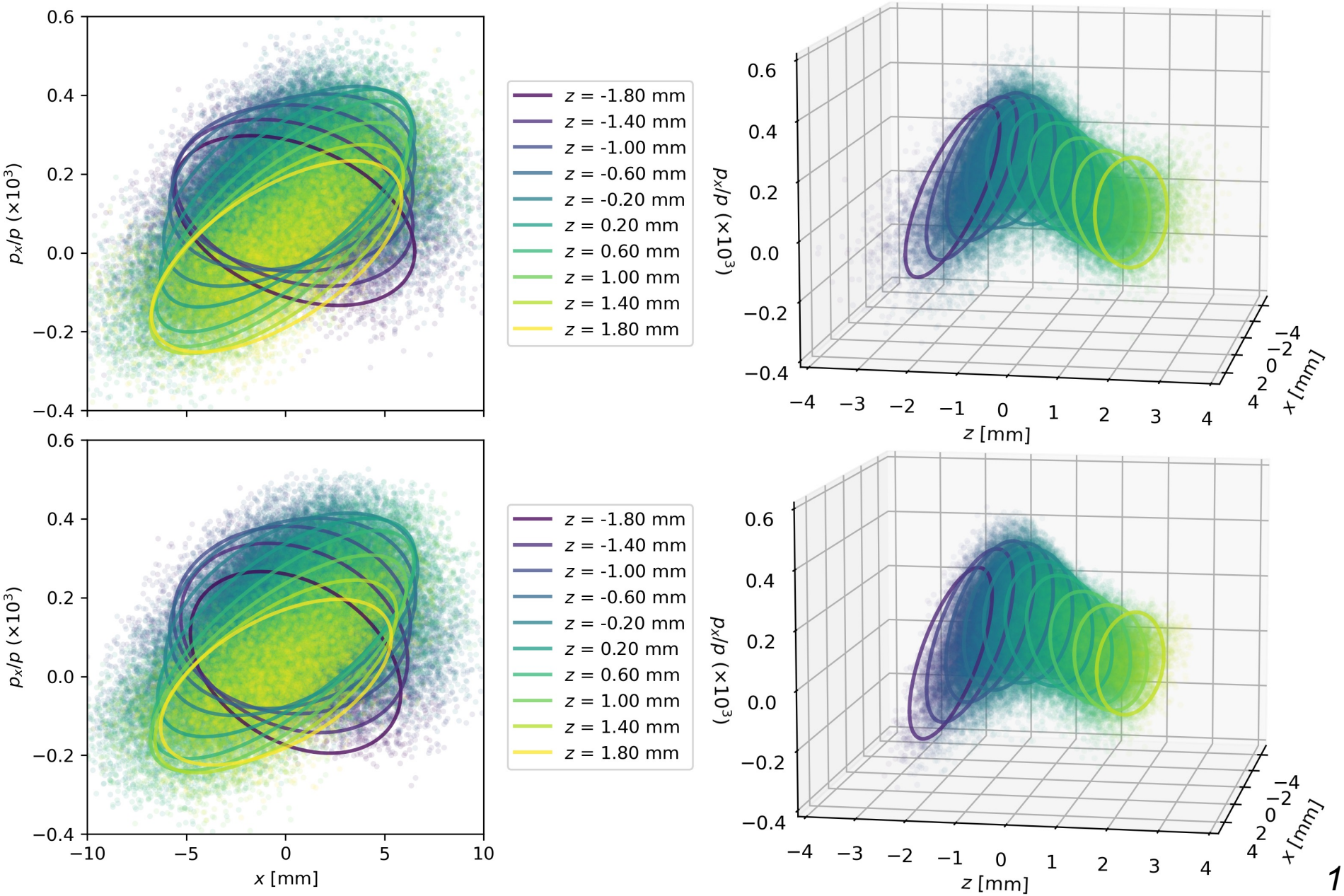
Detailed $x - p_x$ Phase Space Slices

Ground truth

$\varepsilon_x = 4.6$ mm mrad

Reconstruction

$\varepsilon_x = 5.2$ mm mrad



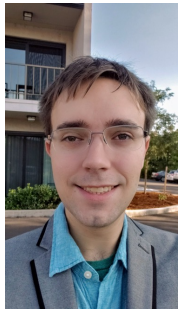
Discussion

- Need of small emittance and energy spread to resolve CSR
  - GPSR struggles to get correct slice rotations when going beyond $\varepsilon_x = 25\ \mathrm{mm\ mrad}$ or under $\delta_E = 0.1\%$ at 1nC
  - It seems that beam parameters are achievable at AWA
- Longitudinal and transverse optics:
  - Could compress beam at last dipole to promote CSR wake with larger beams:
    - Hardware: linac RF cavity phase to induce longitudinal chirp
  - Could test transverse optics to change Twiss parameters:
    - Hardware: quadrupoles
- Define metrics to compare >2D beam distributions
  - How can we compare high-dimensional beam distributions quantitatively?

Summary

- AWA double dogleg can produce significant CSR effects
- Simulations show 6D GPSR can resolve CSR effects in the $\varepsilon_x = 25\ \mathrm{mm\ mrad}, \sigma_x = 3\ \mathrm{mm}$ case
  - Only 20 x-y beam profiles
  - ~10 min, 8 Gb GPU
- Need small ε_x and δ_E to resolve CSR effect
  - Further study of transverse optics is necessary
- Future work:
  - Experimental demonstration coming soon

Team



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(SLAC)

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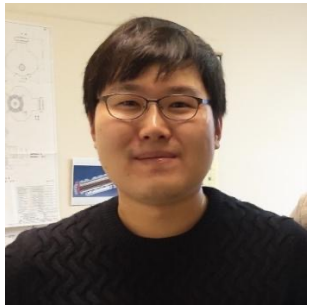
Philippe Piot
(NIU and AWA)



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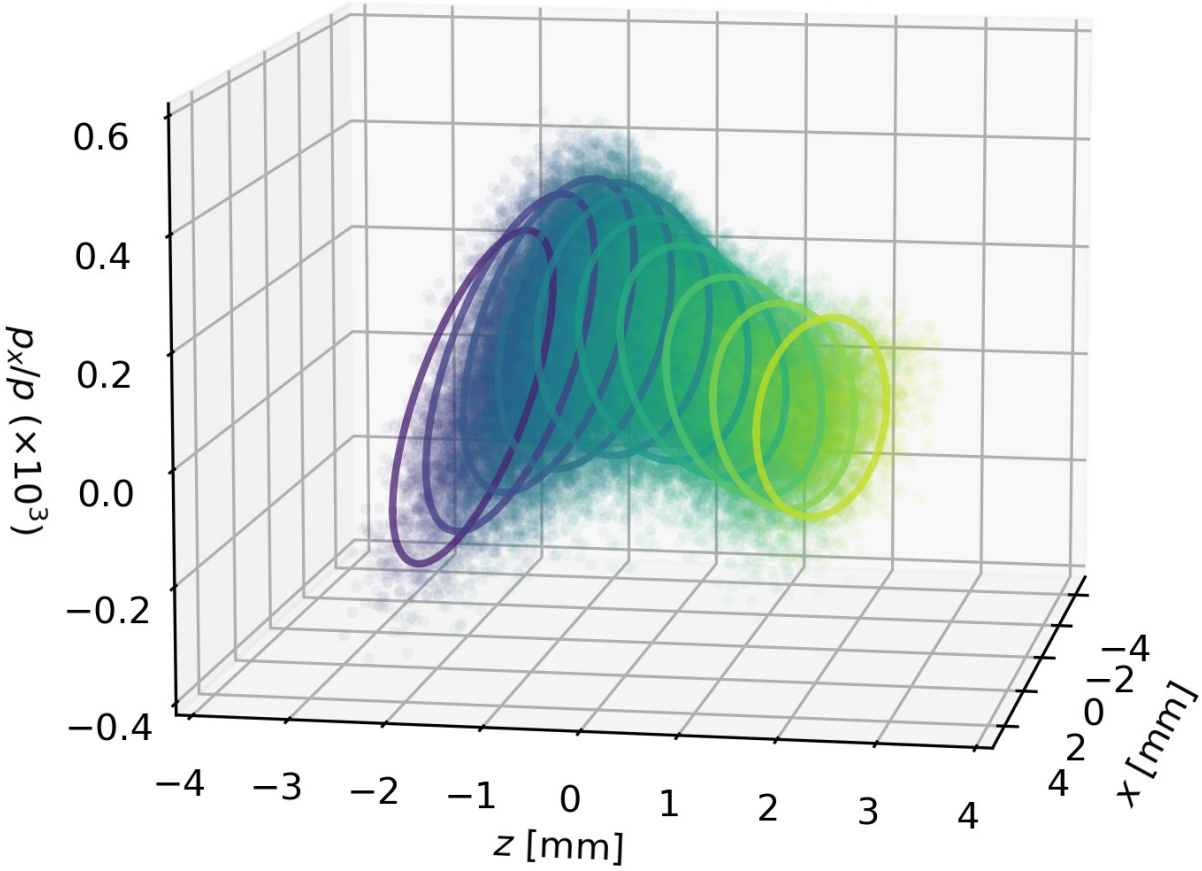

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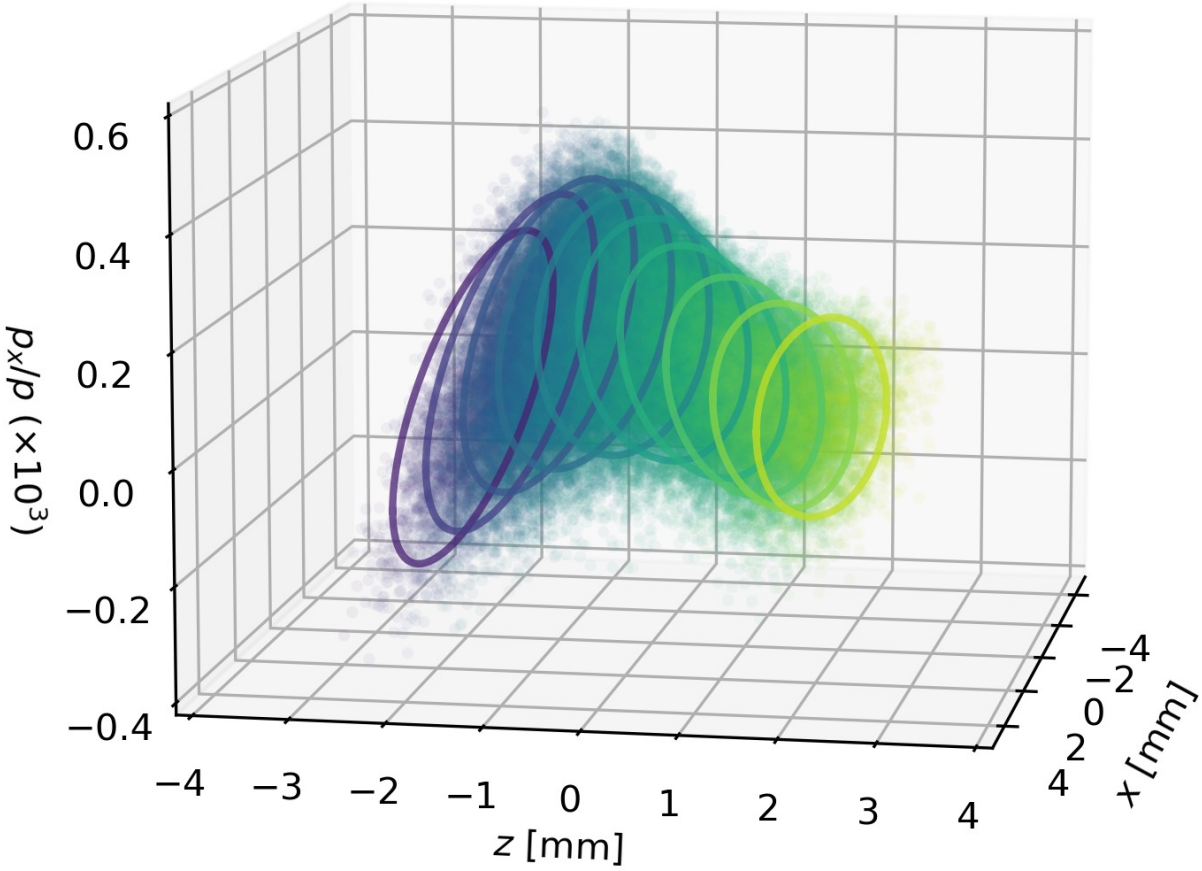
Thanks!
Questions?



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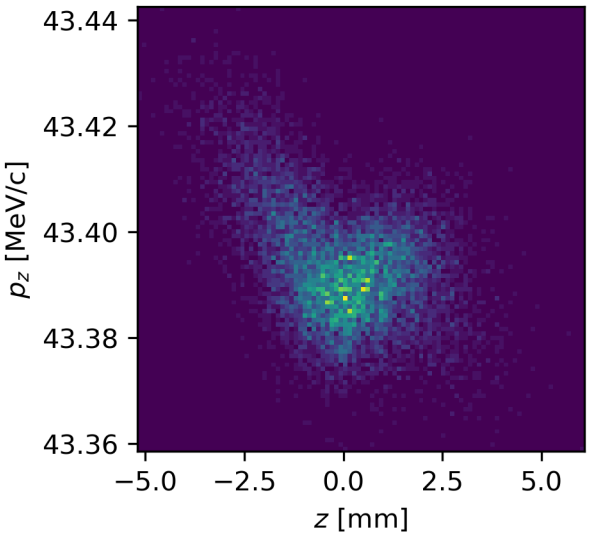
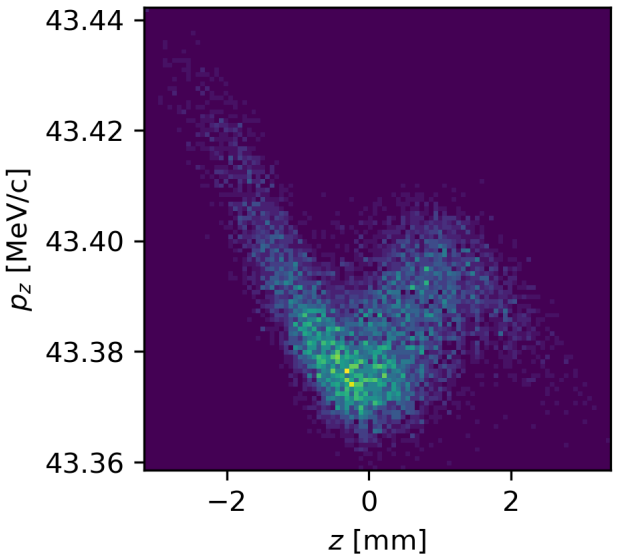
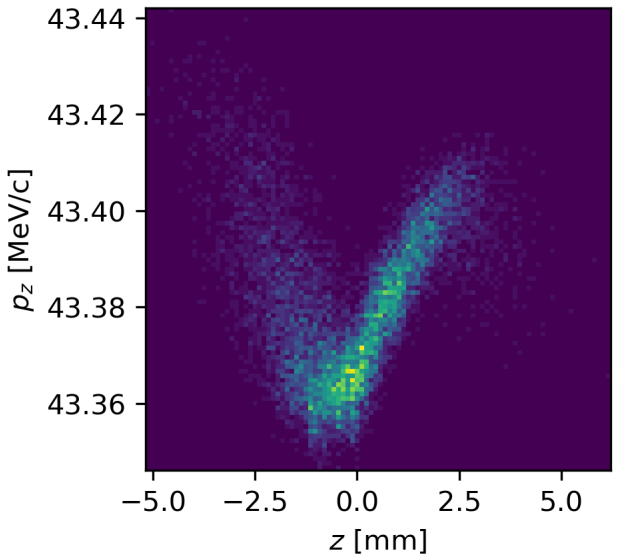
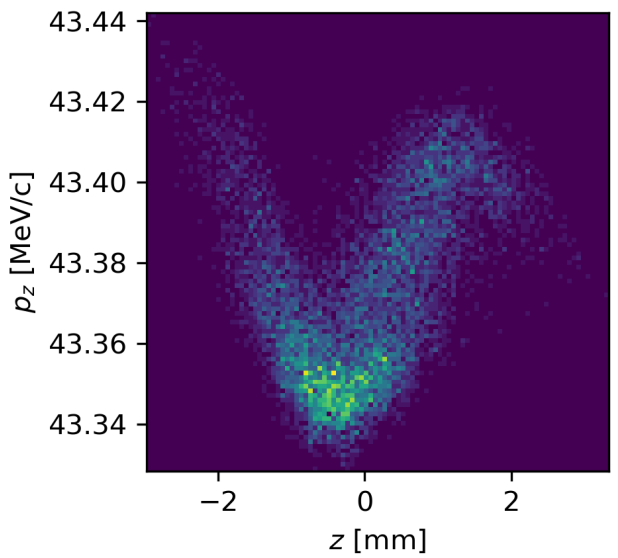
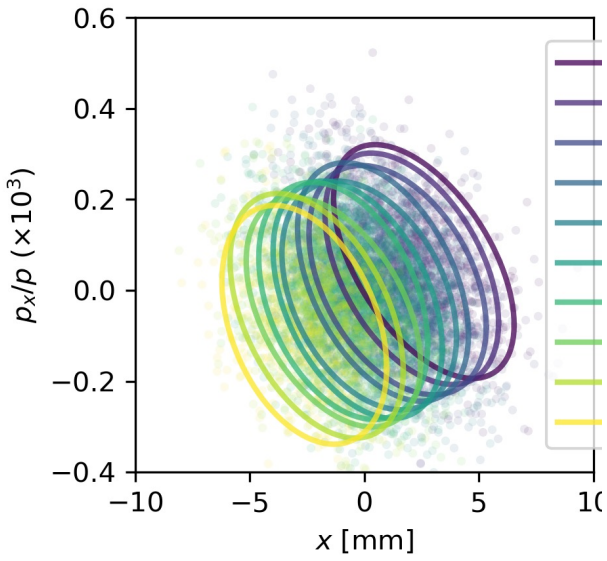
Backup: CSR effects after every dipole

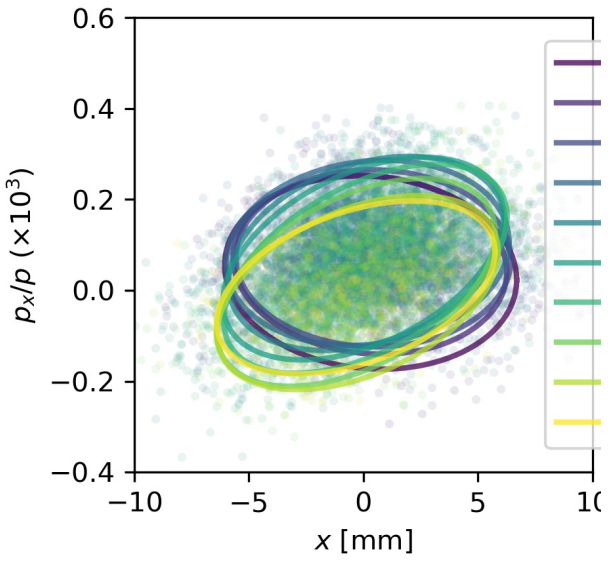


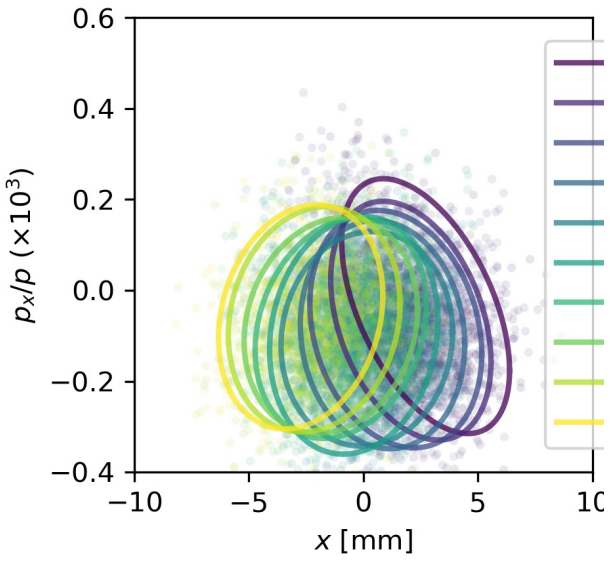


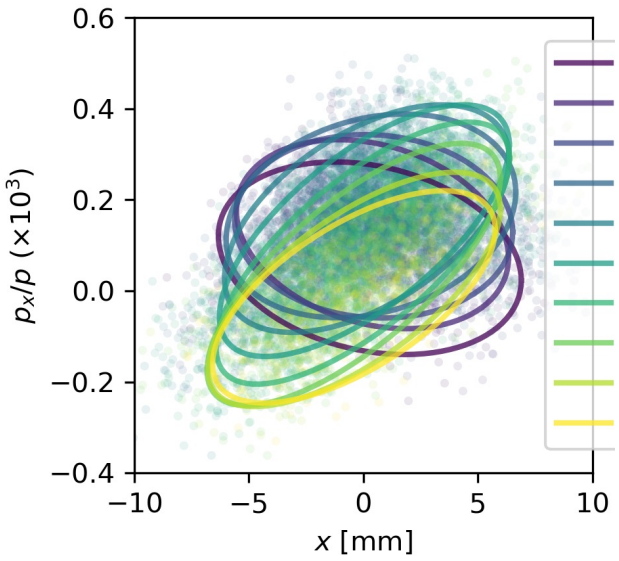




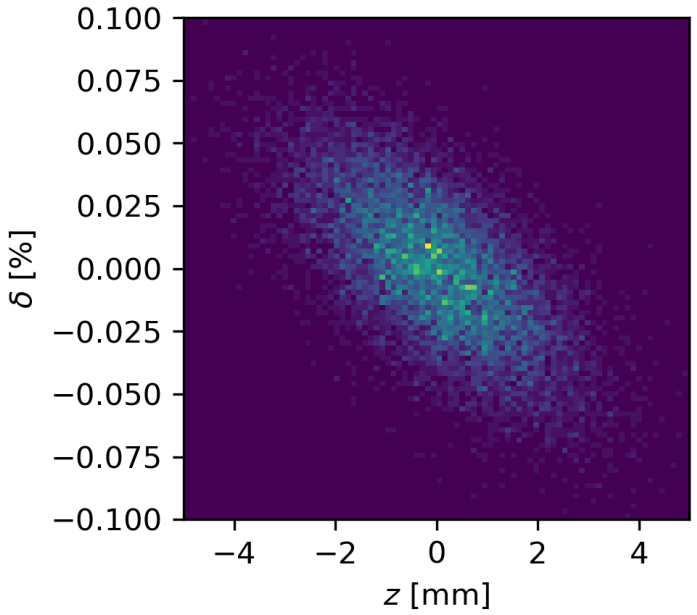


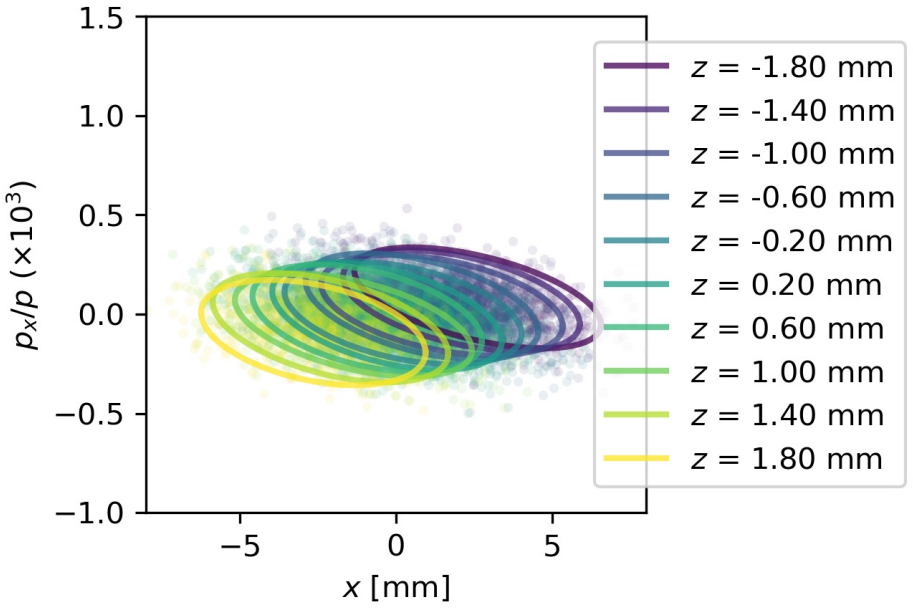


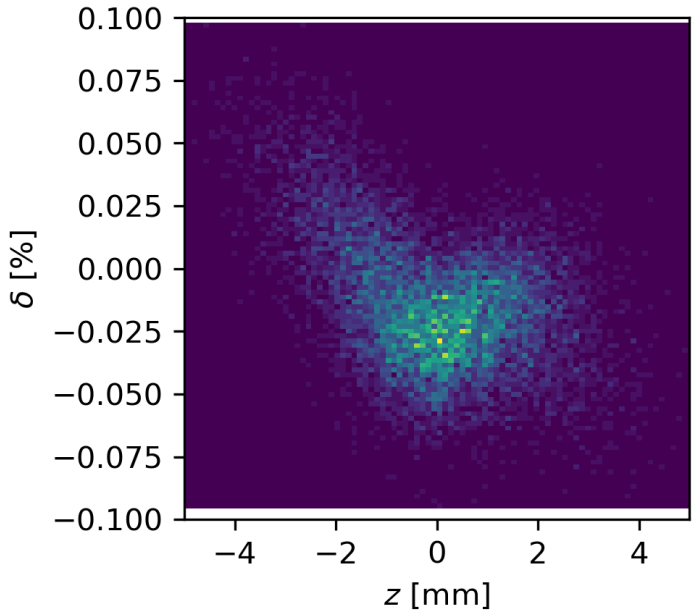


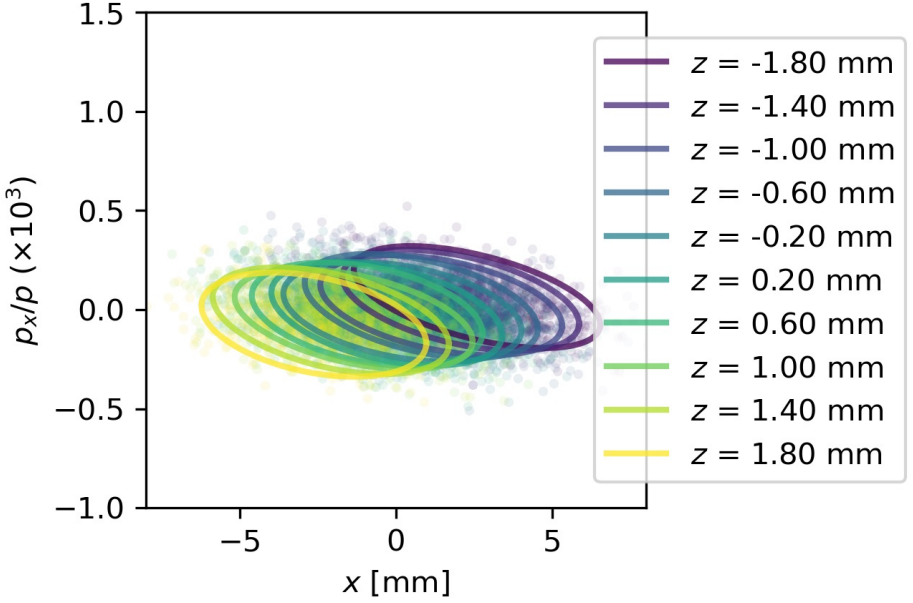


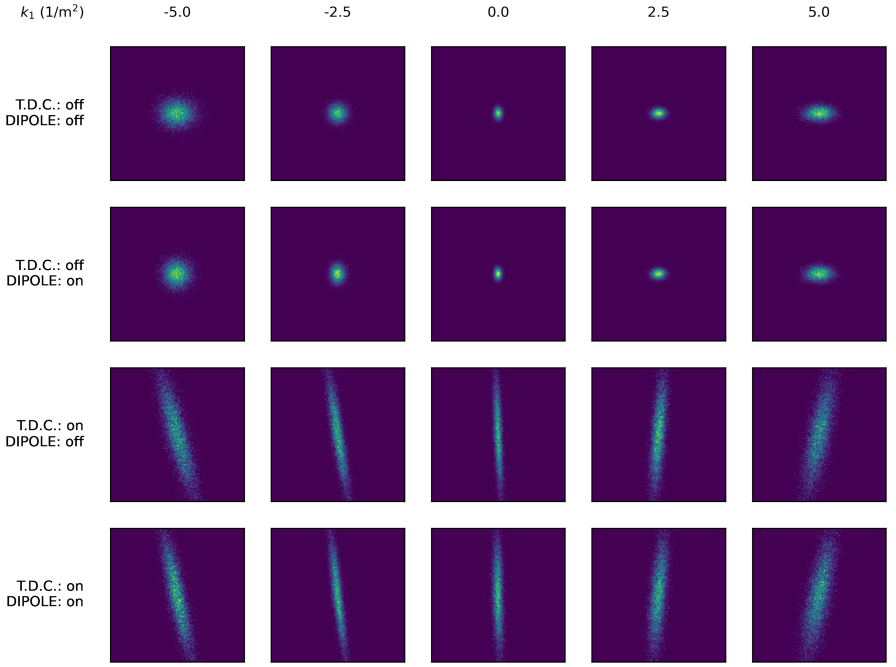
Backup: CSR Effects at Diagnostics Spectrometer











Backup: OPAL CSR Settings

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        NPOINTS = 20,
        NLEFT = 4,
        NRIGHT = 4,
        POLYORDER = 4;

CSR_WK:
        WAKE,
        TYPE="1D-CSR",
        NBIN=300,
        FILTERS=CSR_FILTER;
```