OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

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Benchmarking PIC Simulations at the SNS Beam Test Facility

Tony Wood

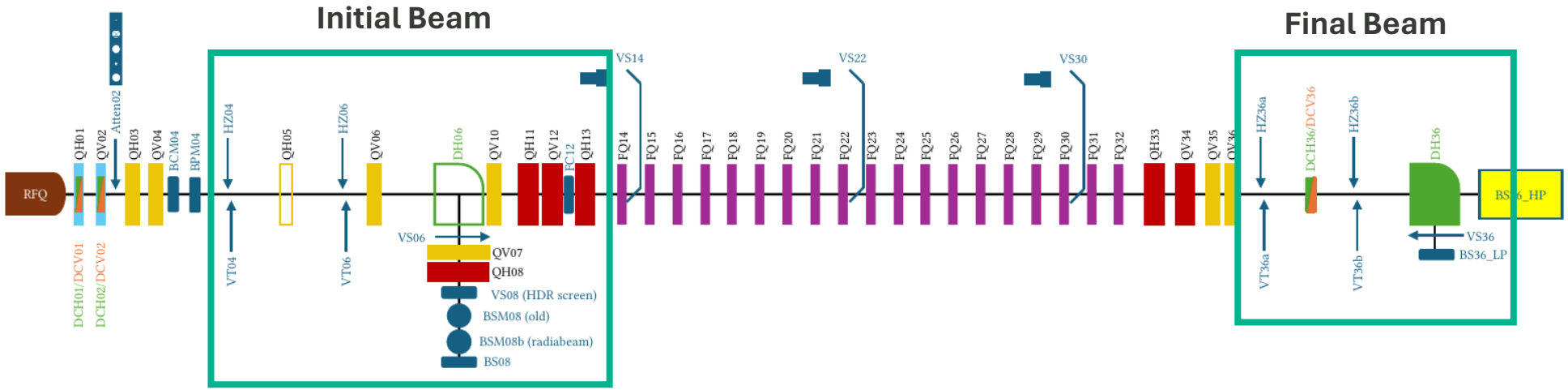
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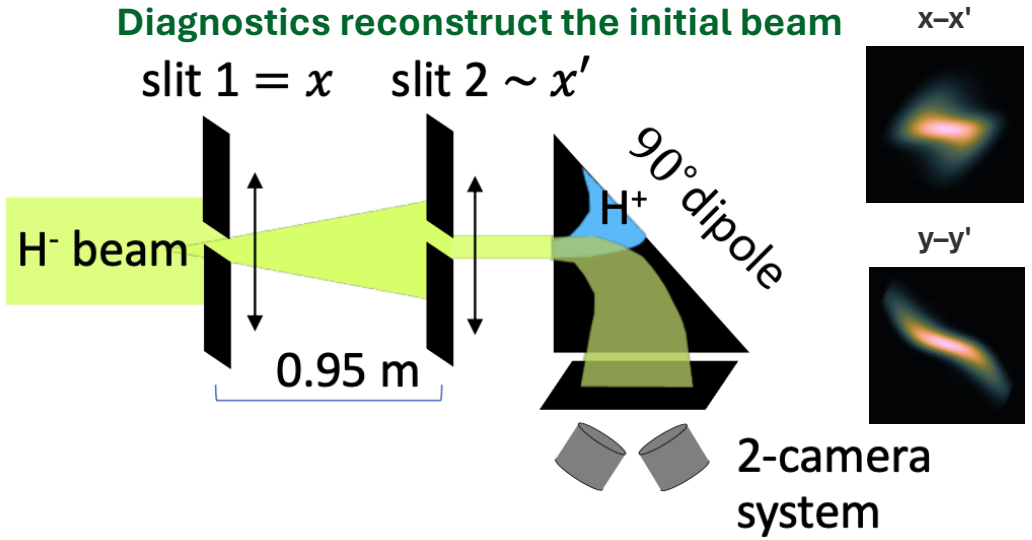
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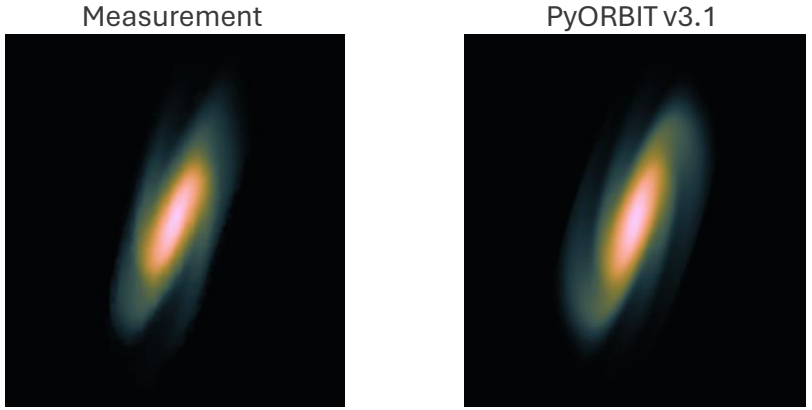
The Beam Test Facility



Diagnostics reconstruct the initial beam



Measurement tests the prediction

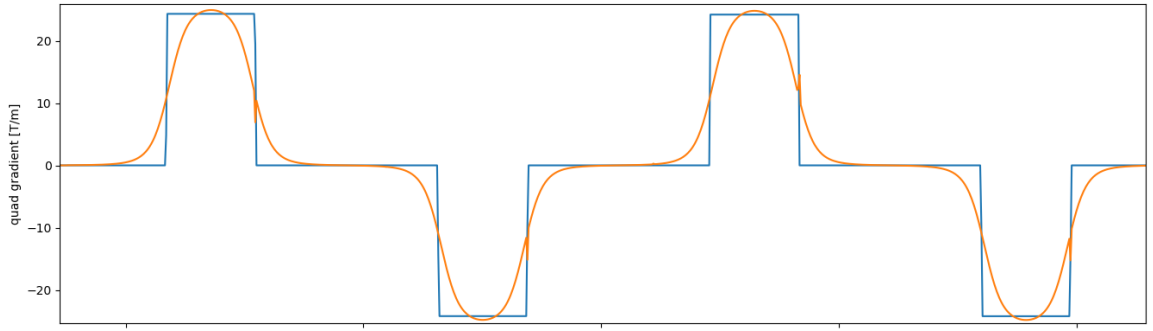


Outline

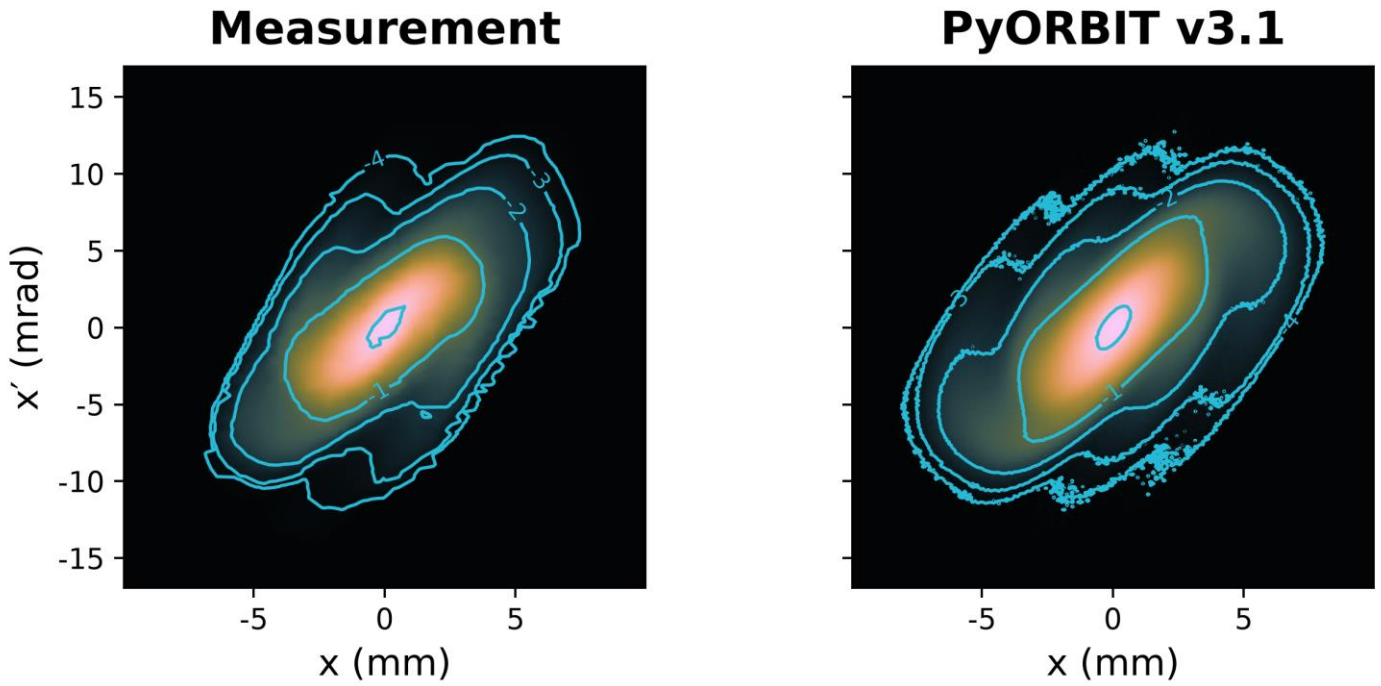
- Given the measured initial beam, how well do the models predict the downstream phase spaces?
- How does model agreement look across different simulation frameworks?
    - e.g., PyORBIT vs. ImpactX
- What are the gaps in our models?

PyORBIT Nominal Configuration

Component	Specification
Beam energy	2.5 MeV
Beam current	50 mA
Numerical resolution	**100 million macroparticles**
Space charge	**3D FFT w/ multi-bunch solver, 64x64x64 grid**
Quadrupoles	**Standard: Soft-profile PMQs, Hard-profile EMQs Pure quadrupole fields**



How we compare measurement and model



PyORBIT output is projected onto the measurement grid and cropped to the measured range.

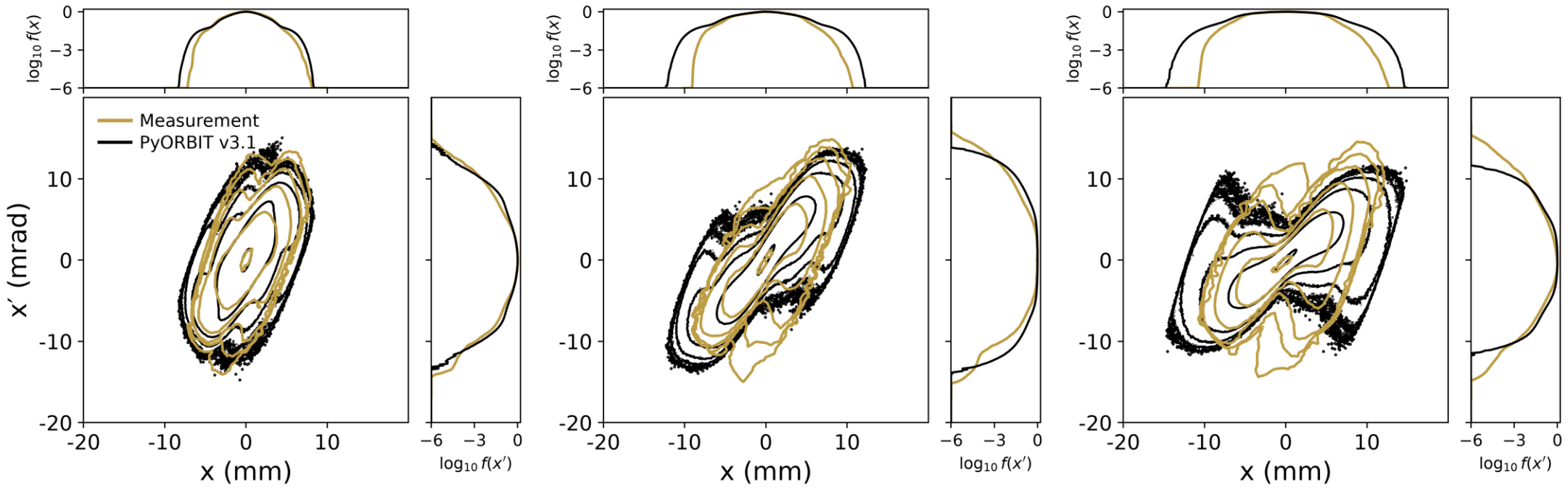
Each complete 2D profile is normalized to peak and overlaid with log contours for shape comparison

Contours: log10(f / fmax) = −0.05, −1, −2, −3, −4 -> 10%, 90%, 99%, etc.

Core shape checks dominant transport. Outer structure probes nonlinearities and halo

Data vs. Model Comparisons

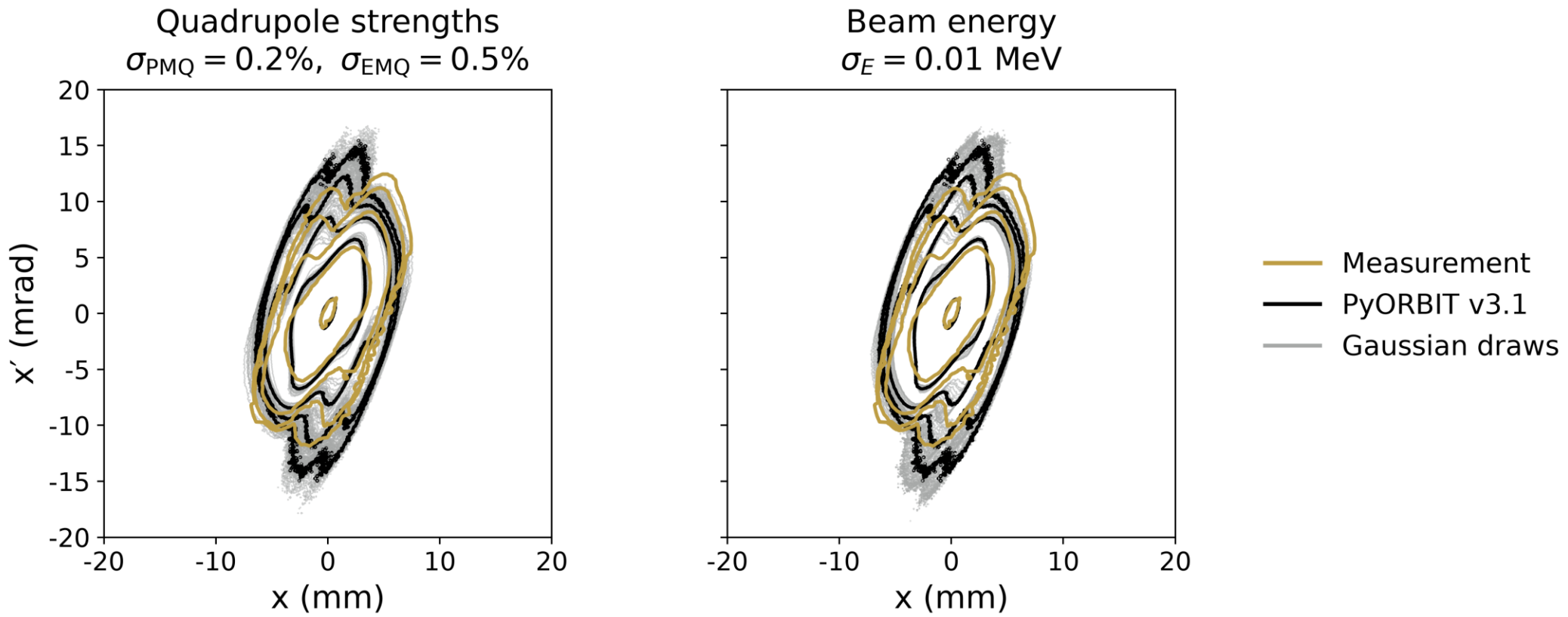
Increasing mismatch



The model captures the core across the three cases, while differences grow in the outer contours.

Contours: log10(f / fmax) = −0.05, −1, −2, −3, −4

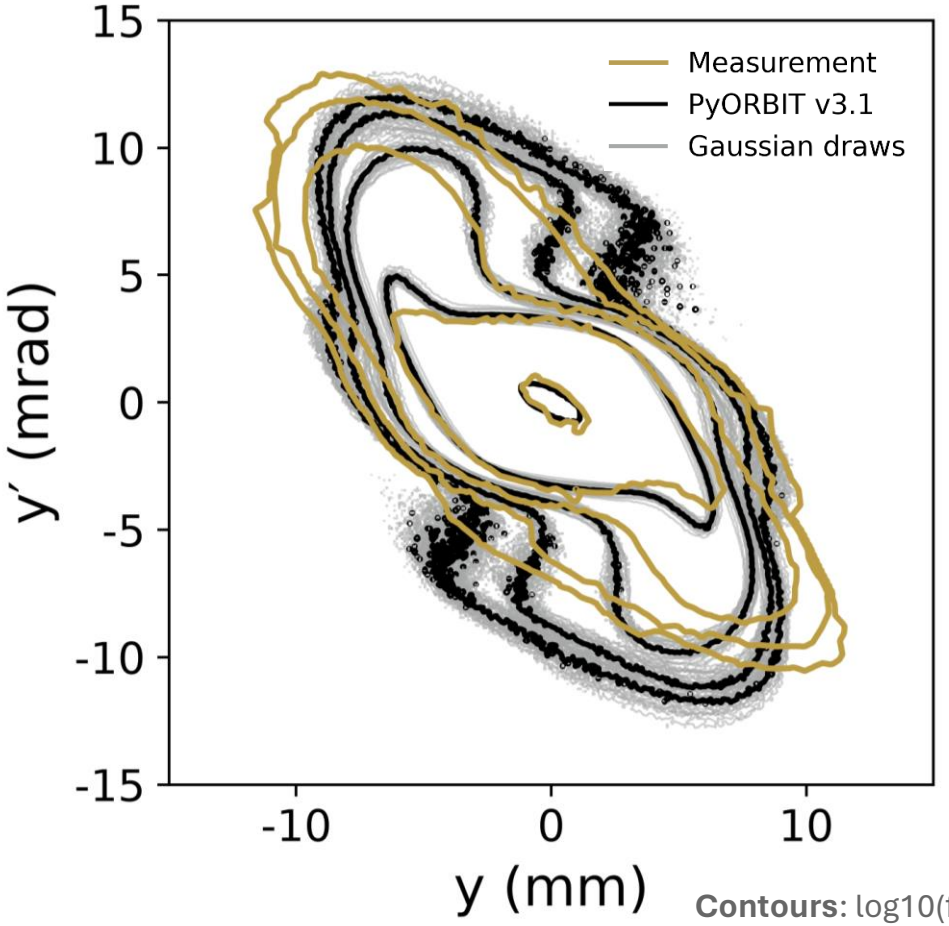
Quadrupole and energy uncertainties don’t cover disagreement

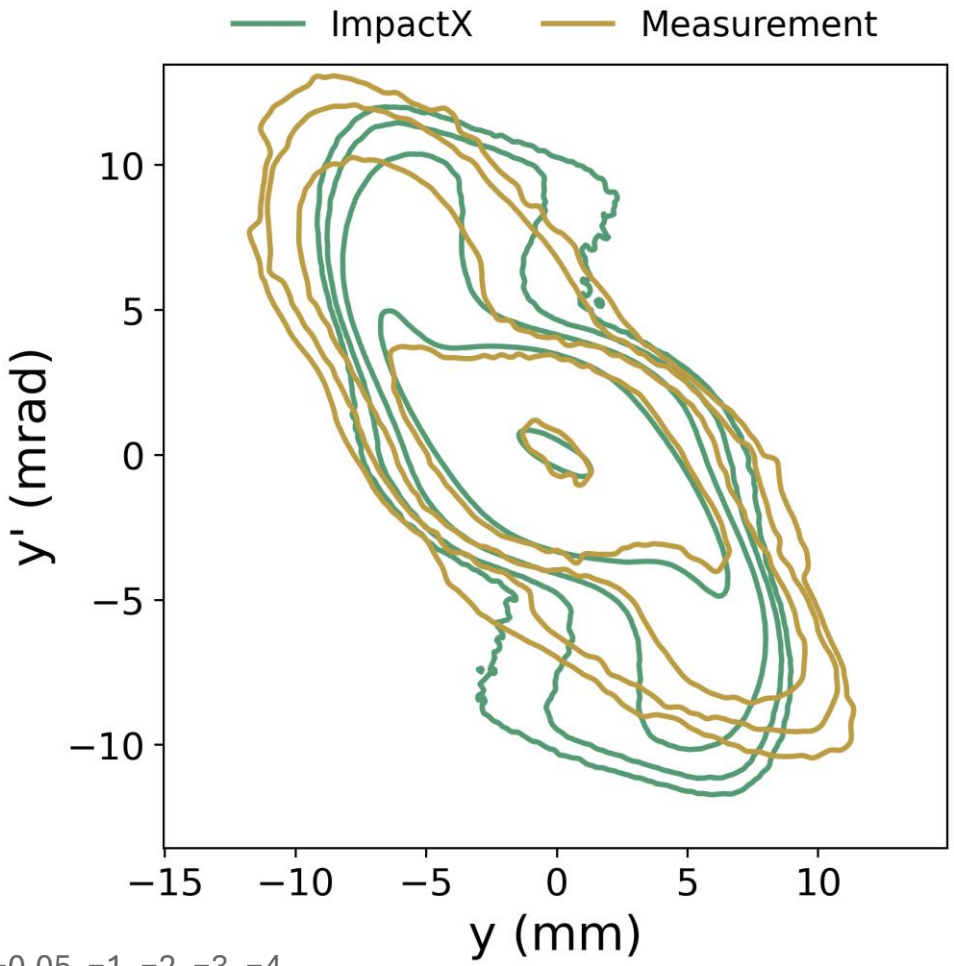


Contours: log10(f / fmax) = −0.05, −1, −2, −3, −4
Gray contours are a visual sensitivity envelope

Next: nonlinear field components and transverse offsets.

Cross-code benchmark with ImpactX





Contours: log10(f / fmax) = −0.05, −1, −2, −3, −4

Core agrees well up to 90% of the beam

Beyond: modeling differences start to appear in the tails → appears to be tied to energy spread.

Summary

- The BTF enables us to benchmark models against measurements

- The models agree well at the RMS-level, but are less successful at predicting the evolution of the full beam distribution

5D measurement available on Zenodo:

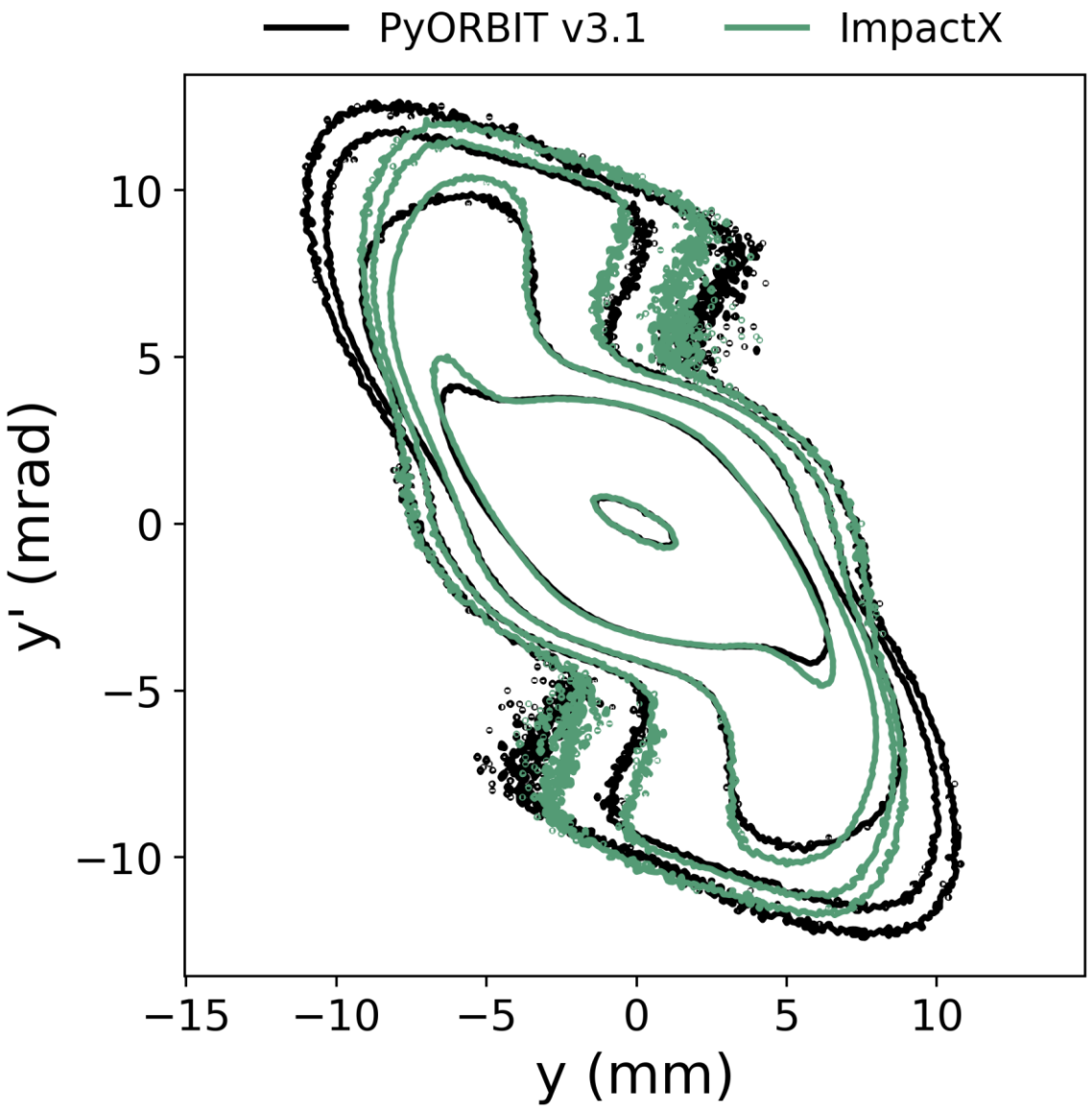
Hoover, A., Ruisard, K., Aleksandrov, A., Zhukov, A., & Cousineau, S. (2023). Five-dimensional phase space measurement at the Spallation Neutron Source Beam Test Facility (Version 0.1.5) [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.10368144

PyORBIT SNS-BTF Benchmark

Ruisard, K., Hoover, A., & Thompson, T. (2025). SNS-BTF simulation benchmark (Version 0.0.2) [Figure]. Zenodo. https://doi.org/10.5281/zenodo.14902814

Discussion Points

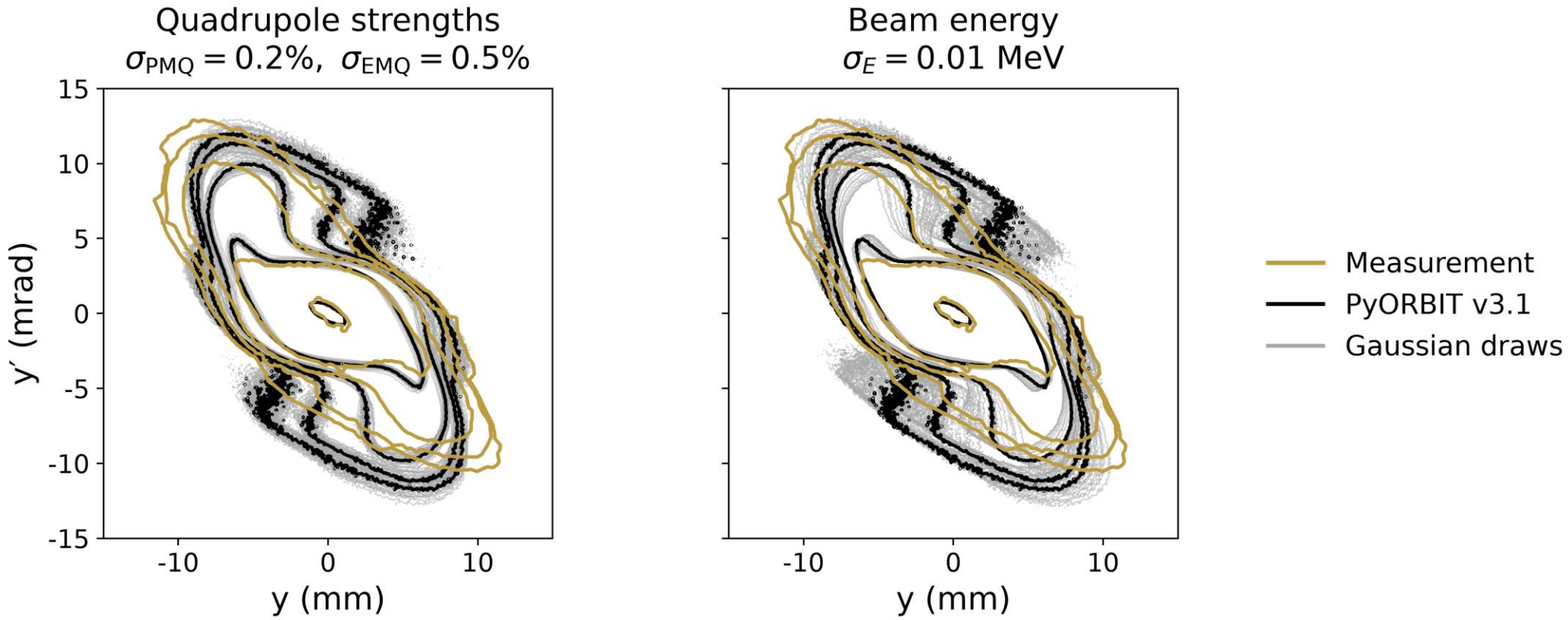
- s-based vs. t-based?
- Magnetic field modeling
- PyORBIT's paraxial transport vs. ImpactX's exact Hamiltonian
- Differences in the space charge solve?
  - Point-based Green's function vs. integrated
- Is the full 6D initial distribution important?



Contours: log10(f / fmax) = −0.05, −1, −2, −3, −4

Thank you for your attention

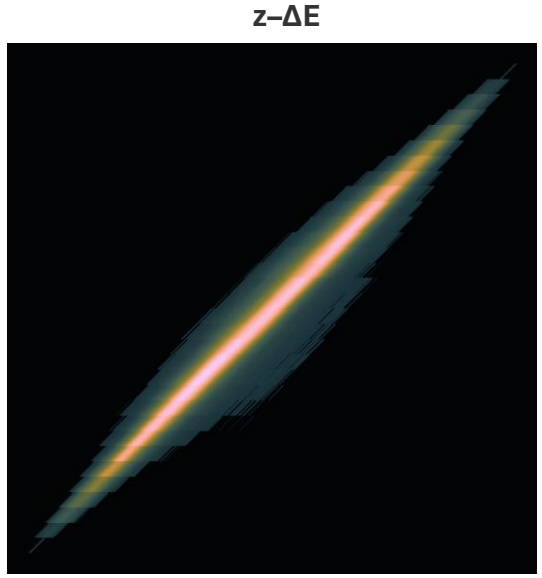
Vertical phase-space uncertainty

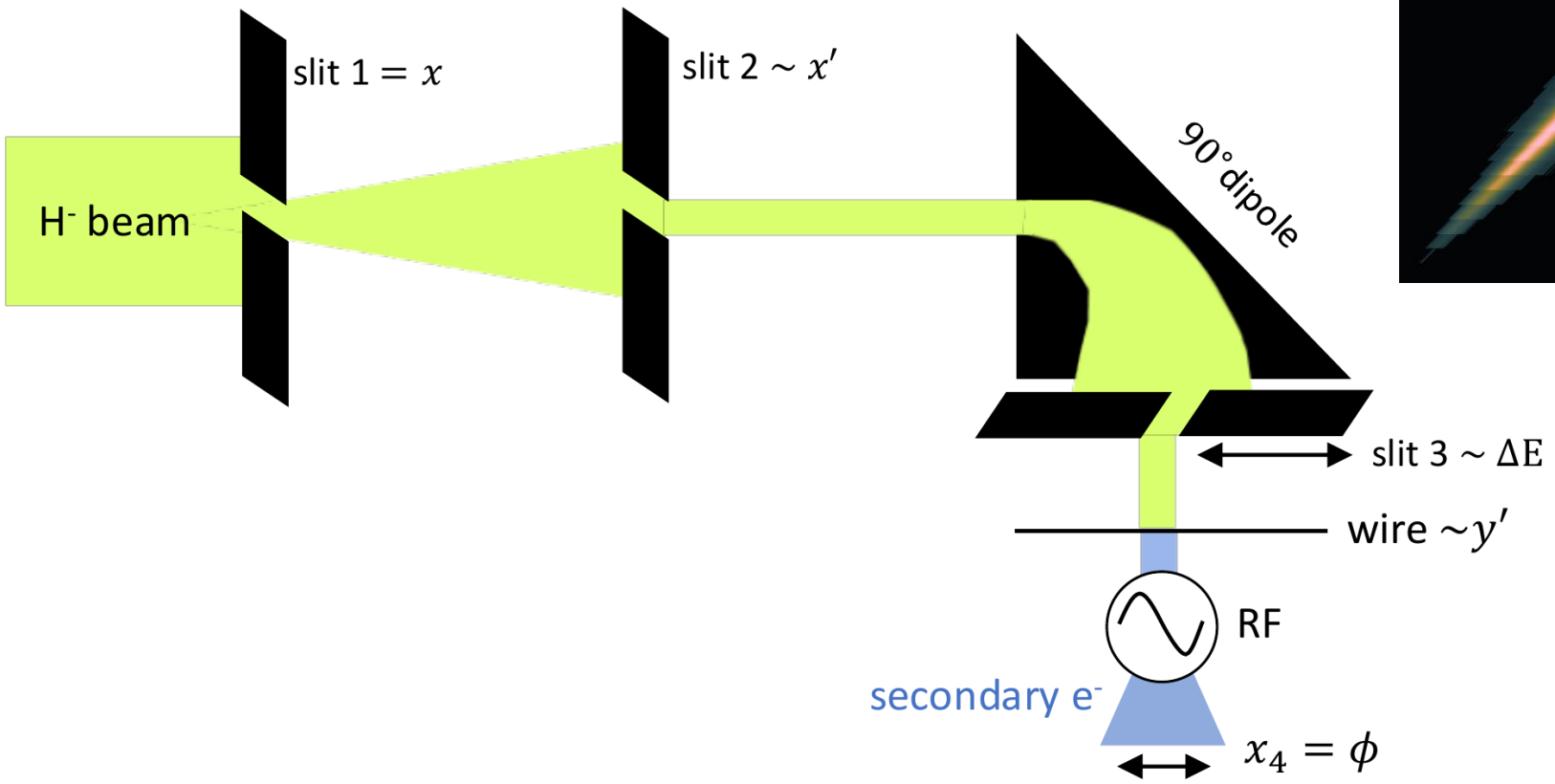


Matched y-y' phase space; gray contours show representative Gaussian parameter throws.

Visual sensitivity envelope, not a calibrated confidence region.

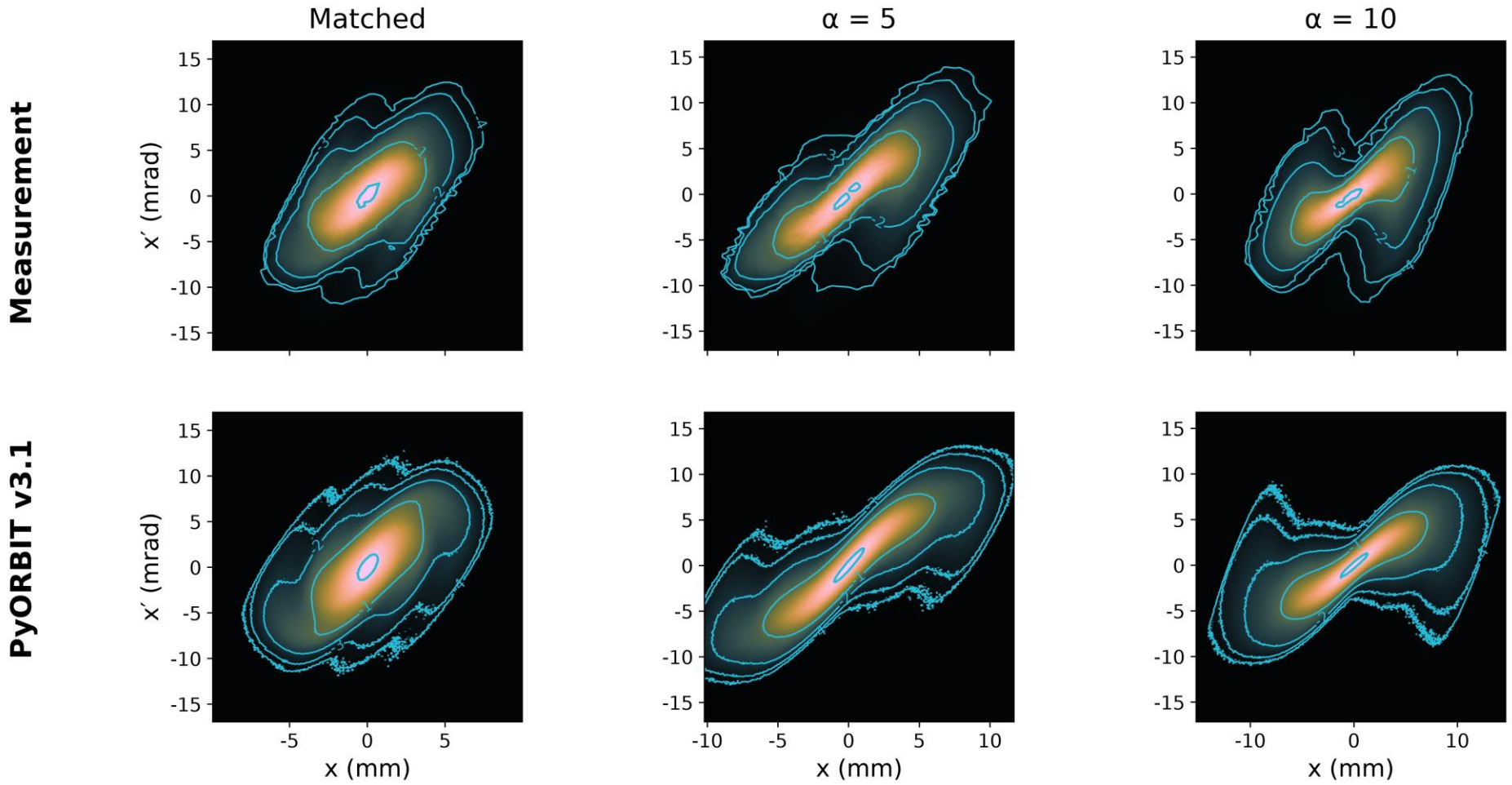
BTF Diagnostics





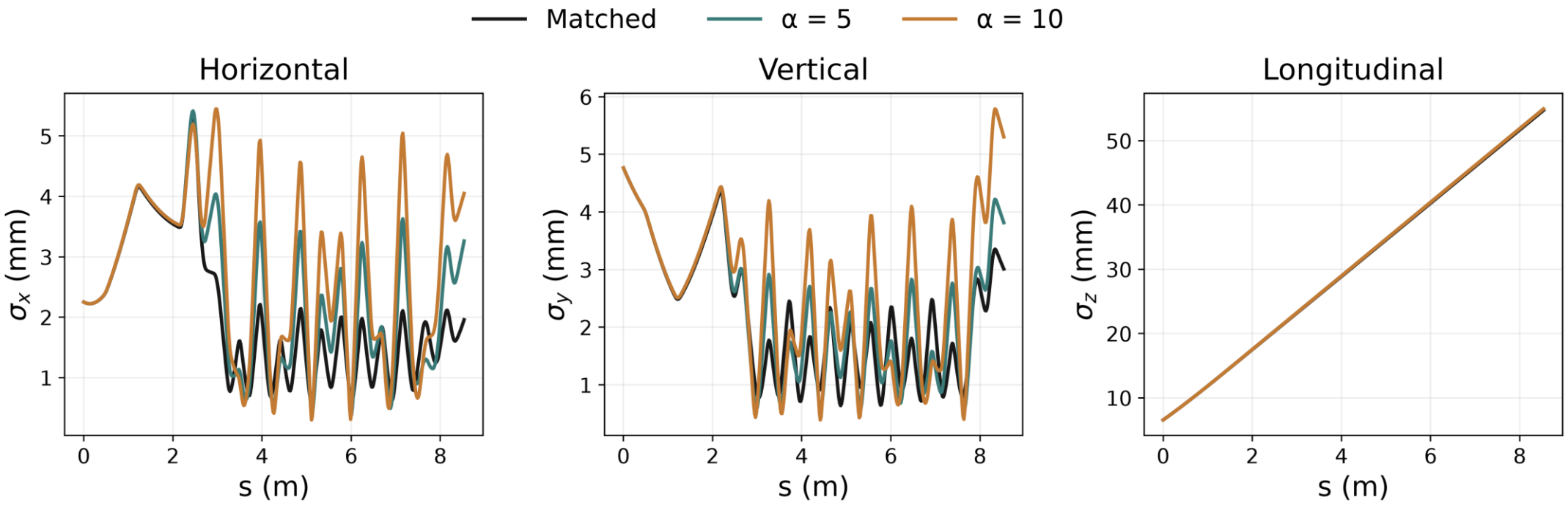
Slit pairs resolve transverse coordinates; the dispersive slit selects energy; the bunch-shape monitor resolves RF phase.

Measurement and model phase spaces



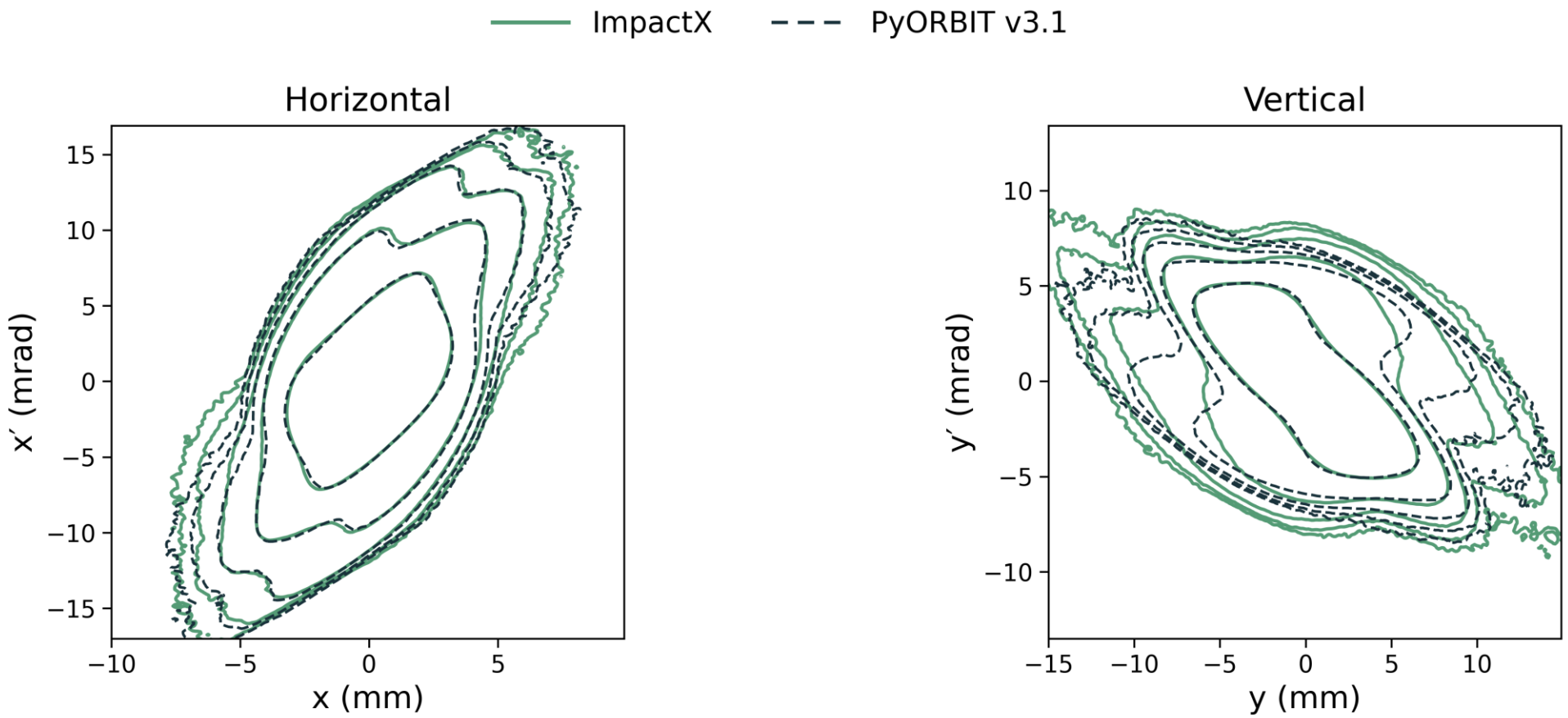
Cyan contours: log10(f / fmax) = −0.05, −1, −2, −3, −4.

RMS beam sizes along the BTF



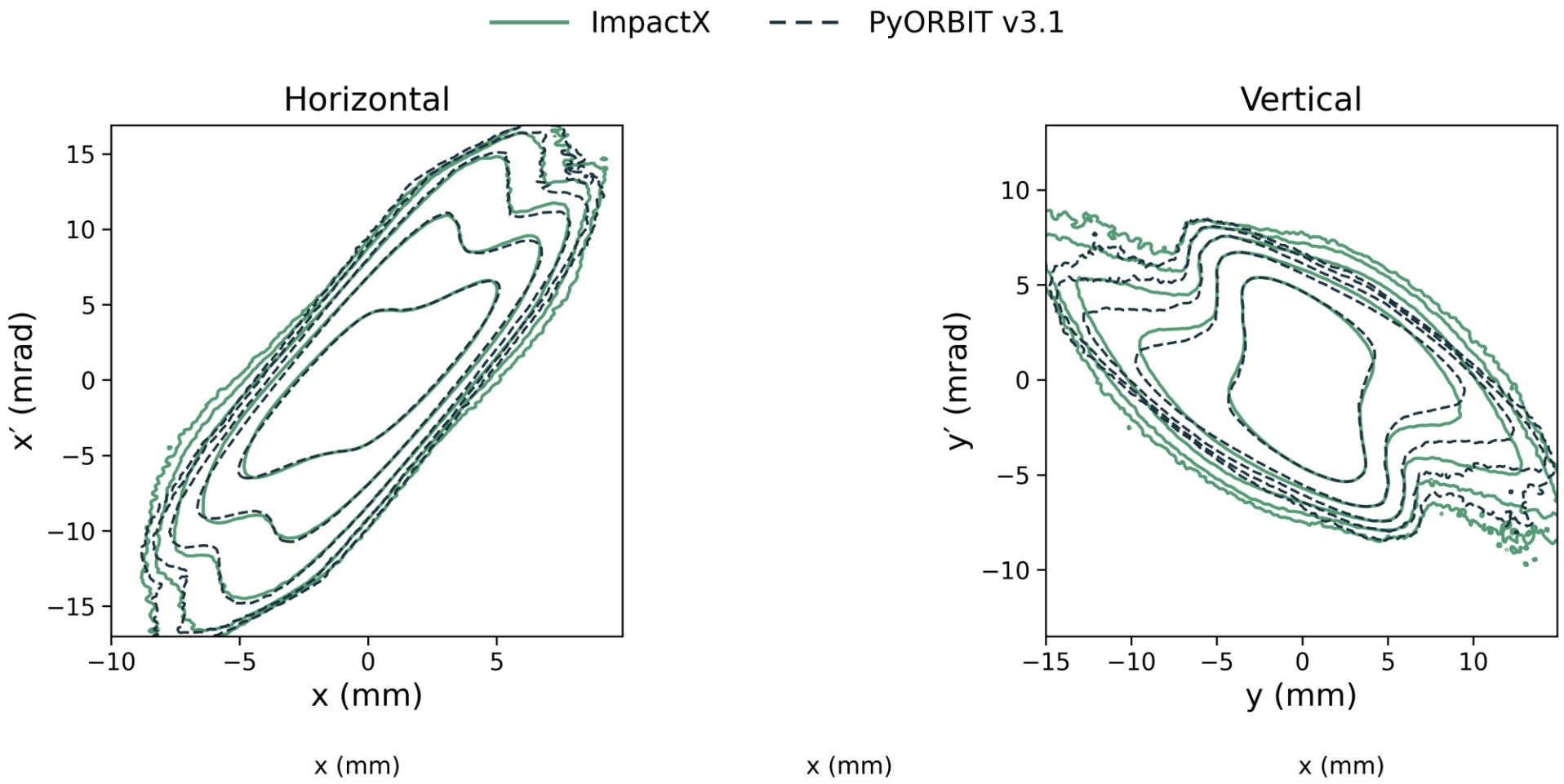
All-soft-edge PyORBIT model for matched, α = 5, and α = 10 optics.

Hard Profiles w/ SC



Hard-edge optics remove the soft-field-profile difference. Residual outer-contour differences remain.

Hard profiles w/o SC

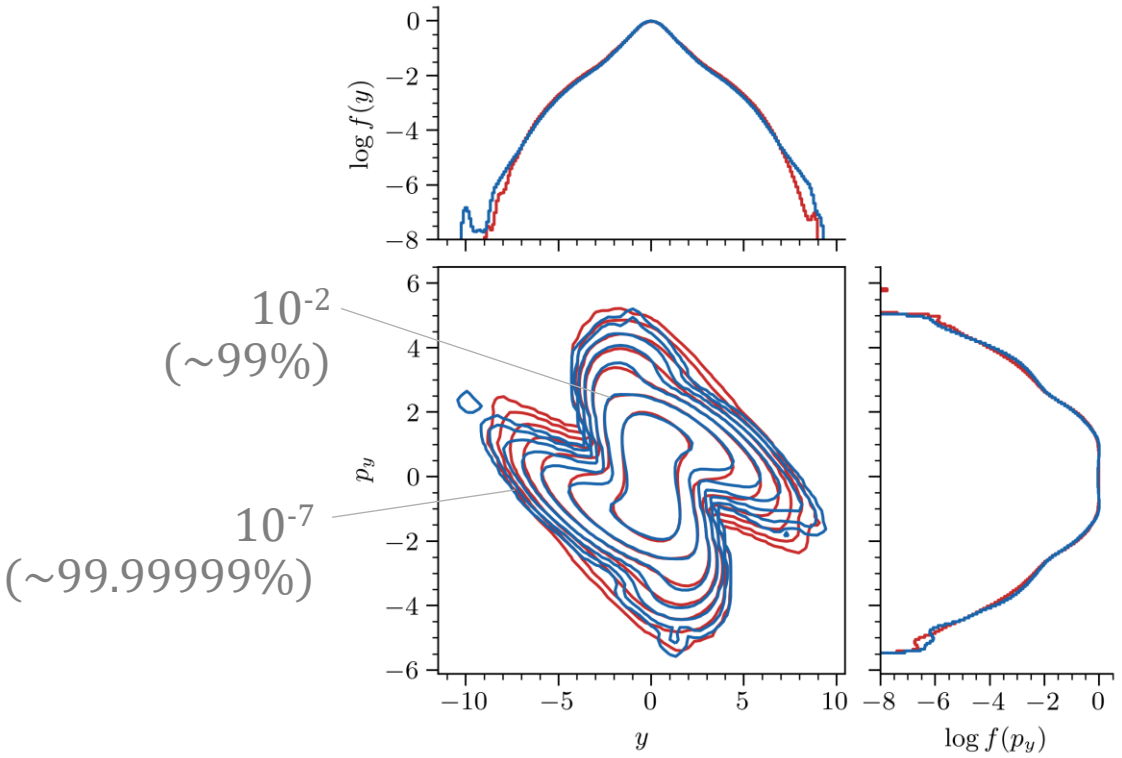


Contour differences remain without the space-charge solve, so space charge is not their sole source.

6D bunch predicted to have small effect

As inferred from simulations with PARMTEQ initial bunch. We have never tracked a bunch based on full-and-direct 6D measurement!

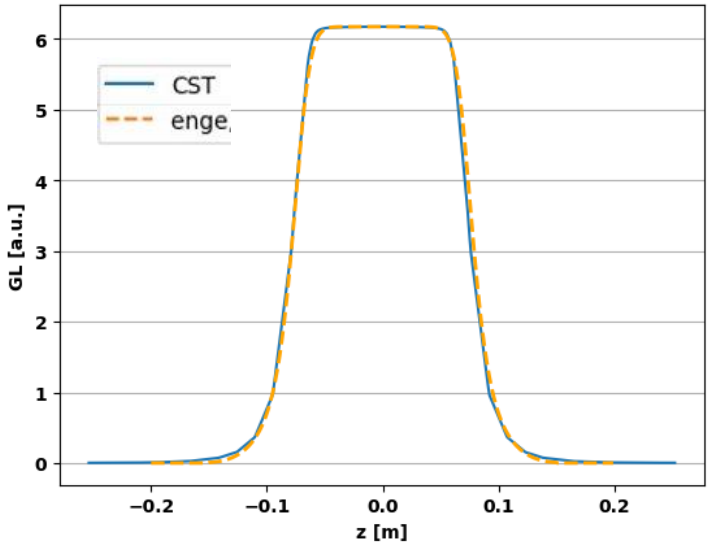
Beam distribution (1D profiles) evolving with/without full 6D beam (simulated):

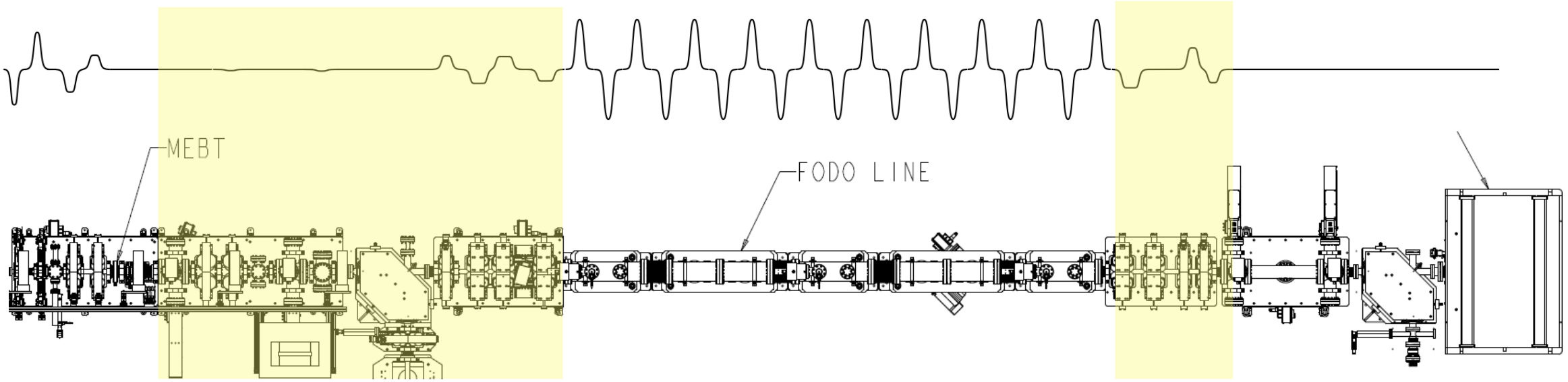


Hoover et al, High Brightness Workshop, CERN (Oct 2023)

Iron-core quadrupole model

- No gridded 3D fields!
- Pure quadrupole field
- Soft-edged profile modeled with Enge function
- Gradient/current curves from rotating coil measurements





Permanent magnet quadrupoles

- Pure quadrupole field
- Soft-edge modeled with analytic expression from Halbach
- $1\sigma \sim .2\%$ in rotating coil gradient measurement



