OAK RIDGE National Laboratory

Exploring Initial Distributions at the Beam Test Facility

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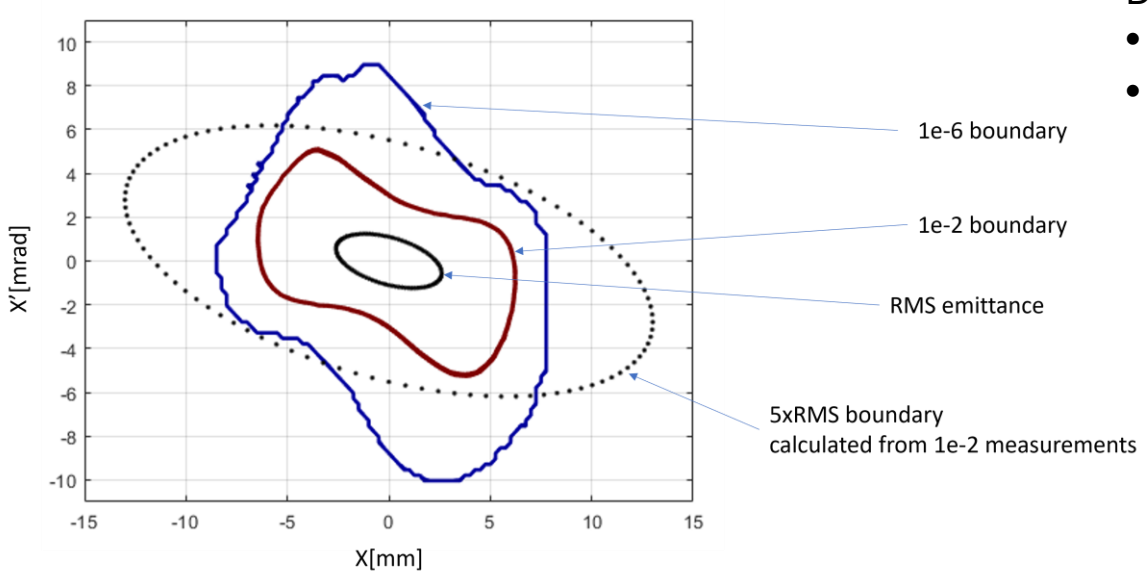
5th ICFA mini-workshop on Space Charge
Oct 25, 2022

ORNL is managed by UT-Battelle LLC for the US Department of Energy

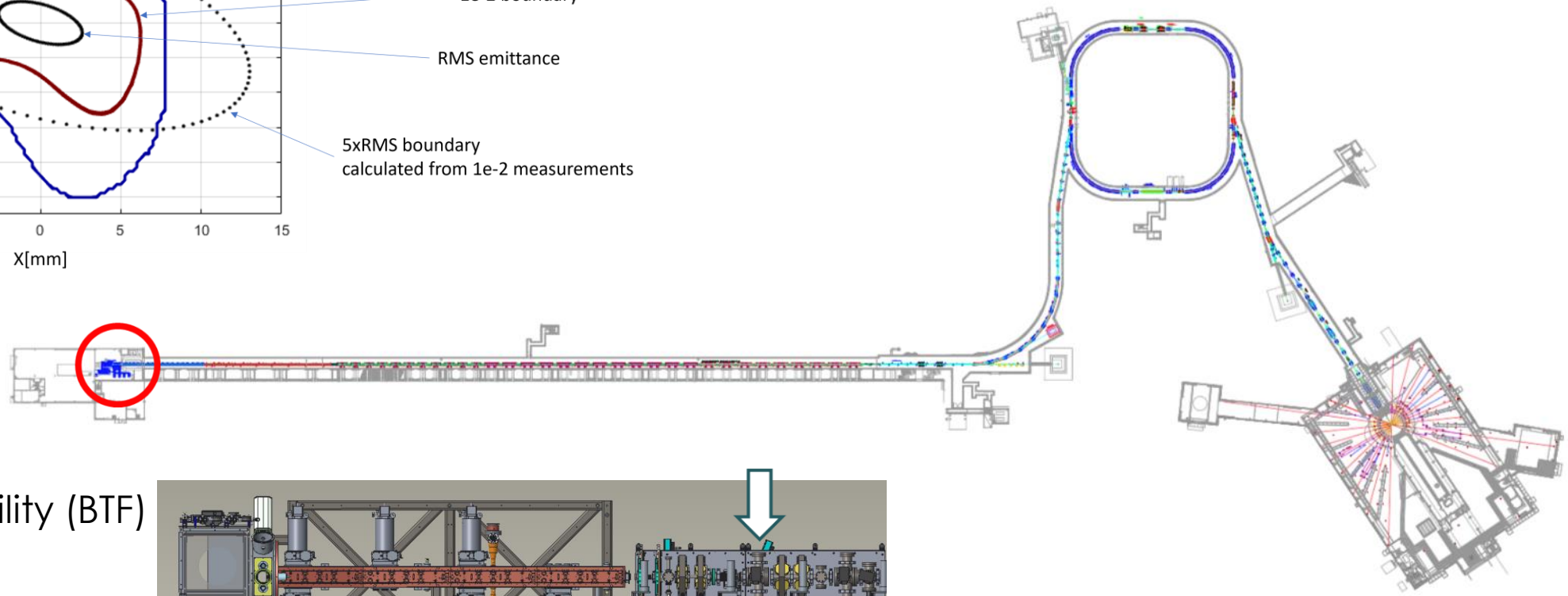
U.S. DEPARTMENT OF ENERGY

Background and Motivation



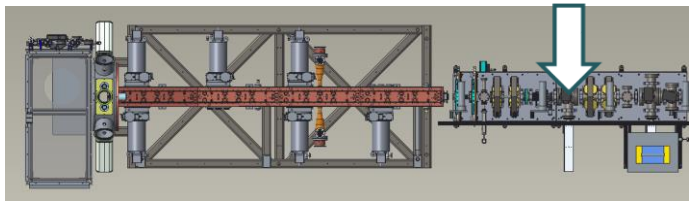
Broad goals:

- predictive modeling for beam distribution with halo
- better understanding of beam losses

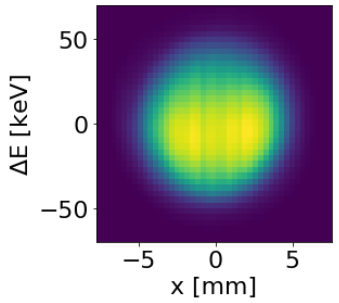


Beam Test Facility (BTF)

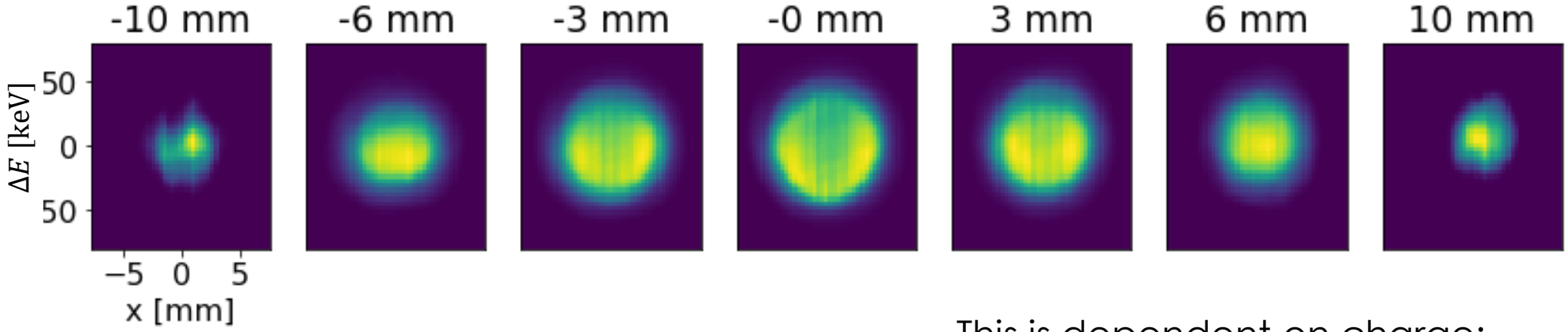
After RFQ, beam core is hollowed

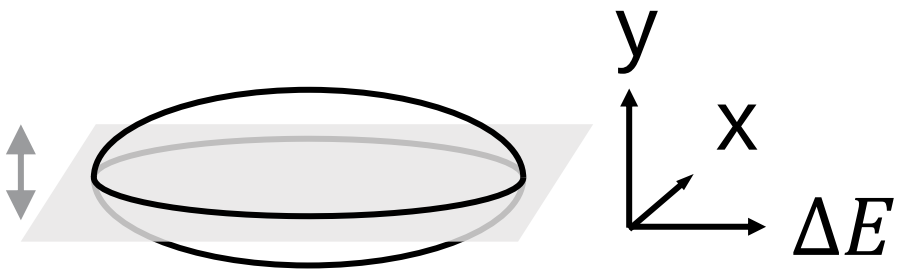


Full projection:

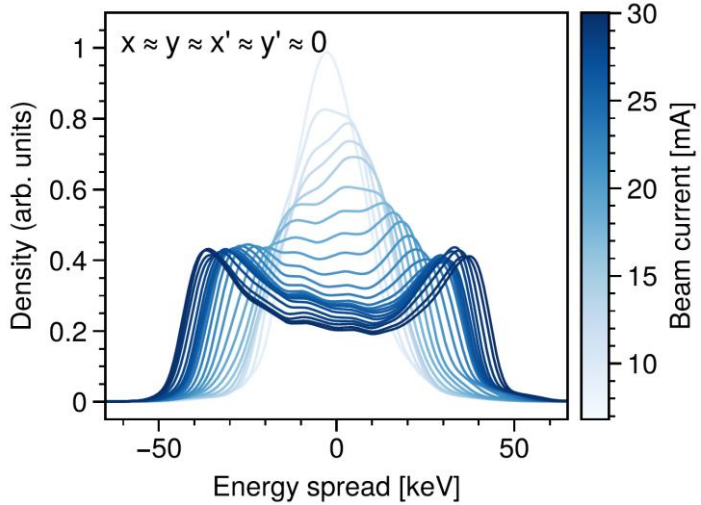


Slices in y:





This is dependent on charge:



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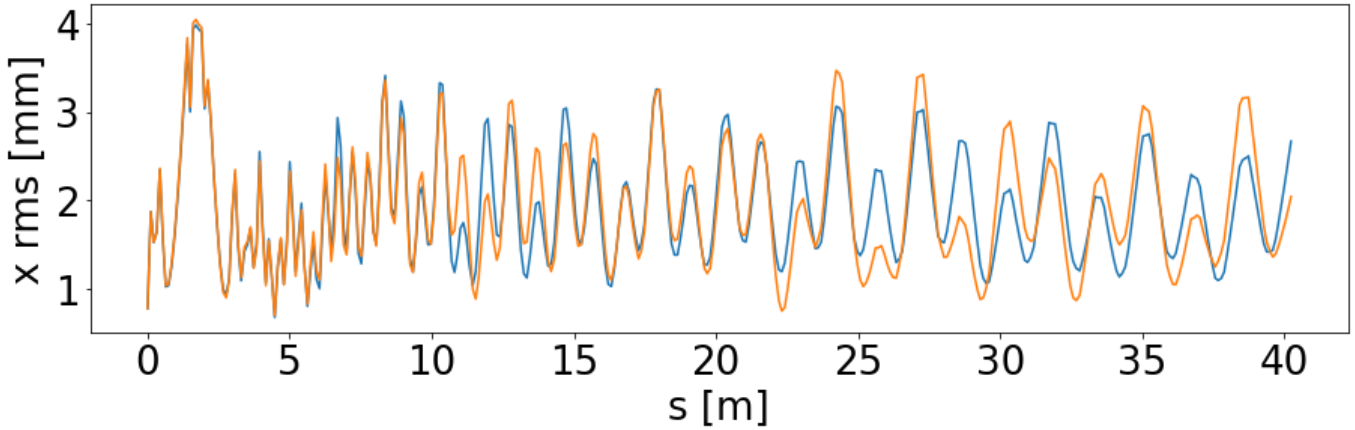
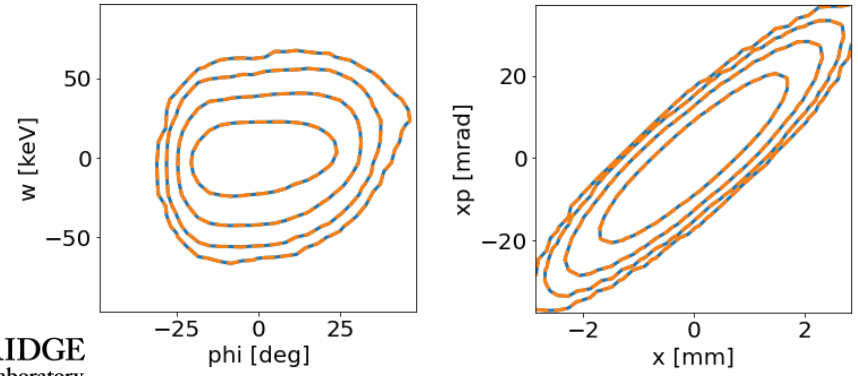
In simulation of MEBT, we predict that neglecting correlations will affect rms sizes and beam shoulders/tails

PyORBIT simulation of SNS linac (MEBT+DTL) **with**/**without** interplane correlation:

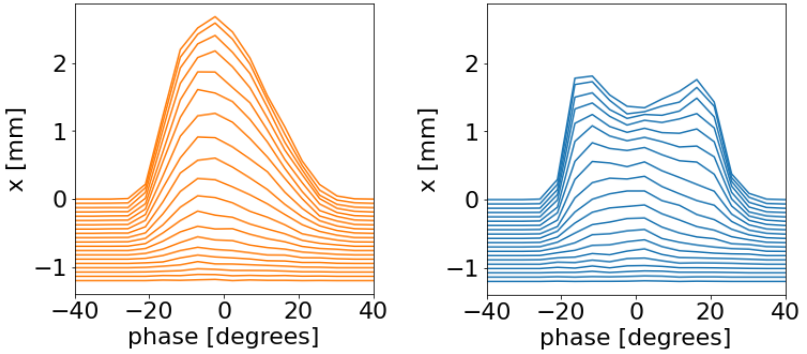


Initial simulation bunch from Parmteq simulation:

Full projections:



Phase distribution for $y=0, x'=0, y'=0$ and $x=x_i$



Fully correlated,
Not fully correlated

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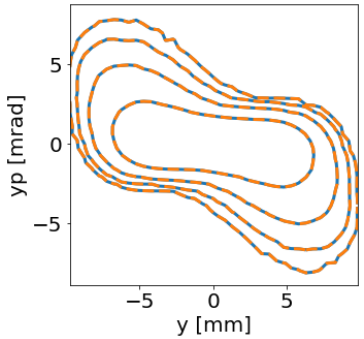
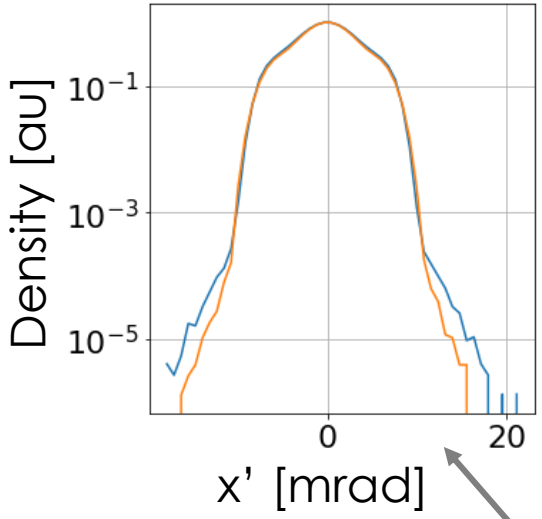
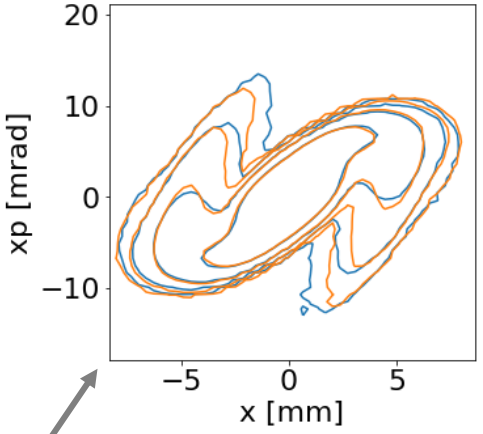
For BTF experiment, we expect effect at 3 orders of magnitude below core density

Initial bunch from PARMTEQ, 8M particles



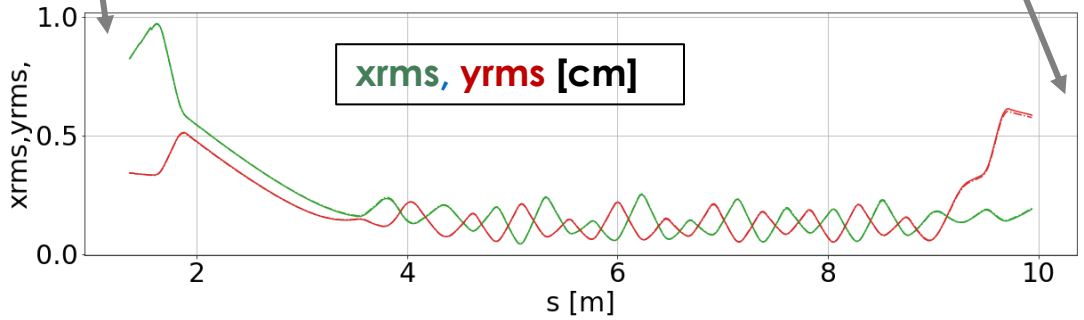


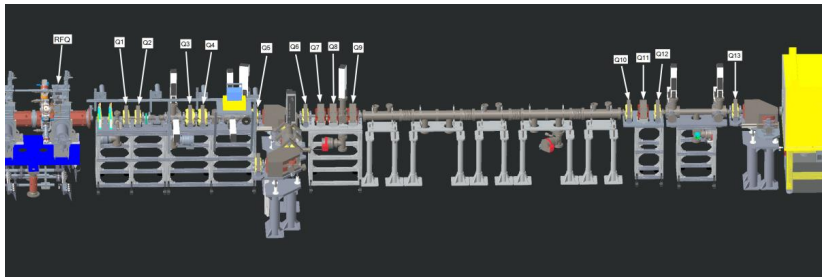


Fully correlated,
Not fully correlated

Contours at 10%, 1%, .1%, .01% of peak

output





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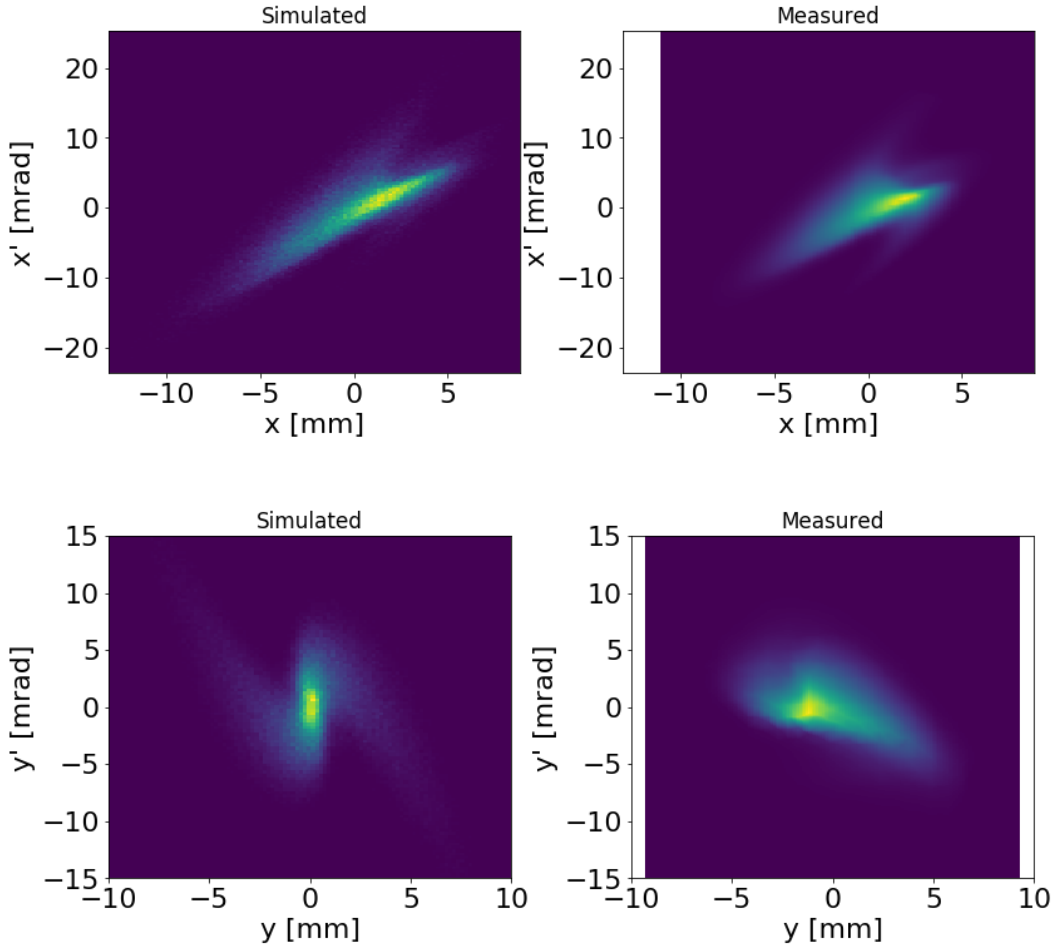
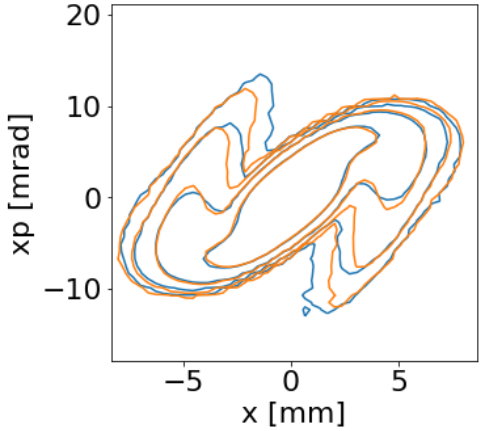
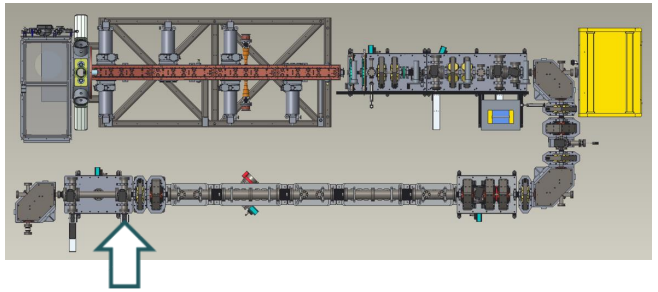
Right now, lattice errors far exceed sensitivity needed to examine effect of 6D





Fully correlated,
Not fully correlated

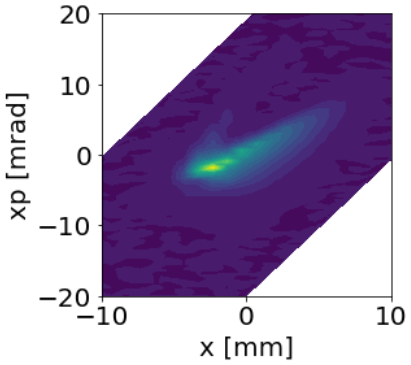
High chromaticity in BTF causes sensitivity to RFQ output energy

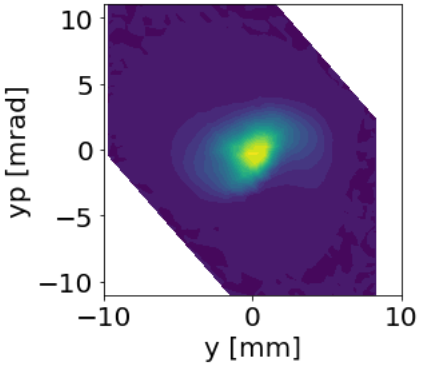


Per FODO cell, $\Delta\nu_{cell} = -0.07 \left[\frac{1}{MeV}\right] \delta E$

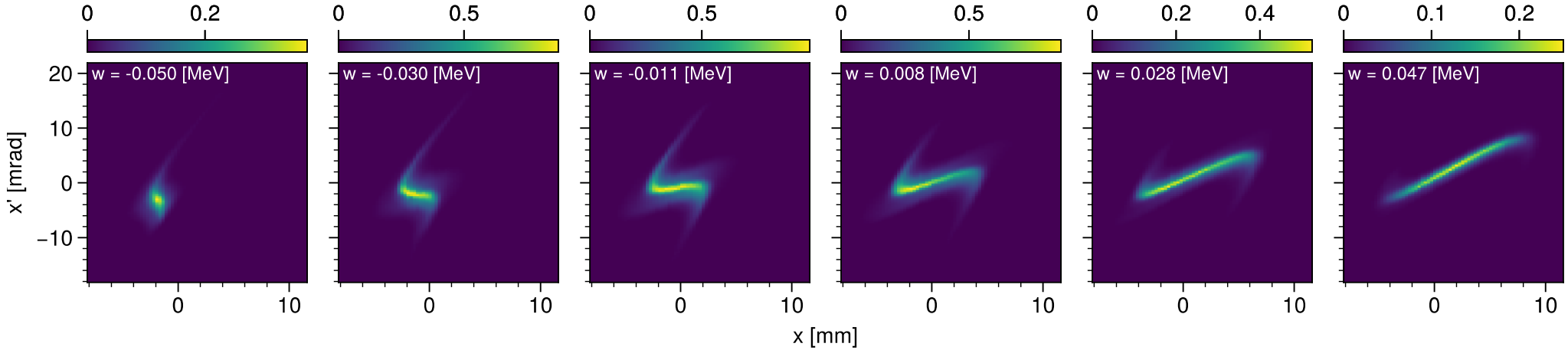
For 50 keV RMS width and 9.5 cell FODO, $\Delta\nu = -12.5°$

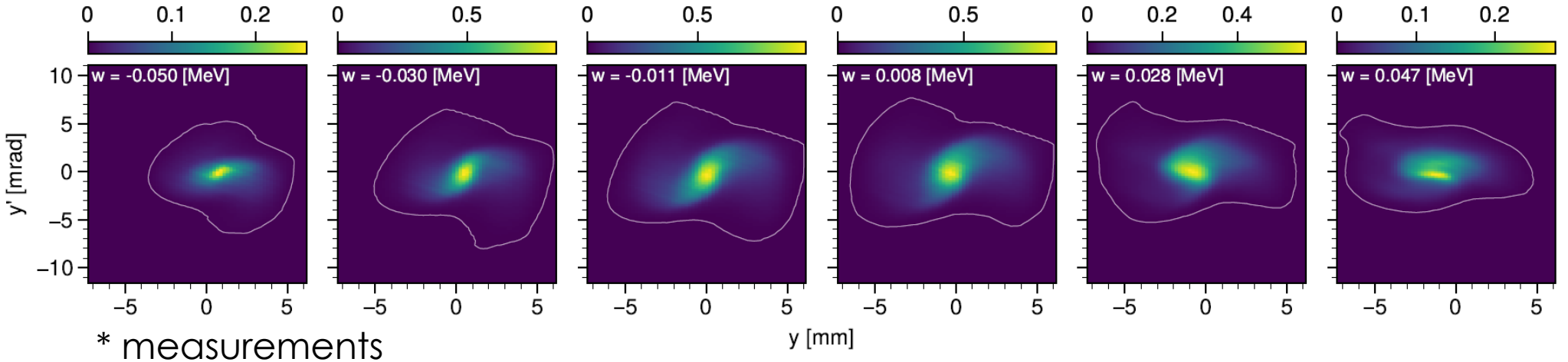
Full projection phase spaces:





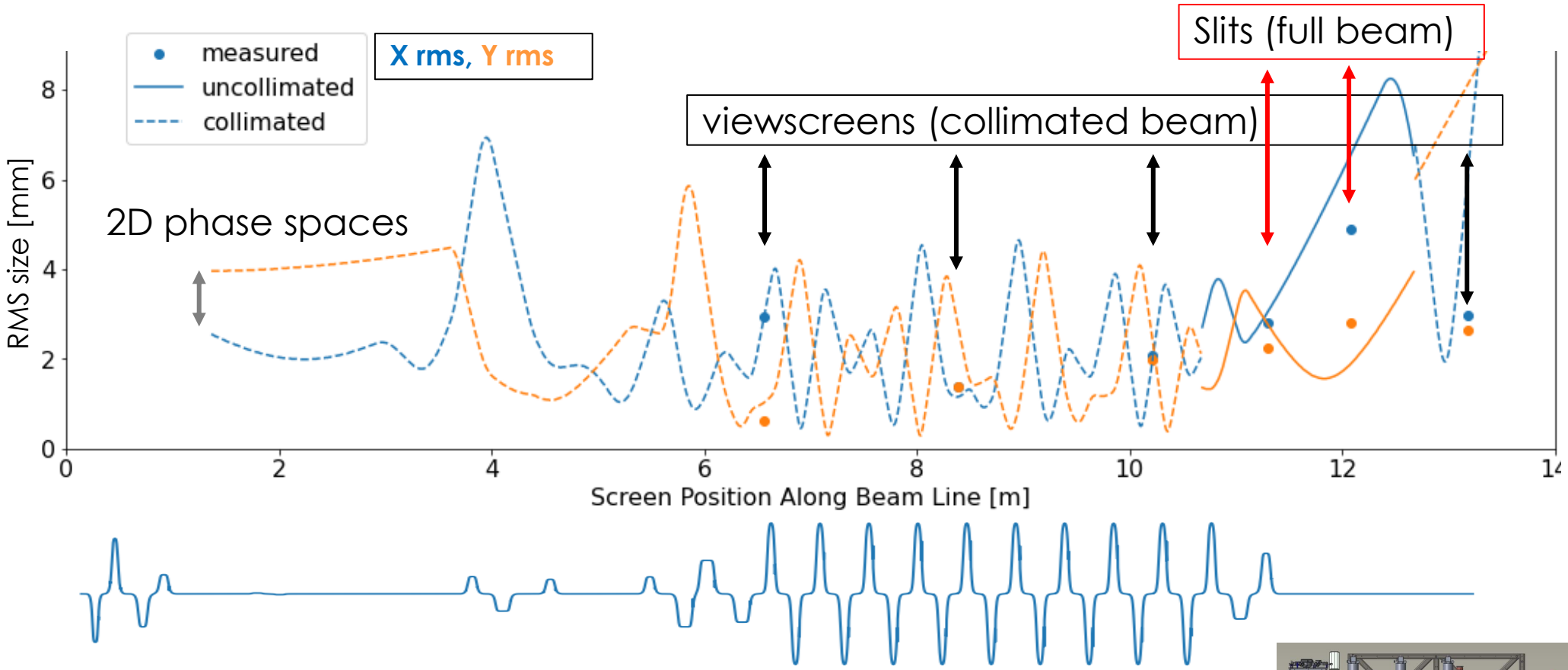
Phase space for different energy slices:

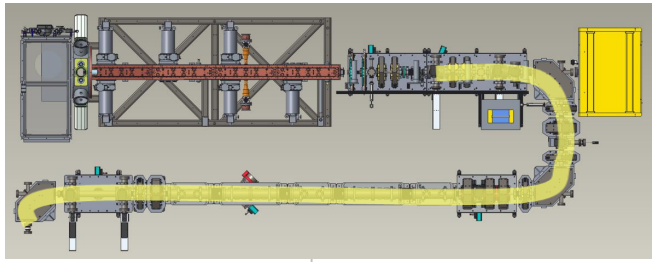




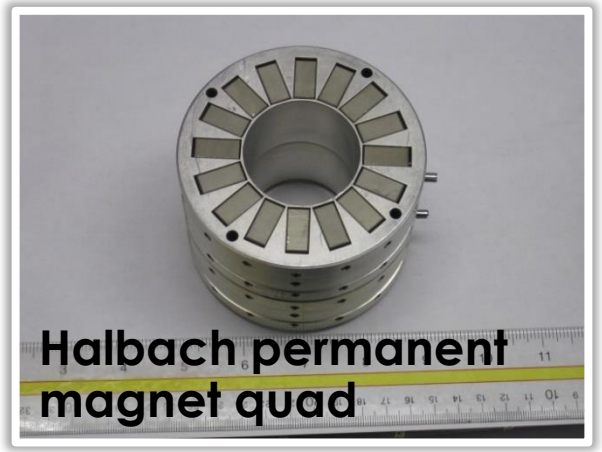
* measurements

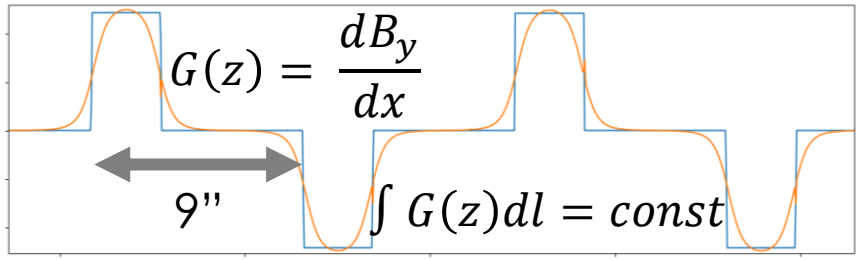
Current benchmark status: there is no RMS agreement

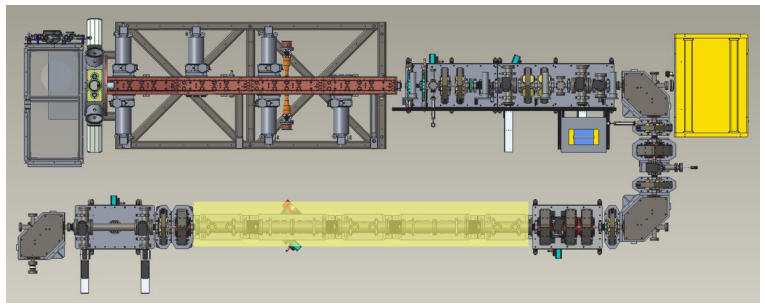


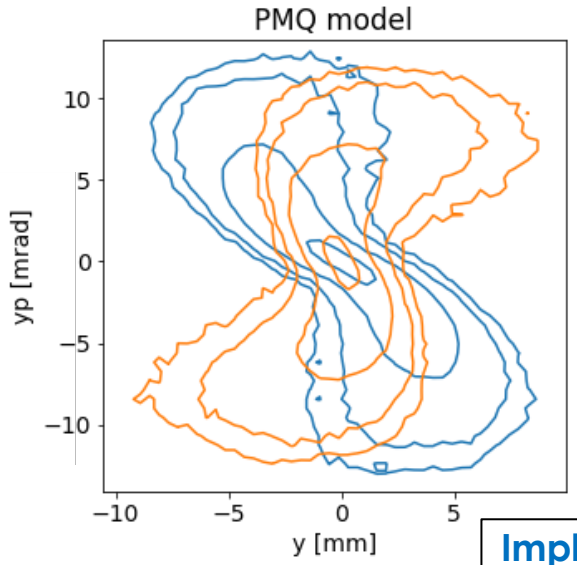


Soft-edged field profiles matters for permanent magnets in FODO section



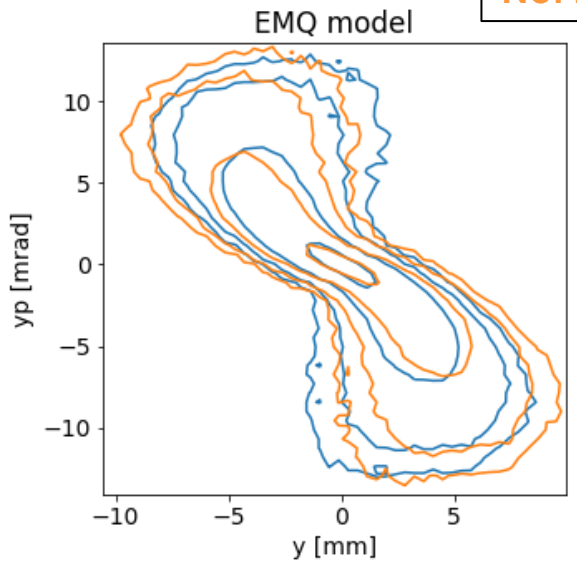






Contours:
60%,
10%,
1%,
.1% of peak

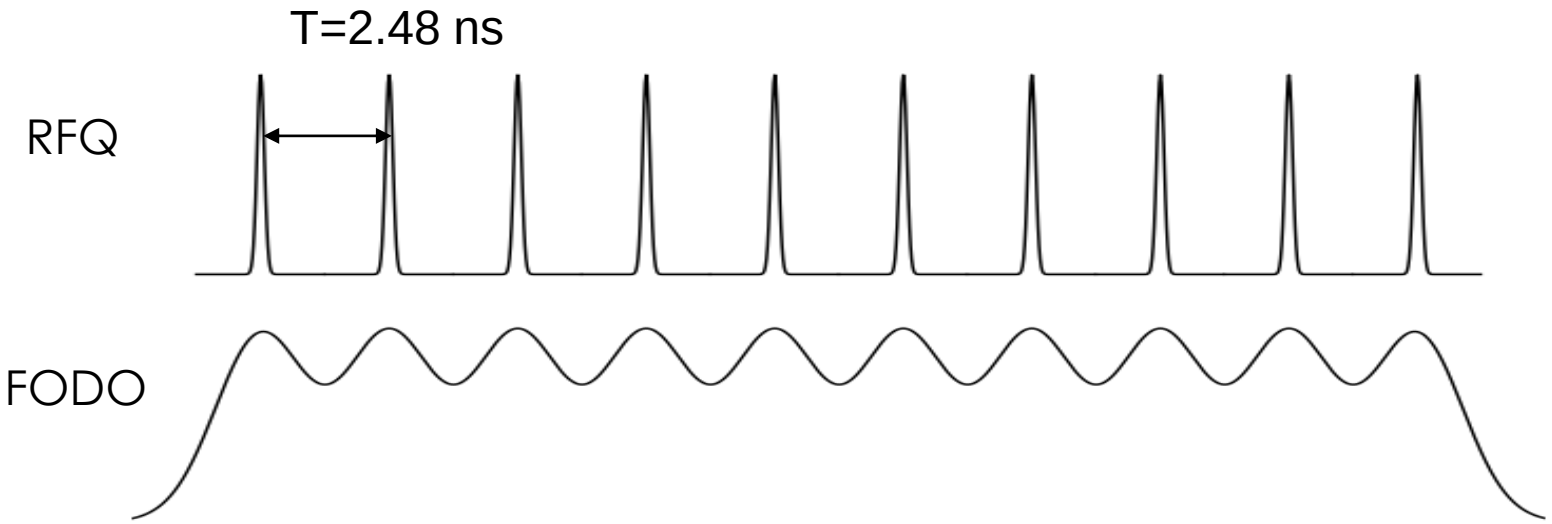
Implemented,
Not implemented

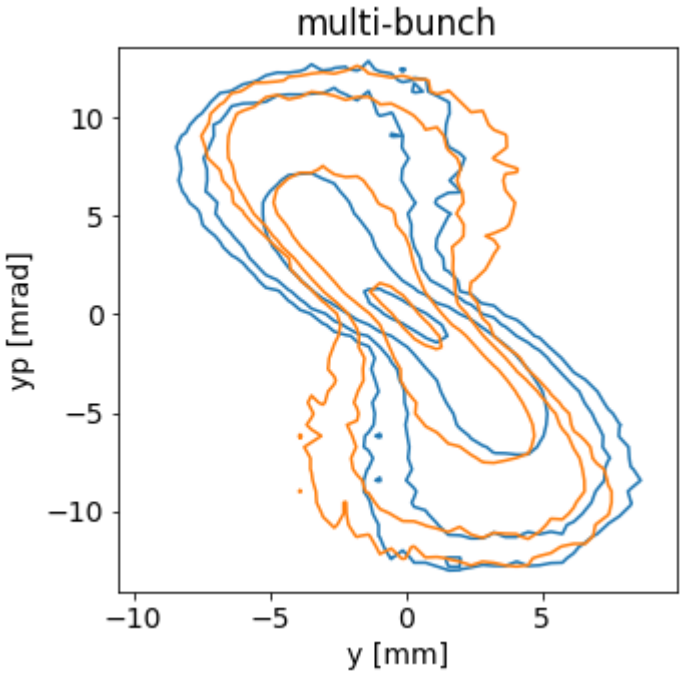


We still (mostly) trust hard-edged model for electro-magnet quads! Are we wrong?

Py-orbit multi-bunch solver is required to get space charge right,

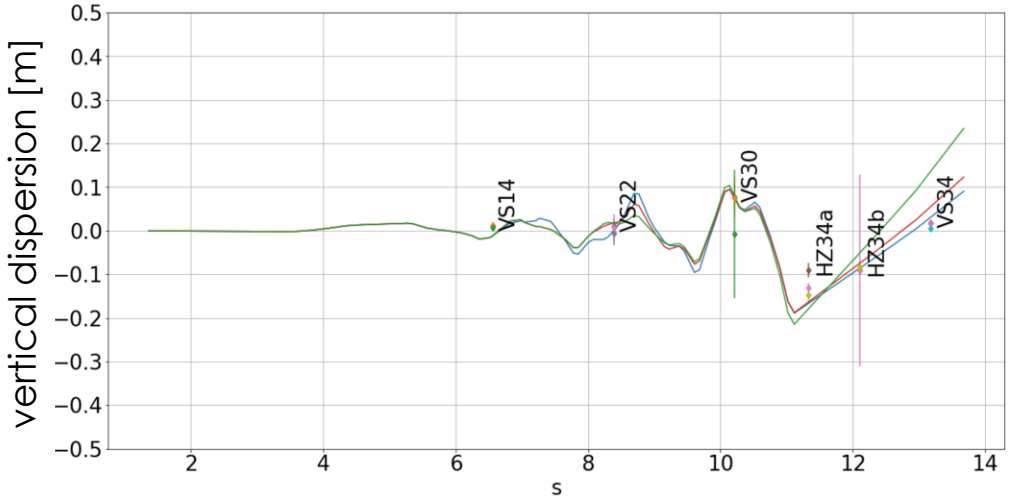
Beam rms width at FODO entrance > 180°

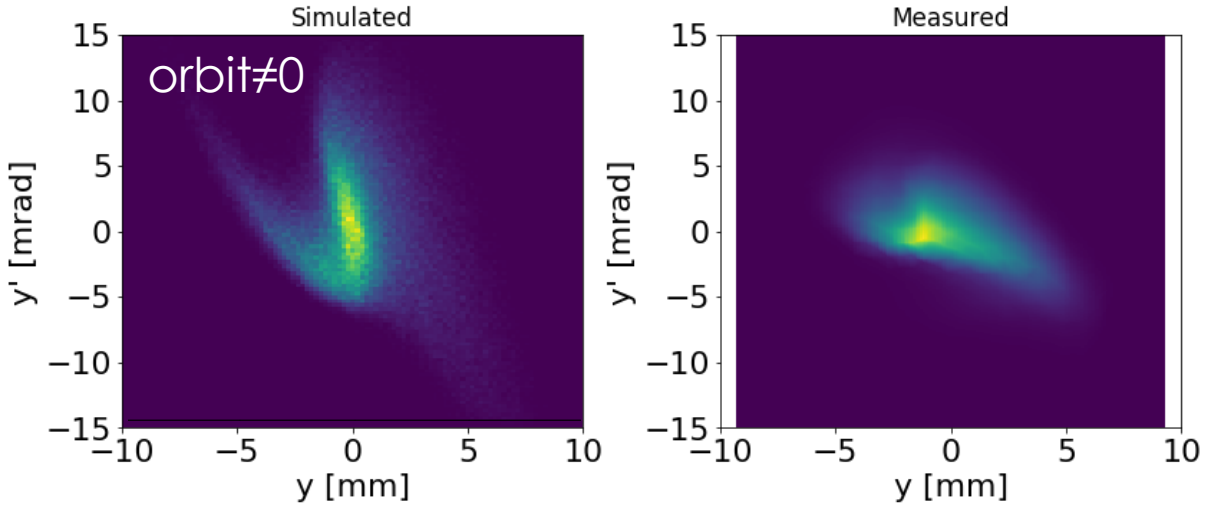


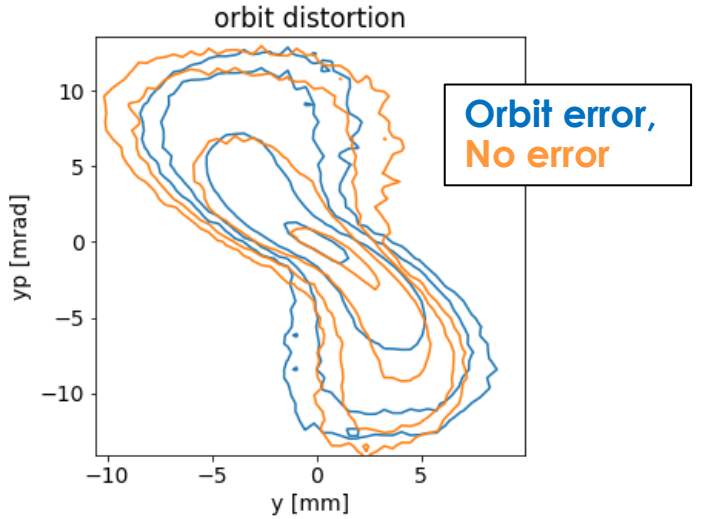


Implemented,
Not implemented

Residual vertical dispersion explains asymmetry in vertical phase space







Summary #1

- Motivation: predicting halo extent
- Initial bunch: core-hollowed due to nonlinear space charge
- Status: Lattice model errors exceed distribution errors

- Ranked importance:
  - Field profile for PM quads
  - Overlapping bunches
  - Dipole model?
  - Residual dispersion
  - Energy, via chromaticity
  - Field profile for electromagnet quads
  - 6D initial distribution

Summary slide, 5th ICFA mini-workshop on Space Charge
Theme: Bridging the gap in space charge dynamics

Summary:
This talk presented a study of the initial distribution and transport of (up to) 50 mA, 402.5 MHz H^- bunches at the SNS Beam Test Facility. The purpose of this work is to demonstrate prediction of beam halo + halo losses

From your perspective, where is the gap regarding space charge effects?
The gap is in our ability to predict beam evolution *with space charge* with desired accuracy

What is needed to bridge this gap?
(1) Careful validation of models, including initial beam distribution
- Sufficient diagnostics
- efficient methods for calibration and error identification

(2) Responsive simulation development (e.g., multi-bunch solver)
(3) Other effects for linacs: Cavity models, longitudinal dynamics

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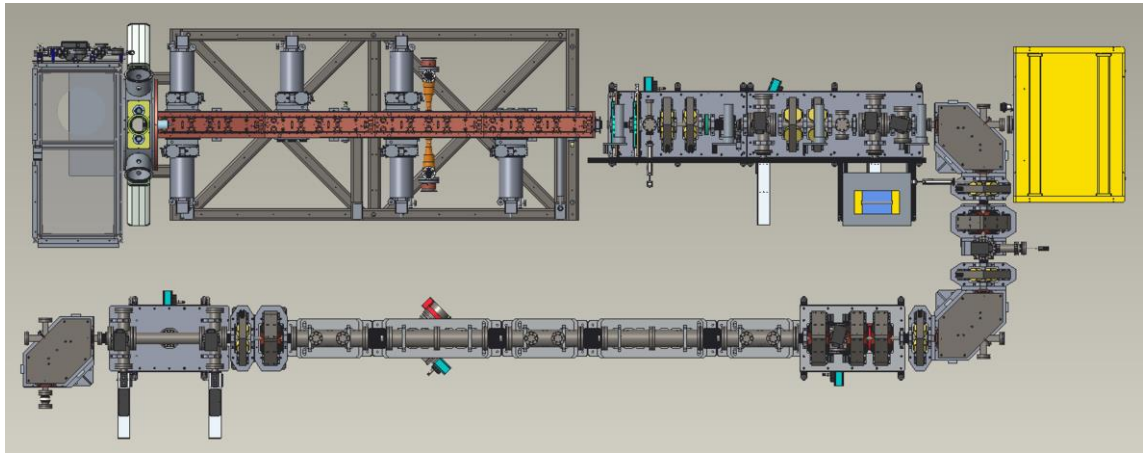
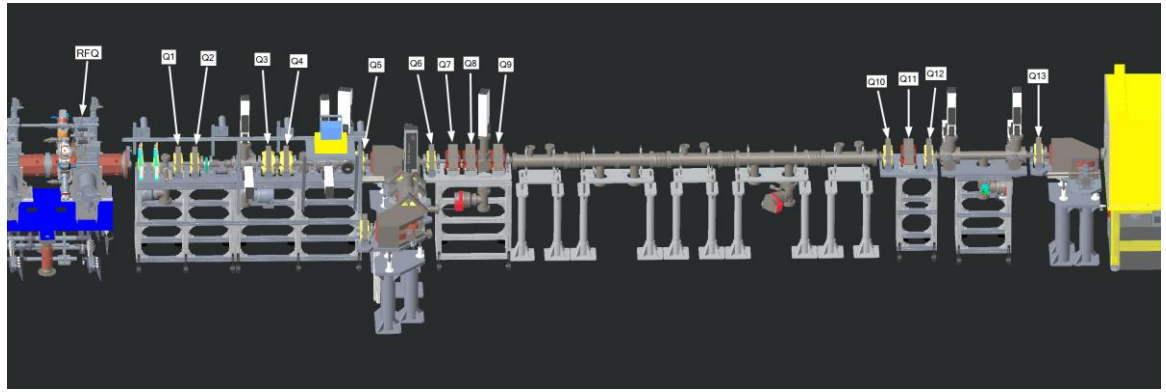
Backup

Project Status

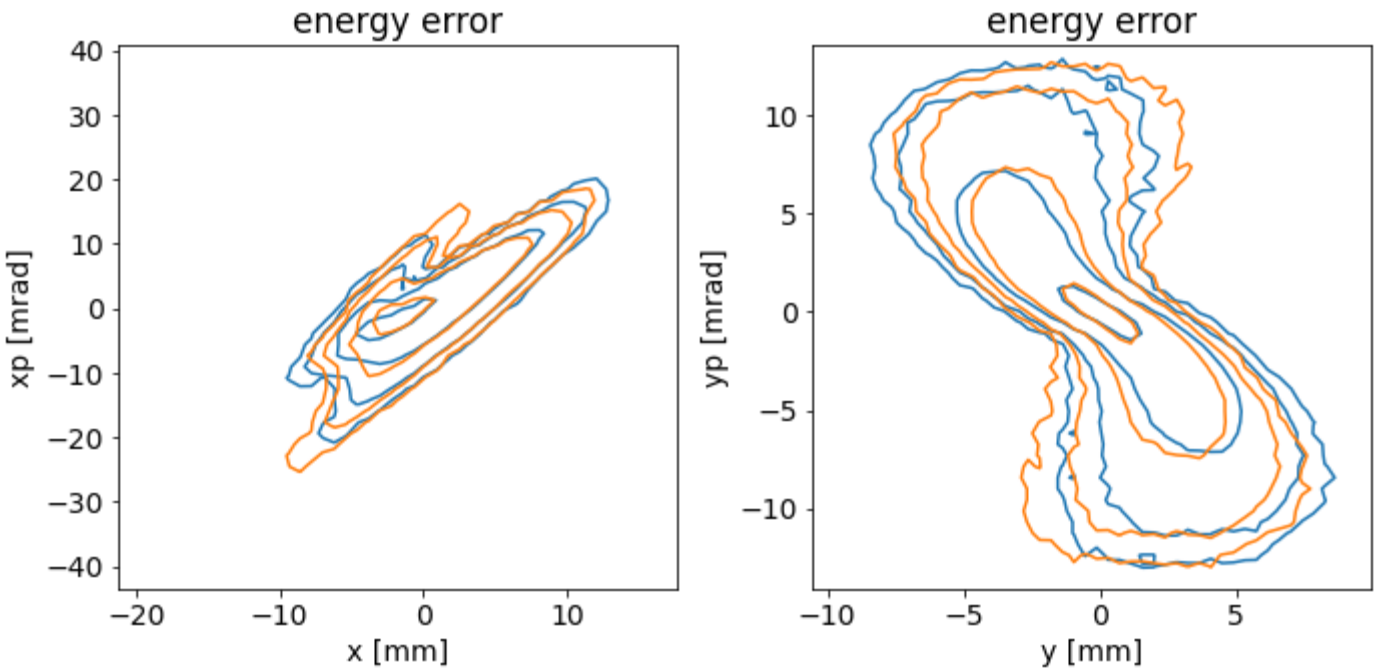
- Shutdown August 2022
- New RFQ commissioning
  - ~Nov 2022
- Straight BTF in 2023

Species	H^-
Energy (MEBT)	2.5 MeV
Energy (LEBT)	65 keV
RFQ	449 cells 402.5 MHz
Beam current	Up to 50 mA



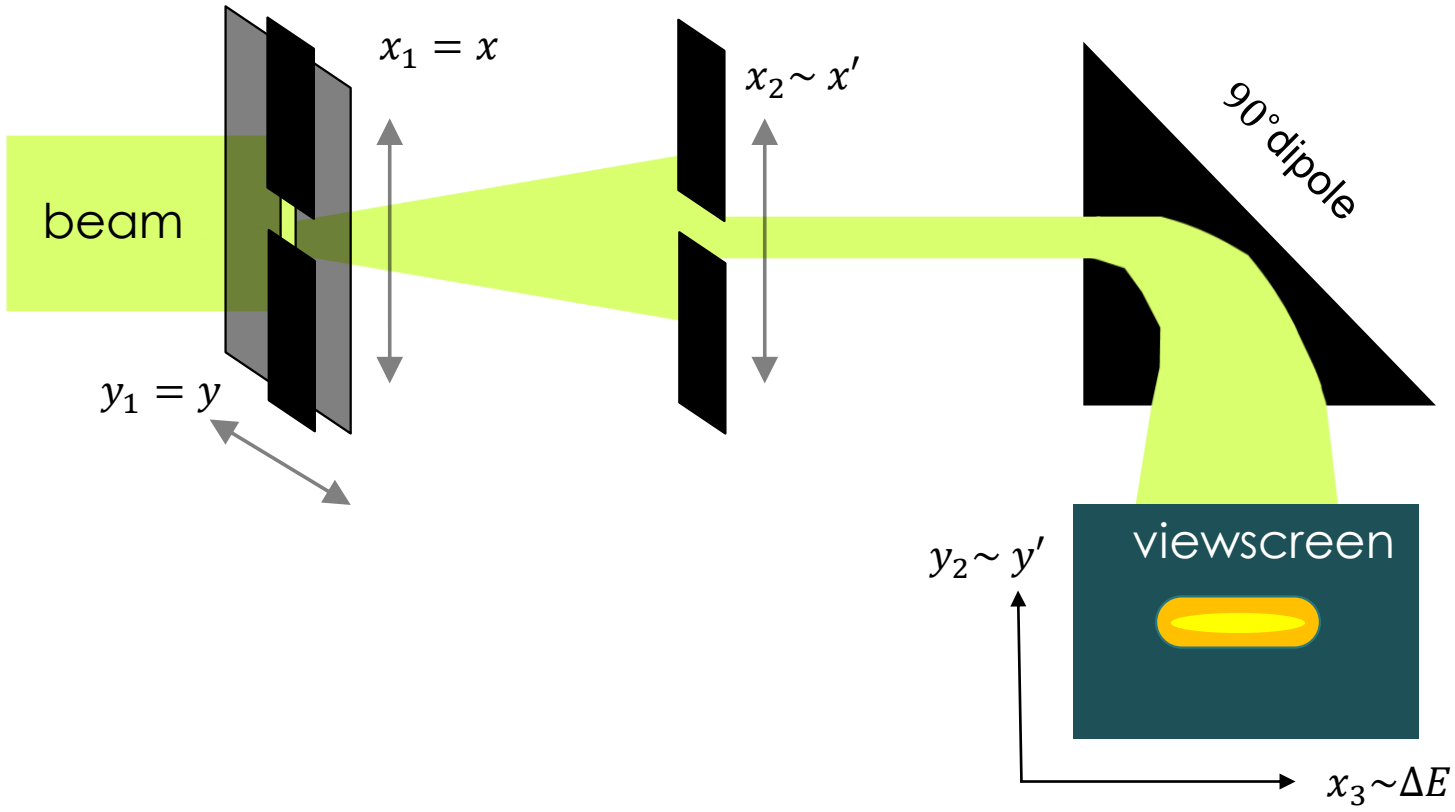


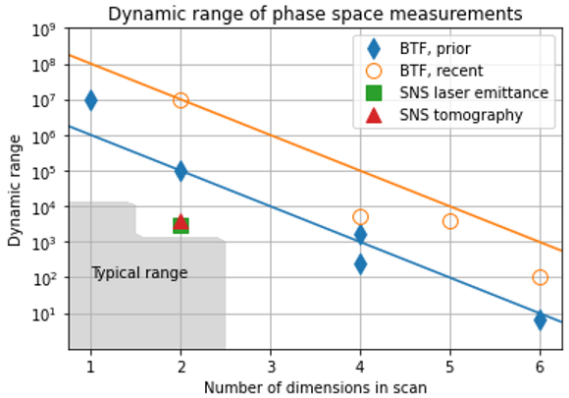
Energy error (chromatic effect)



Orange is 2.5 MeV-20 keV
Blue is 2.5 MeV

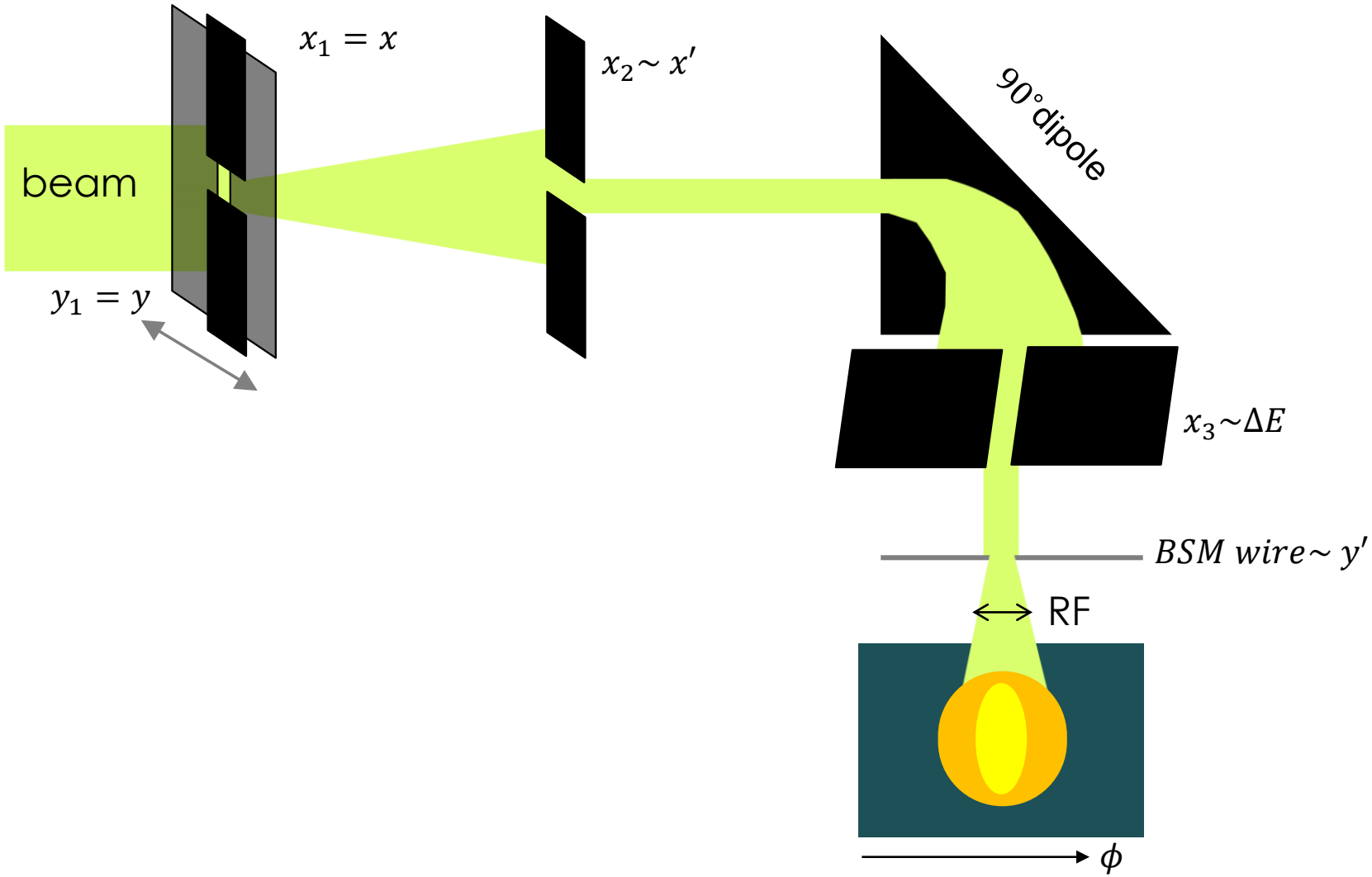
5D method





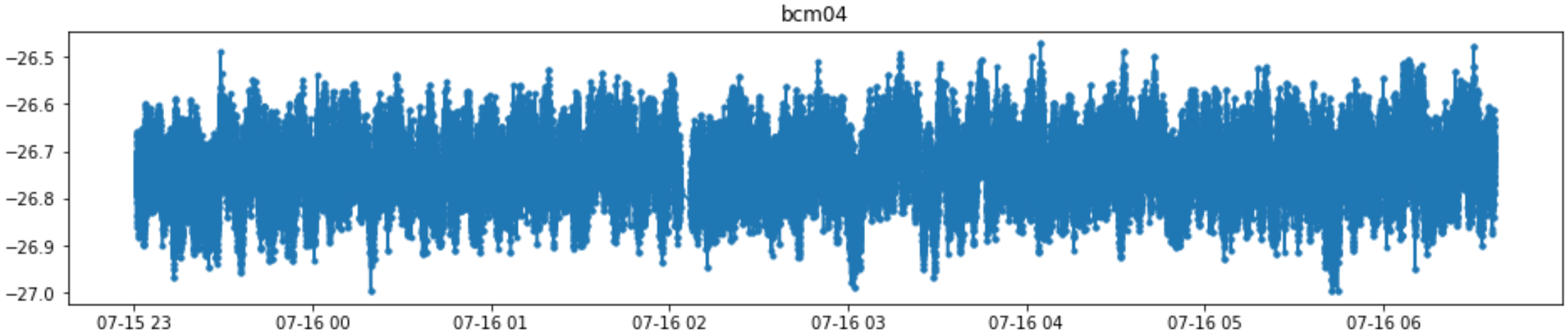
6D apparatus

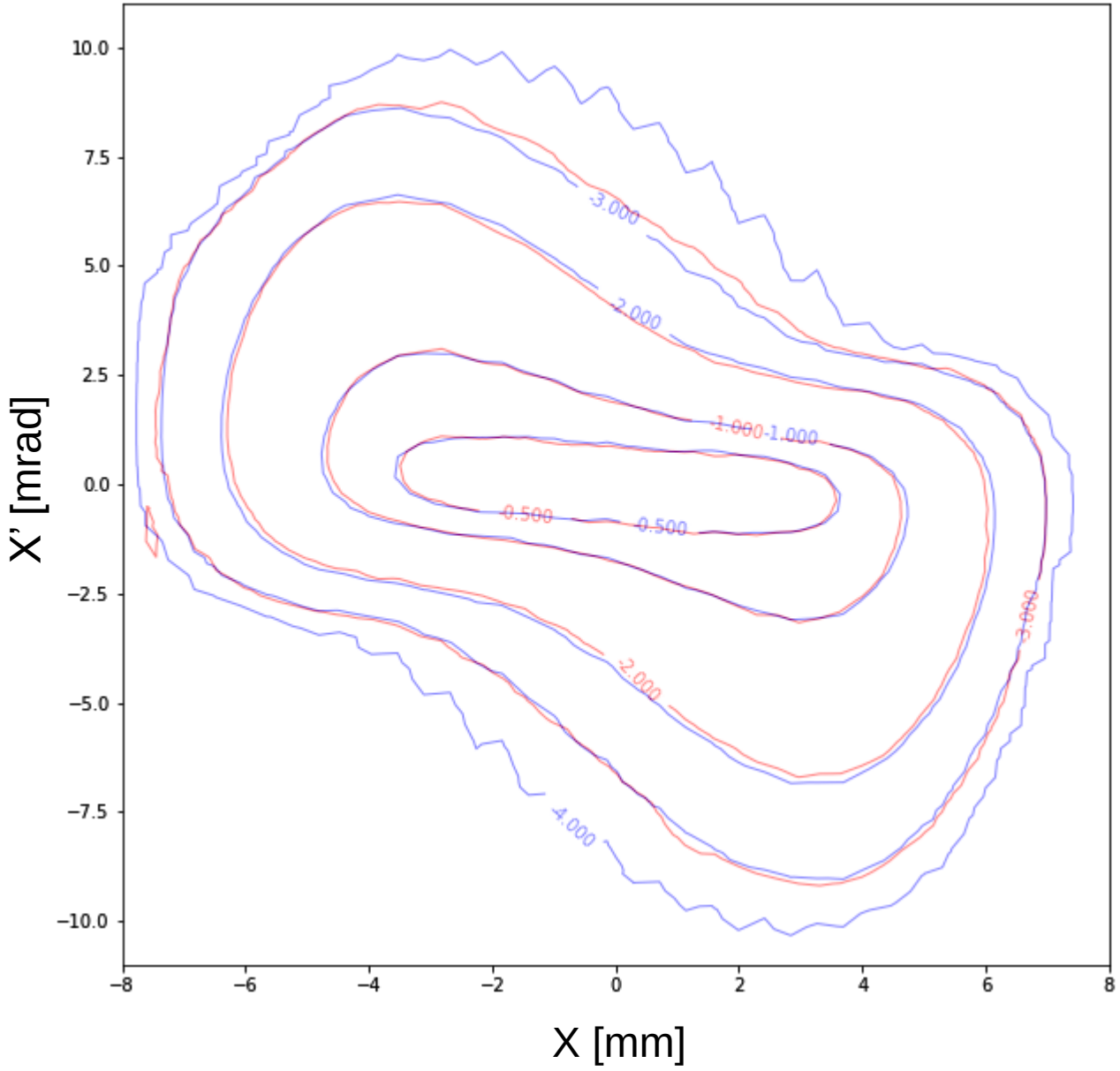
grid 9x 9 x 9 x 9 x 9 x 512, ~24 hours



Beam current during 7.6-hour scan

average BCM current = -26.73 +- 0.06 mA





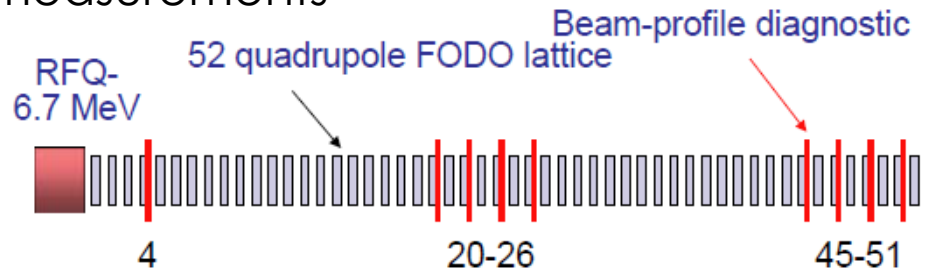
Comparison of 2 datasets taken 2 weeks apart

5D scan (integrated along other 3 dimensions)
7.6 hours

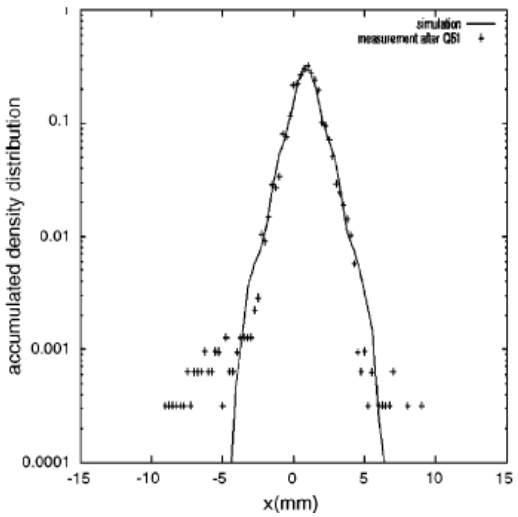
2D scan
~15 minutes

BTF follows footsteps of earlier attempts to benchmark medium-energy beam evolution

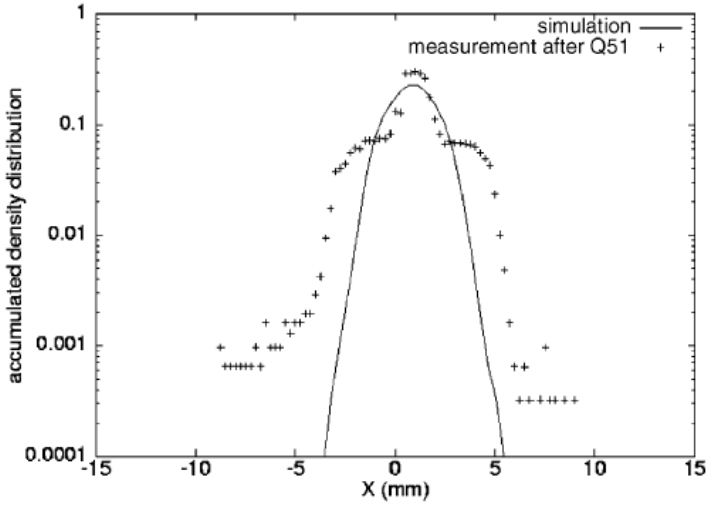
LEDA @ LANL: extensive simulations aimed at benchmarking halo evolution measurements



matched



mismatched



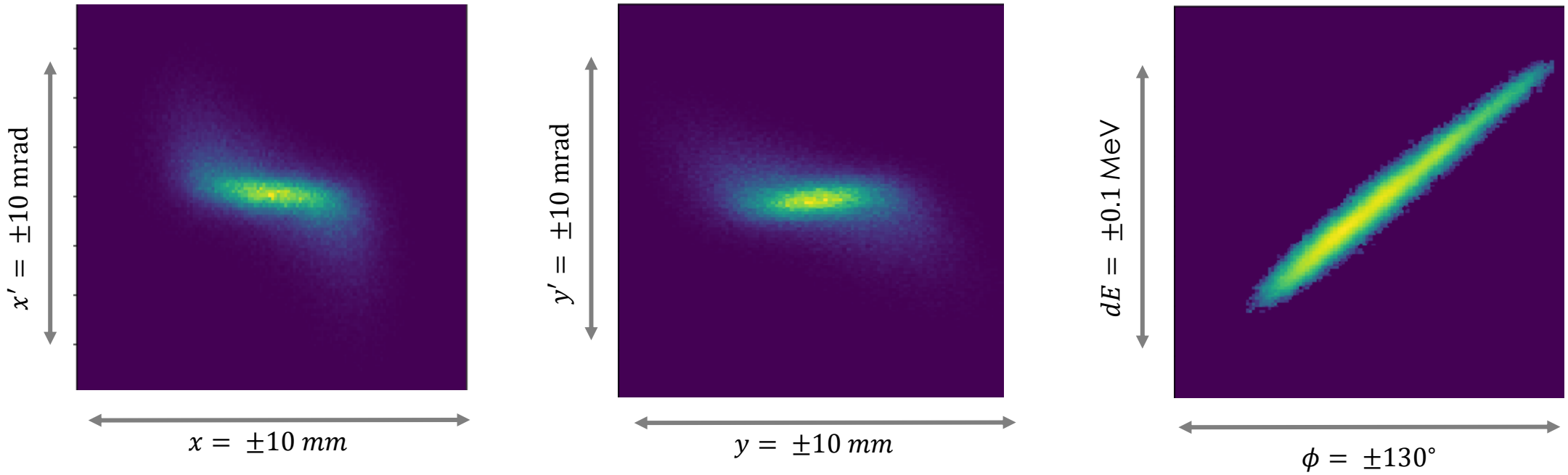
Qiang, J., Colestock, P. L., Gilpatrick, D., Smith, H. V., Wangler, T. P., & Schulze, M. E. (2002). Macroparticle simulation studies of a proton beam halo experiment. *Phys Rev ST-AB*, *5*(12), 35–47 .

Simulations of high-intensity ion front-ends benchmarked to RMS agreement but cannot reproduce tails/halo.

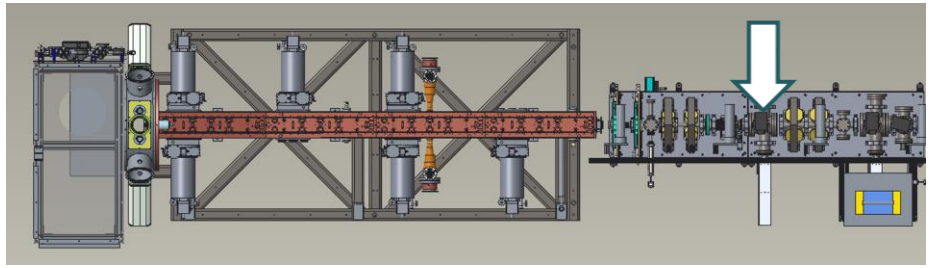
Hypothesis: Limited knowledge of initial distribution to blame for discrepancies

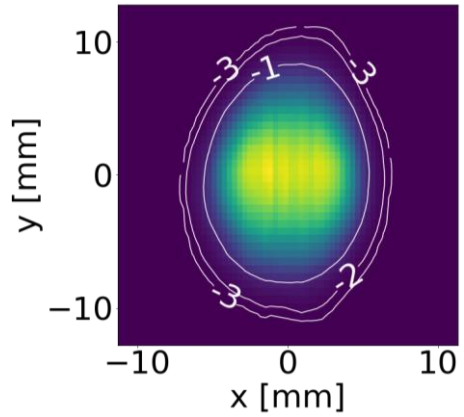
Typical input distribution based on 2D projections

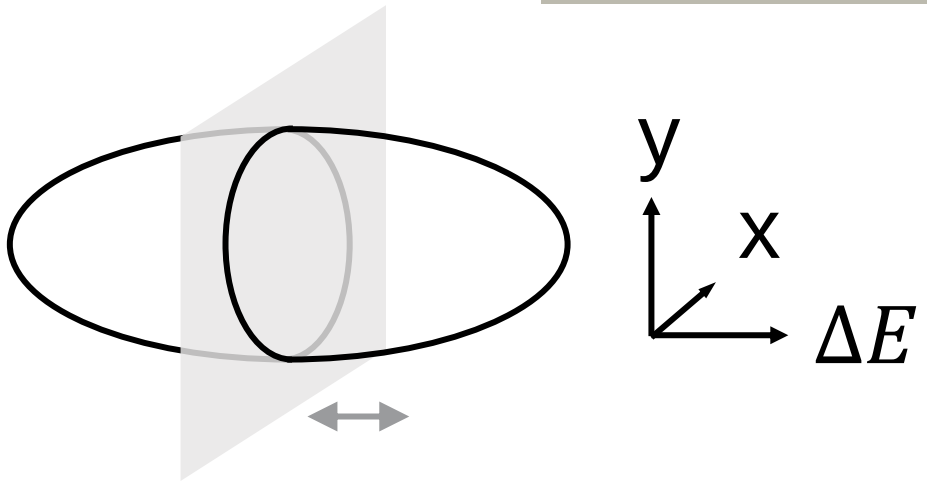
Assumption: $f(x, x', y, y', z, dE) = f(x, x') * f(y, y') * f(z, dE)$

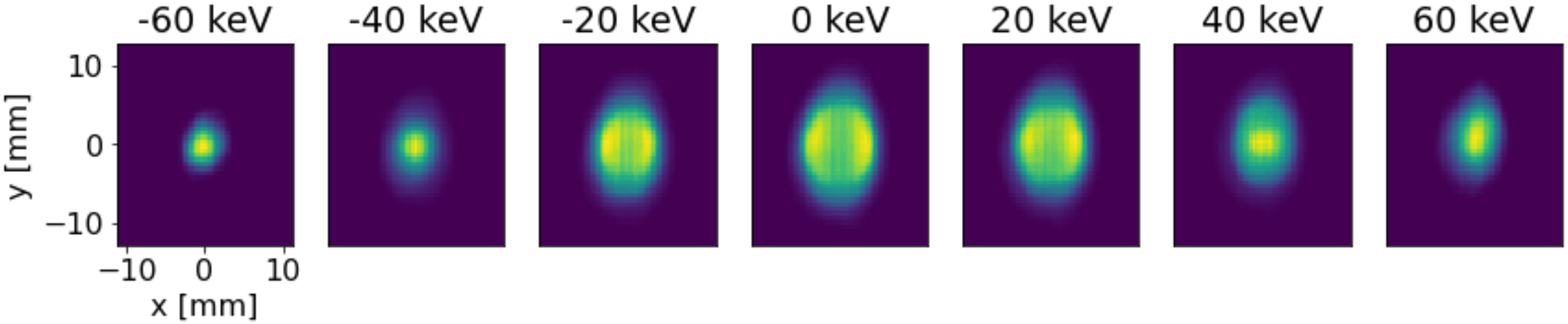


After RFQ, core is hollowed









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Initial bunch
from PARMTEQ,
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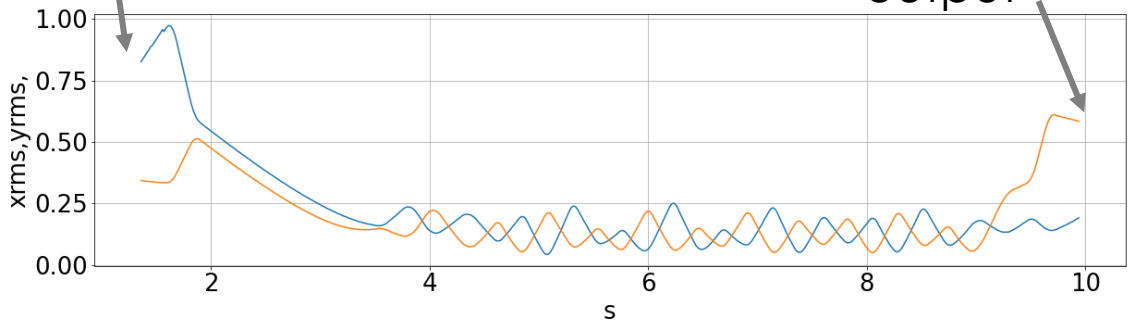
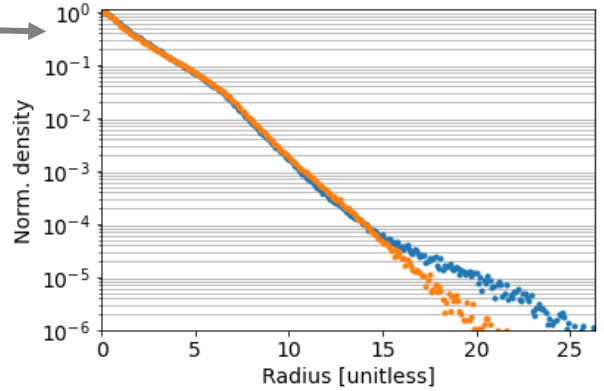
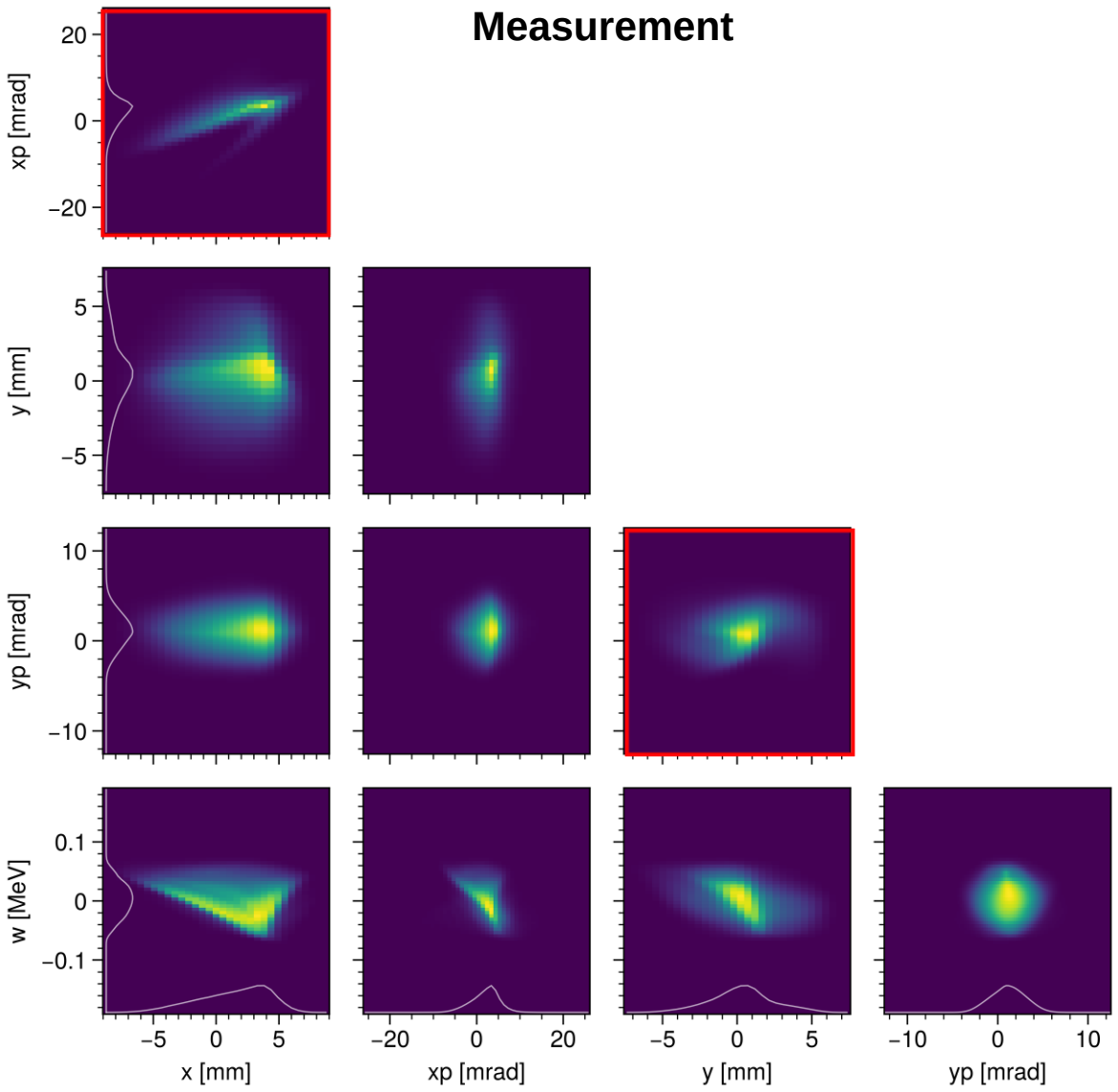
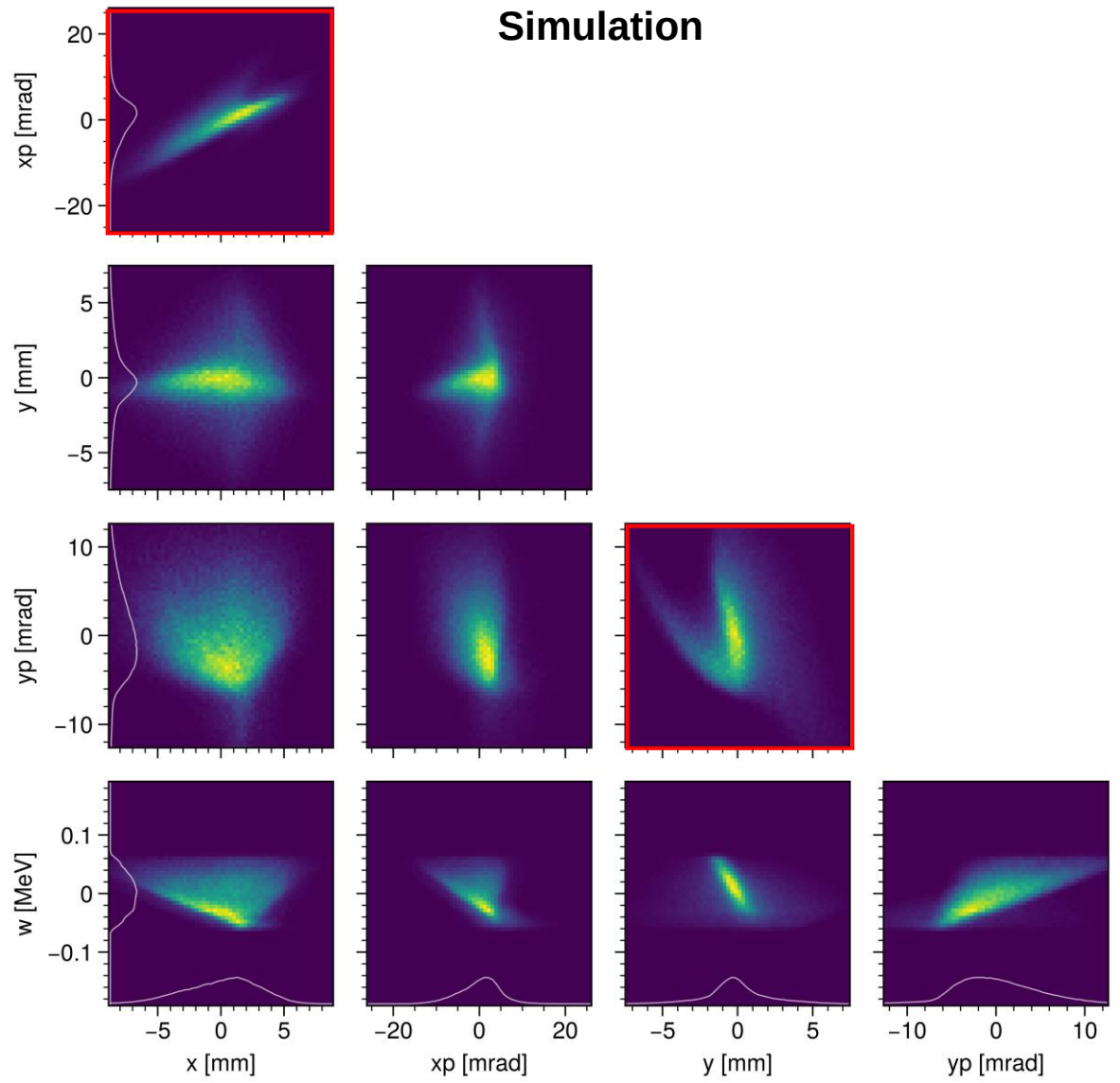




Correlated,
De-correlated

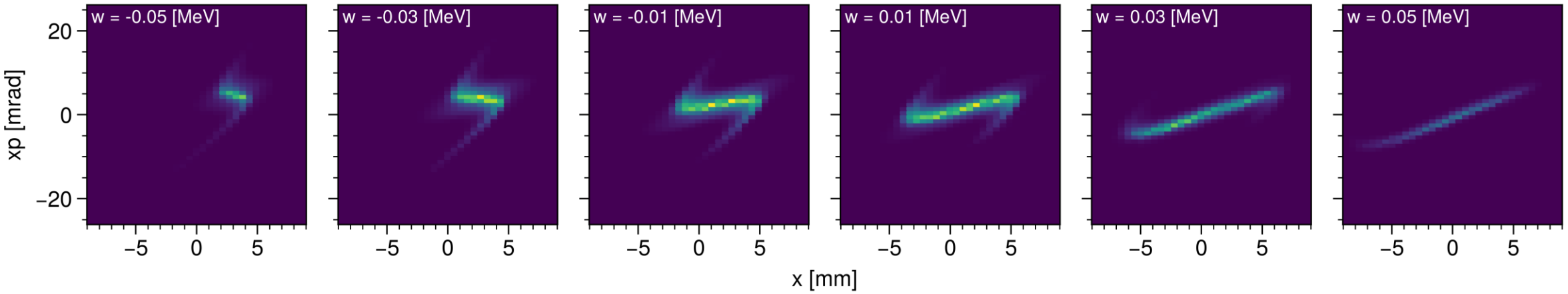
High-dimensional benchmark at end of beamline



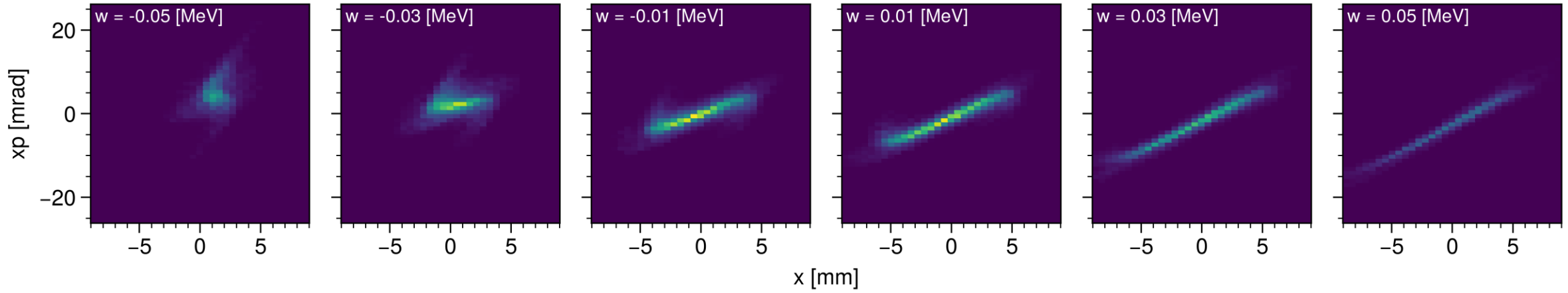


2D projected phase space viewed at energy slices

Measurement

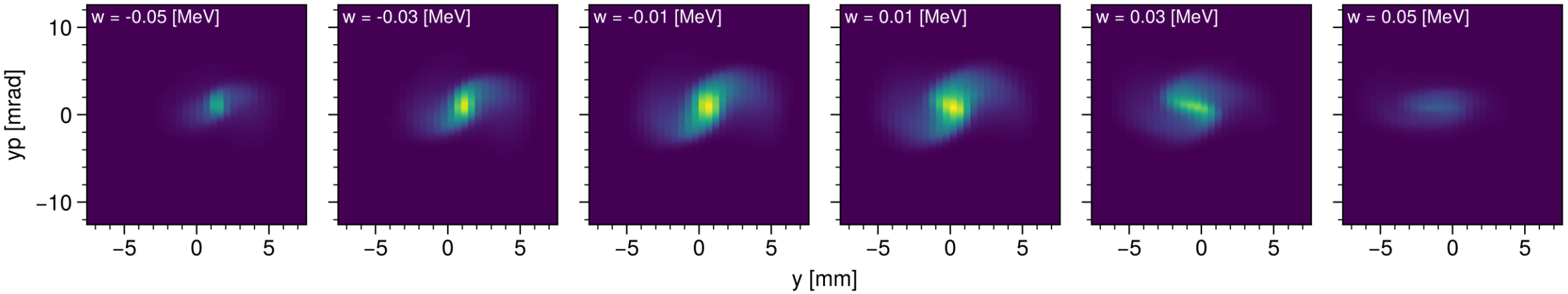


Simulation

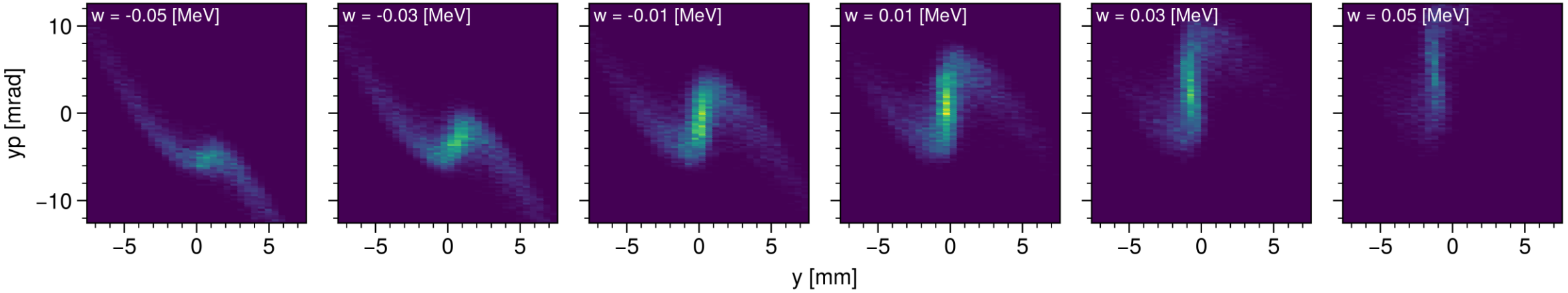


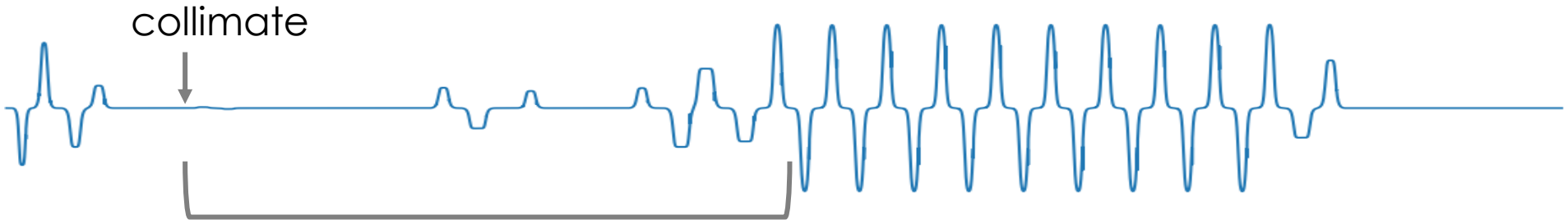
2D projected phase space viewed at energy slices

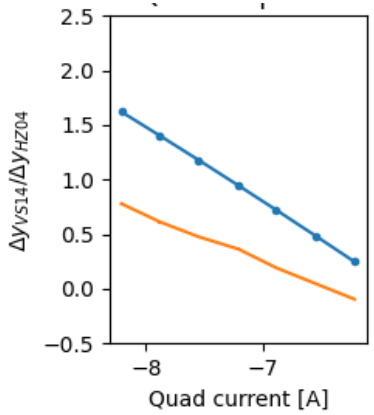
Measurement



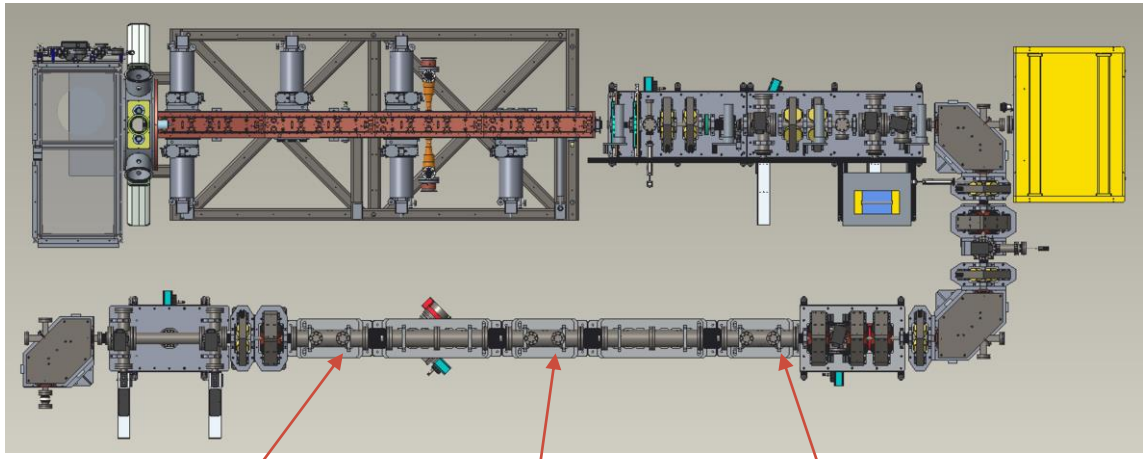
Simulation

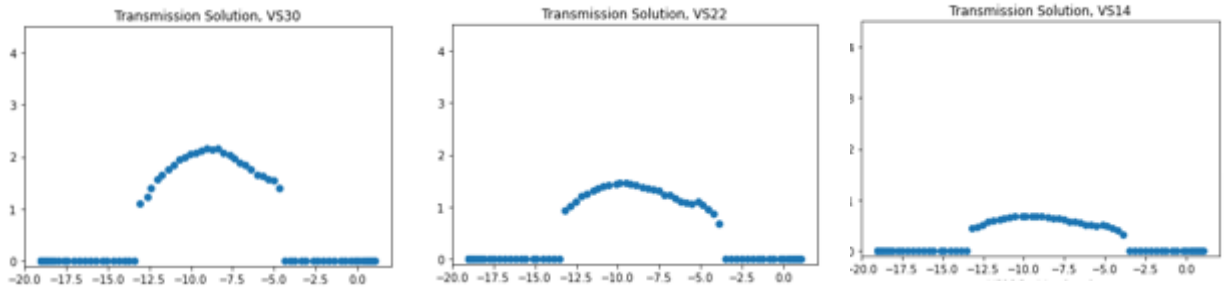






Chromaticity in FODO line





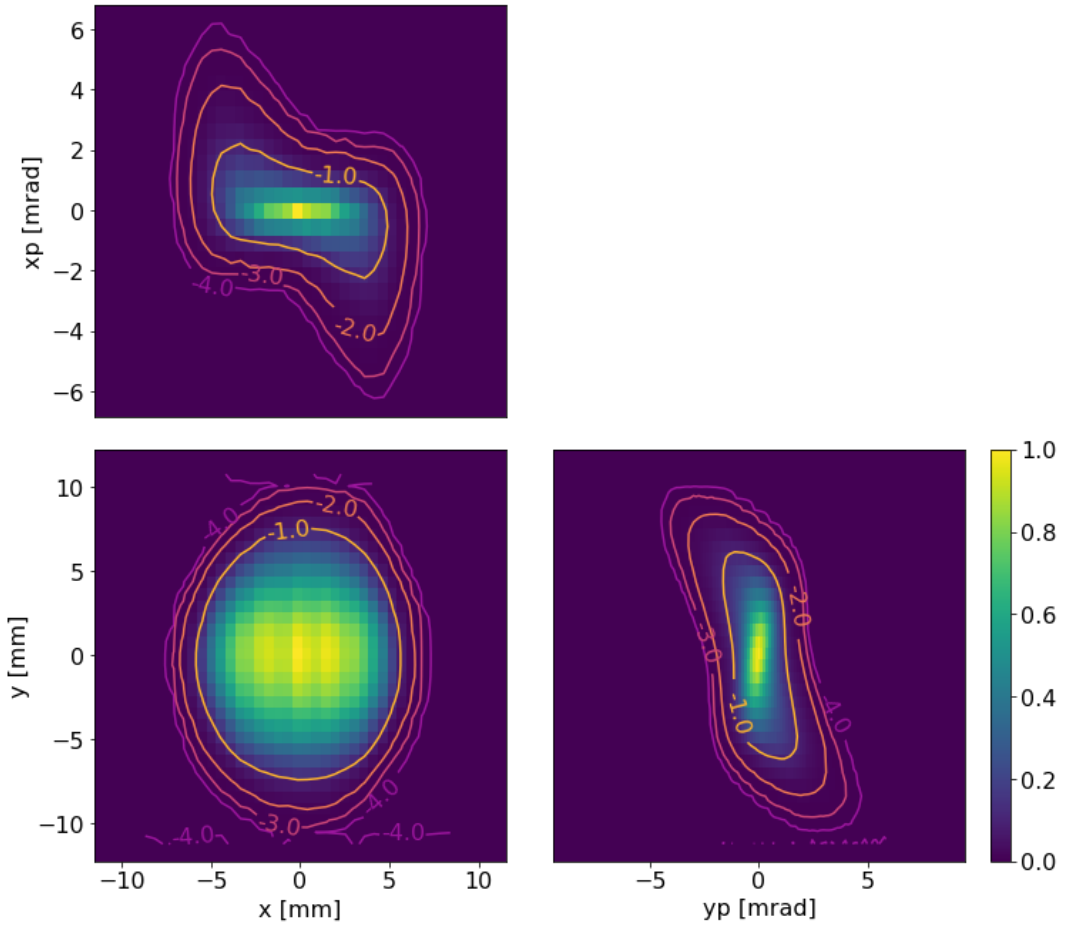
8 mm ~ ?? keV

Per FODO cell, C = -0.00007 / keV

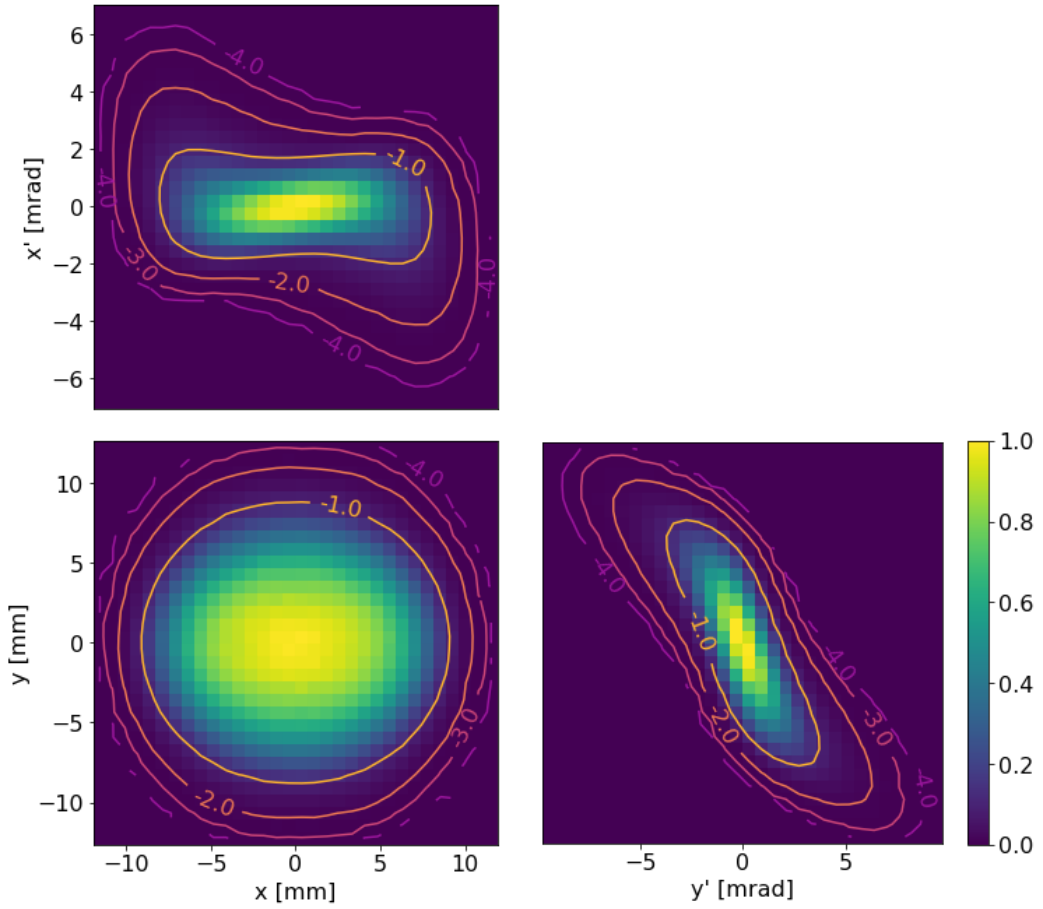
For 50 keV RMS width and 9.5 cell FODO, $\Delta\nu = -12.5^{\circ}$

RFQ Benchmark, full-projection

Measured



Simulated



RFQ Benchmark, slices