Oak Ridge National Laboratory

May 22, 2026 | IPAC’26, Deauville, France

Beam Dynamics in the SNS Linac and Beam Test Facility

Kiersten Ruisard

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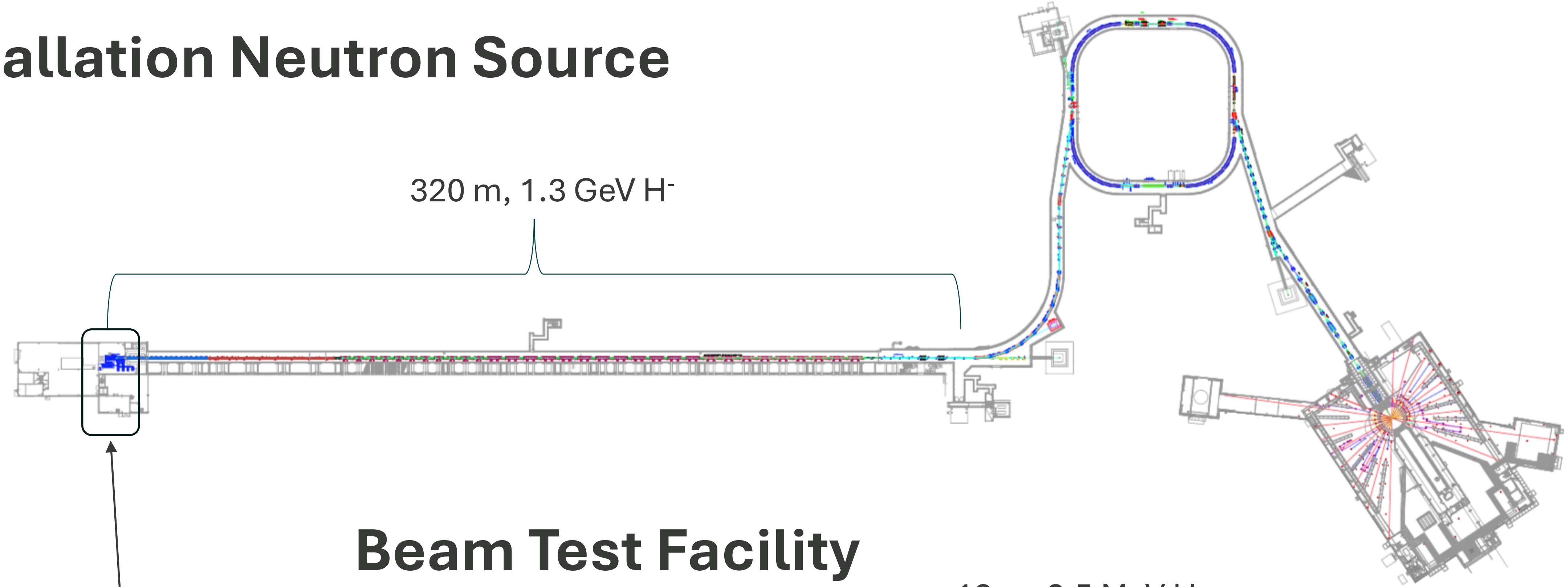
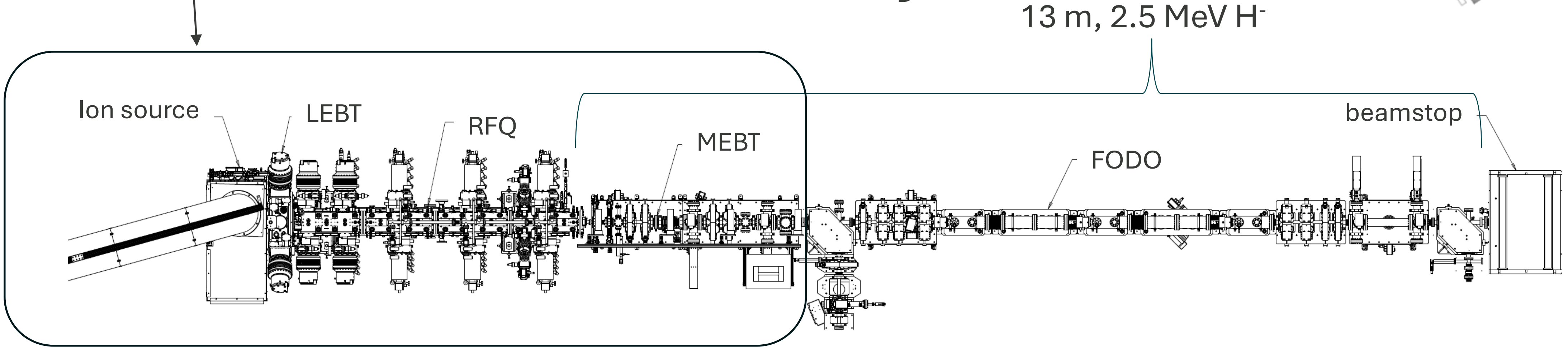
Spallation Neutron Source

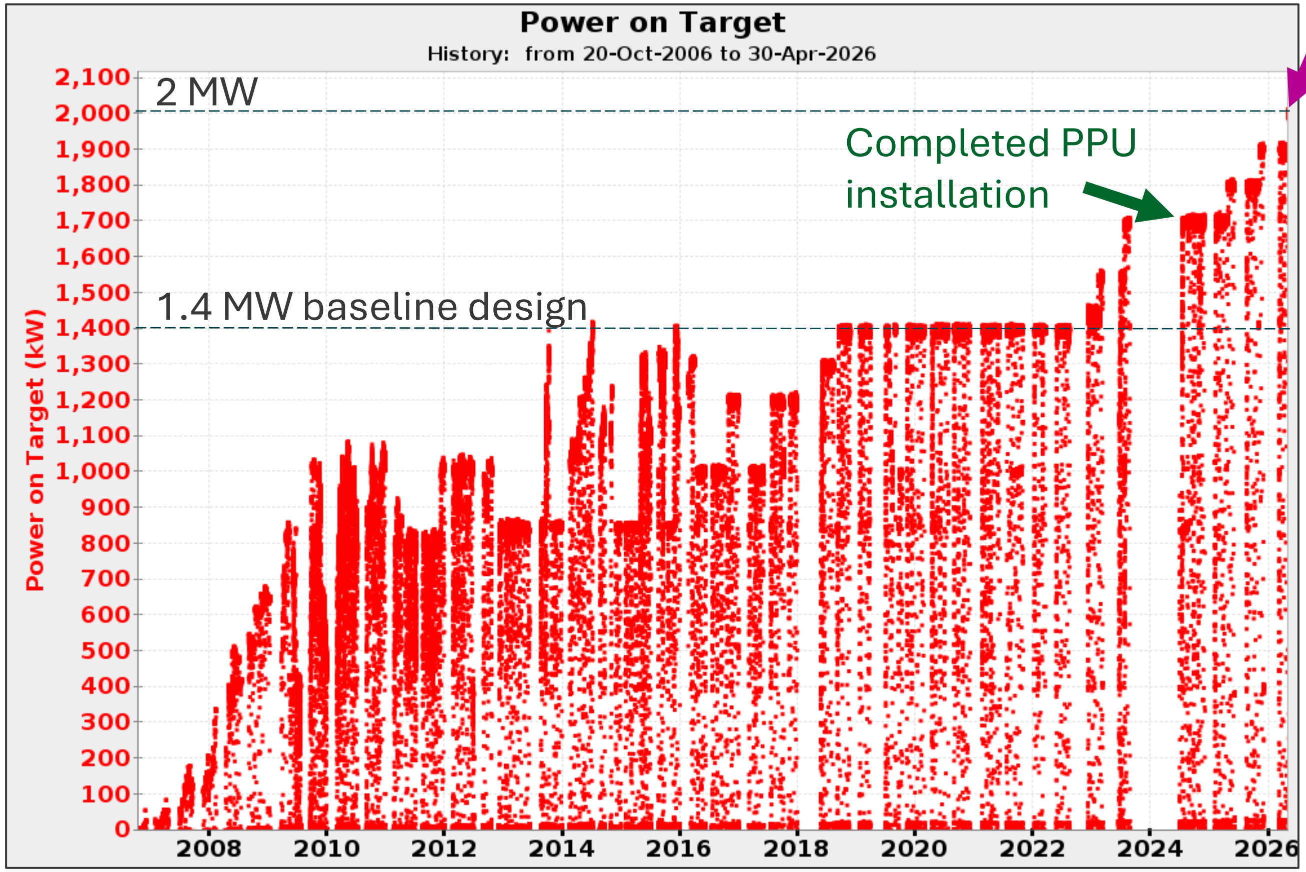


Beam Test Facility



The SNS Linac is currently operating at 2.0 MW (as of April 23, 2026)

The Proton Power Upgrade increased SNS beam power on target from 1.4 MW to 2.0 MW, mainly through 30% increase in beam energy (1 GeV → 1.3 GeV)

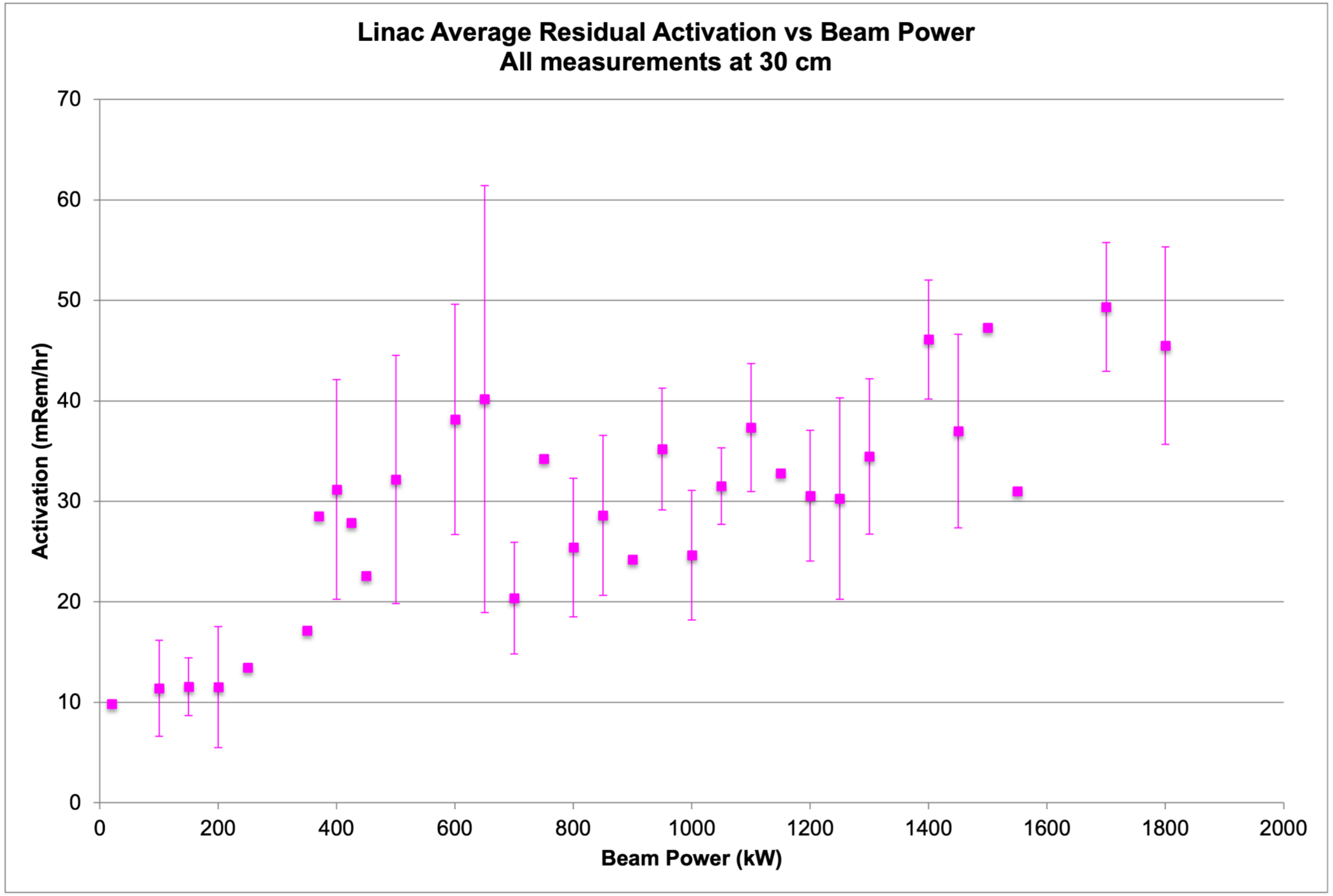


20th anniversary of SNS beam on April 28!

After completion of Second Target Station, SNS will ramp to 2.7 MW

Beam current will increase by 50% from SNS design value

Increased beam loss at 2+ MW brings technical challenges



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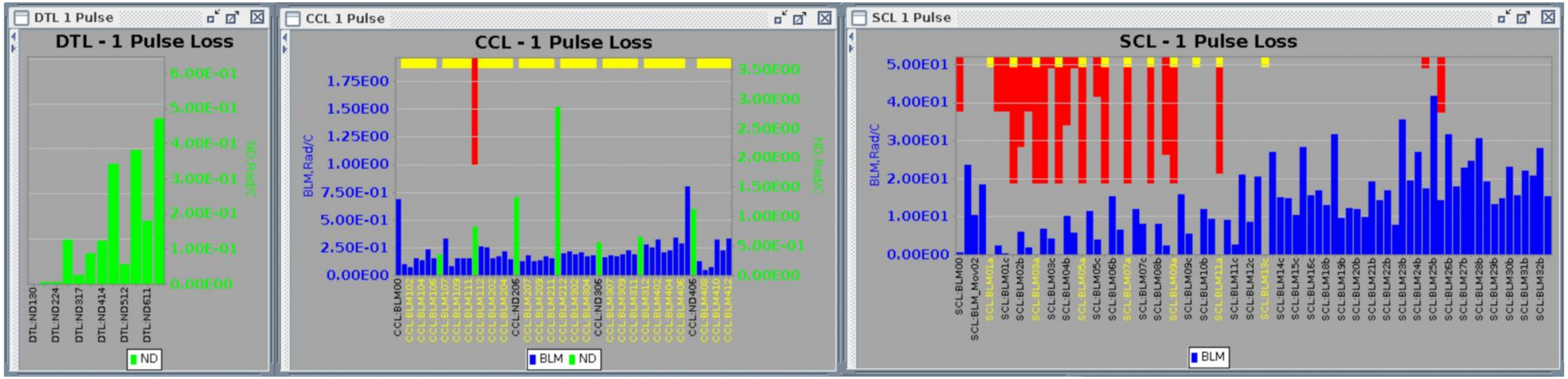
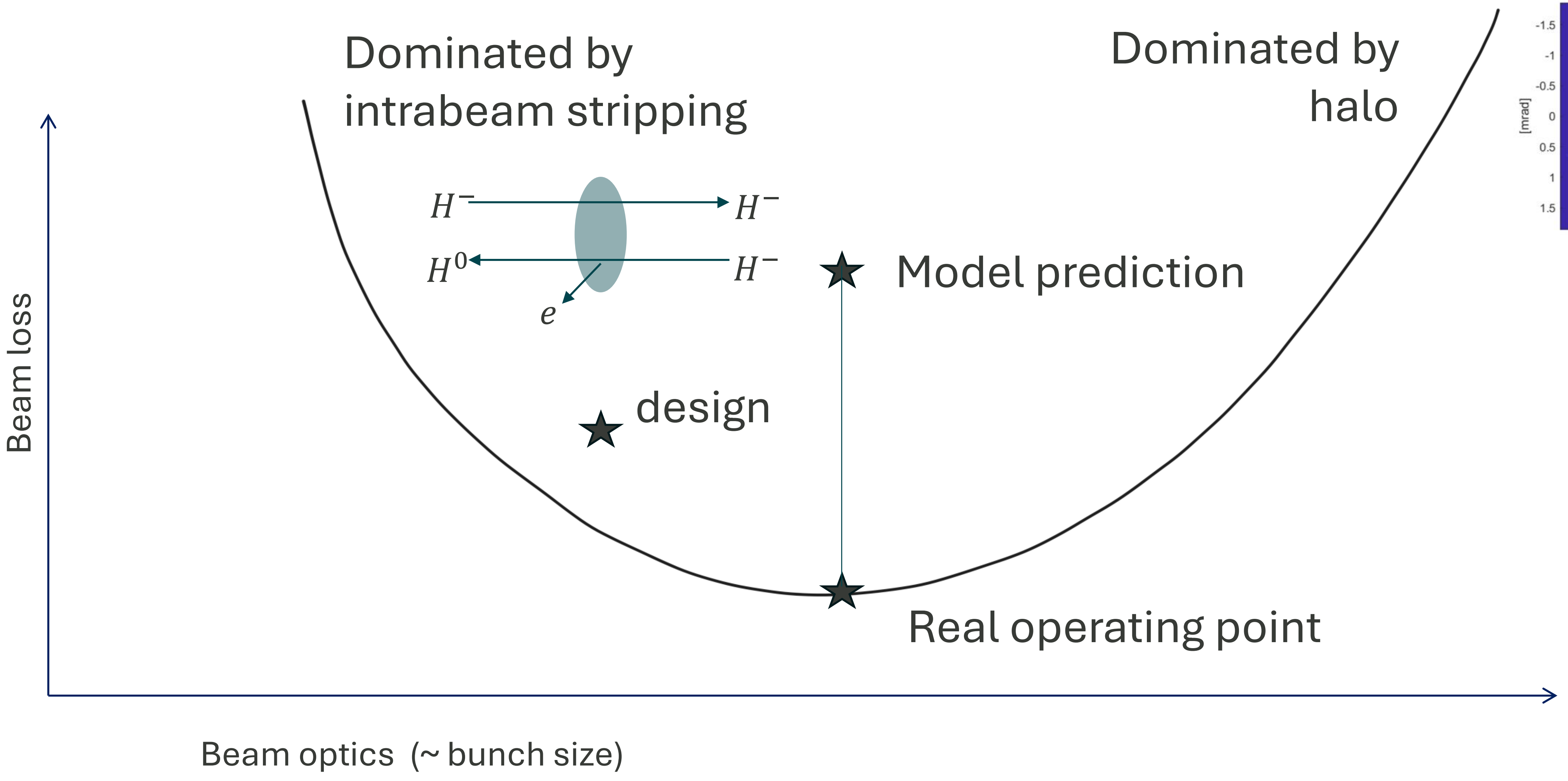
Currently, beam loss control is human-driven and empirical

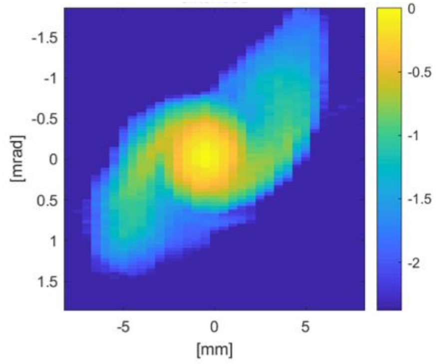


Automated beam loss tuning is in the near future

- ☑ Empirical understanding
- ☐ Physics understanding

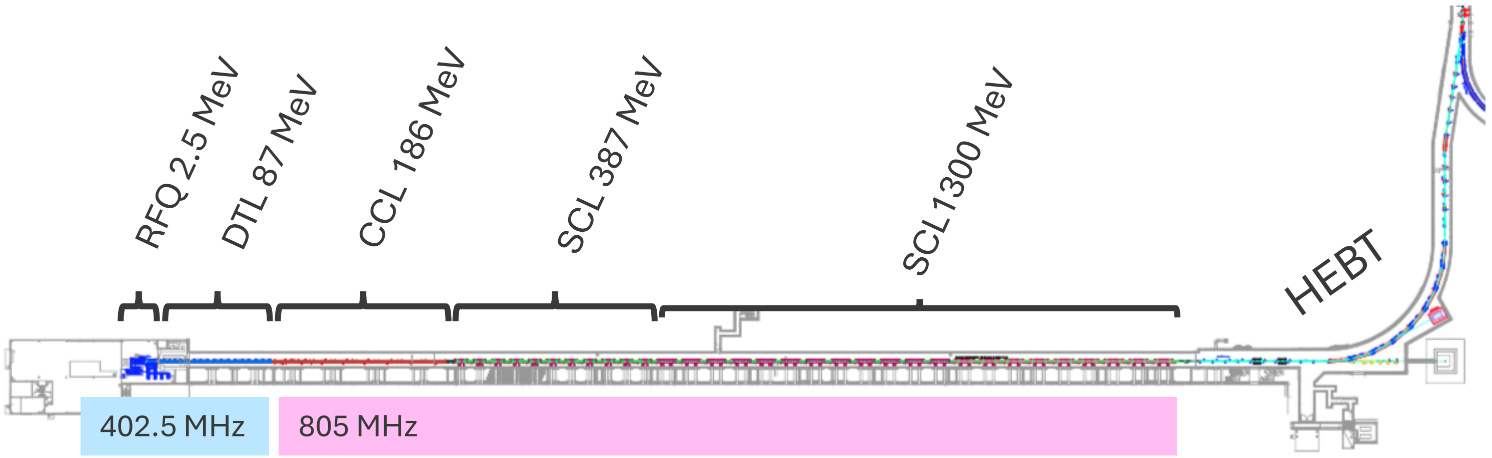
Beam dynamics mechanisms for LINAC beam loss





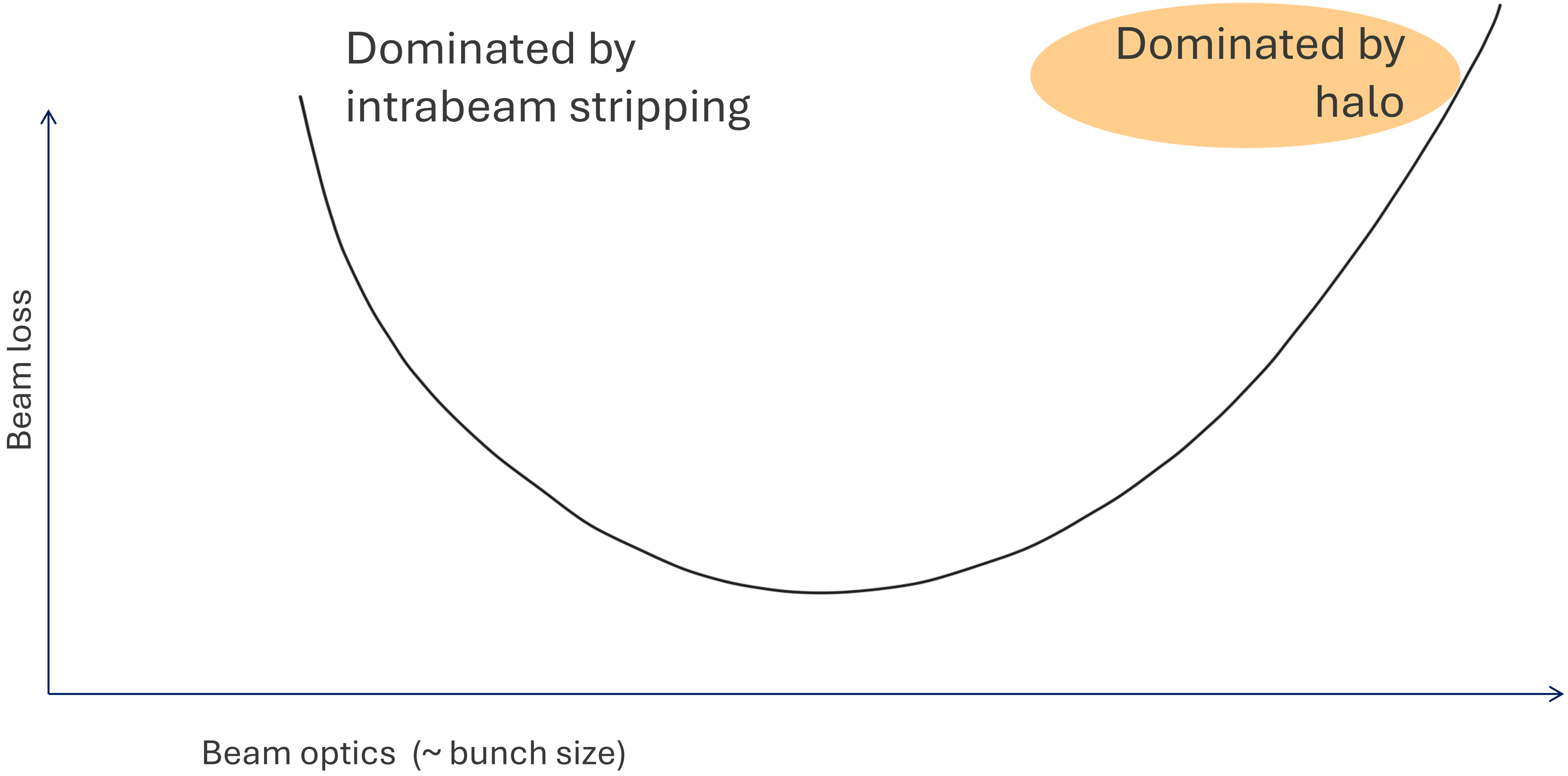
We do use model to understand linac dynamics

- Model-based tuning of cavity phases/amplitudes is fast and reproducible
    - Can be done in 1 hour
    - Re-scaling around tripped cavity achieves accuracy of 1.5 MeV (0.1%)
    - Cavity phase/amplitudes known to within 1%
    - Require only phase scans to fit energy, cavity phase, cavity amplitude
- Centroid model is benchmarked for whole linac, model-based orbit correction works (to within 0.1 mm)
- Model for rms Twiss is benchmarked in HEBT



But…

- We do not rely on transverse model or transverse diagnostics to define operating point
- Modeling the operating point predicts large losses. What is wrong with the model?



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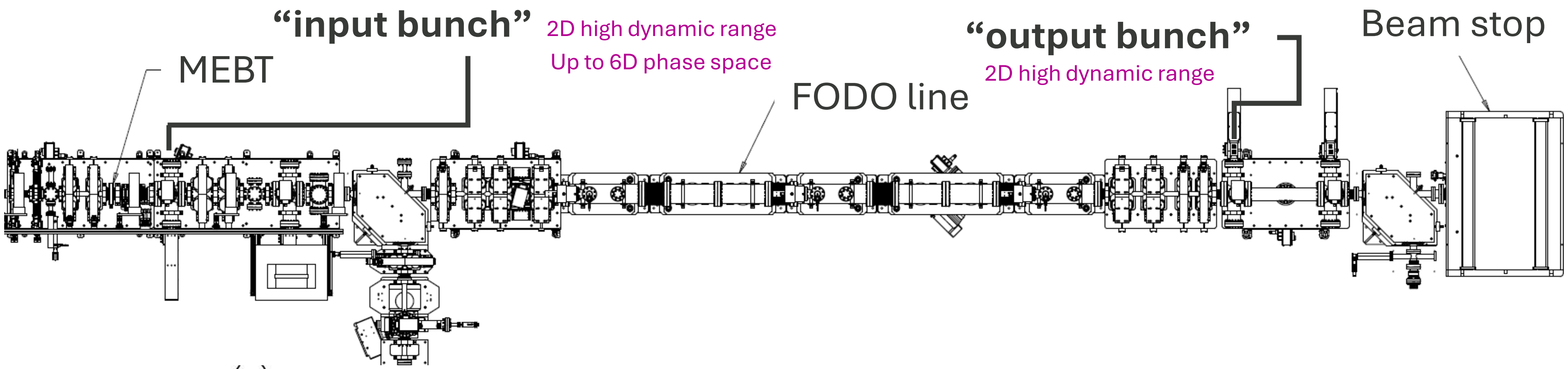
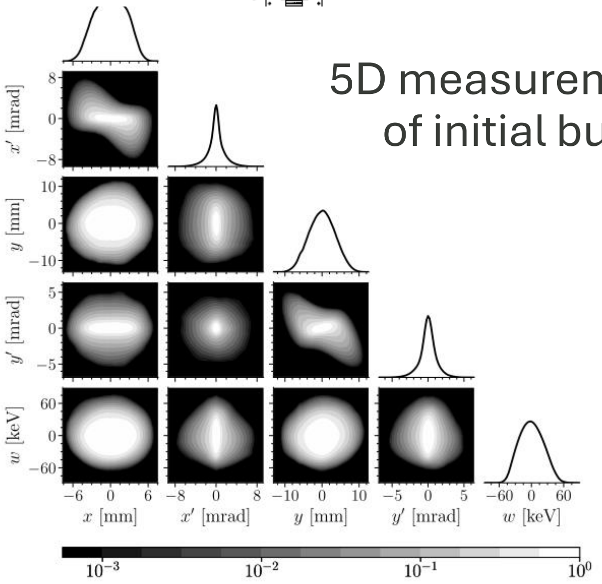
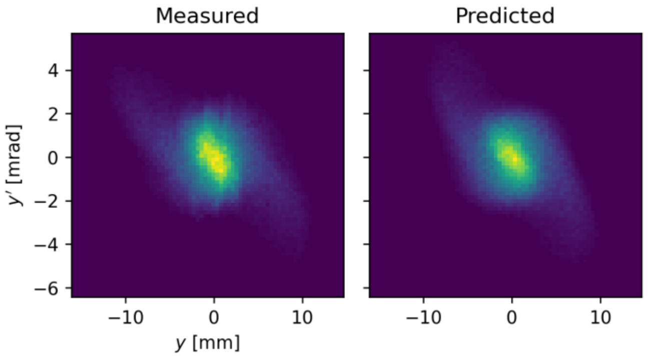
Scope of BTF project is to accurately model halo development over short, 2.5 MeV transport line





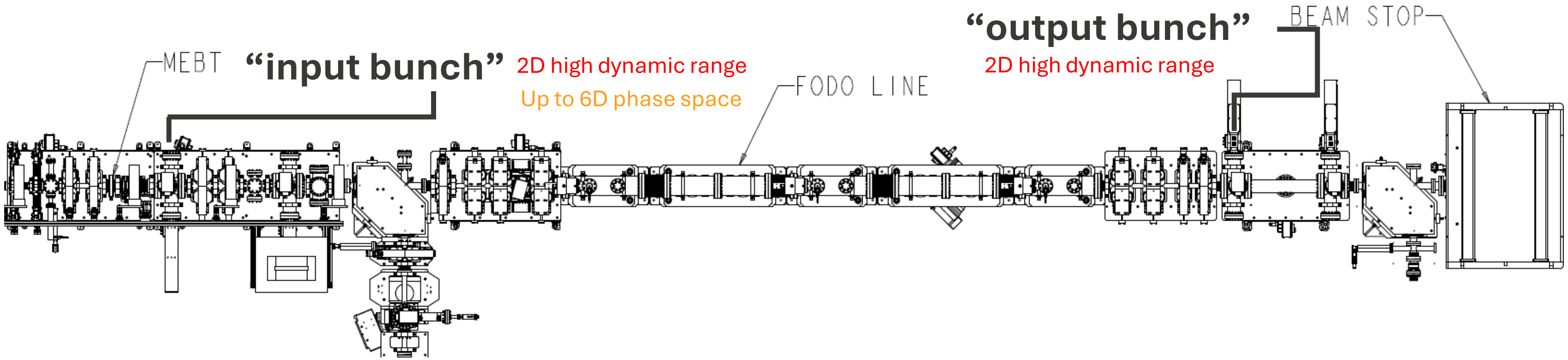
5D measurement
of initial bunch

Hoover et. al (2023). PRAB 26, 064202

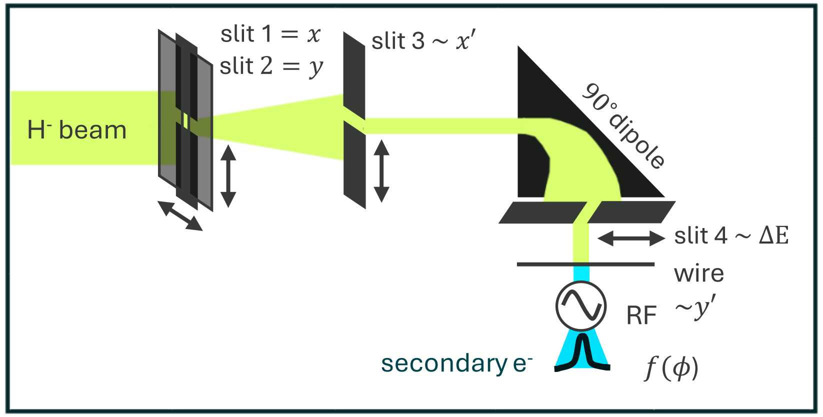


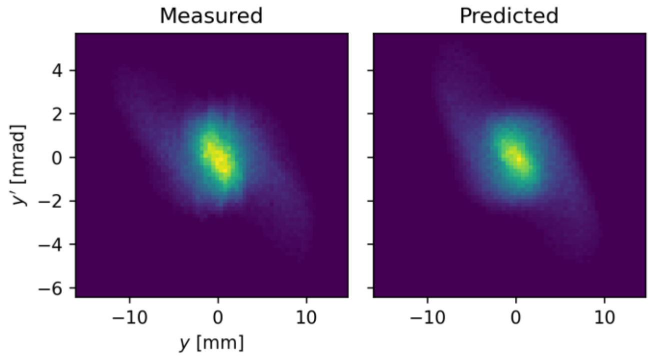
2D phase space measurement
(Linear scale, dynamic range of 10^2)

Scope of BTF project is to accurately model halo development over short, 2.5 MeV transport line



6D measurement
of initial bunch





2D phase space measurement vs model
(Linear scale, dynamic range of 10^2)

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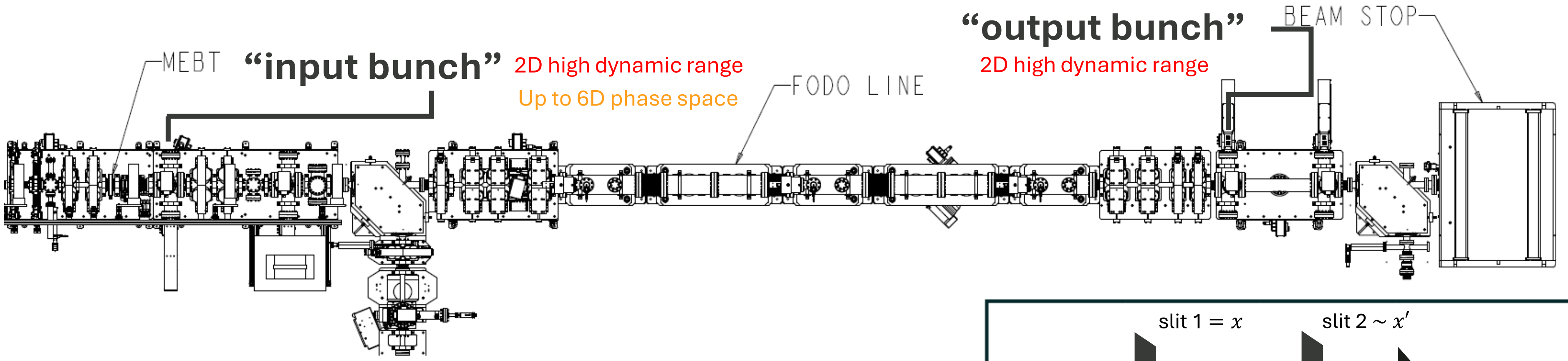
Scope of BTF project is to accurately model halo development over short, 2.5 MeV transport line



6D measurement
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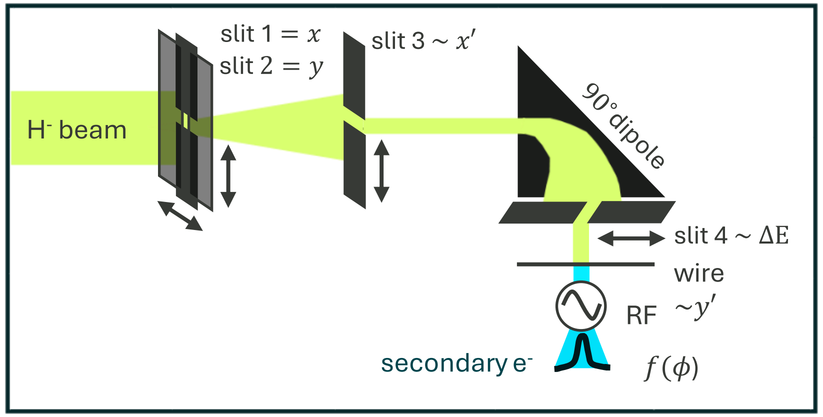
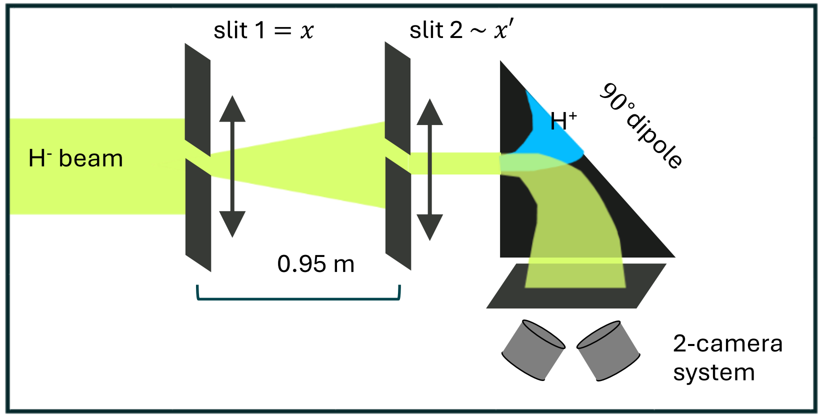


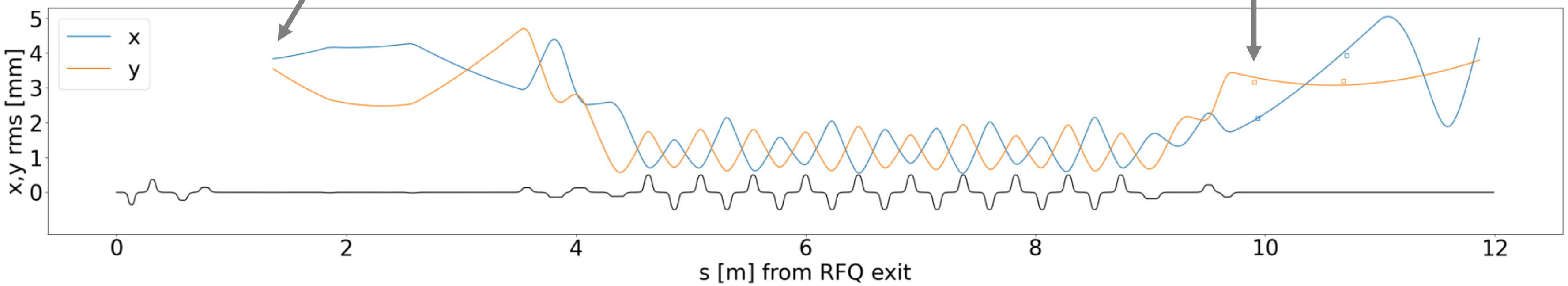


2D phase space measurement

Test beamline is periodic and is long enough to form halo

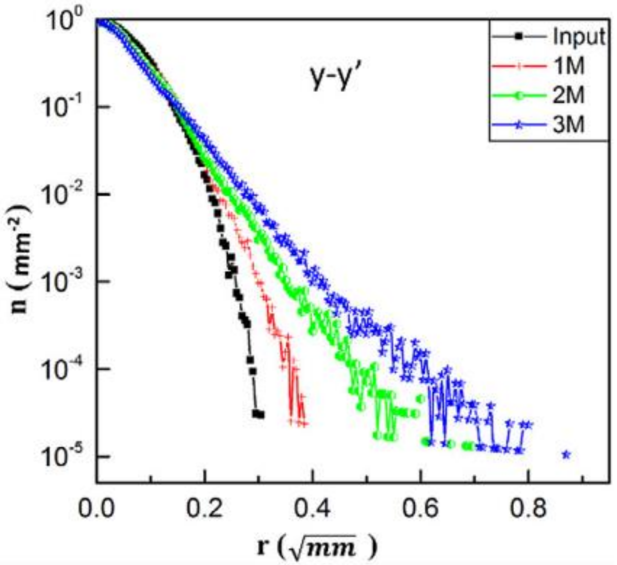
“input bunch”

“output bunch”



Relatively strong-focusing FODO line:

- 9.5 cells
- 105 degrees per cell
- Permanent magnet quadrupoles



Zhang, Z., et. al (2020). NIM-A, *949*, 162826.

2016: First beam in BTF

2017: First **full and direct 6D** measurement of MEBT distribution

2020: First mapping of 2D phase space projection with **6 orders of dynamic range**

2025: First systematic measurement of **beam distribution vs. mismatch** with 6 orders of dynamic range

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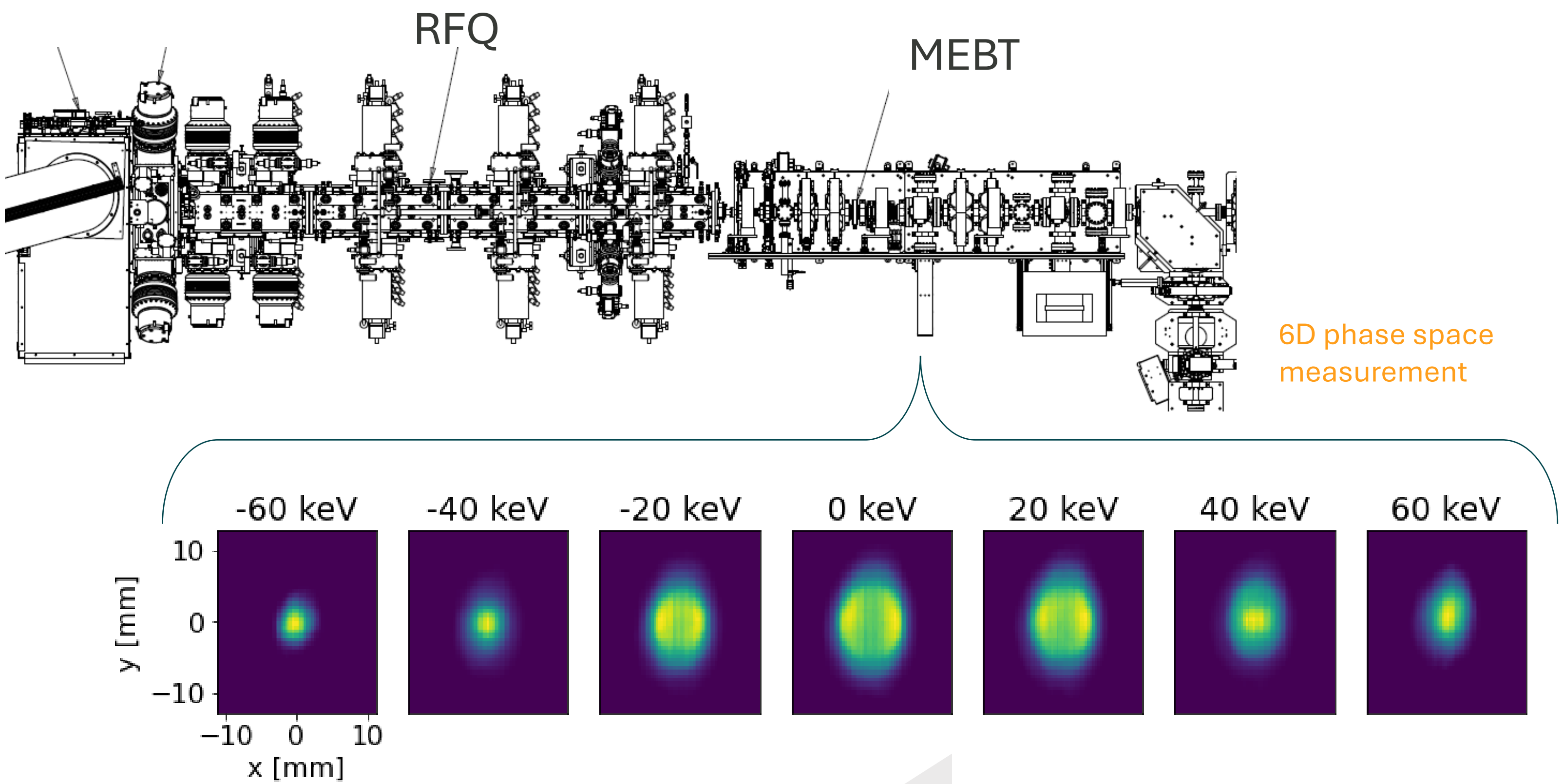

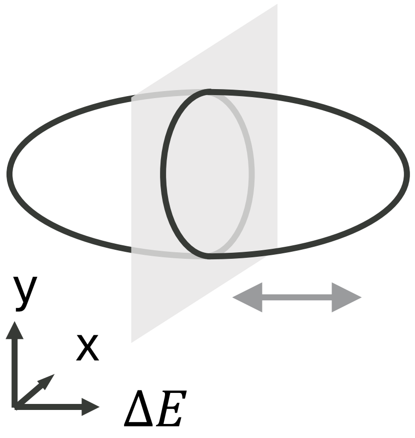

Slice of distribution, f(x,y) depends on ΔE

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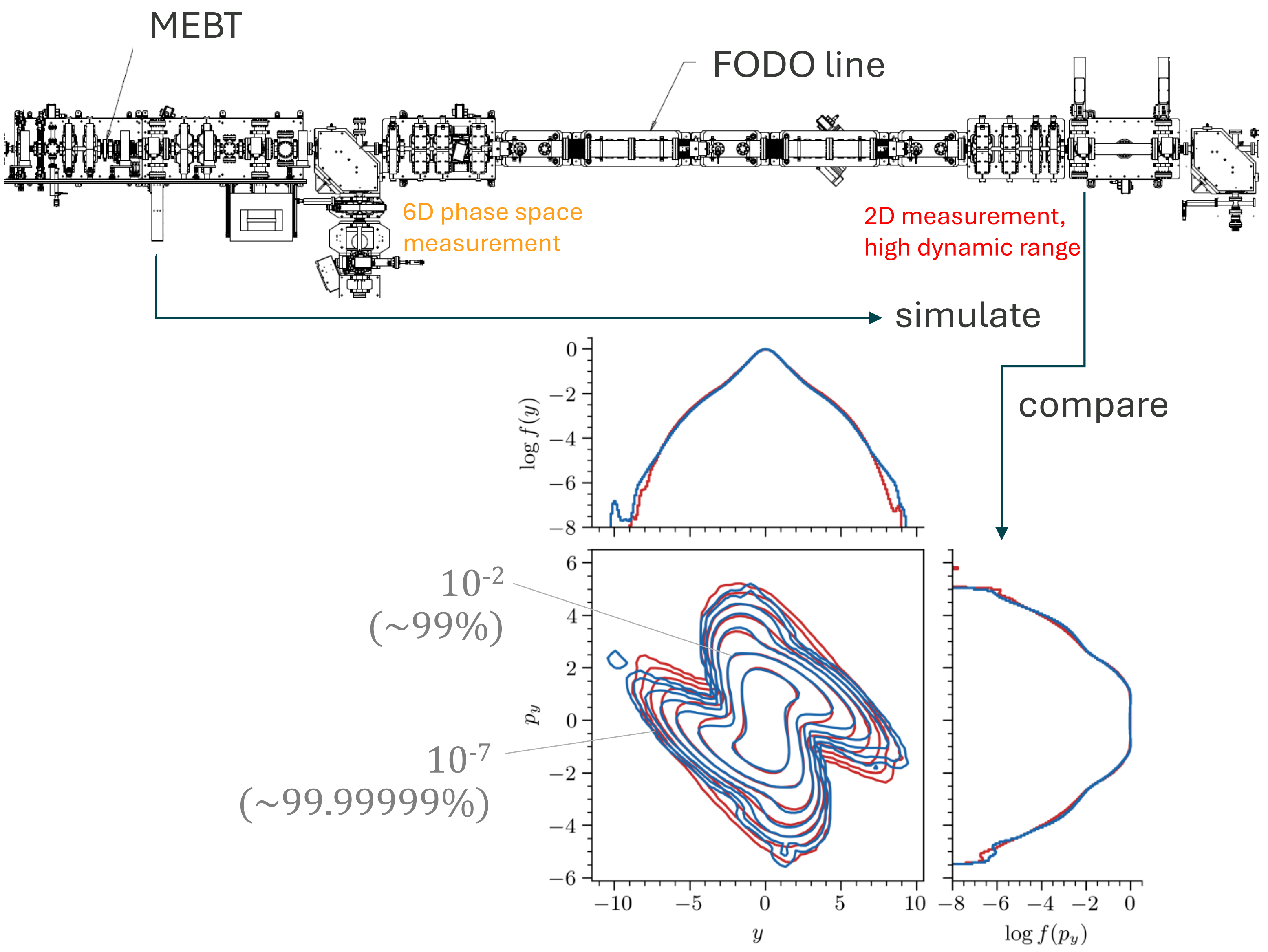

Hoover et al, High Brightness Workshop, CERN (Oct 2023)

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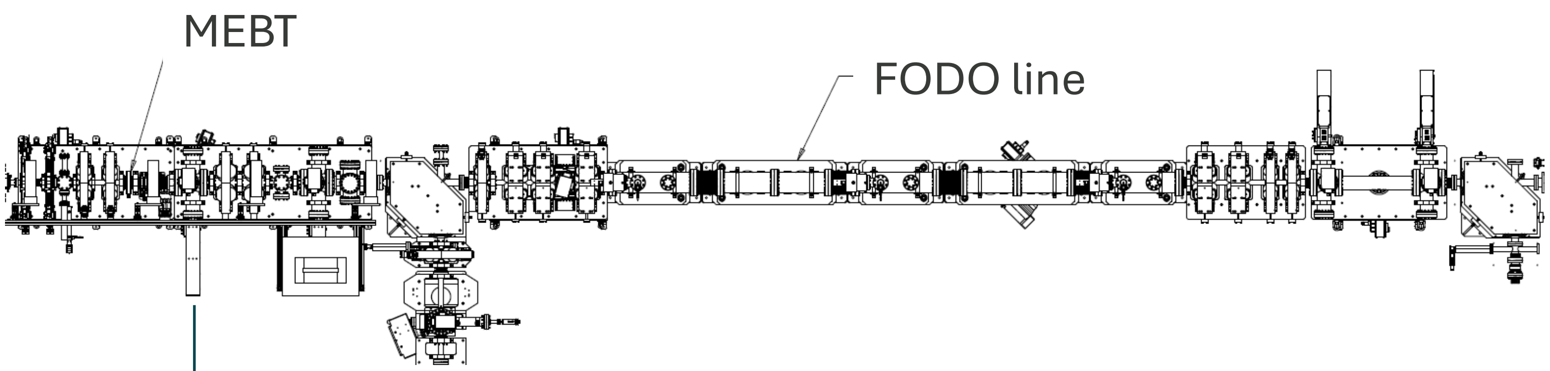

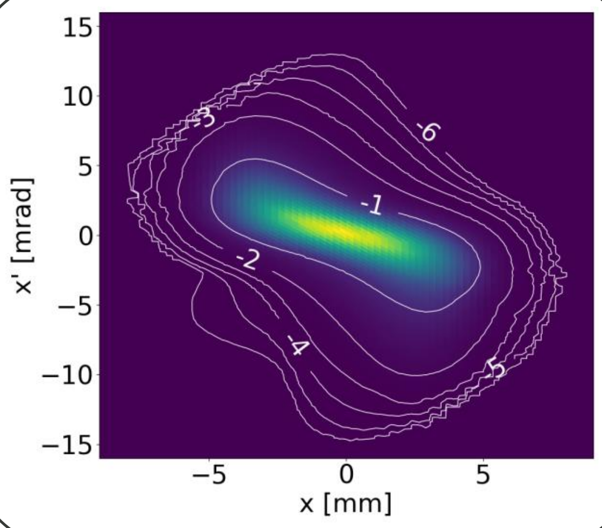

2D phase space measurement with high dynamic range

2016: First beam in BTF

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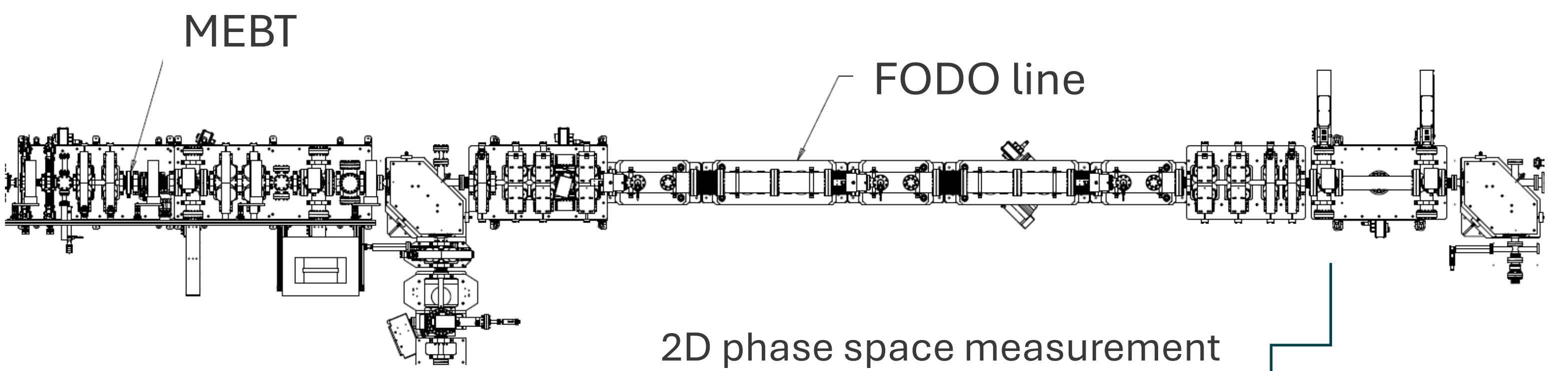

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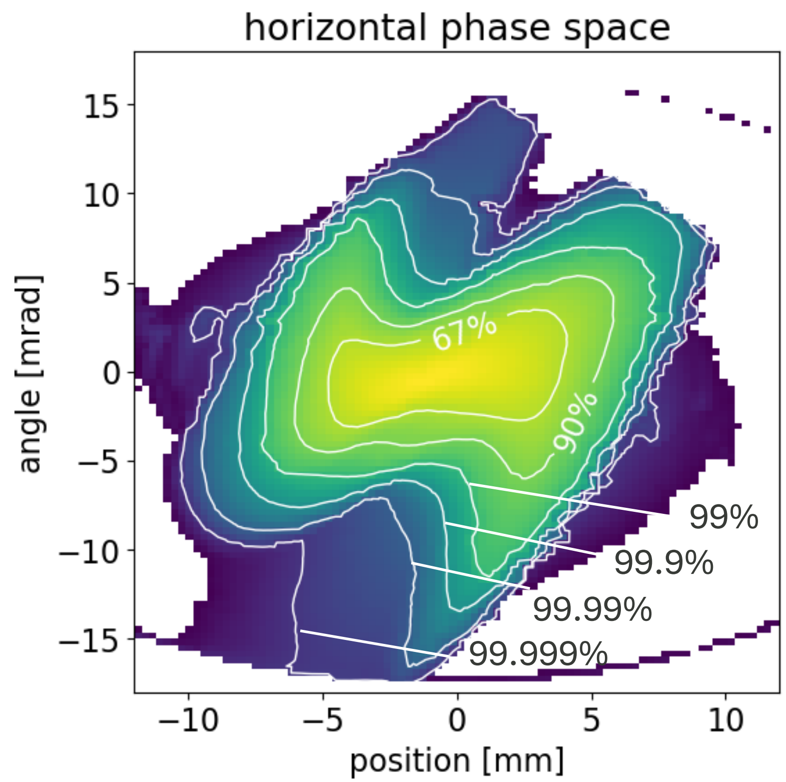

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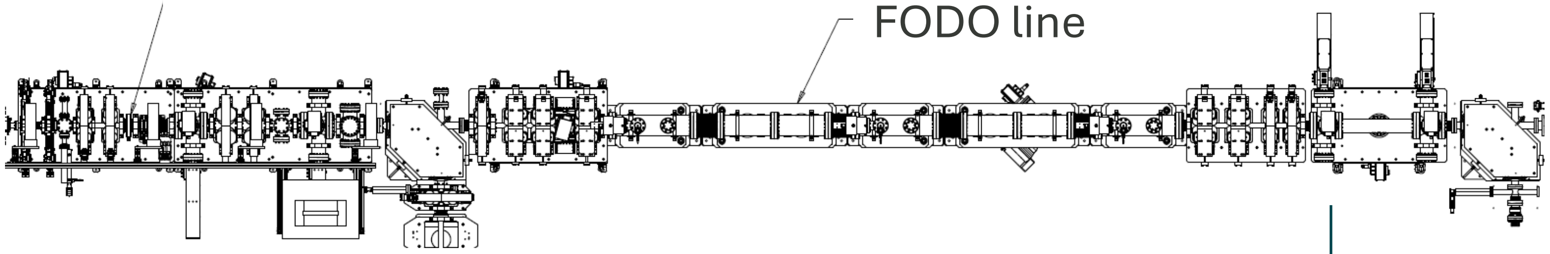
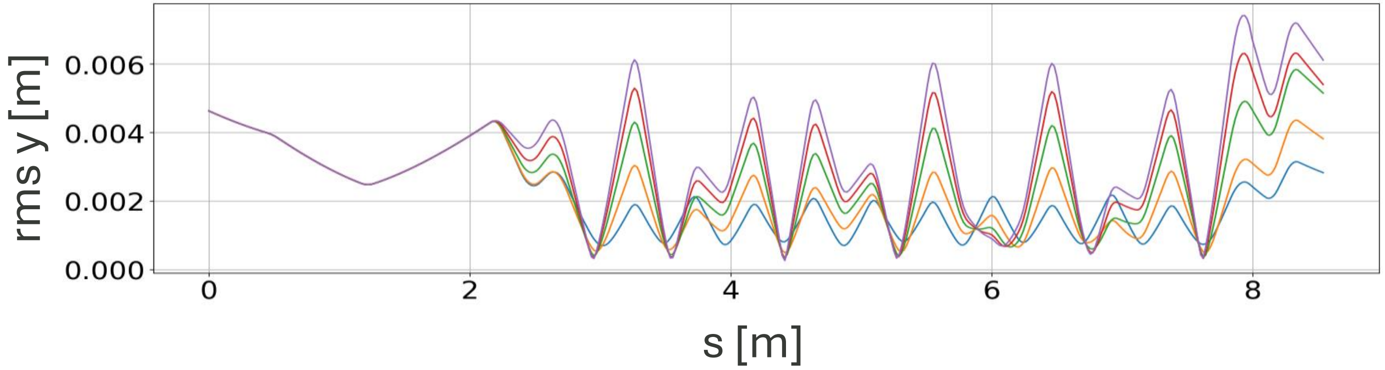
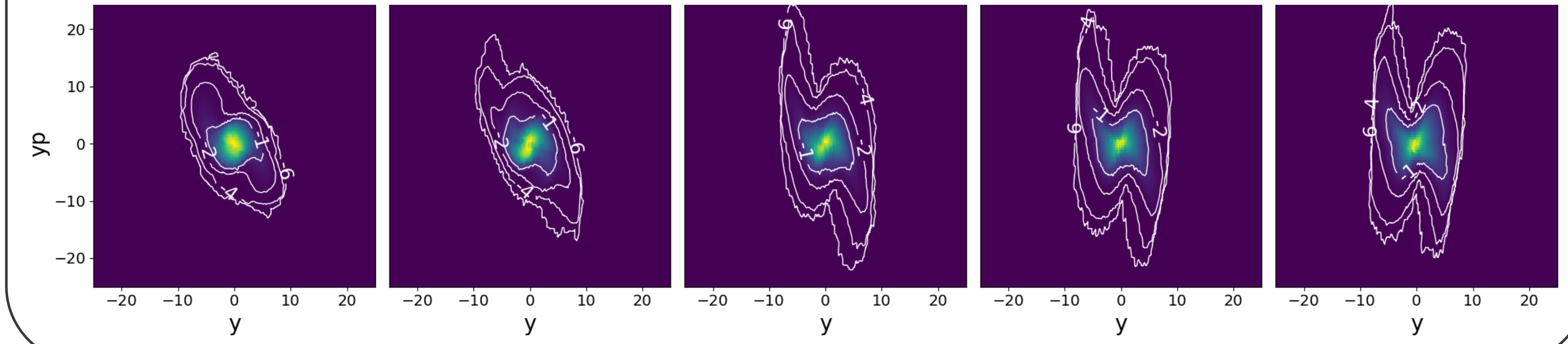
Trent Thompson, Poster THP5349



Plot shows 5 optics cases with varying level of mismatch:

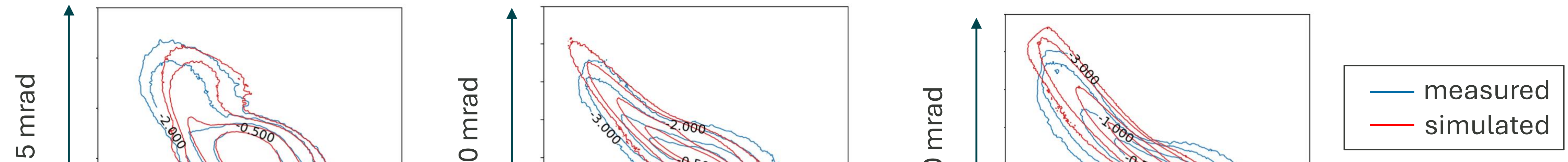


Increasing mismatch parameter



Benchmark of PyORBIT simulation has best agreement for matched case

Increasing mismatch parameter →

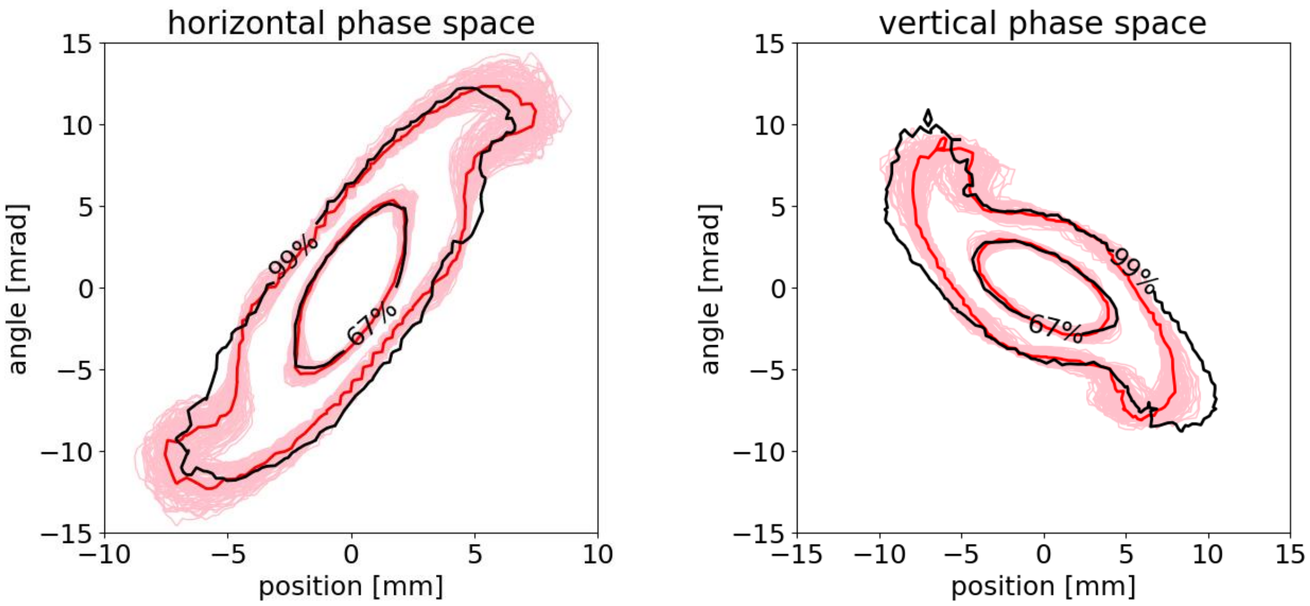


Contours are at 31%, 10%, 1%, 0.1% of peak density

PyORBIT PIC simulation uses 100M macroparticles for 40 mA average bunch current

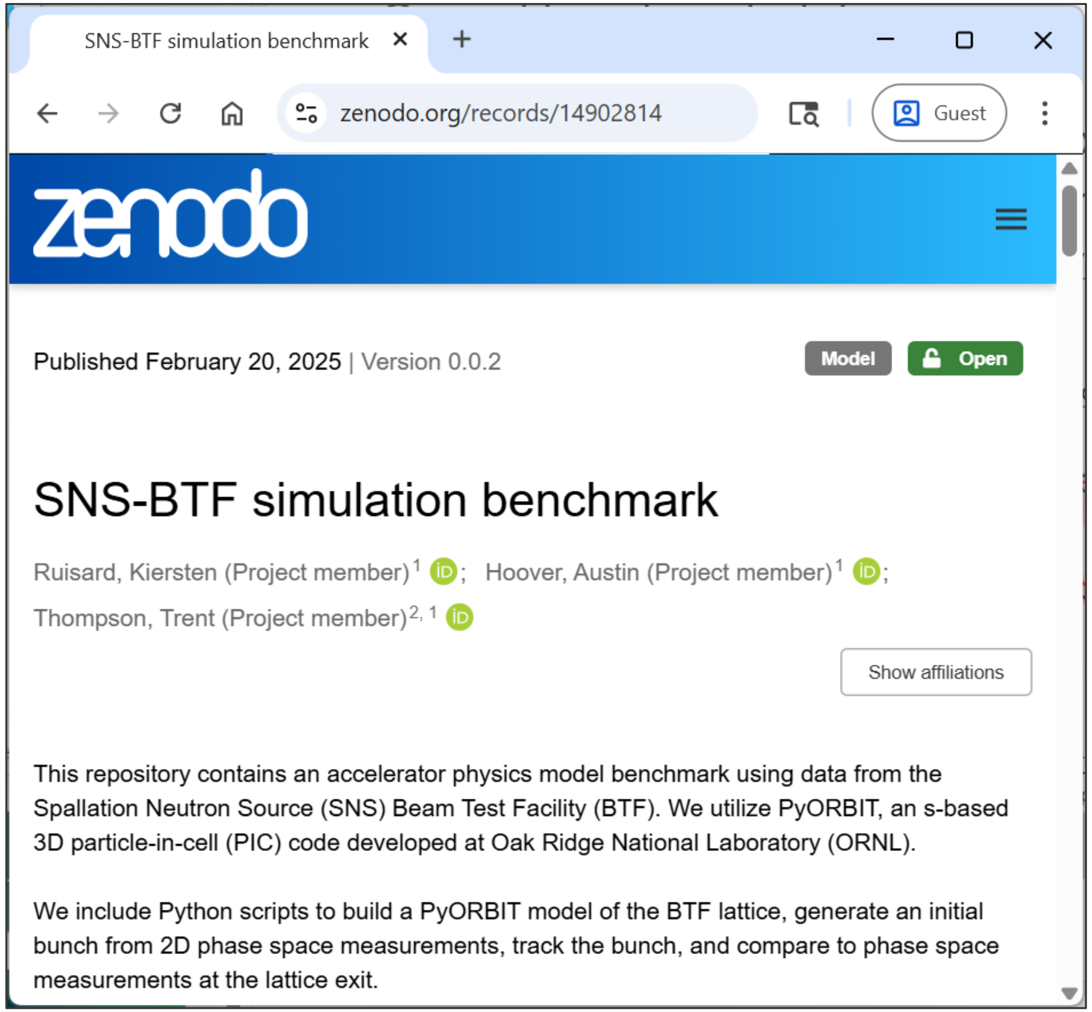
Current benchmark status:

- Good agreement for core
- Fair agreement to 10^{-2} tails (99% of beam)
- Larger disagreement for mismatched beams
- <u>“Halo benchmark” not achieved yet</u>



Red: simulation model
Black: measurement
Pink: simulation uncertainty

uncertainty random errors:
quadrupole strength, 0.2%-0.5%
beam energy error 1%


SNS-BTF simulation benchmark

zenodo.org/records/14902814

Guest

zenodo

Published February 20, 2025 | Version 0.0.2

Model

Open

SNS-BTF simulation benchmark

Ruisard, Kiersten (Project member)[1]; Hoover, Austin (Project member)[1];
Thompson, Trent (Project member)[2, 1]

Show affiliations

This repository contains an accelerator physics model benchmark using data from the Spallation Neutron Source (SNS) Beam Test Facility (BTF). We utilize PyORBIT, an s-based 3D particle-in-cell (PIC) code developed at Oak Ridge National Laboratory (ORNL).

We include Python scripts to build a PyORBIT model of the BTF lattice, generate an initial bunch from 2D phase space measurements, track the bunch, and compare to phase space measurements at the lattice exit.

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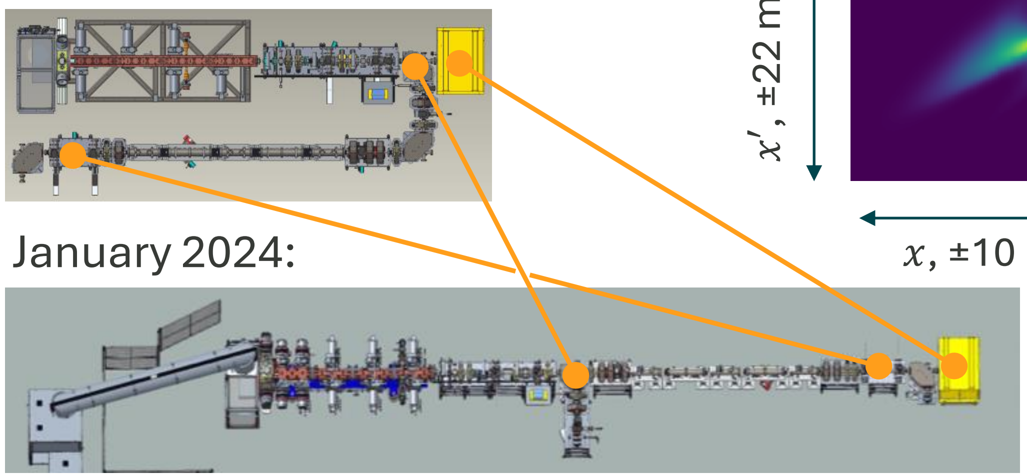
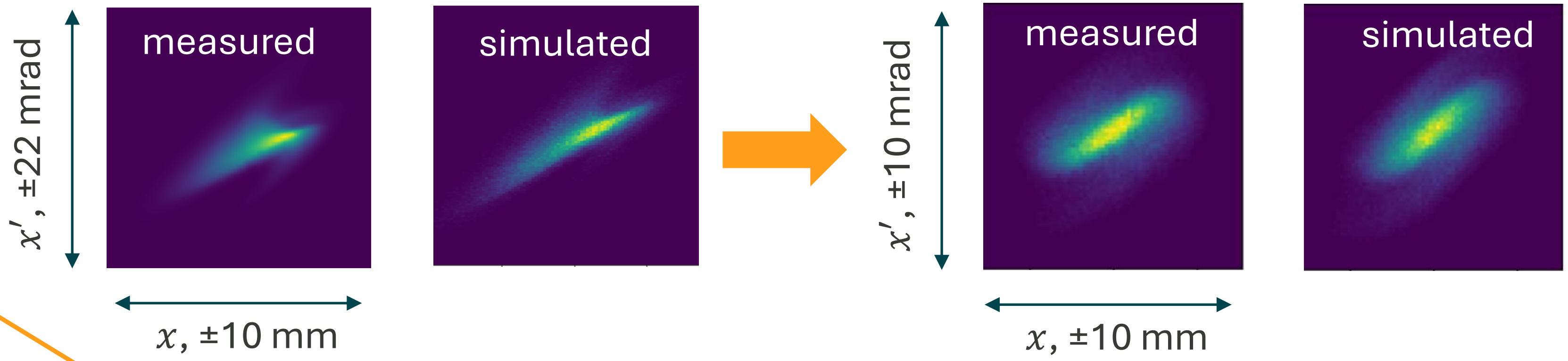
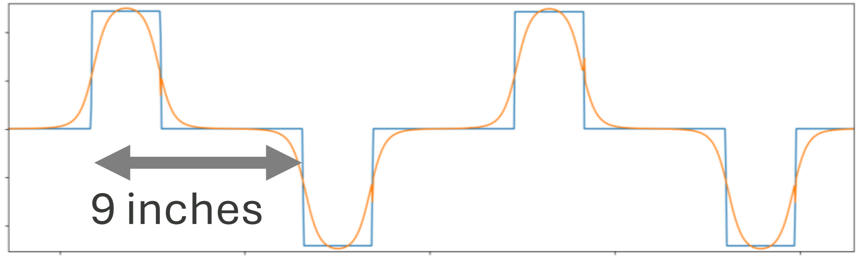
BTF "core" benchmark took years to achieve

2018 - 2022

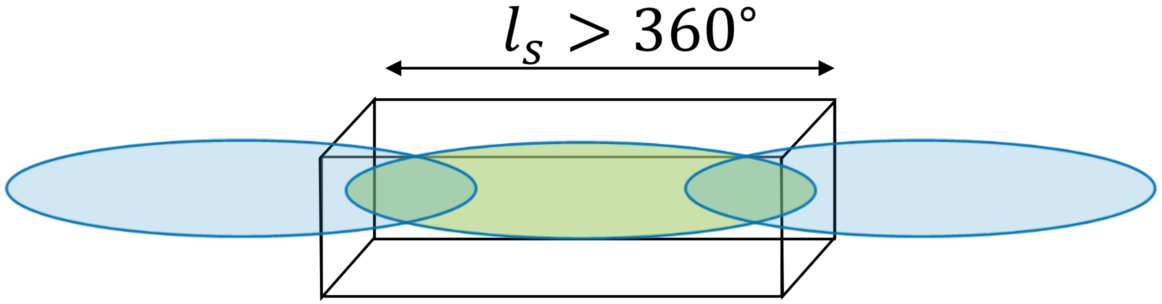




Modeling short FODO quads:



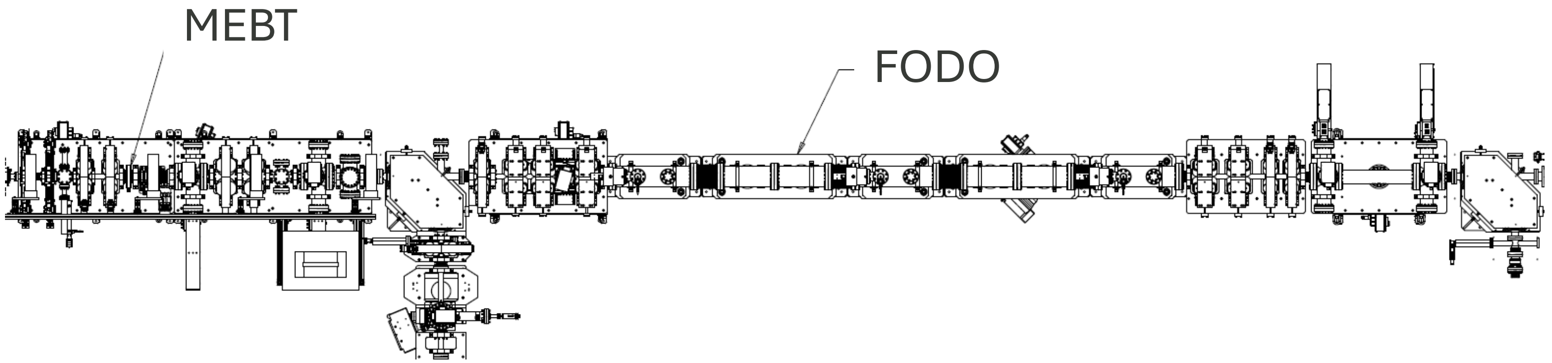
Modeling multi-bunch interaction:

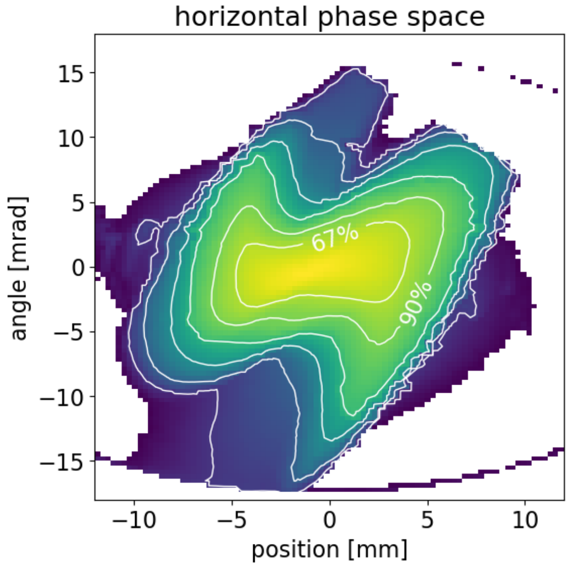


How can we fix this discrepancy to do halo prediction at the test facility?

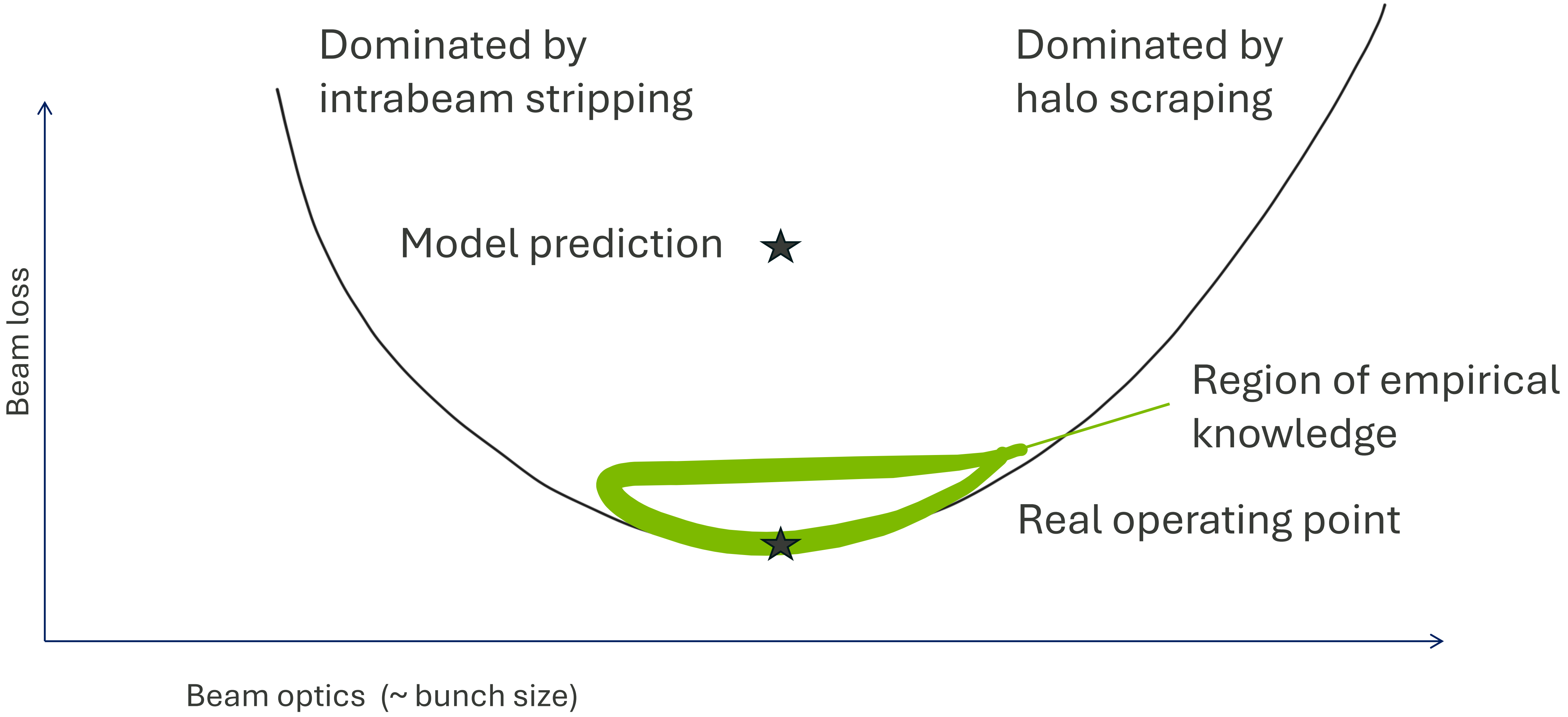
- Nonlinear components of quadrupoles
- Improve transmission with added trajectory correctors
    - Even matched beam has 3% loss
- What else?

R&D at Beam Test Facility is in "halo" era – providing a very clear picture of early halo growth





Increased "physics intuition" will benefit operations



Thanks for your attention!

This presentation summarizes efforts of many SNS personnel over 2 decades of operations. Similarly, many hands are needed to keep the BTF project moving forwards, too many to list here.

This work is supported by the U.S. Department of Energy, Office of Science,
Office of High Energy Physics and Office of Basic Energy Sciences (DE-AC05-00OR22725).

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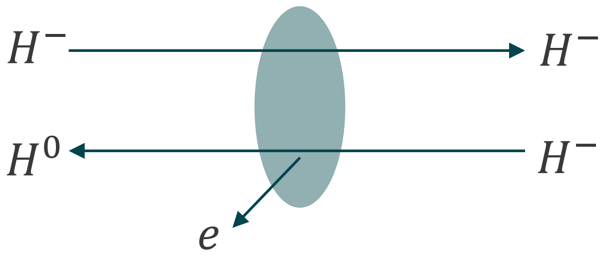
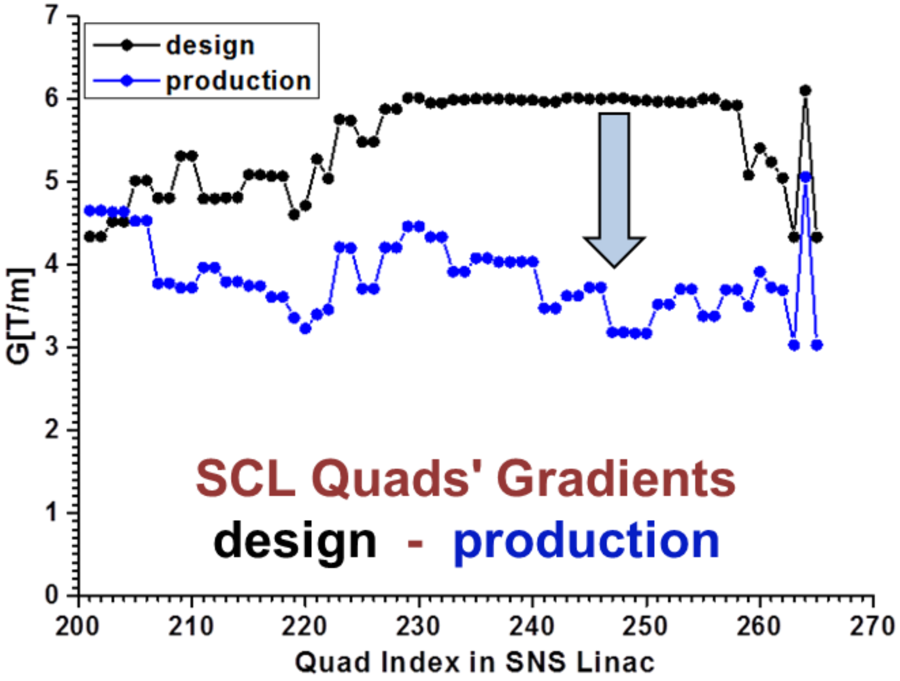
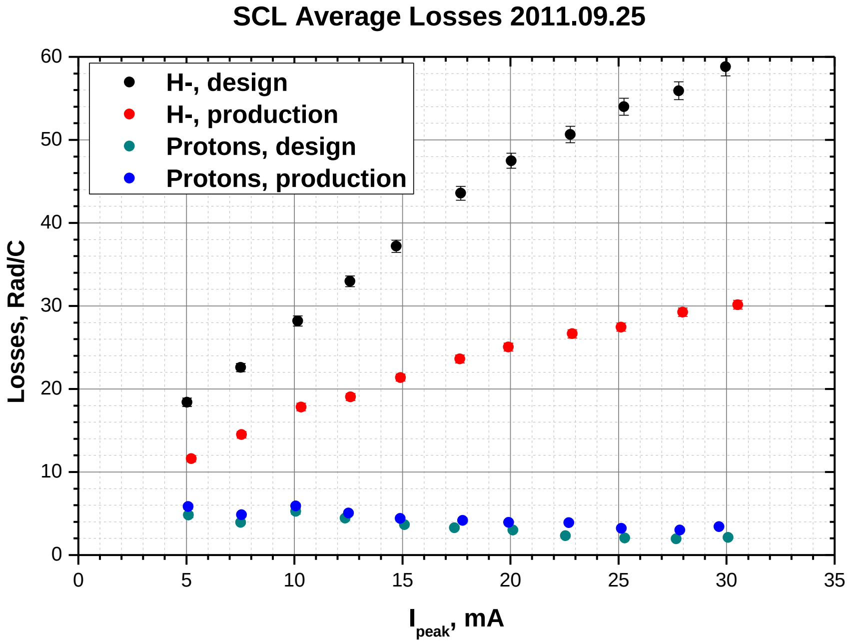
Intrabeam stripping loss was a major hiccup in initial commissioning of SNS to 1.4 MW







A. Shishlo, J. Galambos, A. Aleksandrov, V. Lebedev, and M. Plum, PRL 108, 1 (2012)

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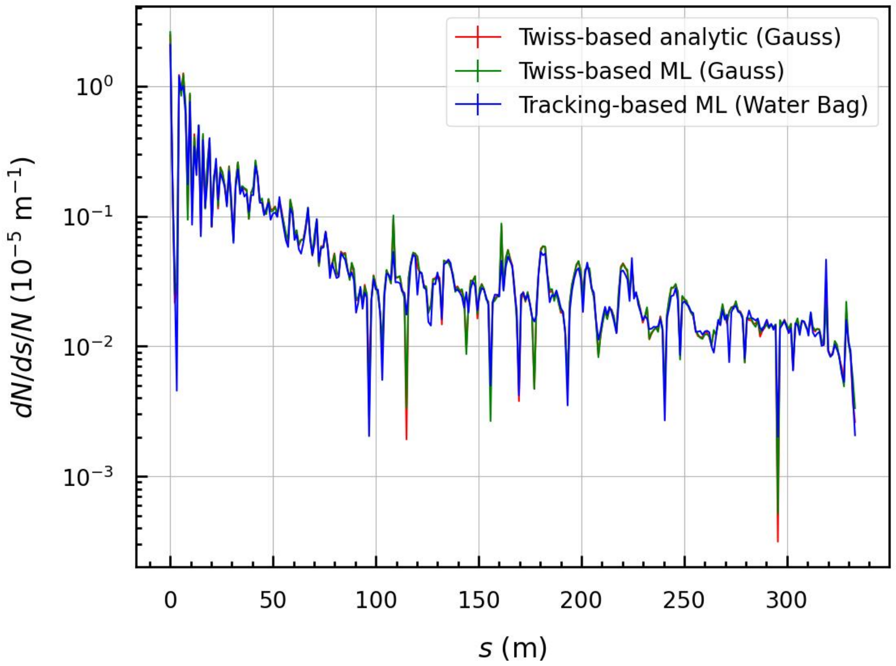
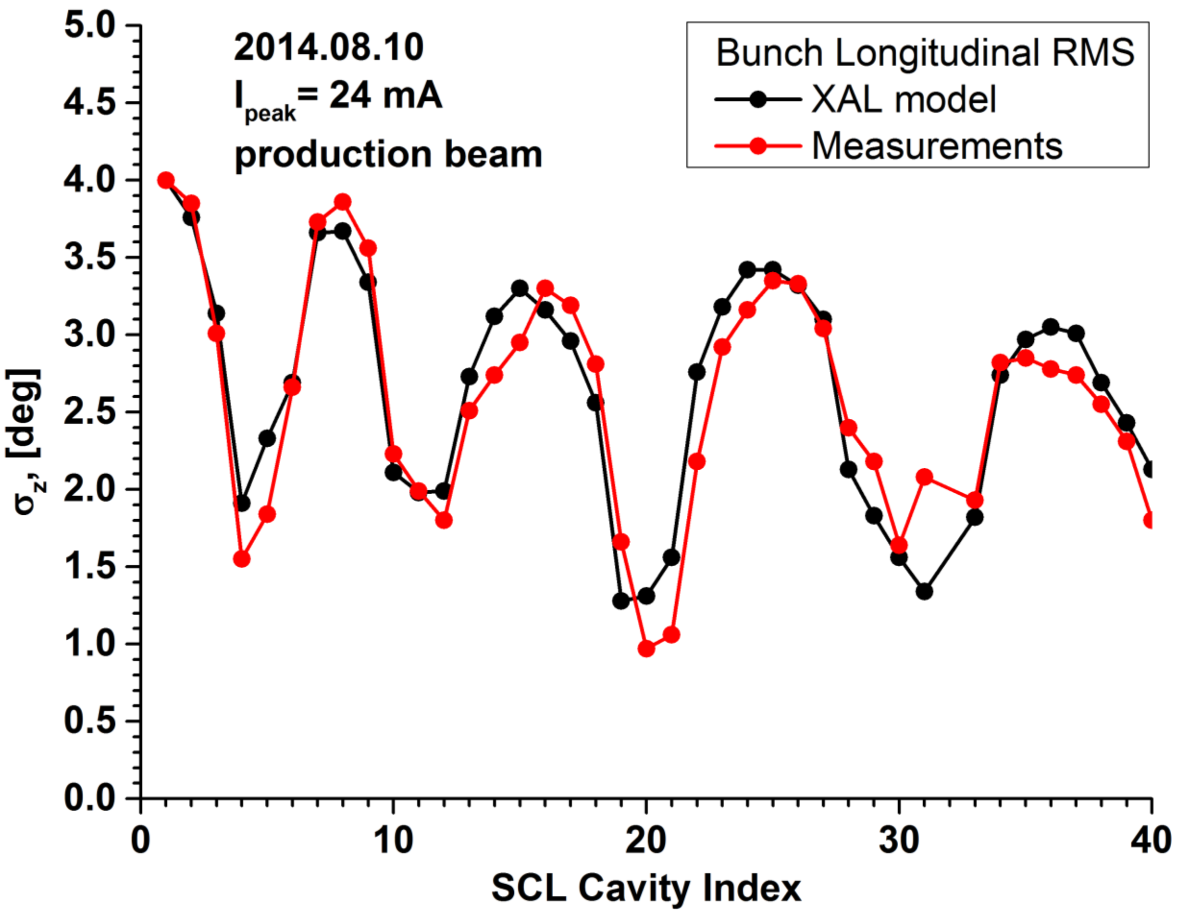
intrabeam stripping loss rate in model tracking



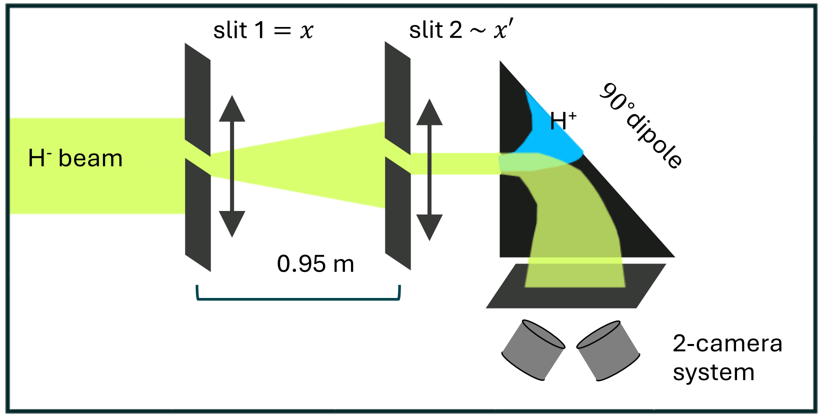
Plot courtesy of Vasiliy Morozov

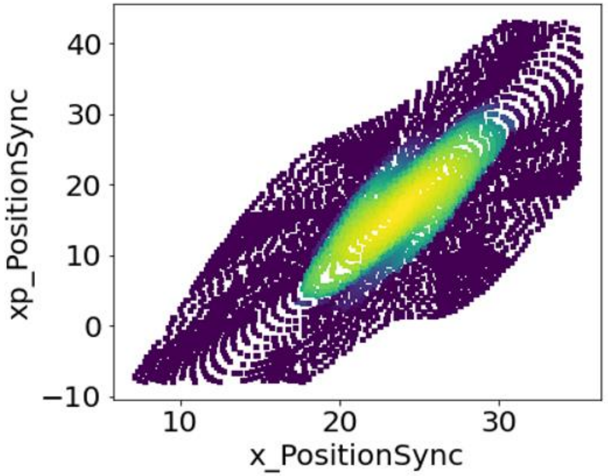
SCL rms benchmark for production (mismatched)

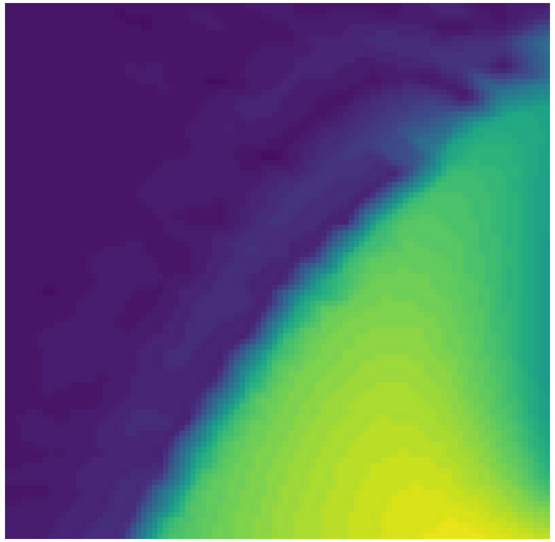


Shishlo, LINAC2014

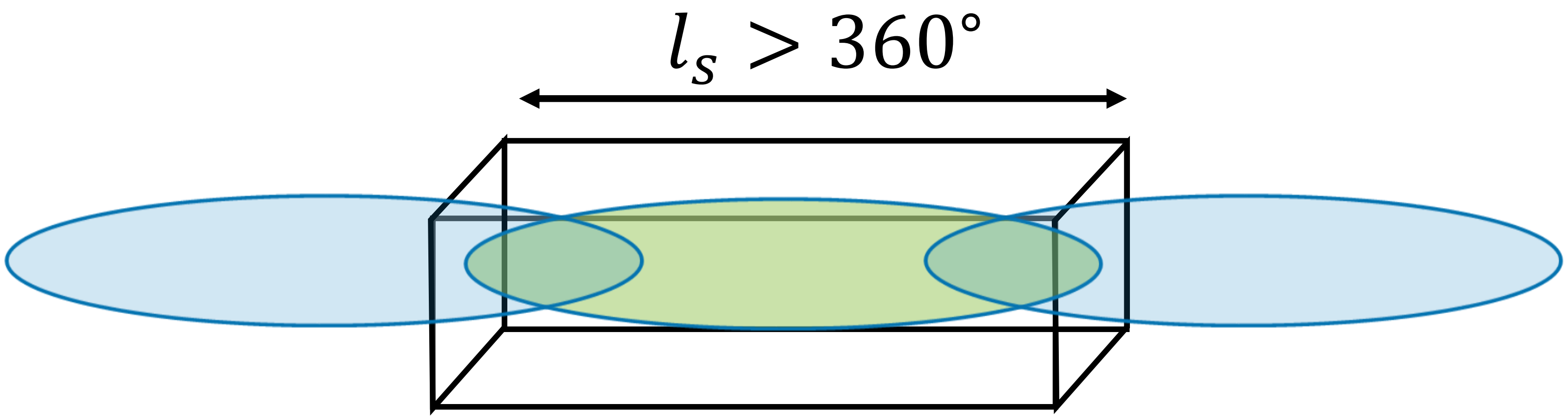
High Dynamic Range (HDR) Phase space measurements



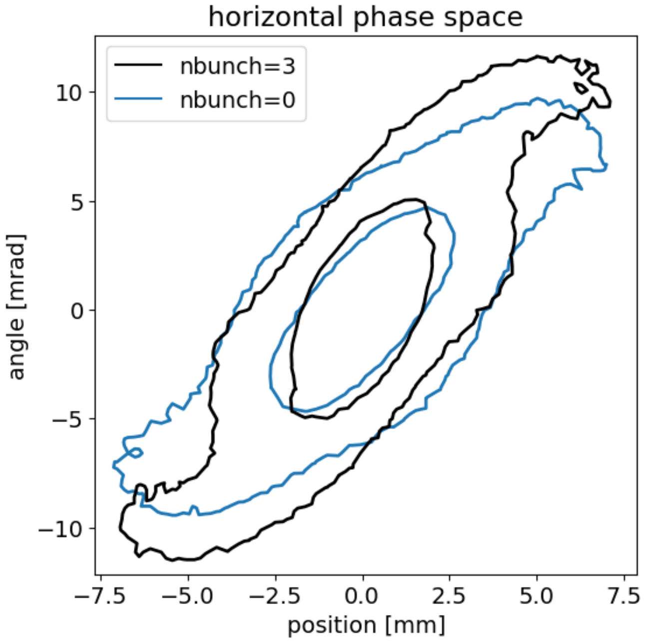


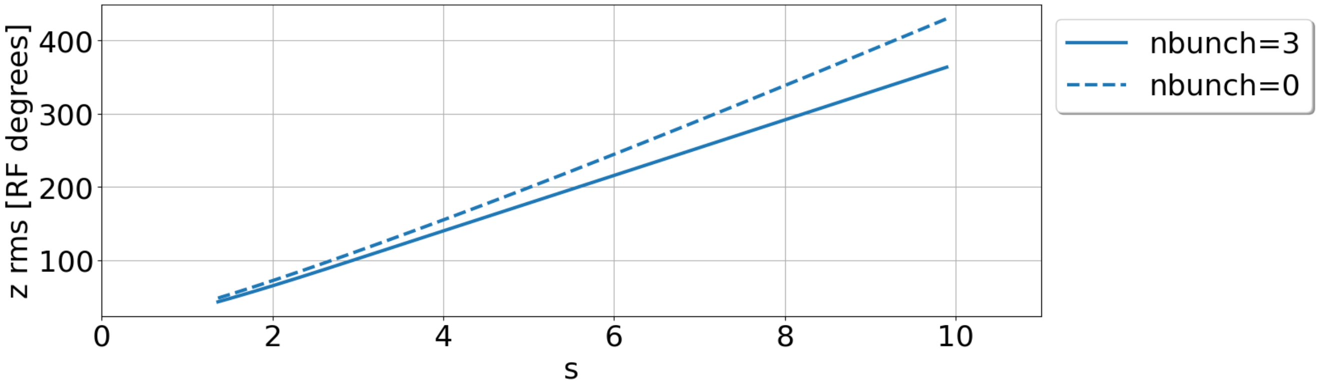


PyORBIT has multi-bunch field solver



Poisson solver :
3D FFT
nx,ny,nz = 64
n_particles = 200k
stepsize <= 0.01 m
n_bunches = 3

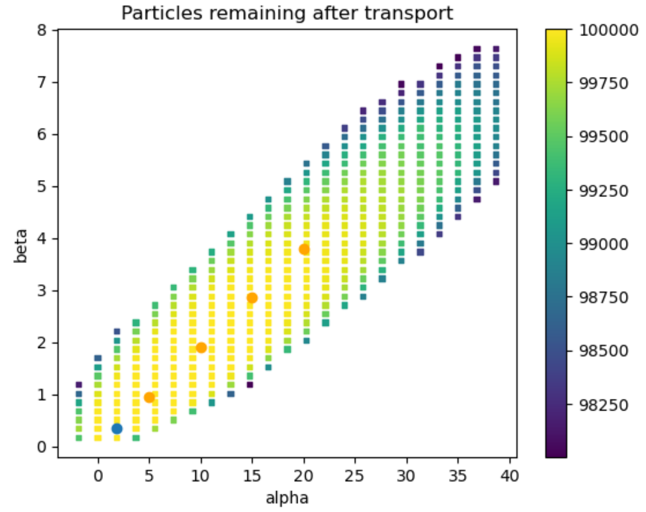


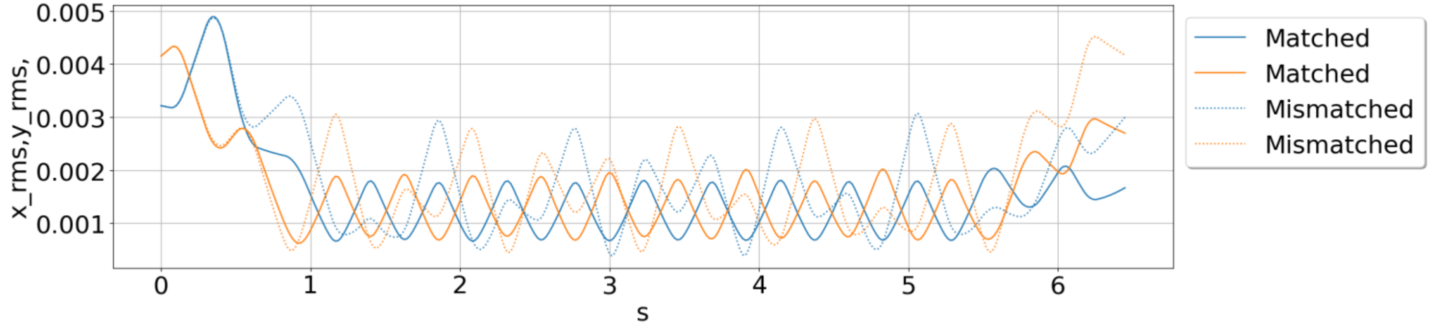


Defining mismatched beams

$$M = \left[1 + \frac{\Delta + \sqrt{\Delta(\Delta + 4)}}{2}\right]^{1/2} - 1$$

$$\Delta = (\Delta\alpha)^2 - \Delta\beta\Delta\gamma$$





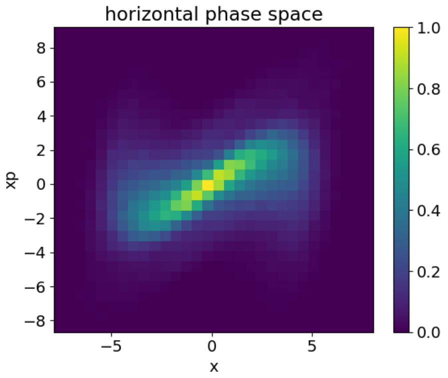
Alpha	Beta	Mismatch Factor	Transmission
1.84	0.34	0	95%
5	0.94	0.67	94%
10	1.90	1.36	93%
15	2.86	1.90	90%
20	3.80	2.35	86%

Large energy spread and longitudinal correlation means large chromaticity

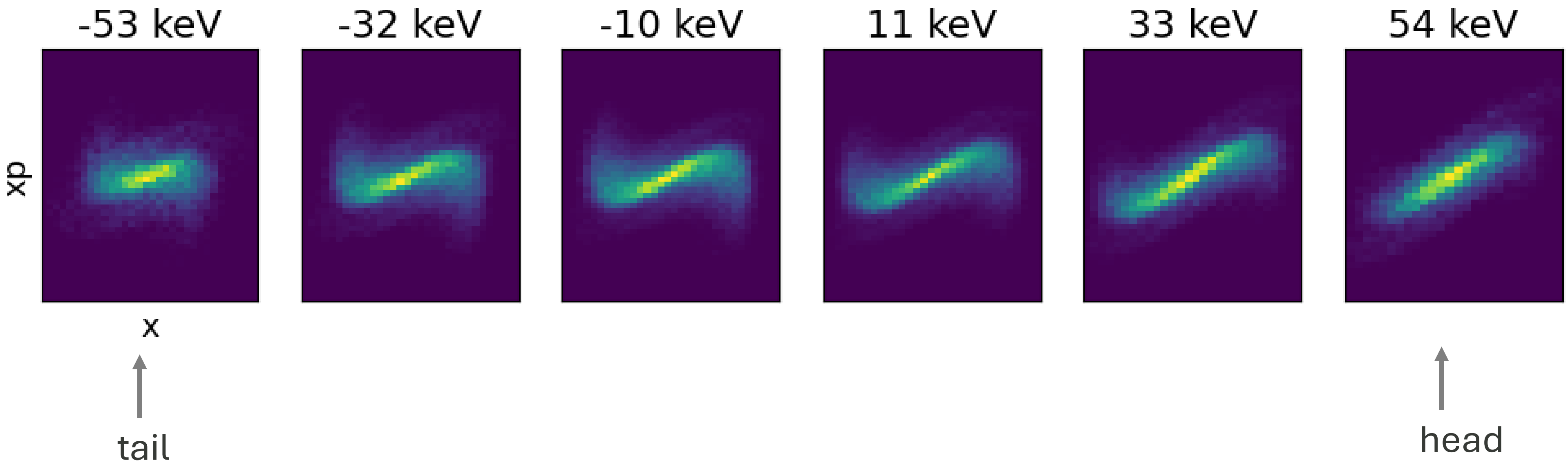
Per FODO cell, $\Delta\nu_{cell} = -0.07 \left[\frac{1}{MeV}\right] \delta E$

For 30 keV RMS width and 9.5 cell FODO, phase advance varies by $\pm 7°$

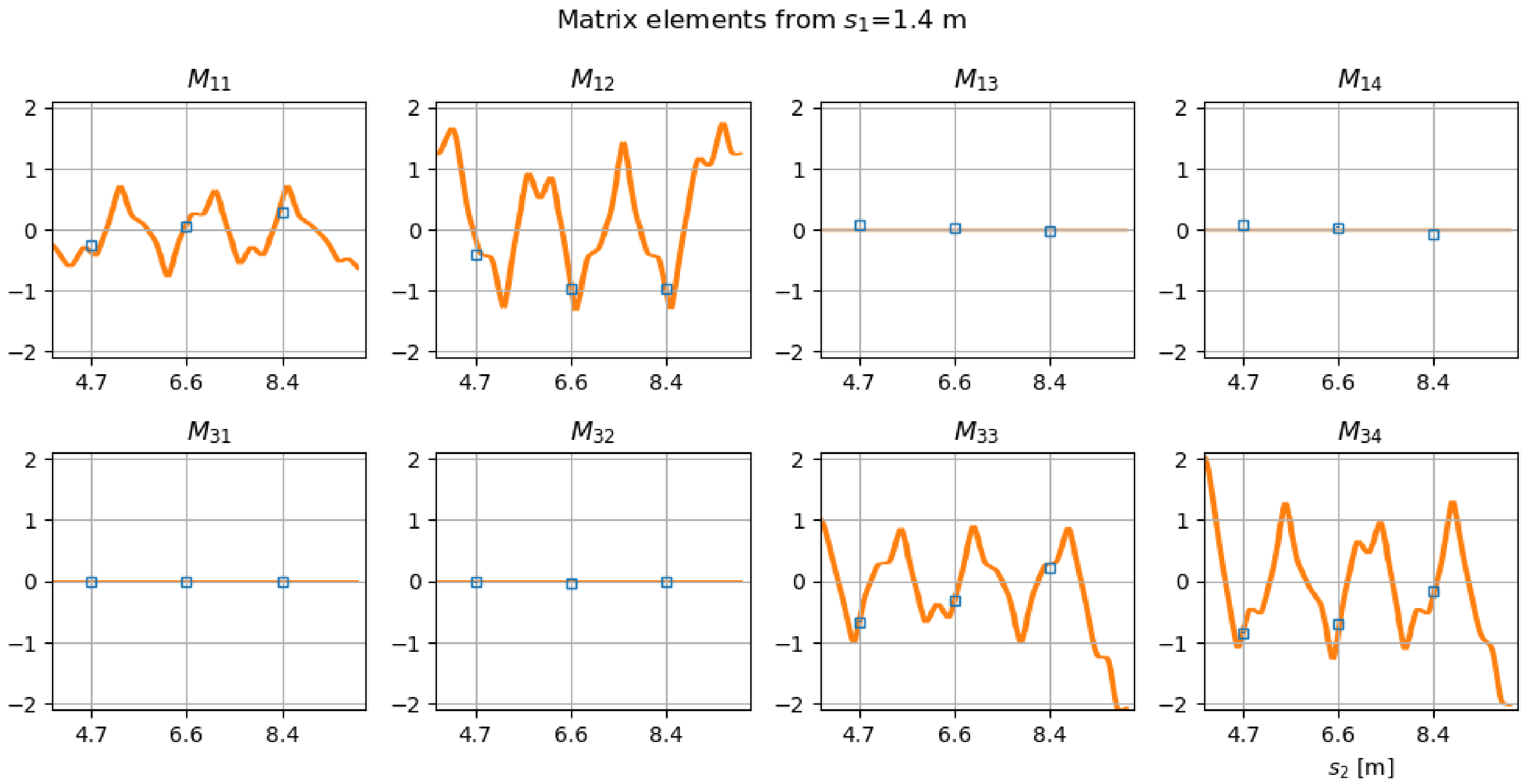
Full projection phase spaces:

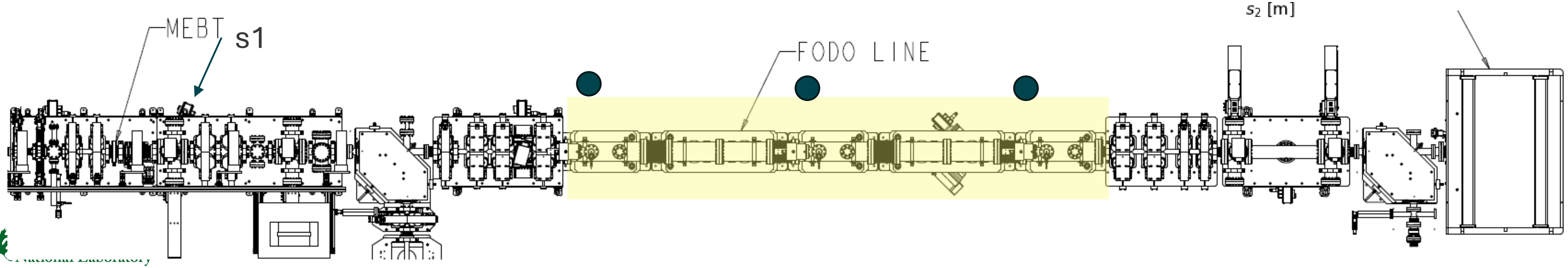


Phase space for different energy slices:



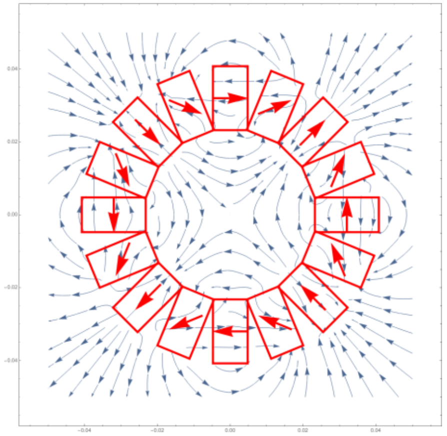
Measured 0-current matrix elements compared to simulation:

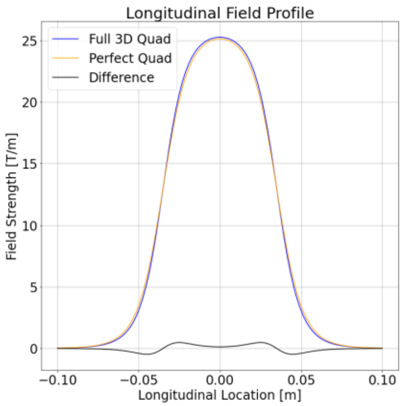


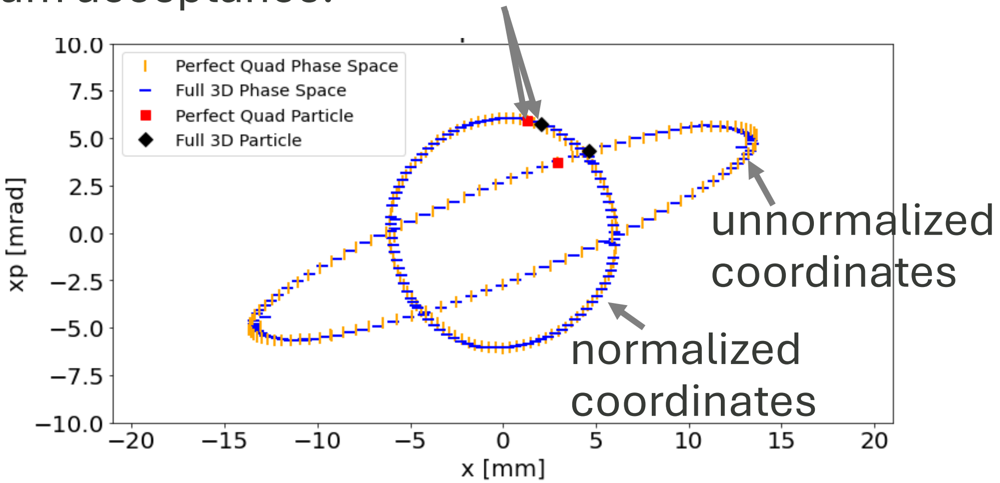


Self consistent model of PMQs has little effect on dynamics

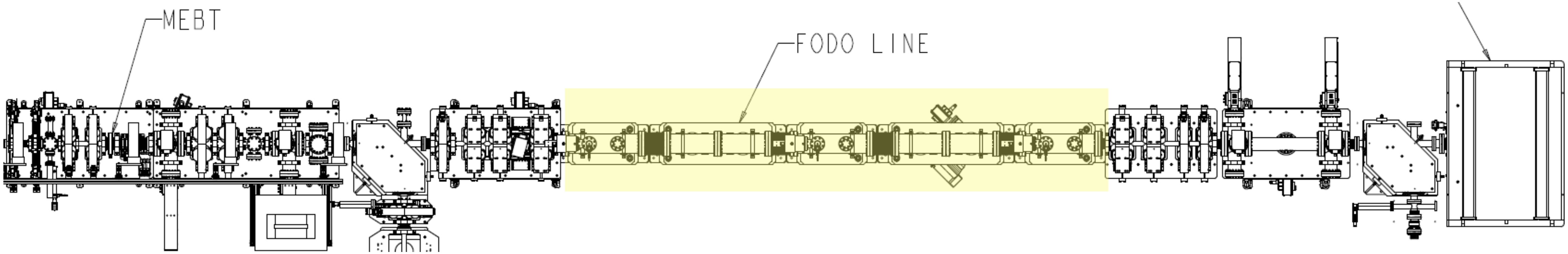
$\Delta\nu = 0.03$ for a single particle at maximum acceptance:







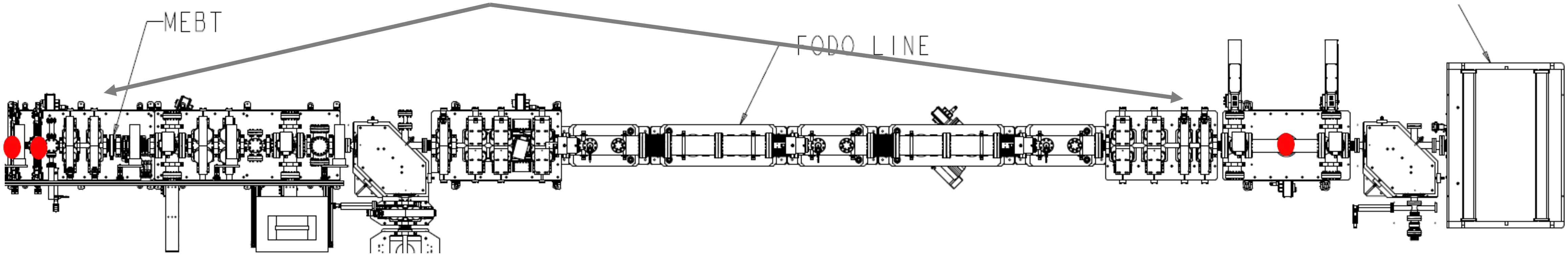
Thompson, Gorlov, et al, High Brightness Workshop, CERN (Oct 2023)



Large losses and steering kicks

Losing a least 3% of 50 mA beam by end of beamline

Existing correctors



Measure centroid to be as much as 0.5 cm offset in this area
Aperture r=4 cm, x,y rms ~ 0.5 cm