OAK RIDGE National Laboratory

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

Beam Dynamics in the SNS Linac and Beam Test Facility

PRESENTED BY

Kiersten Ruisard

Oak Ridge National Laboratory

U.S. DEPARTMENT of ENERGY

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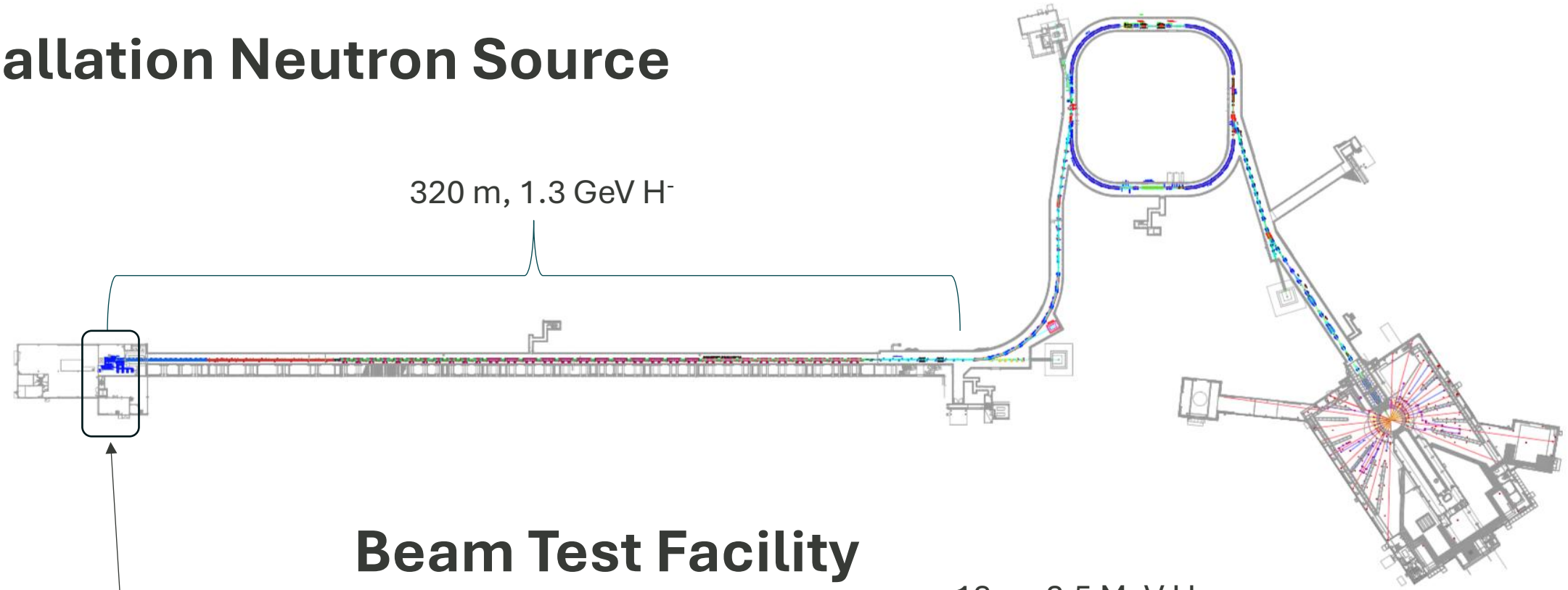
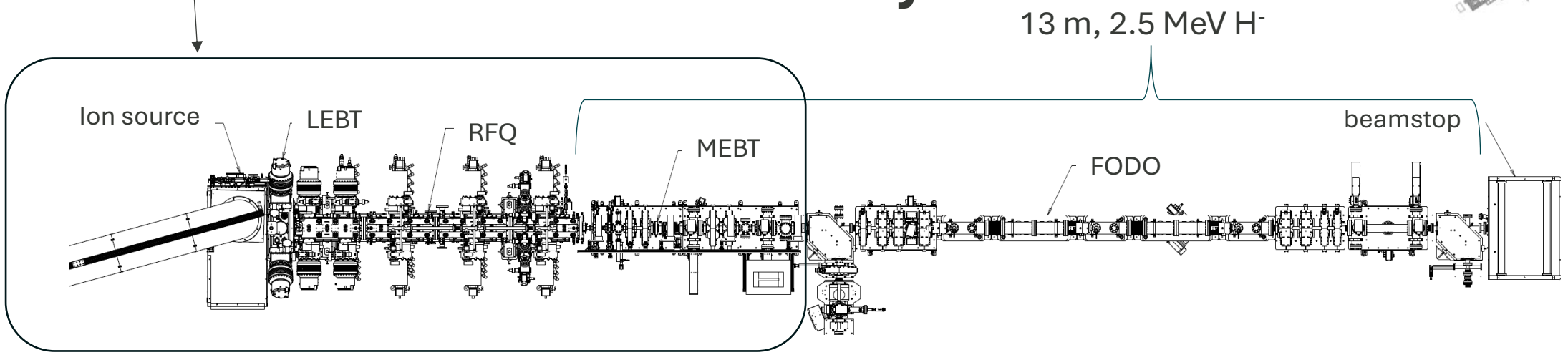
Spallation Neutron Source

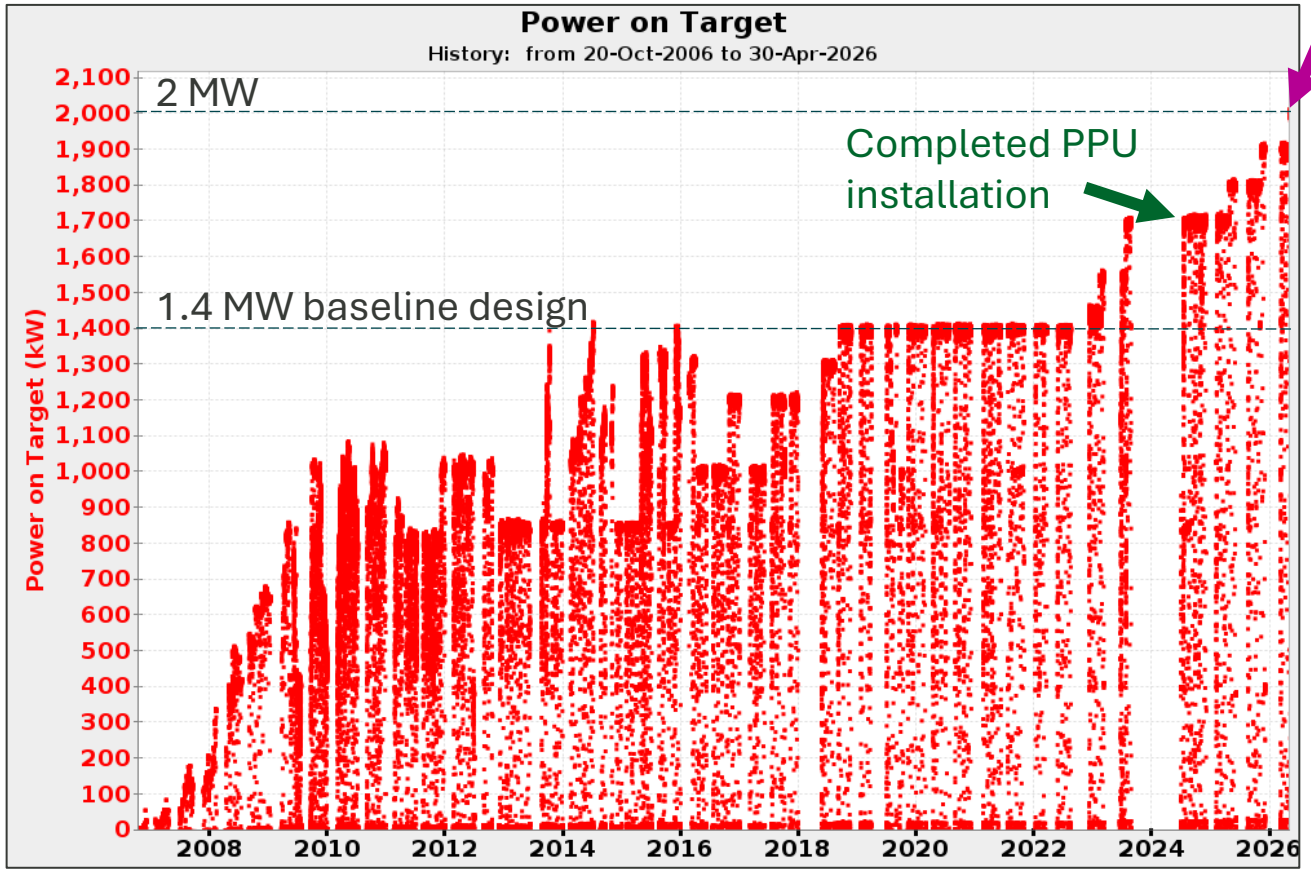


Beam Test Facility



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)

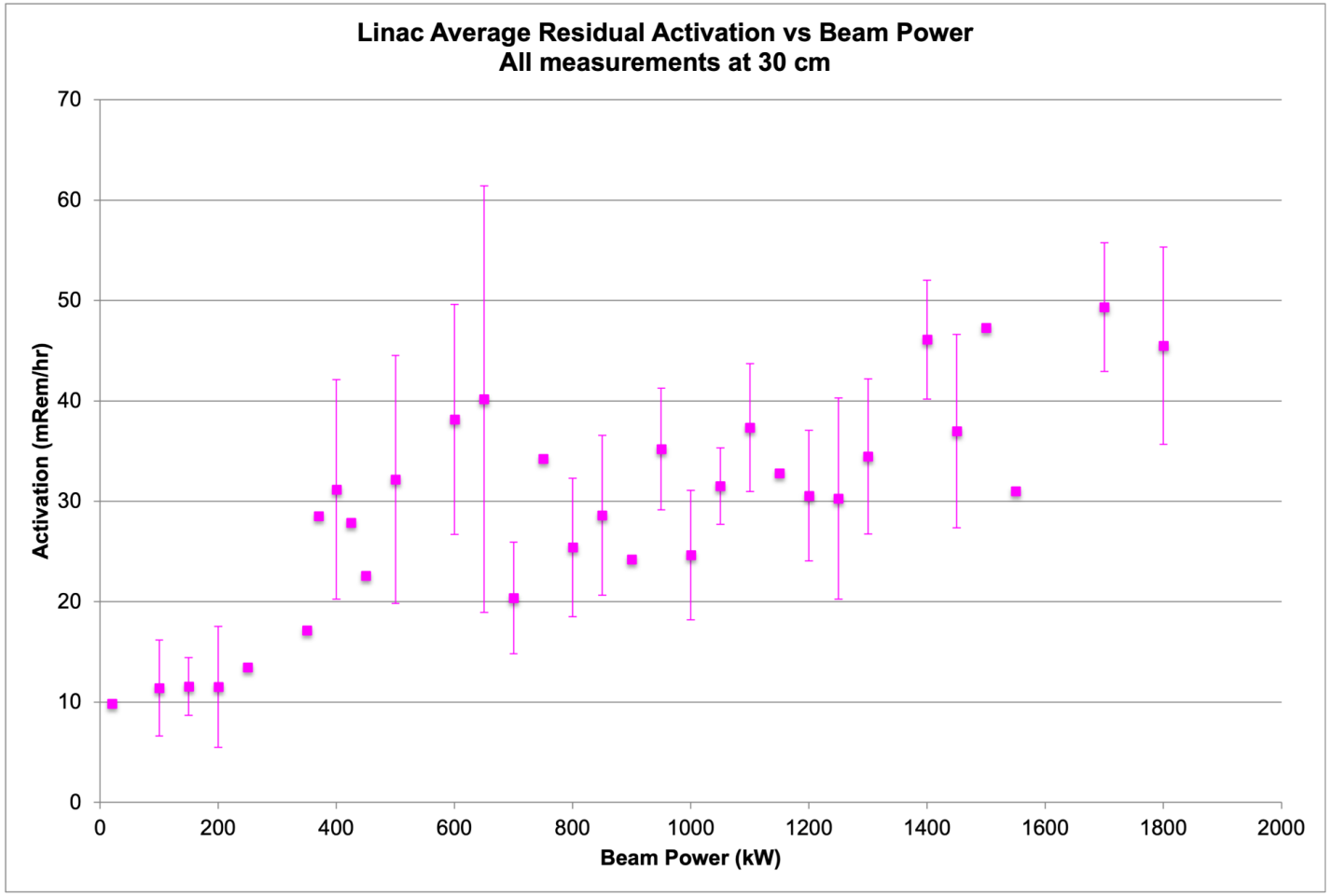


20th anniversary of SNS beam on April 28!

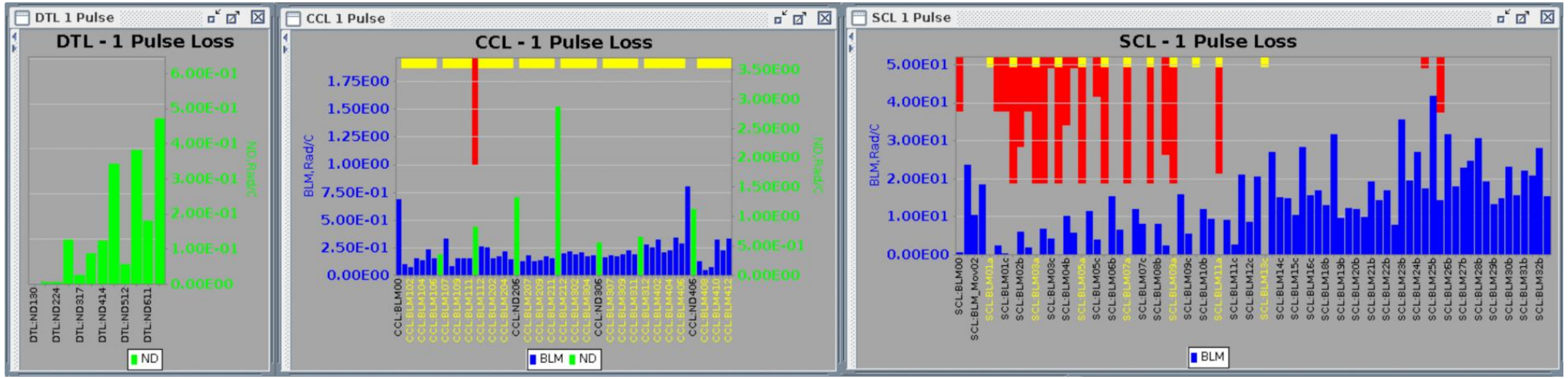
After completion of Second Target Station, SNS will ramp to 2.7 MW

Beam current will increase by 50% from SNS design value

Increased beam loss at 2+ MW brings technical challenges



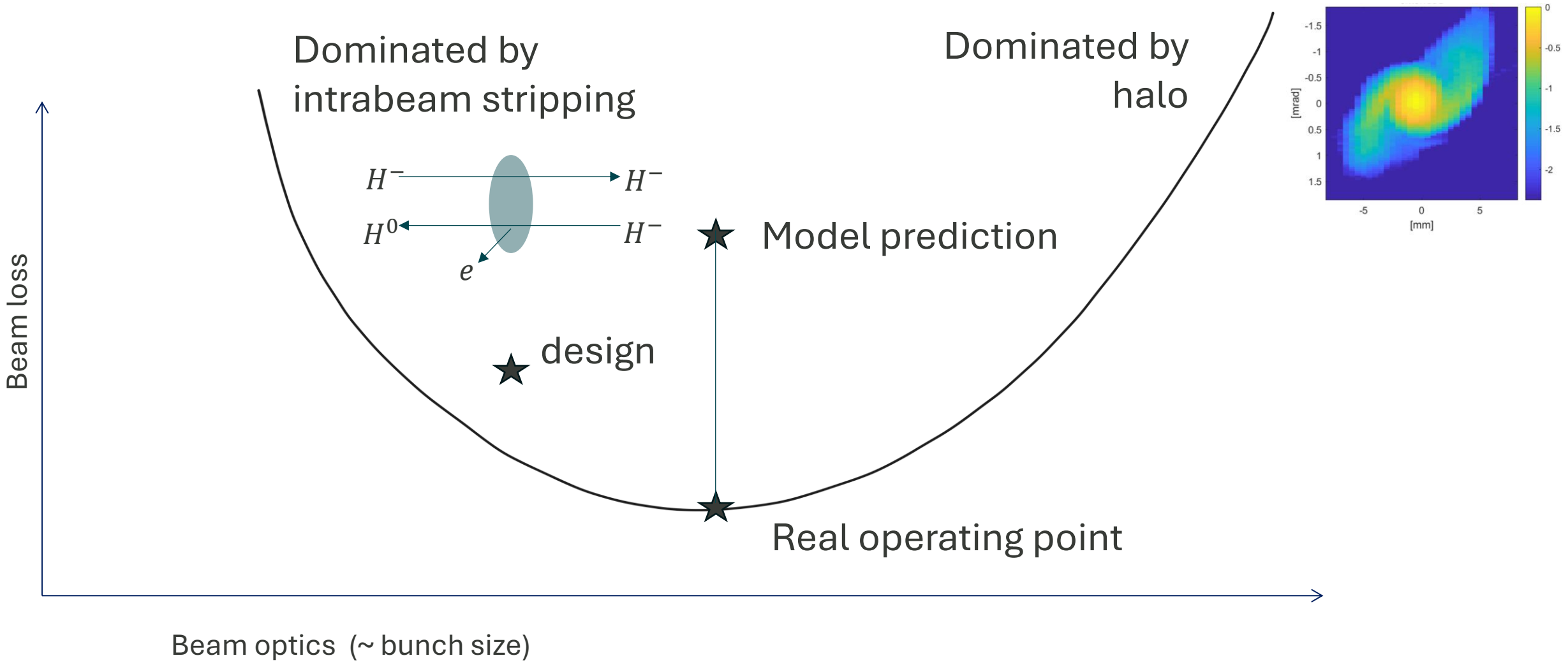
Currently, beam loss control is human-driven and empirical



Automated beam loss tuning is in the near future

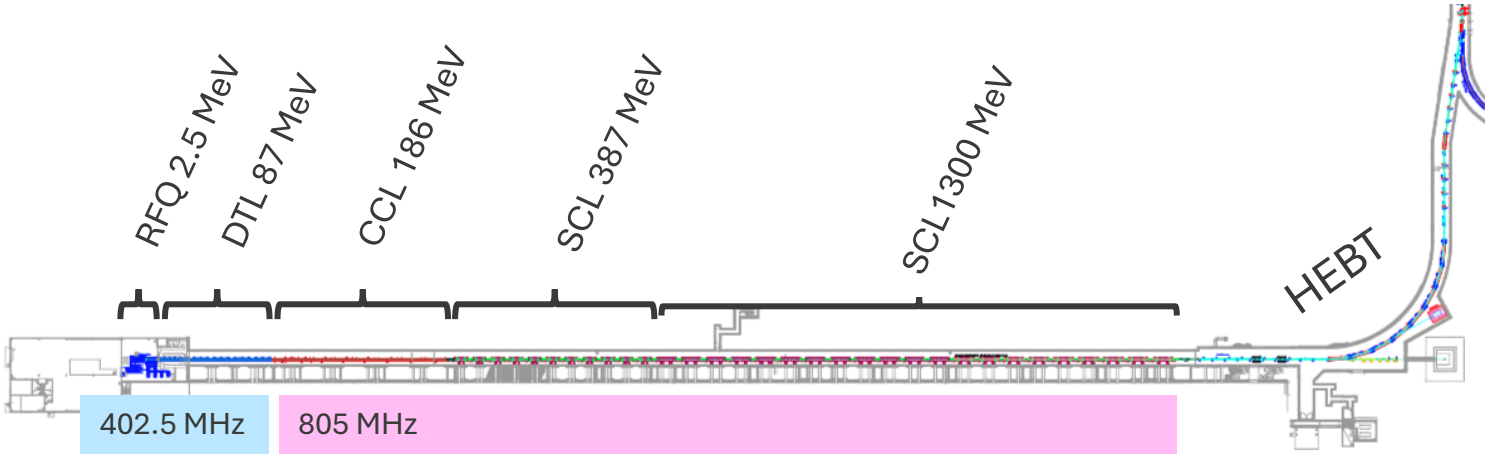
- [x] Empirical understanding
- [ ] Physics understanding

Beam dynamics mechanisms for LINAC beam loss



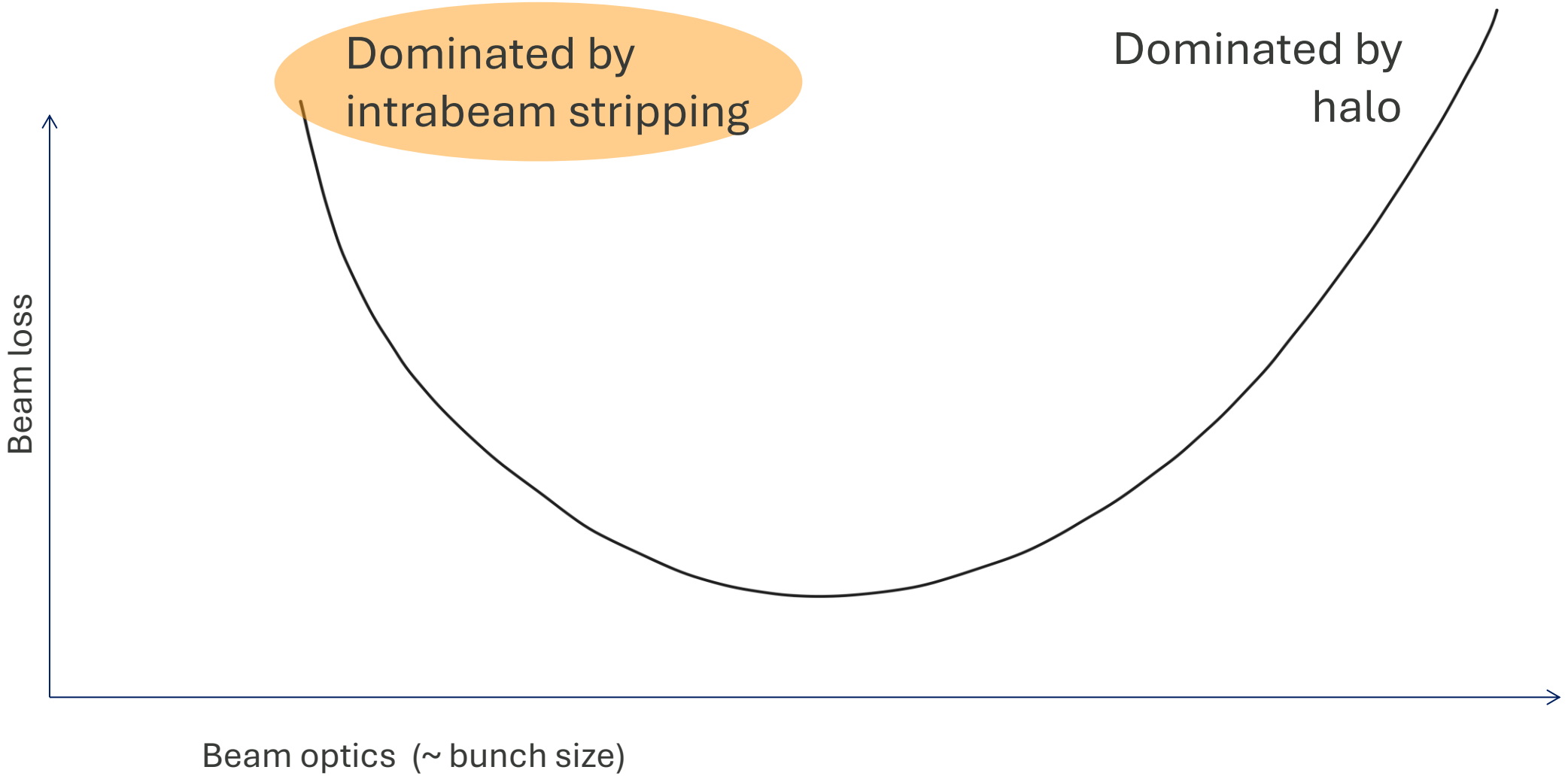
We do use model to understand linac dynamics

- Model-based tuning of cavity phases/amplitudes is fast and reproducible
  - 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…

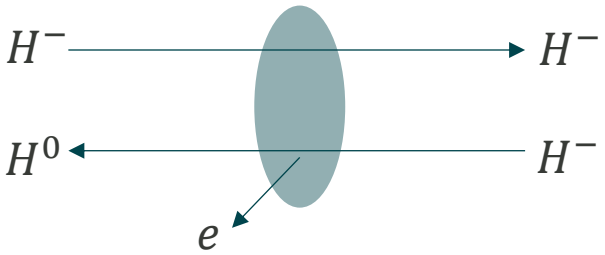
- We do not rely on rms beam sizes (model or measurement) to define operating point
- Model at operating point predicts large losses. What is wrong with the model?

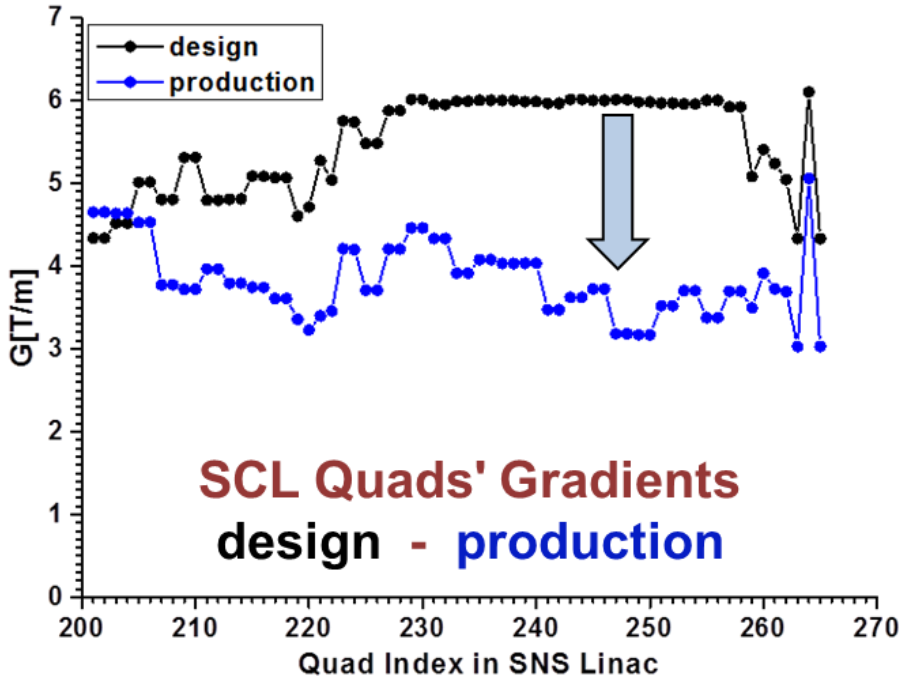

Dominated by
intrabeam stripping
Dominated by
halo
Beam loss
Beam optics (~ bunch size)

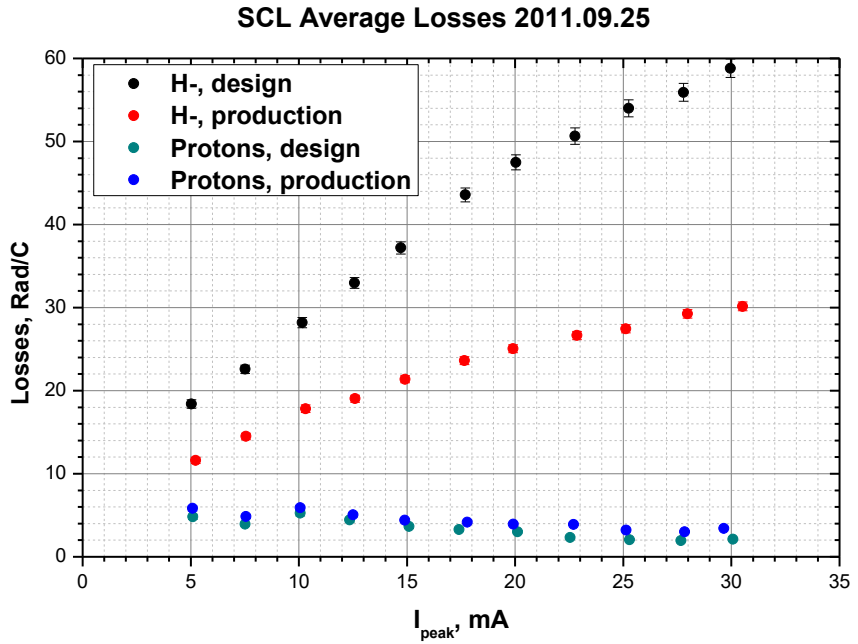
Intrabeam stripping loss was a major hiccup in initial commissioning of SNS to 1.4 MW

Shivam Kakkar, poster WEP4348

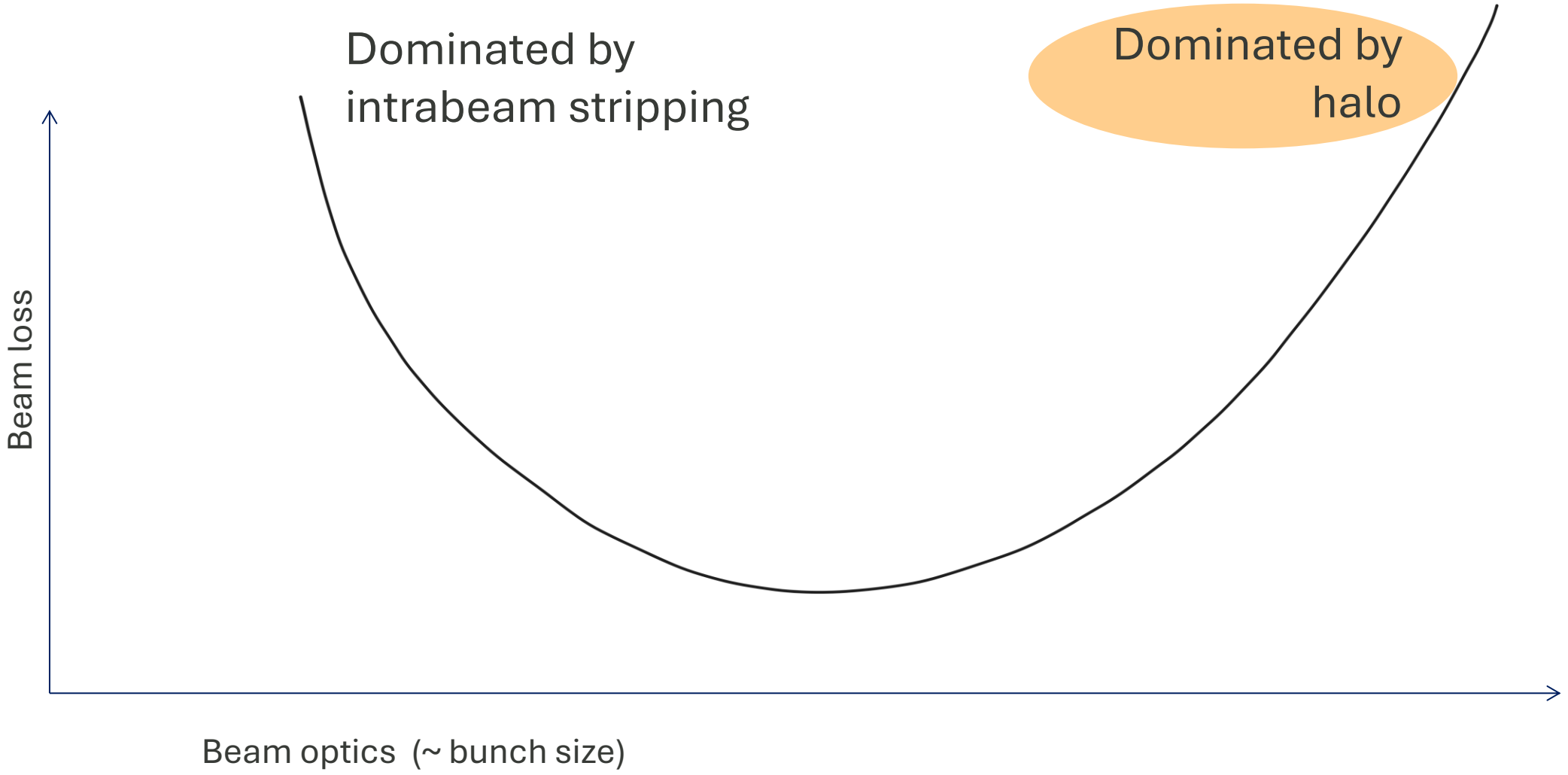
IBSt loss modeling







A. Shishlo, J. Galambos, A. Aleksandrov, V. Lebedev, and M. Plum, PRL 108, 1 (2012)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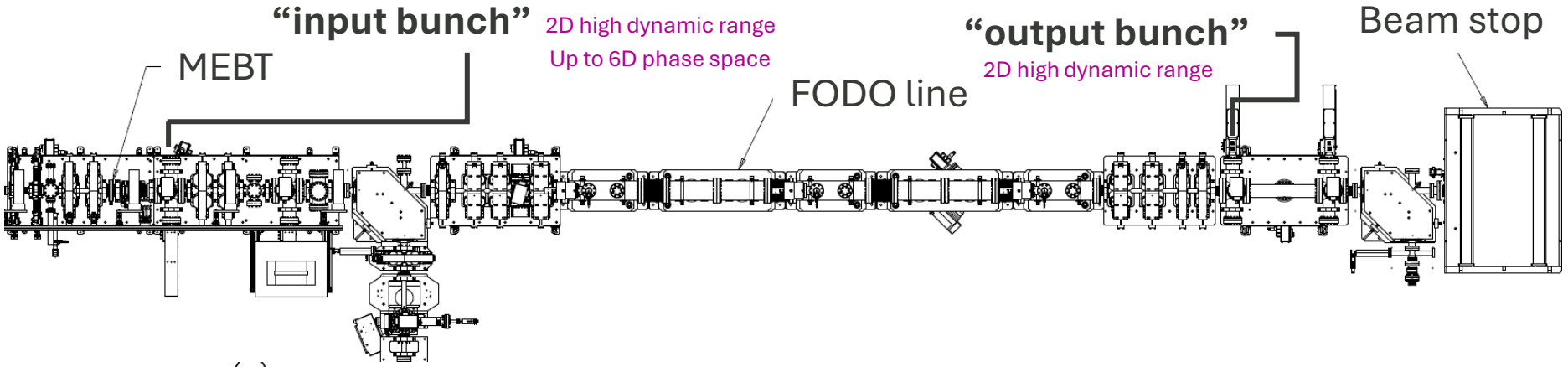
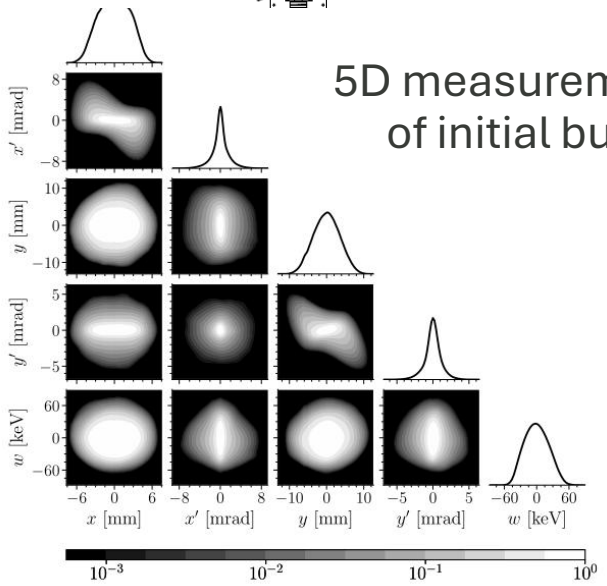
Beam optics (~ bunch size)

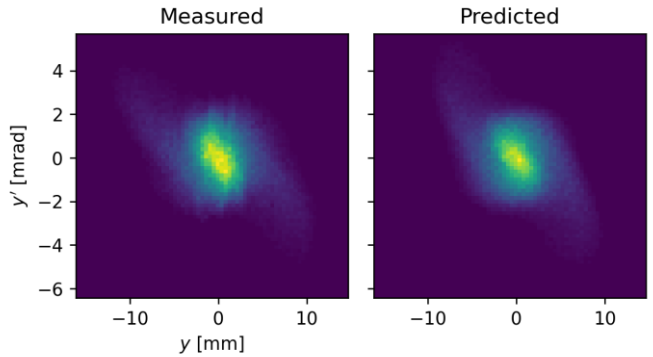
Scope of BTF project is to accurately model halo development over short, 2.5 MeV transport line





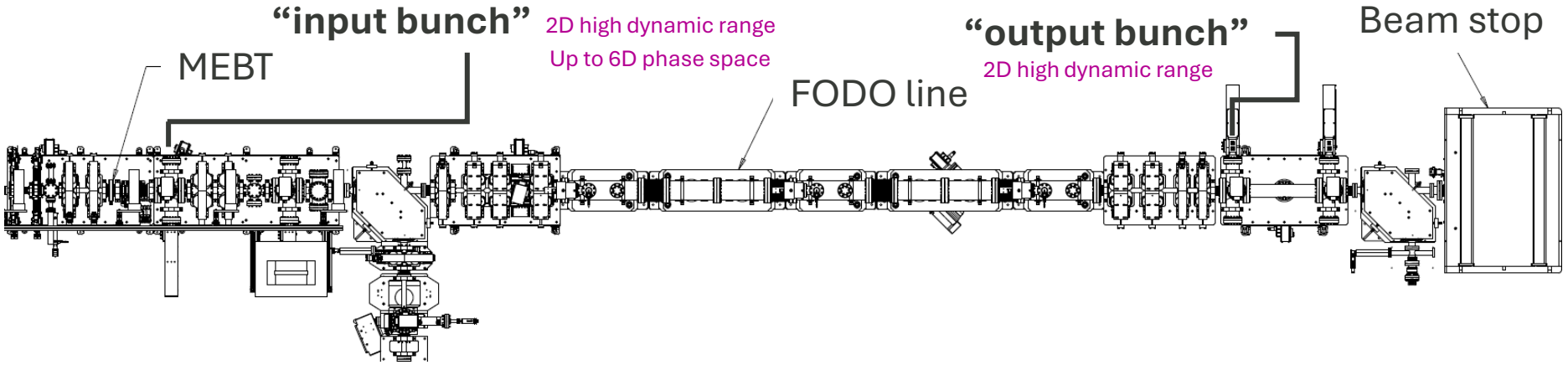
5D measurement of initial bunch

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

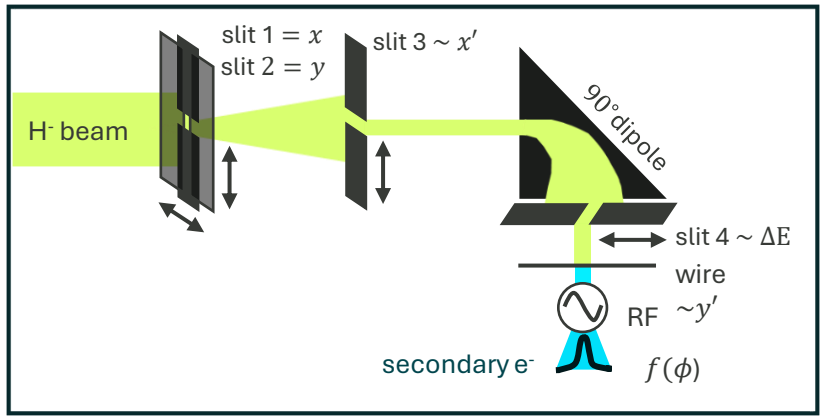


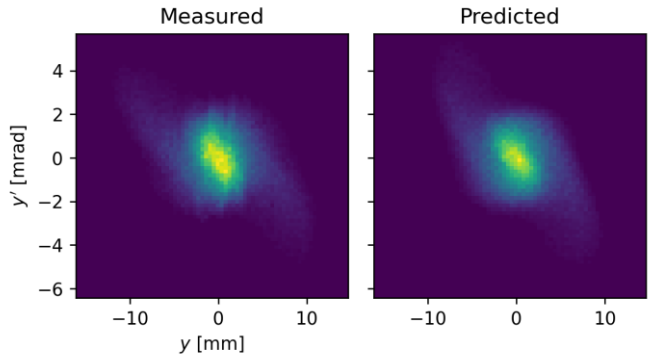
2D phase space measurement (Linear scale, dynamic range of 10^2)

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



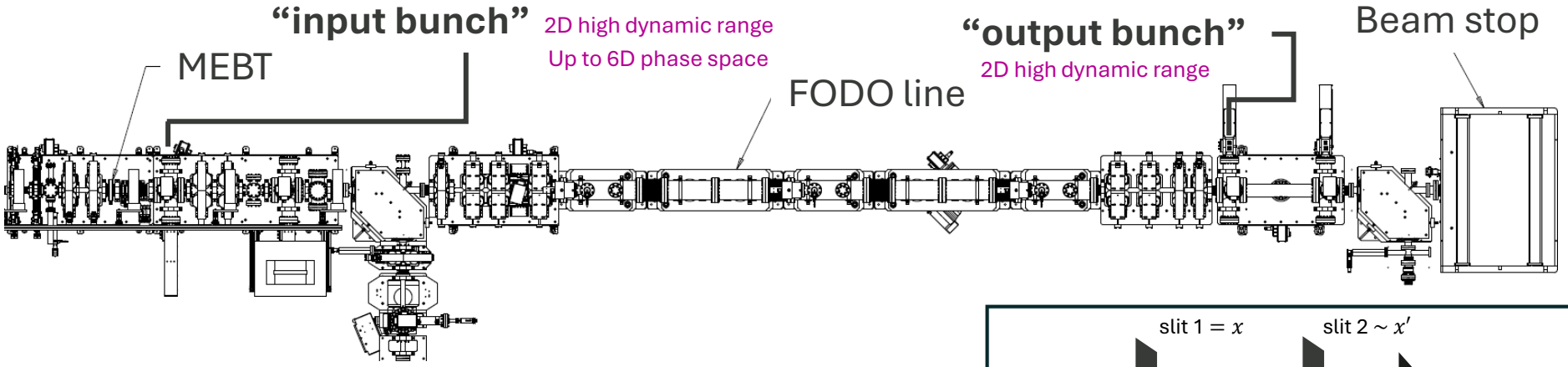
6D measurement of initial bunch





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

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



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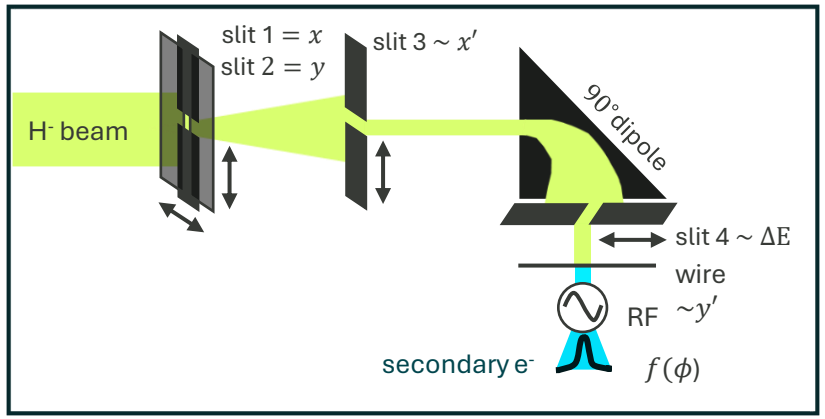
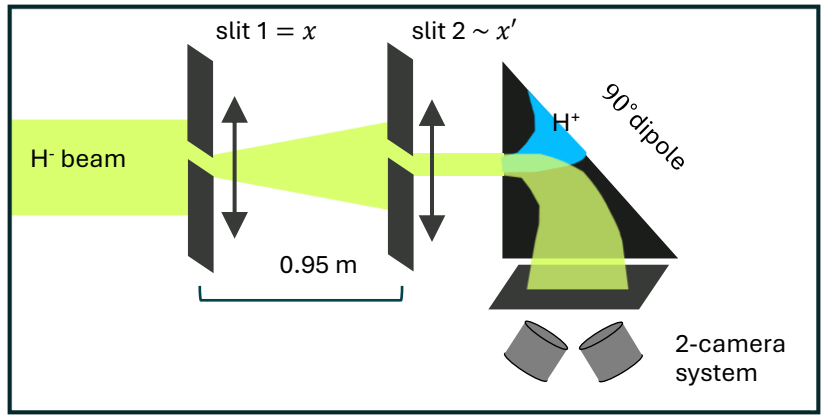
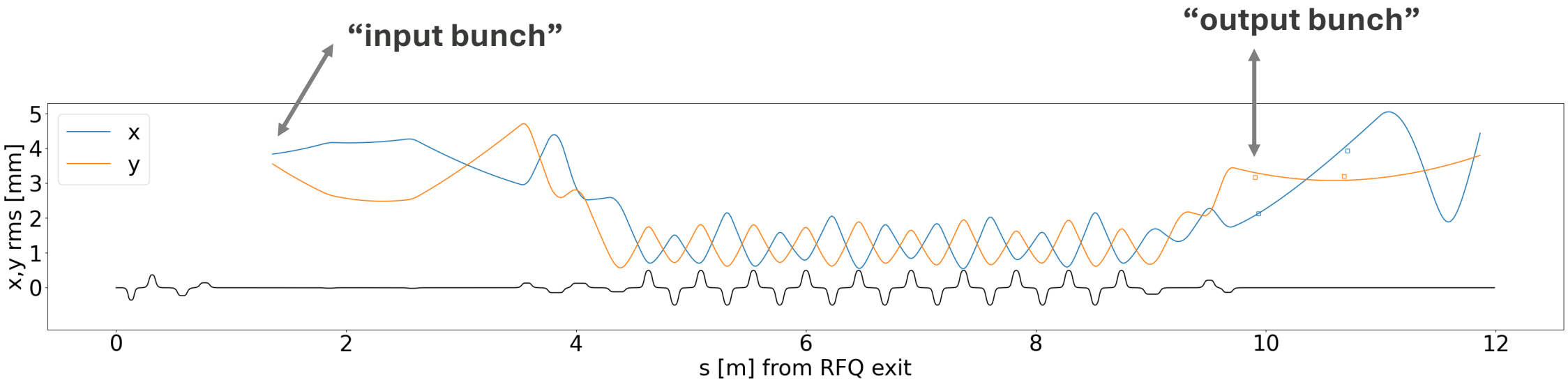




2D phase space measurement

Test beamline is periodic and is long enough to form halo



Relatively strong-focusing FODO line:

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

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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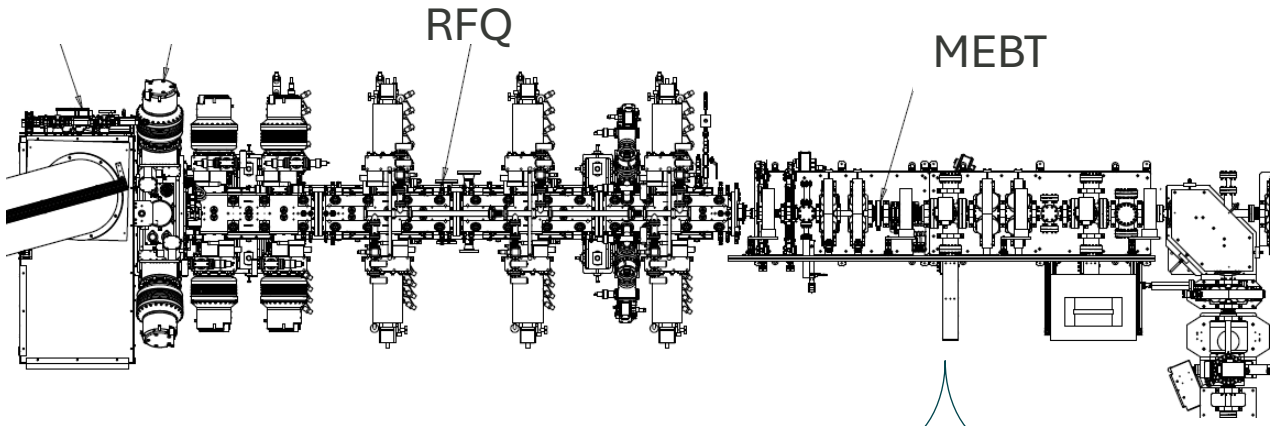
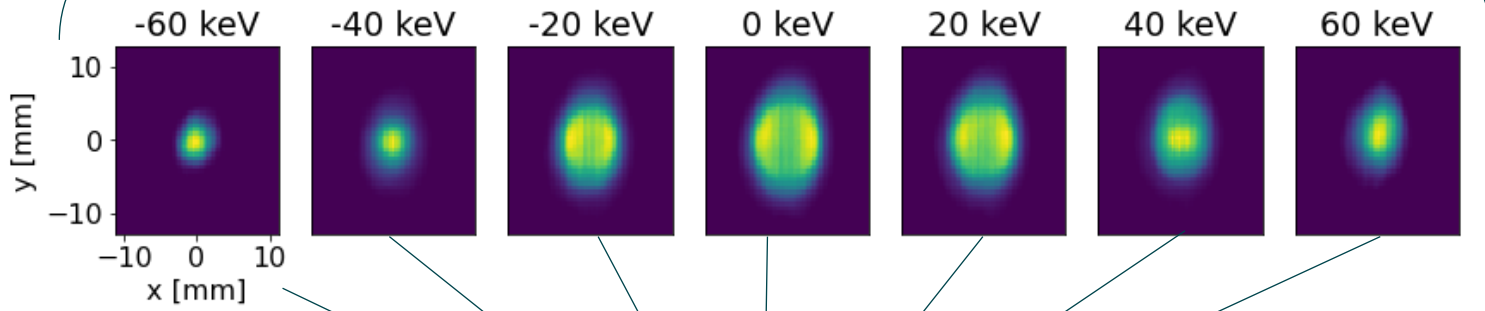
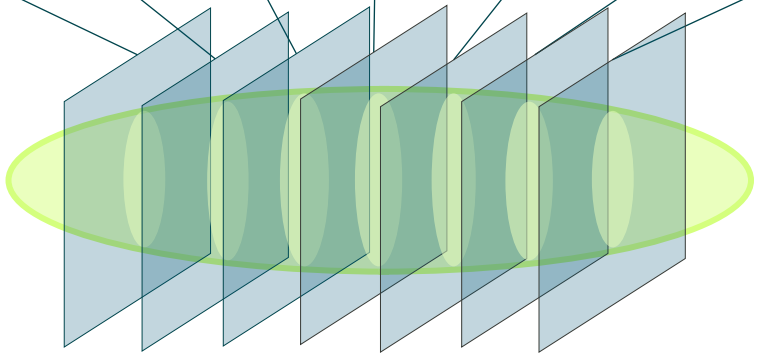
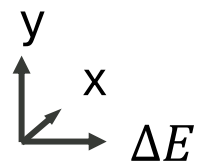


6D phase space measurement



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





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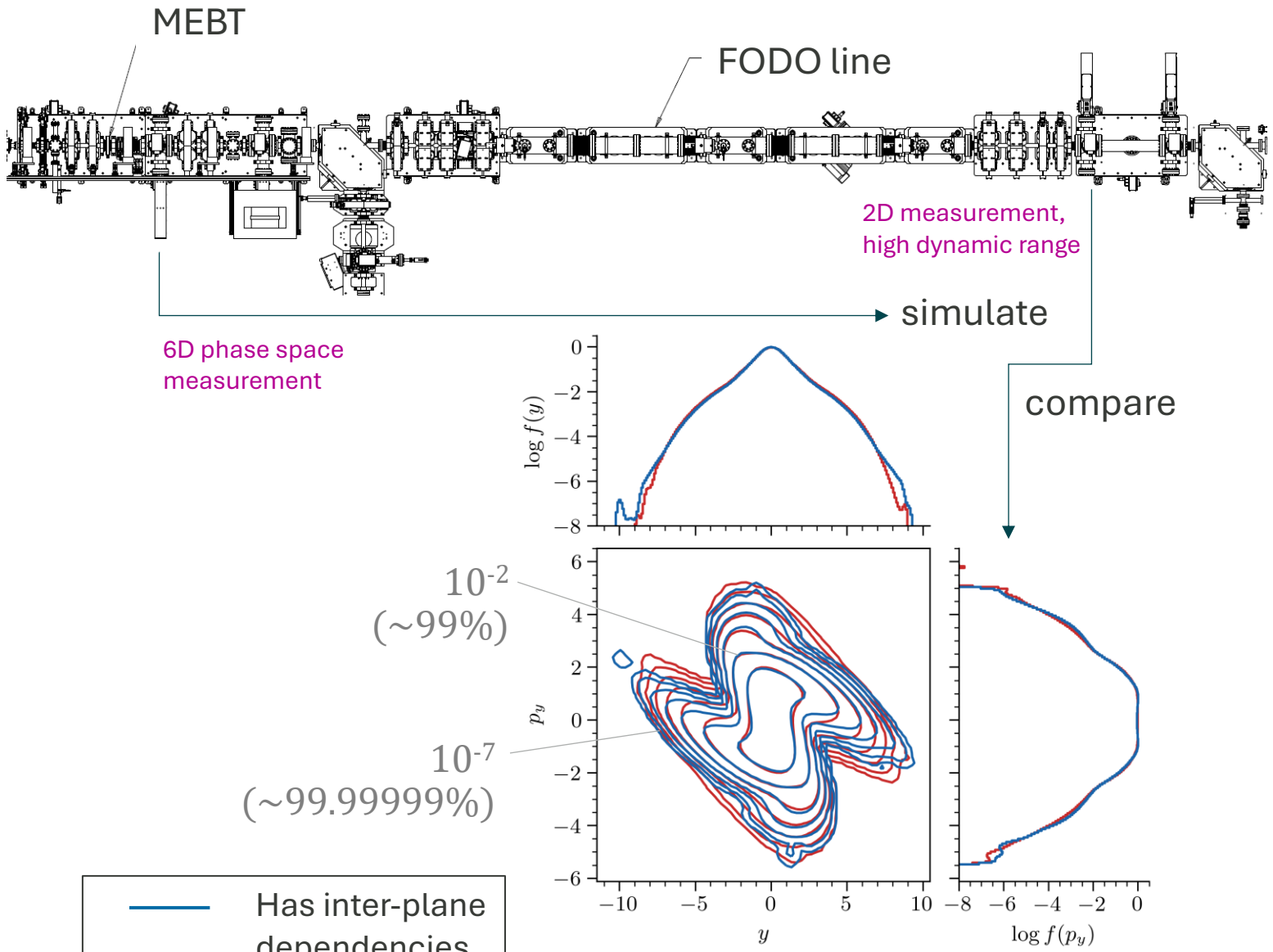

Hoover et al, High Brightness Workshop, CERN (Oct 2023)

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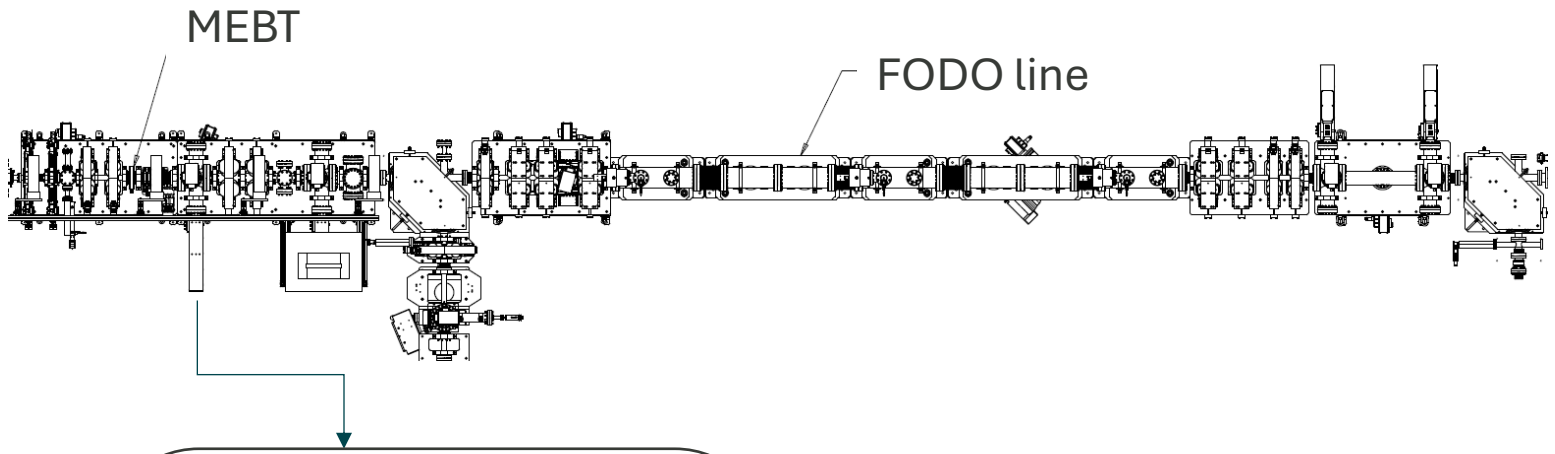

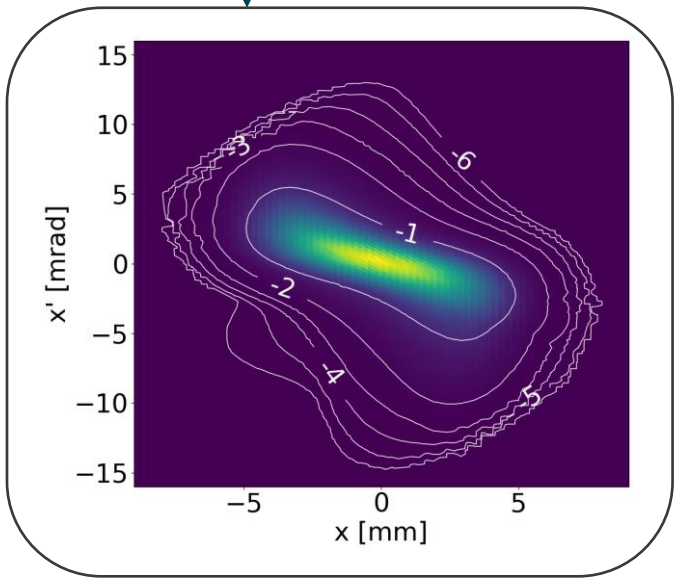

2D phase space measurement with high dynamic range

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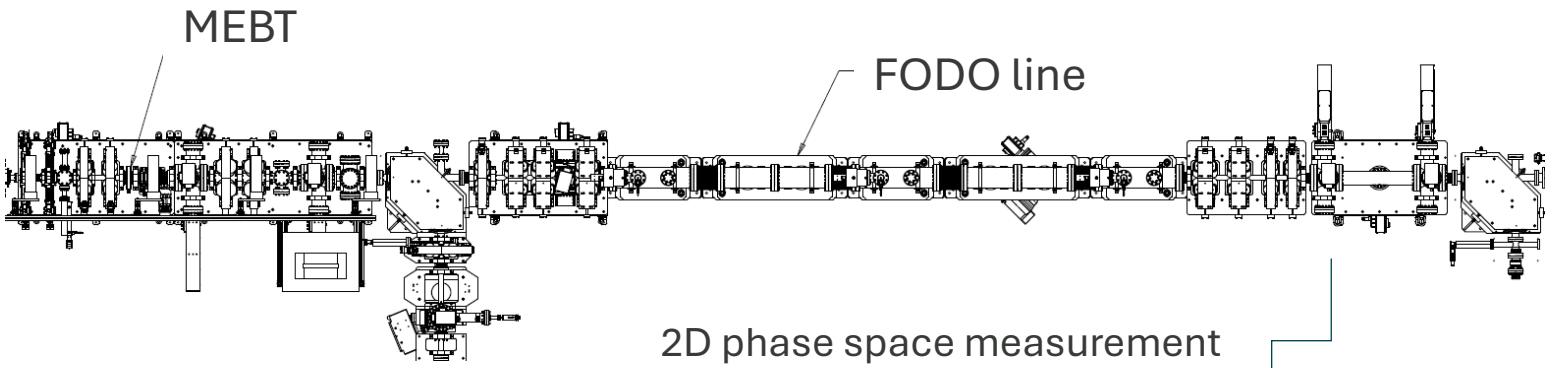

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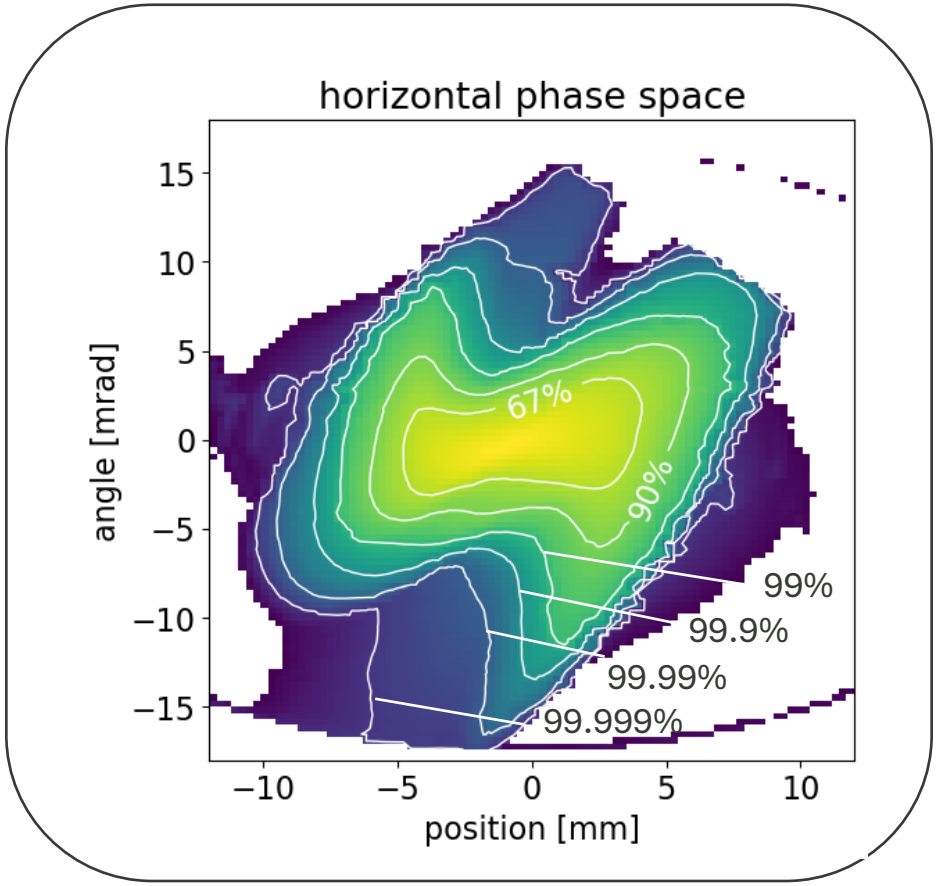

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Trent Thompson, Poster THP5349

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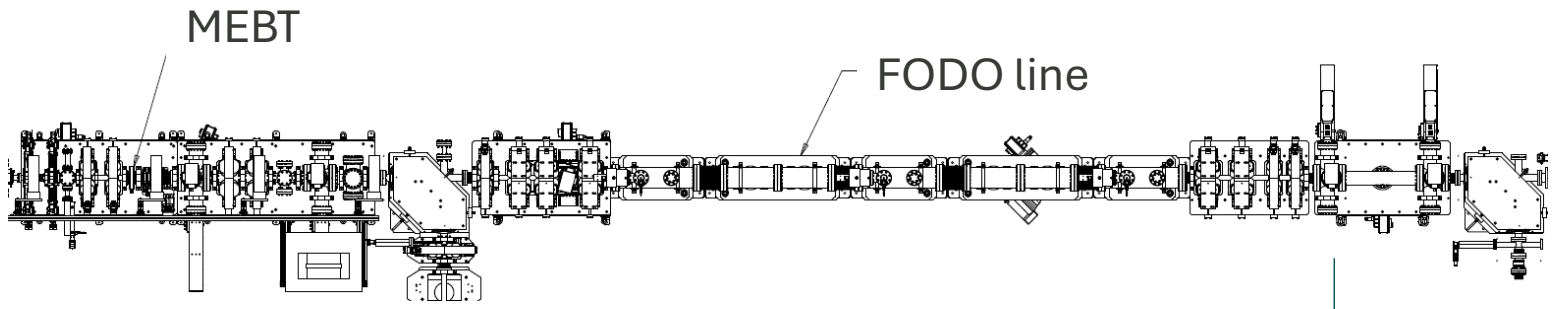
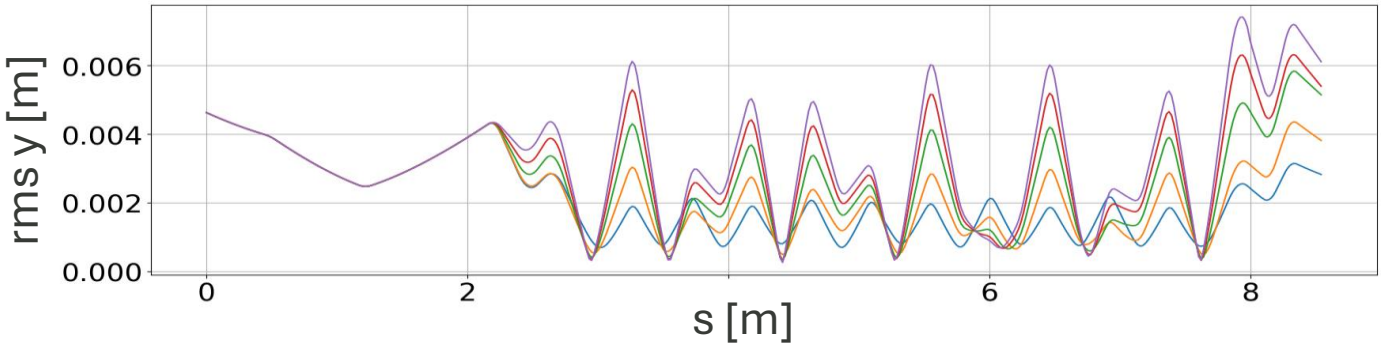
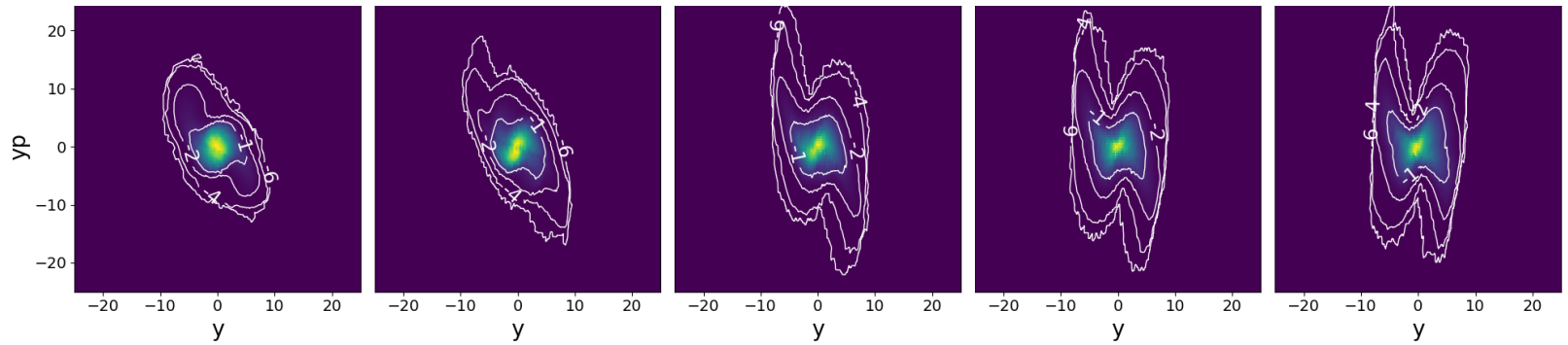


Plot shows 5 optics cases with varying level of mismatch:



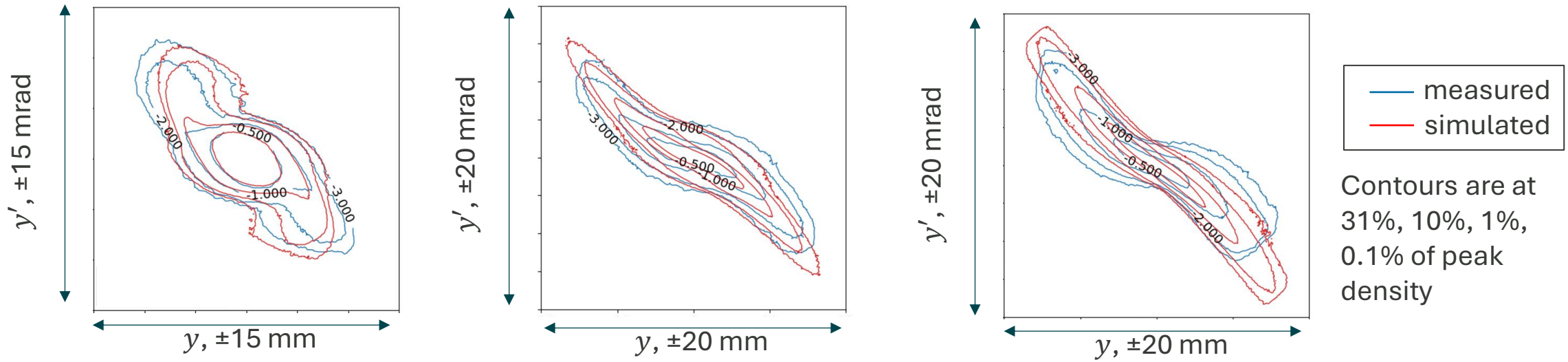
Increasing mismatch parameter



Vertical phase space of output bunch
contours are at 10%, 1%, 0.01%, 0.0001% of peak density

Benchmark of PyORBIT simulation has best agreement for matched case

Increasing mismatch parameter

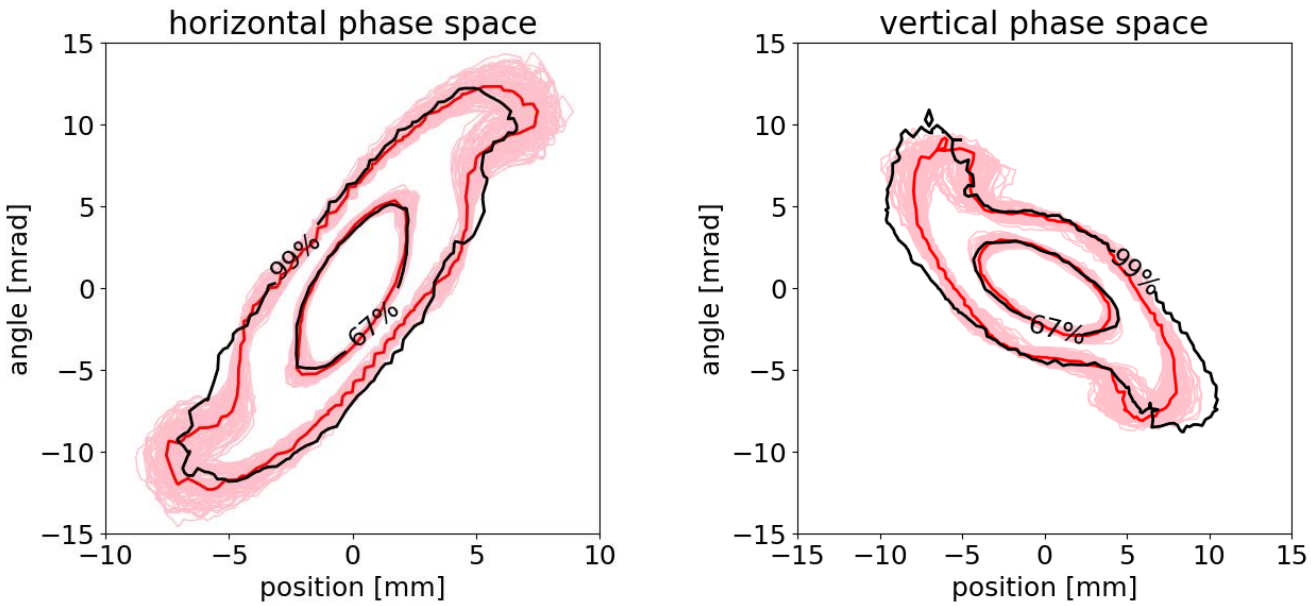


Contours are at 31%, 10%, 1%, 0.1% of peak density

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

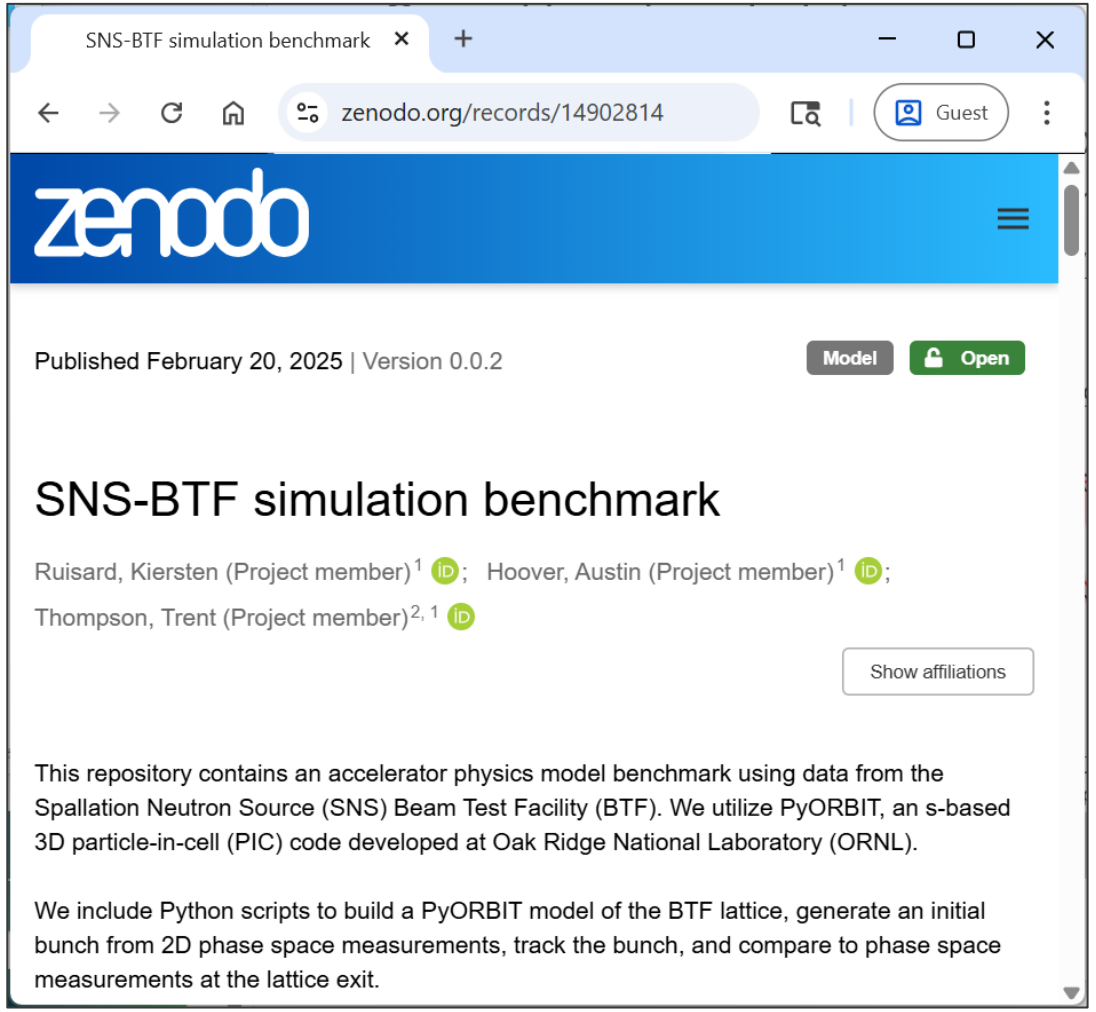
Current benchmark status:

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



Red: simulation model
Black: measurement

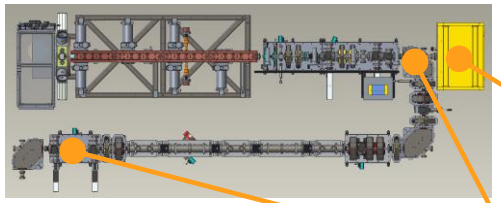
uncertainty from random errors:
quadrupole strength, 0.2%-0.5%
beam energy error 1%



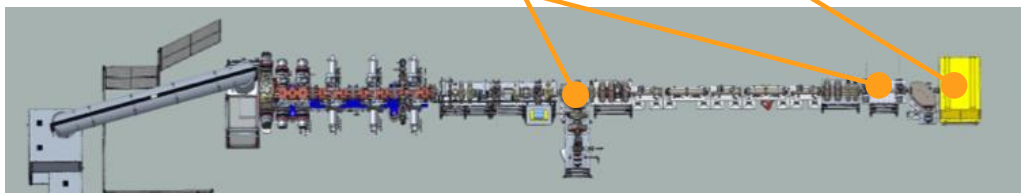
BTF “core” benchmark took some effort

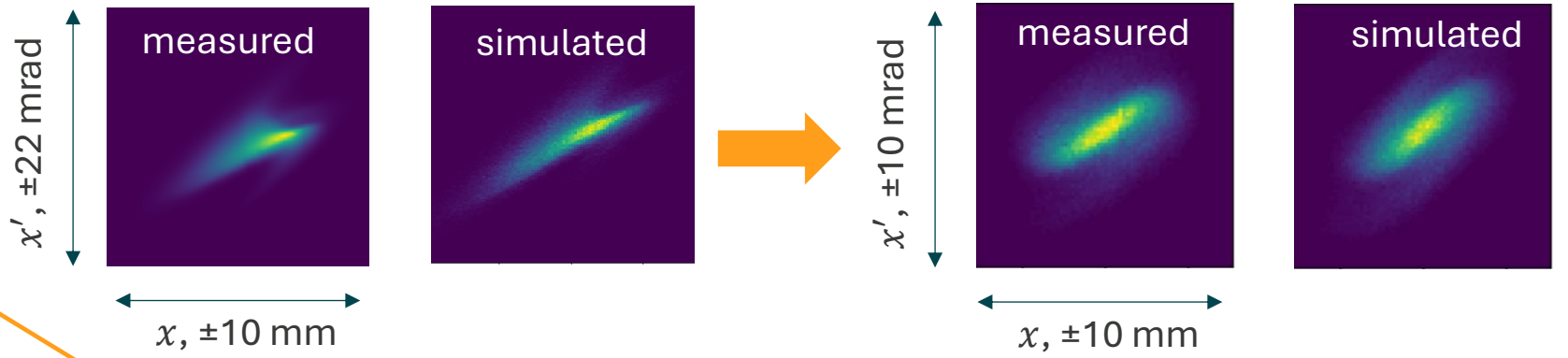
Straightening beamline:

2018 - 2022

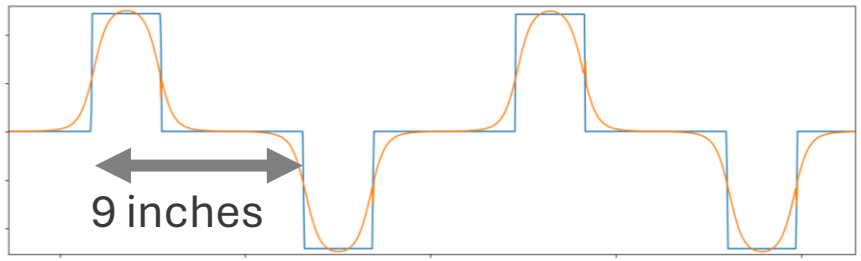


January 2024:

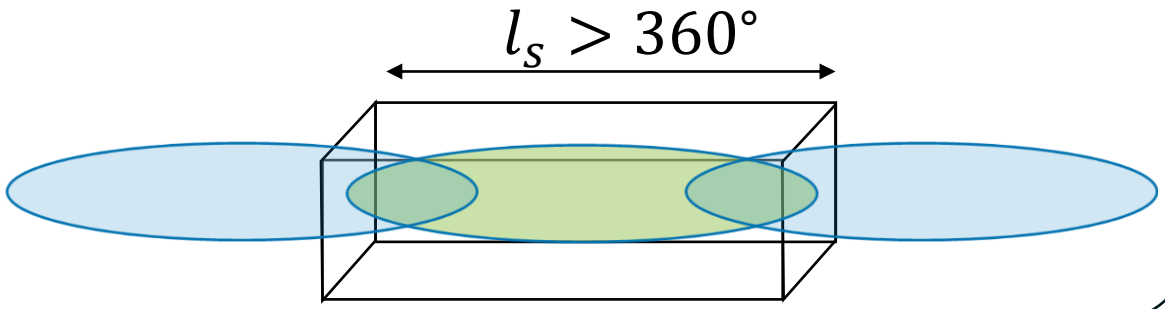




Refining FODO quad model:



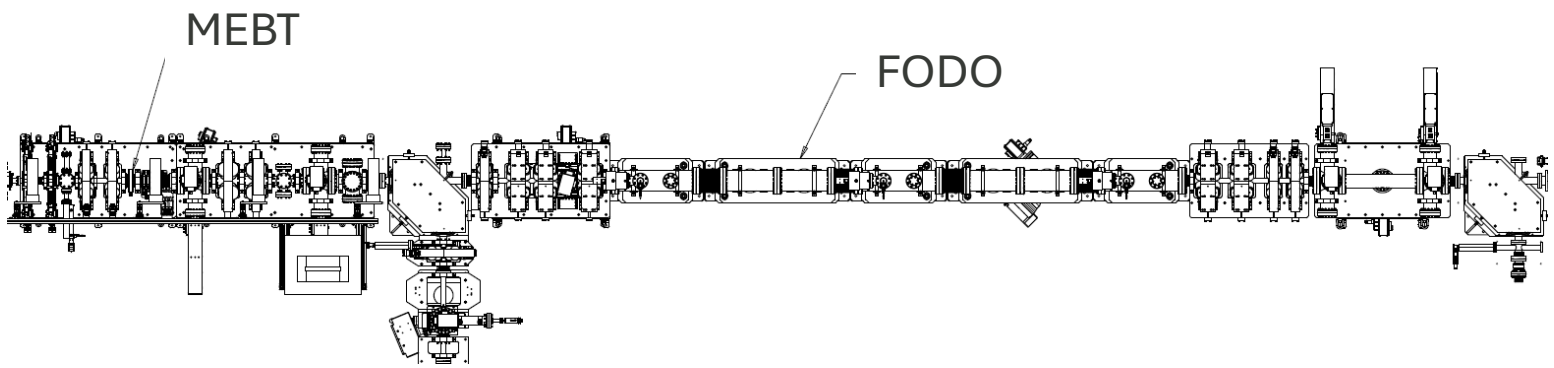
Calculating multi-bunch interaction:

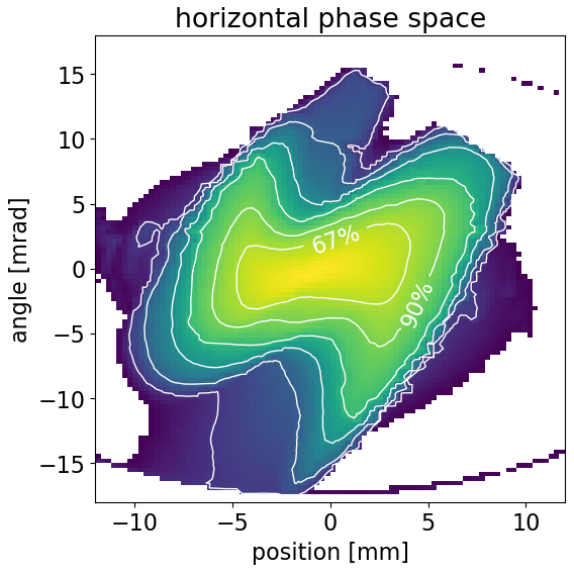


How can we fix this discrepancy to do halo prediction at the test facility?

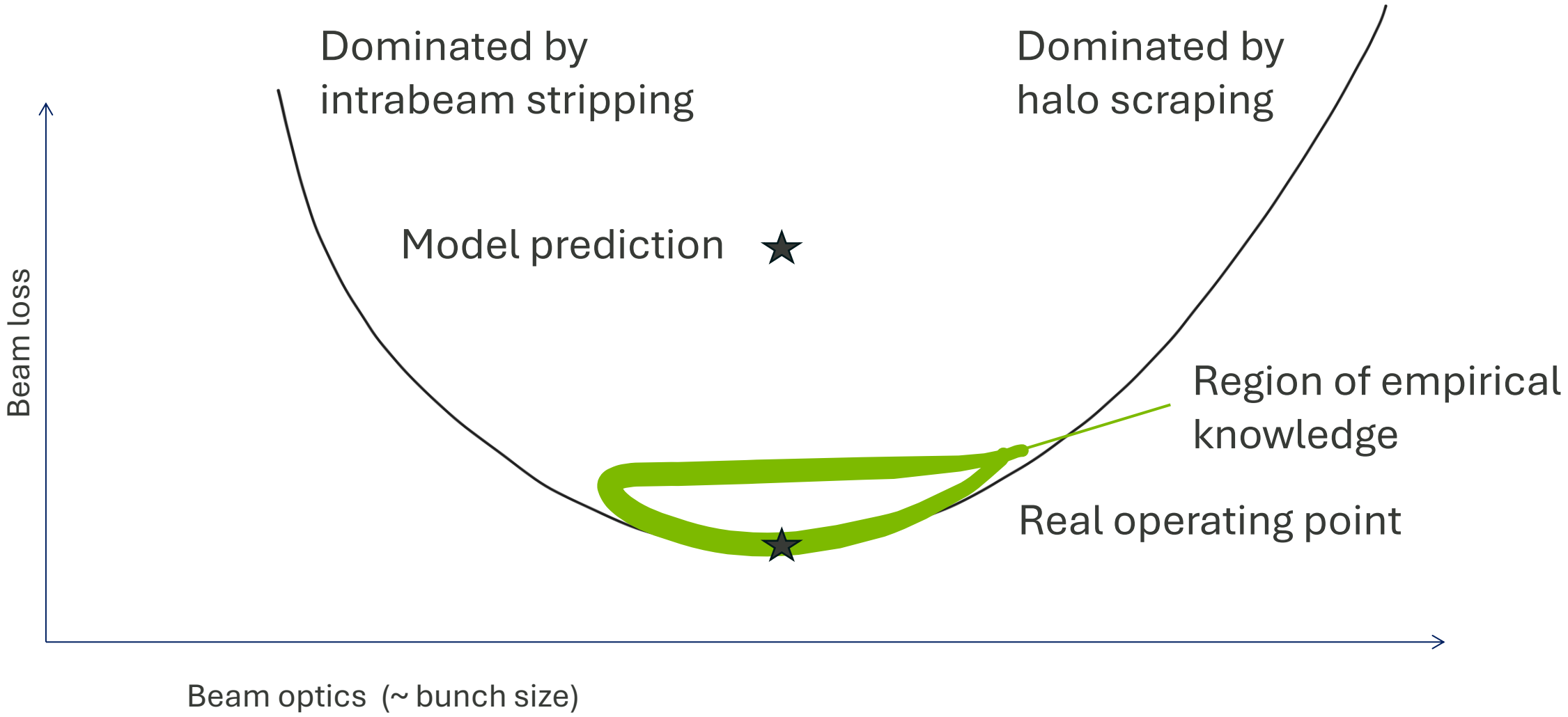
- Nonlinear components of quadrupoles
- Improve transmission with added trajectory correctors
    - Even matched beam has 3% loss
- What else?

R&D at Beam Test Facility is in “halo” era – providing a well-resolved 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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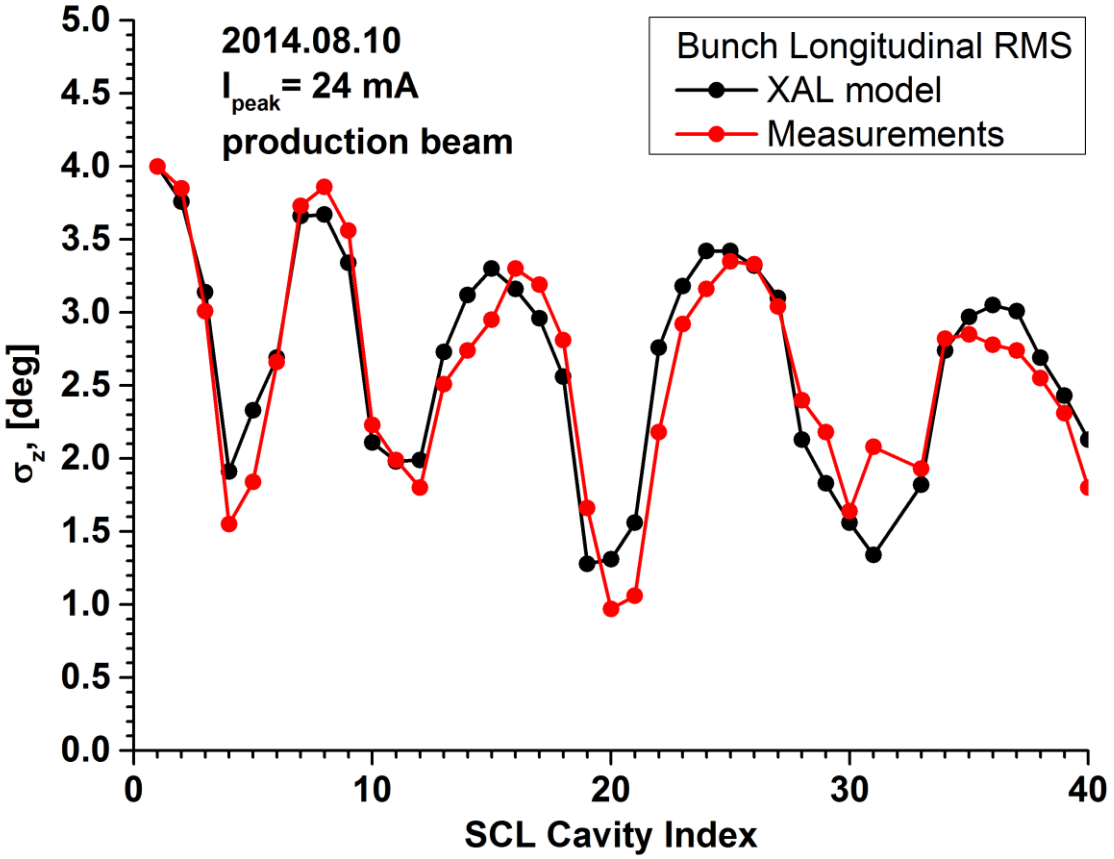
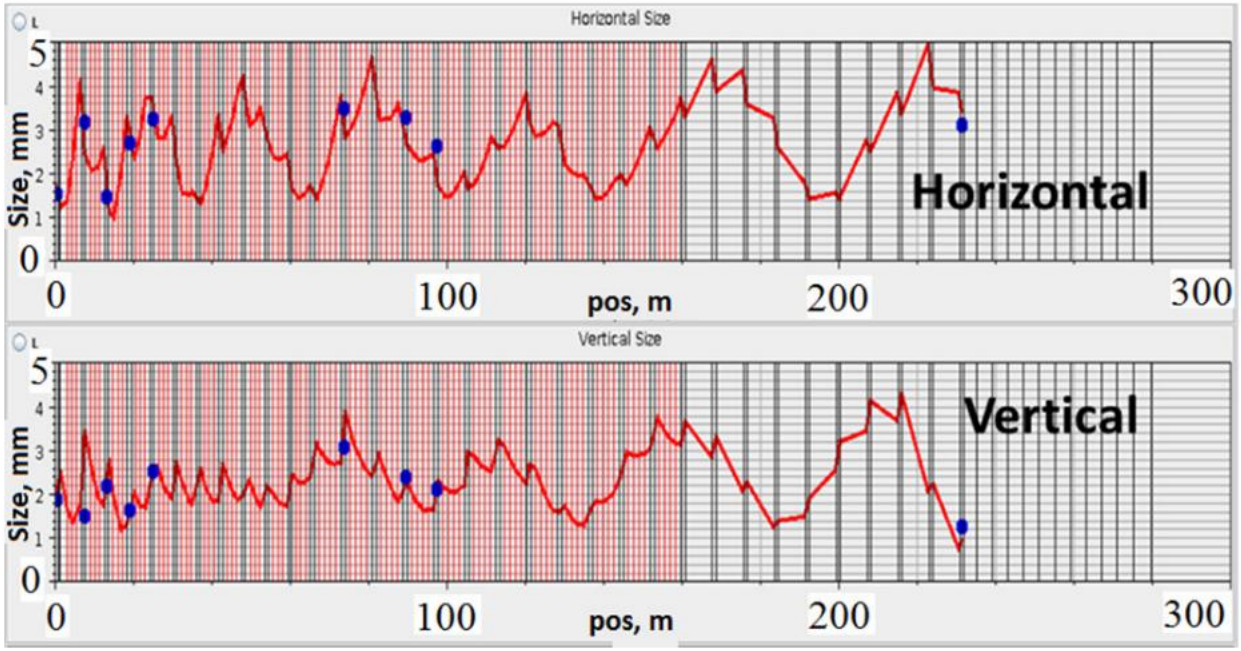
FOR THE US DEPARTMENT OF ENERGY

SCL rms benchmark for production (mismatched)





Shishlo, LINAC2014

High Dynamic Range (HDR) Phase space measurements