Characterization and modeling of high-intensity beam evolution in the SNS Beam Test Facility

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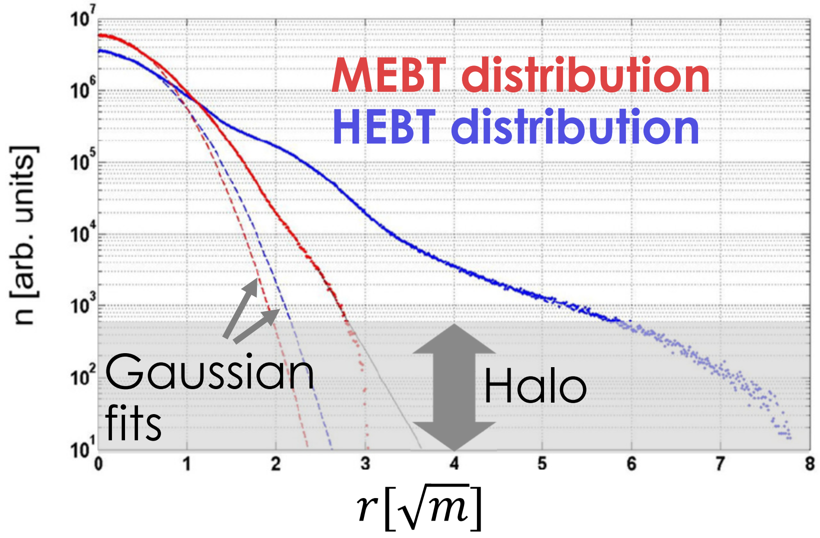
Outline

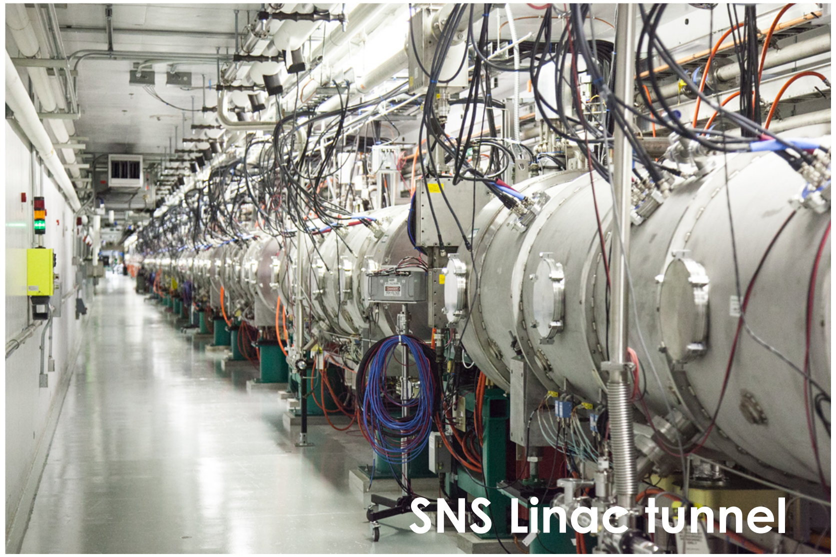
- Background
  - Motivation for better modeling of beam/halo evolution
  - SNS Beam test facility
- Prior work
  - Preceding halo studies at other facilities
  - 6D distribution measurements
- Ongoing beam/halo studies
  - Preliminary characterization of initial halo
    - High dynamic range emittance measurement
  - Pathway to accurate halo prediction

Halo is a concern in high-power hadron accelerators

- Halo = low-density, large extent feature of beam distribution
  - $10^{-4} - 10^{-6}$ of peak
  - contributes to uncontrolled losses
- Loss limit < 1 W/m to maintain safe environment for maintenance
- Current SNS operation at 1.4 MW within acceptable limits but…
  - We want the 10 MW horizon without 10x the amount of uncontrolled loss
  - Require 1 ppm accuracy in simulation to predict and control/mitigate halo

SNS MEBT/HEBT beam profiles,
Source: A. Aleksandrov

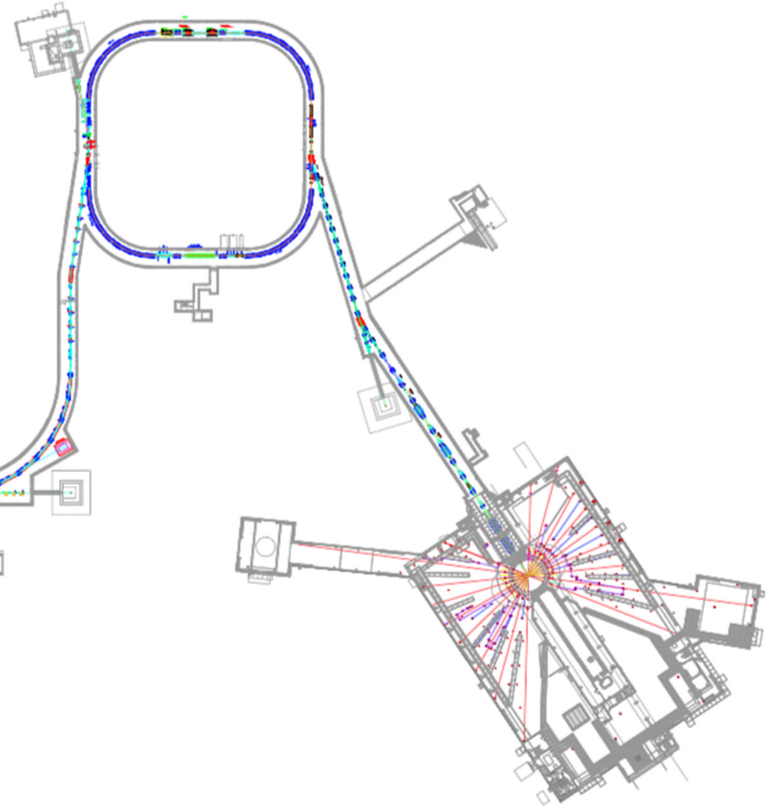


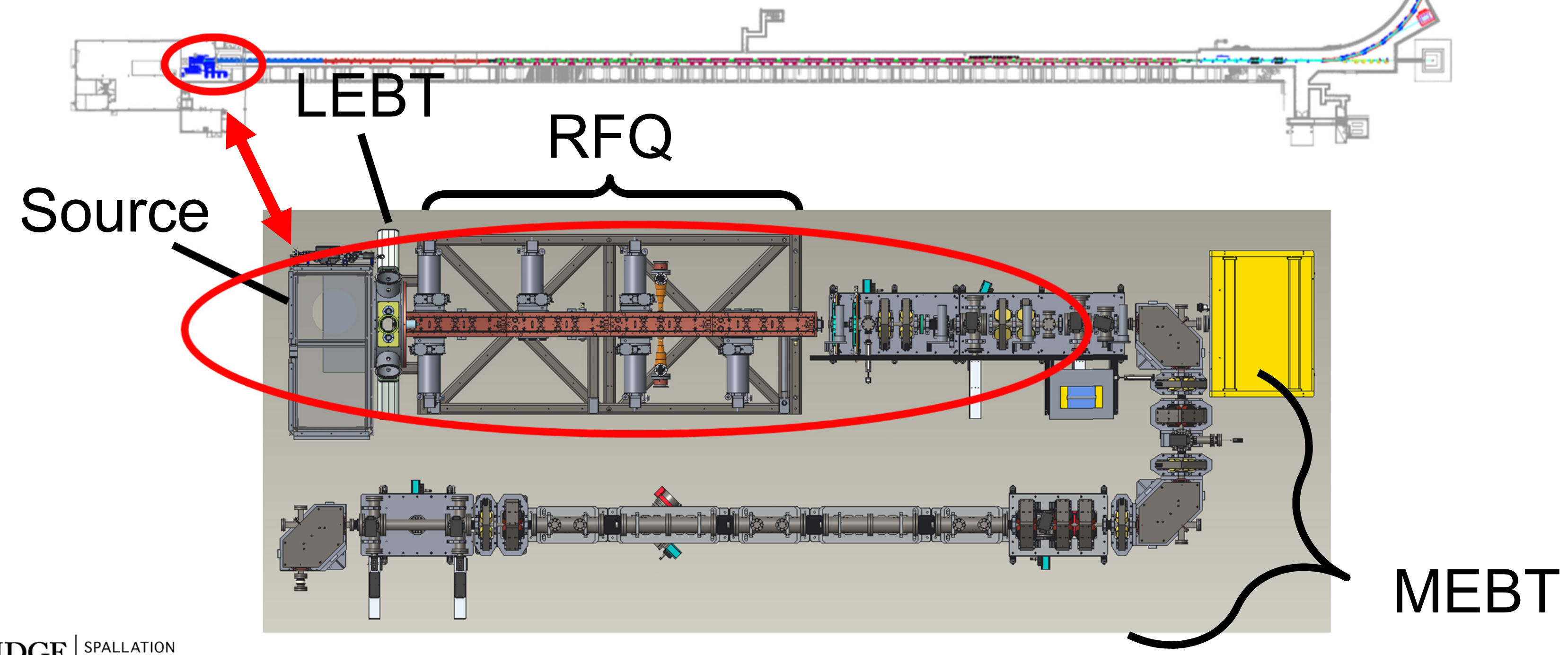


BTF replicates conditions in SNS front-end; platform for understanding early, high-intensity beam evolution

Species	H^-
Energy	2.5 MeV
Current	<= 50 mA

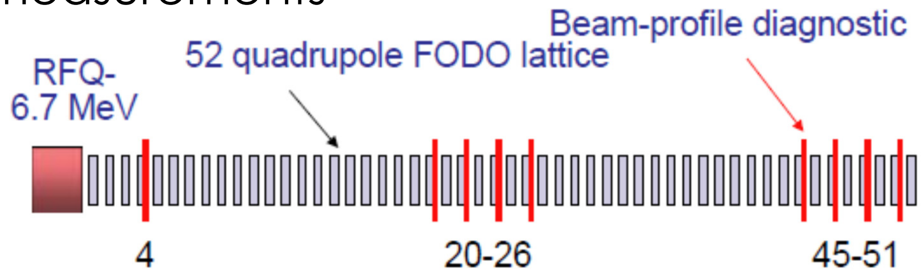
Pulse width	<= 1 ms
Rep rate	<= 60 Hz
Beam Power	<= 7.5 kW



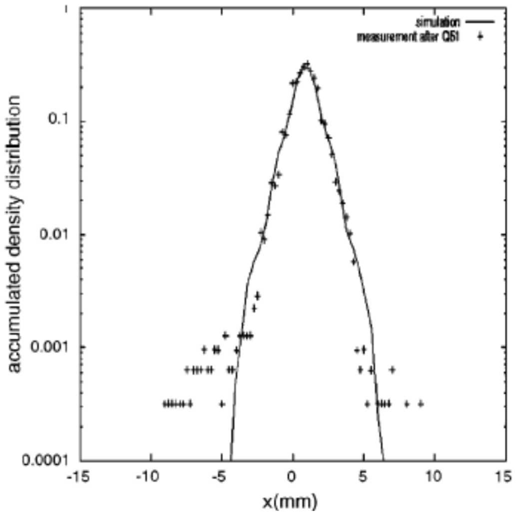


BTF follows footsteps of earlier attempts to benchmark medium-energy beam evolution

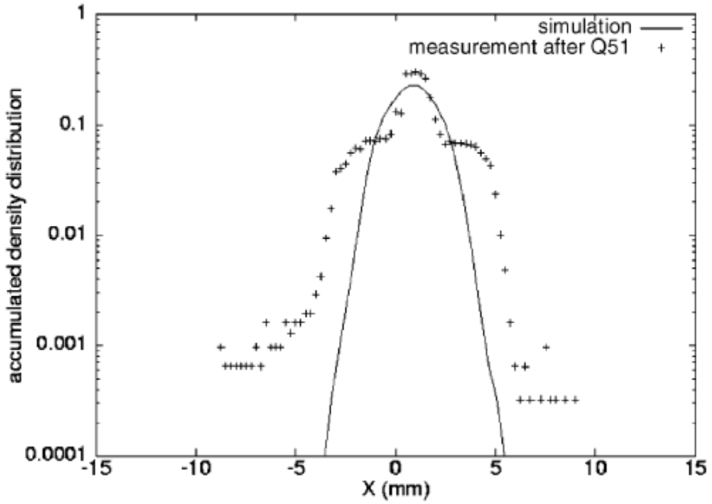
LEDA @ LANL: extensive simulations aimed at benchmarking halo evolution measurements



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.

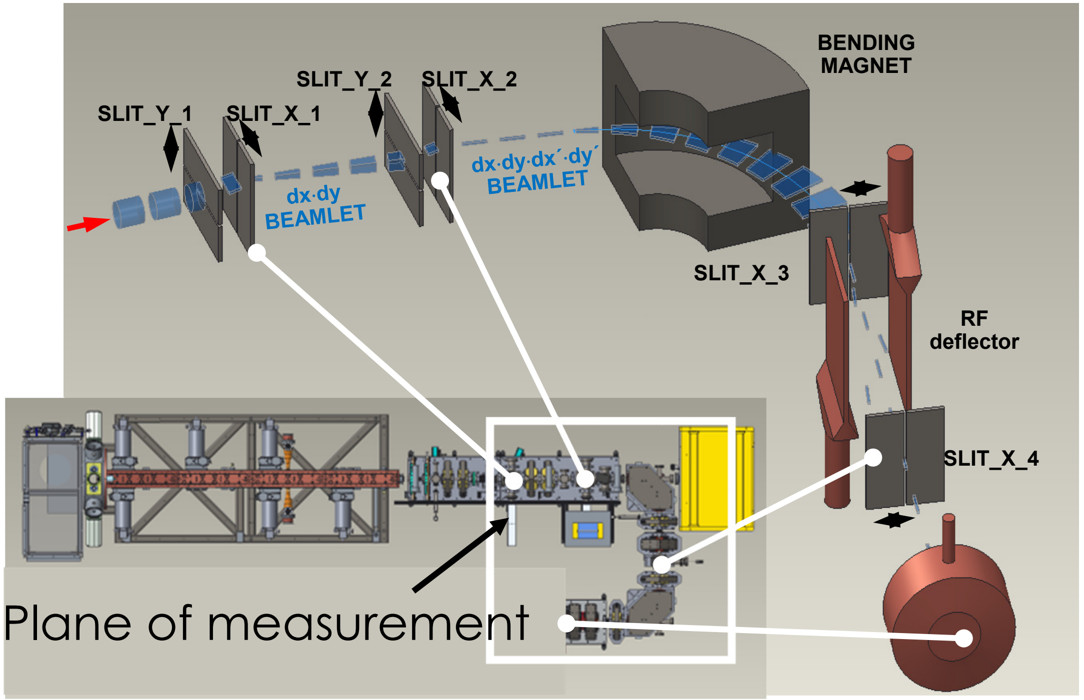
Hypothesis: Limited knowledge of initial distribution to blame for discrepancies

What's the missing ingredient? (for 1 ppm simulations)

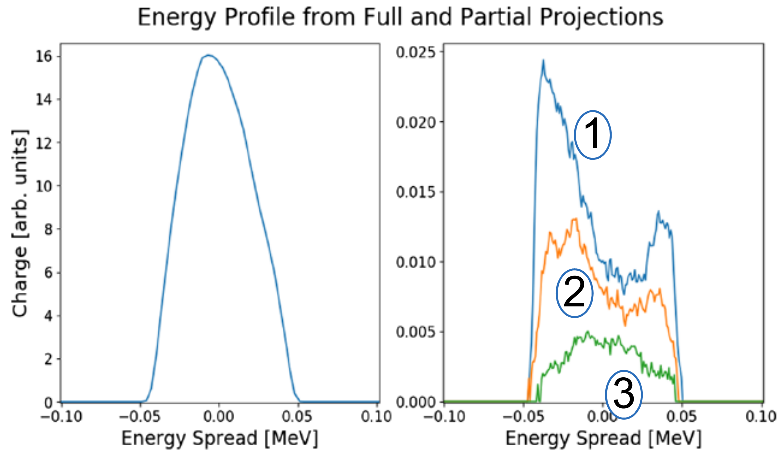
- Completeness of accelerator (PIC) codes
  - Believed to capture all relevant physics
- Accuracy of accelerator model
- **Complete knowledge of initial beam distribution**
  - **Full 6D beam distribution measurement**
- Benchmarking with high-dynamic range measurements
  - Goal: 1 ppm (10^{-6}) 2D emittance measurement

First 6D measurement (Oct. 2017) revealed correlation between energy and transverse planes

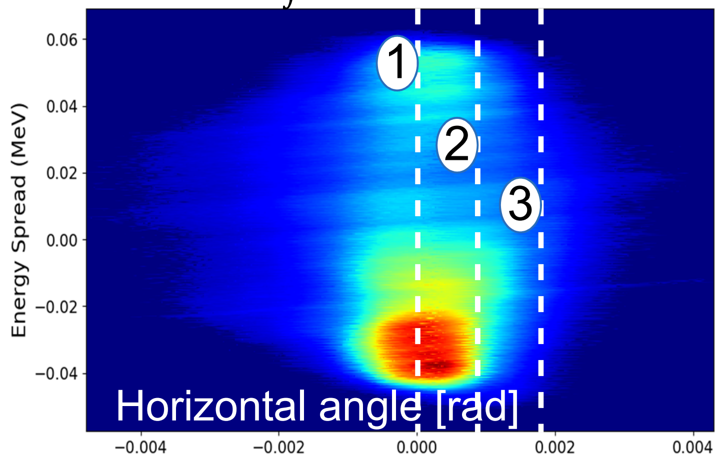
System for 6D measurement



Conclusion: $f(x,x',y,y',z,dE) \neq f(x,x') * f(y,y') * f(z,dE)$



$$f(x',w) = \int dt \cdot f_6\,(t, x = y = y' = 0)$$



Curse of dimensionality: Resolution and dynamic range are challenges!
1 out of 10^7 particles will reach Faraday cup when measuring the core

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Cathey, B., Cousineau, S., Aleksandrov, A., & Zhukov, A. (2018). *Physical Review Letters*, *121*(6), 064804.

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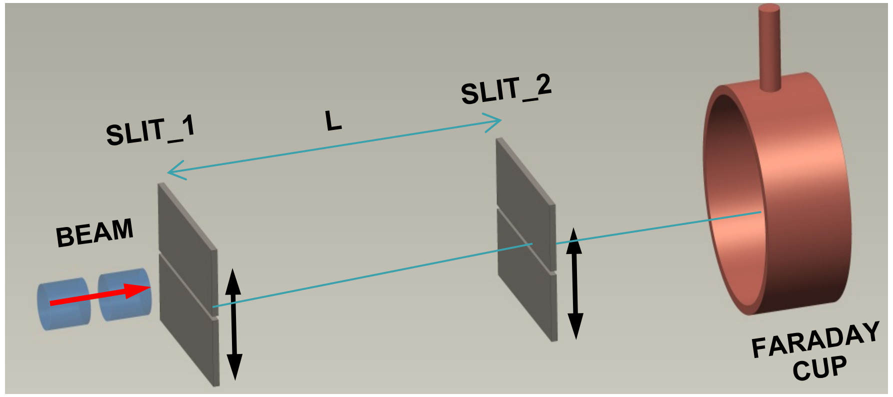
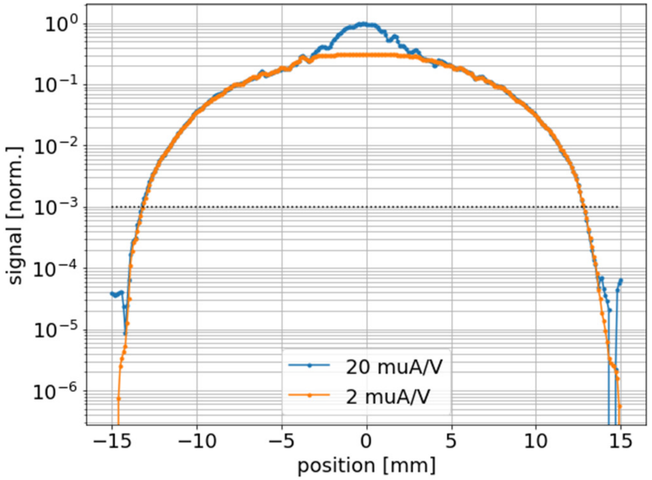
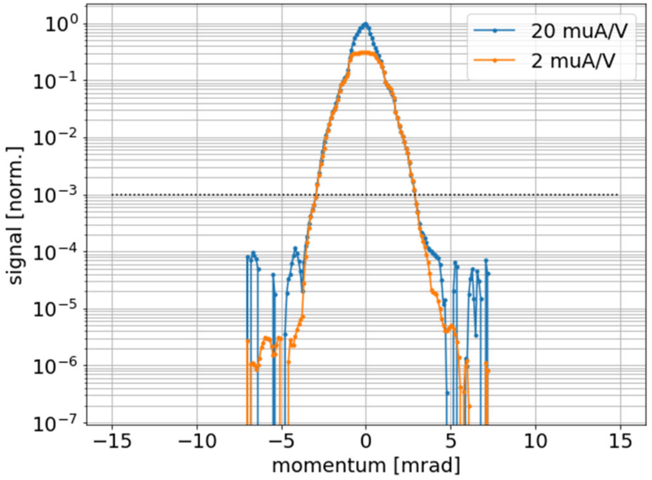
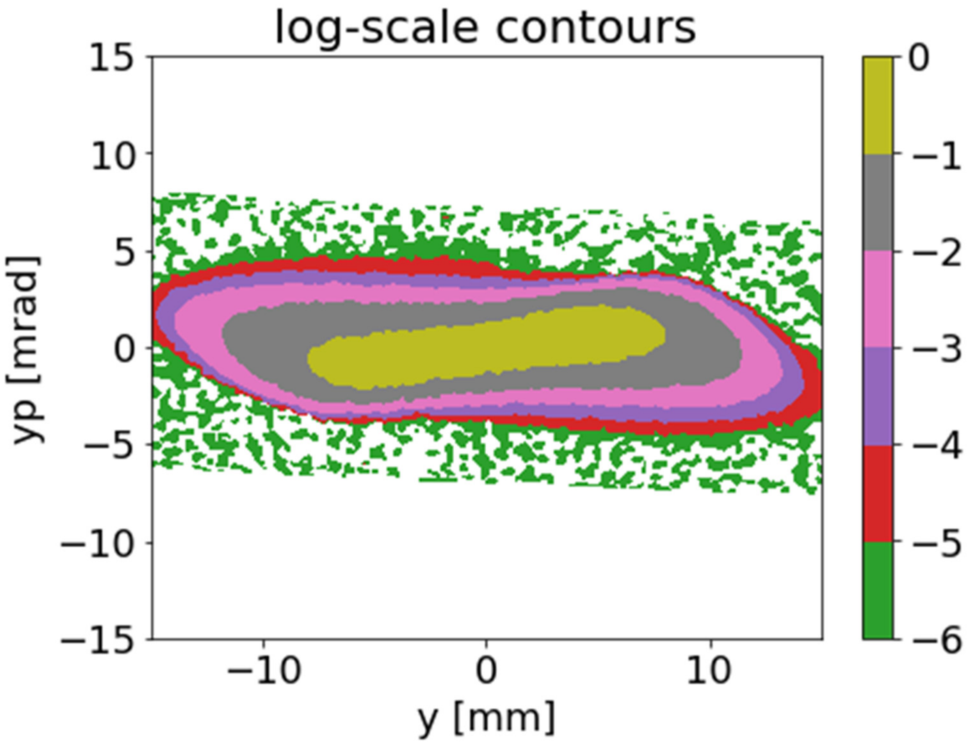
2D dynamic range is attainable (with care)



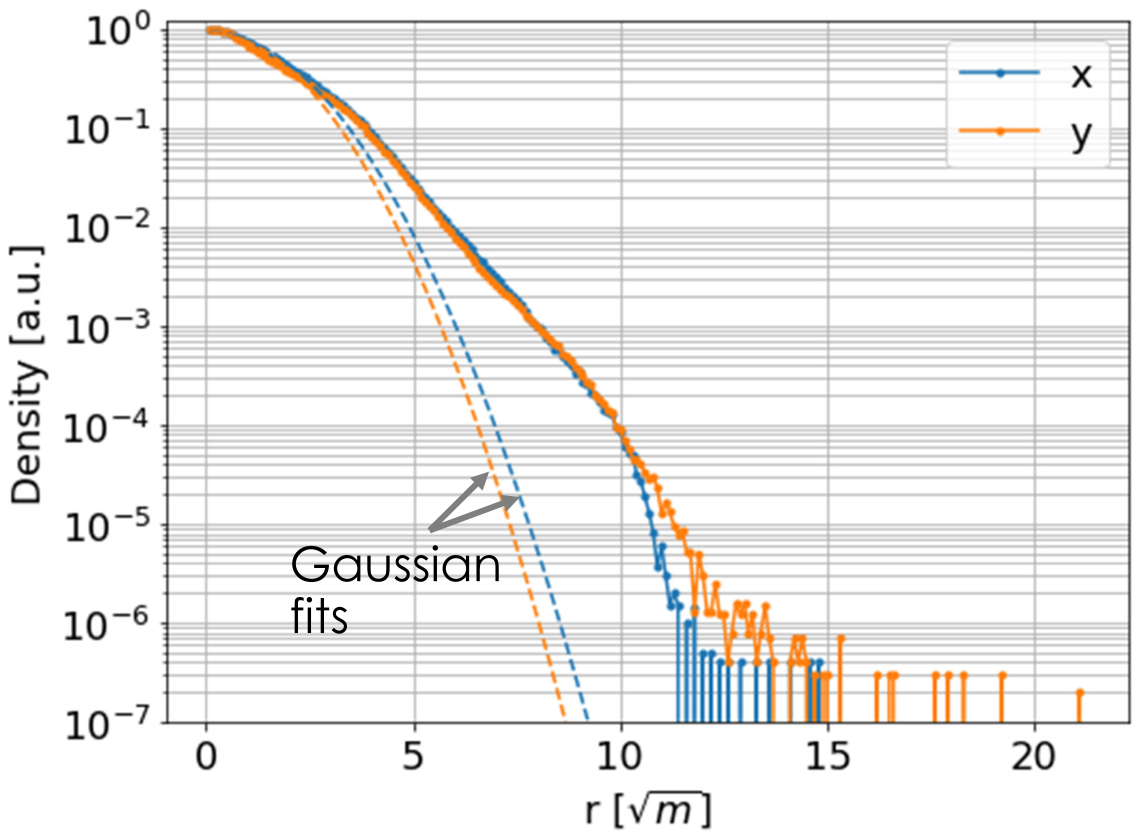


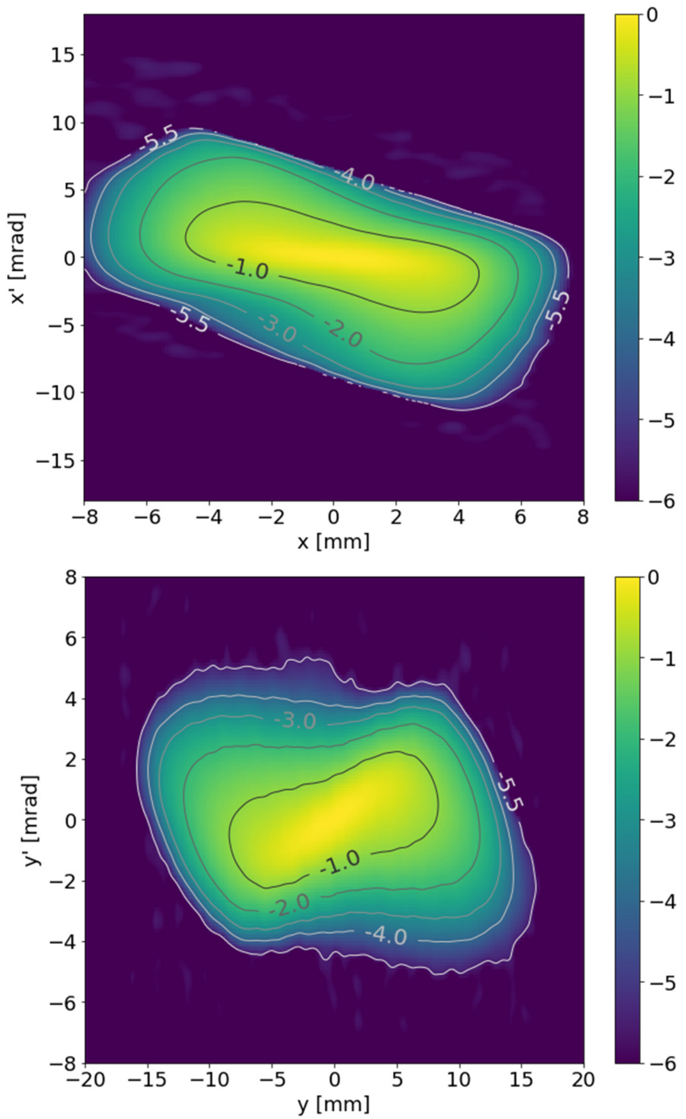




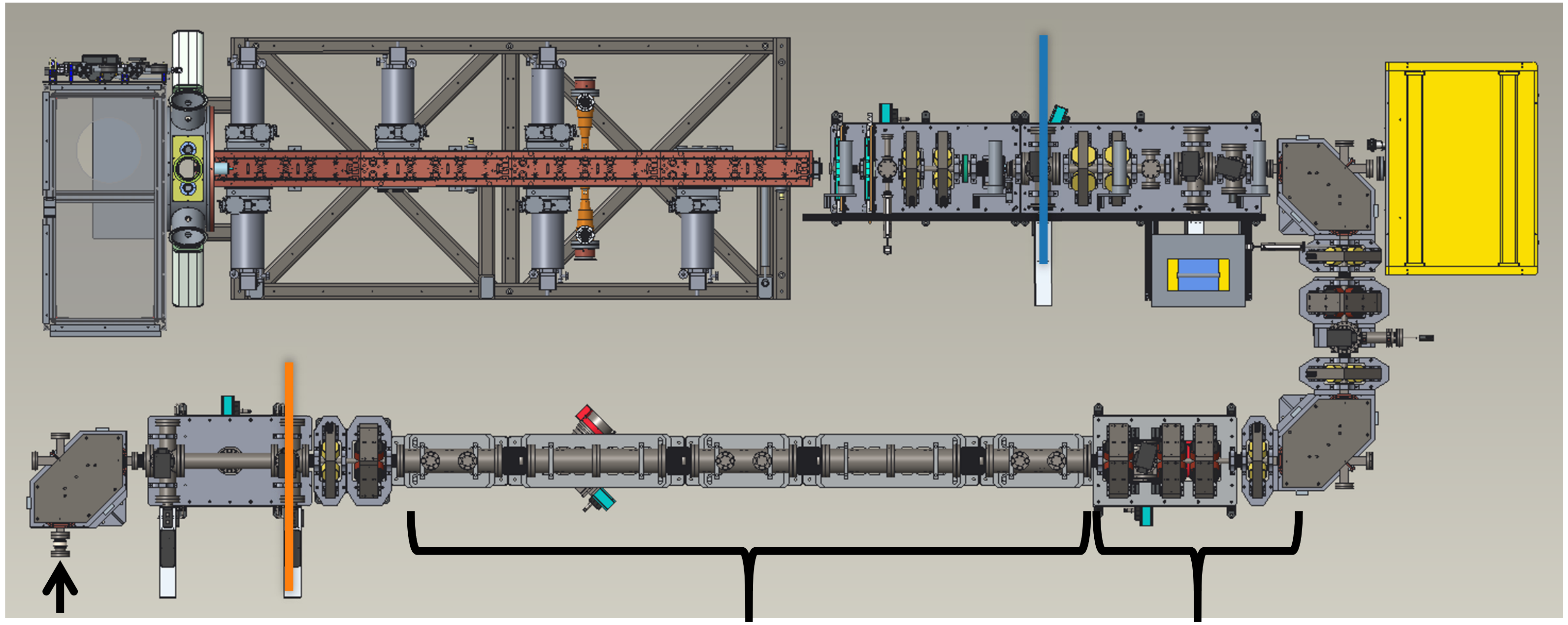
Post-RFQ 33 mA beam has modest amount of halo

2D phase space density measured downstream of RFQ





FODO-line extension installed at BTF in Nov 2018

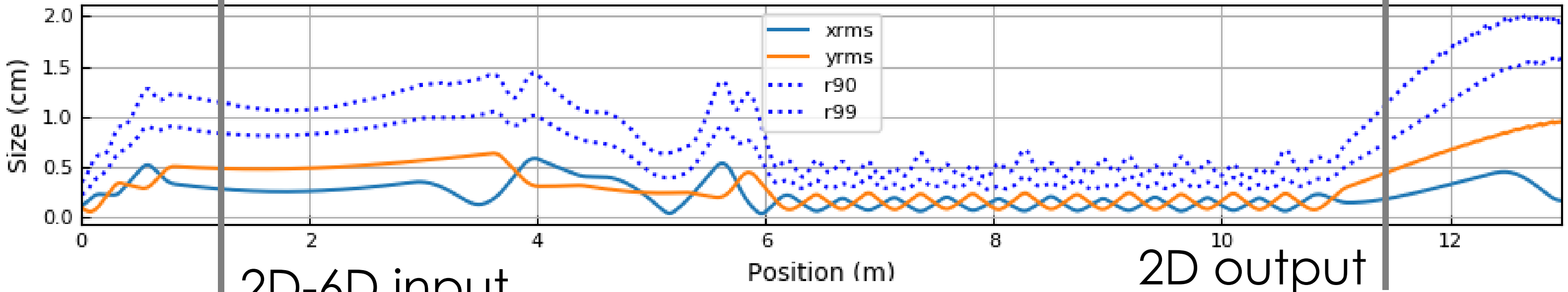


Final beamstop (BS34)

FODO line (19 permanent magnet quads)

Matching optics (4 quads)

Matched beam solution in pyORBIT model



2D-6D input

2D output

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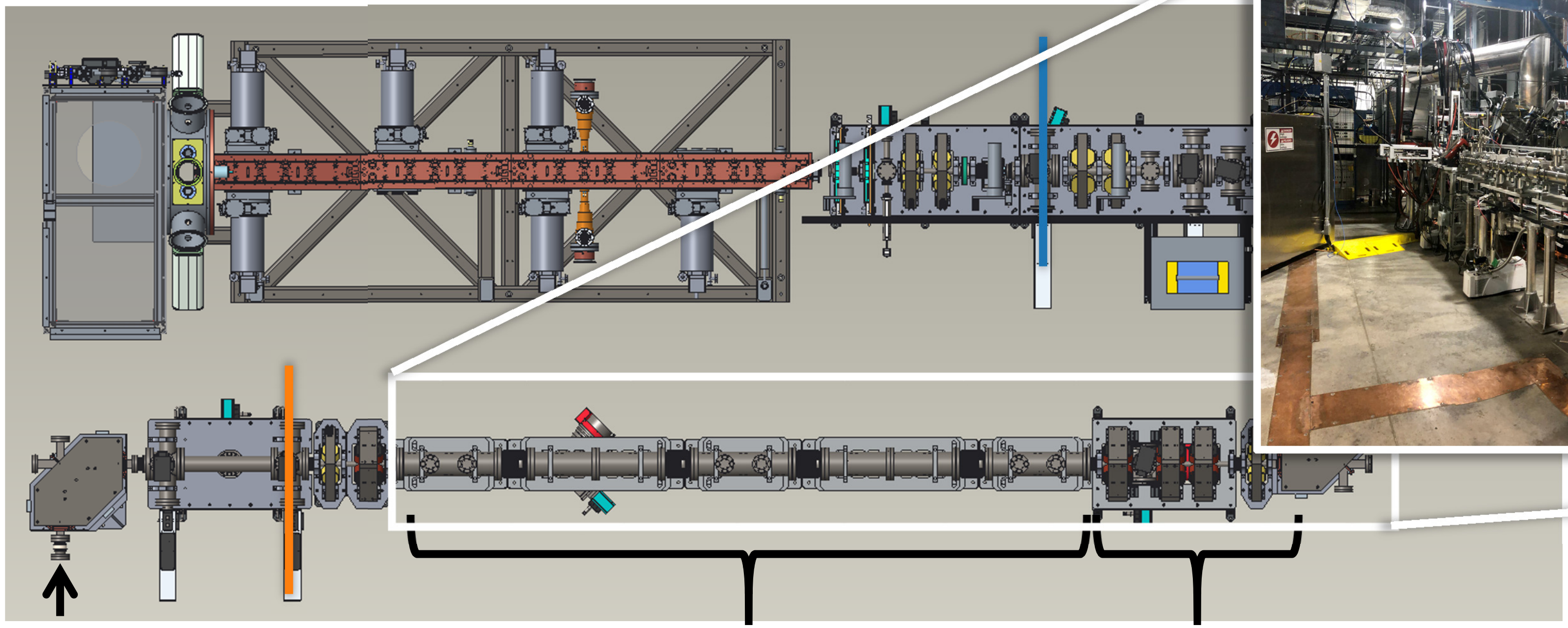

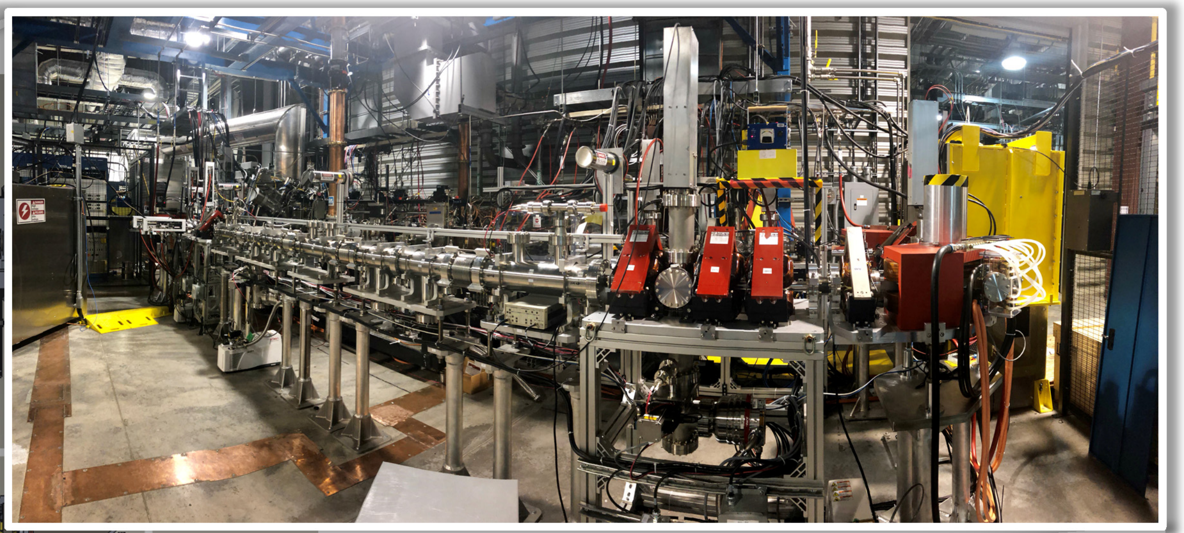

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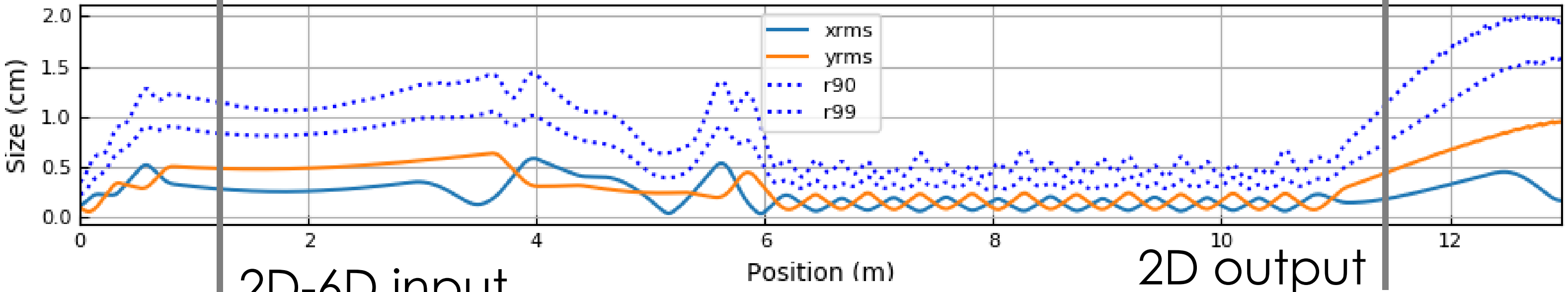

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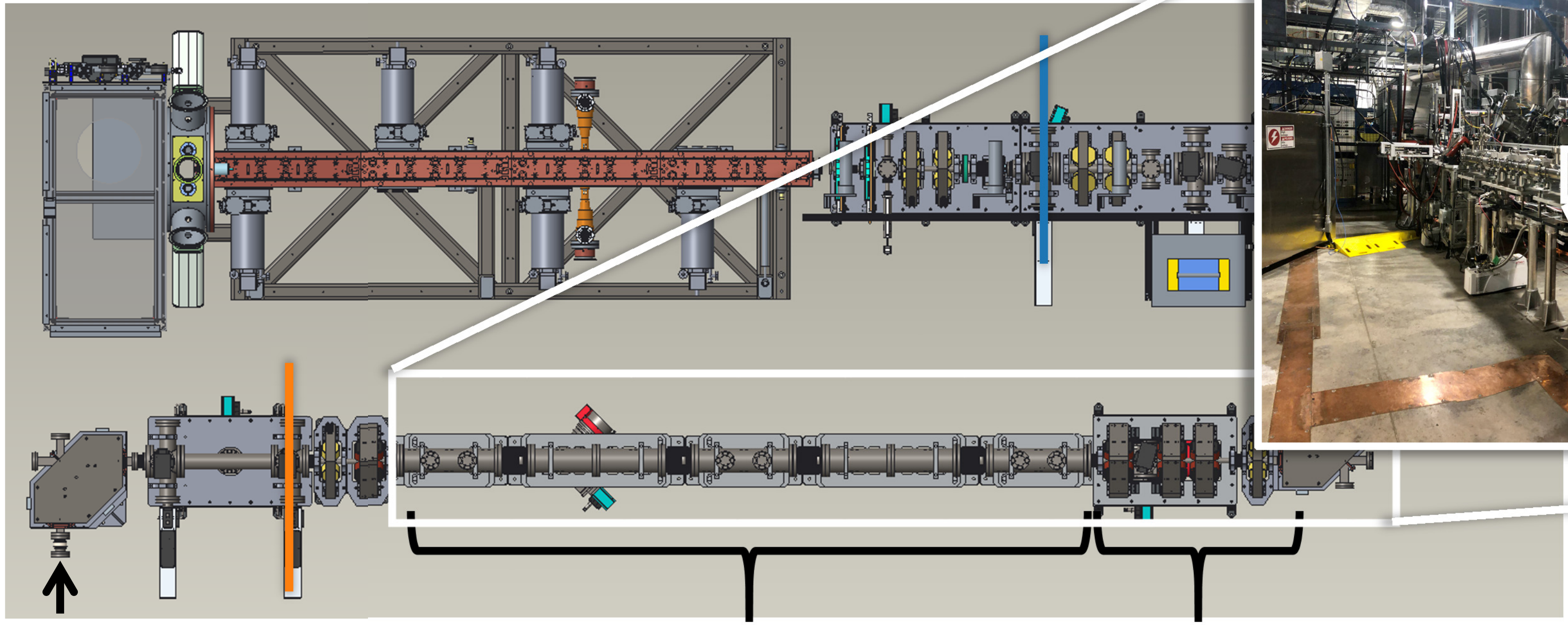

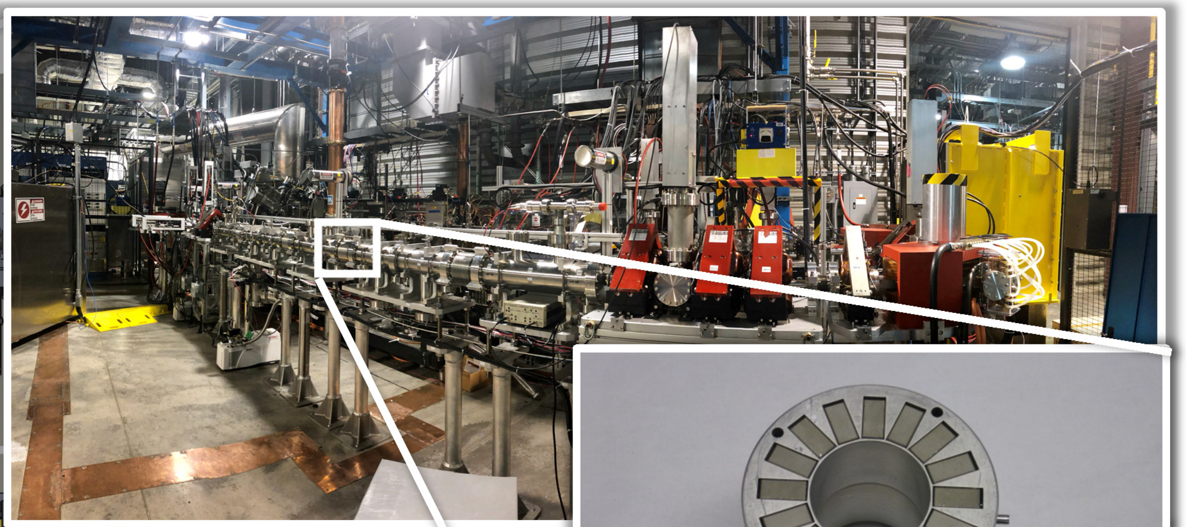

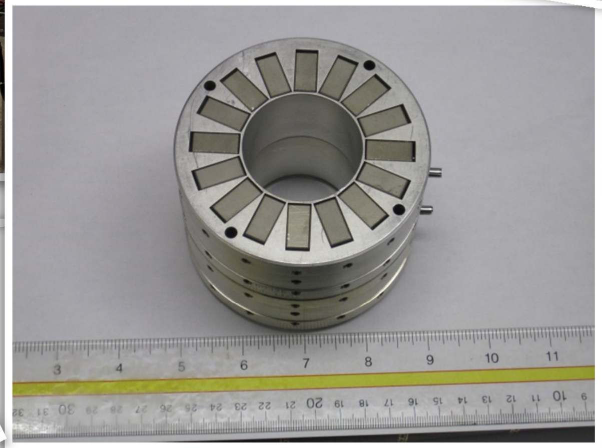

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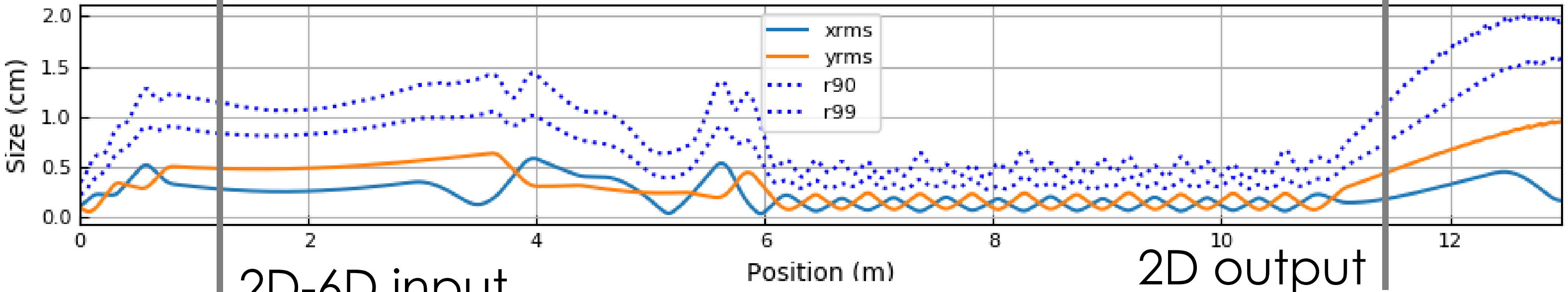

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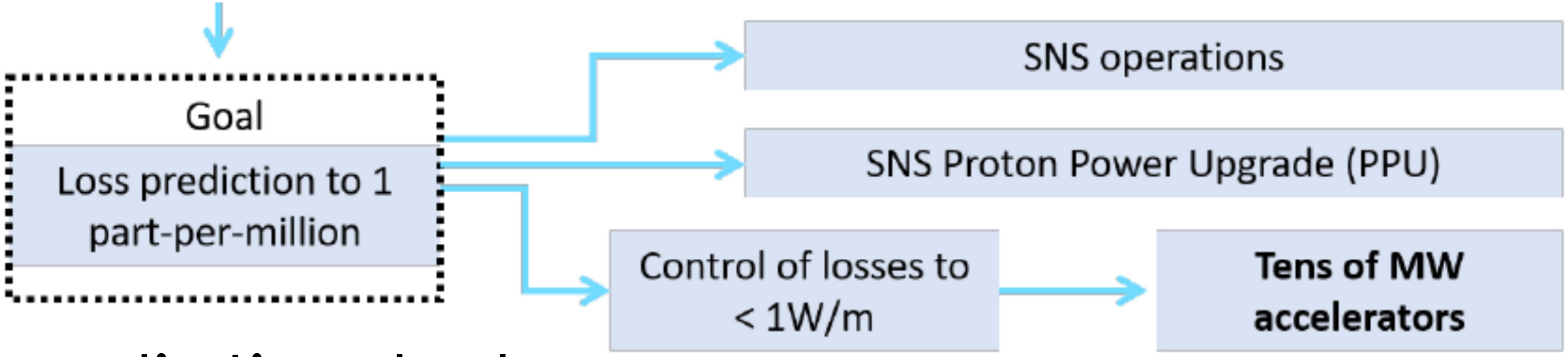

The pathway to predicting halo

(1) Measure initial beam distribution
   (1) High-dimensionality to fully resolve core correlations

(2) Measure evolved distribution
   (1) High-dynamic-range including halo (down to 1 ppm in 2D phase space)

(3) Simulate beam evolution (pyORBIT)
   (1) with resolution to 1 ppm
   (2) Search for agreement with measurement

Summary

- Halo is a concern for future intensity machines, where uncontrolled loss could limit operation
- PIC simulations have demonstrated capability to predict core/rms evolution in matched beam
- Prior experiments unable to resolve halo; poor agreement for tails
- Source of discrepancy cited as incomplete knowledge of initial beam distribution
- SNS BTF equipped to for both full 6D distributions and halo-sensitive 2D emittance measurements