Self-Consistent Injection Painting for Space Charge Mitigation

HB 2023

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Outline

- Danilov Distribution
- Space Charge Mitigation
- Painting Requirements
- The Spallation Neutron Source
- Experiments to date

{2,2}-Danilov* Distribution is Self-Consistent

1. Uniform real space distribution (linear space charge)
2. Elliptical envelope
3. Maintains (1),(2) under any linear transport (including space charge)

A uniformly filled circular mode is a Danilov distribution. By (3) we can match this to any linear optics and maintain a Danilov distribution.

* We call the {2,2} *the* Danilov distribution

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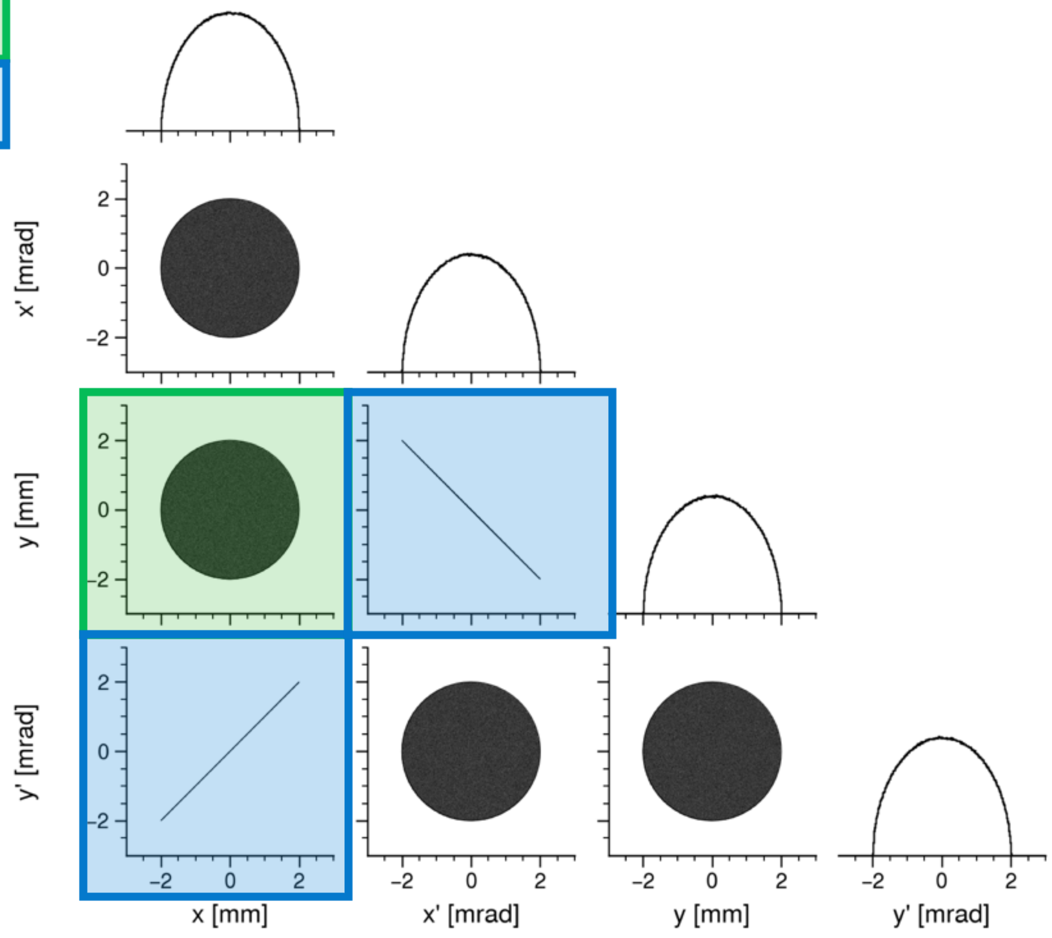
Self-consistent time dependent two dimensional and three dimensional space charge distributions with linear force

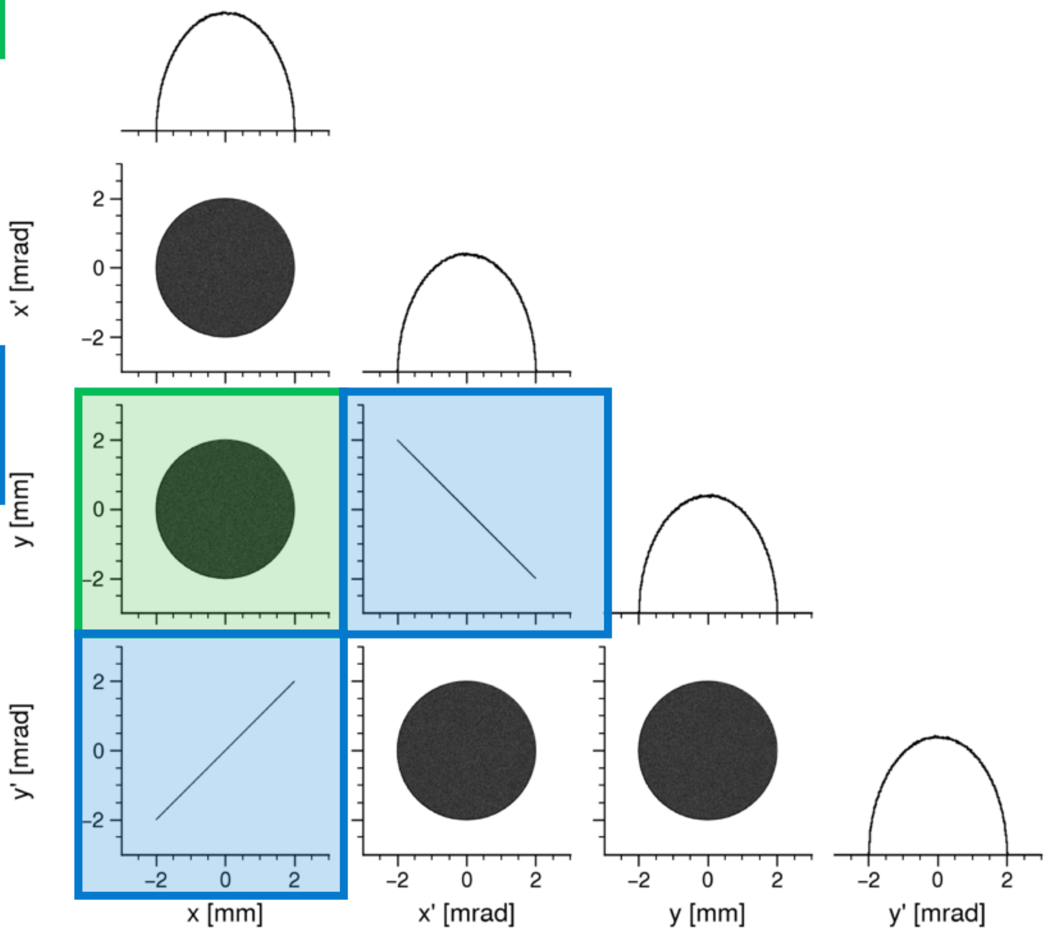
V. Danilov, S. Cousineau, S. Henderson, and J. Holmes

{2,2} Danilov Distribution



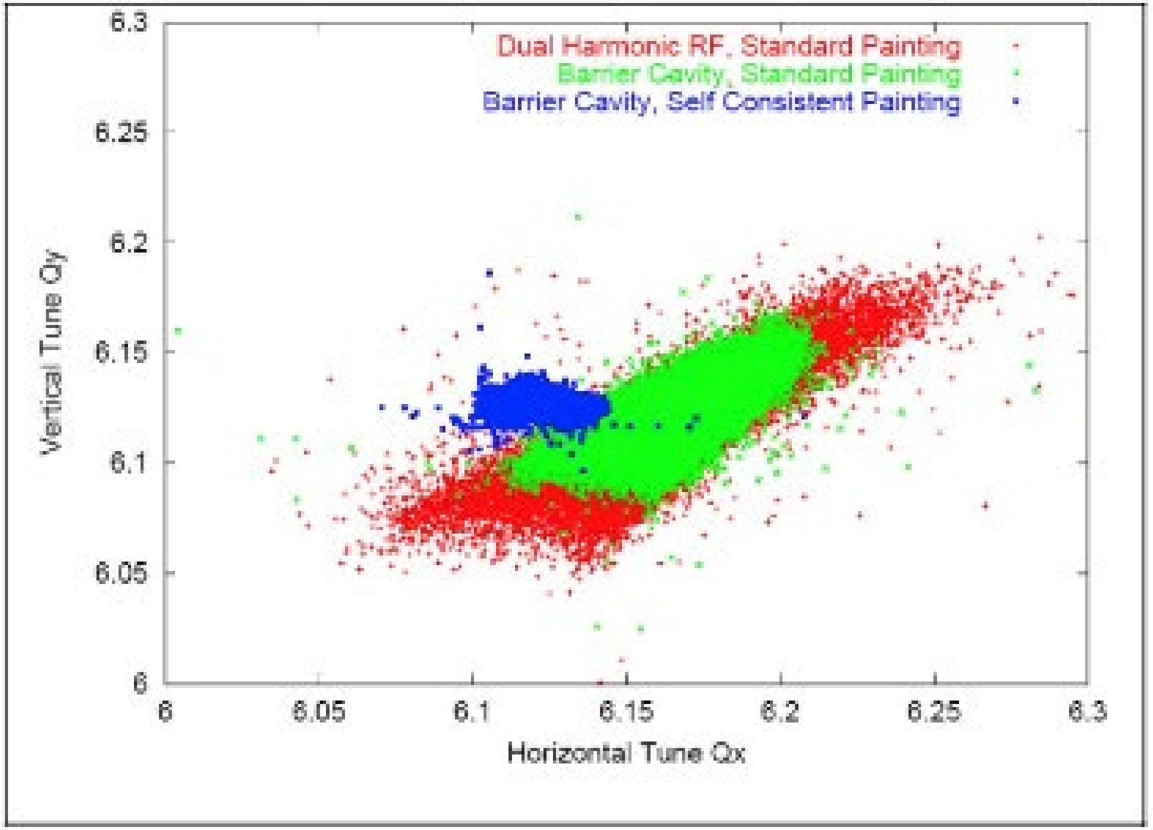
Danilov Distribution Key Features

- Uniform space charge implies reduced tune shift, and minimal spread
- When matched to a coupled ring elliptical envelope means distribution is unform over a mode – (could use equal tunes, but then modes are degenerate)
- eigenmode implies vanishing 4D emittance
- ***Invariant proportional to real space radius meaning we can add more beam at the edges, painting beam while maintaining self-consistency*** – this is a scalable procedure



Space Charge Mitigation

- Footprint is much smaller than standard SNS tune footprint
- Low 4D emittance implies brighter with same physical size (many benefits of circular modes apply) (Burov et al. PR.E 2002, Burov PRAB 2013)



Relevant blobs are blue and green – same RF, different painting

Blue footprint covers ~30% of tune space occupied by green

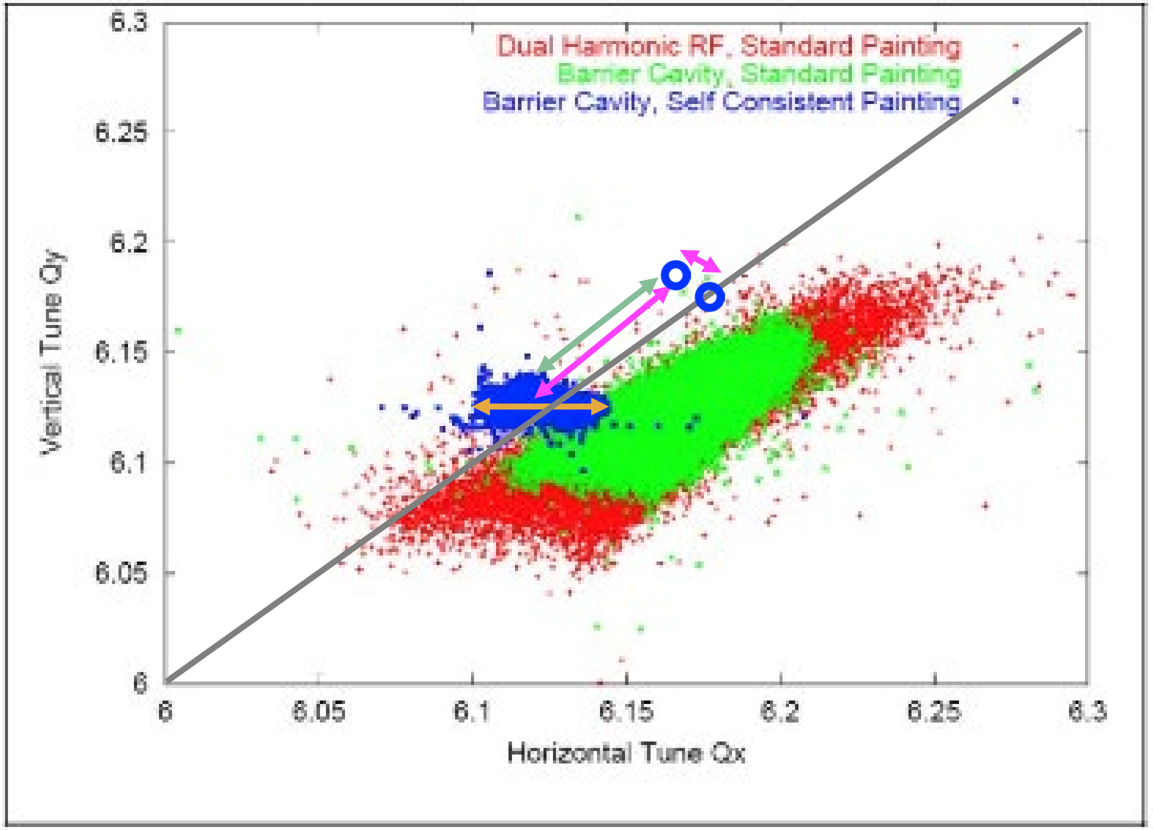
THAW03 Proceedings of HB2006, Tsukuba, Japan

RF BARRIER CAVITY OPTION FOR THE SNS RING BEAM POWER UPGRADE

J.A. Holmes, S.M. Cousineau, V.V. Danilov, and A.P. Shishlo, SNS, ORNL, Oak Ridge, TN 37830, USA

Space Charge Mitigation

- Decoupling tune shift and spread opens possibility for intense space charge



This tune shift is partly due to solenoid breaking degeneracy, need to isolate space charge tune shift.

Bare lattice tunes Self-consistent
Tune Spread
Tune Shift
Sparse tail

THAW03 Proceedings of HB2006, Tsukuba, Japan

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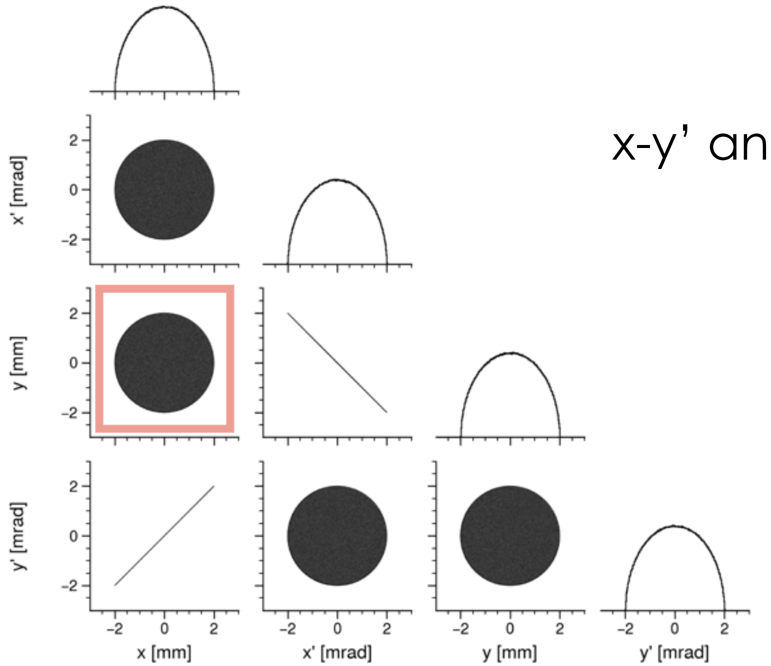
SNS Project Goals

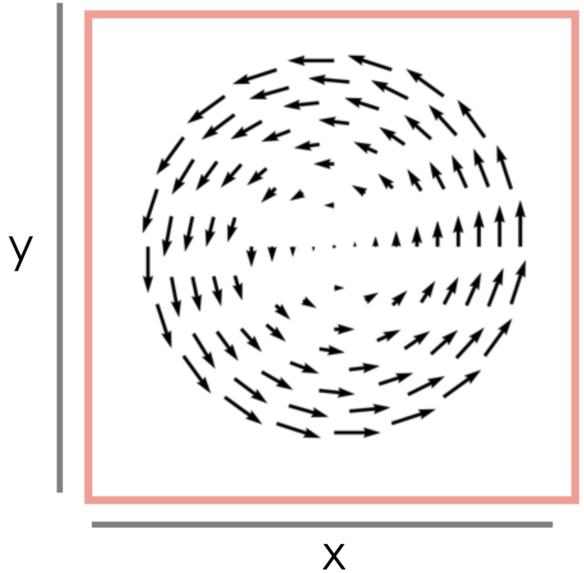
- Proof-of-principle painting of a uniformly filled, elliptical bunch in the SNS ring (approx. {2,2}-Danilov distribution, *the Danilov distribution*)
- Study evolution of the Danilov dist. during painting and storage



x-y’ and y-x’ correlations give a rotating beam

This is a uniformly filled circular mode

Arrows indicate x’,y’



Painting Requirements*

Low 4D emittance

1. Small injected emittance relative to larger of final emittances
   - Initial emittance (size of the paintbrush) defines the achievable ‘emittance ratio’
2. Non-planar modes
   - either through equal tunes or lattice coupling
   - Correlated closed orbit paths in x and y planes in time

Uniformity

3. Amplitude of injection should increase as Sqrt(t) along well-defined path in 4D phase space

Detailed feasibility study:

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Injection of a self-consistent beam with linear space charge force into a ring

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*Painting into one plane in the ‘flat’ portion of a round-to-flat transformer (Derbenev, 1993), then transforming to round would eliminate 2,3. Would it work as well, better?

The Spallation Neutron Source

- 1 GeV H- linac
  - Norm RMS emit = 0.46 mm · mrad (design)

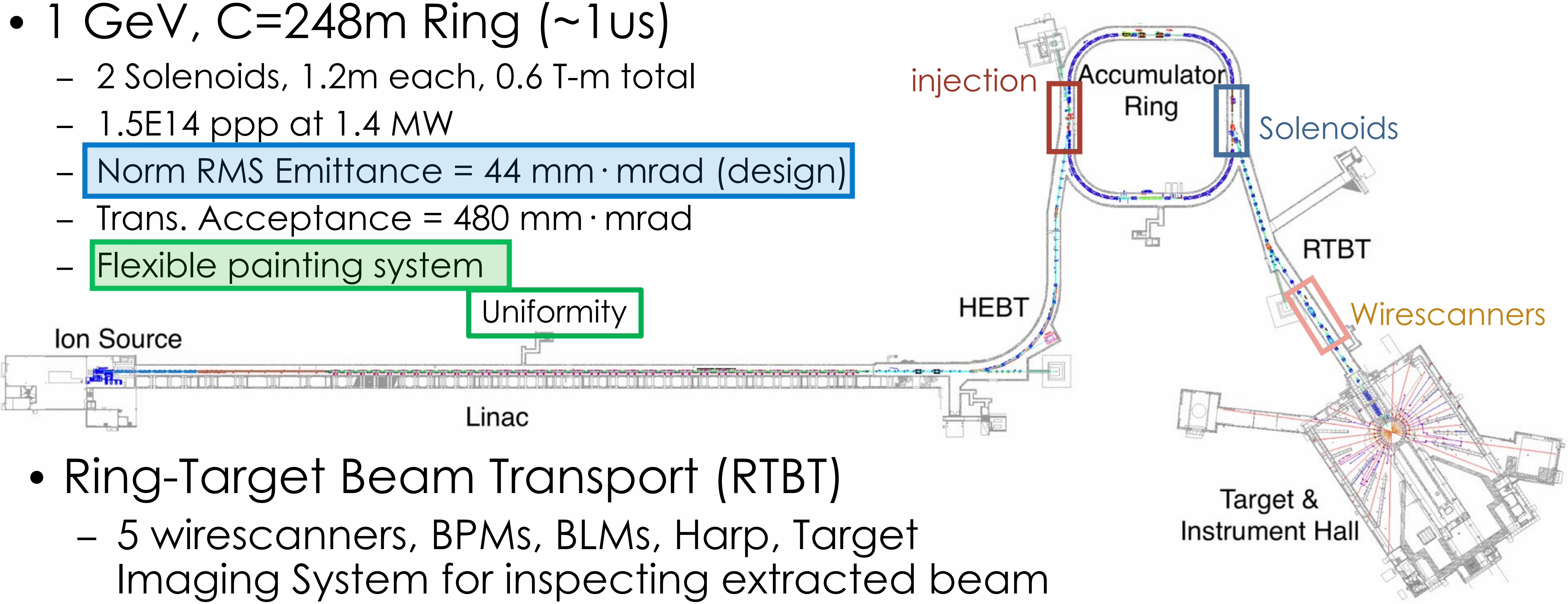
Low 4D emittance

- 1 GeV, C=248m Ring (~1us)
  - 2 Solenoids, 1.2m each, 0.6 T-m total
  - 1.5E14 ppp at 1.4 MW
  - Norm RMS Emittance = 44 mm · mrad (design)
  - Trans. Acceptance = 480 mm · mrad
  - Flexible painting system

Uniformity

Operational Parameters give:

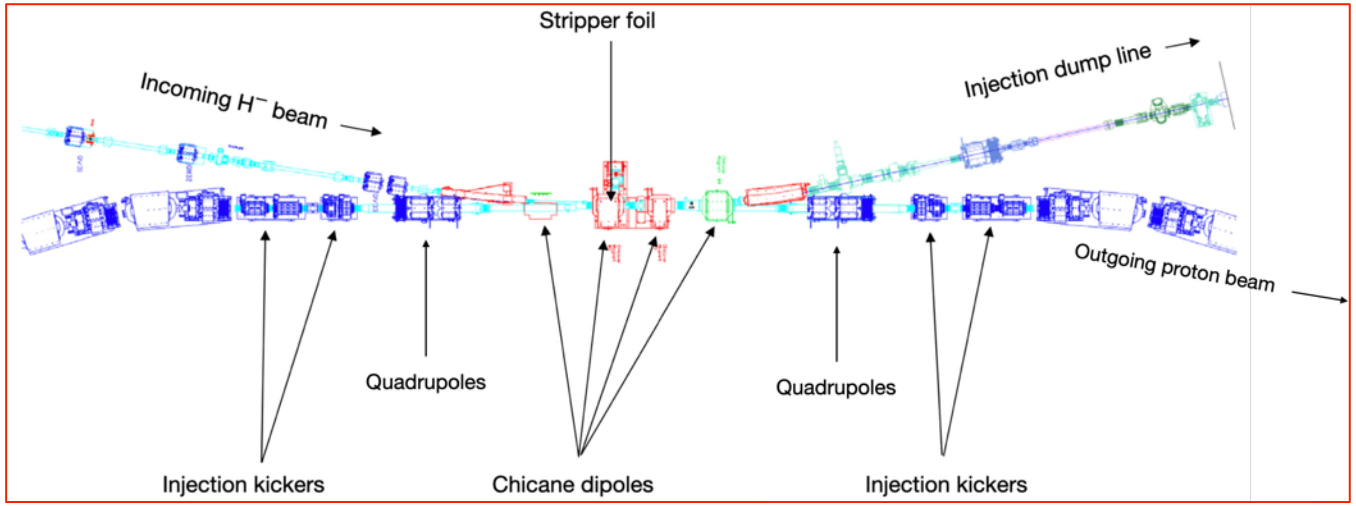
Space charge tune shift: 0.15
Uniform beam tune shift: 0.1

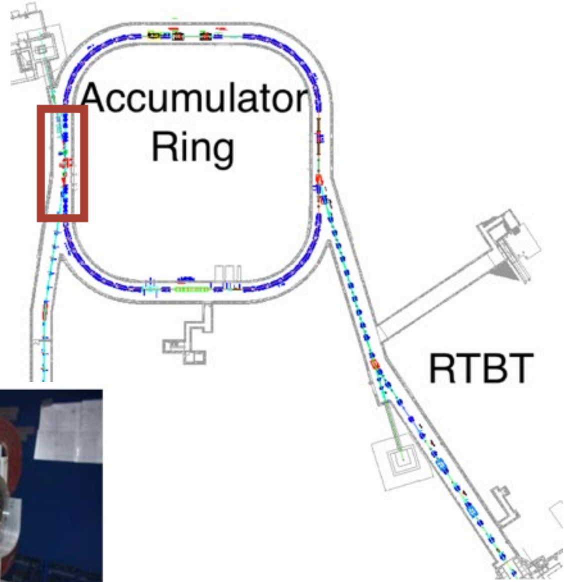


- Ring-Target Beam Transport (RTBT)
  - 5 wirescanners, BPMs, BLMs, Harp, Target Imaging System for inspecting extracted beam

SNS Painting System

- 4 time varying magnets in each plane to create closed bumps with offset at foil
- Time varying position and angle of ring closed orbit at injection point





	Max Kick*	
	1 GeV	800 MeV
H/V kickers 1&4	15.4 mrad	17.8 mrad
H/V kickers 2&3	8.5 mrad	9.9 mrad

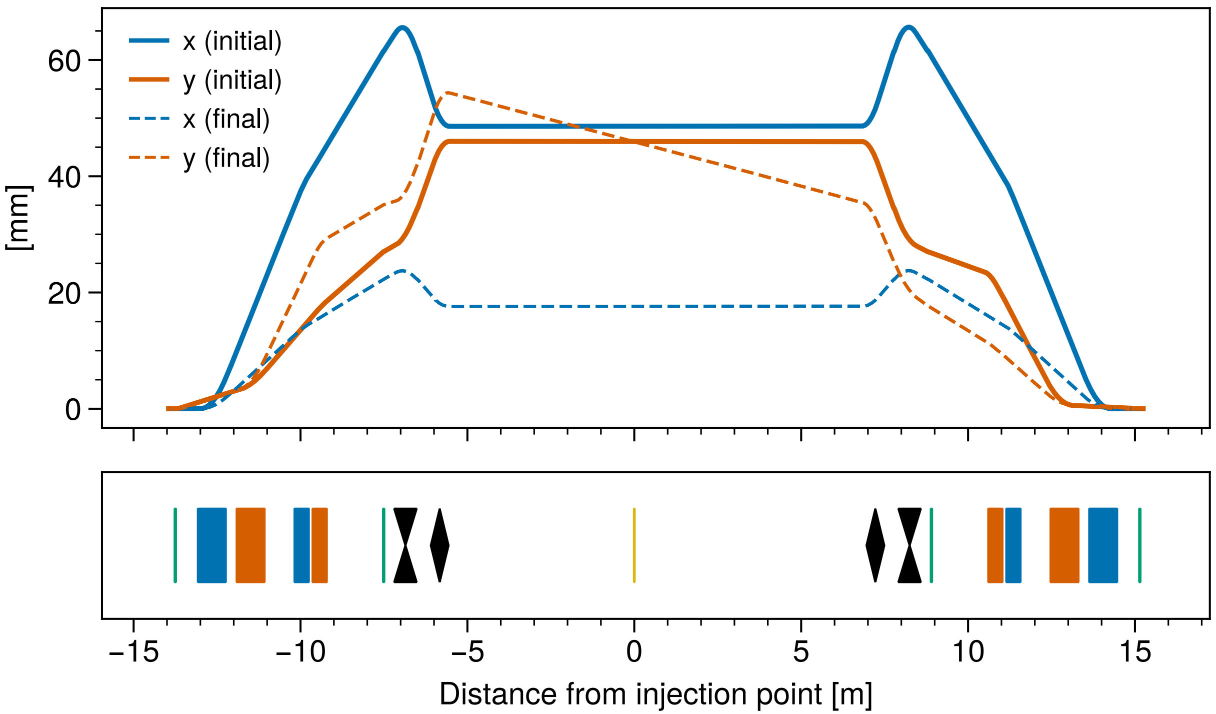
*Numbers after kicker upgrade – original simulations done at 600 MeV with old kicker limits, identical to current 800 MeV operation

Figure 8: Long Injection dynamic bum magnets with Beam Pipe and Bellow.

Raparia, 2005

Painting Trajectory

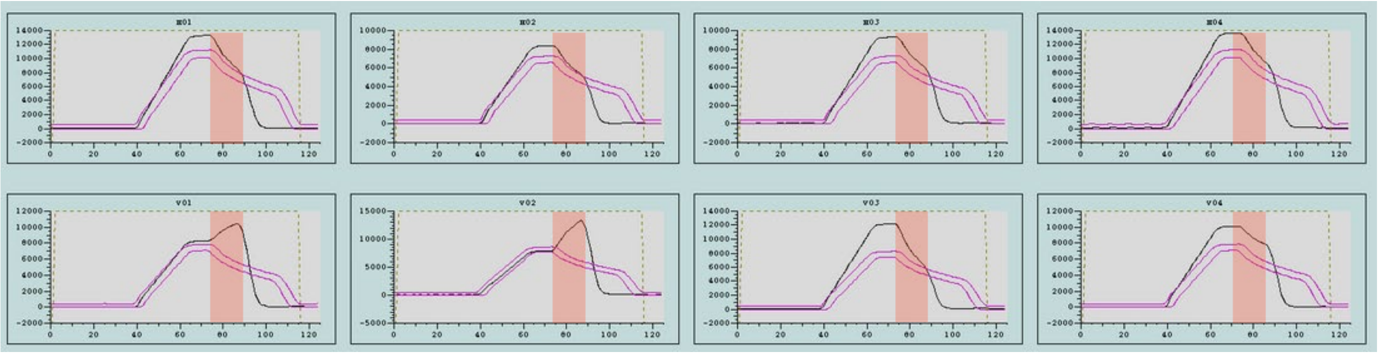
Fixed chicane bump not shown



- Pure x bump
  - all kickers decrease with time
  - injecting on closed orbit is only kicker limitation
- Pure y' bump
  - some kickers kick more some less than position bump
- We can ease kicker limitations by:
  - biasing the closed orbit with correctors – has to be determined on-line
  - Reducing beam energy – 800 MeV is lower limit because of timing system*

Horizontal Kickers

Vertical Kickers



Experiment WF

Production WF

*we've gone to 600 MeV, but it's very tough, not necessary

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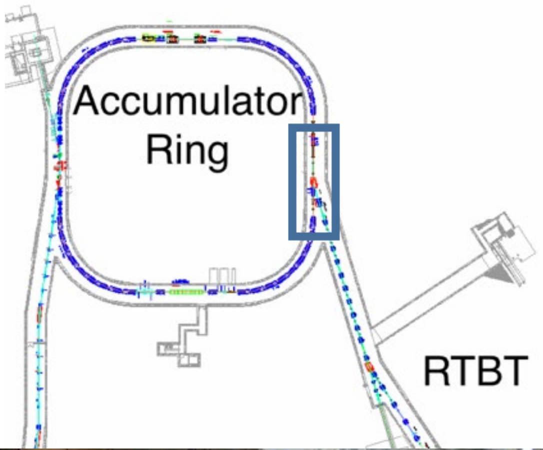
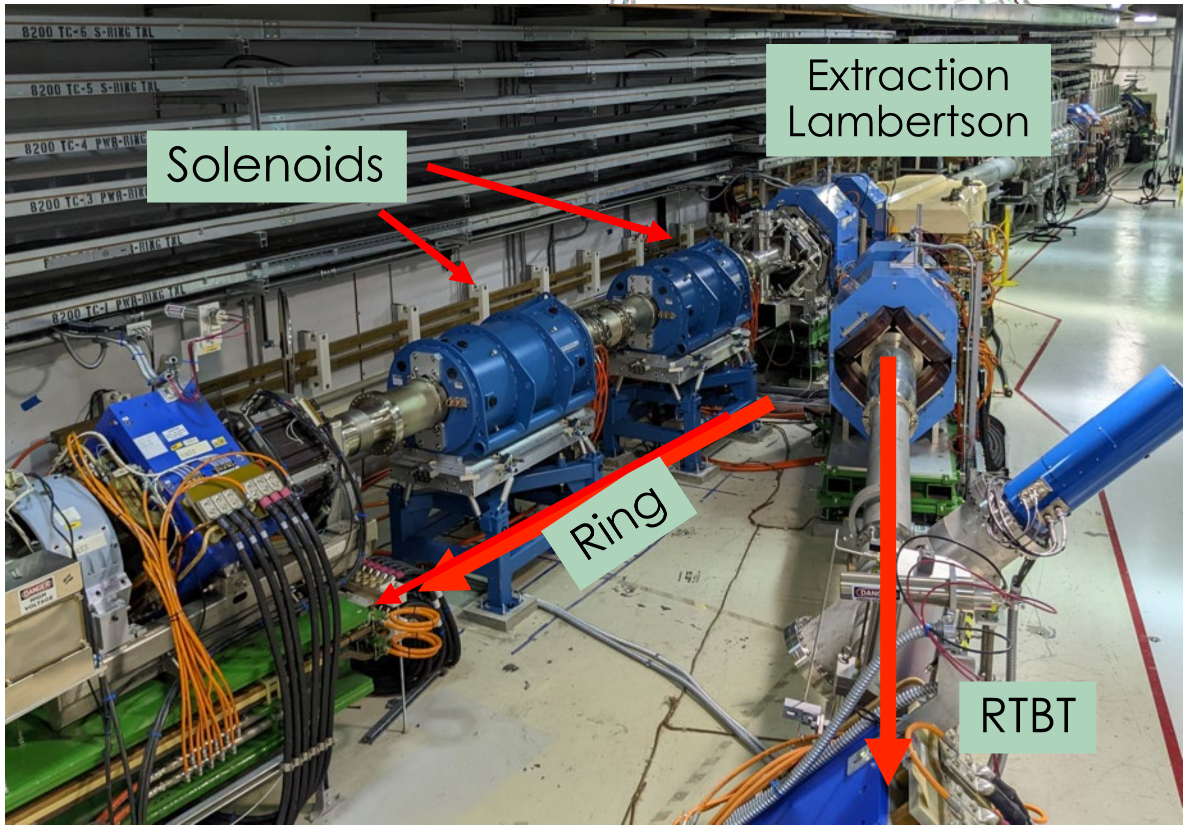
SNS Solenoids

- Solenoids were designed and built by Stangenes Industries
- Installed late Nov. 2022
- Solenoids (0.6 T·m, peak $B_{||}$= 0.26 T) split equal tunes

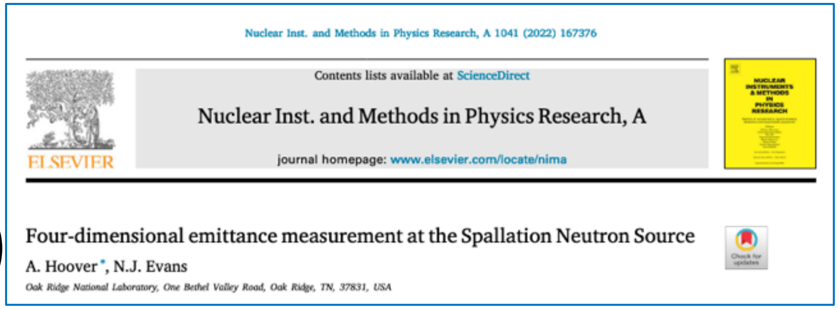




RTBT Diagnostics

Four RTBT wire scanners allow measurement of 4D emittance
(requires slight mod of RTBT optics to avoid poorly conditioned matrix*)

*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Four-dimensional emittance measurement at the Spallation Neutron Source

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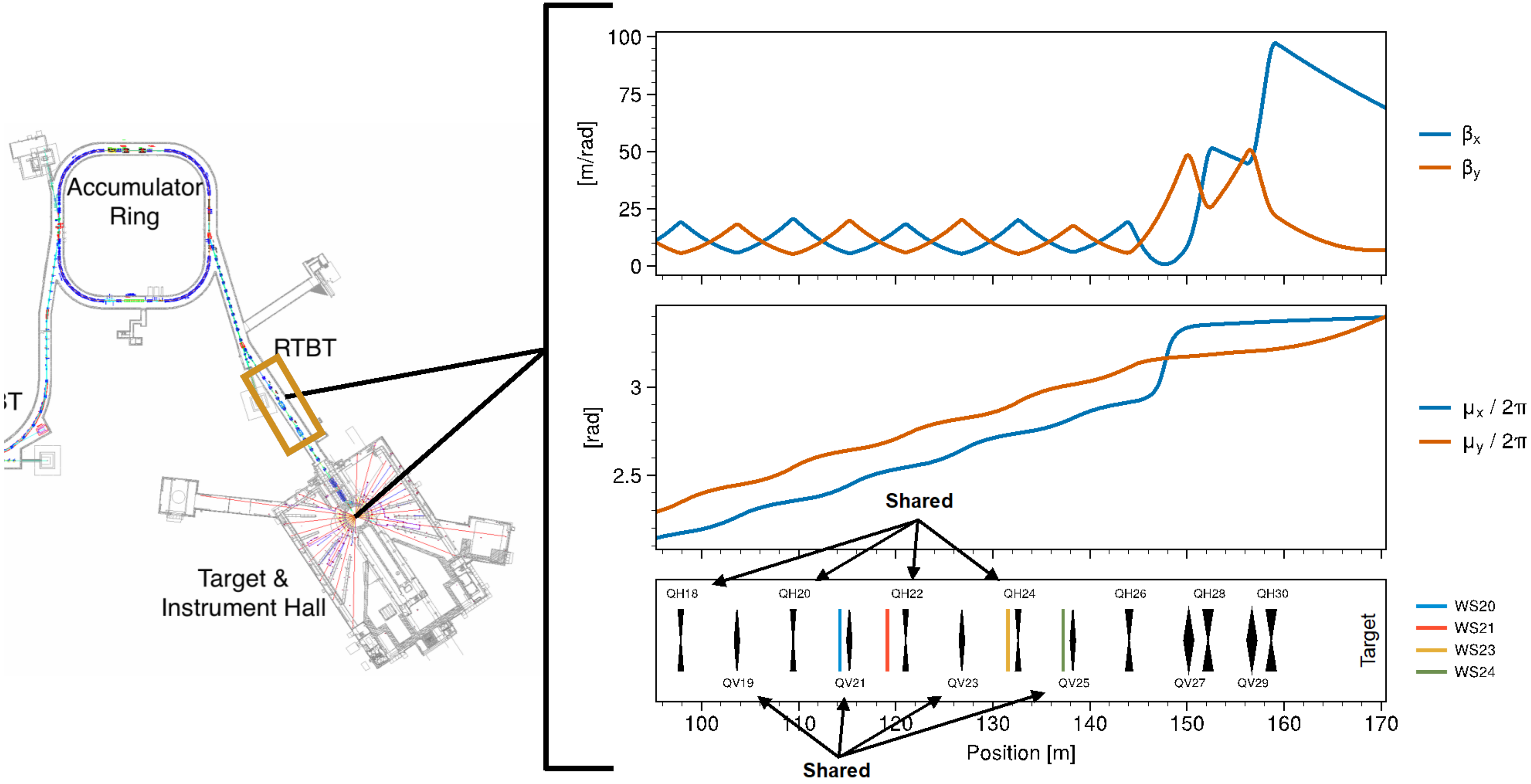


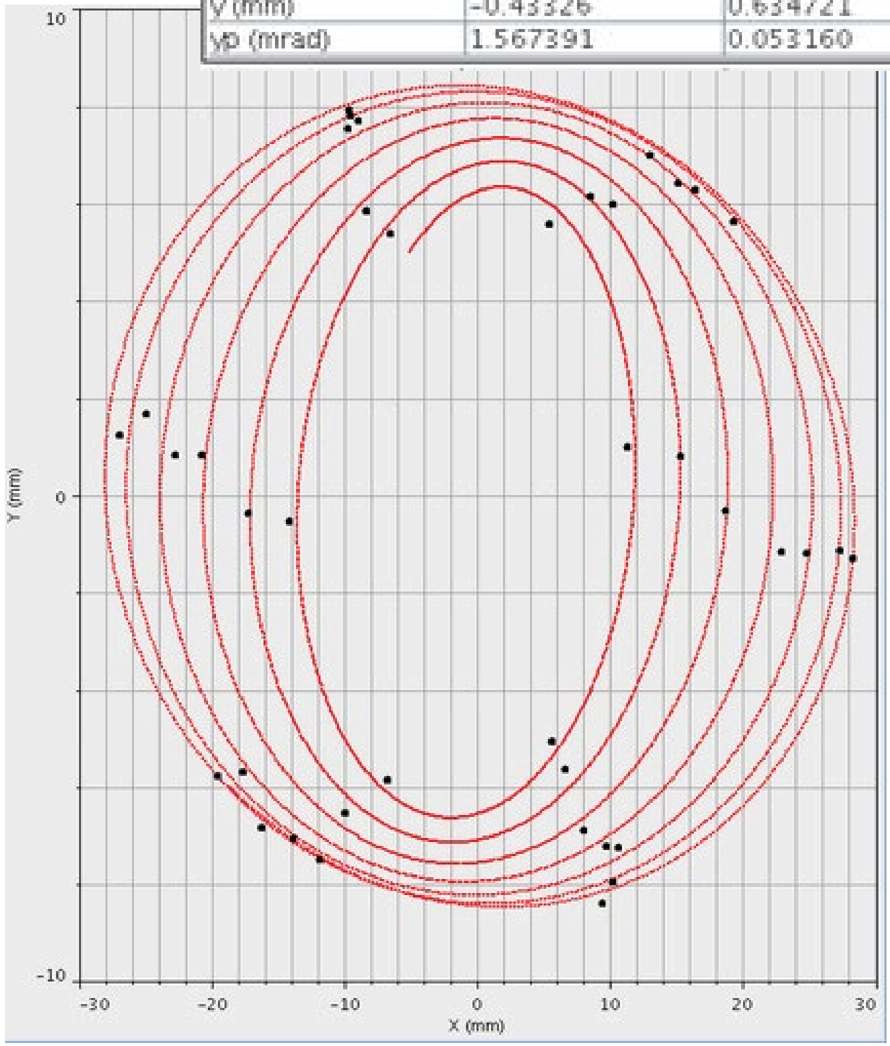
x

Procedure for Eigenpainting

1. Setup ring with equal tunes (~6.177)
2. Inject single pulse off closed orbit
3. TBT BPM data to + linear model to establish injection parameters (x,x',y,y')
4. Find kicker settings to inject on closed orbit these are t_0 kicker settings
5. Energize solenoids to split tunes
6. Fit coupled tunes
7. Inject on eigenvector coordinates*:
   1. A**v**= A*(v_x,$v_{x'}$,v_y,$v_{y'}$) these are t=t_{max} kickers
8. Draw waveforms – **v***A*Sqrt(t_0/t_{max})
9. Paint

Measured phase space parameters at the foil

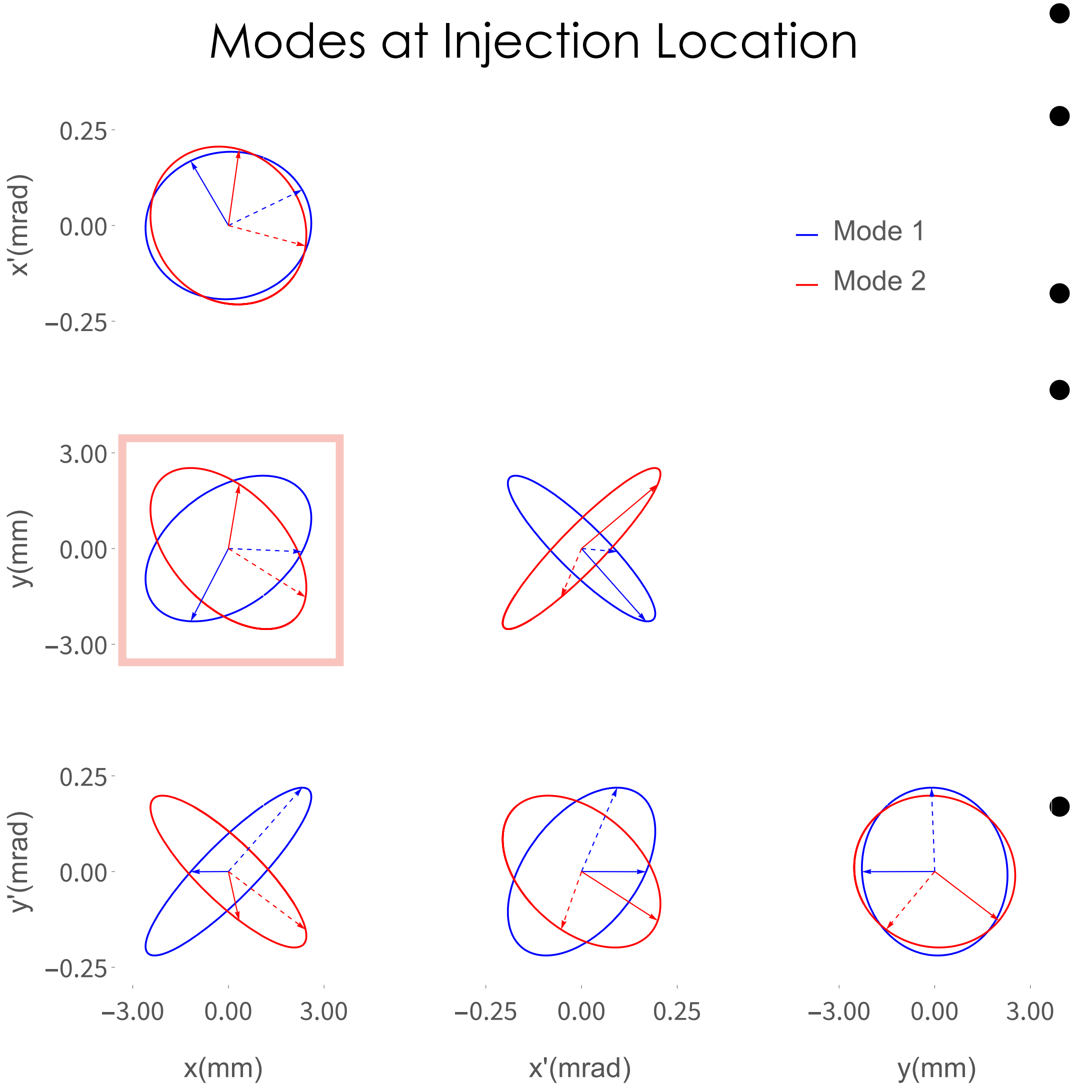
	average	sigma
x (mm)	26.62396	0.819318
xp (mrad)	0.096851	0.136217
y (mm)	-0.43326	0.634721
yp (mrad)	1.567391	0.053160



Turn-by-turn BPM data for a single pulse injected with final kicker settings

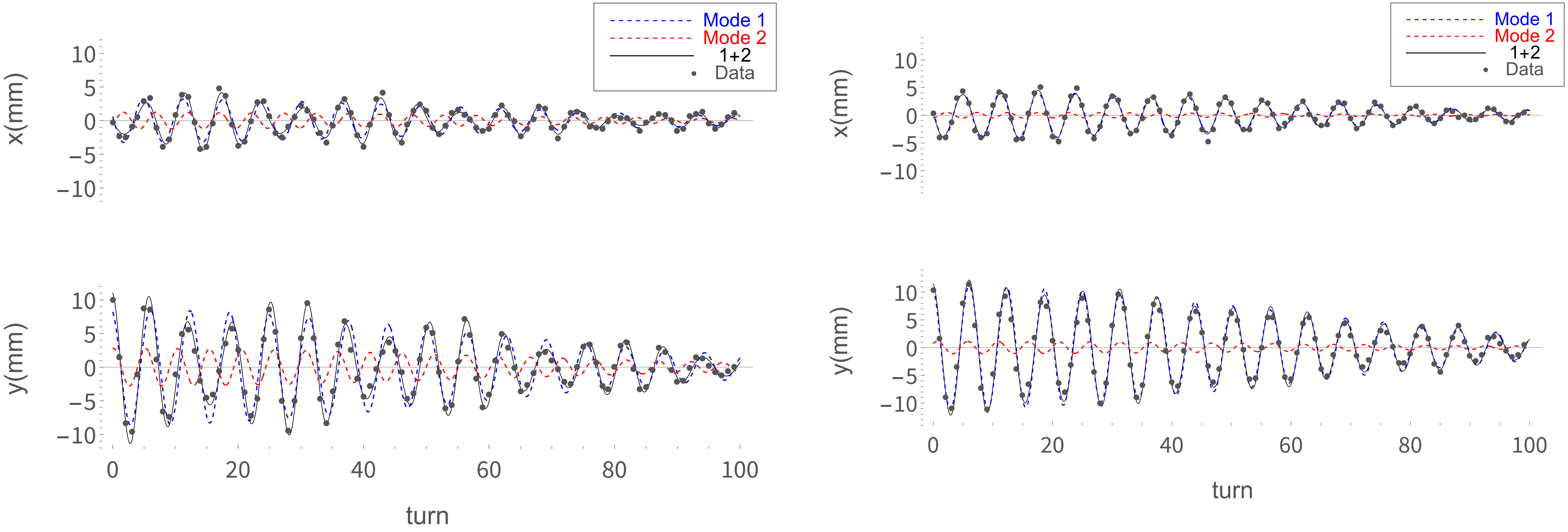
Online model doesn't have solenoids – we can turn them off for

Modes with Solenoids



- Equal tunes $\nu_x = \nu_y = 6.1754$
- Solenoids on at full power for tunes of nu1=6.1584, nu2=6.1956
- Tune split 0.0372
- Tunes calibrated to measured TBT data using two free parameters:
  - solenoid strength
  - equal tune value used to match observed tunes
- We will inject on dashed blue line

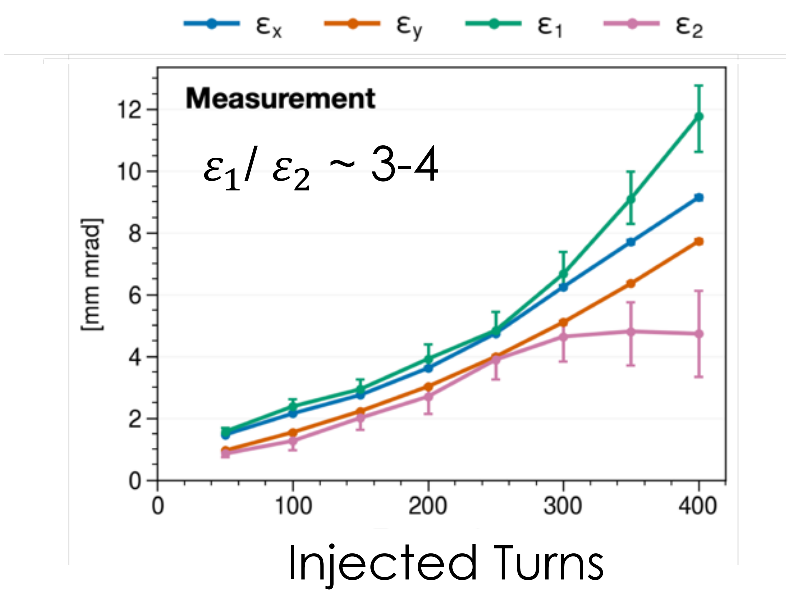
TBT data fit with calibrated model



Parameter	Arbitrary Inj.	Single Mode
$A_1(\sqrt{mm \cdot mrad})$	3.22 ± 0.010	4.19 ± 0.012
θ_1	0.150±0.0005	0.148 ± 0.0004
$A_2(\sqrt{mm \cdot mrad})$	1.16±0.010	0.46 ± 0.012
θ_2	0.432±0.001	0.320 ± 0.004
$\frac{\epsilon_1}{\epsilon_2} = \left(\frac{A_1}{A_2}\right)^2$	7.71±0.14	80.37±4.00

Single turn injection off-axis
Performance here defines upper limit on painting

Measurement without Solenoids



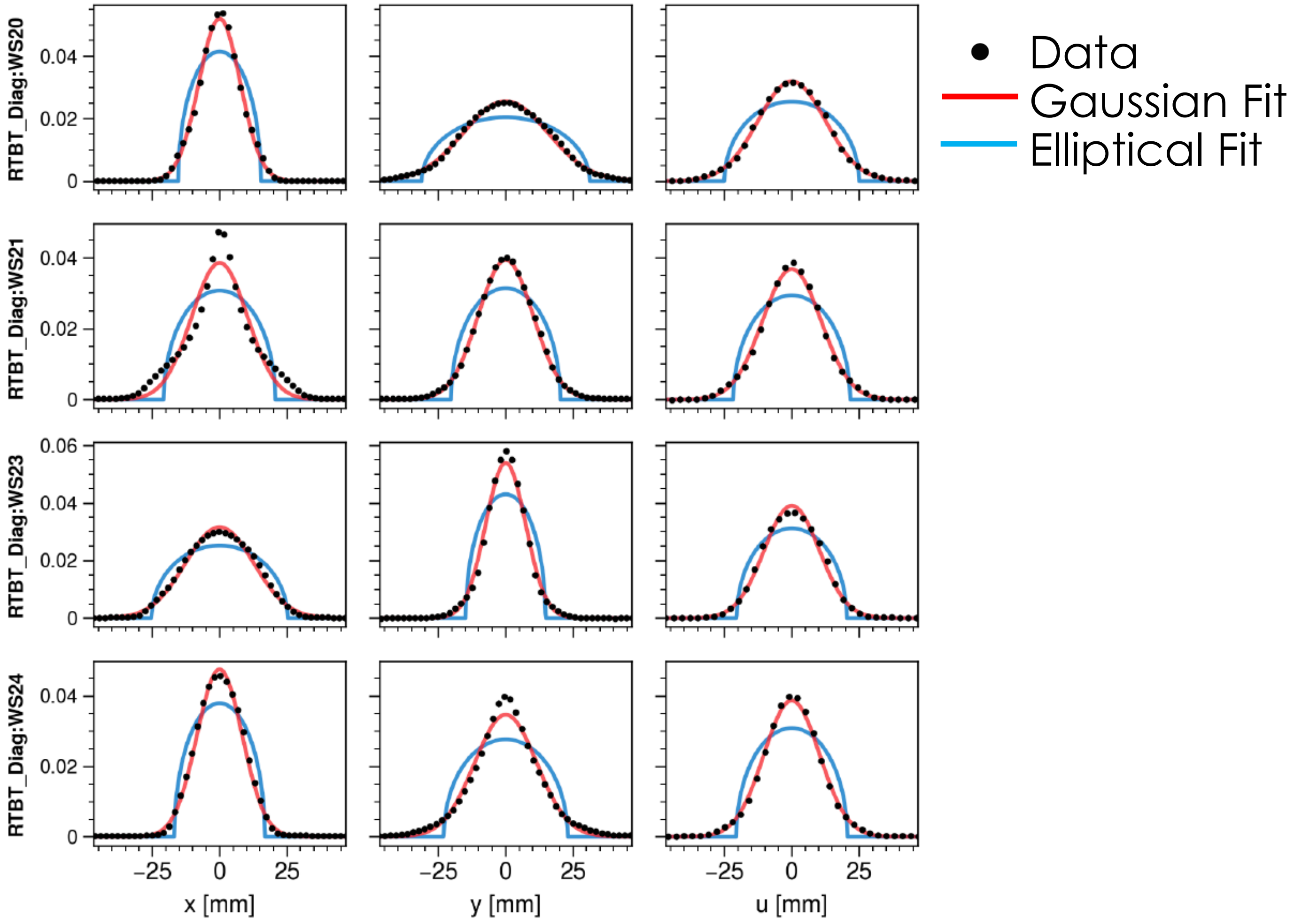
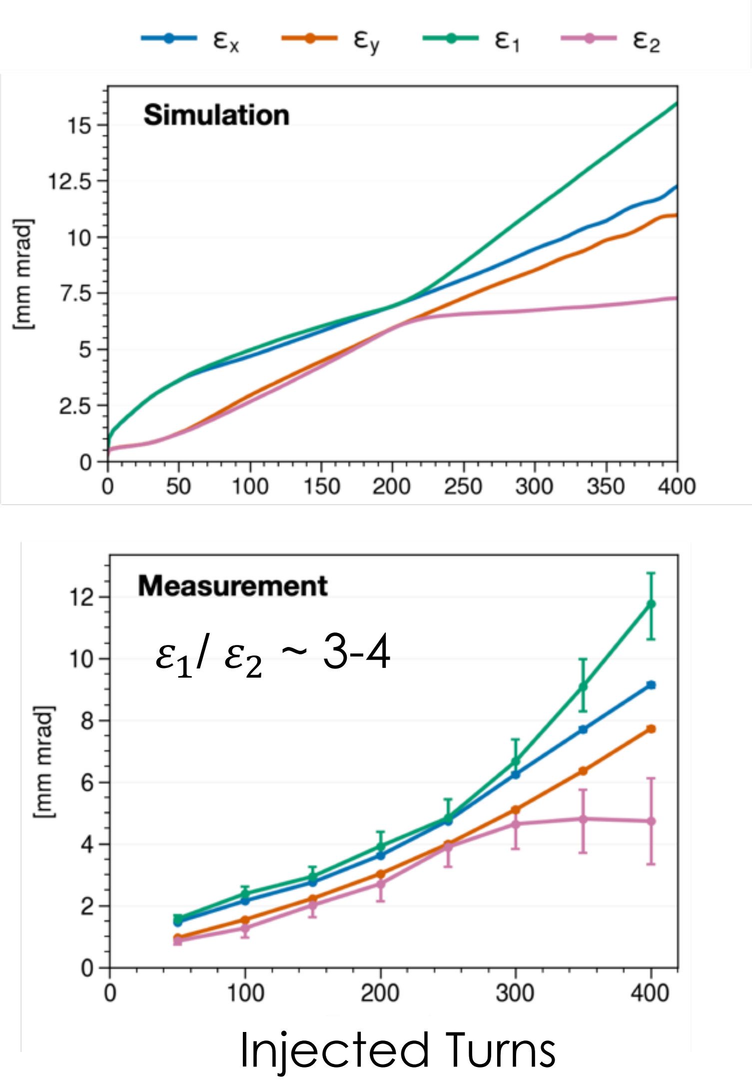
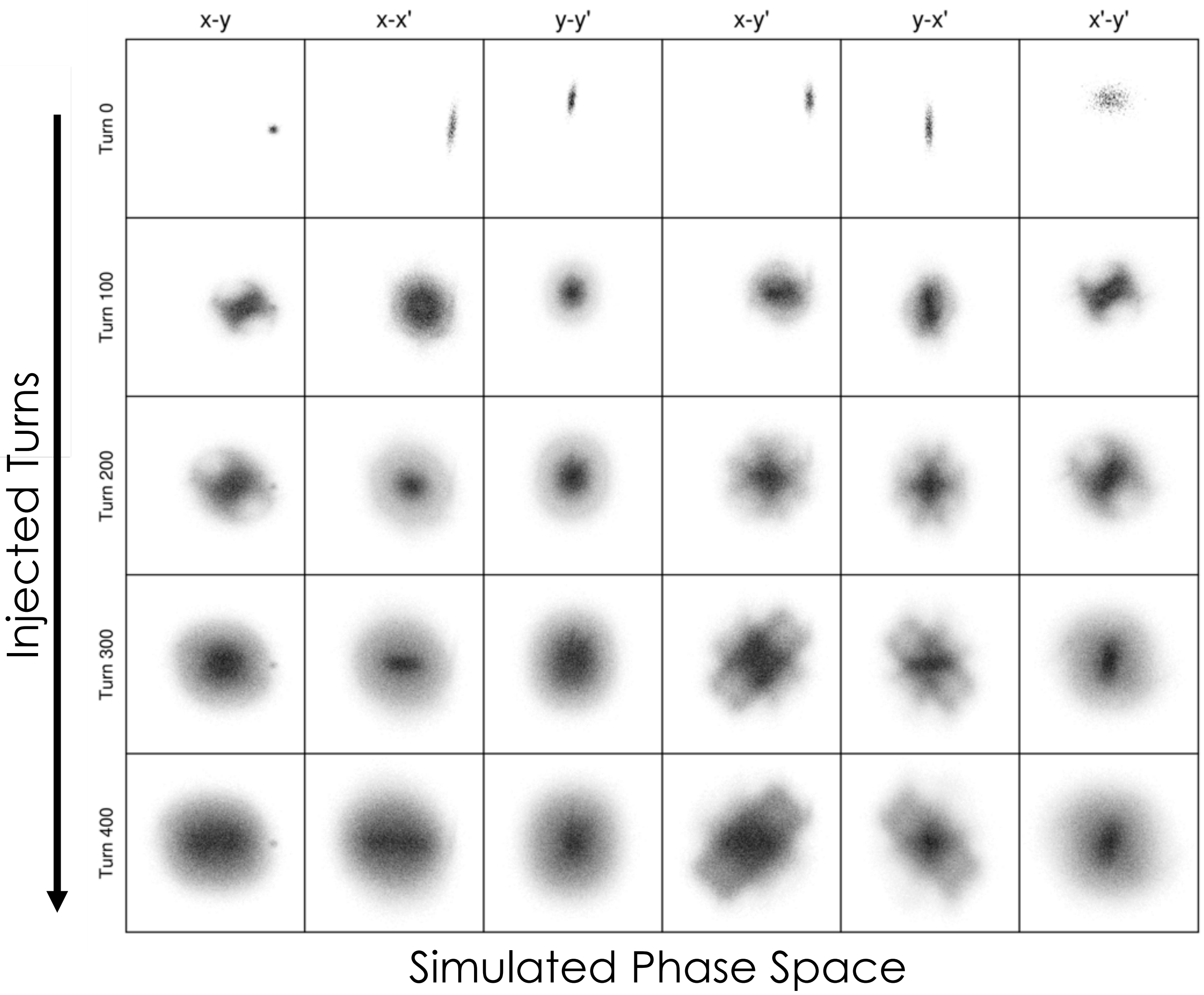


Figure 5.20: Measured wire-scanner profiles for the final distribution in Experiment 3.

Nice emittance ratio, but profile not very elliptical.

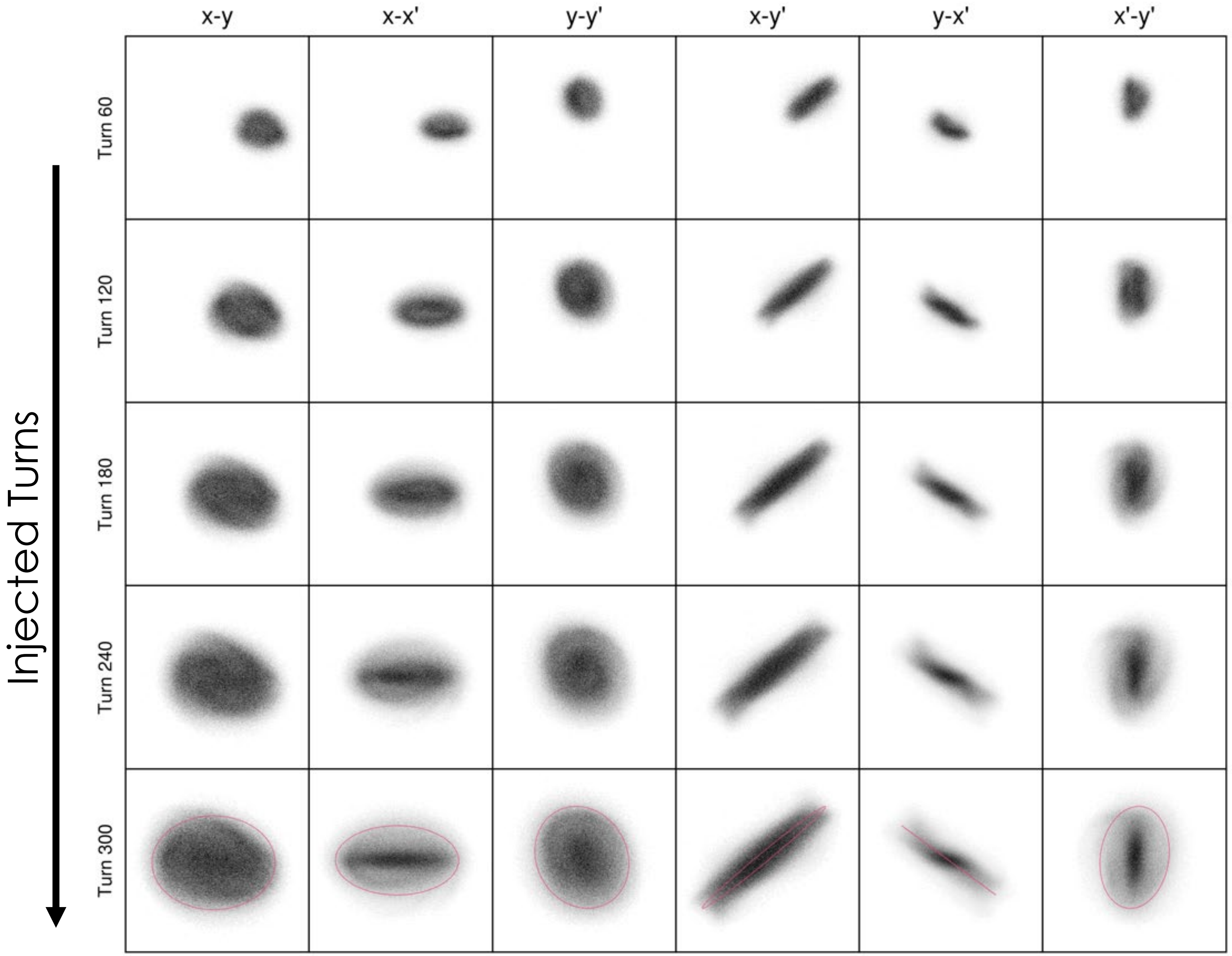
Simulation vs. Measurement – No Solenoids Experiment



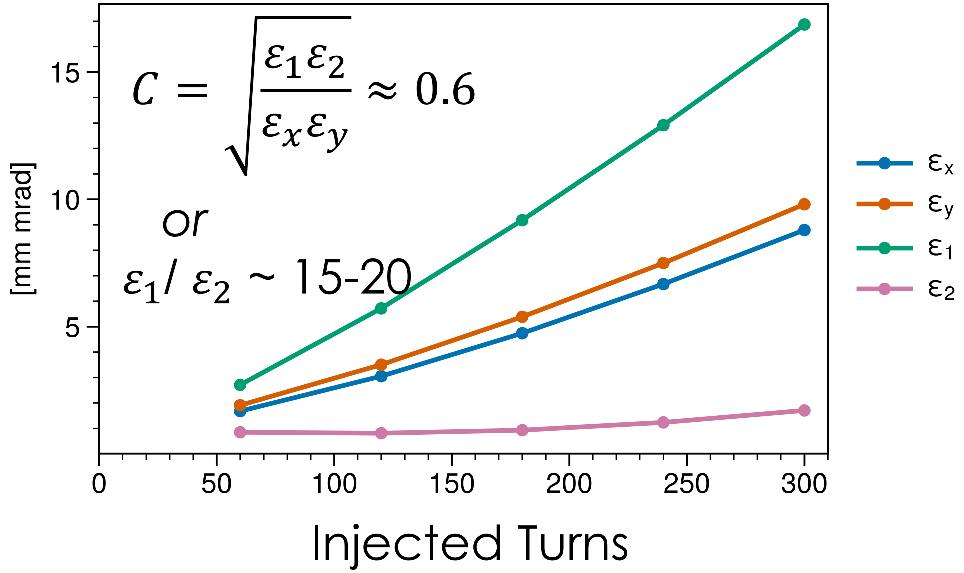


Extract beam after N turns are accumulated and measure evolution of emittance.

Simulation with Solenoids



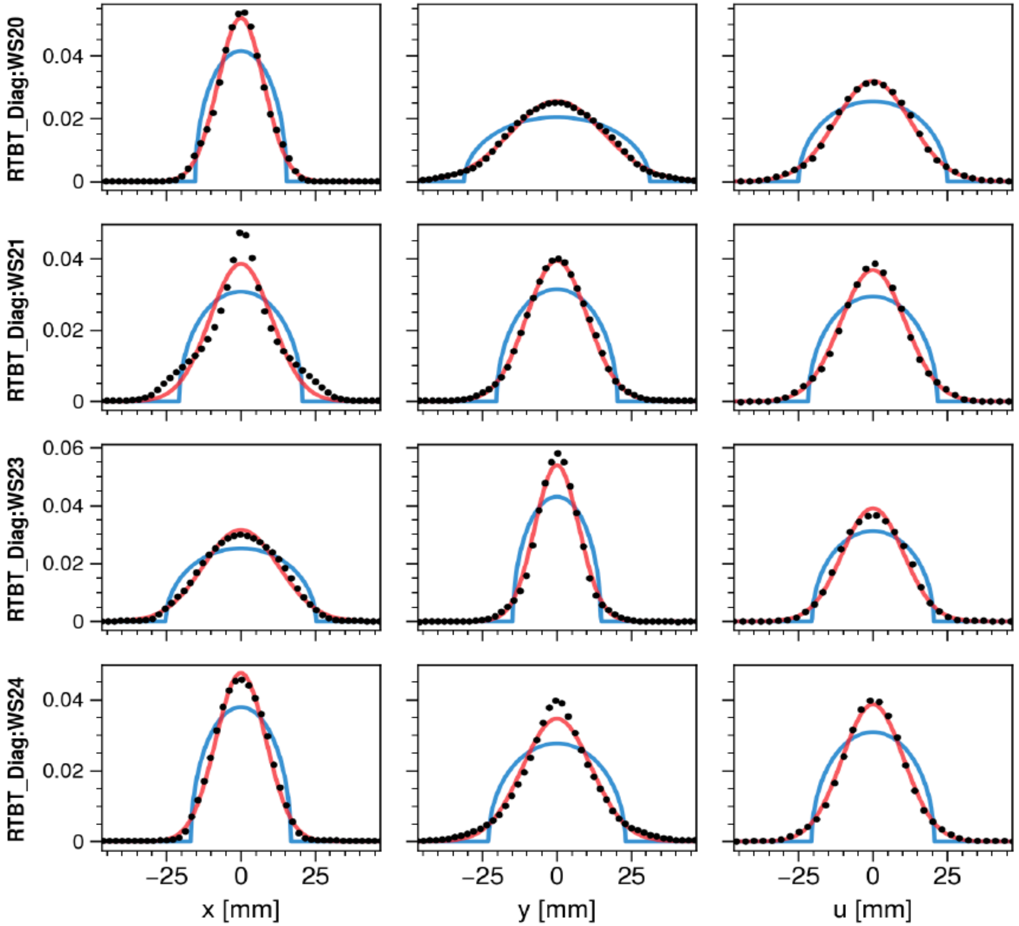
Simulated Phase Space



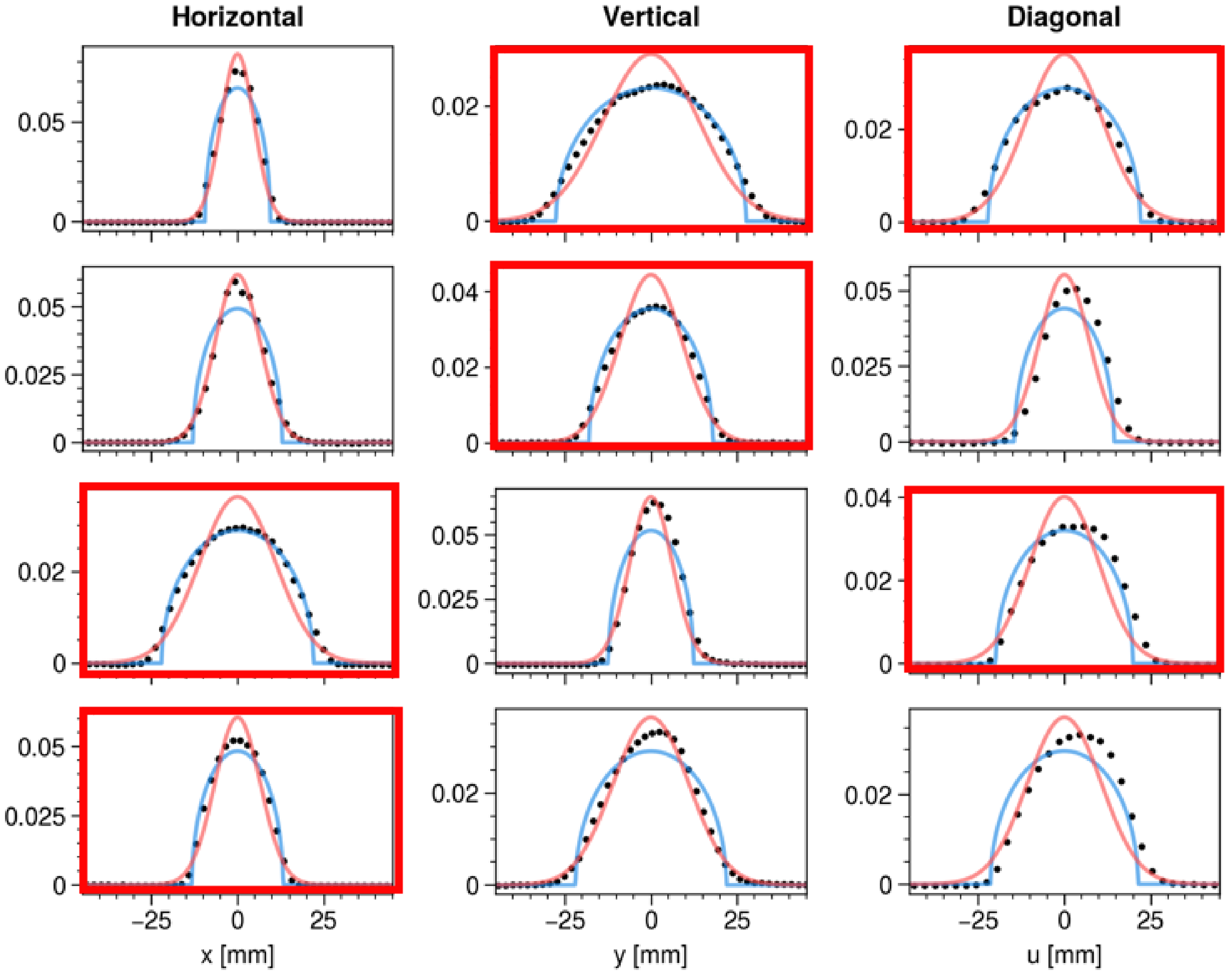
This is a representative "best case" – have not finished with simulation of recent results.

Wirescans with Solenoids

Without Solenoids



With Solenoids



Red profiles are most elliptical.

Summary Outlook

- We can ‘eigenpaint’ in the SNS ring
- Clear difference between case with/without solenoids
- We are interested in exploring behavior of eigenpainted Danilov (or other) distributions over longer storage times, ideas for space charge mitigation both in simulation and experiment

Acknowledgements

- Thanks to Jeff Holmes, Tim Gorlov, Charles Peters, Dave Brown, Vasiliy Morozov and Austin Hoover for providing simulations, slides, tools, time, and discussion in no particular order