Oak Ridge National Laboratory

Self-Consistent Injection Painting for Space Charge Mitigation

HB 2023

Geneva, Switzerland

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October 9-13th, 2023

U.S. DEPARTMENT OF ENERGY

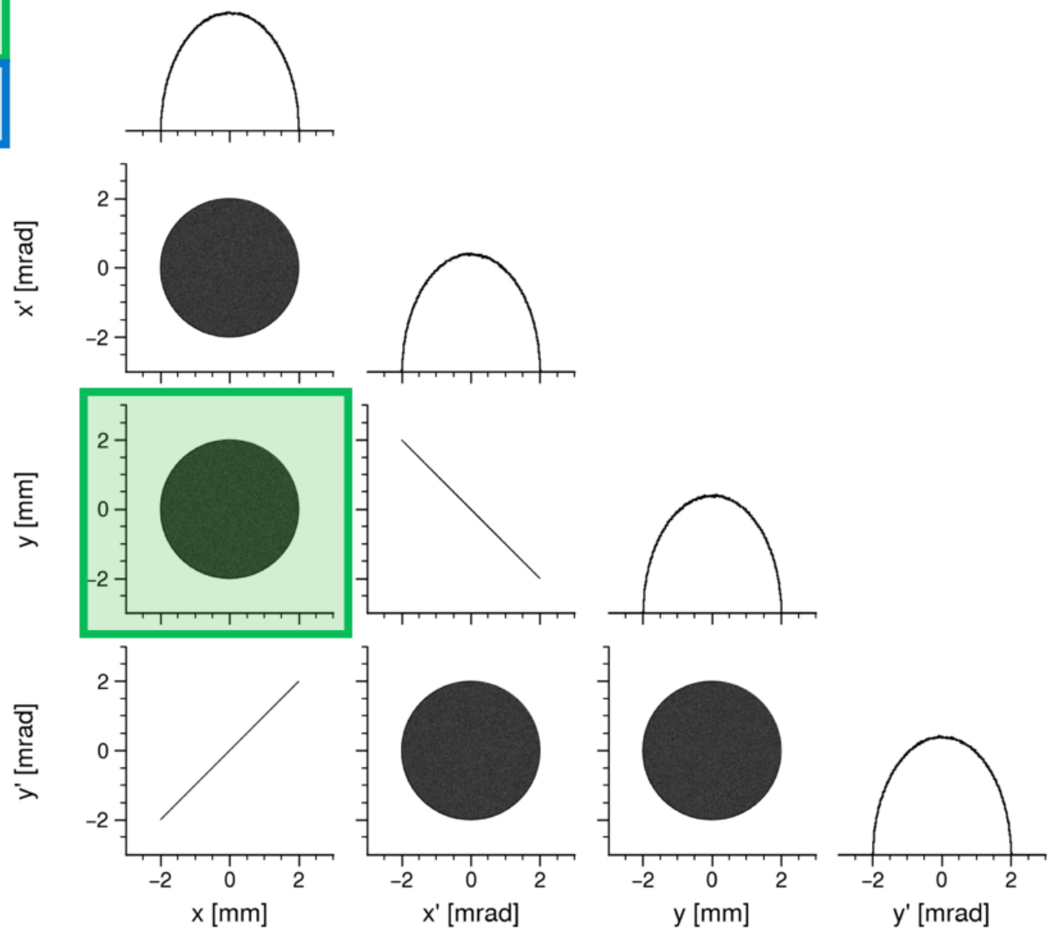
Outline

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

Danilov Distribution is Self-Consistent

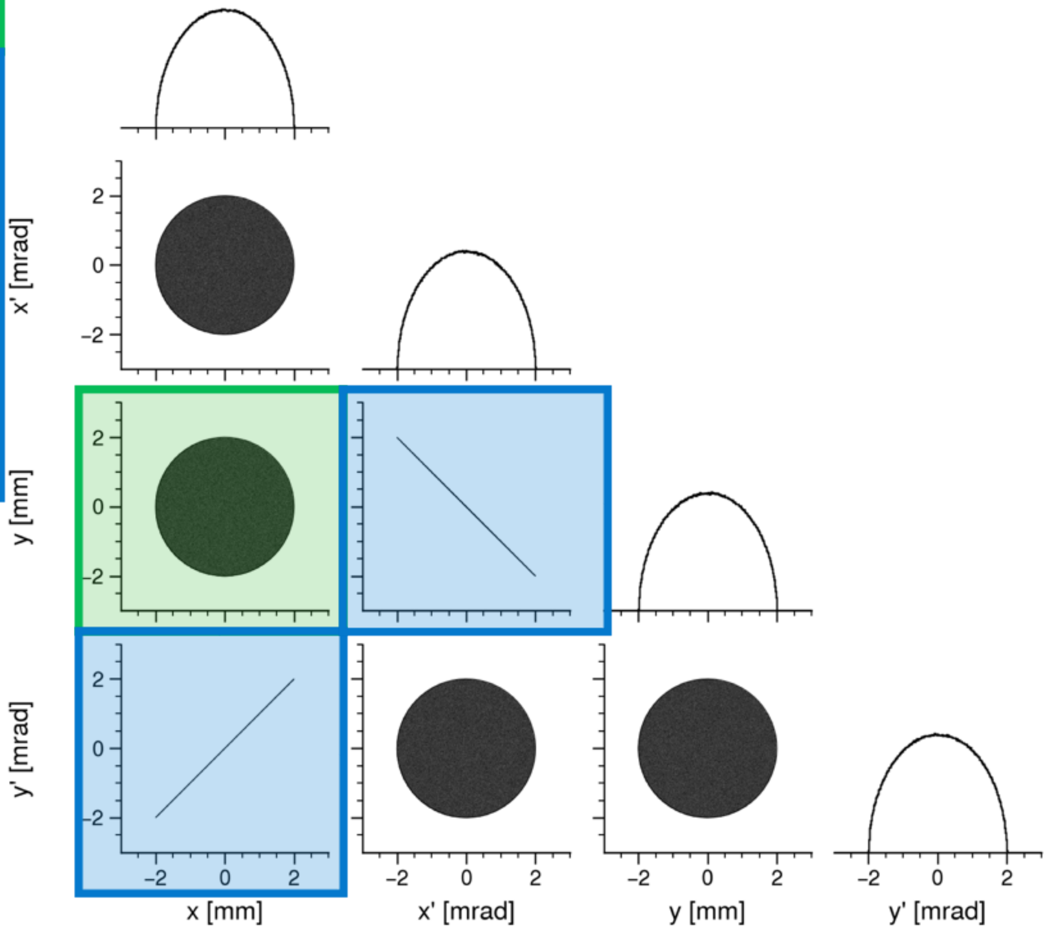
1. Uniform real space distribution (linear space charge)
2. Elliptical envelope
3. Maintains (1),(2) under any linear transport (including space charge)

{2,2} Danilov Distribution



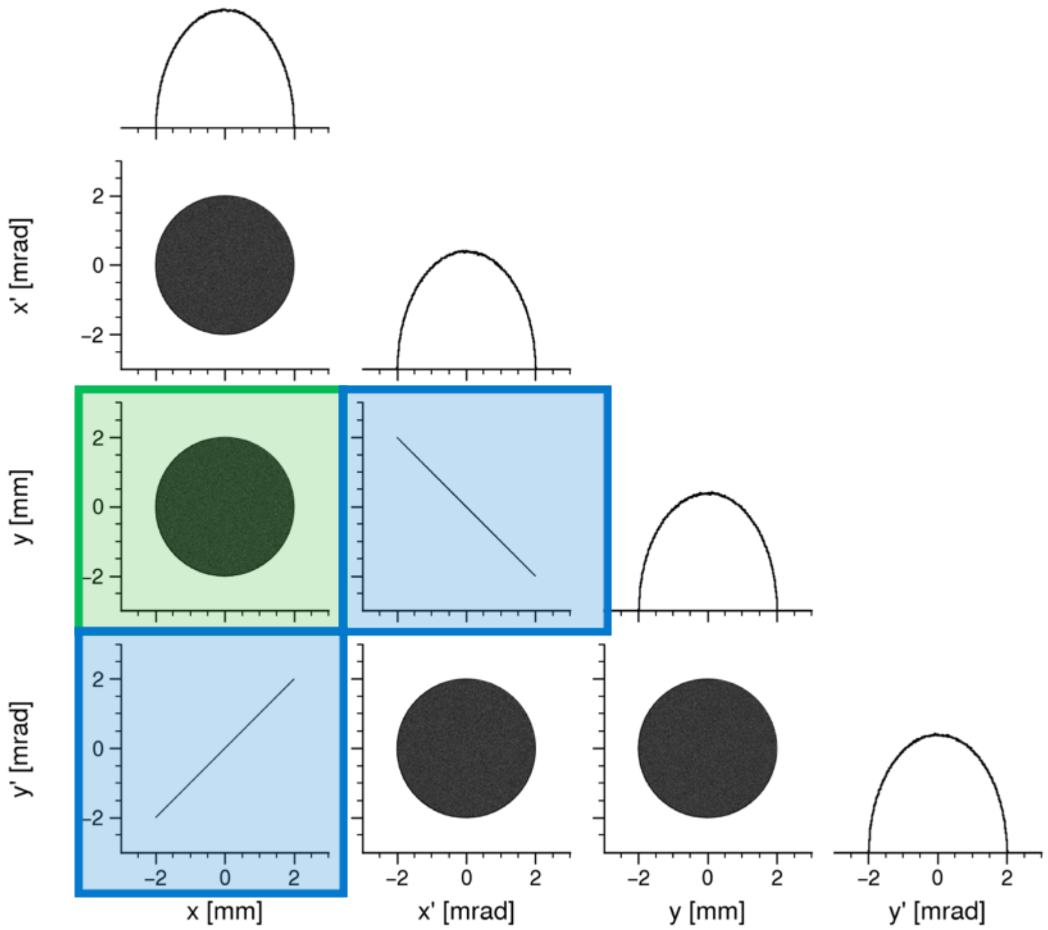
Danilov Distribution Key Features

- Uniform space charge implies reduced tune shift, and minimal spread
- Elliptical envelope comes from distribution being eigenvector of ring lattice + linear space charge – defines painting trajectory
- eigenvector implies vanishing 4D emittance
- Invariant increases with real space radius meaning we can add more beam at the edges, painting beam while maintaining self-consistency – this is a scalable procedure



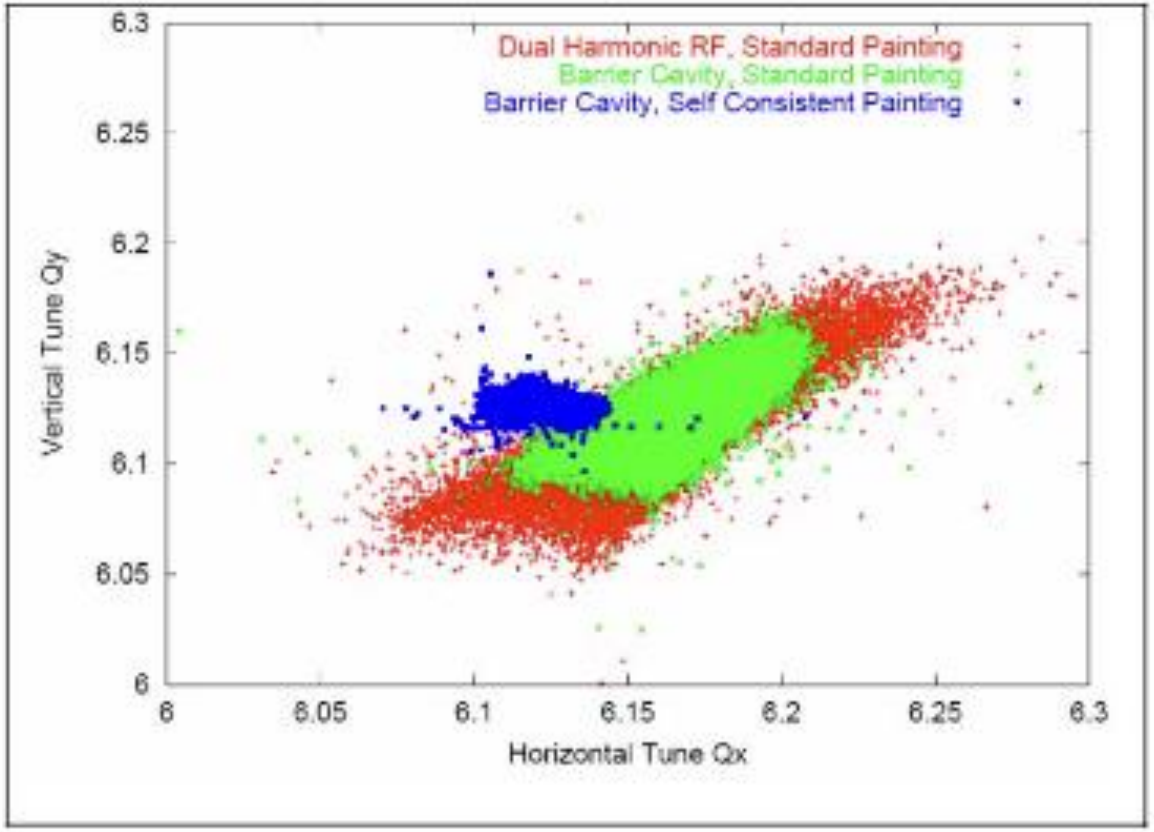
Danilov Distribution Key Features

- To verify eigeninjection we look for low 4D emittance
- To verify uniformity of eigeninjection we look for half-elliptical profiles



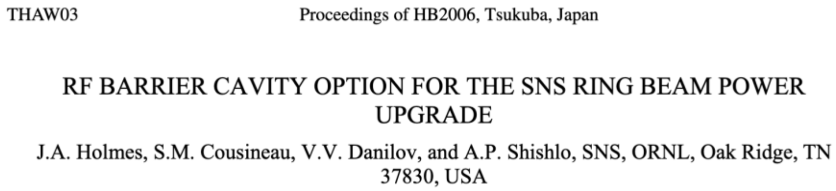
Space Charge Mitigation

- Footprint is much smaller than standard SNS tune footprint



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

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

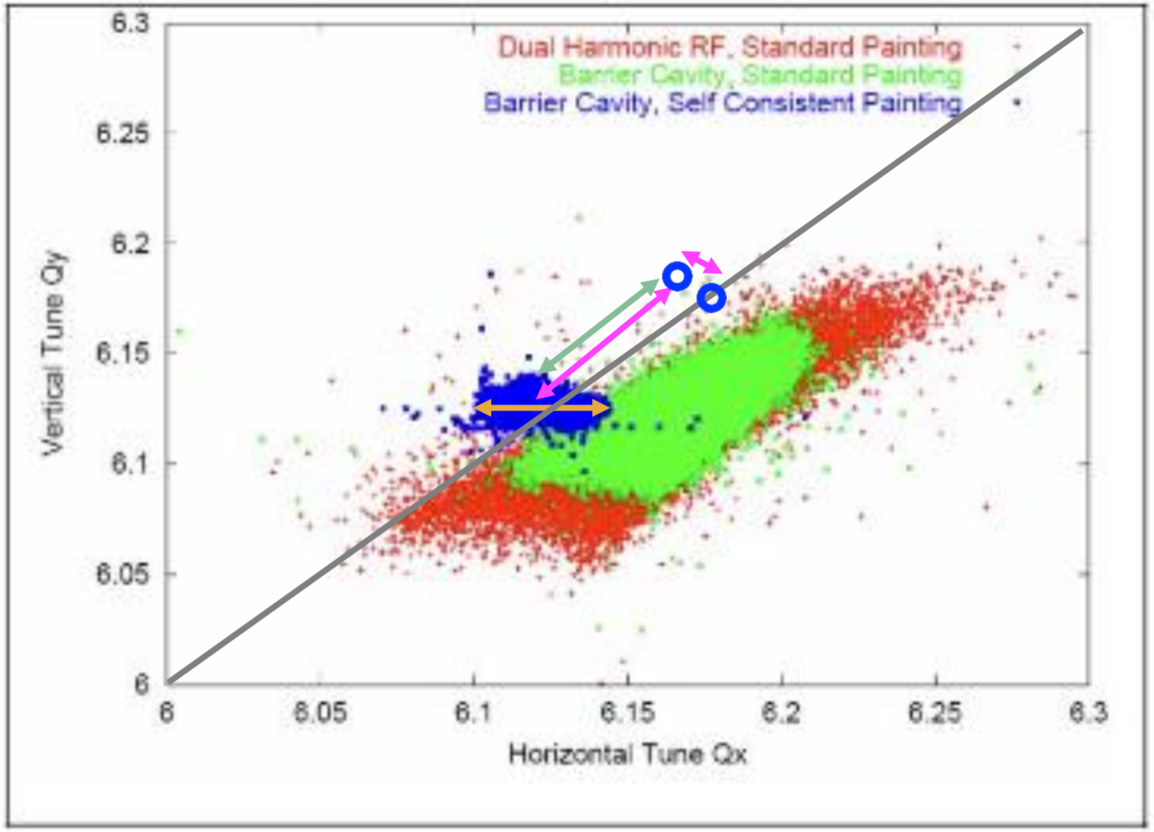

THAW03 Proceedings of HB2006, Tsukuba, Japan

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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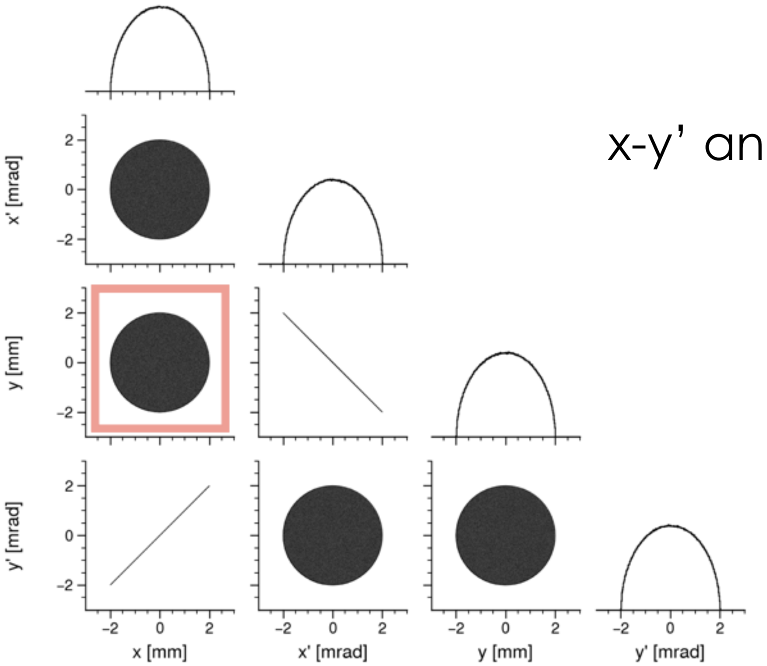
Project Goals

* PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **6**, 094202 (2003)

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

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

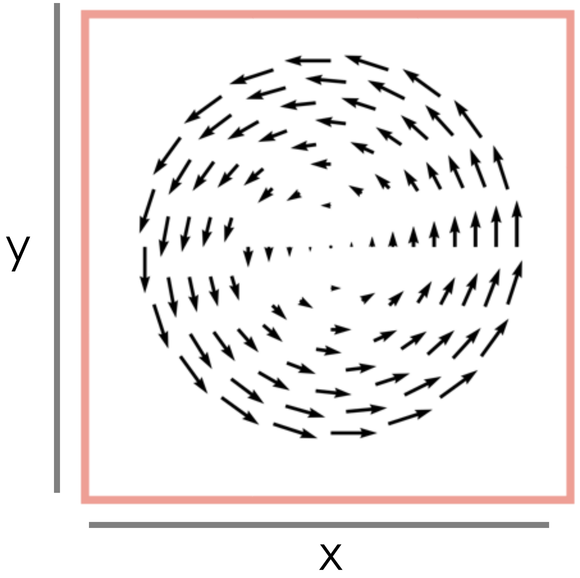
- Proof-of-principle painting of a uniformly filled, elliptical bunch in the SNS ring (approx. {2,2}-Danilov* distribution, *the Danilov distribution*)
- Study evolution of the Danilov dist. during painting and storage



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

Uniformity

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

Detailed feasibility study:

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 124403 (2018)

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

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(Received 15 May 2018; published 17 December 2018)

*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)

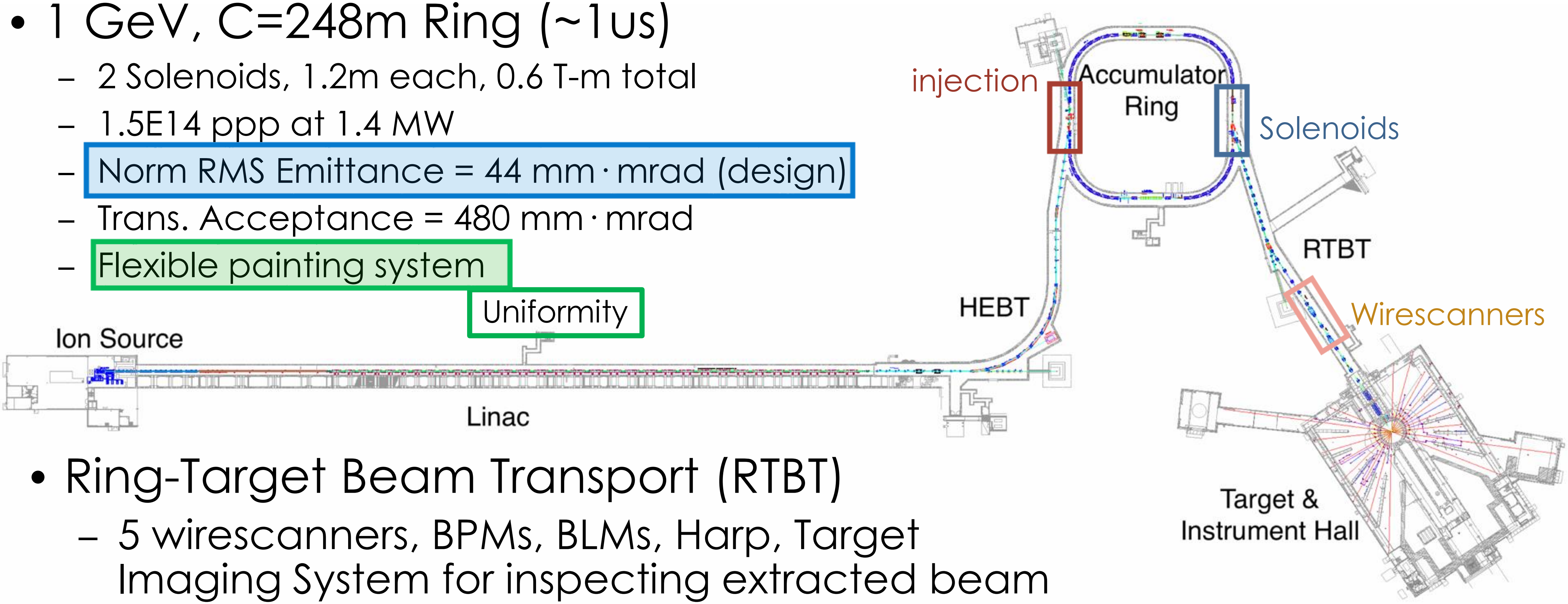
Low 4D emittance

- 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:

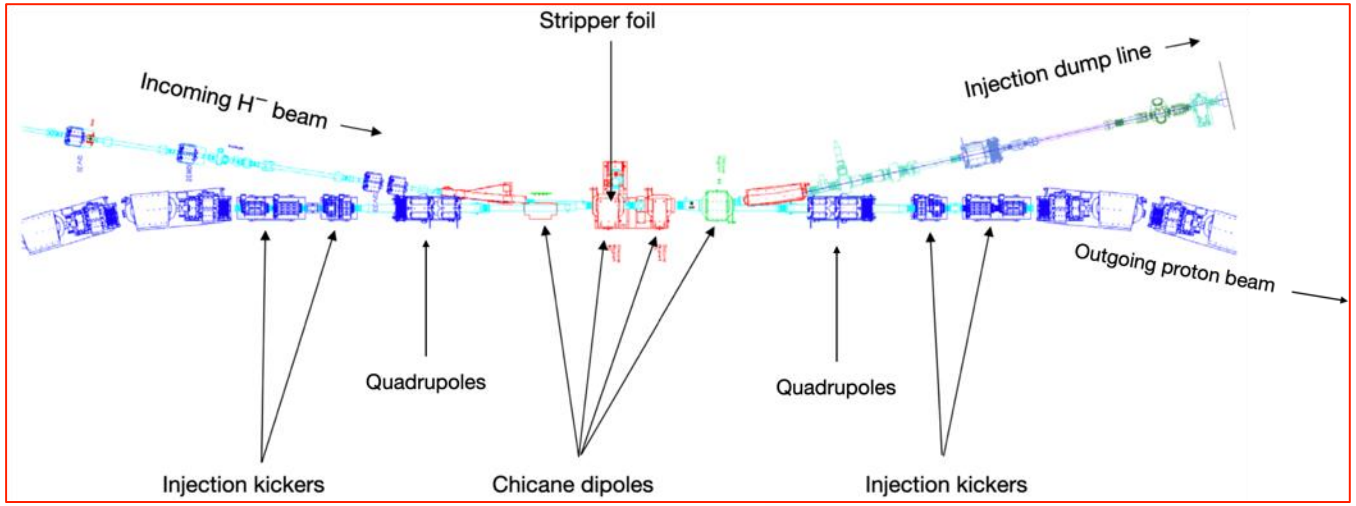
Space charge tune shift: 0.15
Uniform beam tune shift: 0.1

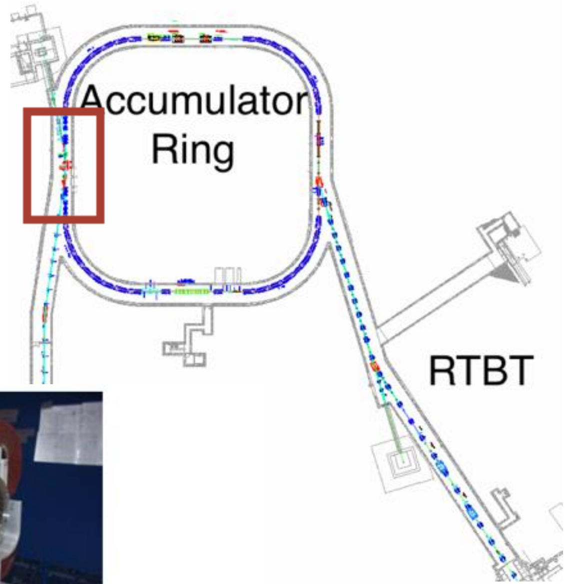


- Ring-Target Beam Transport (RTBT)
  - 5 wirescanners, BPMs, BLMs, Harp, Target Imaging System for inspecting extracted beam

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

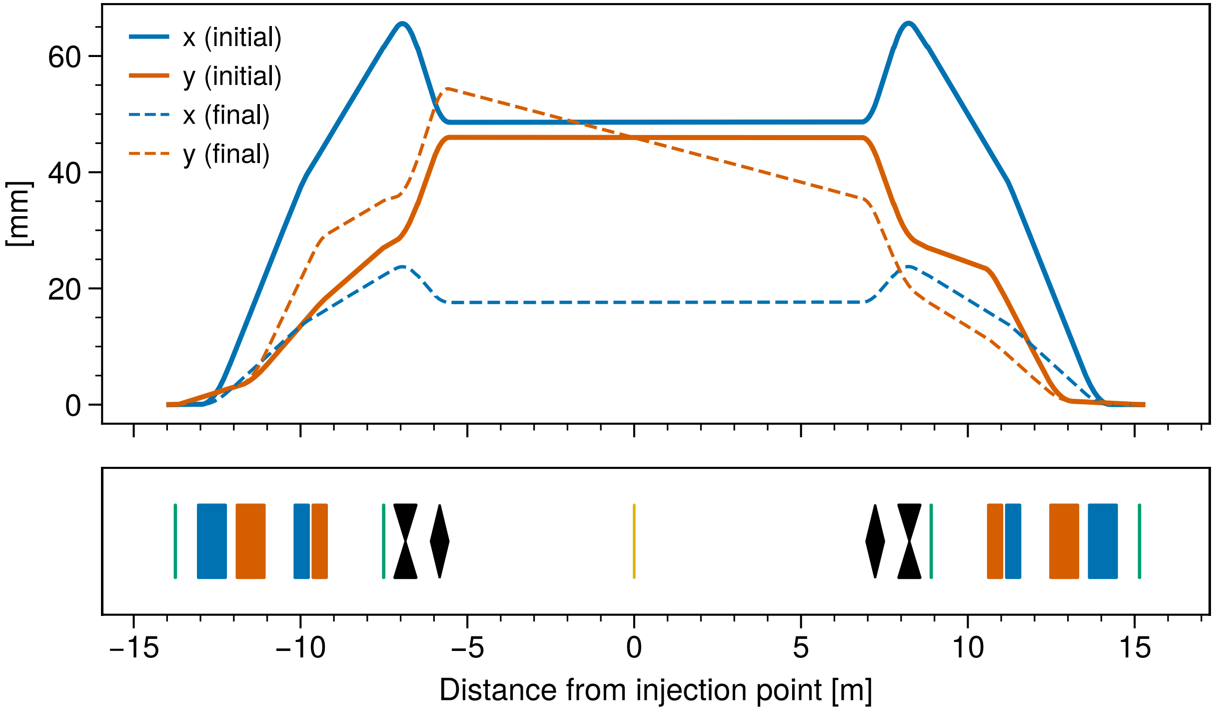
*Numbers after kicker upgrade – original simulations done at 600 MeV with old kicker limits, identical to current 800 MeV operation

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

Raparia, 2005

Painting Trajectory

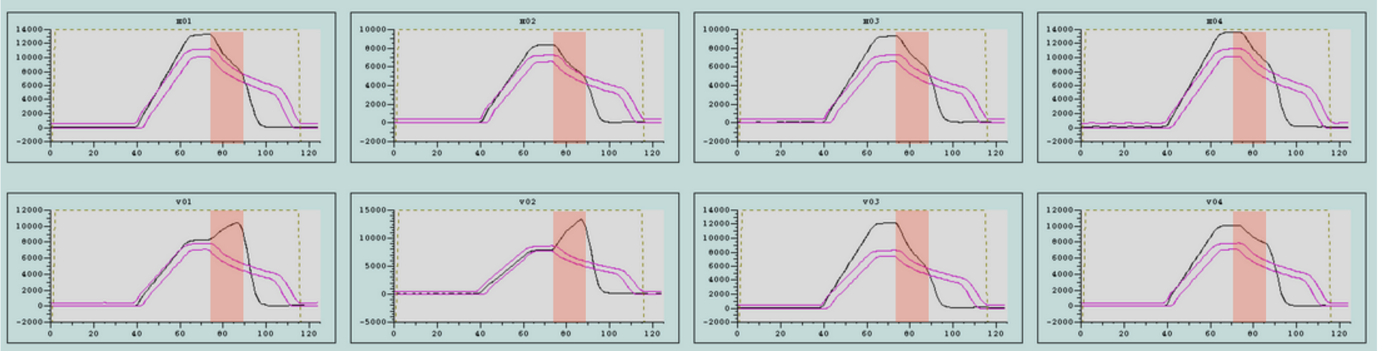
Fixed chicane bump not shown



- Pure x bump
  - all kickers decrease with time
  - injecting on closed orbit is only kicker limitation
- Pure y' bump
  - some kickers some stronger get weaker
  - Vertical Kicker 2 reaches full power limiting angle at 800 MeV
- 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



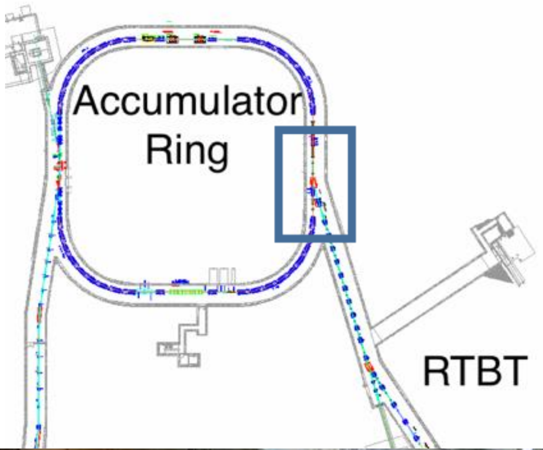
Experiment WF

Production WF

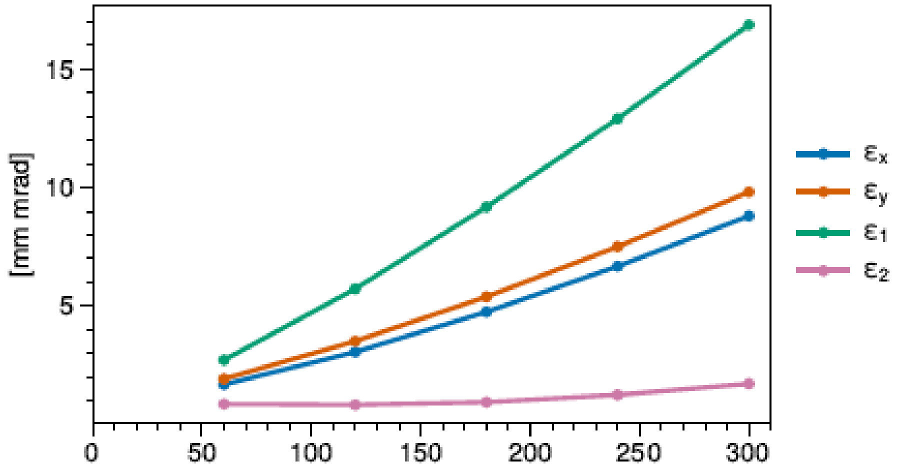
*we've gone to 600 MeV, but it's very tough, not necessary

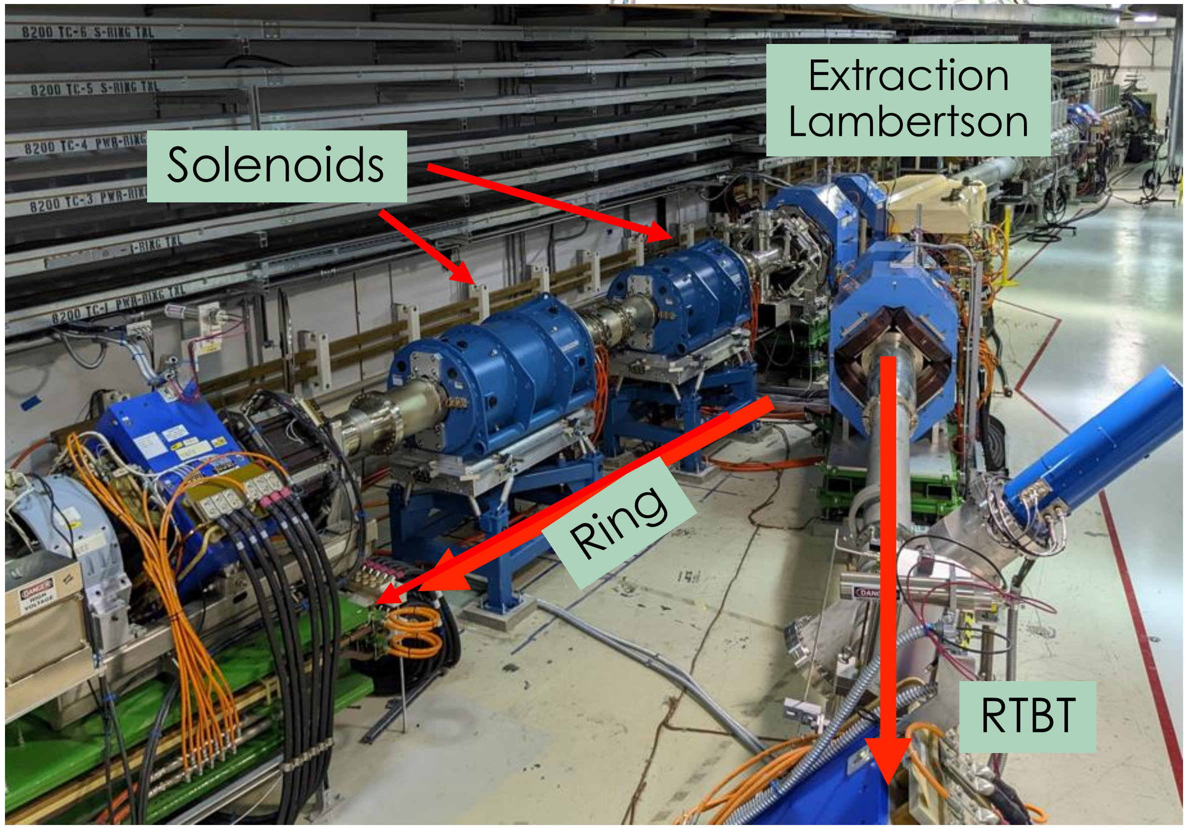
SNS Solenoids

- Solenoids were installed late Nov. 2022
- Solenoids (0.6 T · m, peak $B_{||}$ = 0.26 T) split equal tunes sufficiently to achieve result seen below



Simulated "best case" with Solenoids





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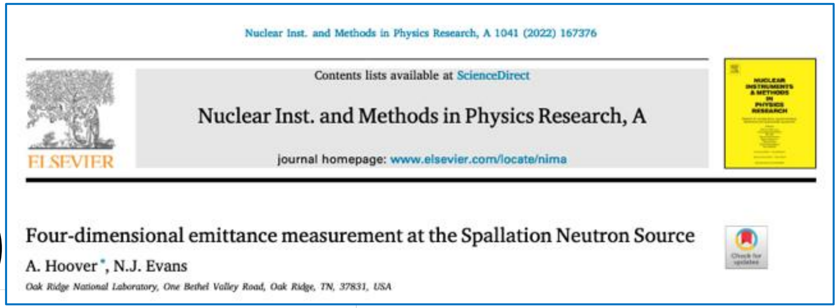
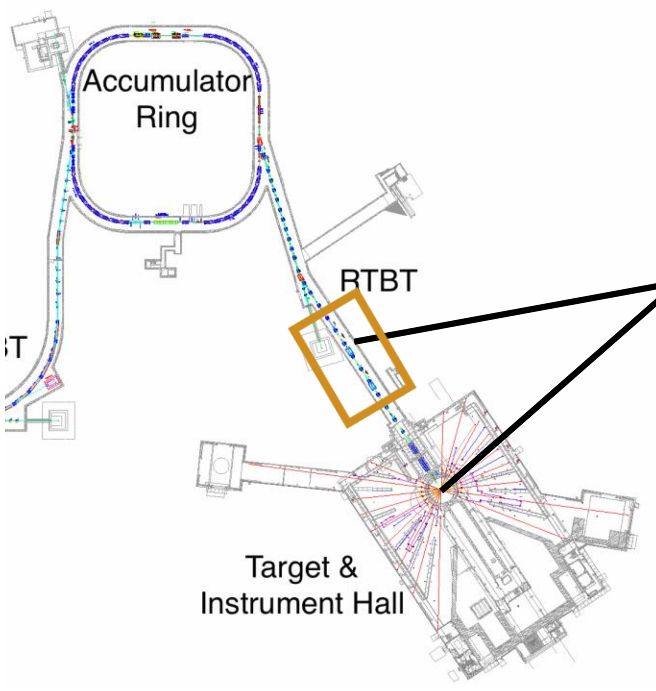
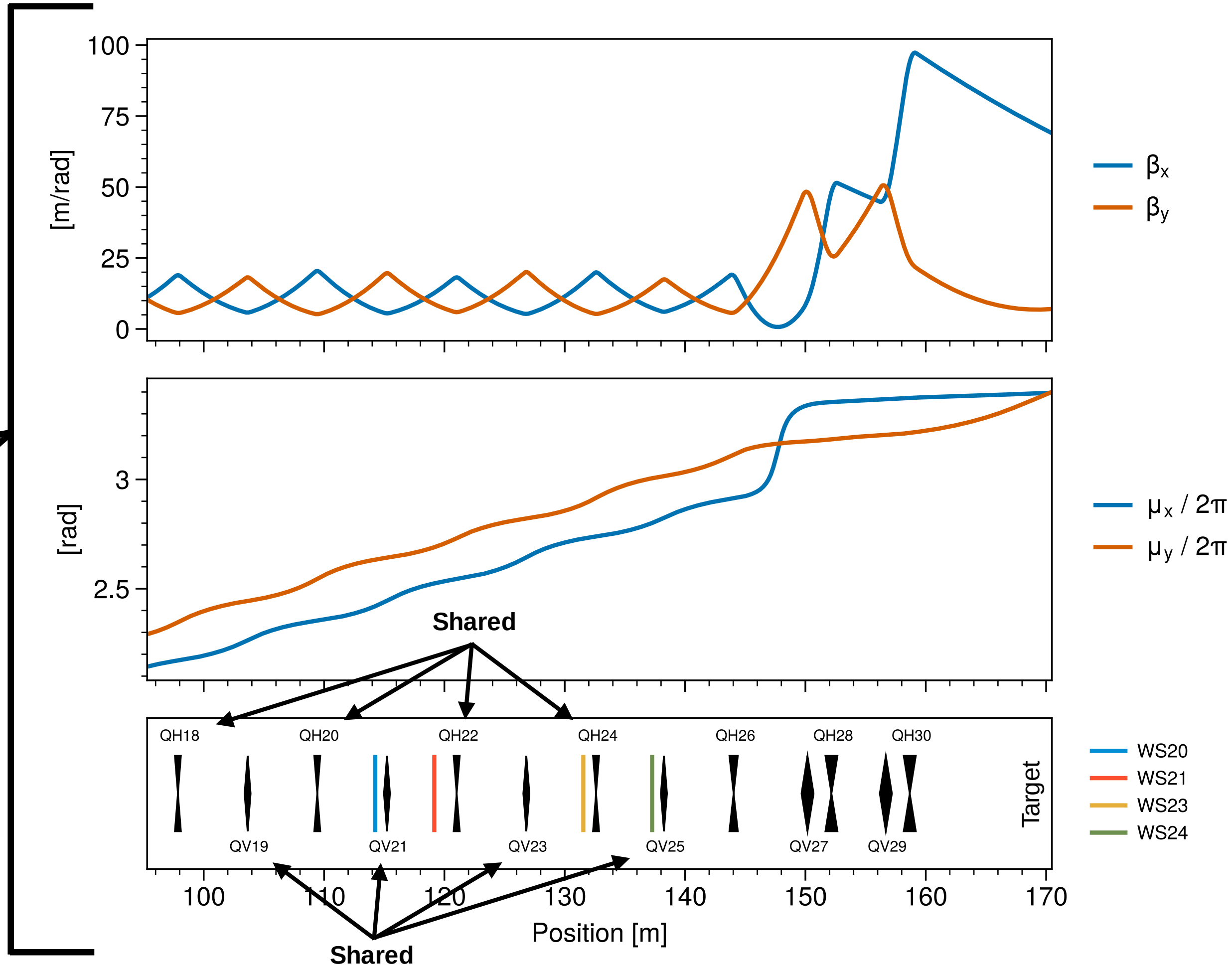
RTBT Diagnostics

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







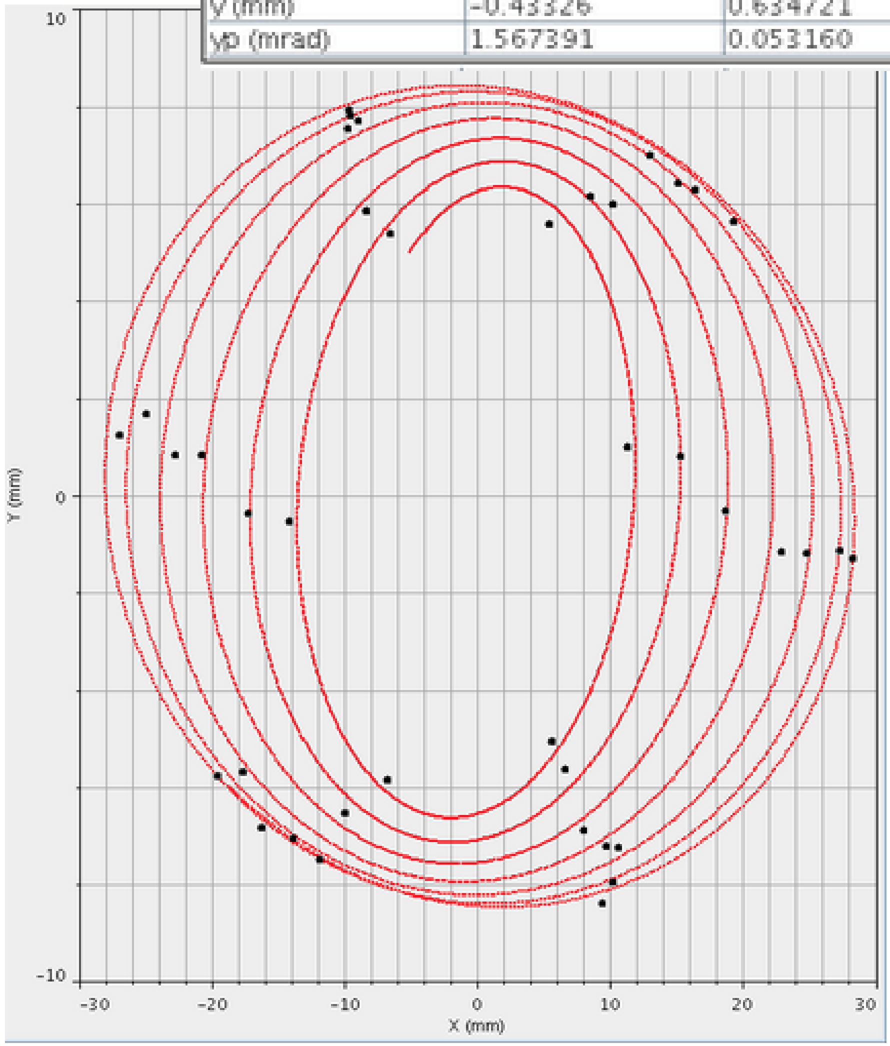
x

Procedure for Eigenpainting

1. Setup ring with equal tunes (~6.177)
2. Inject single pulse of beam off closed orbit
3. Use TBT BPM data to + linear model to establish injection parameters (x,x’,y,y’)
4. Find kicker settings to injection on closed orbit these are t=0 kicker settings
5. Energize solenoids to split tunes
6. Fit for coupled tunes
7. Inject on eigenvector coordinates:
   1. a**v**= a*(vx,vx’,vy,vy’) these are t=tmax kickers
8. Draw waveforms – **v***a*Sqrt(t/tmax)
9. Accumulate beam

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

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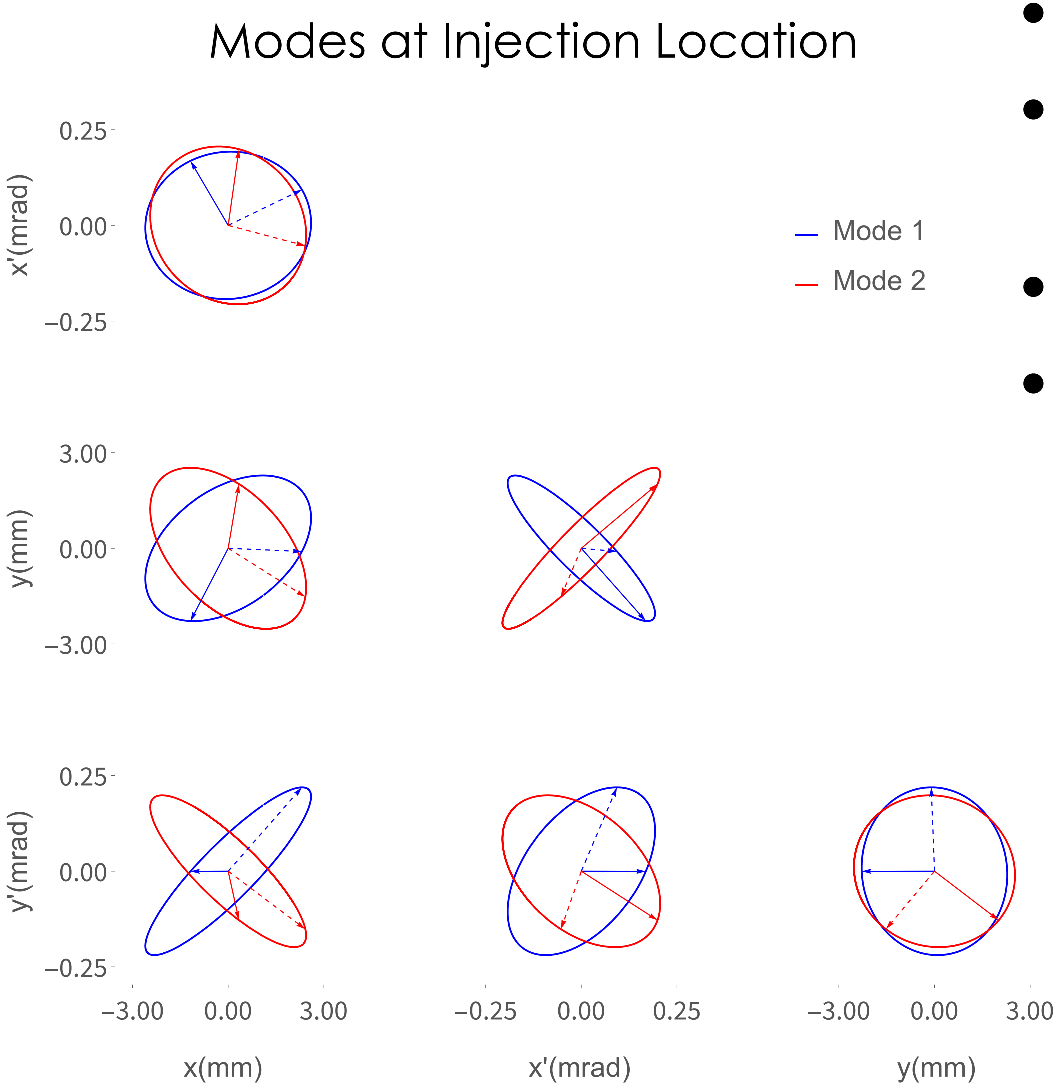
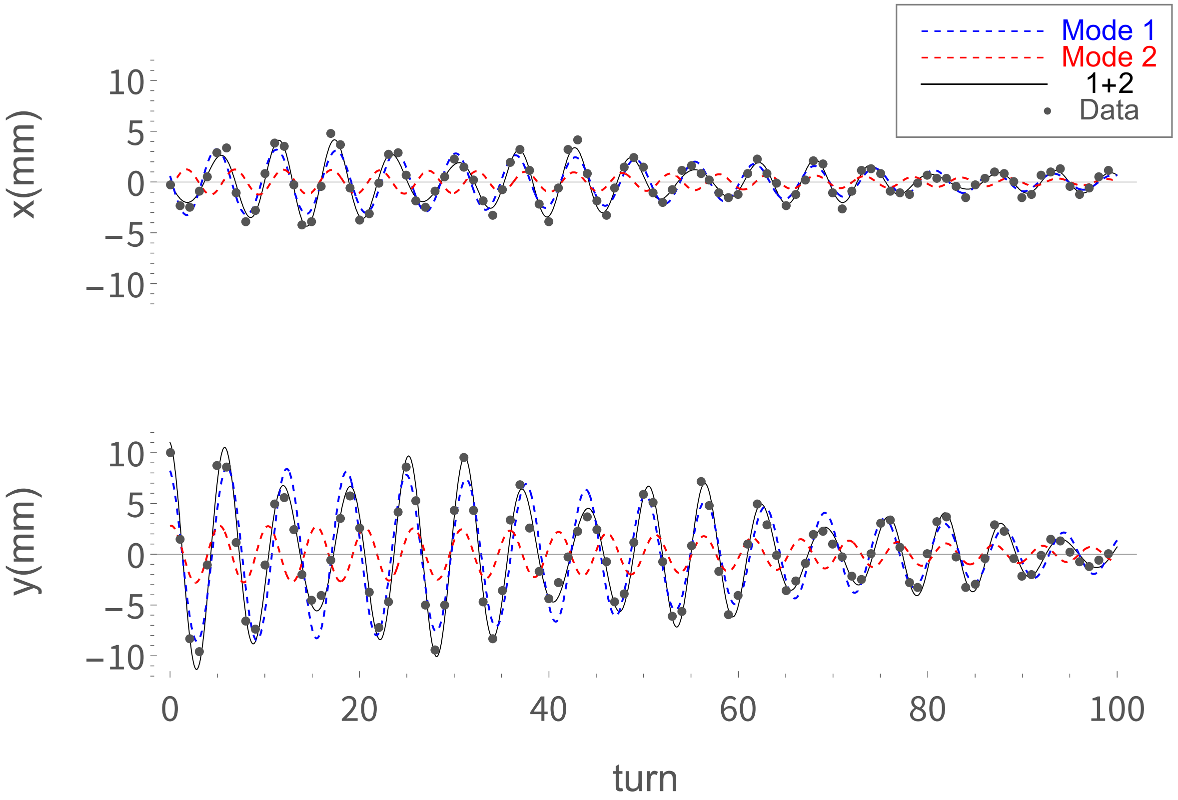
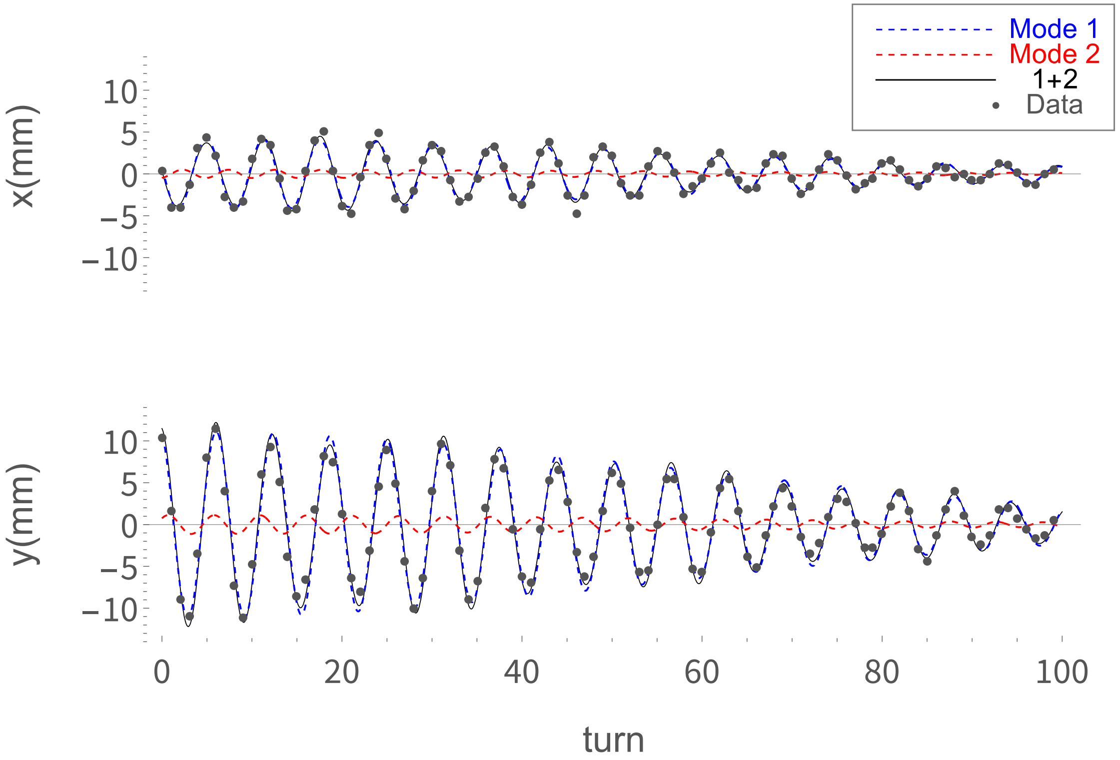
Modes with Solenoids



- Equal tunes nux=nuy=6.177
- 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

TBT data fit with calibrated model

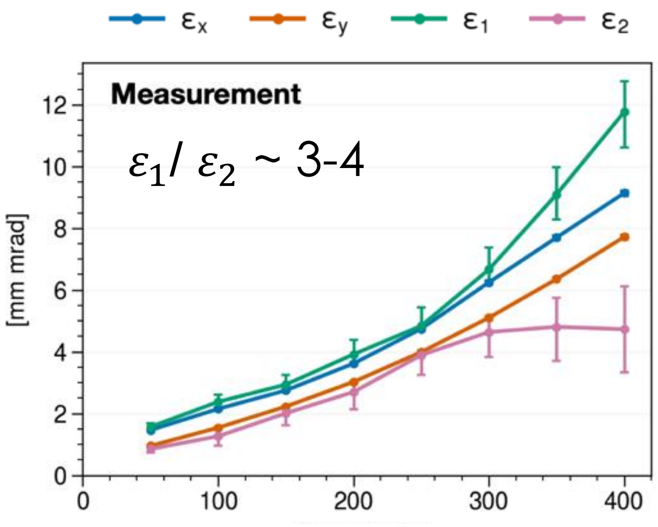




Parameter	Arbitrary Inj.	Single Mode
$A_1(\sqrt{mm \cdot mrad})$	3.22 ± 0.010	4.19 ± 0.012
θ_1	0.150 ± 0.0005	0.148 ± 0.0004
$A_2(\sqrt{mm \cdot mrad})$	1.16 ± 0.010	0.46 ± 0.012
θ_2	0.432 ± 0.001	0.320 ± 0.004
$\frac{\epsilon_1}{\epsilon_2} = \left(\frac{A_1}{A_2}\right)^2$	7.71 ± 0.14	80.37 ± 4.00

Single turn injection off-axis
Performance here defines upper limit

Measurement without Solenoids



Injected Turns

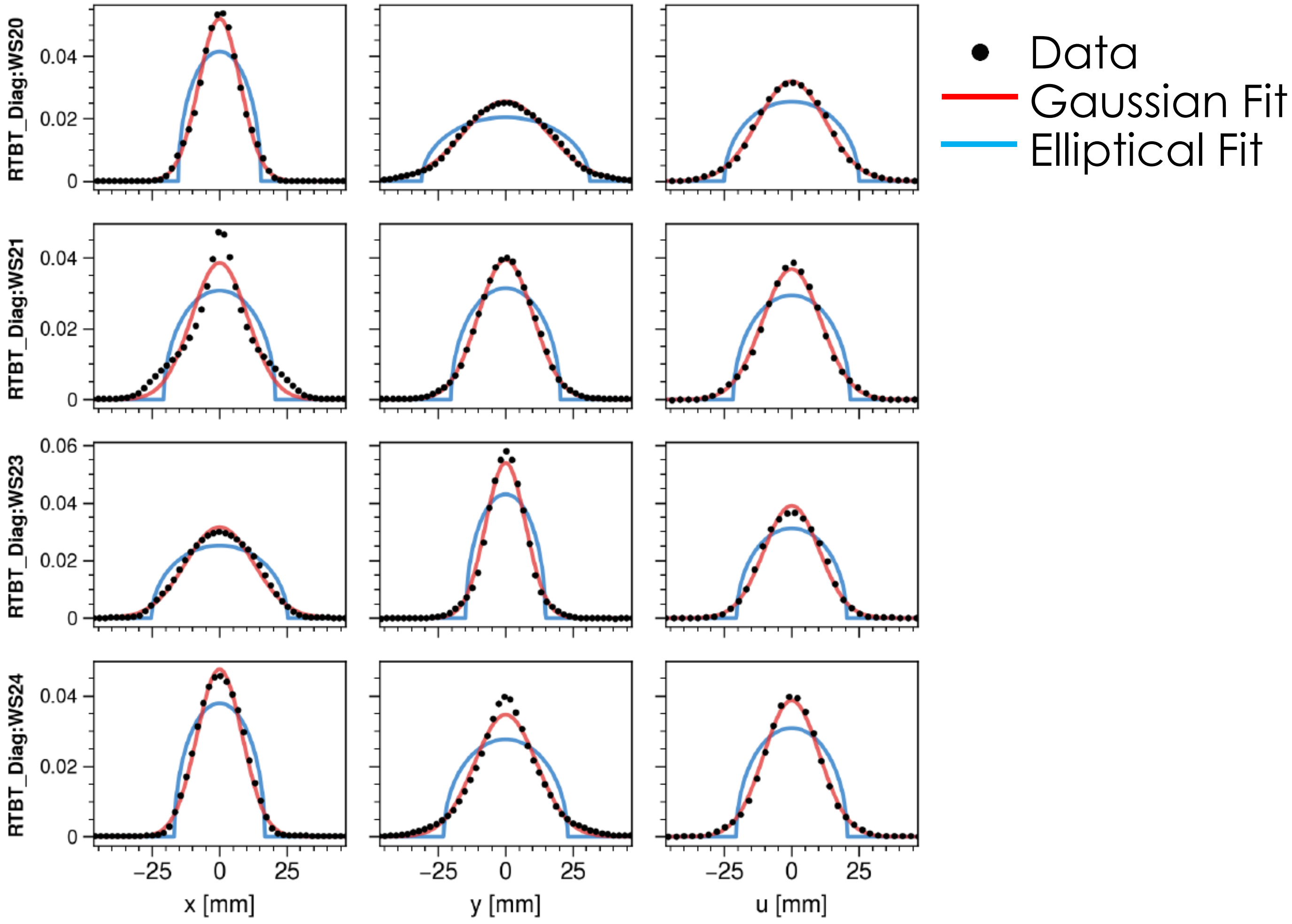


Figure 5.20: Measured wire-scanner profiles for the final distribution in Experiment 3.

Nice emittance ratio, but profile not very elliptical.

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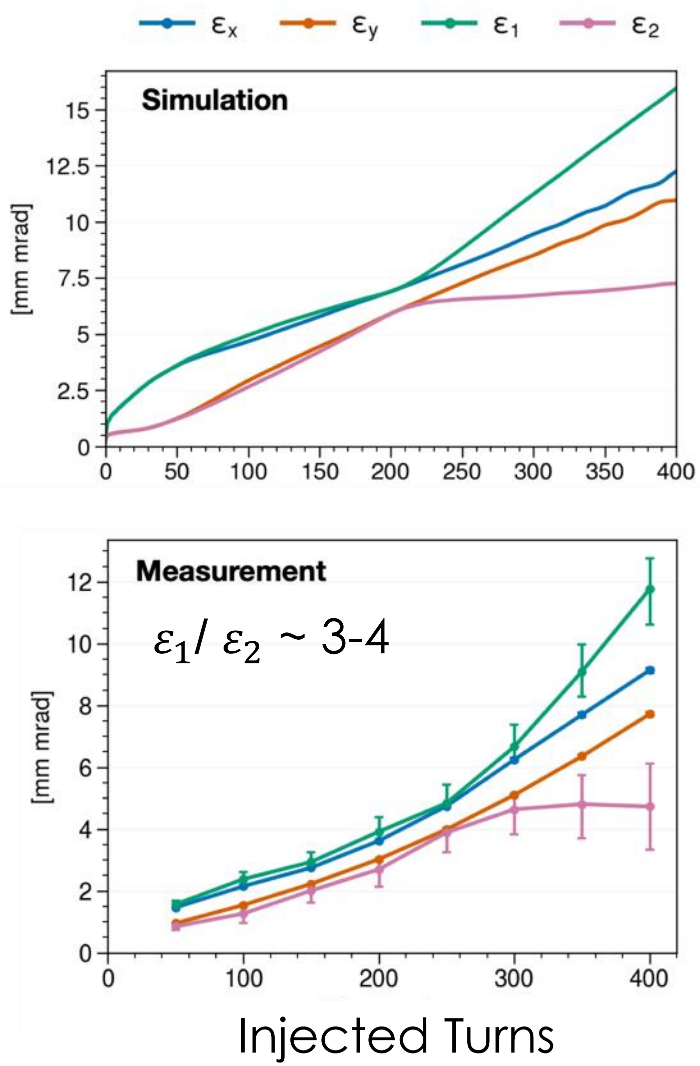
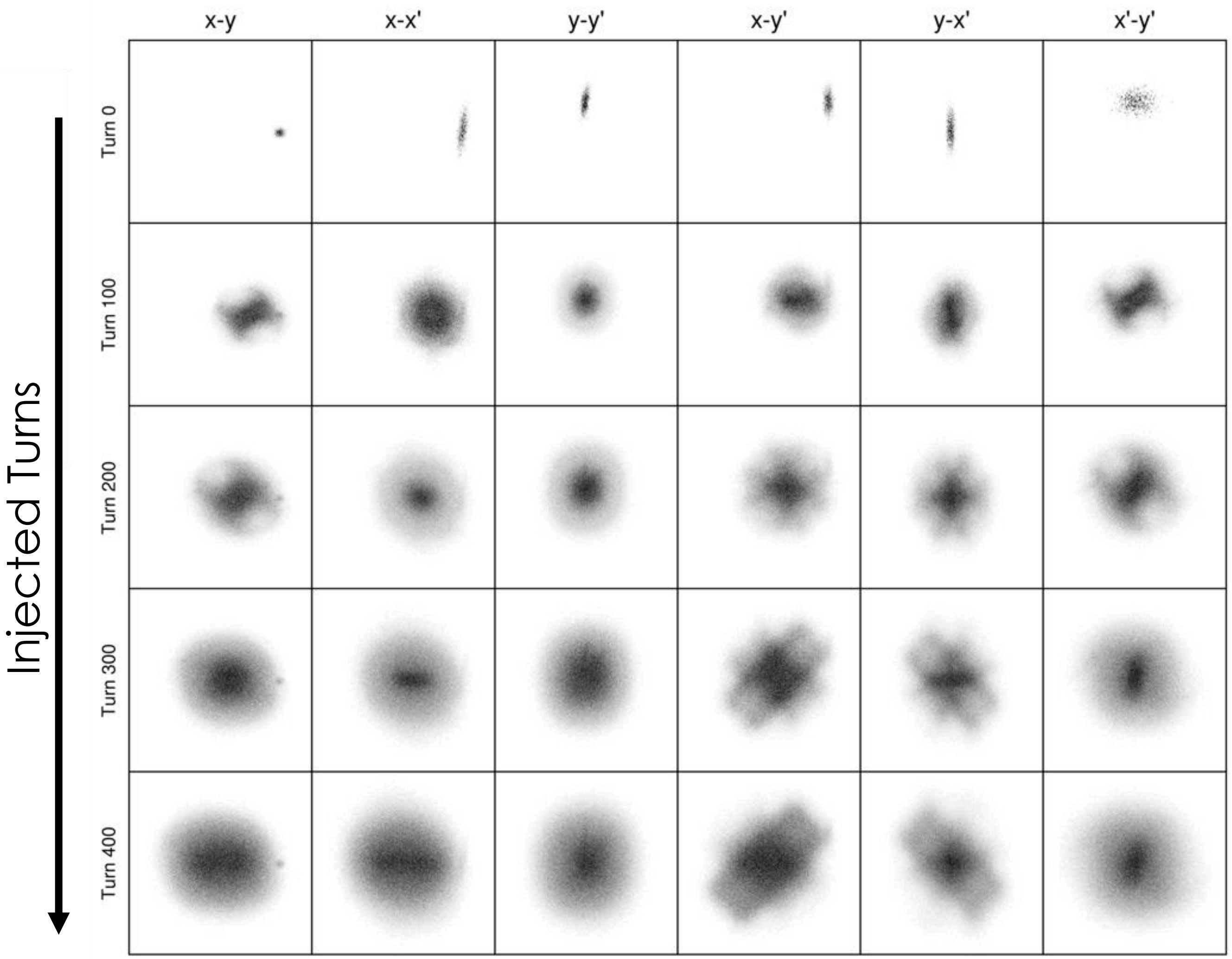
Simulation vs. Measurement – No Solenoids Experiment



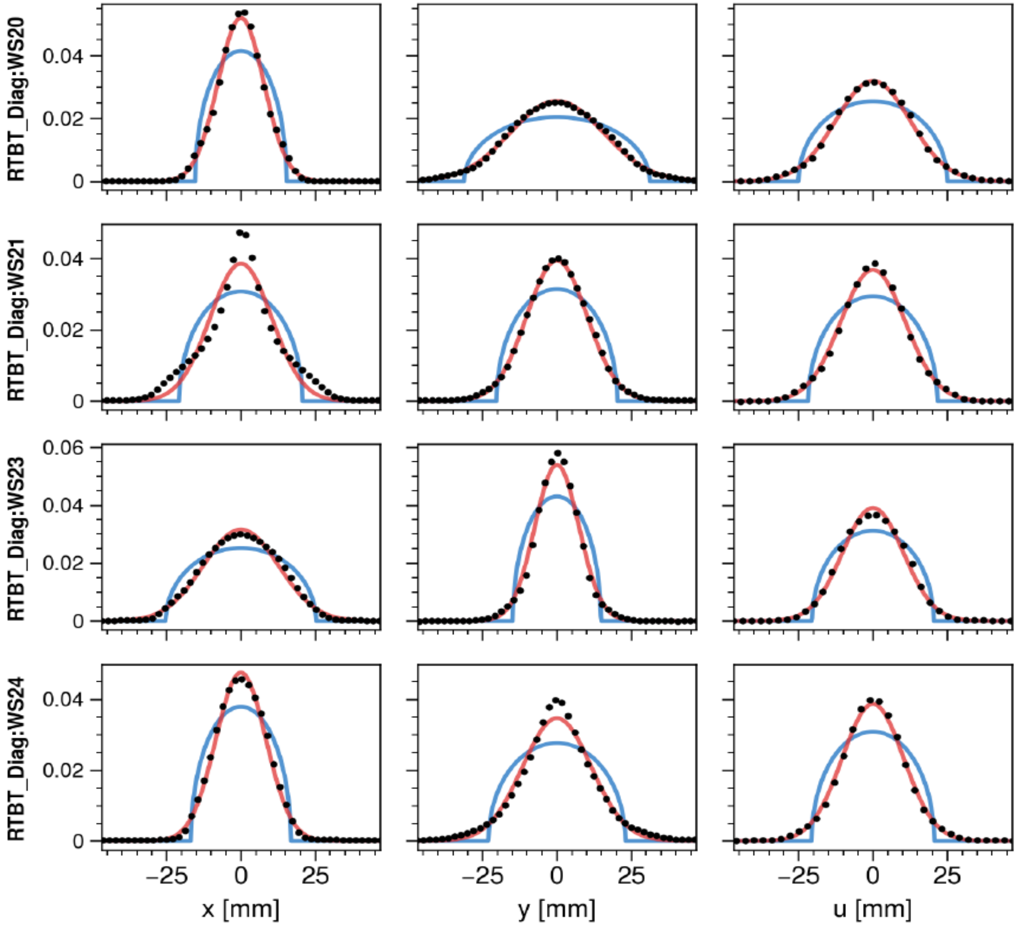


Simulated Phase Space

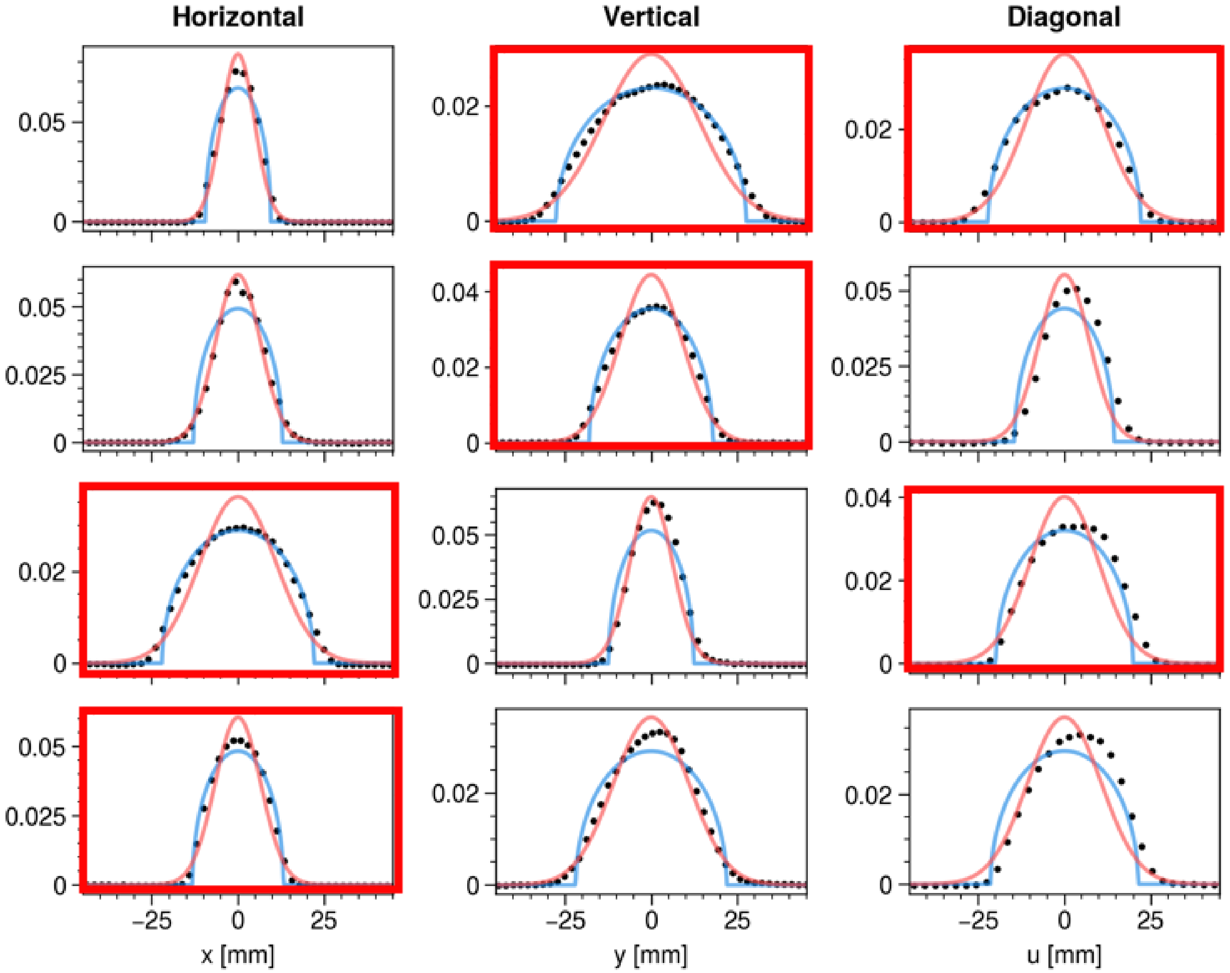
Extract beam after N turns are accumulated and measure evolution of emittance.

Wirescans with Solenoids

Without Solenoids

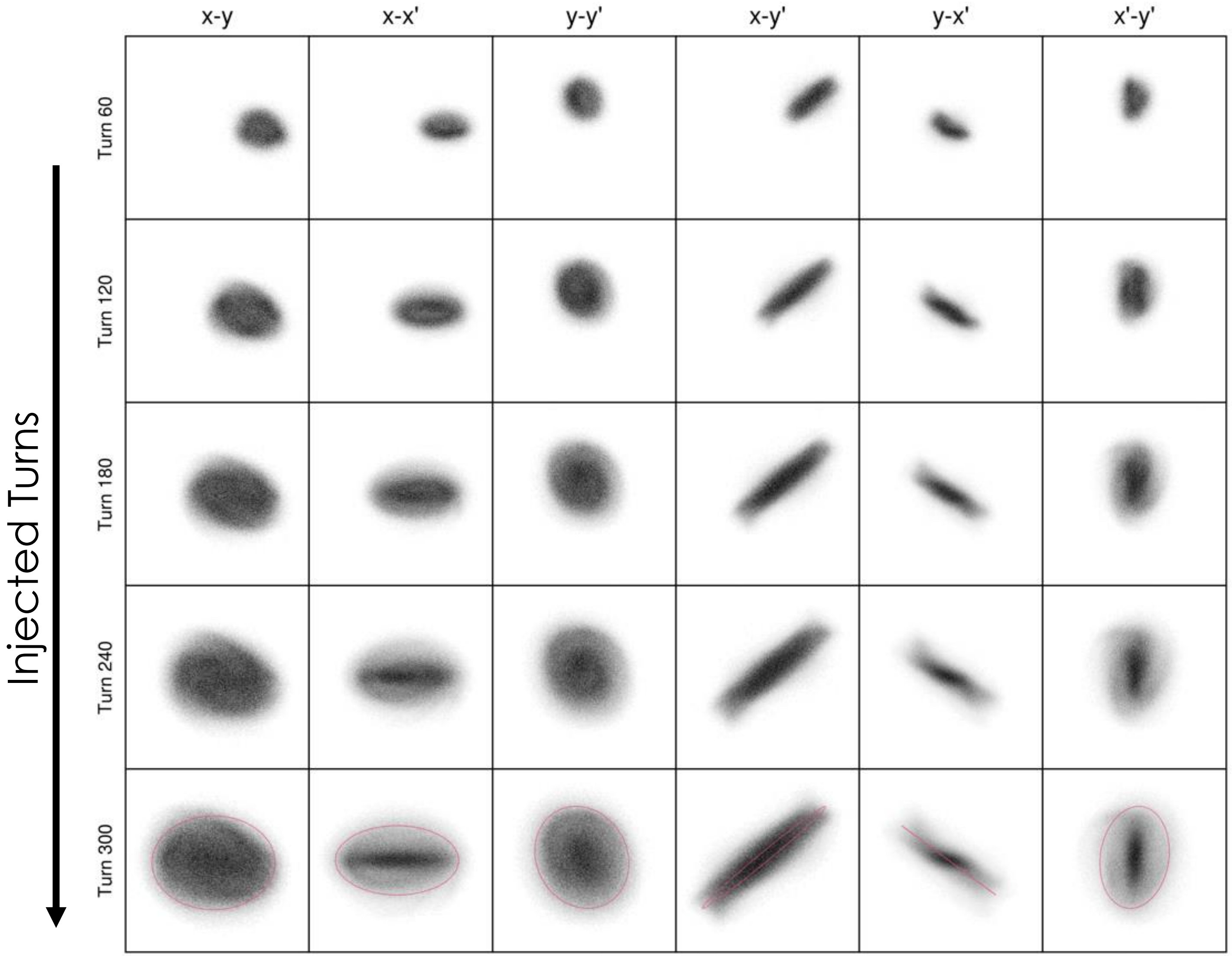


With Solenoids



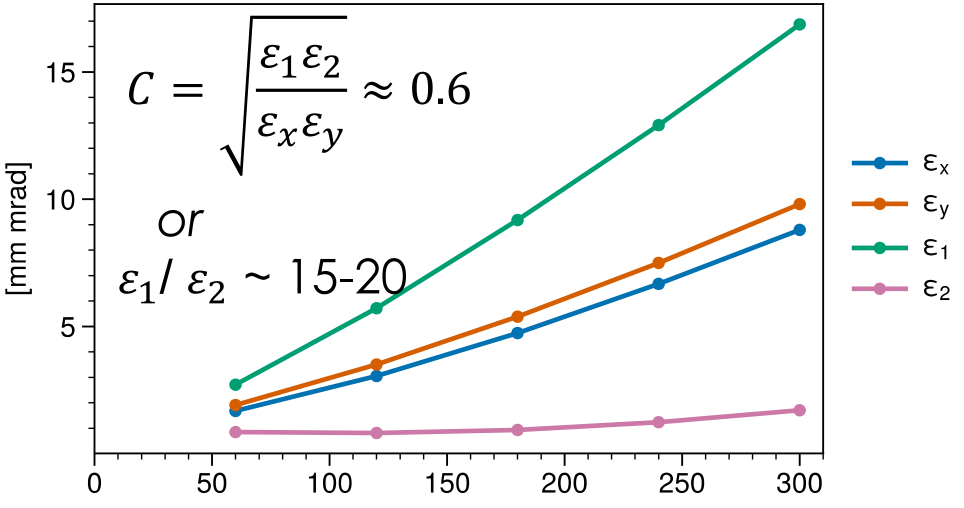
Red profiles are most elliptical.

Simulation



Simulated Phase Space

Simulated "best case" with solenoids



Injected Turns

Outlook

- We can ‘eigenpaint’ in the SNS ring
- Clear difference between case with/without solenoids
- We are interested in exploring behavior of eigenpainted Danilov distributions over longer storage times, ideas for space charge mitigation
- Compare SNS correlated painting, eigenpainted Danilov distributions, or eigenpainted gaussian e.g.
- Working on getting SNS electron scanners back – may offer a way to optimize quickly

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

Backup Slides

Long Kickers

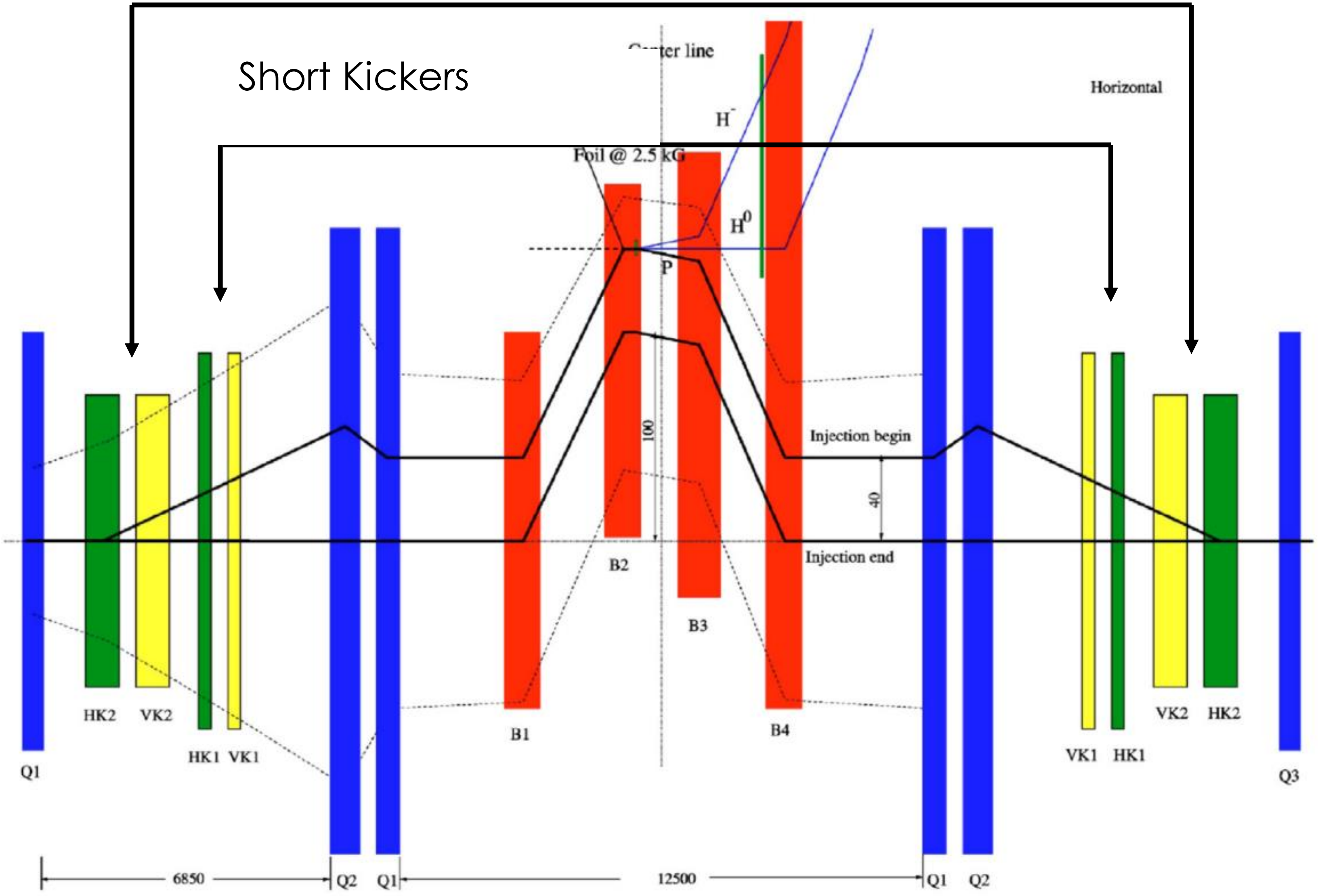


Fig. 87. Schematic layout of the horizontal plane of the beam injection region of the accumulator ring. Reprinted Figure with permission from Ref. [89] (http://link.aps.org/abstract/RMP/v75/p1383). Copyright 2003 by the American Physical Society.

Long Kickers

Short Kickers

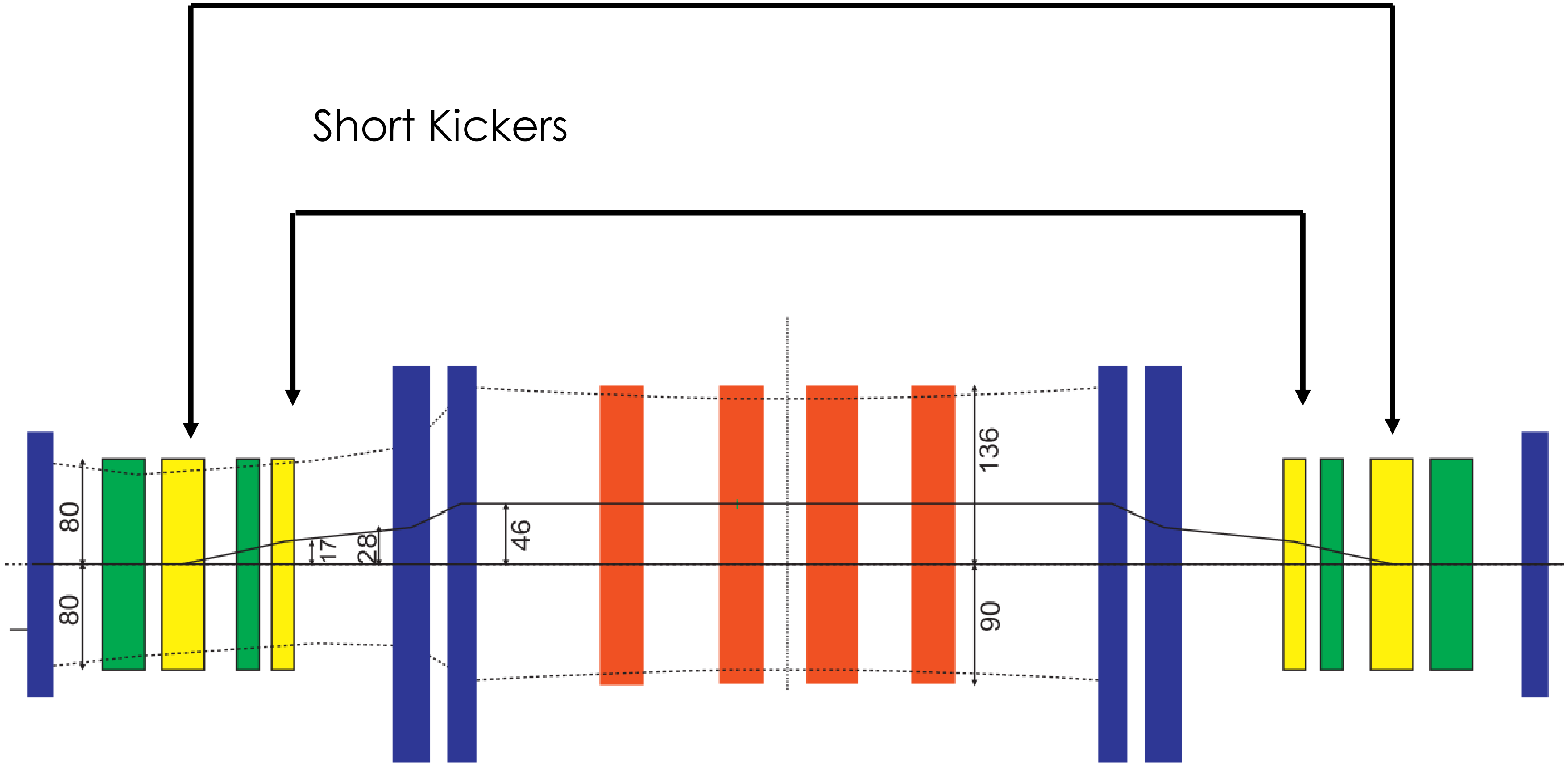


Fig. 88. Schematic layout of the vertical plane of the beam injection region of the accumulator ring.

Wirescanner Data – Correlated Painting

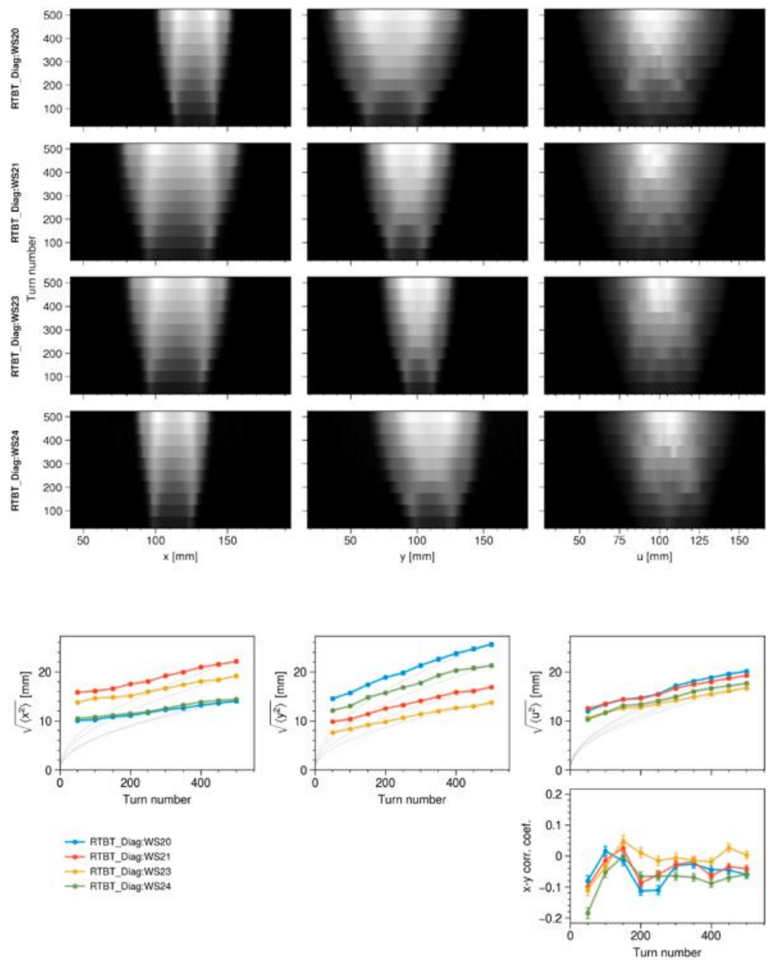


Figure 5.1: Measured wire-scanner profiles from Experiment 1a. The top figure shows the measured profiles on each wire as a function of time. The bottom plots show the moments extracted from the profiles.

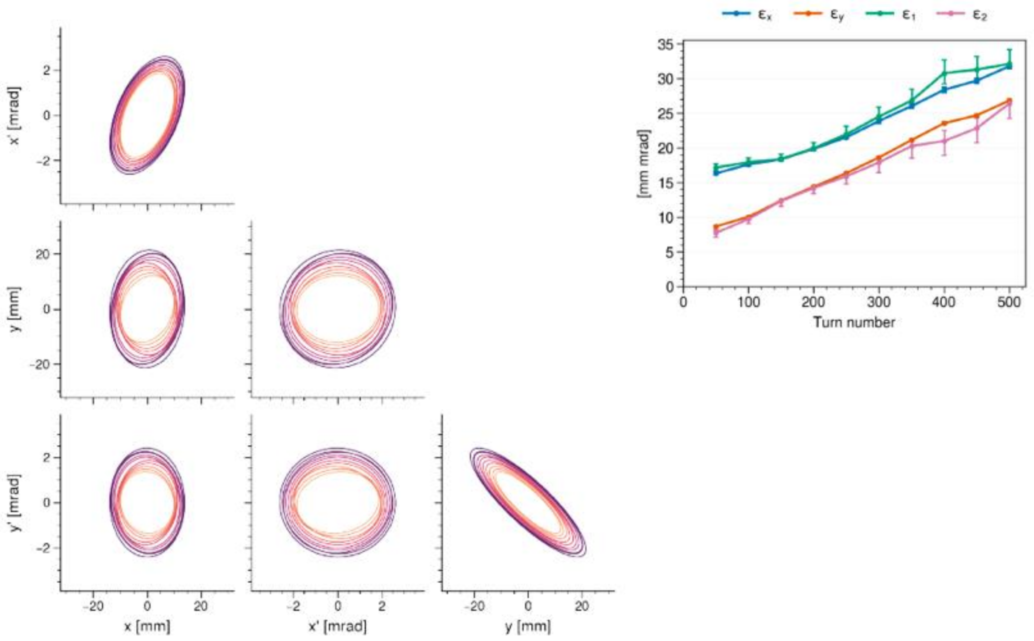


Figure 5.2: Reconstructed emittances and covariance ellipses from Experiment 1a. In this and subsequent figures, the reconstruction is performed at BPM17 and the light/dark ellipses correspond to the start/end of injection.

Wirescanner Data – Current best case – no solenoids

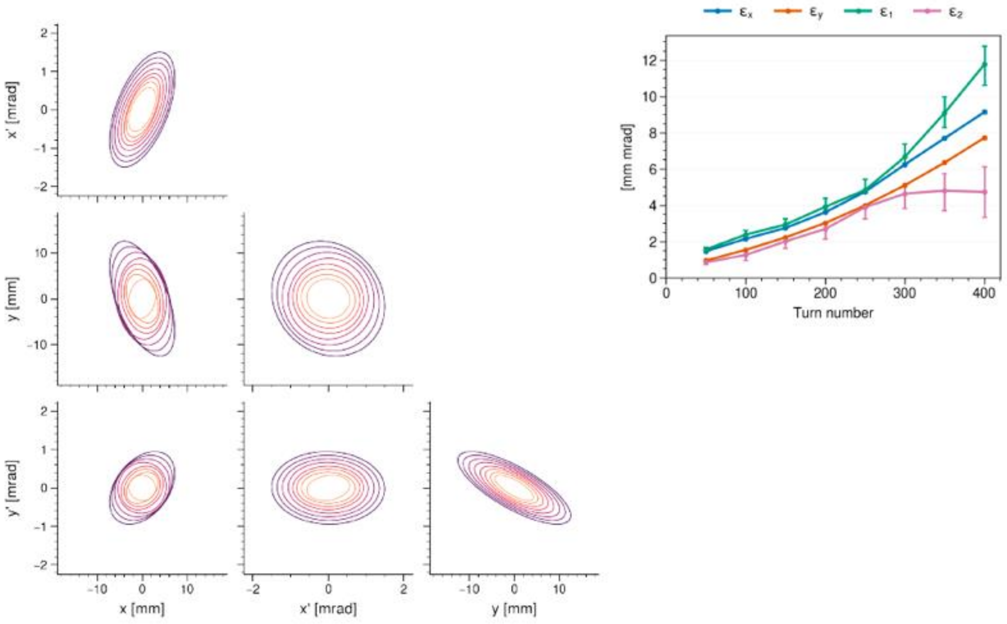


Figure 5.12: Reconstructed emittances and covariance ellipses from Experiment 3.

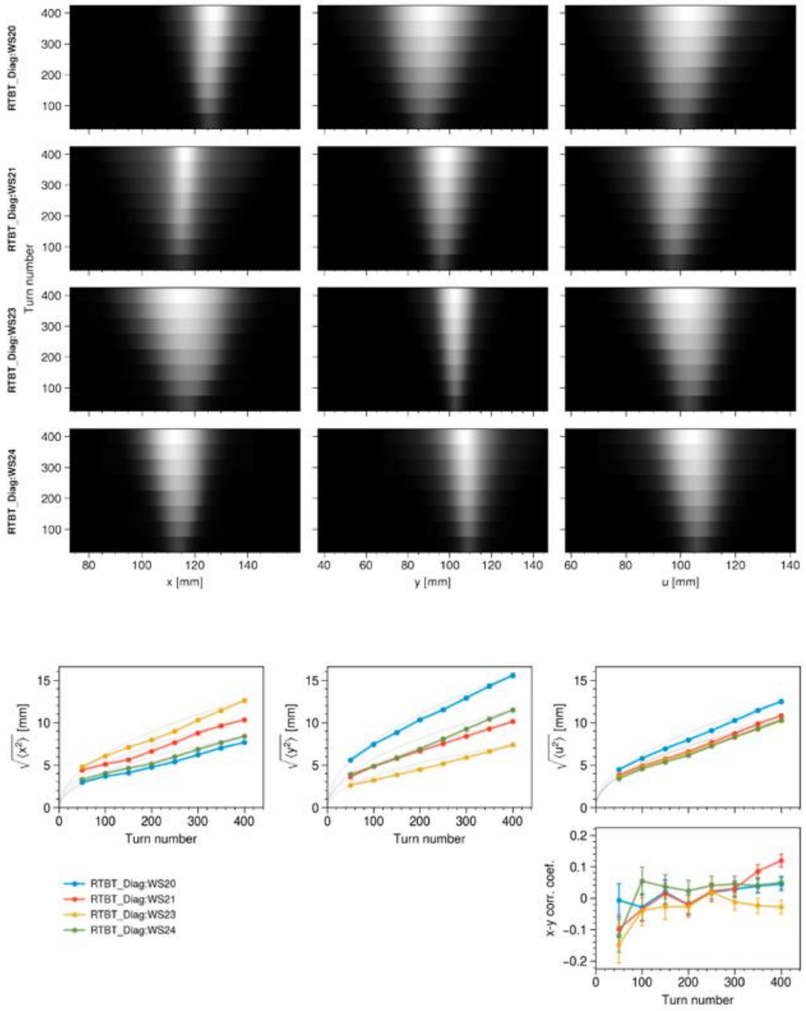
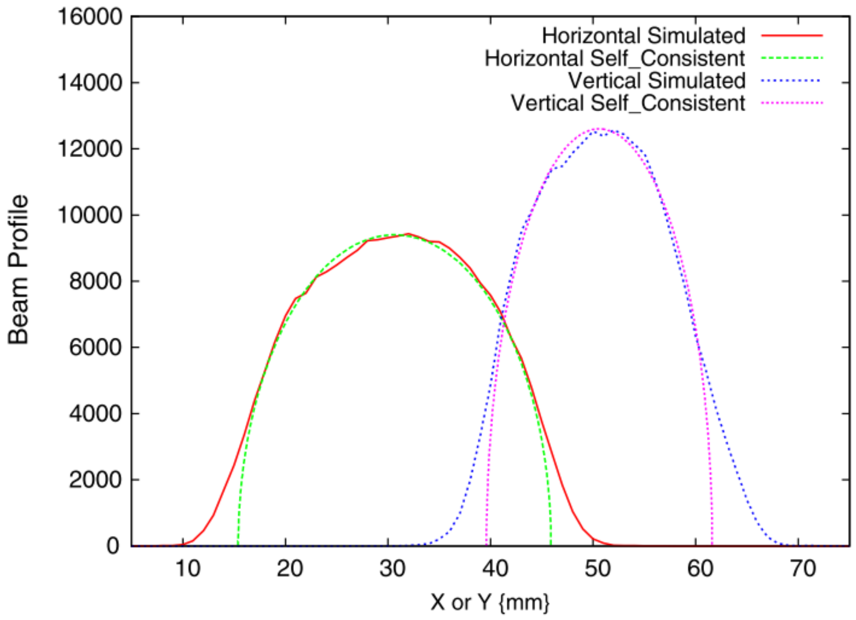
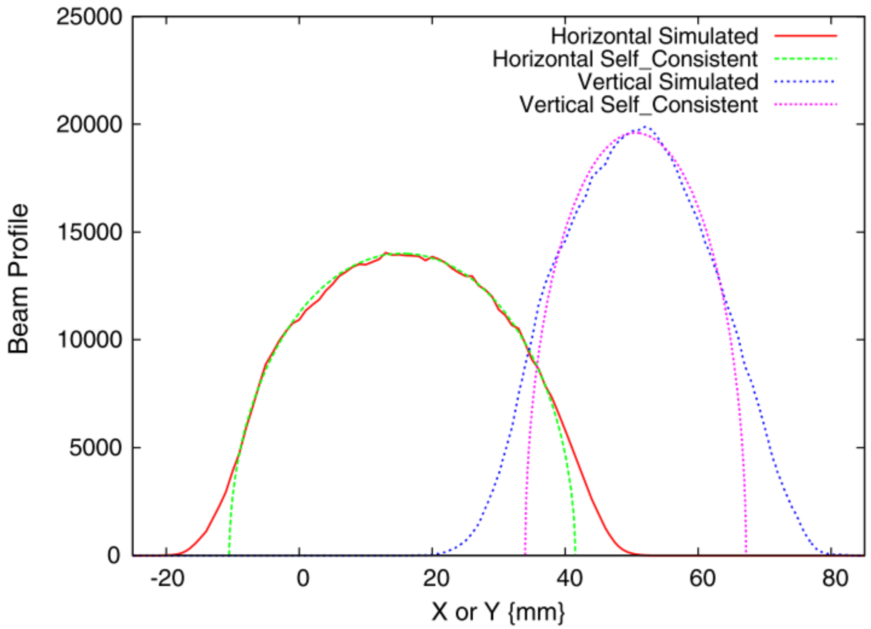


Figure 5.11: Measured wire-scanner profiles from Experiment 3.

"Best case" simulated profiles





Eigenvectors and Tunes

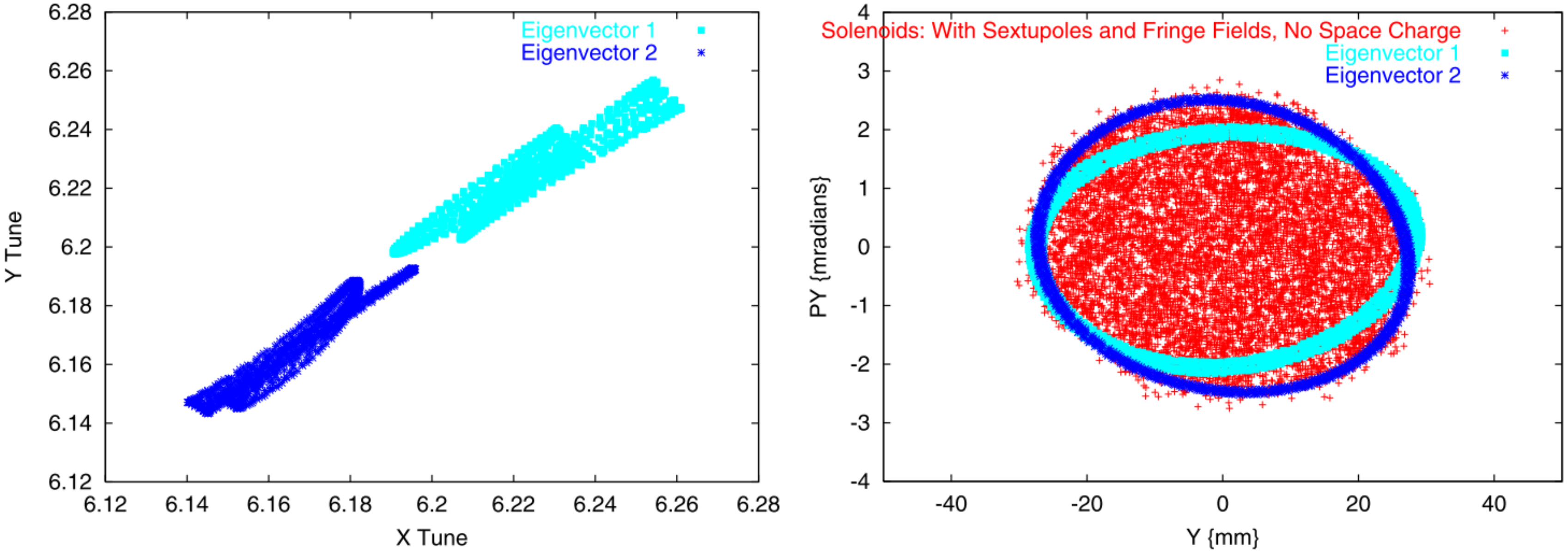


FIG. 2. (Left) Tune footprint for the two eigenvectors, each taken turn by turn over 1000 turns. (Right) Eigenvector projections in vertical phase space, together with self-consistent beam distribution painted to one (dark blue) of the eigenvectors.

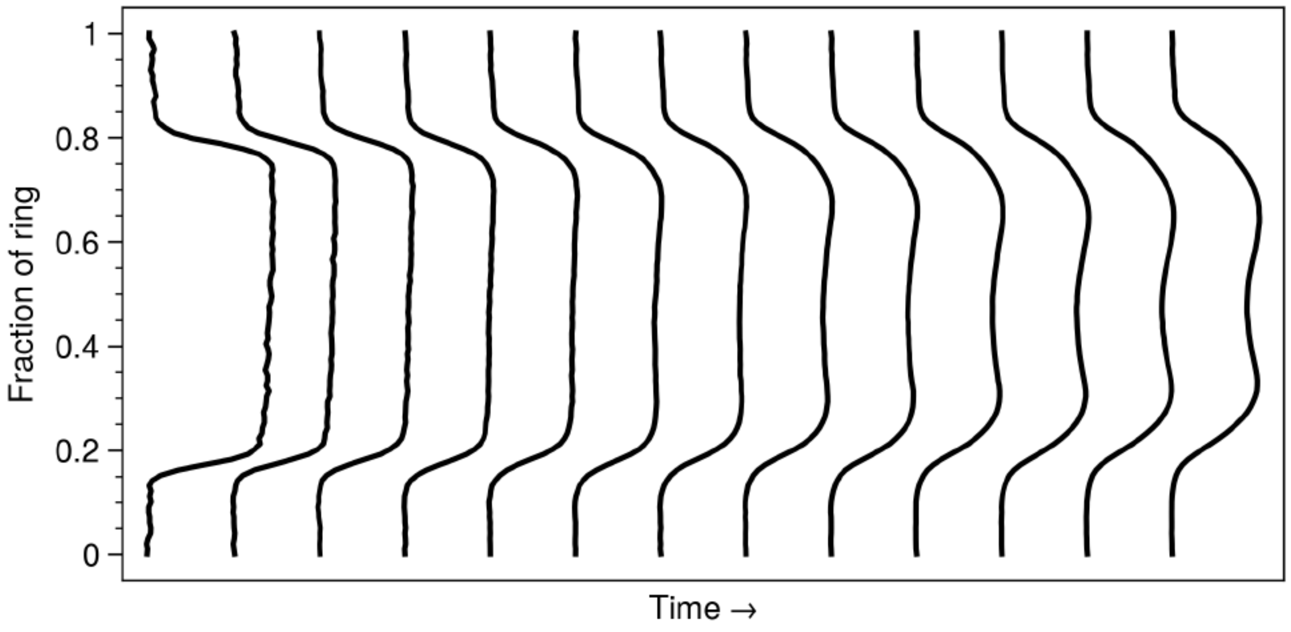
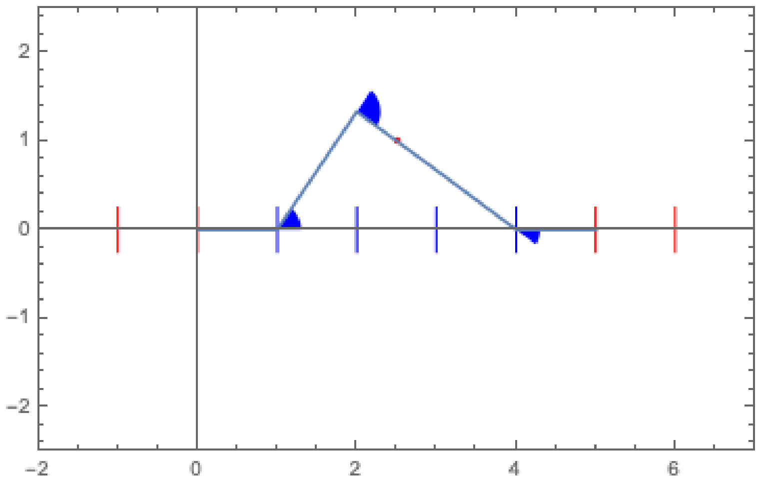
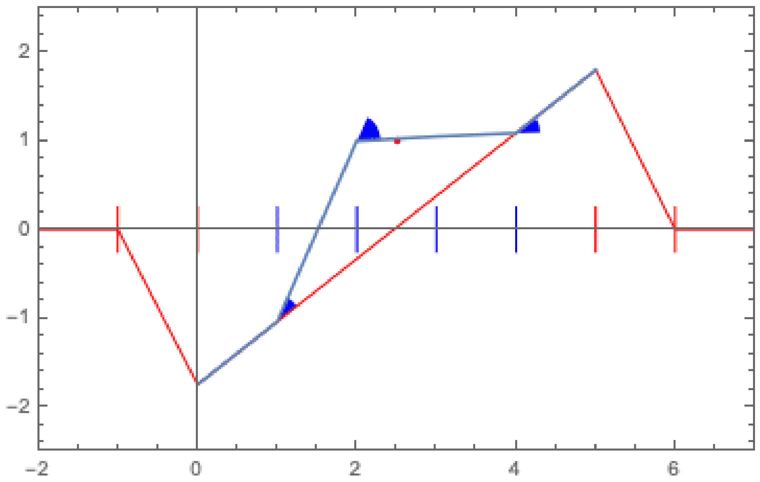


Figure 5.9: Evolution of the longitudinal distribution in the ring as measured by a beam current monitor (BCM).

Principle: Orbit Biasing with Correctors – Just a cartoon!



Full range of angles is much bigger though – we're leaving a lot on the table

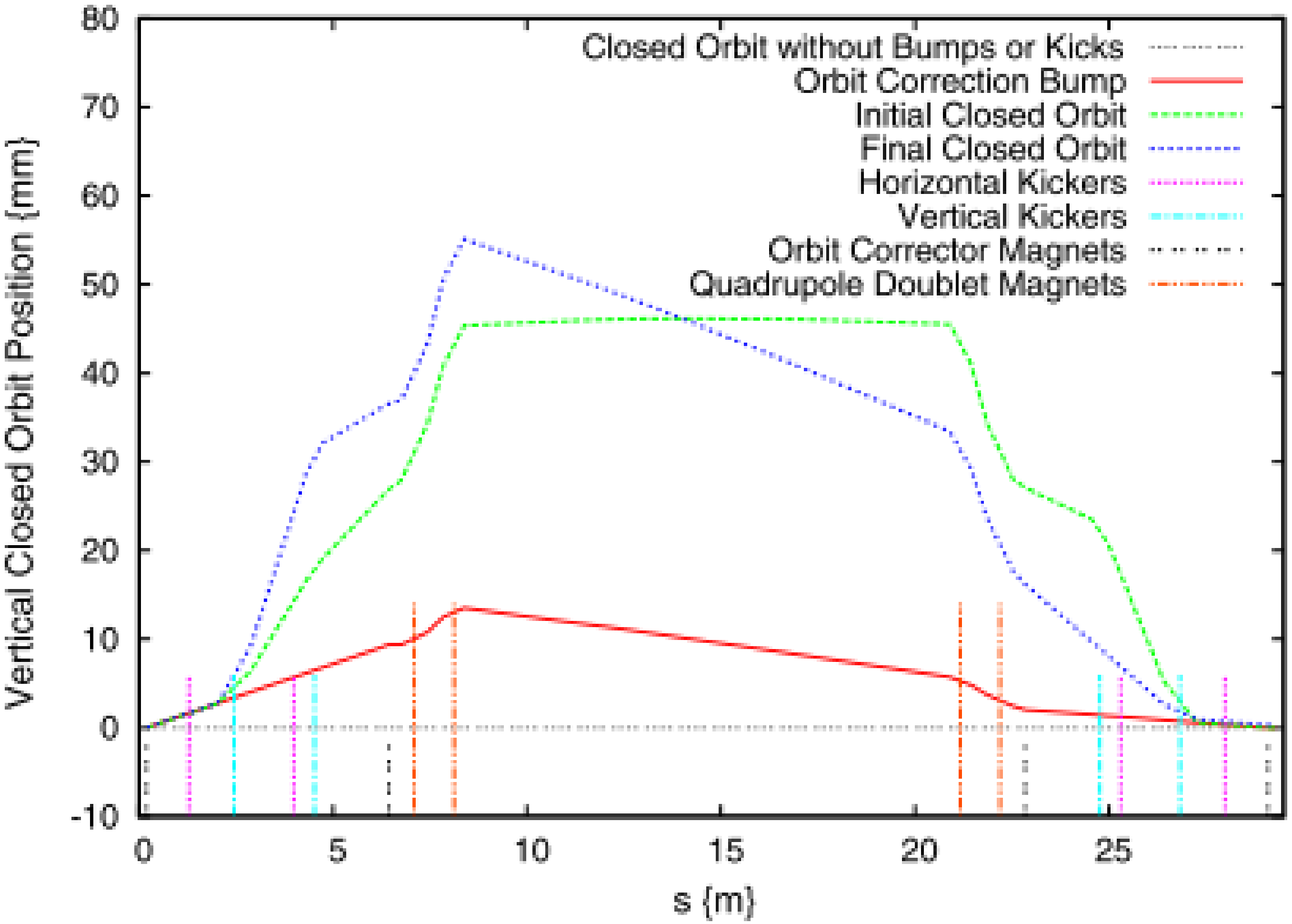


If we use correctors to provide a static 'bias' bump we can utilize the full range of the kickers

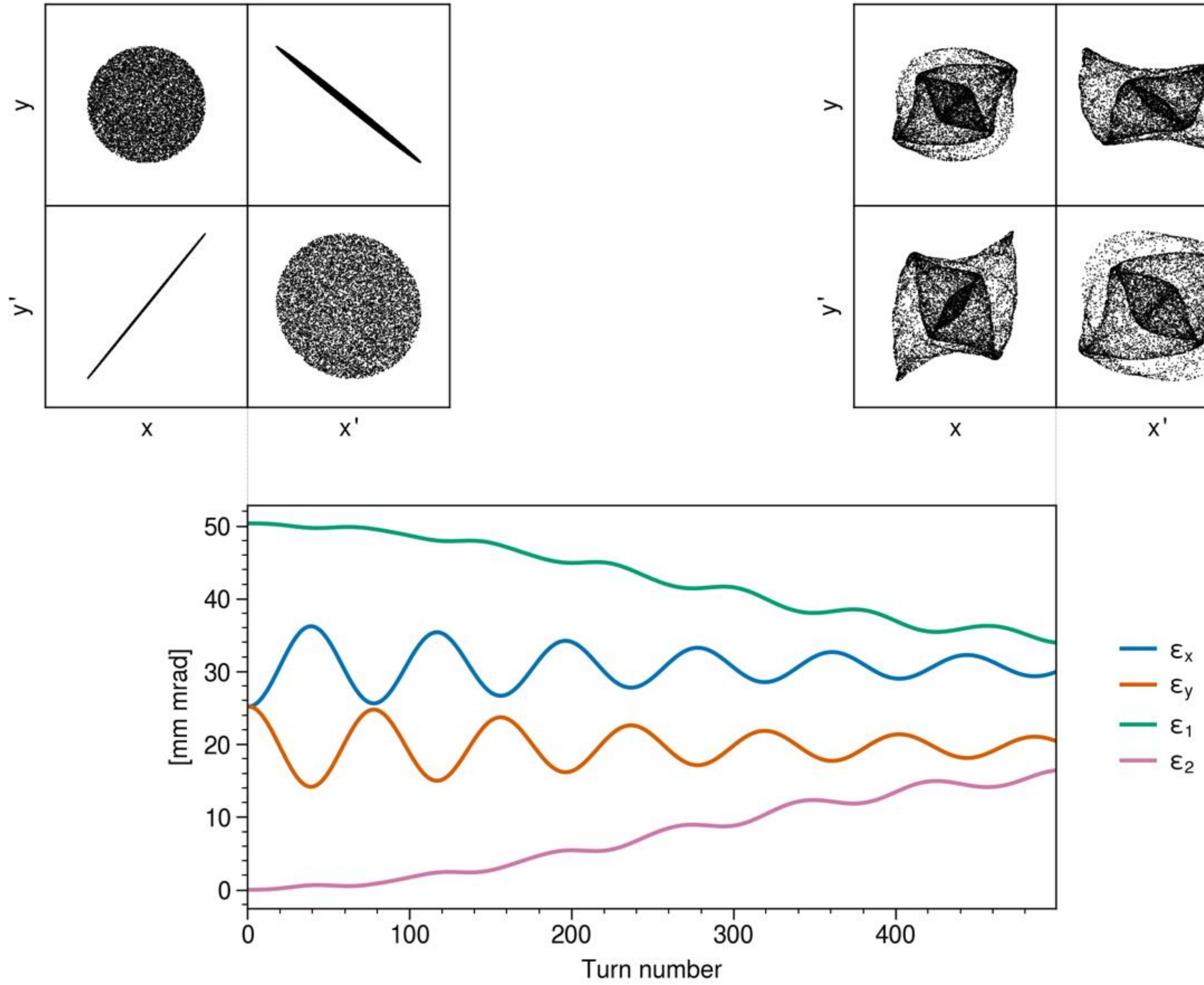
We can use this in both position and angle as needed

Simulation of Closed Bump From Correctors – Holmes (2018)

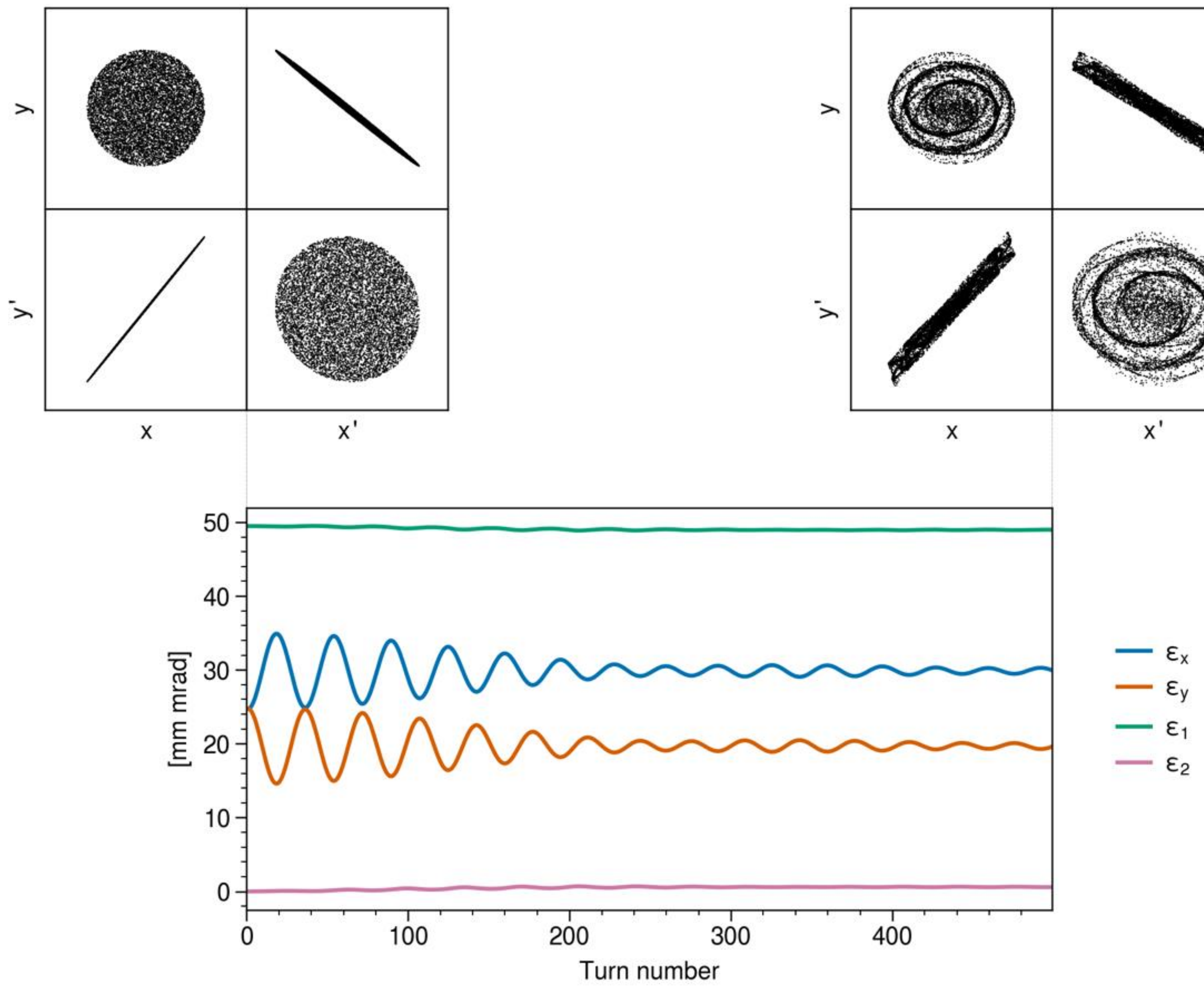
- Bumps add linearly, red bump is from correctors only
- To implement this I modified Orbit Correction App
- Problem is correctors are already used to correct!



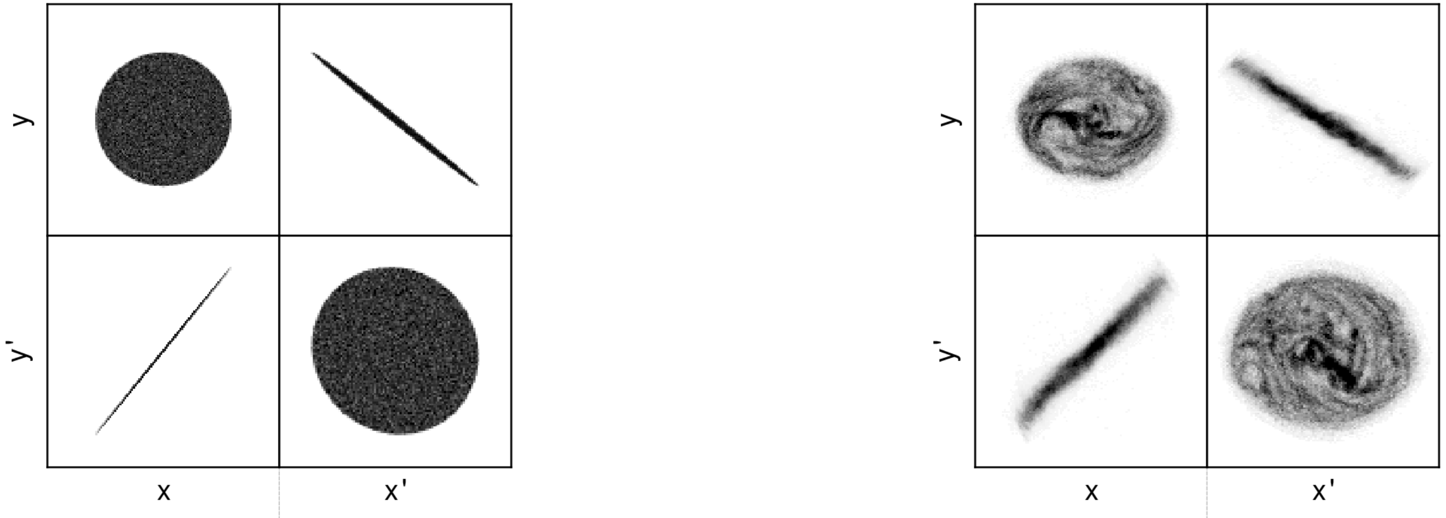
Nonlinear fringe fields can degrade beam quality near difference resonance

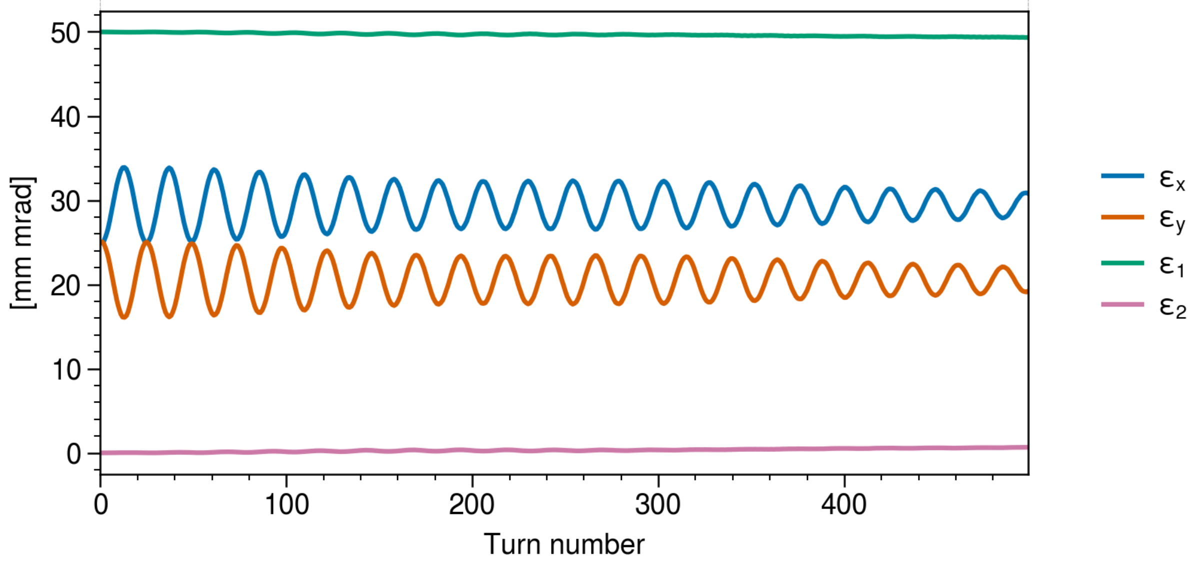


Linear coupling (split tunes) alleviates this problem



Linear coupling can also be provided by the beam





Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

SNS INJECTION AND EXTRACTION DEVICES*

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

Table IV: Specification for dynamic bump magnets

	Long	Short
Number	4	4
Core length	64 cm	21 cm
Aperture	19.55 x 22.58 cm	21.55x24.48cm
# of Turns	10	12
Max. Current	1230 A	1400A
Max. Field	0.079 T	0.1 T
Ceramic Vac. Chamber ID	16 cm	18 cm