Injection of a Self-Consistent Beam into the SNS Accumulator Ring

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Motivation

- Self-consistent beams may suppress space-charge induced halo growth → reduced beam loss in high intensity rings.
- The beam density is uniform → better for targets.
- They can be manipulated to give flat beams when space charge effects are weak → increased collision rates for colliders and heavy ion fusion applications.
- From 2003-2006, S. Danilov and J. Holmes studied self-consistent distributions from a mathematical and computational standpoint.
- The idea was to find beam distributions satisfying the Vlasov equation
  - that are elliptical with uniform density in real n-dimensional space and
  - that retain these properties, shape and density, under all linear transport, even accounting for space charge forces.
- We called these distributions self-consistent.
- Our goal: Find self consistent distributions that could be practically achieved in a real-life ring (SNS), and that would be robust under real transport, space charge effects, nonlinearities, impedances, and other loss mechanisms.

First Results: Theory

- The initial 2003 journal article was mainly a mathematical exercise. It showed:
  - There are an infinite number of self-consistent distributions,
  - How to construct these distributions mathematically,
  - That these distributions are singular – they occupy hypersurfaces in n-dimensional phase space,
  - That one such distribution, a 2D coasting beam "rotating" distribution, is a good candidate for painting into SNS.
- Some conditions had to be met to inject the rotating distribution:
  - The painted horizontal and vertical emittances had to increase linearly in time in order to yield constant charge density.
  - The horizontal and vertical tunes had to be equal during injection.
  - The painted horizontal and vertical phases had to differ by 90°.

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

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First Results: Computational

- Computational feasibility studies for injecting the rotating distribution into SNS were undertaken, starting with simple models and adding physics:
  - Coasting beam injection into a single rotating eigenfunction with simple linear transport was successful.
  - Adding nonlinear effects (sextupoles and/or fringe fields) destroyed self-consistency by coupling degenerate, oppositely rotating eigenfunctions.
  - Addition of solenoids into the lattice broke the degeneracy, again allowing for injection into a single rotating solution.
- With the solenoids in place, further effects were included:
  - Self-consistency withstood the addition of space charge, impedances, and foil scattering.
  - Injection kicker waveforms were calculated for one potential injection scenario, and found to be feasible with modification of some of the power supplies. These were not tested in simulations because ORBIT included only artificial injection bumps at the time. (Sarah Cousineau)
- Coasting beams were replaced by bunched beams, first with barrier cavities, and then with the SNS dual harmonic cavities with design voltages.
  - Although barrier cavities worked, the SNS cavities at design voltage did not.
  - Also, SNS was beginning operation and the project was shelved for later.

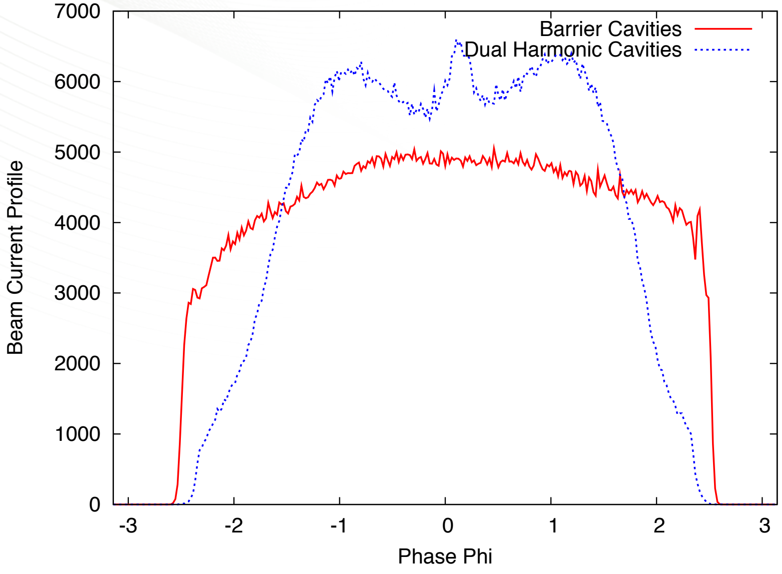
A Decade Later: Revived Interest

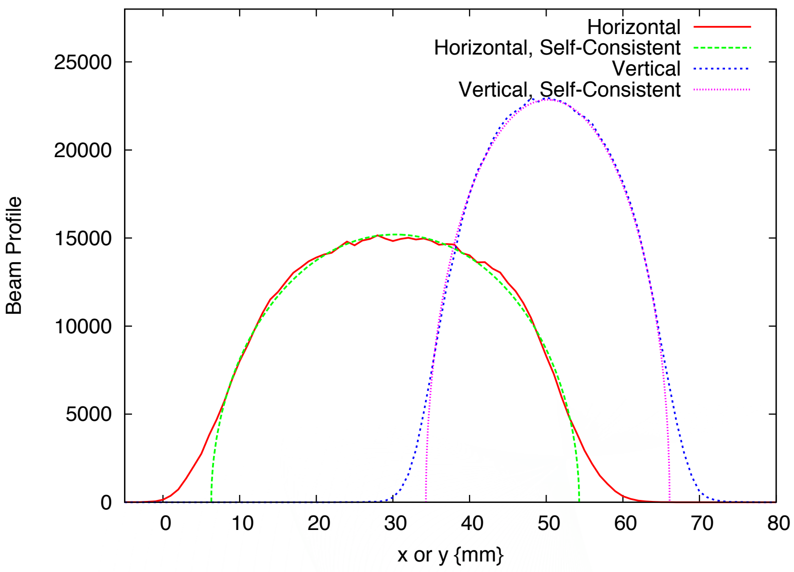
- With the SNS accelerator performing well, we now have more freedom to play. Meanwhile, operation of the accumulator ring has evolved to much lower RF voltages than the design values, meaning less peaking of the bunched beam.
- With that, and support from the DOE Office of Science, we have revived the self-consistent beam studies. The goal is to paint a rotating self-consistent beam into the SNS ring.
- First steps include simulations with all relevant physics:
  - Demonstrate feasibility of self-consistent injection.
    - Use actual kickers for painting, rather than artificial bumps.
    - Use production RF settings for bunched beams in the ring.
    - Incorporate all relevant physics: space charge, impedances, nonlinearities, fringe fields, scattering and losses, etc.
  - Optimize the injection scenario with respect to
    - Beam quality,
    - Painting scheme,
    - Losses,
    - Hardware requirements (solenoids and kickers).
- Then carry out necessary hardware changes and do the experiments.

Barrier Cavities -> Existing RF

- In the original (2003-2006) studies, barrier cavities were necessary to maintain self-consistency in bunched beams.
- The design SNS ring RF cavities were to operate with 40 kV first harmonic and 20 kV second harmonic voltages, which destroyed the uniform density beam current profile.
- Today, we actually operate with much smaller (<10 kV) ring RF voltages, even though the design values are available.
- When we apply these operating voltages in the self-consistent beam simulations, self-consistency survives.
- The results presented here were calculated using 4 kV first harmonic and 4 kV second harmonic RF voltages, which is entirely adequate to maintain the beam gap.

Effect of Dual Harmonic RF Cavities

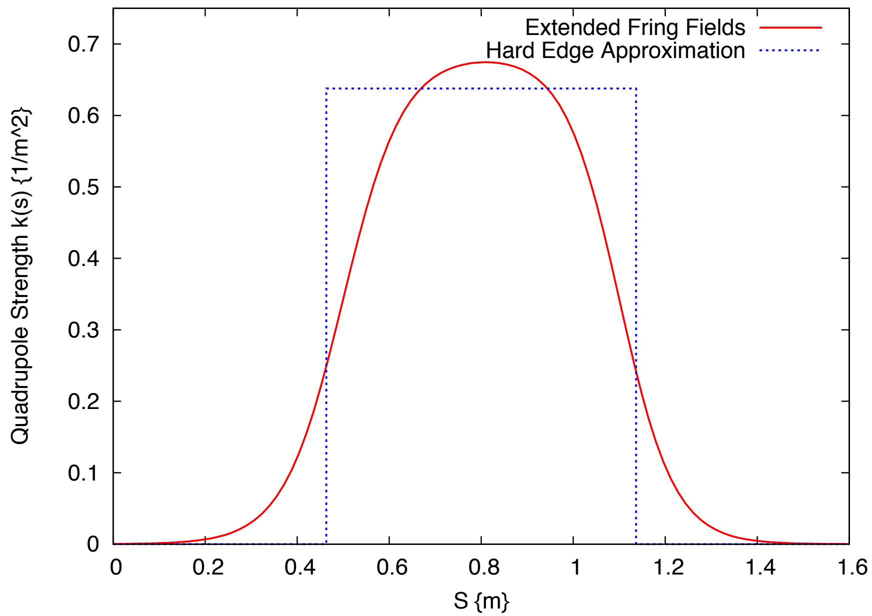


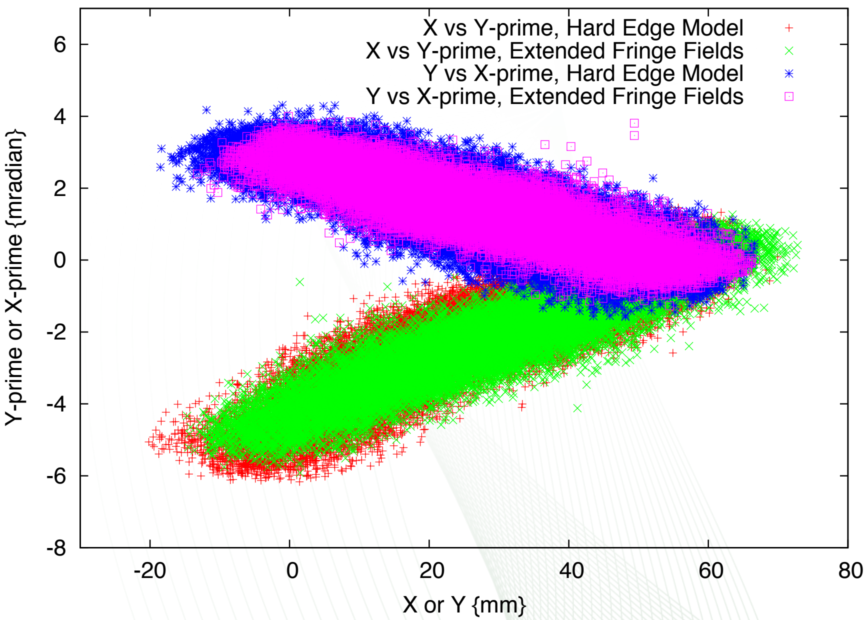


- V_{RF} = 4kV (both harmonics)
- Longitudinal profiles peak up somewhat
- Little effect on transverse properties

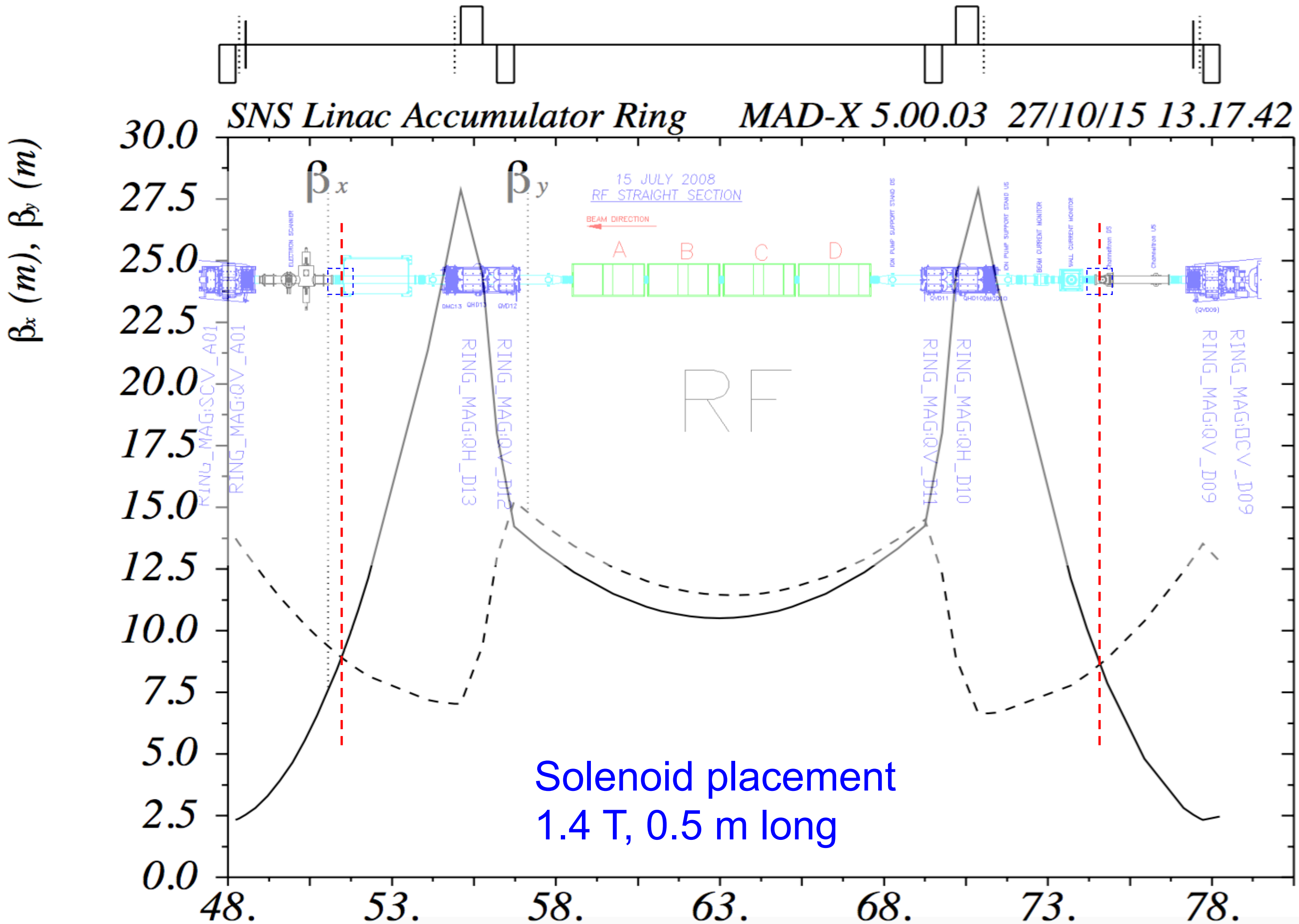
Painting and Extended Fringe Fields

- A_x = -k'/12*(x^3+3xy^2) - k_s'/6*y^3 + O(4)
- A_y = +k'/12*(3x^2y+y^3) - k_s'/6*x^3 + O(4)
- A_s = k/2*(y^2-x^2) – $k_s$xy + O(5)





Sensitivity Study: Placement of Solenoids



Note: beam is left to right on MADX plot, right to left on CAD image

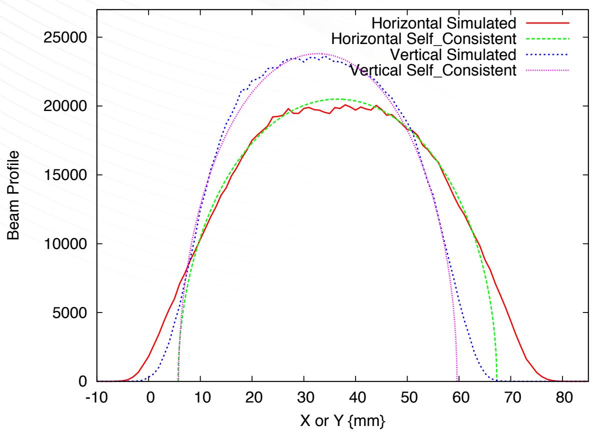
Sensitivity to Placement of Solenoids

- In order to determine the sensitivity to the position of the solenoid magnets, four calculations, identical to a base case except for solenoid placement, were carried out:
  - A) First solenoid downstream 1.016 m, second solenoid upstream 1.016 m
  - B) First solenoid upstream 0.987 m, second solenoid downstream 0.805 m
  - C) First solenoid upstream 0.987 m, second solenoid upstream 1.016 m
  - D) First solenoid downstream 1.016 m, second solenoid downstream 0.805 m
- Results in all these cases were virtually identical, so self-consistency is not sensitive to placement of the solenoids.

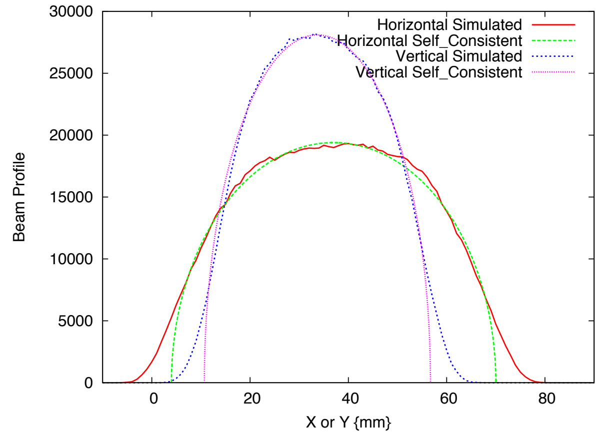
Sensitivity to Tune Separation

- Because painting a round self-consistent beam requires equal tunes we tested the sensitivity to this condition by comparing cases with bare tunes of $Q_{0x} = 6.18$ and various Q_{0y} ranging from 6.13 to 6.23.
- What we found was a pleasant surprise:
  - Self-consistency is easily achieved for Q_{0y} near Q_{0x}.
  - The robustness of self-consistency versus tune split improves with intensity.

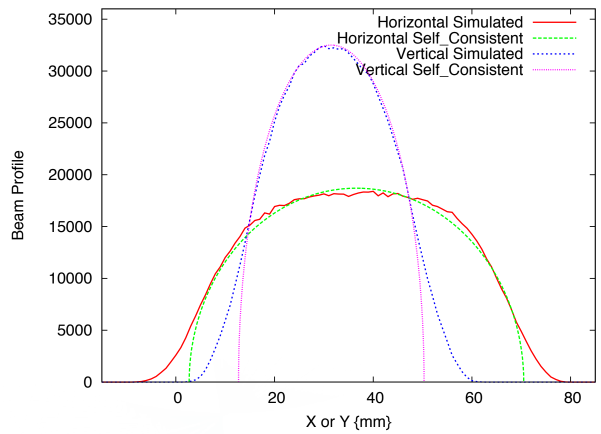
Beam Profiles: Full Design Intensity



$Q_{y0} = 6.13$



$Q_{y0} = 6.18$



$Q_{y0} = 6.23$

Varying the vertical tune for a fixed horizontal tune $Q_{x0} = 6.18$ gives self-consistent beams over a sizable range of tunes.

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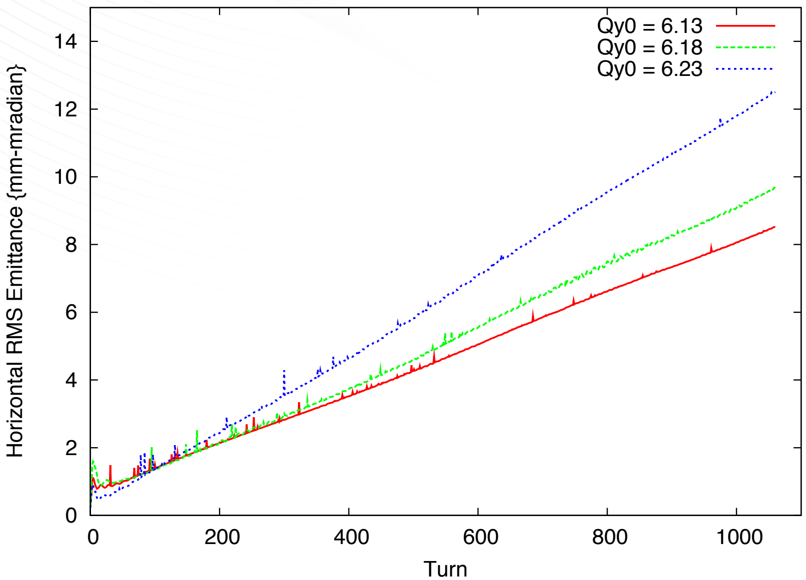
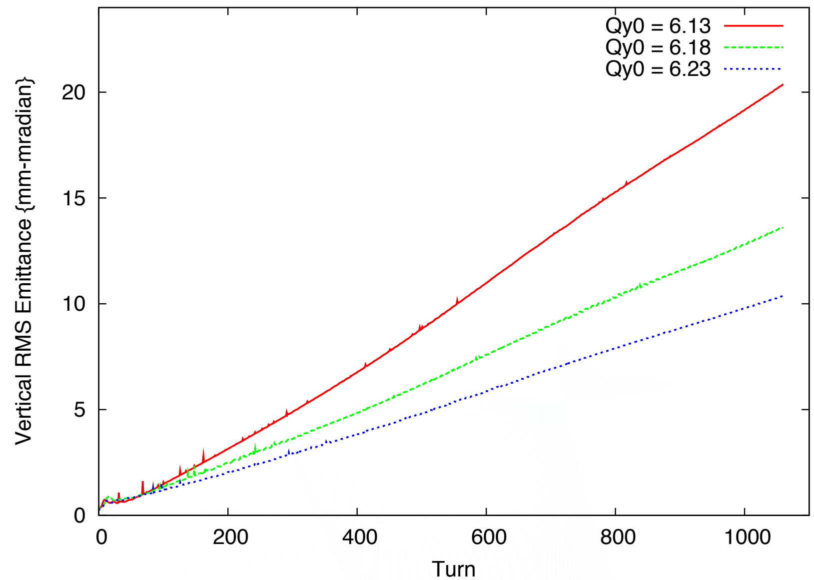
Emittance Evolution at Full Intensity



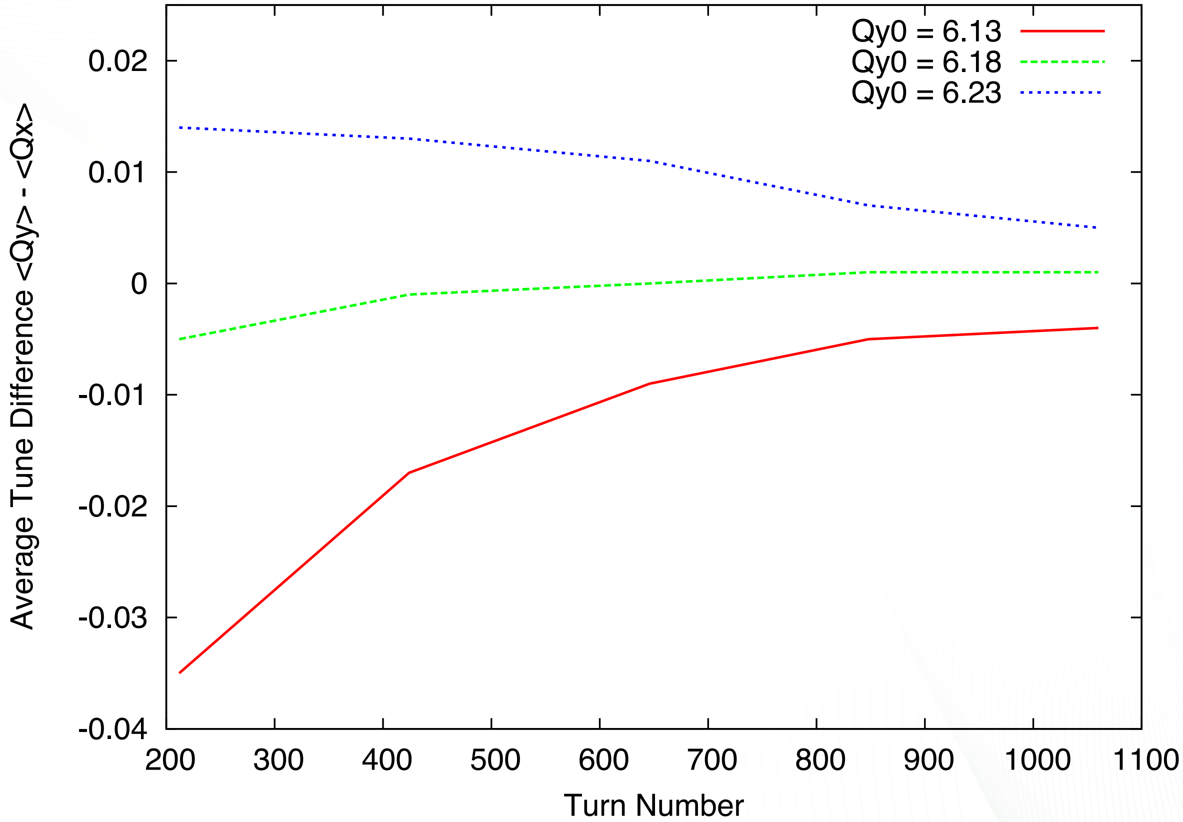
Horizontal Emittances



Vertical Emittances

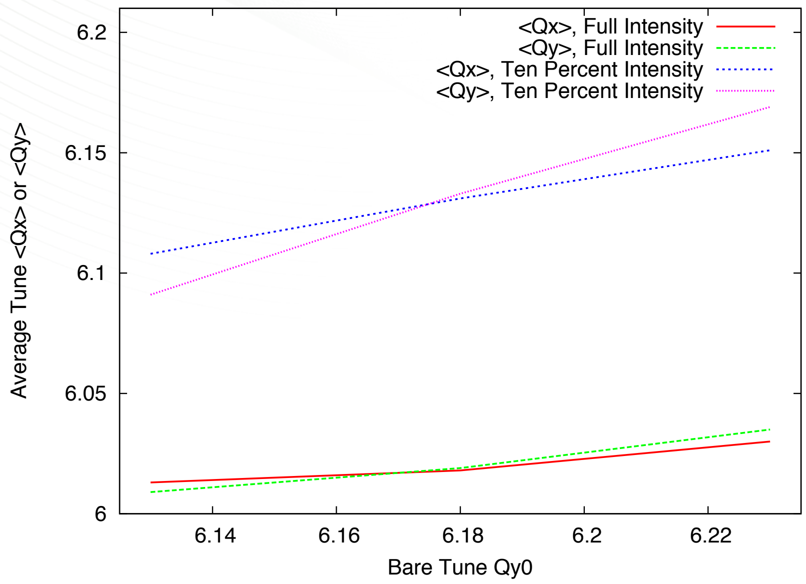
Vertical beam broadening at lower tune: half integer resonance.
Horizontal beam narrows – interesting.

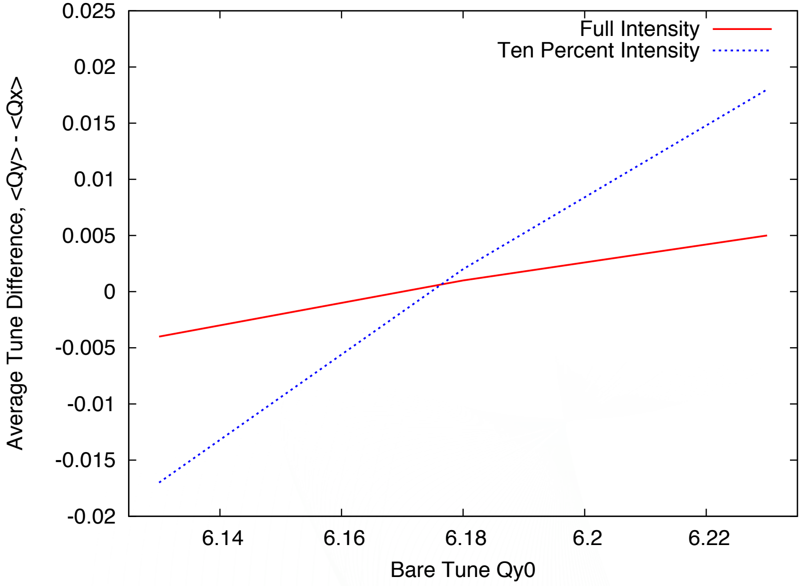
Average Incoherent Tune Evolution



Differences between vertical and horizontal average tunes are much smaller than the bare tune differences.

Final Average Incoherent Tunes

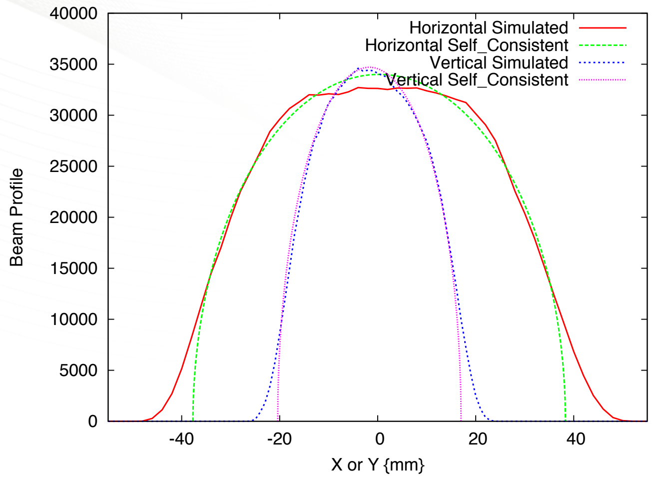




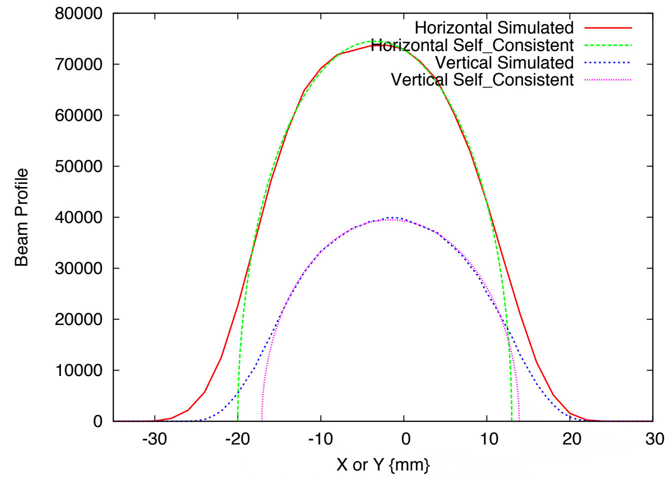
Differences between vertical and horizontal average tunes are smaller than the bare tune differences, and are smaller for high intensity beams than at low intensities.

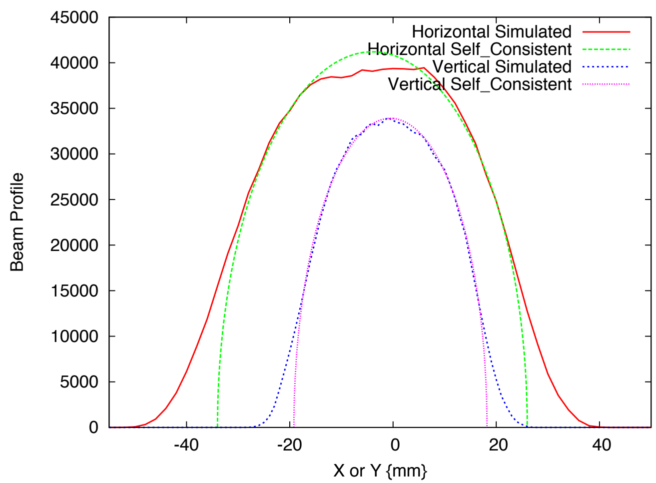
What Might We Measure?

WS20

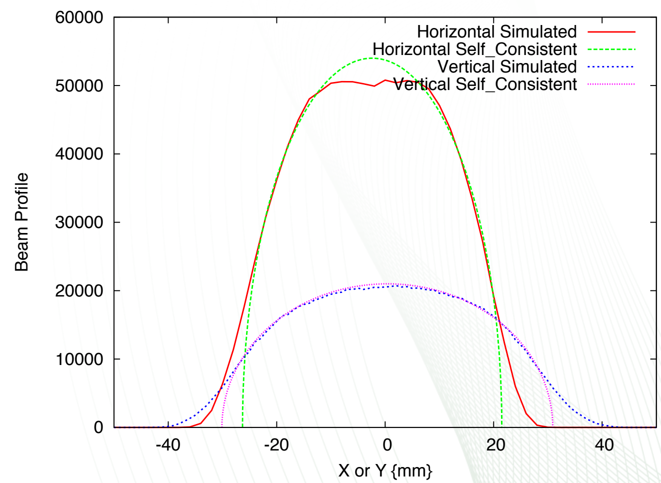


WS21



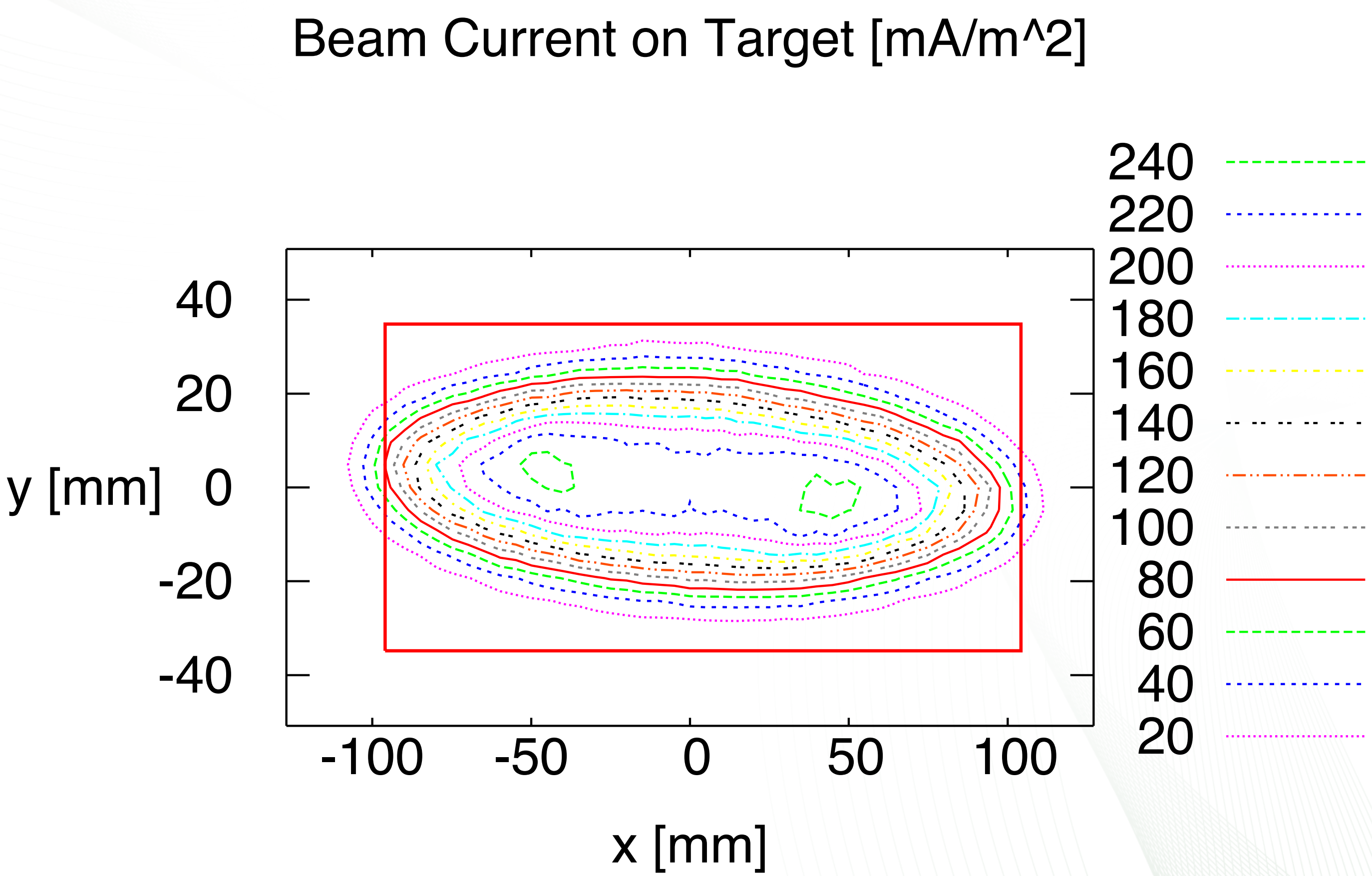


WS23



WS24

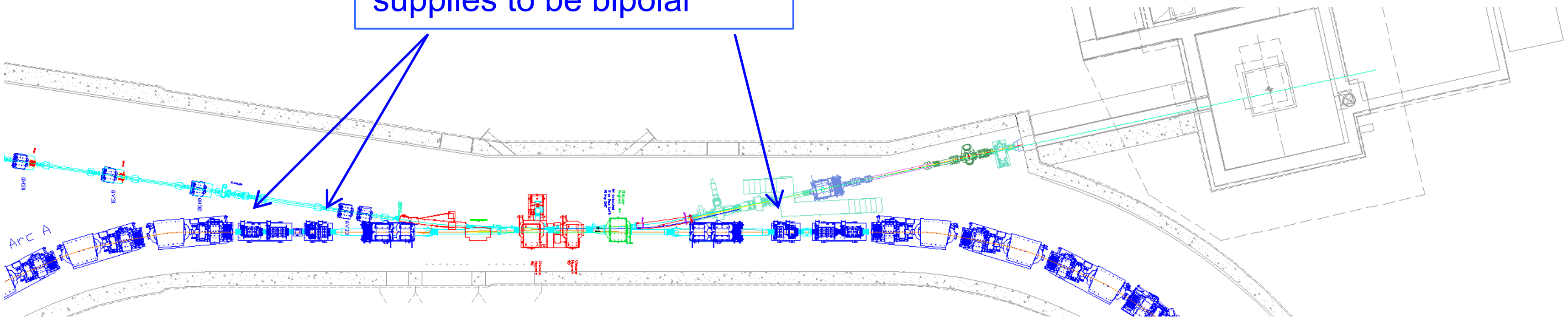
Beam on Target



Ring modifications req'd for this experiment

- Add two solenoid magnets in locations where the horizontal and vertical betatron functions are equal.
- Modify injection kickers to be bipolar (at most two horizontal and one vertical, we now think this may not be necessary).

Upgrade H1, H2, V3, injection kicker power supplies to be bipolar

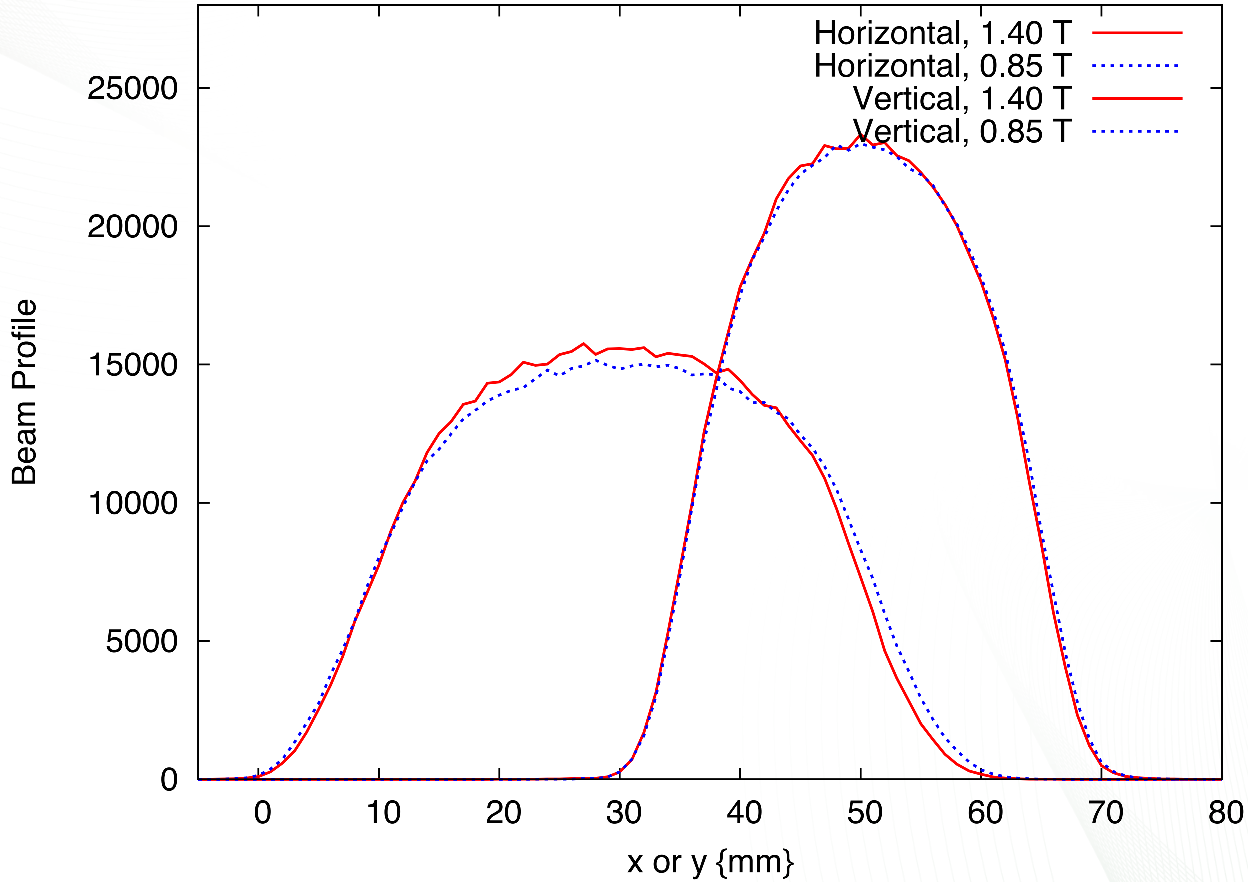


Ring injection section

Further Optimization

- Until recently, studies were subject to a few drawbacks:
  - Solenoid strengths of 1.4 Tesla are large.
  - Up to three injection kicker power supplies must be modified.
  - Beam losses of about 1% are predicted.
- Subsequent studies are being conducted to answer the questions:
  - Can solenoid strengths be reduced?
  - Can self-consistent beams be painted without modifying power supplies?
  - Can losses be reduced?
- The answers appear to be affirmative.

Reducing Solenoid Strengths



Calculations with solenoids set at 0.85 T give very similar results to those at 1.4 T

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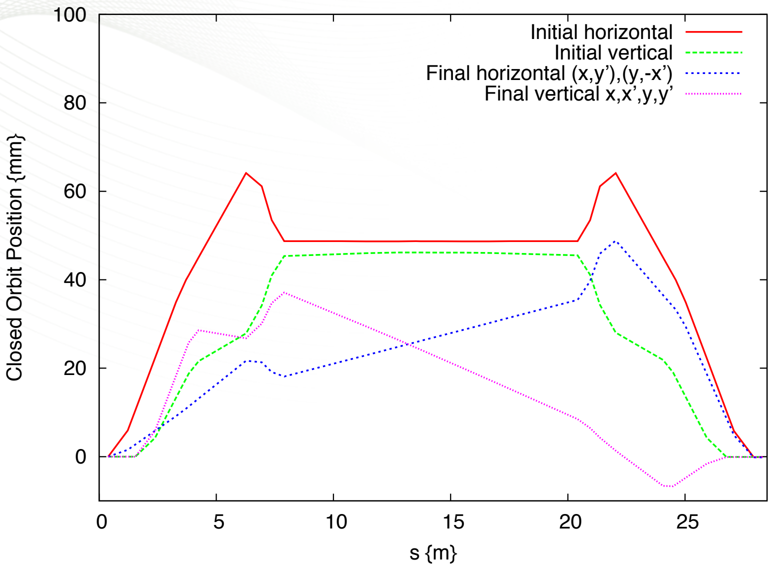
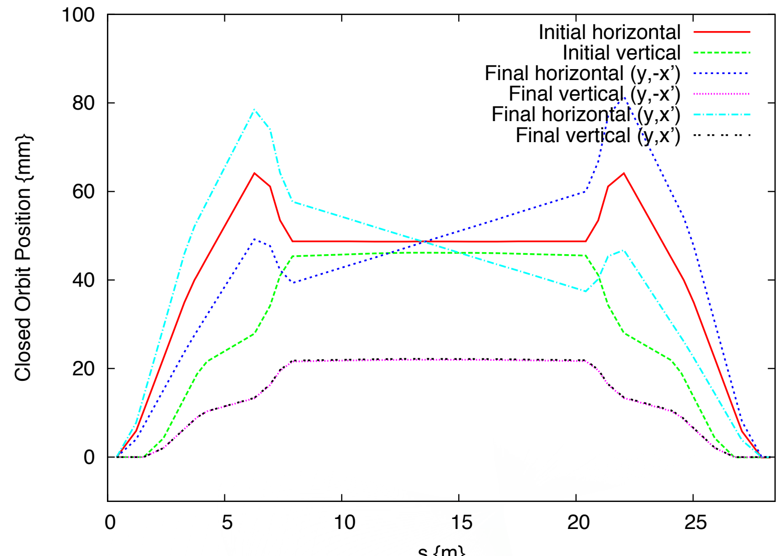
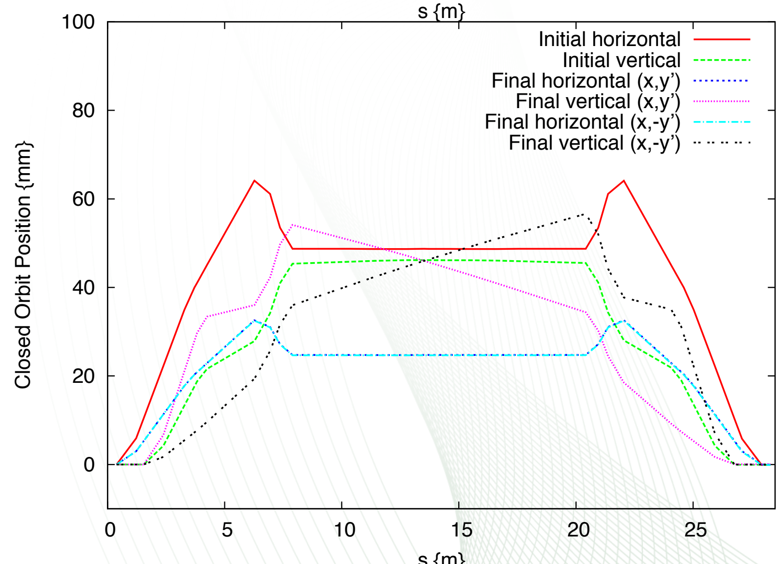
Painting Options





Timofey Gorlov pointed out that there is freedom to choose from a range of injection painting scenarios. We have found one scenario that results in acceptable losses without Requiring bipolar injection kickers.



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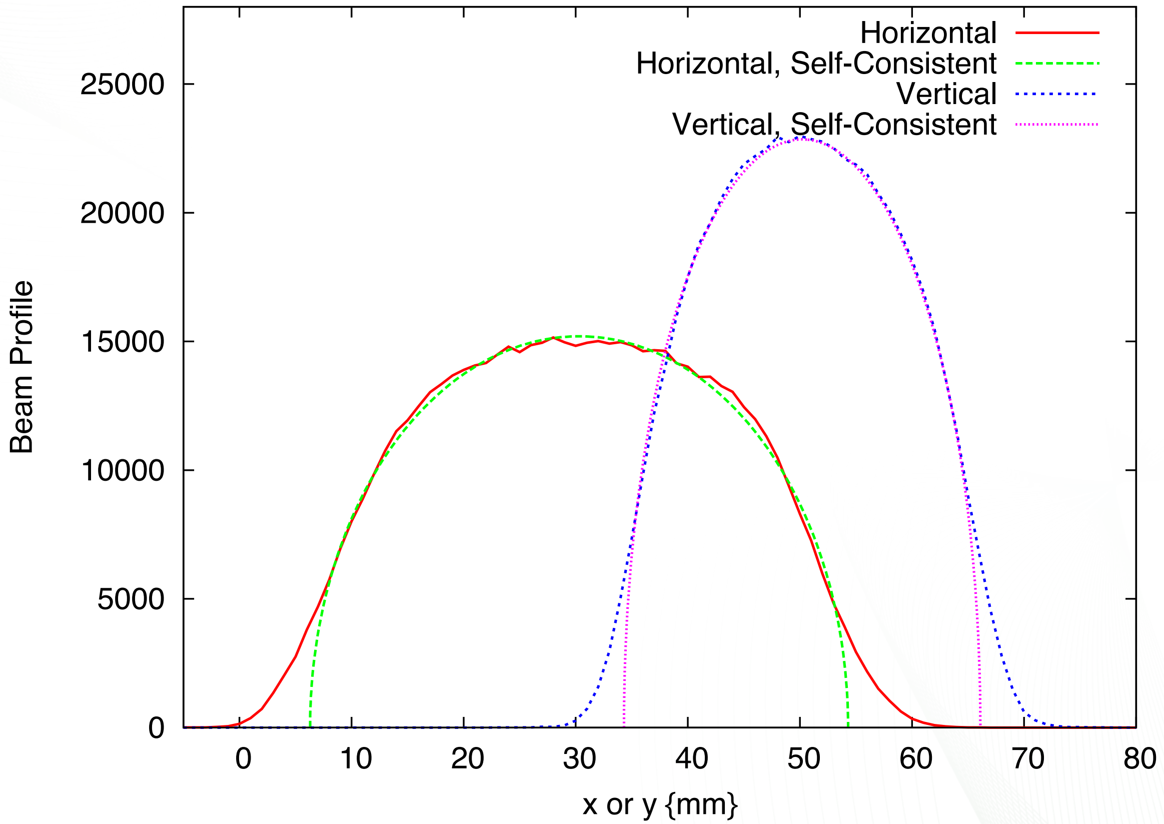
Reducing Losses



By reducing the injected beam intensity from production settings of $1.47*10^{14}$ to $0.75*10^{14}$ protons/pulse, we reduce losses by an order of magnitude from ~1% to ~0.1%.

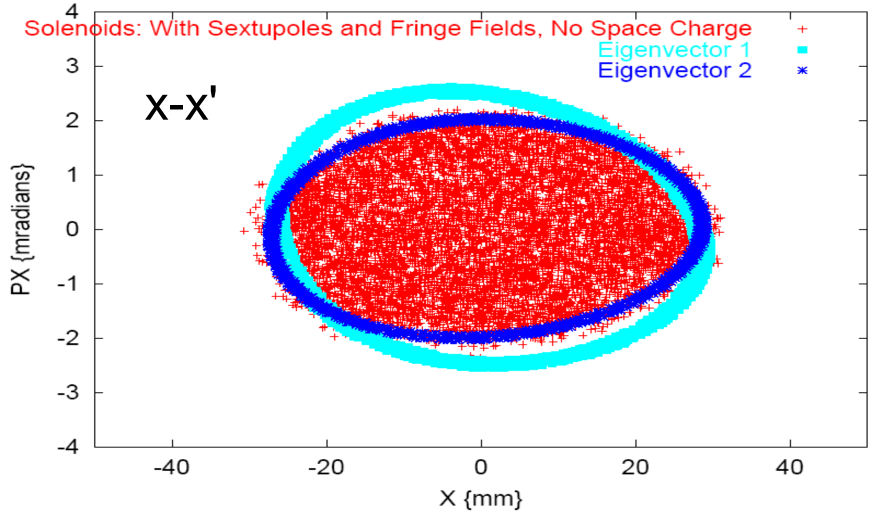
Summary

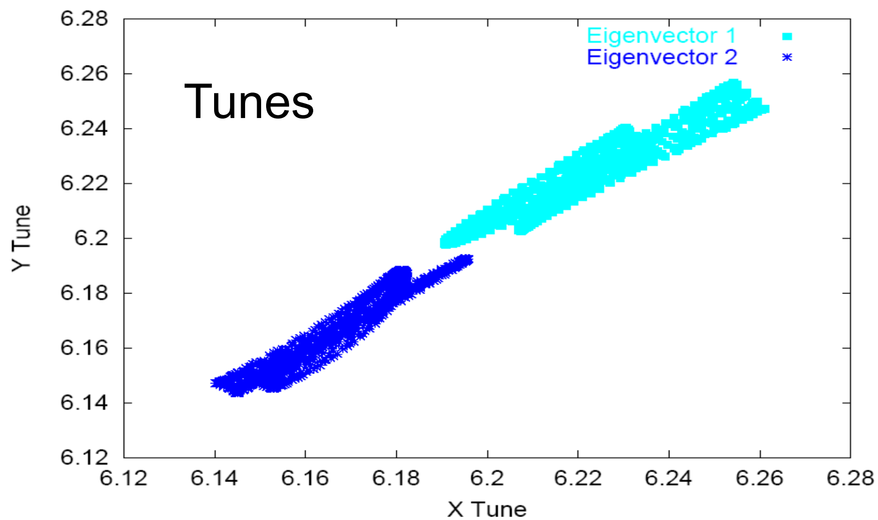
- We have demonstrated the feasibility of injecting a self-consistent beam into the SNS accumulator ring.
- Simulations have been performed to optimize the injection scenario for successful injection with
  - minimal hardware changes and
  - acceptable beam losses.
- The next steps will be to implement the hardware changes (add two solenoids) and to consider diagnostic and experimental requirements.

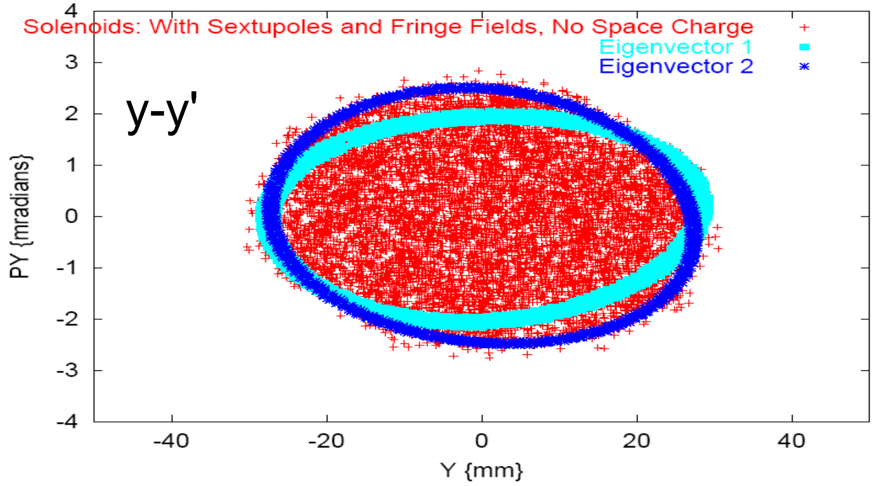
Backup Slides

Include Solenoids to Split Tunes and Paint to the Desired Eigenfunctions

- For the SNS lattice, include two solenoids symmetrically in RF straight section to split tunes and paint a rotating distribution to the desired rotating eigenfunctions.
- Results show painted beam in phase space and tune separation and spread of eigenvectors.







How to paint a Self-Consistent Rotating Distr.

Injection bump trajectories vs. distance

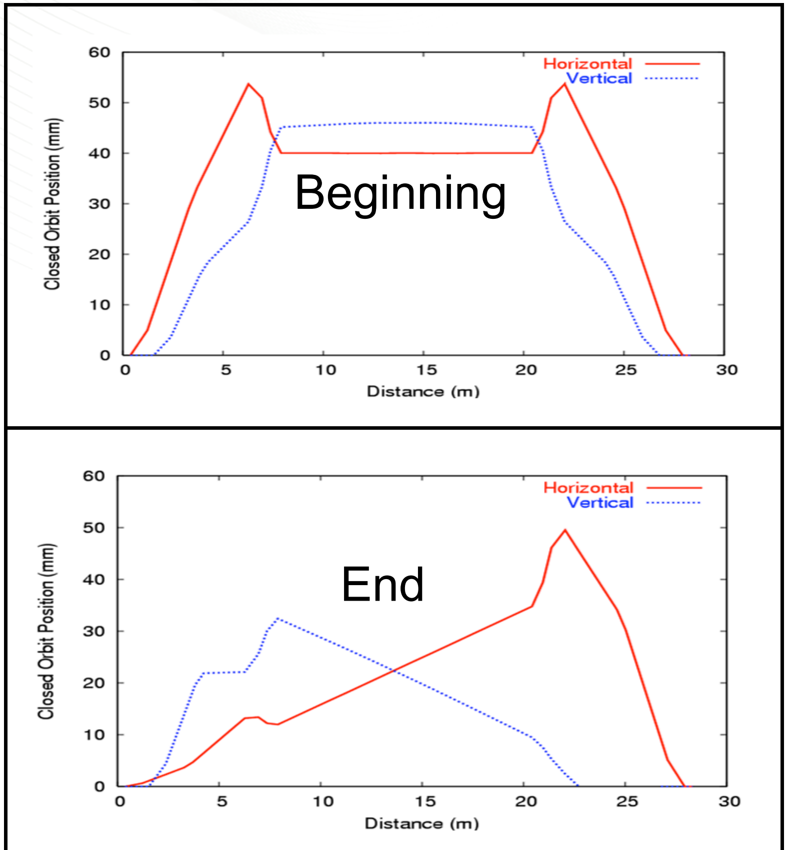
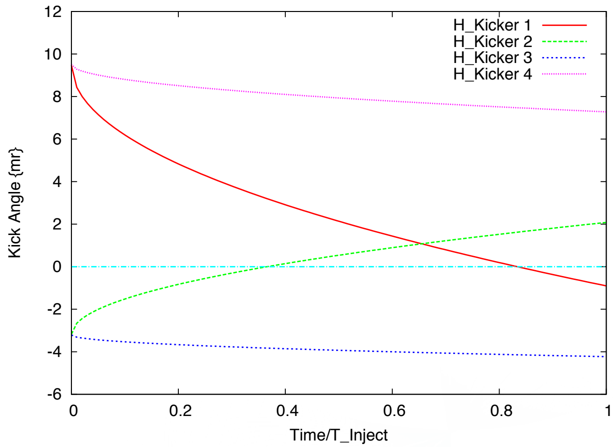
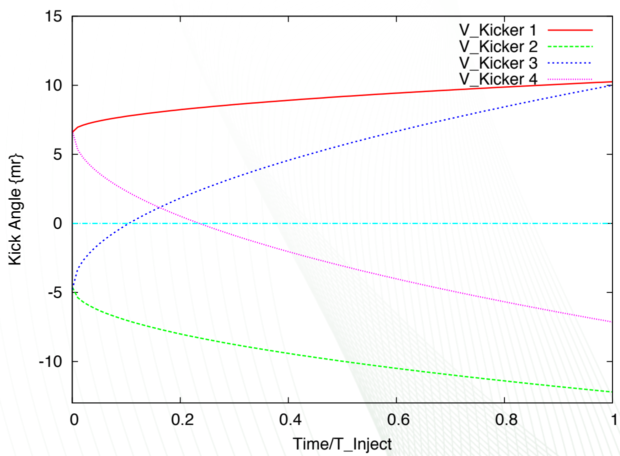


Figure 3: Closed orbit behavior during injection. Upper plots show the beginning and lower plots show the end of injection.

Injection kicker angles vs. time





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