Ring Beam Dynamics Progress

Jeff Holmes

Sarah Cousineau, Slava Danilov, Tom Peleia, Mike Plum, Andrei Shishlo, and Zhengzheng Liu

Accelerator Advisory Committee

February 3, 2010

Outline

- A detailed understanding of ring beam dynamics requires experimental study, theoretical insight, and painstaking computational benchmarking.
- Ring Optics Analysis
  - Linear optics and beta beating
  - Resonance map
- Benchmarks of accumulation and painting
- Losses in the injection chicane
- Instabilities
  - Benchmark of extraction kicker instability
  - Electron cloud observations
- ORBIT Code status
  - Support and develop ORBIT for many users
  - Migration to Python-based ORBIT

Ring Optics (Zhengzheng Liu and Sarah Cousineau)

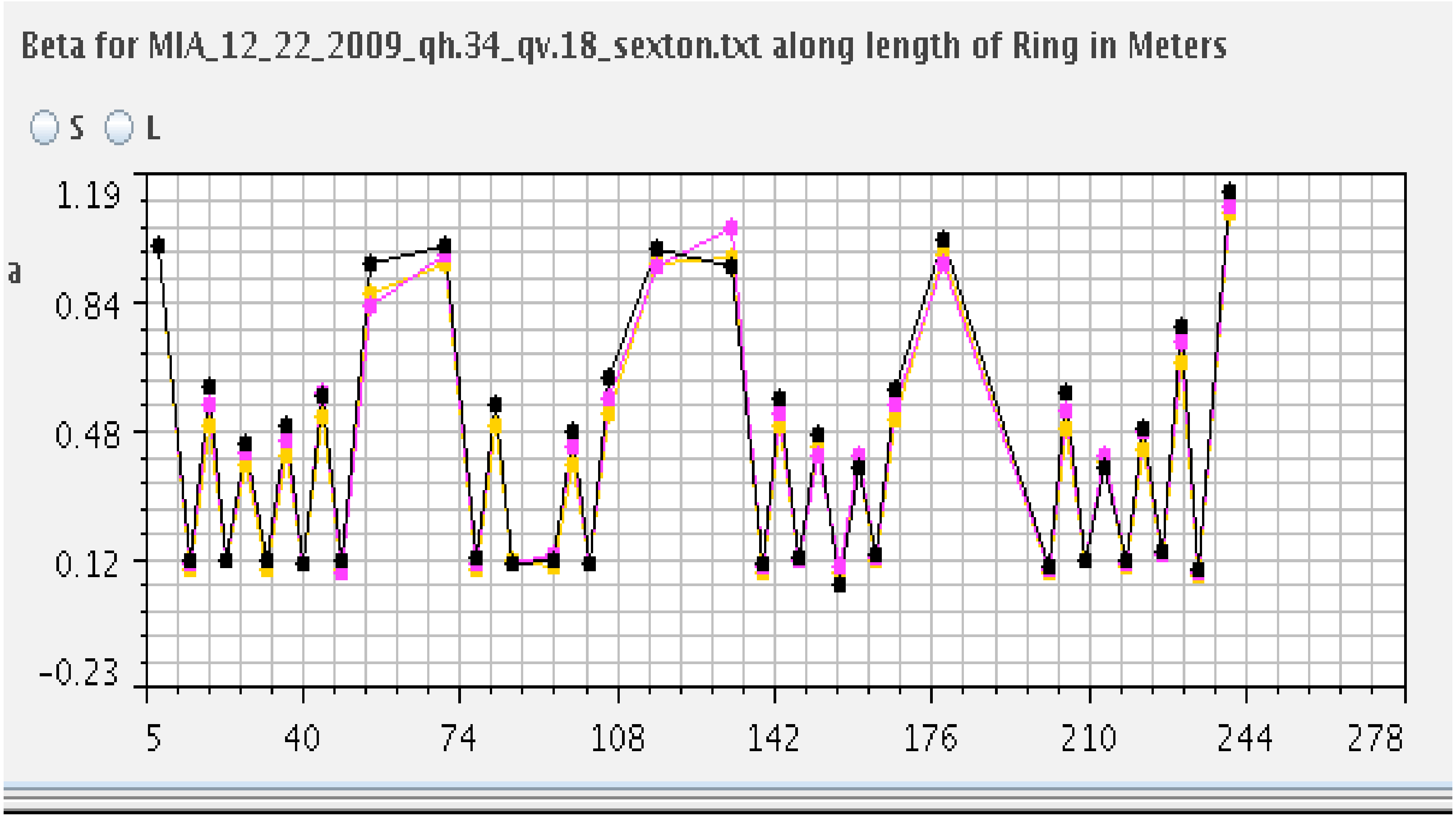
- **One year ago:**
  - The ORM method had been used to determine correction factors for the six quadrupole magnet families, and these were included in the online model and the tune setpoint generator.
  - With the correction factors, the predicted tunes were within 0.01 over ν_x = 6.23-6.41 and ν_y = 6.20-6.37.
  - The corrected dispersion and the averaged β function had been measured for the "production" set point.
  - With the corrected quadrupole strengths, the model predicted small β_x beating, but there was still significant beating in β_y.

Present Situation and Next Steps

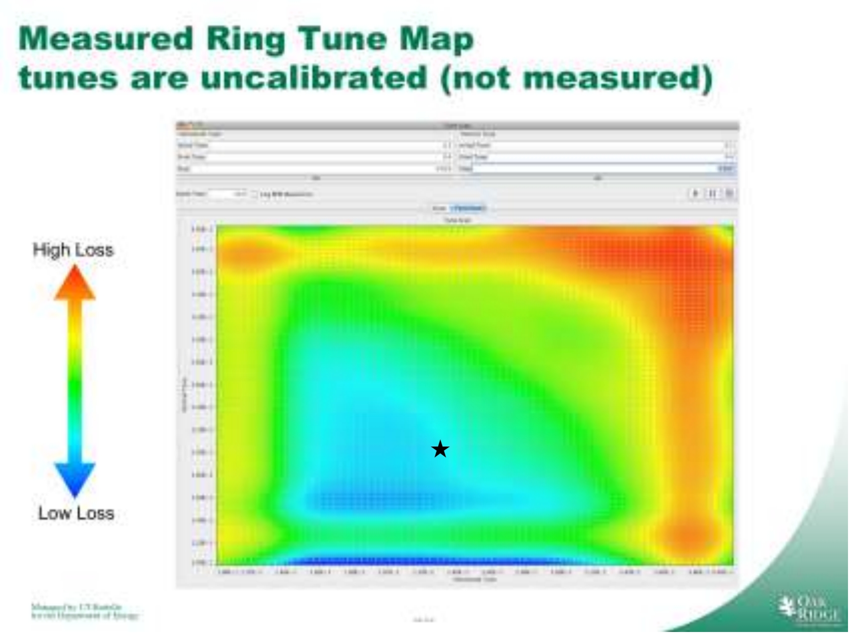
- **Today**
  - **We routinely use the ORM-derived correction factors to determine the lattice setpoints.**
  - **However, beta function measurements using Model Independent Analysis (MIA) show significant amounts of beta beating in both horizontal and vertical planes. The beta beating is not fourfold symmetric.**
  - **Computational studies are underway to determine the extent of possible correction**
    - **using the six symmetric knobs, and**
    - **using the quadrupole correctors.**

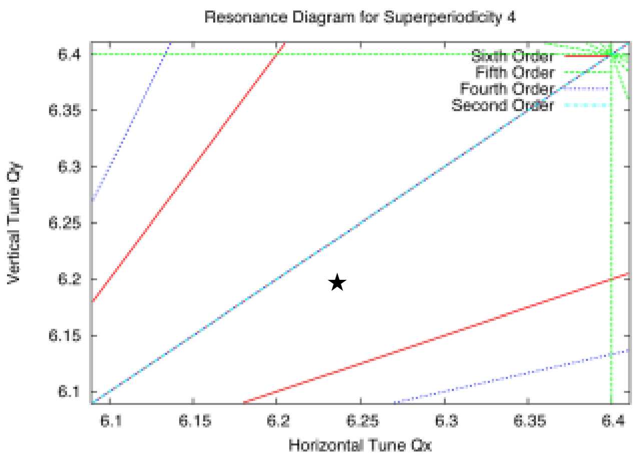
MIA Beta Function Measurements

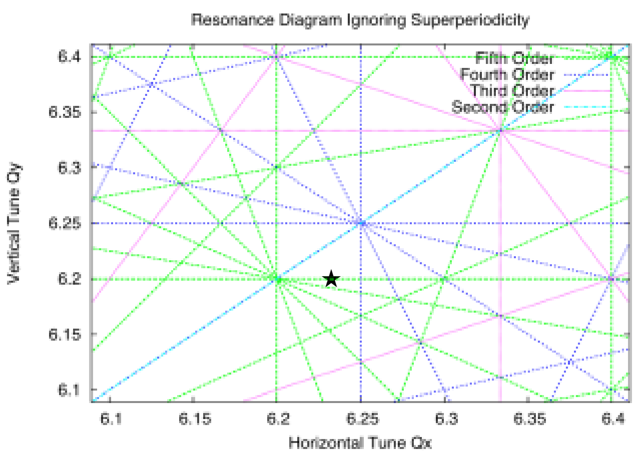
Horizontal Beta



Ring Losses with Tune: Resonance Diagram (Tom Pelaia)







ORBIT Benchmarks of Accumulation
(Sarah Cousineau)

★ Experiment: Accumulate and extract beam. Measure profiles of extracted beam at wire scanners in RTBT.
★ Simulate with ORBIT and compare calculated and measured profiles in RTBT.

Simulations included the following beam dynamics:

- Full injection description, real bumps
- Foil scattering
- RF focusing
- Chicane multipoles
- Apertures
- Symplectic tracking
- 2.5 D Space charge
- Longitudinal impedance, space charge

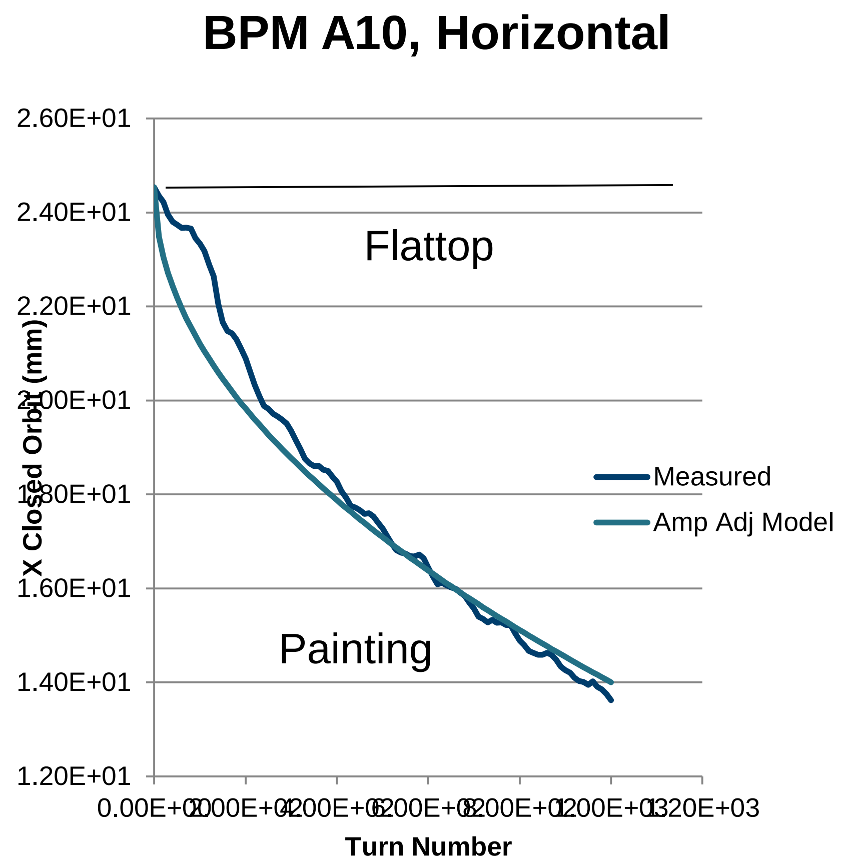
Computational Caveats:
1) Profiles adjusted ~5% for optics differences.
2) Quad fringe field turned off due to large coordinate amplitude breakdown of hard edge model.

First attempts failed miserably:

- ➢Measured distribution shape changes significantly from WS to WS.
- ➢Beam on target tilted.
- ➢Found and fixed x-y coupling in the extraction septum.

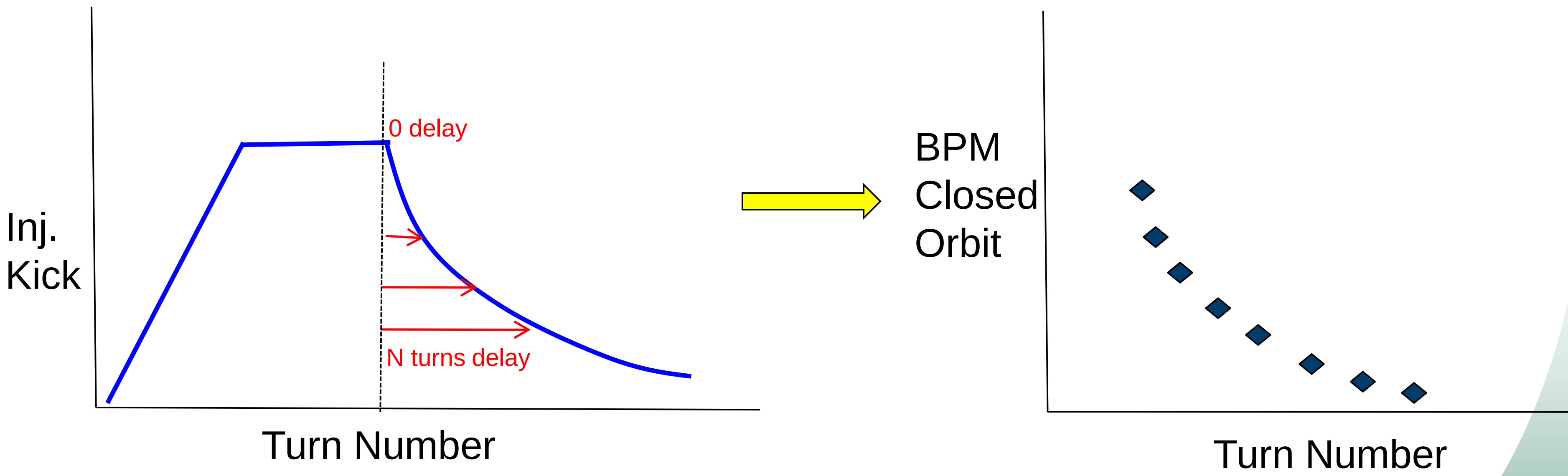
Back to Benchmarks of Accumulation

- Started with flat-topped injection kickers:
  - Achieved excellent agreement.
  - Profiles matched at low and moderate intensities.
  - Emittances agreed within 5%.
- Then considered standard painting with injection kickers.
  - Moderate intensities agreed.
  - Disagreement at low intensities.
  - Suspicious of injection painting model versus actual kicker waveforms.
- At moderate intensities, effect of space charge was to smooth out and fill in profiles. Insufficient intensity to give profile broadening.



Experiment

- We tested the injection kicker waveforms by varying the injection turn delay and measuring the closed orbit on BPM A13. This gave us the actual functional form of the waveform, to compare with the assumed painting. We found
  - Paint start delayed by 50 – 60 turns.
  - Less painting in measured data than in model.
  - Bump in waveform from 100 – 250 turns.
  - J. Tang informed us that all kickers have separate start delays. This can lead to a strange net waveform. The problem has been corrected.

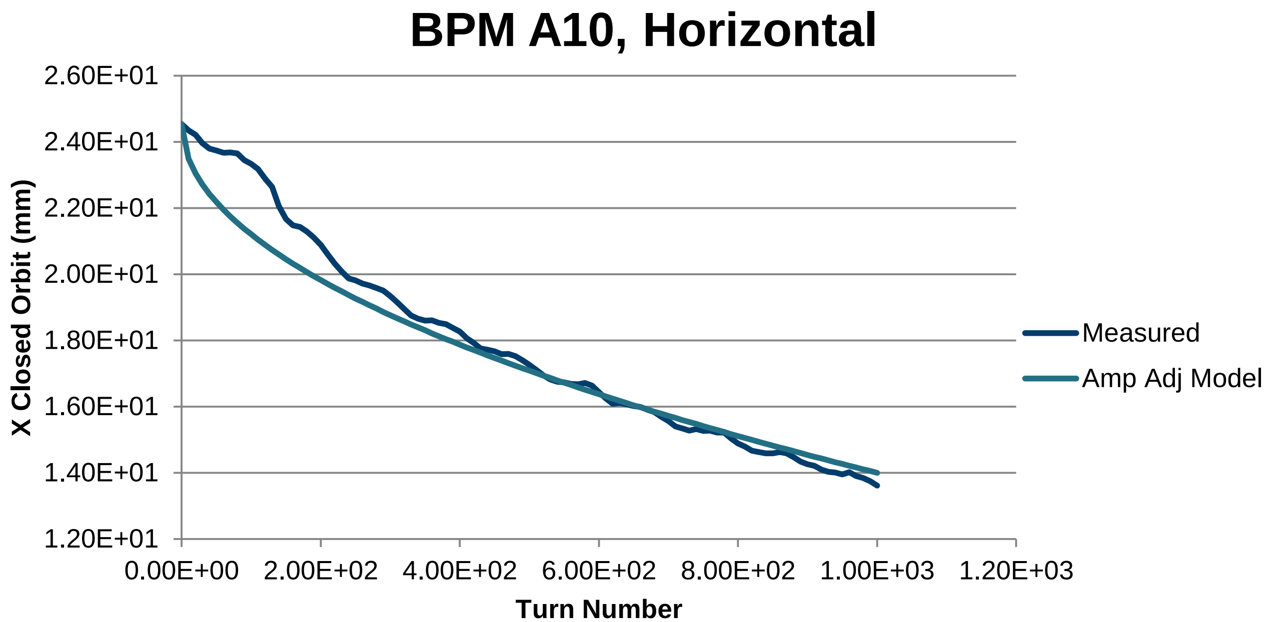


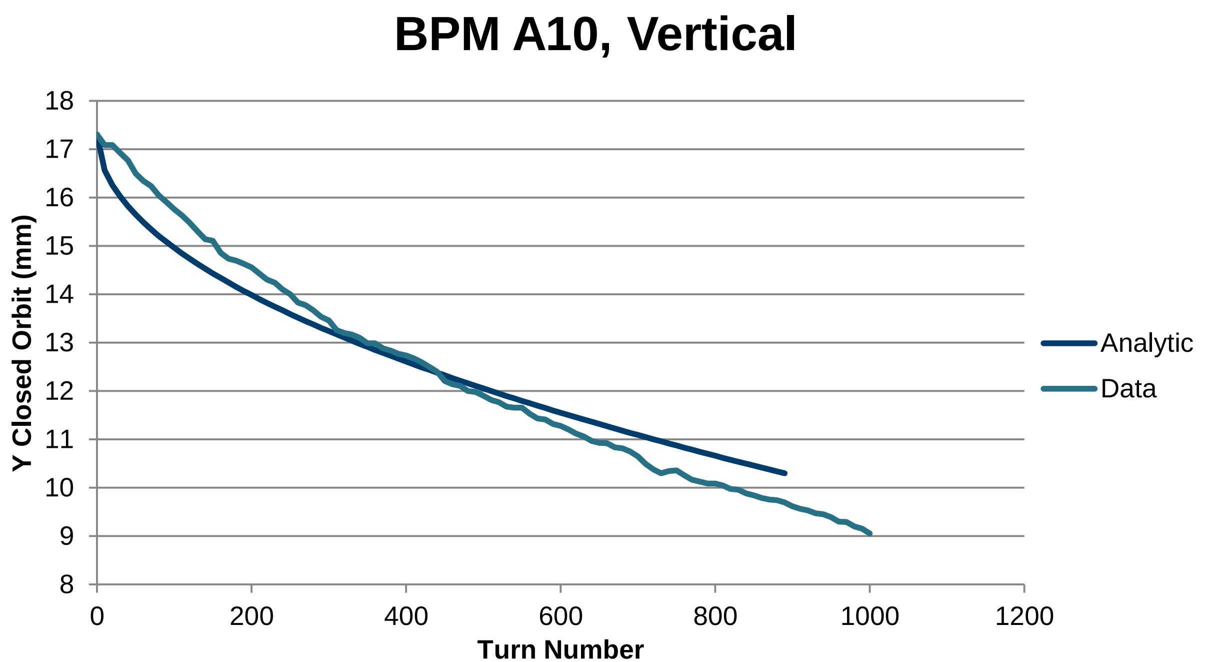
Back to Benchmarks Again

Measured Oct. 2009.

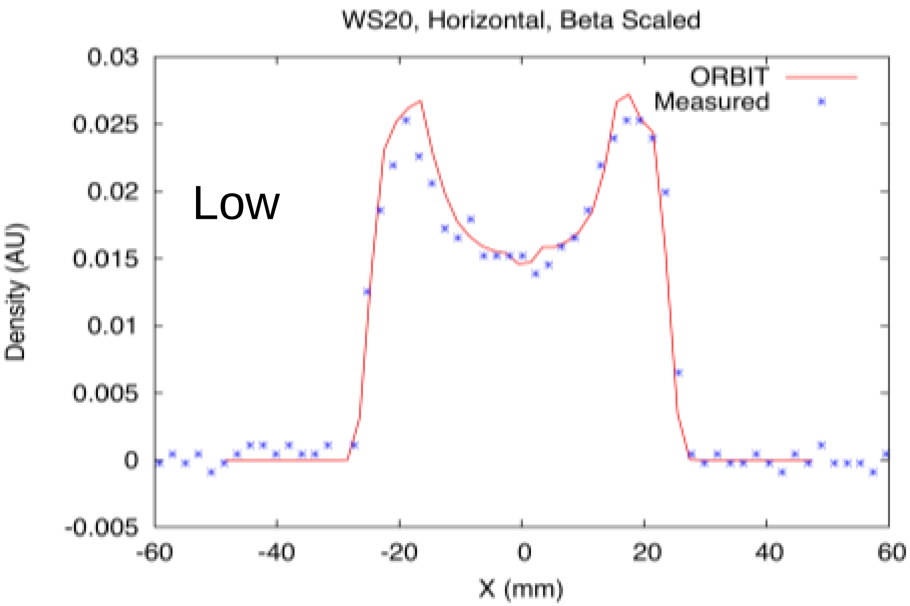
~80us timing offset corrected in both planes.

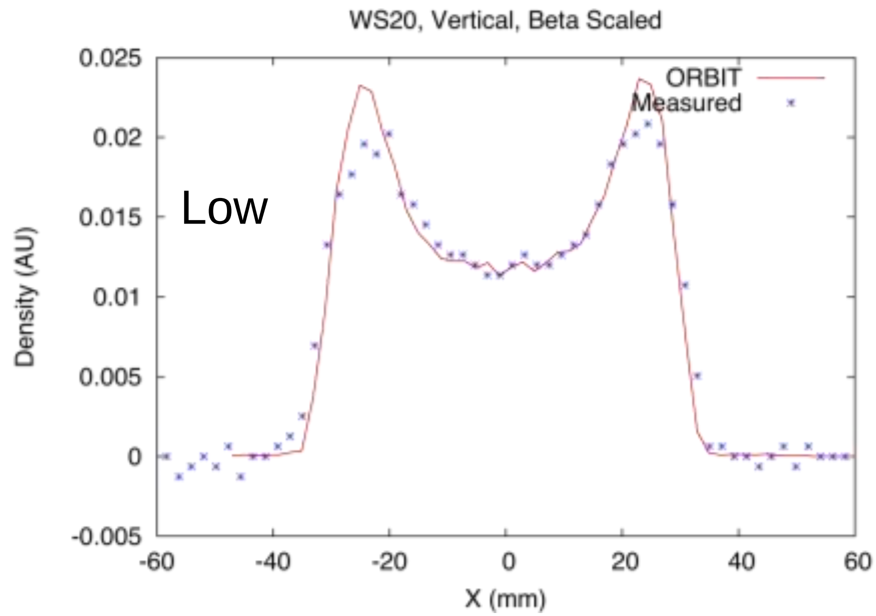
Measured kicker waveforms were used in ORBIT simulations.

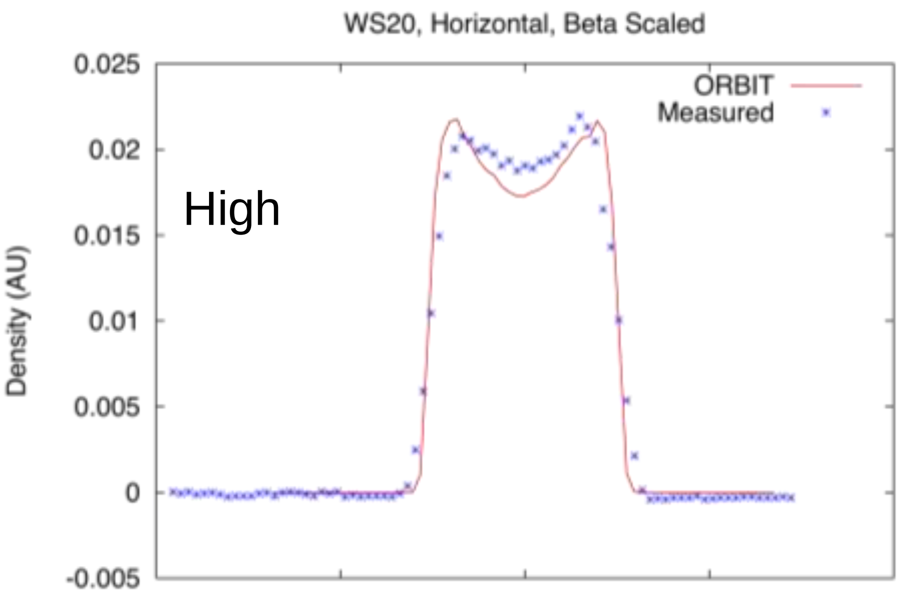


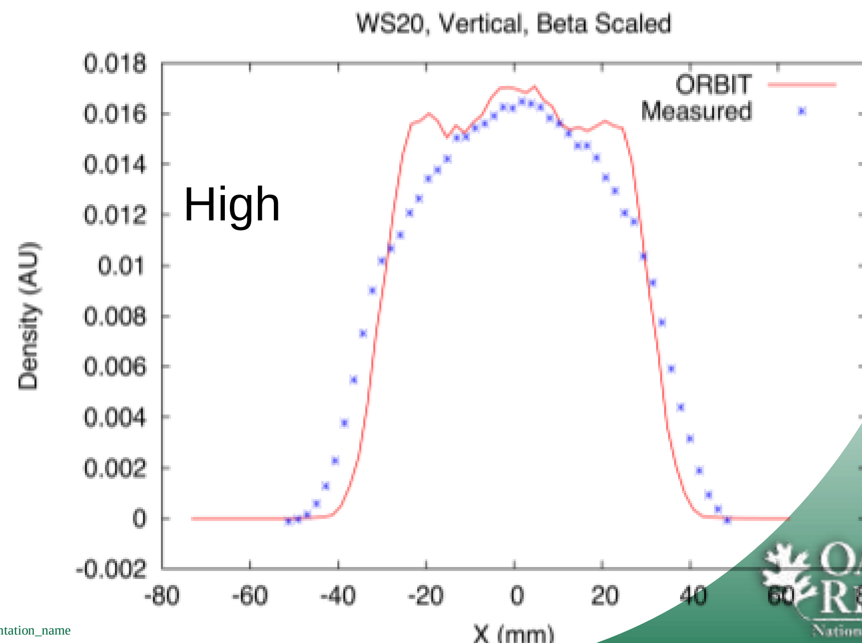


Painted Beams with Corrected Kickers









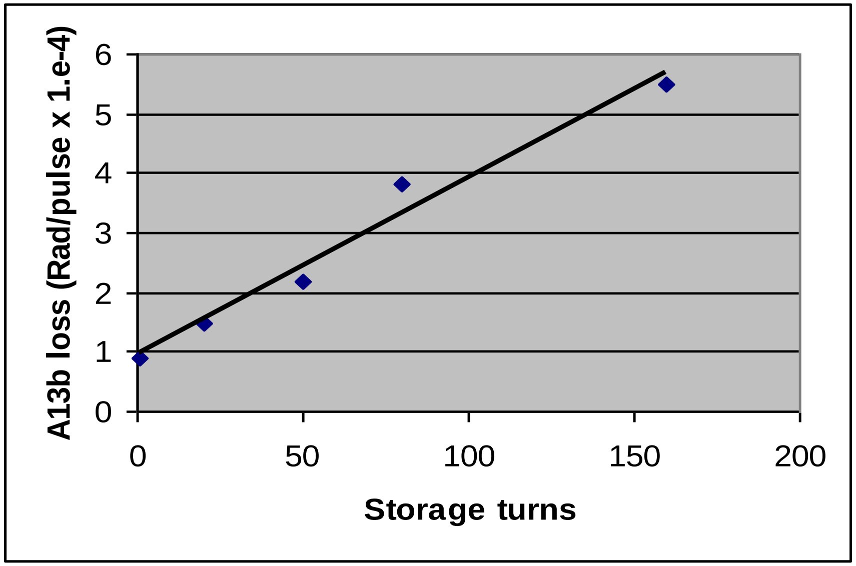
Summary of Results

Progress Report:

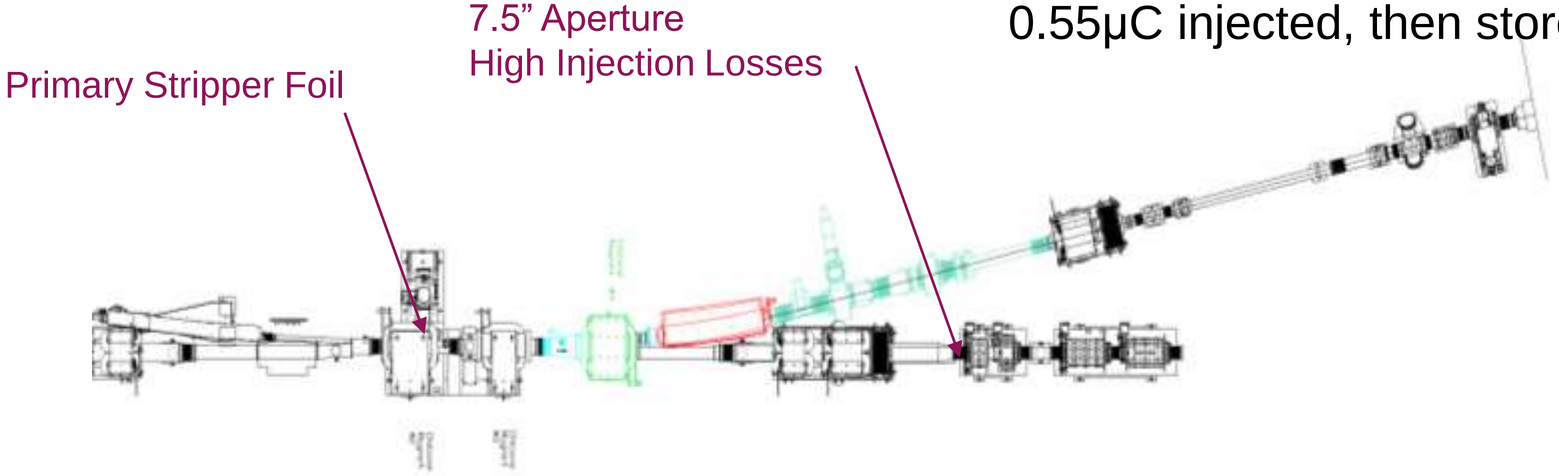
- ✓ **Flattop, low intensity, both planes**
- ✓ **Flattop, high intensity, both planes**
- ✓ **Painted, low intensity, both planes**
- ✓ **Painted, high intensity, Horizontal**
- X **Painted, high intensity, Vertical.**
  - X **This is now under study, but it appears that the profiles are sensitive to the beam intensity. Also, $Q_x \approx Q_y$, so there could be some x-y coupling.**

Injection and Collimation Losses: Primary Stripper Foil Scattering or Space Charge?

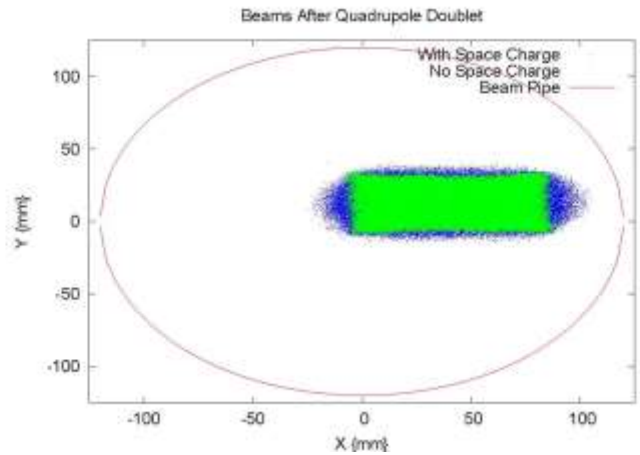
- **Beam losses are high in the downstream side of the injection region.**
  - **The beam pipe narrows.**
  - **The beam is off center.**
  - **Primary foil scattering is suspected.**
- **Primary foil thickness ~350cm^2.**



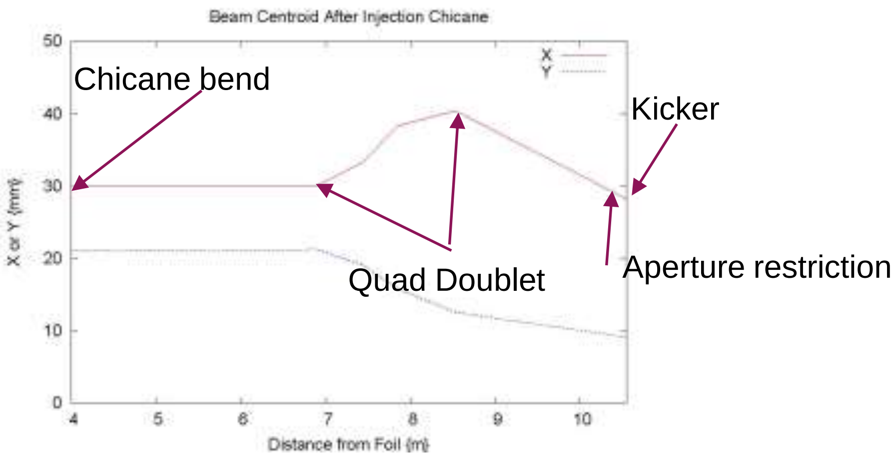
0.55μC injected, then stored.

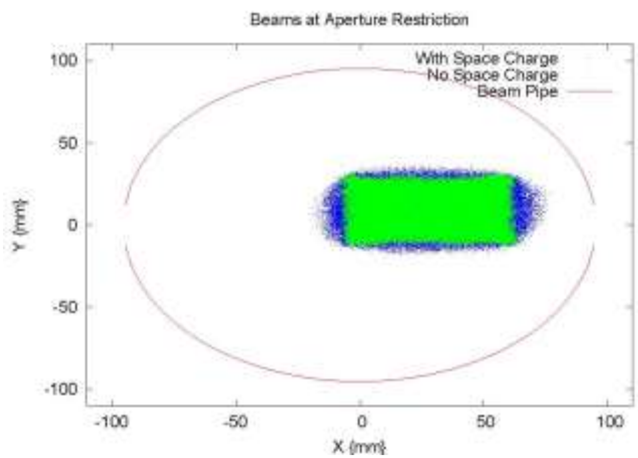


Injection Region: Beam is Off Center



End Quad Doublet





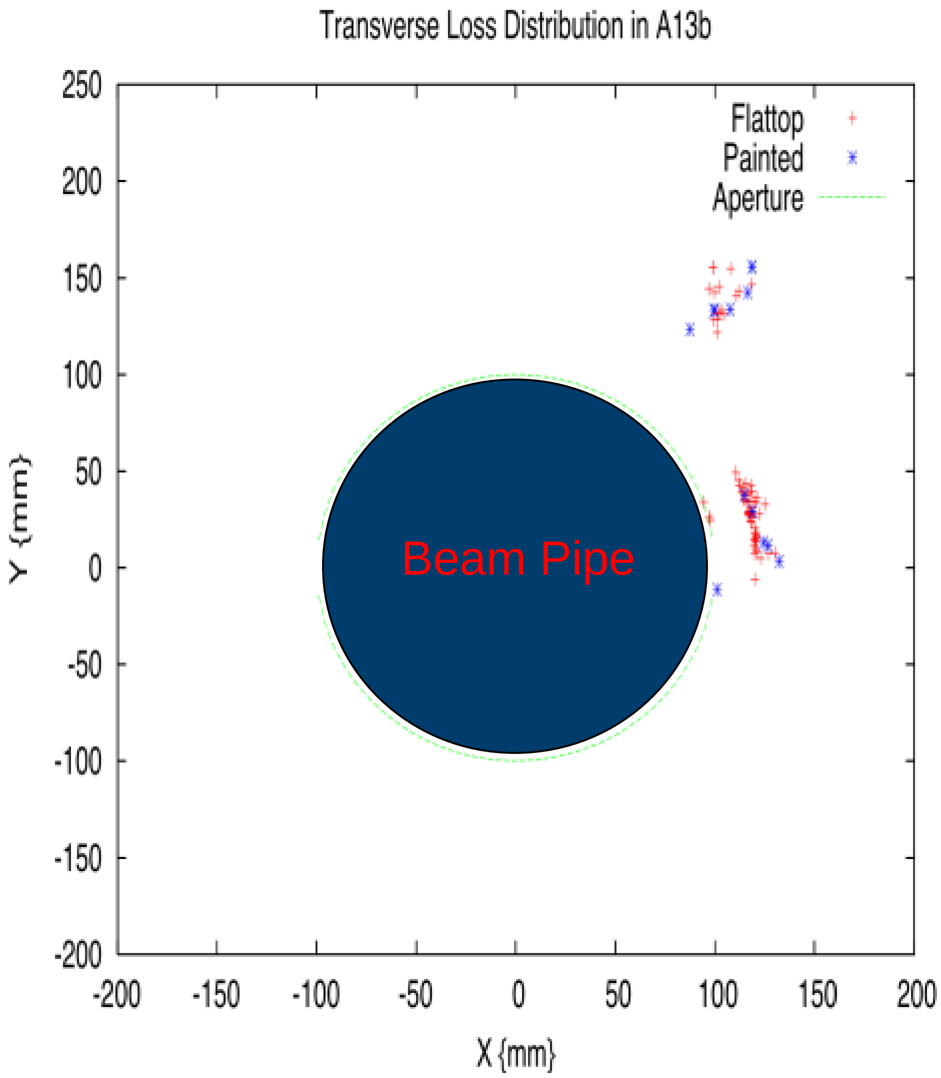
At Kicker

- **Experimental studies:**
  - **Steer toward center using chicane dipoles**
  - **Steer toward center using injection kickers**
  - **Perform studies both with flat-topped and painted beams**
- **Simulate using ORBIT**

A13b Loss Studies

- **Experiment:**
  - Steer beam down and in using chicane bends (affects waste beams, so bump not closed).
  - Steer beam down and in using injection kickers.
  - Do experiments both with flattop and painted injection.
- **Results:**
  - Steering has no effect on A13b losses.
  - Flattop losses are about 2.5 times greater than losses with painting -> foil scattering?
- **Simulation:**
  - Do flattop and painting with careful matching of machine setup.
- **Results:**
  - The flattop case has 2.65 times as many foil hits as the painted case and 2.4 times as much loss at A13b.
  - Fractional beam losses in vicinity of A13b are ~10^{-5} for flattop case.
  - Losses go away when foil scattering is turned off.
  - Loss distribution is up and outside, consistent with experiment.

A13b Losses are High and Outside



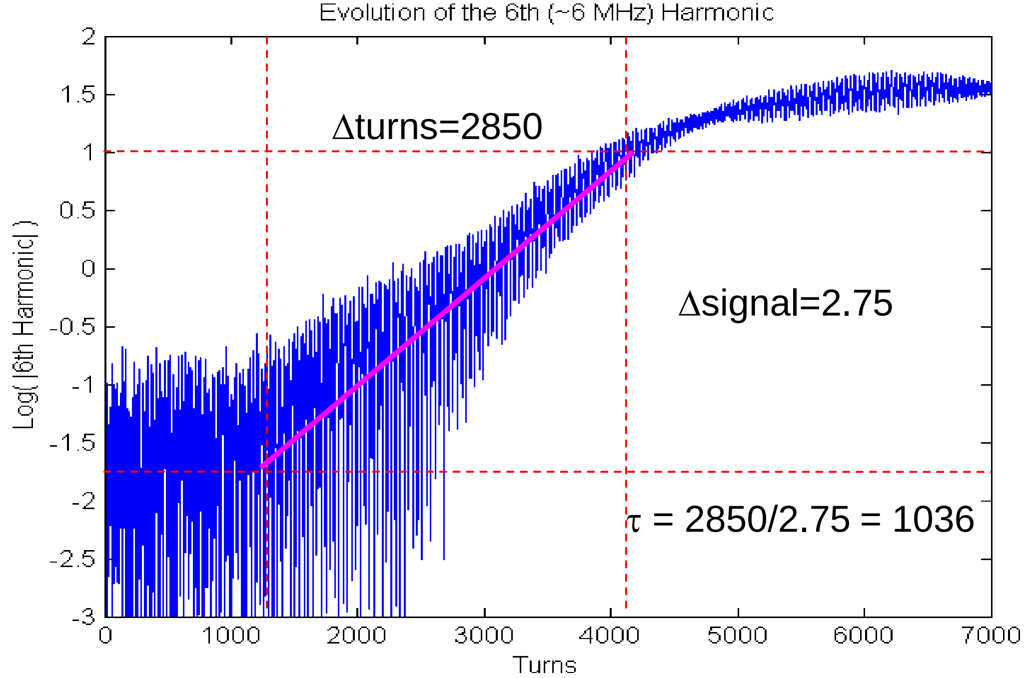
Extraction Kicker Instability

- ***Observed Experimentally***
  - Tune settings $(Q_x,Q_y) = (6.23,6.20)$.
  - The ring RF cavities were turned off.
  - The ring chromaticity was zeroed.
  - Unchopped coasting beam was used.
  - Injected 7.7×10^{13} protons per pulse at 860 MeV over 850 turns.
  - Stored until beam was lost in ring (~10000 turns).
  - **Observed transverse instability in the vertical direction for a stored coasting beam.**
    - Dominant harmonic at 6 MHz and noticeable excitation in the 4→10 MHz range.
    - "Slow" mode → harmonic n = 12, and excitation in the range $10 \le n \le 16$.
- ***Simulated***
  - Used all settings above.
  - Assumptions:
    - RMS energy spread of 0.5 MeV, consistent with experiment.
    - Symplectic single particle transport.
    - The laboratory-measured longitudinal and transverse impedances for the extraction kickers.
    - 3D space charge model.
    - ORBIT foil scattering model.
    - Complete set of apertures was included to incorporate beam losses.
    - The number of macroparticles in the simulation was 4.25 million.

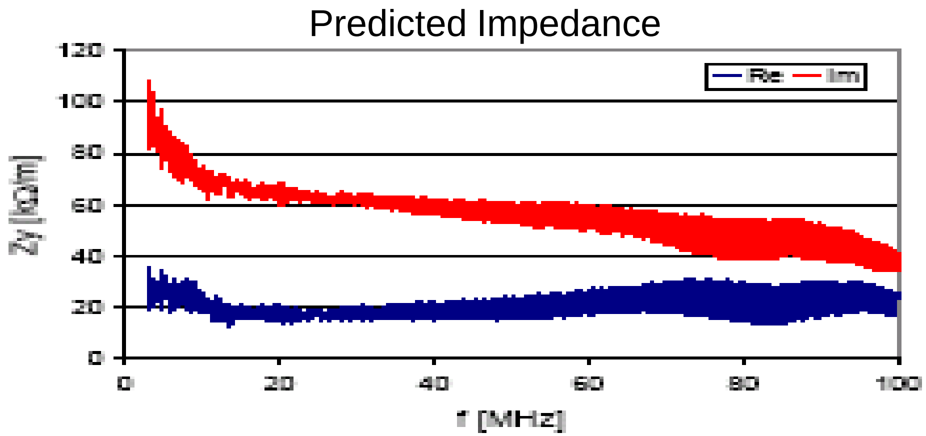
Estimation of Extraction Kicker Impedance
(Slava Danilov)

Can derive impedance from experiment using formula:

$$\mathrm{Re}(Z) = \frac{2\gamma\beta^2 E_o}{\tau\beta_{twiss} I_{ave}}$$



Experimentally-measured impedance: Z ≅ 21 KΩ/m

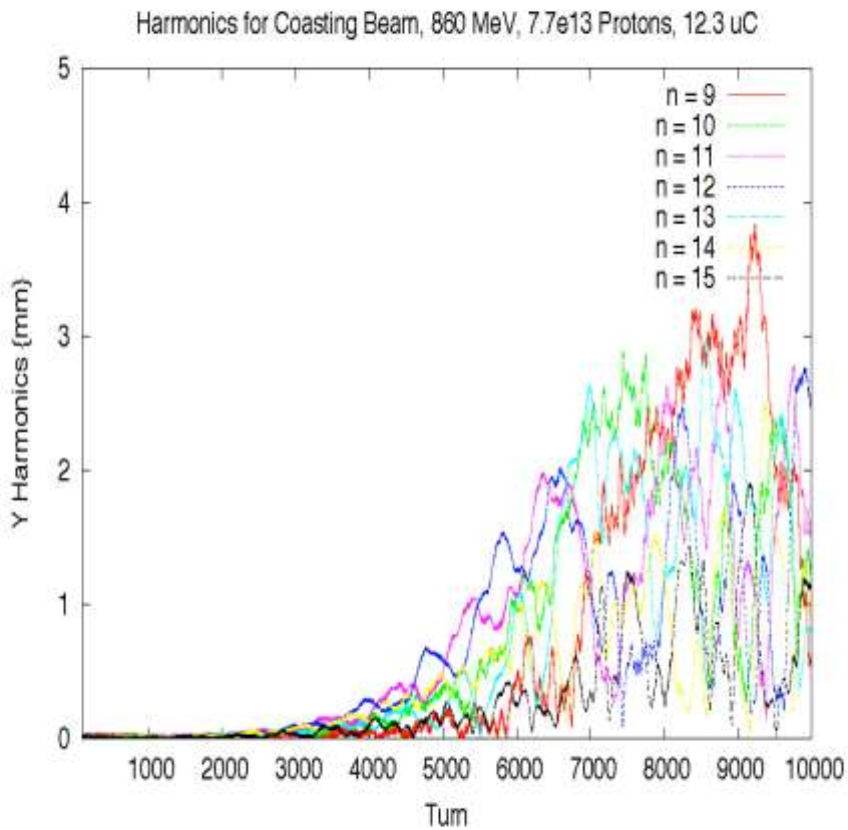


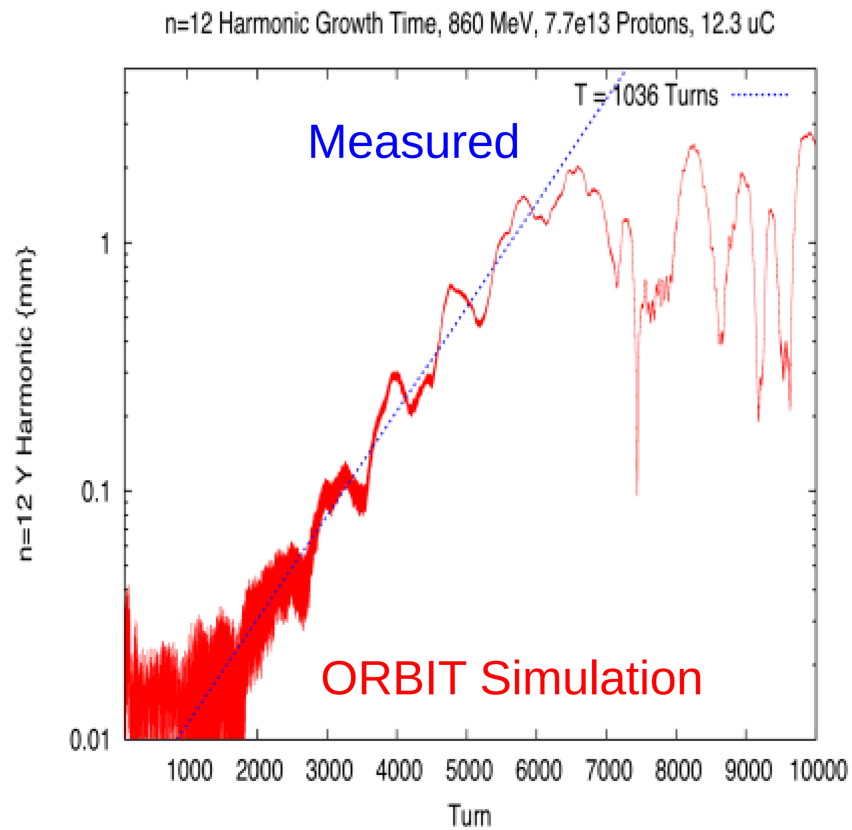
Lab-measured impedance: Z ≅ 25 KΩ/m

*H. Hahn, PRSTAB, **7**, 103501*

Extraction Kicker Instability Simulation

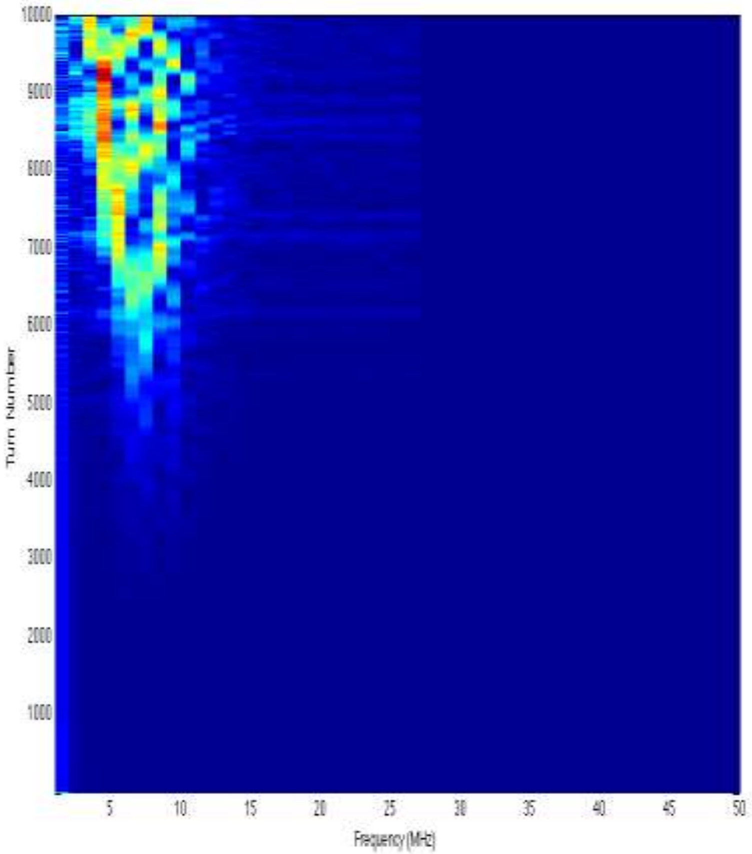
Simulated using ORBIT with extraction kicker impedance, 3D space charge, 7.7×10^{13} protons and corrected (zero) chromaticity.



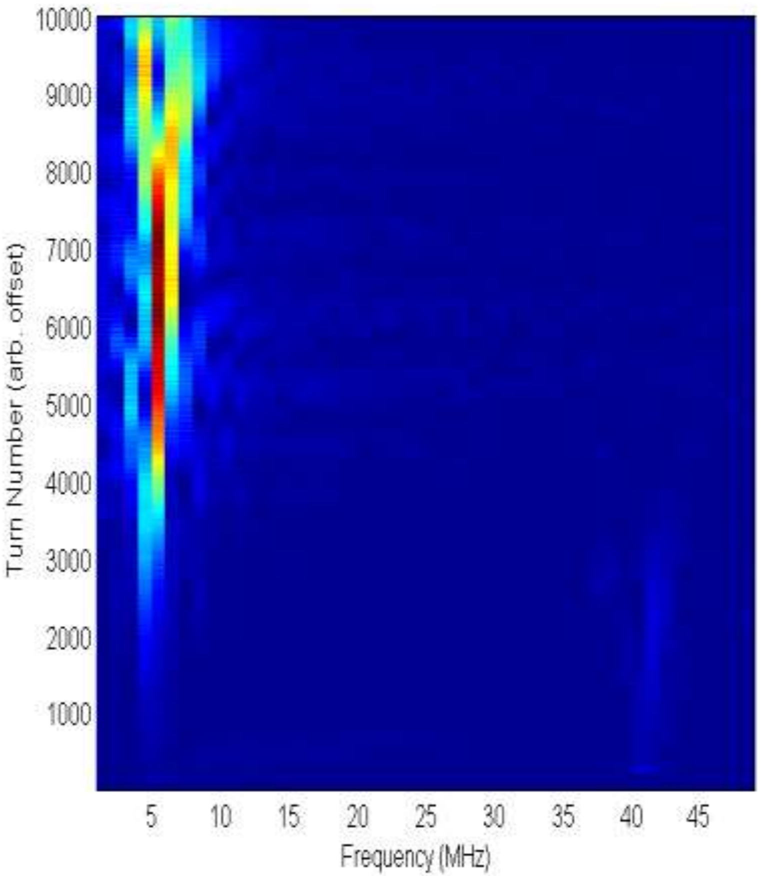


Turn-by-Turn Frequency Spectrum

Simulation



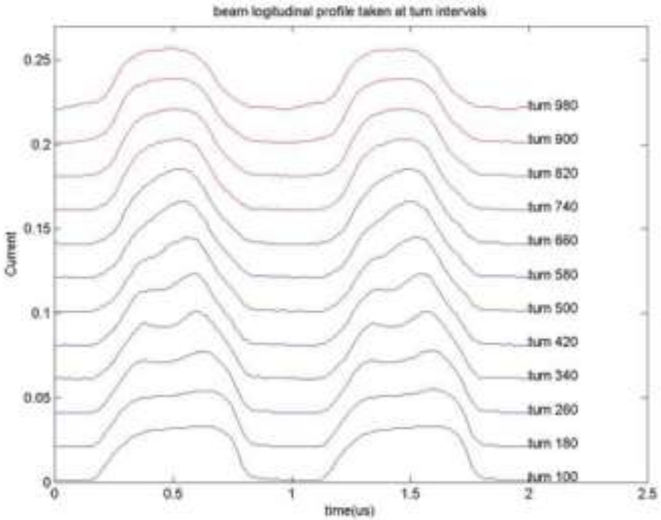
Experiment



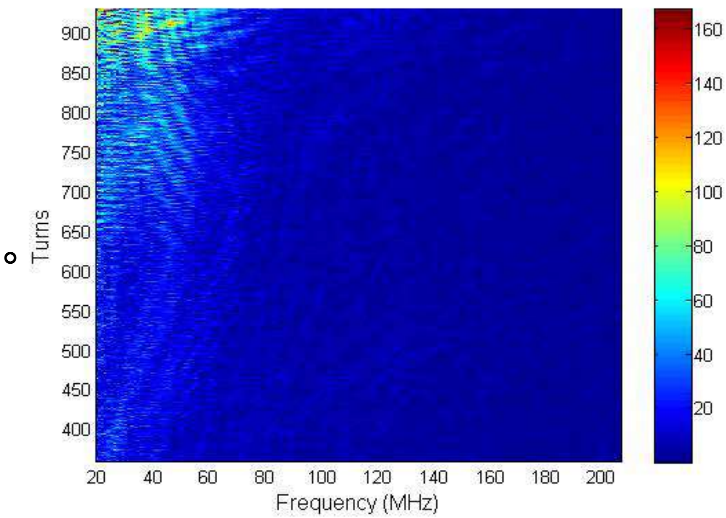
Electron Cloud Instability Remains Cloudy (Zhengzheng Liu, Slava Danilov, Andrei Shishlo)

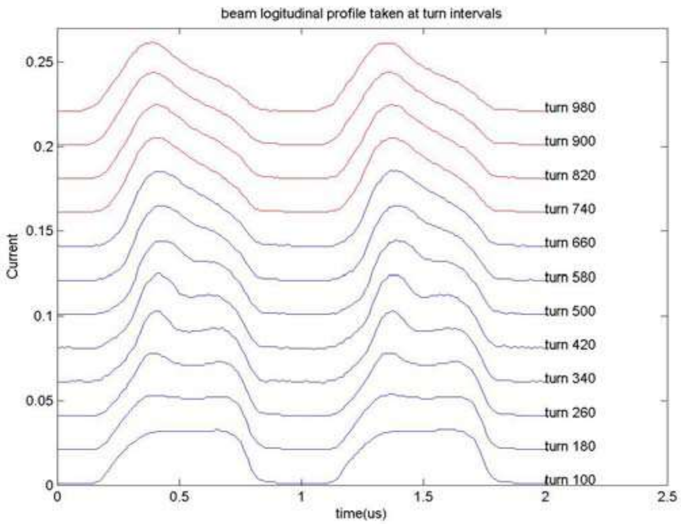
- Previous studies showed qualitative agreement between experiment and ORBIT simulations for coasting beams.
- We are now examining e-p instability for bunched beams.
  - So far, we only have spotty data taken from a few dedicated high intensity shifts.
  - Our best data so far show:
    - Changes in activity with variations in longitudinal current profile, obtained by varying second harmonic RF phase or first harmonic RF voltage: long, gradual tails lead to greater instability.
    - Instabilities are seen for natural, as well as for zero, chromaticity.
- There is progress with feedback stabilization (vertical plane below 100 MHz), but it's a work in progress.

Vary Phase of Second Harmonic RF

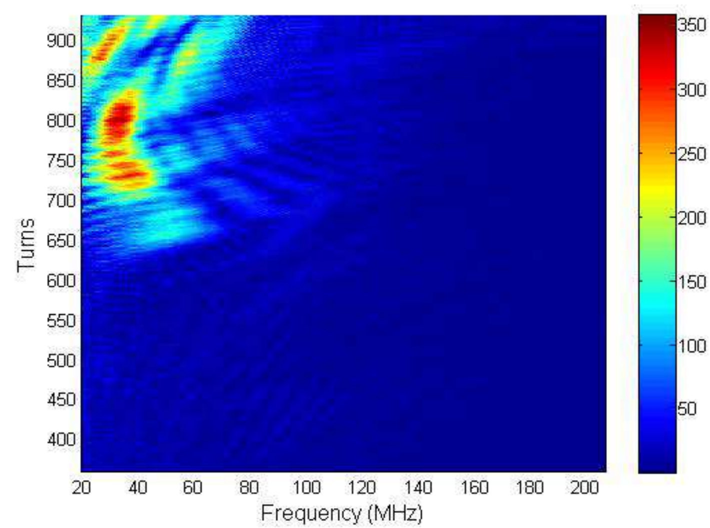


Φ=-35°





Φ=25°



Status of the ORBIT Code

- **ORBIT serves as our workhorse code for ring simulation:**
  - **Benchmark accumulation, storage, and transport.**
  - **Study various loss mechanisms.**
  - **Impedance-driven and electron cloud instabilities.**
  - **Electron collection at stripper foil.**
  - **…**
- **We continue to make incremental improvements to the various modules: now working on time dependent magnets and internal lattice function calculations.**
- **More people are using ORBIT, both in the US and abroad.**
- **New model development is being carried out in pyORBIT (Andrei Shishlo):**
  - **Laser stripping dynamical model (Timofey Gorlov).**
  - **Porting existing ORBIT models to pyORBIT goes slowly. We hope to get more support for the work.**

Summary

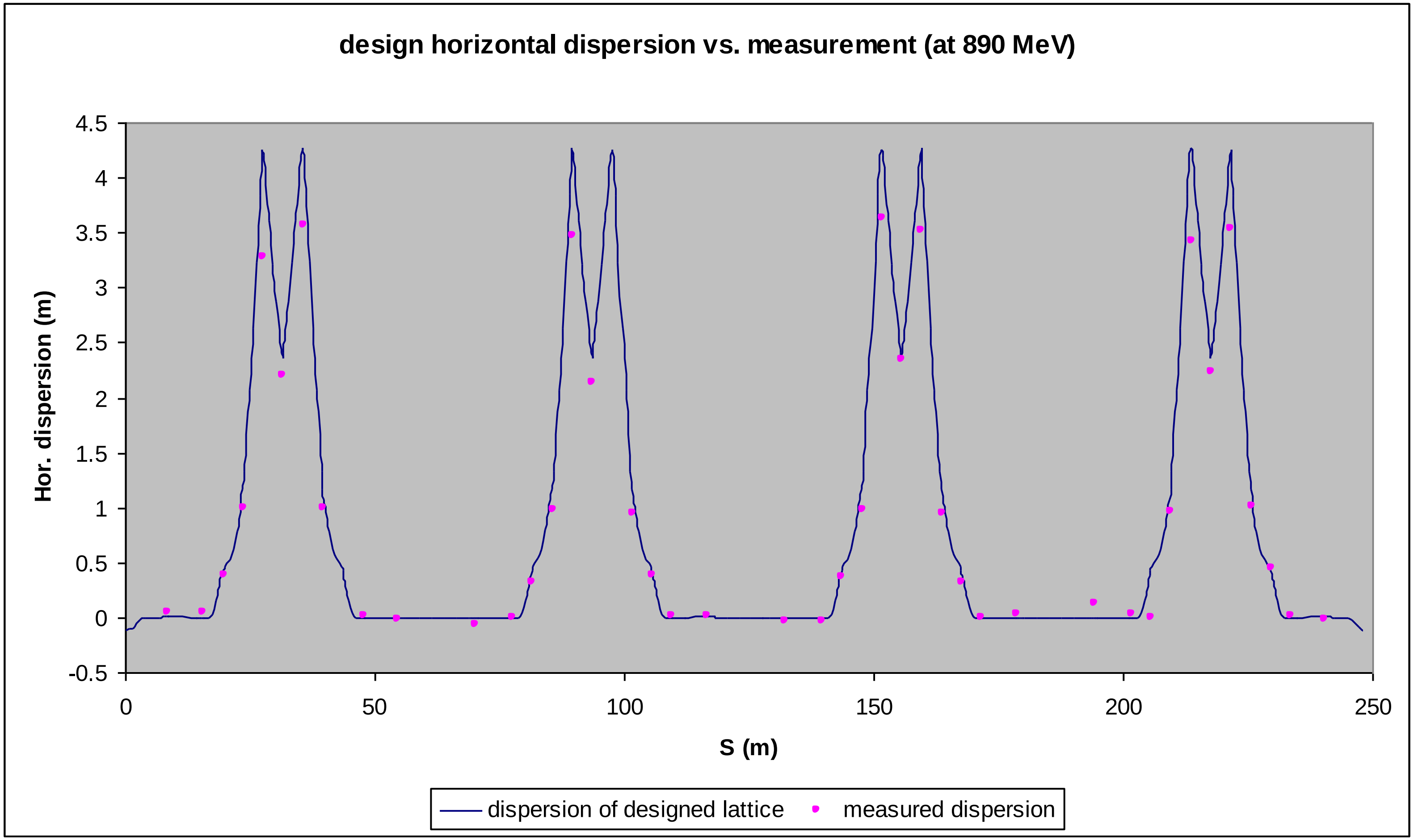
- Understanding SNS ring beam dynamics requires experiment, theory, simulation, and great care.
- There is good agreement between simulated and experimental results, and it gets better as we refine our understanding of the ring.
- Benchmarking has already allowed us to identify hardware problems, including:
  - Significant x-y coupling in the original ring extraction septum magnet.
  - Improper performance of the injection kicker painting waveforms.
- Successful benchmarks include:
  - Ring injection process at low and medium intensities.
  - Losses at A13b.
  - The extraction kicker impedance instability.
- We are gathering e-p instability data during dedicated high intensity shifts.
  - This data shows systematic variation of e-p activity with longitudinal beam profile, controlled by varying the relative phases of the ring RF cavities.
- We continue to support and develop ORBIT, which is used at an increasing number of labs.

Supplemental Material Follows:

Overview

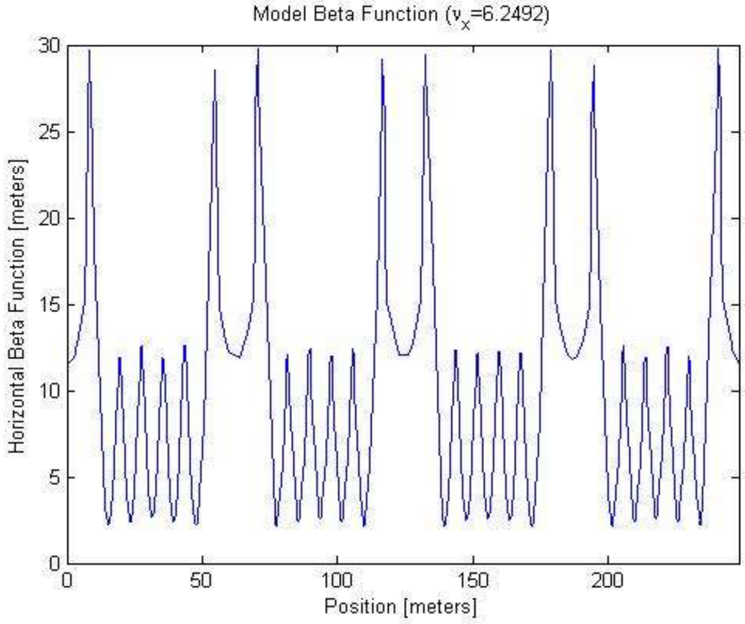
- **SNS progresses toward full power of 1.44 MW.**
  - **SNS has run at 865 kW during production with low losses.**
  - **Current energy 930 MeV ➔ nearly 10^{14} protons on target per pulse.**
  - **We have injected, stably accumulated, extracted, and transported 1.55×10^{14} protons (24.8 μC) to the target. The SNS ring has now exceeded the design intensity of 1.5×10^{14} protons per pulse.**
  - **However, losses at high intensity continue to present a challenge and instabilities lurk nearby.**
- **In order to achieve acceptable losses and to avoid instabilities as we increase the beam intensity, we continue to enhance our understanding of the underlying beam dynamics. This requires experimental study, theoretical insight, and painstaking computational benchmarking.**

Ring Optics: Dispersion Measurement vs Design Values



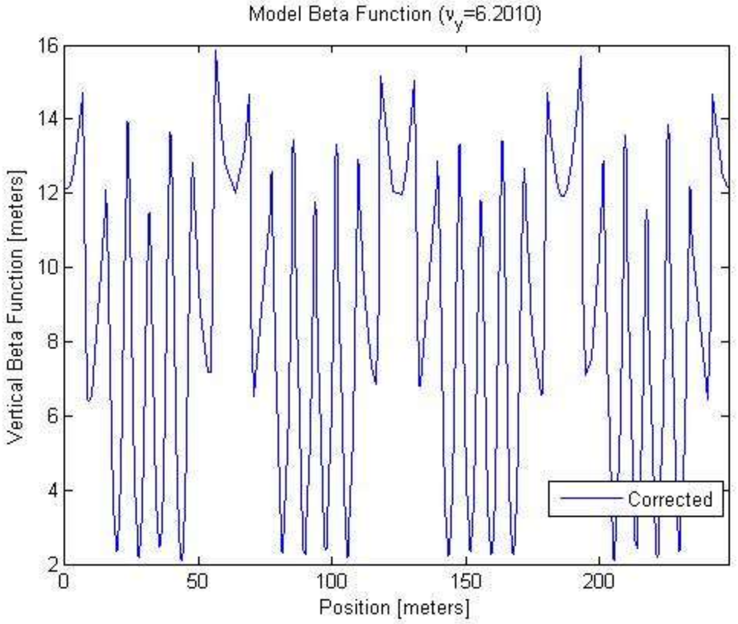
Ring Optics: Ring Beta Functions

Horizontal



Model calculation of horizontal beta functions.
~4% beta beating.

Vertical



Model calculation of vertical beta functions.
~13% beta beating.

Ring Losses with Tune (Tom Pelaia)

Ring Tune Scan Measurement

- A Tune Scan script is under development and was tested on Dec. 23, 2009
  - Production configuration with modifications
    - 100 mini pulses
    - 1000 turn storage
    - decreased horizontal and vertical injection kickers 0.5 units
  - Fractional tunes (based on model) from 0.1 to 0.4 in steps of 0.025
  - Measured sum of BLM losses in collimation region at each tune
  - Repeated measurements using single mini pulse and recording BPM waveforms for tune calibration
  - data is awaiting full analysis

Back to Benchmarks of Accumulation

- We returned to benchmarks of accumulation with the corrected extraction septum.

- Started with flat-topped injection kickers (no painting).
  - Varied intensities 8.6×10^{12} (80 turns) ➔ 5.3×10^{13} (460 turns) ppp.
  - Results agreed very well.

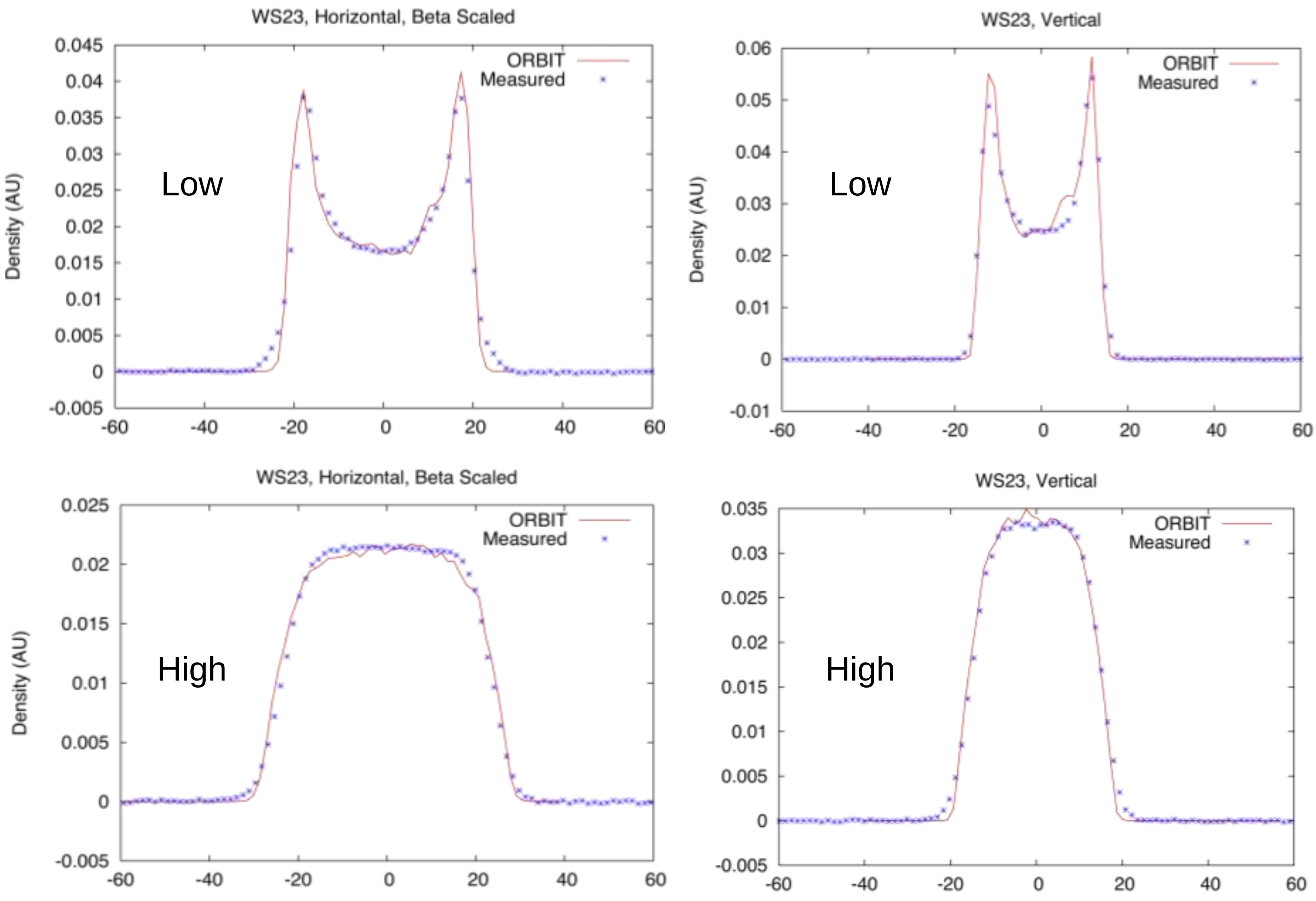
- Then considered standard painting with injection kickers.
  - 640 turns.
  - Varied intensities 8.2×10^{12} ➔ 7.5×10^{13} ppp.

- Computational caveats:

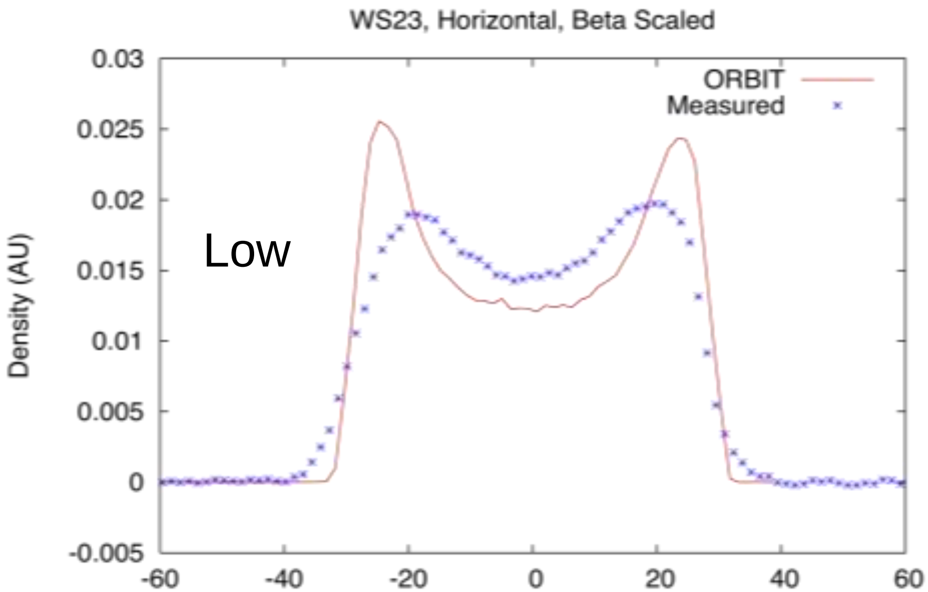
  - Corrected the ORBIT profiles for measured RTBT optics differences on the order of ≤5% in beam size.

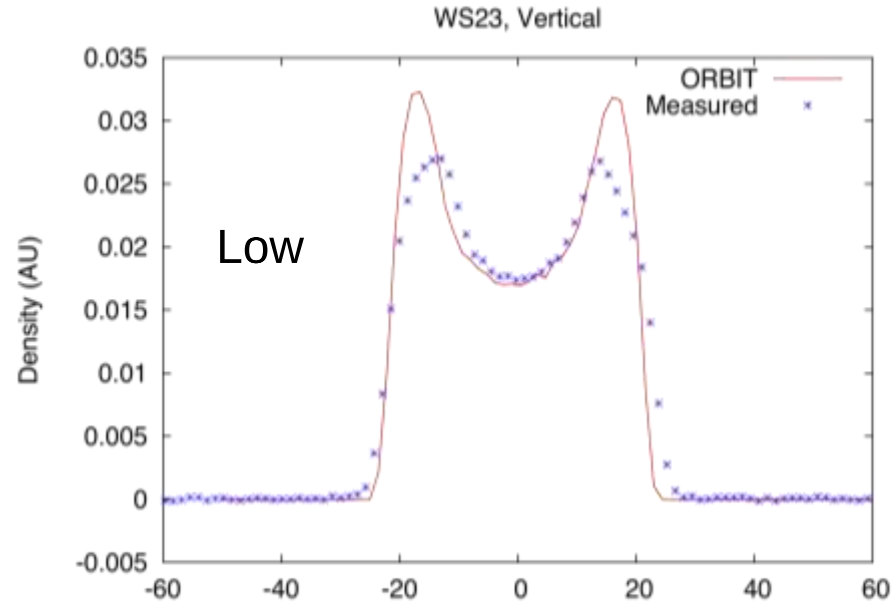
  - Also shut off quad fringe field effects because they caused unrealistically large horizontal emittance growth due to off-axis tracking in injection straight.

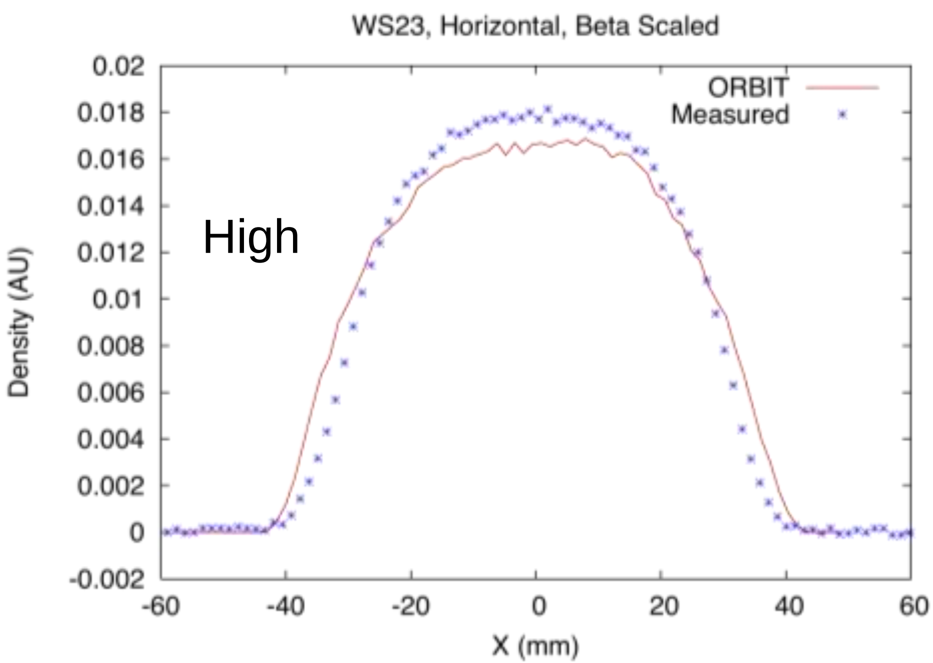
Low and High Intensity Flat-top Beams

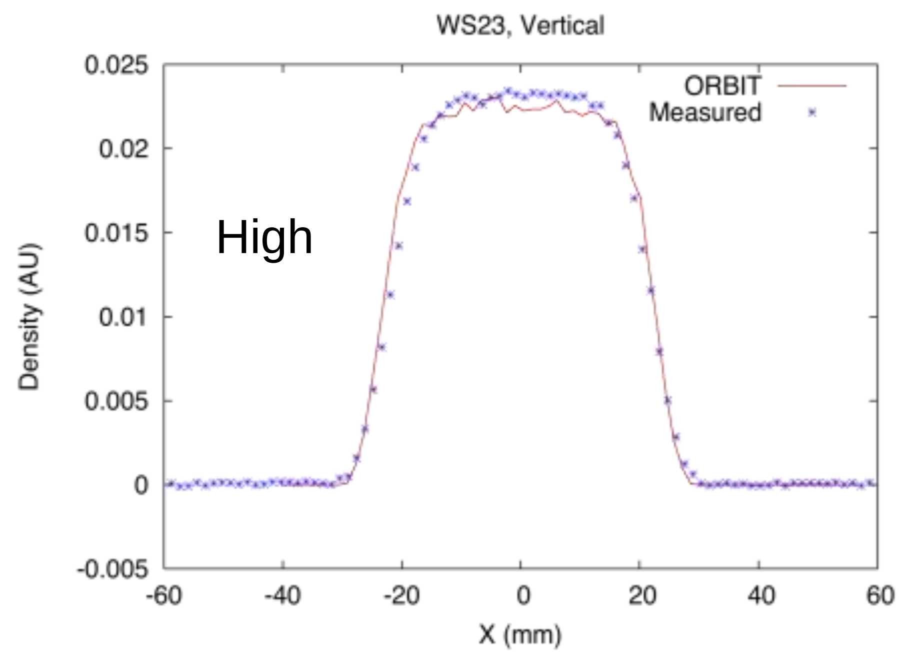


Low and High Intensity Painted Beams









Accumulation: Emittance Comparison and Summary of Flattop Benchmark Results

Intensity	Experiment (H,V) π mm mrad	ORBIT (H,V) π mm mrad
8.6×10^{12} ppp	(13.3, 13.1)	(13.7, 12.6)
5.3×10^{13} ppp	(13.8, 13.1)	(13.2, 12.5)

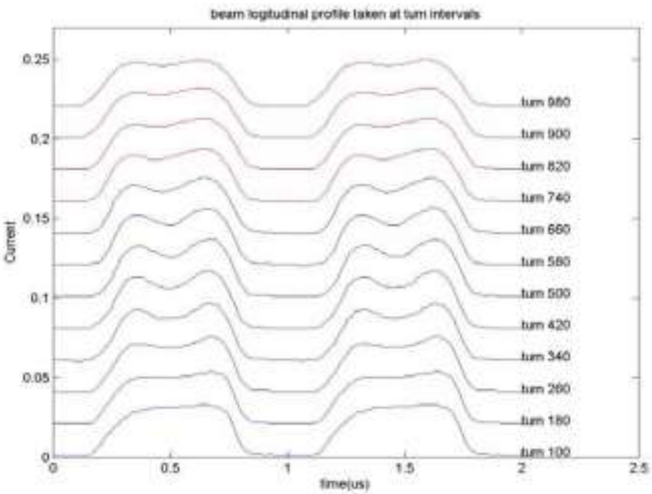
Calculated and measured emittances agree to within 5%.

Good agreement between experiment and simulation was found over the entire range of intensities. In comparison with the low intensity profiles, the moderate intensity profiles fill in the centers and broaden slightly due primarily to space charge. The broadening is not substantial, however, because the maximum incoherent space charge tune shifts, estimated using ORBIT, are only about 0.07, so the coherent tune shift is perhaps 0.04. With the bare tunes of the ring set at $\nu_x = 6.23$ and $\nu_y = 6.20$, there is not sufficient space charge in the beam to activate the half integer resonance at $\nu = 6$.

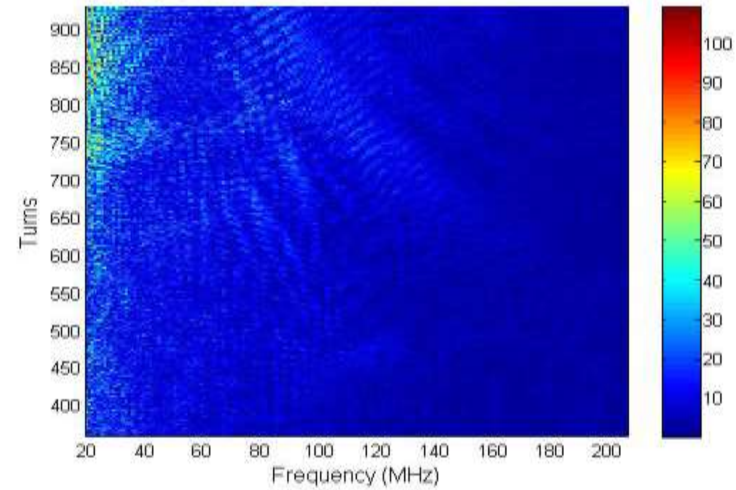
Now, what about injection painting?

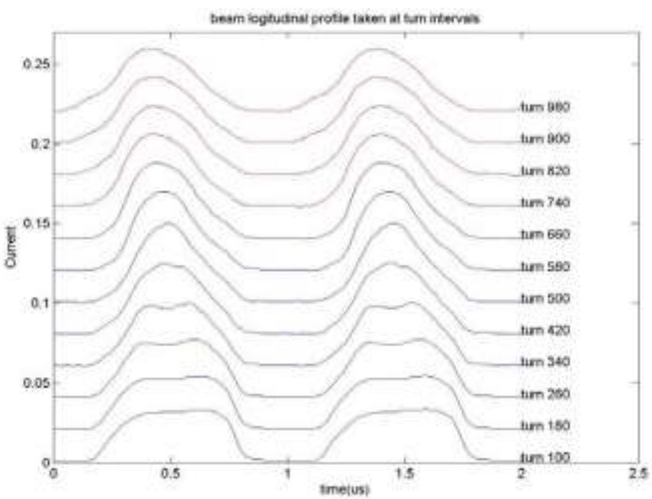
OAK RIDGE National Laboratory

E-P: Vary Voltage of First RF Harmonic

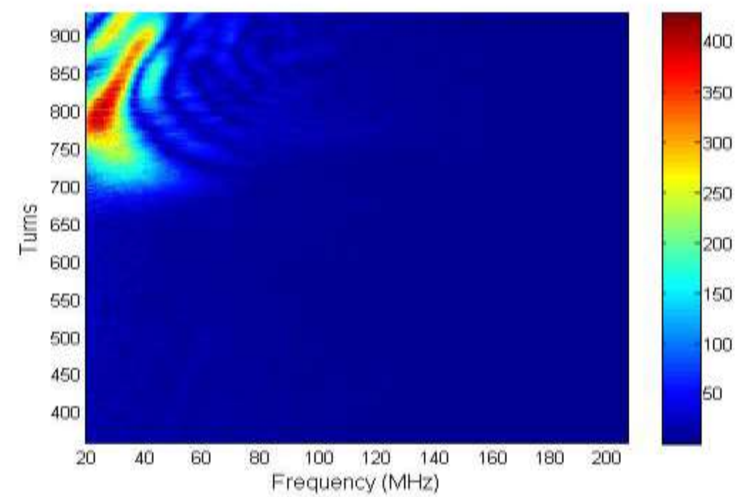


V=5.5kV





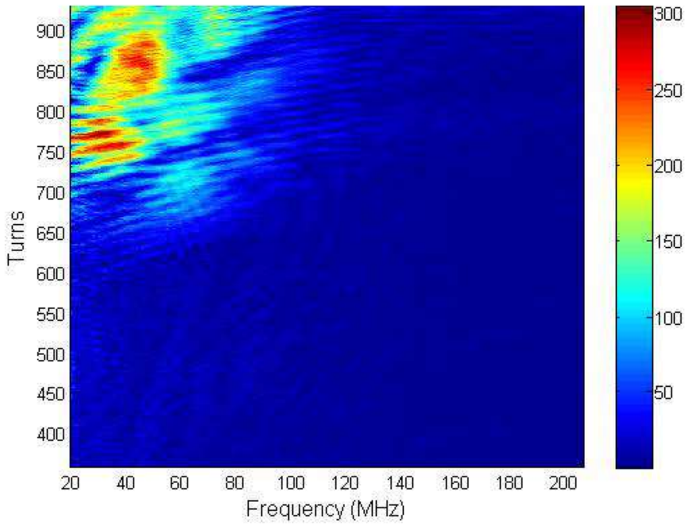
V=12.5kV

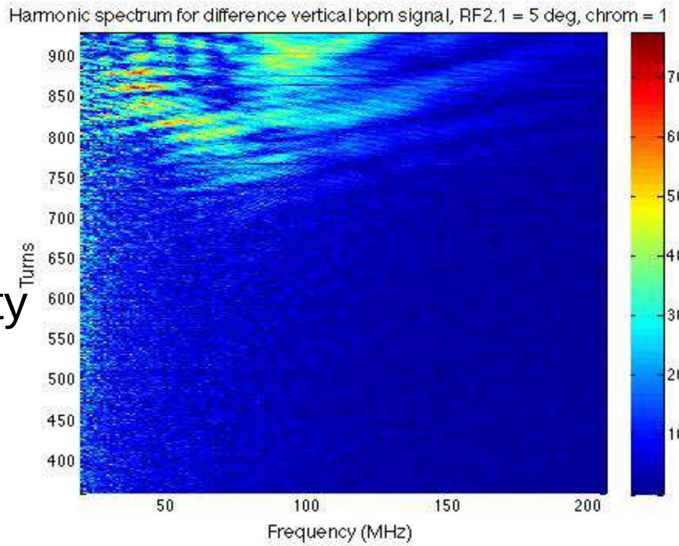


E-P: Effect of Chromaticity

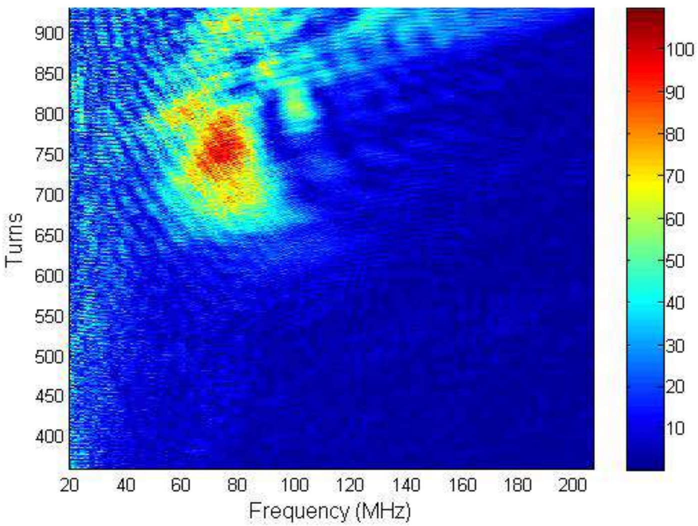
Horizontal

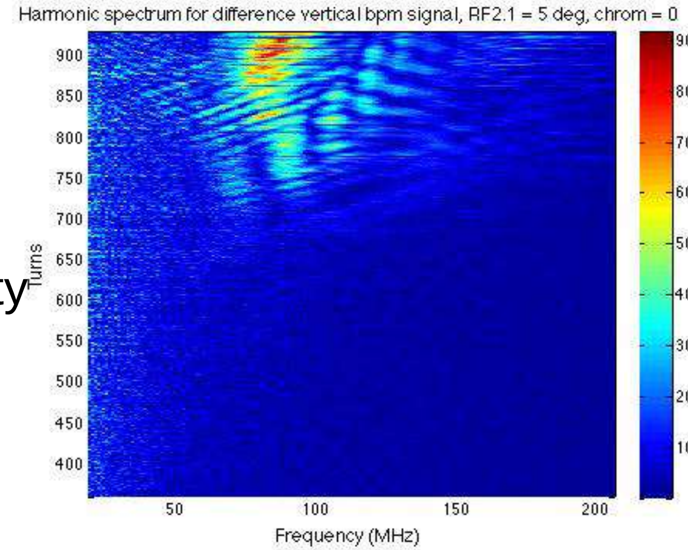
Vertical





Natural Chromaticity





Zero Chromaticity

Detailed Summary

- Understanding SNS ring beam dynamics requires experiment, theory, simulation, and great care.
- Benchmarking has already allowed us to identify hardware problems, including:
  - Significant x-y coupling in the original ring extraction septum magnet.
  - Improper performance of the injection kicker painting waveforms.
- There is good agreement between simulated and experimental results.
- We have benchmarked the ring injection process at low and medium intensities.
  - In these cases, the main effect of space charge is to fill in the hollow central region of the beam.
  - So far, the space charge tune shifts are insufficient to cause beam broadening through the half integer resonance.
- We have also completed a careful benchmark of the extraction kicker impedance instability.
  - The calculated and experimental growth rates are in perfect agreement.
  - Comparison of the spectral evolution of the experiment and simulation out to 10000 turns shows qualitatively similar results. However, the detailed evolution in the nonlinear stage of the instability after 5000 turns is somewhat different.
- We are gathering e-p instability data during dedicated high intensity shifts.
  - This data shows systematic variation of e-p activity with longitudinal beam profile, controlled by varying the relative phases of the ring RF cavities.
- We continue to support and develop ORBIT, which is used at an increasing number of labs.