

ORBIT SIMULATIONS AND RESULTS

Jeff Holmes
Accelerator Physicist

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ORBIT: Application to SNS



- ORBIT incorporates **realistic physics and engineering assumptions** to allow the investigation of detailed physics and design issues in high intensity rings.
- In this presentation I will summarize a number of **ongoing SNS ring studies** using ORBIT:
 - **Postponement of HEBT RF cavities until after CD-4** (Holmes, Henderson)
 - **Effect and correction of ring magnet errors** (Bunch, Holmes, Cousineau).
 - **Debunching of Linac Beam in Ring for Single Turn Injection** (Bunch, Holmes, Plum)
 - **Inclusion of injection chicane lattice** (Holmes, Henderson, Wang).
 - **Painting self consistent uniform elliptical beams** (Danilov, Cousineau, Henderson, Holmes).
 - **Initial electron cloud studies** (Sato, Shishlo, Holmes).

ORBIT : Assumptions for Studies



- **Dynamics**
 - **Symplectic** single particle tracking, including hard edge **fringe fields**.
 - Collective effects including **space charge** and dominant ring **impedances**.
 - Use 1 GeV proton beam unless specified.
- **SNS Ring Lattice**
 - Reference tunes $Q_x = 6.23$, $Q_y = 6.20$ and natural chromaticity unless stated otherwise.
 - **Magnets** organized into chosen **families**, including dipole and quadrupole **correctors**.
 - **Magnet errors** and **correction** as appropriate.
 - 44 horizontal and vertical **BPMs** at correct locations.
 - Detailed **injection chicane** when appropriate.
- **Lattice and Dynamics**
 - Injection **painting** and **foil** hits with proton/foil interactions.
 - Dual harmonic longitudinal **RF** with four cavities at correct locations.
 - **Collimators and apertures** for proton losses.
- **Diagnostics**
 - Profiles and moments.
 - Emittances and tunes.
 - Distributions and losses.

CD-4 HEBT RF Cavity Postponement



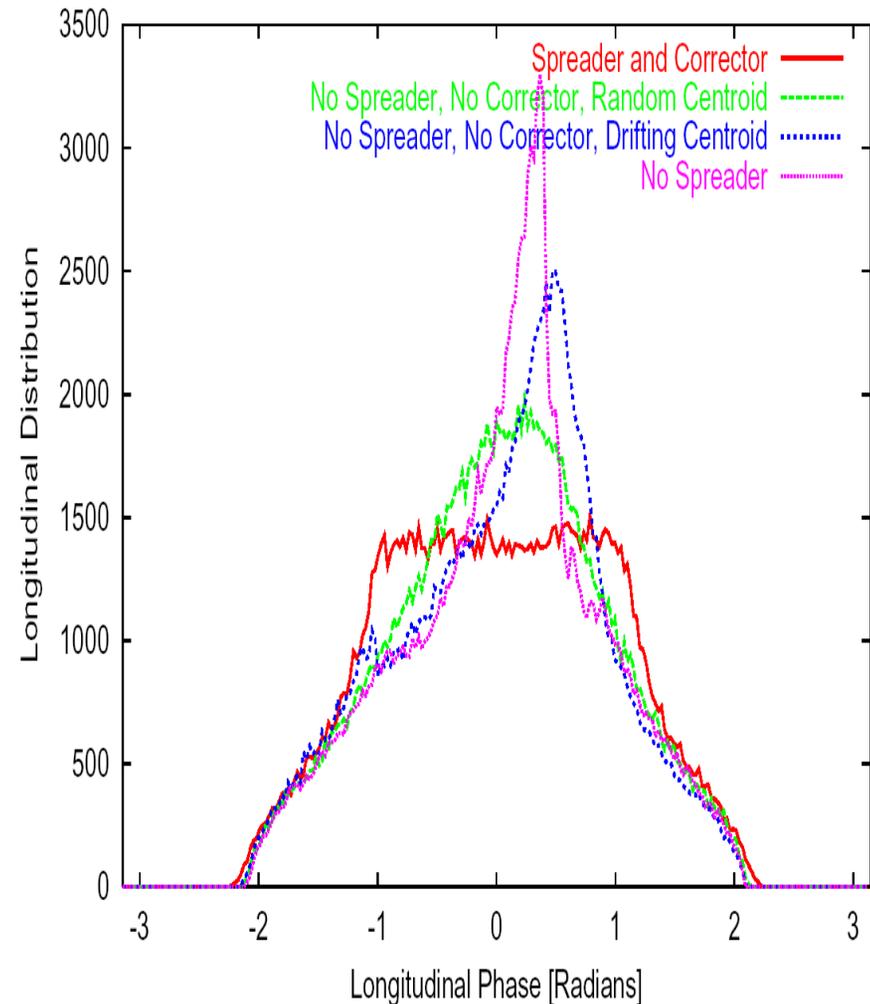
- As part of endgame plan, delay of the HEBT energy spreader and corrector cavities until after CD-4 is under consideration.
- While this should present **no problems for low intensity** operation, it is **necessary to demonstrate that 1.0 MW operation can be conducted** using the CD-4 accelerator configuration.
- ORBIT studies were carried out to investigate 1 MW operation without the HEBT RF cavities.
- The default ORBIT SNS injection routine includes the effects of both the HEBT energy spreader and corrector cavities. We studied the effects during accumulation in the ring of
 - removing the energy spreader cavity only, which gives a perfect linac beam, and
 - removing both the energy spreader and corrector cavities.

CD-4 HEBT RF Cavity Removal



- With 1MW, 1060 turn injection and default painting scheme, removal of HEBT ESC and/or ECC changes injected energy distribution, which leads to peaked longitudinal distributions and increased losses due to bunch factor effects:
- Losses
 - With both cavities: 0.006%
 - Remove spreader only: 0.41%
 - Remove spreader and corrector, random centroid jitter: 0.003%
 - Remove spreader and corrector, drifting centroid: 0.22%

Longitudinal Distributions After Injection, No Collimation

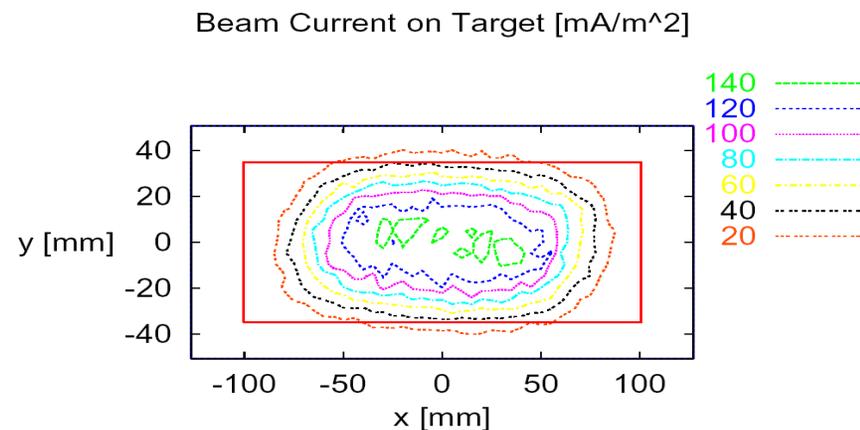
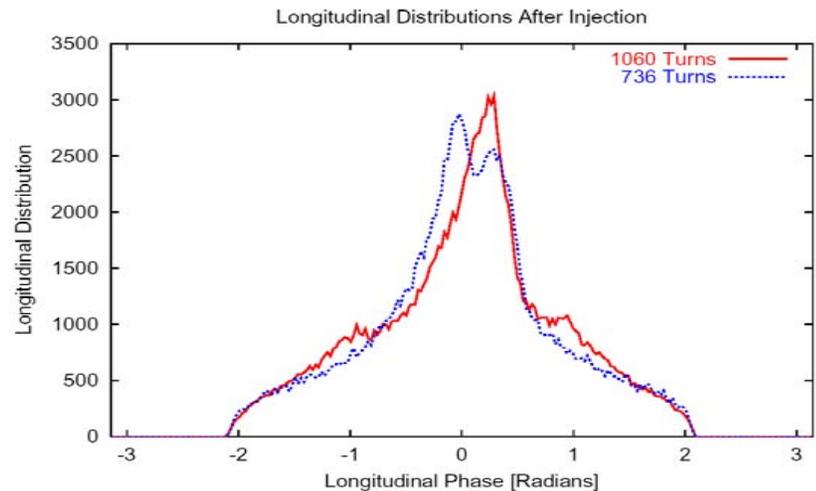


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CD-4 HEBT RF Cavity Removal



- Concentrate on **worst case** – energy spreader removed, which is equivalent to a **perfect linac with both cavities removed**.
- **Adjust painting**
 - **736 turns** at full linac intensity cures bunch factor effects. The longitudinal distribution still becomes peaked, but there isn't time for significant beam loss. Losses become: 0.014%
 - Paint **broader transverse distribution** to limit maximum current density. Beam on target parameters: 93% reaches target footprint, 155 mA/cm² peak current density.
- **Conclusion: We can operate the ring at 1 MW without the ESC and ECC.**



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- **Comprehensive studies of ring magnet errors and their correction are underway.**
- **We present here the results of some initial studies on the effect and correction of dipole and quadrupole displacement and field strength errors.**
- **Displacement errors are horizontal or vertical misplacements of a magnet without pitch, yaw, or roll. ORBIT contains models for those effects, but they have not yet been studied.**
- **Field strength errors are incorrect values of the field strengths. ORBIT contains models incorporating higher field harmonics, but those have not yet been studied.**

Errors Perturbing the Closed Orbit



- Dipole and quadrupole position and dipole field strength errors alter the closed orbit.
- For these errors, we **focus on orbit deflection and losses**:
 - In addition to the closed orbit, deflection of a “standard pencil beam” is studied
 - Initial coordinates at injection point placed on desired closed orbit
 - Losses are studied for full 1.44 MW injection scenario:
 - $1.5 \cdot 10^{14}$ protons at 1 GeV
 - Scrapers, collimators, and beam apertures around the ring are included
- Consider **individual as well as random sets of errors**.
- Note: Orbit deflections due to errors follow the ring superperiodicity; losses due to errors do not.

Correction of Errors

Perturbing the Closed Orbit



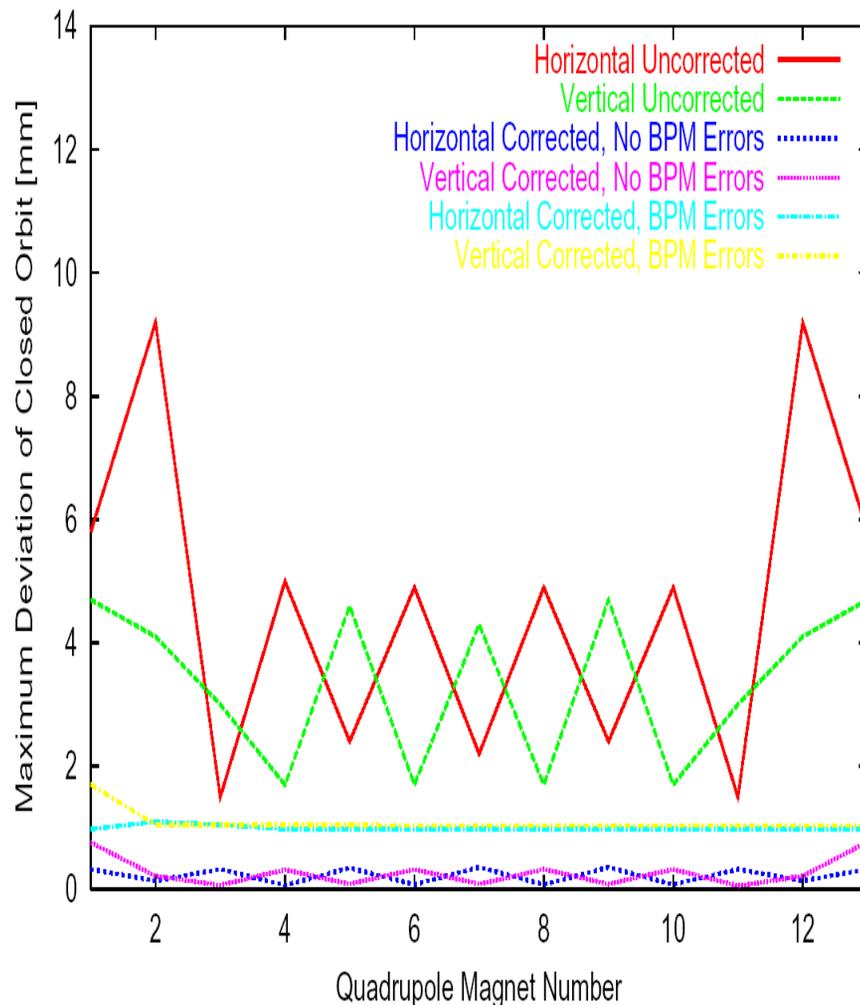
- Carry out error **correction for standard pencil beam by setting dipole corrector strengths to minimize BPM signals**:
 - 44 horizontal, 44 vertical BPMs - **with or without random BPM signal errors**
 - Truncated gaussian distribution: $\sigma=0.5$ mm, Max = 1 mm
 - 24 horizontal, 28 vertical dipole corrector strengths
 - Least squares:
 - Minimize sum of squares of BPM signals (beam dipole moments)
 - Use standard pencil beam
 - Apply scheme to individual as well as to random sets of magnet displacements.
- **Calculate losses with full injection simulations** for uncorrected and corrected cases, with and without random BPM errors.

Individual Magnet Errors: Maximum Closed Orbit Deviations



- **1 mm dipole displacements (SNS expects 0.25 mm):**
 - 0.25 mm uncorrected
 - 0.025 mm corrected (no BPM error)
 - 1 mm corrected (BPM errors)
- **1 mm quadrupole displacements (SNS expects 0.25 mm):**
 - (2–10) mm uncorrected.
 - < 1 mm corrected (no BPM error)
 - (1–2) mm corrected (BPM errors)
- **0.1% dipole strength errors SNS expects 0.01%):**
 - 2 mm uncorrected
 - 0.2 mm corrected (no BPM error)
 - 1 mm corrected (BPM errors)
- **~1 mm assuming comparable BPM errors, better otherwise**

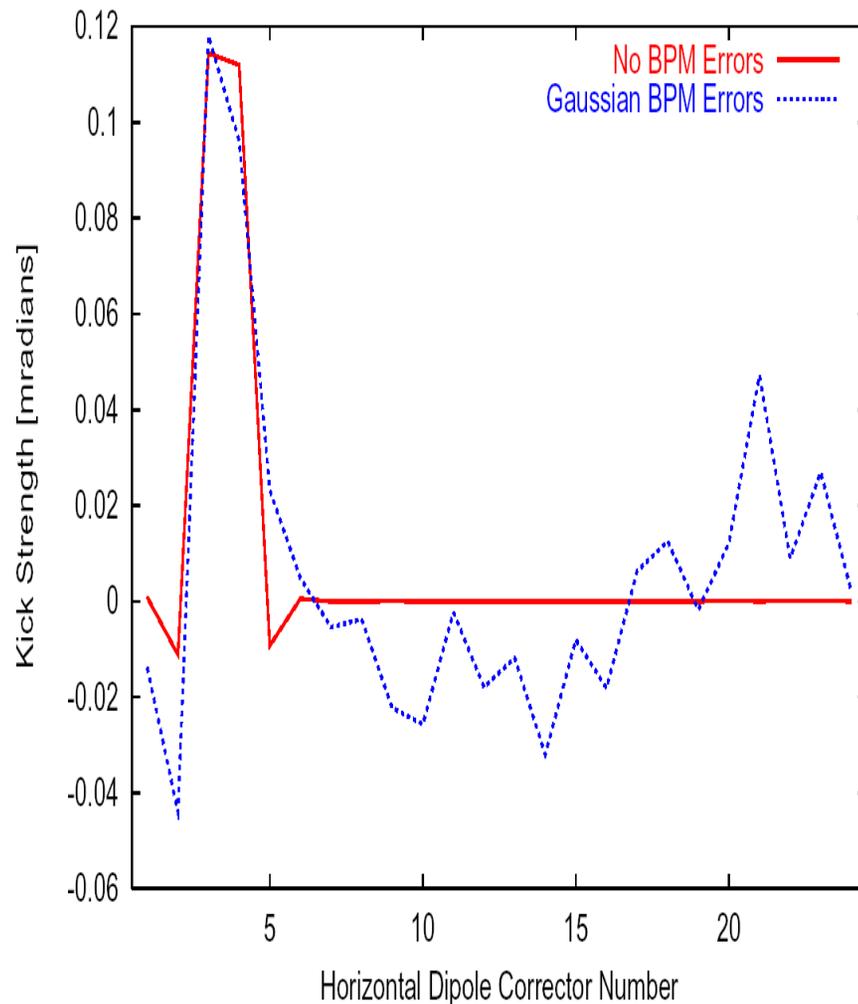
Maximum Closed Orbit Deviation for 1 mm Quadrupole Magnet Displacement



Individual Magnet Errors: Dipole Corrector Kick Strengths

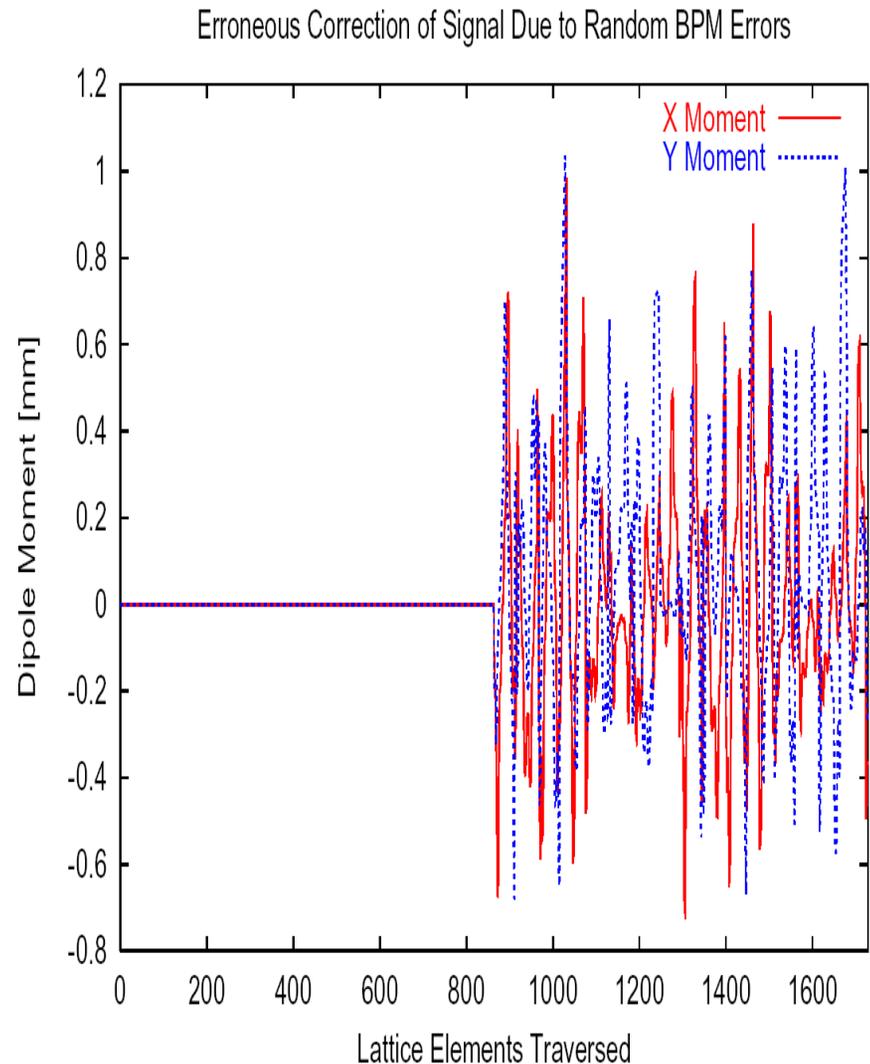
- **With exact BPM signals:**
 - **Least squares optimizer chooses 3 bump scheme**
 - **Primarily 2 adjacent dipole corrector magnets activated**
 - **Orbit deviation is confined to region between displaced magnet and its 2 adjacent dipole correctors**
- **BPM signal errors:**
 - **all dipole corrector nodes activated, most at a low level**
 - **Orbit deviation small, but some noise everywhere**
- **Necessary corrector kick strengths:**
 - **< 0.02 mr for 1 mm dipole disp.**
 - **< 0.5 mr for 1 mm quad disp.**
 - **< 0.15 mr for 0.1% dipole field.**
- **There is ample kicker capability to correct any foreseeable orbit deviation due to magnet errors.**

Calculated Horizontal Corrector Strength With and Without BPM Errors



Effect of BPM Signal Errors

- Assume magnet errors are zero, but random BPM errors provide signals: Gaussian distribution, 0.5 mm RMS, 1 mm cutoff.
- Apply dipole corrector kicks to BPM signals.
- These kicks generate orbit displacements comparable in size to the assumed BPM errors, as shown.
- Correction with BPM signal errors of a given size leads to comparably sized erroneous orbit deviations.

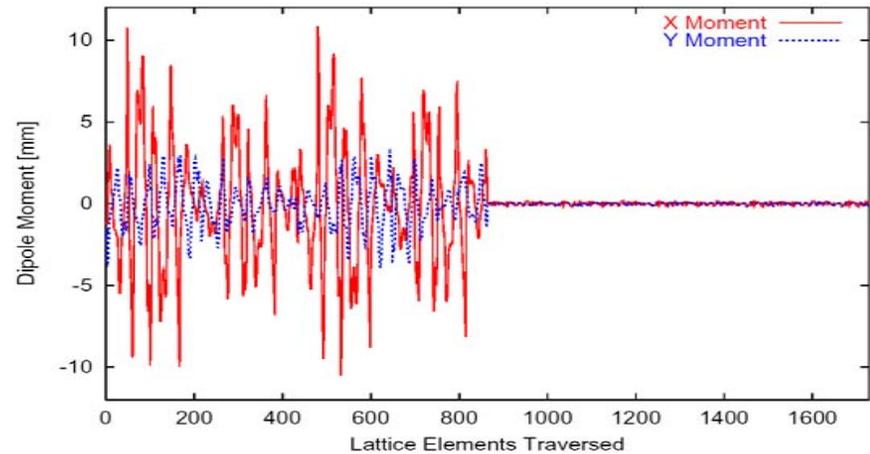


Random Errors: Results for a Case With All 3 Errors and Significant Losses

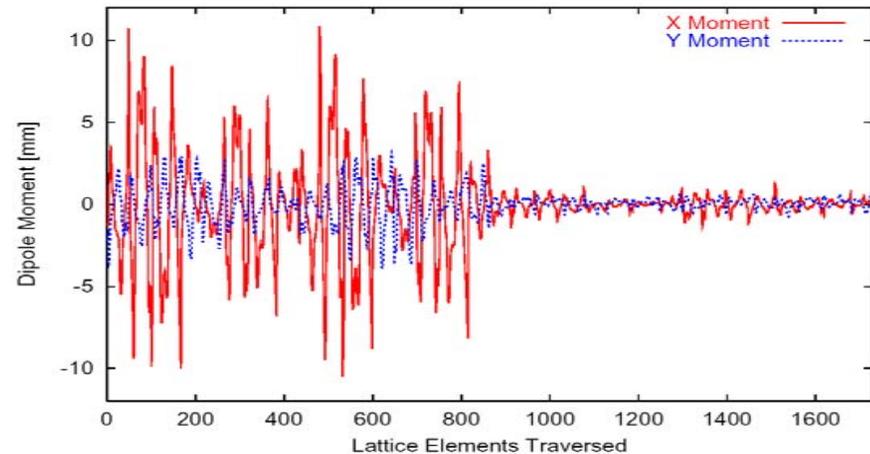


- Calculations were carried out with simultaneous activation of **random sets** of all 3 types of errors:
 - **SNS tolerances, or worse, were used**
 - 0.25 mm for all displacement errors
 - 0.1% for dipole field errors
 - Random seeds were varied to find some bad loss cases
 - **Losses with errors varied from less than 1% to > 10%**
 - **Correction was applied to some cases with significant losses**
 - Both exact BPM signals and BPM signal errors were considered
- Note: Summation of individual error corrector strengths over all errors agrees closely with direct optimization.

Three-Bump Dipole Correction of Random Errors in All Magnets, No BPM Error



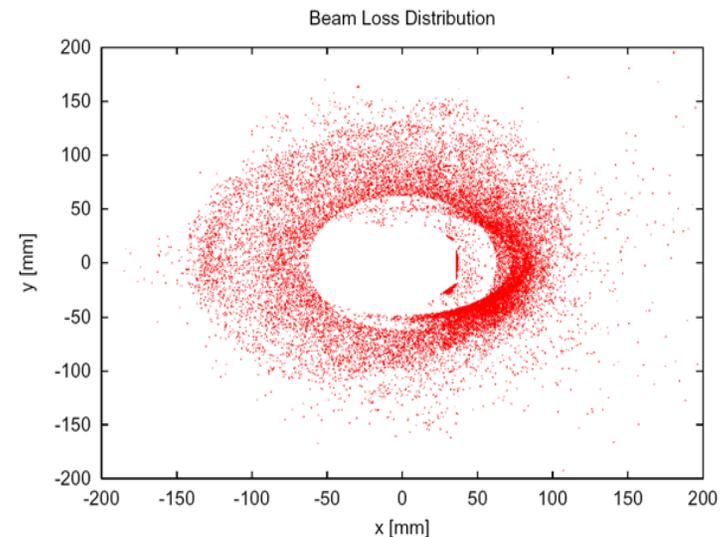
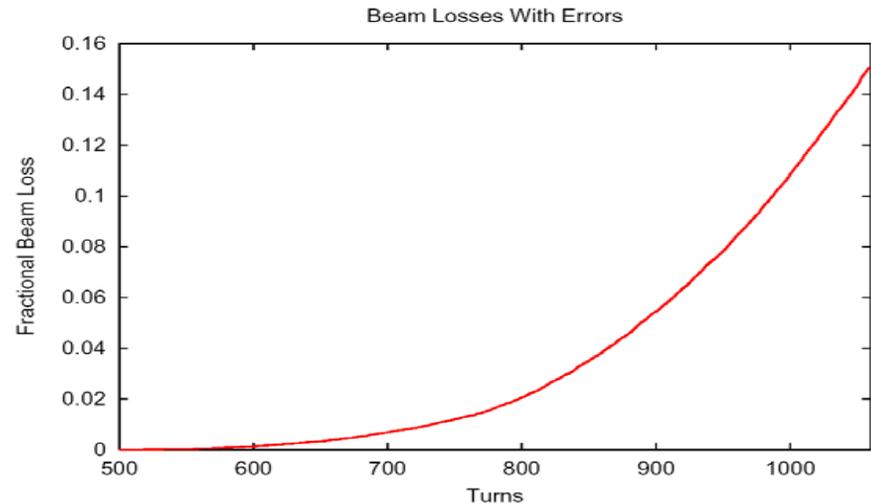
Three-Bump Dipole Correction of Random Errors in All Magnets, With BPM Error



Calculation With All 3 Errors: Losses



- **Without correction, 15%** of the beam is lost, starting around 600 turns.
- **With orbit correction, assuming no BPM errors, losses are $< 10^{-4}$.**
- **With random BPM signal errors, losses are still $< 10^{-4}$.**
- **These results have been found to hold in general to cases considered thus far.**



Quadrupole Field Strength Errors and Correction



- **Quadrupole field strength errors alter the beta functions, dispersion, and tunes.**
- For these errors, we **focus on betatron phase advances and losses**, with the loss calculations as before.
- We now consider family as well as random sets of errors:
 - There are 6 main quadrupole families in the ring, each on its own power supply.
 - Random errors within families are at the 10^{-4} level, which we include, but family errors in the percent range are dominant.
- Carry out error **correction by setting trim quadrupole strengths to match betatron phase advances calculated from BPM signals**:
 - 44 horizontal, 44 vertical BPMs - with or without random BPM signal errors
 - Gaussian distribution: $\sigma=3.6^\circ$
 - **6 main families** and 16 additional trim quad families. So far, only using 6 main families.
 - **Least squares**:
 - Match **horizontal and vertical betatron phase advances at BPMs**.
 - Apply scheme to individual as well as to random sets of magnet field errors.
- Calculate losses with full simulations for uncorrected and corrected cases, with and without random BPM errors.

Quadrupole Field Strength Errors and Correction: Results So Far

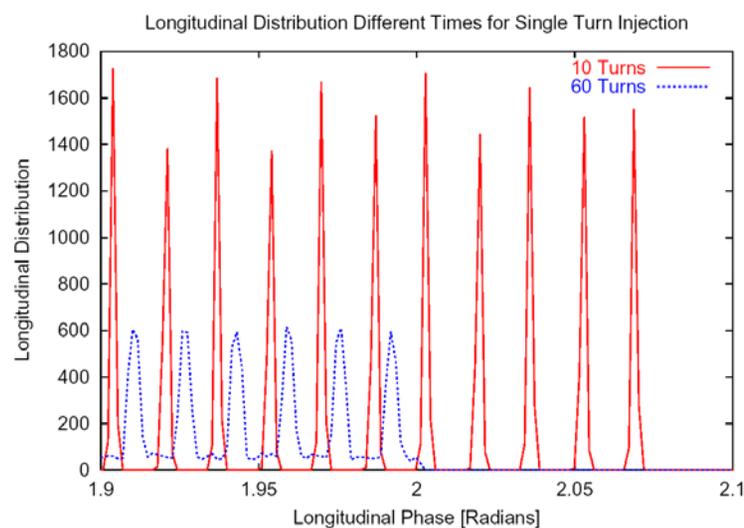
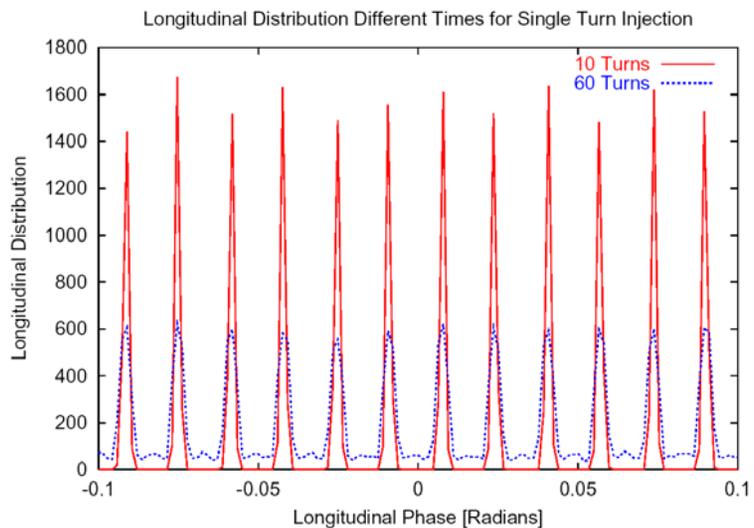
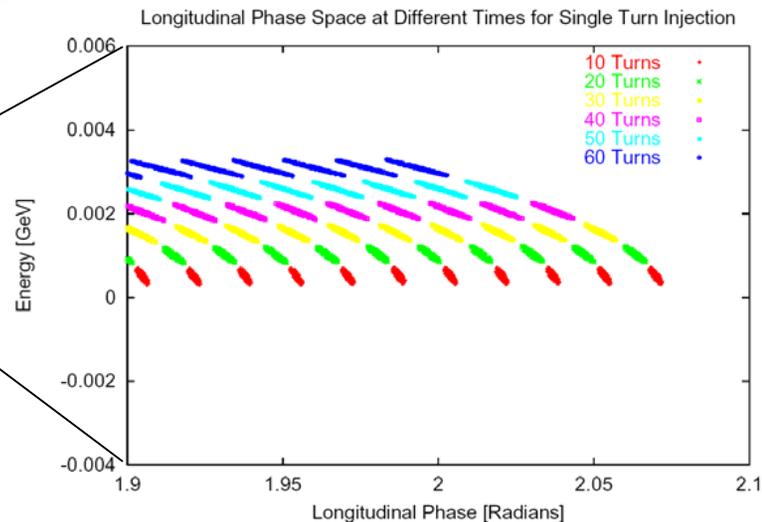
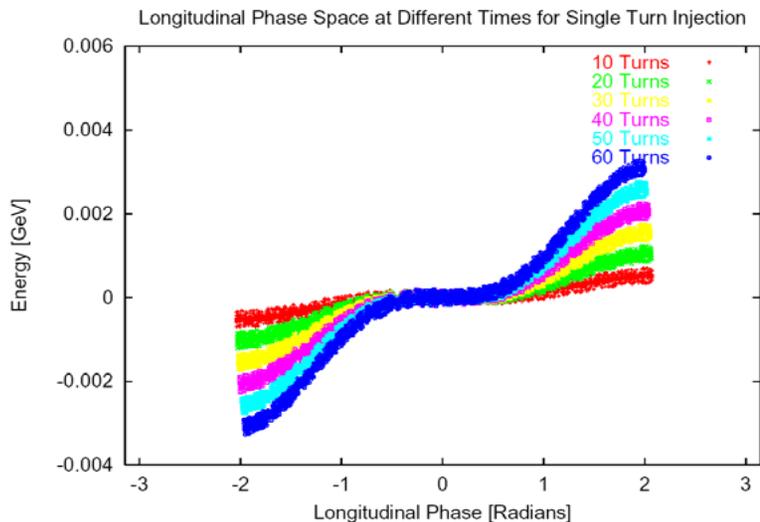


- **Individual family field errors at the 2% level** have been studied.
- Such errors of this size can lead to beta beating, dispersion in the straight sections, and tune errors.

Family	KDC	KDF	KDEE	KF	KD	KF26
$\Delta\beta_y$	> 10%	> 10%	~ 20%	0	~ 10%	0
ΔD_x	0	0	0	~ 5 cm	~ 8 cm	30 cm
$\Delta Q_x, \Delta Q_y$	-0.08	0.15	-0.01	0.06	-0.02	0.06
	0.07	-0.05	0.04	-0.01	0.10	-0.01
Losses, Uncorrected	14.6%	1.15%	$< 10^{-4}$	0.19%	0.52%	0.06%
Losses, Corrected	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
Losses, Corrected, BPM Errors	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$

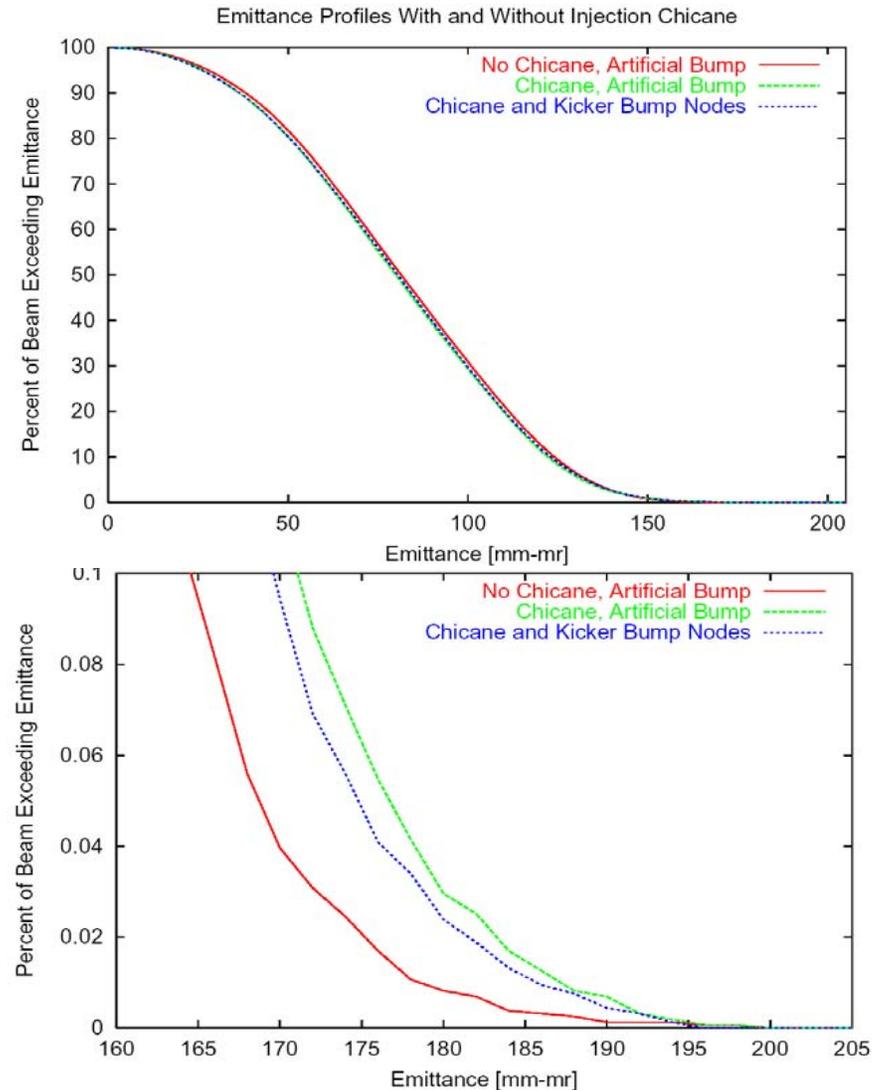
- **After correction, assuming zero BPM phase error, tunes are accurate to within $3 \cdot 10^{-4}$ and, with BPM phase errors, the accuracy is comparable to the error.**

Phase Determination From BPMs: Debunching of Linac Beam in Ring



Injection Chicane

- We have begun detailed studies of the effect of the injection chicane.
- So far, we have:
 - Incorporated the chicane lattice,
 - Developed time-dependent kicker nodes with programmable kicks, and
 - Tested these capabilities on a standard injection case.
- The next step will be to replace the present simple models for the chicane bends by realistic chicane bend models based on the measured fields. These models are yet to be developed.



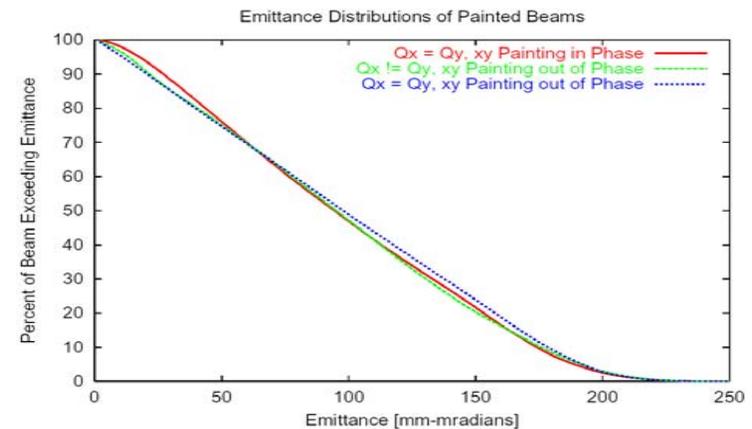
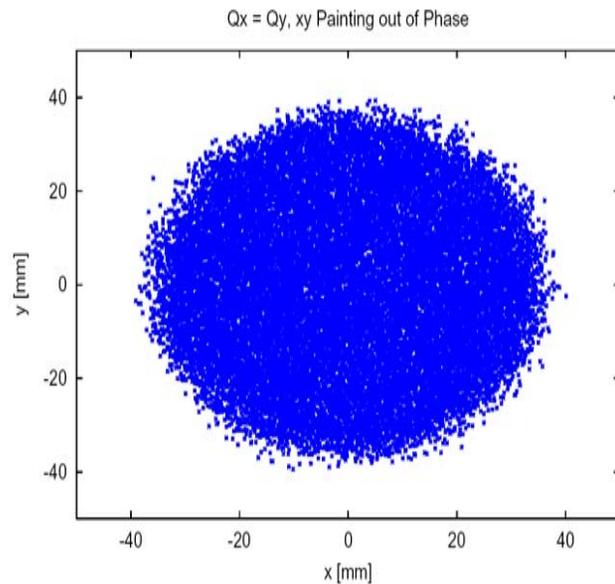
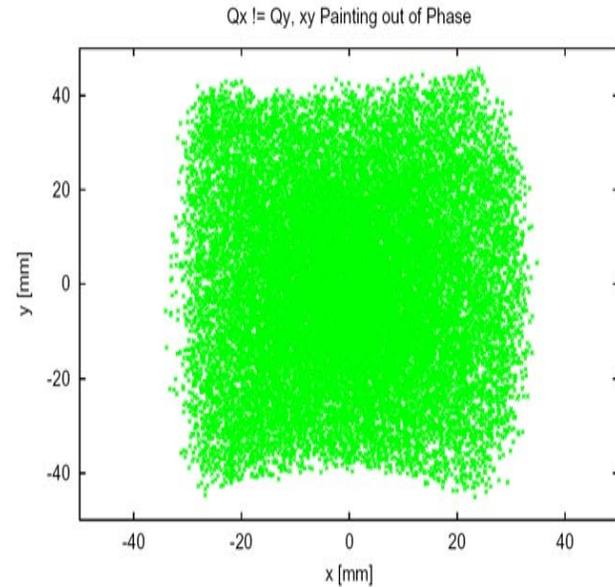
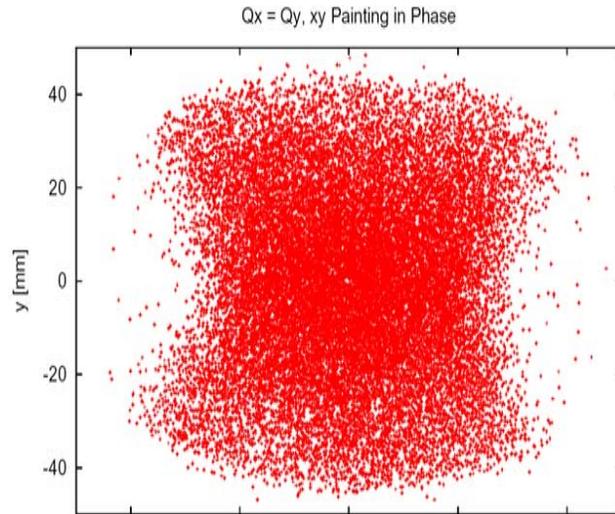
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Self Consistent Uniform Elliptical Beams



- **We have demonstrated** (Danilov, et al, accepted by PRST-AB) that
 - there are an **infinite number of uniform density elliptical KV-like beams** that
 - **retain their uniformity and ellipticity under all linear transformations.**
- Such distributions could provide **advantages for SNS:**
 - Uniform density is desirable from the standpoint of **target requirements.**
 - Uniform distributions have **lower space charge tune shifts.**
- We have demonstrated a **painting scheme to create such a beam in SNS.** The scheme requires **painting in x' and y' as well as in x and y .** Specifically, it is required
 - to use nearly equal horizontal and vertical betatron tunes,
 - to paint with linearly increasing (in time) emittances $\epsilon_x = \epsilon_y = \epsilon_f * t / t_f$,
 - to paint with 90° phase difference between the x - x' and y - y' planes.

Self Consistent Uniform Round Beams



Rationale: Study effect of electron cloud on dynamics of proton beam.

Present status:

The ORBIT E-Cloud Module is a stand-alone collection of C++ classes. It uses files of proton bunch particle coordinates generated by ORBIT.

Simulation model includes:

- The 3D potential and density of the **proton bunch**.
- The 6D coordinates of the **electrons** in the E-cloud 3D and its potential and density.
- **Initial electron generation** induced by **protons grazing the vacuum chamber**.
- **Initial electron generation** induced by **residual gas ionization**.
- A **secondary electron emission model**. This model is essentially a simplified model of M. Pivi and M. Furman.
- The ability to include **external magnetic and electrostatic fields**.

Ongoing and Future Development:

- **Improvement and benchmarking** of the secondary electron emission model.
- Merging the original ORBIT code and the ORBIT E-Cloud Module.
- Apply electron cloud effects to proton beam.

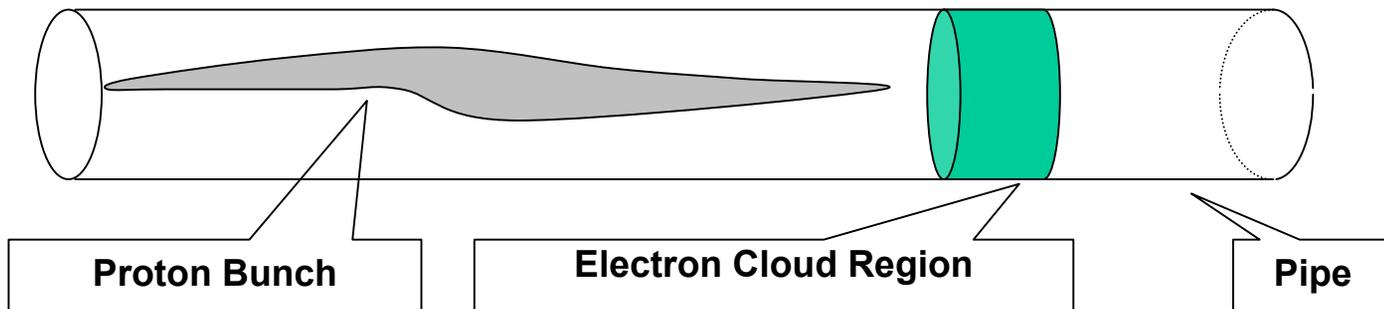
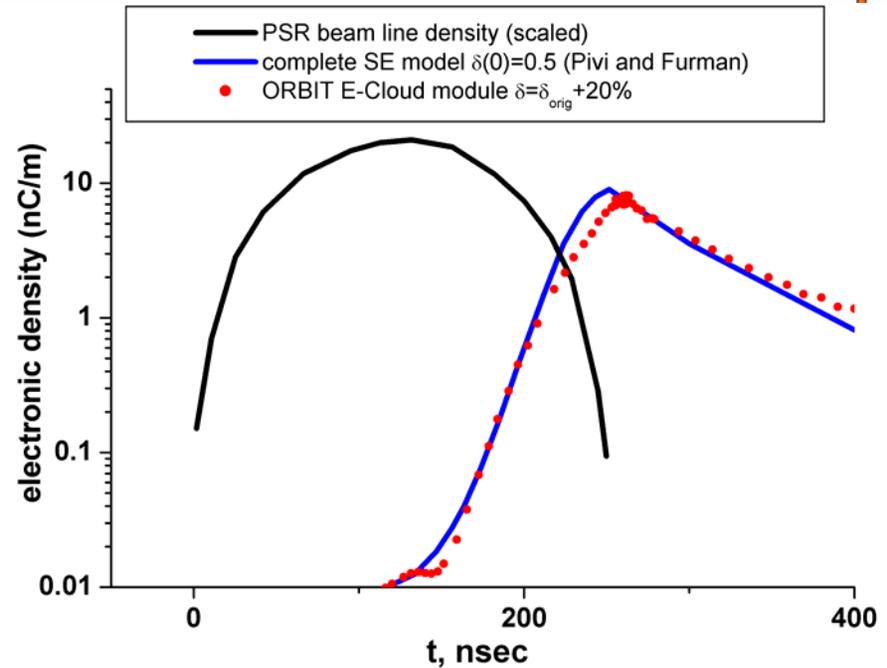
ORBIT E-Cloud Module Benchmark

Simulated electron density during the first bunch passage (PSR)

— ECE (Electron Cloud Effect) code
M.T.F. Pivi and M.A. Furman, LBNL
PRST AB V6 034201 (2003)

● ORBIT E-Cloud Module

— PSR beam line density



- **The ORBIT Code, which was developed to perform realistic simulations of high intensity rings, and SNS in particular, is now being applied to a wide range of SNS ring issues.**
- **These applications require the continuing development of new models and code diagnostics**
 - **To increase the physics capabilities of ORBIT and**
 - **To align ORBIT more closely with actual accelerator applications.**
- **The results of these studies provide insight into the physics and the assurance to guide decisions.**