Computational Beam Dynamics for SNS Commissioning and Operation

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Contributors

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Spallation Neutron Source (SNS)

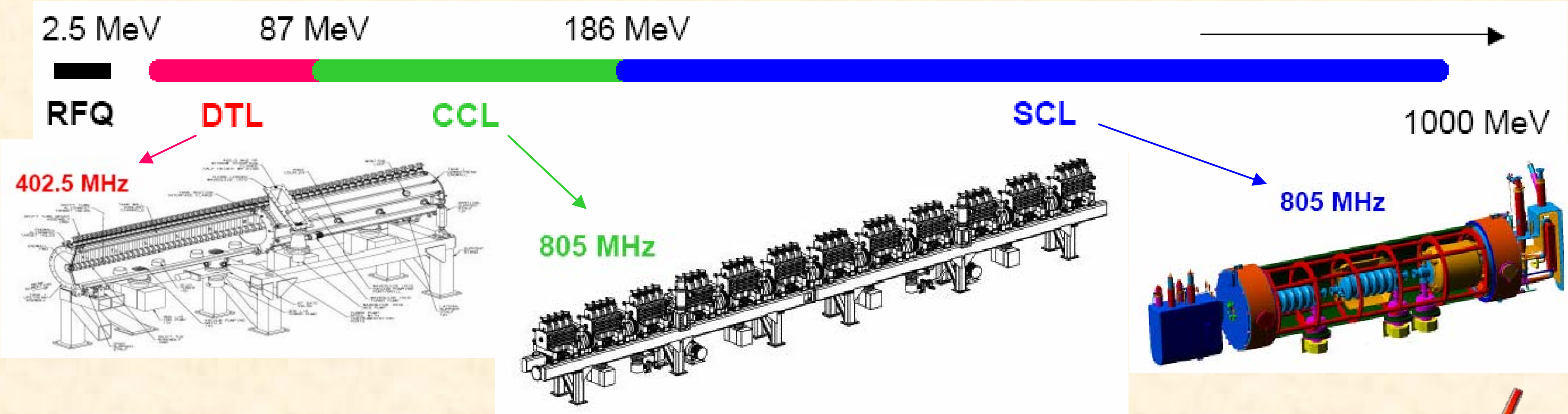
H^- ions are created and bunched.

Ions are accelerated to 1GeV.

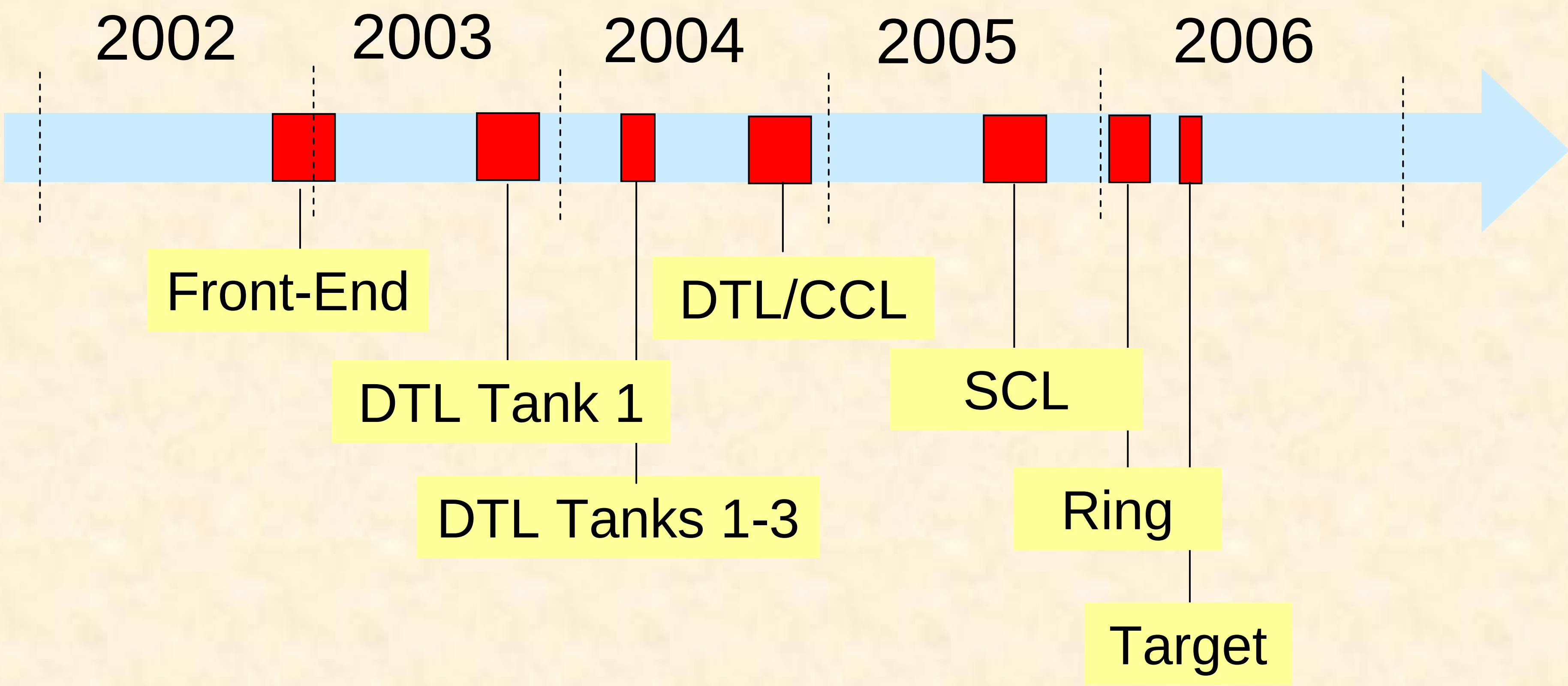
Delivers 1micro-second pulses.

Liquid mercury target produces neutrons.

60 Pulses/second, 1.5×10^{14} protons/pulse, 1.44 MW



Commissioning Timeline



Summary of Beam Parameters Achieved in Commissioning

Parameter	Baseline/ Design	Achieved	Units
Linac Transverse Output Emittance	0.4	0.3 (H), 0.3 (V)	π mm-mrad (rms,norm)
CCL1 bunch length	3	4	degrees rms
Linac Peak Current	38	> 38	mA
Linac Output Energy	1000	952	MeV
Linac Average Current	1.6	1.05 (DTL run)	mA
Linac H-/pulse	1.6×10^{14}	1.3×10^{14} (DTL run) 1.0×10^{14} (Ring run)	Ions/pulse
Linac Pulse length/Rep-rate/Duty Factor	1.0/60/6.0	1.0/60/3.8	msec/Hz/%
Extracted protons/pulse	1.5×10^{14}	5×10^{13}	Protons/pulse
Power to Target	1.44 MW	10 (4 hours) -> 30 2 (routine) -> 10	kW

SNS Status

- **Commissioning is completed**
- **October-April run:**
  - **Increase beam power to 100 kW**
  - **Work up beam parameters toward 100 kW:**
    - **10 Hz**
    - **25mA peak current**
    - **600 microseconds**
    - **900 MeV**
- **Full power by October, 2009.**

What I Will and Will Not Discuss

- **There are numerous applications of computing to SNS commissioning and operation.**
- **I will confine this presentation to beam dynamic calculations that address operational issues or examine experimental results.**
- **I will not consider the numerous on-line applications developed to operate, diagnose, and correct the machine from the control room.**
  - **They are based on simple, fast physics models.**
  - **They are created by teams of physicists, diagnostics experts, and controls scientists.**
  - **They are indispensable in operating the machine.**

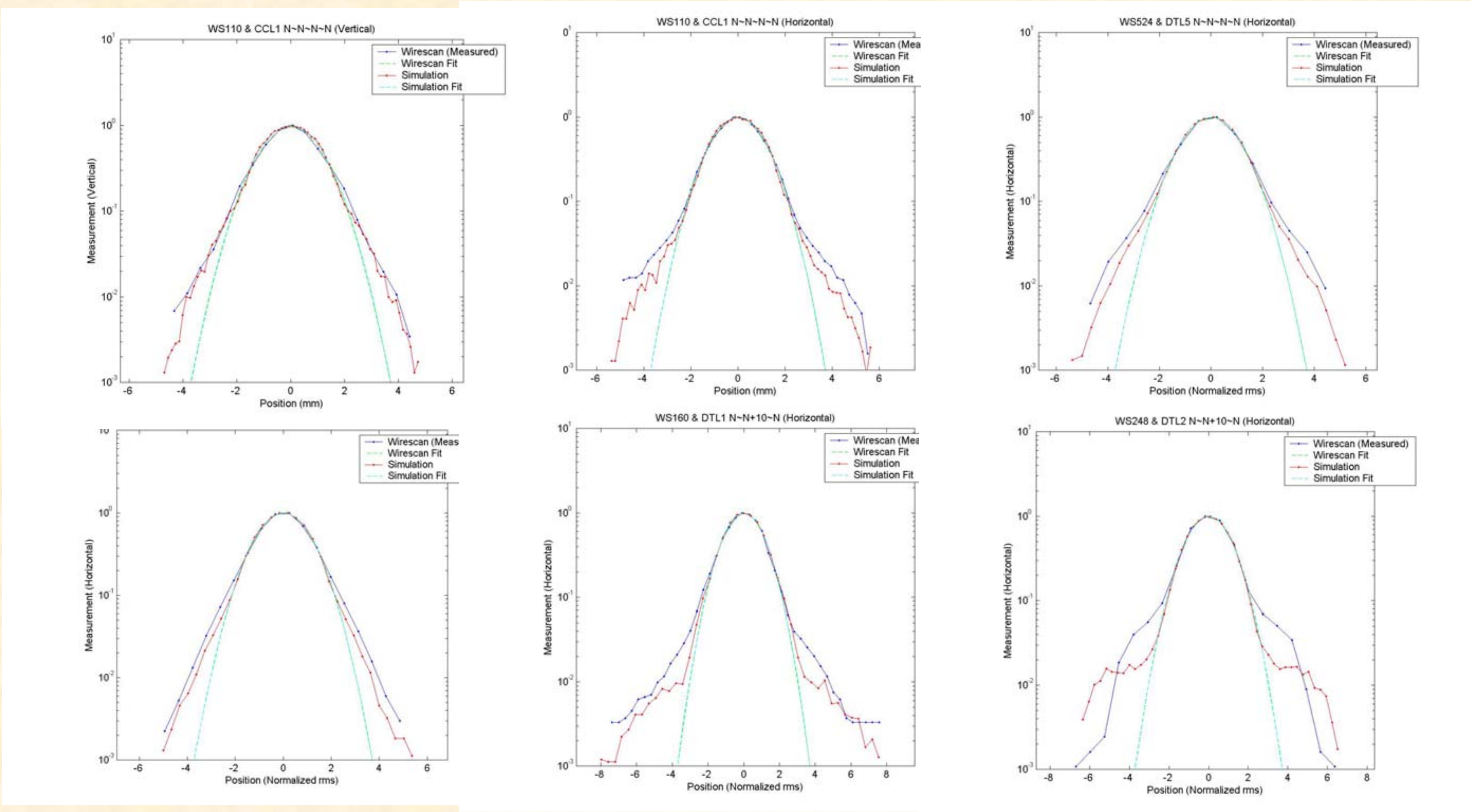
Outline

- **Linac Simulations:**
  - **Codes used include Parmila, Impact, and Trace3D**
  - **Examples**
    - **Beam halo in the warm linac.**
    - **SCL fault studies.**
- **Ring Simulations:**
  - **Codes used include ORBIT supported by MAD**
  - **Examples**
    - **Magnet errors and correction.**
    - **Measuring tunes.**
    - **Transverse stability limits (extraction kicker impedance).**
    - **Electron cloud studies.**
- **Concluding Thoughts**

Beam Halo Simulations in the Warm Linac

- **MEBT quadrupole strengths were varied to optimally match the beam from the RFQ into the DTL.**
- **For these varied settings, wire scanner measurements were made at several locations in the warm linac.**
- **The wire scanner measurements showed various levels of beam core and beam halo, depending on location and magnet settings.**
- **These data were simulated using Parmila:**
  - **Object: determine the degree of systematic agreement regarding beam core and halo.**
  - **Three initial distributions: reference, Gaussian, waterbag.**

Simulation vs. Experimental Data



- **Partial success in simulating profiles.**

Warm Linac Beam Halo Results

- **Beam core calculations agree well with measured values for all distributions.**
- **Both experimental and simulated beam halo varied with MEBT quadrupole settings (matching) and both tended to decrease through the CCL.**
- **Detailed systematic agreement between calculated and measured beam halo (below a few % of peak) was not obtained. The same was true comparing halo for different distributions in the simulations.**
- **Main uncertainties were the lack of detailed knowledge of**
  - **the initial beam distribution from the RFQ,**
  - **the values of the lattice functions, and**
  - **the precise phase advances through the linac**

at the time of the measurements.

SCL Fault Simulations

- **Beam losses in an SCL cryomodule may**
  - **quench the cavities,**
  - **generate arcs at the power couplers,**
  - **severely activate or damage components.**
- **The most dangerous faults in the SCL are those with the most localized beam losses.**
- **Because of the serious consequences of SCL beam losses, a thorough simulation of SCL beam faults has been conducted.**

SCL Fault Simulation Studies

- **Parmila (magnet failures):**
  - **Beam survives single quad or steerer faults.**
  - **Chain of quads fails -> 90% of beam is lost over two cryomodules (~10% in each cavity in that range).**
  - **All SCL quad strengths increase or decrease by 50% -> beam losses spread over range of SCL with maximum localized losses ~50% in individual cavities.**
- **IMPACT (RF cavity failures)**
  - **First MB cavity, cryomodule, or modulator**
  - **A HB cavity, cryomodule, or modulator**
  - **Rapid beam blow up may be triggered if**
    - **the amplitude of the first medium beta cavity is reduced 40% or the phase is shifted 20 degrees.**
    - **First modulator fault: when amplitude of the first 12 cavities is reduced ~5%, catastrophic beam losses in the SCL will happen. It is a challenge to the LLRF feed-forward system as the influence of beam loading to the cavity amplitude only, is more than 5%, and it is known that cavity phase is also affected by the beam loading.**
- **Thus, the most dangerous faults involve RF failures: Cavity, cryomodule or modulator. MPS response as fast as practically available is very important for safe commissioning.**

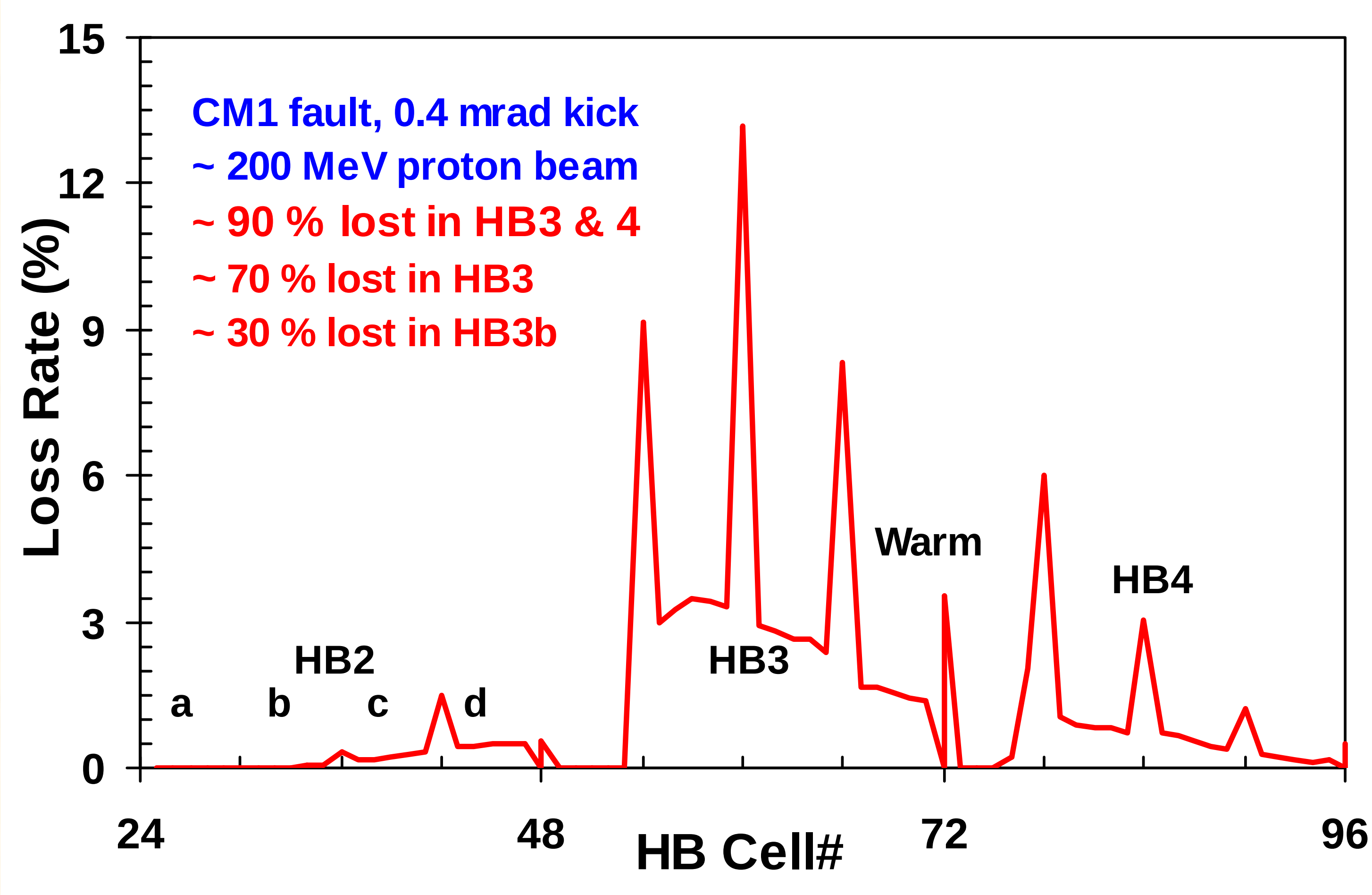
Example: First modulator amplitude at 90%

Cav#	MB1a deg	90% MV/m	MB1 deg	90% MV/m	CM1 deg	90% MV/m
1a	-20.4	13.4	-20.4	13.4	-20.4	13.4
1b	-16.3	14.7	-16.2	13.2	-16.2	13.2
1c	-17.1	14.9	-15.2	13.4	-15.2	13.4
2a	-13.5	14.9	-1.0	14.9	-0.9	13.4
2b	-1.6	14.2	13.6	14.2	15.9	12.7
2c	-13.1	14.9	5.0	14.9	11.4	13.4
3a	-14.7	14.9	12.0	14.9	37.1	13.4
3b	-15.9	14.9	12.8	14.9	49.5	13.4
3c	-17.5	14.9	12.9	14.9	68.0	13.4
4a	-22.9	14.9	12.8	14.9	161.7	13.4
4b	-24.4	14.9	11.6	14.9	-129.6	13.4
4c	-25.3	14.9	9.9	14.9	-36.9	13.4
5a	-26.3	14.9	3.3	14.9	-106.6	14.9
5b	-26.0	14.9	-0.1	14.9	16.2	14.9
5c	-25.0	14.9	-4.2	14.9	132.6	14.9
6a	-21.0	14.9	-18.4	14.9	-161.3	14.9
6b	-19.6	14.9	-23.4	14.9	21.2	14.9
6c	-18.4	14.9	-27.7	14.9	-164.1	14.9
7a	-15.4	14.9	-37.8	14.9	81.6	14.9
7b	-14.7	14.9	-39.3	14.9	-53.6	14.9
7c	-14.5	14.9	-38.6	14.9	163.9	14.9
…Energy (MeV)		1000		998		180

An "Actual" Fault of the 1st Modulator

~10 % acceleration field change of 12 cavities

~ 20° RF phase change of only the first MB cavity would give similar results



Summary

MPS response time is a critical parameter

- **< 25 μs – no disastrous beam loss in SCL for a single cavity or cryomodule fault, but a modulator fault could be damaging.**
- **< 10 μs – single modulator fault may not be dangerous to SCL and all downstream systems.**
- **Single doublet and/or single steerer fault can be handled 'safely' in SCL.**
- **Result of a chain or all SCL quads fault is determined by fault type and response time.**

ORBIT Overview

- ORBIT is a particle tracking code in 6D phase space. It uses s, not t, as its independent variable.
- Its purpose is the design and analysis of high intensity rings. We also use it on beamlines when appropriate.
- To accomplish its purpose, ORBIT incorporates a sizeable collection of physics, engineering, and diagnostic models.
- The emphasis in developing ORBIT has always been the incorporation of models that allow application to realistic accelerator problems.

ORBIT: Computational Approach

- ORBIT is written in object oriented C++, which provides a clean and safe environment for modular code development.
- Driver shell approach supports calculations from interactive command line interface or from shell scripts, interactive error reporting, and "on-the-fly" programming.
  - Present version uses SuperCode.
  - Python version is under development.
- ORBIT supports parallel processing in MPI. This is essential for calculations involving 3D space charge and the electron cloud model. ORBIT has been installed on many systems.

ORBIT: Inventory of Models

- ORBIT is designed to simulate real machines: it has detailed models for
  - Injection foil and painting.
  - Single particle transport through various types of lattice elements.
  - Magnet errors, closed orbit calculation, orbit correction.
  - RF and acceleration.
  - Longitudinal impedance, including 1D longitudinal space charge.
  - Transverse impedance.
  - 2.5D transverse space charge with or without conducting wall beam pipe.
  - 3D space charge* (in s).
  - Feedback for stabilization.
  - Apertures and collimation.
  - Electron cloud model, including proton beam response.
  - Tracking in 3D Magnetic Fields.

- ORBIT has an excellent suite of routines for beam diagnostics.

SNS Ring Studies for Commissioning and Operation

- **Design:**
  - HEBT energy spreader and corrector cavities
  - Collimation
- **Commissioning:**
  - Injection without painting
  - Magnet errors
  - Orbit and error correction
  - Tune measurement
  - Nonlinear single particle transport effects, higher order multipolar contributions, and fringe field effects
  - x-y coupling measurement and analysis
  - Stripper foil: incomplete stripping
  - Waste beam studies
  - Ring extraction and transport to target
  - Beam-on-target footprint
- **Operation:**
  - Stripper foil: foil hits
  - Injection Studies: optimization of painting
  - Transverse and longitudinal impedance stability thresholds and effects on accumulation and losses
  - Feedback stabilization of RF instability
  - Total foil-to-target simulation
  - Detailed treatment of injection chicane for circulating beam
  - Electron cloud studies
  - Ring fault studies
- **Future Considerations:**
  - Self-consistent beams
  - Barrier cavities
  - Laser stripping

Magnet Errors and Their Correction

- **We performed a thorough study of effects of misalignments & strength errors in the ring, including their correction. ORBIT was primary tool in study.**
- **Errors were generated with a random, uniform distribution.**
- **The assumed magnitude of errors was always taken to be greater than or equal to the SNS tolerance.**
- **BPM signal errors were assumed, generated randomly within Gaussian distribution with σ_{rms}=1.0 mm, σ_{cutoff}=2.0 mm.**

Dipole			
Error Type	SNS Parameter Tolerance	Tolerance Used in Simulation	% of Beam Lost (worst case)
Offset	**0.1 mm**	**0.25 mm**	**0.010**
Field	**0.01%**	**0.1%**	**0.004**
Roll	**0.2 mrad**	**0.2 mrad**	**0.006**
Pitch	**0.5 mrad**	**0.5 mrad**	**0.011**
Yaw	**0.5 mrad**	**0.5 mrad**	**0.050**

Quadrupole			
Error Type	SNS Parameter Tolerance	Tolerance Used in Simulation	% of Beam Lost (worst case)
Offset	**0.1 mm**	**0.25 mm**	**47.623**
Field	**0.01%**	**1%**	**11.914**
Roll	**0.2 mrad**	**0.2 mrad**	**0.007**
Pitch	**0.5 mrad**	**0.5 mrad**	**0.010**
Yaw	**0.5 mrad**	**0.5 mrad**	**0.011**

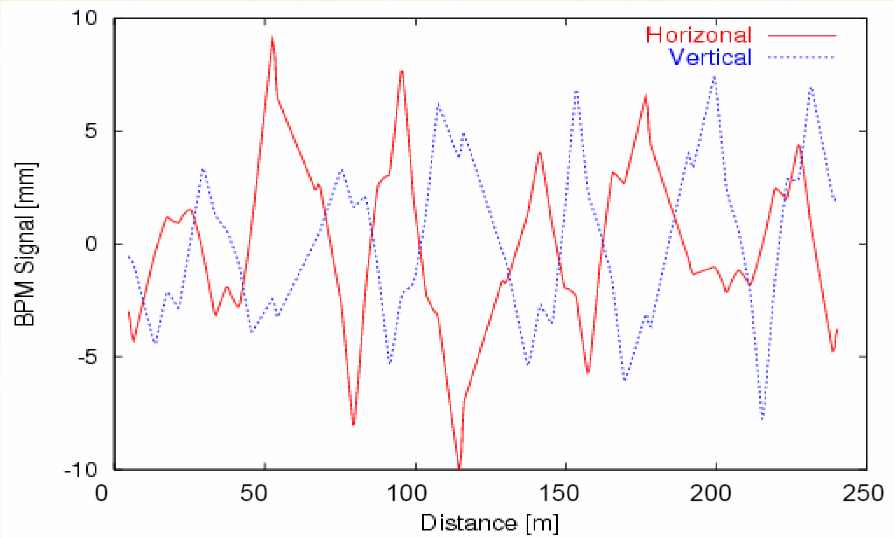
✓ In all cases, correction resulted in total losses of < 0.02%, including cases with all errors simulated at once.

Error Correction

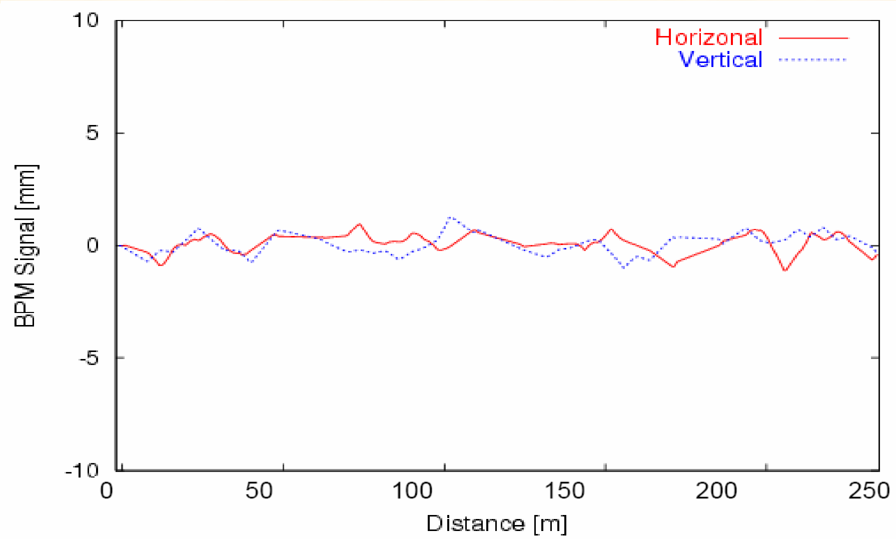
- **Quad and dipole roll errors were not corrected (no significant effect on beam).**
- **Quad strength were errors corrected using phase advance information.**
- **Closed orbit were corrected by adjusting dipole corrector strengths to minimize BPM signals.**
- **Two methods employed: Least square minimization & 3-bump method.**
- **All correction calculations considered magnet families (common power supplies).**

Example: Case with all error types included

BPM signal before correction

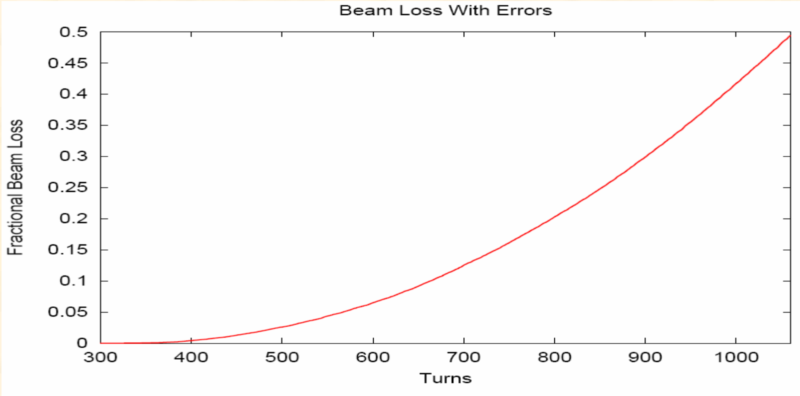


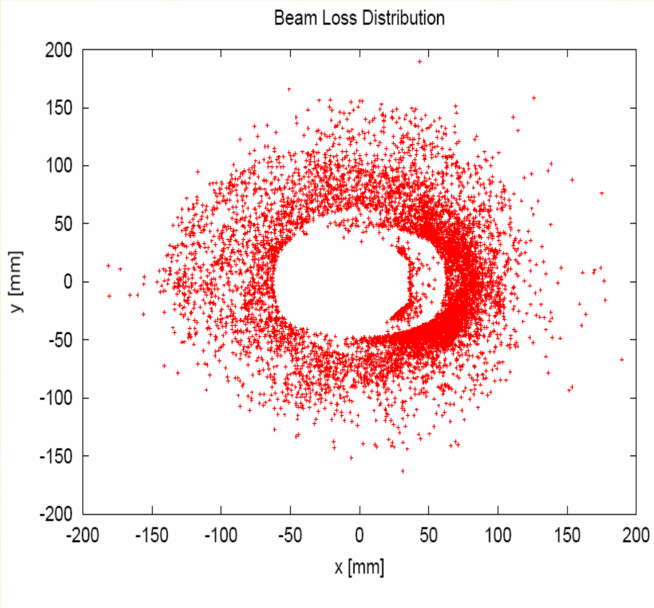
BPM signal after correction



Results: Losses With and Without Orbit and Phase Correction

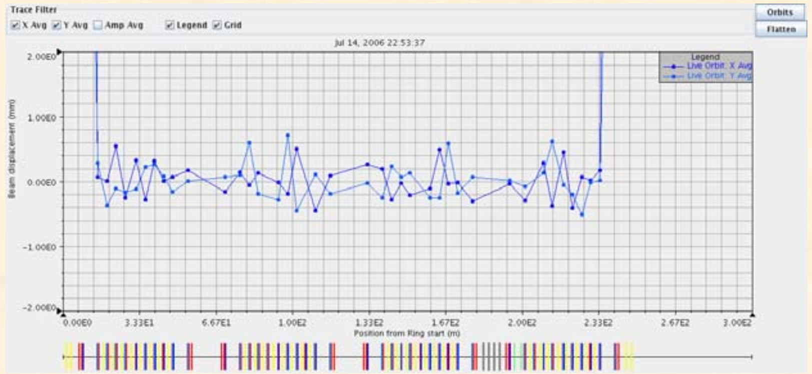
- Consider cases with all errors simultaneously activated.
- Without correction, the worst case beam loss is 49%, starting before 400 turns.
- With orbit correction, assuming no BPM errors, losses are $< 10^{-4}$.
- With random BPM signal ucertainties, losses are still only 1.7×10^{-4}.
- These results have been found to hold in general.
- Key ORBIT Models: Errors, BPMs, Dipole Correctors, Apertures and Collimators





Experimental Closed Orbit Correction

- **Orbit correction results**
- **Posted: Fri, Jul 14, 2006 22:59**
- **After having changed the skew dipole corrector polarities for the horizontal correctors, we achieved a very good orbit using the orbit correction application.**
- **Ring orbit error is less than plus/minus one millimeter.**

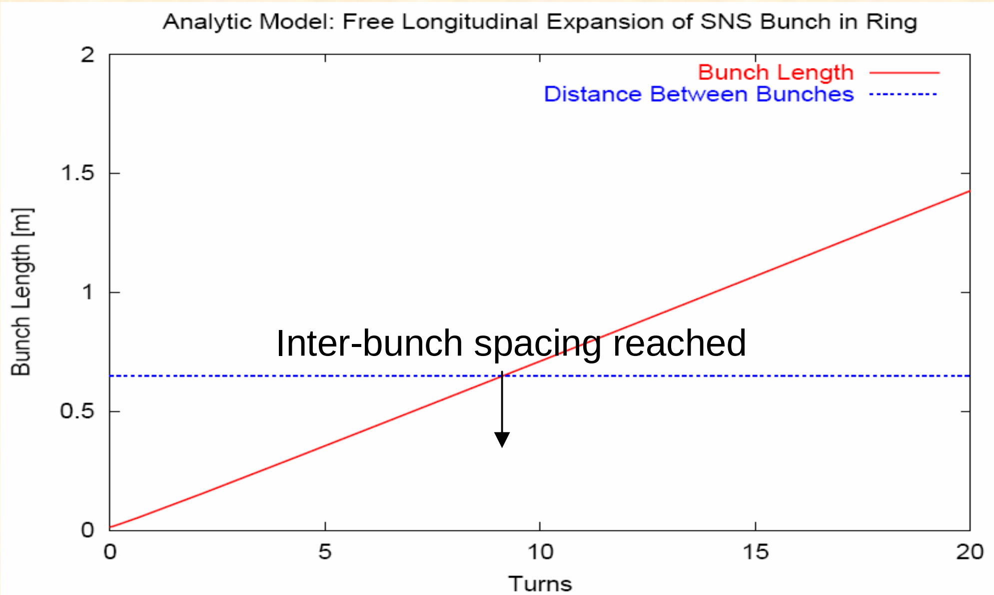


Tune Measurement: 402.5 MHz Signal Decoherence

- **BPMs will be used to measure betatron tune and phase advance in the ring.**
- **BPMs have both base-band (a few MHz) and narrow-band (402.5 MHz) capability.**
- **402.5 MHz has higher resolution at low intensity (single turn injection) → need to assess the lifetime of the 402.5 MHz structure.**
- **Two models used: Analytic model, ORBIT simulations.**

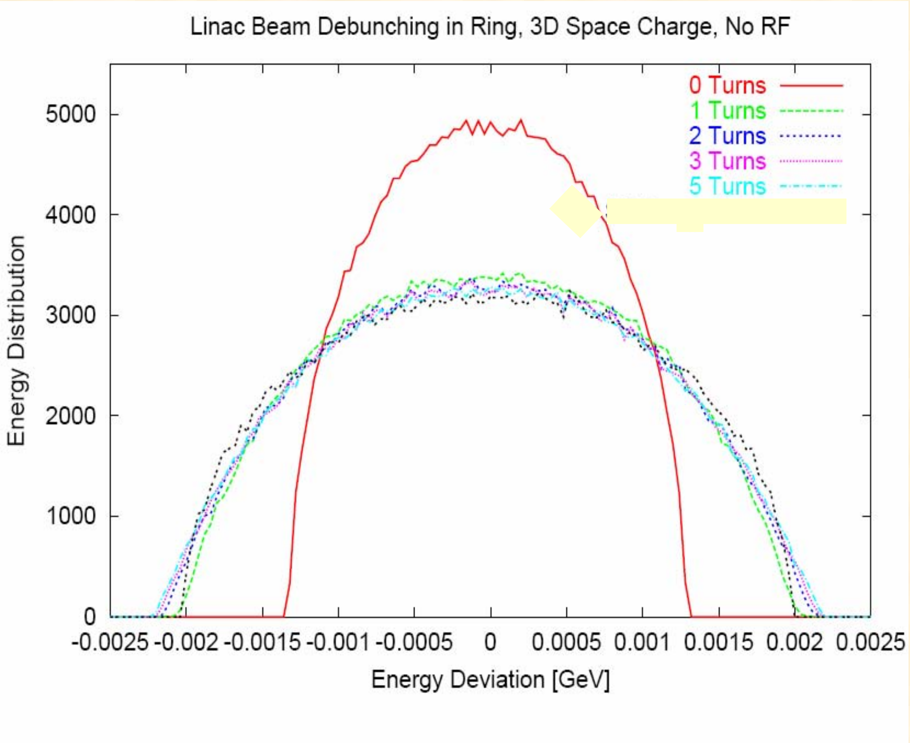
Analytic model:
• Ellipsoidal beam, uniform density.
• Transverse uniform focusing channel.
• Used expected energy distribution at end of SCL.
• Allow free longitudinal expansion

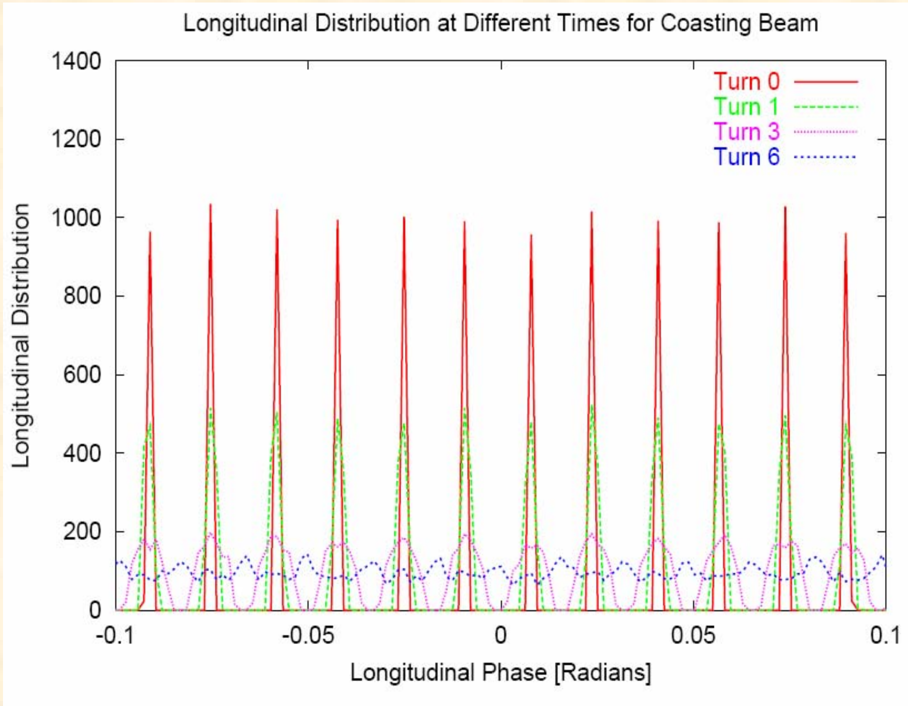
➢ All space charge effects occur in first ~250 meters.
➢ Microbunches reach inter-bunch spacing in ~9 turns.



ORBIT Studies of 402.5 MHz Signal Decoherence

- **ORBIT particle tracking simulations show decoherence of 402.5 MHz signal in ~5 turns.**





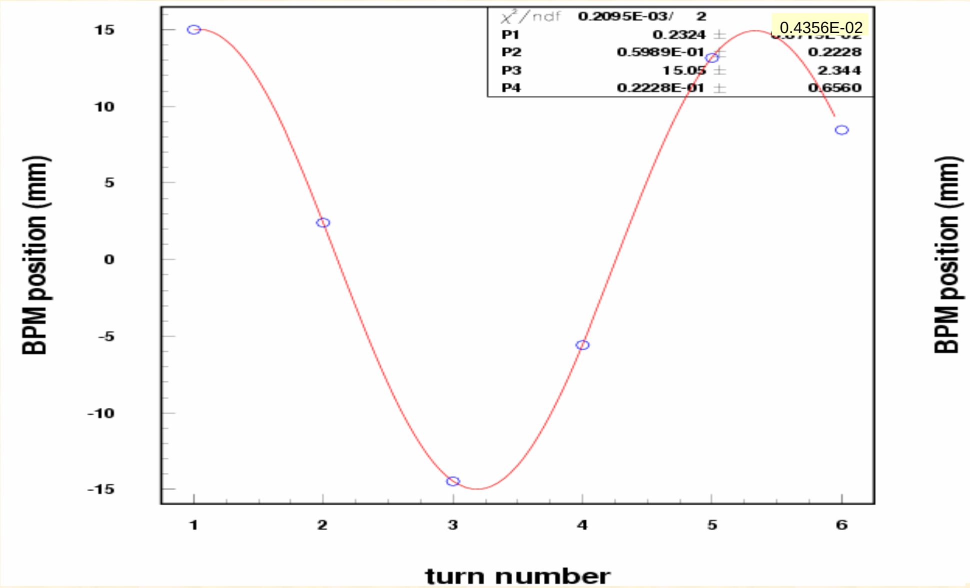
- **Single shot narrow-band BPM data** $\rightarrow$ **useable, but expect larger error due to low # of turns.**

Single Injected Turn Betatron Tune Measurement

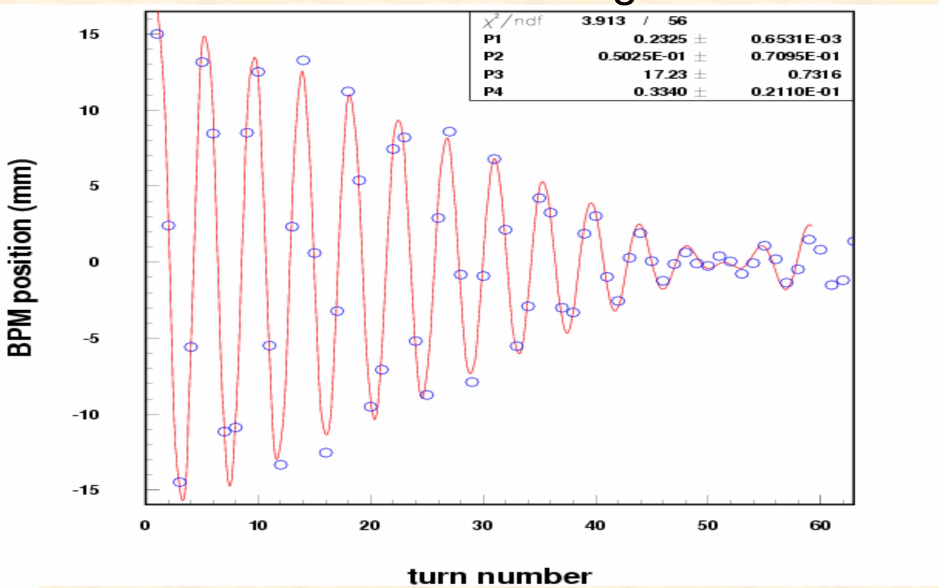
- **Single shot BPM data simulated with ORBIT, post-processed and fit with CERN Lib program.**
- **BPM error of 1.0 mm assumed for narrow band, 2.0 mm for base band fitting.**
- **Results:**

Narrow band fit: $Q_x = 0.2324 \pm 0.0044$
Base band fit: $Q_x = 0.2325 \pm 0.00065$

Narrow-Band Signal



Base-Band Signal



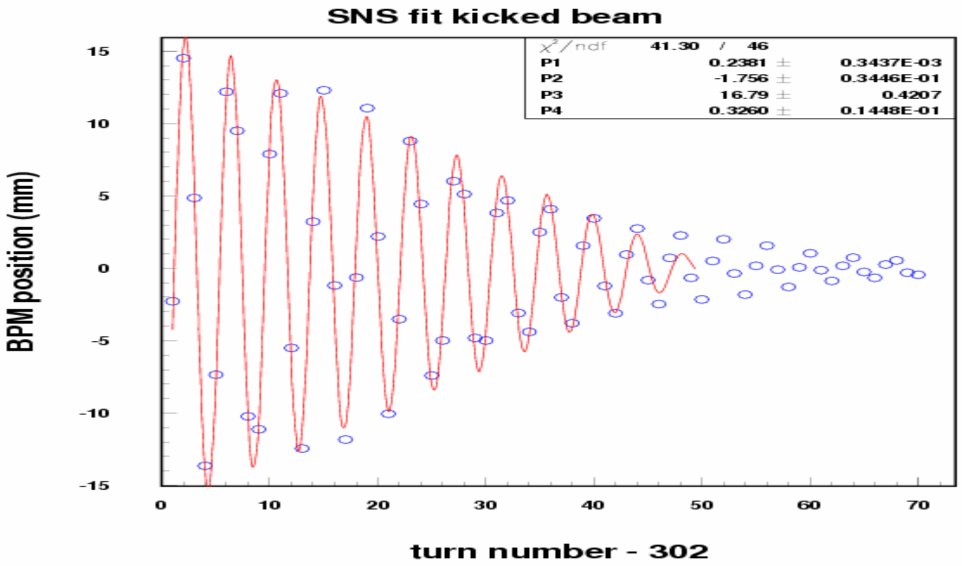
Kicked Beam Betatron Tune Measurement

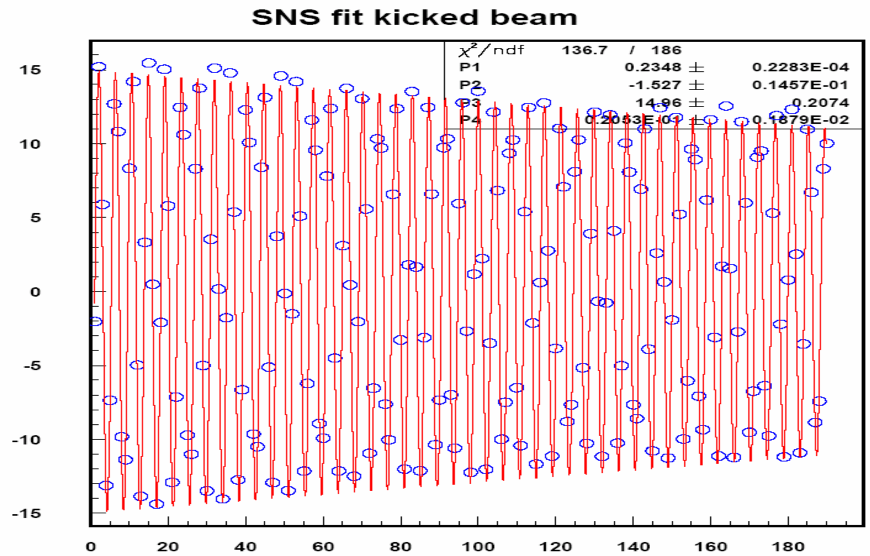
- **Beam accumulated for 50 turns, kicked at 300 turns.**
- **BPM error of 1.0 mm assumed for fitting → smaller error than single-shot measurement due to higher beam intensity.**

Fit: $Q_x = 0.2381 \pm 0.00034$

• Error fit scales linearly with BPM error.

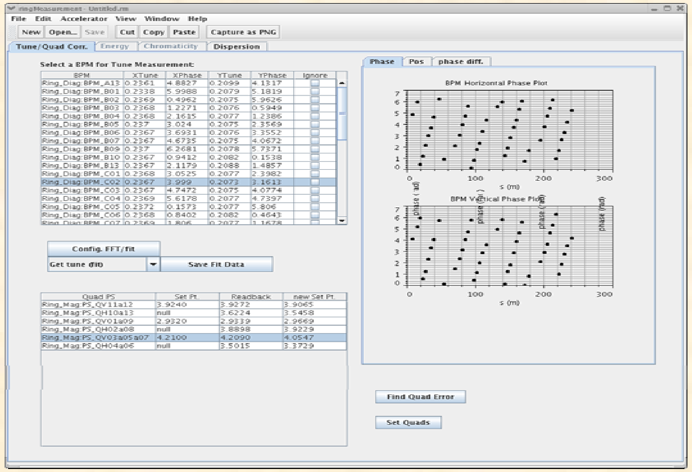
➢ Chromaticity correction will result in even better tune measurement.

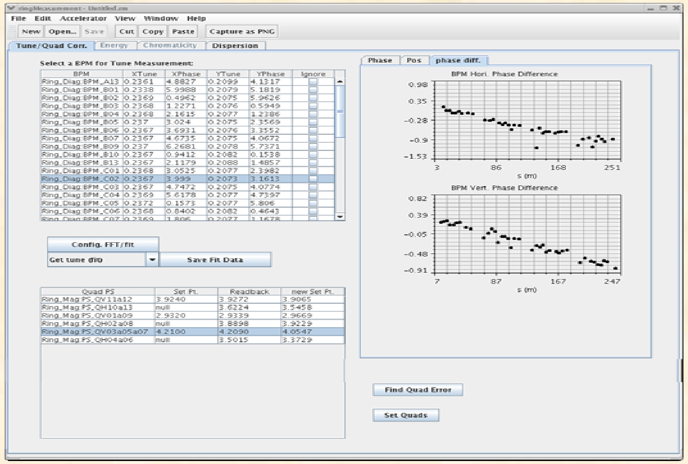




Experimental Tune Measurement and Quadrupole Errors

- **Ring Tune Measurement and Quad Errors**
- **Posted: Thu, Feb 02, 2006 14:57**
- **Ran the RingMeasurement app to measure the ring tune and quad error. The data was taken with single mini-pulse injection. The BPM phase plot clearly shows 6 oscillations in both planes (from 0 to 2pi), i.e. both tunes are 6.x. The fractional tunes are ~0.237 for X and ~0.208 for y.**
- **The 2nd part of the app is to fit the quad error with online model. The result lists here:**
- **PS Set_pt. readback fit_set_pt. error (fit-set)/set**
- **QV11a12 3.9240 3.9272 3.9065 -0.446%**
- **QH10a13 3.6210 3.6224 3.5458 -2.077%**
- **QV01a09 2.9320 2.9339 2.9669 +1.190%**
- **QH02a08 3.8930 3.8898 3.9229 +0.768%**
- **QV03a05a07 4.210 4.2095 4.0547 -3.689%**
- **QH04a06 3.5039 3.5015 3.3729 -3.739%**
- **The fit is accurate to ~3.5deg of BPM phase. We will take more data and run the fit routine longer to get better statistics.**
- **Measured BPM phases plotted in the right panel and some BPMs' fractional tunes shown in the upper left table. In the plots, the x-axis is along the beam line (starts from the foil) and the vertical axis is BPM phase (between 0 and 2pi).**
- **Fitted quad set points are shown in the lower left table. Unfortunately 3 quad power supply set points are not shown but they are: QH10a13=3.6210, QH02a08=3.8930 and QH04a06=3.5039.**

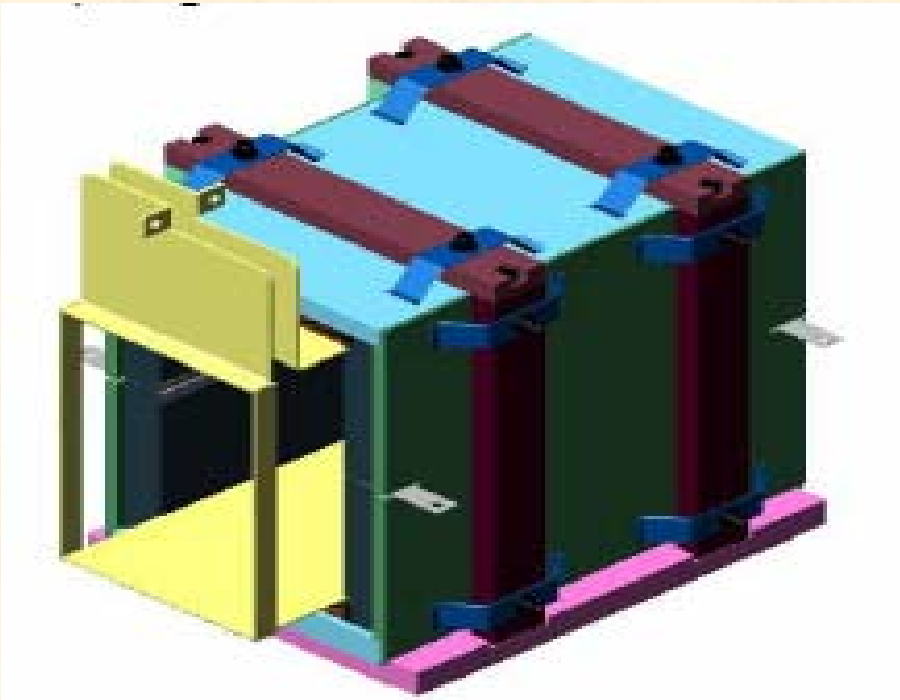




Transverse Stability Studies

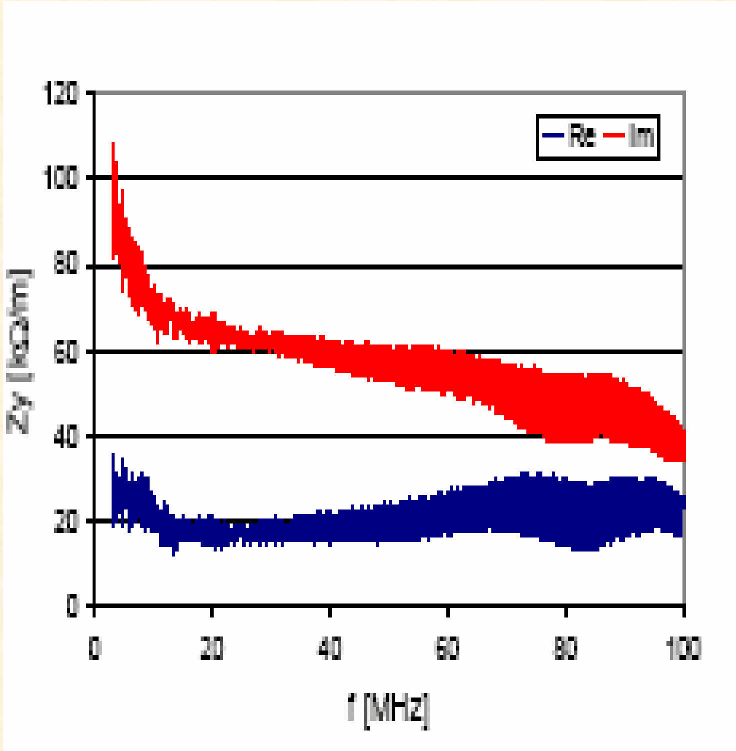
High intensity -> transverse instabilities are a concern.
We have studied the transverse stability of the SNS ring in depth.

Dominant impedance is due to extraction kickers.



Extraction Kicker RF Cavity Impedance

(measurements by H. Hahn)

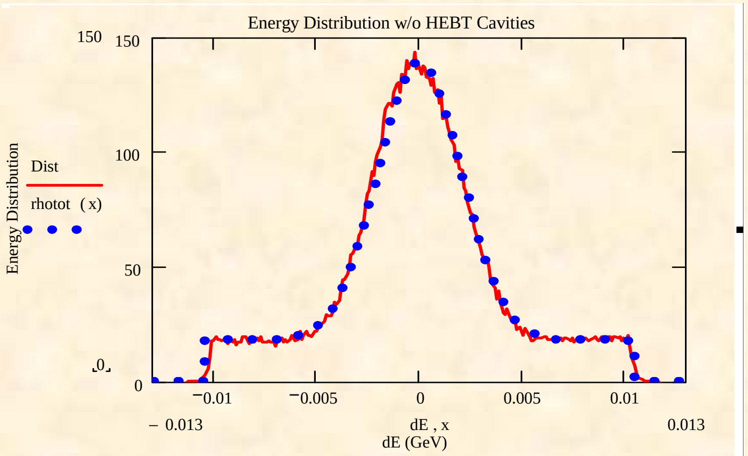


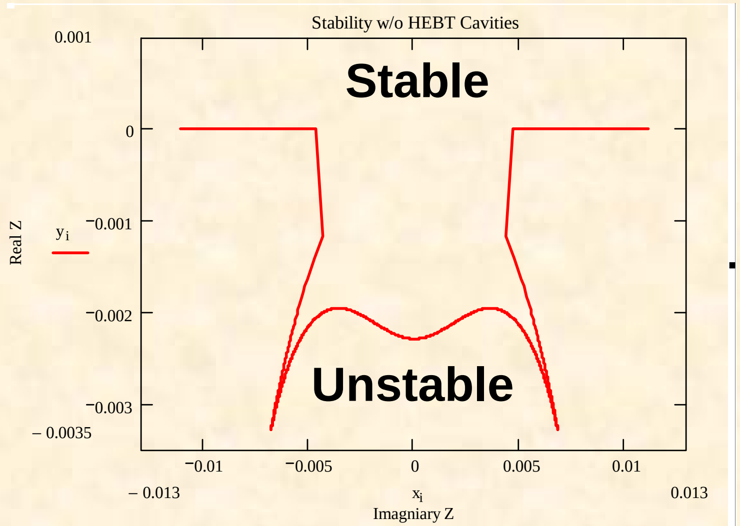
Stability for Coasting Beams

- **We began by studying analytic coasting beam models to benchmark the transverse stability model.**
  - **We used KV transverse beam distributions.**
  - **We varied all relevant parameters:**
    - **analytically solvable energy distributions,**
    - **Chromaticity,**
    - **space charge.**
- **We extended the coasting beam calculations to "SNS coasting beams":**
  - **Using ORBIT, we injected a beam of 1.5×10^{14} protons over 1060 turns into the ring.**
  - **Full beam dynamics: transverse painting, symplectic tracking, space charge, the ring RF focusing, and the longitudinal and transverse impedances from the extraction kickers, which dominate the ring.**
  - **We used peak distribution at the longitudinal center of the bunch to generate a coasting beam of the same shape and intensity.**
  - **We analyzed this both analytically and with ORBIT.**
- **We then carried out stability calculations for realistic bunched beams obtained during injection:**
  - **These were first carried out with single harmonic impedances.**
  - **Finally, transverse stability was calculated for the full injection process using the measured extraction kicker impedance, which is dominant in the ring.**

"SNS Coasting Beam" Analysis

- **The top plot shows the energy distribution at the peak longitudinal density at the end of injection for a 1.44 MW case.**
  - **Red curve is obtained directly from ORBIT.**
  - **Blue curve is a computed fit: sum of Heaviside and Gaussian.**
- **The bottom plot stability diagram resulting from the fitted energy distribution.**
  - **Horizontal axis -> imaginary component of impedance.**
  - **Vertical axis -> real component of impedances.**
- **The stability diagram is valid for different values of phase slip factor, chromaticity, intensity, and mode number, but the scales depend on all these factors.**





Comparison of Thresholds – Coasting Peak Distribution

In order to compare the analytic results with ORBIT predictions, we take the post-injection fully evolved peak beam energy distribution and subject it to a given impedance. Here we use a coasting beam with $N=3.75\times10^{14}$, which corresponds to a bunch factor of 0.4 in SNS. We focus on the n=10 mode.

Coasting or Bunched	Lattice (SNS)	Dynamics	Analytic ($k\Omega$/m)	ORBIT Highest Stable	ORBIT Lowest Unstable
Coasting	Linear MAD	No Space Charge	25.6	25	30
Coasting	Zero Chromaticity	No Space Charge	25.6	30	40
Coasting	Natural Chrom	No Space Charge	242	200	300
Coasting	Linear MAD	Space Charge	$\sim0^{+}$	0	10
Bunched	Natural Chrom	No Space Charge		800	1000

Experimental Instability Studies

- No instabilities have been seen thus far under "normal" conditions
- We searched for instabilities by i) delaying extraction, ii) operating with zero chromaticity, iii) storing a coasting beam
- The first instability observed had central frequency 6 MHz, growth rate 860 μs, for 10^{14} ppp.
- It was driven, as expected by the extraction kicker impedance
  - Z_{calc} ~22-30 kOhm/m,
  - Z_{meas} ~ 28 kOhm/m.

Transverse Stability for the Extraction Kicker Impedance and Bunched Beams

Analytic bunched beam stability evaluation is a difficult problem, although a potential approach involving many coupled equations has been formulated by Danilov. Present studies are purely computational, but indications are that bunched beams are more stable than coasting beams under otherwise identical conditions.

Case (SNS, N=1.5×10^{14})	Lattice	Dynamics (Extraction Kicker Impedance)	Analytic	ORBIT Highest Stable	ORBIT Lowest Unstable
Stored Beam After Injection	Linear Transport	No Space Charge		Z×0.5	Z×0.6
Stored Beam After Injection	Symplectic Nonlinear Zero Chromaticity	No Space Charge		Z×0.6	Z×0.8
Stored Beam After Injection	Symplectic Nonlinear Natural Chromaticity	No Space Charge		Z×5	Z×7
Stored Beam After Injection	Linear Transport	Space Charge		Z×1.5	Z×2.0
Injection	Linear Transport	Space Charge		Z×1.5	Z×2.0
Injection	Symplectic Nonlinear Zero Chromaticity	Space Charge		Z×2.0	Z×3.0
Injection	Symplectic Nonlinear Natural Chromaticity	Space Charge		Z×3.0	Z×4.0

Studies are underway for SNS upgrade, which should be near stability limit.

Summary of Transverse Stability Studies

- **Increasing energy spread and/or chromaticity are stabilizing (Landau damping).**
- **Space charge effects**
  - **Destabilize coasting beams (stability diagrams).**
  - **Stabilize bunched beams (variable tune spreads).**
- **Bunched beams are more stable than comparable coasting beams.**
- **For smooth energy distributions and for approximations to real distributions ORBIT and analytic coasting beam thresholds agree well.**
- **Most pronounced discrepancy – the coasting beam model predicts instability (already seen experimentally) for SNS ring energy distributions and intensities, while realistic simulation with 3D space charge shows the beam is stable, even for zero chromaticity.**
- **Several reasons:**
  - **betatron tune spread due to space charge,**
  - **bunched beam spread of betatron tunes varies along the longitudinal coordinate due to vacuum chamber and bunch factor effects,**
  - **bunched beam coupling of many modes (from ORBIT simulation bunched beam more stable in case of no space charge only real impedance), etc.**
- **Intermediate conclusion – real bunched beam dispersion relations are required to describe our particular SNS Ring situation.**

Electron Cloud Instability

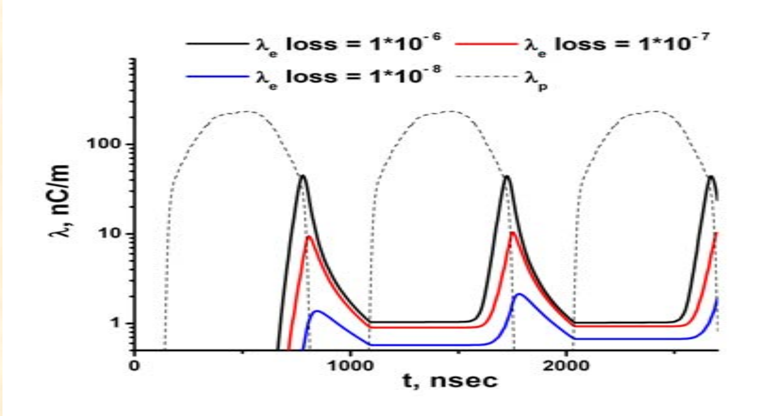
- The instabilities caused by coupled electron-proton oscillations can limit performance of intense proton storage rings.
- The electron-cloud effect (ECE) shows itself very clearly in the Proton Storage Ring (PSR) at Los Alamos National Laboratory.
- Due to similarities between the PSR and SNS storage rings dedicated electron cloud studies and countermeasures have been considered from the early stages of the SNS project:
  - low secondary electron emission titanium nitride (TiN) beam pipe coating,
  - an electron collector near the stripping foil,
  - reserved space for solenoidal magnets to reduce electron buildup in high loss areas.
- The ORBIT code has been used to verify early predictions about the stability of the beam in the SNS ring with respect to electron cloud effects (ECE).

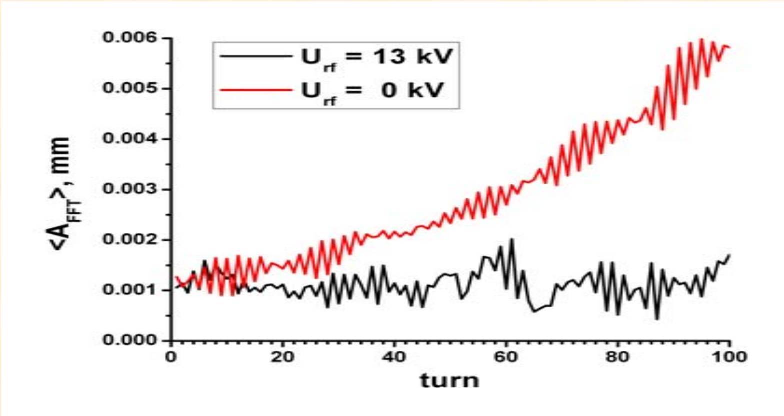
ORBIT Electron Cloud Model

- ORBIT's electron cloud model has been applied to analytic benchmark studies, to PSR, and to SNS. It has the following properties:
  - The model is self-consistent in that both the ambient electrons, modeled as macroparticles, and the proton beam are tracked under their own and each other's space charge forces and external forces.
  - The effects of electron generation and wall interactions have been incorporated using the models of Pivi and Furman.

Electron Cloud Study Results

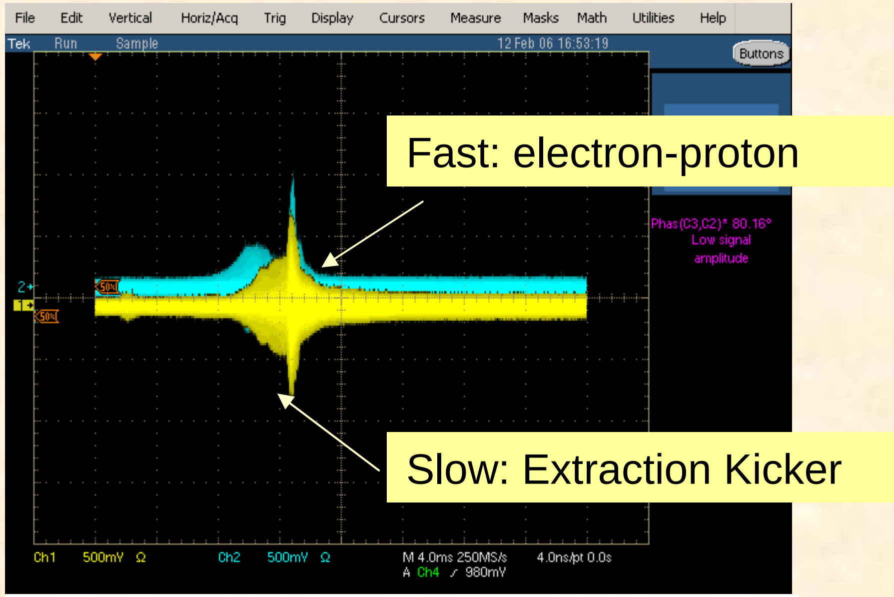
- Simulated electron and proton bunch densities during the first SNS bunch passages for different proton loss rates per turn, assuming magnetic field-free region.
- Average Fourier amplitudes of the horizontal oscillations of the center of the proton bunch in the SNS ring. The averaging is done over 116-120 MHz frequency region.

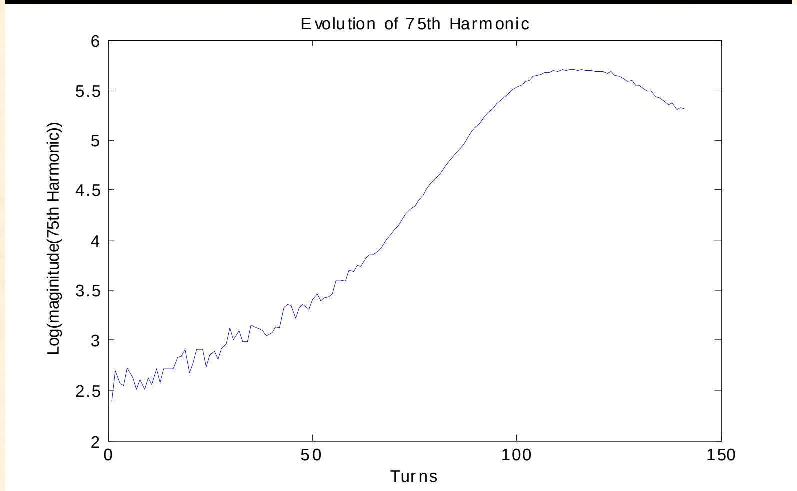




Experimental Instability Studies

- No instabilities seen thus far in "normal" conditions.
- We searched for instabilities by i) delaying extraction, ii) operating with zero chromaticity, iii) storing a coasting beam
- In coasting beam see very fast instability at 0.2-1x10^{14}, consistent with e-p.
  - Growth rate 20-200 turns.
  - f ~30-80 MHz depending on beam conditions.





Electron Cloud Study Conclusions

- The SNS beam appears to be more stable than the beam in PSR.
  - According to simulations for the SNS beam, applying only 30% of the design voltage to the rf-cavities will suppress the ECE instability.
  - This result can be considered as a very conservative estimation.
  - It is in good agreement with previous analytical and numerical studies of the instabilities for SNS by M. Blaskiewicz.
- First experimental results show the ECE instability in the SNS ring at intensity 2.5×10^{13} protons for a coasting beam with no chopping.
  - These results can not be compared with our simulations because of the lack of longitudinal bunching in these experiments. They will be subject of further investigations.

Concluding Thoughts

- **Much of the computing required to support SNS commissioning and operation is not ultra-high performance. Exceptions are**
  - **Transverse instabilities, which require a 3D description of space charge, and**
  - **Electron cloud studies, when the proton beam response is included.**
- **Most important is to incorporate a broad range of physics models to describe the many issues encountered. The variety and sophistication of our models has increased considerably with time.**
- **Because of the need for a broad range of models to address the great diversity of phenomena encountered, it is important to develop modular software and a convenient and flexible user interface.**
- **The main source of inaccuracy/error in simulating hypothetical or measured phenomena is most likely our lack of complete detailed knowledge of the actual operating conditions.**