The SNS Beam Diagnostics Experience, Lessons Learned and Plans

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on behalf of the SNS Beam Instrumentation Team
The Spallation Neutron Source:

is an accelerator-driven user facility for neutron scattering research at Oak Ridge National Laboratory in USA.
Brand new facility
Baseline Beam Parameters

- P beam on target: 1.44MW
- I beam average: 1.44mA
- Maximum Beam energy: 1 GeV
- Duty factor: 6%
- Rep. rate: 60Hz
- Pulse width: 1ms
SNS Accelerator Complex

Front-End: Produce a 1-msec long, chopped, H- beam

1 GeV LINAC

Accumulator Ring: Compress 1 msec long pulse to 700 nsec

2.5 MeV LINAC

Front-End

LINAC

Chopper system makes gaps

mini-pulse

Current

1 ms macropulse

<1 µsec

Current

1 ms

Liquid Hg Target
Multiple commissioning runs helped to integrate new systems (controls, timing, diagnostics, software applications, …)

Less time was available for latter stages than originally planned
Power Upgrade Project: Double beam power to 3 MW by 2016

- Increase proton energy from 1GeV to 1.3GeV
- Increase beam current from 38mA to 59mA
- Enables second target station (in 2020s)
### Run schedule for FY 2010

#### Run Schedule for FY 2010

<table>
<thead>
<tr>
<th>Weekday</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
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#### Run 2010-1
- Neutron Production

#### Run 2010-2
- Accelerator Physics
- Accelerator Startup/Restore
- Machine Downtime Major Periods (Maintenance/Upgrades)
- Downtime Periods Weekly Maintenance Option/Remedial tuning

#### Run 2010-3
- Weekend
- Wednesday
- Holiday
Beam Instrumentation Networking

**Service Buildings**
- VME (VxWorks)
- BLM
- PC-Based (XPe)
- BPM/BCM...
- cRIO-Based (LVRT)
- RFTF BLM
- PXI (XP or LVRT)
- BCM/ELS...

**Office Building**
- SMB/UFS/HFS
- PC-Based (MacOSX)
  - File Sharing
- PC-Based (Linux)
  - EDM/XAL
- PC-Based (Solaris)
  - Oracle/Archiver/
    - Elog
SNS Beam Instrumentation Group

• 7 Instrumentation Engineers
  – Physics, PhD
  – Electrical Engineering / Physics, PhD
  – Electrical Engineering / RF, PhD
  – Physics / Lasers, PhD
  – Electronics Engineer
  – Software Engineer (VxWorks, LabView, EPICS)
  – Software Engineer (LabView)

• 5 Technicians

• 1 - 2 Post Docs

• 2 – 3 Post grad students

• Visitors (1 – 6 months)
**Beam Current Monitors**

- 23 beam current transformers in total
  - Were useful for the 1st hour of commissioning
- 4-6 are in use for operation
  - RFQ output
  - Injection dump current
  - Beam to target current
  - MEBT scrapers protection
  - ~5% accuracy

Beam pulse propagation from RFQ output to linac dump
Beam Loss Monitoring System (BLM)

- Major tool for machine protection and tune up
- Ionization Chamber Detectors (307)
- Scintillation Detectors (55)
  - Neutron detectors
  - Fast loss detectors
- Multichannel analog front-end VME cards
- Digital electronics in VME crate
- VxWorks software
Beam Loss Monitoring System
BIW2010

BLM performance and issues

• Very reliable system overall
  – Less than 10 hours of downtime per year

• Significant background from X-ray near RF cavities
  – Implemented background subtraction using no-beam pulse every 10s. (59.9Hz beam repetition rate)
  – Major limiting factor for S/N improvement

• Blind spots in some areas
  – Increased number of detectors.

• Poor loss localization with neutron detectors
  – Sufficient for machine protection
  – Less useful for machine study
Beam Position and Phase Monitors (BPM)

• Major tool for machine tune up
  – Phase measurements is basis for linac tune up
  – Position measurements for trajectory correction, injection setup and centering beam on dumps and target

• 160 4-electrode strip-line pick-ups
  – 96 “linac type” operate at linac RF harmonic
  – 64 “ring type” operate at low frequency

• Custom made PCI analog front-end and digital cards

• LabView software under embedded Windows XP on individual PCs (one per pick-up)
BPM hardware
BPM performance and issues

- Good phase and position resolution
  - Better than .5 deg (805Mhz) for phase;
  - Better than .5% of aperture for position

RMS = .45 degrees

- Issues with reliability and maintenance
  - Computers hang up
  - Motherboard to PCI card compatibility
History of BPM unscheduled reboots
An individual BPM status log

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Status Code</th>
<th>Status Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/21/2006</td>
<td>1 F</td>
<td>20060921</td>
<td>Installed squirrel cage, rerouted wiring and sensors.</td>
</tr>
<tr>
<td>9/25/2006</td>
<td>1 C</td>
<td>20060925</td>
<td>Calibrated</td>
</tr>
<tr>
<td>9/25/2006</td>
<td>1 C</td>
<td>20060925</td>
<td>Calibrated</td>
</tr>
<tr>
<td>1/12/2007</td>
<td>1 R</td>
<td>20070112</td>
<td>Set RF dist levels, checked calpulsle level &amp; S/N</td>
</tr>
<tr>
<td>1/16/2007</td>
<td>1 C</td>
<td>20070116</td>
<td>Calibrated</td>
</tr>
<tr>
<td>7/9/2007</td>
<td>1 D</td>
<td>20070709</td>
<td>Noise spikes on chld.</td>
</tr>
<tr>
<td>10/10/2007</td>
<td>1 B</td>
<td>20071010</td>
<td>Replaced Battery, reset BIOS.</td>
</tr>
<tr>
<td>1/10/2008</td>
<td>1 L</td>
<td>20080110</td>
<td>No comm. Hard reboot.</td>
</tr>
<tr>
<td>1/14/2008</td>
<td>1 L</td>
<td>20080112</td>
<td>No comm. Hard reboot.</td>
</tr>
<tr>
<td>1/14/2008</td>
<td>1 W</td>
<td>20080114</td>
<td>Reseated cards, cleaned card edge connectors.</td>
</tr>
<tr>
<td>1/14/2008</td>
<td>1 W</td>
<td></td>
<td>Removed CD Rom Drive to improve airflow.</td>
</tr>
<tr>
<td>3/10/2008</td>
<td>1 L</td>
<td>20080310</td>
<td>No comm. Hard reboot.</td>
</tr>
<tr>
<td>4/10/2008</td>
<td>1 M</td>
<td>20080410</td>
<td>Multiple reboots have been required. Replaced 7</td>
</tr>
<tr>
<td>4/10/2008</td>
<td>1 M</td>
<td>20080416</td>
<td>Electrolytic Caps on Motherboard.</td>
</tr>
<tr>
<td>4/16/2008</td>
<td>1 M</td>
<td>20080416</td>
<td>Multiple reboots still required. Replaced memory on</td>
</tr>
<tr>
<td>9/2/2009</td>
<td>1 D</td>
<td>20090902</td>
<td>Replaced DFE.</td>
</tr>
<tr>
<td>9/2/2009</td>
<td>1 M</td>
<td>20090902</td>
<td>Performed memory upgrade.</td>
</tr>
<tr>
<td>9/2/2009</td>
<td>1 O</td>
<td>20090902</td>
<td>Repaired loose connection.</td>
</tr>
<tr>
<td>9/2/2009</td>
<td>1 B</td>
<td>20090902</td>
<td>Replaced Battery, reset BIOS</td>
</tr>
<tr>
<td>9/2/2009</td>
<td>1 M</td>
<td>20090902</td>
<td>Performed memory upgrade.</td>
</tr>
<tr>
<td>9/2/2009</td>
<td>1 C</td>
<td>20090902</td>
<td>Recalibrated, uploaded new config file to database.</td>
</tr>
</tbody>
</table>
BPM reboot statistics

189 total

60 total
Transverse Beam Profile Measurements

• 40 conventional wire scanners in warm linac, transport lines, and beam dumps
  – 32um carbon wire from 2.5 to 186MeV
  – 100um Tungsten at higher energies
  – 50us, 1Hz limit on beam pulse
  – 3 wires on each actuator (horizontal, vertical, diagonal)

• Laser Wire was deployed but not fully operational during the Superconducting Linac commissioning

• No profile measurements were available for the Accumulator Ring commissioning
Wire Scanner Profile Monitor

Fork with wires

Installed wire scanners

Actuator

Amplifier
Wire scanner performance

- Satisfy base line design requirements
  - 5% accuracy of rms size (Gauss fit)
  - Dynamic range of 100 (2-3 $\sigma$ from beam center)

- Sufficient for initial commissioning and for troubleshooting serious problems

- Less useful for beam study
  - Need larger dynamic range, up to $10^4 - 10^5$
  - Need faster scan

Good wire scan reproducibility
(10 profiles overlapped)

Good agreement of RMS beam size with simulations
Increasing wire scanner dynamic range

Cross-talk between wires is the main dynamic range limiting factor for 3-wires scanner

To increase dynamic range:

- Removed diagonal wire and increased wire separation
- Increased wire thickness to 100um tungsten at $E > 20\text{MeV}$
Transverse Emittance

- Had slit-and-harp devices on temporary beam stops for commissioning
  - after RFQ (2.5 MeV)
  - after MEBT (2.5 MeV)
  - after Drift Tube Linac Tank1 (7.5 MeV)
- Installed permanent insertable slit-and-harp device in the MEBT
Emittance scanner performance

- Sufficient for initial commissioning and for troubleshooting serious problems
  - RFQ acceptance test
  - DTL acceptance test
- Less useful for beam study
  - Accuracy and resolution is not sufficient
  - Scan is too slow (~9 min per scan typically)
Typical MEBT emittance scan
Emittance scanner accuracy problem

Disagreement between measured emittance (red line) and simulation, analytical formula

Strong correlation between beam divergence and measured emittance.

Indication of a systematic measurement error
Direct beam imaging

- Phosphor view screens and CCD video cameras
  - Injection and Extraction beam dumps
- Radiation hard analog camera for injection foil imaging
Longitudinal Beam Profile Measurements

- Beam Shape Monitors (aka Feshenko device)
  - 4 BSMs in warm linac
  - 2 BSMs in High Energy Transport Line
  - 50us, 1Hz limit on beam pulse duty factor
Time-resolved longitudinal bunch size measurements

Bunch phase is not constant within macro-pulse due to beam loading

Beam loading is compensated in LLRF system
Longitudinal bunch measurements: linac problems troubleshooting

BSM107
9.2 deg

BSM111
7.4 deg

Measurements

Model
BSM performance

- BSMs performed very well during commissioning
  - Large dynamic range (up to $10^4 - 10^5$)
- Need further improvements
  - Increase resolution. Currently is $\sim 1^\circ \text{ @805MHz}$
  - Reduce effect of stray magnetic fields on BSM tuning

![Typical longitudinal bunch profile](image1)

![Measured longitudinal bunch size vs. model](image2)
What we learned from commissioning and power ramp up experience

- The base line set of the SNS diagnostics and performance requirements were well suited for commissioning and power ramp-up.

- Diagnostics requirements for daily operation and post-commissioning beam study are quite different.

- Development of new or modification of the existing diagnostics on an operating machine takes long time, therefore be proactive in developing the next generation of diagnostics.
Our new goals and priorities

1. Diagnostics required for 24/7 operation (BLMs, BCMs,....)
   - reliability
   - easy maintenance

2. Diagnostics for routine machine tuning (BPMs, harp,...)
   - user friendly interface,
   - speed,
   - accuracy

3. Diagnostics for high intensity beam study
   - resolution, accuracy
   - large dynamic range
   - speed

4. Tools for beam control
   - feedback
   - laser stripping
Beam Loss Monitors System Development

• Front-end electronics upgrade
  – Independent 1 channel per board and 1 power supply per board design (vs. existing 12 channels per board per power supply design)
  – Hot swappable boards

• Dual PMT based detectors
  – Very efficient noise and X-ray background cancellation
  – Dual detector design is immune to single channel failure

Data Acquisition tested at 300 Hz
Beam Profile Measurements

• Upgrade conventional tools to state-of-the-art level
  – Wire scanners
  – Slit/collector emittance scanner in the MEBT
  – Beam Shape Monitors

• Develop non-perturbing diagnostics for H-beam
  – Transverse laser wire in the superconducting linac
  – Longitudinal laser wire in the MEBT (2.5 MeV)
  – Laser wire emittance station in the HEBT (1Gev)

• Develop non-perturbing diagnostics for proton beam in the accumulator ring
  – Electron-beam profile scanner
  – Ionization Profile Monitor
Principle of operation of SNS “laser wire”
Layout of the SNS laser wire system

- Laser room (LR)
- Laser wire station
- Cryomodule number (32)
- Camera
- Mirror
- Power meter

250 m 225 m 150 m 25 m

MEBT DTL CCL SCL

Ring

Target
Laser pointing stability was a problem

\[ \sigma_x = 6.19 \]
\[ \sigma_y = 16.19 \]

\[ \sigma_x = 3.24 \]
\[ \sigma_y = 5.35 \]
Laser pointing stability improvement

Feedback off

Feedback on

May 29, 2009

Apr. 1, 2010

Apr. 22, 2010

6.2×16.2

4.8×9.6

3.4×3.0

3.2×5.4

3.1×3.8

1.2×1.4
Typical laser wire measurements

LW1

LW5

LW9
Profile measurements within a mini-pulse

Shift of the profile peak position was observed

Laser-beam interaction location (~30 ns steps)
Remaining laser wire issues

- Laser power variation at interaction point
  - Uncontrolled reflections, interference?

- Dynamic range limit of ~100
  - Uncontrolled reflections?

![Raw signal from the laser wire Faraday cup](image)

In the beam center

10 sigma off the beam center
Electron scanner principle of operation
Electron scanner hardware for SNS proton accumulator ring

Magnet power supplies

HV power supplies

PXI: Acquisition and Control

Designed and built by Budker Institute of Nuclear Physics in Novosibirsk
Software: Image Analysis
Measurements repeatability

- Twenty profiles taken without changing settings
- Has resolved vertical jitter problem recently
- Absolute calibration is under question (disagreement with the model)
Ring Feedback System Layout

Consists of 2 independent systems

Vertical (Up and Down)
Horizontal (Left and Right)

200 Watts of power per channel
Capable of 800 Watts total for system

Low Level RF

Fiber optic delay
Comb filter

RF Power Amplification

Beam

Pickup + Cable
Kicker + Cable
Pick-up and kicker hardware
Feedback system electronics

Broad band amplifier.
1-300 MHz BW
Damping of vertical e-p instability

Vertical damping **on** 40 dB

Vertical damping **off**

Vertical damping **on** 20 dB

Vertical damping **on** 30 dB
Other non-perturbing diagnostics

• Longitudinal profile laser scanner in MEBT (2.5MeV)
  – Was designed and build quickly for emergency linac troubleshooting
  – Decommissioned due to lack of resources
  – Plan to revive and improve

• Transverse emittance laser scanner in HEBT (1GeV)
  – Have designed and built
  – Install this summer
  – Commission in fall 2010

• Ionization profile monitor for proton ring
  – Being developed
Thank you for attention