Status of the SNS Linac: An Overview

N. Holtkamp for the SNS Collaboration
ORNL, Oak Ridge, TN 37830, USA
SNS is the Forefront Facility for Future High Beam Power Accelerators

Highest Beam Power worldwide under construction

Stepping stone to next generation Spallation Sources

- The SNS will begin operation in 2006
- At 1.4 MW it will be ~8x ISIS, the world’s leading pulsed spallation source
- The peak thermal neutron flux will be ~50-100x ILL
- 5000 hours per year at an availability of >90% ...... !!!!!!!!!! (~ in 2009)

The Spallation Neutron Source Partnership

<table>
<thead>
<tr>
<th>Description</th>
<th>Accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Support</td>
<td>75.6</td>
</tr>
<tr>
<td>Front End Systems</td>
<td>20.8</td>
</tr>
<tr>
<td>Linac Systems</td>
<td>315.9</td>
</tr>
<tr>
<td>Ring &amp; Transfer System</td>
<td>142.0</td>
</tr>
<tr>
<td>Target Systems</td>
<td>108.2</td>
</tr>
<tr>
<td>Instrument Systems</td>
<td>63.3</td>
</tr>
<tr>
<td>Conventional Facilities</td>
<td>378.9</td>
</tr>
<tr>
<td>Integrated Control System</td>
<td>59.7</td>
</tr>
<tr>
<td>BAC</td>
<td>1,164.4</td>
</tr>
<tr>
<td>Contingency</td>
<td>28.3</td>
</tr>
<tr>
<td>TEC</td>
<td>1,192.7</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>100.0</td>
</tr>
<tr>
<td>Pre-Operations</td>
<td>119.0</td>
</tr>
<tr>
<td>TPC</td>
<td>1,411.7</td>
</tr>
</tbody>
</table>

SNS-ORNL Accelerator systems: ~167 M$

At peak: ~500 People worked on the construction of the SNS accelerator.

Oak Ridge, TN
35° 49' N, 83° 59' W
• The Multi Lab Organization of SNS has brought an enormous amount of expertise to the table.

• It has made it easier to transition the required workforce in and out of the project.

• SNS is just one of several models that I'm sure will be used to build large science projects in the future.

• The Multi Lab Org Chart for SNS is in many ways is not different than a typical one, but it does add a few layers of management.
Project Status

- Total cost is $1.4 B (US accounting), peaked in 2002 with $290 M.
- Project has costed or/and awarded almost $1.2B out of $1.4B
  - Overall project design is 94% complete
  - Overall the project is >84% complete (as of July)
  - Within budget and schedule constraints ($1.4B and June 2006 completion)
- ES&H performance outstanding
  - >5 million hours with one lost workday injury (combined hours worked for construction site and SNS/ORNL)
16 Instruments Now Formally Approved

- Fundamental Physics to Engineering
- Chemistry to “Genomes to Life”
Construction Nearing the End
Major SNS Facility Parameters

- Injector 2.5 MeV
- RFQ 86.8 MeV
- DTL 186 MeV
- CCL 387 MeV
- SRF, $\beta=0.61$ 402.5 MHz
- SRF, $\beta=0.81$ 805 MHz
- HEBT 1000 MeV
- To Ring

1 RFQ
6 DTL Tanks
4 CCL Modules

11 Medium-$\beta$ Cryomodules - 3 Nb cavities each
12 High-$\beta$ Cryomodules - 4 Nb cavities each

1.0 GeV Ring
Up to 1.3 GeV

Lq Mercury Target
The SNS Ion Source

• Since Jan. '04 an SNS ion source is almost continuously in operation, 24/7, mostly unattended during nights and weekends.

• Since end of April '04 three runs have achieved a 6% and 5 runs a 7.4% duty cycle. All 8 runs were terminated after 1-2 weeks.

• No antenna failures have been detected.

• An operational run is typically terminated when the source output drops below 20-25 mA.
The SNS Ion Source

• Typically the initial peak current exceeds the average current by ~30%.

<table>
<thead>
<tr>
<th>1st Cesiation</th>
<th>2nd Cesiation</th>
<th>3rd Cesiation</th>
<th>4th Cesiation</th>
<th>5th Cesiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>36 kW</td>
<td>50 kW</td>
<td>60 kW</td>
<td>LDF</td>
<td></td>
</tr>
</tbody>
</table>

Source #3

- begin 2% oper
- begin 4% oper
- 3rd Cesiation
- 2nd Cesiation
- 4th Cesiation
- 5th Cesiation

Typically the initial peak current exceeds the average current by ~30%.
LBNL: Design And Built Front End

2.5 MeV RFQ

Ion Source
Drift Tube Linac Components

DTL 1 in the tunnel ...

Here it goes ...

See S. Aleksandrov's Talk: WE 201
All DTLs

- 402.5 MHz DTL designed at LANL
- Components built to spec in industry (plating at GSI)
- Assembled largely at ORNL

- All DTLs installed with 210 drift tubes in place.
- Operates at 1.3 x Kilpatrick max.
- Drift tubes have integrated permanent magnet quads
- 24 steering dipoles
- 10 beam position + phase monitors
- 12 beam loss monitors
- 6 beam current monitors 6
- 5 wire scanners
- 5 Faraday cups
- 12 neutron detectors
Tank 3 Conditioned to Full Field and 40% Duty Factor in 30 hr!

Increase $P_{\text{peak}}$  
Increase $P_{\text{ave}}$

$r$f Power (kW)

$P_{\text{forward}}$

$P_{\text{reflected}}$

00:00:00  
May 02. 03

20:00:00  
May 02. 03

16:00:00  
May 03. 03
DTL 1-3 Commissioning: 40 MeV

- Can only run very short pulse and little beam power from now on.
- Beam Commissioned DTL1-3 in April 2004:
  - Had beam through DTL3 36 hours after approval for operation:
    - Achieved design 38 mA peak current
    - 100% transmission
Coupled-Cavity Linac (CCL) Construction by LANL done in Industry

- Contract awarded to Industry
- Hot model operated at 130% of peak field and 190% average power

Bridge Coupler 44 final machining
Segment 1-6 fiducial machining
Production Segments
Coupled-Cavity Linac Deliveries Support
September 2004 Commissioning Start

- 55 m long linac divided into 4 modules
- Designed at LANL, build and tuned in industry.
- Operates at 1.3 x Kilpatrick max.
- 48 quadrupoles and 32 steering magnets between segments.
- 10 beam position and phase monitors
- 28 beam loss monitors 1 current monitors
- 7 wire scanners
- 1 Faraday cups
- 3 bunch shape monitors
- 8 neutron detectors
CCL1 Module 1 Successfully RF Conditioned

Achieved: 2.5 MW (~120% of nominal power) @ 20Hz, 1ms after 5 x 12 hour shifts
• 11 HVCM out of 14 for the linac are installed.
• All 11 have been operated/tested.
• Combination of built to spec/built to print contract in industry.
• They have operated a total of ~8000 h at a variety of $\eta$ with approximately 1500 at full load ($\eta=7.5\%$).
• Depending on the klystron the operate between 75 and 115kV driving up to 12 klystrons in parallel.
• Have a very compact IGBT driven high Frequency (20kHz) converter with a compact polyphase transformer.
• The power density in the modulator compared to ~20 y ago went up by ~ x50. .... Which has its challenges!
High-Power RF Installation Progress

- All RFQ / DTL HPRF Systems complete and operational. 2.5 MW - 402.5MHz klystron with 2-3 per HVCM.
- All four CCL systems are complete. 5 MW – 805MHZ klystron with 1 per HVCM.
- 60 of 81 SCL klystrons installed. 550kW- 805MHz klystrons with typically 12 per HVCM.
  - 2 SCL modulators tested
- All klystrons are made in industry in Europe and the US.
• Status of each Klystron, HVCM and transmitters displayed along with a description of its readiness.
DTL-CCL Commissioning And Cryomodule Testing In The Tunnel Sept. 04

- The DTL – CCL enclosure will include the whole linac as one PPS area. Decided to install shielding wall between CCL and SCL to minimize interference with conditioning, commissioning and SCL installation and testing.
- SCL cryomodule testing in the tunnel will begin mid-August.
Superconducting RF Advantages:

1. Flexibility  ➔ gradient and energy are not fixed
2. More power efficient  ➔ lower operational cost
3. High cavity fields  ➔ less real estate
4. Better vacuum  ➔ less gas stripping
5. Large aperture  ➔ less aperture restrictions  ➔ reduced beam loss  ➔ reduced activation
The Superconducting Linac

- All 81 + 25 cavities are built, chemically pre treated and initially tuned in industry

- Linac has a total of 23 CM’s; 11 medium $\beta$ (MB) and 12 high $\beta$ (HB). 9 more slots available.

- Cavities over-perform by ~25 % compared to spec for MB and HB. So far tested at JLab only.

- Linac is 157 m long and has 32 warm sections between CM’s and 67 quadrupoles with h+v steerer windings and a special laser diagnostics for emittance measurements

<table>
<thead>
<tr>
<th>Medium Beta</th>
<th>7</th>
<th>3</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM – in tunnel tested</td>
<td>CM – in tunnel untested</td>
<td>CM – complete at JLab</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High Beta</th>
<th>0</th>
<th>1</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM – in tunnel tested</td>
<td>CM – in tunnel untested</td>
<td>CM – complete at JLab</td>
<td>CM – in progress</td>
<td>Cavities delivered</td>
</tr>
</tbody>
</table>
SNS Medium Beta Cryomodule

3 cavity / CM layout
for Med $\beta$ CM

4 cavity / CM layout
for Med $\beta$ CM

11 CM’s in the SNS Tunnel
High $\beta$ Cryomodule 5 + 6 at JLab

- Test of first 2 CM in the tunnel has started as of last week.

- Testing of cryomodules at JLab includes the first 12. All results shown are from there.

- Test of the remaining eleven is done at SNS in the tunnel.
Med. $\beta$ CM Performance $E_{acc} @ Q_o = 5 \times 10^9$
High $\beta$ CM Performance $E_{\text{acc}} @ Q_0=5\times10^9$
Medium \( \beta \) CM Versus Vertical Test

- MB1, 2, 3, 4, 6
- MB5 Partial Conditioning
- MB8 Improved Procedures
- MB8, 11 Final Procedures

23%
High $\beta$ CM Versus Vertical Test

- HB1 Cavity #1, 3, 5
- HB1 Cavity #7

23%
• If we could keep all cavities @ 100Hz, the presently installed rf system can support ~ twice the beam power.

• 1 HB had a resonance and was x4 out of spec. Not clear why yet.
The Low-level RF Control System

- Production systems 97% complete.
  - Collaboration between LBNL, LANL and ORNL.
  - Production is under way with 20 units delivered.
  - LANL supporting ORNL with ECAD, EPICS vendor QA, acceptance testing, installation (consulting & change-of-station assignments)
  - LBNL continues to do FPGA code development.
- Installation and Integration in the Tunnel is underway.
FCM Test On A Cryomodule

11.3 MV/m, 30 Hz, 1.2 ms, 2.1 K

• specification of ±1%, ±1deg
• ±0.1%, ±0.2deg achieved
SNS CHL Facility

- Cold box specifications are:
  - 8300 Watts on the shield
  - 2400 Watts @ 2.1 Kelvin
  - 15g/s Liquefaction
• Transfer line is installed for 9 additional cryomodules to be ready for the linac energy upgrade

• Transfer line; tested and leak checked. Same for expansion cans and piping.

• Built in house at OR
SNS Warm Compressor

- Procured by JLab in industry

- Warm compressors are operating after initial issue with heat exchangers.

- Three streets with one being redundant.
SNS 4.5 K Cold Box

- Procured by JLab in industry
- 4K Coldbox has operated in 3 different runs and is considered commissioned.
- July: Reached 100% of spec with lowered interstage pressure and somewhat lower efficiency.
- Presently transferline and 2 CM are at 4.5 K for test.
The 2.1K Cold Box

- Procured by JLab in industry.
- Had several issue due to shipment damage of turbines.
- Have still an issue with electrical feedthroughs that drive the turbines.
- Run foreseen in October after 4.5 K cooldown of transferline and cavities for first systems check.
**SNS Diagnostics Deployment**

**MEBT**
- 6 Position
- 2 Current
- 5 Wires
  - [2 Thermal Neutron]—9/04
  - [3 PMT Neutron] —9/04
- 1 Emittance
  - [1 fast faraday cup]—9/04
- 1 faraday/beam stop
- D-box video
- D-box emittance —9/04
- D-box beam stop
- D-box aperture
- Differential BCM
  - [laser prototype]—9/04

**RING**
- 44 Position
- 2 Ionization Profile
- 70 Loss
- 1 Current
- 5 Electron Det.
- 12 FBLM
- 2 Wire
- 1 Beam in Gap
- 2 Video
- 1 Tune

**RING**
- 44 Position
- 2 Ionization Profile
- 70 Loss
- 1 Current
- 5 Electron Det.
- 12 FBLM
- 2 Wire
- 1 Beam in Gap
- 2 Video
- 1 Tune

**IDump**
- 44 Position
- 2 Ionization Profile
- 70 Loss
- 1 Current
- 5 Electron Det.
- 12 FBLM
- 2 Wire
- 1 Beam in Gap
- 2 Video
- 1 Tune

**SCL**
- 32 Position
- 86 Loss
- 1 Wire
- 5 Electron Det.
- 12 FBLM
- 2 Wire
- 1 Beam in Gap
- 2 Video
- 1 Tune

**CCL**
- 10 Position
- 9 Wire
- 8 Neutron
- 48 Loss
- 3 Bunch
- 1 Faraday Cup
- 1 Current
- 6 BLM

**HEBT**
- 29 Position
- 11 Wire
- 46 BLM, 3 FBLM
- 4 Current
- 1 Harp
- 3 FBLM

**LDump**
- 6 Loss
- 6 Position
- 1 Wire

**CCL/SCL Transition**
- 2 Position
- 1 Wire
- 1 Loss
- 1 Current

**EDump**
- 1 Current
- 4 Loss
- 1 Wire

**DTL**
- 10 Position
- 5 Wire
- 12 Loss
- 5 Faraday Cup
- 6 Current
- 6 Thermal and 12 PMT Neutron

**RTBT**
- 17 Position
- 36 Loss
- 4 Current
- 5 Wire
- 1 Harp
- 3 FBLM

**Operational**
- FY04

**New to 2004**

**New to FY04**

**½ Laser in 04**

**FY2004/5**

**FY04**

**FY2004/5**

**New to FY04**

**½ Laser in 04**

**FY04**

**FY2004/5**

**New to FY04**

**½ Laser in 04**

**FY04**

**FY2004/5**
Diagnostics Is Online During Commissioning

- Position, phase
- Current (toroids)
- emittance
- Current (MEBT beam stop)
- Current (DTL Faraday cup)
- Loss (neutron)
- Profile (wires)
- Current (D-plate beam stop)
- Halo
- Bunch shape
SCL Laser Transport-line Installation:
Laser Profile Monitor Progress

- Verification of electron collector for SCL laser profile monitor
- Reliable measurements to about 3 \textit{sigma}
- Anti-reflection coating has been applied to the final windows.
- We expect an order of magnitude improvement in signal to noise ratio.

**Horizontal Profile**

Gaussian fit plotted out to 2.5x Sigma
Sigma = 1.07 mm

**Signal from electron collector**
Top: laser intercepting beam core
Bottom: laser intercepting beam tail
**BNL: The Accumulator Ring and Transfer Lines**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nr of injected turns</td>
<td>1060</td>
</tr>
<tr>
<td>Ring revolution frequency (MHz)</td>
<td>1.058</td>
</tr>
<tr>
<td>Ring filling fraction (%)</td>
<td>68</td>
</tr>
<tr>
<td><strong>Ring transverse emittance (99%)</strong></td>
<td>( \pi \text{mm mrad} ) 240</td>
</tr>
<tr>
<td><strong>Ring transverse acceptance</strong></td>
<td>( \pi \text{mm mrad} ) 480</td>
</tr>
<tr>
<td><strong>Space charge Tune shift</strong> ( \Delta Q_{x,y} )</td>
<td>0.15</td>
</tr>
<tr>
<td>Peak Current</td>
<td>52 A</td>
</tr>
<tr>
<td>HEBT / RTBT Length (m)</td>
<td>170 / 150</td>
</tr>
<tr>
<td>Ring Circumference (m)</td>
<td>248</td>
</tr>
<tr>
<td>RTBT transverse acceptance ( \pi \text{mm mrad} )</td>
<td>480</td>
</tr>
<tr>
<td>Beam size on target (HxV) mm x mm</td>
<td>200x70</td>
</tr>
</tbody>
</table>

**Totals:**
- 235 Low Power Bipolar Supplies (< 5 kW)
- 24 Medium Power Bipolar Supplies (5-50 kW)
- 101 Medium Power Supplies (5-50 kW)
- 42 High Power Supplies (>50 kW)
- 22 Kicker Power Supplies

Baseline: 1.0 GeV, 2 MW
Designed and built for 1.3 GeV

Several commissioning beam dumps
• Beam line installation “Linac to Ring” complete.
• Ring installation ~ 80% complete.
• Beam line installation “Ring to Target” has not started.

• The ring has an aperture of 460 \( \pi \text{ mm} \text{ mrad} \) (~ 15 cm diameter) to allow a 25 A average circulating current.

• Energy per pulse is ~ 25 kJ.
Prompt dose levels during operation (2 MW) – 1500 rem/hr@ working area (Franz Gallmeier)
Residual levels 2 hours – 1 week after shutdown, factor of ~1000 less – 1.5 rem/hr
Updated dose rate calculations underway with existing design (Irina Popova)
Recent calculated dose rates for dumps & back streaming from target (DH13) are very high
Status as of July 2004 with construction activity limited to Target & Central Laboratory building and Nano Science Center
Target Monolith Region

Monolith Installation - Sept 2003

Core Vessel and Shielding
Target Installation
The SNS Target: 2-MW Design

- Cavitation-induced pitting is an issue.
- Options for mitigation:
  - Materials, Geometry → Mitigation
- 25 kJ/pulse at 7x15cm beam size sets of transverse and longitudinal shock wave.
- “Peanuts” compared the Muon target!
- Needs to be exchanged every 3 months

Pits on inner surface in this geometry
Primary Concern: **Uncontrolled Beam Loss**

- Hands-on maintenance: no more than 100 mrem/hour residual activation (4 h cool down, 30 cm from surface)
- 1 Watt/m uncontrolled beam loss for linac & ring
- Less than $10^{-6}$ fractional beam loss per tunnel meter at 1 GeV; $10^{-4}$ loss for ring
## A 20-Year Plan - The Long Term Future for SNS

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Upgrade</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy, $E_k$ [MeV]</td>
<td>1000</td>
<td>1300</td>
<td>1400</td>
</tr>
<tr>
<td>Beam power on target, $P_{\text{max}}$ [MW]</td>
<td>1.4</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Chopper beam-on duty factor [%]</td>
<td>68</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Linac beam macro pulse duty factor [%]</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Average macropulse H- current [mA]</td>
<td>26</td>
<td>42</td>
<td>65</td>
</tr>
<tr>
<td>Peak Current from front end system</td>
<td>38</td>
<td>59</td>
<td>92</td>
</tr>
<tr>
<td>Linac average beam current [mA]</td>
<td>1.6</td>
<td>2.5</td>
<td>3.9</td>
</tr>
<tr>
<td>SRF cryo-module number (med-beta)</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>SRF cryo-module number (high-beta)</td>
<td>12</td>
<td>12 + 8 (+1 reserve)</td>
<td>12 + 8 (+1 reserve)</td>
</tr>
<tr>
<td>Number of SRF cavities</td>
<td>33+48</td>
<td>33+80 (+4 reserve)</td>
<td>33+80 (+4 reserve)</td>
</tr>
<tr>
<td>Peak gradient, $E_p (\beta=0.61 \text{ cavity})$ [MV/m]</td>
<td>27.5 (+/- 2.5)</td>
<td>27.5 (+/- 2.5)</td>
<td>27.5 (+/- 2.5)</td>
</tr>
<tr>
<td>Peak gradient, $E_p (\beta=0.81 \text{ cavity})$ [MV/m]</td>
<td>35 (+2.5/-7.5)</td>
<td>31</td>
<td>34</td>
</tr>
<tr>
<td>Ring injection time [ms] / turns</td>
<td>1.0 / 1060</td>
<td>1.0 / 1100</td>
<td>1.0 / 1110</td>
</tr>
<tr>
<td>Ring rf frequency [MHz]</td>
<td>1.058</td>
<td>1.098</td>
<td>1.107</td>
</tr>
<tr>
<td>Ring bunch intensity [$10^{14}$]</td>
<td>1.6</td>
<td>2.5</td>
<td>3.8</td>
</tr>
<tr>
<td>Ring space-charge tune spread, $\Delta Q_{sc}$</td>
<td>0.15</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Pulse length on target [ns]</td>
<td>695</td>
<td>691</td>
<td>683</td>
</tr>
</tbody>
</table>
Summary

• The SNS project is still on track for achieving a June 06 finish date within the appropriated 1.4 Billion $. The construction is more than 85% complete.
• The program has benefited from enormous support in Washington with funding appropriated every year as planned.
• Commissioning has progressed as installation continues with 40MeV achieved at full spec.
• The next major step is the commissioning of complete warm linac (DTL + CCL).
• The full linac should be in commissioning next spring during PAC 05.

• It has been and still is a very successful collaboration between six partnering DOE laboratories.
• Please come visit us next year during PAC or whenever you get a chance.
PAC05

• PAC 05 will be in Knoxville, TN, 25 miles from the site.
• There will be a site tour on Saturday
• Please come to visit us…..