Status of the Spallation Neutron Source: Machine and Science

Stuart Henderson
Oak Ridge National Laboratory

PAC 2007
June 25, 2007
The Spallation Neutron Source

- The SNS at Oak Ridge National Laboratory is a short-pulse neutron source, powered by a 1.4 MW proton accelerator.

- At 1.4 MW it will be ~8x ISIS beam power, the world’s leading pulsed spallation source.

- The SNS construction project, a collaboration of six US DOE labs, began in 1999 and was completed on-time and within budget in June 2006 at a cost of 1.4 B$.

- SNS began formal operation in October 2006, and now routinely provides neutron beams to three scattering instruments.

- SNS will become the world’s leading facility for neutron scattering.
Why Neutrons?

1. Neutrons have the right wavelength
   Neutrons probe a broad range of length scales

2. Neutrons measure the velocity of atoms
   Neutrons follow catalysts in action; transport through biological membranes

3. Neutrons see the nuclei
   Can offer greater contrast than x-rays (e.g. H); isotopic contrasting

4. Neutrons see light atoms next to heavy ones
   Crucial Oxygen positions in Hi-Tc superconductors; neutrons see H; study H-bonds (chemistry and biology)

5. Neutrons penetrate deep into matter
   Study material properties deep inside materials; characterizing deep welds and their associated stresses

6. Neutrons see elementary magnets
   Study magnetic structure of materials; advanced magnetic materials
The Beam Power Frontier for Protons

- Central challenge at the beam power frontier is controlling beam loss to minimize activation
- 1 nA protons at 1 GeV, a 1 Watt beam, activates stainless steel to 80 mrem/hr at 1 ft after 4 hrs
- Demands careful control of beam injection/extraction

Courtesy J. Wei
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

Liquid Hg Target

2.5 MeV

1000 MeV

Chopper system makes gaps

mini-pulse

1 ms macropulse

Current

Current

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PAC 2007, June 25, 2007
• First Beam on Target, First Neutrons and Technical Project Completion goals were met April 28, 2006
  - $10^{13}$ protons delivered to the target
  - Neutron flux goals exceeded

• The SNS Construction Project was formally Completed in June 2006
SNS Linear Accelerator

- Front-end was designed and built by Lawrence Berkeley National Laboratory
- Multicusp Cs-enhanced volume production H- ion source
SNS Linear Accelerator

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- Multicusp Cs-enhanced volume production H- ion source
- Electrostatic LEBT (Low-energy beam transport)
- Chopping of 65 keV beam in LEBT and 2.5 MeV beam in MEBT
SNS Linear Accelerator

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- Multicusp Cs-enhanced volume production H- ion source
- Electrostatic LEBT (Low-energy beam transport)
- Chopping of 65 keV beam in LEBT and 2.5 MeV beam in MEBT
- 402.5 MHz RFQ with 2.5 MeV output energy
- Front-end design parameters:
  - 38 mA peak current
  - 68% beam-on chopping
  - 1.0 msec, 60 Hz, 6% duty
  - 1.6 mA average current
SNS Linear Accelerator

- SNS linac is the world’s highest energy proton/H- linac
  - Achieved 1.01 GeV in a demonstration run

- SNS linac architecture consists of
  - Conventional normal conducting structures to 186 MeV
  - Superconducting structures to 1 GeV
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- DTL system consists of 6-tanks, each powered by 2.5 MW, 402.5 MHz klystron
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- DTL system consists of 6-tanks, each powered by 2.5 MW, 402.5 MHz klystron

- CCL system consists of 4 modules, each powered by a 5 MW, 805 MHz klystron; 12 segments form a module
SNS Linear Accelerator

- World’s first high-energy superconducting linac for protons
- Cryomodules designed and built by Jefferson Laboratory
- Two cavities geometries, ($\beta_g=0.61$, $0.81$) are used to cover broad range in particle velocities

[Diagram showing a linear accelerator with stages: H-, RFQ, DTL, CCL, SRF, $\beta=0.61$, SRF, $\beta=0.81$, Reserve]

Medium beta cavity

High beta cavity

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**SNS Linear Accelerator**

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- SCL consists of 81 independently-powered 805 MHz cavities, each driven by a 550 kW klystron, in 23 cryomodules
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- SCL consists of 81 independently-powered 805 MHz cavities, each driven by a 550 kW klystron, in 23 cryomodules
- Space is reserved for additional cryomodules to give 1.3 GeV
- He plant supports operation at 4 or 2 degrees K
Linac RF Systems
Champion (FRXC01)

- Designed by Los Alamos Nat. Lab
- All systems 8% duty factor: 1.3 ms, 60 Hz
- 7 DTL Klystrons: 2.5 MW 402.5 MHz
- 4 CCL Klystrons: 5 MW 805 MHz
- 81 SCL Klystrons: 550 kW, 805 MHz
- 14 IGBT-based modulators each providing 1 MW average power
- Digital RF controls with feedback and feedforward
- 2nd largest klystron and modulator installation in the world!
Front-End Commissioning and Performance

- Challenges:
  - High current (38 mA) and duty factor (6% beam duty)
  - Small emittance
  - Chopping system performance
  - Source lifetime

- Ongoing R&D program to develop long-lived ion sources at design parameters; Welton (FRAA902)

- Front-end emittance specifications are met at design current

- LEBT and MEBT chopper systems meet risetime and extinction ratio specifications

- Reliability of chopper systems has been a limitation in early operation; Aleksandrov (TUPAS073)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline Design (Front-End)</th>
<th>Achieved (Ion Source)</th>
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<tr>
<td>Peak Current</td>
<td>38 mA</td>
<td>60</td>
<td>50</td>
<td>17</td>
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<tr>
<td>Pulse Length</td>
<td>1.0 msec</td>
<td>1.25</td>
<td>1.0</td>
<td>0.3-0.5</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>60 Hz</td>
<td>60</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Average Current</td>
<td>1.6 mA</td>
<td>2.5 mA</td>
<td>1.05 mA</td>
<td>70 μA</td>
</tr>
<tr>
<td>Emittance (rms,norm)</td>
<td>&lt;0.3 πmm-mrad</td>
<td>0.22</td>
<td>0.29, 0.26</td>
<td>N/A</td>
</tr>
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SNS Linac Operation and Performance

- **Challenges**
  - Stringent beam loss constraints of 1 Watt/m
    - Requires accurate RF setpoint determination
    - Careful phase-space matching
  - Output beam quality, particularly emittance growth
    - Requires careful matching
    - Good stability of phase/amplitude
    - Compensation of heavy beam loading with adaptive feedforward methods
  - Evolving SC cavity setpoints
    - Rapid methods to use inherent flexibility of individually powered cavities

- **Longitudinal Setpoints** determined with “Phase Scan Signature Matching” that uses time-of-flight measurements with a model-based algorithm to determine
  - input energy
  - beam-RF phase and
  - RF amplitude

Galambos, TUOCC01
Superconducting Linac Operation
Campisi (WEPMS072), Kim (WEPMS076), Stout (MOPAS082)

- Operating at 30 Hz, 2.1 K, 890 MeV, with 75 cavities online of 77 available (one CM has been removed)
- Operating gradients are shown; individual cavity limits are higher
- We are operating ~6 cavities with unusual HOM signals that indicate electron activity
- The inherent flexibility of individually powered cavities is used to “tune-around” an unpowered cavity.
- A rapid method (1 minute) for “fault recovery” is used to rephase the linac in response to RF setpoint changes
- We are constructing an SRF Facility for maintenance, repair and development

**Graph:**
- Accelerating Gradient (MV/m)
- Cavity number
- Design gradient
- Average operating gradient

**Annotations:**
- Large fundamental power through HOM coupler
- Field probe and/or internal cable (control is difficult at rep. rate >30 Hz)
## SNS Linac Performance Specifications

**Aleksandrov (TUPAS074, THOAAB01)**

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<th>Baseline Design</th>
<th>Achieved</th>
<th>Routine Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>1000</td>
<td>1010 ✓</td>
<td>890</td>
</tr>
<tr>
<td>RMS normalized</td>
<td>&lt;0.4</td>
<td>0.3, 0.3 ✓</td>
<td></td>
</tr>
<tr>
<td>output emittance (π mm-mrad)</td>
<td></td>
<td>(25 mA, 50 µs)</td>
<td></td>
</tr>
<tr>
<td><strong>Pulse to pulse jitter</strong></td>
<td>+/- 1.5 MeV</td>
<td>+/- 1.3 MeV ✓</td>
<td></td>
</tr>
<tr>
<td><strong>Average current</strong></td>
<td>1600 µA</td>
<td>100 µA</td>
<td>70 µA</td>
</tr>
<tr>
<td><strong>H-/pulse</strong></td>
<td>$1.6 \times 10^{14}$</td>
<td>$1.0 \times 10^{14}$</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td><strong>RF phase/amplitude stability</strong></td>
<td>1 deg/1%</td>
<td>0.5 deg/ 0.5% ✓</td>
<td>1 deg/1% ✓</td>
</tr>
</tbody>
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- Emittance growth can be controlled
- SNS linac, with independently powered cavities is extremely flexible
- Linac beam dynamics can accommodate unpowered SC cavities with little or no impact on beam quality
Accumulator Ring and Transport Lines

- Designed and built by Brookhaven National Lab
- Accumulates 1-msec long beam pulse by multi-turn charge exchange injection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Circum</td>
<td>248 m</td>
</tr>
<tr>
<td>Energy</td>
<td>1 GeV</td>
</tr>
<tr>
<td>$f_{rev}$</td>
<td>1 MHz</td>
</tr>
<tr>
<td>$Q_x, Q_y$</td>
<td>6.23, 6.20</td>
</tr>
<tr>
<td>Accum turns</td>
<td>1060</td>
</tr>
<tr>
<td>Final Intensity</td>
<td>$1.5 \times 10^{14}$</td>
</tr>
<tr>
<td>Current</td>
<td>26 A</td>
</tr>
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</table>
Accumulator Ring Performance
Plum (THXAB03), Cousineau (TUOBKI01)

- Challenges
  - High-intensity
    - Careful consideration and control of collective effects
  - Stringent beam loss constraints < 1 W/m
    - Phase-space painting
    - Dual-harmonic RF
    - 2-stage collimation
  - Beams from H-stripping inefficiency must be cleanly transported

- World Record proton intensity accumulated and extracted from a storage ring: $0.96 \times 10^{14}$ protons

- No instabilities with 1000 turns storage!
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<tr>
<td>Protons/pulse extracted</td>
<td>$1.5 \times 10^{14}$</td>
<td>$0.96 \times 10^{14}$</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td>Protons/pulse on target</td>
<td>$1.5 \times 10^{14}$</td>
<td>$5.3 \times 10^{13}$</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td>Current</td>
<td>26 Amps</td>
<td>17 Amps</td>
<td>5</td>
</tr>
<tr>
<td>Turns Accumulated</td>
<td>1060</td>
<td>830</td>
<td>500</td>
</tr>
<tr>
<td>Space charge tuneshift</td>
<td>0.15</td>
<td>0.10</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Ring Beam Current Monitor:
15 µC, 33 Amp peak
Ramp Up to SNS Design Capability

- Beam Power Goal
- Neutron Production Hours
- Reliability

Months since October 1, 2006

FY07 FY08  FY09

0 12 24 36

0 50 100 1500

0 500 1000 1500

Beam Power (kW, Production Hrs)

Reliability
Accelerator Performance Highlights

- SNS began formal operations October 1, 2006
- “Brightest” pulsed spallation neutron source: highest single pulse intensity in routine operation, 6 kJ/pulse
  - 30 kW, 5 Hz, 6.7 μC per pulse
- Routine operation at 60 kW for neutron production
  - 15 Hz, 890 MeV, 4.5 μC/pulse
- Achieved 90 kW in demonstration run
  - 15 Hz, 890 MeV, 6.7 μC/pulse
- We recently passed a readiness review to allow operation up to 2 MW beam power
Ramp-Up Progress to Date: Beam Power on Target

Energy and Power on Target

Accumulated Energy (MWh)

Date

Power (kW)

10/01 2006
10/31 2006
11/30 2006
12/30 2006
01/29 2007
02/28 2007
03/31 2007
04/30 2007
05/30 2007
06/29 2007

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Ramp-Up Progress to Date: Beam Power on Target

![Graph showing energy and power on target with dates from 10/01/2006 to 06/29/2007. The graph indicates the accumulated power and energy over time, with a marked increase in power as of 03/31/2007. There is also a highlighted section labeled "Administrative Power Limit." ]
Ramp-Up Progress to Date: Beam Power on Target

Energy and Power on Target

Accumulated Energy (MWh)

Power (kW)

Date

10/01 2006
10/31 2006
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06/29 2007

Half-shift Demonstration

Administrative Power Limit

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PAC 2007, June 25, 2007
- Reliability is a performance limitation we are actively addressing:
  - Beam chopper systems, modulators, ion source, cryogenic moderator refrigerator, accelerator cooling water system
Integrated Beam Power in FY2007: Actual vs. Goal

Weeks Since October 1, 2006
Beamloss Status at 60 kW Operation
Plum (THXAB03), Zhukov (FRPMN060)

- BLM signals and activation levels (after 30 hr cooldown) from a recent 10 day run at 60 kW (15-25/Mar/07)

- Losses in most of the accelerator are in line with expectations

- We measure higher than desired losses in the Ring Injection region

- We recently re-worked part of the injection dump line to better transport the waste beams from the stripping process; Holmes (THPAS076), Wang (THPAS078)

Activation levels in mrem/h @ 30 cm
Mercury Target System and Supercritical H₂ Moderator

Target installed on Carriage with phosphor view-screen

Target Change-out Test performed after mercury testing

Hg Pump

Remote-handling Control Room

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Instrument Commissioning and First Science

Backscattering Spectrometer:
Measures diffusive motion of water on TiO$_2$ (rutile) nanoparticles
Related to environmental science issues in diffusion and transport of water in minerals

Liquids Reflectometer:
Data from poly-electrolyte multilayer in *in-vivo* conditions
Data shows interference fringes between deuterated markers
Related to biomedical aspects of drug delivery (controlled release)
SNS Upgrade Plans

1. SNS Power Upgrade Project
   - Doubles beam power capability to 3 MW
   - DOE 20-year plan, mid-term priority
   - Cost range: $160-183M, project duration 5 years
   - Seeking CD-1 approval now

2. Second Target Station
   - Doubles neutron scattering instruments and scientific productivity
   - Lower power and repetition-rate than existing target station
   - In pre-conceptual stage defining science and beam requirements
   - DOE 20-year plan, mid-term priority

Active R&D in many areas:
- Laser-stripping injection: Danilov (THYKI02)
- Stripper foil development: Shaw (MOPAS081)
- E-p active damping: Deibele (WEXC01, MOPAS080)
- Ion Source: Welton (FROAAB02)
- LEBT Design: Han (TUPAS075)
Conclusion

- The SNS is now an operating facility
- We’re making rapid progress toward full design capability
- We are 8 months into an expected 3-year performance ramp
- We are on-track with our ramp-up plans
- SNS is open for business: initial user program begins this summer, expect full user program the following year
- Science results from SNS instruments are emerging