# STATUS OF THE SNS* PROJECT

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*Abstract*

The Spallation Neutron Source (SNS) [1,2] is a second-generation pulsed neutron source under construction at Oak Ridge National Laboratory. SNS is funded by the U.S. Department of Energy's Office of Basic Energy Sciences and is dedicated to the study of the structure and dynamics of materials by neutron scattering. A partnership of six national laboratories (ANL, BNL, JLab, LANL, LBNL, and ORNL) is responsible for the design and construction of the various subsystems. The facility will begin operation in 2006 and will deliver a 1.0-GeV, 1.4-MW proton beam with a pulse length of approximately 700 nanoseconds to a liquid mercury target. The expertise of the different laboratories has been exploited to enhance the delivered beam power by almost an order of magnitude compared to existing neutron facilities. The achievable neutron-scattering performance will exceed present sources by more than a factor of 20 to 100. To achieve such a big step, the subsystems require substantial improvements compared with existing accelerators. The challenges, the status of the project, and potential upgrades are presented here.

## INTRODUCTION

The Spallation Neutron Source (SNS) [1, 2], authorized for construction in fiscal year 1999, is 63% complete. The accelerator, Central Laboratory and Office Building (which includes the central control room), Center for Nanophase Material Sciences (CNMS), and the Joint Institute for Neutron Science (JINS) are shown in Fig. 1, together with an artistic overlay of the facilities on top of a photo of the actual construction site. JINS will be operated in conjunction with the University of Tennessee in support of the users program. CNMS is one out of five nanophase science centers under construction in the United States.

Currently, all of the SNS accelerator-associated buildings and tunnels are completed and are ready for accelerator component installation. The goal for SNS is to deliver a proton beam of up to 1.4-MW beam power to a mercury target for neutron spallation. In a recent proposal, even higher beam power operation, following moderate upgrade proposals, was discussed [3]. The site layout (Fig. 1) has possible future upgrades incorporated, for example, the second target station (shown shaded) and

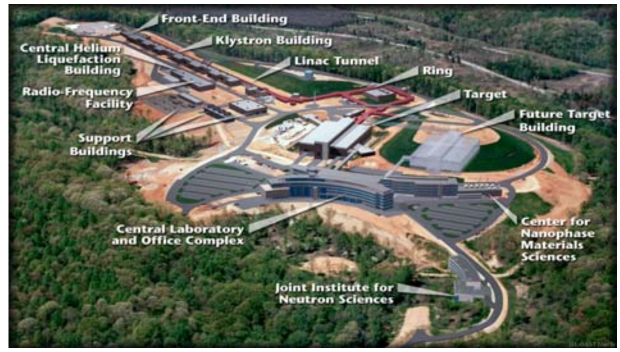


Figure 1: Artist's conception of the SNS facility overlaid on a early site photo of the Chestnut Ridge construction site at ORNL.

space next to the radio-frequency (RF) building for a superconducting RF (SRF) facility that will be needed to maintain the existing cryomodules, as well as to develop and build new ones at a rate consistent with a two-year upgrade schedule. Empty spaces in the tunnel allow for installation of an additional nine cryomodules to increase the energy to more than 1.3 GeV. The accelerator systems, basically a full-energy injector linac and an accumulator ring, operate at a repetition rate of 60 Hz and an average current of 1.6 mA. The accelerator systems consist of a negative hydrogen ($H^-$) RF volume source capable of delivering more than 50 mA of peak current, a low-energy beam transport (LEBT) housing a first-stage beam chopper, a 4-vane RF quadrupole (RFQ) for acceleration up to 2.5 MeV, a medium-energy beam transport (MEBT) housing and a second-stage chopper, a 6-tank drift-tube linac (DTL) up to 87 MeV, a 4-module coupled-cavity linac (CCL) up to 186 MeV, an SRF linac with 11 medium-$\beta$ cryomodules (up to 379 MeV) and 12 high-$\beta$ cryomodules (up to 1000 MeV), a high-energy beam transport (HEBT) for diagnostics and collimation, and an accumulator ring for compressing the 1-GeV, 1-ms pulse to »700 ns for delivery onto the target through a ring-to-target beam transport (RTBT) beam line. Neutrons are produced by spallation in the mercury target, and their energy is moderated to useable levels by supercritical hydrogen and water moderators. The basic parameters of the facility are summarized in Table 1.

The simultaneous performance goals of 1.4 MW of proton beam power and ultimately having more than 90% facility availability place significant operational-reliability demands on the technical and conventional systems. Hands-on maintenance capability, made possible by low activation in the accelerator, is key, and requires maintaining beam loss of < 1 W/m. Figure 2 is a schematic layout of the different linac structures as a function of beam energy.

*SNS is a partnership of six U.S. national laboratories: Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Thomas Jefferson National Accelerator Facility (JLab), Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratory (ORNL). SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

 

Table 1: Summary of SNS Facility Parameters

| Parameter | Value | Unit |
|---|---|---|
| Proton beam energy on target | 1.0 | GeV |
| Proton beam current on target | 1.4 | mA |
| Proton beam power on target | 1.4 | MW |
| Pulse repetition rate | 60 | Hz |
| Beam macropulse duty factor | 6 | % |
| H- peak current from front end | >38 | mA |
| Average current per macropulse | 26 | mA |
| Chopper beam-on duty factor | 68 | % |
| Linac length, incl. front end | 335 | m |
| Ring circumference | 248 | m |
| Ring fill time | 1 | ms |
| Ring extraction gap | 250 | ns |
| Protons per pulse on target | $1.5 \times 10^{14}$ | |
| Liquid mercury target | 18 tons | 1 $m^3$ |
| Number of moderators | 4 | |
| Minimum initial instruments | 8 | |

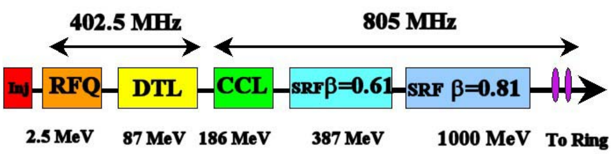


Figure 2: Schematic layout of the linac structures as a function of beam energy.

## ACCELERATOR SYSTEMS

### *Front-End System (FES) (LBNL)*

The FES, shown schematically in Fig. 3 (top left), consists of a multicusp, volume-production, cesium-enhanced, RF-driven, H- ion source; an electrostatic LEBT; a 4-vane RFQ with π-mode stabilizers that accelerates the 65-keV beam from the ion source to 2.5 MeV; beam-chopping systems; and a beam-transport, rebunching, and matching section (MEBT). Current-, profile-, and position-monitoring diagnostics are incorporated into the FES. Primary beam chopping is performed by the LEBT, with final chopping in the MEBT. Large beam eccentricity in the MEBT leads to nonlinear space charge forces that can lead to halo in the CCL; thus, collimation is necessary to prevent losses. Collimation is performed in the MEBT, reducing halo at the CCL by 97%. Collimator locations are shown in Fig. 3 (bottom).

FES commissioning at LBNL was performed in May 2002 by a multilaboratory team led by LBNL. A peak beam current of more than 50 mA was produced at low duty factor, and a 25-mA beam was produced at 6% duty factor. In December 2002, these results were reproduced with a fully integrated system at the SNS site (Fig. 4). The MEBT rms output emittance was $\varepsilon_x \sim 0.3\,\pi$ mm mrad / $\varepsilon_y \sim 0.27\,\pi$ mm mrad at 25 mA, meeting the SNS requirement within measurement accuracy.

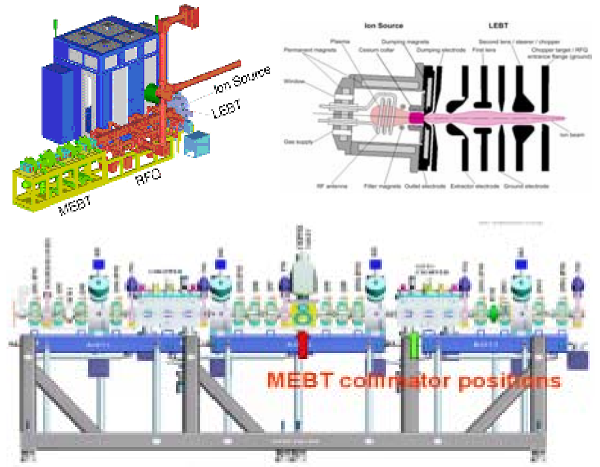


Figure 3: (top left) FES layout, (top right) H- ion source, and (bottom) MEBT collimator locations.


Fig. 4. FES installed at the SNS site.

### *Normal-Conducting Linac (LANL) and High-Power RF Systems*

Downstream of the MEBT, beam is accelerated to 87 MeV by a 216-cell, six-tank DTL, provided by LANL. Each DTL tank is driven by a 402.5-MHz, 2.5-MW (peak power) klystron. Permanent magnet quadrupoles, beam position monitors, current monitors, and steering dipoles are integrated into the drift tubes. Diagnostic sections are between each tank. The third of the six DTL tanks was installed and operated in May 2003. Fig. 5 shows a photograph of the DTL, and the inset shows the drift tubes. DTL 3 conditioned up to full field in less then 24 hours and achieved 40% of its design average power within 48 hours.

The CCL, operating at 805 MHz and powered by four 5-MW (peak) klystrons, accelerates the beam to 186 MeV. The CCL has four modules with a total of 384 cells and is made of oxygen-free copper. A CCL hot-model prototype, including a bridge coupler, was successfully power tested at LANL.

The high-power RF systems design of the linac is finished, and klystron deliveries are in full swing. Klystrons to be installed in the ~330-m-long klystron gallery include 7+4 (installed + spares) 402.5-MHz, 2.5-MW; 4+5 805.0-MHz, 5-MW; and 81+20 805.0-MHz, 0.55-MW klystrons. The klystrons are powered by 13 high-voltage converter modulators (HVCMs), which were specifically developed for SNS (Fig. 6). Extremely high-power density and efficient high AC-to-DC high-voltage conversion are the main features. High-frequency (20-kHz) switching using IGBT technology and newly developed boost transformers allow for a very compact design that saves investment cost as well as real estate. The HVCMs typically operate at 11-MW peak power and ~1-MW average power, feeding between 2 CCL and 12 superconducting linac (SCL) klystrons. Integrated into the design are rectifiers and transformers, control racks, and SCR regulators.

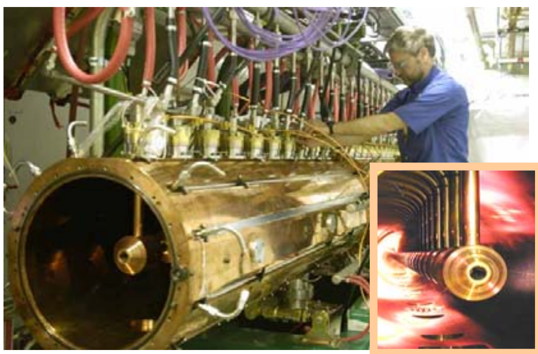

Figure 5: DTL tank 3 in the tunnel during final installation. Tank 3 contains 33 DTs.

Figure 6: HVCM driving the RFQ and DTL 1 klystron (402.5 MHz, 2.5 MW) installed in the klystron gallery. The graph shows the flat top of a full 1.3-ms-long pulse.

### *SRF Linac (JLab)*

SNS will be the first large-scale superconducting proton linac that provides high beam power. Advantages offered by the superconducting structures, as well as progress over the last decade in reliably achieving high-performance accelerating structures, led to the design choice. The most prominent arguments for an SCL are large aperture, operational flexibility, high gradient, less real estate, lower operating costs, small wakefields, excellent vacuum, and very high efficiency.

The velocity of the $H^-$ ions within the SCL varies from β=0.55-0.87. The most economic approach (balancing the number of different types of cells versus the accelerating efficiency) is a two-cavity geometry with β=0.61 and β=0.81. Some design parameters for both types are listed in Table 2. Beam is accelerated from 186 to 387 MeV by 11 cryomodules (CMs) with 3 medium-β (β = 0.61) cavities each and to 1 GeV by 12 CMs with 4 high-β (β = 0.81) cavities each, or a total of 81 cavities.

Table 2: Some Cavity Design Parameters

| Parameter | β=0.61 | β=0.81 | Unit |
|---|---|---|---|
| No. of cells | 6 | 6 | |
| $E_{peak}$ | 27.5 | 35.0 | MV/m |
| $E_{peak}/E_{acc}$ | 2.71 | 2.19 | |
| $B_{peak}/E_{peak}$ | 2.10 | 2.14 | mT/(MV/m) |
| Cell:cell cplng | 1.61 | 1.61 | % |
| Q at 2.1 K | $>5 \times 10^9$ | $>5 \times 10^9$ | |
| Active length | 0.682 | 0.906 | m |

Fig. 7 shows the surface, on-axis, and effective accelerating fields for both cavity geometries, as a function of the velocity (β) of the particles. Particle tracking shows that there is almost no emittance growth in the SRF linac.

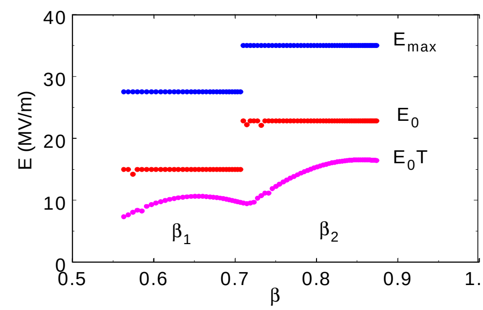


Figure 7: Surface ($E_{max}$), on-axis ($E_0$), and effective accelerating ($E_0T$) fields for both optimized cavity geometries, as a function of particle beta.

The SRF cavities are manufactured by industry out of high-purity RRR 250 niobium sheets. They are then shipped to JLab for surface treatment, where they are subjected to standard cycles of buffered chemical polishing, high-pressure ultrapure water rinsing, and vacuum degassing, after which they are RF-power tested in a radiation-shielded vertical Dewar. Electropolishing, a technique that has been demonstrated to further improve surface gradients, will be applied to the high β cavities to guarantee good performance. The gradient performance achieved with a total of 14 medium-β cavities and 1 electropolished high-β cavity is shown is Fig. 8. So far, all medium-β cavities have exceeded the specification during cw testing, some of them by more than 50%. The first electropolished high-β cavity shows a gradient of 21 MeV/m, compared with a 16.5-MeV/m specification.

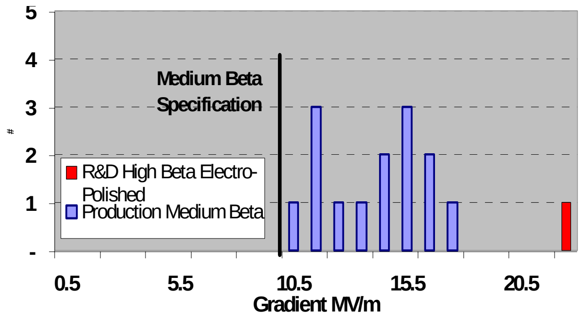


Figure 8: Performance of cavities in the medium β cryomodule at the design $Q_0$ of $5 \times 10^9$. Also shown is the first electropolished high β cavity.

Three medium-β and four high-β cavities in their helium vessels are connected together, and RF couplers, HOM couplers, field probes, and gate valves are installed, forming a cavity string. All couplers, all medium-β CMs, and 2 out of the 12 high-β CMs have been or will be tested in a dedicated test stand at JLab before installation in the tunnel. The first production cryomodule is shown in Fig. 9 in its assembly area. This CM, as well as the prototype, performed well in initial testing, giving confidence to proceed with mass production.

Figure 9: The first production medium-β cryomodule in the assembly area. A second string of cavities can be seen in the background.

Because SNS is a pulsed accelerator, compensation of Lorentz force detuning effects is a concern. The RF system has adequate margin to accommodate 470 Hz of detuning, but the real detuning depends on cavity stiffness, and decisions had to be made before cavity production started. Fast piezoelectric tuners are installed on all cavities to further reduce power requirements for resonance control. Test results indicate that these tuners are unnecessary at baseline gradients as the detuning is below 470 Hz and that the piezo tuners are able to reduce detuning even further by a factor of three.

It is critical that particulates not be introduced into the SRF cavities, as the resulting field emission would severely degrade their performance. A nonintercepting beam profile diagnostic, the laser wire, is being developed and tested. A laser scanned through the H- ion beam strips off electrons, which are collected and sampled. The position of the laser versus electron intensity can replicate the transverse and longitudinal profile (up to single bunch resolution) and down to the $10^{-4}$ resolution level, as shown in Fig. 10.

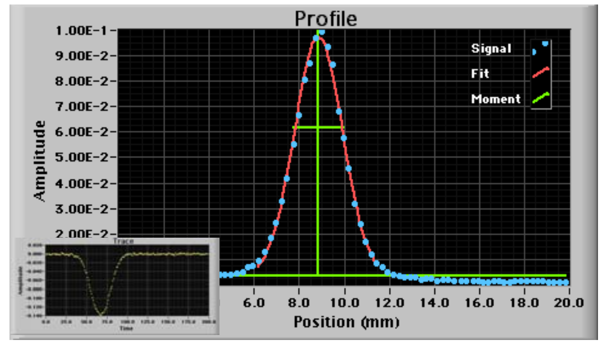


Figure 10: Profile generated with a laser beam scanned across the H- ion beam. The electron collector current is shown in the lower left corner. This system will be used throughout the SCL.

Helium to cool the SRF linac is provided by the central helium liquefier (CHL), major parameters of which are listed in Table 3. Gas flows from two pairs of warm screw compressors, through oil removal, a coalescer-demister, and charcoal filters. It is then piped to the 4.5 K cold box where a standard liquefier cycle sends helium through cryogenic transfer lines to the cryomodules.

Table 3: Refrigeration Parameters

| 32 CMs | Primary | Secondary | Shield |
|---|---|---|---|
| Temp. (K) | 2.10 | 5.0 | 35-55 |
| Pressure (bar) | 0.041,3 | 3.0 | 4.0-3.0 |
| Static load | 850 W | 5.0 g/sec | 6125 W |
| Dynamic load | 600 W | 2.5 g/sec | 0 W |
| Capacity | 2,850 W | 15 g/sec | 8300 W |
| Margin | 100% | 100% | 35% |

Joule Thompson valves on the cryomodules produce 2.1 K, 0.041 bar liquid helium for cavity cooling and 4.5 K helium for fundamental power coupler lead cooling. Cooling boil-off goes to four cold compressors capable of 120 g/s steady state, recompressing the stream to 1.05 bar and 30 K for counter-flow cooling in the 4.5 K cold box. Transfer line and CHL installation are under way, and commissioning of the CHL will begin at the end of this calendar year.

## *Accumulator Ring (BNL)*

The 1-ms-long linac pulse is compressed to a single 695 ns bunch in the accumulator ring through multiturn, charge-exchange injection. To minimize space-charge effects, transverse phase-space painting is used to increase the total beam emittance to 240 π mm mrad, thereby reducing the space-charge tuneshift to ~0.15. The resulting halo is removed by a two-stage collimation system. A 1-MHz RF system maintains a clean beam gap that is longer than the extraction kicker rise time. After accumulation, the extraction kicker directs the beam into the RTBT line that takes it to the target. Major ring parameters are listed in Table 4.

Table 4: Major Parameters of the Ring

| | | |
|---|---|---|
| No of injected turns | 1060 | |
| Revolution frequency | 1.058 | MHz |
| Filling fraction | 68 | % |
| Transvrs emittance 99% | 240 | π mm mr |
| Transvrs acceptance | 480 | π mm mr |
| Space charge tune shift | 0.15 | $\Delta Q_{x,y}$ |
| Ring peak current | 52 | A |
| HEBT/RTBT Length | 170/150 | m |
| Circumference | 248 | m |
| RTBT transvrs acceptance | 480 | π mm mr |
| Beam size @ tgt (H × V) | 200 × 70 | mm × mm |

A variety of technical issues that come with high-intensity operation of the accumulator have been addressed in the meantime to further ensure operation of up to 2 MW at 1 GeV. To control the e-p instability, solenoidal coils have been added to certain areas of the vacuum chamber and special electron collectors have been included in the present stripping area, while coating of the interior vacuum chamber with titanium nitride continues. At the same time, a research and development (R&D) program to develop higher power stripping foils based on a diamond substrate is under way and will be reported on this conference. Dynamic detuning of the RF system has been demonstrated, and kicker rise and fall times are consistent with the design specifications. Meanwhile, installation of the HEBT beam line and ring tunnel components has started and is making good progress.

### *Controls*

Controls for the SNS complex are distributed among the partner labs but are coordinated at ORNL. SNS relies on an EPICS control system and does make use of a distributed network between partner labs. Also integrated into EPICS are the controls for the utilities and the power distribution systems, which were developed by a commercial vendor that worked on the SNS software platform.

## TARGET AND INSTRUMENTS

The SNS target consists of 1 $m^3$ of liquid mercury that weighs ~18 tons. The mercury circulates constantly to aid the target system's ability to survive the tremendous thermo-mechanical shocks resulting from the pulsed beam energy of ~20 kJ/pulse. Evidence of cavitation-induced pitting in the steel has been investigated in detail in a dedicated R&D program over the last 12 months, and several ways to mitigate these effects are under way. Test data show that at ~1 MW the present design will sustain the effect for at least two weeks. Construction of the target conventional facilities is proceeding apace. Many of the major components are now on site, and target installation has begun.

Selection of SNS instruments is based on scientific merit, and a peer-review body provides advice in that regard. So far, 16 instruments have been approved, 5 of which are funded within the SNS project: a high-resolution backscattering spectrometer; vertical surface (magnetism) reflectometer; horizontal surface (liquids) reflectometer; extended Q-range, small-angle diffractometer; and a third-generation powder diffractometer. Three additional instruments are funded by instrument development teams: a wide-angle thermal chopper spectrometer, cold neutron chopper spectrometer with 10- to 100-$\mu$eV resolution, and an engineering materials diffractometer. Funding is being sought for the remaining approved instruments: a high-pressure diffractometer, disordered materials diffractometer, fundamental physics beam line, high-resolution thermal chopper spectrometer, and a single-crystal diffractometer.

## CONCLUSIONS

SNS construction is proceeding rapidly. At the time of this conference, the total project is 62% complete. More than 1.3 million cubic yards of earth have been excavated, the accelerator tunnels and buildings have been turned over for component installation, and support buildings are progressing well. SNS is on schedule to be completed, within budget, in June 2006. Three million person-hours of work have taken place without a lost-time injury. Up-to-date information about SNS can be found on our web site [1]. Many SNS papers from other accelerator conferences, as well as this one, can be found using the JACOW web site and its excellent search engine [5] (an apology for the incomplete citation, but a complete list would go beyond the available framework of this article). Many of the developments mentioned here are reported in detail in other papers submitted to this conference, and consulting those papers is encouraged.

## ACKNOWLEDGMENTS

This paper is presented on behalf of all our SNS colleagues whether they are members of the partner labs or are among the many friends and colleagues worldwide who collaborate with us on this project. We gratefully acknowledge their contributions, whether intellectual or practical, as their efforts have been crucial to SNS.

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