STATUS OF THE SNS PROJECT*

David K. Olsen for the SNS Partnership, ORNL, Oak Ridge, TN 37820, USA

Abstract

The Spallation Neutron Source (SNS) is a collaboration of six DOE National Laboratories (ANL, BNL, LBNL, LANL, TJNL and ORNL) to build an intense pulsed neutron source for neutron scattering materials science research at ORNL and is funded by DOE's Office of Basic Energy. The baseline parameters require a 1.0-GeV, 1.4-MW proton beam on a liquid Hg target at 60 Hz with 700-ns pulses. The Project started in October 98 and is schedule for completion in June 06. After 5.5 years of construction, the Project progress, status, particular challenges and possible future upgrades will be discussed.

INTRODUCTION

The Spallation Neutron Source (SNS) [www.sns.gov] authorized for construction in FY99 has been a line-item construction project for 5.5 years and is scheduled for completion in about two years in FY06. In January 04, the facility was 94% designed, 77% complete and $1.2B of the $1.411B total had been costed. Figure 1 shows a recent aerial photo of the SNS construction site. All the buildings for the accelerator system have been completed including the front-end building; tunnels; klystron gallery; CHL and RFTF; and HEBT, Ring and RTBT service buildings. The Central Office and Laboratory building is scheduled for completion in late summer 04. The DOE

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 macropulse current	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	1.5×10^{14}	
Liquid mercury target	18 tons	1 m^3
Number of moderators	4	
Umber of instruments	24	

Center for Nanophase Material Sciences (CNMS) and the State of Tennessee Joint Institute for Neutron Science (JINS) are also shown.

Figure 1: Jan 04 aerial photo of the SNS site.

The SNS goal is to deliver a 1.4-MW proton beam to a mercury target for neutron spallation. The accelerator system is a full-energy linac and accumulator Ring, operating at 60 Hz and an average beam current of 1.4 mA. It consists of a 40-mA H- ion source, an RFQ up to 2.5 MeV, a six-tank Cu drift-tube linac (DTL) up to 87 MeV, a Cu coupled-cavity linac (CCL) up to 186 MeV, a SRF linac with 11 β=0.61 cryomodules up to 379 MeV and 12 β=0.81 cryomodules up to 1000 MeV, a high-energy beam transport (HEBT) for diagnostics and collimation, an accumulator Ring for compressing the 1-ms pulse to a 700-ns pulse for delivery onto the target, and a ring-to-target beam transport (RTBT) beam line.

Hands-on maintenance capability is crucial and requires maintaining beam loss of < 1 W/m. This is a difficult requirement for a 1.4-MW system with greater than 90% reliability. The SNS represents an advance by almost an order of magnitude in beam power compared to existing spallation neutron facilities. The basic parameters of the facility are summarized in Table 1. Figure 2 shows the linac layout.

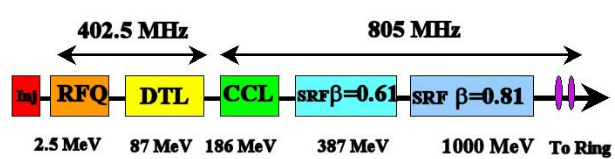

Figure 2: Schematic layout of the linac structure.

FRONT-END SYSTEM (LBNL)

The Front-End System (FES) was designed, built and commissioned at LBNL and then re-commissioned on the SNS site. The FES consists of a 40-mA, H-, multicusp, volume, cesium-enhanced, RF-driven, source followed by an electrostatic low-energy beam transport (LEBT) housing a first-stage beam chopper. The 65-keV LEBT beam is accelerated to 2.5 MeV with a 402.5-MHz, 3.76-m-long, 4-vane, RFQ with π-mode stabilizers. Ring RF beam gaps of about 340-ns at 1.056 MHz are created in

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the MEBT with two traveling wave choppers. The MEBT also rebunchs and matches the RFQ beam to the DTL.

In May 02 FES commissioning was performed at LBNL by a multi-laboratory 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 02, these results were reproduced with a fully integrated system at the SNS site, shown in Fig. 3. The MEBT rms output emittance was 0.30π mm-mrad horizontally and 0.27π mm-mrad vertically at 25 mA, meeting the SNS requirement.

Figure 3: FES installed at the SNS site.

Ion source improvements have continued. A hot spare ion source stand has been built at ORNL and up to 60 mA has been extracted. More importantly reliability is improving dramatically. Approximately 40 mA of beam at 6% duty cycle for over 21 days was extracted without source maintenance with trip-free periods up to four days. The development of a long-life ceramic RF ion source antenna was particularly important.

NORML CONDUCTING LINAC (LANL)

Following the MEBT, the beam is accelerated to 87 MeV by a 216-cell, six-tank DTL, provided by LANL. Permanent magnet quadrupoles for transverse focusing beam position monitors, current monitors, and steering dipoles are integrated into the drift tubes. Diagnostic chambers are between each tank. The first DTL tank has been installed and beam commissioning completed in November 03 with very positive results: the transmission was measured to be 100% within uncertainty, the RMS transverse emittance core is 0.2-0.3π mm-mrad, and the microbunch length is 25 deg. RF. Beam commissioning of the accelerator system up to DTL tank 3, shown in Fig. 4, is scheduled to start the first week of April 04. All the components for the remaining three tanks are ORNL and are rapidly being assembled, tuned, connected and installed.

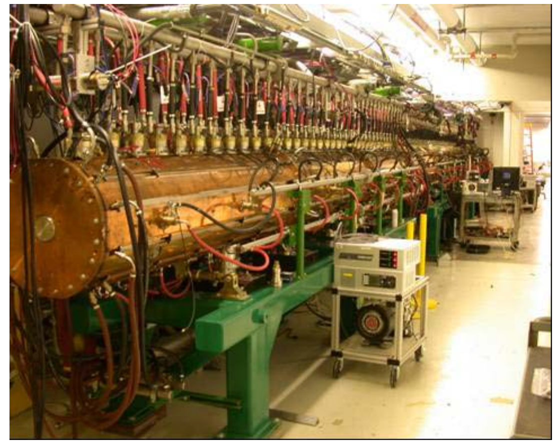

Figure 4: DTL Tanks 1, 2 and 3 in the SNS tunnel.

The RF frequency increases by a factor of two between the DTL and CCL. The 384-cell side-coupled CCL accelerates the beam up to 186 MeV and has four RF modules each, with 12 segments, separated by quadrupole singlets for transverse focusing, pumps and diagnostics. Figure 5 shows CCL module 1 assembled, RF tuned, installed in the SNS tunnel, and awaiting high-power RF conditioning. The last RF module is scheduled to be shipped to ORNL in April 04. The beam commissioning of the accelerator system up to and including CCL module 3 is scheduled to start in August 04.

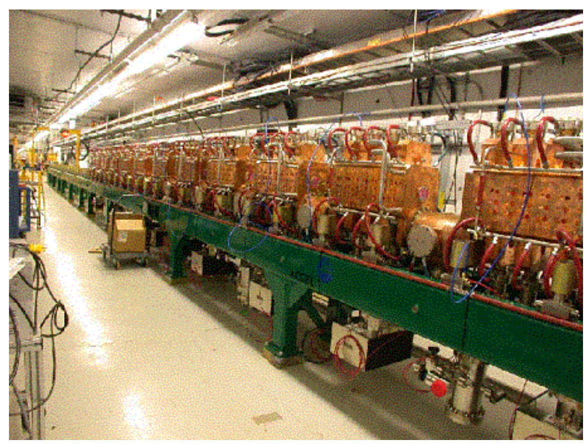

Figure 5: CCL RF module 1 in the SNS tunnel.

SRF LINAC (JLAB)

The SNS will be the first large-scale superconducting proton linac that provides high beam power. Advantages offered by the superconducting structures and progress over the last decade, particularly for TESTA, led to the design change two years into the Project. The most prominent arguments for an SCL are large aperture, operational flexibility, high gradient, less real estate, lower operating costs, smaller wakefields, excellent vacuum, and very high efficiency. The ion velocity within the SCL varies from β=0.55 to 0.87. The most overall optimal approach is a six-cell geometry with eleven β=0.61 three-cavity “medium-beta” cryomodules and twelve β=0.81 four-cavity “high-beta” cryomodules, for a total of 81 cavities. Figure 6 shows a medium beta cavity.

Figure 6: SNS 6-cell medium beta cavity.

Figure 7 shows the surface, on-axis, and effective accelerating fields for both cavity geometries, as a function of velocity. Particle tracking shows that there is almost no emittance growth in the SRF linac. On axis average electric fields for acceleration of 10 and 15 MV/m are required for the medium and high-beta cavities, respectively, for matched the particle velocity.

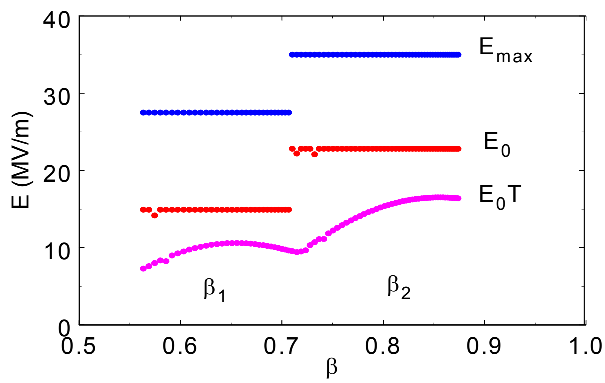

Figure 7: Surface (E_{max}), on-axis (E_0), and effective accelerating (E_0T) fields for both optimized cavity geometries, as a function of particle velocity.

The SRF cavities are manufactured by industry out of high-purity RRR ≥ 250 niobium sheets and are shipped to JLab 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 vertical Dewar. A majority of the medium-beta cavities have been processed and the gradient performance achieved for most have exceeded the specification, some of them by more than 50%. The cavities in their helium vessels are connected, and RF couplers, HOM couplers, field probes, and gate valves are installed, forming a cavity string. All couplers, all medium-beta and 2 of 12 high-beta CMs have been or will be tested in a 1-MW test stand at JLab before tunnel installation. Beam commissioning of the complete linac is scheduled for March 05.

Because the SNS is pulsed, compensation of Lorenz force detuning from RF filling of the cryogenic cavities is a concern. The system has adequate power margin to accommodate 470 Hz of detuning; nevertheless, following an R&D program that demonstrated effectiveness and fast piezoelectric tuners have been installed on all cavities to further reduce power requirements for resonance control. These could be used to reduce the RF power margins allowing higher beam power with the existing RF plant.

Because it is critical that particulates not be introduced into the SRF cavities, a nonintersecting beam profile diagnostic, the laser wire, has been developed, tested and is being installed. A laser, scanned through the H- ion beam, strips off electrons, which are collected and used to construct the transverse and longitudinal profile (up to single bunch resolution) and down to 10^{-4} resolution level.

Helium to cool the SRF linac is provided by the central helium liquefier (CHL) that can disapaite 2.85 kW at 2.1K. 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 transfer lines to the cryomodules. Joule Thompson valves on the cryomodules produce 2.1-K, 0.041-bar helium for cavity cooling and 4.5-K helium for fundamental power coupler lead cooling. The cryogenic transfer lines and CHL plant installation are essentially complete, commissioning of the CHL has started, and cooldown is scheduled for summer 04.

The SCL has considerable upside potential. The baseline contains 23 cryomodules. The linac tunnel has space for nine additional cryomodules and the cryoplant is sized for these additional cryomodules. The power couplers baseline is 0.55 MW peak and they have been tested up to 0.75 MW. The piezo tuners are available.

LINAC RF SYSTEM (LANL)

The Linac RF system is a major undertaking. The klystrons are powered by high-voltage converter modulators (HVCMs) which were specifically developed for the SNS by LANL with 20-kHz switching using IGBT technology and newly developed booster transformers allowing a very compact design that reduces capital cost as well as real estate. Extremely high-power density and efficient high AC-to-DC high-voltage conversion are the main features. The HVCMs typically operate at 11-MW peak power and 1- MW average power. Fourteen HVCMs are needed: three for the RFQ and DTL, four for the CCL, and seven for the 81 SCL klystrons. At the time of this paper nine HVCMs have been installed of which two are operating and five more have been tested.

Each DTL tank is driven by a 402.5-MHz, 2.5-MW (peak power) klystron. These klystrons have been installed. One of the four 805-MHz 5.0-MW CCL klystrons has been installed and tested. About half of the 81 805.0-MHz, 0.55-MW klystrons for the SCL have been delivered and the first 12, powered by the first SCL HVCM, have been tested. Each klystron has a full-power circulator and load. Figure 8 shows 36 SCL klystrons in place in the 330-m-long klystron gallery.

Figure 8: 805-MHz SCL tubes in the klystron gallery.

ACCUMULATOR RING (BNL)

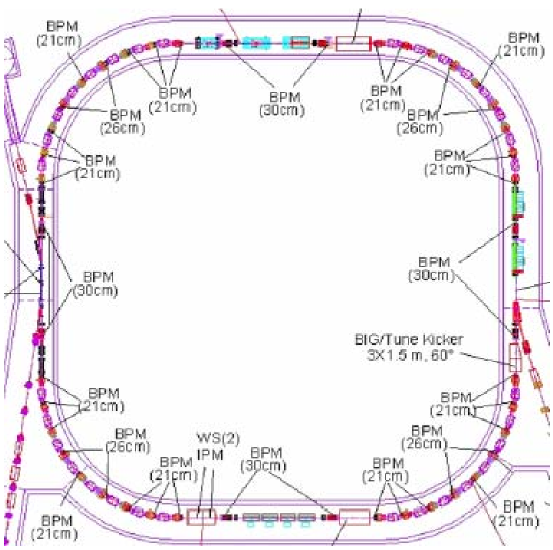

Figure 9: The SNS Accumulator Ring.

The 1-ms-long linac H- pulse is compressed to a single 700 ns H+ bunch in the accumulator Ring through 1060-turn, charge-exchange injection using a carbon foil. The H- beam is transported from the linac to the injection foil through a 170-m HEBT beam line. The HEBT contains a 90 deg. achromat and associated beam dump to provide momentum collimation and also horizontal and vertical foil collimators and beam dumps to provide hallo collimation prior to ring injection. The HEBT has two additional beam dumps: a 7-kW straight-on dump for linac tuning and a 200-kW injection dump for beam that is not injected into the Ring. The HEBT lattice components have mostly been delivered and installed and the beam line is under high vacuum.

Figure 9 shows the accumulator Ring lattice that has a circumference of 248 m and consist of four 90 deg. achromats and four disperssionless straights, each with two symmetric quadrupole doublets for tune adjustment. Each 90 deg. achromat has a tune of one and consist of eight half cells that were designed and built at BNL. The Ring contains strong sextupoles for chromaticity control.

Figure 10: Ring half cell installed in the SNS tunnel.

Figure 10 shows some of these half cells installed in the ring tunnel at ORNL.

The four straight sections are devoted to injection, collimation, extraction and RF. The injection straight section contains a four-dipole horizontal chicane with some of these magnets specifically optimized to reduce foil beam loss at 1.0 GeV. This straight section contains eight kicker dipoles to paint the beam both horizontally and vertically into the ~240 pi mm mrad ring collimator acceptance. The space charge tune shift is 0.15 for 1.4 MW. The resulting halo from injection, space charge, impedance and other effects is removed by three large collimators, each capable of dissipating 20 kW and has been extensively optimized with numerical simulations. Single-turn extraction is accomplished with 14 fast ferrite kicker sections, only 13 are needed, with a rise time of 250 ns, and a 2.47-m Lambertson. The dual-harmonic RF system maintains a clean beam gap and consists of four two-gap biased-ferrite cavities with a 1.06-MHz first-harmonic, total voltage of 40 kV, and second harmonic voltage of 20 kV. The detuning of the RF system has been demonstrated for beam accumulation. All the straight section hardware has been designed, fabricated in some cases, assemble and tested at BNL. Many of these components have been delivered to ORNL; however, most straight section installation will occur in FY05. The RTBT beam line is 170-m long and is constructed from the ring 21-cm-bore quadrupoles, and contains another large collimator. Final focus is achieved with two large 36-cm-bore radiation hardened quadrupole doublets. The 20 cm x 7 cm target beam spot will be set up with a removable harp.

Ultimately ring space charge and instability beam loss may be the limiting factor for beam power and six years have been spent developing the ORBIT code for its numerical simulation. ORBIT is state-of-the-art and has many detailed models including: injection foil and painting; symplectic single particle transport; magnet errors; closed orbit correction; RF and acceleration; longitudinal and transverse wall impedances; 1D, 2D, and 3D space charge; feedback for stabilization; apertures and collimation; electron cloud model; and beam diagnostics. ORBIT has been used extensively for SNS ring design issues and has been benchmarked against LANL PSR measurements of transverse broadening of intense beam from space charge; injected bunch dynamics; longitudinal instability; and persistence of 200-MHz bunch structure. Calculations indicate that the SNS Ring can operate with low beam loss at 1.4 MW and this benchmarking gives some faith that these predictions will be accurate. The e-p instability seen in the LANL PSR is of particular concern. Specific mitigation efforts for the e-p instability include: very good vacuum at 1.0E-8 Torr, 100-nm TiN coating to reduce secondary electrons, careful collection of injection foil electrons, implementing solenoid windings in collimation straight, clearing electrode hardware in injection assembly and BPMs, and dedicated lattice space and studies for active dampers.

For future upgrades, the HEBT, Ring and RTBT have all been designed for 1.3-GeV operation. The tunnels, and in particular the H- HEBT achromat and Ring H- injection straight have been sized for 1.3-GeV operation. All the magnets, accept two-injection chicane magnets will operate at 1.3 GeV. In addition, most power supplies will support 1.3-GeV operation.

TARGET & INSTRUMENTS

The SNS target is shown in Fig. 11 and consists of 1.5 m^3, about 18 tons, of liquid mercury flowing in a stainless steel container. Thermal shock from the baseline 23 kJ pulses is a major issue and it is generally believed that above about 1 MW of beam power a liquid target will be required to survive these tremendous thermo-mechanical shocks.

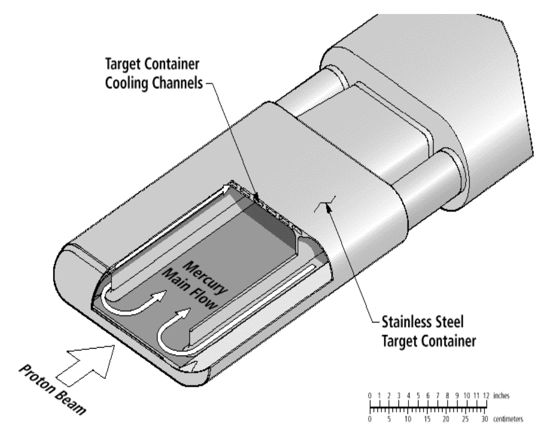

Figure 11: The SNS neutron producing Hg target

Early on in the Project cavitation-induced pitting on the inside surface of the stainless steel container was a major concern; however, R&D has reduced these concerns somewhat. Materials are a factor for reducing pitting and cold-washed stainless and Kolsterising help. Geometry and repetition rate are also large factors. Injection of bubbles into the mercury could also significantly reduce cavitation. Test data show that at 1 MW the present target design will sustain the effect for at least two weeks. Figure 12 shows assembly of the target monolith with eleven of the guide rails for the target shutters in place.

Figure 12: SNS target monolith in January 2004.

The SNS target hall has 18 flight tubes and 24 instrument stations. Selection of SNS instruments is based on scientific merit, and decisions are made by a peer-review body. To date, 16 instruments have been formally approved. Two target-instrument upgrade proposals are being given serious consideration: SING, Spallation Neutron Source Instruments – Next Generation, is for $75M to build five new state-of-the-art instruments to be installed from 2008 to 2011; and a second target station and associated beam power upgrade.

CONCLUSIONS

SNS construction is proceeding rapidly and in January 04 the facility was 94% designed, 77% complete and $1.2B of the $1.411B total had been costed. The SNS has been a line-item construction project for five and a half years with about two years remaining. The remaining start-of-beam-commissioning milestones are: DTL1-3 in April 04, CCL in August 04, SCL in March 05, HEBT and Ring in July 05, and first beam on target in February 06. The SNS Project is on schedule and within budget to meet these beam commissioning milestones. After start of operations, the SNS has considerable upside potential for power upgrades to the 3-5 MW level with much of the hardware already in the design.

This paper summarizes the work of many people at many laboratories who have made this project a success. Their contributions are gratefully acknowledged.