THE SPALLATION NEUTRON SOURCE (SNS)*

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Abstract

The Spallation Neutron Source [1, 2], located in Oak Ridge, TN, is a next-generation neutron-scattering facility now under construction by a partnership of six national laboratories. The facility is composed of a high-power particle-accelerator system, a liquid-mercury target-moderator system, and a suite of world-class scientific instruments. An ion source produces 1-ms-long negative-hydrogen-ion (H-) pulses. The ion beam is accelerated to 185 MeV by three types of normal conducting linear accelerator structures. Ions are further accelerated to 1 GeV by 81 superconducting radiofrequency cavities [3]. The ion beam is stripped, and 1060 turns of protons are stacked in an accumulator ring. The resulting 700-ns-long proton pulses are extracted onto the target at a 60-Hz rate. Neutrons are produced by spallation in the mercury. Their energy is then moderated to useable levels by water and supercritical-hydrogen moderators. The simultaneous performance goals of 1.4 MW of proton beam power and 95% facility availability in the accelerator complex require excellent performance and operational reliability in the conventional and technical systems. An overview of the SNS, including components and status, is presented with particular emphasis on the linac.

1 INTRODUCTION

The Spallation Neutron Source [1,2], located in Oak Ridge, TN, is a next-generation neutron-scattering facility now under construction by a partnership of six national laboratories. The facility is composed of a high-power particle-accelerator system, a liquid-mercury target-moderator system, and a suite of world-class scientific instruments. An ion source produces 1-ms-long negative-hydrogen-ion (H-) pulses. The ion beam is chopped in a transport section and subsequently accelerated to 185 MeV by three types of normal conducting (NC) linear accelerator (linac) structures, a radiofrequency quadrupole (RFQ), a drift-tube linac (DTL), and a coupled-cavity linac (CCL). Superconducting radiofrequency (SRF) Nb cavities, operating at 2.1 K, accelerate the ions to 1 GeV [3]. Beam is transported and collimated by a high-energy transport line (HEBT). The ion beam passes through a stripping foil and is then stacked in a ring that accumulates the 1-GeV, 1-ms-long proton pulse in 1060 turns. The resulting 700-ns-long proton pulses are extracted onto the target at a 60-Hz rate. Neutrons are produced by spallation in the mercury, and their energy is moderated to useable levels by supercritical-hydrogen and water moderators.

The simultaneous performance goals of 1.4 MW of proton beam power and 95 % facility availability place significant operational-reliability demands on technical and conventional systems. Hands-on maintenance capability, made possible by low activation in the accelerator, is key to achieving excellent availability. Maintaining beam losses of < 1 W/m is critical. A layout of the SNS facility is shown in Fig. 1. Figure 2 is a schematic layout of the different linac structures as a function of beam energy. Major facility design parameters are listed in Table 1. The SNS project is currently 48 % complete, and will begin operation in June 2006.

Figure 1: Overview of the SNS in Oak Ridge, Tennessee. Major facility buildings are superimposed on an aerial photograph of the construction site.

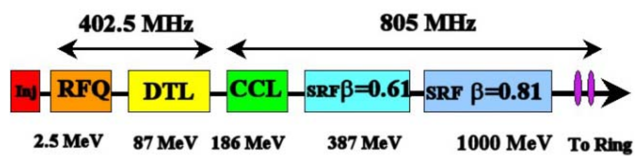

Figure 2: Schematic layout of the linac structures as a function of beam energy.

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	1.5×10^{14}	
Liquid mercury target	18 tons,	1 m^3
Number of moderators	4	
Minimum initial instruments	8	

* SNS is a partnership of six US 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.

2 ACCELERATOR SYSTEMS

2.1 Front-End System (FES) (LBNL)

The FES, shown schematically in Fig. 3a, consists of a multicusp, volume-production, Cs-enhanced, RF-driven, H- ion source; an electrostatic low-energy beam transport (LEBT); a 4-vane RFQ with π-mode stabilizers that accelerates the 65 keV beam from the ion source [4] 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%, as shown in Fig. 3b, with collimator locations as shown in Fig. 3c [5, 6].

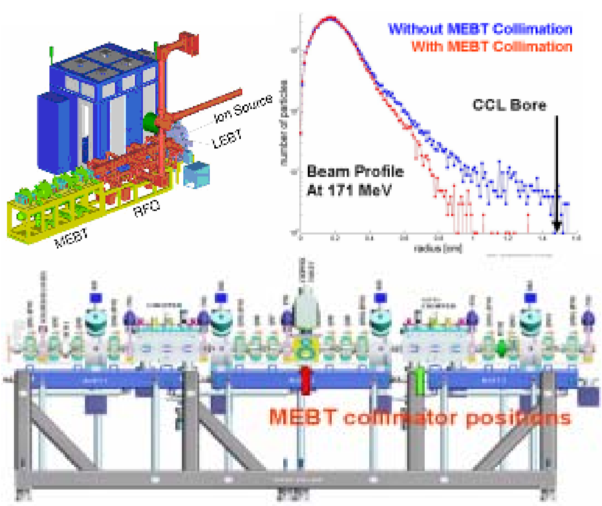

Figure 3: a) FES layout, b) CCL halo reduction by MEBT collimation, and c) MEBT collimator locations.

FES final commissioning at LBNL in May 2002 [7,8,9] was performed by a multi-laboratory team led by LBNL. A peak beam current of 50 mA was produced at low duty factor, and a 25-mA beam was produced at 6% duty factor. A 25-mA beam at 3% duty factor was stable during commissioning. The MEBT rms output emittance was $< 0.3\ \pi$ mm mrad vertical and horizontal at 25 mA, meeting the $0.27\ \pi$ mm mrad requirement within measurement accuracy. In June '02, after successful commissioning at LBNL, the FES was dismantled and transported to ORNL where it is now re-installed in the Front-end Building, as shown in Fig. 4. Later this year, re-commissioning will take place at SNS.

2.2 NC Linac (LANL)

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. The first DTL tank was assembled at LANL, and the rest are assembled at ORNL. Fig. 5a is a photograph of the DTL, and Fig. 5b shows the RFQ and DTL1 klystrons installed in the klystron gallery.

Figure 4: Front-End System installed at SNS-ORNL.

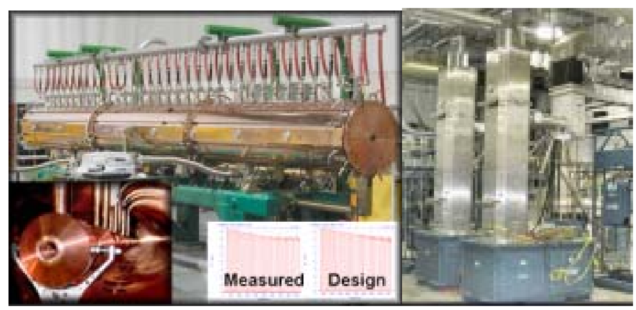

Figure 5: a) DTL tank 3 at ORNL; inserts show (left) a drift tube and (right) data from tank tuning demonstrating measurements consistent with design. b) RFQ and DTL1 klystrons installed at SNS.

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 high-conductivity copper. A CCL hot-model prototype, including a bridge coupler, was successfully power tested at LANL. It operated stably, exceeding design peak and average power specifications, giving us confidence to proceed with production [10]. A resonance-control system, provided by LANL, uses water to maintain the correct RF frequency in all normal conducting linac cavities.

Installation of downstream accelerators parallels FES re-commissioning. Commissioning of the DTL, CCL [11], SRF linac, and ring follow sequentially.

2.3 SRF Linac (JLab)

Acceleration from 93 to 1000 MeV in the original 465 m-long SNS linac was accomplished by a CCL. Late in the project, we adopted SRF technology because of the enormous advantages offered by the superconducting structures: large aperture, operational flexibility, high gradient, less real estate, lower operating costs, no wakefields, excellent vacuum, and very high efficiency.

A worldwide collaboration that was quickly assembled in the fall of 1999 addressed both physics and technology issues. SNS benefited from technologies, systems, component designs, and processes developed at other facilities; expertise in beam and cavity-dynamics optimization; and from an overwhelming amount of enthusiasm to help design and construct the world's first high-power H- ion linac using SRF technology.

Designing complex low-β cavities to replace the entire CCL was too ambitious. Two cavity geometries [12] were chosen as the most efficient way to accelerate the beam to 1 GeV. Some design parameters for both cavities are listed in Table 2. Beam is accelerated from 186 MeV to 387 MeV by 11 cryomodules (CMs) with 3 medium-β (β = 0.61) cavities each, and on to 1 GeV by 12 CMs with 4 high-β (β = 0.81) cavities each, or a total of 81 cavities.

There is space at the end of the linac tunnel for 9 CMs to provide additional beam power to users in the future.

Table 2: Some Cavity Design Parameters.

Parameter	**β=0.61**	**β=0.81**	**Unit**
Frequency	805	805	MHz
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 2.1K	$>5\times10^9$	$>5\times10^9$	
Active Length	0.682	0.906	m
Actual Length	1.067	1.291	m

Fig. 6 shows the surface, on-axis, and effective accelerating fields for both optimized cavity geometries, as a function of beta of the particles. There is no emittance growth in the SRF linac, as shown in Fig. 7.

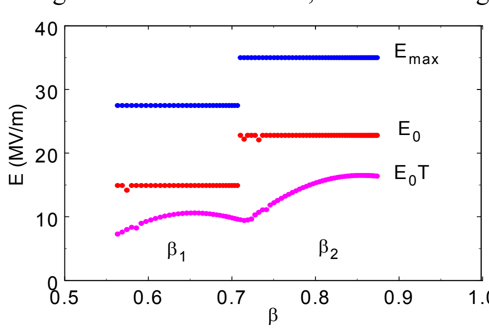

Figure 6: Surface (E_{max}), on-axis (E_0), and effective accelerating (E_0T) fields for both optimized cavity geometries, as a function of particle beta.

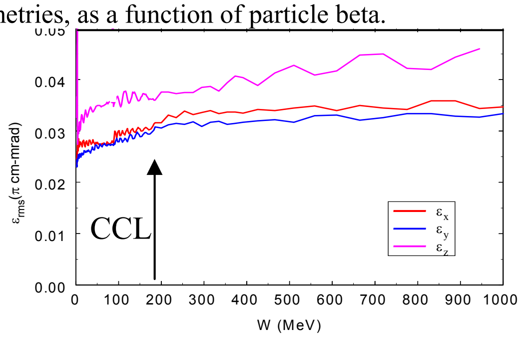

Figure 7: There is no emittance growth in the SRF linac.

The SRF cavities are manufactured by industry out of high-purity RRR ≥ 250, eddy-current-scanned Nb sheets. They are then shipped to JLab for surface treatment, where they are subjected to standard cycles of buffered chemical polishing, high-pressure ultra-pure water rinsing, and vacuum degassing, after which they are RF-power tested in a radiation-shielded vertical dewar.

Inner surfaces of high-β cavities are electropolished so they can achieve the higher gradients. After successful completion of the rf power tests, cavities are attached to their helium vessels in a cleanroom. Cavity tunes are rechecked, followed by light chemistry and a final high-pressure rinse. Three medium-β or 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. The cavity string is evacuated and leak tested, and installation of cavity tuners is performed. The string is transferred to a clean area so that CM assembly can take place. Thermal and magnetic shields are installed, the string support is transferred to the space frame, and sensors, instrumentation, and cabling are installed and verified. The cold mass is inserted into the vacuum vessel, and end caps and couplers are installed.

Prototype medium-β and high-β cavities are shown in Fig. 8. A prototype medium-β CM, shown in Fig. 9, was manufactured at JLab. It performed well in initial testing, giving us confidence to proceed with mass production.

Figure 8: Prototype high-β (above) and medium-β (below) bare e-beam-welded Nb cavities. Fundamental and HOM coupler ports and stiffening rings are visible.

Figure 9: Prototype medium-β CM in JLab's test cave.

The prototype cavities performed very well, though two cavities, heat treated at 800 C for 6 hours, became soft.

The yield strength decreased significantly, making it difficult to maintain field flatness during handling. Cavities treated at 600 C for 6 hours retain mechanical strength, and hydrogen degassing eliminates Q-disease, as verified in cavity tests. All cavities and their couplers [13] exceeded requirements in Q and gradient in the CM tests; one example is in Fig 10.

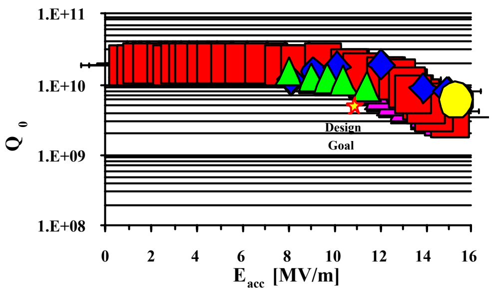

Fig. 10: Excellent med-β cavity performance in the CM.

Since SNS is a pulsed accelerator, compensation of Lorentz force detuning (LFD) 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, without electronics, are installed on all cavities as a conservative measure. Results shown in Fig. 11 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 by a factor of three [14, 15].

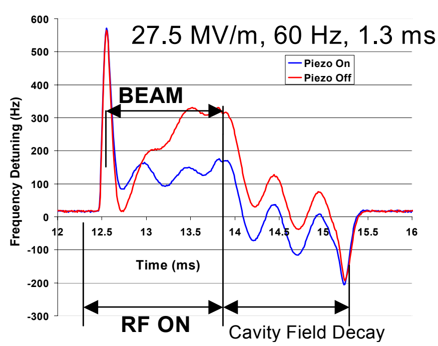

Figure 11: Fast piezoelectric tuners can reduce LFD by about a factor of three.

It is critical that particulates not be introduced into the SRF cavities, as the resulting field emission would severely degrade their performance. A non-intercepting beam profile diagnostic, the laser wire, is being developed in collaboration with other labs [16, 17].

Controls for the SNS complex are distributed among the partner labs, but are coordinated at ORNL. SNS relies on the EPICS system and will make use of the global accelerator network.

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, coalescer-demister, and charcoal filters. It is then piped to the 4.5K coldbox where a standard liquefier cycle sends helium through cryogenic transfer lines to the cryomodules.

JT 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 4.5K coldbox. Transfer line and CHL installation are already underway.

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%

2.4 Linac RF Power Systems (LANL)

The high-power and low-level RF systems are provided by LANL [18]. The linac and HEBT RF system is composed of 96 operating klystrons and their support systems. The RFQ and DTL are powered by 7 402.5-MHz, 2.5-MW (peak) klystrons, the CCL and the HEBT cavities by 6 805-MHz, 5-MW klystrons, and the 81 SRF cavities by 81 805-MHz, 550-kW klystrons [19]. All klystrons are powered by high-voltage converter modulators (HVCM) designed by LANL [20]. The HVCM design is based on IGBT fast switching technology and nanocrystalline transformer cores, resulting in compact equipment layouts in the klystron building. Each of the 14 HVCMs delivers ~1 MW of average power to up to 12 klystrons simultaneously. The LANL prototype operated at full voltage and 50% of the design duty cycle. Build-to-print construction of the HVCM units is ongoing, and delivery begins this fall. The low-level RF systems are being designed by LANL, and prototype components have been delivered to JLab for the integrated CM test this September [21].

2.5 Accumulator Ring (BNL)

The 1-ms-long linac pulse is compressed to a single 695 ns bunch in the accumulator ring through multi-turn 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 risetime. After accumulation, the extraction kicker directs the beam into the ring-to-target beam transport tine that takes it to the target. Major ring parameters are listed in Table 4 [22].

Table 4: Major Parameters of the Ring

Nr of injected turns	1060	
Revolution frequency	1.058	MHz
Filling fraction	68	%
Transvrs emittance 99%	240	πmm mr
Transvrs acceptance	480	πmm 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	πmm mr
Beam size @ tgt (H×V)	200×70	mm×mm

3 TARGET AND INSTRUMENTS

The SNS target consists of 1 m^3 of liquid mercury, weighing 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 power. Currently, there is evidence of cavitation-induced pitting in the steel, but several ways to mitigate these effects are under study. Construction of the target conventional facilities is proceeding apace. Many of the major components are now on site and installed.

Selection of SNS instruments is based on scientific merit, and a peer-review body provides advice in that regard. So far, 13 instruments are approved or are close to approval, 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 3rd-generation powder diffractometer. Three additional instruments are funded by instrument development teams: a wide-angle thermal chopper spectrometer, cold neutron chopper spectrometer with 10-100 μeV resolution, and an engineering materials diffractometer. Funding is being sought for the remaining approved instruments: a high-pressure diffractometer, disordered materials diffractometer, fundamental physics beamline, high-resolution thermal chopper spectrometer, and a single-crystal diffractometer.

6 CONCLUSIONS

The SNS is under construction. At the time of this conference, the total project is 48% complete. More than 1.3 million cubic yards of earth have been excavated, the accelerator tunnels are mostly poured, support buildings are progressing well, and installation of technical components has begun. SNS is on schedule to be completed, within its budget, in June 2006. One million person-hours of work have taken place without a lost-time injury. Up-to-date information about SNS can be found by looking at our website [1].

Many SNS papers from other accelerator conferences can be found using the JACOW website and its excellent search engine [23].

4 ACKNOWLEDGMENTS

This paper is presented on behalf of all 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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