STATUS OF THE SNS* LINAC: AN OVERVIEW

N. Holtkamp, ORNL, Oak Ridge, TN 37831, USA

Abstract

The Spallation Neutron Source (SNS) is a second generation pulsed neutron source and under construction at Oak Ridge National Laboratory. The 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 collaboration composed of six national laboratories (ANL, BNL, TJNAF, LANL, LBNL, ORNL) is responsible for the design and construction of the various subsystems. With the official start in October 1998, the operation of the facility has begun recently as planned and delivers a close to 1.0 GeV beam, ultimately reaching 1.4 MW average power proton beam with a pulse length of approximately 700 nanoseconds on a liquid mercury targert. The multi-lab collaboration allowed access to a wide variety of expertise in order to enhance the beam power delivered by the accelerator by almost an order of magnitude compared to existing neutron facilities. The SNS linac consists of a combination of room temperature and superconducting structures and is the first and highest energy pulsed high power sc linac worldwide. The accumulator ring designed for 2 MW at 1.0 GeV is already constructed for > 3 MW at 1.3 GeV. The project challenges and the commissioning achievements over the last 5 years will be described in the paper.

GENERAL PROJECT OVERVIEW

The Spallation Neutron Source (SNS) [1, 2], authorized for construction in fiscal year 1999 is officially completed as of May 30, 2006 and has seen first beam April28,2006 achieving the initial design specification of more than 1.0×10^{13} protons per pulse on target. The project finished one month ahead of schedule and ~ $6.5M under budget compared to a schedule, cost and scope baseline that was frozen in 2001. Only changes in some of the technical systems, driven by focused R&D to improve performance were added to the scope (laser profile monitor systems, fast feedback systems and stripper foil developments) while very little other original scope was deleted without compromising the design baseline as it is described in table 1.

Looking at SNS today it can be described in summary terms as:

- The first high energy proton linac largely built with superconducting RF structures (0.812 GeV out of 1.0 GeV).
- The worlds highest energy (H^-) proton linac.

* SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy. SNS is a partnership of six national laboratories: Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos and Oak Ridge

Figure 1: The photograph shows the SNS site with the finished accelerator facilities in the upper left and the Target building, Central Laboratory Office and the Center for Nanophase Material sciences in the foreground.

- The second largest accelerator RF installation in the US.
- The first Multilab collaboration with fully distributed responsibility for accelerator construction.
- A project that finished "on time and within budget" according to a schedule/budget set in 2001.

and a facility that should in the future be

- The highest intensity proton storage ring of its kind.
- The highest average beam power available in the world.
- The most advanced Neutron scattering facility with the best in class instruments.

This is very well summarized in figure 2 which shows the development of neutron sources (fission and spallation) and the step that SNS will provide once in full operation.

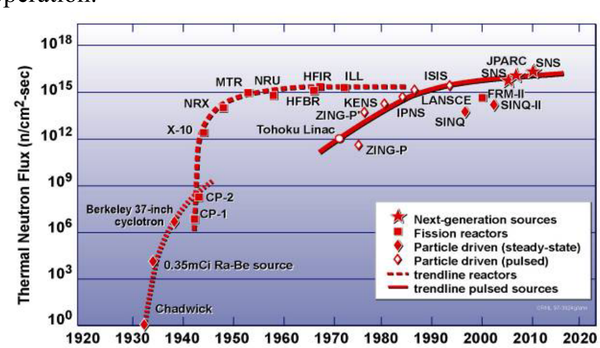

Figure 2: Neutron Source Development over the last 70 years for fission and spallation sources.

The accelerator, Central Laboratory and Office Building (which includes the central control room) and the Center for Nanophase Material Sciences (CNMS), are shown in Figure 1. The Joint Institute for Neutron Sciences (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 in operation or under construction in the United States. As to the status of construction, all associated buildings are completed while instrument installation in the target building continues in order to achieve the full suite of 24 instruments by approximately 2013.

PROJECT SUMMARY

The SNS project was officially authorized for construction in FY1999 and finished end of May, 2006 with the signature of the Critical Decision 4 documents at a total project cost of M$1,405.2 (versus M$1,411.7 planned) one month ahead of the scheduled finish date. At this point all criteria for completion were fulfilled:

- An accelerator-based neutron scattering facility capable of at least 1 megawatt proton beam power on target
- Five specific research instruments
- 1.0E+13 protons per pulse
- 5.0E-3 neutrons/steradian/incident proton, viewing a moderator face.

While originally anticipated as 1GeV normal conducting linac with two accumulator rings attached, the final configuration was fixed in 2001. Among the major changes, the transition from a normal conducting to a superconducting linac as well as the increase of the ring energy to a 1.3 GeV design with a single ring, were the two outstanding ones. In addition several lower level changes were implemented in combination with R&D programs to improve performance or to manage to cost.

From the B$1.4 roughly one half was spent on the accelerator systems with a distributed lab collaboration in which the partner labs were generally responsible for the design and construction of components while SNS/ORNL managed the integration, installation, testing and commissioning. In 2003 the SNS accelerator division reached the peak work force of 500 people while only about 200 are required during operation. The smooth transition of the expertise into and out of the project back to their home laboratories was a strong advantage of this organization. Through this collaboration SNS had access to an enormous amount of expertise which allowed the timely and successful execution the project. As a result the SNS model should be, and is, considered as one of the possible models for future large science projects.

GENERAL PROJECT DESCRIPTION

The project goal for SNS is to deliver a proton beam of up to 1.4MW beam power to a mercury target for neutron spallation. Longer term, higher beam power operation by increasing the beam energy and doubling the user access with a second target station is envisaged as summarized in DOE's 20 year outlook of science facilities for the future [3]. These upgrades are incorporated in the site layout with an identified area for the second target station. Also, 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, 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; 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 and a superconducting linac (SCL) with 11medium-β cryomodules (up to 379 MeV) and 12 high-β cryomodules (up to 1000 MeV). The linac produces a 1 msec long, 38 mA peak, chopped beam pulse at 60 Hz for accumulation in the ring. A high-energy beam transport line (HEBT) for diagnostics and collimation after the linac injects into an accumulator ring for compressing the 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% availability of the facility 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 3 shows a schematic layout of the different accelerator systems and their geometric arrangement.

Table 1: Summary of SNS Facility Parameters

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
Aver. 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	

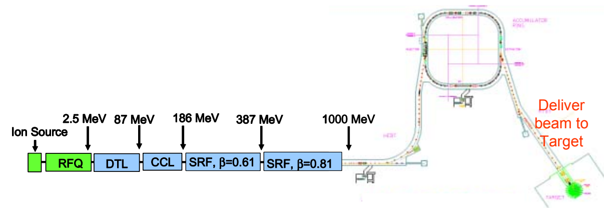

Figure 3: Schematic layout of the linac and the accumator ring.

THE COMMISSIONNG RESULTS OF THE SNS ACCELERATOR

The Linac consists of four sections: it begins with the Front End System (FES), designed, built and originally commissioned at LBNL, followed by the DTL and the CCL. The DTL, CCL, as well as all the High-Power RF systems for the complete linac, were designed and procured by Los Alamos National Laboratory (LANL). Finally the SCL and the cryogenics support systems, which were largely designed by JLab with many contributions from LANL and ORNL. The beamlines from the linac to the ring, the ring itself and the transport line to the target were under the responsibility of BNL.

The Room Temperature Linac

Originally commissioned at LBNL in May 2002, the FES were re-assembled and re-commissioned at ORNL in late 2002. The front-end consists of a volume H- Ion source with 50 mA peak current, 6% duty factor and an electrostatic low-energy beam transport (LEBT) line to provide a properly matched, 65 keV beam for injection into the RFQ. Pre-chopping is performed by the LEBT chopper which deflects 32% of the beam onto the front face of the RFQ with a rise/fall time of 40 nsec. The RFQ is designed for 38 mA peak output current, operates at 402.5 MHz and provides 2.5 MeV output beam energy. Stable operation with excellent transmission has been demonstrated at a variety of currents between 15 and 55mA. The medium energy beam is transported to the drift tube linac via the MEBT, which contains four RF rebuncher cavities to properly match the beam longitudinally, a set of matching quadrupoles, and a fast chopper system with 10 nsec rise/fall time to remove the "partially chopped" beam from the LEBT chopper and further reduce the beam extinction ratio to below 10^{-4}.

In subsequent DTL commissioning runs, the Front-End Systems have operated at full 1 msec pulse length, and provided 1 mA average current (4% duty factor) beam for injection into the first DTL tank. At higher energies beam stops capable of handling the beam power do not exist.

The Drift Tube Linac consists of six accelerating tanks with a final output energy of 87 MeV. Permanent magnet quadrupoles are distributed through the 210 drift tubes providing transverse focusing arranged in a FFODDO lattice. Twenty-four steering dipoles as well as 10 BPM are integrated into otherwise empty drift tubes. The DTL operates at 402.5 MHz, the same bunch frequency as the RFQ. Tanks are individually powered with klystrons of 2.5 MW peak power and 8% duty factor capability. Some empty drift tubes contain beam position monitors and dipole correctors. The intertank sections contain toroidal beam current monitors, wire scanners and energy degrader/faraday cups.

During Front End and DTL 1 commissioning, a peak current of 38 mA was accelerated and also 1mA average current beam with 100% beam transmission was demonstrated.

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. The linac has been designed at LANL and built by industry. It operates at 1.3 times the Kilpatrick limit and includes 48 quadrupoles, 32 steering magnets, 10 beam position and phase monitors and seven carbon wire scanners.

Compared to the design the measured energies are summarized in table 2 for the normal conducting part of the SNS linac.

Table 2: Accelerating fields achieved in the normal conducting part of the SNS linac.

Module	Design [MeV]	Measured [MeV]	Deviation [%]
DTL6	86.83	87.48±0.03	0.75
CCL1	107.16	107.36±0.12	0.19
CCL2	131.14	131.53±0.14	0.40
CCL3	157.21	158.08±0.40	0.55

The Superconducting Linac

SNS is the first large-scale high energy superconducting proton linac that provides high beam power utilizing H^- beams. The most prominent arguments for an SCL are large apertures, operational flexibility, high gradient leading to less real estate required, lower operating costs, small wakefields, excellent vacuum with concurrently less H- stripping followed by beam loss, and very high electrical to beam power conversion efficiency. These arguments lead to the baseline change for SNS from a normal conducting CCL structure to the SCL structure in 2000, relatively late in the project. Within three years the detailed design had to be finished and series production begun. With the delivery of the last cryomodule (nr 23) in June 2005 and its subsequent installation, commissioning of the SC linac together with the nc linac was a major project milestone, which was achieved in August of the same year.

The velocity of the H^- ions within the SCL varies from β=0.55-0.87. The sc linac has a two-cavity geometry with β=0.61 and β=0.81to cover this velocity range. The beam is accelerated from 186 to 387 MeV by 11 cryomodules (CMs) with 3 medium-β ($\beta = 0.61$) cavities each and to 1 GeV by 12 CMs with 4 high-β ($\beta = 0.81$) cavities each, or a total of 81 cavities.

Table 3: Measured versus design emittances throughout the linac (not always at design current).

	Measured ε (H, V) norm. π-mm-mrad	Parameter List ε (H, V) norm. π-mm-mrad	Notes
MEBT Entrance	0.22, 0.25	0.21	RFQ Exit Twiss study
CCL Entrance	0.22, 0.25	0.33	From 7 CCL profile sets
SCL Entrance	0.27, 0.35	0.41	From 3 SCL profile sets
Linac Dump	0.26, 0.27	0.41	1 wire, vary quads

After final installation, testing of the cavities was performed at 4.5 Kelvin and at 2.0 Kelvin. Surprisingly the performance was essentially identical. At the higher temperature the residual Q is approximately 25 times higher but since enough cooling power from the cryo-plant was available up to a repetition rate of 30 Hz, most of the beam commissioning was actually done at 4.5 Kelvin. The average beam power was again limited by the availability of an appropriate beam dump (limited to 7 kW average, but full peak intensity), High intensity beams were accelerated with almost full pulse length and up to $8x10^{13}$ ppp. The beam energy during these runs varied from 600 to 925 MeV. Up to 7 cavities were permanently off due to various issues related to cavity performance, tuning range, tuner problems and others that will be repaired in subsequent maintenance periods.

The commissioning of the sc linac was done in less than 6 weeks going from first beam to the highest intensity achieved, which was only possible due to excellent preparation and readily available beam diagnostics, a theme that follows through the SNS success story.

The beam parameters of the SNS linac were measured at the various interface points from one accelerating subsystem and the next and the result is presented in table 3. The measurements have been done under various beam conditions and not necessarily at the design current, which leaves some final questions open, but they confirm the basic validity of the design.

The Accumulator Ring

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: Basic parameters of the accumulator ring.

Nr of injected turns		1060
Ring revolution frequency	MHz	1.058
Ring filling fraction	%	68
Ring transverse emittance 99%	**πmm mrad**	**240**
Ring transverse acceptance	**πmm mrad**	**480**
Space charge Tune shift	**$\Delta Q_{x,y}$**	**0.15**
Peak Current	52	A
HEBT / RTBT Length	m	170 / 150
Ring Circumference	m	248
RTBT transverse acceptance	πmm mrad	480
Beam size on target (HxV)	mm x mm	200x70

With constant delivery of components through ‘04 and ’05 and subsequent installation in the ring and beamline tunnels, the ring was ready for commissioning in January 2006. Beginning with beam transport at an energy of ~925 MeV beam reached the injection beam dump quickly. Followed by charge exchange injection tests and final extraction of the first seven accumulated batches of a 7 μsec long beam pulse the whole setup required two days. Again with the availability of all major diagnostic systems, extraction of the design commissioning intensity of $>1x10^{13}$ ppp was possible within two weeks.

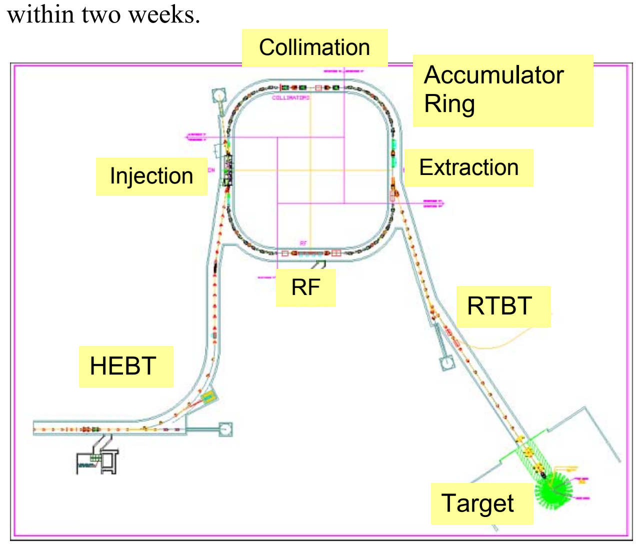

Figure 4: Layout of the accumulator ring and the associated beamlines.

High intensity studies immediately began and up to $5.5x10^{13}$ ppp of bunched beam were stored and extracted, while coasting beam studies went up to $1x10^{14}$ ppp with no signs of instability during the 1 msec storage time. This so far is a good conformation of the design values, testing the facility under various conditions of delaying extraction, operating with zero chromaticity and storing a coasting beam. A circulating beam pulse can be seen at $3.0x10^{13}$ ppp and $5.5x10^{13}$ ppp in figure 5. In the lower plot at the higher intensity the extraction kicker gap is starting to fill up with protons due to a not perfectly tuned rf system. These pulses were sent either to the extraction dump or the target.

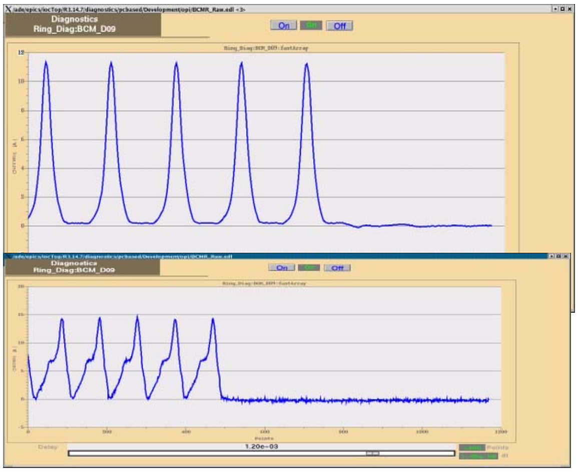

Figure 5: 3.0x10^{13} ppp (upper) and 5.5x10^{13} ppp (lower) are shown circulating in the ring shortly before extraction.

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 few years, and several ways to mitigate these effects have been implemented. In April 2006 the target was certified to run up to 100kW of beam power with a pending certification to 1.4 MW or more following in spring 2007.

Beam testing began on April 28th and within hours the beam was dumped into the target for the first time. Soon after that the design commissioning intensity was demonstrated and neutrons streaming off the target into one of the instrument beamlines were measured. A later picture of a fully painted proton beam on target, as recorded by a specially set up view screen in front of the target face, is shown in figure 6.

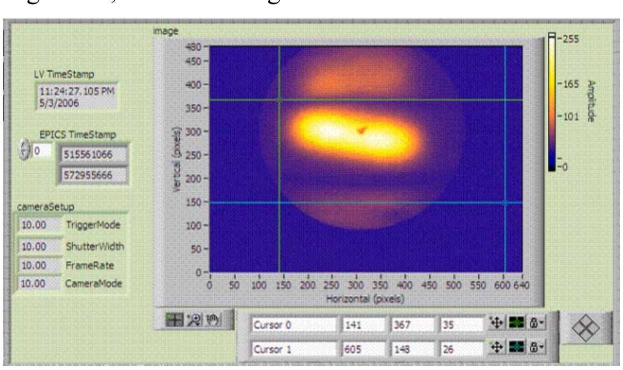

Figure 6: View screen picture of a fully painted proton beam on target with almost nominal beam size.

During the months of April and May several beam runs with an average beam power of ~7kW were carried out. The initial availability was of the order of 60-70% and first experiments have been performed to calibrate the suite of instruments that are available.

Selection of SNS instruments is based on scientific merit, and a peer-review body provides advice in that regard. So far, 18 instruments have been approved, 5 of which are funded within the SNS project. The total number of available beamlines is 24 and should be fully built out by 2013. During this period of time the product of beam availability, beam power and number of user hours is planned to go to >90%, 1.4 MW and more than 5000 hours per year with reaching the MW level at high availability in approximately 3 years from now. All this is laid out in a plan that originated in 2003 and was communicated in a timely manner to the user community in order to manage expectations on both sides.

Summary

Over the last 7 years, the SNS collaboration has, with the successful delivery of the project milestones and in many cases a performance that goes beyond, completed the project under schedule and below cost. Only due to the demonstration of this success, SNS got initial approval for a power upgrade program already in November 2004. The Power Upgrade Project is funded over the next 7 years and will double the neutron capability of the systems. The collaboration within and execution of the project has been a great success for all participants and SNS is well on its way to continue to deliver as promised.

Acknowledgement

This paper is presented on behalf of the SNS collaboration and many people from different laboratories all over the world, who have helped to make SNS such a timely success. Within the collaboration, the enormous support from the management of the various laboratories involved was crucial. The SNS is also indebted to the Department of Energy and its management. Most importantly, their continuous support was key to the successful and timely completion. I have not attempted to make an accurate list of references. Much of the work reported here in general has been described in great detail over the past years in conferences such as this one and can easily be accessed through the JACoW web page at: http://www.jacow.org/

REFERENCES

[1] SNS web site: www.sns.gov.

[2] NSNS Collaboration, NSNS Conceptual Design Report, NSNS-CDR-2/V1, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., 1997.

[3] R.Orbach, "Facilities for the Future of Science: A Twenty-Year Outlook", DOE/SC-0078, December 2003.