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 Energyís 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 will begin in 2006 and deliver a 1.0 GeV, 1.4 MW average power proton beam with a pulse length of approximately 700 nanoseconds on a liquid mercury target sixty times a second. The multi-lab collaboration allowed access to a large 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 will be the first pulsed high power sc linac in the world. The challenges and the achievements will be described in the paper.

GENERAL PROJECT OVERVIEW

The Spallation Neutron Source (SNS) [1, 2], authorized for construction in fiscal year 1999, is 85% complete. 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 under construction in the United States.

Currently, all of the SNS accelerator-associated buildings and tunnels are completed with installation and staged commissioning of the accelerator components ongoing. The project goal for SNS is to deliver a proton beam of up to 1.4-MW 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 envisioned as summarized in DOEís 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, 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; a

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, with civil construction still ongoing.

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 11 medium-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

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	

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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 2 is a schematic layout of the different linac structures as a function of beam energy.

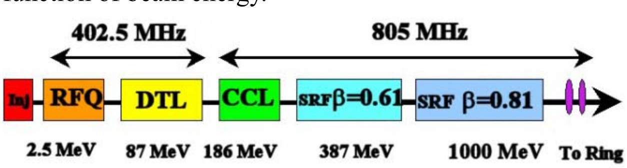

Figure 2: Schematic layout of the linac structures as a function of beam energy.

THE STATUS OF THE SNS LINAC

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. A separate talk was given during this conference on the Front End and DTL commissioning results [4].

The Front End Systems

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 15-40mA. 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 ìpartially choppedî beam from the LEBT chopper and further reduce the beam extinction ratio to below 10^{-4}.

A peak MEBT output current of 50mA was demonstrated, surpassing the design goal of 38 mA. In subsequent DTL commissioning, 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 DTL. In parallel to operating the source on the linac, a hot spare stand is in operation to foster the development of more reliable, higher intensity sources. So far a variety of slightly modified sources have been tested at currents starting at 40 mA or higher and at nominal duty cycle. Typically after 7-10 days, currents reduced to below 20 mA and operation was interrupted to exchange the source.

The DTL Status and Commissioning Results

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. 24 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.

To date, the entire DTL has been RF tuned and installed in the linac tunnel. DTL tank tuning has resulted in longitudinal fields within the specification of ±1% of design.

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. Subsequently, DTL Tanks 1-3, with an output energy of 40 MeV, were commissioned during spring of 2004. Peak currents of 38 mA transported through all three tanks with 100% transmission were demonstrated as well. Beamstop and residual radiation considerations limited the beam pulse lengths to less than 50 microseconds, and repetition rates to 1 Hz maximum.

During commissioning availability of all subsystems was tracked in order to prepare early on for repairs that allow long term higher reliability operation, which is at this point ~ 60% of the time dedicated.

The Coupled Cavity Linac

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 in industry. It operates at 1.3 times the Klipatrick limit and includes 48 quadrupoles, 32 steering magnets, 10 beam position and phase monitors and seven carbon wire scanners.

The CCL is fully assembled in the SNS tunnel and has been tuned with final field values between ± 1% of design specification. The first 3 of the four modules are conditioned to full field, pulse length and 20 Hz rep rate. Conditioning went smoothly over a period of approximately 3-5 days per module.

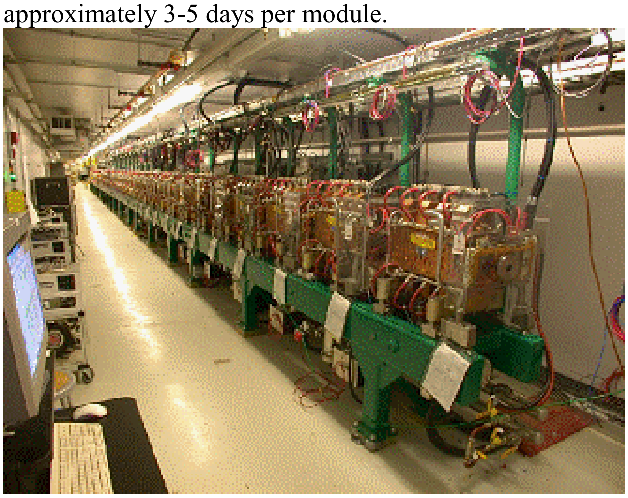

Figure 3: The CCL fully installed in the SNS linac tunnel.

The next beam commissioning begins in September 2004 and will include three out of the four modules and boost the beam energy to ~150 MeV. Average beam power generation will again be minimal to reduce residual contamination of the temporary beam stop within the tunnel.

The Superconducting Linac and the Cryogenic Support Systems

SNS will be the first large-scale superconducting proton linac that provides high beam power. The most prominent arguments for an SCL are large apertures, operational flexibility, high gradient, less real estate, lower operating costs, small wakefields, excellent vacuum, and very high electrical to beam power conversion efficiency.

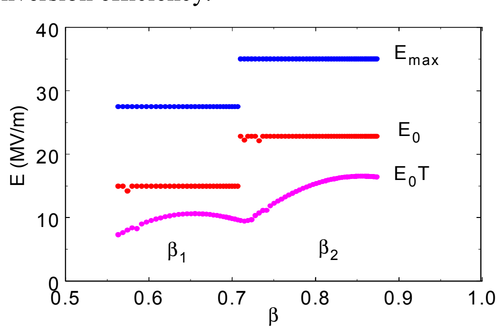

Figure 4: Surface, on-axis, and effective accelerating fields.

The velocity of the H^- ions within the SCL varies from β=0.55-0.87. The SNS approach (balancing the number of different types of cells to be used versus accelerating efficiency, compare figure 4) a two-cavity geometry with β=0.61 and β=0.81was chosen.

Table 2: Some Cavity Design Parameters

Parameter	β=0.61	β=0.81	Unit
No. of cells	6	6	
Epeak	27.5	35.0	MV/m
Epeak/Eacc	2.71	2.19	
Bpeak/Epeak	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

Some of the 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.

All 11 medium β CMs are built and 10 are located in the SNS tunnel. The production of the high β CMs is well advanced and nr 5 and 6 are nearing completion. One out of the 12 CMís is at the SNS site already. The overall schedule shows completion of CM construction in March 2005 and beginning commissioning of the linac shortly thereafter.

The SRF cavities are manufactured by industry out of high-purity RRR 7 250 niobium sheets. They are 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. While Electro-polishing, a technique that has been demonstrated to further improve surface gradients, was originally foreseen, the performance of the cavities today is 25% above spec even without applying this technique. Some of the cavities over-perform by as much as 60%. While vertical single cavity tests are performed in continuous mode, cryomodule testing is done in a pulsed mode at nominal duty cycle, which allows even higher gradients for operation (Figure 5).

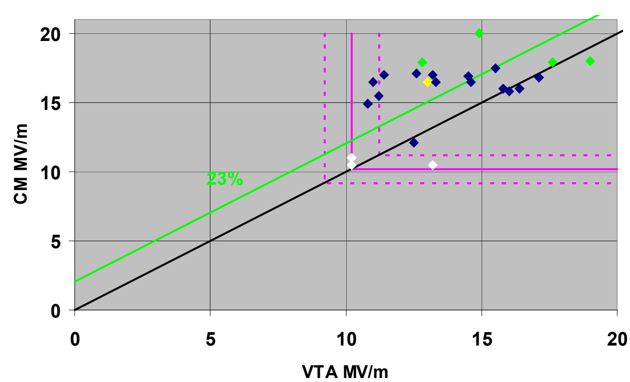

Figure 5: Comparison of single cavity test gradients (VTA, cw) with fully assembled cryomodule (CM) test results (6% duty cycle) for a variety of medium β cavities.

Three medium-β and four high-β cavities in their helium vessels are connected together per cryomodule. Figure 6 shows a picture of the 12 cryomodules in the SNS tunnel. One of the cryomodules is connected and the liquid helium transferline is cooled down to 4.5 K. RF testing at this temperature is ongoing until the 2 K cold box is operational.

Figure 6: Twelve out of 23 cryomodules are located in the SNS tunnel.

The Cryogenic System

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 cold box where a standard liquefier cycle sends helium through cryogenic transfer lines to the cryomodules.

Joule Thomson 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 cold box. Transfer line installation is complete and allows for a total of 32 cryomodules to be connected (23 are part of the present baseline design and 9 spots are available for future upgrades). CHL installation is largely finished with all three warm compressor streets as well as the 4.5 K cold box being commissioned. All baseline parameters have been verified up to this point. Slightly lower efficiency in the cold box has been observed so far and mitigation is underway. Operation of the 2 K cold box will start after final installation in September of 2004.

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%

The RF Systems

The high-power RF systems are installed in a ~330 m long klystron gallery. They 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 one cavity per klystron layout allows a lot of flexibility in operations but also leads to a very dense population of RF systems in the gallery (compare Figure 7).

Figure 7: Klystron installation in the area of the superconducting linac. The one cavity per klystron layout requires a very dense population of rf equipment.

The klystrons are powered by 14 high-voltage converter modulators (HVCMs), which were specifically developed for SNS. Extremely high-power density and efficient AC-to-DC high-voltage conversion are the main features. High-frequency (20-kHz) switching using IGBT technology and newly developed boost transformers based on nanocrystalline transformer cores 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 CCLs and 12 superconducting linac (SCL) klystrons. Integrated into the design are rectifiers and transformers, control racks, and SCR regulators. Between the nine HVCMs that are currently operating on the site, approximately 8000 h have been accumulated at a variety of power levels. 1500 hours were accumulated at design duty cycle of 7.5%. Weak spots of the design, like the switch design or the SCR units, are systematically identified and removed.

The low level rf system (LLRF) was designed and built within a collaboration at LBNL, LANL and ORNL. The very high external Q of the superconducting cavities (~$7x10^5$) requires very tight amplitude and phase control to within ±0.5% and ±0.5 degree in spite of deteriorating effects like Lorentz Force Detuning (LFD) and mechanical vibration. The recently deployed system thatís now delivered has demonstrated ±0.1% in amplitude and ±0.2 degree in phase on a superconducting cavity operating at design gradient. In addition the field control module incorporates a feed-forward loop that activates LFD piezo controllers. They reduce the frequency deviation during the pulse typically to 100 Hz and therefore minimize the rf overhead required on the klystron output. All superconducting cavities are equipped with piezo controllers.

The klystrons as well as the HVCMs have a significant margin designed into them. To achieve the baseline beam power of 1.4 MW, many of the systems only have to operate at 50-70% of the design load which should increase the reliability substantially and later on allow for an upgrade in beam power quite easily.

Special Diagnostics Development for the Linac

Superconducting cavities are especially prone to contamination. At the same time it is very desirable to have non interceptive beam diagnostics available to monitor beam quality during normal operation. A Nd-Yag laser based transverse profile monitor system that would neutralize H^- ions fulfils both of these requirements, while traditional carbon wires would imply repetition rate as well as beam pulse length limitations when used. The number of electrons that are knocked off as a function of laser beam position can be measured with very high sensitivity into the 10^{-3}-10^{-4} range. Since the laser pulse is only ~ 10 nsec long, measurements can also be performed along the bunch train to see eventual changes of the beam emittance along the train. The laser beam is transported in an enclosed beam pipe in the linac tunnel over distance of approximately 200 meters. It can then be switched into each warm section between cryomodules. A typical measurement of a beam profile is shown in Figure 8. The laser transport pipe as well as the laser are fully installed and the first measurement stations in the superconducting linac are being assembled.

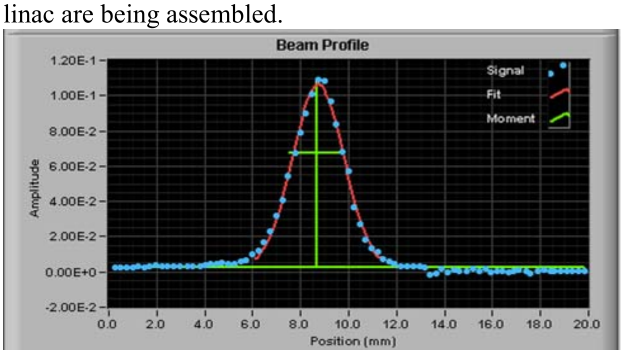

Figure 8: A beam profile measurement of a 2.5 MeV beam with a Gaussian fit plotted out to 2.5 sigma.

The High Energy Beam Transferline

The ring and all transferlines between the linac and ring and ring and target are designed and constructed by BNL and is 92% complete. Much of the hardware is installed in the tunnel and especially the HEBT with its collimation is completely in place. This allows beam transport from the linac to the dedicated commissioning beam dump straight ahead of the linac. In this beamline an experiment is prepared that will test the feasibility of highly efficient laser stripping of H- ions [5]

Summary

Over the last 5 years, the SNS collaboration has successfully met the project milestones and with the completion of the Front End Systems and the room temperature linac and rf systems two major contributors have transitioned out of the construction project. Major achievements were made during these years. In addition, an advanced technology, namely superconducting rf, as well as several other new ideas (laser profile monitors, highly efficient and compact high voltage converter modulators and advanced LLRF systems) were employed by the project and successfully further developed while in construction.

The SNS project at the time of this conference has another 22 months before completion and is well en route to achieve that goal. Future major commissioning steps include the superconducting linac in spring of 2005 and accumulator ring commissioning later that year finishing up with target commissioning in spring of 2006.

Acknowledgement

This paper is presented on behalf of the SNS collaboration and many people from different laboratories all over the world that have helped to make this a success so far. Without the enormous support from the community and the hard work of the collaborators it would have not been possible to be where SNS is today. I have not even attempted to make an accurate list of references since this would take a major fraction of the paper and I apologize. Much of the work reported here in general has been described in great detail over the past years in conferences likes this and can easily be accessed through the JACow web page at: http://www.jacow.org/

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