STATUS AND PERFORMANCE OF ORNL SPALLATION NEUTRON SOURCE ACCELERATOR SYSTEMS *

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Abstract

The Spallation Neutron Source (SNS) accelerator systems have been performing continuously and progressively since commissioning in 2006 to deliver the neutrons to beamlines. The 1.4 MW design beam power has been demonstrated during 24/7 operation while developments and investigations for system improvements are still ongoing to achieve the full design beam power and availability. Numerous difficulties that impeded reaching the full performance of the SNS accelerator systems have been identified and are being eliminated through repairs, upgrades, and developments. In this report, operational performance and developments of the accelerator systems are presented along with the efforts for future upgrades of the SNS.

INTRODUCTION

The SNS consists of the front-end with an H^- ion source, a 2.5 MeV RFQ, and a MEBT, the 186 MeV normal conducting RF linac with six DTL tanks and four CCL sections, the 1.0 GeV superconducting RF linac with eighty-one 6-cell medium-beta and high-beta cavities, and the accumulator ring [1]. The linac and the accumulator ring have performed as designed but with shortcomings of certain components and subsystems which caused limitations in attaining full system performance.

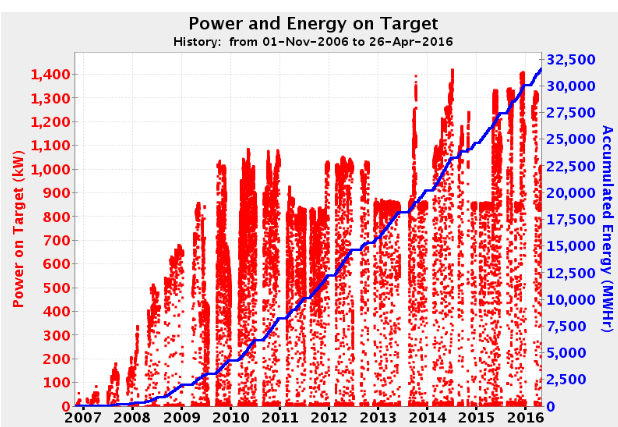

Figure 1: The beam power and energy delivered to target in SNS since commissioning in 2006.

The ion source, RFQ, HVCM, target, and other subsystems instigated limitations in SNS operation at 1.4 MW, the full design beam power and > 90% system availability even with initially successful beam power ramp-up. Actually, with efforts for performance improvements of the components and subsystems that needed the attention, the availability and the reliability of the accelerator systems have improved significantly during the last several years. However, since 2011, the startling failures of major subsystems such as the target and the MEBT that took much time for recovery lowered the overall system reliability considerably. Figure 1 shows the history of the beam power and energy delivered to the target in SNS. Table 1 shows the parametric performances of SNS achieved so far and compared to the design. The operation has demonstrated that SNS is capable of sustained operation at power levels up to 1.4 MW.

Table 1: Performances Relative to Design Parameters

	Design	Best Ever	Routine Operation
Kinetic Energy [GeV]	1	1.07	0.957
Beam Power [MW]	1.4	1.427	0.8-1.40
Linac Beam Duty Factor [%]	6	6	5
Modulator/RF Duty Factor [%]	8	8	7
Peak Linac Current [mA]	38	42	36
Average Linac Current [mA]	1.6	1.6	1.1-1.49
Linac pulse length [msec]	1	0.98	0.975
Repetition Rate [Hz]	60	60	60
SRF Cavities	81	80	79-80
Ring Accumulation Turns	1060	1020	1008
Peak Ring Current [A]	25	26	14.5-25.8
Ring Bunch Intensity	$1.5x10^{14}$	$1.74x10^{14}$	$0.87\text{-}1.5x10^{14}$
Ring Space Charge Tune Spread	0.15	0.14	0.09-0.16

SUBSYSTEM PERFORMANCE

Front-End

Updates and corrective maintenance of the front-end systems on the ion source, LEBT, RFQ, and MEBT have been significant since commissioning. The SNS H^- ion source that is a cesium-enhanced, multicusp ion source has been continually revised to deliver the beam current and the reliability with improved lifespan [2]. The beam current from the ion source has increased steadily and successfully that is now considered adequate for the full beam power at the target.

The high current beam pulses are generated with 50-70 kW from a pulsed 80-kW, 2-MHz amplifier superposed with 300 W, 13-MHz RF supply for continuous low-power plasma for ignition. The amount of the beam current and the beam transmission through the RFQ have been a concern in the front-end systems for the higher beam power operation through the years. The beam

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transmission through the RFQ has degraded and been measured lower than the design minimum of 80%. In the summer of 2013, the RFQ was retuned after observation of field tilt. Then, the transmission increased from 72% to 77% for a 45 mA input current which is still not satisfactory. Lately, the chopped beam on the RFQ entrance flange was measured >50 mA that was being injected into the RFQ under nominal conditions.

Antenna failure rates have been reduced significantly due to improved quality control; there has been only one antenna failure during past 12 months. There is an ongoing optimization of source parameters due to the influence of hydrogen gas from the ion source on RFQ performance, especially considering the close coupling between the source and RFQ. This optimization required better understanding of the RF ignition process of the source plasma with the 2-MHz and 13-MHz RF interaction [3].

The two-lens, electro-static LEBT is 12-cm long. The second lens is split into four quadrants to steer, chop, and blank the beam. The short electrostatic LEBT has been operating reliably with a routine change-out of LEBT that is done twice a year due to insulator coating which seems to be a good plan to maintain the reliability.

The external antenna ion source development has been continued and the test has been done on the test stand with improvement compared to the internal antenna [4]. It is expected that this type of ion source will most likely be the more reliable solution for the future.

DTL and CCL

The normal conducting accelerating structures have been performing well except the issues with the RF ceramic windows at the power coupling waveguide ports. The failures of the windows often came with fractured ceramic disks that were due to excessive ceramic RF heating and braze joint failures resulting in vacuum leaks or cooling channel leaks. One DTL and three CCL windows have failed with the ceramic fractures so far. The 805 MHz CCL window ceramic disks have smaller diameter and thickness and are more vulnerable to thermal damage compared to the heavier 402.5 MHz DTL window ceramic disks. The windows are deemed working more reliably with the efforts to improve the vacuum performance and to optimize the cooling around the windows. IR temperature sensing has been added to monitor the CCL window ceramics for improved management in addition to the existing monitoring with the coolant calorimetry.

SCL

The availabilities have been 99.5% for the SRF system alone and 98% for the SCL including RF, HVCM, control, vacuum, etc. during the last 5 years. Operation for extended periods has shown performance degradation in some cavities. It is learned that thermal cycling and careful reconditioning starting from low repetition rate are needed to recover the accelerating performance with the maximum achievable energy in the SCL. After studies with the plasma processing [5], in-situ plasma processing technique has been developed and being performed in the linac tunnel starting with the medium beta cavities. The processing has delivered positive results with increased field gradient.

The HOM couplers originally installed in the cavities against the potential interference with the beam were found unnecessary in SNS. The HOM couplers have been either disabled or removed from the cavities since they presented difficulties in cavity processing and in operation at SNS. DC-biasing has been added on the input power couplers for better operational stability with suppression of multipacting.

HVCM

Multiple HVCM/Klystron configurations being used in the linac are shown in Figure 2. 92 klystrons are powered by 15 HVCMs in 3 different configurations. The 15 modulators are: 3 in DTL, 4 in CCL, and 8 in SCL with 1 added in 2008. The operation voltages are: 115 kV for RFQ, DTL 1-2, 125 kV for DTL 3-6, with 402.5 MHz 2.5MW klystrons, 135 kV for CCL 1-4 with the 805 MHz 5MW klystrons, and 75 kV for SCL 6-cell SRF cavities with the 805 MHz 550 kW klystrons. So far, on all modulators, approximately 1×10^6 combined operational hours have been recorded.

A key vulnerability to reliable operation of the HVCM has been the boost capacitors in the normal conducting linac. Current strategy is to replace them every 12-18 months. Investigation of alternate capacitor designs and technologies is still ongoing. New IGBT gate driver circuits deliver improved reliability, lower losses, enhanced

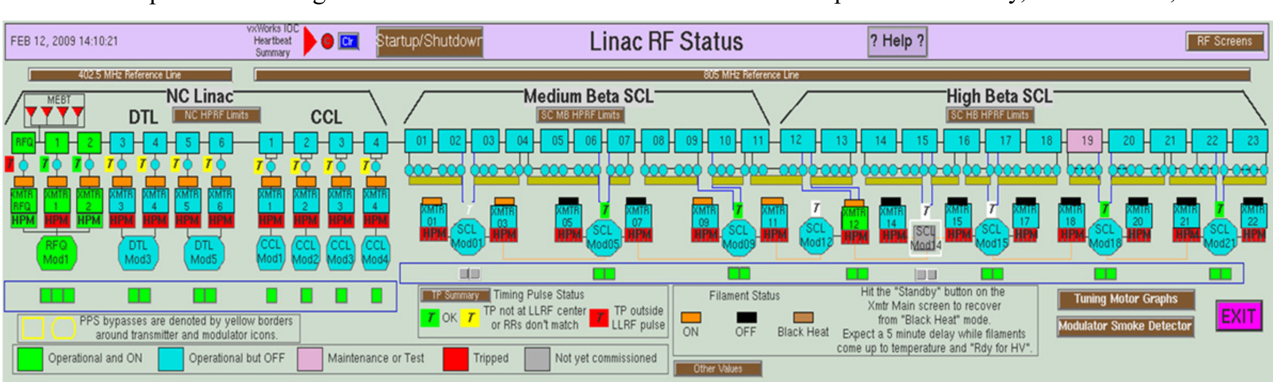

Figure 2: 15 Modulators in 3 different configurations power 92 klystrons to support operation of the Linac.

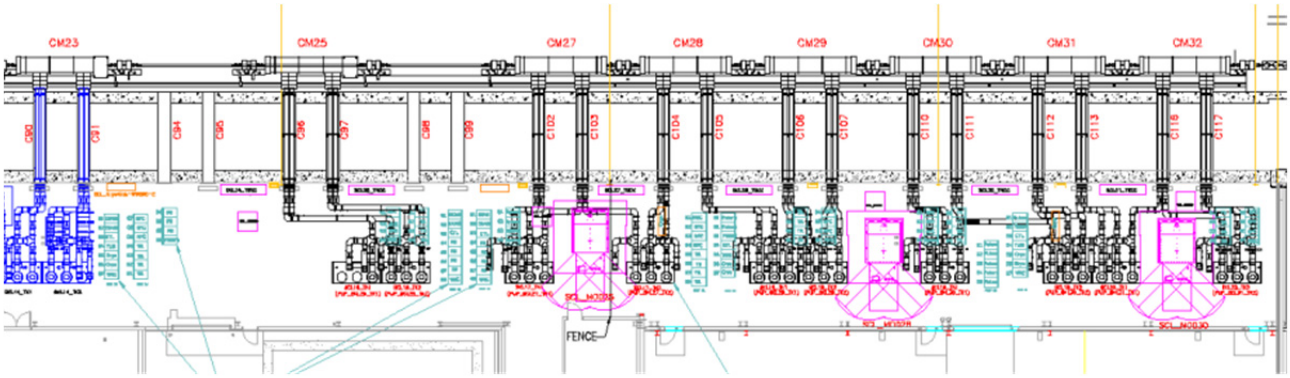

Figure 3: Addition of 7 high-beta cryomodules with 3 new HVCMs in the linac planned for the PPU and the STS.

IGBT protection and reduced ripple. About 30% reduction of IGBT switching loss has been demonstrated.

Adding IGBT snubbers permits higher voltage operation, reliable higher current IGBT operation, and elimination of over-voltage fault problem. The snubbers were installed on 12 of 15 operational modulators and 2 test stands. So far, >100,000 combined operational hours have been recorded with no issues. Pulse flattening that was necessary for improved RF performance and IGBT reliability has been successfully developed. Demonstration of the pulse flattening has been made in Mod-18 output voltage with 17.8 to 23.0 kHz frequency modulation.

RF Systems

Ten years of operation reveals some increases of component failures. Most of the 92 klystrons have exceeded the specified life of 50,000 operational hours. Operational management of klystrons is now focused on promoting long tube life for the aging. High power waveguide circulators after many years of operation pose significant operational risk although the failures are mostly due to leaks in the cooling circuit. New spares have been ordered for the failed units with ferrite disks and onsite repair program has been setup for the seal repairs.

In LLRF system, majority of failures have been limited to the RF output module of the field control module. The system has several obsolete components including the FPGAs. For the support of the STS project, redesign of the LLRF system is underway for more and deeper history buffers and improved time resolution and triggering functions. Redesign of the high-power protection module is underway and the prototype test board has been utilized to verify the VXI interface and ADC functionality.

PROTON POWER UPGRADE

The Second Target System (STS) project has gained weight for the future of the SNS accelerator complex to be the world's leading facility for neutron scattering research. The Proton Power Upgrade (PPU) project became a necessary part for the STS project and the detailed study started. The major change will be the addition of seven high-beta cryomodules (see Figure 3) that accommodates twenty-eight 6-cell SRF cavities all together to increase the beam energy to 1.3 GeV and the beam power to 2.47MW. Other subsystems will need changes and upgrades in SNS [6].

Three additional HVCMs will be needed to power the SRF cavities in PPU. Modification of boost transformers will be required to achieve higher output voltages, especially for 3.0 MW klystrons for the DTLs in warm linac.

For the new SRF cavities in PPU, high RRR end group material will be used for improved thermal stability over the previous reactor grade material to improve the performance of the linac [7] since the heating of the end group driven by electron activity has been a limiting factor. Updated input power couplers for higher power will be installed in the new cavities for added reliability to support higher beam current.

BEAM TEST FACILITY

A new Beam Test Facility (BTF) has been constructed to validate the performance of the new RFQ, to study ion source improvements, and to support neutron moderator development and six-dimensional phase space measurements for SNS [8]. The 2.5 MeV BTF includes an H^- ion source, Radio-Frequency Quadrupole (RFQ), and Medium Energy Beam Transport (MEBT) beam diagnostics systems.

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