TECHNOLOGICAL CHALLENGES ON THE PATH TO 3.0 MW AT THE SNS ACCELERATOR*

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Abstract

The Spallation Neutron Source (SNS) is a ~1 GeV pulsed hadron linear accelerator (linac) and accumulator ring capable of delivering ~23.3 kJ, 700 ns pulses of protons at 60 Hz to a mercury spallation target to produce intense pulses of thermal and cold neutrons. Oak Ridge National Laboratory (ORNL) proposes to build an innovative Second Target Station (STS) at SNS to meet the U.S. demand for neutrons. The current STS design requires 46.7 kJ, 700 ns pulses at 10 Hz to meet the needs of the scientific program[1]. The Proton Power Upgrade (PPU) project aims to double the available accelerator complex power from 1.4 MW to ~3.0 MW to meet these needs. This paper describes the technological challenges that must be addressed to achieve this objective.

STS CAPABILITIES

The STS as envisaged would be value engineered to provide the world's highest peak brightness neutron source to meet five high-level requirements:

- Provide cold neutrons with enhanced beam focusing and neutron spin manipulation to address nanoscale to mesoscale phenomena and slow material dynamics.
- Provide intense pulses at 10 Hz to limit heat deposition in a compact target and moderator assembly, enable utilization of wavelength dispersive methods, permit simultaneous access to a wide range of length and time scales, and sufficient flux to support extreme sample environments with limited angular access.
- Utilize high performance computing for real-time manipulation and visualization of massive data sets, and to combine and interpret multi-technique data.
- Provide innovative neutron scattering instrument concepts with multi-modal and flexible configurations that provide order of magnitude performance gains compared to current and currently envisaged capabilities.
- Provide high peak neutron brightness to enable in-situ sample synthesis, non-equilibrium studies, reaction kinetics, microspot scanning and parametric studies.

The envisaged pulse structure for one particular neutron wavelength compared to that currently available at the SNS First Target Station (FTS), the Japan Proton Accelerator Research Complex (J-PARC) and the European Spallation Source (ESS) currently under construction is shown in Figure 1.

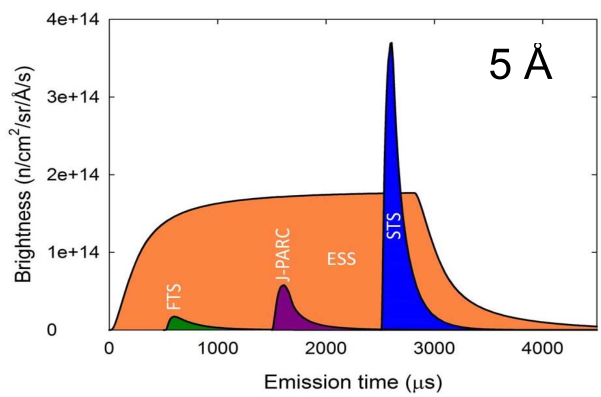

Figure 1: Temporal flux of 5Å neutrons from SNS-FTS, J-PARC, ESS and SNS-STS.

CURRENT SNS MACHINE PERFORMANCE

To fully appreciate the technological challenges related to doubling the current available beam power it is helpful to understand current machine performance and capability. The SNS has delivered a remarkable 33.844 GW-Hr of proton beam to target over the past ~10.5 years and has demonstrated sustained operation at beam power levels up to 1.4 MW. Since 2012 overall reliability against schedule has been affected principally by mercury target vessel performance, varying from 72.5% to 89.5%. However if target end-of-life events are removed, basic accelerator and accumulator ring reliability varies from 89.6 to 93.2% over the same period, with only one year below 90%. Beam power and total energy delivered since commissioning are illustrated in Figure 2.

For the SNS, the average beam power is derived from the peak current injected into the RFQ, the chopping fraction, RFQ transmission, the final beam energy, and the RF duty factor.

Duty Factor

The SNS has achieved stable long-term performance at a repetition rate of 60 Hz and a beam pulse width of 965 μs for a macroscopic beam duty factor of 5.79%. Note that the RF duty factor is somewhat higher to allow structures to fill and stabilize before the beam is accelerated.

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Ion Source Performance

The SNS H- ion sources have, for three years, steadily and reliably provided long-lifetime peak currents of 45-60mA for chopping in the Low Energy Beam Transport (LEBT) chopper prior to injection into the RFQ[2]. Since 2015 injected currents have routinely exceeded 50 mA, more than sufficient to sustain routine operation at 1.4 MW. A program of continuous improvement in source operation will yield routine injected peak currents of ~60 mA.

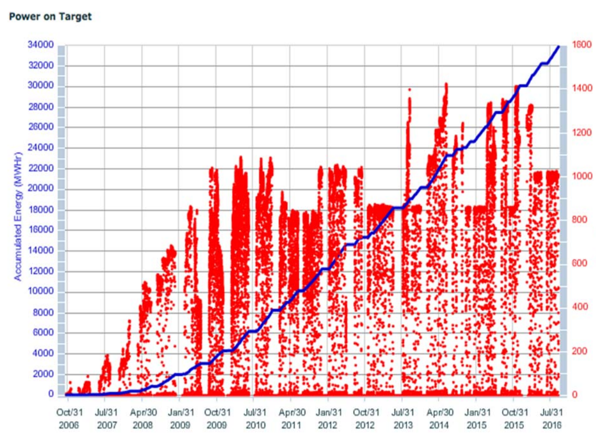

Figure 2: SNS Operational History from October 2006 to the present.

Chopping Efficiency

Significant improvements have been made to the pulsed power drivers for the four-segment electrostatic field chopper that introduces the gap in the sequential beam pulses needed for effective accumulation and extraction from the accumulator ring. These improvements have resulted in a reduction of the gap length from ~300 ns FWHM to ~200 ns FWHM, thereby increasing the effective accelerated peak current by about 14%[3]. This advancement has permitted routine high power operation despite RFQ transmission that is less than desirable.

RFQ Transmission

Transmission through the RFQ structure has degraded significantly over the more than 10 years of structure operation. The structure has been re-tuned three times to accommodate shifts in the resonant tune frequency and field flatness. X-ray end-point energy measurements have revealed that the current maximum attainable vane voltage is about 84% of the design value of 83kV[4]. Vacuum and thermal (resonance) instabilities prevent operation at higher vane voltage, so transmission is significantly reduced relative to design. This is the most significant factor that limits beam power available to the neutron spallation target.

Beam Energy

The SNS has yet to achieve routine operation at the design energy of 1 GeV. The history of beam energy during neutron production operation is shown in Figure 3. A beam energy of 0.972 GeV (with reserve) was achieved during the most recent facility operating period, and represents the highest energy achieved for standard operation. Substantial research and development was undertaken to develop a successful in-situ plasma processing technique that has been used to remove surface contaminants from the interior of the superconducting cavities in the high-beta portion of the superconducting linac[5]. This process has recently been applied to two cryomodules each with four six-cell cavity strings, resulting in an average increase in accelerating gradient of about 25%. Beam energy was increased from 0.938 GeV to 0.972 GeV after this processing and further processing of other cryomodules is planned to achieve the full design energy of 1 GeV.

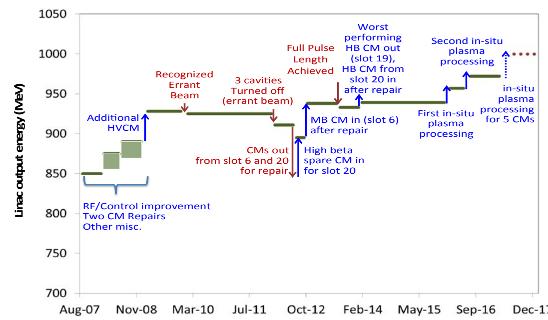

Figure 3: Evolution of SNS Beam Energy Since 2006.

Mercury Target Lifetime

Since 2012 SNS has experienced six in-service target end-of-life events. Four (two in 2012 and two in 2014) were attributable to structural defects in weld joints. A focused program of engineering analysis and design changes, together with improved and simplified manufacturing techniques and quality assurance process, has addressed the structural defects. The two most recent events have resulted from cavitation damage erosion (CDE) in the front of the target module but away from the direct area of beam impingement. Installation of new diagnostic capabilities on the mercury target vessel has enabled direct measurement of structural response (strain) to single and multiple beam pulses for the last two targets. These results have validated engineering models of dynamic response, leading to increased confidence in structural design. Mitigation of cavitation damage erosion in the direct beam impingement area has been demonstrated (albeit for a very short period of time) by modifying the mercury flow in this region. Mitigation of CDE away from the beam impingement region remains to be developed[6].

Routine operation at an average beam power of 1.4 MW or above is presently constrained by the following technical challenges:

- Front-end RFQ transmission (currently 65-70%),
- Beam energy (currently 0.972 GeV), and
- Predictable target lifetime driven by the rate of cavitation damage erosion for beam power above about 1.2 MW.

The Path to Sustainable 1.4 MW Operation

SNS has undertaken an aggressive program of improvements to address accelerator technical barriers to routine operation at 1.4 MW. These include:

- Replacement of the RFQ structure with a new structure that is currently undergoing acceptance testing with beam. Initial measurements indicate that this more robust mechanical structure should restore beam transmission to ~90%, providing sufficient available power for 1.4 MW operation.
- Plasma processing of up to 5 additional high-beta cryomodules (20 cavity strings) to permit routine operation at the design beam energy of 1 GeV with a margin of 2-3%.
- Full implementation of closed-loop voltage regulation after replacement of all the controllers for the high-voltage converter modulators (HVCM) that provide the pulsed DC voltage for the klystrons to provide an additional control margin of ~5%.

These projects are scheduled for completion by July 2017 at the conclusion of the first long shutdown (~4 months) in the history of the facility to replace the target system Inner Reflector Plug (IRP) that will reach end-of-life in April 2017.

THE PATH TO ~3.0 MW

The key machine parameters that must be changed to achieve a machine capable of ~3.0 MW proton beam power are summarized in Table 1.

Table 1: Key Machine Parameters Needed for 2.8 MW

Beam Power	Beam Energy	Peak Current	Pulse Length	Repetition Rate
1.4 MW	0.97 GeV	26 mA	1 ms	60 Hz
2.8 MW	1.3 GeV	38 mA	1 ms	60 Hz

As can be seen from the table the beam energy is increased by ~30% to 1.3 GeV, and the peak current (chopped) is increased by ~46% to 38 mA to double the beam power. The machine duty factor remains unchanged. The scope of work described below is being incorporated into a project called the SNS Proton Power Upgrade (PPU).

Increasing the Beam Energy to 1.3 GeV

The baseline capability is assumed to be 1.0 GeV with reasonable margin (~3%), achieved by completing the high-beta cryomodule in-situ plasma processing initiative in July 2017.

Cryomodules The increase of 0.3 GeV is achieved by installing 7 new high-beta cryomodules in the first seven of nine existing empty slots in the linac tunnel. These cryomodules will be built to the same standards as the spare high-beta unit built at SNS and placed into service in 2012[7]. This spare unit achieved an accelerating gradient of 16 MV/m in each of the cavity strings, representing the best performance to date for a SNS high-beta cryomodule and which is the design gradient for the PPU. These cryomodules will also be compliant with pressure vessel code requirements.

The plasma processing technique will also be refined for use on medium-beta cryomodules to ensure that the required accelerating gradients can be sustain, and procurement of a spare medium beta cryomodule will begin in 2017 to ensure that a reduction in beam energy is not required should a medium beta cryomodule have to be taken out of service for repairs.

Klystrons The peak RF power requirement of 700 kW for each superconducting linac cavity string in these additional cryomodules will exceed that of the current SNS 550 kW klystrons. New klystrons capable of supporting this power requirement will be required, and are readily available. Other infrastructure such as circulators and loads are not capable of supporting the planned operating power, and higher-rated devices that do not challenge the state of the art will be procured[8].

High Voltage Converter Modulators (HVCM) Three additional HVCM units will be required to support the 28 additional cavity strings. The higher power klystron output will place a modest additional demand on the performance of the existing superconducting linac HVCM design. The cathode voltage will increase from 74 kV to 79 kV and the internal DC bus voltage will increase from 1140 V to 1190 V. SNS is pursuing a number of improvements to ensure that the existing modulator design can be adapted to provide robust operation with margin for PPU. These improvements include:

- Replacement of all HVCM controllers, enabling closed loop pulse-flattening capability[9],
- Deployment of improved oil cooling and external oil pumps for existing and future modulators,
- Development of laminated high voltage busses substantially to reduce inductance and ripple, and permit removal of most bypass capacitors, and
- Development of an Alternate Topology Modulator to improve power conversion efficiency to 92%[10].

All of these developments have completed prototype demonstration runs with the expected parameters, and are being integrated into a single package for development and use in the PPU. Note that the increased voltage demand for the 700 kW klystrons will required that the first two new modulators drive 9 rather than the normal 10 klystrons, while the slightly lower power requirements for the last 10 cavity strings permit the use of the normal ratio of 10:1 klystrons:modulator.

Miscellaneous Support Systems Standard infrastructure systems such as cooling water, ventilation, controls, power supplies, and transmitters will be extended to accommodate the additional cryomodules, klystrons and HVCM units.

Increasing the Peak Current to 38mA

The un-chopped peak current within the acceptance of the RFQ required from the H- ion source for SNS operation at 2.8 MW is ~54 mA. The existing SNS sources used for neutron production operation routinely operate at or near this peak current. A robust on-going source development program will ensure that this level of performance is maintained or enhanced. As such, significant development is not required to support PPU objectives. Technical challenges reside elsewhere.

"Smart" Chopping Recent improvements to the LEBT chopper that permit higher effective peak currents in the linac have been described above. Further improvements of up to ~10% in charge accumulation per pulse are possible if the extraction gap in the accumulator ring is not preserved for each injection cycle, but is cleaned up during a ramp-down and storage phase after injection is complete as illustrated in Figure 4. This feature requires implementation of time-dependent RF bunching in the accumulator ring during the ramp-down and storage phase[11].

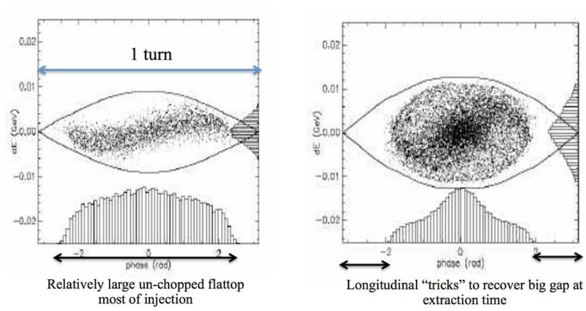

Figure 4: Single-turn and accumulated phase space distributions illustrating the "smart" chopping concept.

RFQ Transmission The SNS has obtained a new RFQ structure with the same physics design as that originally installed in the facility, but with a more rigid and robust mechanical structure. This structure has been installed in a new Beam Test Facility, and has been successfully commissioned to full radio-frequency power at the proper resonant frequency[12]. Forward powers of up to 600 kW have been achieved at full duty factor of 6%, significantly higher than the current in-service structure. The Beam Test Facility also incorporates an H- ion source and LEBT to inject typical SNS beams into the RFQ and a Medium Energy Beam Transport (MEBT) together with a shielded beam stop capable of accepting beam powers of up to 7.5 kW to provide diagnostic capability for full beam phase space and energy characterization.

A full set of low-power commissioning measurements has been completed, verifying the proper beam energy and time structure. Low peak current (~20 mA) transmission of 90% was quickly achieved. Transverse phase space measurements will begin shortly to complete the beam characterization in preparation for full power commissioning and production peak currents. It is anticipated that commissioning and initial 6-dimensional phase space characterization would be complete no later than the end of January 2017 to permit relocation of the new RFQ to the SNS front-end for installation in the planned long shutdown. The new RFQ should be commissioned and ready for operation in the SNS front end by July 2017.

Warm Linac Systems Along with higher beam current comes additional beam loading for the RF systems. Two Drift Tube Linac (DTL) klystrons will have to be upgraded from 2.5 to 3.0 MW peak forward RF power. However, the present 5 MW CCL RF can support operation at the increased beam loading needed for a beam power 2.8 MW This is a modest additional development.

The modulators that support the higher-power DTL klystrons will require modifications similar to those planned for the higher power superconducting linac modulators, particularly the laminated bus and alternate topology to support increased bus voltages.

The RF couplers, irises and windows in both the DTL and CCL should be able to support the increased power. However, new designs are being evaluated to ensure continued high reliability as the accelerator beam power is doubled.

Ring Injection and Extraction

Increasing the beam energy to 1.3 GeV requires evaluation of the capability of all beam transport magnetic elements to support the higher beam rigidity, particularly in the accumulator ring.

At the present time 96% of installed all magnets and power supplies are capable of supporting 1.3 GeV operation. Extended demonstration runs at set-points required for operation at 1.3 GeV have been done to demonstrate suitable cooling and heat rejection capacity in the magnet and power supply cooling systems.

Ring Injection Upgrades The ring injection chicane must be replaced to accommodate the higher beam energy. In particular, it is important to manage Lorentz stripping of excited electron states in neutral hydrogen atoms (H^o) created during the injection process. Initial design of the new magnetic elements is complete and refinements are underway. Changes to the injection chicane also require some modest changes to the waste beam dump line, for which designs are also complete.

Stripping Foils and Laser-Assisted Stripping In recent years significant improvements have been made to the foil holder mechanisms to reduce damage from heating by reflected convoy electrons. The foil changer mechanism has also been re-engineered to address reliability issues. Carbon foil manufacturing capability as been relocated to the ORNL Center for Nanophase Materials Sciences (CNMS) co-located at SNS to permit a more aggressive foil research and development program. This capability has been successfully commissioned and foils manufactured have demonstrated reliable and stable operation at beam powers of 1 MW. Foils have also been successfully used extensively for beam powers ranging from 1.2 to 1.4 MW. However, the vacuum chamber that houses the foil changing mechanism in an injection chicane magnet must be re-designed to accommodate an improved electron catcher to mitigate convoy electron damage as beam power is increased above 1.4 MW. Foils have been demonstrated to survive for several months at beam powers from 1.0 to 1.2 MW, but are typically operated for a 4-week production period to minimize accumulator ring losses and structure activation as foil degradation occurs.

In the event that foils do not prove reliable at higher beam powers SNS has invested in studies of laser-assisted H- ion stripping[13]. SNS has recently demonstrated high efficiency (>99%) laser-assisted stripping for 10μs (10 "mini-pulses" using a >1MW Ultra-Violet (UV) peak power laser with a 402.5 MHz microstructure of 30-50ps pulse width transmitted with 70% efficiency over a distance of 70 meters, including 9 mirrors and 4 windows. This capability would have to be extended by two orders of magnitude to support production beam operation, which presents challenging technology problems in laser power management, reliability, pointing stability, and divergence stability. Further research to extend this capability is under consideration.

Ring Extraction Upgrades SNS currently has twelve extraction kickers in the accumulator ring. The higher beam rigidity presented by operation at 1.3 GeV requires the addition of two similar kickers in existing available space to provide a sufficient extraction kick into the existing ring-to-target beam transport. Current operation permits the availability of an on-line spare unit, but operation at 1.3 GeV would require use of all installed units. Solid-state switches are under development to replace the thyratrons that are currently used as part of the pulse forming networks that drive these devices[14].

Beam Stability and Active Damping Beam instabilities are not routinely observed in the accumulator ring for the charge densities required for operation at 1.4 MW. Nevertheless, an active damping system has been developed to mitigate possible instabilities as the peak charge density is doubled to support operation at 2.8 MW. Machine studies that induce instabilities have demonstrated that the system works as intended, but it is not used during routine SNS operation.

FTS Target Systems

The mercury target at the SNS FTS presents what is perhaps the most challenging problem that must be resolved to fully utilize the available power after the PPU is complete. The STS is being designed with a compact tungsten target, similar to that envisaged for the ESS, and will not present cavitation damage erosion.

As discussed above, the mercury targets have undergone major improvements to establish a robust structural design and a high-quality fabrication process. Structural response engineering calculations have demonstrated good agreement with measured responses using new strain diagnostics during initial target operation with beam. The "jet flow" design has been demonstrated to mitigate CDE in the region of beam impingement.

System re-engineering to accommodate gas-bubble inj ection, and reinforcement of material thickness in regions where mercury flow is low adjacent to the vessel surface will be incorporated into future targets to provide reliable and predictable operation at 1.4 MW, and will be essential to designing a target that can withstand 2 MW.

Some mercury target subsystems (heat exchangers, for example) require enhancement to assure reliable operation at 2 MW.

CONCLUSION

The PPU at SNS, although incorporating some challenging technical aspects particularly relating to injection stripping and mercury target reliability, presents a realistic and achievable path to providing a proton beam power of ~3.0 MW to drive two state-of-the-art pulsed neutron sources by 2023.

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