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OPERATIONS EXPERIENCE OF SNS AT 1.4 MW AND UPGRADE PLANS FOR DOUBLING THE BEAM POWER*

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Abstract

The Spallation Neutron Source (SNS) is a short pulse neutron source facility driven by a high-power proton accelerator. Over the past the past few years SNS has undergone a systematic increase in operational beam power, culminating in operation at the proton beam design level of 1.4 MW. SNS is presently engaged in upgrades including a project to double the proton beam power capability. The recent operational power increase and the plans for upgrades will be discussed.

INTRODUCTION

The SNS facility [1] began operations as a short pulse neutron source in late 2006. The neutron source consists of an H^- linear accelerator that injects 1 msec pulses into an accumulator ring by charge exchange. The accumulated protons are fast extracted in a single turn to a mercury target to provide a high intensity short pulse neutron source. This process is repeated at 60 Hz. SNS was designed to be the first MW class short pulse neutron source, with upgrade provisions included to facilitate a future power level increase.

The power ramp-up to the design level of 1.4 MW is summarized in the following section, with an emphasis on the most recent increase from 1.0 to 1.4 MW. Installation of a new Radio Frequency Quadrupole (RFQ) and improvements in the mercury target vessel are two primary upgrades that enabled steady 1.4 MW power capability. The next section describes SNS upgrades, including the Proton Power Upgrade (PPU) project. This project aims to double the accelerator capability to 2.8 MW, along with target systems upgrades to handle increased power.

THE SNS POWER RAMP-UP TO 1.4 MW

Figure 1 shows the SNS proton beam power history since initial operations. Here this history is divided into three periods: 1) early years from 2007-2011, 2) the intermediate period from 2012-2016 and 3) recent operations from 2017-2019.

2007-2011: Race to 1 MW

The initial transition to operations plan envisioned reaching 1.4 MW operations at 92% reliability within 3 years [2]. There was a strong push to ramp-up the beam power as quickly as possible [3]. Many equipment issues surfaced which limited the ability to run at higher power and 1.4 MW was not reached within 3 years. Three primary areas of equipment issues were: 1) the ion source and front end, 2) the RF high voltage pulse forming network equipment, and 3) the superconducting linac.

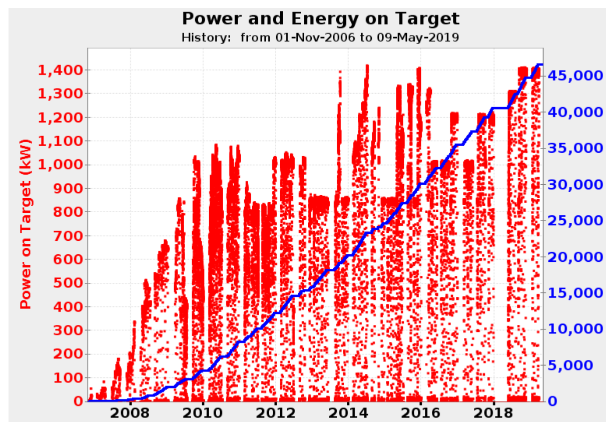

Figure 1: The SNS beam power history.

The ion source and electrostatic LEBT had reliability issues and the source current level sometimes limited the available beam power. Test stand development initiated in the early years has resulted in a robust world class H^- ion source [4]. The high voltage convertor modulators (HVCM) were first of a kind large scale accelerator implementation of solid-state technology for high voltage pulse forming and also experienced reliability issues, sometimes limiting the available beam power during this period. An extensive off line HVCM test stand campaign was initiated early on, and this effort has paid dividends [5]. Finally, issues were identified in operation of the superconducting linac (SCL) cavities in the early years. Initially the beam energy was reduced, in order to allow margin for safe equipment operation and to fix broken equipment. This experience includes removal of unneeded cavity peripherals (e.g. piezo tuners and higher order mode filters), developing and enforcing rigorous operational guidelines, and implementation of an in-situ plasma processing technique to recover operating gradient. With these efforts the beam energy from the superconducting linac has increased, and for the first time reached the design energy of 1 GeV in operation during 2018 [6].

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Improvements initiated in this early period on the ion source, HVCM and SCL have paid dividends, not only in present day operations, but also in the PPU upgrade plans, as discussed later. By the end of 2011, the accelerator was delivering 1 MW.

2012-2016: Target Limitations

The mercury which serves as the spallation source and target coolant is enclosed in a double walled steel vessel. The short proton pulse drives a high pulsed stress on the inner vessel, which is a challenging design [7,8]. Not only is fatigue stress a major concern but cavitation induced erosion is also an issue. During part of the 2012-2016 period, 6 out of 8 target inner vessels experienced leaks, which caused extended unplanned outages. As a result, the beam power was often limited to 850 kW, as seen in Figure 1, even though the accelerator was capable of delivering higher beam power. A number of responses were initiated during this period, including improvements in target design and fabrication oversight, addition of strain instrumentation on the target vessel, careful examination of used targets to understand the damage, and provisions to allow the introduction of small amounts of gas into the mercury to mitigate the pulse stress and cavitation damage.

2017-2019: Systematic Approach to 1.4 MW Operation

The period 2017-2019 is characterized by progressively higher, and steady beam power, as indicated in Fig. 2. A decision was made to run the facility at constant beam power over the life of a target to better gain an understanding of the target damage as a function of beam power. Two technology modifications facilitated this approach: 1) introduction of gas into the target mercury, and 2) replacement of the RFQ.

Helium gas was first injected into the target in Nov. 2017 [9]. An immediate reduction in the target stress of 10%-70% was measured [10], depending on location in the target. Examination of targets operated with gas after removal from service indicate a dramatic reduction in the cavitation induced erosion. This target damage mitigation provided the confidence to operate at higher beam powers, and no targets have experienced leaks in this period.

Another advance during this period was the replacement of the original RFQ in the spring of 2018 [11]. For some years it was recognized that the original RFQ field profile had changed beyond the ability to completely recover by retuning, resulting in a reduction of beam transmission from ~90% to 60-70%. This effective beam current reduction made provision of beam powers over 1 MW more challenging. A new RFQ with the original physics design but a more robust engineering design was fabricated and tested on an offline beam test stand to verify the exit beam quality. After installation of the new RFQ there is an excess of beam current capability. Beam current out of the new RFQ exceeding the SNS upgrade requirements of 46 MA has been measured. This accelerator improvement provides margin in operating the accelerator at 1.4 MW.

The combination of confidence in target survivability and excess accelerator power capability were the key elements that lead to routine operation at 1.4 MW starting in the fall of 2018. Over the past two years, reliability has been similar to previous years, with no meaningful changes in beam trip frequency as a result of increasing beam power. SNS beam downtime has been and continues to be dominated by rare, yet extended downtime periods. The last two such incidents are from an RF seal issue in the RFQ and an issue related to the mercury flow loop in the target system. Neither were related to the operational beam power. Also, the accelerator operational beam power has never been limited by beam loss.

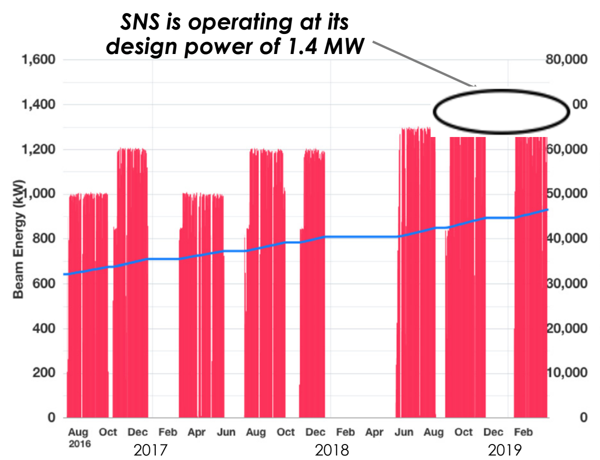

Figure 2: The SNS beam power history since 2017, indicating the approach to the design power of 1.4 MW.

SNS UPGRADES

Now that SNS is running at its design power of 1.4 MW, two major facility upgrades are being pursued: the Second Target Station and a Proton Power Upgrade.

Second Target Station (STS)

The STS is in the initial design stage and is preparing for conceptual design review readiness. This project [12] consists of a new proton transport line, target station, instrument hall, initial instruments, and associated conventional infrastructure. The target systems employ innovative designs which deliver a much higher intensity long wavelength neutron flux to provide new capabilities. The STS is planned to operate at 15 Hz, these pulses being diverted from the 60 Hz short pulse stream exiting the accumulator ring.

Proton Power Upgrade (PPU)

PPU Overview

The PPU project [13-15] is aimed at doubling the accelerator beam power capability to 2.8 MW, not only increasing the neutron flux at the existing First Target Station (FTS), but also providing a basis for powering the STS. Some high-level parameters are shown in Table 1. The beam power increase is accomplished by a 30% energy increase and 50% beam current increase. The pulse time

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structure is not affected. After completion of PPU the accelerator will operate at lower beam current delivering 2 MW to the FTS, as the FTS systems were designed to accept 2 MW during the original SNS construction. The additional beam power capability will be used to power the STS.

PPU leverages provisions built into the original SNS construction. This includes: 9 existing empty slots in the linac tunnel for additional cryomodules, space in the klystron gallery building to house new RF equipment at the high energy end of the linac, most ring and transport line magnets and power supplies are 1.3 GeV capable, and many target systems are designed for 2 MW.

As previously mentioned, ion source and LEBT development efforts during the past 10 years have provided a demonstrated basis for the front-end systems. The HVCM developments have also provided a basis to quickly implement a solution for the increased power level of the new cryomodules.

Table 1: PPU High Level Parameters

Parameter	Present operation	PPU
Beam power (MW)	1.4	2.8
Beam energy (GeV)	1.0	1.3
Average linac current (mA)	1.6	2.3
Linac macropulse current (mA)	25	39
Beam repetition rate (Hz)	60	60
Linac pulse length (ms)	1	1
Medium beta cryomodules	11	11
High beta cryomodules	12	19
High beta cavities	48	76
High beta klystron power (kW)	550	700

PPU includes addition of 7 new superconducting cryomodules, new RF equipment to power the cryomodules, upgrades to some existing RF equipment to handle the increased beam loading, some Ring upgrades to handle the increased beam energy, target system upgrades to handle the increased beam power and some conventional facilities upgrades.

Superconducting Linac Upgrades

The superconducting cryomodule scope involves a partnership with Jefferson Lab (JLab). SNS is providing the cavities, high power cryomodule testing and other integration activities. The plan is to largely use the design for a spare cryomodule built at SNS and installed in 2012, which has run at PPU gradients (16 MV/m) [16]. JLab is implementing a few design changes to improve manufacturability. The JLab design for the PPU cryomodules is shown in Fig. 3.

RF System Upgrades

The new RF systems powering the new cryomodules will be similar to those already in use (klystrons, transmitters, loads, etc.) The HVCMs for these units will be a new Alternate Topology (AT) design which is capable of powering the klystrons at the higher required power level (700 kW vs 550 kW). A prototype AT HVCM unit has been tested for extended runs at the required duty factor on a test stand (see Fig. 4) and works well. Equipment and beam tests indicate that most of the existing RF and HVCM units meet the PPU requirements. The exception is the Drift Tube Linac (DTL) klystrons, which require upgrade from 2.5 MW to 3.0 MW, along with upgrades to the HVCMs that power them.

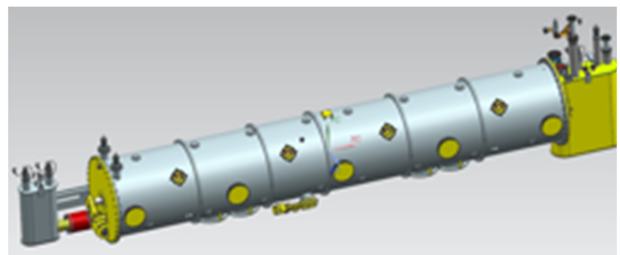

Figure 3: The JLab PPU cryomodule design.

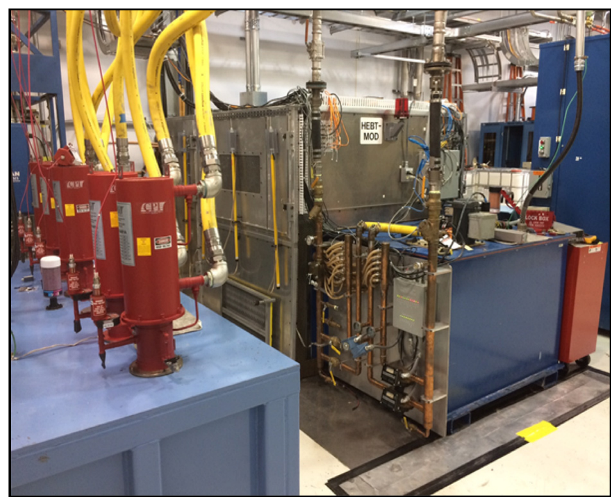

Figure 4: Prototype PPU HVCM during a heat run.

Ring Upgrades

As mentioned earlier, most of the Ring and transport line magnets and power supplies are ready for the energy upgrade. Reference [17] discusses the ring upgrades in more detail. A major component is upgrading some of the magnets in the Ring injection area (Fig. 5), and we are partnering with Fermi National Accelerator Laboratory for this. A recent change in this area is the decision to upgrade the existing power supplies on the installed 14 extraction kickers, rather than install 2 additional extraction kickers and supplies.

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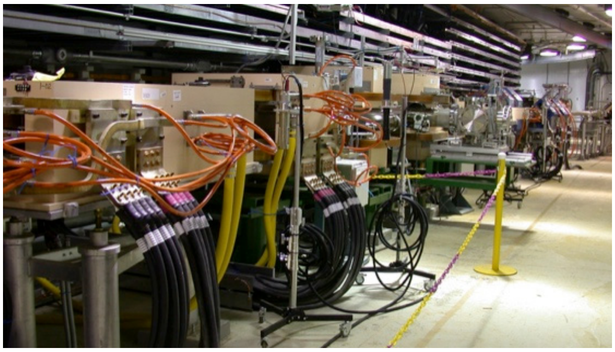

Figure 5: Ring injection area.

Target System Upgrades

Target systems are a critical area of the upgrade. A new target vessel capable of handling higher power is a major aspect of this scope (see Fig. 6). Another important area is provision of large amounts of gas injection for damage mitigation, as was discussed earlier. PPU will provide roughly 10 times more gas flow capability as is presently in use in operations. This will require implementation of a gas recirculation system.

Conventional Facility Upgrades

The building that houses the new RF equipment requires finishing out. In addition to providing conventional bulk cooling, conditioning of the air etc., the design of these systems has been integrated with the layout of the technical systems (klystrons, technical cooling, waveguide, etc.) into a common 3-D model. This will facilitate installation activities. Also, a tunnel stub is being added in the transport line between the accumulator ring and the FTS to ease the tie into a future transport line to the STS (Fig. 7).

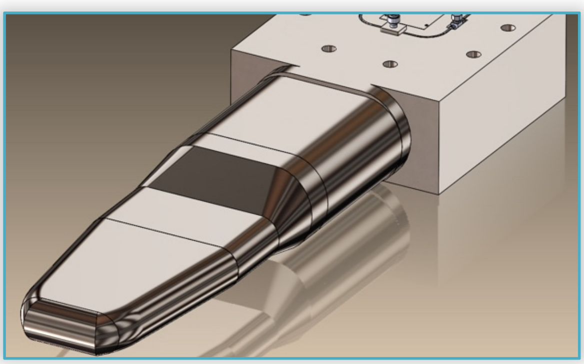

Figure 6: PPU 2 MW target vessel.

PPU schedule

The PPU project is more advanced than the STS and is pursuing preliminary design. A key element of the PPU is that much of the proposed accelerator upgrades leverage existing technology and are at a final design level. The PPU project is tailoring its schedule to adapt to healthy funding and is pursuing advanced procurement of RF equipment, superconducting cryomodules and associated conventional facility work to pull forward the initial installation and use of the new cryomodules. A view of the project activities for 2022-2024 is shown in Figure 8. The shaded regions represent maintenance periods and the clear regions are operational periods. 2022 is a typical year regarding this division. PPU is aiming for installing and using the first two new cryomodules in mid 2022. In 2023 an extended outage is planned, with installation of 3 cryomodules, RF equipment, Ring upgrades, target system upgrades and the tunnel stub work. This will be the only planned maintenance period with a duration significantly longer than normal maintenance periods. In general, when cryomodules are installed they will be used, representing an advancing of the use of new equipment and a more gradual power ramp-up compared to waiting till the end of the project to start the power ramp-up. Early finish for PPU is scheduled for mid 2024.

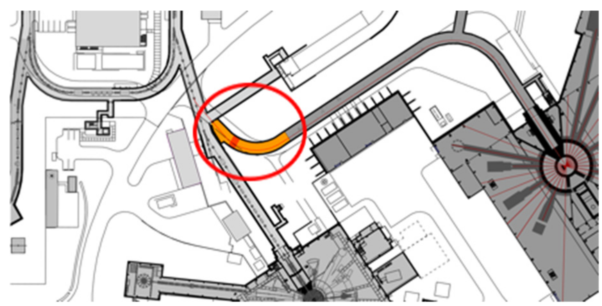

Figure 7: Tunnel stub to STS.

SUMMARY

Over the last 2 years the SNS has systematically increased its operating proton beam power from 1 MW to its design level of 1.4 MW, culminating a 12-year power ramp-up starting with initial operations. Two key enabling elements to this ramp-up were target system improvements and installation of a new RFQ. The PPU project to further upgrade the accelerator power capability to 2.8 MW is well underway. PPU aims to increase the proton beam energy and the average beam current. Initial equipment is being purchased to accelerate the procurement and installation of new accelerating structures, and early finish is scheduled for 2024.

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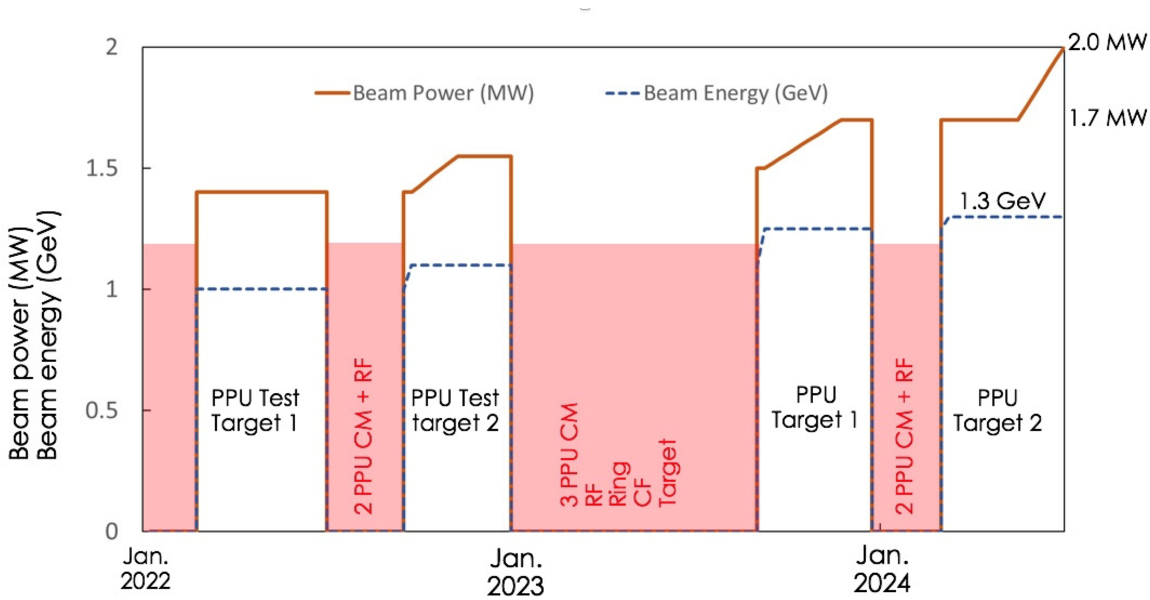

Figure 8: High level view of the last 2 years of the PPU schedule, indicating a power ramp-up occurring over the last 2 years of the project.

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