Status of the New SNS Injector and External Antenna Ion Source

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Abstract. The U.S. Spallation Neutron Source (SNS) now operates with 1.2 MW of beam power on target with the near-term goal of delivering 1.4 MW and a longer-term goal of delivering >2 MW required by the planned Proton Power Upgrade (PPU) and Second Target Station (STS) projects. In early of 2018 we plan to replace the entire 2.5 MeV injector configuration which includes the ion source, the Low Energy Beam Transport (LEBT) and the Radio Frequency Quadrupole accelerator (RFQ) with one which is currently being tested on a research accelerator called the Beam Test Facility (BTF) located at the SNS facility. This report first provides a description of the new injector: the ion source and the cage enclosure, the new LEBT support structure and the new RFQ. Since fall of 2016, this system has been tested extensively with regard to output beam current, beam persistence, emittance and energy. The results of these experiments employing both internal and external antenna ion sources will be summarized here showing the system to be capable of supporting SNS 1.4 MW operations with a significant margin as well as potentially meeting facility upgrade requirements. This represents a significant performance upgrade over the current SNS front end system with the compromised RFQ and will replace that system in early 2018.

INTRODUCTION

The Spallation Neutron Source (SNS) is the highest power pulsed neutron source currently operating worldwide and supports ~1000 users per year. The SNS accelerator system is comprised sequentially of an ion source, an electrostatic Low Energy Beam Transport system (LEBT), a 2.5 MeV Radio Frequency Quadrupole accelerator (RFQ), a series of higher-energy 1 GeV linear accelerators feeding a proton accumulator ring and a liquid Hg target producing neutrons [1]. The ion source produces pulses of H^- ions with a current of 50-60 mA, pulse length of ~1 ms and repetition rate of 60 Hz. A LEBT chopping system divides the 1 ms pulse into ~1000 mini pulses for current accumulation in the ring. Currently the SNS operates at 1.2 MW of proton beam power on target with near term plans to run continuously at 1.4 MW and later up to 2.8 MW to simultaneously support a second target station. Approximately 35 and 46 mA measured at the exit of the RFQ are needed to achieve these target power levels, respectively. After ~10 years of service the transmission of the SNS RFQ started to degrade, which will make it increasing difficult meet the near-term SNS beam current requirement of ~35 mA (at RFQ exit) in spite of excellent ion source performance [2]. Over the years several RFQ detuning events have occurred that seem to contribute to the inability to operate at full design field thereby reducing transmission. Degradation in the structural RFQ integrity either due to brazed joints shifting or surface coating/erosion are believed to have caused these events [3]. In 2009 it was decided to procure a spare RFQ and begin construction of the new linac injector. The Beam Test Facility (BTF), a standalone research accelerator, was also constructed to test and characterize it for eventual use on the SNS as well as conduct accelerator and ion source research [4]. The key feature of the BTF is a 2.5 MeV diagnostic beam line capable of fully characterizing the accelerated beam. In 2016 the first beam tests of the new injector were performed on the BTF and based on the outcome of those tests the decision was made to install the new injector on the SNS in early 2018. This report provides a description of the new injector emphasizing the ion source systems and then summarizes beam tests performed.

THE NEW SNS LINAC INJECTOR

Figure 1a. shows the new SNS injector consisting of an ion source, LEBT electrode assembly, LEBT vacuum enclosure and an RFQ accelerator [4, 5]. An ion source safety cage (not shown) surrounds the source and high voltage components. The LEBT vacuum enclosure provides support for the ion source, LEBT electrodes and vacuum pumps as well as -65kV electrical isolation of the ion source. Located between the LEBT and the RFQ is an electrically isolated Ti-Zr-Mo (TZM) alloy disk containing an aperture through which beam passes called the LEBT chopper target. It nominally stops some of the beam when the LEBT chopping system is operating [6]. The ion source and LEBT electrode mounting structures are identical to those used in the corresponding enclosure on the SNS which allows interchangeable use of all SNS ion sources and LEBT electrode assemblies [2]. The new LEBT chopper target is very similar in design to that employed in the SNS with the exception that the entire assembly can now be serviced without having to disassemble the RFQ structure as is the case on the original RFQ. The new injector also features a revised, personal protection enclosure surrounding the ion source which is tied into the interlock system. It is similar to the existing SNS source cage with the exceptions that the RF matching network has been directly integrated into the structure allowing easy visual inspection. The cage has also been modified to allow easier access for cabling between the ion source and electronics as well as space for RF diagnostics at high voltage [5].

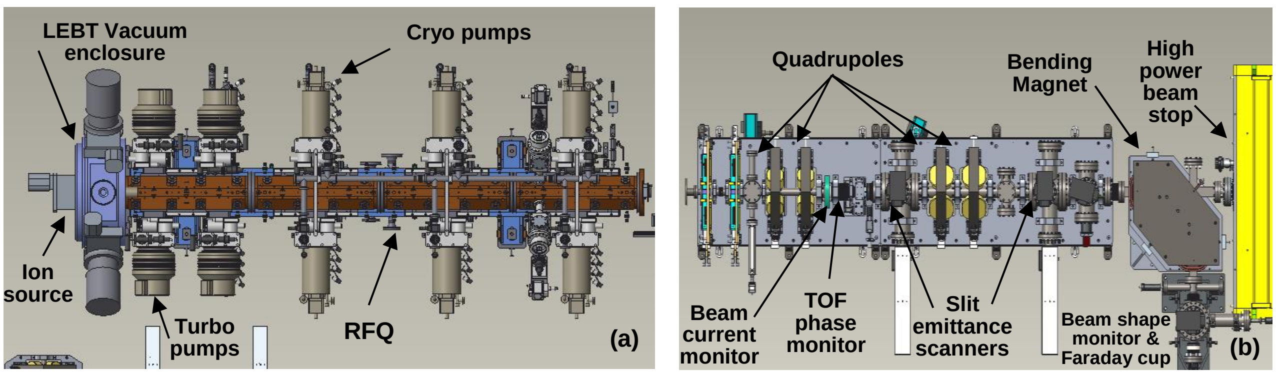

FIGURE 1. (a) The new SNS injector: ion source, LEBT vacuum enclosure and RFQ. (b) The 2.5 MeV BTF Diagnostic beam line.

The SNS Ion Sources and the New RFQ

Figure 2 shows a cross sectional view of both the SNS external and internal antenna ion sources used to commission the new injector on the BTF. Both sources are RF-driven, Cs-enhanced, multi-cusp ion sources and have been described in detail previously [7, 8]. They employ different RF – plasma coupling schemes but utilize identical outlet aperture assembles (see Fig. 2) and identical mounting interfaces so they can be installed and operated interchangeably on the new and existing injectors. Although the bulk of the new injector's commissioning was done with external antenna sources, once the new injector is installed on the SNS, we plan to recommission the system using both ion sources and begin 2018 neutron production with the internal antenna source. Both sources produce similar beam currents and seem to have comparable reliability but we have considerably more operational and routine assembly experience with the internal antenna source. The external antenna source offers better power efficiency and does not rely on a single-vender proprietary internal antenna fabrication process [8]. Figure 2 also shows a new 'double-layer' antenna with the RF-plasma gun of the external antenna source. This change was employed for these studies and seems to represent a reliability improvement of the previously described single-layer antenna [8].

The new 2.5 MeV RFQ was designed at ORNL, manufactured by Research Instruments and subsequently delivered in 2013 [3]. It was designed to be a drop in replacement for the existing SNS RFQ with the same beam dynamics and the mechanical interface flange design as employed in the SNS production RFQ while incorporating significant improvement to the mechanical and vacuum design. It features a 4-vane accelerating

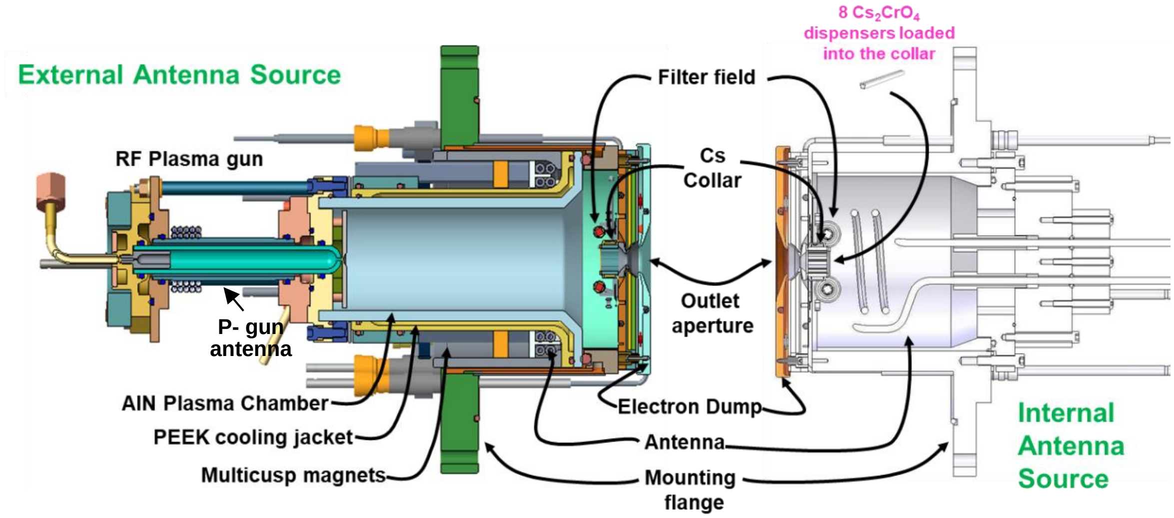

FIGURE 2. The SNS internal (right) and external (left) antenna ion sources.

structure, a mechanically more robust octagonal cross section with a total length of 3.7 m constructed from four longitudinal sections. The key difference between RFQs is that the new RFQ design eliminates the vane–wall brazed joints which were suspected of degrading the performance of the original RFQ, and the more massive octagonal shape confers much greater dimensional stability to the overall structure against vacuum and water excursions. The RFQ operates with ~600 kW of pulsed 402.5 MHz RF power with up to ~10% duty factor and has been designed to accelerate up to 60 mA of H^- current. The new RFQ also differs from the original by having considerably more pumping speed (4 x 1700 l/s turbo molecular pumps and 6 x 2500 l/s cryogenic pumps) as shown in Fig. 1a as well as a more massive, single-material, solid copper structure which is more resistant to deformation.

BEAM MEASUREMENTS

Figure 1b. shows the 2.5 MeV diagnostic beam line of the BTF which is very similar to the Medium Energy Beam Transport (MEBT) currently operating on the SNS. It features an array of quadrupole magnets capable of transporting long pulse beam (1ms) at 6% duty-factor to a high power beam stop as well as transporting short pulse beam (50 us) beam through a 90 degree dipole magnet to study the longitudinal beam properties. The figure also shows the location of a calibrated toroidal beam current monitor (BCM), a movable Time of Flight (TOF) phase monitor, a 2-slit transverse emittance scanner, a beam shape monitor and a low power faraday cup. Unless otherwise stated beam currents quoted in this report were measured by this BCM. Many of these diagnostic systems are similar or identical to those used in the SNS MEBT to allow direct comparison of beam parameters with minimal measurement error [4].

Prior to beam studies, the new RFQ had previously been conditioned to RF power levels of 600 kW at 6% duty factor. Beam testing began in spring of 2016 with extraction of ions from the source, transport through the LEBT and deflection onto the chopper target using a previously developed measurement technique [6]. These initial tests were used to identify installation issues and by summer of 2016 most were resolved and continuous beam operation of up to 60 mA for ~ 1week were demonstrated. Next, X-ray cut-off measurements, without beam, were performed to determine the RF power level needed to achieve the correct inter-vane design voltage of 83kV. We found that ~650 kW of 402.5 MHz power was required to achieve this and all subsequent beam measurements were performed at this power level.

In fall of 2016 beam acceleration was authorized and several internal and external antenna ion sources were cycled through service. In these experiments the ion source always produced beam with a repetition rate of 60 Hz and a beam pulse length of 1 ms while the RFQ could be operated to accelerate either the full ion source pulse (long pulse mode) or a short 50us pulse sampled from the middle of the long source pulse. Most of the experiments described here were performed in this short pulse mode. Initially, beam current from the ion source was slowly increased to perform RFQ transmission measurements by comparing the measured LEBT current with that measured by the BCM at the output of the RFQ. Transmissions of 85-90% were observed for a BCM current of ~40 mA and nominal RFQ RF power.

Beam energy measured using the TOF phase monitor shown in Fig. 1b. was found to be 2520 ± 20keV, a value which remained the same regardless of ion source used. Transverse beam emittance out of the RFQ was next measured using the 2-slit scanner (1m separation) also shown in Fig.1b. The measured normalized RMS emittance was determined to be 0.25-0.35 π mm mrad which varied depending on beam current and diagnostic beam line tune. This was similar to emittances measured on the SNS by a very similar scanner. Figure 3 shows the rendered horizontal emittance plots from this measurement for the external antenna source operating at ~24 and 45 mA. The RMS longitudinal emittance was also measured by the beam shape monitor, also shown in Fig. 1b, and found to be ~0.25 MeV Deg @ 405.5 MHz [4].

A two hour, high-power beam test with the RFQ operating in long pulse mode was conducted to verify the RFQ stability under the nominal production beam loading conditions at the design SNS duty factor of 6%. The most important thermal and RF parameters were recorded during the test and the new RFQ demonstrated good stability and fast recovery after RF power and/or input beam interruption. A maximum peak beam current of 50 mA was achieved by maximizing the ion source current and increasing the RFQ RF amplitude by ~2%. The injector performed well during this test.

Since spring of 2016 three internal and two external antenna sources have been cycled through service on the new injector and each have performed well producing at least 40mA out of the RFQ. The internal antenna ion sources collectively operated for over ~1650 hours and external sources operated for a total of ~2750 hours. Figure 4 shows an example of persistent and stable beam current delivered by the external antenna source. Such beam stability allowed extensive study of 4, 5 and 6D beam phase space where data was collected for periods as long 30 hours [4]. A notable example of source performance came from an external antenna source installed on the BTF from June 2017 to October 2017 when the facility was shut down to transfer the injector to the SNS accelerator. The source delivered over 38 mA of beam current for 1 month of continuous operation with essentially no degradation, provided requested lower currents for ~2 weeks, survived two major BTF shutdowns where only rough vacuum was available and, at the end of the run, was able to provide a very stable 46 mA demonstration for ~9h of continuous operation, the maximum time the schedule allowed.

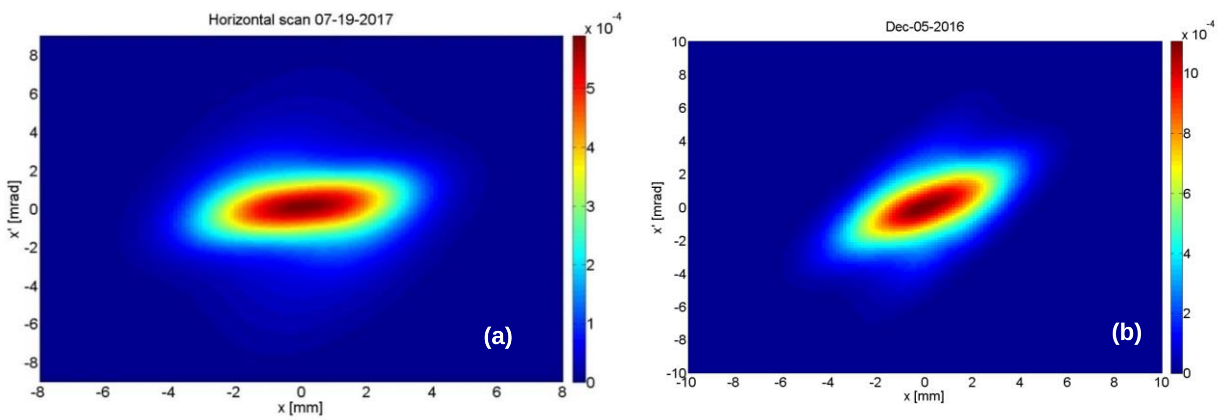

FIGURE 3. Transverse Horizontal beam emittance plots at 2.5 MeV for the external antenna source, (a) was measured with ~24mA of beam current and yielded an RMS value of 0.27 π mm mrad and (b) was measured with ~45 mA and yielded and RMS emittance of 0.29 π mm mrad. RMS values were dependent on quadrupole tune.

CONCLUSION

The new injector was extensively tested on the BTF with beam for over a year. Beam current, beam persistence, longitudinal and transverse emittance and beam energy were all measured and found to meet the SNS requirement with each source producing > 40mA when requested. The clear performance benefit of the new injector as well as the risk of continued degradation of the existing SNS RFQ justify installation on the SNS which will begin on Dec 2017 be completed & recommissioned in April 2018.

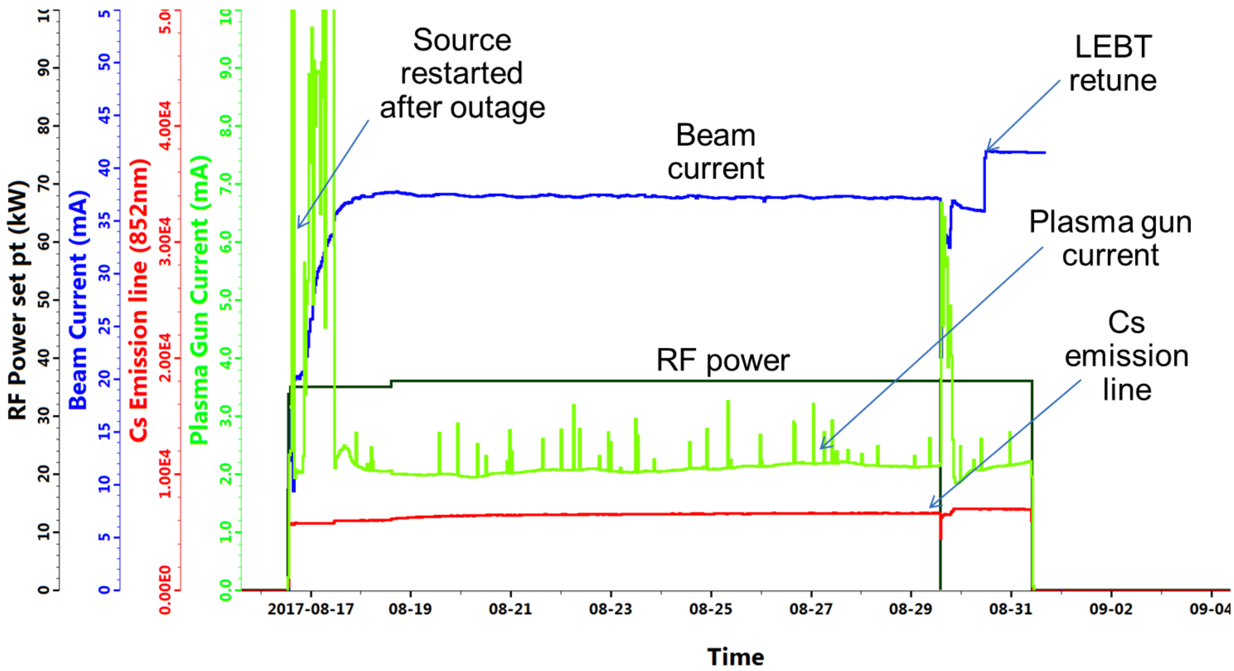

FIGURE 4. Example of source parameters after restarting an external antenna source after a BTF shut down.

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