Installation and Commissioning of the Ion Source Systems for the New SNS 2.5 MeV Injector [a)]

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The U.S. Spallation Neutron Source (SNS) is a state-of-the-art neutron scattering facility delivering the world's most intense pulsed neutron beams to a wide array of instruments which are used to conduct investigations in many fields of engineering, physics, chemistry, material science and biology. Neutrons are produced by spallation of liquid Hg by bombardment of short (~1μs), intense (~40A) pulses of protons delivered at 60 Hz by a storage ring which is fed by a high-intensity, 1 GeV, H^- LINAC. This facility has operated nearly continuously since 2006 but has recently undergone a 4-month maintenance period which featured a complete replacement of the 2.5 MeV injector feeding the LINAC. The new injector was developed at ORNL in an off-line beam test facility and consists of an ion source, Low Energy Beam Transport (LEBT) and Radio Frequency Quadrupole (RFQ). This report first describes the installed configuration of the new injector detailing the ion source system. The first beam current, RFQ transmission, emittance and energy measurements from the injector installed on the SNS are reported. These data not only show a significant performance improvement for our existing facility but will also make accessible the higher beam current requirements for future SNS upgrade projects: the Proton Power Upgrade (PPU) and Second Target Station (STS).

I. INTRODUCTION

The Spallation Neutron Source (SNS) is the highest power pulsed neutron source currently operating worldwide and typically supports ~1000 users per year. The SNS accelerator system is sequentially comprised 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 linear accelerators producing a 1 GeV beam injecting a proton accumulator ring which subsequently directs beam onto 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 beam stacking into the ring and a fast kicker magnet then directs the stacked beam (~35 A at 1 GeV, ~1 μs induration) onto the Hg target at 60 Hz. Currently the SNS operates at 1.4 MW of proton beam power on target with plans to eventually reach 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 at the SNS, the original RFQ (designed and built at Berkeley National Laboratory) started to experience a degradation of beam transmission, which made it increasingly difficult to meet the near-term 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 seemed to contribute to the inability to operate at full design field thereby reducing transmission. Degradation of the structural RFQ integrity either due to brazed joints shifting or surface coating/erosion is 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 constructed to test and characterize it for eventual use on the SNS as well as to conduct accelerator and ion source research [4]. Many improvements to the ion source / LEBT systems, which would later be incorporated in the new 2.5 MeV SNS injector, were first tested on the BTF and as well as on the Ion Source Test Stand (ISTS) also located at the SNS. These upgrades include: a completely redesigned High Voltage (HV) enclosure surrounding the source featuring an integrated matching network, improved water and electrical feeds, increased HV gaps, a ground-based H_2 gas delivery system, an easily serviceable chopper target in the LEBT as well as a new LEBT-RFQ gate valve. 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 [5,6]. This report first provides a

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description of the new injector emphasizing the ion source systems and then summarizes beam commissioning results on the SNS front end as well as a brief discussion of the injector's operational history since installation.

II. THE NEW SNS LINAC INJECTOR

Figure 1 shows the new SNS injector consisting of an ion source, LEBT, RFQ and the source HV enclosure which is shown without the screen mesh boundary to permit visibility of the internal ion source system components. The LEBT vacuum enclosure provides mechanical support for the ion source, LEBT electrodes and vacuum pumps as well as a large -65kV isolation insulator surrounding the source. Located between the LEBT and the RFQ is an electrically isolated TZM alloy disk containing an aperture through which beam passes called the LEBT chopper target which intercepts a fraction of the beam during chopping. The new LEBT chopper target is electrostatically equivalent to the previous generation except that the entire assembly can now be serviced from the LEBT side without disturbing the RFQ structure [5]. Beam current measurements in the LEBT are performed by deflecting the full beam onto the chopper target [7]. The interface to mount the actual ion source and LEBT electrode assembly to the injector is identical to those used in the previous SNS injector (as well as the BTF and ISTS) allowing use of the same ion sources and LEBT assemblies as previously employed [2]. Not shown in Figure 1 are two large access doors which permit entry into the enclosure for ion source and LEBT changeouts; both doors are redundantly interlocked to the front end's existing personal protection system. The new ion source HV enclosure features an RF matching network that has now been directly integrated into the cage structure allowing larger air gaps and easy visual inspection. Electrically, the new matching circuit is equivalent to the one used in the previous SNS injector.

The new injector also features easier access for cabling between the ion source itself and supporting electrical systems as well as space for RF diagnostics at high voltage, see Figure 1. Deionized cooling water feeds have also been improved for better flow and modular replacement. H_2 bottles were removed from the high voltage platform and moved to ground and currently feed the source though a 12 cm ceramic vacuum break operated slightly above atmospheric pressure. A LEBT-RFQ gate valve was also installed with the new injector to allow the RFQ to remain under vacuum during source and LEBT changeouts.

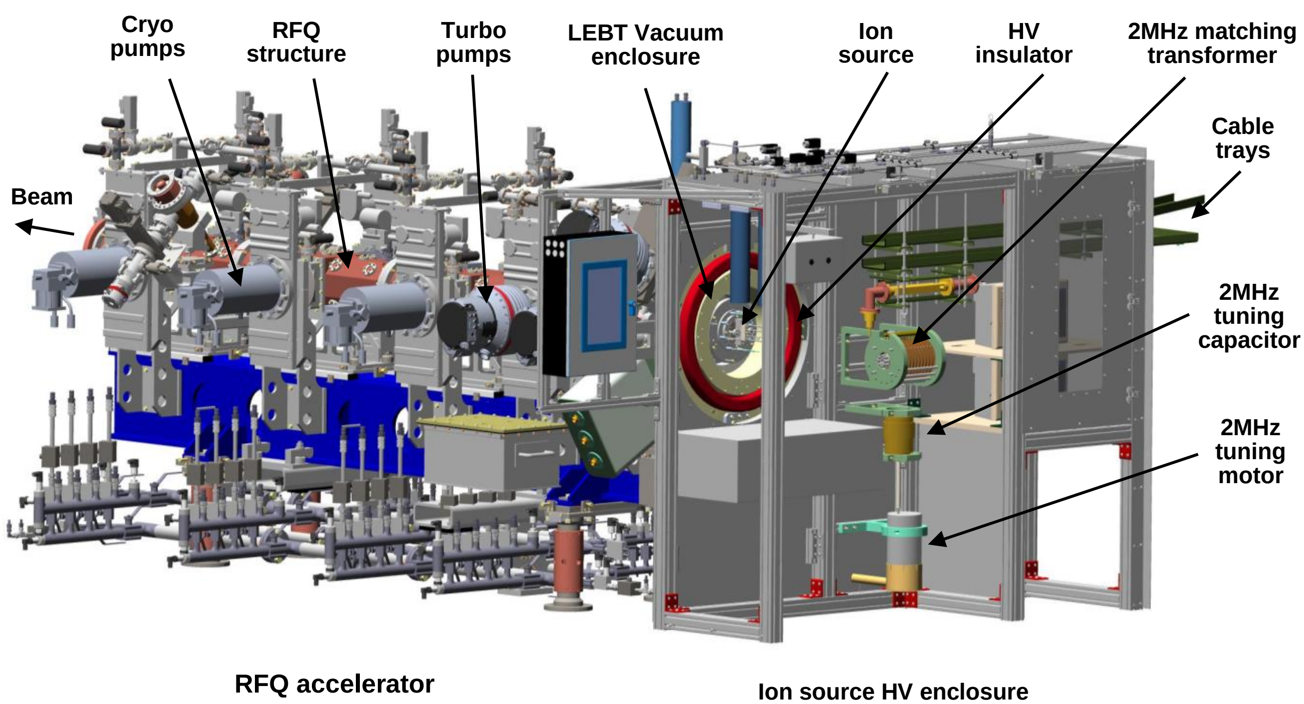

FIG. 1 The new SNS injector. Note that the screen mesh and access doors surrounding the ion source HV enclosure have been removed to permit visibility of the interior ion source system components.

III. SNS ION SOURCES AND THE NEW RFQ

Figure 2 shows a cross sectional view of both the SNS external and internal antenna ion sources. Both sources are RF-driven, Cs-enhanced, multi-cusp ion sources and have been described in detail previously [8, 9]. They employ different inductive RF – plasma coupling schemes which directs up to 80 kW of 2 MHz RF power into the plasma. Both sources feature mechanically identical outlet aperture assemblies which include the electron dump, outlet aperture, Cs collar and filter field magnets. This feature enables improvements to these structures to be applied to either ion source. Although most of the new injector's initial commissioning on the BTF was done with external antenna sources, once the new injector was installed on the SNS, standard SNS production ion sources were employed. The SNS employs 6 internal antenna and 4 external antenna sources across 3 facilities: the main SNS injector, BTF and ISTS. Each source is identified by a sequential number: #2, #3, #4, #5, #6, #7 and ext1, ext2, ext3 and ext4. Source #2, #4 and #6 are the standard SNS production ion sources.

The original SNS 2.5 MeV RFQ was designed and built at Lawrence Berkeley National Laboratory (LBNL) and delivered to the SNS in the early 2000's. The new SNS RFQ, discussed here, was designed at ORNL using the Berkeley physics design, and was manufactured by Research Instruments in Germany and delivered to the SNS site in 2013 [3]. It was designed to be a drop-in replacement for the Berkeley RFQ having identical beam dynamics while incorporating significant improvements to the mechanical, thermal and vacuum design. It features a 4-vane accelerating 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 which confers much greater dimensional stability to the overall structure against vacuum and water perturbations. The RFQ operates nominally 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 can be seen in Figure 1 as well as a more massive, single-material, solid copper structure which is more resistant to deformation.

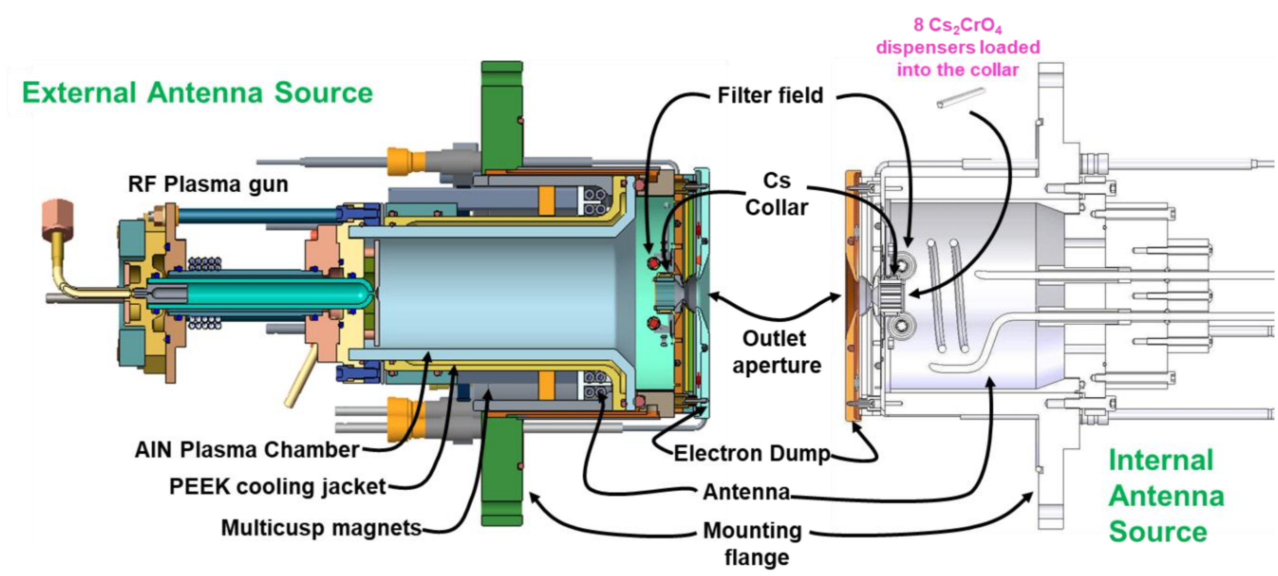

FIG. 2 The SNS internal (right) and external (left) antenna ion sources.

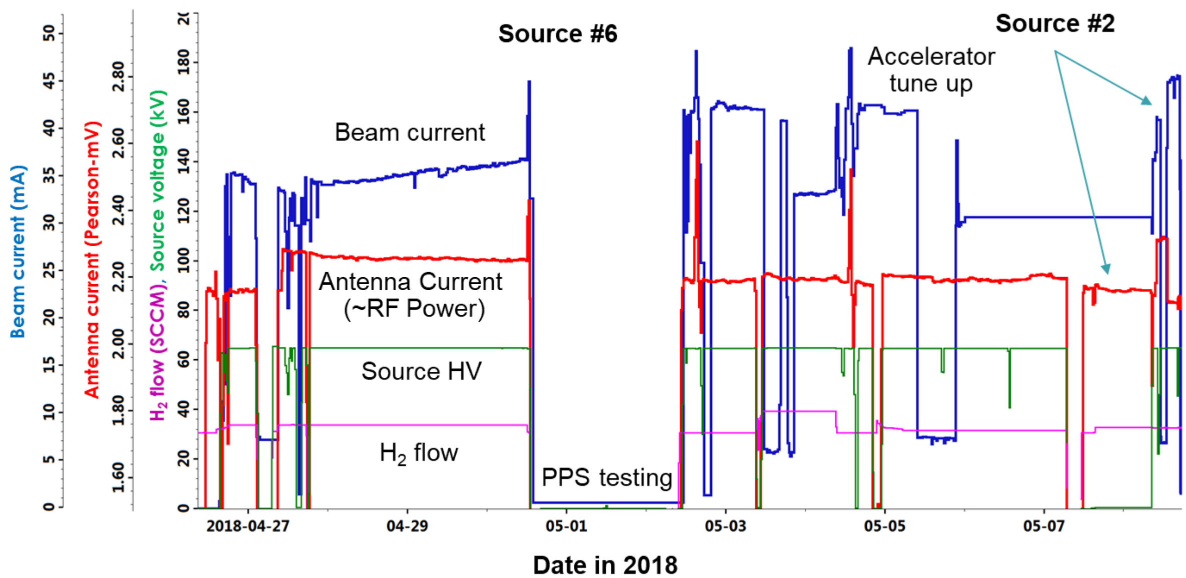

FIG. 3 The archived record of the beam commissioning period. The plot shows beam current in mA, H_2 flow into the source in SCCM, source HV in kV and the 2 MHz ion source antenna current expressed in mV across the Pearson current transformer. RF power is approximately linear with Pearson voltage with the conversion being 2.25 mV ~ 50 kW.

IV. BEAM MEASUREMENTS

In March of 2018, the new injector was installed on the SNS front end by attaching it to the existing Medium Energy Beam Transport (MEBT). The MEBT functionally matches the beam output from the RFQ to the SNS linac and contains a full suite of beam diagnostic instrumentation. In early April, system testing, and checkouts began: HV and cooling-water testing began as well as RFQ conditioning to full power (600 kW) and RF pulse width (~1 ms). RFQ conditioning (without beam) only took a couple days and we encountered no significant issues. Source start-up and initial beam commissioning began later in the month with the RFQ initially operating in short-pulse mode (50 μs). Note that the ion source always produces 1 ms beam pulses at 60 Hz while the RFQ RF pulse length can be changed between 50 μs and 1 ms modes. Internal antenna source #6 was first utilized in beam commissioning and the neutron production run started with internal antenna source #2. Figure 3 shows the archived history of the beam commissioning effort from the initial source start-up through the start of neutron production. Beam current was measured just downstream of the RFQ using a Beam Current Monitor (BCM) located near the entrance to the MEBT and the 2 MHz antenna current was measured by Pearson current transformer installed on the antenna loop of the matching network.

On May 2, the 2 MHz RF power to the ion source was varied throughout it's operational range and the beam current in the LEBT and exiting the RFQ was plotted in Fig. 4. The RFQ was operated at nominal power of ~600 kW and an RFQ transmission of > 90% is evident in Fig. 4 throughout this range of beam currents. Fig. 5 shows the current and historical RFQ transmission measurements from the original and new SNS injectors dating back to 2010. Prior to 2010, we could not measure the RFQ transmission since the LEBT beam current measurement technique had not yet been developed but we believe the transmission was also in the 90% regime since the beginning of operations in the early 2000's. Degradation of the original injector using the Berkeley RFQ therefore, likely, occurred in the 2011-12 time period. A transmission of ~90% is expected from Parmteq calculations of the RFQ using ISTS emittance data as an input [7]. Figure 6 shows the measured, normalized, RMS emittance of the 2.5 MeV beam exiting the RFQ as measured by a 2-slit scanner located in the MEBT with the RFQ operated with pulse widths of 50 μs and nominal RF power of ~600 kW. These data were thresholded at 0.6% and, as expected, were very similar to earlier measurements taken on the original SNS injector using the Berkeley RFQ. Phase scans of the RF buncher cavities in the MEBT were also conducted and the RFQ output energy was found to be 2.5 MeV ± 50 kV.

Overall ion source and RFQ commissioning with beam proceeded smoothly, with the expected results, and after ~10 days, the transition to neutron production ensued. We only encountered minor issues with a loose LEBT thermocouple wire and loose chopper target feed wire which were both quickly resolved. In Nov 2018, during routine neutron production, the RFQ experienced an end-wall, RF gasket failure which is currently being addressed by running the RFQ at reduced power, regular inspections, and routine gasket replacement. Note that the last 5 data points in Fig. 5 were taken with the RFQ at reduced power. In the future, this issue should be resolved by redesigning of the gasket area inside the RFQ which is the subject of ongoing work.

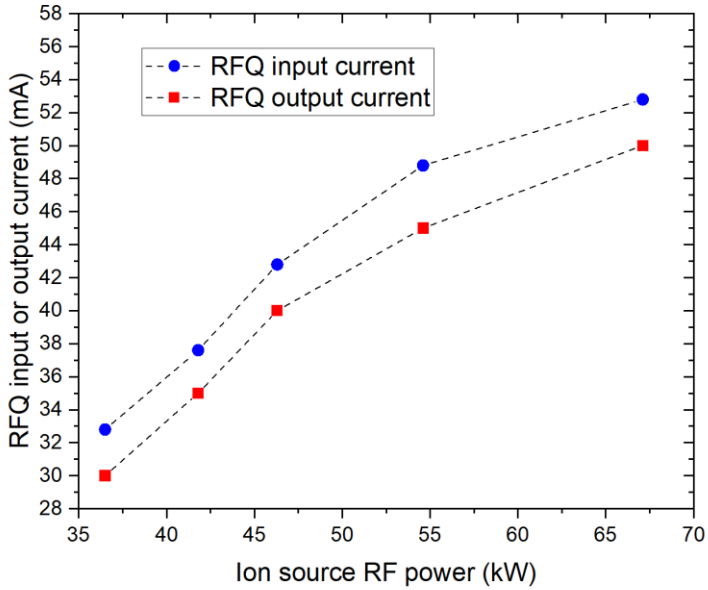

FIG. 4 RFQ input (LEBT) and RFQ output beam current (BCM) plotted against 2 MHz RF power supplied to the ion source antenna.

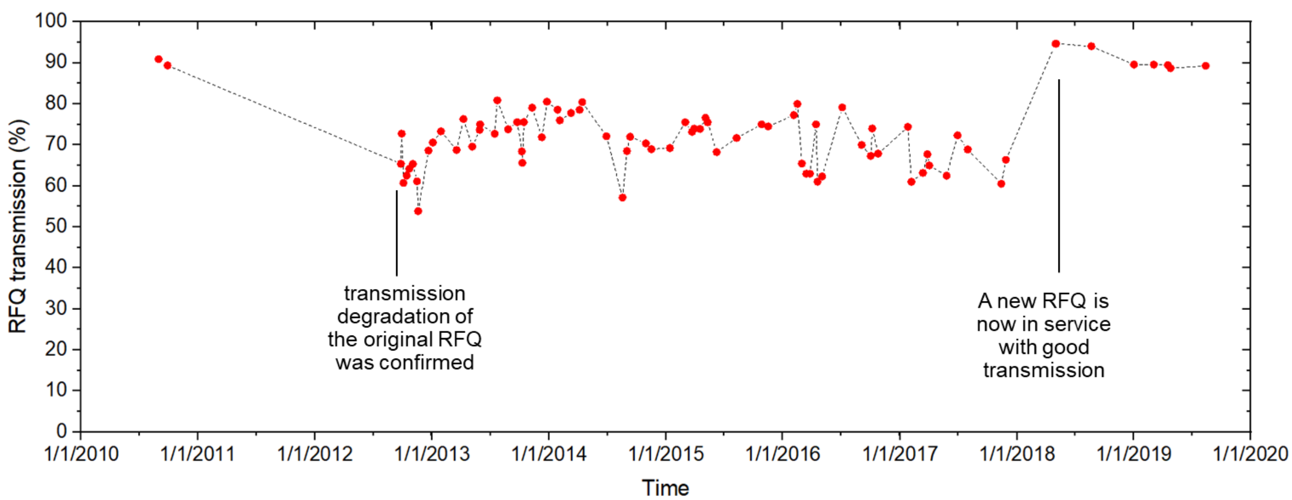

FIG. 5 Current and historical periodic RFQ transmission measurements taken since the beginning of logging transmission measurements at the SNS. Data after May 2018 is with the new injector and earlier data is with the original injector.

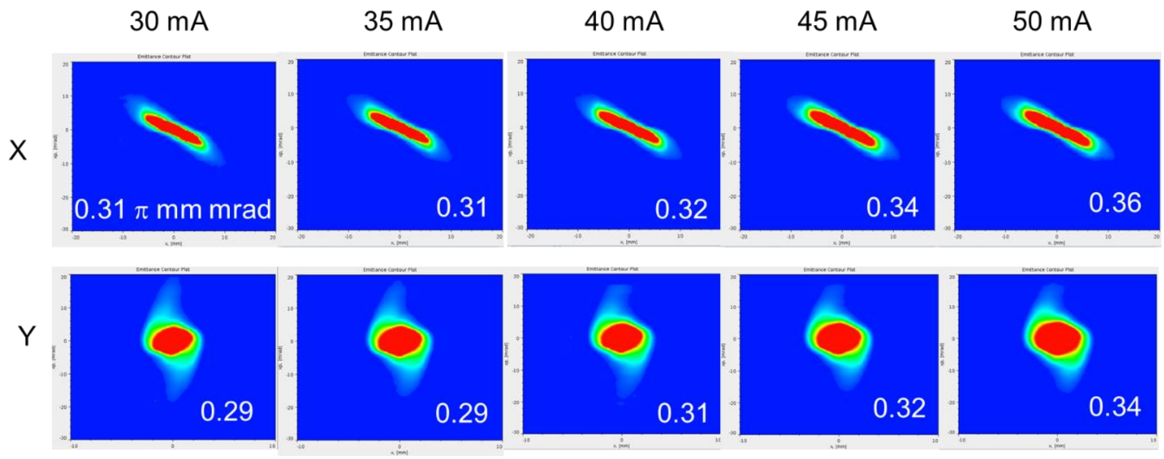

FIG. 6 RMS, normalized transverse horizontal (X) and vertical (Y) beam emittance plots at 2.5 MeV for internal antenna source #6, measurements were made with the ion source and RFQ under nominal operating conditions.

V. CONCLUSION

The major components of the new SNS injector have been developed and tested on the BTF and ISTS located at the SNS facility. The basic injector configuration ran on the BTF for over 4100 hours allowing considerable operational experience with the new RFQ while supporting an accelerator physics research program using mainly the external antenna source [10]. In March of 2018 the new injector was installed and commissioned on the SNS front end. Beam current, beam persistence, transverse emittance, energy and energy spread were all measured and found to meet and exceed the SNS requirement. Overall, for about a year and half now, excluding the gasket failure, the new injector has operated reliably for neutron production with an ion source / LEBT availability of > 99.5%. Most importantly, this upgrade increased the available SNS beam current by ~20%, dramatically reducing the challenge of meeting the current 1.4 MW SNS beam current requirement on a routine basis. The higher beam current requirements of major SNS upgrade projects should now be routinely achieved which was not possible with the original injector due to transmission degradation.

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