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CONSTRUCTION, TEST, AND OPERATION OF A NEW RFQ AT THE SPALLATION NEUTRON SOURCE (SNS)*

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ABSTRACT

A new RFQ was successfully installed recently in the SNS linac to replace the old RFQ that was used for more than a decade with certain operational limitations. The new RFQ was completely tested with H- ion source in the Beam Test Facility (BTF) at SNS. For robust operation of SNS at 1.4 MW, the full design beam power and to satisfy the beam current requirement of the forthcoming SNS proton power upgrade (PPU) project, an RFQ with enhanced performance and reliability was needed. The new RFQ was built to have the beam parameters identical to those of the first RFQ but with improved RF and mechanical stability and reliability for continuous operation of neutron production. The tests confirmed that the new RFQ can run with high beam transmission efficiency at around 90 % and notably improved operational stability. In this paper, construction, test, installation, and operation of the new RFQ in SNS are discussed with the performance improvements.

INTRODUCTION

The SNS employs a pulsed linac for 1.4 MW beam power at 1 GeV energy with 26 mA H^- ion beam current (chopped average) that is accelerated in 1msec pulses at 6 % duty cycle [1]. The H^- injector system has the RFQ to deliver 2.5 MeV beam to DTL through the MEBT. The old RFQ was having slow performance degradation over time in terms of the beam transmission efficiency and the stability of RF tunability at full beam current. A distinctive problem of the old RFQ was gradual change of field distribution [2]. For this reason, a new RFQ structure was built, tested, and installed in the linac for enhanced performance. The technical specifications for the new RFQ were developed for the SNS design goal with robust operational performance for the SNS linac and future beam power upgrades in mind. During the extended maintenance outage period in early 2018, the RFQ was installed in the linac with some peripheral improvement in the linac front-end system.

The first RFQ was built and delivered in 2002 at the beginning of the project construction and used in the linac until the end of 2017. Construction of the second RFQ was planned in 2009 and built and delivered in 2014. The new RFQ was then installed in the BTF, a separate low energy test accelerator built for tests of the RFQ and beam experiments for future science with H- ion source [3]. Table 1 shows the parameters of the new SNS RFQ. The RFQ was built to have the same vane tip shapes and tip modulations to preserve the design beam properties of the SNS linac and to have improved RF, mechanical, and operational properties compared to the first RFQ. The new RFQ was designed to be able to handle up to 60 mA beam current that can be needed for the future power upgrades of the SNS.

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Table 1. Specifications for the New RFQ

Operating Frequency	402.5 MHz
Input Energy	65 keV
Output Energy	2.5 MeV
Beam Current	Up to 60 mA
Acceleration Efficiency	> 90 %
Peak Field	40 kV/cm
Structure Power	50 kW average
Duty Cycle	Up to 8 %
Maximum Pulse Length	1.3 msec
Length	3.7 m
rms Transverse Emittance, input	0.35 π mm mrad
rms Transverse Emittance, output	0.27 π mm mrad
rms Longitudinal Emittance, output	0.10 π MeV deg
Dipole mode Separation	2 MHz min
Maximum Surface Field	1.85 Kilpatrick
Vane – Vane Voltage	83 kV

CONSTRUCTION

Figure 1 shows the new H^- injector system in the SNS linac completed with the new RFQ and the ion-source. The new RFQ vacuum port arrangement is also shown. The installation has been completed with other upgrades for the ion source and the LEBT subsystems.

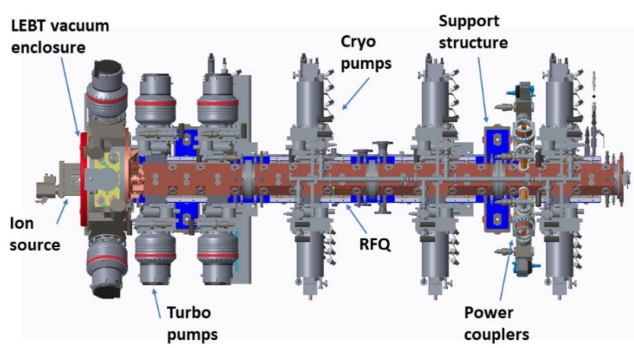

Figure 1. Top view of the new SNS beam injector system: RFQ with ion source, LEBT vacuum enclosure, couplers, and vacuum pumps.

The first SNS RFQ had a square wall cross section in two layers, outer layer in GlidCop for strength and the inner layer in OFHC. The second RFQ has an octagonal wall cross section in a single layer OFHC structure that was considered good for achieving the structural reliability and

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improved manufacturing. The first RFQ was built with pi-mode stabilizing loops (PISLs) while the second one employed end-wall rods for dipole mode stabilization. Detuning due to deformation with vacuum was estimated to be -119 kHz and -18 kHz for the old and the new RFQs, respectively which also tells the improved structural strength. The new RFQ was built in four modules that were joined together and to the LEBT and MEBT side end-walls with stainless steel flanges. 48 field probes and 64 slug tuners were used for field monitoring and tuning, respectively.

Maintaining a robust vacuum in the RFQ has been a challenge with the H^- ion source which inescapably introduces some hydrogen gas. Improving the vacuum pumping was one of the major changes in the new RFQ construction. Four turbo pumps are used on segment 1 to handle the hydrogen load coming from the source and the improved vacuum port design has higher conductance than that for the old RFQ. Six cryopumps were used on modules 2, 3, and 4. At each location, the RFQ has two vacuum ports at right and left sides for covering all four quadrants without breaking the mechanical symmetry around the RFQ structure (see Fig. 2). The new RFQ has four 1700L/sec turbos in module 1 and six 1500L/sec cryopumps in Modules 2, 3, and 4. The old RFQ employed six 1500L/sec cryopumps staggered on two sides of the RFQ.

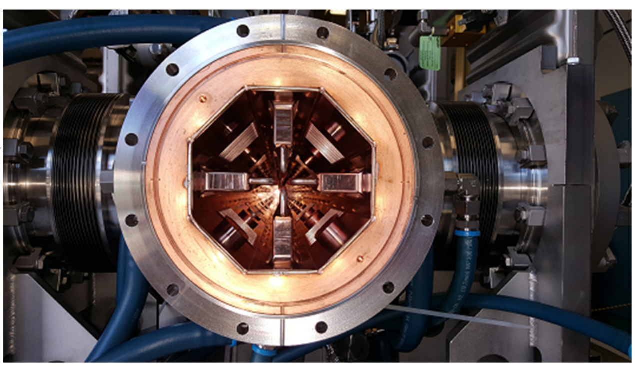
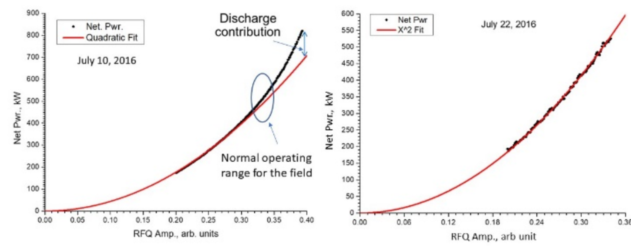


Figure 2: Internal view of the new SNS RFQs at the low energy end. Two turbo pumps are installed to the two vacuum ports each covers two quadrants at each longitudinal location.

The cooling system was designed for more adequately distributing the water coolant for the heat loads of the components of the RFQ and its peripheral equipment. The RFQ is cooled with two separate chillers, one for the vanes and one for the wall. Cooling capacity of each chiller was selected to handle heat loads greater with 20% margin above the loads required at 1.4 MW beam operation. The vane water temperature is adjusted for controlling the RFQ resonance at ~ 31 kHz/°C rate for operation while the wall temperature is fixed.

TESTS WITH RF AND BEAM

The new RFQ structure was successfully tested without and with the H^- ion beam in the SNS BTF which was basically identical to the SNS linac front-end system. The test showed that the RFQ performed reliably and efficiently with RF power delivered up to 600 kW in closed loop operations in 1 msec, 60 Hz pulses. With beam loading, the total power extended to 650 kW or higher without any problem. The thermal permanence of the RFQ with new cooling system showed improvement that the system can operate reliably with decent RF stability. The vacuum system performance also showed substantial improvement. The RFQ cavity and coupler vacuums were both maintained below $2x10^{-8}$ torr and the vacuums were staying at high in 10^{-8} torr range with the beam.



(a) (b)

Figure 3: (a) The old RFQ showed non-quadratic growth in RF power with increasing field. (b) The new SNS RFQ RF power follows the quadratic relationship with no clear discharge contribution.

One of the major improvements observed for the RF stability is shown in Fig. 3. In the old RFQ, when the structure RF power was increased to have the nominal field level for beam operation, the RF power consumption was not following the anticipated quadratic relationship ($P \sim V^2$) for the cavity internal field. This phenomenon was observed after having degraded beam transmission and operational instabilities with the RF resonance control. That anomaly in the RF power conversion in the cavity was considered the culprit that resulted performance degradations. The problem completely disappeared in the new RFQ structure showing the improved stability.

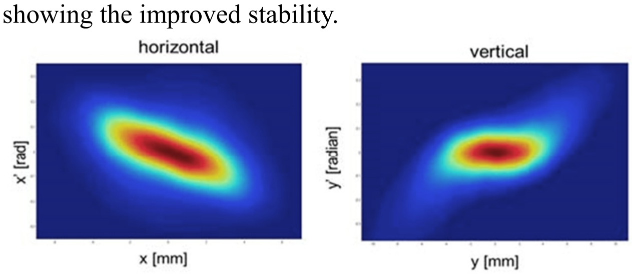


Figure 4: Horizontal and vertical transverse beam emittance measured with slit-slit system.

All measurements with the beam were done with the design inter-vane voltage of 83 kV [4]. Calibration of the amplitude of the RFQ inter-vane voltage was performed using the X-ray spectrum cut-off technique. The beam transverse emittance at the RFQ output was measured and shown in Fig. 4 using two pairs of slits separated by a 1 m drift. At a location, a pair of horizontal and vertical slits that are longitudinally separated by 10mm that moves concurrently were used. The beam charge coming through the slits was measured at the downstream beam dump. The measured rms emittance

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value was in the range of 0.25~0.35 π·mm·mrad depending on the beam current from the ion source using the MEBT optics. The longitudinal emittance was measured using the beam shape monitor (BSM) to be 0.15~0.25 MeV·deg @ 402.5 MHz.

Up to now, the beam transmission through the RFQ has been demonstrated at ~ 90% in BTF for the nominal operation beam current (unchopped peak currents were measured). When the RFQ transmission was measured with LEBT beam currents at around 24 mA, the MEBT current was measured as 22 mA yielding the RFQ transmission of ~91%. With the increased LEBT peak current to 45 mA and 50 mA, the MEBT beam current increased to 39 mA and 44 mA, respectively, that yielded an RFQ transmission of 87~88 %. With full beam operation with the beam production in the linac, more data will be collected to deliver more detailed transmission characteristics with respect to the beam current. The maximum peak beam current from the H- ion source delivered to the BTF MEBT beam stop through the RFQ at 2.5 MeV was 50 mA [5][6].

DISCUSSION

Figure 5 shows the new RFQ that has replaced the old RFQ in the SNS linac following the successful tests with H^- beam in the BTF. Full high-power RF and beam tests verified performance and stability of the RFQ for the production beam loading. The measured beam parameters agreed reasonably well with the design values. The new RFQ demonstrated good stability in terms of RF powering and the resonance control which showed fast recovery after RF power and/or input beam interruption, one of the distinctive improvements over the old system.

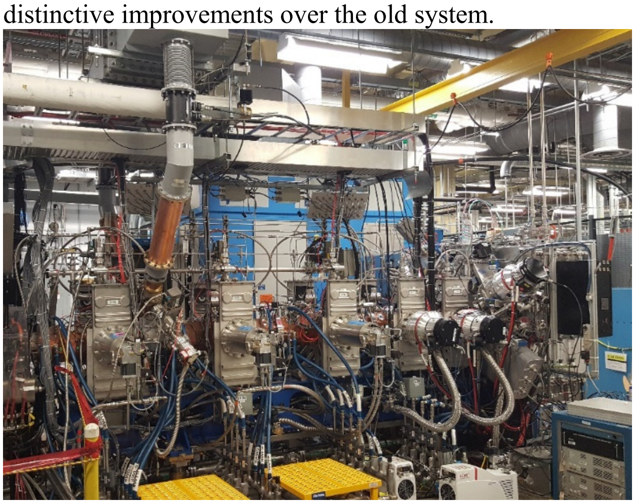

Figure 5: New RFQ was completely installed in the SNS linac. Ion source and LEBT are shown in the right.

The new RFQ was tested with higher beam current from the same type of H^- ion source that has been used in the SNS and continually updated with improved reliability [6]. Using the same type of electrostatic LEBT verified the performance of the new RFQ under the same conditions as in the previous SNS linac.

The new SNS RFQ does not show the field-power discrepancy in the nominal operating field range which was suspected in the old system to cause the operational difficulties.

Additional improvement over the old RFQ is the installation of a gate valve separating source vacuum and RFQ vacuum. The valve eliminates venting the RFQ during ion source changes and limits the possibility of accidental venting.

The old system developed various problems that required diverse workarounds to optimize the performance and to overcome the problems. The tests with the new RFQ showed that the full design performances can be achieved without compromise. For example, at the SNS the beam is turned off by delaying the ion source pulse until after the RFQ RF pulse occurs. So, the beam off condition just means that beam is not accelerated. For beam off, the ion source beam is injected, and is lost in the RFQ. Therefore, beam on/off/on transitions are an unstable heat load on the RFQ cooling system. The old RFQ required significant control adjustments to maintain closed loop operation during beam on/off/on transitions. The new RFQ does not show the same instability currently.

CONCLUSION

The SNS now has the proton power upgrade (PPU) project that will increase the average beam current to 38 mA and 2.8 MW total beam power [7]. The inclusion of the new RFQ in the SNS linac is an important upgrade in SNS for robust operation with the present beam power requirement as well as the future power upgrade that will need the robustness of the linac injector system.

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