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HIGH POWER RADIOFREQUENCY OPERATION OF THE RADIO FREQUENCY QUADRUPOLES IN THE SPALLATION NEUTRON SOURCE*

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Abstract

The Spallation Neutron Source (SNS) recently took delivery of a third Radio-frequency Quadrupole (RFQ03) that has been installed in the Front End of the SNS Linac and ready for operation. The first RFQ (RFQ01) operated in the SNS Front End for about 15 years before being replaced with the second RFQ (RFQ02). RFQ01 was relocated to the Beam Test Facility (BTF) where it operated for five more years. The RFQ02 was initially installed in the BTF for high-power testing and used with H- beam for BTF operation. It replaced RFQ01 in the SNS FE in 2017 and has been operating for beam production since then. RFQ01 had some detuning incidents that resulted in degradation in beam transmission and required RF re-tuning. RFQ02 has performed well but had melted RF seals on both end flanges, which was ultimately mitigated by a redesign of the end flange and RF seals. The SNS decided to order RFQ03 which has a design that followed RFQ02 design closely, but end-wall contacts were modified to prevent RF seal failure. The results of RF power conditioning and beam commissioning at BTF confirmed that the new RFQ03 meets all the design specifications. The status of these SNS RFQs, including design improvements, RF conditioning and commissioning results of RFQ03 are reported in this paper.

INTRODUCTION

SNS Front End is comprised of an RF-driven H- source, an electrostatic low energy beam transport line (LEBT), a 402.5 MHz RFQ, a medium energy beam transport line (MEBT), a beam chopper system, and a suite of diagnostic devices. The SNS RFQ is designed to accelerate 65 keV input beam to 2.5 MeV output energy with a 3.7-meter-long 4-vane structure operating at 402.5 MHz.

To support the reliable operation, there have been three RFQs developed at SNS. The original one, RFQ01, was initially in operation in the FE but suffered from unknown incidents that resulted in unexpected field distortions, frequency shifts, and beam transmission degradations. As a result, a second RFQ, RFQ02, was designed and built to replace RFQ01. The RFQ02 was initially installed and successfully commissioned in the BTF. However, when RFQ02 was subsequently installed in the FE system, it experienced issues with end-wall RF seal failure, which necessitated further improvements. As a result, a third RFQ, RFQ03, was recently built and delivered with design improvements specifically aimed at addressing the issues faced by RFQ02. Table 1 shows the main specifications for SNS RFQs.

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Table 1: Specifications for SNS RFQs

	RFQ01	RFQ02	RFQ03
Frequency	402.5 MHz	402.5 MHz	402.5 MHz
Structure type	4-vane	4-vane	4-vane
Length	3.7 m	3.7 m	3.7 m
Material	Glidcop + Copper	Copper	Copper
Vane voltage	83 kV	83 kV	83 kV
Dipole mode suppression	π-mode stabilizers	4-rod stabilizers	4-rod stabilizers
Tuners	80 slug tuners	64 slug tuners	64 slug tuners
Vacuum	6 cryo-pumps	6 cryo-pumps+ 4 turbo pumps	10 turbo pumps
Beam current	Up to 60 mA	Up to 60 mA	Up to 60 mA
Transmission	>90%	>90%	>90%

RFQ01

The original SNS RFQ (RFQ01) was constructed and installed in the Front-End linac in 2002. The inner layer of the vanes is made of Oxygen-Free High Conductivity (OFHC) copper, while the outer layer is composed of GlidCop® alloy, and they are joined together using brazing techniques [1]. The resonance frequency of the RFQ is controlled using two separate chillers, one for vane cooling (-33 kHz/°C) and another for cavity wall cooling (+27 kHz/°C). Cooling channels are machined into the inner layer to facilitate vane cooling while cooling grooves are located between the brazed joints to enhance wall cooling, shown in Fig. 1.

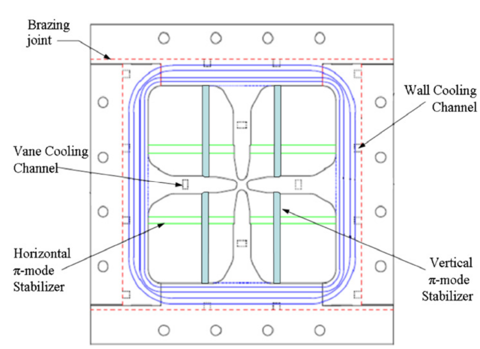

Figure 1: Cross-sectional view of SNS RFQ01.

Two detuning events occurred in 2003 and 2009, which were suspected to be related to the OFHC and GlidCop® brazing joints but inconclusive [2]. The first event

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happened when the cooling water control was down, resulting in a detuning of -450 kHz. The second event occurred when the cooling channel was accidentally overpressurized, resulting in a detuning of -230 kHz. Both events were remedied by adjusting the slug tuners to restore the desired resonance frequency and the longitudinal field flatness.

Difficulties were encountered in maintaining closed-loop operation of the RFQ when increasing the duty-factor, as well as observing a non-quadratic relationship between RF power and RFQ field amplitudes. In response, several operational improvements were implemented, including lowering the field setpoint, reducing hydrogen flow in the ion source, upgrading cooling and vacuum systems, and enhancing the LLRF pulse control.

Despite undergoing a third retuning in 2013, the beam transmission degradation, which had persisted over a two-year period resulting in a reduction of 20-30%, was not restored. Consequently, the decision was made to procure RFQ02 as a replacement. The RFQ01 was removed from the BTF in 2022. Now it is used for the post-mortem analysis.

RFQ02

With identical beam dynamics, RF configurations, and resonance control scheme as RFQ01, RFQ02 was manufactured with some design enhancements, including a single copper (OFHC) layer structure with an octagonal cross-section and four end-wall stabilizer rods, along with improvements to the vacuum and cooling systems [3]. It was commissioned with beam at the SNS beam test facility (BTF) in 2017 and subsequently installed in the Front-End (FE) linac in 2018.

RFQ02 exhibited excellent beam performance and stable operation at beginning. After running at high power and high duty factor for about 4900 hours, RFQ02 experienced a trip and was unable to recover. Upon investigation, damaged C-seals were discovered at both end-walls in November 2018. Figure 2 shows the damaged RF seals on both ends.

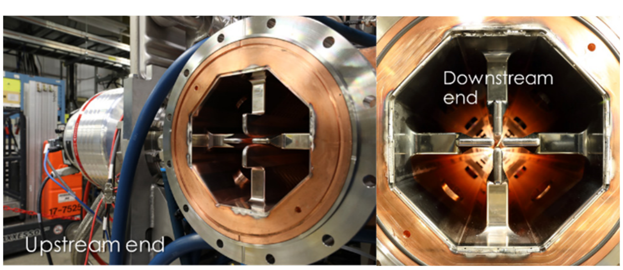

Figure 2: Damaged C-seals on the end-walls of RFQ02.

After extensive iterations of investigations, developments, and operations for addressing the issues with the end-wall and RF seal design, RFQ recovery plans were formulated. As short-term solutions, the MEBT end wall and RF seals were redesigned and replaced to improve their performance. On the upstream side, a new type of RF seal using copper tube with internal Nimonic spring was installed instead of the C-seal. On the downstream side, a new MEBT end wall was designed with elevated boss, and bal-seal on the flat surface where the bal-seal is not directly facing the RF field, shown in Fig. 3. Additionally, a new RFQ (RFQ03) was manufactured with an improved interface between RFQ cavity and end walls for better RF contact to specifically address the previous issues encountered.

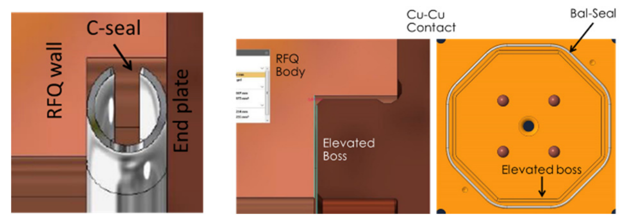

Figure 3: RFQ02 C-seal (original) and improved MEBT end wall with elevated boss and bal-seal.

The RFQ02 was swap out from SNS Front End in March 2023. It will be installed to the BTF as a ready spare in the future. The retuning with bead-pull measurements will be performed before moved to BTF. Figure 4 shows the RFQ02 in a portable cleanroom and ready for retuning.


Figure 4: RFQ02 in the cleanroom ready for retuning.

RFQ03

Improvements on RFQ03 Design

The RFQ03 was built to have RF and beam transport characteristics identical to those of the RFQ02. It consists of 4 longitudinal modules, around 1 meter per module. The RF power is fed into the cavity through two coaxial loop couplers. 64 fixed slug tuners are distributed along the cavity to tune the field profile for 4 quadrants and the cavity resonance frequency. 48 field probes are used for field monitoring.

One of the major improvements on the RFQ03 design was on the upstream and downstream ends with more reliable RF contacts. Based on the experiences learned on the RFQ02, the new RFQ03 was built with copper-to-copper contact on both ends, and the RF seals were moved outside of the RF contact surface, not directly facing the RF field. Figure 5 shows the details of the design.

Maintaining a robust vacuum in the RFQ has been a challenge with the H- ion source which inescapably introduces some hydrogen gas. As the same of the RFQ02, four turbo pumps are used on the module 1 of RFQ03 to handle

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the hydrogen load coming from the source. On module 2, 3 and 4, the vacuum pumping was upgraded with six turbo pumps for better maintenance instead of six cryopumps utilized on RFQ02. Ten turbo pumps can deliver a total of 13,200 l/s of pumping speed for the RFQ03. Two additional small turbo pumps are used on the RF couplers to maintain a good vacuum around the window to mitigate multi-pacting effect.

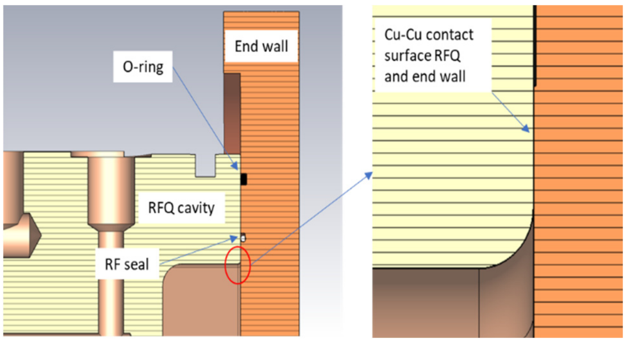

Figure 5: RFQ03 improved design of contact interfaces between RFQ and end walls

Test with RF and Beam

After assembly at SNS, RFQ03 low power RF tests were successful with results of RF frequency and field flatness, in good agreement with measured data from the vendor. Figure 6 shows field flatness results measured at SNS comparing to the vendor's data.

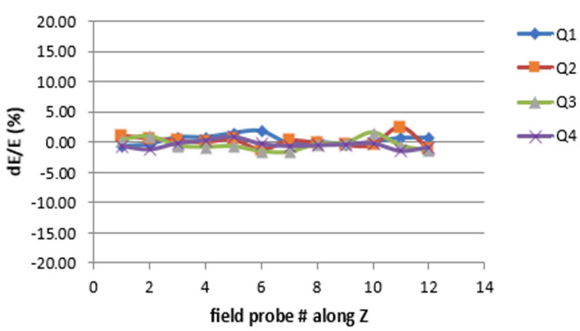

Figure 6: Measured field flatness at SNS vs. vendor's data.

The new RFQ03 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 RF conditioning started with a low duty and low repetition frequency in open loop regime. At low repetition frequency, the RF power and then pulse length was gradually increased respectively towards the design value while the vacuum pressure and reflected power were within an acceptable range. After this process completed, the repetition frequency was increased, and the conditioning process was started over until achieve the design value of 60 Hz. The RFQ03 has been conditioned to the full power of 650 kW with design duty factor of 6% at 60 Hz. Closed loop at high power was also tested before beam commissioning. The vacuum system performance showed substantial improvement. The RFQ cavity vacuum was maintained below 9x10-9 Torr at full power after conditioning completion. Figure 7 shows the conditioning data for about 8 days.

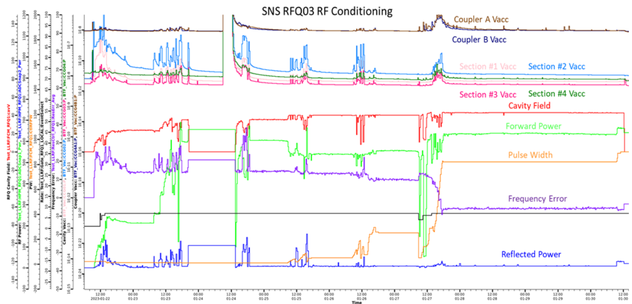

Figure 7: RFQ03 conditioning data plot (~8 days data).

Beam commissioning test was done at a full duty factor in the BTF [4]. The output beam density reached to ~42 mA when the input beam measured on the chopper target was ~45 mA. The beam transmission through RFQ03 was over 90%. The beam emittance and beam energy at the RFQ output were also measured with results satisfying the design requirements.

After test in the BTF, RFQ03 was installed to the SNS Front End for operation starting in June 2023, shown in Fig. 8.

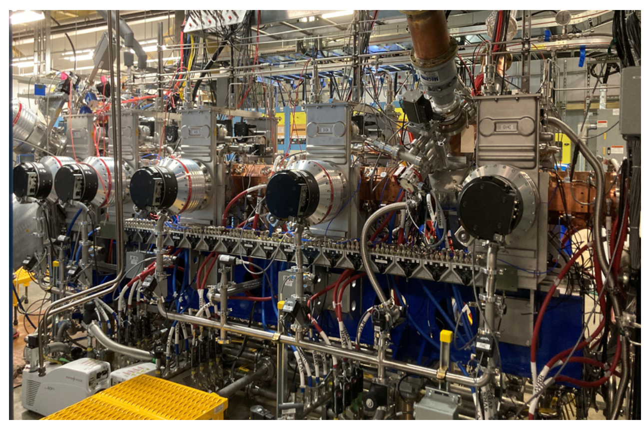
Figure 8: SNS Front End with the new RFQ03

CONCLUSION

Full power RF and beam test verified the performance and stability of the new RFQ03. All measured beam parameters were in good agreement with the design values. The inclusion of the new RFQ in the SNS linac is an important upgrade for robust operation with increased beam power requirements for the proton power upgrade (PPU) project.

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REFERENCES

[1] S. H. Kim *et al.,* "Stabilized Operation of the Spallation Neutron Source Radio-Frequency Quadrupole", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 13, p. 070101, Jul. 2010. doi:10.1103/PhysRevSTAB.13.070101

[2] Y. Kang *et al.*, "Modelling and Simulation of RFQs for Analysis of Fields and Frequency Deviations with Respect to Internal Dimensional Errors", in *Proc. NAPAC'16*, Chicago, IL, USA, Oct. 2016, pp. 810-812. doi:10.18429/JACoW-NAPAC2016-WEPOA52

[3] Yoon Kang *et al.*, "Construction, Test, and Operation of a new RFQ at the Spallation Neutron Source (SNS)", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1113-1116. doi:10.18429/JACoW-IPAC2018-TUPAL046

[4] K. Ruisard *et al.*, "Measurements at peak operational beam current in the SNS beam test facility", presented at the 14th International Particle Accelerator Conference (IPAC'23), Venice, Italy, May 2023, WEPA027, this conference.