# INITIAL COMMISSIONING EXPERIENCE WITH THE SPALLATION NEUTRON SOURCE VERTICAL TEST AREA RF SYSTEM*

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*Abstract*

The Spallation Neutron Source (SNS) has developed a vertical test area (VTA) for the testing and qualification of superconducting radio frequency cavities. The associated RF System successfully supported the initial commissioning of the VTA system and has been utilized for cavity testing at both 4 and 2 K. As operational experience was gained, improvements to the RF system were implemented to better utilize the dynamic range of the system, and software updates and additions were made to meet operational needs. The system continues to evolve as we gain better understanding of the testing needs.

## INTRODUCTION

The Spallation Neutron Source (SNS) project was completed in 2006 and is now routinely operating at power levels of 1.3 MW on target. Our Linac consists of both normal conducting structures and superconducting cavities to generate the nominal 1000 MeV H- ion beam. To maintain our operational readiness we have invested significant effort in the infrastructure of the Radio Frequency Test Facility (RFTF) to include a vertical test area (VTA) for the qualification of superconducting radio frequency cavities [1]. The RF systems utilized in the VTA are based on the systems developed at both Jefferson Lab (JLAB) and Fermi National Accelerator Laboratory (Fermilab).

The RF system shown in Figure 1 is a combination of commercial-off-the-shelf (COTS) equipment and custom designed hardware to implement a self-excited loop style control system. This design process was chosen due to experiences at other laboratories and the time constraints for system implementation. The custom hardware functions have been separated into five modules consisting of a cavity input/PLL module, a VCO/RF drive module, a power monitoring module, and two signal conditioning modules. The hardware is controlled via a National Instruments PXIe 8133 quad-core controller running LabView to support the processing requirements. Data acquisition and control of the custom hardware is accomplished with a PXI-6229 multifunction data acquisition card. Standard test equipment is used as part of the system where possible and includes two dual channel power meters, two single channel power meters, a frequency counter, and a signal generator [2].


Figure 1: VTA RF Control System.

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RF power for the system is provided with a 2 kW solid state amplifier consisting of four 500 watt modules capable of both CW and pulsed operation. A three watt and 30 watt amplifiers are provided for calibration of the system.

## TEST RESULTS

Four testing cycles have been completed; the first three cycles were conducted at 4 K operation using the cryogenic test facility (CTF). Between the third and fourth test, the CTF's Kinney pumping skid was commissioned allowing for 2K testing. The fourth cavity test was performed successfully at both 4 and 2 K operation. Figure 2 shows a bare SNS 805MHz cavity being lowered into the VTA dewar prior to testing.

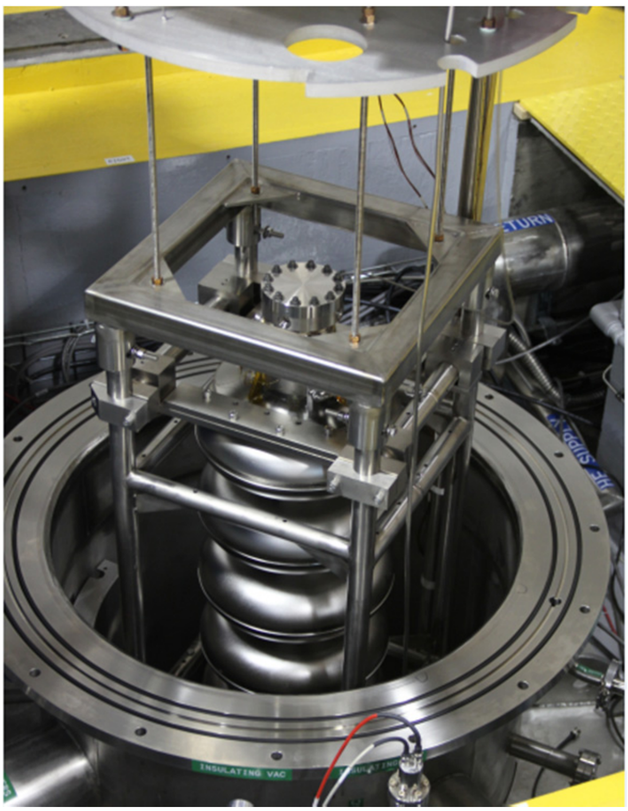

Figure 2: Cavity insertion into Dewar.

### *SNS VTA Test 1*

The initial test of the system was used for commissioning and verification of basic operation of the equipment. The test consisted of three major tasks: verification of the cryogenic components, measurement of the VTA shielding effectiveness, and initial checkout of the RF systems. The test cavity chosen was a high beta cavity (HB-74) previously tested at Jefferson Lab. This allowed for a comparison of our measurements with known results to verify system performance.

While the cryogenic and shielding aspects of the test are critical to the overall functionality of the facility, this paper will concentrate on the RF performance, improvements, and calibration of the system. The original SNS VTA LabView RF control and data acquisition software was based on a modified version of the Fermilab code received. Most of the software was rewritten but the underlying logic was reused. Several modifications were implemented to customize the application to our hardware. A few examples of these modifications are:

- The VCO's magnitude and phase values are set independently.
- An automatic mixer input level control algorithm was implemented to increase the input dynamic range (>60 dB) which improves the PLL's sensitivity on the cavity probe signal.
- A bi-sectional peak finding method was implemented for VCO output phase optimization algorithm. This tunes the PLL's loop phase automatically based on the minimum cavity RF reflection and maximum cavity field probe signal level.

This test was limited to CW mode operation at 4K. The program and hardware successfully tracked the frequency of the cavity and locked the loop. The system handled the pressure fluctuations in the dewar while remaining locked. Errors in the reflected power measurements were unacceptably high, and a few signal levels were too low indicating a need for further optimization.

### *SNS VTA Test 2*

SNS VTA test 2 was similar to the initial test with the exception of the use of a high beta cavity with a helium vessel installed (HB-59). As with the first test, the temperature was limited to 4K and the cavity data was available from a previous test at Jefferson Lab.

One of the issues noted during the first CW test was that the system had significant delays of ~100 milliseconds to read the power meter data due to the use of GPIB communication for the instruments. These delays were unacceptable for pulsed RF operation so several modifications to both the hardware and software were implemented. Some of the highlights are:

- Active power detectors (>50 dB dynamic range) were installed in the power measurement module to improved signal measurement rates.
- The decay measurement routine was removed from the main sequencer to speed up the main loop operation.
- Two directional couplers were replaced to improve the dynamic range of the system. Attenuation in the hardware modules was also fine-tuned to maximize the phase detector sensitivity.

This test was the first attempt at pulsed operation and the results were promising. This test was also utilized to make improvements to the cryogenics portion of the system. The ability to determine and control liquid level in the dewar, plus cool down, top off liquid and warm up the system while controlling dewar pressure was verified.

### *SNS VTA Test 3*

SNS VTA test 3 was the last of the 4K only tests and the high beta cavity (HB-74) utilized for the initial test was reused. This test verified the improvements to the cryogenic system. The new 25 kW heater was tested to control return gas temperature and to minimize process gas temperature swings.

The RF system benefited from a few minor improvements. The main loop of the software was segmented into smaller sequential loops grouped by functionalities in an attempt to improve overall speed.

### *SNS VTA Test 4*

SNS VTA test 4 was the first test of the system at 2K. The cavity chosen for this test was a modified high beta cavity (HB-62) with improved end groups and removed HOM couplers. The cavity was outfitted with an adjustable fundamental power coupler (FPC) so that the cavity coupling could be remotely adjusted during the test.

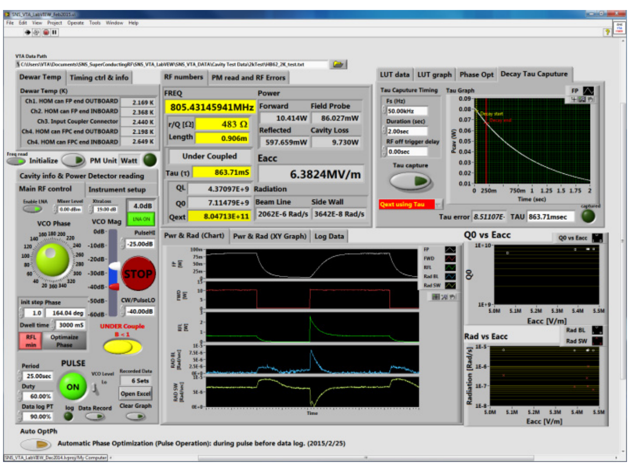

Figure 3: VTA Main Screen – 2K pulsed operation

This test was straight forward at 4K and the initial tests of the cavity were as expected. At 2K operation, the system performed adequately. Figure 3 shows the cavity at 6.3 MV/m pulsed RF operation. The cavity was successfully tested up to 11.9 MV/m without issue. Unfortunately, shortly after this power level, the RF drive cable in the dewar failed due to a software initialization error.

While the test was successful, the system did exhibit some issues that needed attention. Some of the issues that have been addressed are:

- Attenuation in the cavity input/PLL module was reduced by 3 dB to increase input sensitivity.
- The directional coupler for the reflected signal was replaced with a higher directivity coupler.
- Jitter in the drive signal was improved with improved filtering in the loop amplifier.
- Changed the software initialization scheme to better support system reboots.
- Limited the output power of the 2 kW amplifier to 500 watts at the dewar lid.
- Verified the reflected power calibration.

## CALIBRATION

Proper cable calibration is one of the most critical issues to ensure that accurate, reproducible results are obtained from the cavity tests. All cables and components that are in the drive, feedback, and measurement paths for the system were characterized prior to installation in the system for baseline numbers. Dues to the inherent errors associated with arithmetically combining loss numbers, this combined loss value is used for reference only. Our present calibration scheme is similar that used at the JLAB vertical test system where signals are injected and measured with a reference power meter [3]. A vector network analyser is used to measure the S11 of cables located inside the dewar.

Some power agreement issues have been noted during the four tests performed. The forward power reading was repeatable and the accuracy acceptable, the reflected power error was high due to poor directivity of the dual directional coupler. This coupler was replaced with a higher directivity coupler but there is still concern that under certain phase conditions the measurement may have an unacceptable error [4]. In tests with injected signals, the replacement coupler performance has been acceptable with errors within a few percent, but a cavity test is needed to fully validate the performance.

A secondary reflected power measurement port is under development using a directional coupler installed between the circulator port 3 and the circulator load. Because there are minimal standing waves in this transmission line, errors due to coupler directivity will be reduced. In tests with injected signals, this coupler tracks the reflected power and shows good agreement. If this solution provides the expected results during the next cavity test, the system will be modified to utilize this signal for reflected power readings.

## SUMMARY

The SNS VTA system has been successfully commissioned and has completed four test cycles at both 4 and 2K. All required functions of the RF systems have been verified and improvements have been made to support CW and pulse operation. The software has been streamlined to improve the response time of the system and improve the user interface. Reflected power measurement errors have been addressed and will be validated during the next cavity test.

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## REFERENCES

[1] J. Saunders, et al, "Status of SRF Facilities at SNS", Proceedings of IPAC' 14, Dresden, Germany, 2014.

[2] S-W Lee, et al, "RF Control System for the Vertical Superconducting Cavity Test Area at the Spallation Neutron Source", LLRF13_Poster_63, 2013.

[3] T. Powers, "Theory and Practice of Cavity RF Test Systems", SRF Workshop 2005, Ithaca, NY, USA, 2005.

[4] D. Jorgesen and C. Marki, "Directivity and VSWR Measurements, Understanding Return Loss Measurements", Marki Microwave, Morgan Hill, CA, http://markimicrowave.com/assts/appnotes/directivity_and_VSWR_measurements.pdf, 2012.