

TECHNIQUES FOR ACHIEVING HIGH RELIABILITY OPERATION OF THE SPALLATION NEUTRON SOURCE HIGH POWER RADIO-FREQUENCY SYSTEM *

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Abstract

The Spallation Neutron Source (SNS) high power radiofrequency (HPRF) system operates with high reliability to support the goals of the SNS user program. In recent operational periods the availability of the HPRF system has exceeded 97 percent while the neutron source availability overall is typically greater than 90 percent. SNS has a unique set of 92 HPRF stations that operate at either 402.5 MHz or 805 MHz with peak output power ranging from 550 kW to 5 MW and average power ranging from 49.5 kW to 450 kW. The HPRF transmitters consist of chassis-mounted power supplies, solid-state amplifiers and other equipment that support the operation of the klystrons that ultimately provide the RF power to the accelerating structures. Management of the operation and maintenance of the HPRF system has increasingly focused on reliability and sustainability in recent years. Techniques for klystron lifetime preservation and optimization of transmitter reliability have been developed and will be described.

INTRODUCTION

The major components of the SNS HPRF transmitters include the klystron, the klystron solenoid, the waveguide circulator, the circulator load, the klystron high voltage tank, the transmitter cooling cart (TRCC) and the rack set that contains all of the chassis-mounted power supplies, amplifiers, controls and the user interface necessary for operation. While their operation is essentially the same, the transmitters are classified based on the cavity type that they drive: The Radiofrequency Quadrupole (RFQ) transmitter, the Drift Tube Linac (DTL) transmitters, the Coupled-Cavity Linac (CCL) transmitters and the Superconducting Linac (SCL) transmitters. Figure 1 shows typical equipment racks for the different transmitter types.

The RFQ and DTL transmitters use 150 W solid-state amplifiers to provide the RF input for the 2.5 MW, 402.5 MHz klystrons. The klystrons in these transmitters

operate with cathode voltages of 125 to 133 kV and cathode currents of 30 to 35 A. There are three high voltage converter modulators (HVCM) driving the klystron cathodes. The first modulator powers three klystrons and the remaining modulators power two klystrons each.

The CCL transmitters use 100 W solid-state amplifiers to provide the RF input for the 5 MW, 805 MHz klystrons. The klystrons in these transmitters operate with cathode voltages of 128 to 134 kV and cathode currents of 66 to 70 A. There are four HVCMs driving one klystron each in the CCL.



Figure 1: Typical SCL and DTL/CCL Transmitter Racks.

The SCL transmitters use 17 W solid-state dual amplifiers mounted in a single chassis to provide the RF input for two klystrons. The klystrons in the SCL range from 550 to 700 kW at 805 MHz and operate at cathode voltages ranging from 75 to 80 kV and cathode currents ranging from 9 to 11 A. There are eight HVCMs in the SCL driving a minimum of nine to a maximum of 11 klystrons each. Table 1 summarizes the transmitter types below.

It is important to the facility that these systems operate consistently and reliably. Recent RF system performance, major failures and the subsequent improvements made to the operation and maintenance techniques will be described in more detail below.

Table 1: SNS HPRF Transmitter Type Summary

Transmitter	Frequency	Pre-Amp Pwr	Klystron Pwr
RFQ	402.5 MHz	150 W	2.5 MW
DTL	402.5 MHz	150 W	2.5MW
CCL	805 MHz	100 W	5 MW
SCL	805 MHz	17 W	550 - 700 kW

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RF SYSTEM PERFORMANCE

Reliability is a key operational metric for the SNS RF transmitters. In recent operational periods, the availability of the RF system has exceeded 95 percent. Availability for fiscal years 2007 through the first quarter of 2017 is shown in Figure 2. From 2010 to the present, availability has exceeded 97 percent with an increasing trend starting in fiscal year 2013. The system availability for the first quarter of 2017 exceeded 99 percent [1].

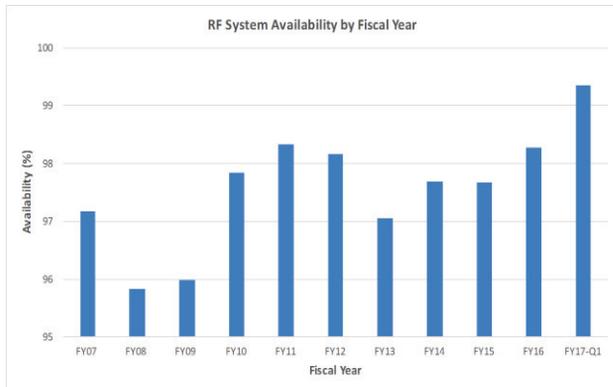


Figure 2: HPRF availability is trending upward since FY2013 [1].

EQUIPMENT FAILURES

From March 2013 to October 2014, six klystrons were replaced at SNS. The reasons included one cathode end-of-life indicated by decreased emission, two second cavity load failures and the disruption of three cathode filament circuits. These incidents pointed to the need for a focused effort on transmitter maintenance and operations that emphasized preventing sudden equipment loss. The outcome of this focused effort directly contributes to the high reliability necessary for the HPRF systems to support the high availability goals of the neutron source.



Figure 3: Failed Load.

Second Cavity RF Load Failures

The DTL klystrons are equipped with an external 50-ohm load for the purposes of coupling power out of the second cavity in order to stabilize the klystron output. The original loads were made of a ceramic resistor with copper plated contacts immersed in a deionized water loop for cooling. Operational experience found that, over

time, the water eroded the metallic contacts, eventually leading to an inoperable load as shown in Figure 3 [2].

Figure 4 shows the results of a second cavity load failure. It was determined that the loss of the load caused high reflected power on the second cavity RF connection. The forward power of the klystron became unstable, and subsequent investigation found this connector had disintegrated.

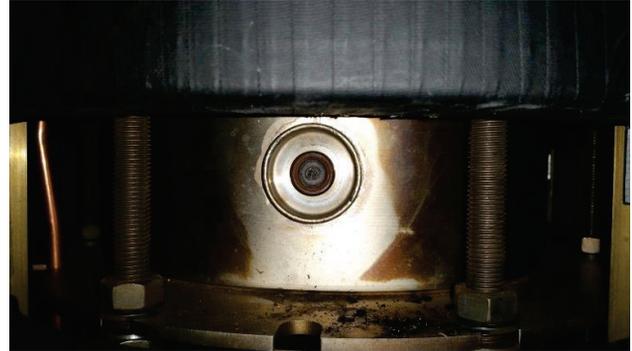


Figure 4: Failed second cavity connection attributed to failed 50-ohm load.

Klystron Failures

Four more klystrons were replaced for problems with the electron gun. One CCL klystron was replaced for reduced cathode emission. Two CCL klystrons and one SCL klystron were replaced for filament circuit failures.

The first CCL klystron to be replaced, Thales number TH2168007, was originally located in the CCL-4 RF transmitter position. It was removed due to reduced cathode emission. This klystron is still used on occasion for testing, but it is no longer considered viable for use on the machine.

The second and third CCL klystrons to be removed were Thales numbers TH2168001 and TH2168005. They were located in transmitters CCL-2 and CCL-3, respectively. Both were replaced due to filament failures.

The fourth failed klystron was CPI model VKP-8291A serial number 023. It was removed from the SCL-1C position. Like the CCL klystrons, it was replaced due to a filament failure. Serial 023 was returned to CPI for analysis which revealed a defect in the potting material that insulates the filament from the cathode. The defect led to localized heating that resulted in opening of the wire. The electron gun was replaced and the klystron is now in the spares inventory [3].

OPERATIONAL AND MAINTENANCE IMPROVEMENTS

As a result of the events described above, the practices in place for HPRF system maintenance and operation were revised. Focus was placed on failure prevention. Simple, but effective practices such as periodic testing and reducing the number of power cycles on equipment have been put into place with success.

Second Cavity Load Maintenance and Replacement

After the initial failure, a preventive maintenance program that included regular impedance checking helped to identify problematic loads in advance of their failure. Ultimately, the decision was made to replace the water-cooled load with air-cooled loads shown in Figure 5. Like the water-cooled loads, the preventive maintenance on the new air-cooled loads includes regular impedance measurements with a reflectometer operating at 402.5 MHz



Figure 5: Air-cooled load, installed in DTL-5.

Cathode Health Monitoring

Cathode health is monitored through the annual collection of cathode emission data. The filament supplies are current controlled. Therefore, the emission data plots are a function of filament current. Emission data is collected by monitoring the cathode current as the filament current is reduced in 0.3A steps. The result is the curve shown in Figure 6.

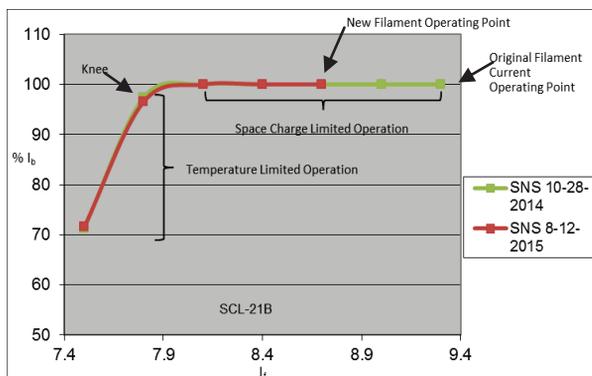


Figure 6: Typical emission graph. The Y-Axis is cathode emission percentage. The X-axis is filament current in amperes.

Emission data is used in two main ways. First, the data shows any decreases in cathode emission over time. Multiple curves superimposed on one another show encroachment of the “knee” towards the filament set point. This encroachment is a good indicator of cathode end of life.

Second, the filament current set point is compared to the setting at which the cathode current has decreased to 98 percent emission. The filament set points are adjusted to one ampere above this point. This ensures that the cathode is operating in the fully space charge limited region, but cathode depletion is minimized.

Filament Operational Management

In addition to monitoring the cathode emission and adjusting the filament set points, care has been taken to minimize the number of filament power cycles. During maintenance periods that require the transmitters to be turned off, work schedules are set such that the filaments are turned off once at the start of the period and turned on once at the end of the period. During neutron production, klystron filaments are always warm.

An added benefit of minimizing the cycling of the klystron filaments is the reduction of cycling on all transmitter equipment. Operational experience indicates that reduction in the number of power cycles helps promote overall system reliability.

Filament Standby Mode

There are times where the klystron cathodes will not be at high voltage but the filaments will be warm. Over long periods, the barium in the cathodes can evaporate onto the anode and adversely affect cathode function. One method for preventing the evaporation is to utilize a standby mode where the filament current is reduced to 50 percent [4]. This stops the cathode from emitting while keeping the filaments warm without a large thermal cycle.

SNS has implemented a filament standby when the cathodes will not be at high voltage for more than 24 hours. During this mode, called “Black Heat”, the transmitter control system first verifies that the cathode is not at high voltage and that the cathode current is less than two amperes. When recovering from black heat, the control system permits the cathode to receive high voltage only after the klystron filament has thermally stabilized.

SUMMARY

Reliability is the primary performance metric at SNS. The focus of the techniques currently used to operate and maintain the HPRF systems is to provide high reliability in support of the user program and maximize component lifetime. The development of future practices will continue this focus and help provide for long-term sustainable operation.

ACKNOWLEDGEMENTS

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