Reliability Optimization Techniques in High Power, High Duty Factor Klystrons

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Abstract: *The Spallation Neutron Source (SNS) Radiofrequency (RF) Systems have enjoyed high reliability (> 97.5 percent) over the past five years due in large part to the techniques used to optimize the operation of the klystron amplifiers. SNS klystrons operate at up to an 8 percent duty factor with a peak RF output power of up to 5 MW. Reliable operation starts with the process used to characterize each klystron and adjust its operational parameters in situ for the best performance. Techniques are described here with examples.*

Keywords: Klystron; high peak power; high duty factor; high average power.

Introduction

The SNS RF Systems operate three distinct types of klystrons in 92 high power transmitters along the Linac. Each klystron type is specific to the four Linac sections which include the Radiofrequency Quadrupole (RFQ), the Drift-Tube Linac (DTL), the Coupled-Cavity Linac (CCL), and the Superconducting Linac (SCL). There are seven 402.5 MHz, 2.5 MW peak RF power klystrons operating in the RFQ and DTL, four 805 MHz, 5 MW peak RF power klystrons operating in the CCL, and 81 805 MHz, 550 to 700 kW peak RF power klystrons operating in the SCL. The klystrons are pulsed at a 60Hz repetition rate with pulse widths up to 1.385 µS and cathode voltages ranging from 78 kV in the SCL up to 140 kV in the CCL.

Klystrons are a critical part of the SNS RF systems as they provide the amplification needed for the RF fields in the accelerating structures. They also present some of the highest operational risks. Klystrons contribute to the bulk of the RF downtime, are difficult to procure in budget-constrained environments, and can take months to fabricate. SNS has developed systematic practices to help mitigate these risks.

RF System Reliability

In order to increase RF system reliability, it is important to understand which components are causing downtime and in what manner. SNS operations methodically records and organizes accelerator downtime in several subcategories, one of which is RF systems. The past five years of RF downtime is summarized in Table 1.

Table 1. RF Downtime

FY	2015	2016	2017	2018	2019
Hrs	153	109	46	38	240

Klystron Downtime: All klystron-related downtime is recorded under RF and can be further distilled into two main sources, cathode overcurrent faults and general RF instabilities. The ability to mitigate these faults is key to obtaining SNS operational goals.

Initial Characterization

The first step in realizing reliable klystron operation is thorough characterization of the klystron, its solenoid, and its associated high voltage (HV) tank.

Klystron: Klystrons are systematically processed over increasing voltage and duty factor. Klystron gain and cathode emission is characterized carefully over several operating voltages. Collecting the data at various parameters while quantifying fault rates at those parameters, as shown in Figure 1, helps determine the best operating point.

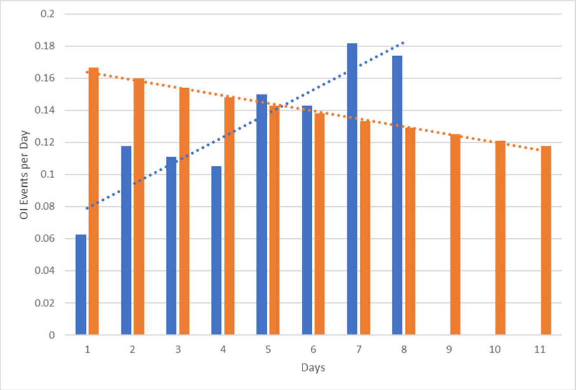

Figure 1. Example overcurrent fault rate analysis – rate was increasing (blue) until parameters were modified (orange)

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Solenoid: All klystron settings start at the factory acceptance test levels. Adjustments are made as needed to hone RF operation.

HV Tank: The most critical component of the tank is the cathode current monitoring circuit. SNS carefully characterizes each tank using a low voltage pulsed source and calibrated shunt. Sample results are shown in Figure 2.

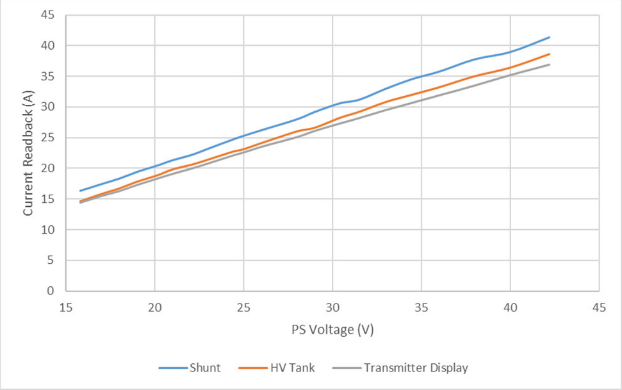

Figure 2: Cathode current as measured during calibration by the shunt (blue), the HV tank current test point (orange), and the user display (gray)

In Situ Optimization

Gaining a thorough understanding of each klystron, solenoid, and tank system through a systematic approach is key to operational success. However, it is often necessary to make in situ adjustments to alleviate operational problems.

Cathode Overcurrent Faults: Over a given operational period, overcurrent faults are the main source of klystron related downtime. Typical adjustments include cathode voltage, cathode pulse width, and filament temperature. Overcurrent rate is meticulously recorded for a given parameter set and is used as the key metric. A typical overcurrent event is shown in Figure 3.

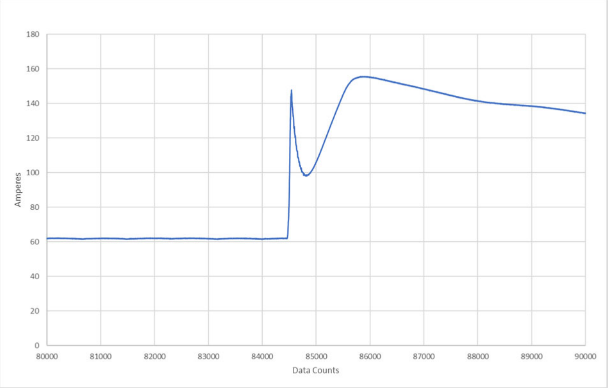

Figure 3: Overcurrent waveform – fault occurred at approximately 690μsec from the start of the HV pulse

RF Instabilities: In general, an RF instability refers to any fault that can be correlated to RF operation of the klystron. While the source is not always obvious, secondary electron discharge is suspected as the primary cause of most instabilities.

Vacuum Excursions: While cathode gas can be the source of a vacuum excursion, the high vacuum levels often present in the klystrons during RF recovery likely result from secondary electron emission. Solenoid adjustments help to dampen these vacuum bursts.

RF power output oscillations: When operating in closed-loop control, klystron output power oscillations typically manifest themselves as low cavity field trips. When operating in open-loop control, output power oscillations are clear. Solenoid adjustments, cathode voltage adjustments, and RF conditioning are all used to mitigate these oscillations. Again, RF induced electron discharge is believed to contribute to these oscillations.

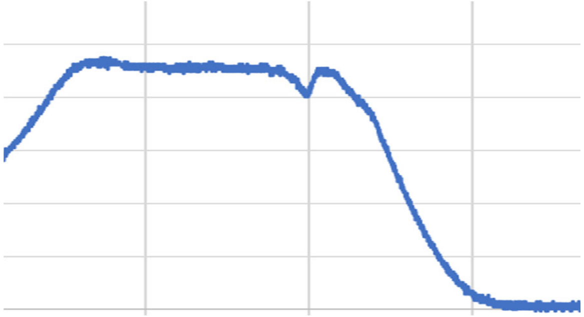

Figure 4. Closed loop klystron output power oscillation - sharp dip at the end of the pulse

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