SPALLATION NEUTRON SOURCE HIGH-POWER RF TRANSMITTER DESIGN FOR HIGH AVAILABILITY, EASE OF INSTALLATION AND COST CONTAINMENT *

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Abstract

The availability goals and installation schedule for the Spallation Neutron Source (SNS) have driven the availability and installation of the SNS linac's high-power RF systems. This paper discusses how the high-power RF systems' availability and installation goals have been addressed in the RF transmitter design and procurement. Design features that allow RF component failures to be quickly diagnosed and repaired are also presented. Special attention has been given to interlocks, PLC fault logging and real-time interfaces to the accelerator's Experimental Physics and Industrial Control System (EPICS) archive system. The availability and cost motivations for the use of different RF transmitter designs in the normal-conducting and super-conducting sections of the linac are reviewed. Factory acceptance tests used to insure fully functional equipment and thereby reduce the time spent on installation and commissioning of the RF transmitters are discussed. Transmitter installation experience and klystron conditioning experience is used to show how these design features have helped and continue to help the SNS linac to meet its availability and schedule goals.

1 OVERVIEW OF SNS TRANSMITTER SYSTEMS

The Spallation Neutron Source (SNS) is currently under construction at Oak Ridge National Laboratory (ORNL). The RF systems for the 1 GeV proton linac in the SNS are the responsibility of Los Alamos National Laboratory (LANL). Each RF system consists of a Converter /Modulator, a transmitter, one or more klystrons, RF loads, circulators and waveguide to deliver the RF power to the accelerating cavities. Details of the klystrons and Converter/Modulators can be found in other papers at this conference [1], [2].

1.1 Transmitters Types

The transmitters in these systems are divided primarily into two different types. The first type of transmitter accommodates a single 2.5 MW, 402.5 MHz klystron or a single 5 MW, 805 MHz klystron. Eleven of these transmitters are used in the normal conducting (NC) portions of the accelerator and two more in the High Energy Beam Transport (HEBT) systems, as shown in blue in Figure 1. This single-klystron transmitter will be referred to in this paper as an NC transmitter.

The second type of transmitter accommodates up to six 550 kW klystrons and is used exclusively in the superconducting (SC) sections of the linac. This transmitter type will be referred to in this paper as an SC transmitter. Fourteen of these transmitters are used in the current configuration of the SNS linac as shown in blue in Figure 1.

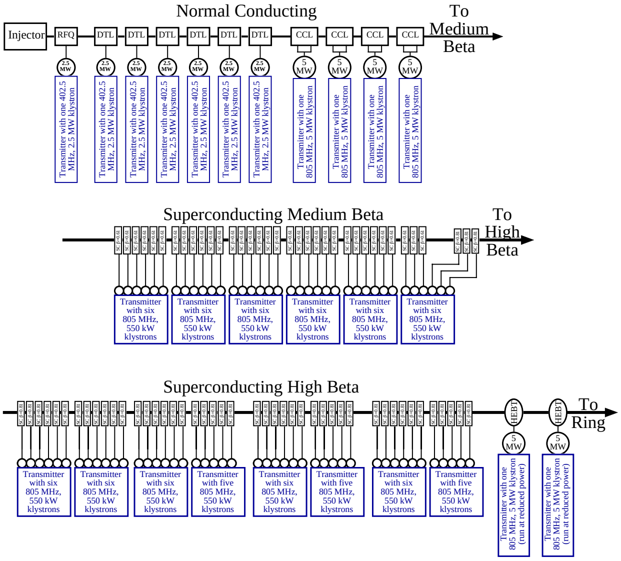

Figure 1: The SNS linac uses 13 single-klystron transmitters and 14 six-klystron transmitters.

1.2 Transmitters Functions

Both types of transmitters provide support and protection for the klystron or klystrons installed within them. This support includes all cooling flow metering and diagnostics for the klystrons, RF loads and circulators. It also provides focus electromagnet power, filament power and vac-ion pump power for the klystron. In addition, the transmitters include a solid state RF pre-amplifier for each klystron and interlocks on all required klystron parameters to shut down the modulator when the klystron is in danger of damage. In the SNS project, the power Converter/Modulator that provides cathode voltage and current to the klystrons is considered as a separate system and is discussed in another paper [2].

Each transmitter consists of three major sub-units: a control rack, a cooling metering cart and a high voltage enclosure. The sub-units for each type of transmitter are shown in Figures 2 and 3. The high voltage enclosures provide support for each klystron and contain the klystron's filament transformer and cathode current monitor. The cooling metering carts contain cooling diagnostics.

The NC transmitter cooling carts also include a blower to provide air cooling for the klystron windows. The control racks contain the interlock circuitry and solid state RF amplifiers to drive the klystrons. The 402.5 MHz version of the NC transmitters contains a 402.5 MHz solid state RF amplifier in the control rack and a separate cooling circuit in the cooling cart for 50% glycol/water cooling of the 402.5 MHz RF loads. The 805 MHz version of the NC transmitter contains an 805 MHz

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amplifier in the control rack and no separate glycol/water cooling circuit in the cooling cart. Aside from these characteristics the NC transmitters are functionally identical.

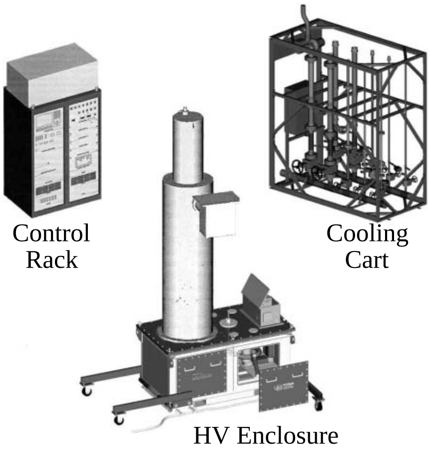

Figure 2: Each NC transmitter supports a single 2.5 MW or 5 MW klystron.

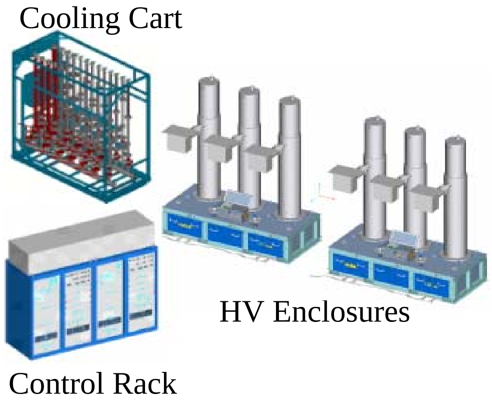

Figure 3: Each SC transmitter supports up to six 550 kW klystrons.

2 DESIGN FOR HIGH AVAILABILITY

2.1 SNS and Transmitter Availability Goals

The availability goals for the SNS transmitters were driven by the availability goal for the total SNS system. The availability goal for the entire SNS system is ≥90% by June 2008 [3]. To achieve this goal, the total availability for all systems within the linac must be greater than 98% [4].

In addition to the transmitters, the linac includes all accelerating cavities, circulators, klystrons and all Converter/Modulator power supplies [3]. For this reason, the transmitters were allocated only a small portion of the allowable down time for the linac. Therefore, the transmitter availability goal was chosen to be >99.5%.

Availability is defined here as the percentage of time that all transmitters are operational during the time that they are being required to be operational. Scheduled maintenance performed during time when the rest of the accelerator is shut down is not included.

A prediction of availability can be calculated using the Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) as follows:

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF+MTTR}} \quad .$$

An availability of 99.6% (>99.5%) implies that the ratio of MTBF to MTTR be 249:1. This value applies to the entire set of 27 transmitters, so the ratio for each transmitter is 27 times greater, or 6723:1.

2.2 MTTR Goal

MTTR includes both the time to diagnose the problem and the time to repair the problem. The LANL high power RF team's past experience with high power RF systems formed the basis of a goal of one hour to diagnose and repair a transmitter component failure. This goal was written into the transmitter specification and the vendor was required to provide calculations to justify their estimate of MTTR. Explicitly requiring a MTTR analysis helped the vendor to keep ease of repair in mind from the very beginning of the design process.

The time to diagnose a failure was minimized by a sophisticated first fault recording system within the transmitter control rack. A fault log with time stamps on each fault and notations on the first fault allow the user to determine the chronology of a multiple stage failure.

The time to repair a failure was minimized by using a very modular design in the transmitter sub-units. Chassis within the control rack included rails to allow for quick chassis change out. Connectors on the back of the chassis in the control rack were clearly labeled and keyed to reduce the chance of a cross connection during a chassis change out. Fully complete drawing packages and schematics were explicitly required in the transmitter statement of work to insure that the transmitter vendor would provide usable documentation.

2.3 MTBF Goal

Once the MTTR goal was established to be one hour, the MTBF goal was implied to be >6723 hours. An MTBF goal of 8000 hours was written into the transmitter specification to allow for a margin of error. The vendor was required to provide calculations to justify their estimate of MTBF.

MTBF calculations were based on published MTBF data for individual components. Preliminary MTBF calculations in the design reviews lead to many design changes that would not have been found otherwise. Design modifications included adding redundancy on components with lower reliability such as cooling fans and power supplies, and additional cooling where it would significantly improve the MTBF. The MTBF calculations took into account the unique characteristics of the klystron gallery at the SNS facility, and the transmitters were designed to maintain their reliability in an ambient temperature of 30 degrees C.

3 DESIGN FOR EASE OF INSTALLATION AND COMMISSIONING

The installation schedule for the SNS linac is aggressive. Conditioning and commissioning of the RF systems near the front of the linac is performed at the same time RF system installation is being done further down the linac gallery. The transmitters were designed to minimize the amount of labor required to install and commission them.

The high voltage enclosures were provided with air pads to allow them to be moved by hand, even with klystrons attached and while filled with oil. The transmitter sub-units (control rack, water cart and HV enclosure) were delivered fully assembled to reduce the amount of installation labor. Finally, all cables and water hoses were delivered with lengths pre-cut to match the most up-to-date layouts of the klystron gallery and cable trays.

Requirements for complete operating and installation manuals were written into the transmitter contracts from the start of the project. This has produced well done, quality manuals and instructions that have significantly aided in the installation process.

The transmitter contract included an option to require the vendor come on site to assist in the installation process. This proved effective in the first transmitter installation at LANL. Installing the first transmitter as a test stand at LANL helped us work out any problems in the installation process and helped make the first installations at SNS to go more smoothly.

Extensive factory acceptance testing was performed to reduce the frequency of "infant mortality" failures during commissioning. This testing included a 96 hour full power heat run of all solid state RF amplifiers and a 24 hour heat run of the complete integrated transmitter system while operating every sub-system at full rated power.

4 DESIGN FOR COST CONTAINMENT

Warranty requirements for the transmitters were explicitly defined in the statement of work in order to reduce the cost of any transmitter repair in the early stages of SNS operation.

Costs were also reduced as the project developed. The NC transmitters were specified to have a full complement of protective interlocks for the klystrons, RF loads and circulators. When the choice was made to go with a superconducting linac with one klystron per cavity, the number of klystrons in the superconducting section dramatically increased. Eighty one 550 kW, 805 MHz klystrons are now required in the superconducting portion of the linac. Because of the large number of relatively small klystrons, it was decided that fourteen separate transmitters would each support 5 or 6 klystrons, as shown in Figure 1. The single klystron per SC cavity design offered a significant performance advantage, and this performance advantage was traded off against the increased transmitter cost caused by the additional klystrons.

SC transmitter cost was then traded off against functionality. The elimination of transmitter diagnostics such as cooling temperature measurement will make the diagnosis of faults in the RF systems more difficult to determine, increasing MTTR for the RF systems. A comparison of features in the NC an SC transmitters is shown in Table 1.

SC transmitter costs were also reduced by slowing down the specified response time for the transmitter interlocks. Slower interlock systems were less expensive to implement. The tradeoff is that a slower interlock can allow a fault condition to occur for a longer period of time and cause more damage to the component protected by the interlock. Increased damage leads to a decreased MTBF and an increased MTTR. Table 2 compares the specified interlock response times for the NC and SC transmitters.

Table 1: Comparison of Transmitter Features

Feature	NC Transmitter	SC Transmitter
PLC Fault Logging	Y	Y
Cooling Flow Interlocks	Y	Y
Cooling Temp. Interlocks	Y	N
Calorimetric Pwr Interlocks	Y	N
Calorimetric Pwr Recording	Y	N

Table 2: Comparison of Transmitter Response Time Requirements

Fault	NC Transmitter	SC Transmitter
Cathode overcurrent	<1μs	<100 ms
Vac-ion overcurrent	<50 ms	<100 ms
Klystron Magnet Current	<1μs	<100 ms
Klystron Magnet Voltage	<1μs	<100 ms
Klystron Body Temp.	<50 ms	N/A
Klystron Body Flow	<50 ms	<100 ms
Klystron Body Power	<50 ms	N/A
Klystron Collector Temp.	<50 ms	N/A
Klystron Collector Flow	<50 ms	<100 ms
Klystron Collector Power	<50 ms	N/A
RF Interlock fault	<50 ms	<100 ms

5 CONCLUSIONS

The development of the RF transmitter systems for the SNS project has been a challenging endeavor. The balance between reliability, ease of installation and cost shifted over the course of the project. These changes can be seen in the differences in design between the NC and SC transmitters. The performance advantages of the one-klystron-per-superconducting-cavity design and the drive to minimize costs were deemed to outweigh the corresponding decrease in reliability and availability of the transmitters in the superconducting section of the linac.

REFERENCES

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[3] N. Holtkamp, "SNS Project Update", 11th ICFA International Mini-Workshop on Diagnostics for High-Intensity Hadron Machines, October, 2002.

[4] B. Miller, "System Requirements Document for WBS 1.4 Linac Systems", SNS Internal Design Document.