5 MW 805 MHz SNS RF SYSTEM EXPERIENCE

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Abstract

The RF system for the 805 MHz normal conducting linac of the Spallation Neutron Source (SNS) accelerator was designed, procured and tested at Los Alamos National Laboratory (LANL), and then installed and commissioned at Oak Ridge National Laboratory (ORNL). The RF power for the room temperature coupled cavity linac (CCL) of the SNS accelerator is generated by four, pulsed 5 MW peak-power klystrons operating with a pulse width of 1.25 ms and a 60 Hz repetition frequency. The RF power from each klystron is divided and delivered to the CCL through two separate RF windows. The 5 MW RF system advanced the state of the art for simultaneous peak and average power. This paper summarizes the problems encountered, lessons learned, and results of the high power testing at LANL of the 5 MW klystrons, 5 MW circulators, 5 MW loads, and 2.5 MW windows.

HIGH POWER TEST RESULTS

5 MW Circulators

Twelve circulators were ordered from AFT and five were high power tested. The 805 MHz circulator is a three port "Y" junction circulator rated for 5.0 MW forward peak power into a short at any phase. The insertion loss is specified to be less than 0.07 dB, the isolation greater than or equal to 20 dB, and the return loss less than –20 dB at the center frequency of the circulator. The circulator is pressurized with sulfur hexaflouride (SF_6) to 15 Pisa to prevent RF breakdown. The SF_6 system is confined by three Kapton windows, one on each port. The system was vacuum leak checked at a pressure less than 100 mTorr to a leak rate of less than 30 mTorr per hour. A digital Temperature Compensating Unit (TCU), also supplied by AFT, controls the circulator. The circulator is equipped with an arc detector port, and an additional arc detector port was used on the adjoining waveguide to protect the Kapton window on the output RF power port (Port 2).

The problems encountered with the circulators can be grouped into three areas: Kapton window problems, arcing problems and high return loss problems. The proper torque on the bolts on the Kapton flange is essential to the ability of the Kapton window to withstand the pressure difference created during the vacuum tests. While undergoing the vacuum tests before the circulator is filled with SF_6, the Kapton windows depend on the structural rigidity of the connecting waveguide flanges. Several windows were damaged because either the torque on the Kapton window bolts was not adequate or because the connecting waveguide was not installed when the vacuum test was performed. In addition, damaged threads on the bolt holes in the aluminum flange led to inadequate torque being applied to the bolts, which caused failure of the Kapton sheet.

Arcing on the Kapton window at power levels above 4 MW peak was a problem. After initial high power testing, a design change was made to the Kapton window to improve the RF contact between the two flanges enclosing the Kapton foil. The arcing at the Kapton window was eliminated after the design change was implemented and a careful assembly procedure was developed. During the high power testing of the circulators, the cleaning procedure of the ferrites was found to be very important to prevent arcing. In some circulators, *in situ* adjustment of the TCU settings was necessary for the circulator to meet the return loss specifications.

The circulator tests were done in two parts. The first part was a test into a matched load to 5 MW peak power at 60 Hz and 1.25 ms pulse width. The second was a test into a short at 5 MW peak power and the same pulse width and repetition frequency. Ideally, a sliding short would be used to continuously vary the phase over 180 degrees while transmitting 5 MW through the circulator. However, during the first high power circulator test the sliding short failed. Therefore, the circulator was tested at three discrete phases: the phase where the highest power is dissipated in the circulator, the phase where the return loss is the maximum, and an arbitrary phase between the two other phases. A detailed test procedure was developed which started with a short pulse width and low power level and adjusted the bias on the TCU to decrease the return loss. The power level was increased in steps to 5 MW peak power at a low duty factor. Then the duty factor was gradually increased. While at each step, the return loss was checked at all phases and adjustments were made if necessary. Nevertheless, if the return loss was over-optimized at one phase, it would be out of the specification at another phase. Therefore the circulator required a careful tuning. A four hour heat run was done at the phase with the highest return loss.

5 MW Klystrons

Nine 5 MW klystrons were ordered from Thales and five were high power tested at LANL for installation on the CCL [1]. The installation and commissioning is summarized by McCarthy, *et al* [2]. The klystron specifications are summarized in Table 1. Thales could not test to the full pulse width; therefore, the klystrons were tested to 5.0 MW peak power at 60 Hz and a 1.25 ms pulse width at LANL. They were operated at a nominal beam voltage of 135 kV and a beam current of 72 Amps. No discontinuities greater than 0.5 degrees were permitted in the phase transfer curves as the drive power was varied from 20% to 100% of the saturated drive power. The linearity of the power transfer curve over a range of 20%

Table 1: 5 MW, 805 MHz Klystron Specifications.

Operating Frequency	805 MHz
Peak Output Power	5 MW
RF Duty Factor	9%
Pulse Repetition Rate	60 Hz
DC to RF efficiency	55%
Beam Voltage	140 kV, Maximum
Beam Current	88 A, Maximum
RF Power Gain	50 dB, Minimum
Bandwidth at saturation	± 1.3 MHz, 1 dB minimum
Bandwidth at 80% sat.	± 1.0 MH, I dB minimum

to 80% of the nominal output power was verified. A 96 hour heat run was done at full power. The klystrons were conditioned to the full power and duty factor at LANL by following the conditioning procedure provided by Thales. The vacuum in the tube led to a conditioning time of 3 to 5 days if no major problems were encountered. Cathode current trips and klystron arcs occurred as part of the healthy conditioning processes. In general, above 4 MW the arcing in the output waveguide was the major challenge.

Most of the problems encountered during the klystron testing were related to the lead shielding, arcing in the output waveguide, and meeting the minimum 55% efficiency. Additional X ray shielding was added at the gun and the output waveguide miter bend to bring the klystron within the specification of 3 mR/hr at a distance of 1 foot from the klystron. The plumbing circuits had to be modified to accommodate the lead shielding. This problem arose because the plumbing and final version of lead shielding were never assembled together at the factory. The output waveguide was filled with SF_6 to 15 Pisa to prevent arcing in the waveguide. The SF_6 region, bounded between the alumina RF klystron window and a Kapton gas barrier window, includes a miter bend and a WR 975 to WR 1150 transition. The SF_6 system was fitted with a pressure relief valve set to 15 Pisa, a fill port, a pressure gauge and an arc detector to protect the Kapton window. To ensure no SF_6 leaked out, the system was vacuum leak checked to a leak rate of less than 30 mTorr per hour at a pressure less than or equal to 100 mTorr. Before the system was filled with SF_6, it was evacuated to a pressure of 50 mTorr and then backfilled with SF_6. Gas leaks were found on every waveguide joint in this system, so the design of the output waveguide flange on the klystron was modified. The Kapton window was purchased from AFT and was based on the Kapton window for the 5 MW circulators. After initial high power testing, AFT redesigned the window to improve the RF contact around the Kapton foil. An aluminum waveguide section was replaced with a copper plated stainless steel section to improve the electrical contact and eliminate vacuum leaks. Eventually, the O-ring seals between the waveguide transition and taper were replaced with Parker seals. Of the five klystrons tested, none could make the 55% efficiency. Negotiations between LANL and Thales led to accepting the two klystrons with the lower efficiency in exchange for two klystron rebuilds.

2.5 MW Windows

A total of twelve windows were ordered from Thales for the CCL , eight were high power tested and installed on the linac, leaving four untested spares. The 805 MHz, 2.5 MW window consists of full-height WR 975 waveguide on both the air and the vacuum side of a high purity alumina ceramic disk. The airside of the window waveguide is aluminum and the vacuum side is copper plated stainless steel. The windows are water cooled around the circumference of the ceramic. Before testing, the windows were baked to between 150 and 200 degrees Celsius and kept at this temperature until the vacuum was below 5E-7 Torr. The average bake out time for the eight windows tested was 13 hours.

The windows were first conditioned to high average power into a matched load and then conditioned to high peak power into a short. The high average power conditioning was done to achieve 2.5 MW at a 1.25 ms pulse width and 60 Hz rep rate. The windows were conditioned up to 2.5 MW in the following manner. The RF power was interlocked to turn off when the vacuum increased above 1.0E-7 Torr. The conditioning began with a small pulse width (600 μs). If the vacuum was consistently above 1.0E-7 Torr during conditioning, then the pulse width was decreased to 400 μs. After the windows were conditioned up to 2.5 MW at 600 μs, the pulse width was increased to 1.25 ms, and the windows were re-conditioned up to 2.5 MW. The average conditioning time up to 2.5 MW at the full duty factor for the eight windows was 14 hours, as shown in Figure 1. Next, a 4-hour heat run was done at 2.5 MW with full average power (60 Hz and 1.25 ms) to ensure no problems at the high average power.

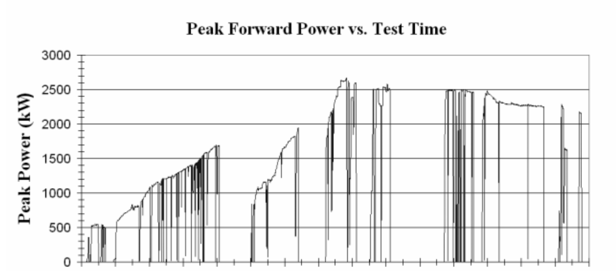

Figure 1: RF Power Test Time for the Windows

The windows were then tested for high peak power to test the durability of the windows during the fill transient when high reflected power can produce a standing wave in the window. In this test the pulse width was decreased to 100 μs and a waveguide short was placed after the

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window to reflect power back through the window. The test was done three times at 2.5 MW forward power, with the short in three different positions. First, the short was positioned to place the highest electric field in the ceramic. Second, the short was positioned to place the highest currents are located in the ceramic, and the third position was an intermediate phase.

Only a few problems were encountered during the window testing. On Serial Number 4, a water leak was found on the braze joint between the stainless steel flange and the copper housing around the ceramic. This window was sent back to Thales and was repaired. The second problem was an RF leak on Serial Number 9 near the water inlet and outlet. At 600 kW peak forward power, 0.97mW/cm^2 was measured on contact. After contacting Thales, the bolts around the ceramic were retorqued. After tightening the bolts, no RF leakage was measured, when operating at 1 MW peak forward power into a short.

5 MW Loads

Twelve 805 MHz, 5 MW loads were ordered from SureBeam and five were conditioned and high power tested. The 805 MHz, 5 MW load consists of a cylindrical cavity with circulating de-ionized water. A ceramic window is used as the barrier between the water filled cavity and the airside waveguide. The RF seal and water seal are made using o-rings. The waveguide flange is a WR 1150 flange. The load is equipped with an arc detector port. The loads were tested to 5 MW peak power at 60 Hz and 1.25 ms pulse width. The nominal flow rate was 94 to 98 gpm of de-ionized water. The VSWR of the load was specified to be 1.07:1 or better over a ± 1 MHz bandwidth. After each load was conditioned to the full power and duty factor, a four hour heat run at 5 MW, 1.25 mSec and 60 HZ was preformed.

The problems encountered with the loads during high power testing occurred at the airside surface of the ceramic window near the O-ring. In the first design, the RF losses were too high in the O-ring which caused heating and arcing. This problem was solved when the material of the O-ring was changed to a low loss RF material. In another case, arcing occurred due to a poor RF contact between the flanges because the flanges did not meet the flatness specification. After the flanges were faced off, this load successfully passed the high power test.

LESSONS LEARNED

A problem encountered during the high power testing of the circulators was a high VSWR in the waveguide between the klystron and the circulator because of reflections from bellows used in the waveguide between the klystron and circulator. The bellows had been deformed more than its design allowed. This was a difficult problem to diagnose because it was thought the circulator was not compensating properly. In addition, arcing in the waveguide was diminished and reliability increased by using WR1150 instead of WR975. The number of miter bends was minimized and the spacing between them maximized to prevent arcing. Sweeps were found to be less arc prone than miters.

The window testing and conditioning went very smoothly and this is attributed to the high temperature vacuum bakeout previously shown to be important. The initial Thales lead shielding assembly procedure for the klsytron was very difficult to follow, and it took up to four days to assemble the lead shielding. After modifications and feedback to Thales, the procedure was improved, and the assembly time was reduced to a half of a day. A high accuracy test stand was found to be important because of the low test stand accuracy at the klystron vendors. At LANL, after summing the calibration errors, the accuracy of the klystron current and voltage measurements was found to be within 2 percent. The electrical power measurements also agreed with the calorimetric measurements of the power dissipated in the RF load and the collector.

CONCLUSIONS

The 5 MW, 805 MHz RF system for SNS was successfully designed, procured, high power tested and installed on SNS. The high power testing done at LANL was very important to the SNS program because it solved many problems that would have arisen during the installation and commissioning. For the klystrons and windows, conditioning on the LANL test stand saved many hours of commissioning time at SNS. It was proven that the 5 MW klystrons are interchangeable in the 5 MW focusing magnets. The problem of low klystron efficiency and unacceptable arc rates in the output waveguide of the klystron were found early on, and the SF_6 system was implemented. Thales does not have the capability to test to full pulse width, thus high power testing at LANL was very important. A cleaning procedure was developed for cleaning the ferrites in the circulators to reduce the arcing. Filling the circulators with SF_6 finally solved the arcing problem; however, several design iterations were required on the Kapton SF_6 barrier window to eliminate arcing. The final design was proven by the high power testing at LANL. On the windows, arcing at a joint was found to be caused by an inadequate assembly procedure. The procedure was revised and the problem eliminated. The importance of the high temperature bake out was re-verified. O-ring failures on the loads that caused arcing were discovered during the high power testing. The O-ring design was changed and successfully proven out in the high power testing. These components are now installed and operational the SNS CCL at ORNL.

REFERENCES

[1] D. Rees, "The SNS Linac High Power RF System Design, Status, and Results," PAC'03, Portland, OR, 2003.

[2] M. McCarthy *et al*, "Spallation Neutron Source Installation and Commissioning Progress," PAC'05, Knoxville, TN, 2005.