SPALLATION NEUTRON SOURCE SUPERCONDUCTING LINAC KLYSTRON TO CAVITY MISMATCH EFFECTS AND COMPENSATION*

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Abstract

Observations of several of the 81 klystron output waveforms into their respective superconducting cavities do not correspond with their rectangular klystron inputs in open loop mode. This can't be completely explained by a drooping high voltage power supply especially when the waveform is parabolic. Some possible causes and effects of these anomalies are presented.

DISTORTED WAVEFORMS

While optimizing the superconducting linac (SCL) cavity fields of the SNS linac [1] we noted that some of the 81 cavity input power waveforms were not linearly tracking the shape of the input signal (Figure 1). This caused concern that this would be an additional error source that the low level RF (LLRF) control system must compensate.

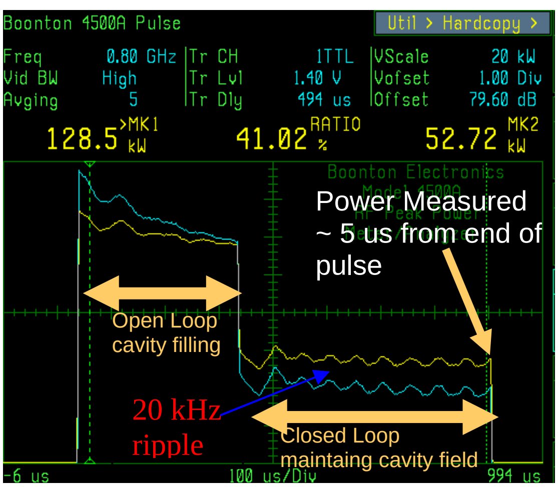

Figure 1: SCL Klystron RF Out and Cavity RF In.

Other sources of error include the phase and amplitude changes that occur during the 1ms RF pulse caused by drooping klystron cathode voltage and the resulting increased delay of the electron beam through the klystron. Also contributing are 20 kHz ripple, cavity resonance drift, beam loading and cable tolerances. Typical cathode voltage droop is ~3%. Klystron power follows cathode voltage to the 5/2 power so we expect an 8% power droop without LLRF feedback (open loop). However, some droops were as high as 32% (Figure 2).

Possible causes of the distortion were:

1) Non-linear measurement device or mis-calibration.
2) Solid State Amplifier (SSA) distortion.

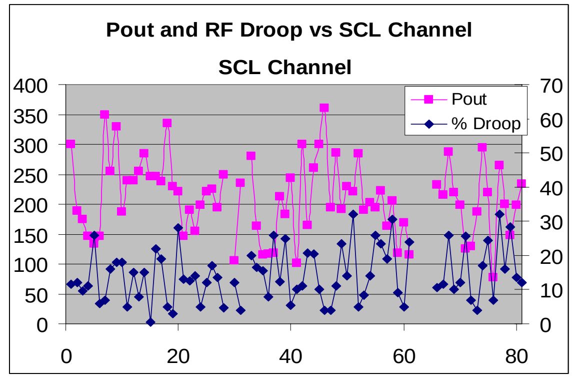

Figure 2: Klystron power and droop by SCL cavity.

3) Impedance mismatch between klystron and circulator caused by:
   a) Bad water-load match.
   b) Harmonics from klystron.
   c) Misadjusted TCU (circulator Temperature Compensating Unit)
   d) Waveguide discontinuity (bent).
   e) Bad circulator matching during full reflected power from cavity.
   f) Heating of the circulator ferrites changing their H-field during the pulse.

These possible causes were investigated; the measuring instrumentation was in calibration and two of the directional couplers were checked on the bench, the SSA met its <1% droop specification, and the waster load had a good 1.05 VSWR. A calculation of the estimated heat deposited in the circulator ferrites over the time of an RF pulse indicated insignificant temperature change. A mismatch between the circulator and the klystron appeared to be the primary candidate for the distortion.

Each TCU is factory matched to a circulator with specific internal look-up tables that compensate for changes in ferrite characteristics as a function of temperature. Over the past five years of SNS commissioning and operation, seven TCUs and two circulators have failed. Because the circulator weighs 250 lbs and hangs 13 feet above the floor, it was not changed when its matching TCU failed. The replacement TCU was tuned in-situ with a factory (AFT: Advanced Ferrite Technologies) proprietary program using a laptop. Because we couldn't vary water temperature while monitoring reflected power, the circulator was optimized for minimum reflected power to the klystron at the nominal temperature and cavity operating field.

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These Y-junction circulators function by cancellation of waves propagating from the input port over two different paths about the ferrite disks in the center magnetic field [2]. A standing wave is formed and then rotated about the circulator Y-axis by the magnetic field. There is a standing wave node at the mouth of one waveguide output port and an anti-node at the other output port, providing isolation and throughput at the respective ports. The circulator ferrites are externally biased with both electro- and permanent magnets.

The permanent magnets in the circulators may be degrading over time. Physical changes like developing cracks or loosened adhesion to the circulator could make the whole device behave differently [3]. Without a baseline measurement of their magnetic fields it is difficult to determine if changes have occurred. In addition, internal inspections of the circulators are very labor intensive and impractical.

If the ferrite is heated over the Curie temperature (over 120~200-deg-C depending on the composition) characteristics might change. That is a possibility if water cooling to the circulator were lost, but the TCU would alarm and the transmitter cooling cart would indicate a low flow, which hasn't happened.

ERRONEOUS READINGS

Our standard waveguide directional coupler couples -63 dB of the forward and reflected power to the LLRF detectors (Figure 3a) with a nominal directivity of 26 dB.

Figure 3 a, b: Waveguide Directional Coupler and 60 dB directivity modified unit.

An average circulator might only reflect 0.5 kW of 200 kW forward power. Thus the signal at the reflected directional coupler is comprised of the forward power (down 63 + 26 dB) and the reflected power (down 63 dB). These two signals are of the same order in amplitude. The signals combine with phases which depend on the physical location of the coupler with respect to the circulator and its distance from the klystron. All 81 systems are physically different. If two signals were in phase it appeared as high reflected power and if they were out of phase it appeared as a perfect well-matched circulator. So our reflected power measurements used to adjust the TCU were based on inaccurate coupler values.

To accurately measure the reflected power with near 1% accuracy a directional coupler (DC) with 47 dB directivity or better was needed. The waveguide coupler has two N-type connectors; one is the output, the other a standard 50 ohm load. The accuracy and part-to-part variation of this standard load is what limits the directivity. This load was replaced with a circuit containing a variable attenuator and variable phase shifter (Figure 3b). These were adjusted to optimize the directivity at 805.0 MHz using a network analyzer. 60-dB directivity (Figure 4) was achieved using this technique and two units were constructed to test on an SCL RF system. With these units we observed that when the reflected power was truly minimized, the klystron output was still distorted.

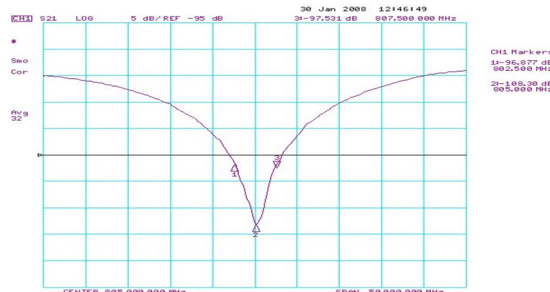

Figure 4: Directivity optimized.

Measurements were made to observe the effect of pulse width and rf power on the distortion with no attributable link. Spectrum analysis showed no significant power outside the band regardless of distortion. However circulator bias coil adjustments did affect circulator port to port isolation, as expected.

KLYSTRON SENSITIVITY TO LOAD

By observing the klystron output power and the cavity input power waveforms simultaneously on either side of the circulator, with a Boonton 4500 power meter, the differences were quite clear. The TCU circulator bias current was adjusted so the waveforms were nearly identical in shape with allowances for differences in coupler calibrations that affect amplitude. This appeared to reduce the slope of the power curve to what was expected but not minimize it. The power reflected from the circulator back to the klystron was five times higher than minimum.

When reviewing the klystron data sheets, the factory (CPI, Palo Alto, CA) measurements indicated that the klystron output varied markedly when driving into a load with a 1.20 VSWR and variable phase. Some of the outputs were considerably higher than the nominal rated output. This would explain why the minimized reflected power point wasn't optimum. A paper from LANL [4] corroborated this observation as well as an AFT technical note [5].

OPERATIONAL ADJUSTMENTS

The physical arrangement of instruments used to make these measurements required turning off the klystron while connections were made. This made the adjustment of the TCU during operations impractical. The adjustment during a maintenance period was also impractical because the RF systems must be off while the linac tunnel is accessible. Fortunately a subset of the measurement appeared to give enough information to make the adjustment during short non-beam periods. Both the SCL klystron output power and cavity input power are recorded by the LLRF High Power Protect Module (HPM) [6]. This is accessible from the control room. The TCUs can be adjusted in-situ with a laptop and auxiliary connection. The problem with using the HPM readouts is the arbitrary scales on each waveform. The actual values can't be read directly. This wasn't a large impediment when it was shown empirically that if the two forward power measurements on the input and output of the circulator had the same slope, the klystron/circulator/cavity match would be satisfactory.

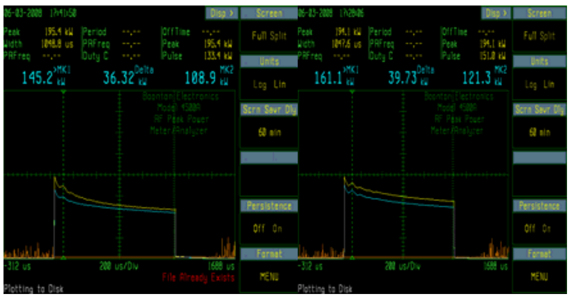

Figure 5: Before (left) and after bias current adjustment with pulse power meter.

AUTOMATIC SLOPE GENERATION

A Perl script was written to automatically compute the slope and ratio of the klystron forward power and cavity input power waveforms. This information was used to adjust the bias current for the TCU for the optimal match among the klystron, circulator, and cavity during one of the RF development time slots with good results. The script allows the operator to select the klystron/cavity pair to be tested and three sample points to measure across the RF pulse (beginning, middle, and end). The RF measurement itself is accomplished in the LLRF system by reading the pulsed power with the HPM.

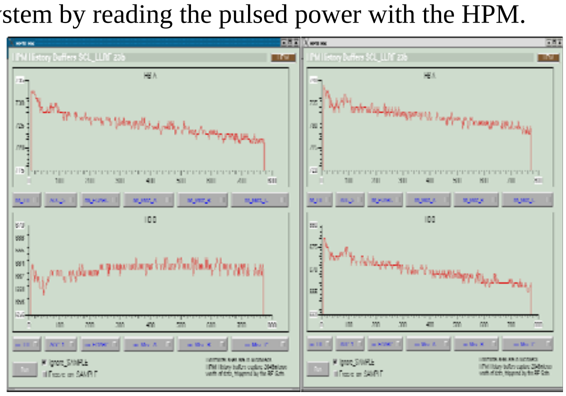

Figure 6: Before and after bias adjustment with HPM.

The slope is calculated utilizing selected beginning and end points and the ratios of all three points are used to determine if the waveform has an unusual shape. In addition to the results from the script, the HPM provides history buffers (figure 6) that allow the operator to visually look at the waveforms of the klystron and cavity to determine if the slopes are grossly different. Typical bad slope values were 6-8% apart, with good values being $\leq$ 2% apart. When a system was found with bad slope values, the TCU current was adjusted locally with a laptop operating the proprietary tuning software until the system was within tolerance. During a recent shift, eight TCUs were successfully adjusted with this technique.

FUTURE UPGRADES

Presently there is no communication with the TCU. A status transfer to the transmitter that includes fault alarms will be implemented. While it is desirable to be able to monitor and adjust the circulator routinely and automatically, this would require a development effort to interface with the TCU and perhaps monitor the actual internal magnetic field rather than inferred ferrite temperatures. A simple feedback circuit could then adjust the bias to maintain that constant magnetic field.

CONCLUSION

The waveguide circulators must be matched to their klystrons for undistorted power transmission. The lowest reflected power between circulator and klystron doesn't provide the best match for the klystron output cavity. Adjusting circulator coil bias until the power waveform slopes into and out of the circulator are equal yields a sufficient match.

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