RESONANCE CONTROL COOLING SYSTEM PERFORMANCE AND DEVELOPMENTS

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Abstract

The Spallation Neutron Source (SNS) is an accelerator-based neutron source being built at Oak Ridge National Laboratory. The warm linac portion, designed by Los Alamos, has been installed and commissioned. The warm linac is comprised of six Drift Tube Linac (DTL) tanks and four Coupled Cavity Linac (CCL) modules. For commissioning purposes the accelerating systems have been operated at less than the design 6% duty factor. During lower power operation there is less RF cavity heating. This decrease in heat load causes operational stability issues for the associated Resonance Control Cooling Systems (RCCSs) which were designed for full duty factor operation. To understand this effect operational results have been analyzed and tests have been performed. External system factors have been explored and the resulting impacts defined. Dynamic modeling of the systems has been done via a collaboration with the Institute for Nuclear Research (INR), Moscow, Russia. New RCCS operation code has been implemented. Increases in system performance achieved and solutions employed will be presented.

DISCUSSION

The DTL and CCL cavities of the SNS linear accelerator (linac) are resonance cavities which have been manufactured to accept 402.5 MHz and 805 MHz RF power respectively. The final matching of the RF frequency to the cavity is done via thermal expansion or contraction of the cavity by a balance of RF heating and water cooling. The DTL structures change their resonant frequency by ~7 kHz per degree C while the CCL cavities are more sensitive at ~14 kHz per degree C. Therefore, providing very stable temperature control to the cavities not only minimizes reflected power due to being off resonance but also takes the burden away from the Low Level RF (LLRF) control system in providing a constant field within the cavity. Table 1 shows the peak power required to achieve the proper cavity field, average power deposited into the cavity at a 7% RF duty factor, and the actual/tested, resonance temperature during conditioning but without beam.

The cooling systems designed and provided by Los Alamos and built by AVANTech were constructed for full duty factor operation and by our operational experience, appear to have a great deal of overhead in cooling capacity. The SNS Project, however, is taking a conservative approach to commissioning and over the first few years of operation will only run in a "beam on demand" mode and will often not need to run the warm cavities at full duty factor RF. The primary reasons are to save stress on the high power klystrons and modulators, minimize x-ray production in the Linac tunnel, and save electricity.

Table 1: Cavity Power and Temperature

Tank	Peak Power (kW)	Average Power* (kW)	Resonance Temperature (C)
1	460	32	25
2	1,365	96	22
3	1,330	93	28
4	1,625	114	19
5	1,284	90	23
6	1,254	88	22
CCLs	2,700	189	20

While stable operation of the cooling systems has been possible, it has not been an easy task to "rein back" their capacity and provide highly stable reduced power operation. To help understand the operation of the RCCS systems a control diagram of the cooling skid is shown in Fig. 1. A variable percentage of the water returning from the cavity (left side of the figure) is bypassed through the heat exchanger by the 3-way, CV-1, valve and then re-introduced into the main stream just ahead of the pump. The heat exchanged in that loop should just equal the amount of RF power which needs to be dissipated plus the pump motor heat load. The flows through the individual cooling loops of the accelerating cavity are shown on another control screen.

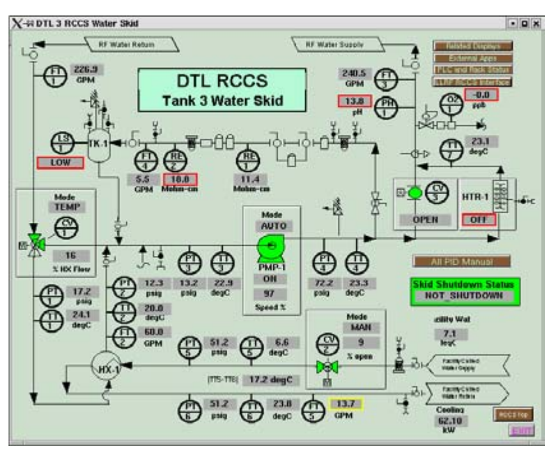

Figure 1: RCCS Control Diagram.

* SNS is managed by UT-Battelle, LLC, under contract DEAC0500OR22725 for the U.S. Department of Energy. SNS is a collaboration of six US National Laboratories: Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Thomas Jefferson National Accelerator Facility (TJNAF), Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratory (ORNL).

The RCCS systems were originally designed to operate within +/- 0.28 degrees C of set point at full power [2]. Under stable conditions this would equate to approximately +/- 2 kHz resonance error in the DTL cavities. To maintain a locked mode for the LLRF operation the resonance error must not exceed +/- 5 kHz.

OPERATIONAL EXPERIENCE

Figs. 2 and 3 help to provide an understanding of the actual DTL cavity and RCCS interaction. Fig. 2 shows how the fluctuations in temperature, reflected power, and resonance error interact with one another. This chart was taken in “Auto” mode meaning that the RCCS would respond to changes in the resonance error and attempt to adjust cavity temperature accordingly. As can be seen, it leads to an oscillation of just under +/- 1.8 kHz in the resonance error with an 80kW variation in peak reflected power. This is not an ideal operating scenario since a constant temperature is not maintained which would help to damp the oscillation. Note that the period of oscillation in this plot is under 1 minute, quite fast, and what is not shown is that after 15 to 20 minutes the resonance error runs away.

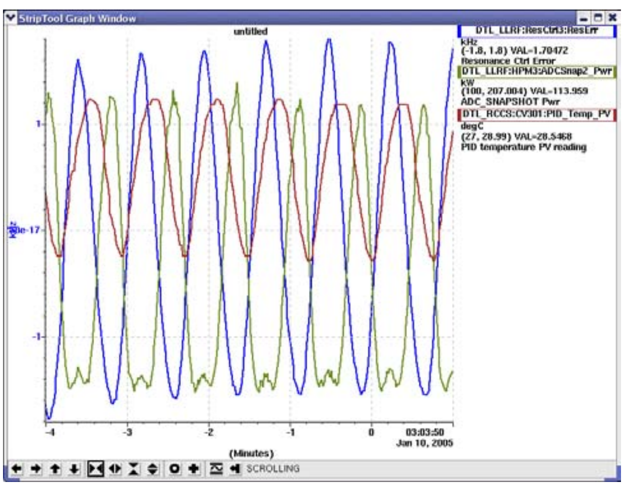

Figure 2: DTL3 operation at 3% duty factor.

Fig. 3 shows a more typical scenario for our lower power testing where the system is operated in fixed temperature mode. There are several items of note on this plot. The total temperature variation from the RCCS is approximately +/- 0.38 ºC around the fixed setpoint and the resonance error, reflected power, and forward power all follow along with its oscillation. Now the temperature response of the RCCS system is defining the oscillations. The underlying factor is the square trace which represents the position of the mixing water control valve, CV-1, and shows its inability to smoothly ramp between values thus not allowing for a constant temperature position to be found. This will be discussed later. Note that the temperature change is nearly identical to the previous example but the oscillation period is now about 2 ½ minutes. One important comment is that while most of this discussion is directly about the DTL cooling all of this applies to the CCL systems as well. The effects are nearly equal in the two types of systems since the higher average power (heat load) in the CCL cavities allows the cooling system to work closer to its design capability which balances out the higher temperature sensitivity of the cavity.

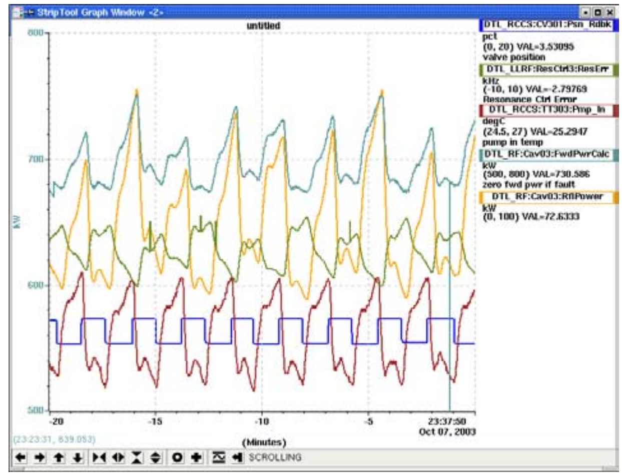

Figure 3: DTL3 operational response.

DEVELOPMENTS

After some analysis the focus was directed on a couple of areas. One of these was the facility chilled water stability and flow control through the RCCSs. It was noticed that the facility chilled water pressure and thus flow rates through the valves were erratic. After some testing this was found to be caused by poor control over the facility heating and cooling system. It was resolved by correcting the P&ID loops in the HVAC system which shares the chilled water system with the RCCS. Before the correction the system pressure would vary by as much as 20 psi and afterward it was within 2 psi of setpoint.

Next examined was the chilled water flow control in the RCCS skid. In operational testing it was found that tight regulation of the chilled water flow was important in maintaining a stable system. A change of as little as 2 gpm in chilled water flow could adversely affect the balance of a steady system. The Final Design Review by Los Alamos discusses in depth the modeling and development of the RCCSs. However, in the final construction, the heat exchanger was sized based on system pressure drop leading to the use of one which was 262% larger than required in the model. The modeled Facility Chilled Water flow rates through the heat exchanger were expected to be on the order of 75 gpm with a flow capacity of up to 160 gpm. In actual operation there appears to be no condition where the rate needs to exceed ~40gpm in the DTLs. These two factors create a great deal of the aforementioned overcooling capability in the system and a very high sensitivity to the flow rate. This led to an attempt at changing the conductance value of the CV-2, valve body. This would create better control in the range of use. The test could not be completed due to an equipment breakage.

Currently we throttle the chilled water flow via the main shut-off valves on each system.

A replacement of the CV-1, the bypass water flow, valve trim was made on DTL3. The new trim dramatically reduced the amount of bypassed flow per unit change in the actuator thus increasing the regulation of the warm side flow through the heat exchanger. The before and after graphs are shown in Fig. 4. The result was a increase in resolution from ~6 gpm to ~2 gpm per actuator step resulting in much more precise bypass water flow control in the range which will be used.

The change was somewhat helpful however Figs. 3 and 4 both show one of the biggest problems which is yet to be overcome; it is the limited response and deadband of the control valve actuators. This is still the dominant problem in the system control. In the LANL Final Design Review a stepper driven control valve actuator was specified with a 500 step resolution. In the production model received at ORNL these were replaced with electro-hydraulic units which manage roughly 50 steps from full close to full open. The opening deadband is quite obvious in Fig. 4, requiring a control input of 5 – 6% for the valve to come off of its seat. At which point the flow rate "jumps" to over 8gpm. This modified valve

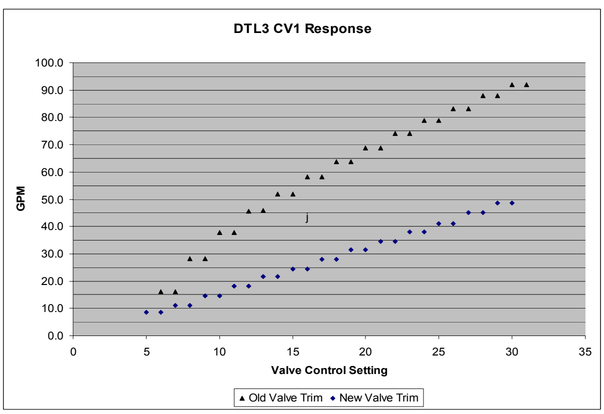

Figure 4: DTL3 RCCS CV-1 valve response.

trim reduced the original opening point from 16gpm. This is a considerable change at low duty operation. The poor control is also shown in the seemingly "step function" response of the 3-way control valve, CV-1, in Figs. 3 and 4. Compensation has been attempted for the actuators response and deadband in the P&ID loop but it is extremely complicated to model and all RCCSs have different valve responses. In an ideal system, operating at a fixed input power, both the CV-1 and CV-2 valves would be nearly static providing a constant cooling power equaling the constant heat load (constant mixed water temperature) instead of operating in this wait and adjust mode.

PLANS

Efforts continue in finding ways to operate the RCCSs more efficiently. The "Auto" or resonance control operating mode has been refined by the Controls Engineers to operate better but the resonance error can still "run away" from resonance during turbulent operating conditions more easily than the fixed "Temperature" mode. Colleagues at INR, using MatLab and Simulink, have created a simulation of DTL3 and its associated RCCS to help explain and predict overall system behavior. Initial results of this simulation show that at high duty factor operation the system can be reasonably stable but that control valve response hampers stability at any lower duty factor. INR has been commissioned to create a simulation for the CCL systems but one can infer a similar response based upon operational performance.

Software was purchased recently to analyze and assist in setting control system P&ID loops in an attempt to compensate for the non-optimal actuator characteristics. This has yet to be employed on the operating system. Consensus opinion is that the CV-1 and CV-2 control valve actuators, if not the valve bodies as well, will have to be replaced on most of the RCCSs to allow for stable operation at the wide range of duty factors which the SNS requires.

REFERENCES

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