2-K pump down studies at SNS

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Abstract. The Spallation Neutron Source (SNS) linear accelerator (LINAC) consists of 81 superconducting radio frequency (SRF) cavities cooled to 2.1 K by a cryogenic refrigeration system. The 2-K cold box consists of four stages of cold compressors with liquid nitrogen cooled variable speed motors. Transitioning from 4.5-K operation to 2.1-K operation in the cryomodules involves pumping the cryomodules down from approximately 1 bar to 0.040 bar. This effort is conducted through the use of several sequences developed as a collaborative effort between Thomas Jefferson National Accelerator Facility (TJNAF) and SNS personnel during the original commissioning of the SNS cryogenic system. Over the last ten years, multiple lessons have been learned about VFD behavior, thermal stability, procedural development and refining the sequences. From 2012 to 2014, there were multiple pump down iterations that were not successful. Studies have been conducted to determine the cause of these unsuccessful iterations. The results of these studies including components replaced and aspects that have not yet been solved are presented in this paper. Future plans to refine the sequence and determine the cause of unsuccessful pump downs will also be presented.

1. Introduction

The design of the SNS cryogenic system is similar to the system deployed at Thomas Jefferson National Accelerator Facility (TJNAF) with some modifications. The SNS system is designed with about sixty percent of the refrigeration capacity of the original TJNAF system [1]. Figure 1 is a simplified diagram of the system. The major components of the system include a helium purifier, helium gas storage, warm compressors, 4.5-K cold box, liquid helium storage, 2-K cold box, LINAC distribution system, and ancillary systems [2].

This system was designed to provide 2400 watts of refrigeration at 2.1 K, 8300 watts of shield cooling at 38-55 K and 15 g/s of 4.5-K liquefaction flow for the fundamental power coupler cooling [2] and handling the transients. The system was commissioned over a period of about a year
subsystem by subsystem, in conjunction with the LINAC commissioning. The 4.5-K system was commissioned first [2, 3] followed by the cryomodules in the LINAC at 4.5 K. The operation of transitioning cryomodules from 4.5 K to 2.1 K by pumping the return vapor pressure down from 1.1 bar to 0.040 bar is referred to as pump down. In December of 2004, commissioning of the 2-K cold box which houses the four cold compressors (CCs) began and took two weeks of manual trials to initially achieve 0.04 bar. Allowing for other commissioning activities, the commissioning of the 2-K system resumed in April of 2005, and an additional two weeks of pump down process path development and testing was conducted [1, 4]. During these initial commissioning periods, a set of sequences were developed to automatically and robustly control the pump down and achieve good pressure stability in the LINAC.

Figure 1. Diagram of Central Helium Liquefier (CHL) at SNS

The system has proven to be reliable and robust. The availability of the cryogenic system is greater than 99.5% for the scheduled beam operations (~4,500 hours per year) for the first ten years of operation. At present, the 2-K cold box averages less than one trip per year during beam operations. The system is primarily operated by the automated sequences which were developed in the initial cryogenic system commissioning time frame of 2004-2005. The control system is equipped with an alarm auto-dialer that calls a cryogenic engineer in the event of an alarm. Currently, the cryogenic system is only manned one shift per day. An example of the pressure stability maintained in the LINAC by the cryogenic system control sequences is presented in figure 2.

The initial pump down was developed iteratively. The goal of that effort was to develop a repeatable, robust pump down sequence as quickly and efficiently as possible. Optimization of the pump down process during commissioning was not a priority due to schedule pressure to commission the remainder of the accelerator.

After the pump down was conducted manually, multiple sequences were developed to control the cryogenic plant during the pump down. The first is the ‘Backfill’ sequence. This sequence prepares the 2-K cold box for pump down by backfilling the LINAC to ~1.1 bar, cooling the 2-K cold box down, establishing the correct flow path, and starting all four of the CCs at a minimum speed. Upon successful completion of backfill, the ‘4-K Pump Down’ sequence is activated. This sequence controls the 4.5-K cold box and cryomodules during the pump down. After this sequence is activated, the ‘2-K
Pump Down’ sequence is initiated. This sequence controls the 2K flow by adjusting the speed of cold compressor 4 (CC4). All three of the other CCs are controlled by preset gear ratios within the sequence. The gear ratio of a CC is the command speed of the CC (i.e: CC1-CC3) divided by the actual speed of CC4. For example if a CC has a gear ratio of 0.175, it is controlled at a speed that is 0.175 times the actual speed of CC4. The gear ratios for pump down are developed to keep each CC in its operating envelope (i.e: between the surge and the stall curves) and within the maximum motor current limit to attain the desired pressure in the LINAC with minimal dependence on process instrumentation (i.e: one speed, one pressure and one flow) during the pump down process.

The ‘4-K Pump Down’ and ‘2-K Pump Down’ sequences are active until a stable pressure of 0.04 bar is achieved in the LINAC. At that point, these two sequences stop. A ‘Heater’ sequence is then activated to control the LINAC pressure. Figure 3 displays a diagram of the 2-K sequences. Typically, a pump down takes about two hours to reach the final 0.04 bar from the starting 1.1 bar in the LINAC.

![Figure 2. Pressure stability of SNS LINAC.](image)

- Controls cryomodule settings
- Controls 4-K plant

![Figure 3. 2K control sequences.](image)

- Backfills return line to 1.1 bar
- Cools 2K cold box
- Starts cold comp. at min. speed
- Establishes loop control of 2-K flow using CC4
- Sets gear ratios of CC1 – CC3
- Controls CM pressure
- Automatically adjusts heat when RF is applied to cavities
During the pump down, the 2-K cold box is protected by multiple interlocks. One of the most important interlocks is for CC surge. Since the actual surge curve for each CC would be complex to program into the control system, a more simplified interlock is utilized. If the differential pressure across the 2K flow meter, located downstream of CC4 and upstream of the 4.5-K cold box injection point, drops by 375 Pa in ten seconds, the 2K box trips on surge.

This logic is simple and reliable. While it is true that every actual surge in the CC train will result in a loss of flow, the SNS protection system is conservative because it trips the box based on a substantial reduction in flow, even if the flow reduction is caused by the system and no surge is actually occurring.

During the initial pump down development, multiple attempts were unsuccessful, and mostly due to surge limit or maximum motor current limit on a particular CC. As a result of the issues encountered, power factor data was collected for each of the CCs. Figure 4 shows the power factor data collected for CC4 during the initial pump down development. This data displayed a 60-Hz dependency with an odd shape indicating that there were discontinuities around 60 Hz multiples in the power factor. Gear ratios were adjusted so that no two CCs would be in a low point in the power factor curve at the same time. By trial and error and adjusting the gear ratios, a successful pump down process path was developed.

![Figure 4. Power factor data with 60-Hz dependency collected during initial pump down efforts.](image)

The cryogenic system commissioning was completed in the summer of 2005 and the commissioning and the initial operation of the LINAC systems continued for the next year or so at both 4.5 K and 2 K. The mature operation of the cryogenic system to support the completed accelerator was achieved by 2007. Pump down became routine at this time. From 2007 through 2011, twenty-six out of twenty-seven pump down attempts were successful. The trips were a result of needing the LINAC at 4.5 K for cryomodule maintenance, utility failures, process upsets and a few 2-
K system component failures. This indicates that the original objective of pump down development was achieved.

2. Description of pump down issues

From the beginning of 2012 to the summer of 2014, pump downs became problematic. In some cases, successful pump downs were performed on the first attempt. In other cases, pump downs would take as many as five attempts to successfully complete. During this two year time period, there was success on fourteen of twenty-nine attempts. Three classifications of causes for an unsuccessful pump down have been identified; VFD issues, sinus filter failure and unknown. Figure 5 displays the dates of unsuccessful pump downs. It is noticeable that twelve of the fifteen unsuccessful attempts occurred on 4 days. Ten of those unsuccessful attempts were attributed to either VFD issues or a failed sinus filter.

At this point SNS requested TJNAF assistance and a meeting was arranged at SNS in March of 2015 to review the issues.

![Figure 5. Unsuccessful pump down attempts during problematic period.](image)

Information was gathered to identify the changes made to the cryogenic system since the original commissioning. Several VFD issues were suspected including the new versions of firmware. Procedural changes were made to minimize the time between a trip and returning the system to 2.1-K operation. Tuning was conducted on the control loop for CC4 to make the pump down smoother. Instruments had aged/drifted and in some cases had been replaced. The original control pressure for the Linac was a pressure transmitter located in the tunnel. Due to radiation, the accuracy was suspect and the control point was changed to the suction of the 2-K cold box within the CHL. All of these changes were considered as potential causes for the change in behavior of the 2-K pump down sequence.

The next step in the process was to classify the unsuccessful pump downs into possible causes. Seven of the fifteen unsuccessful pump downs were determined to be caused by VFD problems. The system was closely monitored during the unsuccessful iterations. If fluctuations in frequency were attributed to a particular CC, then the VFD was replaced. After replacing the VFD, the pump down would usually be successful. These VFDs were sent back to the manufacturer for refurbishment. Twice, the vendor found failed components within the VFD. The failed components of the VFD were replaced and indications of overheating were observed within the control circuit. This confirmed that
four of these seven unsuccessful attempts (thought to be due to VFD problems) were in fact caused by VFD issues. Still, uncertainty remains about the other three unsuccessful attempts.

On June 16, 2014, the pump down was unsuccessful four times as seen in figure 5. Upon inspection, burned wires were found around the sinus filter that is located between the VFD3 and the transformer to the CC motor. Figure 6 shows a block flow diagram of power supply to the VFD and CC. It was determined that the sinus filter had been wired incorrectly by the manufacturer when supplied. It had operated for a period of about ten years and then failed.

Still, there remained multiple pump downs for which the cause was unaccounted. These were identified as pump downs where “VFD slip” was the cause of the unsuccessful iteration. After studying the pump down closely and recording data at 1 second intervals, it was noticed that on occasion the actual speed and VFD output frequency would drop despite the command signal being held constant. This is referred to as VFD slip. Figure 7 shows an indication of VFD slip which resulted in the 2-K cold box tripping during pump down. This command signal to the VFD (CC4 command) stays constant and the actual speed read back (CC4 actual speed) drops slightly. If this occurs on CC4, then all of the CCs slow down because the command speed for those CCs is based on the actual speed of CC4. For simplification, the speeds of these three CCs are represented as a single trace in figure 7.

Figure 6. Circuit diagram for power supply to cold compressor motor.

Figure 7. Graphical representation of indication of a VFD slip.
3. Recent power factor data collection

It was first suspected that the pump down issues had something to do with the odd 60 Hz dependency of the power factor curve presented previously. Further discussions led the team to believe that the 60 Hz dependency originated from the instrument used to collect the data. Therefore, voltage and current waveforms were measured directly to calculate the power factor. The chopped waveform output of the VFD at the motor was monitored with a GMW CPCO series 500A clamp on current probe and a Tektronix 100X voltage probe on each phase. The resultant power factor curve for CC4 is shown in figure 8. This new curve confirmed that the peaks and valleys witnessed previously were most likely due to the diagnostic equipment used to take the measurements.

![Figure 8. Cold compressor 4 power factor data.](image)

Even though the 60 Hz dependency was not present, the power factor for these motors appears to be quite low, especially at low speeds, indicating that the motors are oversized for the load. The VFDs are designed for a power factor between 0.5 and 0.9 and the power factor setting within the VFDs is set at 0.87. When a large scale helium cryogenics system is required for a project, there is often a desire to copy another cryogenic plant design to minimize risk and reduce schedule constraints to a project. This has the benefit of reducing risk in some ways and also allowing two facilities to share spare components as needed. However, unforeseen complexities and risk can arise such as having unusually low power factor values for the CC motors. Completing a thorough process design for the actual requirements while making it a constraint to utilize common equipment with other facilities may be a desirable approach for future projects.

4. Planned pump down studies

In the near future, plans are in place to further study the 2-K cold box pump down in order to understand the reasons for unsuccessful pump downs and to improve the cryogenic system operability. The following are near term activities planned from the March 2015 meeting.

- Rewrite the pump down sequence so that CCs 1-3 are controlled by gear ratios that are based on the command speed of CC4 rather than the actual speed. Though this is not thought to be the cause for the VFD4 slip, it will prevent a negative contribution from the other CCs. With this change, the VFD4 slip would be localized to itself.
- Evaluation of the control system. A study to check that all of the versions of the VFDs, controllers and firmware are compatible is being conducted to ensure that there is not a
momentary loss (‘glitch’) in the communication of the control signal thereby inducing a VFD slip. Additionally, it is being evaluated as to whether the control signal to the VFDs can be switched from analog to digital to mitigate a glitch in the signal.

- Evaluate the voltage/frequency (V/f) curve within the VFDs. The voltage parameters can be adjusted to maximize the torque. During the original commissioning of the 2-K cold box at TJNAF (then known as CEBAF), the vendor supplied V/f curve was modified to maximize CC torque.
- Retake the power factor data for at least CC4 and CC1. These are selected since CC4 controls the other three CCs (via. the gear ratios) and CC1 has the largest wheel diameter and controls the mass (and volume) flow of all other stages. This will give us additional data that will confirm the results of the most recent measurements. It will also provide further information indicating whether changes to the system are beneficial or not.
- Improve the basis for detecting and possibly preventing a trip on surge (due to an individual wheel or the system). An improved basis and procedure will be developed in lieu of the current method.

5. Summary
The original pump down sequences that were developed have proven to be robust and reliable. However since some cryogenic system conditions and equipment have changed which resulted in the pump down difficulties, a reevaluation of the initial pump down process path is needed. Some of the difficulties have been identified as VFD problems and an incorrectly wired sinus filter. These problems have been corrected by replacing the faulty equipment. However, there is still an issue with VFD slip. Work is planned to either eliminate this condition or adjust the system such that it can ‘ride through’ without tripping.

In future 2K cryogenic installations, the capabilities of new generation VFDs and their control options for the CCs should be carefully evaluated before selection. It will be helpful if the VFDs can be tested at the actual load conditions to assess its performance and to separate the potential problems between the motor and the compressor. A lesson learned again is that, a thorough and careful analysis is required to adopt designs even from other similar applications.

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