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OPTIMIZING ROOM TEMPERATURE RF STRUCTURES FOR ACCELERATOR DRIVEN SYSTEM OPERATIONS*

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Abstract

Minimizing beam trip rates is one of the key operational goals at the Spallation Neutron Source (SNS). Trip rates are closely monitored, and real-time statistics are kept during beam operations for immediate analysis. Beam trips are automatically binned by the length of the trip along with the cause for each trip. The shortest beam trips occur with the highest frequency and those trip rates are dominated by the room temperature RF structures. There can be many causes for the RF structure malfunctions, but one area that has had a major impact on trip rates is improvement upon how RF processing is done on structures after extended maintenance periods.

INCREMENTAL IMPROVEMENTS

At the SNS, downtime durations of less than 1 hour occur with the highest frequency and this category is dominated by room temperature RF cavity reliability. Downtimes longer than 1 hour are less frequent, are usually a consequence of design flaws or equipment fatigue, and, therefore, not something typically mitigated by operational adjustments. As a result, reliability of our Radio-Frequency Quadrupole (RFQ), Medium Energy Beam Transport (MEBT), Alvarez Drift Tube Linac (DTL) cavities, and our Coupled Cavity Linac (CCL) cavities have been the focus of Operations. Upon inspection of the underlying issues which culminated in the overall downtime, it was determined that some necessary areas to address were the conditioning procedure requirements and process, vacuum system design, and window preparation process.

Vacuum Improvements

The original design of the vacuum system for our room temperature RF cavities incorporated sputter ion pumps, non-evaporable getter (NEG) Pumps, and cryogenic vacuum pumps. Early project decisions to employ capture pumping had a negative impact on reliability for several reasons. Capture pumps have some distinct disadvantages when applied to Accelerator Driven Systems; there exists a finite capacity for maximum pumping efficiency which is heavily dependent on excess gas in the system. In particular, ion pumps and their common companions, NEG pumps, are intended to be used in ultra-high vacuum applications. Once NEG pumps are "full", they have to undergo a regenerative processing on a regular basis so the vacuum at the window doesn't degrade sufficiently to prevent RF operation [1]. The DTL specifically had issues with large air bursts between RF on and off conditions from component to component thermal expansion differences. Permeation through the o-ring vacuum seals, introduced another gas load to the vacuum pumping. Over time, these large air bursts resulted in a reduction in ion pump efficiency, the culmination of which has the effect of outgassing Argon into the evacuated space.

In order to double the pumping speed and to eliminate at-capacity and outgassing vacuum pumps, the decision was made to implement turbo-pumps backed by a roughing header in the MEBT, DTL, and CCL RF structures vacuum scheme in 2015. After the modifications were complete, the baseline vacuum signature was lowered by a factor of two, eliminating the vacuum system as a cause for excursions, and the resultant overall downtime was reduced by ~1.5%. Our troubleshooting was enhanced by instituting a voting scheme allowing the control system to identify malfunctioning equipment which can be scheduled for repair during a planned downtime.

In Situ Conditioning Procedure Improvements

Since the Spring of 2008 when we first attempted to formalize our RF conditioning activity, the requirements and processes therein have been in a constant state of revision and improvement.

The polyphasic conditioning recipe consists of slow and methodical progression in all steps which begins with delivering low RF power in short RF pulses at a low repetition rate. Once the RF cavity is stable at these levels, RF power is increased to its procedurally defined non-beam loaded level. Then the RF pulse width is extended to its nominal levels, followed by a resting period of about an hour allowing the cavity to reach thermal equilibrium. RF is then turned off, the pulse width is shortened, and the repetition rate is increased. The aforementioned process of increasing RF power and pulse width is repeated until achieving nominal RF power (with no beam loading) at full duty factor. This was not always the complete recipe.

An early approach to conditioning was to ensure that the windows/couplers on the structures were capable of sustaining RF power even under beam loaded conditions. The technique employed to achieve that goal was to push the RF field approximately 10-15 % higher than the nominal field to simulate the power level that would be seen by the window under beam loading. During that time, the only

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equipment of concern during conditioning was the RF related systems and vacuum levels. Increased field, subsequent increased field emission, and increased temperature in the cavities was not suspected to have adverse effects.

Part of our procedure was to isolate the cavities' vacuum systems so that one vacuum system wouldn't affect its neighbor under localized vacuum spike events. The sector gate valves that were installed were stainless steel valves with rubber o-ring seals. With increased field, electron emission grows exponentially [2], and those electrons were subsequently transported to the upstream and downstream ends of the cavity where they impacted the vacuum valves and overheated its o-ring seal (Fig. 1). The entire valve assembly was damaged in short order from heating to the point where the valves were incapable of isolating neighboring evacuated sections.

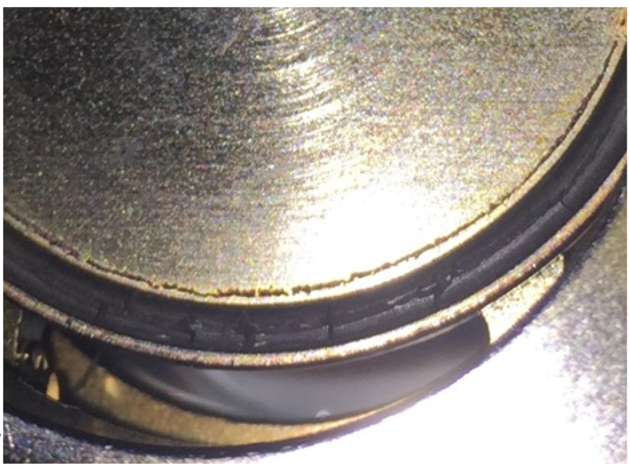

Figure 1: Cracked o-ring around the valve which occurred even with the valve open [3].

Once we identified the heating issues with the vacuum valves, the procedure and the machine protection system were modified to require that vacuum valves be open during RF operations to prevent damage.

Even as we took this action, our beamline components were still being damaged, including open vacuum valves. Additional components damaged were Beam Current Monitors (BCMs) at the beginning and end of the CCL section (Fig. 2). In both cases, electron damage caused a vacuum leak to develop in the ceramic portion of the BCM assembly. The solution to this problem was to remove BCMs with ceramic to air installations in the warm linac. DTL BCMs still exist, but the ceramic is contained within vacuum.

Following all of the improvements already discussed, the focus turned to power levels in the RF structure. During one of the conditioning exercises to higher power levels, in situ, a ceramic window was damaged during one of our conditioning exercises. We resolved to abandon the beam loaded limit conditioning portion of the procedure as it was deemed to be causing more damage and contamination to the RF structure.

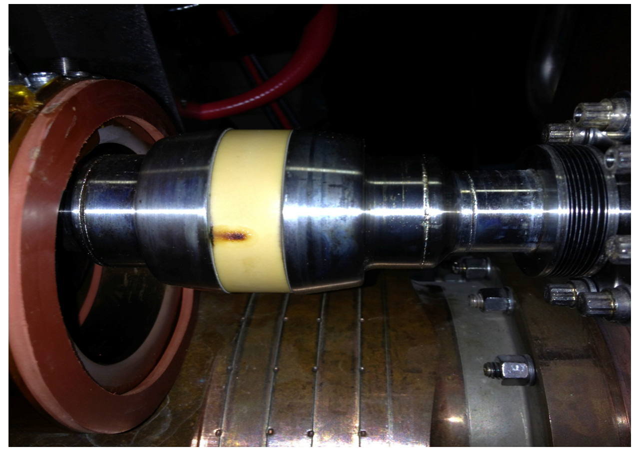

Figure 2: Electron Damage to BCM Ceramic.

Figure 3 shows a Beam Loss Monitor (BLM) signal that is proportional to the field emission from a CCL cavity. Up until April 2015, when the DTL window was damaged, cavities were conditioned to beam loaded levels. For reasons unrelated to field emission, the decision to cease the higher power conditioning level was made. As a consequence of this decision, however, the field emission signal as seen from the BLM began decreasing.

The field emission levels continued to decrease until the summer of 2016 when the CCL vacuum system was upgraded. Having not been under vacuum for about 1-2 weeks, the RF field emission levels increased upon recovery and may have been elevated due to possible contamination introduced through an error in RF field setting. Interestingly, it appears to take years for the field emission to decrease to the point where they are barely measurable by the BLM suggesting that the complete processing of the cavity takes years under vacuum.

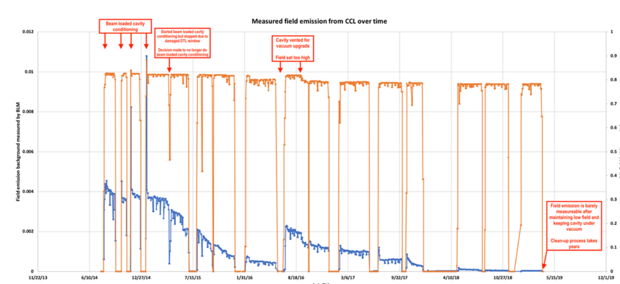

Figure 3: Field Emission measured by a BLM near a CCL cavity.

The result of our efforts can be seen in decreased frequency in CCL faults over time. Though the frequency of trips resulting from issues caused by contamination has been reduced, faults can be caused from any part of the RF transmission network.

Currently, we condition at nominal power levels only, and any conditioning of windows above that level to compensate for beam loading is done in the RF Test Facility (RFTF) where we can decouple the window from the structure and deposit higher RF power onto the window in a

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controlled environment. As a result, faults due to early excess field emission declined over time (Fig. 4).

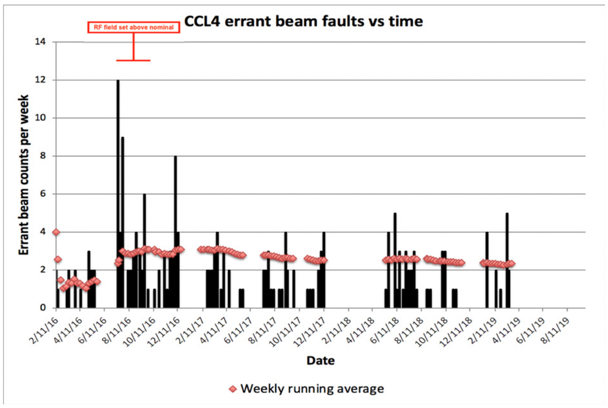

Figure 4: CCL cavity faults per week over time.

FUTURE IMPROVEMENTS

As already stated, RF window conditioning is crucial to the reliable operation of warm section cavities. Challenges faced in this effort included maintaining nitrogen pressure on the window, having a designated storage location, and the lack of a reliable tracking system to provide historical context to troubleshooting efforts.

In an effort to provide additional organization and designate a pre-defined location for all window conditioning activity and storage, SNS commissioned a vacuum header with 6 stations total in the RFTF. The header accommodates two of each warm section window/coupler. (Fig. 5).

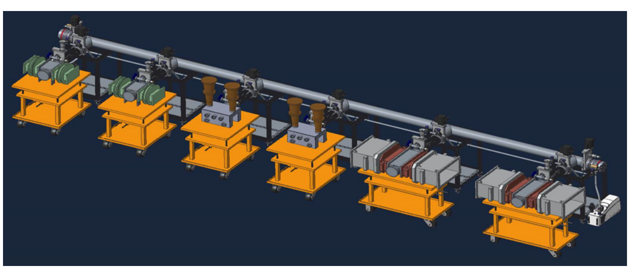

Figure 5: 3D Layout of New Window/Coupler Storage Facility.

Although our conditioning data from RF structures hasn't always been well understood, the more significant driver of downtime has been the inability to determine issues with windows prior to installation in the accelerator. In 2015, a successor window exhibited a behavior which required re-conditioning after running at a beam power of 1.3 MW for a few days. To minimize the downtime the decision was made to keep the beam power below 1.3 MW, and the window performed well at these levels. Before replacing the window, a vacuum leak check revealed that the window had a small leak, but still worked well enough to run at beam powers of 1.2 MW.

A prototype DTL window from a different manufacturer failed after approximately two and a half days of conditioning on the test stand at full RF power and duty factor for (Fig. 6). The only indication of a possible issue was slightly elevated vacuum pressure (still below 1e-07 Torr).

Windows conditioned for a short period of time seem fine on the test stand but some have turned out to have a small defect which didn't reveal itself until sufficient power levels were achieved. Most of the conditioning approach is spent varying the power level and duty factor in order to expose the window to the whole distribution of conditions likely to be encountered.

Conditioning RF windows on the test stand for longer sustained periods at the prescribed level may reveal a potential problem before installation for production.

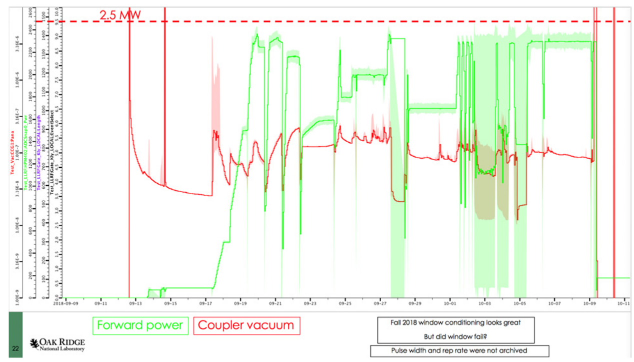

Figure 6: Conditioning Plot of Failed Window.

CONCLUSION

Our lessons learned have steered future plans to improve our conditioning procedures, our vacuum pumping speed and methods, and our window conditioning methods and storage facilities. With all of these improvements we will make strides toward achieving our ambitious goal of 95% availability beam operation.

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