Failure Report for SNS Modulator at End Station B on March 21, 2008

4/17/08

Tony Beukers, Mark Kemp, Craig Burkhart

Introduction and Background

This report provides information on the documented failures of the Spallation Neutron Source (SNS) High Voltage Converter Modulator (HVCM). Information on failures is presented for the single failure at SLAC, which occurred on March 21, 2008, as well as the modulator implementations at SNS. Insight into failures at SNS was gained through personal communication with David Anderson who is manager of power conversion systems at SNS. We communicate with David on a regular basis as part of an ongoing research effort in place at SLAC to develop improvements to the HVCM (supported under an ORNL-SLAC MOU), as well as on issues regarding the operation of the modulator at SLAC.

Initial operation of the HVCM at SLAC began in 2005 and it was subsequently upgraded in 2006 to increase the peak power output. It had operated consistently without a major failure until the incident on March 21. The primary purpose of the modulator is to support ongoing L-band research.

Experience and Perspective from SNS

In total, this version of the modulator has been operated for ~210,000 hours. At SNS, the mean time between failures is 3000-4000 hours. The failure rate has been steady to slightly increasing over the recent past. This increased failure rate may be correlated with increased average power in recent operation but is partially mitigated by numerous upgrades that have been performed on the system. Since April 2006, there have been 33 modulator failures, of which 20 have been related to the switchplate. Of those 20 failures, five have caused fire events with collateral damage and long recovery times. In all incidents of failure, the fires and shrapnel were confined to the enclosure. In several of the failures, no root cause was found. After describing our modulator failure to David Anderson, he stated that it sounded very similar to what they were experiencing.

The operating conditions of the modulator at SNS and SLAC are not the same. The SLAC version of the modulator operates at higher peak power (~16 MW, 5 Hz) and the SNS version operates at higher average power and pulse repetition frequency (PRF) (up to ~11 MW, 60 Hz). Each of these parameters may have contributions to failure mechanisms. If a failure event were correlated with the number of pulses out of the modulator (1/PRF), it would occur ~12 times more quickly in the SNS implementation. There is evidence in the SNS data that suggests the failure rate may be related to peak power. The DTL-Mod1 configuration (the higher peak power version in use at SNS) has the highest failure rate among their HVCMs.

Since the modulator was implemented at SNS, they have developed several schemes to help prevent failures. These include a fault detection chassis, to detect the onset of transformer saturation and disable the modulator, and machining of the switchplates to have greater distances between high voltage conductors, to reduce the electric field strength. Additionally, they have recently upgraded current monitoring instrumentation to quickly shut down the modulator in the event over current conditions are detected. However, it was decided that no quick-fix was adequate and the switchplate needed a redesign. Neither of the above two schemes are currently employed in the SLAC version of the modulator.

Description of Modulator Failure at SLAC:

The HVCM in End Station B (ESB) consists of a low voltage section (±1.25 kV) in air, and a high-voltage section (~120 kV) in an oil tank. On March 20th and 21st, the modulator was being re-commissioned following a replacement of a failed component in the high-voltage oil tank. This component was previously identified as being the cause for the modulator not reaching its rated output voltage. The component is not believed to be related to the March 21st failure.

On March 20th, the modulator was slowly brought up to a charge voltage of ±0.7 kV. The next day, we started at ±0.7 kV charge and stepped the voltage up over about one hour. At this point, the modulator failed at ±1 kV charge voltage, 110 kV output voltage, and a stored energy of ~115 kJ. This occurred after running at ±1 kV charge voltage for several minutes. The modulator failed in the low-voltage air section and caused two high voltage IGBT switches to be fragmented as a result of being in the discharge path.

The failure generated a loud bang comparable to a shotgun blast. The enclosure was designed to provide protection in such an event and functioned as designed. No personnel were injured.

ESB personnel responded immediately, notified 911, shut down the unit's power, discharged a CO2 extinguisher into the enclosure (a preemptive measure), and initiated de-energization and lockout of the modulator.

Initial indications did not suggest any initiation of fire. There was dust or smoke visible within the enclosure as viewed through the enclosure's high-strength windows. A slight "smoke-smell" was present. The call to 911 was initiated to provide fire coverage in the case an undetected fire had been initiated within the equipment.

Failure Investigation Results and Tests During Commissioning:

Investigation results reveal no clear catalyst for the modulator failure. What is clear by the fragmented IGBTs is that rather than the current being steered through the highly inductive path of the transformer as designed, the current traveled through a set of IGBT switches creating a short circuit across the storage capacitors. Failures of this type can be generated by improper timing signals, a short within a transformer, a saturated transformer core, switchplate arching or

IGBT switch failure. Due to our low pulse repetition rate it is unlikely that the modulator failed due to overheating of the IGBTs or malfunctions in the secondary of the modulator.

The following tests were conducted before the modulator was reassembled:

- Complete removal and inspection of non-failed switch plates. This revealed that one of the non-failed transformer bias boards had a blown fuse. However, due to redundancy in the system, this was not a likely cause of the failure.

- The failed switch plate was removed and replaced with a spare switch plate. Analysis of the failed switch plate reveals that an old version of IGBT gate drive card was installed. The spare switch plate includes the most recent IGBT gate drive cards. There are no remaining old versions of IGBT gate drive cards in the modulator.

- Low voltage verification to ensure remaining IGBT switches were operational.

- Low voltage verification to ensure storage capacitors were operational.

- Removal of high-voltage oil basket and visual inspection. This revealed no obvious failure cause but did indicate an area of weak electrical isolation that was remedied.

- High voltage, low energy, verification to ensure the transformers were operational.

- Inspection and calibration of all switch timing control cards. This revealed that there is some timing drift on these cards that may cease once the cards reach thermal equilibrium. A zero-energy timing test of the system will help identify the cause of this effect.

- Switchplates were examined in place for proper location and quality of insulation. Care was taken especially in the areas where the spacing was increased in remachined SNS switchplates to ensure voltage standoff capability. Like many of the switchplates currently operating at SNS, the switchplates on the SLAC HVCM are not remachined.

The following tests must be carried out during the commissioning of the modulator:

- Zero energy timing test of the entire system

- Slowly increasing drive voltage while monitoring transformer current and flux waveforms, IGBT voltage waveforms, and modulator output voltage and current waveforms.

The above tests are similar to the tests performed at ORNL after a HVCM failure.

An examination of how to proceed with the SNS type modulator operation at SLAC:

The SLAC HVCM is the production prototype; it does not have all the upgrades present in the SNS modulators, including a diagnostic chassis that examines transformer saturation, redesigned switch plate cards less likely to generate shorting points, and redesigned transformers. SNS has offered to provide a diagnostic chassis to incorporate into the SLAC HVCM. Redesign of the switch plate assemblies is a work-in-progress and it may be some time before a revised version is complete and tested. The transformers used in the SLAC HVCM are a unique version, built at LANL, and cannot be replaced with any of the SNS versions.

The personnel hazards associated with the modulator include an audible startle hazard and a hearing hazard. Additionally, there is a fire hazard within the enclosure capable of causing equipment damage. The fire danger can be mitigated by having an operator present, connecting the smoke detector, or installing a fire suppression system. Work is underway to install a fire suppression system. Both the startle and hearing hazard can be mitigated through administrative controls. Given that it is possible to mitigate these hazards we regard it as safe to continue the operation of the modulator.