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FAILURE SCENARIOS AND MITIGATIONS FOR THE BABAR SUPERCONDUCTING SOLENOID

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ABSTRACT

The cryogenic department at the Stanford Linear Accelerator Center is responsible for the operation, troubleshooting, and upgrade of the 1.5 Tesla superconducting solenoid detector for the BABAR B-factory experiment. Events that disable the detector are rare but significantly impact the availability of the detector for physics research. As a result, a number of systems and procedures have been developed over time to minimize the downtime of the detector, for example improved control systems, improved and automatic backup systems, and spares for all major components. Together they can prevent or mitigate many of the failures experienced by the utilities, mechanical systems, controls and instrumentation. In this paper we describe various failure scenarios, their effect on the detector, and the modifications made to mitigate the effects of the failure. As a result of these modifications the reliability of the detector has increased significantly with only 3 shutdowns of the detector due to cryogenics systems over the last 2 years.

KEYWORDS: Failure modes, BABAR detector, cryogenic system
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INTRODUCTION

The 1.5 T BABAR superconducting magnet is located in the Positron Electron Project II (PEP II) rings at the Stanford Linear Accelerator Center and has been fully operational since May, 1999. The magnet is made of superconducting Rutherford-type cables fabricated from niobium-titanium and wound around an aluminum alloy cylinder. The critical temperature and operating temperature of the solenoid are T_c = 8.23 K and 4.5 K respectively. A constant current of 4600A is used to obtain a magnetic field of 1.5 T in the solenoid.

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The cryogenic operation of the superconducting solenoid consists of a helium plant and a compressor facility. The helium plant consists of a helium liquefier, a 4000 l supply dewar, and a distribution valve box, while the compressor facility consists of 3 screw compressors. The compressors are ~400 m from the plant and the plant is ~60 m from the magnet. A flow rate of 70 g/s of helium gas is typically used to cool the magnet. FIGURE 1 gives a simple schematic of the cryogenic system for the BABAR detector. Room temperature helium gas flows from the compressors to three filters, a coalescer, adsorber, and LTPD, before entering the first set of heat exchangers where the gas may be precooled using liquid nitrogen. The cooled gas is again filtered through an adsorber before being split before turbo expander 1 at 80 K. Part of the helium gas flows to turbo expander 2 down to 11 K and returned to the low pressure side of the compressors by way of the heat exchangers. The refrigeration gas is split again and expanded in a Joule-Thompson valve where part of the liquid fills the internal dewar of the plant. The rest of the helium is cooled in the internal dewar before filling the external dewar and subsequently the solenoid.

The 4000 l helium dewar is filled directly from the liquefier. This volume provides approximately 30 hours of autonomous operation of the solenoid in the event of a liquefier or a compressor malfunction. The liquid helium from the dewar is supplied by way of the proportional control valves in the distribution valve box. The valves are electro-pneumatically operated and are actuated by process controllers and helium level gauges. Transfer lines that are flexible, vacuum insulated and low loss are used to supply liquid helium and cold helium gas to the magnet. Cold gas is returned to the liquefier by the transfer lines. These transfer lines are compatible with existing lines around the lab so that they serve as spares. Warm helium gas from magnet current leads is returned to the compressor suction via uninsulated piping.

The solenoid has instrumentation sensors for monitoring, controlling and diagnostics. The solenoid, helium plant and the compressors are automated using the Allen Bradley SLC 500/4 programmable logic controllers (PLC). Labview running on a Windows operating system is used as the human machine interface. Monitoring of the plant, compressor and magnet is done remotely through the web. Information exchanged between the cryogenic control system and the BABAR Detector control system are solenoid hardwire interlock status, solenoid and bucking coil power supply status including current read back, operation state of vacuum pumps, compressors, turbines/liquefier and temperature.

The cryogenic operation of the superconducting solenoid requires both liquid helium and cold helium gas for cooldown and thermal shields. The cooldown of the solenoid is accomplished by circulating cold helium gas either directly from the refrigerator or from a storage dewar. This cold helium gas is mixed with warm helium gas so that a maximum temperature difference across the magnet is limited to 40 K. This minimizes thermal stress during the cooldown from 300 to 100 K. Under operating conditions, the magnet is cooled by circulating two-phase helium in the pipes mounted on the coil support cylinder. The forced flow method drives the cooling liquid through a manifold at the bottom of the support cylinder. The radiation shields operate at 40 – 80 K and are cooled by the boil off helium gas from the pot.

In case of a quench, the solenoid is protected by an external dump resistor which will extract approximately 75% of the stored magnetic energy. During a fast discharge, a voltage limit of 500 V is applied across the solenoid. During a quench, the temperature rise in the coil and support cylinder does not exceed 40 K. Although there has not been a spontaneous quench of the magnet, the solenoid has hardwire and software interlocks to protect the solenoid from damage due to quenching. There are 10 software interlocks divided into 2 levels: Level 1

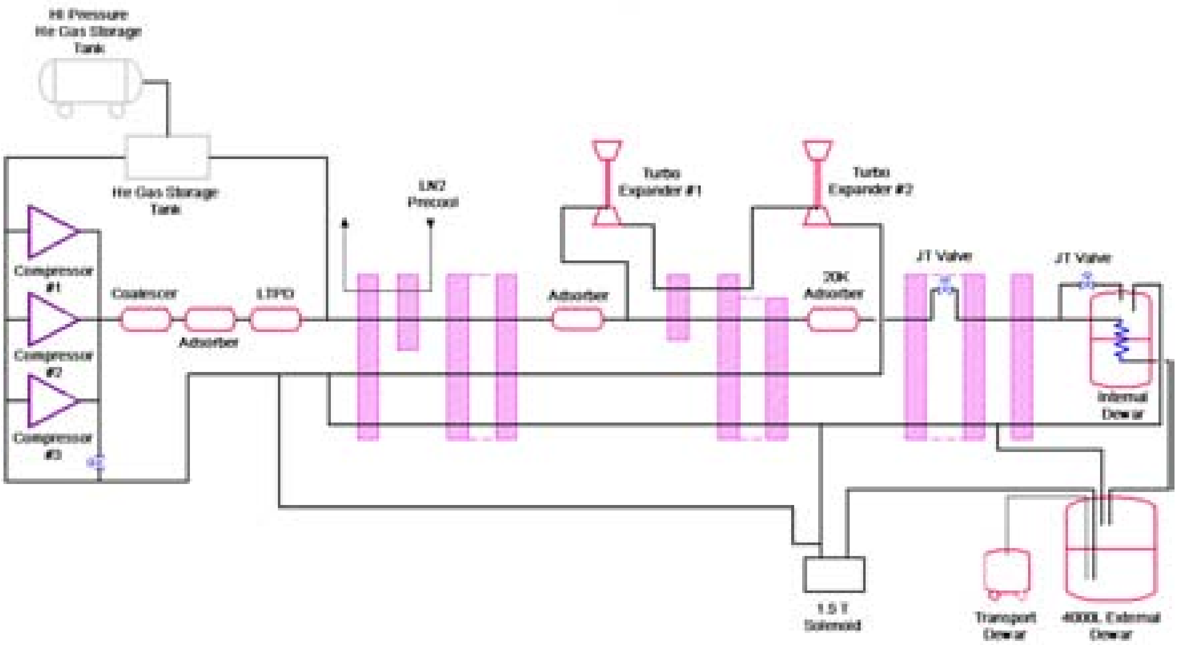

FIGURE 1. Cryogenic system for the BABAR detector at the Stanford Linear Accelerator Center

interlocks stop ramp-up but has no effect if current is already ramped up, Level 2 interlocks trigger the solenoid to ramp-down. The values for Level 1 interlocks are lower than for Level 2 interlocks to alert the operators of a possible problem. Filters implemented by software timers have been installed on all software interlocks to eliminate noise spikes. All interlocks and key sensors are on an alarm system that will activate a continuous automated paging system when an alarm condition exists. Alarms can be acknowledged by telephone and logged to a file to aid in troubleshooting. A historical trend viewer allows operators to monitor key sensors remotely for any deviations. The sensors to monitor are chosen by the operator. Ability to view historical sensor information is essential for troubleshooting. More detail on the operation of the BABAR magnet is available. [1,2,3]

FAILURE SCENARIOS, EFFECT AND MITIGATIONS

Failure scenarios were studied in order to increase the reliability of the BABAR detector. By looking at possible failure modes, the SLAC cryogenic group hopes to increase the availability of the detector for the BaBar experiment. Details on the number and causes of magnet interruptions since 1999 to 2004 have previously been published. [4]

Electrical Power Failure

This is the most common mode of failure for the BABAR solenoid. Electrical power failure is an unplanned power outage that can be site-wide or local and is often associated with the weather. In the case of a power failure, the solenoid will ramp-down when the power supply turns off, due to the lack of a constant current to maintain the field. No damage is caused to the magnet. The ramp-down can take anywhere between 4 minutes by fast discharge to 120 minutes by the free wheeling diodes to complete. Once power is restored and the power supply interlock is reset, current can be ramped up again in 35 minutes. If power is restored before the ramp-down has completed, the ramp-down can be halted and made to ramp-up again.

Vacuum systems and the primary power for control and safety systems will also turn off. Main solenoid vacuum can be maintained without pumping for 2 hours before the vacuum software interlock trip level is triggered. Control systems will not be affected because the operating computers and programmable logic controllers are backed up by an uninterruptible power supply. If in turn the backup power supply fails and the control system (composed of PLCs) faults, all valves return to their safe non-operational state. PLCs have an internal battery that allows the processor to retain the operating program, and so once power is returned the PLCs will resume without operator intervention. Pressure relief valves require no electrical power and no operator intervention to reset. As a further backup, rupture disks are installed in parallel to pressure relief valves and at higher pressure limits.

When there is an electrical power failure, the liquefier will turn off if the compressor stops. The liquefier will restart when compressor restarts without intervention, while operator intervention may be required to reset the turbo-expanders. The solenoid can be maintained at liquid helium temperatures and operational by transferring helium from the external dewar when the liquefier shuts off. Furthermore, liquid helium transfer to the solenoid can be maintained indefinitely. Vacuum systems on the liquefier and transfer lines will however turn off. Vacuum on the liquefier will not be affected when the liquefier is cold due to cryopumping, while the transfer line vacuum can be maintained for approximately 4 hours before active pumping is required.

The compressors will turn off in the event of an electrical power failure but this will not ramp-down the solenoid. Vented helium gas can be made up from stocks onsite and from outside purchases. Helium recovery compressors are set to automatically start recovering gas when the supply pressure rises above a pre-established set point.

Compressor Failure

The compressor and liquefier will stop when the compressors malfunctions. However, the superconducting solenoid will remain operational when the compressors fail. Previously, the differential pressure from the external dewar and the helium reservoir pot of the solenoid was lost when compressor failed. A vent was installed to keep the low pressure side of the compressor low. In addition, the pressure in the external dewar was raised so that the solenoid can remain at liquid helium temperatures and available for physics research by transferring liquid from the external dewar. A backup compressor is also available to resume helium flow.

Liquefier/Refrigerator Failure

The liquefier will not be able to make liquid helium and pump it into the external dewar. When the liquefier shuts off, the solenoid can remain at operating temperatures for ~10 hours by consuming liquid helium from the external dewar. If more time is needed, liquid helium can be purchased and transferred to the external dewar to maintain solenoid at 4.5K. In addition, there are spare turbines, heat exchangers and flexible transfer lines on site to expedite repairs of the helium plant.

Cooling Water Failure

The solenoid will ramp-down when the cooling water is lost to the solenoid power supply and the liquefier’s vacuum system. Liquefier and vacuum systems are connected to a self-contained and standalone water chiller. Even without active pumping, however, vacuum can be maintained when the liquefier is at liquid helium temperatures. The water cooled compressors will also stop. There are portable water coolers to act as a backup when one of the cooling towers fails. An automatic valve is planned to switch the cooling water from the tower to the portable water cooler when needed. Once the cooling water and power is restored, the magnet current can be ramped up.

Compressed Air Failure

Solenoid will ramp-down and fast discharge when there is no compressed air because of the loss of pneumatically actuated control valves. A passive air system in the helium plant is planned to provide compressed air for 24 hours when the primary air supply fails. This passive air system will provide air to the liquefier control valves when the primary air supply fails and the liquefier stops due to the loss of the control valves. Compressors are unaffected because an automatic air compressor becomes active at the compressor facility.

Sensor/Instrument Failure

Sensor failure or noise spikes may result in erroneous hardwire trips and a subsequent fast discharge of solenoid. Only the most reliable sensors, such as voltage taps, are used for quench detection and fast discharges. Filters, implemented by software timers, have been added on all software interlocks to eliminate the possibility of noise spikes triggering a shutdown. In addition, redundant sensors are installed in all inaccessible locations. Although the control systems can monitor multiple sensors, only one sensor is used to control the system.

Control System Failure

Control system failure may interrupt solenoid operations and ramp-down the solenoid. Highly reliable and industrially robust PLCs are used. Operating programs can be uploaded again to the PLC processor if the existing operating program becomes corrupted. Hardware spares for the PLCs and PCs are available on site. Computer failures may interrupt ability to control systems, but the computers only act as interfaces for the PLCs and hence a failed computer will not interrupt solenoid operations. A spare control computer is connected in parallel and can be used and brought online immediately.

Solenoid Vacuum System Failure

Vacuum system will turn off and may cause the solenoid current to ramp-down. Vacuum will deteriorate to software interlock trip set points in approximately 2 hours. Two vacuum systems are installed in parallel to act as an active backup. There is no impact to the liquefier and compressors since cryopumping provides adequate vacuum when running at helium temperatures.

Human Error

Human error may cause the solenoid current to ramp-down. SLAC has regular training sessions with documentation to train operators on the system especially when there are upgrades. Descriptions have been added to key controls to minimize errors. A checklist must be completed before every ramp-up and after every access is permitted in the interaction region halls.

He Purifier Failure

Contamination will cause a loss of helium flow. The purifier consists of two parallel lines out of which one purifies while the other one regenerates. There are a total of 5 purifiers – 3 in the compressor room and 2 in the liquefier. The coalescer removes the oil droplets and a subsequent activated charcoal adsorber removes the oil vapors. The adsorber with activated alumina further removes oil and adsorbs water. The low temperature purifier drier (LTPD) is cooled to 77 K and dries the helium and adsorbs nitrogen, oxygen, and CO_2 impurities. On the liquefier end, the helium gas flows through another adsorber to remove water and a 20 K adsorber to remove neon. Implementation of an oxygen, water and trace gas analyzer to monitor the gas at five different positions is in progress. The analyzer will automatically

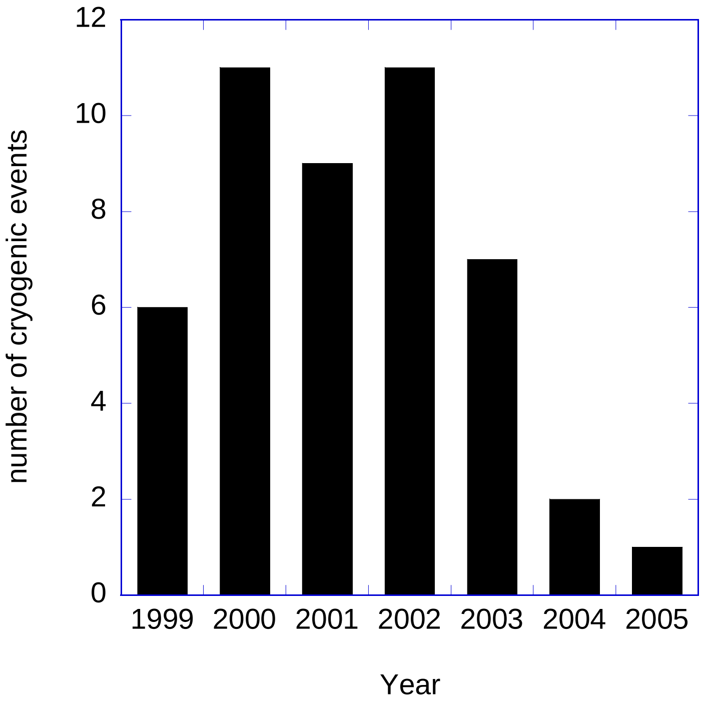

FIGURE 2. Number of detector interruptions caused by malfunctions in the cryogenic system. As failure modes were identified and mitigations implemented, many failure modes have disappeared with time.

monitor the purity of the helium before liquefaction and activate an alarm when a threshold contamination level is reached.

DISCUSSION

Since the start of the BABAR detector, May 1999 to present, cryogenics has been responsible for 47 interruptions to magnet operations. As seen in FIGURE 2, there have been 3 interruptions to the solenoid operations due to cryogenics for 2004 and 2005. These were due respectively to sensor failure, human error and instrument failure. For 2005, the BABAR magnet has been at full current for eight months without interruption to the magnet for cryogenic reasons. The one interruption occurred in August and was due to an instrument failure in the quench detection system.

CONCLUSION

Events that disable the magnet are rare but significantly impact the availability of the detector for physics research. The cryogenics group at SLAC has a continuous program to install backup systems and mitigations. As problems occur, equipment and procedures are evaluated and improved to prevent future ramp-downs. The number of interruptions to the magnet due to cryogenics in 2004 was two and in 2005 so far is one. We hope to keep the interruptions down to our current level through continued careful examination and operation.

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