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Availability and Failure Modes of the BaBar Superconducting Solenoid*

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Abstract

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***Index Terms*—Availability, Cryogenics, Failure Analysis, Superconducting Magnets**

I. Introduction

The sole experiment in the SLAC/PEP II B factory is the BaBar detector. This detector contains a thin 1.5 T superconducting solenoid as part of its particle identification system. This solenoid, which operates with a current of 5 kA and 20 MJ of stored energy, is a critical component of the experiment. If the solenoid is not functioning, the experiment is not taking data. The solenoid is cooled by forced flow liquid helium transferred from a 4000 l storage dewar which in turn is kept at a constant level by a large Linde helium liquefier/refrigerator. The magnet is protected by a set of hardware and software interlocks that will either ramp the current in the magnet down or open a beaker which quickly discharges the current into a dump resistor. Further details of the operation of the magnet system have previously been published. [1, 2].

The refrigerator/solenoid system has been operating quite successfully since May 1999. However, given its importance to the BaBar experiment, continual upgrades to its operation have been made. This paper reports a survey of all the unplanned interruptions (either fast discharge or ramp down) to magnet operation that have occurred since May 1999. These interruptions have been assigned a cause. Steps taken to reduce these failure modes are also discussed.

II. Observed Failure Modes

During the operating life of the BaBar experiment to date (May 1999 – present), there have been a total of 63 unplanned interruptions to magnet operations. None of these can be shown to be the result of a spontaneous quench in the coil. In nearly all cases, the interruptions can be traced to failures in utilities or supporting systems or to human error. Fig. 1 shows the distribution of the magnet failure modes. These failure modes in order of their highest frequency are:

A. *Power Failure*

A power failure refers to unplanned electrical power outages, e.g. during lighting storms. Because this problem is often site-wide, the magnet and cryogenics are not the only systems to experience a breakdown. The magnet/refrigerator control systems are backed by uninterruptible power supplies (UPS) for protection. It is not practical to back up the main magnet power supply or the power for the main refrigerator compressors.

B. *Unknown*

Either the event was not well documented or the cause of the event was not known at the time. If a hardwire quench detection interlock is tripped, it can be difficult to obtain information about what initiated the problem. However, if the cause were known, it would most certainly fit into one of the above categories. A fair number of the unknown events are thought to be caused by electrical noise on the quench detector circuit.

C. *Miscellaneous Liquefier and Compressors*

Malfunctions and shut downs in the liquefier system or compressors cause the magnet to ramp down or fast discharge due to a temperature rise in the superconductor.

D. *Magnet Power Supply*

Normal power supply operations can be interrupted by cooling water failure, ground fault, and especially spurious

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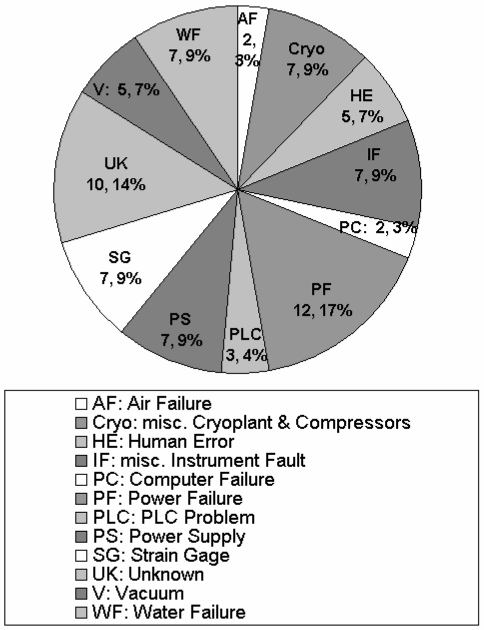

Fig 1. Historical distribution of the failure modes for the BaBar superconducting dipole. The absolute number and relative percent of each failure mode is shown in the chart.

electrical noise, which will cause the power supply interlocks to trip resulting in the magnet ramping down. This specific problem is mostly unpreventable.

E. Miscellaneous Instrument Fault

Sensors reading out incorrect information cause this problem. This can be either due to faulty sensors and data acquisition hardware or due to transient noise spikes that result in incorrect readings.

F. Strain Gage

Strain gages are mounted on the magnet support structure to monitor unusual stresses or deformations. This is a software interlock that will cause the magnet to ramp down if tripped. So far, all trips have been due to strain gage failures and not actual structural problems.

G. Human Error

Failures caused by operators are rare. Nevertheless, the magnet can, without prior notice, ramp down or quench if an operator makes a mistake.

H. Vacuum

One of the resident vacuum systems is for the magnet cryostat. A failure in the vacuum results in high pressure and causes a ramp down. So far, these failures have been the result of short lived pressure rises or vacuum instrumentation failures.

I. Water Failure

The He compressors, magnet power supply, and cryoplant turbines are water-cooled. If this source flow is interrupted, usually occurring site-wide, interlocks are then tripped by temperature increases. There is no cooling backup available for the 30 kW compressors. A standalone cooling system has improved turbine reliability.

J. PLC Failures

Two Programmable Logic Controllers (PLC) provide refrigerator and compressor hardwire interlock and software interlock control. PLC instrumentation failures cause ramp downs. However, these industrial systems are very reliable and have only failed three times in five years and one of these failures resulted from a lightening strike on site.

K. Instrument Air System (IAS)

All valves in the system are pneumatically driven and the system will ramp down if the IAS fails.

L. PC Failure

Two PCs control the LabView programs for the magnet and liquefier systems. A third PC serves as a back up for either of these computers' LabView displays. A failure of PC #1 and consequently a LabView failure would cause a ramp down of the magnet.

III. MITIGATIONS AND THEIR IMPACT

A number of mitigations to these failure modes have been put into place over the last 5 years. They include installing back up systems where possible, eliminating unnecessary and unreliable interlocks and improving training. Major mitigations put in place include:

A. Backup Cooling System

In 2003, an additional vent valve was installed into the cryogenic system. This allows the forced flow of liquid helium from the storage dewar through the magnet to continue even if the entire liquefier and compressor system shuts down. The storage dewar contains enough liquid helium to maintain cooling of the magnet for 8 to 10 hours without operation of the liquefier. Since this system was installed there have been no magnet failures attributed to the cryogenic system.

B. Alteration of the Strain Gage Interlock

The strain gages installed into the magnet support structure have a high rate of failure that results in unnecessary ramp downs of the magnet. Experience has shown that the principal value of the strain gages is to insure that all the magnet supports are reinstalled after maintenance periods. We have altered this interlock so that it will only prevent the magnet current from being ramped up but will have no effect on the magnet once it is at full current. This has eliminated all strain gage trips.

C. Alteration of the Magnet Vacuum Interlock

Experience has shown that all the trips causes by poor magnet vacuum have been due to faulty vacuum instrumentation or transient rises in the vacuum pressure rather than actual failures in the magnet vacuum. There are other, more reliable indications of magnet vacuum problems such as a rise in helium temperature or a loss of helium level in the magnet. Thus, the magnet vacuum interlock has been altered to only prevent initial ramp up of the magnet current; not to cause magnet trips once full current is reached. Deterioration of the magnet vacuum will automatically send an alarm to the operator for further investigation. Since this change has been made, no magnet trips have been caused by vacuum problems.

D. Control Programming Changes

The original design of the control system had all the critical control functions handled by the highly reliable Programmable Logic Controllers (PLCs) with the less reliable Windows PCs serving as the operator interface. However, there were rare cases in which the crashing of a PC would result in the ramp down of the magnet. Changes in the control program have eliminated this possibility. Now any of the PCs may crash and be rebooted without affecting the magnet operation.

Hardware and software filters have been installed to prevent nearly all instrumentation noise spikes from causing a ramp down or fast discharge of the magnet. The exception to this is the hardware based quench detection system. This system does not have any filters in order to ensure magnet safety.

E Training

Regular training classes are held to familiarize cryogenic operations technicians with the proper operation of the BaBar solenoid system. These classes also result in the production of written procedures and documentation. While human error can not be completely eliminated, these classes will help reduce the problem.

The impact of these mitigations over time can be seen in Fig. 2 and Fig. 3. Fig. 2. shows the frequency of magnet interruption on a monthly basis from the start of the experiment until now. Note that there were roughly between one and two interruptions per month until late 2003 (the blank areas in the summer of 2000, 2001, 2002 and fall of 2003 indicate times when the magnet was shut down during BaBar maintenance). After the maintenance period in the fall of 2003, the rate of interruption was noticeably improved. From September to mid December 2003 there were only four interruptions, two of which were due to site power failures. From January to August 2004, there were only four interruptions, one of which was due to a site wide power failure. In 2004 so far, there has been one period of 3 months and one period of 4 months during which there were no interruptions to magnet operations.

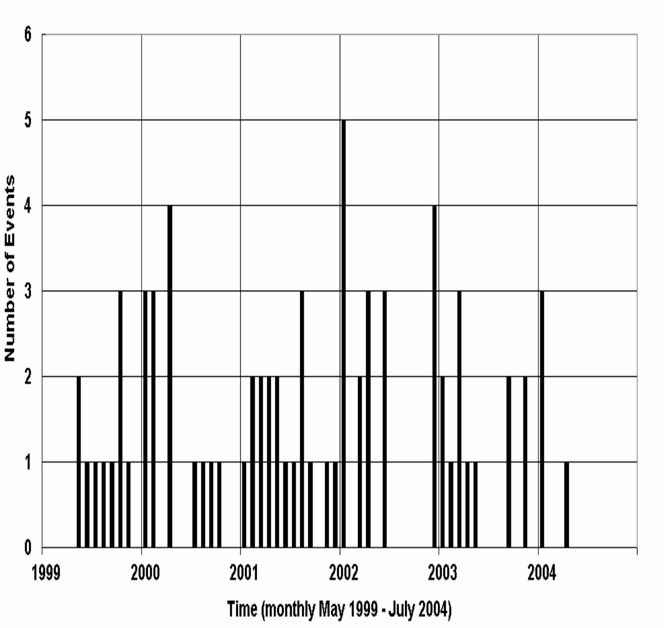

Fig. 2. Number of magnet interruption events per month over the current lifetime of the BaBar experiment.

More telling is Fig 3., which shows the number and causes of the interruptions as a function of year. Notice that after 2001 there are no interruptions caused by strain gage faults, that after 2002 there are no interruptions caused by the cryogenic system or the PCs and that after 2003 there are no interruptions caused by the vacuum systems. This shows the impact of installing backup systems, changing the control programming and removing unneeded interlocks. Notice also that the total number of interruptions in 2004 is significantly less than in previous years and if we can keep the interruptions down to our current level, it will be the best performing year so far. Whether this can be done depends on continued careful operation and some luck as site wide power failures are completely beyond our control.

IV. AVAILABILITY

Since the exact length of down time per magnet interruption has not been consistently recorded, it is hard to calculate an exact availability for the BaBar solenoid. However, some estimates can be made. The BaBar experiment ran for 9.5 months in 2000, 2001, and 2003 and for 8.5 months in 2002. Using the total number of magnet interruptions shown in Fig. 3 for each of those years and assuming that each interruption costs 8 hours of operations time (this is conservative, actual interruptions typically last 2 to 4 hours) the magnet availability in 2000, 2001, and 2003 is between 98% and 99%. In 2002 the availability was 97.8 %. In the case of the 7 months of operation to date in 2004, the magnet availability is greater than 99%.

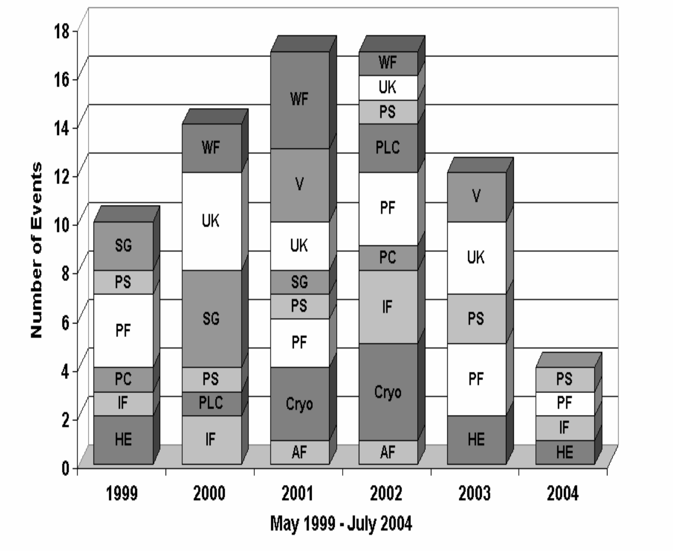

Fig. 3. Number and cause of magnet interruptions as a function of year for the BaBar experiment to date. Note that various types of failure modes disappear as time progresses.

V.FUTURE IMPROVMENTS

All the valves in the BaBar cryogenic system are pneumatically actuated and supplied by the SLAC instrument air system. If the instrument air system fails the valves will close and all cooling of the magnet will stop. This fall a backup air supply system will be installed so that even if the SLAC system fails, magnet operations can continue. In addition to this improvement, there is an ongoing program of component maintenance and upgrades to maintain the current high level of magnet availability. Examples of this include a project slated for the summer of 2005 to simplify the piping in the helium compressor facility and software upgrades to the control program.

VI. CONCLUSION

A historical survey of all of the unplanned interruptions to operation of the BaBar superconducting dipole has been conducted. Failure modes have been identified and this information has been used to reduce the interruptions and thus improve magnet availability. The estimated availability has increase from between 97.8% and 99% in 2000 – 2003 to more than 99% in 2004. In addition, entire failure modes have been eliminated through the use of back up systems and the reevaluation of interlocks. It should be noted that there was no single “magic bullet” that led to these improvements but rather a consistent identification and elimination of weak points in the system. These efforts are ongoing.

ACKNOWLEDGMENT

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