A Comparison of the Availability and Failure Modes of the BaBar Superconducting Solenoid with Similar Magnets at Other High Energy Physics Laboratories

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ABSTRACT

A Comparison of the Availability and Failure Modes of the BaBar Superconducting Solenoid with Similar Magnets at Other High Energy Physics Laboratories. MALLORY A. KNODEL, *Drake University, Des Moines, Ia 50311* and Dr. J. G. WEISEND II, *Stanford Linear Accelerator Center, Menlo Park, Ca 94025*

One of the key technologies in the BaBar detector is the 1.5 T superconducting solenoid. It is imperative that this device operate reliably at its nominal current to allow data taking. While this system is available for physics 98.8% of the time, further improvements are desirable. The object of this project is to survey similar magnet systems, for example those at KEK (Belle), Fermilab (D0 and CDF), DESY (H1 and ZEUS), and CERN (ALEPH and DELPHI), to see how often such magnets stop functioning properly and what the root causes of the failures are. A survey was carried out via e-mail and telephone calls. Information was obtained regarding the operation of superconducting magnets, specifically the BaBar magnet and its ancillary systems, as well as an overview of the use of other such magnets both in the US and overseas. In this work, failure modes will be investigated and compared to the BaBar operational experience. Future investigations can now assess the feasibility of reducing the time the BaBar magnet is nonoperational and unavailable for physics research.

INTRODUCTION

At the Stanford Linear Accelerator Center (SLAC), the BaBar detector was built to study B meson decays produced in the PEP-II storage ring. As part of the BaBar detector, a 1.5 Tesla magnetic field is created by a large superconducting solenoid. This magnetic field separates the charged particles created in an interaction. Other layers of the detector identify and examine the particles, so this magnet must be very transparent, or thin. Coupled with this magnet system is a cryogenic plant, which cools the solenoid so that it remains superconducting. These two components, the helium liquefier and superconducting magnet, are a system that must be closely controlled and maintained at a high level of reliability for the operation of BaBar.

The BaBar detector has been in operation for over three years with few, if any, major shut downs. Many system failures can stop detection, and many of these systems do not fail synchronized with one another. There is, then, a constant pursuit of flawless operation for each system involved in the BaBar detector. In this paper, the operating history of the BaBar solenoid is examined and compared to similar magnets worldwide. Based on this information, additional improvements to the BaBar magnet system are proposed.

First, initial contact was made with other High Energy Physics facilities that have had experience with a detector magnet similar to BaBar's. Next, the failure modes of the BaBar magnet were examined in detail. Interviews were conducted via e-mail and telephone to gather additional information on other magnets.

MOTIVATION FROM BABAR

A comprehensive investigation will produce a consolidated reference and testimony to the progressive and necessary changes made to the magnet and cryogenic system. This close examination of the failure modes of the BaBar magnet proves to be a useful undertaking because,

although the BaBar solenoid operation is conventionally good at 98.8% availability, it reveals issues that should be addressed. Evaluating the magnet's operational history relative to similar HEP magnets is also of interest.

A. Understanding the BaBar Magnet

Resources that carefully document the operational experience of BaBar are very useful in determining what the failure modes of the magnet are, how problems were fixed, and which systems still cause unexpected failure. These documents include logbooks from the various control rooms that operate the magnet and cryogenic systems. For the Experimental Facilities Department, this succinct review of the magnet's major events provides an overall understanding of how and why BaBar is operating as it currently does.

B. Other Magnets

By surveying similar magnet systems, such as the BELLE detector at KEK, CDF and D0 at Fermilab, H1 and Zeus at DESY, and ALEPH and DELPHI at CERN, a comprehensive assessment of the BaBar solenoid can improve operational modes. We can use other facilities' operational experience to scale our own and to define clear ways in which problems can be solved and run-time increased with maximum efficiency.

ANALYSIS OF BABAR FAILURE MODES

The BaBar 1.5 Tesla superconducting solenoid has been in operation since 1999. The superconductor and liquefier system have been operating with high reliability, a fault about once a month on average. The main cause for the magnet to fail is utilities such as power, water, and air. Less than four hours is required for quench recovery.

The solenoid, liquefier, and compressor are monitored by operators remotely. Experts are automatically notified in the event of a ramp down or fast discharge. Data was obtained from

logbooks entries recorded between May 1999 and May 2003.

Types of failure modes and their contribution to the magnet's total unexpected down time are in Figure 1. More details of the magnet's events are listed in Table 1. A time-dependent analysis of the magnet's failure events is shown in Figure 2 and Figure 3.

Each failure mode has been addressed and solutions have been found or are in progress. Operating experience, upgrades, and cause/effect of some common failure modes are discussed below.

A. Human Error

These problems are rare. Nevertheless, the magnet can, without prior notice, ramp down or quench if an operator makes a mistake. There is an ongoing effort to improve operator training.

B. Strain Gage

A strain gage is a software interlock. It trips when external forces deform the magnet and its surrounding support mandrel. This alarm would formerly cause the magnet to ramp down, or slow discharge. So far, all trips have been due to strain gage failures. The real necessity for the strain gage interlock occurs mostly when the magnet is ramping up (i.e. to protect from a case when supports are improperly installed). The interlocks now are set only to prevent ramping and they no longer cause a ramp down.

C. Power Failure

A power failure refers to electrical power outages, e.g. during lightening storms. Because this problem is often site-wide, the magnet and cryogenics are not the only systems to experience a breakdown, PLCs and PCs are backed by an uninterruptible power supply (UPS) for protection. A power failure often shuts down the cryogenic plant (see Miscellaneous Cryoplant and Compressors), which often results in a ramp down or fast discharge of the magnet.

D. Magnet Power Supply

Normal power supply operations can be interrupted by cooling water failure, ground fault, and especially spurious electrical noise, which will cause the power supply interlocks to trip resulting in the magnet ramping down. This specific problem is mostly unpreventable.

E. Water Failure

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

F. Instrument Air System (IAS)

All valves in the system are pneumatically driven and the system will ramp down if the IAS fails. A backup air system is in a design phase.

G. PC Failure

Two PCs control the BridgeView programs for the magnet and liquefier systems. A third PC serves as a back up for either of these computers' BridgeView displays. Previously, a PC #1 failure, and consequently a BridgeView failure, would cause a ramp down. Now, under no circumstances will a PC failure interrupt normal operations.

H. PLC Failures

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

I. Vacuum

One of the resident vacuum systems is for the magnet itself. Failures in the vacuum results in high pressure and causes a ramp down. To prevent ramp downs, the hardwired pressure interlocks are set for a high value and the software interlocks are time delayed to protect against spikes in pressure readings. Two fully redundant vacuum pumping systems are connected to the magnet cryostat.

J. Miscellaneous Cryoplant and Compressors

If the Cryoplant system or compressors were to malfunction and shut down, the magnet would ramp down or fast discharge due to a temperature rise in the superconductor. To alleviate this problem, an ongoing upgrade takes advantage of a 3000 Liter LHe reservoir that is capable of cooling the magnet and maintaining operations for 24 hours.

K. Miscellaneous Instrument Fault

Sensors reading out incorrect information cause this problem. Solutions to this problem are replacing faulty sensors and installing timers prevent transient spikes from shutting down the magnet.

L. 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.

A review of the BaBar operating history shows roughly one failure per month. Most BaBar magnet downtimes are 4 hours or less. Assuming a worst case event of 8 hrs downtime per 30

day month this translates into a average availability (defined here as time magnet system is functioning properly/total time per month) of $712\text{hr}/720\text{ hr} = 98.9\%$. While this is good, we should do better and a number of improvements have been made since 1999 or are planned to address these problems. These improvements are:

1. All critical control and interlock functions have been removed from the PC/WindowsTM systems. Crashes and problems with the Windows operating system or the LabView software will no longer result in an interruption of magnet operations.
2. The strain gage interlocks have been changed to only prevent ramping up of the solenoid. Problems with strain gages will no longer cause the magnet to ramp down.
3. All software interlocks now have timers on them to prevent noise spikes or transient sensor failures from causing failures in the magnet system. This has eliminated a number of the instrumentation faults. It has been judged too risky to install similar delays on the hardwire interlocks.
4. Additional piping and valves should be in place by September 2003 to allow the cooling of the solenoid by the 3000 liters of stored liquid helium even if the entire refrigerator and helium compressors shut down. This should allow us plenty of time (roughly two days) in which to restart the refrigerator system.
5. Before the end of 2003, a backup air supply system (modeled on that used at the Fermilab D0 solenoid) will be in place. This coupled with item 4 should eliminate failures in the air system as a cause of magnet failure.

Taken together, these changes should eliminate 27% of the historic magnet failure modes and greatly reduce the impact of utility failures. The BaBar magnet system will still be susceptible to utility failures at the experimental hall and the main magnet power supply.

OTHER SUPERCONDUCTING MAGNETS

It is important for us to understand how BaBar performs relative to other HEP systems. In talking with representatives from major accelerator facilities worldwide, similarities and differences in the systems lent perspective on BaBar's status among other detectors of its kind around the world.

Not only was making a comparison easier, but also specifically mechanical and engineering difficulties were clarified. The BaBar magnet experiences problems that have already been solved for other systems and that is obviously useful to us. In addition, where there are common threads and recurring themes, conclusions can be drawn about the efficiency of a superconducting magnet system for a HEP detector.

Following is a brief description of each thin superconducting solenoid at these HEP facilities and how they have encountered and corrected relevant failure modes.

A. KEK

The BELLE solenoid has run in conjunction with the KEKB experiment since 1998. It runs for two, 5-month periods each year. The magnet unexpectedly shuts down about once every period. The main causes are cooling water suspension and power failure.

Charging the system through UPS has proved to be very useful. Because the operational sequence at BELLE is not optimized, a quench recovery can take between 8 and 16 hours.

The system is always staffed to operate and maintain three cryogenic plants (solenoid, quadrupole, and sc cavity), vacuum pumps, power source, and magnet. Remote monitoring is also utilized and interlock parameters and time delays are easily controlled through a distributed control system (DCS).

B. Fermilab (CDF & D0)

Collider Detector Facility (CDF): The magnet is on all of the time, except during periodic, 7- to 10-day maintenance checks. In 2.5 years, the magnet has only quenched or unexpectedly ramped down five times, excluding interruptions caused by site-wide power outages.

If the entire site loses power, it is faster and easier to recover the magnet than it is for other detector systems. In light of this, it is not necessary to invest money in to a backup for the He plant.

The magnet can be monitored online as part of a private controls network with limited access outside the site. Few people can actually utilize this online source of information. The magnet's logbook is electronic and online.

Not all system interlocks, such as strain gages, are monitored and this depends on the state of the magnet. For example, some interlocks are only useful for when the magnet is ramping up, so during normal operation these interlocks do not serve a purpose.

Outstanding problems for CDF include water flow switches and aging power supply filters. Time delays are continuously adjusted to optimize interlock performance.

D-Zero: The D0 detector began in March 2001. The magnet unexpectedly fails two to three times per year. It has fast discharged five times total. Less than 20 minutes is required for a full quench recovery. Power outage is the biggest problem for the magnet's operation.

D0 operators monitor the magnet, liquefier, and vacuum systems. Although it is possible to monitor remotely and an auto dialer program notifies experts of alarms, the systems are always attended.

A PLC controls the hardwired and software interlock system. Cryogenic permit interlocks have 1-minute time delays on LHe subcooler level, control dewar insulating vacuum, LHe mass flow

rate to magnet, and coil temperature. Electronic interlocks, which are delayed on the order of seconds, are primarily implemented in the power and safety systems.

The PLC is backed up with UPS and diesel generators. Spare PLC modules are also available as backup units. The control system interface is backed up to ensure operator control. The compressors in the liquefier system are not backed up; however, a 3,000 L dewar of LHe can cool the magnet in case the cryogenics plant is shut down. High-pressure air is stored to back up air compressors.

C. CERN

DELPHI: The DELPHI experiment ran from 1989 to 2000. Operators were responsible for the magnet and liquefier systems, for which one on-call operator was necessary. In the beginning, quenches would occur while the magnet slowly ramped down. It was found that this problem was caused by a small unbalance in the resistivity of the current leads on the input and output ends, which triggered the sensitive quench detection circuitry. UPS backed the magnet control's power supply.

D. DESY

H1: The H1 detector has been in progress since 1991. It unexpectedly stops about once a year with 50% of shutdowns due to cryogenic failure. No software interlocks are used in the system, only hardwired. In case of a dump, four persons are on call. There is a remote monitoring system in place.

CONCLUSION

The operating history of the BaBar magnet has been consolidated, focusing on major shutdowns. This review of operation and failure modes has provided a point of reference for those working in EFD and for the BaBar collaboration. Those working in EFD to organize and

improve the operation of the magnet and cryogenics systems will use the data compiled in this paper throughout the future operation of BaBar.

For thorough examination, BaBar was matched against other detector magnets of its kind. From this comparison, some solutions for BaBar's failure modes have been found in other systems and utilized. Contacts for other magnet systems were made, opening the door to further contact and exchange.

Future improvements of the magnet and cryogenic systems will continue to provide optimal run-time for BaBar and the B-factory experiment.

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TABLES

TABLE I: BABAR MAGNET EVENTS

Events are listed in chronological order. Results are the type of event, how the magnet reacted. Short summaries are based on logbook entries. Abbreviations of root causes are listed in Figure 1.

Date	Time	Result	Reason	Cause
24-May-99	14:50	ramp down	erroneous termination of PC #1 bridge view program	HE
27-May-99	22:00	ramp up interrupted	strain level 1 alarm	SG
1-Jun-99	9:39	ramp down	axial tie rod TS21 failed, strain gage tripped first	SG
21-Jul-99	19:25	ramp down	HT01 > 5K	IF
3-Aug-99	4:50	ramp down	thermo-siphon mode accidentally engaged, magnet warmed up	HE
9-Sep-99	1:47	fast discharge	site-wide power outage	PF
3-Oct-99	4:42	fast discharge	main power supply problem	PF
21-Oct-99	12:03	ramp down	PC #1 bridge view problem	PC
23-Oct-99	20:46	partial ramp down	power supply	PS
20-Nov-99	9:25	fast discharge	power outage	PF
8-Jan-00	17:18	ramp down	HT01 temperature spike	IF
9-Jan-00	13:46	ramp up interrupted	water leak caused cooling system failure	WF
24-Jan-00	7:35	ramp down fast discharge	hardwire trip / hardwire #1	UK
3-Feb-00	12:30	ramp down	requested to investigate false reading	IF
3-Feb-00	19:25	ramp down	strain gage software followed by series of alarms	SG
18-Feb-00	10:20	partial ramp down	CHF PLC breaker accidentally tripped	PLC
9-Apr-00	22:20	ramp down	ground fault alarm	PS
11-Apr-00	12:35	fast discharge	PC 15 began manual mode	UK
12-Apr-00	0:52		PC 15 began manual mode	UK
18-Apr-00		ramp down	magnet trip due to water supply	WF
26-Jul-00	18:15	ramp down	magnet strain interlocks	SG
1-Aug-00	4:30	ramp down	level 1 & 2 trips, strain gage	SG
20-Sep-00	5:50	ramp down	level 2 magnet strain interlocks	SG
30-Oct-00	12:27	fast discharge	hardwire #1	UK
24-Jan-01	8:50	ramp down fast discharge	power supply / LHe level, power outage	PF
9-Feb-01	2:45	fast discharge	HW trip on vacuum	V
11-Feb-01	2:20	fast discharge	power outage	PF
28-Mar-01	2:55	ramp down	per MCC due to water supply	WF
31-Mar-01	3:35	ramp down	per MCC due to water supply	WF
14-Apr-01	22:32	fast discharge	HW #1 trip (PC #2 bridgeview?)	UK
14-Apr-01	16:00	fast discharge	water booster pump failure caused trip due to	WF

4-May-01		ramp down fast discharge	high temperature FI-164 dropped, vacuum interlock	V
16-May-01	9:00	ramp down	reason unknown	UK
15-Jun-01	16:04	ramp down	bad AC breaker / power supply	PS
3-Jul-01	5:00	fast discharge	hardwired vacuum interlock	V
2-Aug-01	13:25	partial ramp down	cold box trip	Cryo
20-Aug-01	8:45	fast discharge	low water to power supply	WF
23-Aug-01	12:30	ramp down	strain software interlock	SG
16-Sep-01	9:00	ramp down (glitch)	ran out of LHe due to air supply	AF
1-Nov-01	16:45	ramp up interrupted	LHe supply	Cryo
2-Dec-01	1:00	ramp down	liquefier and compressor shut down	Cryo
8-Jan-02	13:53	fast discharge	smoke VESDA caused power outage at IR2	PF
14-Jan-02	13:38	ramp down	PLC #1 failed and compressor control lost	PLC
20-Jan-02	21:40	ramp down	requested because sullair 1 stopped	Cryo
28-Jan-02	15:56	ramp down	HT81 too warm	Cryo
29-Jan-02	10:00	partial ramp down (3000A)	warm gas caused software trip	IF
20-Mar-02		fast discharge		WF
26-Mar-02	7:45	ramp down	sullair 1 trip	Cryo
4-Apr-02	23:44	ramp down	air supply	AF
13-Apr-02	0:00	ramp down	LHe supply	UK
30-Apr-02	13:43	partial ramp down	PC #1 restarted	PC
9-Jun-02	10:23	ramp down	power supply / HW #1 tripped / ctrl intlk	PS
		fast discharge	failure	
14-Jun-02	5:15	fast discharge	power supply opened dump breaker	PF
26-Jun-02	9:55	ramp down	temperature spike in HT81	IF
		fast discharge		
14-Dec-02	18:50	fast discharge	cryogenic shutdown caused by lightening storm	PF
15-Dec-02	10:30	ramp down	level 2 interlock, magnet temperature	Cryo
18-Dec-02	16:10	ramp down	temperature spike in HT81	IF
21-Dec-02	23:25	ramp down		PLC
6-Jan-03	7:55	ramp down	s.w. interlock test but error on recovery	HE
24-Jan-03	17:15	ramp down	liq. alarm, "pushed red button", lead voltage trip	UK
20-Feb-03	15:11	fast discharge	vacuum spike during planned "change over"	V/HE
8-Mar-03	7:30		power outage	PF
13-Mar-03	18:07	ramp down	power supply tripped, interlocks 1 & 2 on cryo tripped	PS
14-Mar-03	17:25	ramp down	same as above	PS
1-Apr-03	3:40	ramp down	lead B voltage level 2 trip	UK
20-May-03	23:29	ramp down	vacuum trip and fault in system B	V

TABLE II: SOLENOID PARAMETER SUMMARIES

Data was obtained through published references and direct correspondence. Note that the schematics are very similar for all of the magnets, yet the controls systems and operations are very different.

	units	BaBar	BELLE	CDF	D0	DELPHI	H1	ZEUS
begin		1999	1999	1988	2001	1989	1992	1992
end		ongoing	ongoing	ongoing	ongoing	2000	ongoing	
size (diameter x length)	m	2.8 x 3.7	3.7 x 4.41	3.105 x 5.067	1.42 x 2.73	5.2 x 7.4	6 x 5.75	1.88 x 2.46
field	T	1.5	1.5	1.5	2	1.23	1.15	1.8
current	A	4596	4000	5000	4820	5000	5517	4987
stored energy	MJ	27	36.8	30	5.6	110	120	10.4
cooling		indirect, forced flow two- phase LHe	indirect, forced flow two- phase LHe	forced flow two- phase LHe, forced flow LN	indirect, forced flow two- phase LHe	indirect, forced flow two- phase LHe	indirect, forced flow LHe	indirect, LHe
control system		PLC & Windows PC running LabView			PLC & Windows PC with Intellution IFIX			
detection and interlocks		hardwired & PLC	hardwired & DCS	hardwired & PLC on UPS and gen.	hardwired & PLC		hardwired	
staffing		remote monitoring & manned	RM & manned	manned	RM & manned		RM & manned	
unexpected interruption frequency (per year)		9	2	2	3		1	
quench recovery	hr	~3.5	8 to 16	4	<20 min		4 to 6	

FIGURES

FIGURE I: FAILURE MODE CONTRIBUTIONS

Here is a break down of the categories of failures for the magnet. Type, number, and percent contribution are visible. The biggest contributor by looking at the chart is power failure; although the utilities combined (air, water, and power supply) make up the largest percentage at 23%. All events happened between May 1999 and May 2003. Noticing trends in time (Table I), this percent break down changes over time and now many of these problems have been eliminated.

FIGURE 2: UNEXPECTED DOWN TIME

This chart shows the number of events per year since the solenoid began operation in May 1999. On average, the magnet has been down once a month since BaBar began taking data. Over the total time studied, there have been 66 events.

FIGURE 3: UNEXPECTED DOWN TIME BY EVENT

As in Figure 2, this chart shows the number of events per year. Each failure mode has been separated out. Notice as some problems are fixed over time, such as strain gage failure, they do not appear in later years. Other problems such as power failure, which are site-wide problems, are evenly distributed in general. (See legend in Figure 1.)