INJECTOR POWER SUPPLIES RELIABILITY IMPROVEMENTS AT THE ADVANCED PHOTON SOURCE*

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Abstract

Operational goals for the Advanced Photon Source (APS) facility include 97% availability and a mean time between unscheduled beam losses (faults) of 70 hours, with more than 5000 user hours of scheduled beam per year. To meet this objective, our focus has been maximizing the mean time between faults (MTBF). We have made various hardware and software improvements to better operate and monitor the injector power supply systems. These improvements have been challenging to design and implement in light of the facility operating requirements but are critical to maintaining maximum reliability and availability of beam for user operations.

This paper presents actions taken as well as future plans to continue improving injector power supply hardware and software to meet APS user operation goals.

OVERVIEW

The Advanced Photon Source (APS) has two major components. The storage ring (SR) accelerator is the primary accelerator that delivers X-ray beams to users and uses over 1,400 power supplies. The injector accelerators provide beam to the SR and use 361 different supplies. The control system ranges from the standard VME-IOC and Allen Bradley to GESPAC with additional mini-PLCs for monitoring. Injector power supplies range from ~30 watts DC to a ramped peak of 4.6 megawatts in 250 ms. Finally, all accelerators use pulsed supplies, and some of them deliver peak power in megawatts.

In the SR, each multipole and corrector magnet is separately powered, with only the main dipole magnets on a common bus [1]. Independent power supplies provide increased flexibility, but place additional demands on power supply reliability. The APS reliability goals are 97% availability and 70 hours mean time to unscheduled beam loss. There are 5,129 user hours scheduled per year, 1,315 hours used for machine studies, and the remaining 2,316 hours used for maintenance. The present annual operating schedule provides for three user runs (typically 10 to 12 weeks long), and three machine shutdowns (typically 3 to 5 weeks long). There is one 48-hour period, one 16-hour period, and one 8-hour period of machine studies/intervention for every three weeks of user operation.

Reliability goals for the magnet power supply systems are 99.1% availability, with a mean time between beam losses of 240 hours. This goal translates to a required mean time between power-supply-related beam trips during top-up operations (MTBF) of better than 422,640 hours for each magnet power supply. The failure of any SR magnet power supply can cause loss of beam or, in the injector, prohibit top-up operation [2].

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THE METHODOLOGY

The Objective

The implementation of improvements is particularly challenging because of the variety and number of power supplies involved. In addition, there is potential to create new problems by simply disturbing the equipment. In the following discussion we will focus on the injector.

We have used a three step approach. First, we look at the historical data and determine what will give us the most improvement for the effort. Second, we observe where we are now and determine if we are proceeding correctly, since inadvertently small changes can have catastrophic results. Third, we develop an outline that specifies where we want to go and use this as our guide for implementing specific actions.

The Historical Data

Statistical data on injector availability come from two sources: detailed records maintained by the APS Operations Group, and information maintained by the APS Power Supply Group on equipment failures and repairs that is also used for power supply reliability.

Table 1: Injector Overall Statistics

	Scheduled User Hours	Top-up Injector Availability	Yearly totals
Run 00-4	1000.1	90.2%	90.2%
Run 01-1	1528.2	97.8%	
Run 01-2	1240.0	98.0%	
Run 01-3	1232.0	98.5%	
Run 01-4	1120.0	91.9%	96.6%
Run 02-1	1927.0	95.6%	
Run 02-2	1952.0	97.1%	
Run 02-3	1449.0	99.3%	97.3%
Run 03-1	1647.0	94.9%	
Run 03-2	1816.0	98.5%	
Run 03-3	1666.0	97.6%	97.0%
Run 04-1	1647.0	97.5%	
Run 04-2	1912.0	98.7%	
Run 04-3	1570.0	98.9%	98.4%
	TOTALS	96.7%	95.9%

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Table 1 shows yearly availability statistics for fiscal years 2000 through 2004 with percentage of available beam. One sees that power supply performance and reliability are major contributors to the machine availability.

Current Observations

We have made incremental changes in several areas that require monitoring, and some proposed changes are in development. Over the past three years we have become more proactive in our approach to reliability through maintenance. One of the areas we have reviewed is the grounding of the power supplies and their associated magnets. The APS has a ground grid with cables brought up through the concrete at multiple locations and bussed through the facility. This review was targeted to reduce conducted noise that was affecting other equipment. Using a micro-ohm meter, we found a few connections with higher than expected resistance. All connections have since been reworked.

An area of scrutiny has been the particle accumulator ring (PAR) kickers. The kickers create large amount of electromagnetic interference (EMI) and sometimes can affect other equipment like the beam interlock and current monitoring system called the beam emergency shut-off current monitor (BESOCM) [3]. We have made several changes to the kickers as well as other equipment susceptible to EMI. Improvements range from grounding to rewiring of the instruments. The PAR kicker supplies are undergoing a redesign to address the need to reduce EMI, increase serviceability, and increase maximum operating limits. The servicing of the pulse forming network (PFN) cables is very time consuming; it takes an average of 12 hours to replace a cable. Thus, serviceability along with the EMI has motivated this redesign which is expected to be completed in FY2006.

There have been numerous changes throughout the injector. Changes range from adding diodes for noise reduction on control cards to exchanging the output filter capacitors in the booster quadrupole power supplies where the original caps would overheat from the ripple currents. The replacements are of a different type (film) and support higher ripple current.

The septum power supply regulation needs to be modified to improve the beam injection into the storage ring. The septum power supplies are pulsed power supplies that produce a half-sine-wave voltage output. The voltage pulse produces a current pulse through the septum magnet [4]. It is in the areas of voltage and current regulation that we have identified the need for improvements. For example, thermal drift is presently compensated using software feedforward. The close-loop feedback current regulation to compensate for this drift is under development [5].

There has been an effort to improve the control software and the user interface of the supplies. From an operational standpoint the conveyance of information is important. In early 1993 just after the injector commissioning period, operators manually initiated and monitored all the injector lattice components for beam transport in the linac, PAR, and booster using multiple Motif Editor and Display Manager (MEDM) screens. Starting up and conditioning power supplies and ensuring all the magnets conditioned properly was very time consuming.

About five years ago the demands on the injectors increased, due mostly to the introduction of top-up mode in the SR. In this mode, a small amount of beam is injected every two minutes to maintain SR beam current at 100 mA. Initially, some small shell scripts were written to perform various tasks automatically such as turn on and conditioning. Although the scripts worked well, they were not always reliable because changes to machinery and operational procedures were being made without advice from of the Power Supply Group. Also, most of these scripts were not regulated and did not have any error checking capability.

A combined effort between the Power Supply Group and the Operational Analysis and Operations Groups was undertaken to develop software to manage the various power supply systems. We now have a robust interface control system as well as software to automate equipment start up, shutdown, and conditioning. This new software, known as the Procedure Execution Manager (PEM) [6], has the ability to verify that the conditioning process has performed successfully. In the event a power supply does not turn on, or fails a prescribed conditioning or standardization routine, an error message will be generated to inform the operator.

The PEM is a graphical interface script system that permits the user to execute machine procedures and monitor their execution. Machine procedures are designed to take any accelerator system or subsystem from an initial state to a final state in a well-defined set of steps. Machine procedures serve the important function of standardizing the normal operation of accelerator systems. The power supplies are one system that makes use of the PEM. Machine procedures can be run in series or parallel, thereby allowing many systems and subsystems to be configured at once, which saves time. Machine procedures have been written to configure many different systems for each APS accelerator. Each machine procedure can log its activity so that if there is an error generated during execution, the cause can be easily and rapidly diagnosed.

Figure 1 shows the high-level flow diagram of a machine procedure. The machine procedure normally follows the steps outlined in black. The three principal steps of each machine procedure include determining the initial state, configuring the system based on the initial state, and finally bringing the system gracefully to its final state. If an error is detected during any one of these steps, execution proceeds along one of the red paths shown in Figure 1. Each red path shown in the figure includes steps designed to remediate the error or fault that originally generated red path execution. If the system fault cannot be cleared after a certain number of attempts,

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the system is put into a safe state and execution is terminated. Not surprisingly, most of the software complexity and testing is focused on error remediation or red path execution. This is because each power supply system typically can fault in many different ways, and there are different steps required depending on the exact nature of the fault.

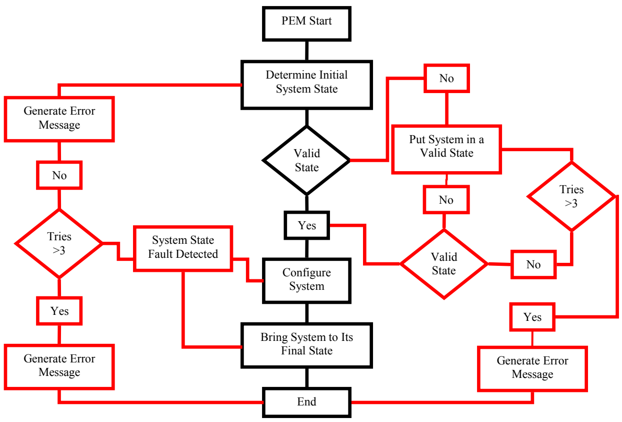

Figure 1: PEM machine procedure high-level flow diagram.

Machine procedure development to date has concentrated on handling the most common system faults that could cause equipment damage if not reset correctly. A good example is the machine procedures used to configure the booster main ramped power supplies. The booster supplies are the only ones that ramp from low to high power during normal operations. These supplies are particularly susceptible to damage due to improper configuration of the various regulator and ramping parameters. The machine procedures have extensive configuration error checking that even includes ramp waveform processing to determine proper functioning of the power supplies. Present booster machine procedure software efforts are aimed at including ever more complex error (red path) processing to handle more subtle and complex fault conditions. Improving error handling is also an ongoing effort for all accelerator system machine procedures.

Future Goals

We plan on having a few high-value projects completed and installed in the near future. As discussed, we expect the PAR kicker redesign will yield a higher operating range for the supply, with increased reliability. We have performed simulations to identify EMI sources and are taking action to reduce EMI to a tolerable level. If a failure in the PFN cable does occur, the time to repair will be reduced by 75% with greater interchangeability of parts. The septum supplies will meet the expected shot-to-shot regulation of 1/2000 and are likely to exceed it. Thermal drift is expected to be minimized while keeping the reliability we currently have. The PEM machine procedures have increased the ease and consistency of control and configuration of the supplies. More PEMs will continue to be developed to add more subtle error checking and fault remediation in the future.

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