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Status Update of the Power Conditioning System in the National Ignition Facility

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ABSTRACT

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory operates the world's largest and most energetic laser. The facility supports studies of high energy density physics with the ultimate goal of achieving ignition and energy gain for the first time in a laboratory setting. The success of its mission depends heavily on key subsystems like the power conditioning system (PCS), where near 100% availability is required in supporting 24/7 laser operation.

The 192 modules of PCS store and then deliver approximately 400 MJ of electrical energy to the laser amplifiers. The sheer number of modules coupled with the aggressive shot schedule present a challenge for both preventive maintenance and the implementation of engineering changes. Because the system comes into play very late during the shot process, it is extremely important to minimize the number of occurrences and duration of reactive maintenance activities. We will discuss PCS performance, training and maintenance strategies, along with a series of development and upgrades that will help assure long-term system reliability and availability while supporting NIF's missions.

1 INTRODUCTION

The 192-beam NIF laser has been fully operational since early 2009. In its role as a "target shooter" it is used to support experiments for the stockpile stewardship, high energy density physics, basic science and inertial fusion. The 10-meter diameter target chamber, equipped with dozens of state of the art diagnostics, is the final destination of the NIF 192 laser beams. The facility has achieved a number of records: compression of a diamond sample to a pressure of 50 megabars (50 million times Earth's atmospheric pressure); the most energetic ultraviolet laser pulse ever produced at 1.875 MJ. The primary near-term goal is to use the NIF laser to achieve ignition by delivering energy from its beams to a pea-sized deuterium-tritium target.

NIF depends on several key systems in order to achieve its mission. The power conditioning system (PCS) is among them.

2 DESCRIPTION OF THE POWER CONDITIONING SYSTEM

The Power Conditioning System (PCS) stores and then delivers approximately 400 MJ of electrical energy to the nearly 8000 flashlamps installed in the main and power amplifiers of the NIF laser. Light from the flashlamps pumps the laser slabs in the amplifiers, providing the gain necessary to deliver high power/high energy laser pulses to a target.

2.1 SYSTEM DESIGN

Electrical energy is distributed to the main and power amplifiers on coaxial cables emanating from the four capacitor bays located within the NIF facility. Each 1150 m^2 capacitor bay supports one cluster (forty-eight) laser beams. The bays are then subdivided into 6 bundles with each bundle comprising eight power conditioning modules that in turn support eight beam lines. Each of the 192 power conditioning modules is capable of storing and then delivering up to 2 MJ of electrical energy to 20 pairs of flash lamps in a critically damped 400μs pulse characterized by a peak current greater than 500 kA. Thus, peak power for the system is ~1TW and peak current exceeds 100 MA. It should be noted that a lower energy pre-ionization pulse is delivered 300μs before the main pulse in order to prepare the flash lamps for the main energy discharge.

The main and power amplifiers are used in a so-called 11-5 configuration, meaning that 11 slabs are used in the four-pass main amplifier while 5 slabs are deployed in the two-pass power amplifier. (See figure 1.) Two additional slabs can be added to the power amplifier if needed. Each PCS bundle has a reserved location for a ninth module that would be used to drive the flashlamps pumping the additional slabs.

During a shot sequence, the PCS system is remotely controlled from the NIF control room. PCS operators monitor the performance of the system, which is controlled by the shot supervisor layer communicating through front-end processors to embedded controllers (in the individual modules) over fiber optic links. Before a system shot, the operators verify the participation of the PCS modules, and then during the shot sequence the PCS system performance is relayed to the operators through top level and lower level Graphic User Interfaces (GUI), which are part of the NIF Integrated Computer System (ICCS). The ICCS software allows the PCS system to be operated in two distinct modes, automatic and manual. The automatic mode is used for system shots, and executes well-defined sequences necessary to the shot; the manual mode allows troubleshooting and independent operations.

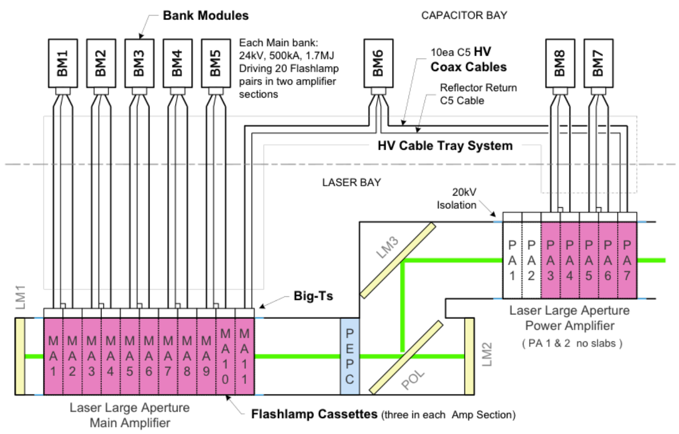

Figure 1. PCS System Diagram for a single Bundle

2.2 PERFORMANCE OF THE PCS SYSTEM

PCS has been very reliable, participating in more than 2000 system shots since 2007. The reliability goal was originally set at 92.01% and PCS has exceeded that goal for the last three years. The availability of the PCS system is kept at a high value by keeping tested working spares for most components in all four capacitor bays and having PCS trained operators/maintenance workers available around the clock. It should be noted that the availability data takes in account both reactive and preventive maintenance that occurs between systems shots. While the PCS system sits idle for a large fraction of the time (coming into play only during the last 3 minutes of a few hours long process system shot sequence) it must be ready to support shot operations on any shift. Due to the architecture of the laser, having a single module down in a bundle is almost certain to keep the entire bundle out of a shot, thus penalizing the system heavily for any failures.

Yearly Average for PCS		
Year	**Availability**	**Reliability**
2009	**96.39%**	**86.83%**
2010	**96.98%**	**95.15%**
2011	**93.31%**	**94.66%**
2012	**93.98%**	**95.67%**

Figure 2. PCS System availability and reliability

3 MAINTENANCE AND OPERATIONAL PHILOSOPHY

NIF operates 24/7. Shots may occur any time of the day or night. This factors heavily into the schedules, training and required competence of the workforce. In particular, the system must be manned at all times with individuals capable of operating and/or maintaining the system, depending on the facility status. Also, because of the amount of energy that is stored in the capacitor banks and the high voltage associated with the functioning of the system a wide range of worker safety hazards needs to be mitigated prior to any maintenance on the PCS system. In addition, the safety issues force most retesting to occur only when the facility is fully prepared ("swept") for laser operations.

3.1 MAINTENANCE DETAILS

All PCS operational problems are documented in problems logs, which are typically written by the system operators who are on duty when the problems occur. The PCS system manager is automatically notified about the problems and makes the decisions on how and when to address them, taking into account their relative importance and the existing shot schedule. For long-term repairs a restriction is issued on a specific module in order to notify operations that it is unavailable for shot participation during the time of the repair. The goal, of course, is to have the entire system available for every shot and the PCS team goes to great length to achieve that goal. The system manager, who is also a PCS engineer, is ultimately responsible for all work occurring on the PCS system.

All maintenance work scheduled on the PCS system has to be authorized under a specific work permit signed by the NIF work control office; this ensures final coordination of all work activities around the NIF facility and also assures that all safety planning has been properly completed. Once the work permit is released, a restriction is put in place on the equipment to be worked on so it can be seen as unavailable for shot operations and/or to signal that retesting will be required before actual shot operations can begin again. Only then can the maintenance work start under the supervision of the Daily Work Team Leader (DWTL) who is responsible for leading and monitoring the work and the team during all the phases.

The PCS maintenance team currently has nine qualified technicians who also double as PCS operators. (In addition, these same individuals also serve as operators for the Plasma Electrode Pockels Cell (PEPC) system. The quality of the operators/maintenance workers is a key to the success of these two systems. A typical PCS/PEPC operator is an electronics technician with a BSET or equivalent experience, often in the military.) These nine workers, split into 4 shifts, cover all 168 hours of a week. The PCS engineering team with three engineers and an engineering associate oversees all the maintenance and engineering associated with the PCS system, developing long-term solutions to existing problems.

Minimizing the downtime of the facility is always the top priority, and detailed maintenance plans must be synchronized with NIF operations. Maintenance must be constantly re-planned to keep up with the dynamic work environment and aggressive shot schedule. NIF has no repair facilities so an offline repair depot has been developed to effect major repairs and test most of the components that are used on the NIF PCS system.

Maintenance activities are split between preventive and reactive type of tasks. Reactive maintenance occurs in response to a specific problem that occurred during a shot. In addition to the immediate repair, the engineering team analyzes each occurrence in order to find systemic problems that could be eliminated by implementing upgrades to the system. Preventive maintenance consists of scheduled inspections and maintenance for components on which there is enough data to help predict failures. An example is the preventive maintenance done on the Main Energy Storage Module (MESM) spark gap switches, which are subject to erosion during each shot, ultimately affecting the seals in the switch. The erosion rate is well characterized (as a function of charge transfer) and monitored for all shots. Preventive maintenance consists of automated monitoring of total charge transfer, automated leak checks after each system shots, and close monitoring of the leak rate and charge transfer results. When a switch leak rate goes above a pre-defined threshold, a problem log is written and it is added to the "watch list" until a second threshold is reached, thereby initiating the refurbishment of the switch.

3.2 TRAINING AND SAFETY CONSIDERATIONS

As noted, each worker goes through an extensive amount of training before being able to work on or operate the power conditioning system. Qualification cards have been developed for all the specific training needed to work on the PCS system, with some of the cards taking many months to complete, even for skilled and experienced workers. Recently, the engineering team has stood up a "pulse power for technicians" training class to give the operator/maintenance workers a better understanding of the system and how it operates.

Maintenance activities are performed in accordance with approved procedures and checklists that are ultimately driven by the NIF amplifier power conditioning system hazard analysis and safety implementation plan and the NIF operational safety procedure document. Until workers are qualified for a task they must be supervised by a qualified worker. Training ensures not only the quality of the system but also the safety of the workers themselves.

Before starting any tasks, the DWTL, who is also a PCS operator/maintenance worker reviews the tasks and conducts a Safe Plan of Action (SPA), during which, each team member is informed of the scope of the work, the hazards and hazards mitigation. The DWTL will then leads the team to accomplish the work safely and reliably within the established guidelines.

3.3 SPARES

PCS is one of the last systems that come into play during a several hour long shot process. Despite all the preparation and maintenance, components can fail during this critical part of the shot sequence. In order to minimize the reactive maintenance times ready spares of the main components are maintained in each of the capacitor bays. In some cases a quick repair will allow the shot cycle to be restarted with little time penalty for shot operations.

For quality control assurance, each spare is tested in an offline test facility, whether it was serviced at LLNL or at a vendor location. This offline test facility is composed of a PCS module with the exactly same characteristics as the ones used on NIF. The test module is also used for training on the special hazards associated with high voltage components and is used to test new designs before they are fielded in the facility.

3.4 UPGRADES

The original design of the power conditioning system has been proven very reliable through the years. However, we are continually working to improve the system. Upgrades may be divided into three major categories as follows:

Control Software: The Integrated Computer Control System (ICCS) upgrades are developed and implemented by the NIF software engineers, working in collaboration with the PCS engineers and operators. These software upgrades are aimed to improve the functionality of the operations of the PCS system and also allow us to continuously implement new tools and diagnostics for the system.

Minor Hardware Upgrades: The minor upgrades, which are technical solutions easily implemented by the PCS team in order to correct known issues. Examples include the improvement of electrical connectors, addressing deficiencies in the implementation of integrated circuit mounting, and replacing worn out, obsolescent or obsolete components.

Major Hardware Upgrades: The major components upgrades have typically been collaborative efforts with our vendors. Major upgrades are developed and implemented on a much longer timescale. An example is the improvement of the preionization/lamp check power supplies. Over the last several months LLNL has worked with the vendor to define and implement required upgrades. The power supplies are extensively tested at the subcontractor facility and at LLNL before being re-installed on the NIF power conditioning system. Due to the shear numbers of components involved, implementing a change can take many months.

4 PROBLEMS ENCOUNTERED AND ADDRESSED

The PCS system sits idle for ~99% of the time and then comes to life in the last minutes of the shot cycle, meaning that most problems occur at critical times. This mode of operation, combined with the large number of modules requires strict attention to any and all issues, with an emphasis on prevention of problems.

Time between shots is used to perform any required reactive maintenance. In parallel the engineering team uses the test facility to develop new concepts that may improve component lifespans or reduce maintenance.

Because the PCS system has been operating for a number of years, we have largely bypassed the infant mortality class of failures. However, because of the harsh environment in which the PCS system operates, we have already started to reach the end of life on some components. In many cases these components have been weeded out by preventive maintenance. An example is the main switch gas pressure transducers, which were replaced in a wholesale fashion after they began to fail one-by-one.

The Engineering team is also working hard to predict component failures (thus moving from reactive to planned/preventive maintenance) and using postmortem information to drive improvements in device performance.

Engineering development aimed to improve existing components performances and therefore lowering the frequency of maintenance activities is also a major part of the PCS Engineering group. The PCS preventive maintenance list contains a group tasks that must be performed periodically, e.g. the verification of torque values on high voltage connections, verification of the integrity of ground connections, status of the dumps and dump resistors in the modules, the calibration of the gas system for switches, and the refurbishment of spark gaps switches.

4.1 OFF-NORMAL EVENTS

The PCS team must respond to events that fall outside the realm of normal maintenance. Recently, a module faulted while being charge for a laser shot. One of the MESM capacitors had failed catastrophically causing a significant amount of collateral damage.

The explosion was well-contained and the integrity of the module enclosure was not compromised, proving the quality of the design and implementation. Maintenance teams were organized to cover all hours except actual shot operations. (No shots were missed during the recovery.) While some applicable methods were already in place, new techniques had to be developed and applied. New procedures were written to cover activities. Safety documents were written, reviewed and approved allowing workers proceed with cleaning, recovery and testing of a damaged module.

As a result of this incident we have instituted additional training for NIF workers and are pursuing collaborations with other disciplines including mechanical engineers, mechanical technicians and high voltage electricians who can bring to bear skills that are not currently available in the existing group. We have also identified a new set of tools that will be maintained in the capacitor bays ranging from oil containment and cleaning kits to high voltage rated tools so we will be better prepared in the future.

5 CONCLUSIONS AND FUTURE WORK

The NIF laser system is constantly improving. The energy and power continue to rise. The shot rate continues to increase. The PCS team must keep improving its own processes and also develop and integrate upgrades in order to keep this system up-to-date and supporting laser shot operations with maximum reliability and availability for many years to come. The goal is to anticipate failures, identify places where upgrades are required. Where and when maintenance is required for the system the goal is to maximize preventive maintenance and avoid, to the greatest extent possible, reactive maintenance. Data collection and analysis are keys to success, as are worker training and quality.

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