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OVERVIEW AND STATUS OF THE POWER CONDITIONING SYSTEM FOR THE NATIONAL IGNITION FACILITY *

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Abstract

The National Ignition Facility (NIF) Power Conditioning System (PCS) is a modular capacitive energy storage system that provides over 34 kilojoules of energy to each of the nearly 8000 flashlamps in the NIF laser. Up to 400 megajoules of energy can be stored in the NIF PCS system, discharged through spark gaps and delivered to the flashlamps through a coaxial transmission line system requiring nearly 100 miles of high-voltage cable.

The NIF PCS has been under development for nearly 4 years. During this time, the system was developed and designed by Sandia National Laboratory in Albuquerque, NM (SNLA) in conjunction with Lawrence Livermore National Laboratory (LLNL). Extensive reliability testing was performed at SNLA on the First Article NIF Test Module (FANTM) test facility and design improvements were implemented based on FANTM test results, leading to the final design presently undergoing system reliability testing at LLNL. Low-cost energy-storage capacitors, charging power supplies, and reliable, fault-tolerant components were developed through partnerships with numerous contractors. Extensive reliability and fault testing of components has also been performed. This paper will provide an overview of the many efforts that have culminated in the final design of the NIF PCS. The PCS system design will be described and the cost tradeoffs discussed. Plans for fabrication and installation of the NIF PCS system over the next 6 years will be presented.

I. Introduction

The National Ignition Facility (NIF) is a laser-driven inertial-fusion facility being built by the Lawrence Livermore National Laboratory for the United States Department of Energy as part of the Stockpile Stewardship Program. The NIF laser, shown in Figure 1, is a 192-beam, flashlamp-driven neodymium-glass laser that will produce 1.8 MJ of light on target. Each of the 192 beams of the NIF laser is amplified in two multi-pass amplifiers, the Master Amplifier and the Power Amplifier. The Master Amplifier and the Power Amplifier will house the 7680 flashlamps that are driven by a modular power conditioning system that was designed and developed by Sandia National Laboratory (SNL) in Albuquerque [1] in close collaboration with Lawrence Livermore National Laboratory (LLNL).

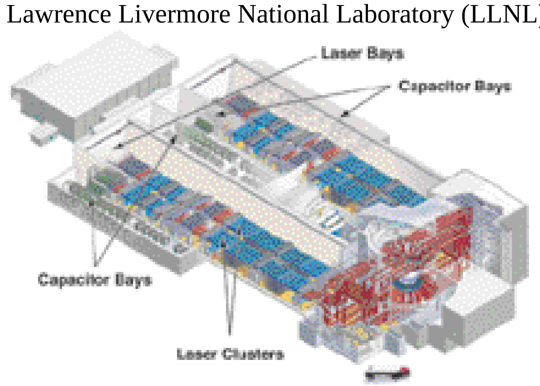

Figure 1. The National Ignition Facility at Lawrence Livermore National Laboratory.

II. Power Conditioning System Description

A. System Configuration

The NIF Power Conditioning System (PCS) resides in four Capacitor Bays, supplying energy to the adjacent Master and Power Amplifiers which reside in the two laser bays. Each capacitor bay will initially house 48 individual power-conditioning modules with room for expansion to 54 modules. A single module, shown in Figure 2, can store over 2 MJ and is independently charged to a maximum of 24 kV in 60 – 80 seconds. The stored energy is discharged through a single spark-gap switch into twenty coaxial cables that carry the energy to the NIF flashlamps. The 1.8 meter flashlamps are

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configured in twenty series-pairs (40 lamps total) in the Master Amplifier and the Power Amplifier.

Figure 2. Photograph of a prototype NIF power conditioning module without side panels installed.

The NIF laser has a total of 192 individual beams configured in groups or "bundles" of 8 beams. Each bundle of eight laser beams is amplified in two stages, first in the 11-section Master Amplifier, and then in the 5-section Power Amplifier. Each amplifier section contains a single slab of neodymium glass per beam. The Master Amplifier is driven by 5 and one-half PCS modules and the Power Amplifier is driven by 2 and one-half PCS modules for a total of 8 independent power conditioning modules as shown in Figure 3. This configuration allows independent operation of beam bundles and provides for phased activation of the NIF laser system.

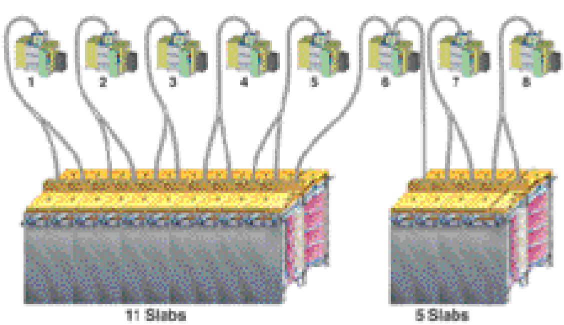

Figure 3. Configuration of NIF power conditioning modules driving a single bundle of laser beams.

B. Ground System

Special consideration was given to designing a grounding system that would ensure acceptable touch potentials throughout the facility in the unlikely event the module energy was discharged into the building ground system. This is a complex analysis problem due to the size and distributed nature of the system. Significant modeling and analysis was done to ensure the design was adequate [2]. The modular configuration of the NIF power conditioning system limits the amount of energy that can be involved in a hardware failure to the energy stored in a single module. Although a ground fault would require multiple simultaneous component failures, this worst-case fault was used for purposes of designing the grounding system.

The touch potentials due to a power conditioning system fault are a function of the impedance of the source and the current-return path to the modules. The impedance of the 12.5 ft copper ground grid embedded in the foundation of the building is inadequate to maintain touch potentials at an acceptable level for this worst-case scenario. As a result, the coaxial cables are enclosed in a large aluminum cable tray that provides a low-impedance return path for any possible fault currents resulting from a highly unlikely ground fault in the amplifier. Analysis has demonstrated any touch potentials that may be generated in the event of a ground fault, i.e., a fully charged PCS module gets dumped into the building ground grid, remain below acceptable levels.

C. Module Sub-System Description

The power conditioning modules were designed to be a cost effective, efficient, reliable, and transportable energy storage system for NIF. Each module is a simple RLC discharge circuit that is capable of being assembled and tested at the vendors site before transportation to NIF for installation and activation. The output requirements of the modules are based on empirically determined optimum drive requirements for the NIF laser. A simplified schematic of the system is shown in Figure 4.

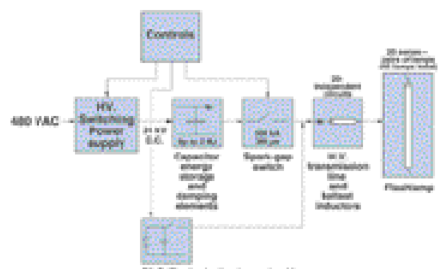

Figure 4. Schematic of NIF Power Conditioning Module.

Each module must deliver a set of two pulses to the NIF flashlamps. The purpose of the first lower energy 100 microsecond pulse is to pre-ionize the lamps prior to delivering the main pulse as shown in Figure 5.

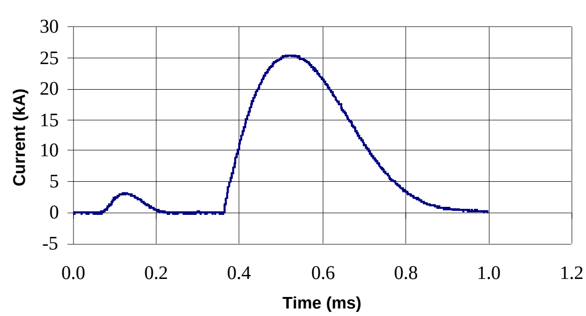

Figure 5. Flashlamp current waveform showing initial pre-ionization pulse followed by main energy discharge pulse.

D. Module Components

1) Capacitors

Each module contains 20 – 24, 84 kilojoule capacitors to store the energy required to drive the NIF flashlamps. The metallized-film capacitors [3,4,5,6] for NIF were the result of a multi-year development effort with vendors to develop a cost effective capacitor that would meet the NIF requirements. ICAR and General Atomics Energy Products are supplying the main energy storage capacitors for NIF. The NIF capacitor specs are:

Capacitance = 290 microfarads
Operating Voltage = 24 kV
Peak Discharge Current = 25 kA
Lifetime = 20,000 shots

2) Damping Elements

The capacitors are connected in parallel through "damping elements" which protect the module from catastrophic capacitor failures by absorbing a large percentage of the bank energy in a fault. A capacitor fault in which a single capacitor shorts can result in peak currents through the damping element up to 400 kA. The damping element was designed to survive one fault without causing any collateral damage to other components in the module. The final damping element design with a resistance of 25 milliohms and an inductance of 9 microhenries has been successfully validated through testing at the actual fault conditions [7].

3) Power Supply

Each PCS module is independently charged with a 25 kJ/sec capacitor charging power supply. The power supplies charge each module to a maximum of 24 kV in 80 seconds. These power supplies, being built by General Atomics Energy Products, maintain a voltage regulation on the bank of ± 12.5 V or ± .05%.

4) Switch

A single ST-300 spark gap is used to switch the energy from the 20 – 24 capacitors into the high-voltage cables that carry the energy to the flashlamps [8]. The ST-300 is operated at 24 kV with a discharge current of approximately 550 kA in the NIF PCS module. A TG-803 trigger generator and a saturable ferrite core is used to trigger the spark gap by providing an overvoltage pulse of approximately 105 kV across the switch gap.

This switch was chosen after extensive testing of many switch options at SNL [9,10,11]. The ST-300 has a limited life of approximately 280,000 coulombs for the NIF application. As a result, the ST-300 must be refurbished or replaced approximately every 1800 shots or every 2 years.

5) Ballast Inductors

"Ballast inductors", ranging in value from approximately 8 – 16 microhenries, are placed in series with each high-voltage cable to ensure a balanced energy distribution to the series-pairs of flashlamps. The inductance of the ballast inductors depends on the length of cable required to connect a specific module to the amplifier. There are four discrete values of inductors that will be used to compensate for the different cable lengths.

Similar to the damping element, the ballast inductors are designed to withstand a single fault on the load end of the high-voltage cable that may have currents as high as 130 kA. The ballast inductors must be replaced after this high current fault, but there should be no collateral damage to adjacent components.

6) Transmission System

NIF will utilize over 100 miles of Underground Residential Distribution (URD) cable to carry the module energy to the flashlamps. The lengths of cables from individual modules to the amplifier will vary from approximately 60 feet to over 180 feet depending on the specific location of the module within the capacitor bays. Unlike RG-220 in which the outer conductor of the coaxial cable is a braid, the outer conductor of the URD cable is actually 26 concentric #2 copper wires, spiraled around the insulated center conductor of the cable. This cable has been tested extensively and meets all of the NIF PCS requirements at considerably less cost than RG-220.

7) Controls and Diagnostics

Each NIF module is controlled remotely through an embedded controller that resides in a control rack adjacent to each power conditioning module. The embedded controller communicates with the main control room through a front-end processor, exchanging current waveform data on each flashlamp circuit and controlling the dc charge level and gas purge for the ST-300 spark gap.

8) Pre-Ionization Lamp Check (PILC) Circuit

In addition to the main energy storage module, each PCS module sub-system has a separate Pre-Ionization and Lamp Check (PILC) circuit to pre-ionize each flashlamp prior to discharging the 34 kJ/lamp, main pulse into the lamps. The flashlamps are pre-ionized with a 500 joule/lamp pulse that precedes the main pulse by approximately 300 microseconds. Pre-ionization of the flashlamps increases the overall efficiency of the laser and stabilizes the drive characteristics of the flashlamps.

The PILC circuit is also used to check the condition of all the NIF flashlamps prior to a system shot to decrease the probability of discharging the main bank into a failed lamp. Current diagnostics on each lamp circuit provide waveforms that are used in post-PILC shot analysis to evaluate the condition of the lamps.

The PILC circuit stores a maximum of 60 kJ to pre-ionize the 40 flashlamps driven by a single PCS module sub-system. The PILC energy storage capacitors are discharged with a T-150 spark gap that is triggered by a TG-103 trigger generator from Titan. The output of the PILC circuit is connected to the output electrode of the main module switch.

III. Performance Summary and Status

A. Performance Summary

The PCS module performance requirements are derived from the laser performance specifications. The primary requirements on the power conditioning system are listed in Table 1 below.

Average Gain Coefficient (AGC) *	≥ 5.0 %/cm
Shot-to-shot variability	≤ ±1.0 % in energy
Lamp-to-lamp variability	≤ ±3.0 % in energy
System Reliability	92%

*AGC is calculated from the output power waveform

Table 1. Primary Power Conditioning System Performance Requirements

The performance of the NIF PCS module has been thoroughly validated through extensive testing at SNL on the First Article NIF Test Module (FANTM) [12,13]. SNL conducted a series of tests that validated module performance into flashlamps and verified the fault tolerance of the module design.

Module reliability is presently being assessed and improved through extensive and continuous testing in the LLNL Prototype Test Facility. A prototype module was built and has been undergoing life testing. The goal is to complete at least one module lifetime test of 20,000 shots before initiating the fabrication of production units.

B. Status

Design of the PCS system is complete and the first 16 modules are being built by Ktech Corporation and Raytheon Technical Services Company. The entire PCS system will be built, tested, and installed by subcontractor(s) over the next five years. Production of the PCS modules will be coordinated with the phased implementation of the NIF laser.

IV. Acknowledgements

The authors would like to acknowledge the contributions of numerous people who have made significant contributions to the design, development, and/ or testing of the PCS system. These people include Doug Larson at LLNL, Bob Anderson of American Controls Engineering, William Gagnon, consultant, the Sandia Team lead by Mike Wilson, and Jud Hammon at the Pulsed Sciences Division of Titan.

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