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Main Amplifier Power Conditioning for the National Ignition Facility

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MAIN AMPLIFIER POWER CONDITIONING FOR THE NATIONAL IGNITION FACILITY

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ABSTRACT

The National Ignition Facility (NIF), being built at Lawrence Livermore National Laboratory (LLNL) will utilize a 1 8 MJ glass laser to study inertial confinement fusion This laser will be driven by a power conditioning system which must simultaneously deliver over 260 MJ of electrical energy to the nearly 7700 flashlamps The power conditioning system is divided into independent modules that store, shape and deliver pulses of energy to the flashlamps

The NIF power conditioning system which is being designed and built by Sandia National Laboratory (SNL) in collaboration with LLNL and industrial partners, is a different architecture from any laser power conditioning system previously built at LLNL This particular design architecture was chosen as the most cost-effective way to reliably deliver the large amount of energy needed for NIF

This paper will describe the development and design of the NIF power conditioning system It will discuss the design objectives as well as the key design issues and technical hurdles that are being addressed in an ongoing component development and system validation program being supported by both SNL and LLNL

I INTRODUCTION

The National Ignition Facility (NIF) is presently being built at Lawrence Livermore National Laboratory (LLNL) for the U S Department of Energy to study inertial confinement fusion (ICF) The NIF is being built in partnership with Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), and the University of Rochester's Laboratory for Laser Energetics and is scheduled for completion in late 2003

One of the primary components of the NIF is a large glass laser system that will deliver a total of 1 8 MJ of optical energy to a fusion target The power to drive this 192-beam laser system is supplied by the Amplifier Power Conditioning System (APCS) The APCS generates and delivers precise pulses of electrical energy to each of the 7680 flashlamps in the NIF laser This paper will describe the requirements, design and predicted performance of the APCS

II SYSTEM DESCRIPTION

The NIF laser is housed in two large laser bays each of which contain two laser "clusters" Each laser cluster is composed of six bundles of eight laser beams This configuration is illustrated in Figure 1

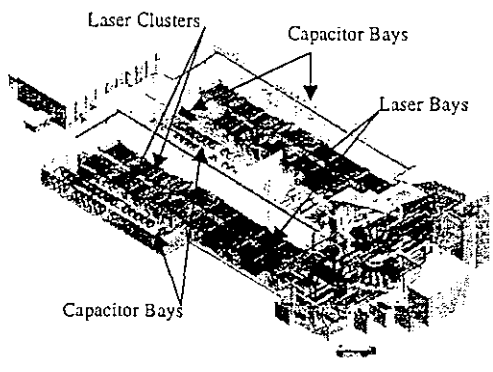

Figure 1. Layout of the NIF facility.

The power conditioning equipment is located in capacitor bays adjacent to each laser cluster Each capacitor bay houses 48 independent, power conditioning modules each having a maximum capacity for energy storage of nearly 2 MJ Each module drives a total of 40 flashlamps which are configured as 20 circuits, each circuit having two lamps in series

Typical voltage and current waveforms for energizing the NIF flashlamps are shown in Figure 2 and Figure 3 This pulse format includes features for triggering, pre-ionization and the main discharge as denoted in the figures

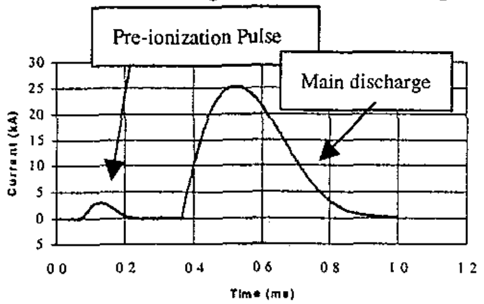

Figure 2. Flashlamp drive current

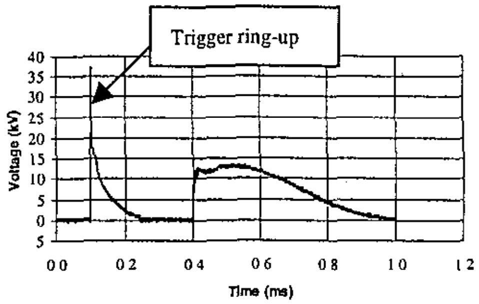

Figure 3. Voltage across flashlamp.

The flashlamp triggering mechanism consists of an initial breakdown from one electrode to the inside wall of the flashlamp This initial breakdown is followed by a streamer that propagates along the wall toward the other electrode [1] Tests have shown that the reliable triggering of a series pair of the NIF flashlamps can be achieved with a 40-50 kV short voltage ring-up that lasts for 5 – 10 microseconds

The purpose of pre-ionization is to prepare or condition the flashlamp for the main discharge It has been shown that pre-ionization strongly effects the radiant efficiency of the flashlamps [2] The required pre-ionization pulse energy is only a small fraction of the energy supplied during the main discharge

In a system the size of NIF it is important to be able to detect the failure of flashlamps The purpose of the "lampcheck" is to verify the integrity of the flashlamps in the system before the laser is fired This is to prevent discharge of the banks into broken or faulty lamps, which may cause excessive damage inside the laser amplifier The lampcheck pulse is identical to the pre-ionization pulse and is provided by the same circuit The only difference is that it is fired independent of the main discharge pulse

III. SYSTEM REQUIREMENTS

The design of the PCS is driven by sub-system design requirements that are derived from the overall performance and operational goals of the laser system These requirements define the performance, lifetime, reliability and maintainability that must be achieved by the PCS This paper will focus primarily on the performance and lifetime requirements

A Performance Specifications

One of the important measures of the NIF laser amplifier performance is the gain coefficient of the amplifier The gain coefficient is a measure of the change in light intensity vs the path length of the light through the laser glass The gain coefficient is dependent not only on the laser glass but also on the temporal characteristics of the light pulses generated by the flashlamps The desired temporal characteristics of the flashlamp light translate directly into requirements on the shape, amplitude and timing of the pulses delivered by the power conditioning system For this reason, the primary requirement for the APCS was written in terms of amplifier gain coefficient

A computer model, GainCalc v1 0, has been developed to calculate the gain coefficient of the NIF amplifier for a given electrical drive input [3] This code is used to verify that the output waveforms of the APCS meet the gain coefficient requirement A summary of the other requirements on the main discharge pulse are also shown in Table 1

The pre-ionization pulse requirements are shown in Table 2 The performance of the pre-ionization system has less impact on the performance of the amplifier than the main discharge The most critical parameters are the total energy delivered and the pulse duration

Main Pulse Characteristics	Requirement
Average Gain Coefficient	> 5 0 %/cm
Discharge Pulse Shape	Duration of power pulse delivered to flashlamps shall be 360 µs ± 10%
Repeatability	Total delivered energy repeatable to ± 1% shot to shot
Resolution	Delivered energy settable to ± 0 5%
Uniformity	Energy variation < ± 3% lamp to lamp

Table 1. Requirements for the main discharge pulse

Pre-ionization Pulse Characteristics	Requirement
Discharge Pulse Shape	Duration of power pulse delivered to flashlamps shall be 100 µs ± 10%
Repeatability	Total delivered energy repeatable to ± 5% shot to shot
Resolution	Delivered energy settable to ± 2 5%
Uniformity	Energy variation < ± 3% lamp to lamp
Energy delivered to lamp	> 500 J

Table 2. Requirements for the main discharge pulse.

IV. MODULE DESCRIPTION

The design of the NIF power conditioning module represents an evolution of development and improvements that have occurred over many years and several generations of lasers [4 5 6] This evolution has been driven primarily by the need to continually reduce the incremental cost of supplying energy to drive lasers as the size of laser systems increase The design of the power conditioning systems for flashlamp pumped lasers has evolved from small independent modules that store less than 100 kJ to the NIF power conditioning system that stores nearly 2 MJ in a single module The direction of the evolution has been to build modules that can handle larger amounts of energy with a smaller number of components

The potential for failures to cause significant damage increases as the amount of energy in a single module increases The present module size and configuration represents an aggressive balance between cost and risk Significant development has been pursued in order to develop components that are either robust against all know failure modes or that fail in a well controlled fashion and can be easily replaced The design and predicted performance of the module will be described in the following sections

A Module Design

The NIF power conditioning module is designed to deliver a minimum of 34 kJ per flashlamp with easy expandability to approximately 40 kJ per flashlamp These two operating scenarios correspond to a total stored energy per module of 1 6 MJ and 1 9 MJ respectively A simplified schematic of a module is shown in Figure 4

Each module contains a maximum of 24 self-healing capacitors connected in parallel A resistive inductor, referred to as a damping element, is connected in series with each capacitor as shown in Figure 4 The purpose of this damping element is to limit fault currents in the event that one of the capacitors short internally or the output bus of the module gets shorted

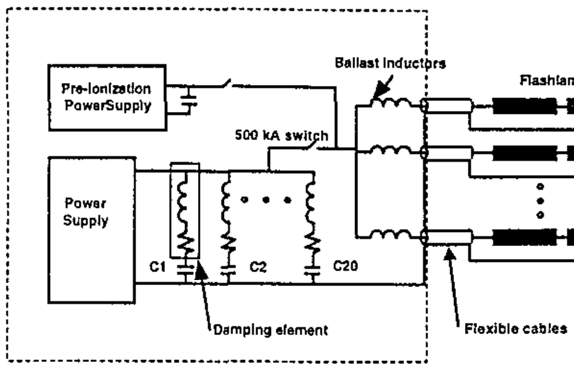

Figure 4. Schematic of power module.

Each module is charged with its own capacitor charging power supply in approximately 60 seconds The 60 second charge time was chosen because it was an acceptable compromise between capacitor lifetime, switch prefire probability and power supply/prime power cost The voltage will be held at the requested charge voltage for a maximum of 15 seconds while other systems in NIF are synchronized and armed for the shot

The stored energy is discharged through a high power spark gap into a distribution network of 20 ballast inductors and transmission lines The purpose of the ballast inductors is to ensure that energy is delivered equally to all 20 flashlamps pairs Each flashlamp circuit will deliver nominally 68 kJ of energy to each flashlamp pair during the main discharge pulse

B Fault tolerance

The mechanical design of the module and its components is very important because of the total energy stored in the module of 1 6 – 1 9 MJ Under normal operation, peak currents of 550kA can exert significant forces on adjacent conductors and connectors It is important to insure that all components can easily withstand these forces during the 20,000 shot lifetime of the NIF To ensure module lifetime, all components are being designed and tested to withstand the mechanical forces of normal operation for 20,000 shots [7]

As the total stored energy in a single module is increased, the potential for significant damage resulting from a failure becomes much greater Under fault conditions, the mechanical design of the system must either withstand the forces or limit damage so that repairs can be completed in the time period between shots which is nominally 4 - 8 hours In many cases, the philosophy adopted has been to limit damage because of the cost associated with building components that are robust against the most severe faults

Five significant faults have been identified for the NIF power conditioning module These faults are listed and described in Table 3

The module, shown in Figure 5, is completely enclosed in a 3/16 inch steel This closed architecture was chosen because it facilitates the containment of both shrapnel and fire in the event of a major failure in the module Damage would be limited to only the module that experienced the fault

Fault	Description
Capacitor fault	Internal short in capacitor
Bus fault	Short between output bus plates
Feedthrough fault	Short at module output connector or in cable
Termination fault	Short in termination block at load
Flashlamp fault	Discharge into faulty or broken flashlamp

Table 3. Summary of potential power conditioning module faults

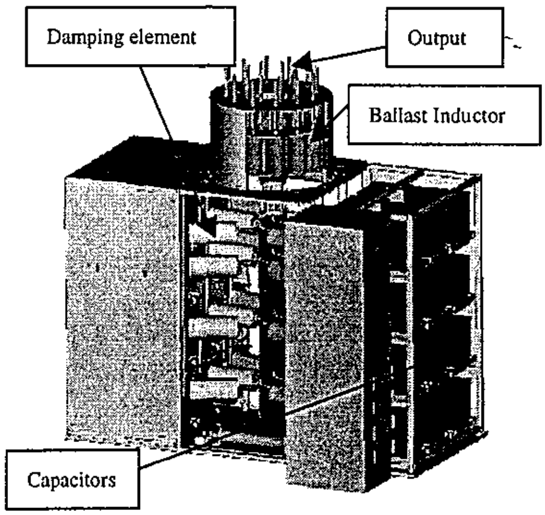

Figure 5. Power conditioning module with 24 capacitors.

The high cost items, such as capacitors, or items that would be difficult to replace, such as transmission lines, are being specified or designed to withstand the worst case fault For example, the worst case fault for capacitors is a bus fault where the peak discharge current from each capacitor can be almost four times its normal discharge current and the voltage reversal can be as high as 65% The capacitors are being designed to survive a limited number of these faults and still meet the overall lifetime requirement of 20,000 shots Cables are also being tested to insure that they can withstand the termination and flashlamp faults which is the worst fault for the cable

C. Predicted Module Performance

The NIF power conditioning system has a total of 192 modules that must each meet the requirements specified in table 1 and table 2 There will be differences in individual module performances because of variations in the components For example, the delivered capacitance tolerance on the capacitors is 10%

Sensitivity studies have been done to ensure that the NIF power conditioning system module design will meet all of the requirements with the expected tolerances on the module components The modeling was done by calculating the output power pulses of the module for a matrix of component values and using GainCalc v1 0 to calculate the gain coefficient that would result from that drive pulse The graph in Figure 6 shows the calculated gain coefficient for the different possible combinations of component values This graph shows that for expected variations in module output due to component variations, slight adjustments in the charge voltage, 1 1 kV maximum, will easily compensate for differences in performance All modules meet the 5 0 %/cm requirement at 275 microseconds

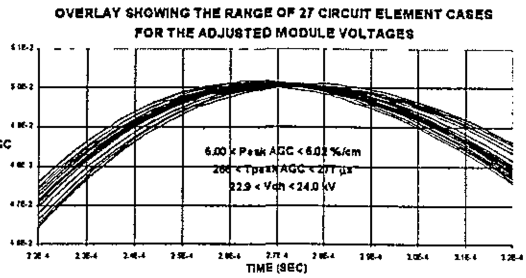

Figure 6. Calculation of gain coefficient for expected outputs from the modules.

V. SUMMARY

The design of the power conditioning system for the NIF laser system is nearing completion Modeling predicts that the design will meet all of the performance requirements The design will be validated through thorough testing before construction of the power conditioning system for NIF

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