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Power Conditioning for the National Ignition Facility

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POWER CONDITIONING FOR THE NATIONAL IGNITION FACILITY

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ABSTRACT

A cost-effective, 320-MJ power-conditioning system has been completed for the proposed National Ignition Facility (NIF). The design features include metallized dielectric capacitors, a simple topology, and large (1.6-MJ) module size. Experimental results address the technical risks associated with the design.

INTRODUCTION

The NIF is a large inertial confinement fusion (ICF) facility designed to achieve ignition of a fusion target in the laboratory.¹ The fusion target is imploded by the focused output of a 192-beam Nd:glass laser system, which produces a total of 1.8 MJ of 351-nm laser energy. The project plan includes facility construction and installation from 1998 to 2002.

The NIF requires a large (320-MJ) power-conditioning system to drive the flashlamps in the glass laser amplifiers. The system must deliver 34 kJ in 360 μ s to each of 7600 43-mm-diameter flashlamps. The system voltage is 24 kV, and pairs of flashlamps are wired in series. The cost goal for the NIF requires a 2.5-fold reduction compared with the LLNL Nova laser power-conditioning system.^{2,3} Achieving the system cost and performance goals requires advances in circuit design and component technology, compared with previous ICF laser facilities. The conceptual design incorporates self-healing metallized

dielectric capacitors, increased energy per bank module, and a simplified circuit topology in order to meet the cost and performance requirements.

SYSTEM DESIGN

The NIF power-conditioning system includes the pulsed power hardware and controls to operate the flashlamps in the NIF amplifiers, as shown in Fig. 1. The system consists of 200 independent modules, each storing up to 1.6 MJ. An advantage of the modular approach is that the design may be validated by thoroughly testing a single module. The essential requirements of the system are summarized in Table 1. Figure 2 illustrates the required flashlamp voltage pulse sequence. A short, 40-kV trigger pulse initiates the formation of a streamer in the flashlamp. A preionization pulse follows, delivering roughly 1% of the energy in the main pulse. Preionization improves the laser pumping efficiency of the flashlamp by increasing the plasma uniformity during the early part of the main pulse. The 360- μ s main pulse delivers 34 kJ to each flashlamp. Each NIF capacitor module drives 40 flashlamps, arranged in 20 series-pairs.

CAPACITORS

Self-healing, metallized dielectrics are advantageous in large capacitor banks.⁴ The capacitors can be designed to operate at higher voltage stress levels, resulting in higher energy density, less space, and lower cost. Capacitor infant

Table 1. Pulsed power system performance requirements.

Item	Requirement	Comment
Output energy	193 MJ < E_{bank} < 260 MJ	Power flashlamps at 0.15 < explosion fraction < 0.2
Pulse shape	360 μ s, critically damped	Match Nd:glass excited state lifetime
Flashlamp preionization	500 J per lamp, 100–150 μ s pulse width	Improved amplifier efficiency and flashlamp reliability
Flashlamp circuit diagnostics	Capability to perform low-energy lamp check shots on each circuit	Check integrity of each flashlamp on each shot
Controls	High-voltage-isolated embedded controller for low-level controls and diagnostics	Interfaces with NIF integrated control system
Full system shot rate	1 shot per 8 hr	Facility shot rate requirement
Single capacitor module shot rate	1 shot per 30 min	Required for activation and troubleshooting

Figure 1. Pulsed power hardware and controls to operate the flashlamps in the NIF amplifiers.

Figure 2. Flashlamp pulse sequence.

mortality is virtually eliminated, since a single dielectric system failure does not cause failure of the entire capacitor. Existing ICF systems (such as the LLNL Nova laser) use

traditional foil-electrode capacitors that can suffer destructive failure due to a single electrical breakdown and resulting short-circuit. The soft failure mode of the

metallized dielectric capacitors is manifest as a gradual, measurable drop in capacitance over time, facilitating preventive replacement during scheduled downtime.

A 13-MJ capacitor bank using a set of 52-kJ metallized dielectric capacitors was built for the LLNL Beamlet laser facility. No early failures occurred on Beamlet capacitors during acceptance testing or 200 subsequent shots. The NIF capacitor reliability was predicted by a Weibull analysis based on data from Beamlet capacitor tests. The results show that there are very few capacitor failures (defined as a 5% loss in capacitance) before 5000 shots (representing the first 8 years of operation) and that the rate increases thereafter.

SWITCHES

A single switch assembly discharges the capacitors from one capacitor module through the flashlamps. The maximum stored energy of a single module is determined by the peak current and the charge transfer capacity of the switch. It is important to maximize the stored energy per module, because this factor determines the number of separate capacitor modules, which, in turn, affects assembly time and fixed costs such as controls, charging supplies, switches, and preionization systems associated with each module. A detailed system cost estimate indicates that increasing the switch capacity has the largest impact on the cost of the design. For this reason, it is proposed to develop a switch with roughly 4 times the capacity of those used in previous laser ICF facilities. The corresponding switch requirements are 500 kA and 130 coulombs per shot with a 24-kV operating voltage. This increased switch capacity corresponds to a stored energy of 1.6 MJ per module. The actual stored energy per module will depend on the success of the switch

development program. Existing ignitron switches have demonstrated adequate lifetime at peak currents up to 200 kA. Spark gaps have demonstrated the desired 500-kA peak current capability, but with very limited lifetime. Table 2 summarizes the NIF switch requirements, and the status of potential switch technologies.

CIRCUIT TOPOLOGY

The NIF pulsed power system uses a simpler circuit topology than in previous laser ICF capacitor banks. The simplified schematics of the NIF and Nova capacitor modules in Fig. 3 illustrate the differences. The NIF circuit uses fewer components, resulting in lower hardware and assembly costs. In the NIF design, a single (or a few) large transmission line(s) deliver the capacitor energy to a junction box near the laser amplifier. The junction box contains ballast inductors, which distribute the current evenly to 20 series-pairs of flashlamps via flexible cables. In the Nova design, each series-pair of flashlamps requires a separate transmission line. A conceptual layout of the NIF capacitor module is shown in Fig. 1. An inexpensive concrete casting encloses the capacitors, switch, charging supplies, preionization system, and controls. The output from twenty 80-kJ capacitors is collected by aluminum bus plates that connect to the switch and transmission line. Each capacitor has an inductive resistor in series with its output for fault isolation. This element limits capacitor current to safe levels in the event of a fault in a neighboring capacitor or in the bus hardware. Each module will contain one spare capacitor. In the event of a capacitor failure, the damaged capacitor is disconnected from the circuit, but is left in place. The spare capacitor is then connected to the circuit. This minimizes the maintenance time required to recover from a single capacitor failure.

Table 2. Status of potential NIF switch technologies.

Switch technology	Peak current (kA)	Operating voltage (kV)	Lifetime (shots)	Comments
NIF requirements	500	24	10,000	1.6-MJ capacitor module, 360- μ s pulse width.
Size "D" ignitron	130	12	20,000	Switch parameters on Nova and other laser ICF banks, 2 in series, at 22 kV, 50 coul.
Size "E"	230	12	1000	Limited life test data is available. Performance at 500 kA is unknown.
Vacuum spark gaps	140	25	7500	Several in parallel required for 500 kA. Possible pre-fire problem at 24 kV. Limited data.
Pressurized air spark gaps	600	50	700	Use series-injection trigger, which requires isolation. Short life necessitates frequent maintenance.
Solid-state devices (SCRs or RSDs)	200	2 kV per device	Unknown	Stacks of devices needed. RSDs require injection trigger. Cost may be too high.

Figure 3. Comparison of Nova and NIF capacitor modules.

EXPERIMENTAL RESULTS

The NIF design has higher technical risk than the Nova circuit in the areas of flashlamp triggering and fault handling. These issues have been addressed with a combination of circuit modeling and subscale experiments.

Flashlamp triggering reliability must be extremely high since all of the stored energy in the capacitor module will be delivered to the lamps that trigger. Therefore, if only a few of the 40 flashlamps trigger, their energy ratings will be exceeded, resulting in a catastrophic failure. The NIF design will achieve the needed reliability with a triggering circuit that relies on passive components and the triggering of either the main switch or preionization switch. The trigger pulse, shown in the early portion of Fig. 2, is generated by the resonance of the ballast inductor and a small capacitor (located in the junction box) wired in parallel with the flashlamps. When either the main switch or the preionization switch is triggered, the capacitor voltage is doubled by the “ring-up” of the small (1–5 nF) trigger capacitor. The efficiency of the resonance is unaffected by the presence of a shorted flashlamp among the parallel set, since the ballast inductors isolate the shorted circuit from the rest. This circuit was simulated and

the results were validated experimentally. The current waveforms of Fig. 4 show the triggering delay of Nova flashlamps (1.5 cm bore, 112 cm arc length), operated in parallel, as a function of capacitor bank charge voltage. Triggering becomes unreliable below 10 kV; well under the 20- and 24-kV operating voltages for the NIF preionization and main capacitor banks. These experiments will be repeated with NIF flashlamps (4.3 cm bore, 180 cm arc length) when prototypes are available to ensure that they exhibit similar triggering characteristics.

Circuit faults are a concern due to the large stored energy in each module and the absence of fuses in the design. Fuses are avoided in the design for two main reasons. First, with a system requiring roughly 4000 fuses, reliability and the cost of replacements become an issue. In addition, the high-voltage transients generated by the circuit inductance when a fuse clears significantly increases the insulation requirements on the system hardware. The fault modes of primary concern are a shorted capacitor, or a short circuit in the capacitor collection bus, switch, or transmission line.

The design handles these faults by adding an isolation resistor in series with each capacitor output and by

carefully distributing the budgeted circuit inductance. Small ($40\text{-m}\Omega$) isolation resistors (see Fig. 3) limit the current to acceptable levels in capacitors neighboring the shorted capacitor. During normal operation, these resistors represent about a 6% energy loss, roughly half the total loss in the circuit.

Bus faults are more difficult because there is no series current-limiting element. The NIF approach is to allocate most of the inductance budget to the capacitors and the ballast inductors and to minimize the inductance in the transmission line and switch. Approximately $10\text{ }\mu\text{H}$ placed in series with each capacitor limits capacitor currents during bus faults to acceptable levels (less than 100 kA each). Subscale experiments with six 52-kJ capacitors validated the circuit model used to predict the fault currents in the NIF module. The simulated bus fault current waveforms shown in Fig. 5 illustrate the good agreement between the circuit model and the experimental results.

CONCLUSIONS

The design presented is reliable and cost effective and meets the NIF power-conditioning requirements. The design maximizes the energy stored per module to minimize the fixed costs associated with each module. The 500-kA output of a 1.6-MJ -bank module requires the development of an improved switch. The module design incorporates a simple circuit topology that operates series-pairs of flashlamps in parallel from a single transmission line. Careful distribution of circuit inductance and isolation resistors provide fault tolerance. Subscale experiments

validate the circuit model and fault calculations. Additional experiments using a full-scale prototype module will fully validate the design.

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Figure 4. Flashlamp triggering delay vs capacitor charge voltage.

Figure 5. Measured and predicted bus fault current NIF scale model.

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