MAIN AMPLIFIER POWER CONDITIONING FOR THE NIF

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Design of the power conditioning system (PCS) for the NIF laser is nearing completion. Modeling predicts that the design will meet all performance requirements. A first-article NIF test module (FANTM), Figure 1, has been built at Sandia National Laboratories (SNL) in Albuquerque, New Mexico. This power conditioning module is being tested to verify the design performance and system lifetime. NIF's power conditioning system will consist of 192 modules. The final design of the module, to be built to drive the NIF first bundle consisting of eight beamlets, will be based on the information and understanding gained from the operation and testing done on the first-article power conditioning module.

The NIF PCS is being designed and built by SNL in collaboration with Lawrence Livermore National Laboratory (LLNL) and industrial partners. Its architecture is different from any laser power conditioning system previously built at LLNL and was chosen as the most cost-effective way to reliably deliver the large amount of electical energy needed for NIF.

The design of the power conditioning systems for flashlamp-pumped lasers represents an evolution that has occurred over many years and several generations of lasers.[1–3] The direction of this evolution has been to build modules that can handle larger amounts of energy with a smaller number of components. NIF's forerunners utilize small, independent modules that store less than 100 kJ. In comparison, NIF's PCS will be able to store nearly 2 MJ in a single module. The move toward fewer components was driven by the need to reduce the cost of supplying energy to drive lasers of this size.

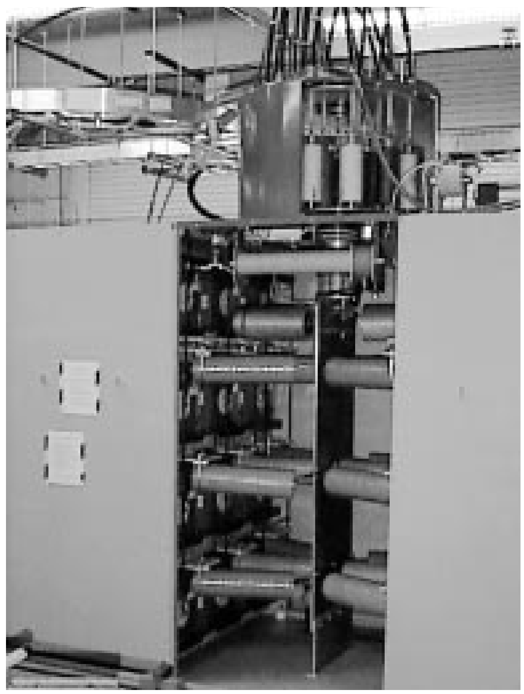

FIGURE 1. The first-article NIF test module (FANTM). (70-00-0399-0763pb01)

The specifications for the electrical performance of the PCS are derived from the

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overall performance goals of the laser system. The PCS must also meet lifetime, reliability, and maintainability requirements that are derived from the operational requirements for the NIF laser system. The overall system performance will be demonstrated through performance and reliability testing using FANTM.

System Performance

An important measure of NIF laser performance is the gain coefficient of the amplifier. Gain coefficient is a measure of the change in light intensity vs the path length of the light through the laser glass. 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 drive pulses supplied by the power conditioning system.

A computer model developed by Ken Jancaitis of LLNL calculates the gain coefficient of the NIF amplifier for a given electrical drive input. This code, GainCalc v1.0, is used to verify that the output waveforms of the PCS meet the gain coefficient requirement of >5.0%/cm.

Power Conditioning Modules

NIF's power conditioning equipment will be located in capacitor bays adjacent to each of four laser clusters. Forty-eight independent power conditioning modules (PCMs) such as the one shown in Figure 2 will drive the lasers in each cluster.

Each module will shape and deliver pulses of energy to NIF flashlamps. A description of an individual module is shown in Table 1.

A schematic of the module is shown in Figure 3. Each module is nominally comprised of 20 nominally 83.5-kJ capacitors connected in parallel through damping elements to limit fault currents. The energy stored in a module is switched to the output transmission lines through a single gas-discharge switch. The peak current through this switch is approximately 500 kA.

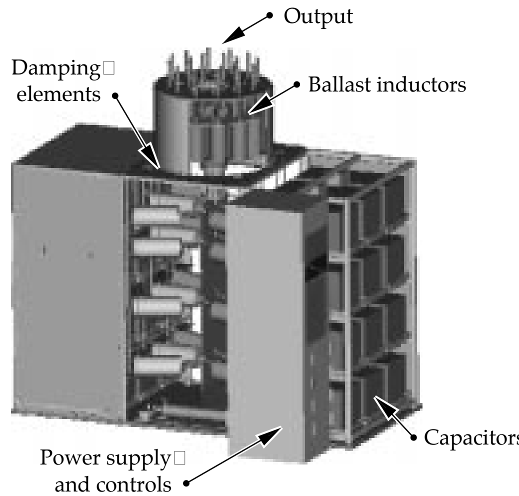

FIGURE 2. Power conditioning module (the switch is not shown) overall size is 10 ft high by 11 ft wide by 5 ft deep. (70-00-0399-0764pb01)

TABLE 1. Power conditioning module specifications.

Operating voltage	23.5 kV
Minimum delivered energy per lamp	34 kJ
Number of lamps per module	40
Pulse duration	360 μs
Peak output current	530 kA
Nominal energy storage*	1.6 to 1.9 MJ
Number of capacitors	20 nominal, 24 maximum

*Modules must each deliver a minimum of 34 kJ per flashlamp with easy expandability to approximately 40 kJ per flashlamp. To deliver 34 kJ per flashlamp, the module must store 1.6 MJ; to deliver 40 kJ per flashlamp, the module must store 1.9 MJ.

Energy is evenly distributed to the 20 parallel flashlamp circuits through the ballast inductors and transmission lines. These flashlamps are configured as 20 circuits, with each circuit having two flashlamps in series. The module will deliver nominally 68 kJ of energy to each flashlamp pair during the main discharge pulse.

Each of the 192 modules will have a maximum energy storage capacity of

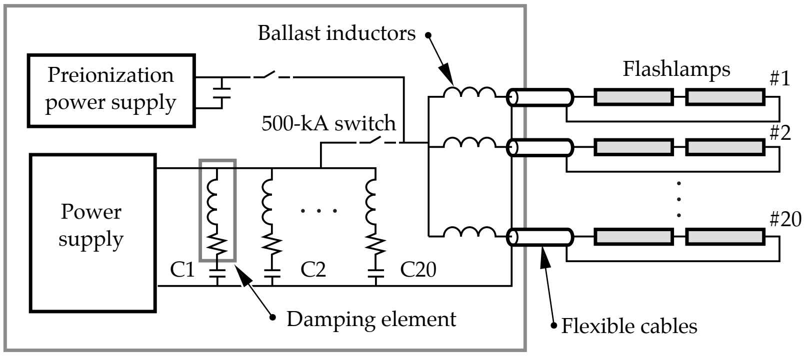

FIGURE 3. Power conditioning module schematic.
(70-00-0499-0826pb01)

nearly 2 MJ. The potential for faults to cause significant damage increases as the amount of energy in a single module increases. Thus, significant investments have been made to develop components that are either robust against all known failure modes, or that fail in a well-controlled fashion and can be easily replaced. The size and configuration of the NIF power conditioning module represent an aggressive balance between cost and risk.

Each module must deliver a very specific quantity of energy and waveshape to each of the flashlamps. Each flashlamp must be preionized with a small amount of energy (500 joules) approximately 300 microseconds before the main discharge to ensure breakdown and to uniform plasma bore-filling of the flashlamps. A minimum of 34 kilojoules must be delivered to each flashlamp during the main discharge. Typical current and voltage waveforms measured for energizing the flashlamps are shown in Figure 4. This pulse format shows the features for preionization and triggering in addition to the main discharge pulse.

Capacitors

Self-healing, or metallized, dielectric capacitors are used to store the energy for driving the NIF flashlamps. Unlike film-foil capacitors used in past laser systems, the metallized dielectric capacitors have a very predictable lifetime. This characteristic allows the design of a capacitor with a mean lifetime tailored specifically to the NIF requirement of 20,000 shots, without the additional cost of excessive design margins.

A summary of the NIF capacitor requirements is shown in Table 2.

The cost of the 3,840 capacitors that NIF will require constitutes 30 to 40 percent of the total power conditioning system cost, the system's largest single cost component. Capacitor reliability will also have a significant impact on the overall system reliability. Significant resources have been invested to

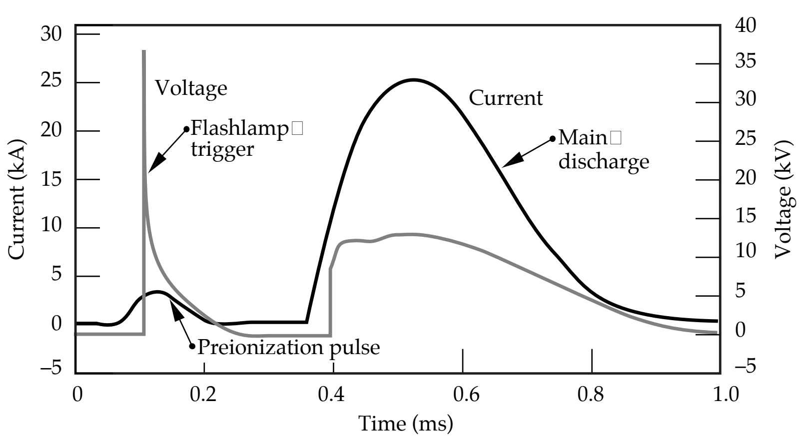

FIGURE 4. (a) Flashlamp drive current (black) and (b) voltage across flashlamp (gray).
(70-00-0399-0762pb01)

TABLE 2. Capacitor specifications.

Type	Metallized dielectric
Nominal capacitance	290 μF (+10%, –5%)
Operating voltage	24 kV
Peak discharge current	30 kA
Voltage reversal	<10%
Lifetime	20,000 shots
Maximum size	36" × 18" × 18"
Duration of discharge	360 μs

TABLE 3. Power supply specifications.

Maximum operating voltage	26 kV
Charge rate	26 kJ/sec
Regulation	±0.05%
Shot-to-shot stability	±0.05%

develop capacitors that carefully balance reliability and cost.

Capacitor development for NIF began nearly three years ago, when LLNL began working with multiple vendors to develop capacitors that would meet NIF specifications. After multiple iterations of design, fabrication, and testing, several vendors (Thomson Passive Components, ICAR, Aerovex, and Maxwell Technologies) have built capacitors that meet the NIF requirements. Development of lower-cost capacitor designs will continue until 1999, when LLNL begins the final design-qualification testing.

Capacitor-Charging Power Supplies

Each module will be charged by its own capacitor-charging power supply. The power supply specifications are shown in Table 3.

We have been working with three vendors (Dell Global Technologies, EMI, and Maxwell Technologies) to develop these power supplies. The specifications for these supplies are very close to those of standard off-the-shelf supplies, with the exception of the regulation and stability requirements. Prototype supplies have been built by the three vendors and have been operated and tested on the first-article power conditioning module.

Each power supply must charge its module's capacitors to 24 kV in a maximum of 80 s. This charge time was chosen because it was an acceptable compromise between capacitor lifetime, switch prefire probability, and power supply/prime power cost. Once a module is charged, it will be held at its charge voltage for a maximum of 15 s while other systems in NIF are synchronized and armed for the shot.

Inductors

There are two different types of inductors in each module. The ballast inductor ensures an equal distribution of delivered energy to each flashlamp circuit. The damping element limits fault currents in the module resulting from capacitor failures and short circuits across the bus. The design of both inductors is driven by a general philosophy that all of the inductors must remain intact during any of the possible fault conditions. However, the individual inductor(s) affected by the fault will be replaced before the next shot. Efforts are under way to optimize both designs to minimize the cost while ensuring that the inductors will meet the fault requirements.

The stored energy is discharged through a high-power spark-gap switch (see the section on switches below) into a distribution network of 20 ballast inductors and transmission lines. The purpose of the ballast inductors is to ensure that the module's energy is delivered equally to all of the 40 flashlamps that it must power.

The two primary requirements of ballast inductors are:

- To provide current shaping over the NIF lifetime requirement of 20,000 shots.
- To withstand fault currents of 100 kA.

We have successfully demonstrated designs that will meet these requirements. Developments are continuing to lower the cost of these units.

The second type of inductor, a resistive inductor or damping element, is connected in series with each capacitor. The purpose of this damping element is to limit fault currents in the event that one of the capacitors fails internally, or in the event that the module's output bus is short-circuited. To minimize damage, the damping elements must be able to withstand a fault current of 400 kA. Considerable effort is being expended to ensure reliability of this system component. Damping element designs have been developed that will meet the requirements, but efforts are ongoing to "value engineer" this component as well.

Switches

Each module must transfer the 2 MJ of energy stored in its capacitors to 40 flashlamps. It does this through a switch, which must meet the following criteria:

- Be highly reliable (no prefires).
- Have a relatively long lifetime.
- Conduct 530 kA.
- Operate at 24 kV.

SNL fabricated a test stand to test various types of switches to identify one that would meet these requirements. The types of switches tested include: spark-gap switch; ignition switch (a mercury-filled arc switch); rotating arc-gap switch; and two solid-state switches.

Maxwell/Physics International's Model ST300, a spark-gap switch shown in Figure 5, was selected on the basis of its performance and relatively low initial cost, even though its operating cost will be higher. Each ST300 will need to be replaced every 1,500 to 2,000 shots throughout NIF's anticipated lifetime requirement of 20,000 shots. A decision was made to utilize this switch instead of a rotating arc-gap switch, which remains an alternate. Although insufficient testing has been done on the rotating arc-gap switch, it appears that this type of switch would meet the NIF lifetime requirement. However, its cost is five to ten times that of the spark-gap switch Model ST300.

Data from SNL's multiple lifetime testing of the Model ST300 spark-gap switch, which has proven to be accurate and repeatable, was used to predict when switches would need to be replaced or refurbished.

FIGURE 5. Spark-gap switch. (70-00-0499-0827pb01)

Controls and Diagnostics

Each of NIF's 192 power conditioning modules will have its own embedded controller, which will control module functions including:

- Charging of the main capacitors.
- Gas-purging of the switch.
- Charging the preionization circuit.
- Charging and firing of trigger circuits.

This embedded controller also serves diagnostics functions. Twelve-bit digitizers are used to collect waveform information from the module during a shot. The controller collects information, including 20 output current waveforms as well as reflector ground current and facility ground current. It collects power-supply-charging waveform information from the main capacitor bank and the preionization capacitor bank. It monitors the waveforms to ensure that they are correct, and it informs the operator if a shot was acceptable. If there were problems inherent in the shot, the controller pinpoints the problem and alerts the operator.

Low-energy preionization lamp check (PILC) shots evaluate the health of all the flashlamps in the NIF system. The embedded controller evaluates waveform information to detect any broken flashlamps. This is a critical step that must precede flashlamp cooling, a procedure that could scatter broken glass and other debris throughout the amplifier and potentially cause significant damage to the amplifier and other laser system components. If no abnormalities are detected during the PILC, the controller will communicate the status to the supervisory control system, which will then initiate flashlamp cooling.

The “FANTM”

The first-article NIF test module, or FANTM, represents the entire power conditioning system from “the wallplug,” or AC power source, to the flashlamps. It was built in October 1998 to test and evaluate power conditioning module mechanical design and electrical performance. Since then, it has been operated and tested at SNL Albuquerque, collecting data to ensure that the module meets all NIF requirements, including fault tolerance and overall reliability. It also has been used to evaluate design improvements and to estimate time and effort required to build PCMs and install them in the NIF laser system.

Resistors initially were used to simulate flashlamp loads during activation and initial operation. In January 1999, NIF flashlamps were installed at Sandia as a load for the first-article module. Testing is under way to fully characterize module performance and reliability when driving NIF flashlamps.

Acknowledgments

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