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K. Whitham, D. Larson, B. Merritt, D. Christie

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NOVA Pulse Power Design and Operational Experience*

K. Whitham, D. Larson, B. Merritt, D. Christie
Lawrence Livermore National Laboratory
Livermore California 94550

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Abstract

Nova is a 100 TW Nd++ solid state laser designed for experiments with laser fusion at LLNL. The pulsed power for Nova includes a 58 MJ capacitor bank driving 5336 flashlamps with millisecond pulses and subnanosecond high voltages for electro optics. This paper summarizes the pulsed power designs and the operational experience to date.

SUMMARY

There are few lasers the size of Nova and few capacitor banks the size of the Nova bank. From the point of view of operational experience and parts reliability alone, the Nova bank is an interesting entity.

The Nova bank is comprised of 1827 separate energy storage circuits made up of 10400 capacitors. It is switched with 117 dual ignitron switch chassis, using 234 size D ignitrons firing together. It is charged to 22 kV in 30 seconds using eight 100 kVA power supplies and six 2 MVA power supplies. The Nova system, operational since 1984, has 700 system shots and thousands of front end shots.

System Description

The laser consists of 10 identical, parallel arms with each arm containing a number of disk amplifiers, rod amplifiers and Farley rotators. Figure 1 shows the staging of these elements and the energy required for each of them.

Table 1. Bank layout

Component	Number per arm	Total number of components	Number of circuits	Total number of circuits	Energy per component (kJ)	Energy per circuit (kJ)	Total energy per component (kJ)	Number of flashlamps per circuit	Total number of flashlamp
Rods	1	16	1	16	50	50.0	800-12.5	6	96-19"
Splitter	6								
9.4 disc	2	20	8	160	174	18.0*	2880-3	2	320-44"
9.4 F.R.	1	11	1	11	21	21.0	231-3		
Splitter	1								
15 disc	1	10	12	120	261	18.0	2160-3	2	240-44"
15 F.R.	1	10	4	40	160	37.5	1500-12.5		
20.8 disc	3	30	8	240	200	21.0*	5040-3	2	480-44"
20.8 F.R.	1	10	5	50	200	40.0	2000-5		
31.5 disc	5	32	10	320	375	33.0*	10560-3	2	640-44"
		18	10	180	375	37.5*	6750-12.5	2	360-44"
31.5 F.R.	1	10	5	50	200	40.0	2000-5		
46 disc	4	40	16	640	600	37.5	24000-12.5	5	3200-19"
				1827 total			33050-12.5		3296-19"
				151 F.R.			4000-5		2040-44"
				1676 lamp			20371-3		

*At 20 kV

Figure 1. Bank Layout

Over 55% of the total energy is used for pumping the disk amplifiers where the quantum states of the Nd: atoms are excited with intense, broadband light from large bore xenon flashlamps.

The remainder of the energy is used to establish magnetic fields in the Faraday rotator glass. These rotator coils are simple inductive loads with time constants in the millisecond regime.

Pump energy is delivered to the flashlamps in approximately 500 microseconds and the peak power requirements far exceed the capacity of the power grid. Thus a large capacitor bank is used as the intermediate storage element necessary to time compress this energy by five orders of magnitude, that is, the 50 megajoules is taken from the grid over a period of 30 seconds and delivered to the loads in less than a millisecond.

Design Criteria

The Nova Laser power conditioning was designed to minimize cost for a given performance. Cost for major components has a direct relationship with life. Since the system has a finite life of total expected shots, a realistic tradeoff between shot life of major components and cost was made. The scientific method used to make this trade off in several cases was the use of Weibull statistics.¹ In other cases the average expected life was designed to be greater than the life of costlier elements. The criteria used was an MTBF greater than 100 system shots.

Subsystem/Component Description

Figure 2 shows the power conditioning circuit. The major components are described in the following. Note the system grounding. The pulse power system was carefully isolated from the building to 40 kV and tied to ground at the switch common. This forces common return current to remain in the pulse power cables and prevents it from taking paths through the building steel. This is critical to prevent electrical noise from interfering with sensitive diagnostics and computer control. With 10 MA of pulsed current flowing, it is an important consideration.

Figure 2. Basic Nova Circuit

Power Supplies

The power supply size was chosen to complement the capacitor life. Each capacitor has a finite life at full voltage. By charging rapidly, the time at voltage is reduced. However, the cost of the power supplies increases with the kVA rating, so there is a cross-over where the cost saved in capacitor life is more than spent in power supply capacity. This analysis was done to size the total power supply complement. The size of individual supplies was chosen for convenience of staging and with an attempt to maximize

the size for economies of scale. A voltage doubler supply-type was chosen to achieve impedance limiting on charge, and so that power supply impedance is highest at full voltage, reducing fault problems. We used voltage doublers on prior systems and were very familiar with their characteristics. Components in the voltage doubler were rated so that their reliability exceeded the bank components.

To date, the power supplies have performed 700 charge cycles. Failures associated with the 2 MVA supplies include a 13.0 KV contactor at the power supply input which stuck closed and several solid state delay relays used for power supply control. The 100 KVA supplies operate with phase controlled 480 V inputs. Failures with these supplies include four pairs of phase control SCR's and several failures of control components.

Switches

The Nova energy storage system uses ignitrons for the switch element. With 234 ignitrons in 117 switch assemblies stressed to 22 KV, a number of steps were taken to insure reliable operation of these tubes. The most troublesome aspect of ignitrons in a large population is random prefire. With Nova, prefire causes several system problems, i.e., asymmetric power flow to the target, distortion of laser glass prior to the shot to name two. To avoid prefire, new tubes are bought to a strict specification. In addition, the cathode of each tube is water cooled to 16°C and the anode heated to 50°C to insure mercury is not condensing on the anode. The tubes are periodically high-potested to check the condition of each tube, and each switch is monitored to detect a weak tube so that it can be replaced before becoming a system problem. Current detectors are placed on trigger leads and on the main current leg of each tube. These are monitored by computer, so if a tube misfires or prefires, it is immediately identified. In addition, to prevent misfire, dual triggers are used at trigger currents of 500 A at 2 KV to insure turn on. Jitter is not an issue with these pulse lengths. Jitter of the order of one microsecond is typically recorded for the ignitrons.

The Nova switch assemblies have proven very reliable. The nominal operating parameters: 140 kA, 70 Coulombs, 11KV have proven quite conservative for the size "P" ignitrons. A recent x-ray of an ignitron from Nova revealed no signs of damage to the ignitor or anode. The only switch related failures to date have been caused by poor connections of the anode lug. Prefire frequency has been very low.

Capacitors

One of the major cost areas for the Nova Laser was capacitors. In order to decrease capacitor cost, we conducted a program to increase capacitor energy density. Three capacitor companies were selected to develop new capacitors with 12.5 kJ energy stored at 22 KV in a volume of one half a Syllac can. All three were successful. A sample from each vendor of 35 units were subjected to realistic, accelerated life tests and the Weibull curve drawn. The system could then be designed with a known capacitor life and capacitor MTBF for pulsed discharge.⁸ Figure 3 shows the capacitor price as a function of energy density in 1980 dollars. Figure 4 shows the Weibull curve for two sets of capacitors for Nova.

Figure 3. Capacitor Cost vs Energy Density

Figure 4. Sample Capacitor Weibull Curves

After 700 charge/discharge cycles in the Nova bank, eight capacitors have failed. Seven of these were the 12.5 KJ capacitors developed for Nova. The majority of failures have been internal short circuits from a bushing to the capacitor case.

Energy Storage Modules

The 60 MJ bank is divided into two physical segments. A small rod amplifier bank is separate from the main bank, since the rod amplifiers on the front end of the laser are used much more often than the main bank.

The banks are segmented into individual modules for each flashlamp or rotator circuit. A module consists of two to eleven capacitors and a pulse forming network (PFN) board. The PFN board consists of a pulse shaping inductor, charge resistor, fuse, damping resistors and dummy load.

The modules are sized as nominal 18 kJ, 37.5 kJ, and 50 kJ units for flashlamp applications. The use of the variety of capacitors was to accommodate the use of the Shiva bank parts in the Nova bank.

The modules are assembled as units on trays and can be removed from the mounting racks with a modified fork lift. The modules are mounted on racks seven shelves high. Figure 5 shows a segment of the bank as installed in the Nova basement. This method of assembly was chosen to be able to change a module within an hour. The concept was to allow a certain number of faults and to design for maintenance between shots, since several hours take place between shots.

Figure 5. Aisle of Nova Bank

A knife switch on each module permits individual modules to be removed from the charging grid and shorted. Manual operation of this switch with a long grounding rod enhances personnel safety during bank maintenance. Bank maintenance typically includes semi-annual inspection and cleaning of the modules and replacement of fuses which blow as a result of flashlamp failure.

High Power Resistors

Since Shiva, a considerable effort was made to improve high power resistors. In particular, extensive testing was performed on resistors for use as dummy loads and dumps. The dummy load is an alternate load for the energy storage modules. The dumps are used in the crowbar system to save the capacitors in the modules. Samples of these resistors are shown in Figure 6.

Figure 6. Nova High Power Resistors

The dummy load resistors were used during bank construction to check out the bank cabling and controls without requiring connection to a laser amplifier. They are now used periodically for troubleshooting the system. None of these resistors has failed.

The dump resistors are used to discharge portions of the bank which were not required to fire into laser amplifiers on a given shot. The voltage these ceramic discs withstand is a strong function of pulse length. The high value (1000 ohms) of these resistors results in a time constant of about 150 milliseconds. Of the 1800 dump resistors in the bank, there have been sixty failures due to voltage stress. This problem is being solved by increasing the length of the assembly from four to five inches.

The requirements for the dummy loads are an impedance of approximately 5 ohms, an energy capability of 50 kJ, and a voltage rating of 22 kV. We use ceramic disc resistors.

The requirements for the dump resistor are an impedance of 1000 ohms, an energy capability of 80 kJ single pulse, and a voltage rating of 22 kV.

Flashlamp Loads

The flashlamp loads are used to excite the Nd++ ions in the laser glass. The dimensions of the flashlamps were chosen for amplifier requirements. The lamps are filled with xenon gas at a pressure of 300 torr. About half the lamps are 1.1m in length, 1.5 cm bore and have cerium doped quartz walls to dampen the uv to extend amplifier life without causing loss in pump efficiency. The remainder of the lamps are 48 cm in length with 2 cm bore. The gas fill and other specifications are basically the same. The lamps are nonlinear resistive loads with two impedance states. A high voltage pulse is required to break down the lamp. After the lamp is ionized, the voltage and current are related by

$$V=KIB$$

where K relates to the lamp geometry and gas fill and B is about .5 at current maximum. The peak current is about 6 kA and the peak voltage drop at current max is 10 kV.

Lamp reliability is a critical issue with glass lasers. The total number of lamps for Nova is 5396. To insure adequate reliability, the lamps are purchased to a comprehensive specification requiring electrical and mechanical inspections at the vendor and at LLNL. Each lamp undergoes microscopic inspection, 60 kV hipot, and accelerated high power testing prior to use. In addition, before each laser shot, a low power (1% power) discharge is given to each lamp and waveforms are scanned by the computer to look for weak or missing waveforms. These lamps are then replaced before they are fired at full power.

Since the laser amplifiers operate in gain saturation, they can tolerate one or two missing lamp circuits without effecting gain but with slight optical degradation. This allows lamp circuits to be disconnected from the power supply as lamps fail, if necessary. The lamps are replaced after several fail in the same arm of the laser. To date, less than two percent of the lamps on Nova have failed. Most of the failures are the result of the lamp filling with air due to a crack at the electrode seal. Using the technique of replacing failed lamps at convenient times after several have failed allows the system to maintain an acceptable MTBF.

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Faraday Rotators

About ten percent of the bank energy is used to drive pulsed coils for Faraday rotators. These devices act as optical diodes to prevent reflected light from being amplified in the reverse direction in the system. The rotator circuits each have backswing diodes to prevent ringing. The coils are encapsulated in epoxy and are driven with up to 200 kJ of energy and 15 kA to achieve the fields necessary for the rotator glass. The only failure associated with the faraday rotators have been due to breakdown of the diode stack assemblies.

Conclusions

The design considerations used for the Nova Pulse Power have been successful. The approach of using Weibull statistics to design failure rates to achieve cost goals is a viable technique for designing a large system. The actual performance of the components characterized this way met expectations. The elements which gave the greatest problem, high power resistors, are being modified to have a more conservative design.

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