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NOVA PULSE POWER SYSTEM DESCRIPTION AND STATUS

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The Nova laser system is designed to produce critical data in the nation's inertial confinement fusion effort. It is the world's largest peak power laser and presents various unique pulse power problems. In this paper, pulse power systems for this laser are described, the evolutionary points from prior systems are pointed out, and the current status of the hardware is given.

Inertial confinement fusion is being vigorously pursued at LLNL. The Nova laser system is the latest in a series of increasingly large lasers that have been built to characterize fusion targets and to approach a demonstration of break even. The Nova laser will deliver 2.0 kJ of 1.06 micron light on target when it is completed. At this time DOE is considering frequency conversion of Nova to 2 and 3 μ . The amplifiers for this system use Nd-doped phosphate glass as the amplifying medium. The pump energy to excite this medium is supplied by flashlamps which in turn are driven by energy stored in capacitors. Each lamp pair is driven by a circuit storing from 25 to 50 kJ of energy. The total stored energy for the Nova system is about 100 MJ.

Because of the size of the Nova bank, many areas were studied to require cost yet retain needed levels of performance. The one with the most leverage was capitalization. For this component, ventures were selected and a development of energy-intensive capabilities. A specification derived from a statistical study of the desired reliability of the Nova bank.

A second subassembly where significant cost savings were realized was the power supplies. By going to standard-size supplies and placing them outside the laboratory building, savings were realized in economies of scale in the supply and in building space.

The number of components were reduced wherever possible to eight. The dashlamp drive system, for example, consisted of many circuits grouped around common switches to conserve switch count. Figure 11 illustrates how up to 21 circuits make use of one switch, yet retain individual fuses for isolation.

There are many other areas where evolutionary improvements have been made to enhance performance or reduce cost. New high power resistors have been developed, for example, that have ten times the energy absorbing capacity of the earlier versions.

In addition, LLNL has been working with the University of Texas to develop rotary energy storage devices such as the Compensated Pulsed Alternator and the Active Rotary Flux Compressor. The goal of this effort is to provide lower cost energy storage for pulse power. The application these devices will find no doubt be in a larger system than Nova, perhaps rep-

The flashtube drive system, however, is not the only pulse power element in the laser, albeit the largest physically.

A major effort in pulse power is directed toward driving the several optical shutters found in each chain. There are three basic types of shutters used. For small apertures (1-5 cm) Pockels cells are employed. These are single crystals of LiNbO_3 which when placed in an electric field rotate the plane of polarization of incoming polarized light. By placing this crystal between polarizers and switching the electric field, a fast optical shutter is created³. Switching times in the 10 ns regime are realized using this technique and applications are in the optical switch-out and in the feed-end of each laser chain. For optical apertures from 5 to 35 cm, Faraday Rotators are used. These devices are a similar, nonreciprocal device including an optically magnetic rather than electric field effect. Because of this the Faraday rotation cannot be rapidly switched but instead is used as an optical delay, transmitting forward light down the chain but diverting reflected light back toward the Faraday Rotator requires a great deal of stored energy for large sizes (e.g., 200 J for 20.8 cm aperture). Because of the cost of stored energy and the cost of rotator optics, alternative shutters have been studied. The Plasma shutter is such an alternative.⁴

The plasma shutter explodes a wire and puffs it across a pinhole to block reflected light from propagating down the chain. This pulser requires 550 kA of current and 400 ns rise time to obtain the needed closure time.

These devices are discussed further below.

The Nova relay storage system uses ignitrons for the switch element. In order to insure reliable operation of these tubes, a number of steps have been taken. The most troublesome aspect of ignitrons in a large population used for a system like Nova is their propensity for prefire. New tubes are now brought to a specification that sets a maximum prefire rate under incoming test conditions. In addition, the cathode of each tube is water cooled to 16-18 degrees C, and the anode is heated to 50 degrees C. Anode heating was accomplished in the past by hot lamps. On Nova, direct contact heaters powered by isolator transformers are used. This has reduced the power consumption from 500 watts per tube to 26. In addition, to prevent prefire, two tubes are placed in series in each switch and a voltage divider is used to equalize tube voltage. Periodic high voltage to

Figure 1: Nova Power Conditioning Circuit

MOH

25 kV ac is also performed to check the condition of each tube. In order to detect and localize any prefire that might occur, a voltage monitor is placed in each switch rack. This monitor is fiber optic coupled to the control system, so if a prefire occurs the event is immediately recognized and action is taken. Ignitor failure is another failure mode of ignitrons. On Nova, both ignitors on each tube are fired on each shot, and current transformers monitor each trigger. This trigger information is fiber optic coupled to the control system as well, so that failures can be localized and repaired quickly. A large current transformer, called a stem bug, is used to monitor the main switch current as well, so that each switch is fully diagnosed.

In the Nova system, effort was made to separate the power conditioning system physically as much as possible from the laser, both for safety and in order to operate the bank as a separate entity for test and debug. For this reason the bank diagnostic system, LCD, and its sensors, current bugs, are located in the bank. The current bugs are located in the switch and monitor current flowing in the power conditioning ground leg of each lamp circuit. This choice was made to be able monitor all high current fault modes associated with flashlamp circuit failures.

One hundred thirty, dual, size-D ignitron switches are used in Nova I. An integral number of amplifiers must be connected to an individual switch to prevent partial firing of an amplifier's flashlamps and possible damage. The switches are staged so that individual beam lines may be fired. The largest amplifiers have 46 cm aperture for the laser beam and use 80 leads each connected 5-in-a-series in 16 circuits. Each amplifier uses a single switch assembly. The staging of the amplifiers is shown in Table II.

All parts of the subsystems are all designed. Long lead orders have been placed, and requests for quotation from three vendors for qualification to the new specification are in progress.

Energy Storage Modules

The 200 MJ energy storage requirement for Nova is split into two 50 MJ segments. These are one end-on and one flashlamp end-on circuit. A module consists of two 12.5 kJ units or seven 3 kJ units firing in parallel (see Figure 2). The 200 MJ segments of a pulse shape, including charging circuitry, firing, damping resistors, and dummy load. A typical module is shown in Figure 2.

Figure 2: 50 kJ Energy Storage Module

The capacitors used for Nova I are built in 3 kJ, 5 kJ, and 12.5 kJ sizes. The 3 kJ and 5 kJ units will be salvaged from the Shiva and Argus laser systems. The 12.5 kJ units were especially developed for the Nova program. The salient features of these high density capacitors are given in Table I. Basically we have traded capacitor life for energy

density. The capacitors physically are all about the same size, i.e., about 175 lbs. As evident from Table I the high energy capacitors, 12.5 kJ units, have much higher operating stresses and correspondingly lower lifetimes.

The modules are sized as nominal 18 kJ, 25 kJ, 37.5 kJ or 50 kJ units for flashlamp applications. The 18 kJ modules are similar to those used on Shiva consisting of six 3 kJ capacitors. The 25 kJ units will consist of two 12.5 kJ units or seven 3 kJ units operated at 22 kV; the 14.5 μ F capacitors are rated 3 kJ at 20 kV. The 37.5 kJ units will be three 12.5 kJ units or eleven 3 kJ units run at 22 kV. The 50 kJ units will consist of fourteen 3 kJ cans run at 21.8 kV; these will be used to power the rod amplifier circuits only.

To date we have tested about 120, 12.5 kJ capacitors from three different sources. Our results indicate these capacitors will have a system mean time between failure of at least 100 shots, which was our original design goal. This failure level was determined by applying Weibull statistics to our test data. LLNL will purchase about 25 MJ of these capacitors for Nova I at a cost of \$0.052/module.

The staging of the capacitor bank for Nova I is detailed Table II.

At this writing orders for capacitors for Nova I have been placed.

High Power Resistors

Since Shiva, a dummy load resistor was made to improve the ignitron firing reliability. In particular, ignitron firing was improved by resistors for a dummy load and a dummy load. The dummy load is an aluminum load that is a storage module. The large energy is stored in the system to give the ignitron firing reliability. Samples of these resistors are shown in Figure 3.

Figure 3: High power resistors

The requirements for the dummy load are so impedance of 1000 ohms, an energy capability of 500 kJ at a voltage rating of 21 kV. We have found that the perfect resistors that meet these requirements. The first two types are ceramic disc types - one made by Allen Bradley of England and the other made by Carbonum's Japanese affiliate; the Japanese also have cooling fins. The third type is a tubular ceramic made by Carbonum. All three of these types are capable of absorbing 200 kJ in a single pulse. The resistors have also been tested at 50 kJ per pulse at a five minute repetition rate. The ceramic disc types have achieved thousands of shots before failure. The tubular type has over 1000 shots before failure; this type of resistor should cost significantly less.

The requirements for the dump resistor are an impedance of 1000 to 2000 ohms, an energy capability of 200 kJ single pulse, and a voltage rating of

22 kV. We have tested two types of resistors for this application; a ceramic disc made by Allen Bradley of England and a tubular ceramic made by Carborundum. Both types are capable of absorbing 200 kJ in a single pulse. Both resistors have been tested at 50 kJ per pulse at a five minute repetition rate. Both types have also achieved over 1000 shots before failure.

Power Supplies

To charge the Nova bank within 30 seconds, as required for adequate bank lifetime, 12 to 14 MVA of dc power must be applied to the bank. Large substation sized power supplies have been designed to supply this much power at an efficient cost. Smaller, Shiva-type, 100 KVA supplies will be used to charge the modules for the rod amplifiers and rotators, but most of the bank will be charged by six large supplies located in the substation area outside the Nova lab building.

These supplies are designed as three phase voltage doublers. Each supply is capable of charging 12 MJ of capacitors to 22 kV in thirty seconds. They are powered via a fused disconnect from the 13.8 kV ac power mains. They draw approximately 2.0 MVA peak power. A picture of the prototype Nova power supply is shown in Figure 4.

Figure 4: Nova 1 MVA Power Supply

There are differences between these and the Shiva supplies. These MVA supplies are electrically 15 times larger than the Shiva units. They use oil cooled transformers and rectifiers, while Shiva units are air cooled. The control element is a vacuum contactor on the primary which eliminates costly silicon arcs on the Shiva units. Due to economy of scale and the use of contactors, the estimated cost of the Nova supplies is \$0.02/VA vs \$0.15/VA for Shiva (both in constant dollars).

The order for all seven large Nova power supplies has been placed with Avdin engineering of Palo Alto. The first unit is in test at LLNL and has been accepted. The remaining six are to be delivered during calendar '81.

Optical Shutter Pulsers

In order to pulse the Pockels cells in the nanosecond regime, a number of techniques have been used. Pockels cells in the laser chains must each be switched simultaneously. To accomplish this, on Shiva a spark gap was used to switch a parallel group of charged cables into 20 cells. This system worked well but required more maintenance than was desirable for Nova, so the N-way fanout was redesigned to be switched with a hydrogen thyatron. Risettime was degraded from 3-5 ns to 15 ns but for chain Pockels cells the increase in reliability is more important.

In the case of front-end cells, the risetime had to be maintained at 1-3 ns with 200 ps jitter. For this application, planar triode pulsers were used. The planar triode is a 3000 MHz device which can be operated in a switched mode. In this mode for 5-25 ns pulses the rated cathode current can be greatly extended and a single tube is capable of putting out 30 amperes with several kilovolts of anode swing. A picture of a planar triode driver chassis for a 5 cm Pockels cell is shown in Figure 5.

Figure 5: Planar Triode Pulser Chassis

This unit uses 6 tubes in parallel to obtain 1.6 MW of drive power. We have contracted with Varian Associates, supplier of the currently used 7690, to develop a larger diameter cathode to provide more drive current per tube and thus cut down on the number of various places in the laser program.

The Faraday rotating pulser system is very similar to the flashing system with the exception that the circuit uses no inductor for pulse shaping. The load is the coil in the rotator body that generates the magnetic field. The LC of the energy storage and the load coil would ring at about 2.4 kHz if the backswing diode were not used. The ringing would not be deleterious to the rotator's performance since there is sufficient time at the first negative peak to satisfy system requirements, but the ringing exchanges a great deal of charge through the switch and many additional switches would be required were the diode not utilized.

The plasma shutter pulse power system has been described in detail in several papers.⁴ In summary it utilizes four vacuum illuminated rail gaps, low inductance capacitors, a plasma dielectric system, and coaxial geometry to obtain the required 650 kA in 400 ns in a small package that fits in the laser chain. The system has been successfully tested in a Shiva arm and has stopped Nova intensity beams in the time frame required.

Control System

Pulsed power devices in the laser system are controlled and monitored by a computerized system, illustrated by Figure 6.

Figure 6: Power Conditioning Control System

Pulsed power devices are connected to the FEP's in a redundant fashion as shown in Figure 6.

The FEP's internal bus is serialized and extended to service numerous devices listed in Figure 7. The interconnection network is called Novabus and divides the devices among 12 parallel chains.

Communication between the computers and the pulsed power devices must take place in a hostile environment of high voltage, high currents, and

Long lead components are on order. Most design is complete and prototype hardware is built and in test in a 1 MJ test bank at LLNL.

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	14.5 F	25 F	52 F	82 F
Operating Voltage (kV)	20	20	22	22
Energy Storage (kJ)	2.9	5	12.5	12.5
Number of Series Sections	4	2	2	2
Voltage Per Section (kV)	5	10	11	11
Operating Stress (kV/mm)	2583	2584	5000	3133
Dielectric Type	Paper/ castor oil	Paper/ castor oil	Paper/ poly/opp	Paper/ castor oil
DC Life (n)	2000	1200	1000	1000
Pulsed Life ^a (shots)	10 ⁶	500,000	200,000	200,000

^aNonreversible (3 kA).

Component	# Total	Circuits per Component	Circuits Total	Energy per Component	Energy per Circuit	Energy Total	Lamps per Circuit	Lamps Total
Rod	16	1	16	50	42*	672-3 kJ	5	96-19*
9.4 Disc	20	1	160	144	18	2880-3 kJ	2	320-44*
9.4 F.R.	12	1	12	21	21	252-8 kJ		
15 F.R.	10	4	40	100	25	1000-12.5 kJ		
15 Disc	10	12	120	216	18	2160-3 kJ	2	240-44*
20.8 F.R.	10	5	50	200	40	2000-5 kJ		
20.8 Disc	30	8	240	200	25	6000-12.5 kJ	2	480-44*
31.5 F.R.	10	5	50	200	40	2000-5 kJ		
31.5 Disc	40	10	400	375	33*	13200-3 kJ	2	800-44*
46 Disc	30	16	480	600	37.5	1800-12.5 kJ	2	240-19*
						25000 kJ	5	2496-19*
Total # Circuits = 1558				# 12.5kJ Capacitors = 7500 or 25000 kJ				
# Rotator Circuits = 152				# 3kJ Capacitors = 800 or 4000 kJ				1840-44*
# Lamp Circuits = 1416				# 3kJ Capacitors = 6388		19164 kJ		
						48164 kJ	= Total Bank Energy	

*operated at 22 kV