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ENERGY STORAGE AND POWER CONDITIONING SYSTEM FOR THE SHIVA LASER

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This paper describes the energy delivery system for the world's largest glass laser. Shiva(1), a multi-arm 25 TW, 10 kJ fusion research laser is currently under construction at the Lawrence Livermore Laboratory. (See Fig. 1).

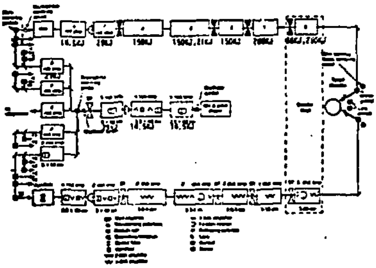

Figure 1. Shiva Laser Block Diagram. Bank Energies Required for Pumping are Shown below each Amplifier Block.

Approximately 22 megajoules of energy must be supplied for flashlamp pumping of the glass laser disks. The low conversion efficiency of electrical energy to laser energy makes necessary a large commitment of capital to the energy storage and power conditioning systems. Analytical models have thus been developed and used to optimize the transfer of energy from the capacitor banks to the inverted population of neodymium ions in the laser glass.

In addition to developing analytical circuit models, all the major electrical hardware components for Shiva have been designed and tested on our operating lasers. The power conditioning systems for Janus (400 kJ), Cyclops (1 MJ) and Argus (7.0 MJ) lasers have been fruitful testing grounds for Shiva prototype hardware.

Special attention has been paid to the problems associated with the high current, high voltage pulse power systems. The electrical noise associated with this environment is extreme. In order to study both the normal pulse behavior and the numerous possible fault modes of the system, a model of the transient equivalent circuit has been developed and analyzed. *This analysis has been verified experimentally on* the prototype laser systems.

Finally, a detailed cost estimate has been developed from our internal experience and the results of cost optimization studies carried out under contract to LLL(2). The results of this evolution are shown in a discussion of the Shiva power conditioning system as presently envisioned.

Circuit Modeling

Several computer models of Shiva subsystems have been developed. The first of these is concerned with optimizing disk pumping factors such as bank stored energy, reflector configurations, circuit time constants and glass aging.

In order to determine the effect on amplifier output of parametric variations from the nominal circuit values, a representation of the gain was required. Unsaturated amplifier gain is given by

$$G = \exp(\alpha \ell)$$

where α is the gain coefficient and ℓ is the amplifier path length. The α in this equation may be determined from the rate equation

$$\dot{\alpha} = \text{Const.}\ \eta\ (j)\ P\ (t) - \alpha/\tau - \text{Non-Linear Loss Terms}$$

where the constant is analytically and empirically determined for a given amplifier, η is a function of the current density, P is the power delivered to the system at any point in time, and τ is the time constant of the glass. The form of η which best fits the data is of the form

$$\eta \approx (j)^{-0.8}.$$

This has been used to study various single and *multiple mesh configurations* as well as *to anticipate* what gain changes will be realized from various energy inputs to given circuits.

Another use of the gain equation has been to calculate the optimum drive pulse shape, which is shown in Fig. 2. *This is a rising exponential with a time* constant about half the fluorescent decay time of the glass. An improvement in gain coefficient of 16% may be obtained for a constant input energy if this shape is used instead of a single-mesh pulse shape. If the peak gain is held constant, a 26% decrease is pump energy may be achieved with this shape. However, after investigating a large number of possible circuit configurations in an attempt to approximate a rising exponential, it was concluded that the single mesh circuit presents the best option in terms of cost effective, physically realizable hardware. Figure 3 shows a comparison between the model output and the

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gain of an actual amplifier as a function of time.

Figure 4 shows a beta size (9.5 cm beam diameter) disk amplifier. Flashlamps are arranged in series pairs. The total arc length for the lamp pair is approximately two meters and provides a fairly optimum impedance match to a 20 kV, 18 kJ bank module. A circuit configuration (See Fig. 5) has been developed which will charge and switch many parallel flashlamp circuits from a single power supply and switch. Each parallel circuit branch consists of a flashlamp pair, pulse forming inductor, a set of parallel capacitors which store 18 kJ and an isolating fuse. Thirty-two parallel branches are tied to a common ignitron switch in the ground leg. Typical voltage and current waveforms for a single branch are shown in Fig. 6. The full equivalent circuit is shown in Fig. 7.

This circuit was modeled using a high level language designed for modeling electrical networks(3).

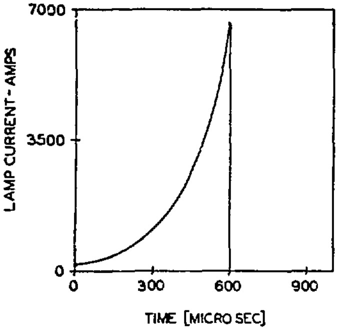

Figure 2. Optimum Lamp Current Waveform for Disk Pumping.

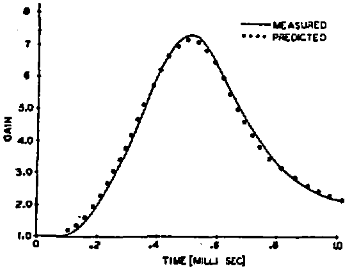

Figure 3. A Comparison of Predicated and Measured Amplifier Gain.

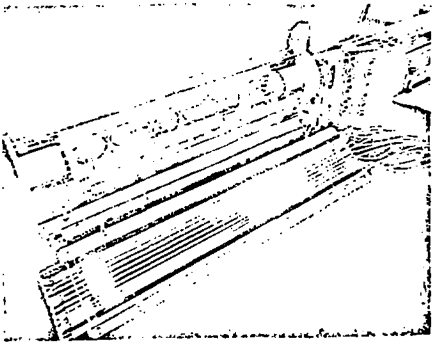

Figure 4. Beta Disk Amplifier

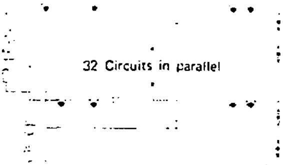

Figure 5. *Circuit Developed and Tested to Switch 32* Lamp Circuits in Parallel Through a Common Switch. Each Branch is Isolated with a High-Voltage Fuse. Total Current Switched is 150 kA; Total Energy Switched is 600 kJ.

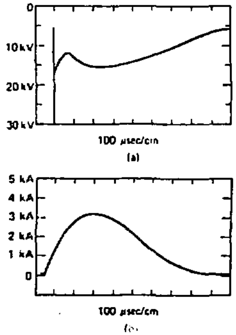

Figure 6. Typical Voltage and Current Waveforms for Capacitor-Bank Flashlamps: (a) Flashlamp; (b) Flashlamp Current.

The particular language used also allows the solution of any non-linear first order differential equation to be obtained. This feature has been used to determine total charge through switches, energy actually delivered to the lamps, peak energy stored in the rotators and a relative measure of gain. The model is flexible and provisions have been made to change cable lengths, number of parallel circuits per switch, and lamp parameters such as diameter, length, and pressure. Of particular interest is the transient response of thecircuit shortly after switching. This is because initial ionization of the flashlamps is accomplished by a pre-determined voltage overshoot from the trigger electrode to ground. After breakdown occurs at the trigger electrode a streamer propogates along the lamp wall to the opposite electrode. At this point, the lamp volume begins to ionize. This process of triggering takes place during the first 5 to 50 microseconds of the pulse. During this time the lamp presents a small capacitive load to the banks. As shown in Fig. 7, the combination of lamp capacitance C6, cable capacitance C5 and inductance L2 forms a resonant circuit at about 160 kilohertz. If left undamped during the initial triggering period the transient voltage across the lamps could reach approximately 2 Vo where Vo is the DC bank voltage. On the basis of triggering data from a large number of lamps[4], *this initial overshoot is set in the range* of 25 to 30 kV by selecting appropriate values for damping resistors R2 and R3 (Fig. 7).

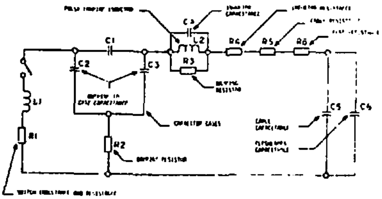

Figure 7. Transient Equivalent Circuit for a Single Branch Bank. Parameters were Measured and Calculated in Order to Construct a Computer Model; *Good Agreement Exists Between the* Model and Real Measured Performance on Operating Banks.

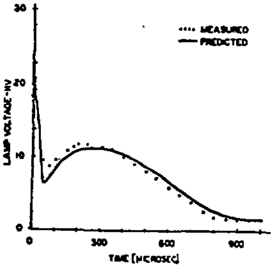

Figure 8. A Comparison of Predicted and Measured Lamp Voltage.

Figure 8 shows the calculated overshoot from the model and the actual measured waveform. It can be seen that there is good agreement.

Because the flashlamps present a non-linear, time varying impedance to the banks, special consideration had to be given the lamp equation in the circuit model. The voltage across the lamp was taken as

$$V = K_o \, i^{1/2} + \frac{d}{dt}(Li)$$

The first term of this equation is well known and given by Emmett and Markiewicz[5]. The second term is a time dependent inductance term which is used to approximate the inductance of the lamp during growth. An inductance of the form

$$L = L_o \exp(-t/\tau)$$

where both Lo and τ are picked to match emperical data from a given lamp configuration, gives an adequate fit to the observed ringup for all test cases measured to date.

The resistance term as a function of time used in the model is thus

$$R = \frac{K_o}{V_{lamp}} - \frac{L_o}{\tau} \exp(-t/\tau)$$

The equations in this form provide a transition from an inductance dominated circuit to a resistance dominated circuit during the first 50 microseconds of the pulse.

Hardware Considerations

Unlike particle accelerators or mirror experiment which have relatively short cycle times, Shiva will have a typical time between firings of 1 to 3 hours. The probable result of a power conditioning failure during a shot would be to seriously compromise the physics experiment and perhaps damage the laser. Reliability is achieved by building redundant hardware wherever possible and by charging and switching large blocks of energy storage capacitors as a unit in order to minimize the total component count. The design approach stresses simplicity of circuitry for easy maintainability and standardization of modules wherever possible. A considerable effort has been devoted to on-line testing of hardware in our operating lasers.

Energy Storage Capacitors

Two types of energy storage capacitors will be used in the Shiva power conditioning system. The first is similar to the capacitors developed some fifteen years ago for use in the Sherwood Program. This unit has a castor oil craft paper dielectric system and thin aluminum foil electordes. A cutaway view is shown in Fig. 9. This unit was designed for high voltage reversible service (ringing or undamped conditions) *and large peak currents.* Several hundred units from four vendors have been tested under these conditions. The mean life for these units was found to be 70×10^3 pulses. However, these test conditons are more severe than the actual operating conditions in which the capacitors see voltage reversal only during an occassional fault and the peak currents are considerably smaller then those of the test condition. The cost of the Sherwood type capacitor is 12 cents per joule. An alternate, lower cost (5 to 6 cents

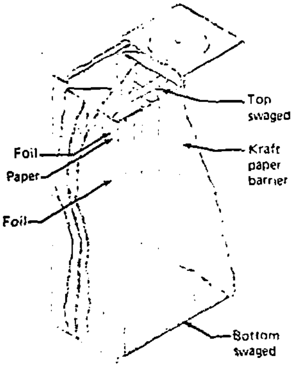

Figure 9. Energy-Storage Capacitor for Pulsed-Laser Systems. The Unit has a Castor Oil-Kraft Paper Dielectric System with Thin-Aluminum-Foil Electrodes.

per joule), higher energy density design is now being tested(6). This unit represents an attempt to lower cost by driving the design toward the specific requirements of the laser fusion. By using the basic construction of 14.5 μF units, but allowing the dielectric stress to rise from 2100 to 2600 volts per mil, a higher energy density and lower materials and labor cost are obtained. This gives an overall system cost savings because fewer capacitors are required for a given amount of energy storage. However, the life of the capacitor is a function of dielectric stress, percent voltage reversal and ringing frequency. By scaling from the reference point of the 14.5 μF unit with a mean life of 70×10^3 pulses in high voltage reversal use, the life in laser fusion use is 10^6 pulses for the 14.5 μF capacitor and 0.3×10^6 pulses for the high density design. An operational laser fusion facility such as Shiva might be expected to operate 50,000 pulses over a ten year period. Clearly, the projected wearout life of the high density unit better fits the immediate requirements. Initial testing of the prototype unit has verified the projected life of the higher density unit.

Pulse Forming Inductors

These pulse forming inductors are in the range of 300 to 600 microhenrys and carry peak currents of approximately 4,000 amps. A Brook's coil design is used. An electrical grade aluminum flat strip is used as the conductor. Turn to turn insulation consists of alternate layers of polyester mat and solid mylar. The entire coil is impregnated with a non-rigid potting compound. Several hundred of these inductors are currently in use in the program and have demonstrated high reliability.

Figure 10. Three-Phase Voltage Doubler: Reactance of C1 Limits Maximum Phase Current; Circuit can Operate Continuously into a Short Circuit.

Power Supplies

The Shiva bank charging power supplies are designed for 20 kV output and 0.1% regulation. Charging times are 30 to 120 seconds. A major requirement of these supplies is the ability to operate reliably into the short circuit presented by the banks at the on-set of each charging cycle. The three-phase voltage doubler circuit shown in Fig. 10 can operate continuously into a short circuit, because the reactance of secondary capacitance C2 limits the maximum phase current. For this circuit, the time to charge capacitor C2 to voltage Vo is

$$t = \frac{-\ln[1-(V_o/2V_p)]}{3F\ln(a+1)},$$

where Vo is the desired bank voltage, Vp is the peak of the line to neutral secondary voltage, F is the 60 hz line frequency, and a = C1/C2. (C1 = series doubler capacitor; C2 = bank capacitance). This is shown in graph form in Fig. 11. For example, a typical design requirement would be to charge a 3000 μF bank to 16 kV in 60 sec. For 2 Vp = 27 kV, Vo/Vp = 16/27 = 0.6, $N = 1.1 \times 10^4$ cycles and $a = 10^{-4}$. This results in a value of 0.3 μF for C2. A suitable choice would be a standard 25 kVAR, 0.39 μF, 13 kV power-factor-correction capacitor.

The maximum output current per phase occurs at the beginning of the charge cycle, when C2 is uncharged. This current is limited by the reactance of C1:

$$I = \omega C_1 V_p = 2\ A,$$

where $\omega = 2\pi F$.

From the current and duty-cycle requirements, a suitable transformer kVA rating can be specified.

In order to achieve 0.1% regulation against line-voltage variations, silicon-controlled-rectifier regulators have been developed for the 480-V three-phase line-voltage input to the supplies. Phase control is not required during the initial portion of the charge cycle. The regulator acts as a contactor until the output voltage approaches the desired value. At this point, the regulator phase controls and holds the output voltage at the desired level.

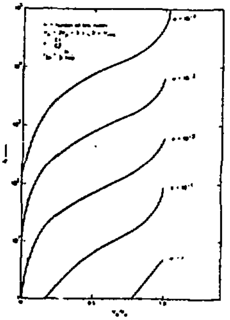

Figure 11. *Number of Cycles to Change Capacitor to* V_o/V_p for Five Values of a.

A number of these supplies have been constructed and integrated into our Nd: glass laser systems. For a 100 kVA unit capable of charging 1 MJ to 20 kV in 60 s, the known cost for construction, installation, and debugging is $11,000, or $110 per kVA. Operational experience indicates this approach to be a reliable, simple, cost-effective way to charge large energy-storage banks.

Fault Conditions

A number of possible faults can occur in this bank configuration, and these have been examined in detail. The most probable fault is a flashlamp explosion in a laser amplifier. When one lamp explodes, there is a high probability that neighboring lamps will fracture. This produces a conducting plasma inside the amplifier and essentially couples the banks together, with the plasma acting as a common load. In this case, the fuses in series with each flashlamp circuit will open and prevent the entire bank from discharging into the fault.

Another probable fault condition is that of an internal short in an energy discharge capacitor. When this occurs, the series fuses prevent the remaining parallel bank segments from discharging into the short. In the case of a large-aperture amplifier, as many as 32 parallel branches are directly connected. The potential maximum stored energy that might be delivered to this fault is approximately 0.5 MJ. This particular fault has been simulated a number of times on full energy banks, and in every case the fuses opened before significant damage occurred.

There are many other potential fault conditions of lesser significance, but they are beyond the scope of this report. Major emphasis has been placed on the concept of isolating bank segments so as to prevent large amounts of energy from discharging into a common fault.

Summary

An optimal energy delivery system for the world's largest glass laser system has been designed based on computer modeling and operation of laser hardware. Components of the system have been tested on operating lasers at LLL. The Shiva system is now under construction and will be completed in 1977. The energy supply described here will provide cost-effective, reliable power and facilitate the gathering of data in pursuit of controlled thermonuclear reactions.

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