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THE NEAR AND LONG TERM PULSE POWER REQUIREMENT FOR LASER DRIVEN INERTIAL CONFINEMENT FUSION*

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ABSTRACT

Inertial confinement fusion research is being vigorously pursued at the Lawrence Livermore Laboratory and at other laboratories throughout the world.

At the Lawrence Livermore Laboratory, major emphasis has been placed upon the development of large, Nd:glass laser systems in order to address the basic physics issues associated with light driven fusion targets.

A parallel program is directed toward the development of lasers which exhibit higher efficiencies and shorter wavelengths and are thus more suitable as drivers for fusion power plants. This paper discusses the pulse power technology which has been developed to meet the near and far term needs of the laser fusion program at Livermore.

Introduction

The Laser Fusion Program[1,2,3,4] is making rapid progress toward achieving thermonuclear fusion. One of the keys to this rapid progress is the sequence of laser facilities with increasing power (Fig. 1) developed at LLL in pursuit of the laser fusion program goals. Janus has yielded an extensive catalogue of laser fusion data and measurements of alpha particles demonstrating the TN nature of the implosion reaction, thus achieving the first milestone. Cyclops focused 0.6 TW on target from a single laser chain and has served as a prototype for the large, multi-arm Shiva and

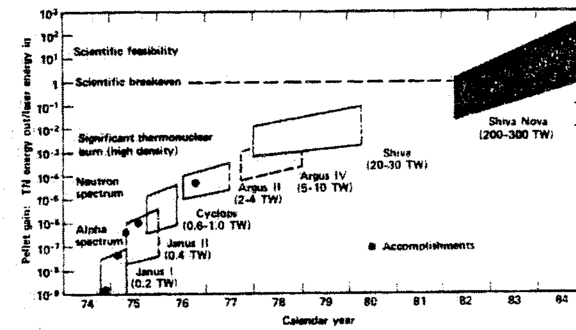

Fig. 1: LLL laser-fusion yield projections and laser systems. A series of increasingly powerful Nd:glass lasers has been built for laser fusion experiments.

and Argus systems. Argus has operated at greater than 4 TW from two laser chains and has now produced more than one billion neutrons on a single shot, with a pellet gain of 2×10^{-5}. Shiva, a 20 arm, 20 TW system has been operational since February 1978 and has produced a neutron yield of 2.7×10^{10} and compressions of 50X liquid density. Nova[5], currently under construction, will produce several hundred TW of output power and demonstrate the feasibility of net energy gain with high gain microexplosions.

Each laser system in this progression has increased in both size and complexity. The pulse power hardware represents about one-quarter of the total project cost for each of these systems. For Shiva, this amounted to $7M and for Nova we expect the pulser power system cost to exceed $30M. We have developed reliable, cost effective, and scalable pulse power technology specifically suited to meet the needs of large Nd:glass lasers.

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14. ABSTRACT
Inertial confinement fusion research is being vigorously pursued at the Lawrence Livermore Laboratory and at other laboratories throughout the world. At the Lawrence Livermore Laboratory, major emphasis has been placed upon the development of large, Nd:glass laser systems in order to address the basic physics issues associated with light driven fusion targets.

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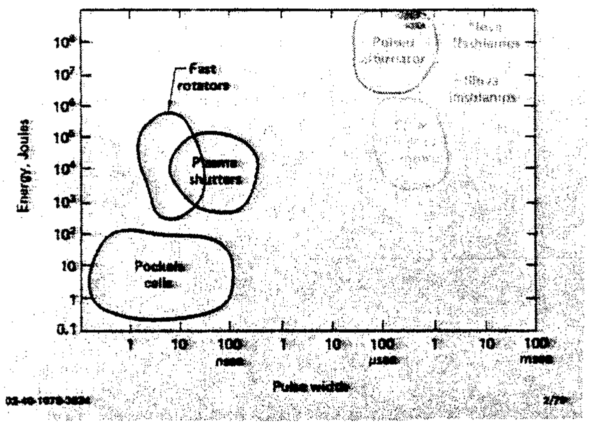

Fig. 2: Energy versus pulse width parameters for the major pulse power requirements of the laser fusion program.

Figure 2 shows the parameter space in which these pulse power requirements lie. The low energy, fast pulse circuitry addresses the needs for very fast optical switches which act to suppress amplified spontaneous emission within the laser chains, as well as to protect the laser from target reflected light. The high energy, relatively slow pulse circuitry addresses the pump requirements for these lasers, and it is in this area that most of the system cost is accounted for. This technology has been the focus of a great deal of effort[6,7] aimed at improving both its performance and cost effectiveness.

This paper will describe the pulse power hardware which has been developed and implemented at the Lawrence Livermore Laboratory for these large laser systems, as well as discussing some promising alternative technologies which are currently under development.

Laser Pumping Requirements

The laser amplifiers (see Fig. 3) are pumped with intense broadband light output from large bore xenon flashlamps. The pump energy is delivered in approximately 500 microseconds and the peak power requirements (shown in Fig. 4) far exceed the capacity of the power grid. Thus, large capacitor banks are used as intermediate storage elements. The xenon flashlamps are nonlinear resistive loads[8] with two distinctly different impedance states - roughly corresponding to the time during which the lamps are in the ionization or triggering mode and the time at which the full volume of the lamp is conducting current. Typical voltage and current waveforms for a series lamp pair are shown in Fig. 5. The 35 kV voltage pulse required to initiate the ionization process is deliberately produced by the transient behavior of the bank circuitry. After full volume ionization within the lamp, the voltage and current are related by the nonlinear relationship

$$V = KI^B$$

where K is a constant determined by the geometry and gas fill pressure of the lamp. The exponent B is approximately .5 at current maximum.

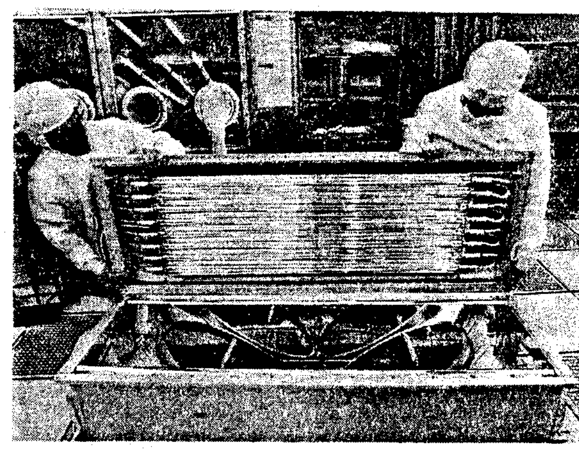

Fig. 3: A 34 cm clear aperture disk amplifier. The 16 xenon flashlamps (8 top and 8 bottom) require a total energy of 300 kJ.

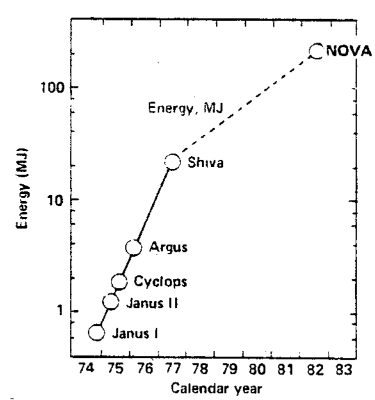

Fig. 4: The peak power requirements for lasers in the LLL Program have become increasingly large.

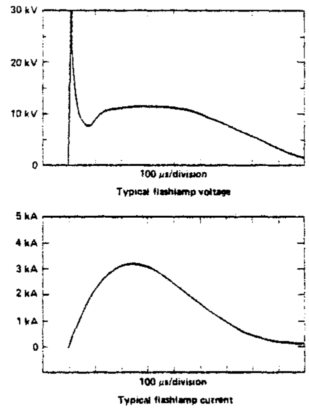

Fig. 5: Voltage and current waveforms for large bore xenon flashlamps.

The required energy per lamp depends upon the length and diameter selected. This varies from a few hundred joules for the small lamps to almost 20 kilojoules for the larger lamps. The lamps are arranged in series pairs and driven by a capacitive energy storage module which is tailored to provide the necessary energy and pulse shape. Each module contains the necessary energy storage capacitors, pulse forming inductor, dump resistors and high voltage isolating fuse. The modules are assembled as integral units and are moved with a modified fork lift. Shown in Fig. 6 is a 2.5 MJ segment of these modules as installed in the 25 MJ Shiva energy storage system.

<u>Controls</u>

The design of the controls and diagnostics for these pulse power systems is dictated by severe operational requirements.[9] A large number of control and diagnostic points must be addressed and these generally lie close to the pulse power circuitry where they are exposed to transients of several kilovolts. Thus a high degree of electrical isolation is essential. The early systems (Janus, Cyclops and Argus) were small enough to allow the use of hard wired relay control systems with limited diagnostic capability. Shiva and Nova are substantially larger and these control systems must be able to carry out pre-shot diagnostics, detect real time malfunctions, and implement data storage and

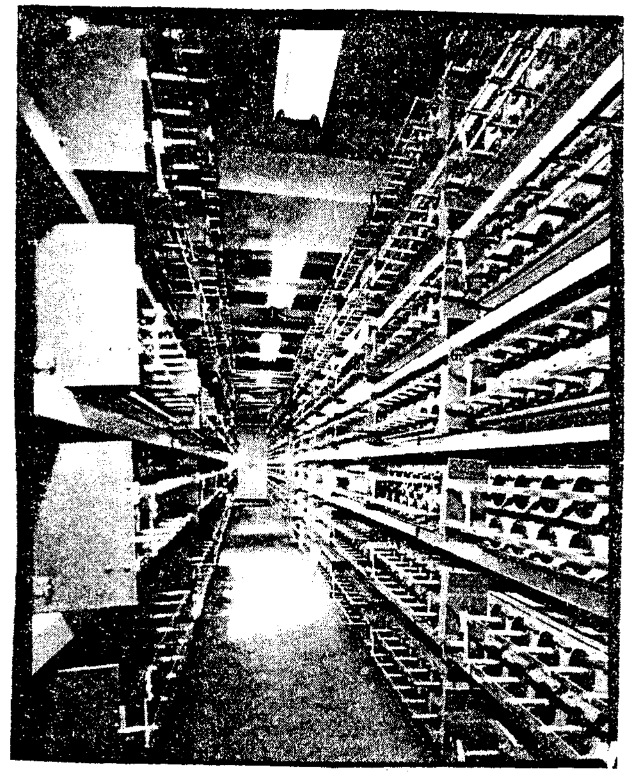

Fig. 6: A 2.5 MJ segment of the 25 MJ Shiva capacitor bank.

retrieval functions to aid in post shot trouble-shooting.

With this in mind, we have developed a digital based control and diagnostic system with a high degree of electrical isolation. The control system is organized around the LSI-11 micro-computer as shown in Fig. 7. The LSI-11 internal

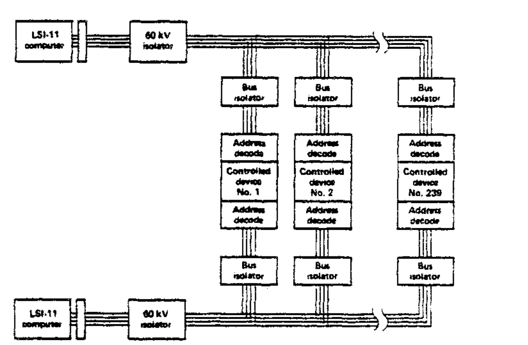

Fig. 7: Block diagram of the Shiva pulse power control system.

data bus is extended throughout the laser bay and energy storage areas to include all control and diagnostic points. As shown (Fig. 7), a 50 V, low impedance data bus extends from the LSI-11 to the interface points, 60 kilovolts of optical isolation is employed between the LSI-11 and the bus, and 3.5 kilovolts is employed between the bus and any interface point. This system has been operating successfully in the Shiva laser for the past 18 months.

For Nova, the same approach will be implemented, however, fiber-optic links will be used extensively. A prototype for the Nova control system is currently under test.

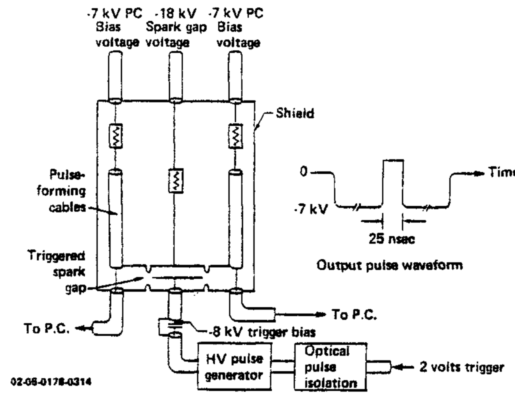

Fig. 8: Two 20-way pulsers like the one shown above are used to drive the Shiva Pockels cells. The switch can be either a triggered spark gap or a hydrogen thratron

Optical Gates

A variety of optical gates have been developed for use within the laser chains. These can be catagorized as either opening gates (used to prevent amplified spontaneous emission during the pump period) or closing gates (used to protect the laser from target back reflected light).

At the small aperture points ($\leqq 10$ cm) in the laser chain, Pockels cells are used as opening gates. At apertures larger than 10 cm, Pockels cells are no longer practical because of the difficulty of growing large diameter crystals. For the large aperture applications we have developed fast rotating shutters which will be located at the focal points of the spatial filters where the beam diameter is a few millimeters.

In general, the Pockels cell circuitry supplies pulses of about 10 kV with rise times of a few nanoseconds and pulse widths of several tens of nanoseconds. The circuit[10] shown in Fig. 8 is currently in use in both the Shiva and Argus lasers. As shown, a single spark gap (or thyratron) switches the shields on 20 separate cables. The pulse width is set by the pulse forming cable and the load cables feed the Pockels cells. Pulse to pulse jitter is less than 10 nanoseconds.

The rise time and jitter requirements for the Pockels cells used in the oscillator switch-outs are considerably more severe. Here, a very narrow pulse is needed ($\leqq 10$ ns) with pulse to pulse jitters of much less than a nanosecond. For these applications we have developed planar triode pulse circuitry such as shown in Fig. 9. The use of planar triodes, constant resistance networks and high frequency circuit techniques[11] has made possible a family of pulse amplifiers with nanosecond rise times and jitters of less than 100 ps. Typical outputs are in the range of 5 to 15 kV.

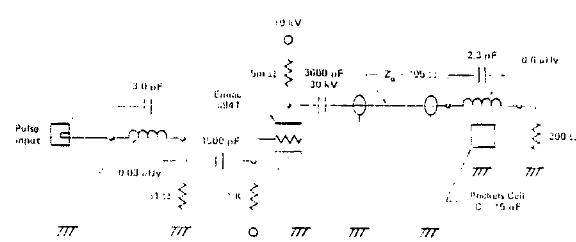

Fig. 9: Shown above is one example of a fast planar triode pulse amplifier. A number of these are currently in operation producing output voltages across Pockels cells of 3 - 5 kV with rise times of 1 - 2 ns.

Closing shutters are used to prevent target back-reflected light from reentering the laser chain and damaging optical components. Present systems employ Faraday rotator/polarizer combinations as optical gates. However, this is an expensive solution, especially at large apertures, because the energy contained in the magnetic field in the rotator glass increases directly as the volume. In addition, the rotator glass adds nonlinear path length to the beam. We have developed an alternative fast closing shutter[12] which is located at the final spatial filter pinhole. This shutter (shown in Fig. 10) rapidly injects a plasma of density greater than $10^{21}/cm^3$ (the critical density for 1.06 micron light) across the spatial filter pinhole after the outgoing light pulse has passed. A plasma velocity of about 1 cm per microsecond is required to insure the pinhole is blocked before the reflected light returns. The plasma is produced by sublimating a small mass of aluminum foil with pulsed energy from the low inductance PFN shown in Fig. 11. Eight of these PFN's are Marx charged to 50 kV and discharged through multichannel gaps into the foil. A total energy of approximately 10 kJ is required.

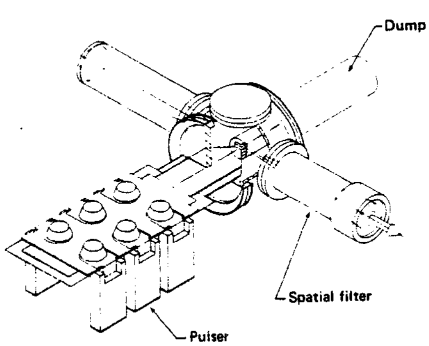

Fig. 10: A fast plasma shutter is used to inject a dense plasma across a spatial filter pinhole to block back-reflected beam from reentering the laser.

Long Term Requirements

In the near term, we are meeting the laser fusion pulse power requirements by implementing hardware solutions which are based upon existing technology of moderate extensions of existing technology. The longer term requirements involve developing

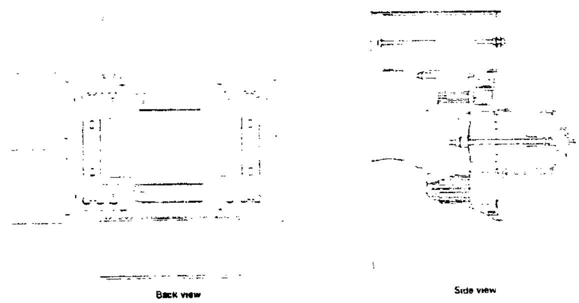

Fig. 11: Cross section of the plasma shutter pulser.

hardware which will operate reliably for 10^7 to 10^8 shots on a rep-rated basis. Further, the installed costs must approach a few dollars per joule in order for any of the inertial confinement fusion driver options to be economically feasible. This implies the development of lower cost, rep-rateable energy storage systems, reliable, high power solid state switches, and system configurations which do not involve stressing dielectrics into the corona regime. One such concept is illustrated in Fig. 12. As shown, the use of a fast discharge (50 to 100 μs) primary energy source makes possible a system which eliminates the requirement for a transfer capacitor and allows for rapid charge of the output pulse forming line.

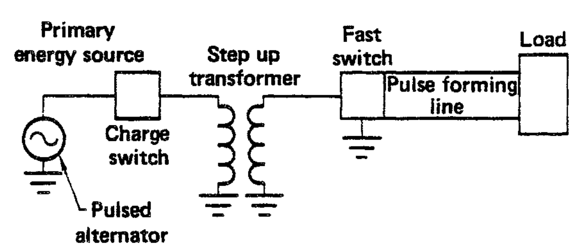

Fig. 12: The basic elements of a fast charge/discharge rep-rateable pulse power system.

A key element in this concept is the high peak power pulsed energy source and the University of Texas, Center for Electromechanics at Austin, is currently developing such a device[13,14] (the compensated pulsed alternator) for the Laser Fusion Program. This machine, shown in Fig. 13, is a rotating flux compressor capable of producing megajoules of output energy over a pulse width range from several milliseconds to below 100 μs. The prototype, currently under test, is designed to drive flashlamp loads with a half millisecond pulse of about 100 kA at 6 kV. After verification of the prototype performance, a larger machine, in the several megajoule class and with an open circuit voltage of approximately 15 kV will be built. We hope to implement this technology for Phase II of the Nova project.

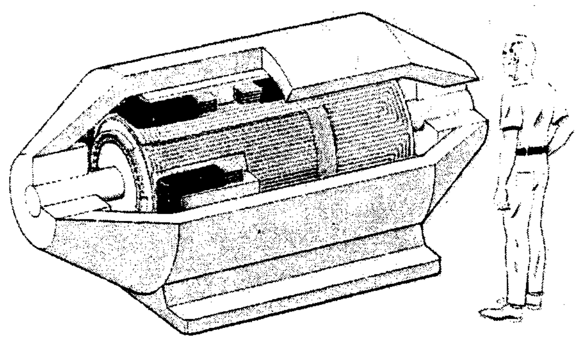

Fig. 13: Artists conception of the compensated pulsed alternator.

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