Section 2
ADVANCED TECHNOLOGY DEVELOPMENTS

2.A Explosion Fraction Measurements on Water-Cooled Xenon Flashlamps

Large-bore, xenon-filled flashlamps have been the main pump source for all Nd:glass fusion drivers. The graybody emission of these lamps at high loadings approximates a 10,000 to 14,000°K blackbody. This is as measured in the wavelength regions of significant Nd^{+3} absorption and occurs over a time comparable to the fluorescence lifetime of the Nd^{+3} ion (~300 ms). The lamps are made of fused quartz tubing with 1.5- to 2.5-mm-thick walls and have bore diameters in the range of 1.5 to >2.0 cm. Typical arc lengths, measured from electrode to electrode, range from 25 cm to >200 cm. Xenon gas, used for its high electrical-to-optical conversion efficiency, fills the lamp to 300 Torr. Seals at either end connect the quartz tube to electrical connectors. Typical designs are shown in Fig. 48.11.

Because of the high energies involved per lamp (> 10 kJ) and the high peak powers (>20 MW), simple L-C circuits are used to drive these lamps. A switch is included to prevent prefiring of the lamps. Circuit resistance is carefully controlled to limit losses. A small (< 500-mΩ) resistive loss may be left to limit peak currents in case of a fault at the lamps. An OMEGA rod-amplifier drive circuit is shown schematically in Fig. 48.12. Figure 48.13 shows the circuit currently used in a prototype disk amplifier at LLE. The disk-amplifier circuit has the additional capability of ionizing the lamps several hundred microseconds prior to the main discharge.

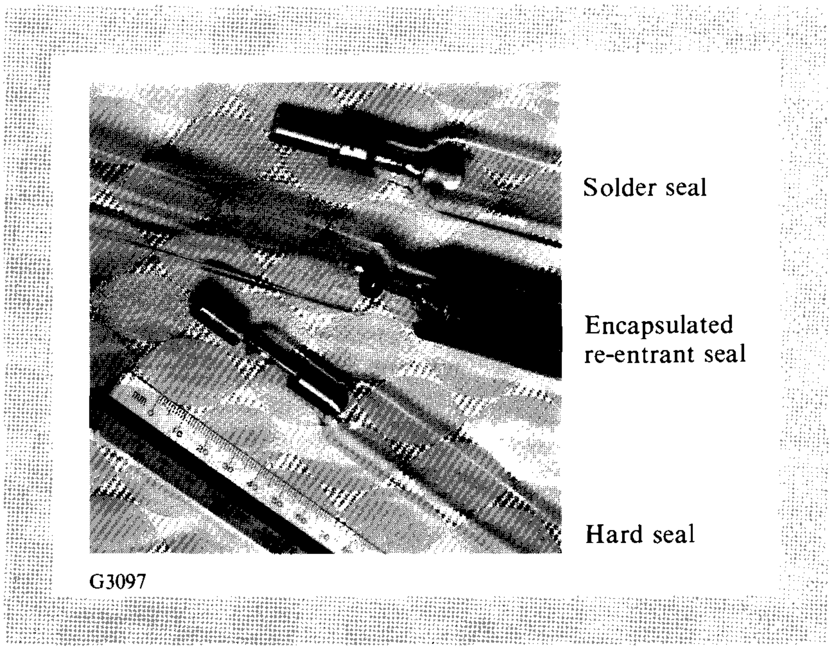

Fig. 48.11
Three flashlamp designs. The top lamp is a water-cooled, solder-seal design. The middle lamp is an encapsulated re-entrant seal design. Part of the lamp seal is covered by the metal end tube. The bottom lamp is a water-cooled, hard-seal lamp used in the disk amplifier.

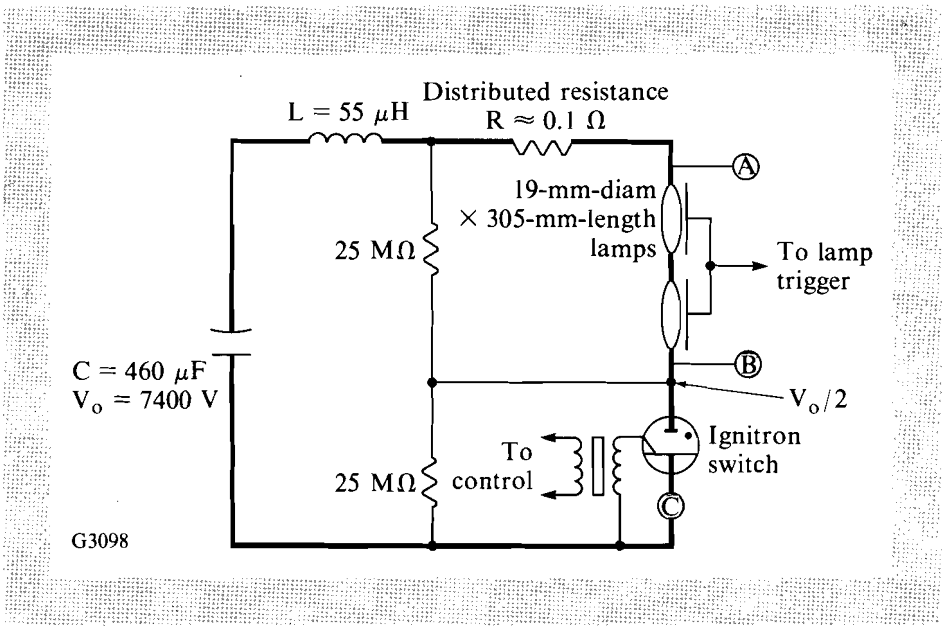

Fig. 48.12
Drive circuit used for OMEGA rod amplifiers. Differential voltage measurement was made at point A and point B. Current was measured at point C. Charging circuitry is not shown.

These large flashlamps, when operated in air, can experience catastrophic failure.[1] Typically, the lamp envelope fails during the early portion of the shot, breaking up into numerous small (< few millimeters square) pieces that are violently expelled from the arc region. The cause of these failures is still uncertain, but several hypotheses have been advanced: (a) small cracks in regions of the envelope placed under severe tensile stress during the shot, (b) pre-existing regions of stress in the lamps, (c) excessive Lorentz forces from neighboring lamps, and (d) power-conditioning failures that electrically overload the lamps. Catastrophic failures can be particularly costly in disk-geometry amplifiers where large, polished surfaces of laser glass face the flashlamps. Blast windows are used in disk amplifiers to limit damage from such an event.

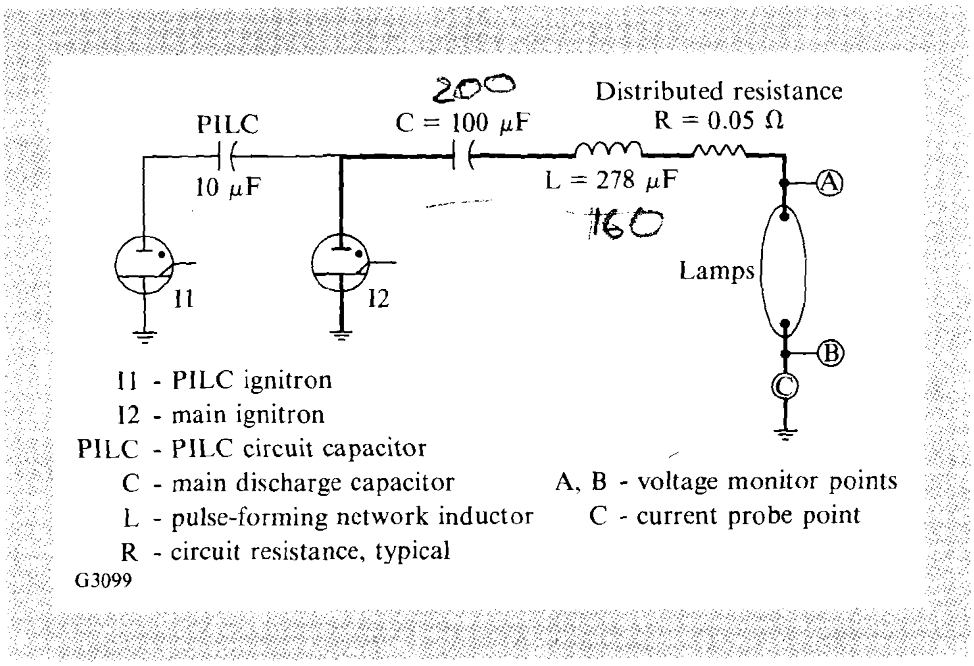

Fig. 48.13
Drive circuit for the prototype disk amplifier.

A measure of the average number of shots until failure of an air-cooled flashlamp was developed a number of years ago[2] based on the so-called explosion fraction at which the lamp operates. The number of shots N expected before failure is given by

$$n \sim \left(\frac{E_0}{E_x}\right)^{-8.5},$$

where E_0 is the total energy in joules delivered to the lamp, and E_x is the explosion energy of the lamp in joules calculated from the empirically determined expression $E_x = 2 \times 10^4\, ld(LC)^{1/4}$, where l and d are the arc length and bore in cm, and L and C are the inductance in henrys and capacitance in farads of the driving circuit, respectively. The ratio E_0/E_x is denoted f_x and is known as the explosion fraction. A typical large, air-cooled lamp might operate at 15%–20% explosion fraction.

Extensive quality-control programs have been developed[3] that minimize the occurrence of catastrophic failure in air-cooled lamps operated at 15%–20% of explosion fraction. Important steps in these programs include infant mortality testing at elevated explosion fractions (>30% f_x) for a limited number of shots, microscopic inspection of the quartz walls of each lamp for cracks,[4] and inspection in a polarimeter for regions of wall stress.[5]

The OMEGA system contains 680 1.9-cm bore by 30-cm arc-length lamps. The OMEGA lamps are water cooled by operating the lamps inside 25-mm-ID Pyrex™ water jackets. The original OMEGA design called for operation of the lamps at an explosion fraction of 30% as defined for air-cooled lamps. Fewer than six catastrophic failures have been observed over the 23,000+ shot lifetime of the system despite the relatively high operational explosion fraction. Even these few catastrophic failures were relatively benign, resulting in large fragments that generally remained in the original lamp vicinity. The more typical fault mode is a failure to trigger, which is often caused by the lamp filling with water. Incoming lamp inspection for OMEGA has been limited to dimensional checks and tesla-coil tests for lamp breakdown.

The large amount of pump energy required for the disk amplifiers in a laboratory microfusion facility (LMF) has led to an interest in large-bore lamps operated at relatively high explosion fractions (30%–40%). This is to minimize costs. Water cooling offers the potential for substantially reducing the possibility of catastrophic failure at high explosion fractions. A cooperative effort between groups[6] at LLE and Lawrence Livermore National Laboratory is attempting to understand OMEGA's outstanding experience with large-bore, water-cooled lamps.

The first step in understanding OMEGA's success was to determine the actual explosion fraction at which the OMEGA lamps are operated. This required precision measurements of the instantaneous voltage across the lamps and the instantaneous current through them. A joint LLE/LLNL team performed these measurements; the results are described in this article.

Two flashlamp drive circuits were tested. The first circuit was a spare 90-mm-rod amplifier module for the OMEGA system. The equipment was in every way identical to actual OMEGA hardware. The second circuit was a disk amplifier test circuit driving a single, isolated "brick" of five flashlamps, connected in series, and located in a large enclosure. Voltage measurements were made as close as possible to the lamps to reduce the inductive and resistive effects of the interconnecting wire. About 1.5 m of #6-gauge wire was used to connect the probe to the lamp-end electrodes. Differential voltage measurements were performed across the lamps on both systems to eliminate ground-referencing problems.

The measurements were made using LLNL-supplied current transformers and voltage probes. The voltage probes (Tektronix P6015) were calibrated just prior to the experiment at the LLNL calibration facilities to an accuracy of ±2%. The current probe (Pearson, Inc.) was calibrated by the manufacturer, also to an accuracy of ±2%. Data was recorded on two Tektronix 2440 digitizing oscilloscopes, which were calibrated in 1990 to a vertical (voltage) accuracy of ±2%. The time base on the oscilloscopes is crystal controlled and has a manufacturer-stated accuracy of 0.00015%. The resulting overall accuracy of these measurements is approximately 3% for current or voltage and 4% for power or energy. The resulting possible error for the explosion fraction is 7% of the measured fraction; the additional error is caused by inaccuracies in measurements of the circuit parameters and lamp dimensions. The accuracy of the probes and current transformers was consistency-checked with LLE equipment.

The lamps in the OMEGA rod amplifier are triggered into conduction by a high-voltage, low-power trigger pulse applied to a backplane adjacent to the lamp. The ignitron switch is triggered simultaneously with the lamp. The lamp current rises as its impedance drops. Eventually, all of the energy stored in the capacitor is delivered to the lamps.

The disk amplifier circuit includes a pulsed lamp-preionization circuit (PILC).[7] The PILC pulse serves to ionize most of the gas volume in the flashlamp prior to the main discharge initiation. Ignitron "I1" is fired 250 µs before the main ignitron "I2," discharging the PILC storage capacitor into the lamps. The combination of this capacitor and the inductor "rings up" the voltage on the cable capacitance high enough to provide initial lamp breakdown. In both the OMEGA rod- and disk-amplifier circuits the voltage was monitored at points A and B (see Figs. 48.12 and 48.13), recording the signals in separate oscilloscope channels. Lamp current was monitored at point C.

Sample voltage and current waveforms versus time are shown in Figs. 48.14 and 48.15 for the rod and disk amplifiers, respectively. Instantaneous power in the lamps is shown in Figs. 48.16 and 48.17 for the same charging voltage. The time integral of the instantaneous power over the entire pulse was calculated using a commercial spreadsheet program. In Figs. 48.18 and 48.19 the explosion fraction is plotted versus charging voltage. Typically, OMEGA rod amplifiers operate at 7.4-kV charging voltage (V_0), which corresponds to a delivered explosion fraction of 34%. The corresponding explosion fraction for the disk amplifier's 13.5-kV charge voltage is 25%.

The current waveforms displayed in Figs. 48.14 and 48.15 are the classical near critically damped waveforms. This was the design criterion for the circuit. The voltage waveforms for both the rod and the disks display several features: At point A in the plots there is a brief spike that is the lamp trigger. Then the voltage drops rapidly as the arc expands to fill the bore of the lamp at point B. The modulation observed on the traces at point C is hypothesized to be caused by acoustic effects inside the lamp. Efforts are underway to correlate this signature with accelerometer measurements. Finally, the voltage decays as all of the bank energy is dissipated.

In conclusion, these measurements indicate that the water-cooled flashlamps used in the OMEGA laser system have been routinely operating at a delivered explosion fraction of 34% without catastrophic failure. Furthermore, this has been accomplished without the use of an extensive quality-control program. Thus, large-bore, water-cooled lamps may be an attractive solution for operation at high explosion fractions in LMF-scale laser systems.

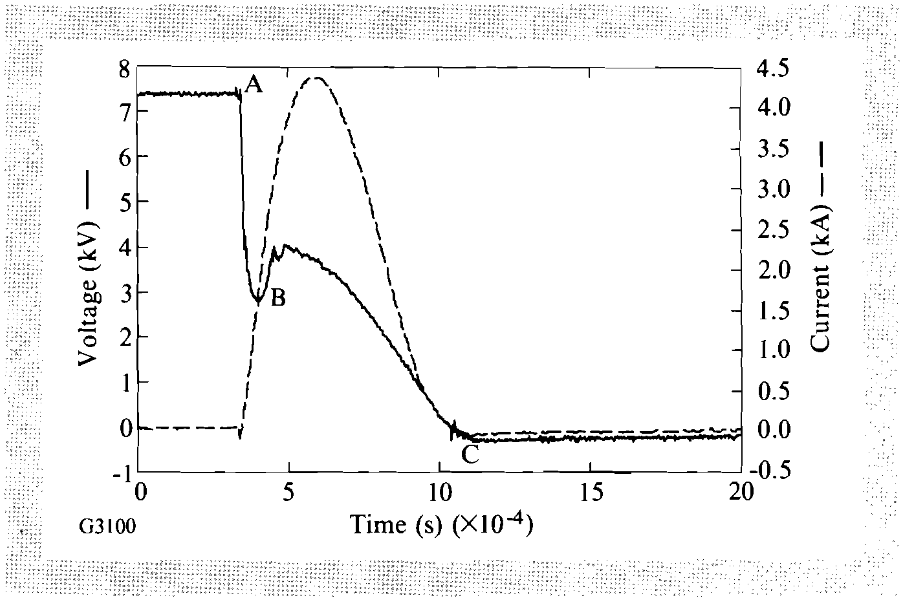

Fig. 48.14
Current and voltage versus time for the 90-mm-rod amplifier at 7.4-kV charging voltage.

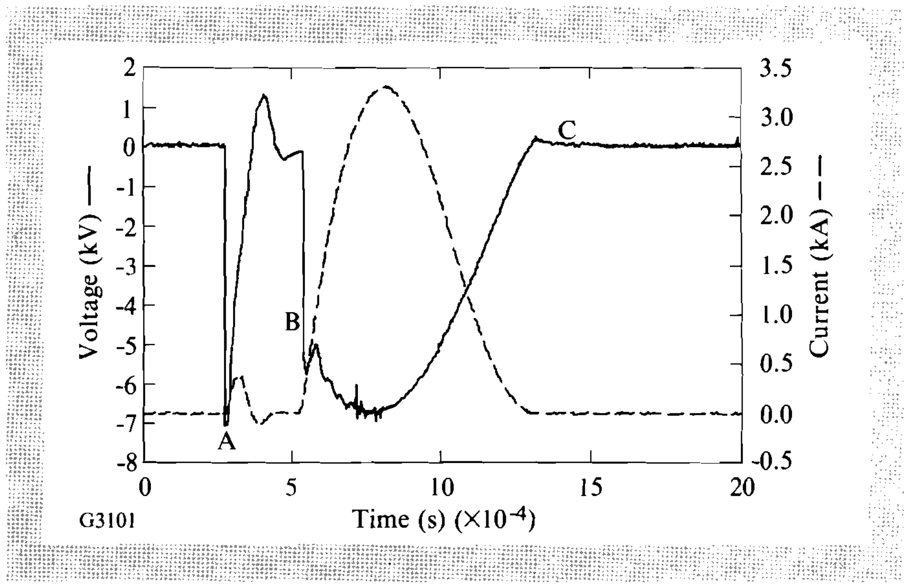

Fig. 48.15
Current and voltage for the prototype disk amplifier at 13.4-kV charging voltage.

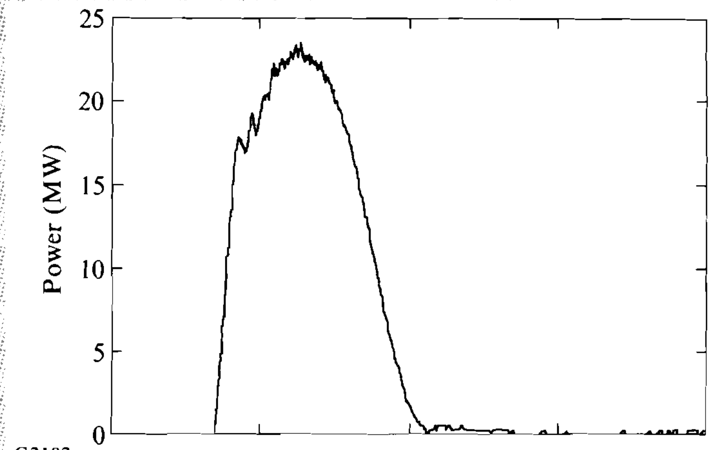

Fig. 48.16
Power versus time for the 90-mm-rod amplifier at 7.4-kV charging voltage.

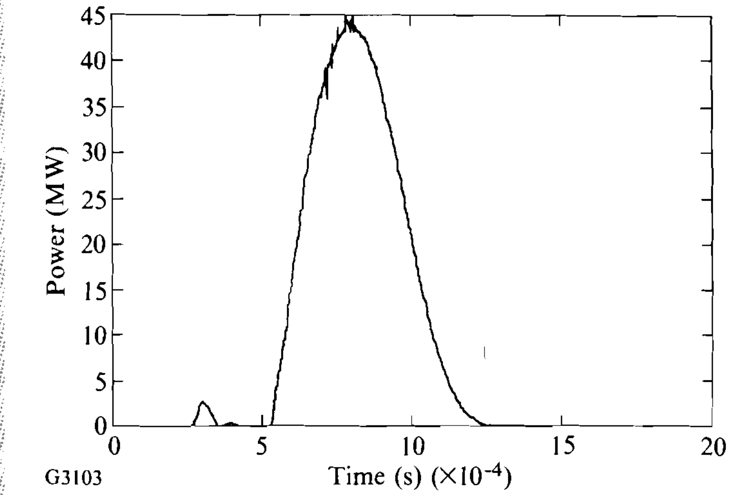

Fig. 48.17
Power versus time for the prototype disk amplifier at 13.4-kV charging voltage.

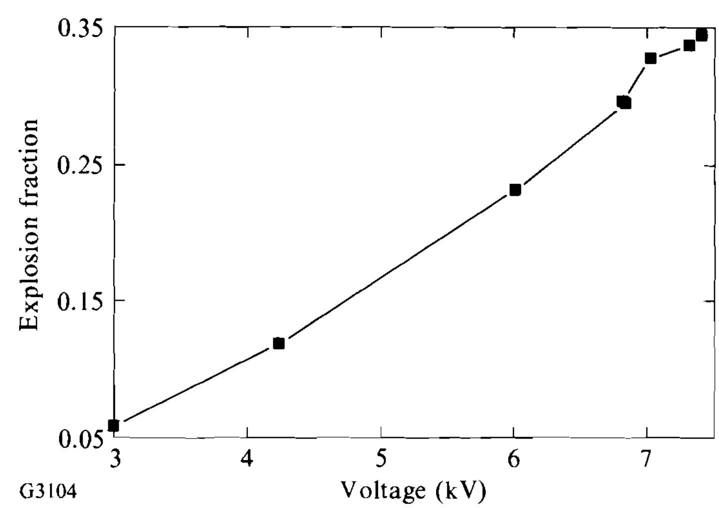

Fig. 48.18
Explosion fraction for the 90-mm-rod amplifier lamps versus charging voltage.

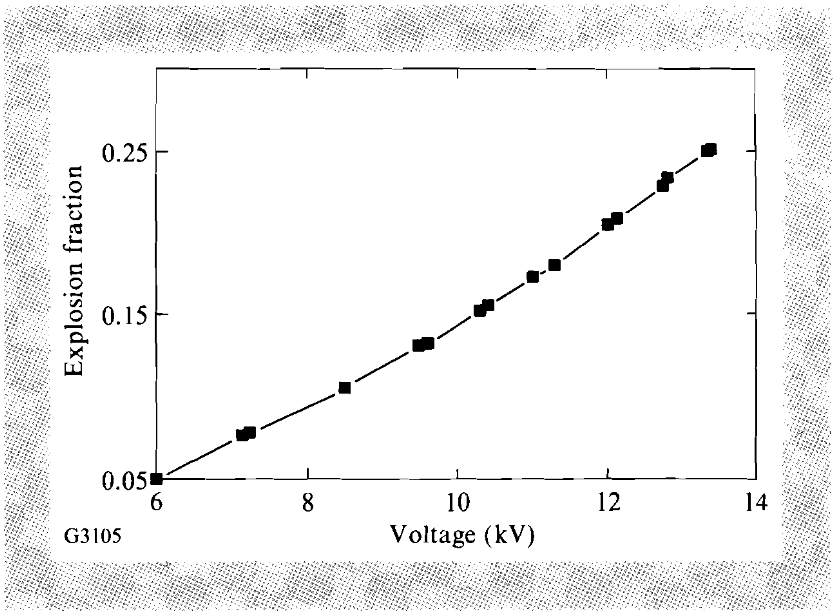

Fig. 48.19
Explosion fraction for the prototype disk-amplifier lamps versus charging voltage.

ACKNOWLEDGMENT

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6. We are indebted to E. A. Campbell, A. C. Erlandson, and D. W. Larson for their efforts on behalf of this collaboration.
7. Laser Program Annual Report 1985, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-50021-85, pp. 7–18 (1986).