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SHIVA LASER SYSTEM PERFORMANCE

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June 15, 1978

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ABSTRACT

On November 18, 1977, after four years of experimentation, innovation, and construction, the Shiva High Energy Laser facility produced 10.2 kJ of focusable laser energy delivered in a 0.95 ns pulse. The Shiva laser, with its computer control system and delta amplifiers, demonstrated its versatility on May 18, 1978, when the first 20-beam target shot with delta amplifiers focused 26 TW on a target and produced a yield of 7.5×10^9 neutrons.

Summary

The Shiva High Energy Laser Facility was conceived in 1972 to achieve a goal of 10 kJ in a subnanosecond laser pulse for laser-fusion target irradiation. On November 18, 1977, at 9:35 P.M., we measured 10.2 kJ of focusable laser energy delivered in a 0.95 ns pulse. This successful Shiva milestone culminated four years of experimentation, innovation, and construction. This performance was achieved within the line item budget and on schedule. With the addition of the delta amplifiers, Shiva can produce 15 kJ in 1 ns or >30 TW in a 100-ps pulse.

The project goals were:

Promised:	\$25 million budget* 10 kJ in October 1977 ± 3 months†
Achieved:	\$25 million cost 10.2 kJ in 0.95 ns (10.7 TW) demonstrated November 18, 1977

The High Energy Laser Fusion Project has been accomplished within the budget allocated by Congress and the Department of Energy (DOE) and very close to the original schedule. In addition, the Shiva laser, with its computer control system and delta amplifiers, is a much more versatile instrument than orginally conceived. This versatility was demonstrated on May 18, 1978, when the first 20-beam target shot with delta amplifiers focused 26 TW on a target and produced a yield of 7.5×10^9 neutrons. This power output and neutron yield represent world-record performances.

Construction

The completion of the Shiva laser construction (see Fig. 1) culminated the design activity started in December 1972, when the Shiva project was formally established. At that time, basic laser design began and, concurrently, program-supported research lasers were constructed. The data gathered from the Cyclops, Janus, and Argus lasers served to define the Shiva optical design. The building was begun in August 1974, and in June 1975 the number and size of the laser beams were frozen. Also during this time period, detailed component design began and the automatic alignment systems was defined. In January 1976, a \$1.8 million contract was awarded for the long lead time neodymium doped glass. At that time, the decision was also made to implement a multilevel, digital computer control

*Based on the final Schedule 44 for HELF, dated 12/74, which provided \$25 million. The earlier Schedule 44, dated 12/72, was revised because of a slower than expected authorization rate (\$2 million in FY 74 rather than \$10 million), and the 15% real inflation experienced during those years.

†Letter to Gen. J. K. Bratton dated February 27, 1976. In 1974, the estimated completion date was spring 1977.

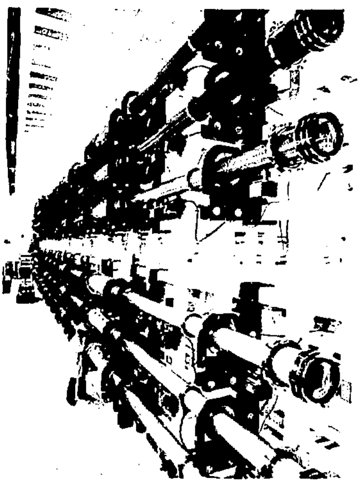


Fig. 1. View of the Shiva laser from the gamma to delta spatial filter toward the rod amplifiers at the beginning of the laser chain.

system, a departure from our previous manual control system.

In February 1976, a formal commitment was made to Maj. Gen. J. K. Bratton to demonstrate the 10 kJ, subnanosecond performance by October 1977 ± 3 months. During 1976, the detailed hardware design was completed and approximately one-half of the laser system contracts were awarded. In July 1976, beneficial occupancy of Building 391 was taken and installation of the spaceframe started. The spaceframe installation was completed in October and the laser installation followed. In late 1976 the new actively mode-locked oscillator design was demonstrated and chosen for the Shiva system.

By May 1977, all contracts of greater than $100,000 had been awarded. On August 3, the first Shiva arm was successfully fired at 525 J. This verified that the system design was sound and would be capable of meeting its performance objectives. During October, the first five arms were operated at the kJ level. In early November, the remaining 15 arms were tested in groups of 5 to demonstrate their integration into the system. On November 18, all 20 arms were fired simultaneously and yielded an output of 10.2 kJ in 0.95 ns.

Milestone Performance with 10-kJ Output

During the 10-kJ experiment, all the major laser subsystems operated satisfactorily and the chain components, through the gamma amplifier stages for all 20 beamlines, including spatial filters, performed up to expectation. Moreover, no optically induced damage to either glass substrates or thin film coatings occurred. The average beam energy of 510 J is in good agreement with the prediction of our design codes. The codes include both linear and nonlinear models of beam propagation, spatial filter transmission, and gain saturation. Figure 2 compares the measured output energy of each arm with the computer simulation. While the calorimeters on each arm measured the energy to better than 1%, the arm-to-arm variation in chain energy is close to 10%. This variation is readily accounted for by arm-to-arm variations in chain input energy, gain, and pinhole alignment. Figure 3 is a photograph of the near-field beam taken at the output of arm 20 (550 J). Note that the beam is free of the high spatial frequency modulation that leads to loss of focusability and damage to optical coatings.

Shiva Single-Arm Prototype Performance (Long Pulse)

In advance of the operation of all 20 arms, experiments were conducted on one arm (No. 5) of the Shiva laser system to assess performance in the long

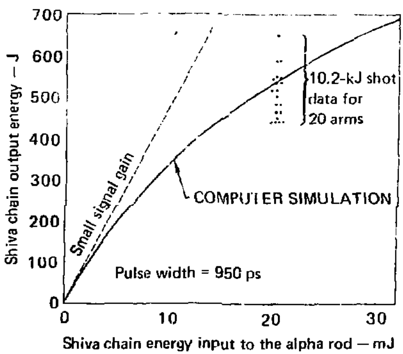


Fig. 2. Comparison of the measured energy for each Shiva arm with a computer simulation that includes linear and nonlinear models for beam propagation, spatial filter transmission, and gain saturation.

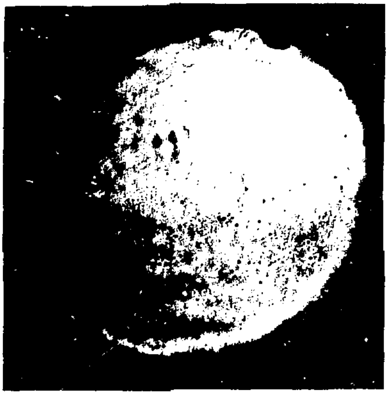


Fig. 3. Photograph of the output beam from Shiva arm No. 20 at 550 J in 0.95 ns. Small spots on the photograph are caused by dust on the beamsplitter that immediately precedes the film.

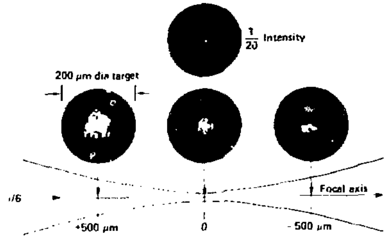


Fig. 4. Typical focal pattern of the Shiva laser taken from an array camera. The 200-μm-diam circle represents a target that could have been irradiateu on this laser shot. The 1/20-intensity picture shows the best focus at 1/20 of the intensity of the typical focal pictures. These pictures indicate that 90% of the beam is focusable within a 25-μm-diam circle.

(~1 ns) pulse mode of operation and to identify system problems in a timely manner. On August 3, we obtained 525 J from arm No. 5. This experiment confirmed the laser staging calculations, but some small-scale damage was observed on the input lens of the beta-to-gamma spatial filter following this shot. We traced the principal source of this damage to a beam-pointing error caused by vignetting in the preamplifier stage and to insufficient spatial filtering. This caused nonuniform illumination of the beam-defining aperture at the input to the amplifier chain, resulting in very high peak-to-average spatial intensity distributions. Diffraction modulation from small imperfections, superimposed upon this locally intense beam, self-focused sufficiently to cause some damage. After this problem was corrected, further shots with spatial filter pinholes in place satisfied all our performance goals. Since that date, we took shots with clusters of 5 arms fired simultaneously; subsequent shots taken with all 20 arms confirmed the prototype-arm performance.

To examine qualitatively the focusability of high energy beam, array-camera photographs, typified by Fig. 4, were taken on several high power shots. It can be seen that the focused spot is easily contained within a 200-m circle near the plane of best focus. A small amount of residual astigmatism is noted, but it is clear that nonlinearly induced phase aberrations do not unduly degrade the focal spot. Our certainty that the entire beam is focusable onto a fusion target is supported by the absence of any observable beam breakup on the streak camera record (see Fig. 5), by the lack of any evidence of small scale self-focusing in the near- and far-field beam pictures, and by the low accumulation of nonlinear phase retardation, ΔB, after the final spatial filter pinhole (see Fig. 6). Our experience in interpreting this data, gained from Janus, Cyclops, and

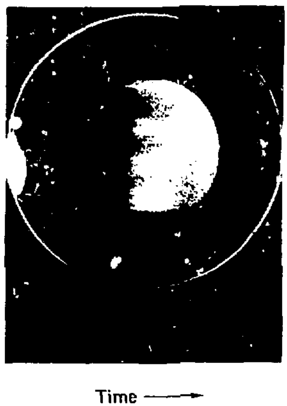
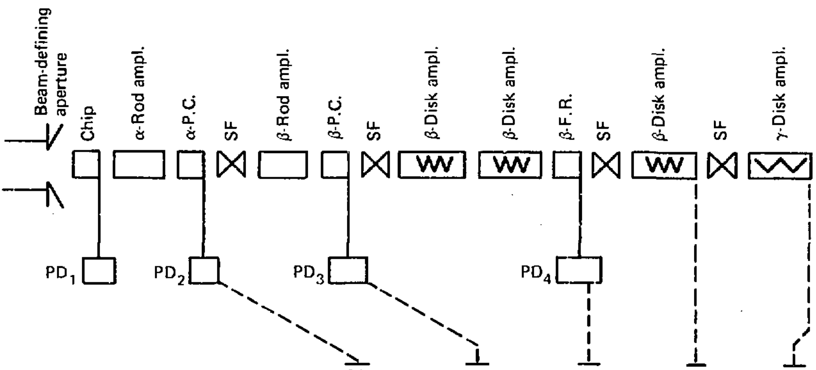


Fig. 5. Streak-camera record of the output of Shiva beam No. 5 at 485 J. Pulse FWHM measured by the input streak camera was 0.9 ns. The spatial filter pinhole sizes were the same as those used on the 10.2-kJ system shot. No evidence of temporal distortion from self-focusing or pinhole closure is present in this record.



Beam diam, mm	21	44	92	92	145
SF pinhole diam, mm	1.5	0.4	0.6	0.6	—
SF acceptance angle, mrad	1.8	0.9	0.65	0.65	—
Fluence (@ fill factor = 0.7), J/cm^2	0.28*	0.90	2.5*	5.5*	4.4
Energy @ 950 ps, J (calculated)	0.68	7.8	89	260	542
Energy @ 950 ps, J (measured)	—	9.6	—	—	510
ΔB (calculated)	0.13	0.43	0.55	0.94	0.63
ΣB (calculated)	0.13	0.56	1.11	2.05	2.68

*Estimated

Fig. 6. Summary of Shiva typical arm performance—shot 77111807. Total energy—10.2 kJ.

Argus experiments, told us that all the energy that exits the beta-gamma spatial filter and the gamma amplifier will focus onto a laser fusion target.

Shiva Short Pulse Performance

After the laser milestone experiment on November 18, 1977, we began to activate the system for a full-power 20-beam target experiment. This work included setting up the laser for 100 ps operations, adding the δ amplifier booster stages, integrating the target diagnostics, and implementing the beam-handling optics for final target irradiation.

A 1-beam target experiment took place on February 3, 1978; a 4-beam experiment occurred on March 1, 1978; a 10-beam, single sided experiment took place on April 7, 1978; and on May 18, 1978, a 20-beam 26 TW, 95-ps target experiment occurred. This 26-TW laser target shot yielded 7.5×10^9 neutrons, which is a new world record for both laser power and fusion yield. This experiment was conducted under almost complete automatic control. All major laser and target diagnostic subsystems performed flawlessly.

ACKNOWLEDGMENTS

The combined efforts required to design, build, and test the Shiva laser system totaled over 250 man-years of LLL effort, combined with more than 17 million of industrial contracts. We cannot possibly acknowledge the individual efforts of everyone who contributed, but we would like all the participants to be aware of our gratitude for their dedication, creativity, and fine craftsmanship. We would especially like to thank J. L. Emmett and A. C. Haussmann for their constant leadership and support; H. G. Ahlstrom and the staff of the Fusion Experiments Program for their support and for the activation of the Shiva laser leading to the 26-TW target experiment; and J. H. Nuckolls and his group for their constant encouragement. In addition, we thank W. F. Krupke and J. I. Davis for their leadership of the Solid State Program and the Shiva Project during its formative years.

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