MASTER PREPRINT UCRL-82117

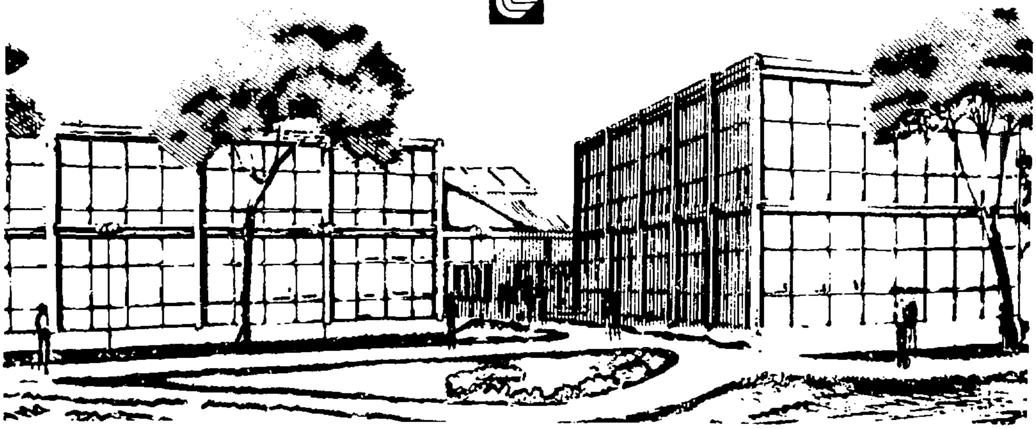
Lawrence Livermore Laboratory

PERFORMANCE OF SHIVA AS A LASER FUSION IRRADIATION FACILITY

D. R. Speck, E. S. Bliss, J. A. Glaze, B. C. Johnson, K. R. Manes, R. G. Ozarski,
P. R. Rupert, W. W. Simmons, C. D. Swift, C. E. Thompson

June 6, 1979

This paper was prepared for submission to
1979 IEEE/OSA Conference on Laser Engineering and Applications
Washington, D.C., May 30 - June 1, 1979



PERFORMANCE OF SHIVA AS A LASER FUSION IRRADIATION FACILITY*

D. R. Speck, E. S. Bliss, J. A. Glaze, B. C. Johnson, K. R. Manes,
R. G. Ozarski, P. R. Rupert, W. W. Simmons, C. D. Swift, C. E. Thompson

University of California
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, California 94550

I. Introduction

Shiva is a 20 beam Nd:Glass Laser and Target Irradiation Facility at the Lawrence Livermore Laboratory. The laser system, a photograph of which is shown in Figure 1, and integrated target facility evolved during the last year from a large, untested, experimental laser system to a target irradiation facility which has provided significant laser driven inertial confinement fusion data.

Shiva, as shown by Figure 2, is the latest in a series of progressively larger Nd:glass irradiation facilities constructed at Livermore to study the target design physics of laser driven inertial confinement fusion. The current series of facilities began with the Janus Facility in 1974,(1) progressed through the Argus Facility in 1976,(2) has now reached Shiva and will continue with Nova(3) in 1983 which will provide the capability to reach scientific breakeven. Our work with Shiva has concentrated on experiments with ablatively driven targets since this is the path which leads to the high fuel ρr necessary to reach thermonuclear ignition.

* Research performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48.

The concept of inertial confinement fusion based on this type of target is shown on Figure 3.[4] Laser beams heat the surface of the fusion target forming a surrounding plasma envelope. The thermonuclear fuel is compressed by the blow-off or ablation of the surface material. When the fuel reaches 1,000 to 10,000 times liquid density and 100,000,000^{0}C, ignition of the fuel occurs. Under these conditions the fuel burns rapidly by thermonuclear reactions yielding many times the driver input energy. Our first goal with Shiva has been to produce significant compression of the DT fuel in ablative targets. As you will see later in this talk we have achieved this goal.

This year the shot rate with Shiva increased from one shot per week in April 1978 to a high of ten shots per week by March 1979. Figure 4 shows the monthly shot rate since January of 1978. During the time shown we irradiated 106 fusion targets. Of this total 18 shots were fired with short 90-100 ps pulses in exploding pusher implosion experiments and approximately 80 shots were fired with longer 0.5 to 1.0 ns pulses in ablatively driven implosion experiments. The balance of the experiments were foil irradiation experiments for plasma studies and diagnostics checkout. In addition, we performed numerous laser beam energy balance tests, beam propagation tests, and amplified spontaneous emission measurements. Presently we can perform two well instrumented, full system, target irradiation experiments per day. With system improvements which we will soon make, the laser system will be capable of 3 to 4 shots per day and will not be the principal constraint to the shot rate. We find that in carrying out high quality, well diagnosed experiments, other portions of the progam such as target design and fabrication, diagnostics installation and checkout, and data analysis frequently limit the shot rate. It was these constraints which prevented us from firing more than 35 shots/month during February and March.

II. System Description

Figure 5 shows the basic elements of the Shiva laser design. The optical pulse originates in an actively mode-locked Nd:YAG oscillator[5] whose pulse duration is readily tunable from 90 ps to 1.5 ns. The pulse is amplified, expanded, and divided into 20 equal beams in the preamplifier and beamsplitter array. Following the beamsplitter each beam passes through an optical delay whose length is adjusted with the aid of the pulse synchronization system to provide simultaneous arrival of the twenty beams at the target to within ± 5 ps. Bert Johnson will described this system in more detail tomorrow.

Optical alignment of the laser system and of the beams to the target is aided by computer controlled automatic alignment systems.[6] Erlan Bliss will describe these systems in more detail in an invited paper tomorrow. These systems greatly reduce the time consuming and tedious tasks of maintaining system alignment and of aligning the beams to small targets. With the integration of an automatic spatial filter pinhole alignment system, now in preparation, the shot preparation time will be significantly reduced and an increased shot rate will be possible.

Three sets of half-waveplate attenuators provide the necessary gain control for the system. Two waveplates in the preamplifier adjust the intensity at the bleachable dye cell to compensate for changes in the pulse duration from the oscillator and set the drive for the amplifier chains to produce the desired output. The third set of waveplates, at the input to each beam, balance the laser chain output energies. With this control we are able to maintain maximum energy spread among the 20 beams of $\pm$ 10% even though the gross gain of individual arms may differ by up to a factor of 2.

Figure 6 shows the elements in a Shiva laser chain. A 9.5 mm diameter aperture at the input to each beam defines the spatial beam. In each amplifier chain this 9.5 mm diameter, 1-10 mJ, input beam is expanded to fill the 200 mm output aperture and amplified to energies up to more than 500 J. The amplifier chain design follows the Argus design,(2) using glass rod amplifiers in the small diameter stages up to 50 mm diameter, and increasing aperture disk amplifiers of 95, 145, and 200 mm diameter as the high power amplifiers. Currently six vacuum spatial filters(7) in each chain control small scale beam instabilities and act as beam expanders and relay elements(8) to maintain all of the amplifiers in the near field of the input aperture.

In the target bay, Figure 7, two turning mirrors, computer controlled by the chain output pointing system, center each of the beams on its focusing lens and point it at the target. Ten beams are directed to the top of the target chamber and ten beams to the bottom. These two clusters of beams are focused on the target by twenty f/6 focusing lenses.

The target chamber, Figure 8, is a 1.6 meter diameter stainless steel vacuum vessel equipped with two 1500 liter/second turbomolecular pump capable of pumping the system to less than 10^{-5} torr. The chamber contains twenty entry ports for the beams and 200 ports for target diagnostic and alignment equipment.

Energy preceding the laser pulse which might damage or destroy fragile fusion targets is of concern in large systems such as Shiva. In target damage experiments, short pulses containing less than 1 mJ focused onto targets have fractured the target shells.(9) Thus the pulse contrast at the output of Shiva should be maintained at less than 10^{-7}.

We control oscillator prepulses from Shiva with a double Pockels cell switchout and a bleachable dye cell in the preamplifier system. Routine monitoring of the ratio of prepulse to selected pulse energies at the output of the dye cell assists in maintaining oscillator prepulse contrast at approximately 10^{-9}. Another source of prepulse energy is amplified spontaneous emission and flashlamp light from the system amplifiers. Figure 9 shows the ASE from a single Shiva arm measured behind a 400 μm diameter pinhole in the center of the target chamber. The combination of the preamplifier dye cell and two Pockels cells in each arm limits this

ASE signal. The measured ASE pulse shown in Figure 9 consists of a broad 300 μs FWHM pedestal of ASE and flashlamp light from the disk amplifiers with a sharp spike on top occurring during the Pockels cell open time. The figure shows the measured energies resulting from shots with laser settings appropriate to 30 TW output with 100 ps pulses. To obtain total energies on target one must multiply by 20.

To insure that a target design will not be damaged by ASE or prepulses we conduct ASE tests on typical targets. These consist of firing the full laser with the oscillator switchout disabled and the beams aligned to the target in the target chamber. The target is removed after the shot and carefully examined for damage. We have never damaged a target in such a test with Shiva.

III. Laser Performance

Target irradiations with 90 ps pulses during the last year provided up to 20 TW on target with little penalty to the laser and beam focusing system.

Figure 10 shows the average beam output energy and system output power versus the average output energy of the beta rods in the amplifier arms. The solid curve is the result of system calculations using the component design data as input. The agreement is good. Energy measured at this mid-chain location is particularly useful for system operations since it monitors the output of the last rod amplifier in each chain and allows direct tuning of the drive energy input into the disk amplifiers. The rod amplifiers can be fired at a much higher repetition rate than the disk amplifiers. The damage limits shown are conservative lower limits at which damage starts to occur on the target room turning mirrors and focusing optics.

During the last year target experiments at 0.5 to 1.0 ns pulse duration called for 6.0 to 10.0 kJ on target. Shiva provided this output routinely without stressing the laser system. More than 80 high energy laser irradiations were fired at this pulse duration. Figure 11 shows the average beam output energy and total system power versus the average output of the beta rods. Data is shown for the flashlamp banks on the output amplifiers charged to 20 and to 22 kV. As in the previous figure the solid curves are the result of calculations using component design data. The damage threshold shown arises from the flux limit at the input lens of the mid chain beta-gamma spatial filter.

Focusability of the Shiva beams at 1.0 TW output is illustrated in Figure 12. This data was taken from an array camera in an incident beam diagnostics package.(9) It shows beam photographs taken in planes optically equivalent to 450 μm before, at, and 450 μm behind best focus, with the linear dimensions scaled to conform to the beam in the target chamber. At the bottom of the figure are radial average intensity plots obtained by computer reduction of microdensitometer scans of the photographs. One sees these beams are readily focusable into a 200 μm diameter and the peak intensity exceeds 10^{16} watts/cm^2. This is typical of Shiva beams.

Computer simulations reproduce the focal pattern of typical beams when they include one wave of astigmatism and $\lambda/4$ to $\lambda/2$ of spherical aberration.

Initial short pulse experiments with up to 27 TW on target produced several optical damage spots of 1-3 mm diameter on some target room turning mirrors and focusing lenses. Near field photographs of the beam taken at 1.5 TW output showed the cause of this damage to be 1-3 mm diameter spikes which were more than ten times the average beam intensity; well above the damage threshold of thin film coatings on the mirrors and focusing lenses. Figure 13 shows a reproduction of one of the beam photographs and a densitometer scan through a portion of the photograph containing one of these spikes. Analysis with a system simulation propagation code indicated these spikes arise from self-focusing of intensity bumps which have spatial frequencies below the bandpass of the spatial filters. While these bumps are controlled in the laser chain by the relaying of the spatial filters they can grow to catastrophic proportions in the long propagation path from the last spatial filter output to the target chamber. We prevented this high spike growth during this last year's operations by limiting the output power to 20 TW. At this power the self focusing growth of these bumps is not large and no damage occurs.

Output spatial filters which complete the relay to the target chamber are an obvious way to control this problem. To implement this fix we recently installed 20 centimeter aperture, f/14, spatial filters in the target bay between the output amplifiers and the first turning mirrors. Figure 14 is a near field photograph similar to that shown in the previous figure taken after the installation of the output spatial filters. The peak hump intensity, as shown by this photograph, has been reduced to less than 4X the average intensity. It appears that routine 30 TW operation is now possible without causing damage to the beam turning and focusing optics.

Figure 15 summarizes Shiva performance to date. Shown is total system power versus pulse duration. The conservative power limit assigned to insure no optical damage to chin film coatings occurs in the system is shown by the solid line. The shot data is shown by the points. The scatter in the points resulted largely from the variety of pulse lengths and energies requested for particular experiments. For any given shot the laser output was predictable to ± 5%. Now that output spatial filters have been installed the permissable output power will rise by 50%.

IV. Target Experiments

With Shiva we have irradiated both exploding pusher and ablatively driven targets with a strong emphasis on the ablative targets. Exploding pusher targets are typically irradiated with short high intensity laser pulses while the ablative targets are irradiated with longer, lower intensity pulses. For most efficient compression of the fuel in ablative targets complex pulse shapes are required,(4) however, in our Shiva experiments to date we have used only simple gaussian pulse shapes. We irradiated exploding pusher targets with 15 to 20 TW in gaussian pulses of 90 to 100 ps duration and the ablative targets with 6 to 10 kJ in gaussian pulses of 0.5 to 1.0 ns duration.

In the Hyperion Campaign, during September and October of 1978 we irradiated 15 exploding pusher targets. Figure 16 summarizes this series of experiments. The target performance fit very well the scaling laws for exploding pushers determined from earlier Janus and Argus experiments. Measured ion temperatures were up to 4.5 keV and neutron yield was up to $3X10^{10}$.

Figure 17 shows the neutron yield plotted versus the energy absorbed in the target in joules per nano-gram and the yields predicted for these targets from the simple scaling laws derived from Janus and Argus experiments.[10] One sees the data agrees well with the predictions.

From November 1978 to March 1979 we conducted 80 experiments on ablatively driven targets with the goal to demonstrate significant compression of the DT fuel.

Figure 18 shows the results of these experiments. Shown here is the DT fuel density at the time the fusion reactions occur versus the 14 MeV neutron yield. The solid circles are data from ablatively driven targets of two different designs and the open circles data from exploding pusher targets. The bars on the circles show the uncertainties resulting from the uncertainty in the neutron yield measurements and in the experimental uncertainty in the density measurement. The colored band represents the uncertainty in inferring the DT fuel density from the measured data by the various calculational models. From these data we conclude that the highest density targets reached densities of at least 50 times liquid density and may have reached densities as high as 100 times liquid density.

V. Conclusion

During the last year we have irradiated more than 100 targets with Shiva, most of these in the seven month period from September 1978 to March 1979. During this period the laser was run conservatively with output limited to less than 20 TW for 100 ps pulses and to less than 10 kJ for 1 ns pulses. During this year no significant damage occurred to the laser optics from beam propagation effects.

In these experiments we irradiated 80 ablatively driven targets with 6 to 10 kJ in 0.5 to 1.0 ns pulses. Neutron yields of up to $2X10^8$ and ion temperatures of 0.5 to 1.0 keV resulted. We inferred with high confidence, fuel densities of between 50 and 100X liquid density for the most highly compressed targets.

In the immediate future we will be characterizing Shiva with newly installed f/14 output spatial filters. These filters will allow us to continue the experiments described here with higher laser output energies. In the longer term we will be investigating other target designs in preparation for breakeven experiments to be done on the now under construction Nova laser system.

VI. Acknowledgements

In a project as large as Shiva it is difficult to acknowledge everyone who has played a significant role. A large fraction of the staff of the Lawrence Livermore Laboratory Laser Fusion Program has participated in the Shiva Project. The authors of this paper are the professional staff of the Shiva Laser Operations Group and a staff member (W. W. Simmons) who aided in evaluation and design of the output spatial filters. The authors would particulary like to thank the technician crews who ran the system in accumulating the data shown here and the members of the Laser Plasma Interaction Group who participated in the target irradiation experiments described.

References

1. J. F. Holzrichter and D. R. Speck, J. Appl. Phys. 47, 2459 (1976).

2. W. W. Simmons, D. R. Speck, and J. T. Hunt, Appl. Opt. 17, 999 (1978).

3. T. J. Gilmartin, C. P. Benedix, E. S. Bliss, R. J. Foley, W. L. Gagnon, R. O. Godwin, W. F. Hagen, F. W. Holloway, J. F. Holzrichter, C. A. Hurley, R. G. Ozarski, F. Rienecker, W. W. Simmons, S. E. Stokowski, I. F. Stowers, J. B. Trenholme, E. P. Wallerstein, and K. Whitham, 1979 IEEE/OSA Conference on Laser Engineering and Applications, Technical Digest, p. 66, May, 1979.

4. J. Nuckolls, L. Wood, A. Thiessen and G. Zimmerman, Nature 239, 139 (1972).

5. D. J. Kuizenga, Opt. Commun. 22, 156 (1977).

6. E. S. Bliss and G. J. Suski, 1979 IEEE/OSA Conference on Laser Engineering and Applications, Technical Digest, p. 95, May 1979.

7. W. W. Simmons, S. Guch, Jr., F. Rainer, and J. E. Murray, IEEE J. Quantum Electron. QE-11, 300 (1975).

8. J. T. Hunt, J. A. Glaze, W. W. Simmons, and P. A. Renard, Appl. Opt. 17, 2053 (1978).

9. D. R. MacQuigg and D. R. Speck, Bull. Am. Phys. Soc. II, 21 1174 (1976) and Lawrence Livermore Laboratory Report UCRL 78447, Sept. 1976.

10. E. K. Storm, H. G. Ahlstrom, M. J. Boyle, L. W. Coleman, H. N. Kornblum, R. A. Lerche, D. R. MacQuigg, D. W. Phillion, F. Rainer, V. C. Rupert, V. W. Slivinsky, D. R. Speck, C. Swift and K. G. Tirsell, "Laser Fusion Experiments at 4 TW", Phys. Rev. Lett. 40, 1570, 1978.

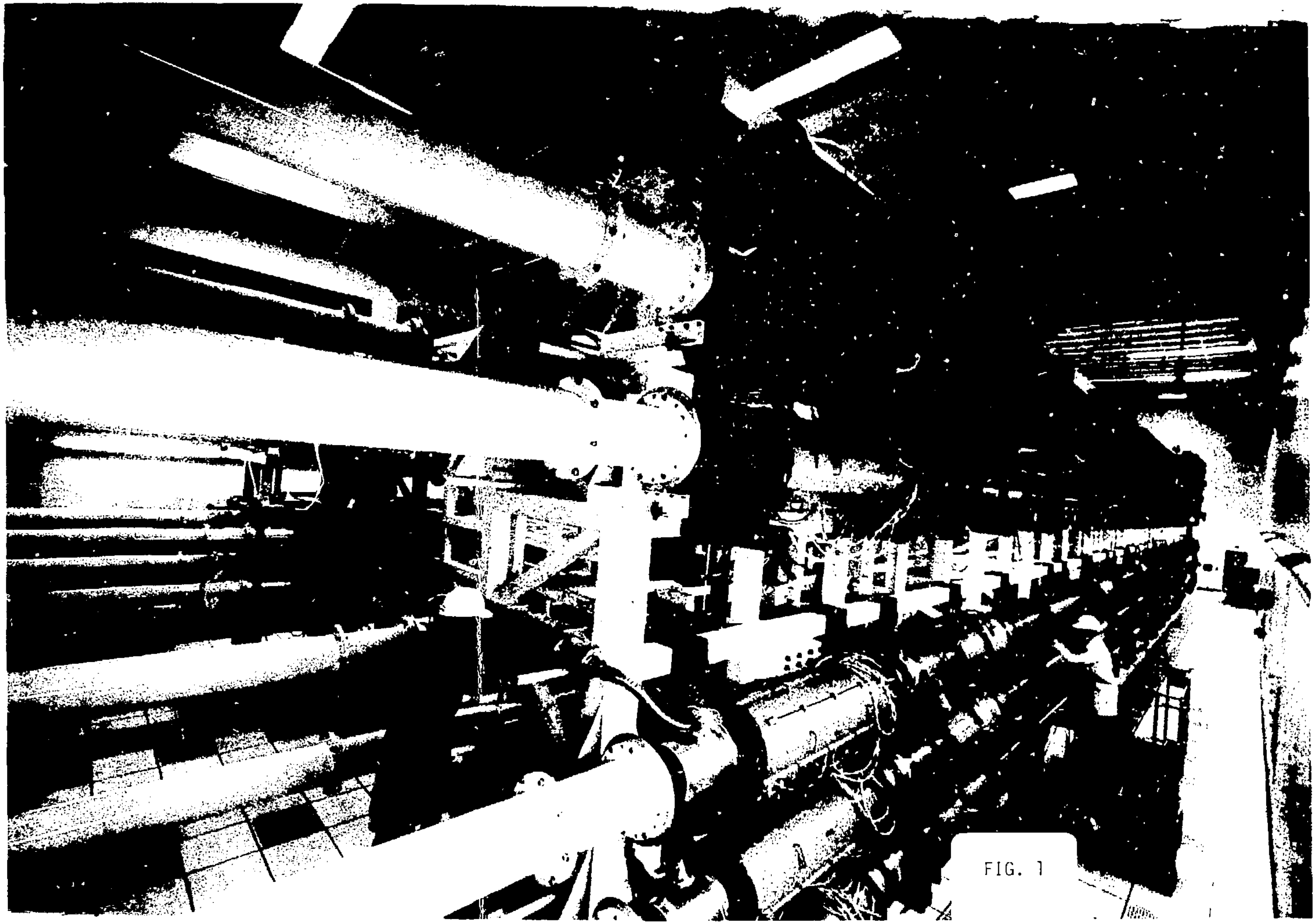


FIG. 1

LASER FUSION – PROGRESS PROJECTIONS

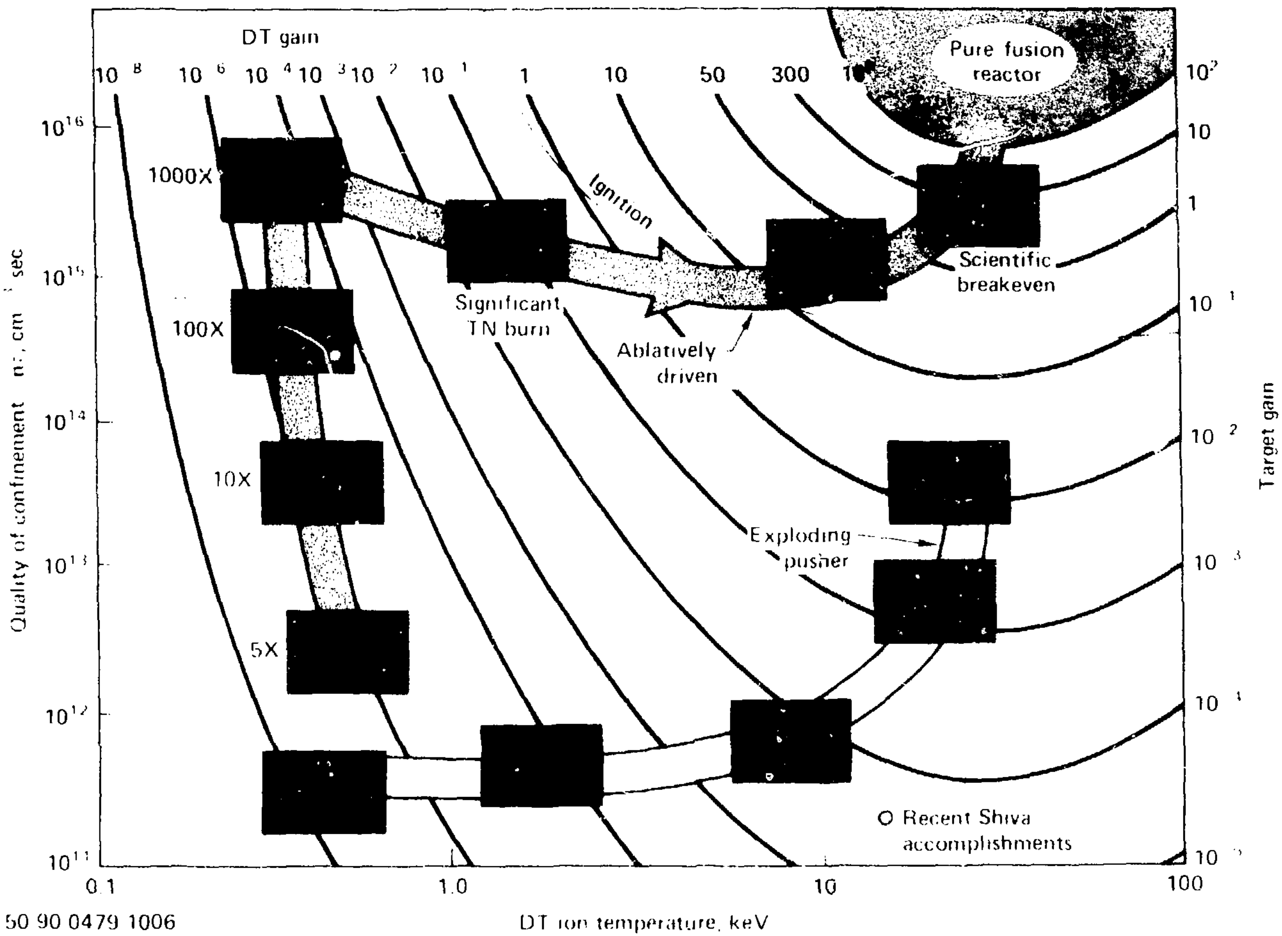


FIG. 2

INERTIAL FUSION CONCEPT

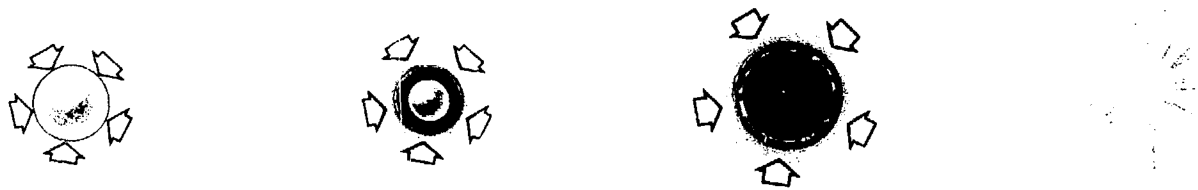


FIG. 3

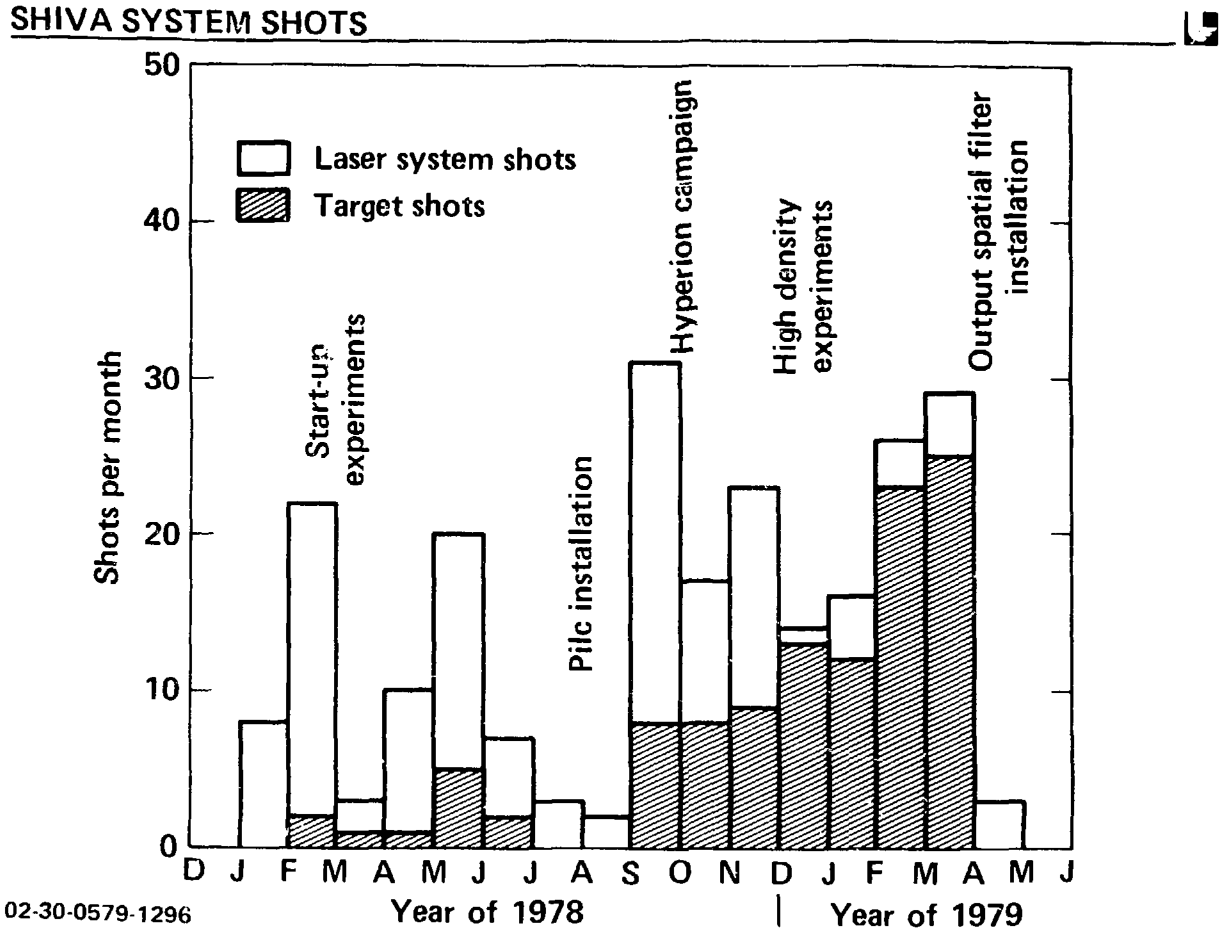
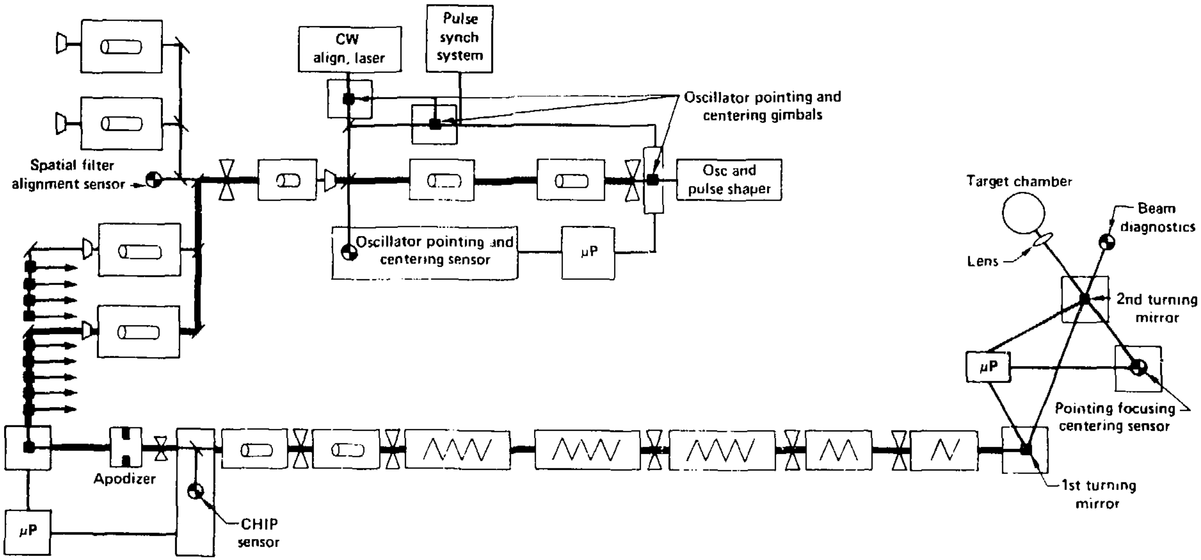

SHIVA SYSTEM SHOTS
Laser system shots
Target shots
Shots per month
50
40
30
20
10
0
Start-up experiments
Pilc installation
Hyperion campaign
High density experiments
Output spatial filter installation
D J F M A M J J A S O N D J F M A M J
Year of 1978
Year of 1979
02-30-0579-1296

FIG. 4

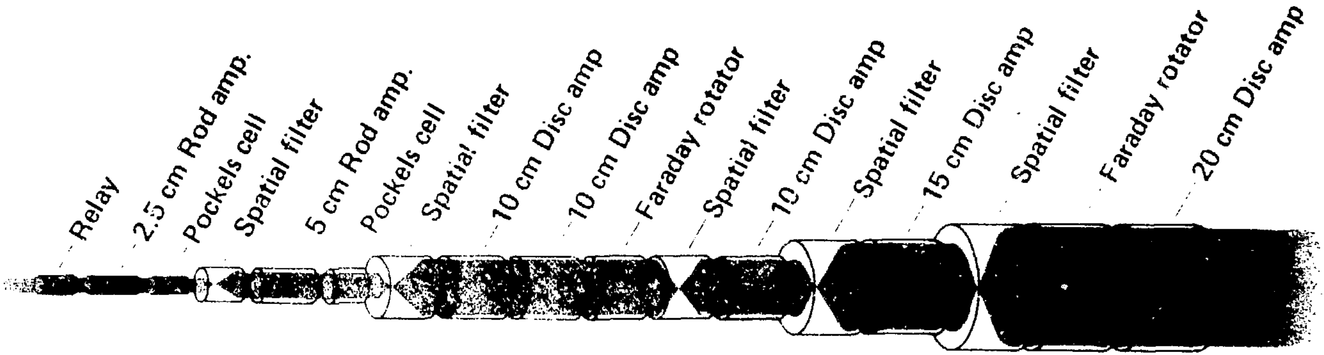
SHIVA BEAM LINE

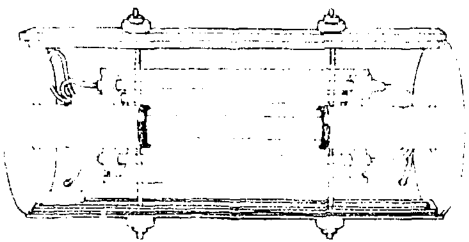


02-12-0178-0185

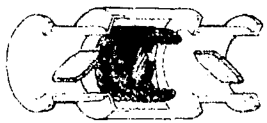
FIG. 5

SHIVA LASER CHAIN





Rod amplifier

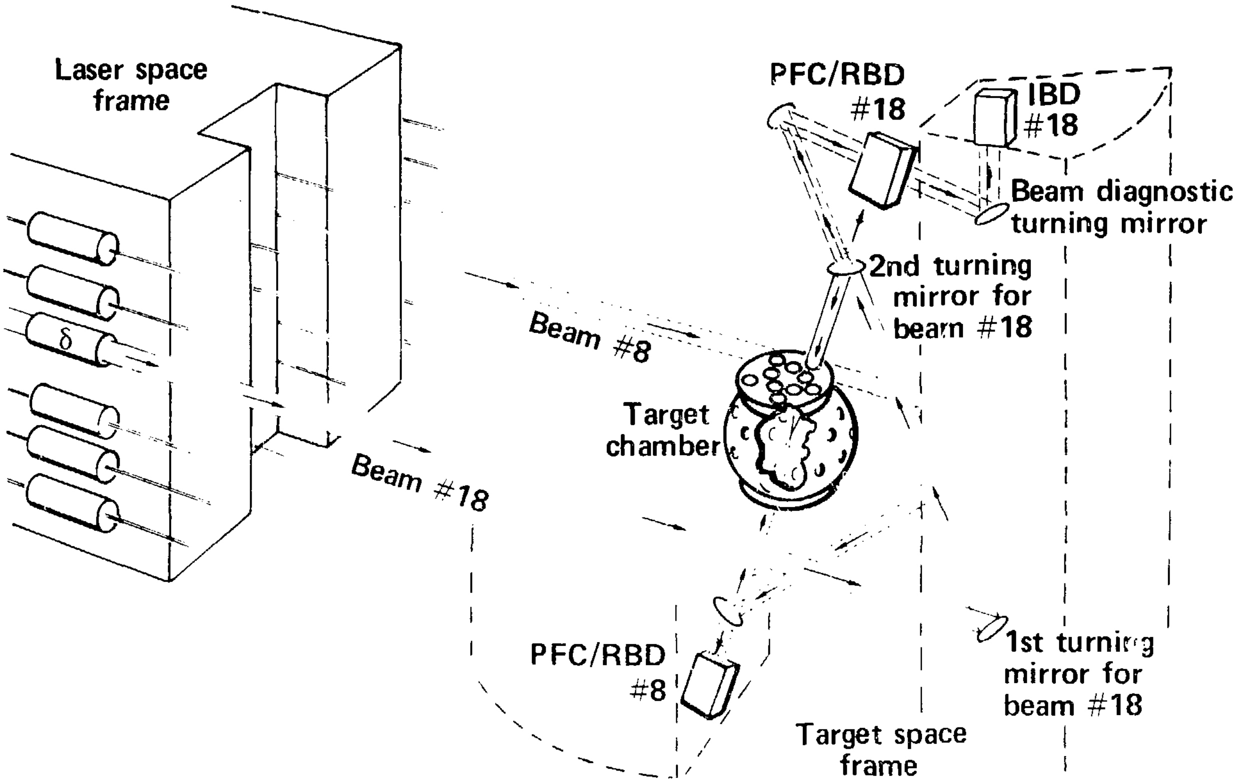


Faraday rotator

Disc amplifier

FIG. 6

TYPICAL SHIVA BEAM ROUTING



20-01-0977-2092

11/77

FIG. 7

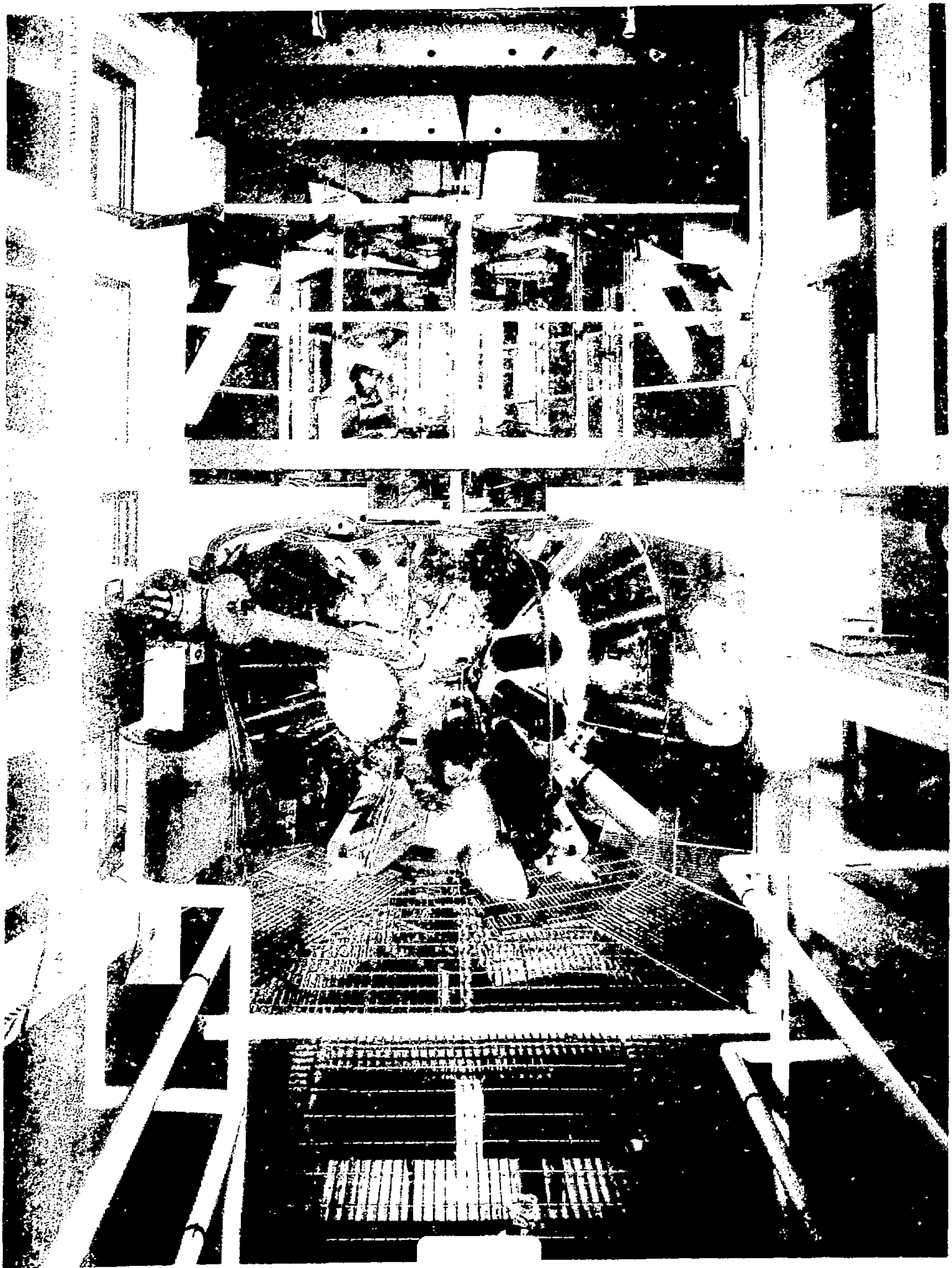
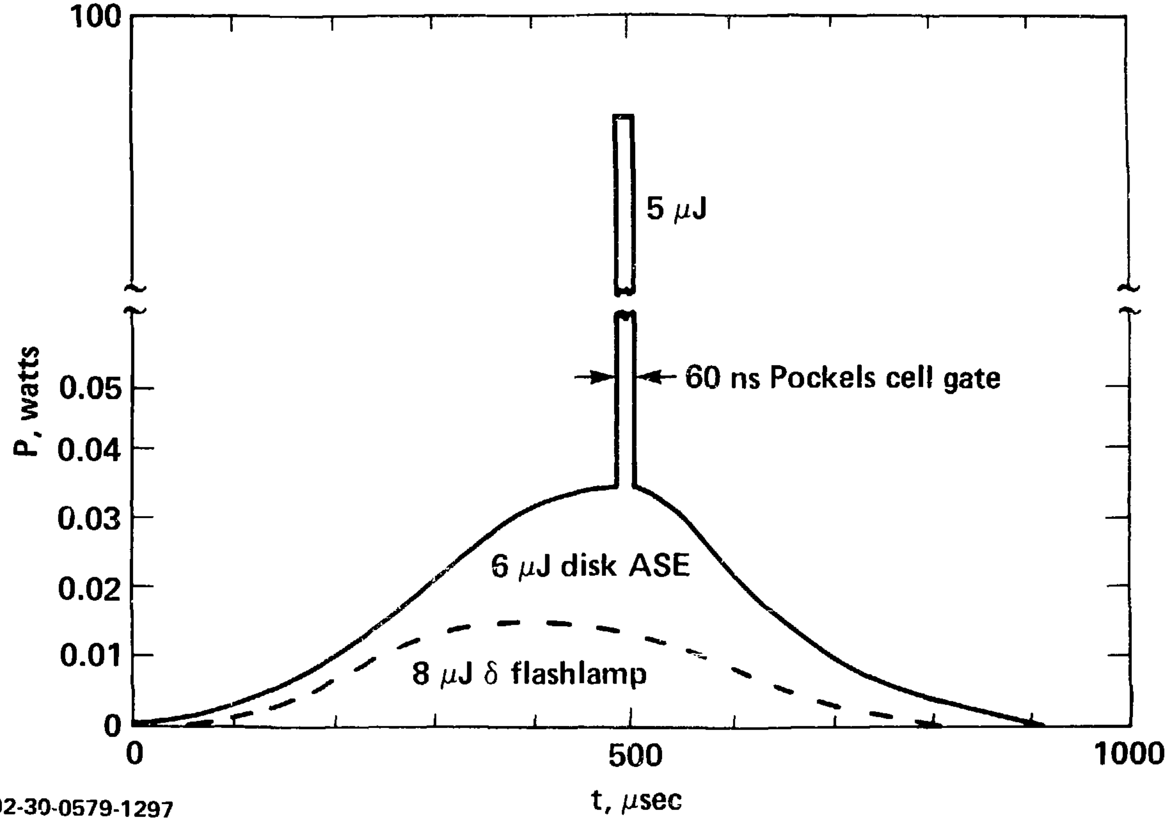


FIG. 8

SHIVA – ASE ON TARGET FROM A SINGLE ARM

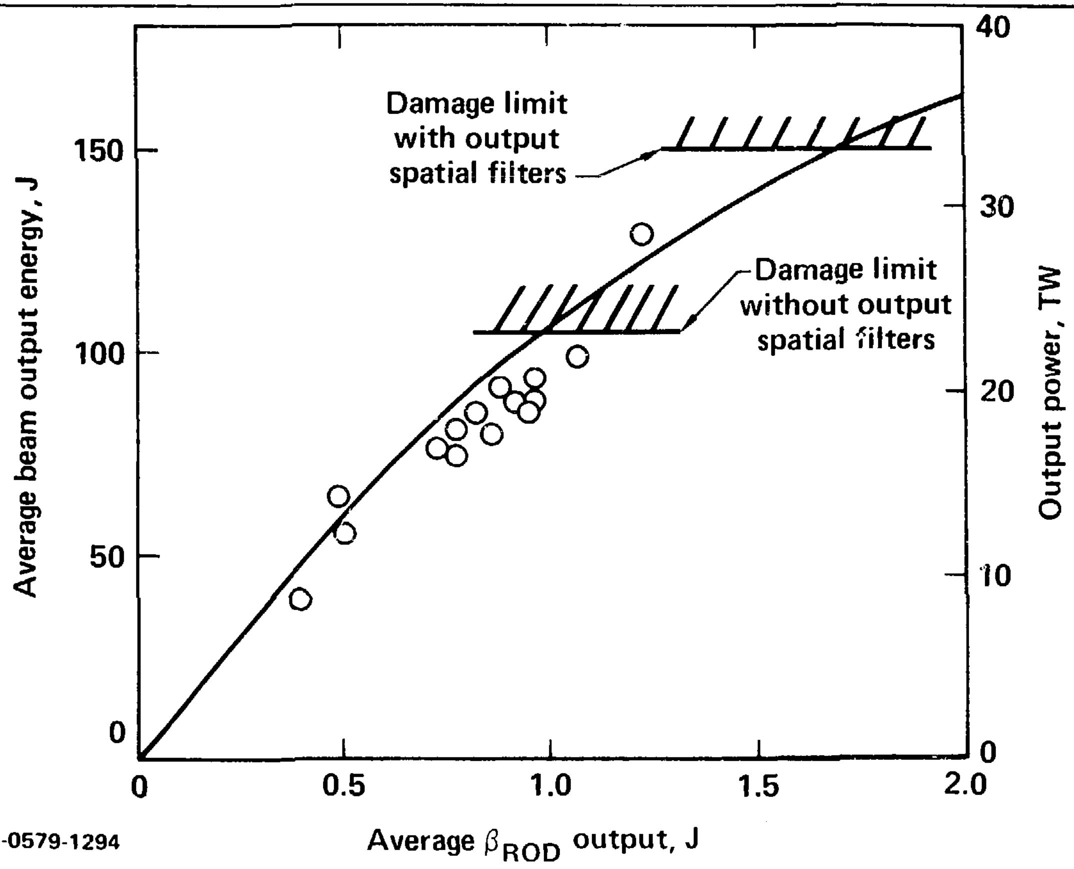
Measured with 30 TW-100 ps Laser Settings



02-30-0579-1297

FIG. 9

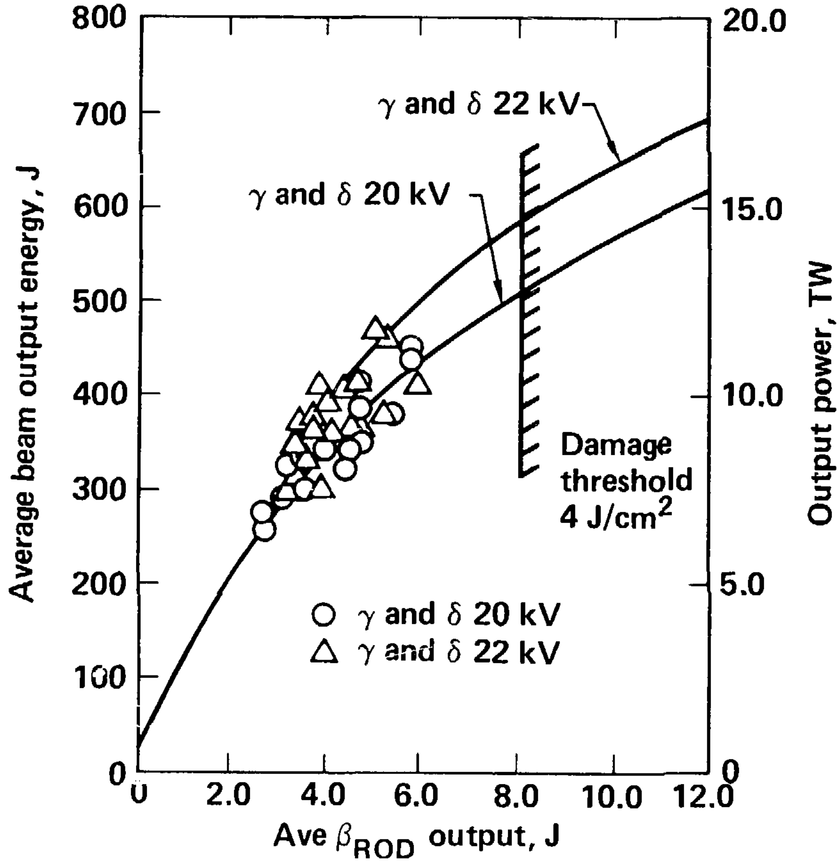
SHIVA – DESIGN AND ACTUAL PERFORMANCE AT 90 ps PULSE DURATION



02-30-0579-1294

FIG. 10

SHIVA – DESIGN AND ACTUAL PERFORMANCE AT 0.8 ns PULSE DURATION

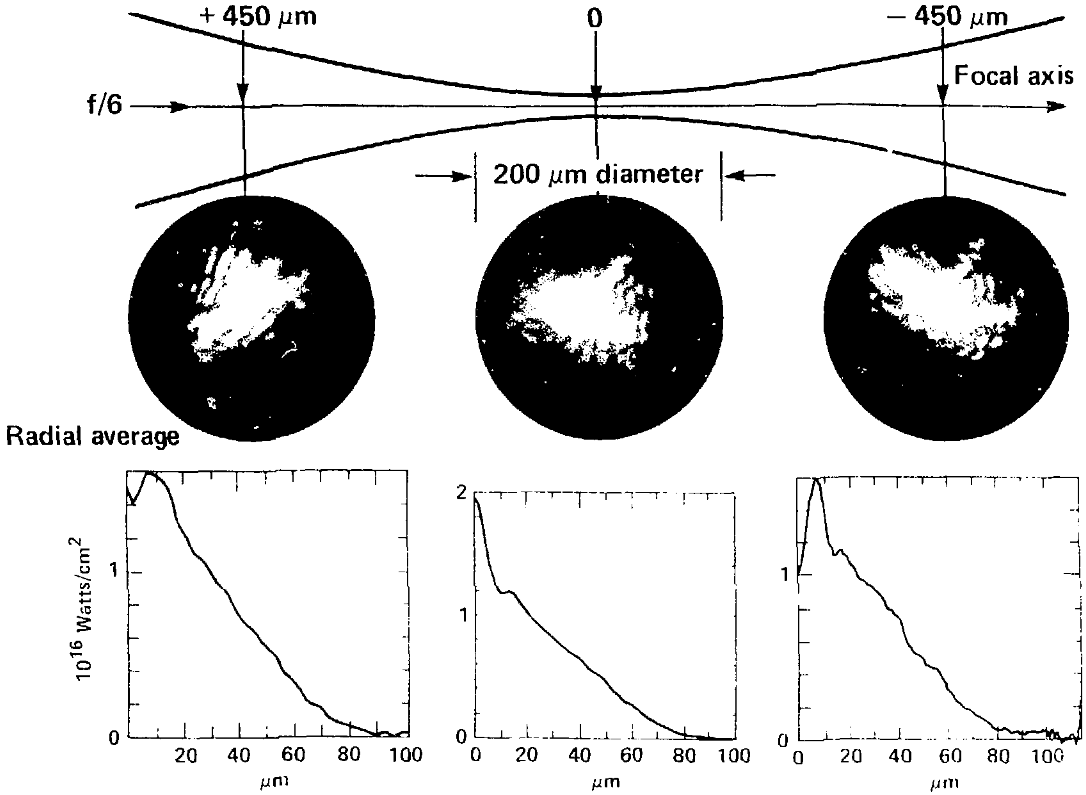


02-30-0579-1293

FIG. 11

SHIVA – SINGLE ARM FOCAL PATTERN AT 1 TW

Shot 88101308 Beam 8



02-30-0579-1599

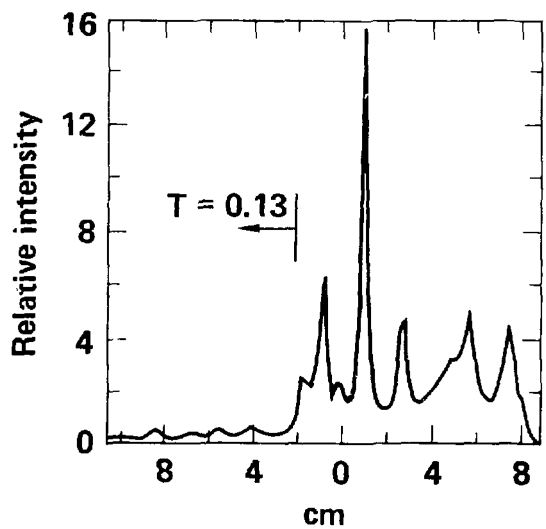
FIG. 12

SHIVA-TARGET CHAMBER INPUT BEAM

Shot #88062017 Beam 6
Power 1.5 TW
Before installation of output spatial filters

- Photograph

- Densitometer scan



02-12-0279-0593

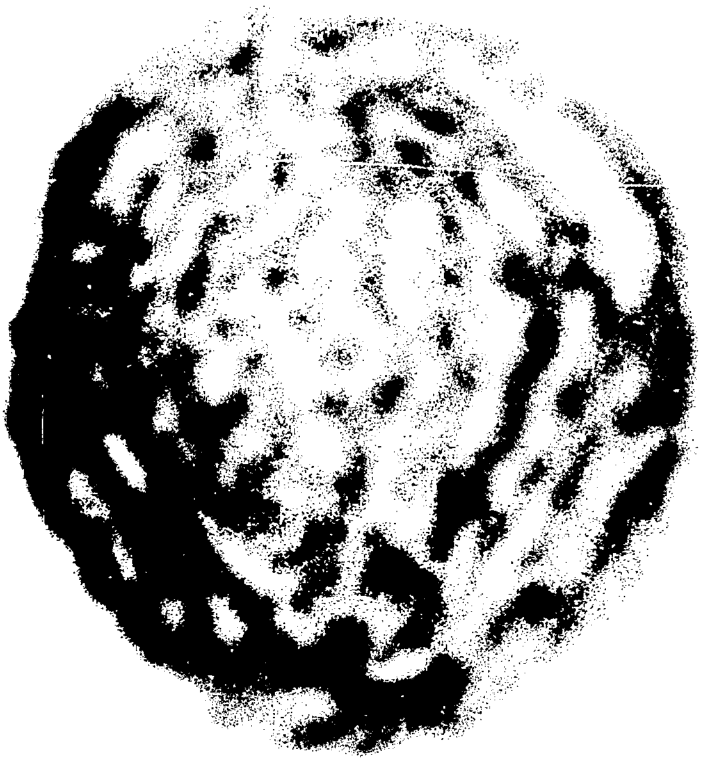
FIG. 13

SHIVA – TARGET CHAMBER INPUT BEAM

Shot 89051820 Beam 6

Power 1.5 TW

After installation of output spatial filters

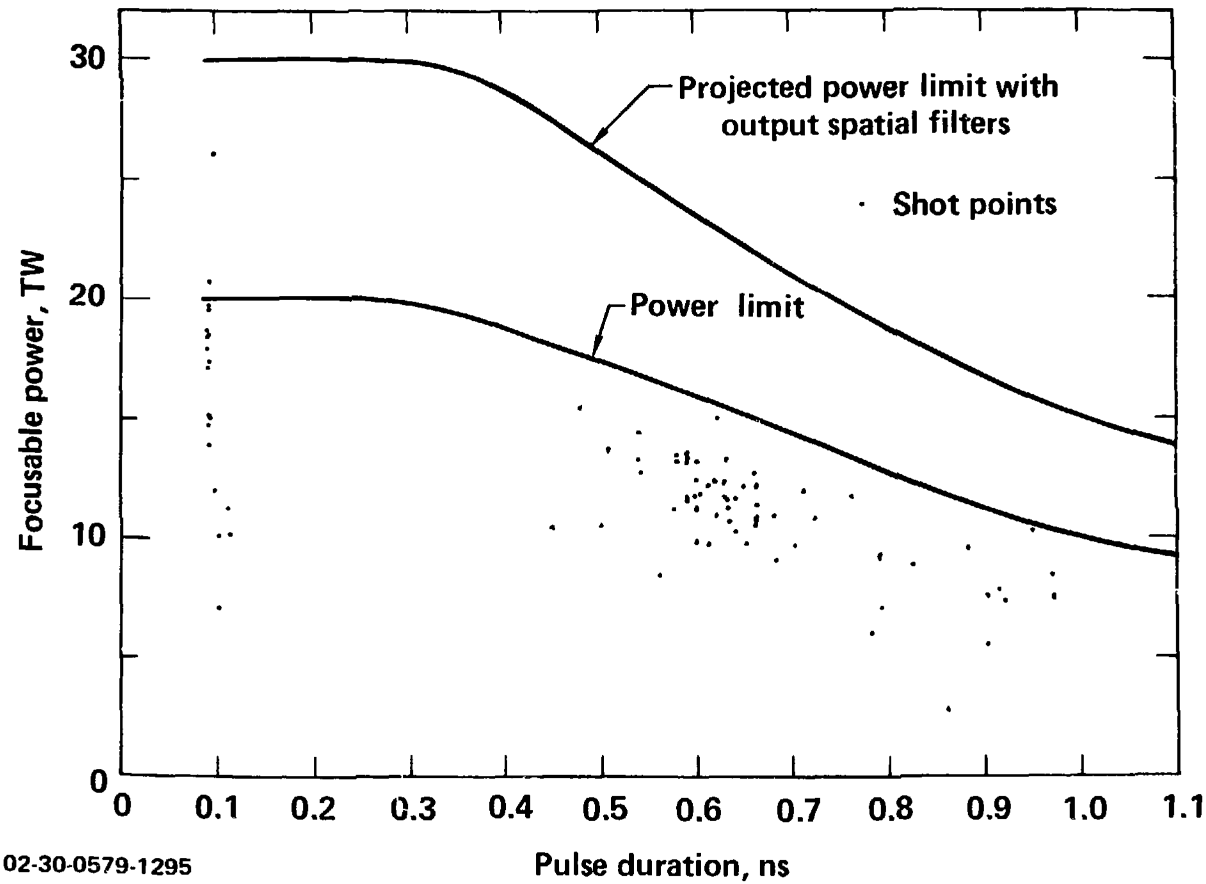


Peak/average intensity less than 4.0/1.0

02-30-0579-1760

FIG. 14

SHIVA PERFORMANCE



02-30-0579-1295

FIG. 15

SHIVA – EXPLODING PUSHER TARGETS

Hyperion Campaign Sept-Oct 1978

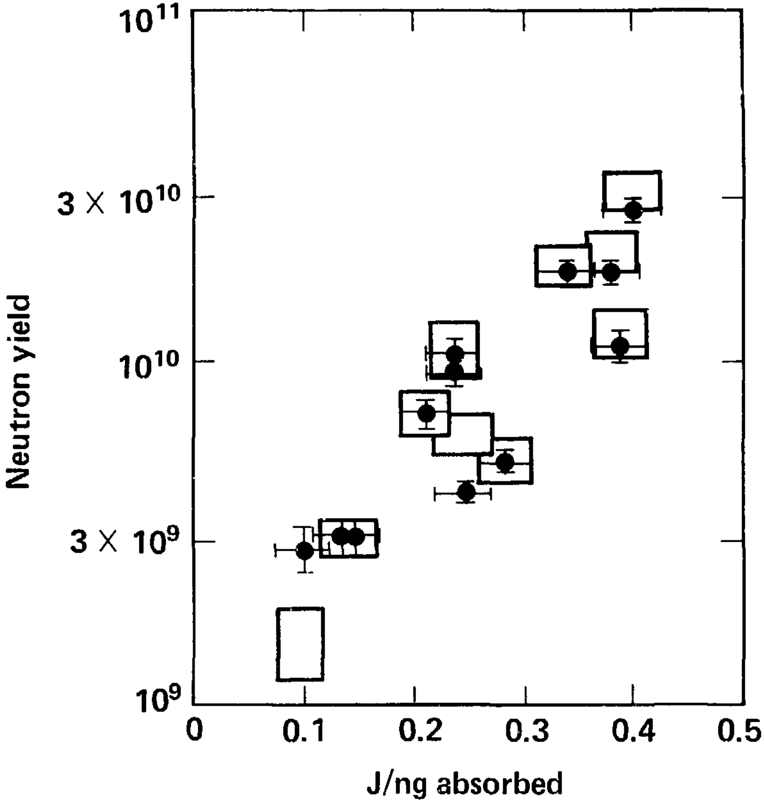
- 15-20 TW on target in 90 ps
- Ion temperatures up to 4.5 keV
- Neutron yields up to 3×10^{10}

Data fits scaling laws determined from Janus and Argus experiments

02-30-0579-1299

FIG. 16

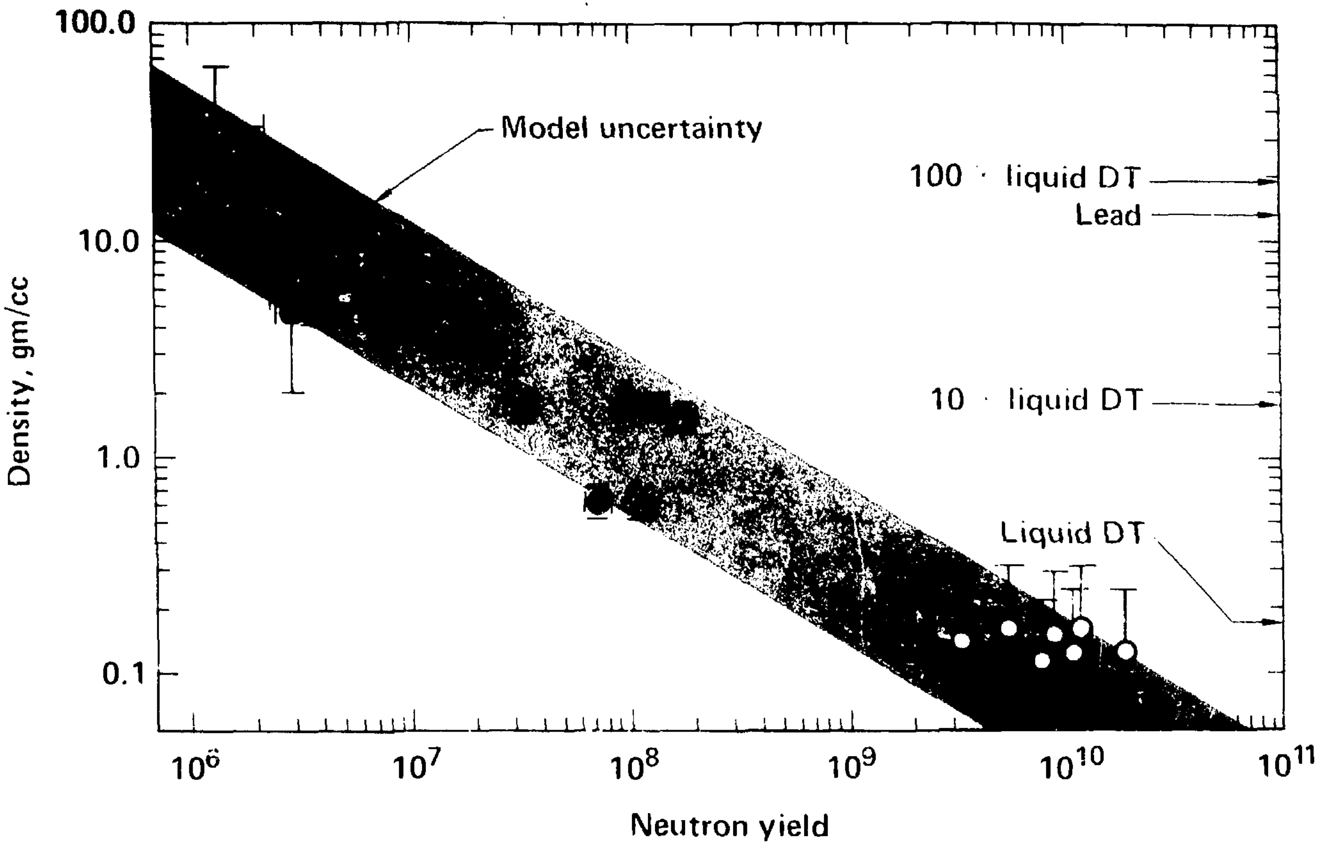
NEUTRON YIELDS & PREDICTIONS GIVEN MEASURED ABSORPTIONS



20-90-1078-3761

FIG. 17

FUEL DENSITY AT BURN TIME VERSUS NEUTRON YIELD



20-15-0579-1727

FIG. 18