LA-UR- 93-0330

Title: MERCURY: THE LOS ALAMOS ICF KrF LASER SYSTEM

LA-UR--93-330

DE93 007363

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Submitted to: Proceedings of the International Conference on Lasers '92

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Mercury: The Los Alamos ICF KrF Laser System

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Abstract

The *Mercury* KrF laser facility at Los Alamos is being built with the benefit of lessons learned from the *Aurora* system. An increased understanding of KrF laser engineering, and the designed implementation of system flexibility, will permit Mercury to serve as a testbed for a variety of advanced KrF technology concepts.

INTRODUCTION

For several years, continuing until early 1991, Los Alamos assembled and tested a prototype KrF laser system, called Aurora,[1,2] which was designed to test key concepts of KrF technology and to provide laser energy for inertial confinement fusion experiments. The results of these tests were generally successful, and key elements essential to the use of KrF lasers for fusion research were demonstrated. These included angular multiplexing, rapid multibeam alignment to target and large-volume electron-beam amplifier technology. Several features of the implementation were, however, of limited success, including the use of amplifiers in single-pass geometry, a partially-refractive optical train, and a complex control system.

Since the original conception of the Aurora design, theoretical and experimental work has generated renewed interest in direct-drive targets, broad-bandwidth and flexible pulse-shaping capability. In order to investigate these KrF technology issues, as well as to provide a cost-effective, reliable local target facility for the Los Alamos laser-fusion program, a new configuration of the Aurora laser was defined and is currently being implemented. The design is sufficiently different so as to warrant a new name, Mercury. The Mercury system uses those components from Aurora that were successful and replaces those that were marginal. The design decreases the number of amplifiers and reduces the e-beam voltages and pulse durations to improve the reliability of the pulse power systems. It also replaces the refractive optical system with an all reflective design, which should provide a much higher beam quality. Finally, the nominal fixed operating pulse length of 5 ns was replaced with capability for an adjustable pulse length of from 200 ps to 5 ns. The combination of shorter pulse length and improved focusability (approx 200 micron spot size) will result in an available power output of 4 TW at an intensity of 10^{16} W/cm^2 for the predicted nominal 1 kJ that Mercury will be capable of producing. That intensity level provides a useful capability for both direct and indirect drive ICF experiments.

MERCURY DESIGN

By reducing the number of amplifiers and by using each one in a double-pass configuration, the Mercury design results in considerably higher stage gains than obtained at Aurora. The predicted energy output (approx 1 kJ), however, is not much lower than that reached with Aurora. Improved reliability for the pulse-power systems is being achieved by reductions in the charge voltages, currents and pulse lengths (i.e., reduced electrical stress), which provide increased time-between-failures for the output switches and bushings. Mass-flow gas mixing and improved gas flow distribution in the amplifier laser heads will allow future investigation of system issues associated with higher shot rates (an important issue for inertial fusion energy applications).

The partially-refractive optical system from Aurora has been replaced with an all reflective design, which provides a much improved beam quality. Only three components in the optical train are powered, and they are long-radius spherical mirrors used at near-normal incidence. All optical components have modest specifications for figure and are readily manufactured by standard optical-fabrication practices. A *code-V* analysis of the optical train yields focal spots consistent with the established optical error budget. This combination of an all-reflective optical system and double-pass amplifiers is similar to the architectures

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proposed for the Laboratory Microfusion Facility and other ignition-class KrF laser facilities.

TWO-PHASED APPROACH

Mercury is being built in two phases: the first phase serves essentially as a whole-system design verification test, and the second phase as a straightforward engineering completion.

Phase-II

A schematic diagram of the *final* phase-II Mercury laser system is shown in Fig. 1. The front end consists of an oscillator and several discharge amplifiers with multiple Pockels-cell switches, generating a single pulse of variable shape and duration. The resulting beam is replicated 12-fold with angle and time encoding (5-ns beamlet spacing) by aperture division and is then amplified in a double pass through a 12 x 12 x 100 cm^3 electron-beam-pumped amplifier (A1). This 12-beamlet train is then further replicated 2-fold by amplitude division and is angularly encoded before a double-pass through a 20 x 20 x 100 cm^3 intermediate amplifier (A2). Finally, each of the two 12-beamlet envelopes is again replicated 2-fold by amplitude division, and is angularly encoded for a double pass through the final 55 x 55 x 200 cm^3 amplifier (A3). The resulting 48 beamlets then pass through an optical "decoder" system, which removes their time delays and focuses all of the beams simultaneously onto the target. This system is expected to deliver 500 to 1000 J to target, depending on pulse length.

Phase-I

Phase-I will be a demonstration laser system at the 100-J level, which will incorporate all of the important design elements, but which will have a reduced number of beams and a smaller final amplifier aperture. A schematic diagram of it is shown in Fig. 2. In this phase, only the front end, first e-beam amplifier (A1), reduced-aperture final amplifier (A2) and a 24-beam version of the reflective optical system are utilized. Essentially, the phase-II intermediate amplifier is by-passed for phase-I, as shown in Fig. 2. During this phase, A1 will be upgraded by the addition of a magnetic field and a reconfiguration of the laser chamber/hibachi interface to increase the small-signal gain and the gain uniformity. In addition, the front end will be reconfigured for short pulse generation and the reflective optical system will be installed. The final amplifier for this phase will consist of a laser chamber with a 40 x 35 cm^2 aperture and a 200-cm active length, driven by a single-sided pulse-power system.

Experiments will be performed to demonstrate focusability, the required stage-gains, short-pulse energy extraction, and the reliability of the pulse-power – all at levels comparable to those in the final system. (The phase-I final amplifier is smaller in cross section than the phase-II amplifier and is only pumped from one side, while the phase-II device will be pumped from two sides.) Effects of ASE on short-pulse energy extraction can be tested in the smaller phase-I final amplifier by increasing the reflectivity of the walls of the laser chamber.

Conversion to phase-II will then consist of installing the additional optical elements required for the second 24 beams, replicating the pulse-power of the final amplifier to provide double-sided pumping, replacing the final laser chamber (A3) with one of a somewhat-larger size, and installing the phase-I final amplifier (A2) as the phase-II intermediate amplifier (A2). All of these modifications would essentially be engineering replications of tested hardware and, therefore, should have a high probability of success.

A detailed description of the design and predicted performance of the phase-I system is contained in Ref. 3. The principal specifications (for 200-ps pulse operation) are summarized in Table 1.

LASER MODELING

Predicting the laser performance of a KrF amplifier requires the modeling of a number of different physical phenomena.[4] We do not integrate these separate processes into one large computer code but, rather, treat each of them separately in an iterative fashion. The steps that are followed generally involve computing:

1. the pulse-power and diode performance
2. the e-beam deposition in the laser gas
3. the partitioning of the deposited e-beam energy into the initial molecular excitation of the laser medium
4. the complex kinetics of the excimer laser medium
5. the amplified spontaneous emission (ASE) that is produced
6. the energy that is extracted by the input beam in the presence of ASE.

In an earlier paper,[5] the models used for each step have been described, and the pulse-power performance and energy deposition of the Mercury system were presented. We will not repeat that discussion here but will, instead, briefly describe the ASE and extracted energies predicted for the system (i.e., steps 5 and 6).

Amplified spontaneous emission (ASE) is an important, although not dominant, factor in modeling large KrF lasers, especially for short-pulse operation. Consequently, we have developed an extensive ASE code[6,7] that has demonstrated general agreement with experiment.[8,9] The code uses an iterative procedure to arrive at a self-consistent, steady-state solution to the 3-D distribution of coherent and incoherent fluxes within the amplifier. Two-pass energy extraction, spectral distributions, wall reflectivity, and non-uniform excitation are included in the model. The input parameters consist of the small-signal gain, gain-to-loss ratio, saturation intensity, wall reflectivity, and the amplifier dimensions. The model predicts the effects of ASE on amplifier performance. It calculates the reduction in the measured small-signal gain, the external ASE that will be observed, and the energy that can be extracted from the amplifier. A complete description of the ASE model is given in Refs. 6 and 7, and a more thorough discussion of KrF lasers is contained in Refs. 4 and 10.

For the Mercury system, two models (quasi-dynamic and fully-dynamic) for the ASE and energy-extraction have been employed. The *quasi-dynamic* model uses the 3-D steady-state analysis for the ASE and a time-dependent analysis for the pulsed extraction. It assumes that any changes in the ASE during the extraction process are slowly varying. Since ASE is a *volume-averaged* phenomenon, this approximation is thought to be justified. For long-duration laser pulses, there is little doubt that this approach is valid. (Long duration implies laser pulses longer than about 3 ns for our case in which channel-to-channel separation is 5 ns.) The energy predictions of this model for 5-ns pulses are shown in Fig. 3 for phase-I under the pumping conditions in Table 1. An output of 12.5 J/beam is predicted for the expected A2 input of approx 80 mJ/beam. This would correspond to a 200-J on-target energy. (Transmission from the A2 amplifier to target is assumed to be 70%.)

However, there was some question about the accuracy of this quasi-dynamic model for the shortest Mercury pulses (i.e., a train of 200-ps pulses, separated by 5-ns.) Consequently, a more *fully-dynamic* model was developed that incorporates time-dependence in both the ASE and extraction. (In this case a psuedo 2-D geometry is used and wall reflectance is further approximated.) Figure 4 compares the predicted energies for the two models for phase-I with 200-ps pulses. Good agreement is observed, thus demonstrating that the quasi-dynamic model is generally valid, even for the short-pulse case. For the nominal 30-mJ/beam input to A2, an output of 6 J/beam is predicted with a total on-target energy of about 100 J. It is also seen from this figure that for such a train of short pulses, ASE reduces the amplifier output by about 48%; this penalty is much smaller for the case of a train of longer 5-ns pulses. Comparison with Fig. 3 indicates that the 200-ps output is about 50% of that obtained with the longer 5-ns pulses.

Finally, Fig. 5 shows 5-ns-pulse output energy for the final A3 amplifier for Phase-II, as predicted by the steady-state model. The figure indicates an output energy of 37 J/beam for a g_o of 4.0%/cm and an input of 2 J/beam, which corresponds to a total on-target energy of 1 kJ. Output for 200-ps pulses will be somewhat less. However, there are at present a number of design uncertainties in both the geometry of the system (e.g., the exact size of the A3 aperture and the length of A2) and in the pulse-power and laser parameters (e.g., e-beam transport efficiency and the small-signal gain). These questions will be resolved by phase-I experiments before the phase-II upgrade is initiated.

RECENT PROGRESS

At present, the first phase of Mercury is about 60% complete. The front-end components have been reconfigured into a more flexible system with faster Pockels cells that can generate a rich variety of pulse lengths and shapes, as demonstrated in Fig. 6. A preliminary experiment[3] has shown that the 200-ps pulses are effectively propagated in the e-beam amplifiers. The A1 amplifier has been upgraded, as discussed earlier, and has undergone extensive pulse-power testing. The observed improvement in the small-signal gain exceeds that required for nominal performance (Fig. 7). Energy extraction tests on A1 are about to begin.

For the final amplifier (A2), a new cathode and a novel high-transmission hibachi are being fabricated. The pulse-forming line and Marx bank have been rebuilt, the laser box is complete, and pulse-power tests are under way. The large A2 windows (47-cm square) have been received and satisfactorily tested, and the mirror (64-cm diam) is being polished.

A preliminary single-beam focus test has been conducted, in which a 7 x 7 cm^2 beam was propagated through the entire system (front end to target), except that the amplifiers, together with their windows and mirrors, were by-passed. The spot in the target plane had a measured diameter of 122 um for 90% encircled energy. This spot was dominated by astigmatism from components early in the system, which can be easily corrected to yield an expected spot for this test of 50 um. Both the presently-measured and ultimate spot sizes are well within the estimated design value of 150 um for the present test configuration. This implies that the complete Mercury system should produce a focal spot well within the 200-um design specification.

Two beam-diagnostic stations have been designed and are being installed at the inputs to A1 and A2. Each station will be capable of simultaneously measuring the total energy in 12 or 24 beams, the energy in each beam, the power in all beams at low resolution, the temporal pulse shape at high resolution on several beams, the spatial profile of each beam at low resolution, and the beam quality of any single beam. Thus, Mercury will be a well characterized system that is thoroughly modeled from end-to-end.

CONCLUSION

The Mercury KrF laser, which is presently under construction at Los Alamos, has been conservatively designed to be a flexible, cost effective, and reliable system. This laser will serve as a testbed for a variety of advanced KrF technology concepts and will also serve as a local target facility for the Los Alamos inertial-fusion program.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy.

A large number of people have contributed to the design (including the preliminary design) and implementation of the Mercury laser facility (including facility preparation). Among them are G. Allen, R. Anderson, R. Berggren, N. Busch, A. Dragt, J. Figueira, G. Gallegos, H. Garcia, C. Gosscin, J. Jolin, J. Jones, V. Lazazzera, D. Martinez, M. Martinez, B. Mauro, J. Ratliff, V. Romero, L. Rosocha, S. Salazar, R. Schmell, S. Steele, C. Tallman, J. Telle, W. Torrez, R. Watt, and G. Woodfin.

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TABLE. 1 Pulse-Power and laser specifications for the front-end (FE) and A1 and A2 amplifiers for Mercury Phase-I with 200-pulses.

	FE	A1	A2
Pulsed power parameters:			
pump duration [ns]		150	475
voltage [kV]		320	550
cathode size (L x H) [cm]		100 x 12	200 x 40
e-beam transport efficiency		0.66	0.40
avg J on foil [A/cm^2]		20	18.0
Laser parameters:			
gas pressure [Torr]		900	600
avg pump density [kW/cm^3]		175	104
gain volume (L x H x W) [cm]		100 x 12 x 17	200 x 40 x 56
aperture (H x W) [cm]		11 x 11	39 x 41
E_{sat} [mJ/cm^2]		3.2	3.2
g_o [%/cm]		4.5	3.7
g_o/a_o		10	10
Extraction parameters:			
number of beams	2	12	24
beam-to-beam angle [mrad]		5.3	2.6
input beam size (H X W) [cm]	3.0 x 2.5	7 x 7	38 x 38
pulse width [ns]	0.2	0.2	0.2
pulse spacing [ns]		5.08	5.08
total E in [J]		0.0135	0.76
I in (peak) [MW/cm^2]		0.11	0.11
F in per beam [mJ/cm^2]		0.022	0.021
energy stage gain		130	190
F out per beam [mJ/cm^2]	2.0	2.9	4.1
I out (peak) [MW/cm^2]	10	14.6	20.5
total E out [J]	0.030	1.77	140
transmission to next stage	0.45	0.43	0.68
total E to next stage [J]	0.0135	0.76	—
total E to target [J]	—	—	100

<table corrected January 19, 1993 11:30 AM – Cz >

FIGURE CAPTIONS

1. Mercury Phase-II Schematic. Angular encoding is not shown explicitly; 12 beams are amplified in A1; 24 beams, in A2; and 48 beams, in A3.

2. Mercury Phase-I Schematic. Angular encoding is not shown explicitly; 12 beams are amplified in A1; and 24 beams, in A2.

3. Predicted A2 output for phase-I with 5-ns pulses with a g_0 of 3.7 %/cm. An output of 12.5 J/beam should be obtained for an input of 80 mJ/beam.

4. Expected short-pulse (200-ps) output from A2 for phase-I. An output of 6 J/beam should be obtained for an input of 30 mJ/beam. Predictions of the two models agree. Upper curve is the performance that would be obtained in the absence of any ASE.

5. Predicted A3 (56 x 56 x 200 cm^3) output for phase-II with 5-ns pulses. An output of 37 J/beam should be obtained for an input of 2 J/beam.

6. A variety of ICF-relevant pulse shapes and durations have been generated with the new front end.

7. Increased gains (top curve), exceeding the required design point, have been measured on the rebuilt A1 amplifier. Lower curve represents previously measured gains when this device was used in Aurora.

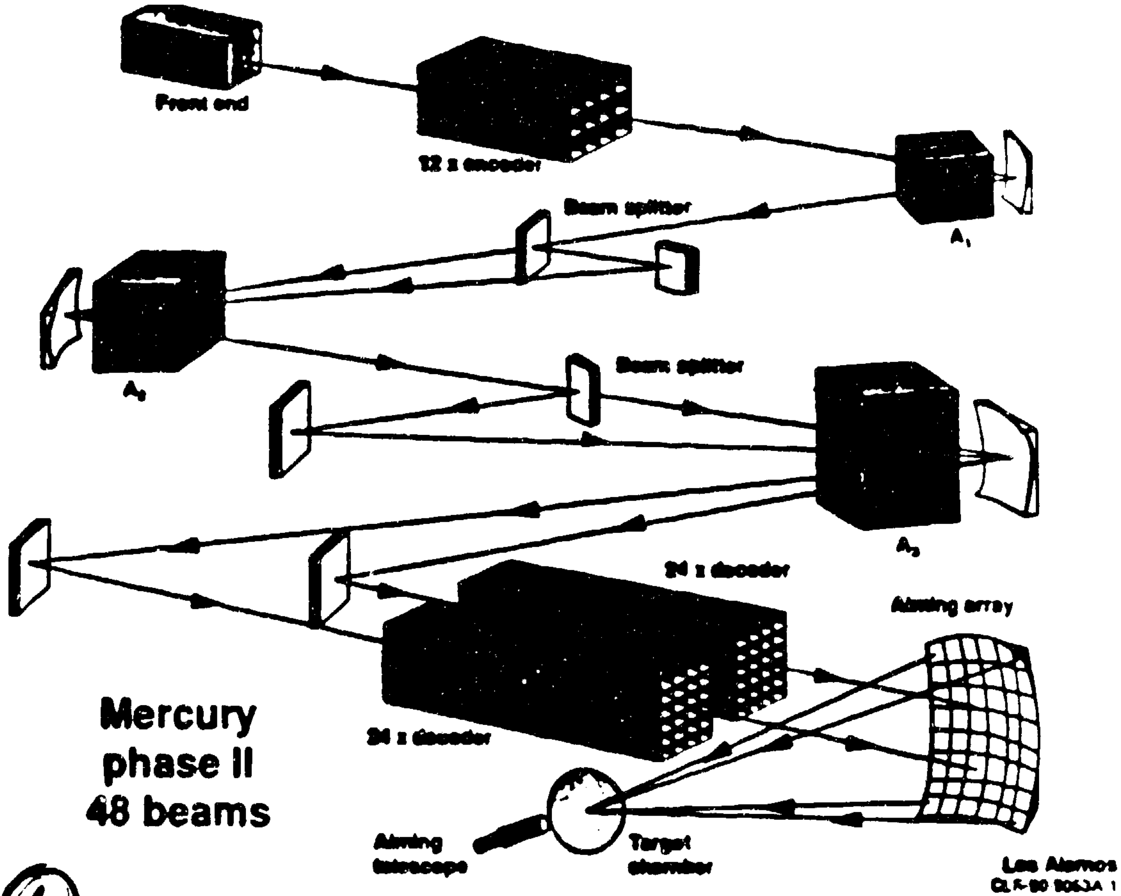
Front end
12 x encoder
Beam splitter
A₁
A₂
Beam splitter
A₃
24 x decoder
Aiming array
Mercury
phase II
48 beams
24 x decoder
Aiming telescope
Target chamber
Los Alamos

Fig. 1

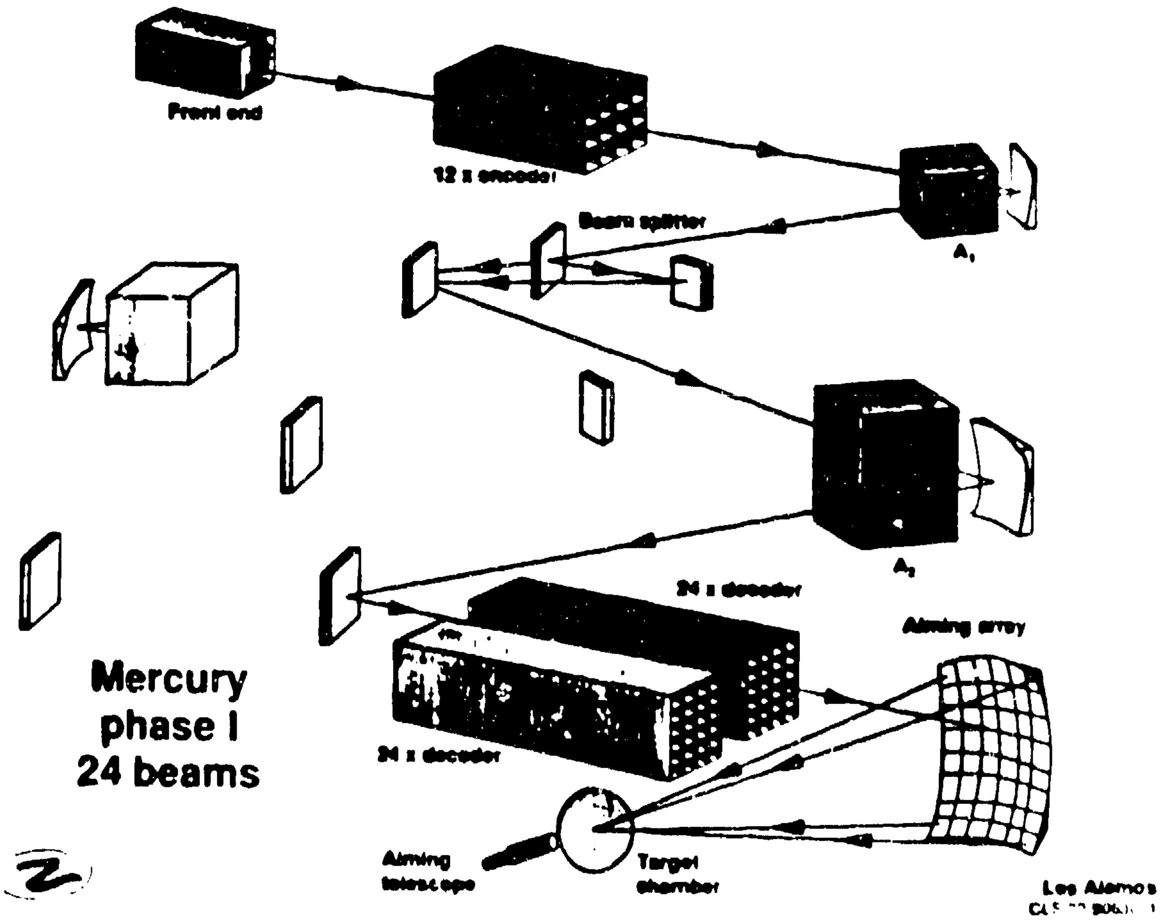
Front end
12 x encoder
Beam splitter
A₁
A₂
24 x decoder
Aiming array
Mercury
phase I
24 beams
24 x decoder
Aiming telescope
Target chamber
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Fig. 2

Phase-I A2, 5-ns pulses

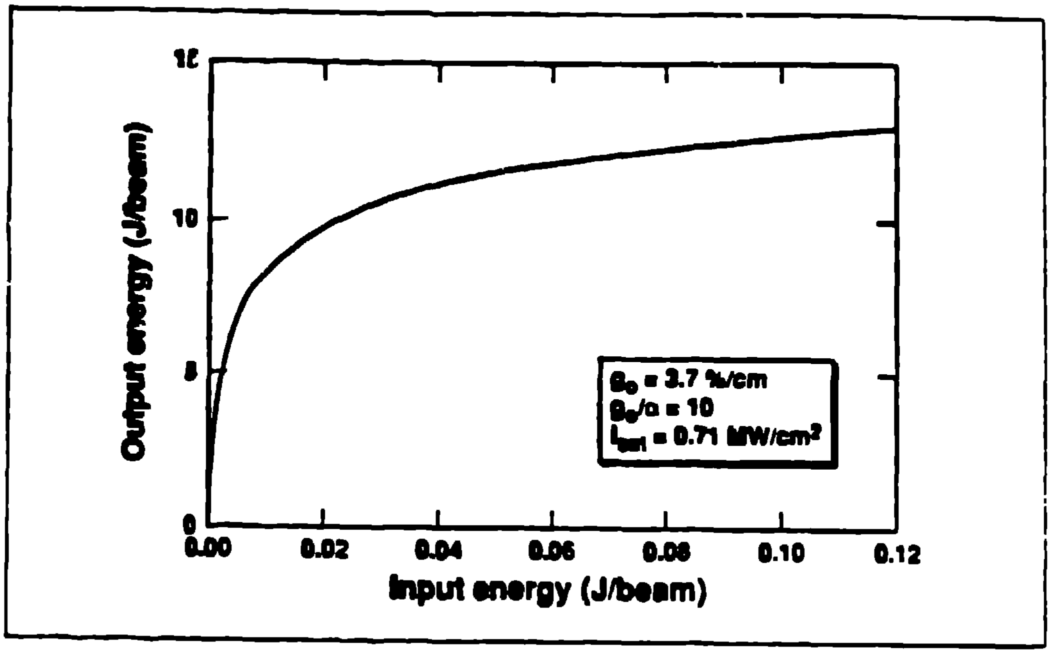

Fig. 3

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Predictions of the Two Models Agree

200-ps Mercury Phase-I, A2 Performance

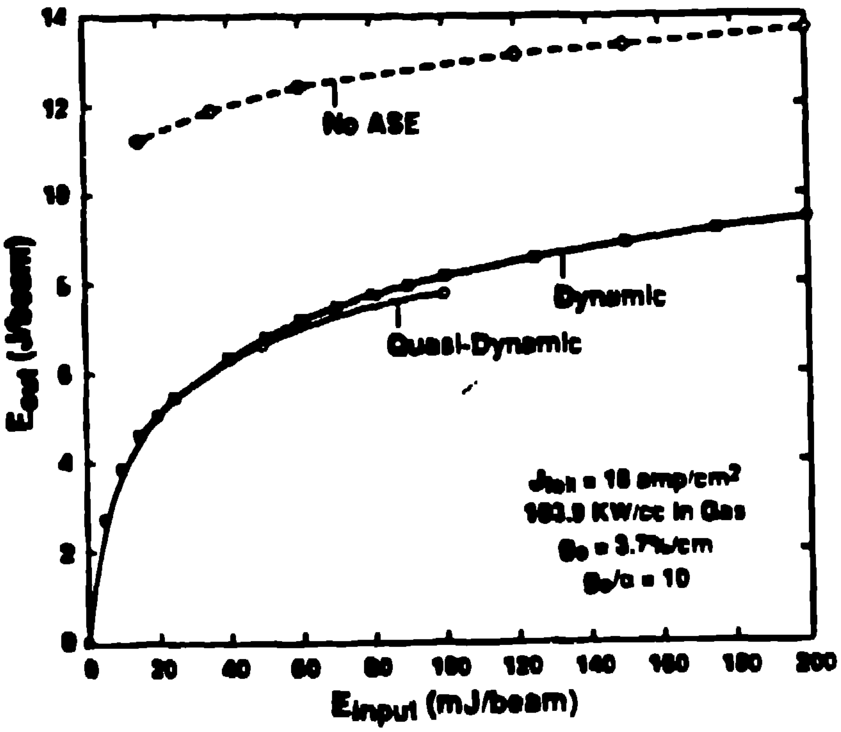

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Fig. 4

4

Phase-II A3 (56 x 56 x 200 cm^3) 5-ns

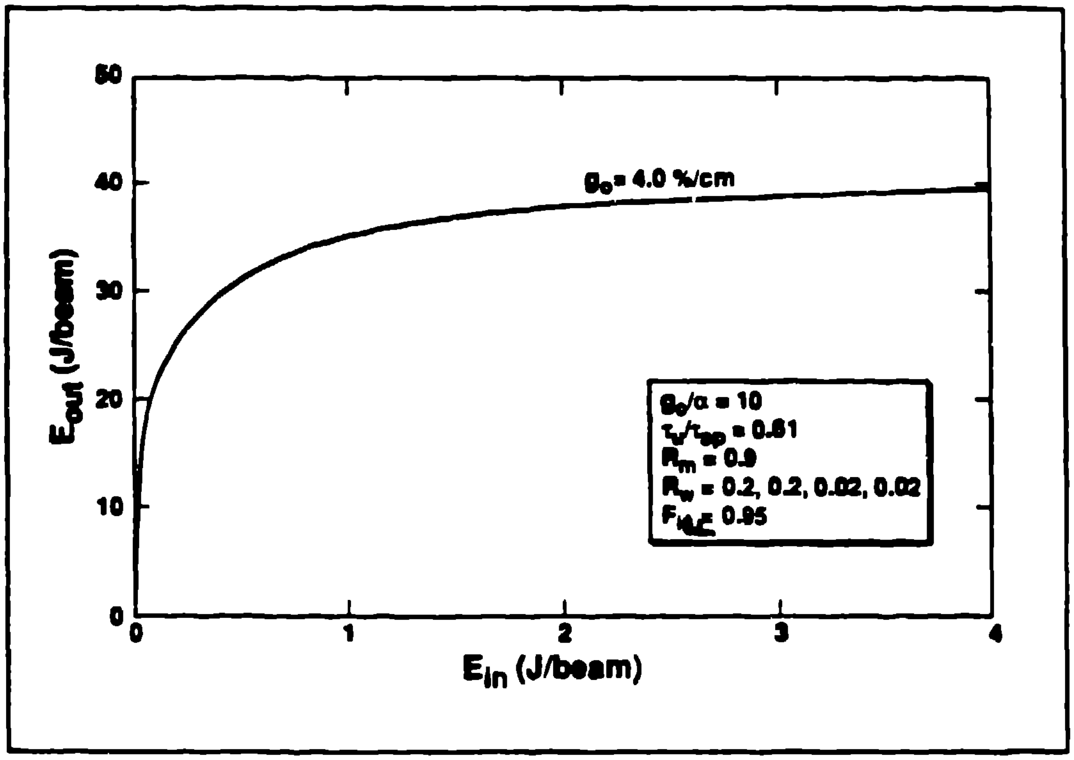

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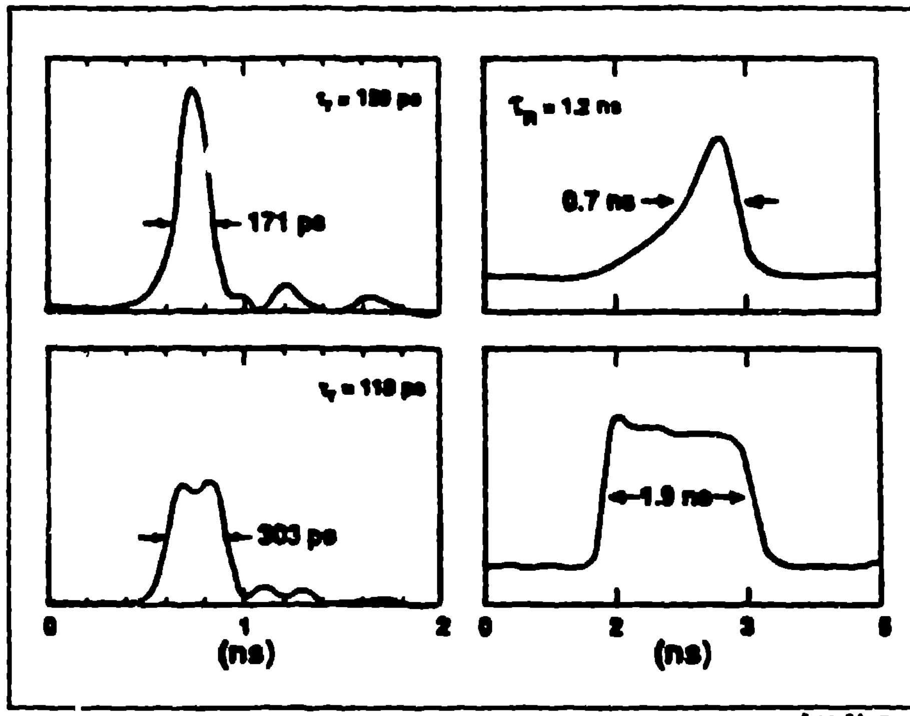
Fig. 5

New front end generates ICF-class short, long, and shaped pulses



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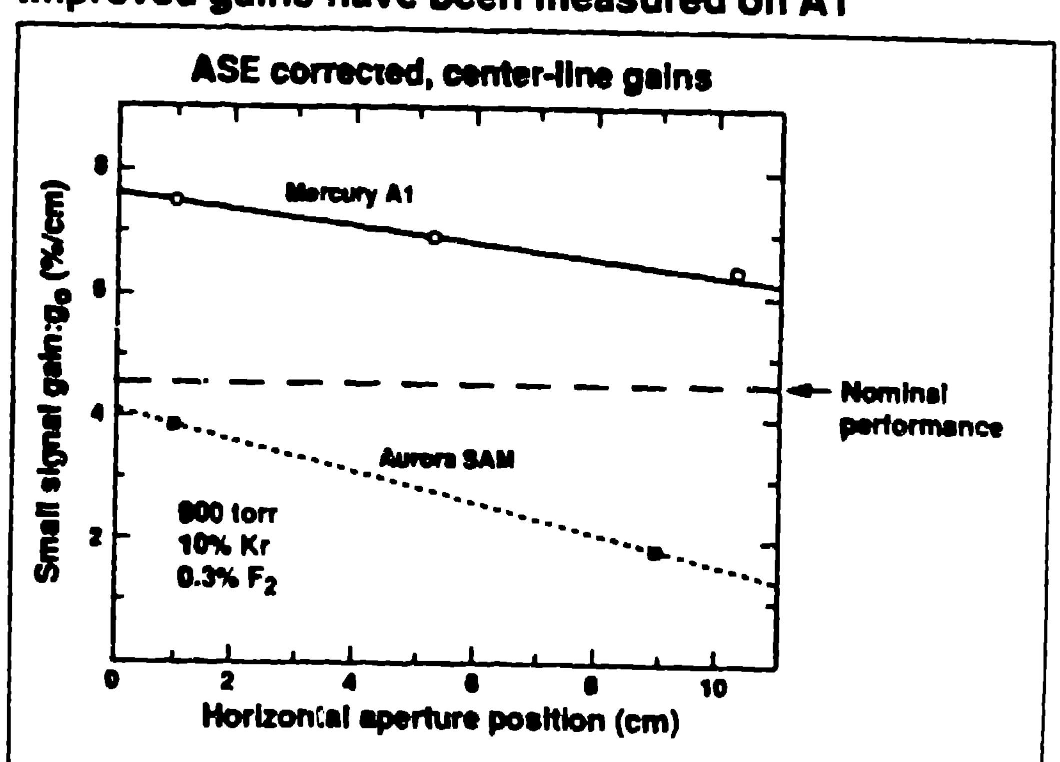
(6)

Improved gains have been measured on A1



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