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MULTI-MEGAJOULE Nd:GLASS FUSION LASER DESIGN

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MULTI-MEGAJOULE Nd:GLASS FUSION LASER DESIGN*

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INTRODUCTION

Virtually inexhaustible controlled fusion power motivated the construction of high power lasers during the last decade. A sequence of ever more powerful machines evolved at the Lawrence Livermore National Laboratory, each design taking advantage of information gathered with its predecessor. The largest and most recent laser of this group is a 100-kJ machine called Nova, which is even now irradiating its first targets. From the review paper by J. H. Nuckolls, L. L. Wood, A. R. Thiessen and G. B. Zimmerman in 1972 to the present day, it has been clear that between 1 and 10 MJ will be needed to demonstrate high gain in an inertially confined fusion plasma.[1] Controversy over where ignition at low gain will first be observed raged throughout the 970's. Nova and its smaller antecedents have been research machines dedicated to studying the physics of plasmas at high temperatures, pressures and densities. The

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results provide the measured efficiencies needed to accurately predict gain in ICF pellets. There has never been any doubt that a large enough driver can ignite a fusion event; nuclear weapons tests have often demonstrated the feasibility of this process. However extrapolation from laser driven experiments is a far from certain calculation; nevertheless, Fig. 1 shows that the size of a laser capable of efficiently causing fusion fuel to burn would need to deliver between 3 and 10 MJ to the fusion target, given today's best simulations.[2]

Inertial Confinement Fusion research, since the early 1970s, has been paced by driver technology.[3] Laser power and energy levels thought to be needed to reach significant thermonuclear gains have remained in the neighborhood of 10^{14} to 10^{15}W or 3 to 10 MJ in 10 nsec shaped pulses for several years. At the Lawrence Livermore National Laboratory, the Nd:glass laser was chosen as the major tool for research on the lasar-plasma interaction in 1971. It has served this purpose well as exemplified by recent experiments on Novette and Nova. However scaling of the Nova-like laser designs to the multi-megajoule level while technically feasible have lead to extremely expensive systems. New technologies have recently emerged that make Nd:glass a candidate for high gain facility that is within reason economically.

Many high power laser architectures exist which conform to prevailing wisdom on medium saturation, parasitic oscillation and nonlinear intensity driven phase distortion limits. A sampling is shown in Fig. 2. Nova is of the traditional Master Oscillator Power Amplifier or MOPA design, in which the laser pulse makes a single pass through the amplifying medium.[4,5] Since the largest aperture gain medium employed in a MOPA is generally its most expensive component, multipassing it to void the cost of smaller aperture components while efficiently extracting its stored energy on the final pass becomes attractive. Multipass designs concentrate on optimum utilization of this amplifier, the major cost center, and vary from angle multiplexed systems to various types of regenerative amplifiers. Among these, the the most cost effective will be the ones which avoid expensive components and pack into the least high quality volume. We are led to the last two designs in the figure, the harmonic-switched regenerative amplifier and the Cassegrain design, both of which can be "front fed", i.e. the input pulse originates near the target plane. In the following, designs with arrayed multi-pass laser architectures using harmonic-switchout, target plane holographic injection, phase conjugation, continuous apodization and higher amplifier storage efficiencies than those found in Nova will be described. Manufacturing economies of scale including higher-volume glass production, rapid harmonic crystal growth, capacitor sizing and packing to handle larger blocks of energy and standardization of parts, all of which reduce costs compared to Nova, will be discussed.

All high power lasers must manage three aspects of the fields within them: amplitude, phase and polarization. The Nova laser and its predecessors were designed to maximize output consistent with optical damage limits. In these MOPA designs, beam expansion was used to keep the average flux within tolerable limits. Image relaying ensured uniform beams on components, and periodic spatial filtering removed high spatial frequency noise. Random phase gradients were divided by the magnification of each beam expander as it was traversed. Automatic alignment and centering was used to avoid clipping which would lead to intense damaging fringe patterns within the high power beams. The patial coherence of the laser was maintained by these means such that the beam could be focused on to the targets. We seek less expensive and more efficient scalable technologies which nevertheless can still perform these functions.

Ten Megajoule Laser System

As indirect drive targets grow in size, the minimum aberration limited spot size of the irradiating laser's beam in the target plane may be proportionally enlarged. While direct drive targets demand exquisite uniformity of illumination and much effort and thought has been devoted to meeting these requirements, there is little to be gained by striving for very uniform illumination of indirect drive targets. These depend upon conversion of the laser pulse to soft X-rays which implode the fuel container. This opens the option of using a large number of almost independent beams, clustered to reduce systems costs, but between which no attempt need be made to maintain spatial coherence. The major parameters of the 10 MJ laser system that we envision are that it have 24 beams, 12 beams per side, each of which is made up of 6x6 array amplifier modules of 35 cm x 35 cm projected element size. Altogether there are 864 elements or cells in 24 groups of 36. As will be shown below, such a system should be capable of achieving the power and energy goals given reasonable technological advances during the next few years. The magnitude of this enterprise, over 100 x the energy of Nova, can be appreciated by noticing that it will require a capacitor bank capable of storing approximately a billion Joules.

Pulse Propagation Path for one Cassegrain Cell

The fundamental building block is a single 35 cm x 35 cm cell. We have carried analysis of a Cassegrain cell far enough to see that it is capable of achieving our aims. A potentially superior regenerative amplifier design has also been studied, but in less detail. Figure 3 is an optical schematic of a single Cassegrain cell. It features target plane injection using a holographic lens, multi-pass extraction of a 20 disk amplifier, phase conjugation half way through the optical train to remove passive aberrations, a resonant acousto-optic modulator and a Pockels cell for dynamic isolation, and second harmonic switchout.

Figure 4.1 through 4.9 follow the laser pulse through a Cassegrain cell. In Fig. 4.1 the input wave from the oscillator system can be seen as the pulse first reaches a holographic lens, which is integral with the target. This input pulse illuminates a toroidal region around the target, but the delicate target is untouched. For example, a standard 4" x 5" photographic plate could be used with the target mounted within a 3 cm x 3 cm square in its center. About 100 square cm of film area is left which should be capable of directing about 0.1 J/cm^2 for a total of 10 J in 10 nsec. We will need about 2 to 3 mJ input to each cell for a total of 2.6 J in 10 nsec or roughly 25% of the energy directed by the hologram toward the lens. At the holographic lens, each cell will subtend an 0.76 cm square spot whose location will be determined by the wedge on the final turning mirror shown in Fig. 3. Typical offsets might be 3 to 4 cm requiring a 3 to 4 mrad wedge if a 10 m focal length focusing lens is used. As we must specify the amplitude (uniform), phase (uniform) and polarization (linear and horizontal) of the field entering each cell, we must start with a well polarized "plane wave" and set it's amplitude and phase with the hologram.

Figure 4.2 shows a typical infrared pulse on its way to the focusing lens. It passes through the front surface of the wedged final turning mirror, which is coated for high reflectivity at 0.53 um but high transmission for 1.05 um light, reflects from the rear surface and then is directed into the cell by the first turning mirror. When this several millijoule beam reaches the dichroic mirror in Fig. 4.3, it encounters a 12 cm x 12 cm obscuring mask which occults the central third of the aperture. The edges of this shadowed region, like the edges of most of the optical components in this device, are apodized by bead blasting. Here a Gaussian stripe 1.5 cm wide with a Gaussian radius of 0.7 cm would hold diffraction ripple to less than 3% of a plane wave input at 60 m. A spherical dome with a radius of curvature of 24 m and almost parallel inner and outer surfaces, this dichroic mirror is designed to transmit green light, but to reflect 90% of the infrared energy incident on it's inner surface so only 10% of the input field projected from the target plane gets into the cell.

Once inside of the the amplifier cell, the beam passes through the gain region twice as indicated in Fig. 4.4. Here two options have been considered, a 20 disk alumino-phosphate glass having a cross-section of 3×10^{-20} cm^2 which develops a small signal gain of 30 and a silicate glass with a cross section of 2×10^{-20} cm^2 with a gain of 17 per pass. After reflecting from the rear mirror, the pulse is further amplified by a second pass through the gain medium. The field is still much to weak to harmonically convert as it passes through the type I converter crystal. Nor has it been altered by the acousto-optic shutter modulator as we have arranged for it to reach this component at a null in its cycle. This time the pulse reaches the dichroic mirror's inner surface, 90% of it is reflected and focused while 10% proceeds back toward the holographic lens no more than ten times more intense than the input wave.

Focusing the beam through an aperture about 4 mm in diameter, Fig. 4.5, spatially filters the field presented to the central portion of the amplifier on the third pass. In Fig. 4.6 we show the beam being amplified, filtered and demagnified once again. In the 4 cm diameter part of the system, the pulse traverses the Pockels cell, is amplified by a rod with a gain of 15 and reflected by the phase conjugating mirror as indicated in Fig. 4.7. Retracing its path, the beam once again is filtered twice as it extracts about 40 % of the energy stored in the amplifier. Arriving once more at the harmonic conversion crystal, which is in a relay plane, the field is uniform enough and now intense enough to convert to its second harmonic, Fig. 4.8, with an efficiency of 70% to 80%. The green beam so produced traverses the dichroic mirror and proceeds to the target as shown in Fig. 4.9. This time it reflects from the front surface of the final turning mirror and is focused at the target by the lens whose focal length is shorter for green light than for infrared. Unconverted infrared energy must be prevented from reentering the central portion of the amplifier. The planar rear mirror can be tilted about 0.5 mrad in order to prevent this pulse from making it through the spatial filter on this pass. Since the region about 1 cm away from the spatial filter aperture must now intercept one to several kJ, it must be designed carefully to avoid ejecting debris on to optics.

Targeting is simplified in that it is done off line and is totally under the control of the target fabricator who makes and attaches the sacrificial hologram. Figure 5 shows how a holographic lens might be positioned and provide an efficient self-aligning method for injection of the oscillator pulse into the beam lines. It is not necessary for the injected beam to map perfectly on to each lens, rather these beams can illuminate the entire cluster of lenses. Each lens would be bead blasted to apodize the beam passing through it and thereby avoid severe diffractive ripples in the laser field presented to each cell.

After passing through the amplifier several times, the pulse is retroreflected by a phase conjugating mirror. As Fig. 6 suggests, a simple stimulated Brillouin scattering cell may be adequate to automatically point each sub-aperture beam.[6] By setting the trajectories of the infrared input rays, those of the green beam are uniquely determined since the phase conjugator guarantees that the reflected infrared light retrace the same path as the input beam. Our system designs all incorporate relay spatial filters, so the phase conjugating wavefront corrector must always be located in a relay plane. Figure 3 shows how component spacings have been chosen to meet the relay conditions and thus map the uniform input near field beam first presented to the harmonic converter into the plane of the phase conjugate mirror and back into the harmonic converter on the final pass. The phase conjugator is therefore only required to correct pointing within the +/- 200 urad field of view of the spatial filters. On the final transit through the harmonic generator, about 70% of the 2 GW/cm^2 infrared beam should turn green so that the combination of wedged final turning mirror and focusing lens may deliver the green pulse to the target.[7] We have set a nominal tolerance of +/- 50 urad on the pointing accuracy of the laser beam in order to guarantee efficient second harmonic conversion in the type I crystal. This translates into a transverse alignment tolerance of +/-0.5 mm at the target chamber center assuming 10 m focusing optics. Current target diagnostic alignment tolerances used on Nova are often about five times smaller than this, so target diagnostics will probably call for more accurate target placement than will the laser system.

It is worth observing here, that this analogue method for target alignment can equally well apply to an eventual fusion reactor. A reactor target mounted in the center of a holographic lens could be spin stabilized as it was launched toward the center of the reactor vessel. Once near the center of the chamber and within the field of view of the laser, an oscillator pulse could launch the beam from the target. In the few microseconds needed for the pulse to transit the amplifier and be converted in frequency, the target would have moved less than one mm in an easily predicted direction.

Beam centering tolerances are relaxed from those set for Nova because of the use of continuous apodization. As there will be almost 100 m between the target focusing lens and the dichroic mirror, a relay telescope (without filtering focal plane aperture) will be needed. The single 10 to 20 m focusing optic shown in Fig. 3 can be made up of three lenses or a combination of lenses and curved mirrors. Thus far, only simple lenses have been considered and centering tolerances of +/- 0.5 cm on all apertures seem to be adequate. Should this tolerance be exceeded, the result would be a gradual reduction of power delivered to the target, but no significant increase in laser damage risk.

Figure 7 displays another essential component of this type of laser system design. An acoustic standing wave in fused quartz can be used to provide a fast beam shutter for amplified spontaneous emission and retro-pulse suppression. 10 MHz operation of this shutter is shown in Fig. 7 and the the range of frequencies over which this design will provide isolation is determined primarily by the lithium niobate transducers. Cassegrain design dimensions call for a 6.25 MHz resonant "dynamic isolation", well within the demonstrated range of this device. Pulses which arrive at the modulator at some time other than one of its nulls, find a sinusoidal phase plate which adds a sinusoidal phase to the field. In the plane of the spatial filter pinhole then, this pulse will be diffracted into higher orders and not pass through the opening. A Pockels cell placed in the small aperture portion of the beam line on the right hand side of Fig. 3 could prevent the build up of oscillation which circulates at the modulation frequency as in a mode-locked oscillator. Since the phase conjugating mirror is expected to provide very little feedback unless presented with an intense beam, the Pockels cell may not be necessary.

MALAPROP Calculation for one Cassegrain Cell

Laser system simulation computer codes such as MALAPROP have been used to study the beam profile to be expected from a single cell.[8] Realistic imperfections in the optical components are modeled by introducing randomly placed obscurations with a size and density typical of dirt and damage sites found in operating glass lasers. Starting with an ideal plane wave input to the holograpnic lens, MALAPROP predicts that either an alumino-phosphate or a silicate Cassegrain amplifier will produce 12 kJ green beams similar to the one depicted in Fig. 8. Figure 8 is a horizontal line scan from the center to the right edge of a typical beam as it would appear after conversion to green. It is this beam which must be projected to the target focusing lens without further degradation of its quality. The amplitude fluctuations depend on the power level, the density of scatterers assumed to be present in the optical train and the phase error built into each part. Nova baseline obscuration fraction was assumed for this calculation; i.e., 5×10^5 of the area of each optical component was blanked out randomly. Preliminary calculation including random phase errors suggest that this machine could tolerate components with six to twelve times more rms phase error than those now in Nova.

The energy delivered by each cell depends on the input as well as gain and loss in the cell. Energy on target should vary slowly with input energy as shown in Fig.9. The two cm thick type I crystals adopted for this simulation make each Cassegrain cell insensitive to the input energy. Temporal pulse shaping is most easily accomplished by timing the arrival of the 864 individual pulses at the target. Even if the phase conjugating reflector were replaced by a plane mirror and all components are assumed to have the maximum amount of passive aberration allowed for a Nova optic, each cell's beam would focus to a 1/e intensity radius of 1 mm. Centering of individual beams on the target will depend on the hologram's tolerance, but alignment accuracies of one to two hundred um should be routinely achievable as already demonstrated in Novette and Nova target tests. The goal of delivering 10 MJ in a shaped laser pulse 10 nsec long to a focal spot about 1 mm in diameter could be accomplished using this cell design.

Stacking of Laser Cells

Mechanical and electrical costs per cell scale favorably with amplifier size up to some limit determined by handling procedures. At this stage, an amplifier module containing a 6 X 6 array of 4 slabs is thought to be most cost effective. Such a device would resemble the compact high efficiency amplifier structure sketched in Fig. 9. Since 20 slabs are used in each cell, it would take five such modules in series. Adding on the two M = 3 telescopes, rod amplifiers and phase conjugating mirrors, leads to a beam line 48 m long like the one in Fig. 10. An array of 36 Cassegrain cells would produce about 400 kJ of infrared light in 10 nsec and fit into a volume significantly less than that now occupied by Nova. Twelve 6x6 modular beam lines could be fit into a building similar in size to that now occupied by Nova with adequate space left for component handling and maintenance. Figure 11 shows how such laser system would appear with one of its amplifier modules out for maintenance. The space frame will form the structural support for the laser and act as a skeleton for a vacuum tank. Referring again to Fig. 3, components which must be mounted in the center of the cell can be supported by transparent optics so that no spiders will be needed; the amplifier modules, second harmonic converters, mirrors, etc. become an integral part of the optical support system. To avoid large numbers of potentially leaky window arrays, not to mention the optical distortion inherent in 14.7 psi to vacuum transitions across lenses, we propose to evacuate the entire space frame structure. The frame will have to be welded vacuum tight, and a vacuum tight skin will be supported by the space frame. One side, the top, bottom and internal walls will be welded vacuum tight. The isle wall will be made of removable covers with flexure like flanges to accommodate the bolted vacuum seal. Nova space frame rigidity and achieved construction tolerances make such a design feasible.[9]

Beam Transport to the Target

Simulations suggest that our green laser beams should exhibit intensity nonuniformities similar to those seen in Nova beams. For example, a 10 nsec square pulse would deliver about 50% of its power below 1.6 GW/cm^2 and 75% below 1.8 GW/cm^2. Isolated regions of the beam would exceed 2.0 GW/cm^2 and almost all of such a beam would exceed the threshold for significant stimulated Raman scattering in air. With shorter or shaped pulses and thus even higher intensities over the 50 to 100 m path between the laser and the target chamber, the conversion to Stokes and anti-Stokes wavelengths should be efficient. To avoid this loss, we would flood the entire target room, and any beam path not already evacuated, with a low n_2 and low Raman cross-section gas such as Helium. As Helium is essentially immiscible in air, it would displace the air in the target area if the building were adequately sealed. An even simpler, but possibly more expensive, alternative would be to evacuate the air from the path between the output of the laser cells and the chamber.

Power Conditioning

Engineering studies performed over the past three years by W. Gagnon et. al. in support of multi-megajoule system design have turned up several cost saving strategies. Less expensive components can be used, particularly buss bars rather than coaxial cable. Larger units of energy can be switched by using the largest available ignitrons. Nova uses 87 C ignitron switches to gate 400 kJ blocks of energy which is stored in 18 kJ capacitors at 20 kV.

The multi-megajoule system should use the newer 75 kJ capacitors and 1000 C switches to move 10 MJ blocks of energy at about 20 kV. The capacitor bank can be placed directly below the amplifiers so that large room temperature buss bars will be adequate to conduct the energy to the Xe flash-lamps.

Space requirements for the energy storage system are dictated by the capacitor's energy density. Units have been tested at LLNL that have energy densities 0.4 to 0.5 J/cm^3 and shot lives of about 1000. Using these numbers, the volume required is between 2000 and 2500 cubic meters.

Research and Development Issues

Materials

As with all LLNL high power glass lasers, optical damage drives the design of multimegajoule systems. We require laser glass which meets the bulk damage threshold specified for Nova. It is reasonable to expect that high quality optical glass can be fabricated for the $0.20 to $0.30/cc price assumed. Figure 12 plots laser glass costs for Shiva and Nova in 1985 dollars along with one year's production of a high quality borosilicate glass, BK-7, used for camera lenses among other things. For comparison, the retail value of high quality plate glass is also included in order to show how glass costs fall with large volume production. One of the laser glasses acceptable to both Cassegrain and multipass cell designs is the much researched LG-660. As this material is very nearly Nd doped BK-7, it is unlikely that its cost would be significantly higher for the volume required. If this facility is capable of high thermonuclear gain, experiments will soon zero in on the engineering requirements for a power plant driver. Promising crystalline hosts have already been identified for Nd which have the correct properties for an efficient high repetition rate multi-megajoule driver. Materials developement would proceed during the construction and operation phases of the proposed multi-megajoule facility. It is unclear at this point whether a crystalline or an as yet undiscovered ceramic host would be best in a power plant.

Optical coating choices are also dominated by damage and cost considerations. Anti-reflection coatings with damage thresholds adequate for our purposes are now used in Nova. Inexpensive Sol-gel or neutral solution coatings are well suited for this application. The more expensive e-beam evaporated films fail to achieve the damage resistance needed. Figure 13 compares the goal which must be met in order to build a multi-megajoule laser with damage threshold data and reveals that either the sol-gel or the neutral solution process can be used. Both cell designs require high reflectors and dichroic mirrors which have yet to be demonstrated. Sol-gel technology once again seems to be the best path to realizing these reflectors.

The choice of harmonic converter material is another critical choice dominated by cost and damage considerations. KDP, which is now used in Nova, was too expensive to grow and is too lossy to be a viable candidate for a multi-megajoule laser. Much progress has been made toward cost reductions in KDP production so that the price may well be tolerable. Damage thresholds are still twice to low; however. Two materials which can be produced with much the same technology that has been demonstrated for KDP, are KD^*P and LAP. Both of these have loss coefficients and damage properties that look promising, but production in the quantities and at the quality needed for a multi-megajoule laser remains to be demonstrated.

Isolation

Two devices have been proposed to prevent unwanted parasitic oscillations from depleting the gain of the individual cells. A third, the phase conjugating mirror, has the feature that it only reflects intense pulses and this naturally inhibits the build up of noise. The two components designed exclusively to isolate are the acousto-optic shutter and the Pockels cell.

When used in conjunction with a spatial filter, an acousto-optic modulator installed in the beam line forms a phase grating which diffracts the beam out of the spatial filter pinhole forming a sinusoidal shutter. Pulses reaching the modulator filter combination at a null in the modulator cycle pass unaffected while greater than 96% attenuation has been observed for other pulses. The modulator consists of a sol-gel coated fused silica slab with lithium niobate transducers attached to its edges, thus its damage properties and cost are readily projected. This attractive device has been demonstrated at a 5 cm aperture and a developement project intended to achieve a 50 cm unit is moving forward. We have called this technique dynamic isolation and some of the early data is reproduced in Fig. 5.

The large number of quasi-independent beams involved in these architectures make it essential that alignment and diagnostics be simple. Since the laser beam is injected near the target and retro-reflected by the phase conjugator, the alignment procedure becomes essentially a beam pointing task. Continuous apodization by bead

The large number of quasi-independent beams involved in these architectures make it essential that alignment and diagnostics be simple. Since the laser beam is injected near the target and retro-reflected by the phase conjugator, the alignment procedure becomes essentially a beam pointing task. Continuous apodization by bead blasted edges on most optical components make these cells self-centering and ensure high fill factors. Holographic optics of the sort we need are in common use in grocery scanners. It remains to be shown that these components, which seem to behave well in Malaprop simulation, will perform adequately in fact.

Summary

New technologies make multi-megajoule glass lasers economically feasible. Laser architectures using harmonic switchout, target plane holographic injection, phase conjugation, continuous apodization and higher amplifier efficiencies have been devised. A plan for a multi-megajoule laser which can be built for an acceptable cost relies on manufacturing economies of scale and the demonstration of the new technologies presented here. These include continuous pour glass production, rapid harmonic crystal growth, switching of large blocks of power using larger capacitors packed more economically and by using large identical parts counts.

Acknowledgements

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LLNL laser design has progressed rapidly

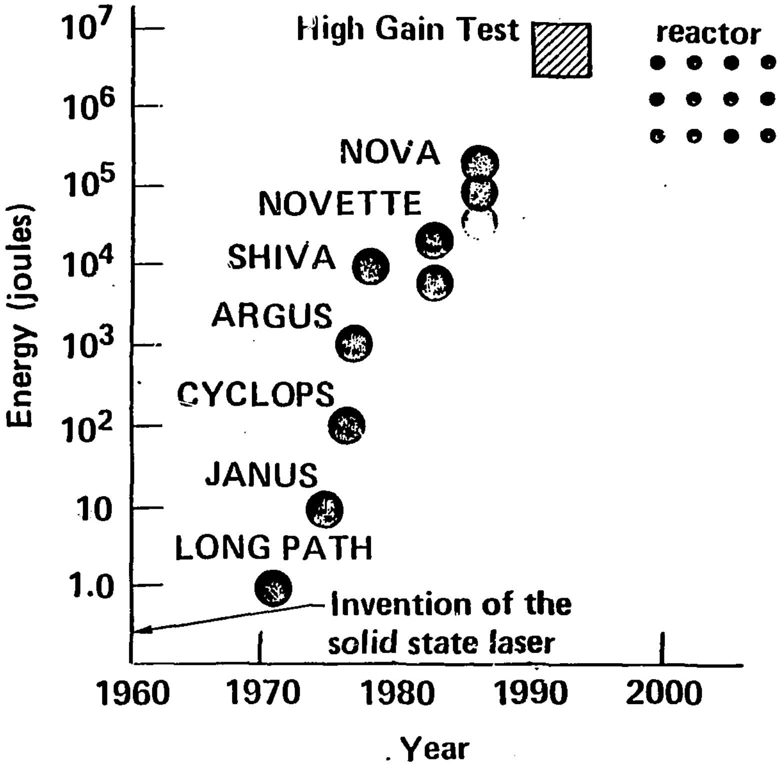

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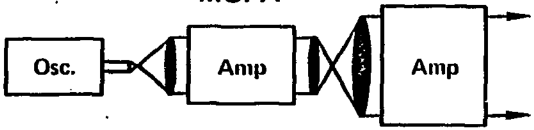
Figure 1

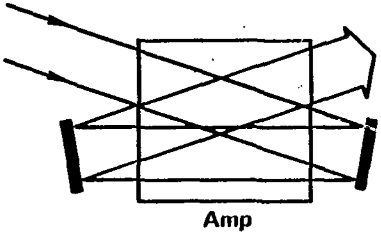
We have invented many new laser architectures

Traditional

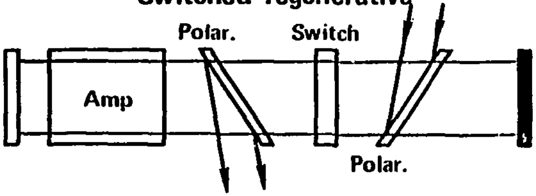
MOPA



Off-axis

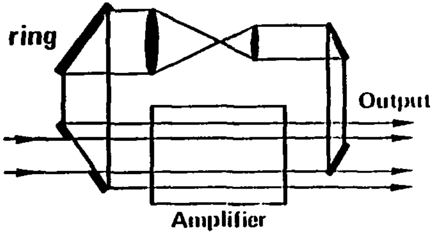


Switched-regenerative

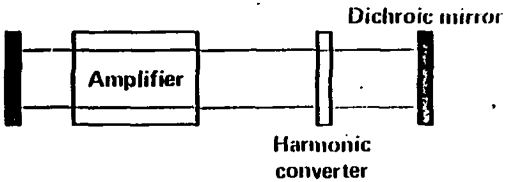


New

Reflex ring



Harmonic-switched regen



Front-feed, harmonic-switched cassagrain

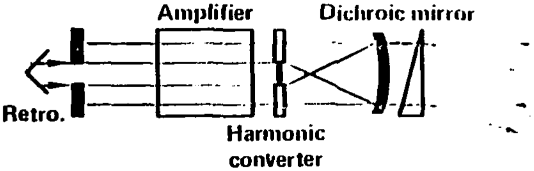


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Figure 2

Cassegrain Cell

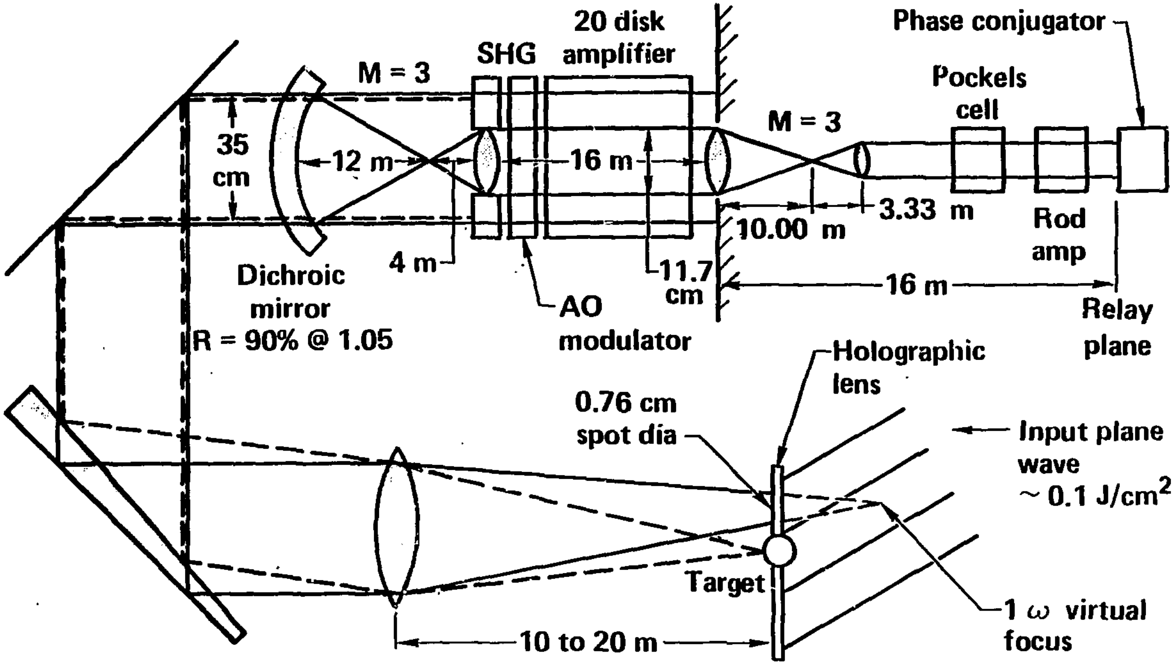

Figure 3

10 megajoule Cassegrain laser propagation 1 – 3

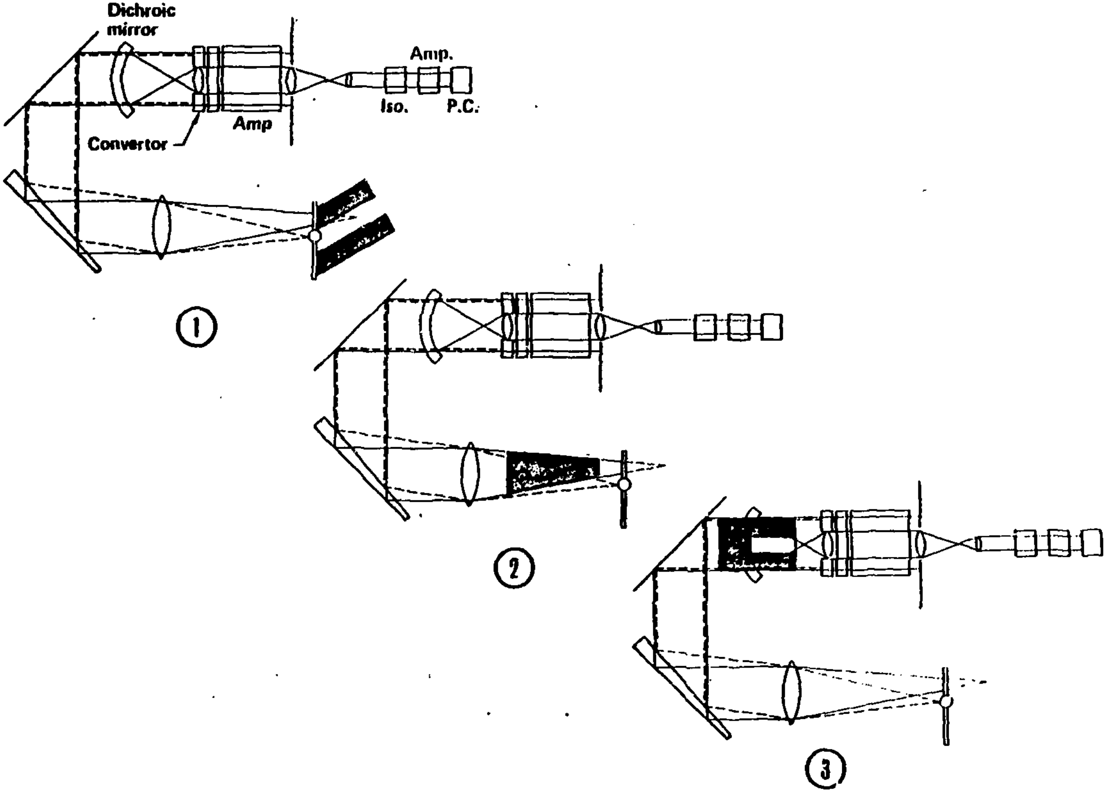

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Figure 4

10 megajoule Cassegrain laser propagation 4 – 6

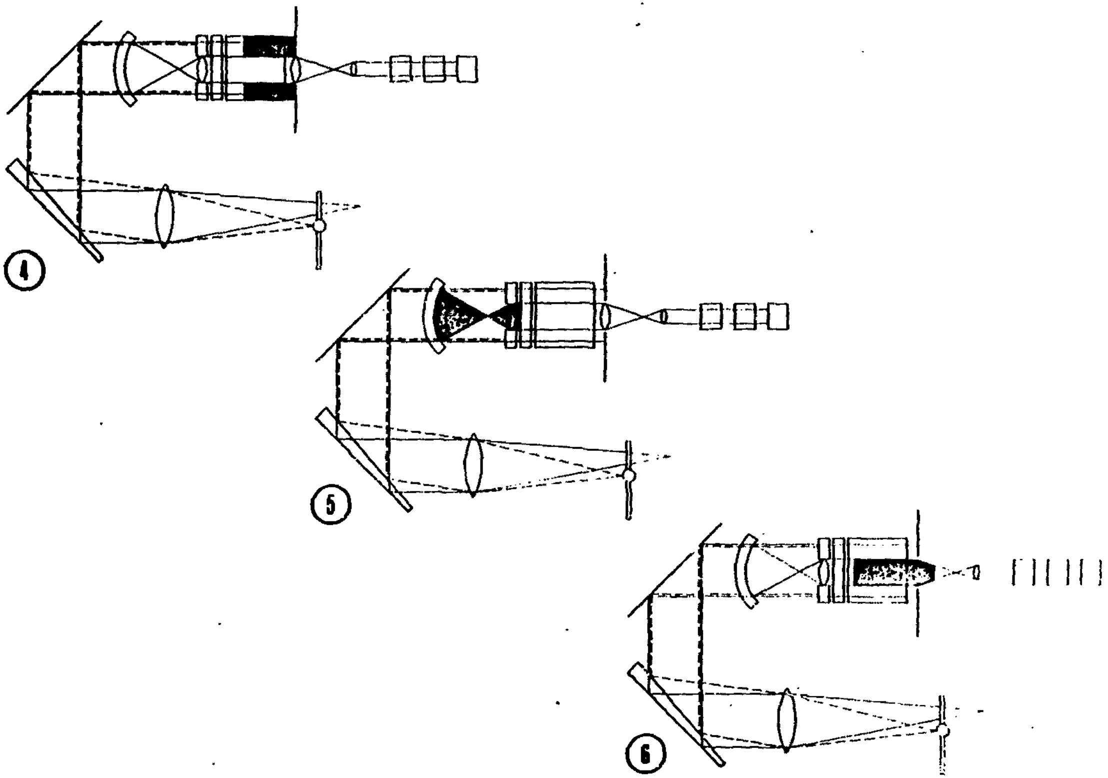

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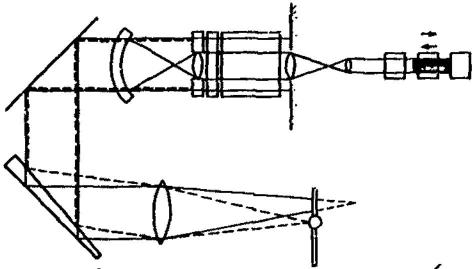
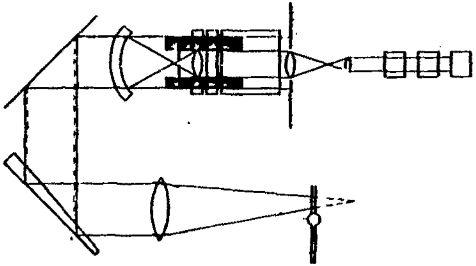
Figure 4

10 megajoule Cassegrain laser propagation 7 – 9



⑦



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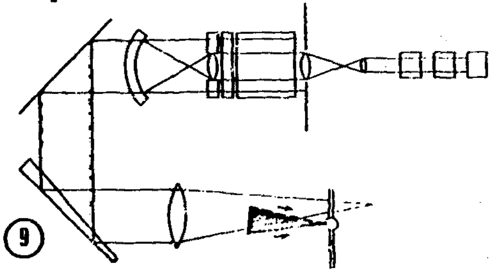

⑨

Figure 4

A holographic lens can provide efficient self aligning injection of the oscillator pulse into the beam lines

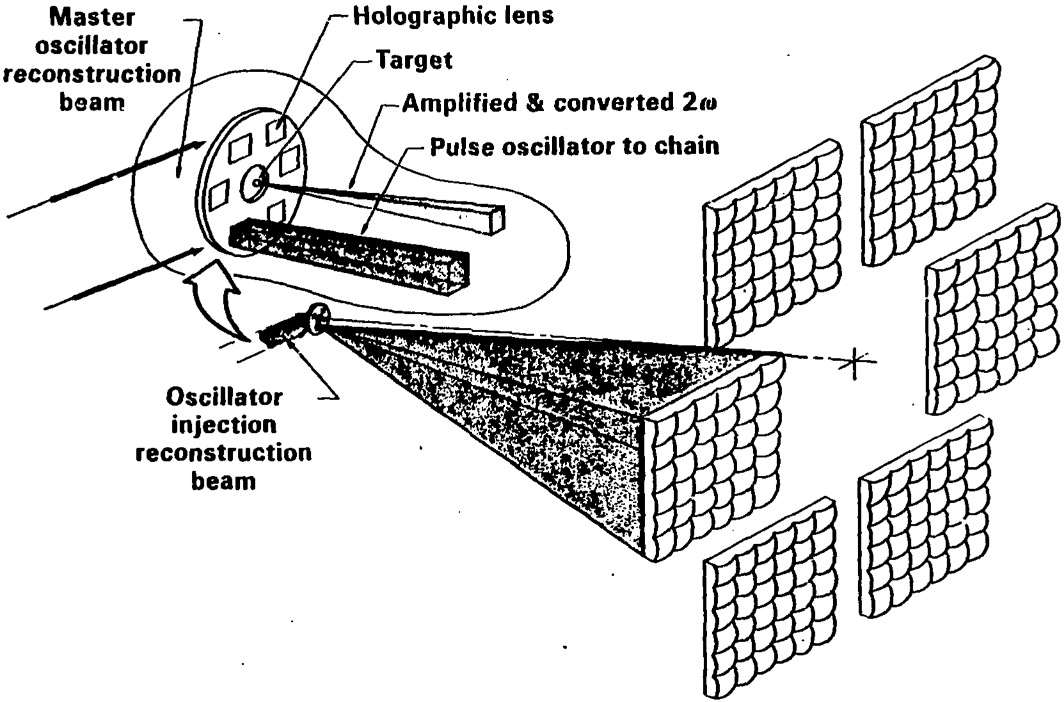

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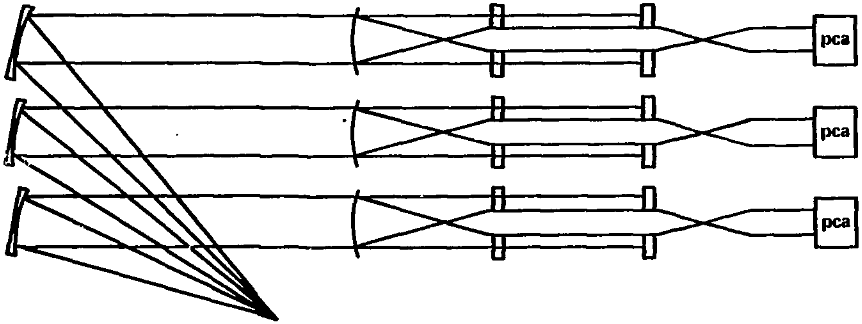
Figure 5

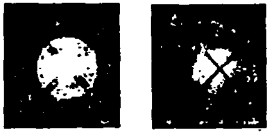
Phase conjugating mirrors correct aberrations and automatically point many laser beams at once



Far field

Input Return

Near field

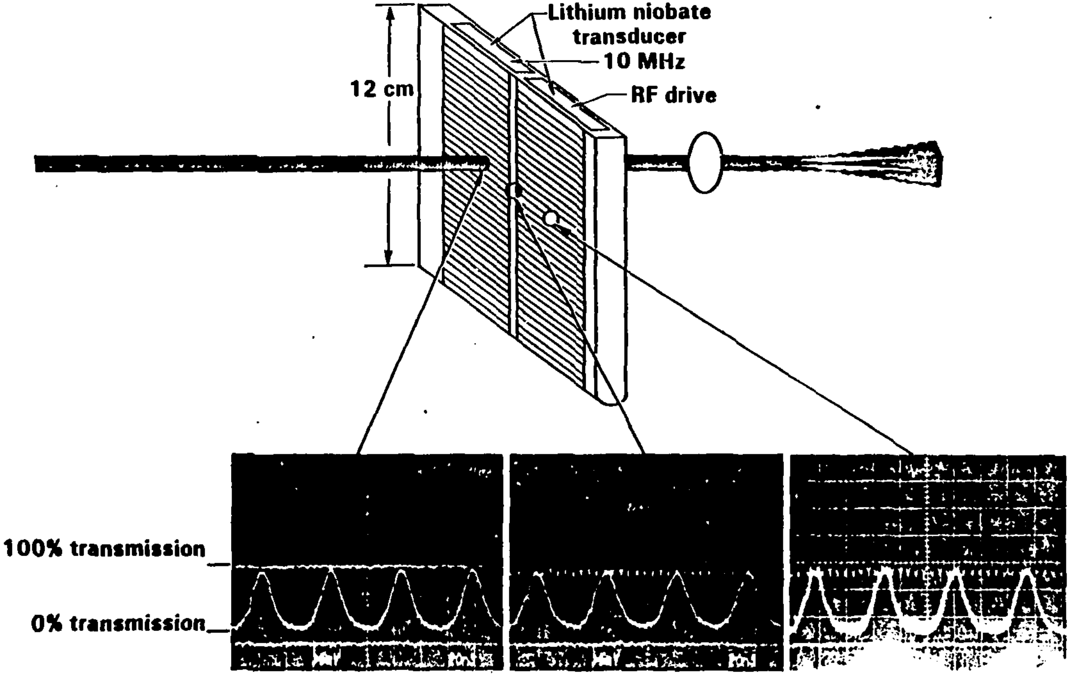


Input Return

02-04-0585-2288

Figure 6

An acoustic standing wave can be used to provide a fast beam shutter for ASE and retro pulse suppression



40-01-0985-4239

Figure 7

MALAPROP calculation of 12 kJ beam

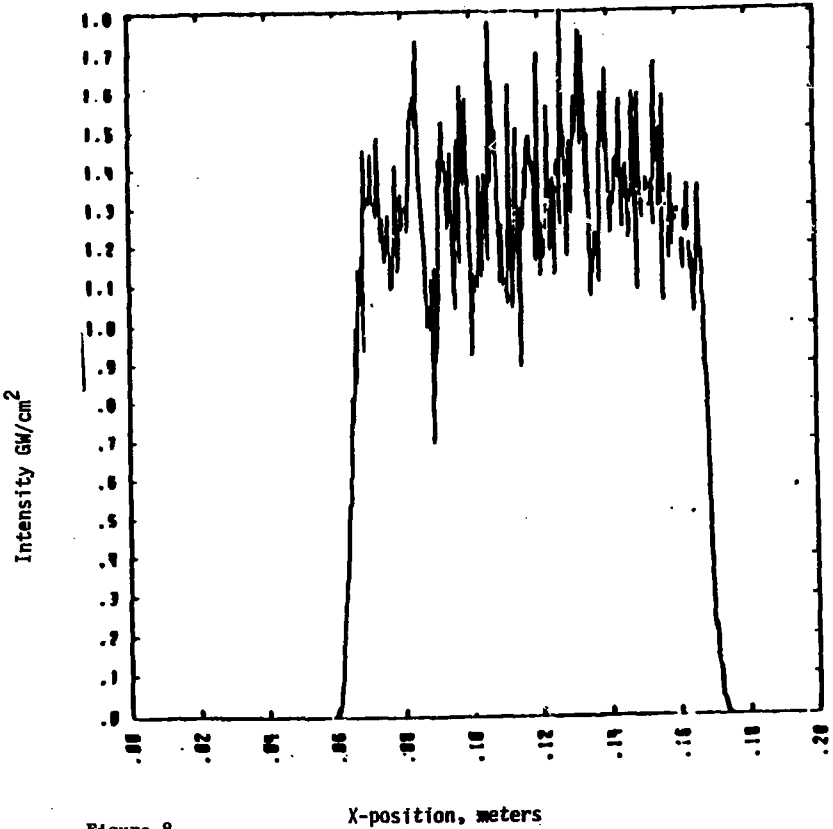


Figure 8

Compact high efficiency amplifier MK I

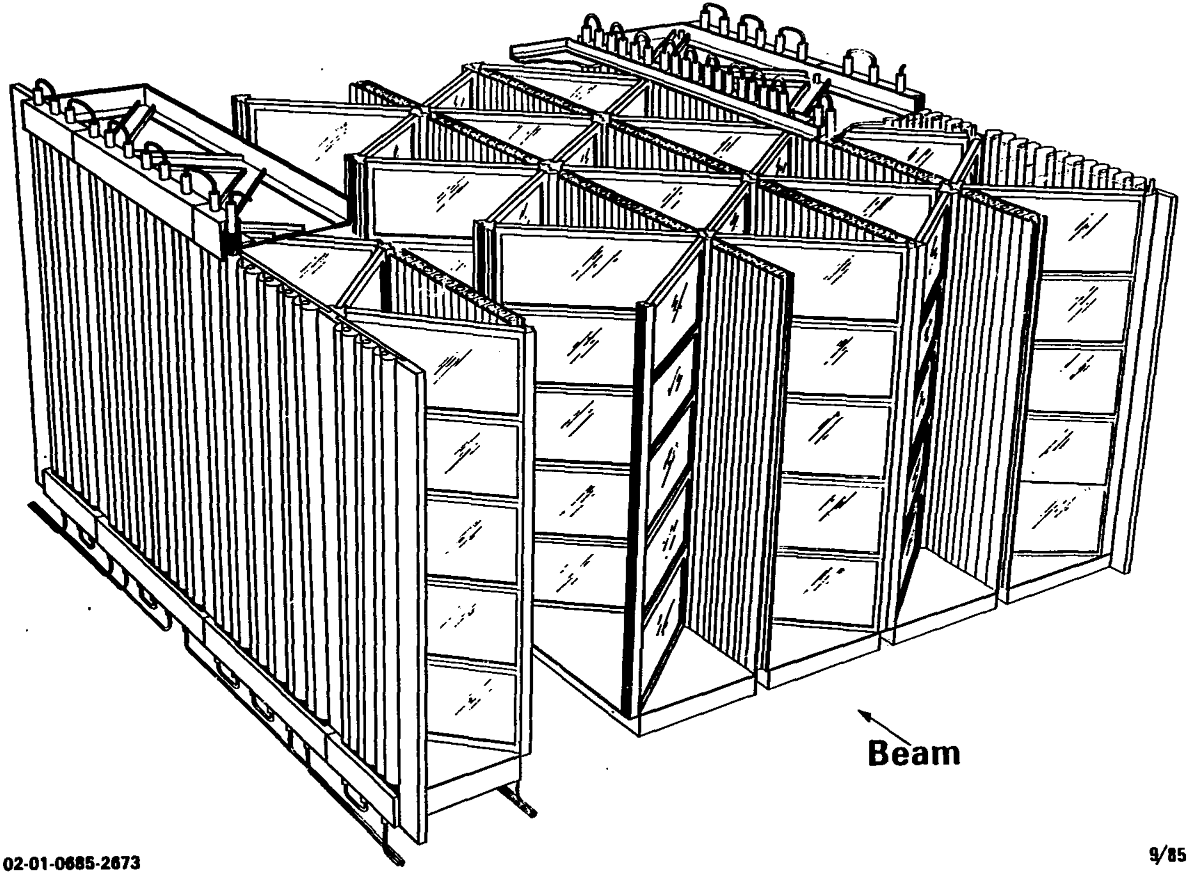


Figure 9

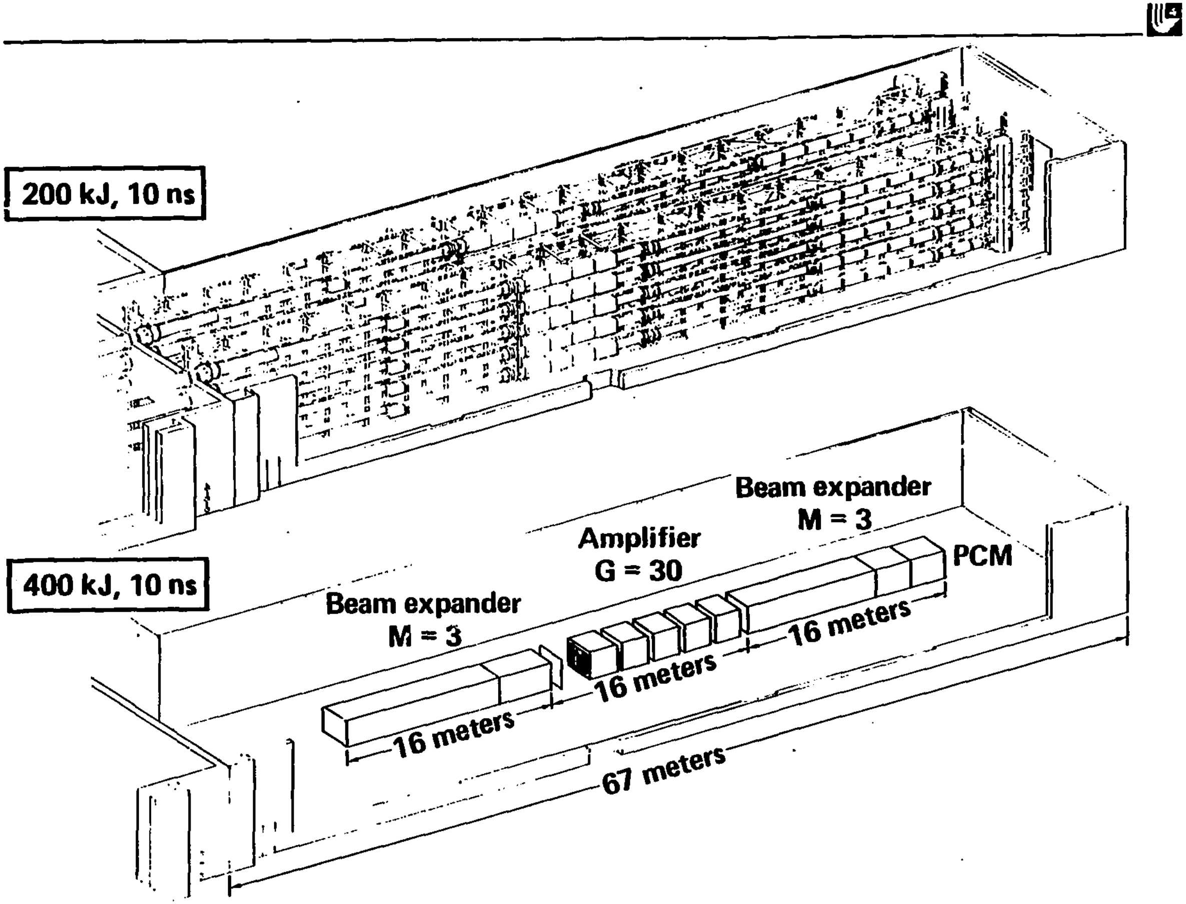

200 kJ, 10 ns
400 kJ, 10 ns
Beam expander
M = 3
Amplifier
G = 30
Beam expander
M = 3
PCM
16 meters
16 meters
16 meters
67 meters

Figure 10

Multi megajoule laser modules

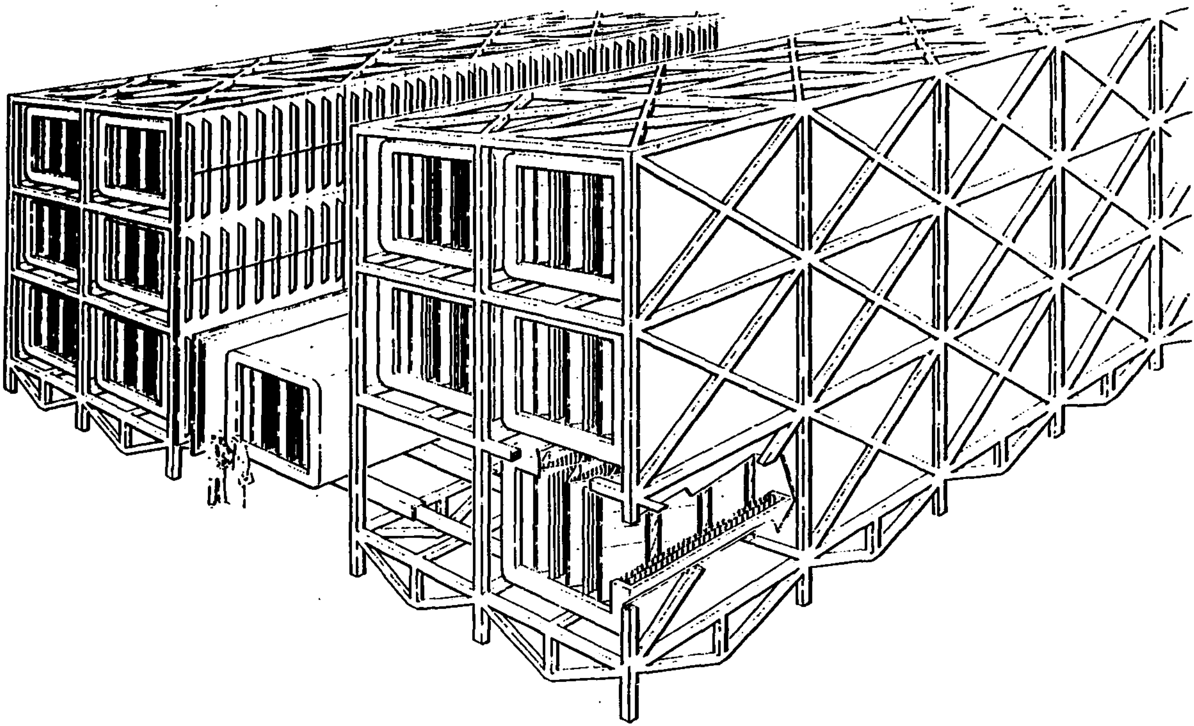


Figure 11

Laser glass costs are consistent with large volume optical glass production ⇒ $6/J laser cost

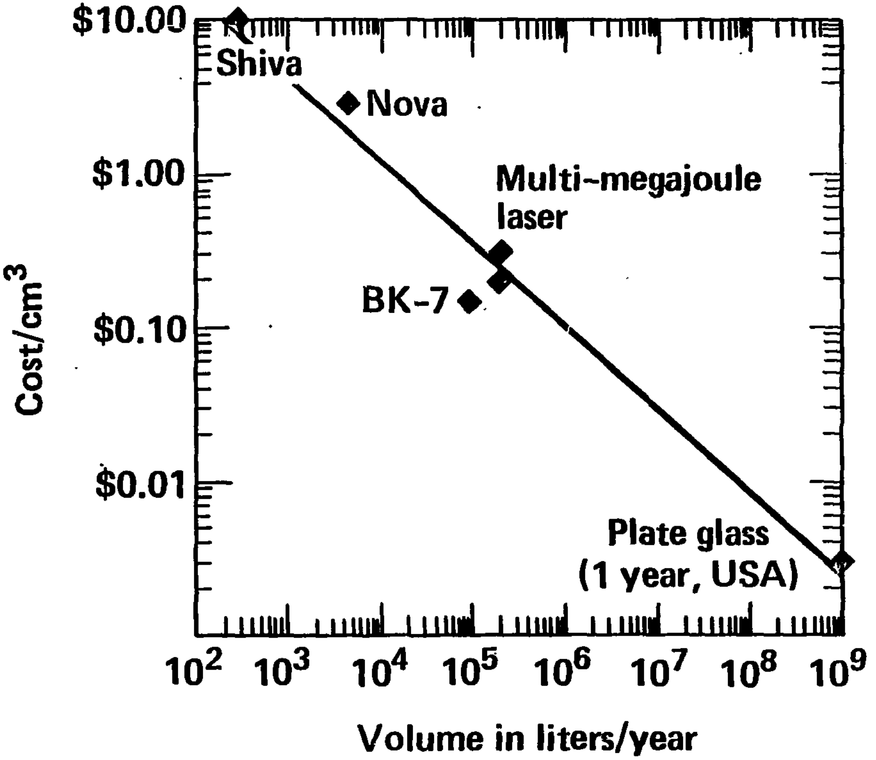


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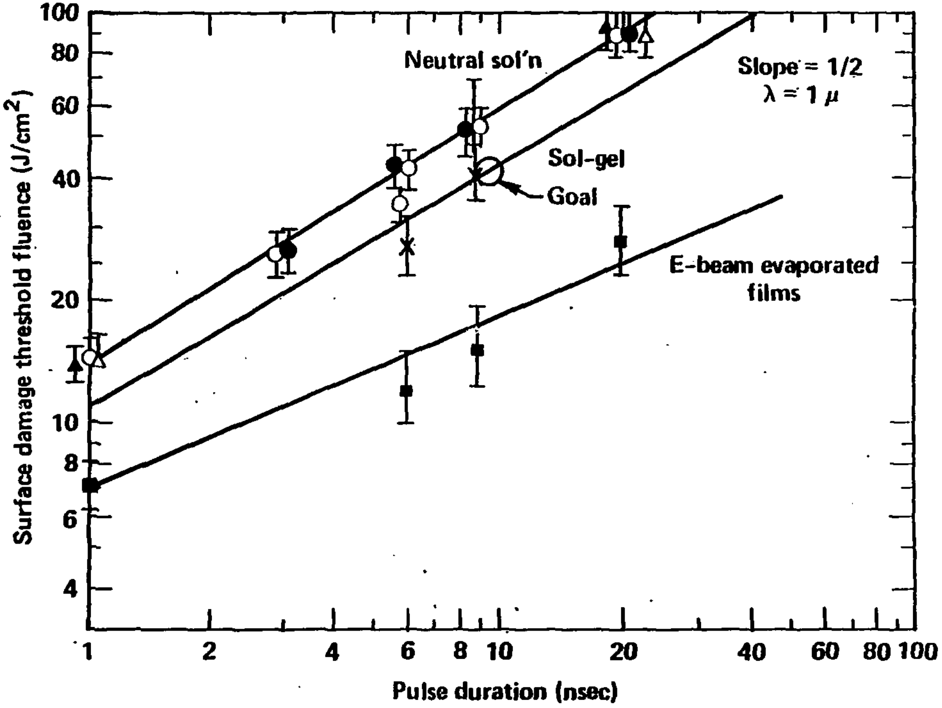
Figure 12

Modern laser anti-reflecting surfaces have damage thresholds consistent with compact, lower cost systems



02-04-0585-2296

Figure 13