

TITLE: LASERS AND POWER SYSTEMS FOR INERTIAL CONFINEMENT FUSION REACTORS

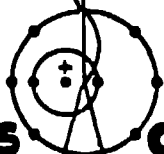
AUTHOR(S): E. E. Stark, Jr.

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LASERS AND POWER SYSTEMS FOR INERTIAL CONFINEMENT FUSION REACTORS

E. E. Stark, Jr.

LOS ALAMOS SCIENTIFIC LABORATORY*
LOS ALAMOS, NEW MEXICO 87544

After discussing the role of lasers in ICF and the candidate lasers, several important areas of technology requirements are discussed. These include the beam transport system, the pulsed power system and the gas flow system. The system requirements, state of the art, as well as needs and prospects for new technology developments are given. Other technology issues and promising developments are described briefly.

INTRODUCTION

The role of lasers in ICF (Inertial Confinement Fusion) is to produce short, pulses of energy and deliver them simultaneously onto small fuel pellets. A schematic diagram of an ICF laser system is shown in Fig. 1. The performance requirements are listed in Table 1. The purposes of laser systems studies are to identify generic technology needs so that they may be addressed on an appropriate time scale, and to provide comparisons of various driver system options so that a prime driver choice can be made when the ICF program reaches its engineering feasibility ~~development~~ phase.

*Work performed under the auspices of the United States Department of Energy.

TABLE 1. Laser System Requirements

Pulse Energy	1-5 MJ
Pulse Length	1-10 ns
Efficiency	> 5%
Six or More Beams	
Each beam focusable to ≤ 1 mm	
Repetition Rate	1-10Hz
Prepulse Limits	50 kW/beam
	1 mJ/beam
	10 mJ total
Interface to Target Chamber at ≤ 0.1 torr.	

Gas lasers are the most attractive ICF laser options because gases can be flowed and cooled for high repetition-rate operation and are not subject to irreversible damage. The CO₂ laser is a leading candidate, with 2% efficiency demonstrated and \approx 10% predicted, and with repetitive operation at 750 Hz⁽¹⁾ and scalability to large sizes already demonstrated. The major classes of advanced laser candidates are listed in Table 2. Most of the discussion in this paper is applicable to both CO₂ and advanced lasers, although the emphasis is on CO₂.

BEAM TRANSPORT SYSTEM

The beam transport system will be a critical part of ICF laser systems because of the large number of optical elements and beam quality requirements. It is normally the highest cost portion of the laser system. The major system elements are mirrors, windows and their mounting structures.

Quality of individual optical elements can be judged by two sets of criteria, one involving loss, damage and related issues, the other related only to the optical quality. The first set must be considered in reference to specific materials while the latter reduces to a single criterion--the error in the optical surface divided by the laser wavelength. Total system quality is defined as the root-sum-square of all element errors from the front-end to the pellet.

The net effect of wavelength in the beam transport system is relatively small, because of two opposite factors. For a given set of elements, the nominal quality will be better for longer wavelengths; but the focal spot size is proportional to λ , and so larger wavelengths require a better beam transport system quality in order to satisfy the focal spot size requirement.

Mirrors

Because of their relatively high damage thresholds, life, and ease of fabrication, mirrors are generally used instead of lenses in high power laser systems.

The development of micromachined (diamond-point turned)^(3,4,5) mirrors in the early 1970s was a significant breakthrough in optical

TABLE 2. Advanced Laser Concepts⁽²⁾

<u>Type</u>	<u>Pump</u>	<u>λ</u>	<u>Efficiency</u>
Group VI Atomic	Optical	.48 μm	1-4%
Metal Vapor	Discharge	.33-	
Excimers		.47 μm	10-15%
HF Channel	E-Beam	2.7 μm	5-10%
Rare-Gas Halide	Discharge	.25-	
and Conversion		.31 μm	5-10%
Resonantly Excited	Discharge	.28-	
Solid State		.45 μm	2-6%
Optically Pumped	Optical	.27-	
Storage		.34 μm	1-7%

technology. For long wavelengths, e.g., $10.6 \mu\text{m}$, micromachined mirrors have excellent optical quality, $\sim .001 \lambda$ in small sizes. They require no hand polishing and are much less expensive, with higher production rates, than conventional mirrors. Typically, the mirror surface is machined onto a copper-plated aluminum blank, to reduce weight and weight-induced mirror distortions. These mirrors have a reflectivity in excess of 99% at $10.6 \mu\text{m}$ and a damage threshold of $\sim 10 \text{ J/cm}^2$, both quite acceptable. They can be fabricated now up to 2 m diameters, and in-situ error measurement and correction systems have been developed. Flat, spherical and off-axis parabolic mirrors have been micromachined. Additional development is under way to increase the quality to acceptable values for even near-infrared and visible wavelengths. The Los Alamos Eight-Beam CO_2 Laser System uses micromachined mirrors where large mirrors are required.

Windows

Windows provide a pressure and gas-species interface between the laser gas and ambient air, and ultimately to the reactor chamber which must be at a pressure ≤ 0.1 torr. As a pressure interface, they must have a mechanical strength sufficient to withstand both static and dynamic pressure loadings. Because they are also optical elements, they should have: low bulk absorption; a high threshold for laser-induced damage; low dispersion so that different laser frequencies may be used; and they should be transparent to visible light for ease of alignment, be available in appropriate sizes, and have a good optical quality.

Solid Windows For CO_2 lasers, there are two attractive candidates--polycrystalline NaCl, and ZnSe fabricated by chemical vapor deposition. Their physical characteristics are given in Table 3. The CO_2 laser experimental systems at Los Alamos all employ polycrystalline NaCl.

Further improvements in both candidates are possible. Doping NaCl with large atoms (e.g., rare earths) to prevent propagation of defects in the microcrystalline structure may significantly increase its yield strength. The bulk absorption quoted for ZnSe is much lower than it was

TABLE 3. Material Window Options for $10\mu\text{m}$

	Polycrystalline NaCl	ZnSe (CVD)
Bulk Absorption	0.1%	0.1%
Index of refraction	1.5	2.4
Damage Threshold ⁽⁶⁾ (1 ns pulse)	6 J/cm ²	1 J/cm ²
Hygroscopic?	yes	no
Yield Strength	~ 2000 psi	~ 7500 psi
Sizes	60 cm	84 cm

several years ago when damage threshold measurements were made,⁽⁶⁾ which may indicate that its damage threshold should be remeasured. The brittleness and variation of refractive index with temperature of ZnSe may still prove to be serious disadvantages.

The increase in laser pulse length for ICF would result in greater design flexibility with NaCl (which now limits pulse energy density due to damage considerations) and an increased feasibility of using ZnSe. This is because the damage mechanisms in NaCl and ZnSe are thought to be electric-field dependent, and hence the damage threshold would increase as the square root of the laser pulse length.

For visible and near-UV wavelengths, the laser pulse length will be crucial to window acceptability. Two-photon damage at shorter wavelengths can be avoided if, for example, 10 ns pulses are employed with intensities below 1 GW/cm^2 .⁽³⁾

The pulse length arguments above for both short and long wavelengths will also depend on the desired laser pulse shape, which cannot now be predicted in detail.

Aerodynamic Windows Numerous concepts have been developed for replacing material windows with flowing regions of gas.^(7,8,9,10,11) These rely on either the centrifugal force of a curved region of gas flow or on a constant shock produced by supersonic gas flow. These have been demonstrated in laser systems that do not have the same beam quality or system efficiency requirements as ICF lasers. Supersonic shock-interface aerowindows appear to consume far too much pumping power, many times greater than the time-averaged laser output power. One potentially attractive option is to employ several stages of subsonic gas flow. The primary uncertainties include aperture size scaling (10 cm is state-of-the-art, ≈ 30 cm would be highly desirable), beam quality, power consumption, and the ability to provide a pressure interface down to the ~ 0.1 torr of the reactor chamber.

PULSED POWER SYSTEM

The pulsed power system must provide an efficient, reliable, compact, long-lived system for the generation, storage, switching, pulse forming,

and transfer of energy in a short flat voltage pulse. The specific requirements are given in Table 4. A flat voltage pulse is desirable in order to maintain the optimum value of E/P, the ratio of electric field to pressure, for most efficient laser gas excitation. The greatest technology difficulty involves system life and capability for repetitive operation. Reliability is also an important requirement, because the pulsed power system will contain at least several thousand discrete components, each of which must perform properly on a successful shot.

Energy Storage

The energy storage system should represent a constant drain on the plant's power output, while providing short energetic high-voltage pulses for the laser system. It should have a high energy density and high efficiency, as well as low inductance to permit short pulse rise and fall times.

At present, the only feasible choice is a bank of storage capacitors. These are typically rated at 60 kV, with 5 kJ energy storage per capacitor. The lifetime is typically 10^5 shots if there is no voltage reversal. Repetition rates up to ~ 1 Hz are possible. Operation at a higher repetition rate will require a new means for heat removal, possibly involving a circulating dielectric liquid or the use of larger size capacitors. Pulse lifetime increase will require improvements in capacitor dielectrics.

Other energy storage options are: kinetic storage, which has been developed for magnetic fusion applications; inductive storage; and charged-line storage and pulse forming. ICF lasers require excitation pulses with a duration too short for kinetic storage, but too long to permit use of charged transmission lines of reasonable length. Inductive storage would be attractive from the viewpoint of efficiency and life if good opening switches become available.

We expect that capacitor development will provide the most likely solution to the energy storage requirement, although the other options will be kept open.

TABLE 4. Pulsed Power Requirements for ICF Lasers, Per Discharge Region

Open-Circuit Voltage	1-15 MV
Maximum Current	1-5 MA
Pulse Length*	2-5 μ s
Lifetime	to 10^9 pulses
Repetition Rate	1-50 Hz
Reliability	\geq 99%
Efficiency	\geq 90%

*This is for CO₂. With the exception of shorter pulse length in some cases, the pulsed-power requirements for other gas lasers are similar.

Switching

High current, high voltage standoff, low impedance operation with low timing jitter and long life are the primary requirements. The present options include conventional spark gaps, solid-state switches, superconducting switches and ignitrons.

Spark gaps are the only feasible choice today. They can operate above 50 kA and 50 kV, but their life is clearly insufficient, $\sim 10^5$ shots at < 0.3 Hz, with degraded reliability and jitter toward the end of their lives. The ultimate potential for spark gaps is not predictable because they have not been completely studied. The uncertainties include failure modes, the dependence of life and performance on operating parameters, and the prospects for improvement in life, reliability and jitter.

Solid-state and superconducting switches are at too early a developmental stage to permit predictions of their utility for ICF lasers.

Advances in pulse transformer technology would solve the switching problem by permitting the use of ignitrons. Ignitrons use a liquid mercury cathode with a low-voltage semiconductor pin trigger. Their design yields high reliability with a virtually unlimited life, but they operate at only ~ 10 -20 kV. If pulse transformers can be further developed to reduce leakage inductance and stray capacitance, then ignitrons could be used for switching on the low-voltage side of the pulse transformer.

General

The difficulty levels in laser pulsed-power requirements are outlined in Table 5. The underlined values refer to existing CO₂ short-pulse laser systems. Some advanced lasers require pulse duration and dI/dt values approaching those in "most difficult" column. It is possible that optimized design of CO₂ power amplifiers will permit operation at an impedance $\sim 10 \sqrt{2}$ or greater easing the problem of impedance matching the power supply system to the gas discharge.

The Air Force Studies Board Summer Study on Pulsed Power, 1977, identified dielectrics and switching as the two major needs in pulsed

TABLE 5. Pulsed-Power Difficulty Levels

	<u>Least</u> <u>Difficult</u>		<u>Most</u> <u>Difficult</u>
Voltage	≤ 20 kV	100 kV	<u>500 kV</u>
Current	≤ 40 kA	<u>200 kA</u>	500kA
Coulombs	≤ 1	10	100
Pulse Duration	μ s	<u>μs</u>	10 ns
dI/dt	$< 10^{10}$	<u>5×10^{11}</u>	10^{13}
Impedance	$> 10 \Omega$	<u>2Ω</u>	$< 1 \Omega$

power technology. Dielectrics are typically used at only 10% of their dielectric strength because of impurities, voids, foil nonuniformities and stresses induced in manufacturing, and their working environment (e.g., heat and radiation). Liquid dielectrics may be attractive for heat removal, but toxicity plagues the most promising known dielectric materials.

LASER GAS FLOW SYSTEM

In ICF lasers, a sizeable fraction of the electrical energy input appears as heat. Because higher temperatures reduce laser efficiency and cause optical beam-degrading gas density gradients, it is necessary to flow and cool the laser gas.

The major concerns are power consumption, effect on optical beam quality and constraints on power amplifier geometry. It appears that power consumption will be acceptable, based on Avco's experience.⁽¹²⁾ The effect of gas flow on system efficiency is to multiply it by:

$$\frac{.9}{1 + \frac{\Lambda f}{E}}, \quad (1)$$

where f is the flush factor (number of gas exchanges between shots); E is the specific electric energy input (J/l-atom) and Λ is determined by the gas characteristics and the system pressure drop. Based on an 8 psi pressure drop,⁽¹²⁾ a multiplier for CO₂ lasers would be ~ 0.7 . There is a clear advantage to minimizing the flush factor to ~ 1 by careful system design employing acoustic absorbers, and E should be maximized.

The issue of optical beam degradation by flowing gas requires further study. Two approaches to minimizing degradation are to prepare the gas with weak, small-scale homogeneous turbulence to equalize optical path lengths; and to employ pulsed gas flow, allowing complete damping of density fluctuations between laser shots.

POWER AMPLIFIER MODULE GEOMETRY

The systems and technology issues explored above have little flexibility in the configuration of power amplifier modules. The pulsed power systems require rectangular geometry for a uniform E/P discharge. The gas flow direction, the discharge, and the optical beam propagation must be mutually perpendicular, leading to the geometry shown in Fig. 2.

Stacking of power amplifiers, whether horizontally or vertically, is desirable in order to reduce fabrication costs and to permit several beams to be handled together. In this case, horizontal stacking will be constrained by the high-voltage cables, and vertical stacking by the gas flow system. Use of pulsed gas flow could remove the vertical stacking constraint because perforated tubes rather than large ducts could be used. Optically pumped systems would have the same horizontal constraint, posed instead by the region in which the optical pump is generated.

ADVANCED AMPLIFICATION CONCEPT

In the past, there has been a large gap between long-pulse (0.1-1 μ s) and short-pulse (1-10 ns) laser system efficiency because the molecular kinetics of some laser systems can only make energy available over the longer time scale. For example, long-pulse efficiencies greater than 30% have been demonstrated in CO₂ lasers,⁽¹⁾ but only ~2% has been achieved in short-pulse systems.

An advanced amplification concept has been developed to close this gap, with immediate application to CO₂, HF, and KrF lasers. The basic idea is to operate the laser amplifier in a quasi-long-pulse mode by amplifying a train of separate short pulses. Then a means is found to separate physically the individual short pulses, after amplification, in order to satisfy the short-pulse requirements of the ICF pellets. This can be done in two ways: By shooting the pulses through the amplifier at different times and different angles, they will separate and can then be handled individually. If the laser system permits, as in CO₂, the pulses can be amplified colinearly, but each pulse is at a slightly different laser frequency. After amplification, a large, efficient

diffraction grating will cause angular separation of the pulses (see Fig. 3). Large gratings useful for this purpose are now under development.⁽¹³⁾

After amplification and separation, the pulses may be used in two ways: They can be delayed individually, then focused simultaneously onto an ICF pellet. Alternatively, the output pulse trains from several amplifiers may be split up so that the first pulse in each train goes to the same reactor chamber, the second pulses to another, etc.

Using a molecular kinetics code to model CO_2 ,⁽¹⁴⁾ a prediction of improved laser efficiency was made using this multiple-pulse amplification scheme. The result is shown in Fig. 4. The solid curves show the history of the small-signal gain. A slow rate of energy transfer from nitrogen vibration to CO_2 vibration is responsible for the continued gain recovery. The circles indicate the cumulative efficiency as successive pulses are amplified, with an interpulse separation of $0.25\mu\text{s}$. The total efficiency exceeds 20%. This prediction is optimistic because it relates total laser energy output to the electrical energy deposited into the gas, with no consideration of other efficiencies. This scheme also helps solve problems of runaway oscillation in laser amplifiers by keeping the peak gain low.

OTHER TECHNOLOGY ISSUES

The CO_2 laser, and all the advanced laser candidates, require an electron gun in a vacuum region and a large, thin e-beam window to provide a pressure interface that will transmit the electron beam. (For lasers using optical pumping, the optical pump source requires e-beam discharge control.) The life and reliability of the electron emitter and the window are important concerns. These may be addressed by advanced materials and fabrication development, careful design of the electron gun chamber to prevent arcing, and prestressing of the window to prevent fatigue induced by gas-discharge-generated pressure pulses. As with all lifetime issues discussed in this paper, inexpensive planned component replacement may compensate for inadequate lifetimes.

Gain isolation can be an important issue in ICF lasers, but the problems and solutions are specific to each laser candidate. The three primary issues are: prevention of parasitic system oscillation; prevention of pellet damage by laser prepulse energy (Table 1), i. e., undesired leakage energy striking the pellet before the main pulse; and laser pulse reflections from the pellet which may travel back through the system, amplifying and threatening damage to optical components. These problems are addressed in the various laser systems by use of saturable laser energy absorbers; integrated system design to help prevent parasitic oscillations; and design of the beam transport system so that an amplifying pellet reflection will cause optical gas breakdown, stopping the reflection.

There are two advanced optics concepts which may ease considerably the design problems in the beam transport system. The first is deformable mirrors, which may be useful in correcting manufactured or slowly-varying errors in beam transport system components.⁽¹⁵⁾ The other is the use of a nonlinear phase conjugate reflector to compensate for virtually all errors, static and dynamic, in the beam transport system including the gaseous amplifying medium.⁽¹⁶⁾ In this concept, a laser pulse is passed through the entire system from the pellet end, picking up the system's full optical degradation. The phase conjugate reflector then inverts the phase information in the pulse, so that after full power amplification the pulse's optical quality will be virtually error-free as it is focused onto the target.

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Figure Captions

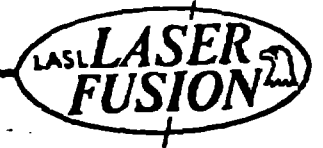
Figure 1. Schematic diagram of major ICF laser systems.

Figure 2. Power amplifier module geometry dictated by pulsed-power gas flow system requirements. In the case of pulsed laser gas flow, perforated tubes might be employed on the gas inlet side.

Figure 3. Schemes for use of the multiple-pulse amplification concept.

Figure 4. Theoretical prediction of multiple-pulse amplification efficiency. The solid lines show the gain history when saturating laser pulses are amplified every $0.25\ \mu\text{s}$. The circles indicate the cumulative electrical-to-laser efficiency.

ROLE OF LASERS IN ICF



- efficiently convert 60 Hz electric power to high power ultra-short pulse
- deliver pulse to small pellet

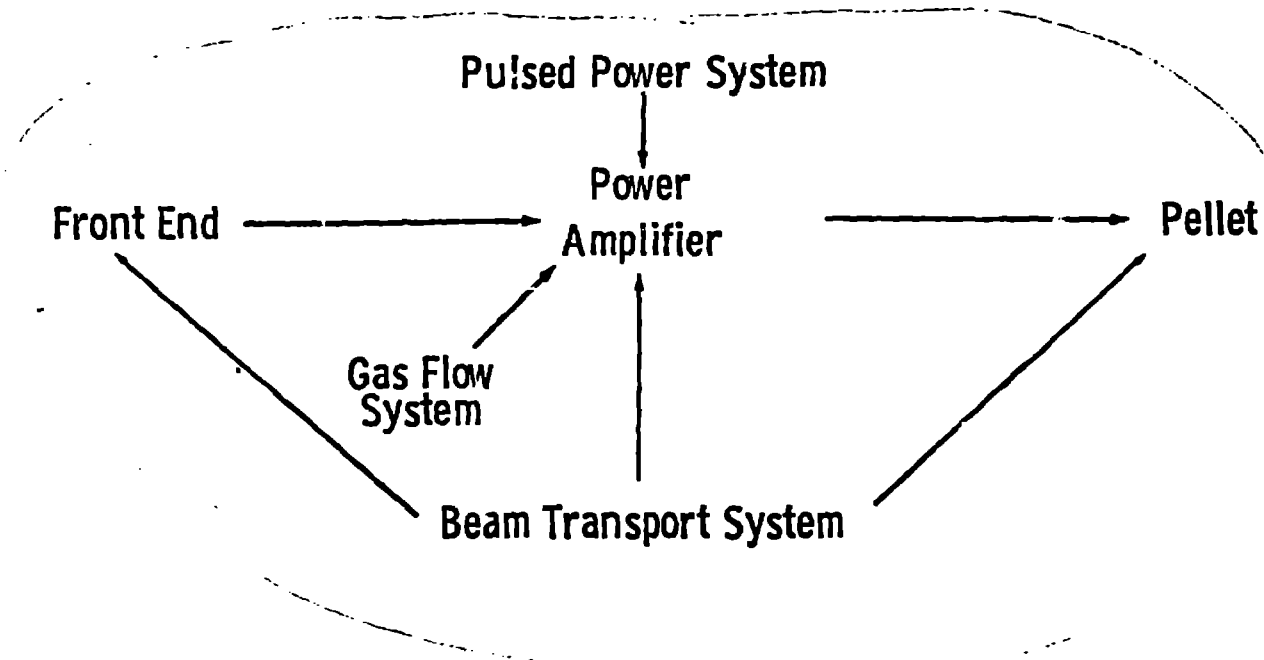


Fig. 1

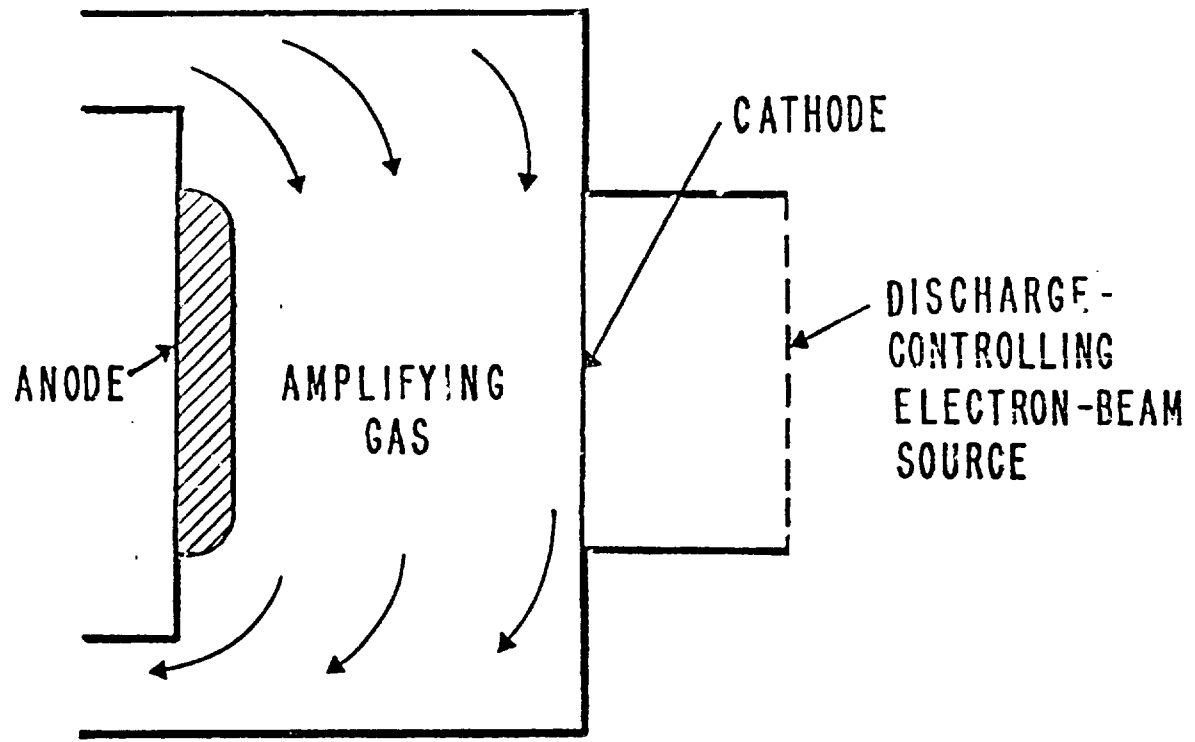
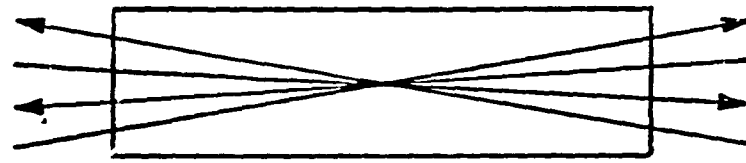
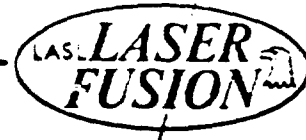
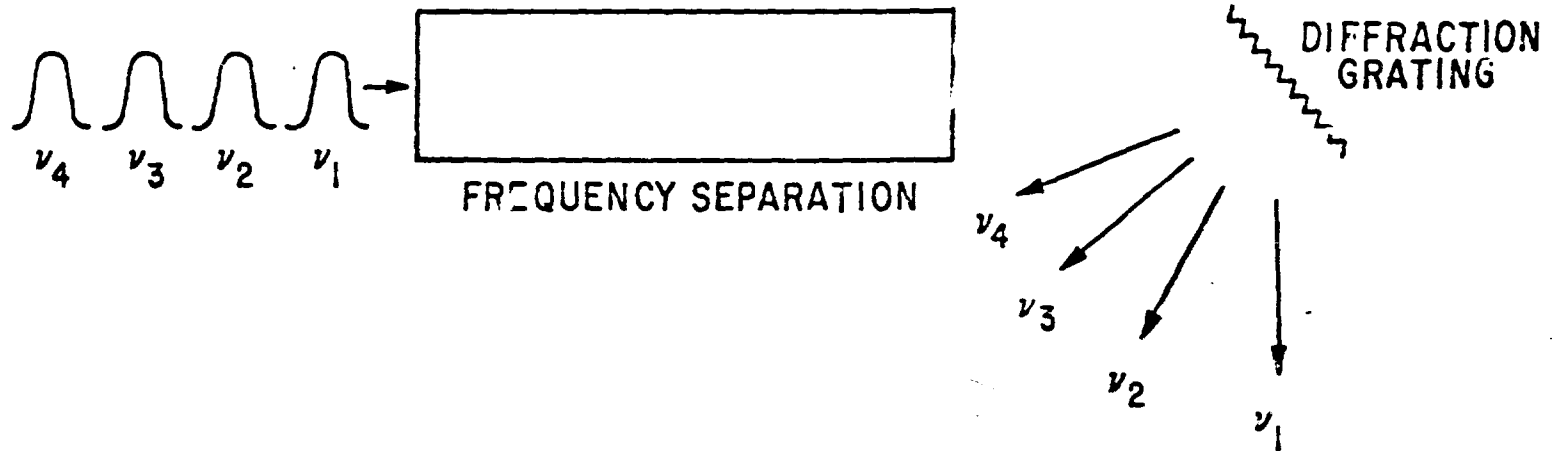


Fig. 2

MULTIPLE PULSE SEPARATION SCHEMES



ANGULAR MULTIPLEXING



APPLICATIONS - PULSES ONTO SAME PELLETT
AFTER EQUALIZING DELAYS
- ONTO DIFFERENT PELLETT

Fig 3

MULTIPLE-PULSE AMPLIFICATION YIELDS
HIGHER EFFICIENCY AT LOWER PEAK GAIN

