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Conceptual Design of a 1.5-MJ, 2-Hz KrF Fusion Laser System

**J. Caird, W. O. Allen, and H. G. Hipkin
Bechtel National, Inc., San Francisco, Calif.**

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**E. V. George, R. A. Haas, W. F. Krupke, L. Pleasance, and L. Seppala
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I. Introduction

Current projections suggest that the future application of laser fusion to power generation will require a short-wavelength laser (from visible to ultraviolet) that will be able to deliver 5- to 20-ns pulses at one or two hundred terawatts with a pulse rate of a few hertz and an overall efficiency greater than 5%. An interest in applying recently developed ultraviolet excimer lasers to this problem has stimulated the present reexamination of optical pulse-compression techniques. In a sense, all lasers suggested for application to laser fusion are compressors that convert a large pump source at low energy density to a very intense pulse on a small target; however, most of these lasers achieve a large part of the required intensity gain by storing energy in excited states during a long excitation pulse and then releasing it to a short optical pulse some time later.

The new excimer lasers, such as the 248-nm KrF laser, cannot be operated in an energy-storage mode since they have high gain and short excited-state lifetimes (≤ 10 ns); efficient operation of these lasers is possible only if energy is extracted during the entire duration of the pump pulse. The design of a pulser that can drive a large laser in a time much less than about 100 ns presents formidable difficulties; in addition, nonsaturable photoabsorption losses within the KrF laser medium limit the output intensity of the laser, for efficient operation, to the range of 10 to 20 MW/cm². Similar limitations exist for the other rare-gas-halide excimer lasers. Thus, even if short excitation pulses could be readily generated, the KrF amplifier output fluence would be only a fraction of a joule per square centimeter. Consequently, application of a nonstorage laser such as KrF to the generation of 5- to 20-ns pulses requires an efficient method for converting KrF pulses, which are longer than 100 ns, to the shorter pulses desired. In addition, some optical means of intensifying the KrF laser radiation is usually required (especially at shorter pump-pulse lengths) to operate at laser output fluences close to damage limits, where optical area and cost are minimized. The potential advantages of an optical pulse compressor are considerable, since present projections of the efficiency of large KrF lasers lie in the range of 5 to 10%, and several other rare-gas-halide or metal-halide excimer lasers may offer similar high efficiencies. These lasers are the most efficient

gas-phase lasers known at wavelengths shorter than the efficient molecular infrared transitions of CO_2 , CO, and HF.

One pulse compression approach uses energy extracted from an efficient KrF laser amplifier, which is pumped for 100 ns or longer, to pump an energy-storing laser medium, such as atomic iodine or other media. A second conceptual approach, illustrated in Fig. 1, is to extract energy from a KrF amplifier using a sequence of short (~ 10 ns) pulses propagating through the amplifier at slightly different angles and different times with respect to each other. These angle-coded time-sequenced pulses could then be applied to the target simultaneously (i.e., pulse stacked)¹ by adjusting the propagation time to the target for each pulse. Yet a third technique for effectively compressing a long (≥ 100 ns) output pulse of an excimer laser is that of backward-wave Raman scattering, which has been recently suggested and subsequently validated scientifically by Murray, et al.² Figure 2 illustrates the principle involved in optical pulse compression using a backward Raman amplifier. A long laser pulse of duration τ_p , called the pump pulse, propagates from right to left into a cell containing a Raman active medium (interaction zone), producing gain at a frequency $\nu_p - \nu_r = \nu_s$. Here, ν_p is the pump frequency, ν_r is the frequency of the Raman transition excited, and ν_s is called the first Stokes frequency. A Stokes pulse at ν_s is injected into the cell at the time when the leading edge of the pump pulse just starts to exit the end of the cell. As the Stokes pulse propagates from left to right, and the pump pulse propagates from right to left, the Stokes pulse is amplified at the expense of the pump pulse. After a time $\tau_p/2$, the Stokes pulse emerges from the cell as an amplified pulse traveling in a backward direction with respect to the pump pulse. The Stokes pulse can be much shorter in time than the pump pulse, as shown in Fig. 2, so the result is to compress a long laser pulse at ν_p to a short pulse at ν_s . There is a net loss of energy since $\nu_s < \nu_p$; also, part of the pump radiation may not be converted and, if not, will pass out through the exit window of the cell. The backward Raman amplifier can also be considered as an energy-storage laser, but one in which the energy is stored in an intense collimated pump beam of photons rather than in excited atoms or molecules. Gain and saturation can then be discussed in terms very similar to those used to describe more conventional energy-storage amplifiers. In recent studies, the two techniques of pulse stacking and Raman pulse compression have been combined (Fig. 3) in an effort to realize efficient, scalable laser systems

Fig. 1. pulse stacking for power multiplication.

Fig. 2. Pulse compression by backward Raman scattering.

Fig. 3. Combined pulse stacking and Raman compression.

with high overall compression factors that would minimize the physical and technological limitations of using each technique separately.

This report presents the results of a conceptual design study of a short-wavelength, repetitively pulsed laser system for use in civilian power-generation applications. The hybrid pulse-stacker/Raman-compressor architecture was chosen to compress a long (400 to 900 ns) KrF laser pulse to the 20-ns. timescale required to drive a fusion target. The technical material presented in Refs. 1 and 2 was assumed as the point of departure for the conceptual design study.

The objective of the study was to identify and examine the key technical issues for short-wavelength fusion-laser technology and to point out places where significant innovation or development is needed to reduce costs and technical risks. The approach was to perform a conceptual design of a KrF fusion-laser system suitable for an experimental test facility (ETF), the first repetitively pulsed fusion driver. We chose design goals that are representative of such a near-term facility: output energy of 1.5 MJ, repetition rate (rep-rate) of 2 Hz, pulse length of 20 ns, efficiency of 5%, and lifetime of 10^7 shots. Choosing an ETF system allowed us to use near-term technology to form relatively concrete technology and cost assessments. Because of funding limitations (\$40K/contractor x 3 contractors = \$120K for the total effort), the scope of the study was restricted to an engineering assessment of a specific point design that appeared at the outset of the study to fulfill the design goals. Alternatives to the point design and further optimizations were only briefly considered. The results of the study clearly indicate that further innovation and optimization of this laser-system concept are essential to make it compelling in the context of civilian commercial-power applications.

This conceptual design is the collaborative effort of Bechtel National, Inc., who did system integration, mechanical design, building, layout, and total laser-system costing; Physics International, who did power conditioning and its costing; Hughes Aircraft Co., who did optical and alignment systems and their costing; and Lawrence Livermore National Laboratory, who provided the KrF-amplifier and Raman-compressor performance parameters, the ETF design goals, and overall direction. The report consists of two major elements: Section II presents an overview of the design study and discusses the major results and conclusions derived from this study; and Section III provides details of the technical analyses and results and presents technical summaries

that discuss e-beam pulsed-power conditioning, optical-system design, mechanical-systems design, facilities, overall laser-system efficiency, and capital costs.

II. Overview of Laser-System Design

1. Laser-System Architecture and Building Configuration

The architecture of the hybrid laser system is shown in Fig. 4. We divide the laser into two subsystems: the pulse stacker and the Raman compressor. A KrF preamplifier and amplifier, operating at 248 nm, prepares 100-ns pulses that are fed into 14 beam lines, each 120 m long, that extend radially outward from a central hub building. The KrF amplifiers and pulse-forming lines are located at the ends of the beam lines in a perimeter building. The laser pulses make three round trips in the beam tubes. In an input delay line, they first reflect off of staggered mirrors to produce a 400-ns train of four 100-ns pulses. These pulses are then double-passed through the KrF amplifier, which is in turn pumped for 400 ns by high-energy e-beams. On the final pass, the amplified pulses are incoherently recombined into a side-by-side array of 100-ns pulses. The 14 arrays of 2×2 pulses, totaling 1.9 MJ, are then simultaneously directed from the hub building through the Raman compressor cell, which contains methane. In the meantime, a Stokes pulse has been prepared that is 20 ns in duration and has a wavelength of 268 nm. This Stokes pulse is counterpropagated through the Raman cell and is amplified to the 1.5-MJ level. This final fivefold pulse compression is accomplished in the Raman cell with 80% conversion efficiency.

A detailed view of the building layout is provided in Fig. 5. The perimeter building contains the KrF amplifiers, Marx banks, associated power supplies, gas cooling and circulation equipment, and energy stores for the guide magnets that are required for the uniform deposition of e-beam energy in the KrF medium. The hub building contains the primary and tertiary mirrors for all 14 amplifier channels and is the point where the laser pulses are reassembled and pointed at the Raman compressor cells. The flow loops for circulating and cooling the methane gas are shown. Brewster-angle windows of fused silica are used in the Raman cells. The entire Raman tunnel is 180 m long, to allow for synchronous double-passing of both the 100-ns KrF pump beams and the 20-ns Stokes beam within each Raman cell.

Fig. 4. Architecture of one-half of the hybrid KrF pulse-stacker/Raman compressor laser design.

Fig. 5. Schematic layout of the perimeter building that houses the KrF amplifiers and Marx banks; the hub building, with its large mirror arrays; and the flow loops that circulate methane through the Raman cells.

2. KrF Amplifier Performance Characteristics

The nominal performance specifications for the final KrF amplifiers are given in Table 1. These specifications were used during the study, although subsequent calculations are somewhat less optimistic. The output energy of 160 μ J per $2 \times 2 \times 3$ m amplifier does not include assumed mirror losses (5% each), window losses (2% per surface) or fill factors (90%), which were separately accounted for. The final amplifier has a nominal energy gain of 20. Each amplifier is equipped with rectangular magnetic-field coils, each 5×3.3 m in size and separated by 5 m, that provide a 1-kG field in the active medium. This Helmholtz coil system gives 20% field uniformity and leads to 90% deposition efficiency. It requires 0.65 MJ of stored energy per pulse, transferred resonantly from a 10-kV capacitor bank. The 15% energy loss estimated per shot leads to a power requirement of 2.8 MW for all 14 amplifiers. In addition, 5.6 MW of power are required for the gas circulation and cooling systems, which flow the gas at 8 m/s.

3. Raman Compressor Performance Characteristics

In Table 2, we give the nominal performance parameters for the CH_4 Raman compressor, which must accommodate all 14 beam arrays. A length of 15 m of Raman scattering medium is required to efficiently deplete the 100-ns KrF pulse. Because of the high quantum efficiency of the Raman scattering in methane (93%), there is little heat deposited, and only a slow flow of methane gas is required. The 1-atm cell pressure and the absence of large overpressures allow the use of a large expanse of fused-silica window panes, which are arranged in 2×7 arrays.

4. E-Beam Pulsed Power

For the e-beams and power conditioning, we examined both pulse-forming networks (PFN) and pulse-forming lines (PFL) in the range from 100-ns to 1- μ s pulse durations. For the 400-ns duration that was chosen, the PFL is preferable despite the fact that the energy must be stored twice (once in the Marx generator and again in the liquid pulse-forming line) and in spite of the requirement for a high-voltage output switch. At this pump-pulse duration, the

Table 1. Nominal performance specifications for each KrF final amplifier.

Aperture	2 x 2 m
Length	3 m
Output fluence	4 J/cm ²
Intrinsic efficiency	10%
Pump time	400 ns
E-beam energy	1.3 MeV
Amplifier output energy	160 kJ
Stacker compression factor	4x
Stacker output pulse time	100 ns
Ar/Kr/F ₂ mixture	0.937/0.060/0.003 atm

Table 2. Nominal performance specifications for Raman compressor using methane.

Stokes pulse length	20 ns
Extraction efficiency	80%
Compression factor	7
Pump pulse length	100 ns
(Cell length)	(15 m)
Cell pressure	1 atm
Stokes output fluence	4 J/cm ²
KrF pump fluence	5 J/cm ²
Output energy	1.5 MJ
KrF pump energy	1.9 MJ
Output aperture (2 x 7 beam array)	3.3 x 11.6 m

PFN is less attractive because the number of parallel elements required to keep the inductance sufficiently low in a PFN increases with the inverse square of the pulse duration. As the number of Marx units increases, the inductance of connections rises with sufficient rapidity that no practical solution appears feasible at the 400-ns pulse length.

In the KrF laser system, there are 28 e-beams and PFLs, each of which is called a "side," since each KrF amplifier is pumped from two sides. In each PFL, the energy is first stored in eight oil-immersed Marx generators that then charge eight water-dielectric pulse-forming lines on a 2- μ s timescale. Each output line (OL) bifurcates, driving two diodes; therefore, each e-beam aperture, measuring 3 x 2 m, consists of 16 modular diodes. Each side stores 1.3 MJ (for a total of 36 MJ stored energy per pulse) in 1.28- μ F, 50-kV capacitors. The energy losses are given in Fig. 6, which also shows the relative sizes of components. The overall electrical system efficiency is 57%.

The system is designed to operate for 10^7 shots with only routine maintenance, and the capacitor voltages are derated by a factor of two to attain this lifetime. The Marx switches will erode about 100 μ g per switch in 10^7 shots at an erosion rate of 50 μ g/C; changing the gas pressure during the lifetime can compensate for widening of the gap.

The output switch for each PFL is gas insulated and command triggered, and it operates through six breakdown channels, each of which carries 53 kA. This switch is currently being developed.

A 900-ns PFN was also designed and costed for a 9-pulse stacker option, should the longer-pulse-length electrical system prove to be substantially less expensive. Unfortunately, we were not able to separately optimize the KrF amplifier design and architecture for each pulse length. However, the cost per joule stored was practically identical for each design considered, leading to a selection of the 400-ns, four-pulse stacker on the basis of a less costly optical system.

5. Optical System Design

The configuration of the optical system is the key to the pulse-compression scheme. To take advantage of the long-pulse-length KrF laser, we feed the final amplifier with an optical delay line that temporally stacks a sequence of N short pulses of length τ through the amplifier at slightly different angles. By slightly overfilling the amplifier with each pulse, we can extract

Fig. 6. Configuration and efficiency summary of a 400-ns pulse-forming line.

the energy over the entire volume for a pulse length of $N\tau$, which allows efficient pumping of the amplifier by long-pulse electron beams. Angular multiplexing of the short pulses allows them to be separated spatially at the output of the amplifier, where their relative delays are removed in a second optical-delay line. The pulses are reassembled into a spatial matrix rather than being superposed, since the latter would require very careful control of the interbeam coherence. The general architecture of this pulse stacker is shown in the perspective view of Fig. 7.

Further pulse compression, beam cleanup, and prepulse isolation are accomplished by using the KrF laser as a pump for a double-pass backward Raman scattering cell filled with methane. This cell converts the 248-nm, 100-ns, 1.9-MJ KrF pump pulse of moderate wavefront quality to a 268-nm, 20-ns, 1.5-MJ Raman-shifted pulse with a smooth wavefront that has negligible prepulse energy.

Effective prepulse isolation is accomplished because there can be very little energy directed toward the pellet in the absence of an input (at the Stokes frequency) that propagates counter to the KrF pump beam in the Raman cell. The Raman input to the cell requires only 1.5 kJ to generate the 1.5-MJ output, and this input in turn is produced in a front end that requires an input of only 1.6 J. This millionfold gain accounts for the effective prepulse isolation control of the Raman cell. The high quality of the output wavefront is essentially independent of the quality of the pump wavefront.

Several design options were considered; e.g., the 4-pulse vs a 9-pulse stacker, different types of mirror substrate, several alignment schemes, solid vs aerodynamic windows (aero windows), and different beam-path gases. The chosen baseline design is a compact four-beam stacker that minimizes the complexity of the mirror mounts and alignment system and that fits in a beam tube with a cross section of only 2.1 x 6.2 m.

An image-alignment system was selected that uses laser diodes mounted on each mirror array as point sources of light. Consider three sequential mirrors in the optical train (M_1 , M_2 , and M_3). The light sources are mounted on the edges of mirror M_1 , and a precision video camera, or CCD, is mounted on M_3 . The mirror M_2 is aligned by looking at the reflected image in M_2 of the point sources located on the mirror M_1 . The video camera on M_3 is used to compare the image with a reference perfect-alignment image, and an error signal is generated; a servomechanism drives the mirror mount until the actual and the reference images agree. The entire optical train is aligned by

Fig. 7. Configuration of the optical train for a KrF pulse stacker.

sequentially continuing this process down the train. All four mirrors of each array are prealigned and fixed relative to each other, so the entire mount is aligned in one operation. The sensitivity and signal-to-noise ratios of this system are adequate with commercially available components.

The mirrors that were chosen are dielectric coated, have aluminum substrates, and are water-cooled. The nominal fluence limits imposed on the mirrors were 5 J/cm^2 at 248 nm and 100 ns, and 4 J/cm^2 for the Stokes pulse at 268 nm and 20 ns; however, the final design has 5.9 J/cm^2 on one of the KrF stacker mirrors. The 10^7 shot lifetime required for multilayer dielectric reflectors at this fluence is orders of magnitude beyond the current state of the art. At 248 nm and 20 ns, the best commercial coatings have survived 10^2 shots at 2 J/cm^2 and single shots at 10 J/cm^2 . Clearly, this is an area requiring technology development.

The KrF amplifier windows are constructed of panes of fused silica, each with a convex curvature to withstand the transient pressure differences; the thickness of each pane is limited to 10 cm by the temperature profile across the thickness. We also investigated aero windows of argon gas as an alternative that might eliminate the need for high-fluence solid windows; however, the gas used for a flowing curtain cannot contain fluorine because of the large absorption coefficient of the latter gas. Our calculations showed that flowing curtains of pure argon in contact with the laser gas resulted in such high mixing rates that the costs of recovering fluorine would be unacceptable. However, it may be possible to design more complex flowing-curtain configurations that could satisfy technical requirements in a cost-effective manner. Because of the large costs associated with solid windows, further studies on gas-curtain windows are warranted.

6. Key Technology Development Issues

Perhaps the most important result of the study is the identification of areas requiring significant or early technological development. The following is an abbreviated list of the most important technology development issues identified in this study.

- o Development of an output switch for a pulse-forming line that would have a shot life of $>10^7$ shots under operating conditions of 2.7 MV, 0.3 TW, and 2 Hz.

- o Development of effective modularized diodes and control of insulator breakdown.
- o Definition by experimental methods of minimum magnetic-guide field requirements.
- o Development of dielectric coatings for both mirrors and windows that, operating in the ultraviolet wavelengths, would be capable of withstanding 10^7 shots in the 4 to 6 J/cm² range.
- o Development of credible designs for fused-silica windows capable of surviving e-beam and pressure loadings, or development of aero windows with appropriate control over mass flow and composition.
- o Determination of the need for helium in beam tubes vs adequacy of dry nitrogen or air.
- o Definition of required optical homogeneity of KrF amplifier medium and beam-conditioning gas and of minimum alignment tolerances required to adequately fill the Raman cell.
- o Definition of shielding requirements for both x rays and noise.
- o Determination of the effects of employing long-pump-pulse technology by varying amplifier sizing and stacker configuration to optimize around less-expensive PFN technology.

The cost of the development time and effort represented in the above list is significant, but the technology is still young; it is highly probable that important innovations lie ahead that can greatly reduce the technological risk, the required development time, and the eventual capital cost.

7. Summary of Laser-System Cost and Efficiency

In conclusion, we observe that the overall efficiency of the laser system (3%) was somewhat less than anticipated. An accounting of the primary energy losses is given in Table 3. It is possible that the e-beam deposition efficiency could be raised (from 57% to, perhaps, 65%), but it is difficult to see where any great improvements could be made. The losses due to amplifier fill factors are already optimistic. However, the losses associated with windows and mirrors can be improved, in principle, if efficient, high-damage-limit dielectric coatings can be developed. The intrinsic efficiency of KrF at

Table 3. Laser-system output and efficiency
(400-ns pulsed power).

Laser electrical efficiency

Source	Efficiency	Power (MW)
Wall-plug input	100%	78.6
E-beam deposition	57%	44.8
Intrinsic KrF medium	10%	4.48
Windows and fill factors	90%	4.03
Mirrors	82%	3.28
Raman conversion	80%	2.63
<hr/>		
Total laser output	3.3%	2.63 MW
	(1.3 MJ/shot)	
Ancillary equipment losses		
E-beam wall plug	78.6 MW	
gas-flow blowers	5.6 MW	
Magnetic guide fields	2.8 MW	
Cooling water pumps	0.7 MW	
<hr/>		
Total system input power	87.7 MW	
Overall system efficiency	$\frac{2.63 \text{ MW}}{87.7 \text{ MW}} = 3.0\%$	

400 ns probably cannot be bettered, and may be somewhat lower. The steady-state power losses due to gas and water circulation and cooling and to magnetic field establishment are 10% effects. Finally, although a pure stacker might save the 80% efficiency factor allocated to Raman conversion, we do not know if the reduced beam quality and prepulse isolation implied by a pure stacker would provide acceptable target performance.

The costs are summarized in Table 4. They correspond to \$2.67/stored joule, which is consistent with previous estimates. It is interesting to note that the costs of the three major subsystems (optical, electrical, and building/mechanical) have total costs that are within 10% of one another, thus implying that there is no single area that could have significant leverage in reducing costs. We must seek to reduce costs by finding improvements in all areas--or seek a major innovation in the conceptual architecture.

Finally, we mention an inconsistency in the design philosophy that should be remedied in future work. We intended the laser system for use in an ETF, for which a lifetime of 10^7 shots is adequate. However, there is a tradeoff between economy and efficiency that received little attention. The cost per unit of output energy is probably the best figure of merit for an ETF system, but we did not have the time or funds to explore some alternatives that might reduce this cost (\$250/J output in a 20-ns pulse in the ultraviolet). For example, welded-steel beamlines are probably not needed if nitrogen could be used instead of helium, separate delay mirrors for the input and output stackers are probably redundant, and facilities savings may be possible by including separate Raman cells in each beamline. In a brief, broadbrush study of this kind, we were not able to arrive at a point design of a recommended laser system. Instead, the greatest benefit of the study lies in both the technology issues identified and the alternative solutions proposed to attain a truly attractive short-wavelength laser driver.

Table 4. Stacker-compressor laser system costs
(400-ns pulsed power).

E-beam generator systems	98.7 M\$
Optical systems	95.9 M\$
Buildings and ancillary equipment	87.2 M\$
Front end (14% of above)	39.4 M\$

Total field	321 M\$
Home office	30 M\$

Total	351 M\$
Contingency (25%)	88 M\$

Construction cost (4th qtr 1979)	439 M\$
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III. Technical Summary: Appendices

Appendix 1. E-Beams and Pulsed-Power Conditioning

J. Benford, Y. G. Chen, D. Dakin, G. Frazier,
T. Naff, and T. S. T. Young

Physics International Company

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Appendix 1. E-Beams and Pulsed-Power Conditioning

1.1 Pulsed-Power Options

The KrF amplifiers are driven from two sides by electron beams (e-beams) which deposit their energy in the gas. This section describes the e-beam apparatus, including the diodes that generate the beams and the magnetic-field system that controls them.

The pulse duration chosen for the KrF amplifiers is an especially important parameter for the pulsed power system. In the range of a few hundred nanoseconds to $1\ \mu\text{s}$, both the lumped-component pulse-forming network (PFN) and the distributed-component pulse-forming line (PFL) systems must be considered (Fig. 1.1-1). The KrF driver requirements are near the upper bound of the PFL for practical length considerations and near the lower bound of the PFN because of the many elements that are required in parallel to give the currents within the short pulse duration. Circuits intermediate between the two are also possible but are not considered here, since they are not as well developed technically. For pulse durations less than $0.5\ \mu\text{s}$, the PFL approach is probably preferable despite the fact that PFLs require the energy to be stored twice, once in the Marx generator and again in the liquid pulse-forming line, and in spite of the requirement for an output switch that must pass all the energy in the system at high voltage.

PFNs obviate the second pulse-charged energy store and have no output switch because the Marx is an element of the network. The PFN approach is made increasingly difficult as the pulse duration is shortened. The number of elements in parallel required to keep the total system inductance low enough to supply the short pulse duration increases inversely with the square of the pulse duration. As the number of separate Marxes increases, the inductance of connections between them takes up a larger proportion of the allowed total; thus, for very short pulse durations, no solution is possible. Preliminary designs for an e-beam driver at 400 ns indicated that no PFN system could be built practically.

From the above considerations, it was decided that two systems would be designed: a PFL system to produce a 400-ns pulse for the amplifier, and a

Fig. 1.1-1. Basic elements of the two pulsed-power systems considered.

900-ns PFN system. Thus, each of the two system types would be operating in a pulse-duration regime appropriate to their best application. In the next section, we discuss both of these systems.

1.2 System Designs

1.2.1 Pulse-Forming Line System

The geometry of the pulse-forming line system is shown in Fig. 1.2-1. The energy is first stored in eight oil-immersed Marx generators, which, upon erection, charge eight water-dielectric pulse-forming lines on a time scale of about 2 μ s. The coaxial pulse-forming lines are in a 2 x 4 array. Each is discharged into an output line through an independent gas switch. The power then converges in two dimensions into eight circular tubes, which feed 16 separate diodes. The losses in this sequence of events are shown in Fig. 1.2-2. The major losses are in charging the pulse-forming line from the Marx and in passing the beam from the diode into the gas. In the first process, the losses are primarily in resistance of the capacitors and the water dielectric; thus, the losses ultimately reside in circulating fluids. Similarly, the energy lost in switching the pulse-forming line to the output line resides in the gas flowing through the switch. The other major loss is to the hibachi and foil and the sidescatter and backscatter of electrons once they enter the gas chamber. The overall system efficiency is calculated to be 57%; therefore, each Marx must store 1.3 MJ. Marx specifications are shown in Table 1.2-1. The basic storage capacitor is 1.28 μ F, 50 kV.

The system is designed to operate for 10^7 shots with only routine maintenance required in this interval. The capacitors in the Marx are derated by a factor of 2 in voltage (4 in volume). Present-day high-stress capacitors just coming on the market have a life of about 2×10^5 shots. Lifetime is proportional to V^6 in this regime; therefore, derating by 2 gives a 2^6 times $2 \times 10^5 = 1.3 \times 10^7$ shot lifetime. The Marx switches will erode about 100 g per switch in 10^7 shots at an erosion rate of 50 μ g/C. This results in some widening of the gap (~ 1 cm), which will be compensated for by changing the gap pressure during the lifetime of the system. The debris will be carried away by flowing the dielectric gas.

An alternative to Marx charging of the PFL is the double resonance transformer technique, whereby a low-voltage capacitor bank charges the

Fig. 1.2-1. PFL module configuration.

Fig. 1.2-2. PFL system efficiencies.

Table 1.2-1. Marx generators for PFL driver.

	<u>Single Marx</u>	<u>Module</u>	<u>Full system</u>
No. of Marx	1	8	224
Erected capacitance	38.9 nF	310 nF	8.7 mF
Stored charge	0.12 C	0.93 C	26.1 C
Stored energy	160 kJ	1.3 MJ	36 MJ
Peak discharge current	84 kA	675 kA	18.9 MA
Charge transfer per switch	~0.2 C	same	same
Series inductance	21.8 μ H	2.73 μ H	NA
No. of stages	28	224	6,272
No. of capacitors	112	896	25,088

pulse-forming line through a transformer. This system has the advantage of being inherently repetitive and eliminating the special connections and systems of the Marx technique. In the United States, Sandia Laboratories has developed this technology to the range of ~ 1 MV output voltage at 0.5 kJ with high efficiency. Comparable values have been achieved in the Soviet Union. In both cases, the charge time of the PFL is 5 to 20 μ s. For KrF, one needs 2.7 MV, 10 to 100 kJ with high efficiency. Using present technology, about 1000 transformers would be needed. The use of larger transformers in smaller numbers would require a longer charge time due to the rather stringent inductance/insulation requirements. This is impractical for water dielectric, because the resistive losses in the water would soon make the system inefficient. Therefore, extensive development would be needed to use this technique for KrF. Consequently, we have projected the use of Marx-charged PFL for this design study.

The diameter of the water-dielectric pulse-forming line is chosen on the basis of the statistics of water breakdown. (Water breakdown is area-dependent since it is a statistical phenomenon.) We designed for a 90% confidence of having no more than one breakdown in 10^7 shots for each line. From the data of Sojka,¹ this requirement translates to a safety factor of $1.62 = F_{\text{break}}/F$, where F_{break} is the Lupton² breakdown field and F is the operating field at peak voltage of the line. This criterion gives a field of approximately 75 kV/cm. The working field in this design was taken to be 60 kV/cm to allow an additional safety factor for unknown effects associated with operation with multiple pulses. With 10% additional time for the rise and fall of the pulse, the double-transit time of the PFL was made 440 ns (Fig. 1.2-3).

The output switch for each PFL is gas insulated and command triggered. Each switch operates through six breakdown channels carrying 53 kA each. This switch can either be one large switch or three to four multistage columns.³ Losses in the switch are about 2 kJ per pulse.

From the output water line, the power converges into eight circular tubes; each tube feeds two diodes. The diodes are arranged in a 2×8 array. The cross-section to each tube (Fig. 1.2-4) is dictated by the 2- x 3-m laser interface and is, therefore, 100 x 75 cm. We have taken as an operating criterion that the vacuum insulator should flash no more than 1 shot in 10^6 . Assuming that three out of the many series insulator sections must fail before overvoltage makes it probable that the remainder fail, one

Fig. 1.2-3. Pulse-forming line components.

Fig. 1.2-4. PFL tube and diode conceptual design.

insulator can be allowed to fail on average in every 100 shots. From this requirement, it becomes clear that a radial insulator configuration is not possible and that, in fact, the insulator must be a tapered stacked insulator. This approach is more expensive than the normal insulator geometry.

The cathode surface in vacuum is prevented from emitting to the walls by both the self-field and the externally applied field. Therefore, the entire tube is magnetically insulated. In the vacuum, the cathode splits (Fig. 1.2-4) into two lines; these rectangular lines carry the energy into the diode region. The length of the separate lines is chosen to ensure even flow of the electromagnetic energy.

The fields in water on the outside of the gradient rings are a concern, since they probably exceed 200 kV/cm. They might be buried in the plastic or, alternatively, a plastic shroud may be fitted over the whole tube and filled with water or weak electrolyte, eliminating the enhancement of the radial field. This liquid could also be used to grade the stack.

1.2.3 Pulse-Forming Network System

For the longer pulse duration of 900 ns, a system employing a type-C pulse-forming network has been designed. It consists of six independent Marx generator modules, each composed of three parallel-connected Marxes. An oil transmission line connects each Marx/PFN to a tube (there are six tubes), and the overall energy transfer efficiency of this system is about 60%.

We have chosen a type-C network with branches formed of Marx generators. A two-section network is employed; it includes the fundamental and third harmonic of the main pulse. The number of branches necessary is determined by the required quality of the output pulse; we have specified a $\pm 10\%$ uniformity flatness during the pulse, with a rise of 10% of the pulse duration and a fall of 20% of pulse duration. Use of an extra section of the network would give 5% uniformity but was not considered to be a cost-effective approach. Two primary Marxes (~90 kJ each) are used for the fundamental frequency, and one smaller Marx (~60 kJ) is used for the harmonic. The PFN module configuration is shown in Fig. 1.2-5, and two Marx modules are shown in Fig. 1.2-6. The Marx layout is a slight extrapolation of contemporary designs. In the entire system, the number of switches is 14,000 and the number of capacitors is approximately 56,000 (50 nF, 50 kV). Both switches and capacitors are derated in the same manner as for the PFL system.

Fig. 1.2-5. PFN module configuration.

Fig. 1.2-6. Arrangement of two Marx modules for PFN system.

The energy-transfer efficiency is determined by losses in transferring energy to the Marx (95% efficient), from Marx to tube (87%), and hibachi and gas-scattering losses (80%). In addition, the slow rise and fall of the waveform result in 85% efficiency due to short deposition in the gas by low-voltage electrons.

All the PFNs feeding one side of a laser module hang in one oil tank, parallel electrically and physically. Current-carrying ground conductors must pass between them to make low-inductance connections to the individual oil lines which connect to the tubes. The six oil lines converge onto six tubes very similar in design to the PFL tube described above (Fig. 1.2-7). One difference is that only 6 diodes are used instead of the 16 in the PFL case. Fewer diodes are used with PFNs because the pinching of the beam in the diodes is much less of a problem due to the lower current in each diode. As can be seen from the layout drawing, this configuration requires less volume and is in some ways simpler than the PFL system.

1.2.3 Diode and Magnetic Field Coils

1.2.3.1 General Diode Parameters

The emphasis of Physics International in this study contract was on the pulsed-power driver system. We determined magnetic field requirements and matched diode and pulsed power modules. It is clear that the diode itself must be modularized to eliminate beam pinching. Magnetic fields can be used to reduce beam pinching and to provide for efficient energy deposition in the gas. Experimental data⁴ at Lawrence Livermore National Laboratory (LLNL) indicate that modularization alone can reduce electron beam angles. Analyses⁴ were conducted at LLNL that scaled beam electron angles with the lateral dimensions of the beam and the anode-cathode spacing. The adequacy of diode modularization alone (no external magnetic fields) for the present beam parameters is doubtful for two reasons. First, in the study it was agreed to assume as a goal 90% beam transmission through the hibachi. It should be noted that present experimental values for hibachi transmission with magnetic fields are between 65 and 80%. This high transmission requires very low electron angles ($\leq 10^\circ$), which are difficult to achieve without external fields. Secondly, reduction of pinching by use of the radial electric fields caused by bringing the anode walls of the diode segments close to the cathode invariably

Fig. 1.2-7. PFN tube and conceptual design.

causes emission from the sides of the cathode. Magnetically insulated flow parameters scale differently with voltage, spacing, and current than for the Child Langmuir diode. Thus, for the present beam parameters, experiments are needed to verify the required efficient transmission through the hibachi with diode modularization alone. In this conceptual design, we therefore use external magnetic fields as well as diode modularization.

It is important to minimize the magnitude of the external magnetic field in order to reduce the energy in the fields and maintain high overall system efficiency. The strength of the magnetic field is determined by constraints on efficient energy deposition in the gas as well as by beam electron angles in the diode.

Magnetic field requirements, diode modularization, and beam deposition are to a large degree independent of details of the diode design. Specifics, such as the type of cathode surface, design of the hibachi structure, foil materials, and cooling, are more appropriate for a point design effort and were not considered in detail in this conceptual study. Some comments, however, might be made. Data on long-life field emission cathodes are minimal. However, both the uniformity and the lifetime of surfaces such as blades, carbon felt, plasma surface flashover, etched metals, and other cathode materials are under active investigation in the community. It is probable that reliable field emission cathode materials will be found with lifetimes in excess of 10^6 shots; these materials might be appropriate for near-term requirements. Two other diode alternatives exist. The first is the plasma-filled diode also under investigation for several applications. At the low repetition rates required for ICF, recovery time in these diodes should not be a limiting factor. The major parameter is the present limit on current density of $\sim 10 \text{ A/cm}^2$. The second is the use of thermionic cathodes. The current densities required ($\sim 30 \text{ A/cm}^2$) have been achieved experimentally. LLNL⁴ has suggested the possibility of grid electrodes in the diode to use the thermionic diode itself as the main output switch, but this possibility was not evaluated further in the conceptual study. One problem was identified for this approach, i.e., the insulator. Designs for low probability of insulator breakdown at pulse lengths of $\geq 1 \mu\text{s}$ are difficult with the limited space available, given the array of modular diodes.

1.2.3.2 Beam Deposition

It has been shown from three-dimensional SANDYL code calculations that, without an external magnetic field, greater than 30% of the beam energy is scattered laterally out of the laser volume for the beam and laser parameters we are considering. With an external magnetic field, the beam loses energy laterally by diffusion. The beam energy-deposition profile transverse to the beam direction and outside the projected area of the beam is then approximately gaussian

$$\exp\left[-x^2/4r_L\right], \text{ with } r_L = 10^3 (\gamma^2 - 1)^{1/2}/|B|.$$

The strength of the magnetic field is then chosen so that the total area in the gaussian wings is less than 10% of the defined laser area (200 x 300 cm). For 1 atm, the required magnetic field is 0.65 kG for 1-MV and 0.9 kG for 1.5-MV electrons. A 1-kG field was then selected to achieve the required 90% energy deposition, as defined at the onset of the study. It should also be noted that, when an external magnetic field is used to constrain the scattering of the beam, energy deposition along the beam can be calculated using one-dimensional Monte Carlo codes. For 1 atm and the given gas mixture, more than 95% of the beam energy is deposited in 200 cm at 1.3 MV. To provide maximum deposition uniformity along the beam, one would also increase the anode foil thickness to scatter the beam and thus increase deposition near the anode; this can be done with negligible energy loss in the foil.

The effect of sidescattered beam electrons on the location of the optical mirrors at the ends of the laser cavity was also addressed in this study. To assess beam-energy deposition in the mirror, one needs both the incident flux (J/cm^2) and voltage of the beam electrons. For those calculations, we chose the position of maximum energy deposition in the beam direction, which occurs approximately 60 cm from the anode. For a 1.3-MV beam, the main electron voltage at this location is ~0.9 MV for one beam and ~0.6 MV for the counterstreaming beam. Since the lateral scattering is a diffusive process, we assume an isotropic velocity distribution of beam electrons incident on the mirror. Assuming a fused-silica substrate with either MgF_2 or Al_2O_3 coating, one can obtain the beam energy deposited in the mirror and compute a temperature rise. With the mirror located 10 to 15 cm from the edge of the beam (as defined at the anode), the temperature rise is only a few degrees.

Thus, with mirror separations of 20 cm or greater from the edge of the beam, it is very unlikely that any damage to the coatings or mirror substrates will occur due to beam electrons.

1.2.3.3 Magnetic Field Coils

The axial magnetic field along the beam direction is produced by a pair of field coils in a Helmholtz geometry. The coils are rectangular (5 x 3.33 m) and are separated by 5 m. This geometry produces a 20% field uniformity in the lasing volume. The cross-section of the coils is 10 x 10 cm and consists of 5 turns. For 1 kG in the center of the laser volume, each coil stores 0.33 MJ of magnetic energy. This energy is transferred resonantly from a capacitor bank at 10 kV. Should 10% uniformity be required over the laser volume, the coil dimensions become 4 x 7 m and are spaced 4 m apart. The corresponding energy in the field for 1 kG in the center of the laser volume is 0.85 MJ/kg^2 for each coil. Since the field energy for these coils is increased by ~ 2.5 , the power-supply energy, power dissipation, and drop in system efficiency would scale by this factor.

The operating sequence has the bank firing about 2 ms before the e-beam system, so that the peak current in the coils is reached when the beams are injected. The full period of the oscillation is 8 ms, at which time the energy has been returned minus small losses to the capacitor bank. At this time, interrupt switches are fired; the switches break the circuit until the next operating cycle. The interrupt switches are either vacuum-arc or liquid-metal plasma valves. The vacuum arc at present can interrupt a few kiloamps at 25 kV and turn on and off in a microsecond; they have been shown to last for 10^8 shots. For this application, vacuum-arc switches must be increased in current, or several must be used in parallel. Present switches handle a few kA; the coils require 75 kA peak.

The power system driving the field coil will dissipate approximately 4 MW during operations, causing a resistive energy loss of about 32 kJ. Total losses in the system are estimated at about 15% of 0.33 MJ per coil. These losses introduce an additional drop in system efficiency of approximately 4%.

1.2.3.4 Diode Modularization

The pulsed-power driver must be modularized to achieve efficiency (PFL) and feasibility (PFN). For maintenance, it may be advisable to make modules of the generator and diode match as much as possible. Therefore, constraints were determined for diode modularization and the number of diode segments selected. The pulsed-power system was then designed to match (one to one for PFN and one generator module for two diode segments, PFL). The number and size of the generator modules are not entirely unique, and some changes in the size or number of diode segments could be accommodated and still match units.

In Fig. 1.2-8, we plot the self-field (B_s) of the beam at the center of the long edge of the cathode as a function of the number of diode segments. The abscissa gives the number of modules in the horizontal (optical-axis) direction, and the two plots correspond to the number of segments along the flow direction. The total number of diode segments thus considered ranges from 4 to 24. The lateral spacing between the cathode and anode in each segment was constrained to be greater than an electron Larmor radius (in the total field) to ensure magnetic insulation. The electron angle with respect to the anode plane is then given by $\theta = \tan^{-1} \left| B_s / B_z \right|$.

This scaling of electron angle has been verified both experimentally and in diode computer codes for a range of beam, diode, and magnetic field parameters. Also shown in Fig. 1.2-8 is the self-field required to achieve $\theta = 20$ deg for a 2-kG applied field (400-ns parameters) and for 1 kG (900 ns).

We note that, even increasing the number of diode modules to 24, one cannot achieve angles less than 15° at the edge of the beam for applied fields ≤ 2 kG (400 ns). At the beginning of this conceptual study, it was agreed to define the required electron angle to be 20° ; the number of diodes selected for the 400-ns beam parameters was therefore 16. Approximately the same electron angles result for 2 kG using 6 diode segments for the 900-ns case, since the voltage and energy were held constant and total current varied inversely with pulse length. As already stated, a field of 1 kG is needed for efficient energy deposition in the gas. The magnet power supplies were designed for a 1-kG applied field. It may be possible to use 1 kG in the diode for the 400-ns parameters by making use of the radial electric fields in the diode. Calculations of electron angle as a function of the ratio of applied and self-magnetic fields, which include finite geometry effects,

Fig. 1.2-8. Constraints on diode modularization.

require diode computer codes and were outside the scope of this study. If the 1-kG applied field is inadequate for the 400-ns case, the overall system efficiency would have to be decreased either as a result of increased losses in the hibachi or increased losses in the magnetic field system. One obvious additional possibility is to use 2-kG fields and superconducting magnets, but the feasibility of superconducting coils with these dimensions was not investigated.

1.3 Cost Structure

The costs of the line and network systems were separately estimated by breaking the system into its major cost factors. These factors are capacitors, switches, insulators (to include liquid insulators, such as oil and water, and solid insulators at the vacuum interface), metal (including oil handling and store and tank mobility system), electrical equipment (including controls, triggers, diagnostics, vacuum apparatus, water circulation, and the power system for charging), tube and diode, and the magnet system. Costs were estimated from current raw-material costs, coupled with estimates of the cost of fabrication, assembly, and testing.

Breakdown of the costs is shown in Table 1.3-1. It can be seen immediately that the capacitors and the means of switching capacitive energy constitute half the cost of the system. The five remaining elements are 10% of the total hardware costs. Fabrication of these hardware items requires about 20% of the hardware costs, and assembly and test another 10%. Assembly and test of the more sophisticated PFL system would be approximately twice the cost of that for the PFN. It should be noted that these costs include spare parts: 10% of the capacitors, 10% of the switches, an oil transmission line for the network system, two spare water lines, and 10% of the vacuum insulators. The spare-part costs total \$2 million for the network and \$2.5 million for the line. Costs also include a small amount for handling and maintenance equipment.

The most striking feature of the cost estimates is their similarity. This, in part, is caused by the basic cost of the energy store, which is about half of the total. The real difference between the two systems, electrically speaking, is that the power is delivered at a level 2.5 times higher in the line system. This level is achieved by the addition of the pulse-forming line and the output switch. Although these components are high-technology items,

Table 1.3-1. KrF laser pulsed-power systems cost breakdown (M\$)
(14 amplifiers).

	<u>PFN (900 ns)</u>	<u>PFL (400 ns)</u>
Capacitors	19.6	20.6
Switches	5	5.6
Insulators	4.6	5.8
Metal	5.8	8.4
Electrical equipment	8.4	10.8
Tube and diode	4.4	4.6
Magnet system	<u>5.0</u>	<u>5.0</u>
Hardware subtotal	52.8	60.8
System fabrication	10.6	12.1
Assembly and test	<u>5.3</u>	<u>6.1</u>
Subtotal	68.7	79
G and A fee	<u>17.2</u>	<u>19.7</u>
Total	85.9	98.7
Cost per joule stored	\$ 2.65	\$ 2.72

their basic cost is not high. The pulse-forming line is simply fabricated metal; the output switch, however, is rather sophisticated. This estimate assumes that the switch has been fully developed and is mass produced at the time of fabrication. The remaining elements, the tube, diode, and magnet system, are identical in the two cases with some allowance for differences in the assembly and testing costs. The two systems differ by a total of approximately 14%, considering that constant energy store cost is about half of the total. The difference between the line and network systems is, therefore, approximately 25% of the remainder. The cost in terms of stored joules is about \$2.70. This rather low cost is due primarily to mass production, a cost-reduction factor that contemporary systems have yet to take advantage of.

1.4 Technology-Development Issues

The primary issue associated with the pulsed power for the KrF system is switching. The most difficult switch in the system is the output switch of the pulse-forming line. The switch must carry substantial current at high voltage and do this repetitively upon a command trigger. The power level required is 0.33 TW. Such a switch does not exist today. Single-shot very-high-power gas switches in the self-break mode are under development at present. One can anticipate substantial progress over the next few years. A repetitive switch at this level is not on the horizon, but there is no fundamental reason why it cannot be developed. It appears that lower-power switches would be developed for some military applications, but it is very likely that the specific switch needed for this system must be developed by the ICF program. It should be pointed out that the switching requirement is held in common among several ICF drivers, most especially the light-ion approach being advanced by Sandia Laboratories. The major issues in the repetitive operation of such switches are the erosion of the electrodes over time and the deposition of debris on the insulator surface. The former problem can probably be addressed by feeding new electrode material in as erosion occurs and the latter by vortex gas flow to carry the debris away.

The other switches in this system are less difficult to develop. The Marx switch is a higher-power version of those available today. The lifetime requirement can be met by decreasing the gas pressure as the gap erodes, as described above. Therefore, development of this switch seems a

straightforward matter. The same can be said of the closing switches in the capacitor bank. However, the vacuum-arc opening switch must be developed. It is not clear that this switch will be developed for other applications, and the ICF program may have to do this job itself.

The remaining technology issues have to do with repetitive operation of insulators and diode components. At present, knowledge of the repetitive breakdown characteristics of dielectrics is sketchy. For the system we've described to be viable, a study of repetitive breakdown of oil and water at the appropriate frequencies should be undertaken. This will determine the safety levels that can be employed in an engineering facility. Similarly, a better understanding of insulator breakdown under long-life repetitive conditions in vacuum would be required. Finally, the longtime behavior of cathode surfaces and anode foils under bombardment by electrons is not well understood. We have designed a system on the basis of experience; further experimentation will be required.

The design we have described employs direct extensions of contemporary pulsed-power technology: capacitive stores and gas closing switches. In the far term, commercial application will put a premium on improved energy density, i.e., compactness and high reliability. These rather basic considerations point toward the eventual introduction of inductive energy storage with, perhaps, rotating energy as the prime energy source. The key component in any magnetic energy-storage system is the opening switch, which must be capable of passing charging currents at minimum impedance and subsequently changing to high impedance to choke the current flow in a short timescale. The $L \, dI/dt$ voltage induced across the store inductor is used to drive the stored magnetic energy at high voltage into a parallel load circuit. The inductive-energy store offers about a 10^3 increase in stored-energy density over capacitive-storage systems, making these units much more compact.

A less-demanding technique is to use a rotating-store opening switch to pulse charge the PFL. For this scheme, switch pulse compressions of only 10 (50 μ s to 5 μ s) are required. In fact, pulse charging with opening switches has already been done by Conte et al.,⁵ using single-shot exploding fuses. The remaining substantial obstacle is to make a repetitive switch.

The rotating store could also be used for charging a pulse-forming line directly through a transformer if it could be made fast enough. The problem at present is that the high-energy-density liquid dielectrics we now use

(primarily water) have resistive losses that would make the system very inefficient for charge times greater than $\sim 10 \mu s$. If a $10\text{-}\mu s$ alternator were produced, fast charging of pulse-forming lines through a step-up transformer would make a very inexpensive, compact system. An alternative is to use solid plastic dielectrics, which do not have a resistive loss but which have lower energy density and, therefore, large volumes.

We conclude that the pulsed-power system described here can be implemented by continual development of contemporary systems. However, great leverage toward truly commercial systems can be obtained by developing inductive storage and/or employing rotating machinery.

1.5 Conclusions

E-beam-driver conceptual system designs have been developed for both 400-ns (PFL) and 900-ns (PFN) long-pulse amplifier pulse durations. Both systems are extrapolations of contemporary technology. The PFN system entails less technology extrapolation; the technology developments for the PFL system, primarily the repetitive, high-power gas output switch, will probably have been developed by the time ETF enters the design phase.

The cost structure of the two designs is quite similar when compared by element. The PFN system appears to be somewhat less expensive than the PFL. A countervailing consideration is that the short-pulse system operates in a more advantageous regime of laser kinetics. Therefore, the increased price and complexity may be worth the effort. The PFN system would be much more difficult to build at shorter pulse duration and is, therefore, restricted to the longer pulses. Construction of a PFL with longer pulse duration would not have substantial cost impact, but the longer pulse duration would increase optics costs and cause poorer kinetic performance of the laser medium.

For commercialization, great leverage can be achieved by developing inductive-energy storage. This concept can result in a much more compact and inexpensive e-beam generator.

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Appendix 2. Optical Systems

M. R. Flannery, G. M. Perron, S. N. Suchard, and D. E. Vandenburg
Hughes Aircraft Co.

L. G. Seppala
Lawrence Livermore National Laboratory

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Appendix 2. Optical Systems

2.1 Introduction

The objective of the optical system is to deliver a high-quality 1.5-MJ, 20-ns light pulse to a fusion pellet with high efficiency, with no prepulse energy on the target, and with a smooth wave front for pointing and focus control. The KrF excimer laser operating at 248 nm has both the high efficiency and short wavelength required of an ideal fusion laser, but this laser suffers from a very short storage time (~ 3 ns). In the present application, this limitation is overcome by using pulse stacking. The power-amplifier module is fed by an optical-delay line that temporally stacks a sequence of N short pulses (pulse stacking) of pulse length τ through the amplifier at slightly different angles (angular multiplexing). By overfilling the amplifier with each pulse, it is possible to extract energy from the amplifying medium for a pulse length of $N\tau$. This allows efficient pumping of the amplifier by long-pulse electron beams. Angular multiplexing of the short pulses allows them to be separated spatially at the output of the amplifier, where their relative delays are removed in a second optical-delay line. The pulses are then reassembled into a spatial matrix of collimated beams that is directed toward the final-focusing optics. This report examines pulse stackers with $\tau = 100$ ns and either $N = 4$ or $N = 9$.

Further pulse compression, beam cleanup, and prepulse isolation are accomplished by using the KrF laser as a pump for a double-pass backward Raman scattering cell filled with methane. This cell converts the 248-nm, 100-ns, 1.9-MJ KrF pump pulse of poor wave-front quality to a 268-nm, 20-ns, 1.5-MJ Raman-shifted pulse with an optical quality dependent on the quality of the Stokes input beam and on effects of gas-density fluctuations in the Raman cell and beam tubes.

Since the KrF pump beam is not aimed toward the target-focusing optics, the prepulse energy arising from scattering crosstalk between the stacked pump pulses does not reach the target. The only prepulse energy that reaches the target is due to scattering of the pump beam in the Raman cell (on both passes) and scattering of the Stokes beam as it is amplified in the first pass. Both effects are small.

The Stokes input to the cell requires only 1.5 kJ to generate the 1.5-MJ output, and this input, in turn, is generated in a smaller Raman cell that

requires an input of only 1.6 J. The general architecture of a four-beam stacker is shown in Figs. 2.1-1 and 2.1-2. (A combination of 14 stackers pumping a common Raman cell is shown in Fig. 3.4-3.)

The optical system is supported by a beam-path conditioning system, a mirror-cooling system, and an alignment system. The beam-path conditioning system removes heat from both the beam-path gas and the Raman gas while maintaining a specified level of turbulence or laminar flow; the mirror-cooling system removes heat from the mirrors to control thermally induced distortion in the large mirrors; and the alignment system--comprising sources, sensors, processing electronics, and servos--senses beam-train misalignments and corrects them by two-axis steering of the system mirrors. The alignment system takes advantage of the separation of the delay mirrors to steer individual beam lines at these mirrors, while the number of servos is reduced by combining the mirrors (either 4 or 9) at the pulse-stacker primary and tertiary mirrors into arrays and then steering all beams in one stacker at these locations. The location of image sensors, mirrors, mirror arrays, and steering servos is shown for one stacker and the Raman cell in Fig. 2.1-3.

2.2 System Options

The major options that were considered in the study are given below. (The preferred systems are indicated by asterisks.)

- o System architecture
 - oo Four-beam stacker with unit magnification in the stacker telescope.
 - oo *Four-beam stacker with 2.45X beam expansion in the stacker telescope.
 - oo Nine-beam stacker with unit magnification in the stacker telescope.
 - oo Nine-beam stacker with 2.45X beam expansion in the stacker telescope.
- o Mirror construction
 - oo Metal- and dielectric-overcoated glass mirrors.
 - oo *Dielectric-overcoated aluminum mirrors.
 - oo Dielectric-overcoated copper mirrors.
 - oo Dielectric-overcoated molybdenum mirrors.
 - oo Dielectric-overcoated beryllium mirrors.

Fig. 2.1-1. Top view of the compact unit-magnification four-beam stacker.

Fig. 2.1-2. Top-front perspective view of the compact unit-magnification four-beam stacker.

Fig. 2.1-3. Sensors and servos in the pulse stacker and the double-pass Raman cell.

- o Mirror-mounting strategy
 - oo All mirrors on individual servo-controlled two-axis mounts.
 - oo *Fixed, prealigned mirror arrays mounted on a common servo-controlled two-axis mount.
- o Mirror-alignment strategy
 - oo Central-beam-reference alignment system.
 - oo Inner-annulus-reference alignment system.
 - oo Outer-annulus-reference alignment system.
 - oo *Image-alignment system.
- o K_rF amplifier windows
 - oo Thin single-pane, spherical-shell fused-silica windows separated from the amplifier by a long acoustic baffle.
 - oo *Thick faceted, spherical-shell fused-silica windows located 5 to 20 cm from the amplifier.
- o Beam-path enclosures
 - oo Individual beam-path tubes in the pulse stacker.
 - oo *A single beam-containment house for each pulse stacker.
- o Beam-path gas
 - oo Argon.
 - oo *Helium.
- o Raman-cell windows
 - oo Sheared-flow inert-gas windows for the Raman cells.
 - oo *Uncoated Brewster's-angle fused-silica windows for the Raman cells.

The justifications for choosing the indicated options are given in the following subsections.

2.2.1 System Architecture

The 4-beam stacker was chosen over the 9-beam stacker because the latter requires a delay line approximately 60 m longer than the former. Although the pulsed-power systems are comparable in cost, the cost trade-off is overwhelmingly dominated by the larger laser-containment building that would be required by the 9-beam stacker.

From an optical standpoint, four-beam stackers have shorter pathlengths; require fewer and less-expensive alignment sensors; have fewer mirrors, mirror mounts, servo loops, mirror-cooling loops, and beam tubes; and require less spaceframe and less dielectric-coated mirror area. However, the four-beam

stackers have larger mirrors, which are more difficult to polish, coat, and mount and which are much more sensitive to thermally induced distortion and to mounting stresses.

A stacker telescope with a net beam expansion ratio of 2.45X was chosen. The unit-magnification stackers are insensitive to optical damage in the input delay line and require a smaller inventory of mirrors and mirrors mounts than stackers with net magnification. However, one can choose a net magnification that simultaneously reduces the area of the input mirrors and still protects the input optics from damage. Savings are realized in mirror blanks, fabrication, and mounting because of the smaller mirror sizes.

2.2.2 Mirror Construction

Dielectric-overcoated aluminum mirrors appear to be the best choice. Beryllium was eliminated because of its high toxicity and cost. The high-power mirrors absorb up to 0.47 W/cm^2 , which requires modest water cooling. The high cost of low-expansion glass and the difficulty of fabricating a high-pressure, small-channel heat exchanger that would maintain the temperature rise of the coatings below 150°C have generally eliminated glass mirrors. Because the thermal requirements are so modest, aluminum is preferable to copper, which is more expensive, more dense, and has essentially zero microyield stress. Since the high rigidity of molybdenum will probably not be necessary to reduce thermal distortions and mounting distortions for mirrors used in essentially fixed positions, its high cost, high density, and the difficulty of fabricating large, complicated substrates from sintered material eliminate molybdenum in favor of aluminum. The final mirror design that was selected is an investment-cast aluminum substrate dip brazed to a thick aluminum faceplate.

2.2.3 Mirror-Mounting Strategy

Since the laser system operates in thermal equilibrium, it appears possible to prealign the mirror arrays on a honeycomb-steel optical table and to maintain the array over long periods of time to within 5 to 10 μrad . Calculations show that such a prealigned optical table with mirrors on one side can be mounted vertically with maximum displacements of only $\pm 10 \mu\text{rad}$. This arrangement would result in large savings in both the cost and complexity of the alignment system.

2 2.4 Mirror-Alignment Strategy

Central-beam-reference alignment systems use either a fraction of the main laser pulse or a co-propagating alignment pulse that is fired between the main laser pulses. These systems were rejected because metal mirror substrates were chosen for thermal and cost considerations. Therefore, access to the beam would require hole-coupling mirrors to pass the alignment beam through the KrF dielectric reflector and then through small holes in the metal substrate. A central-beam reference pulse could be obtained by firing the initial oscillator at twice the repetition rate of the laser system. However, the metal mirrors would require a bonded glass layer (to cover the coupling holes) that would degrade the thermal value of the metal substrate.

An inner-annulus system would overcome most of these objections but would require holes in the centers of the mirrors; these holes would produce a region of untapped gain in the KrF amplifiers.

An outer-annulus system would be the system of choice except that a large number of expensive sensors are needed to gain a large field of view (FOV). This system has the advantage that it uses an outer annulus outside the high-power beam print on all mirrors except the secondary mirror behind the KrF amplifier. In the case of this mirror, if the alignment beam were off the high-power beam print, there would be a region of untapped gain. To avoid this difficulty, special tilted annuli would have to be ground on the primary and tertiary mirrors to insert and extract the reference beam from the high-power beam print on the secondary mirror. These annuli could be made either by diamond turning or by using holographic gratings on the annuli of the primary and tertiary mirrors. In either case, mirror fabrication costs would increase.

The best alignment technique appears to be an image-alignment system that uses auxiliary light sources outside the high-power beam print. The high-power laser mirrors are aligned by tilting them to reflect light from the sources to predetermined locations inside an imaging sensor system that is located outside of the high-power laser beam print. Derated laser diodes, which are both reliable and inexpensive, serve as bright-point light sources for a high-resolution image. The cost of the image-alignment system is a strong function both of the number of delay lines that can be multiplexed to each image sensor and of the distance along each line that the sensor can maintain resolution and collect enough energy to maintain a sufficient

signal-to-noise ratio (S/N). The sensor requirements for the four-beam stackers are relatively modest: two sensors are required for each compact stacker.

2.2.5 KrF Amplifier Windows

The energy required to flow gas through a long acoustic baffle and to recover the fluorine from it is prohibitive. Therefore, four-pane fused-silica windows located from 5 to 20 cm from the amplifier were chosen. The windows could be up to 10 cm thick with a long radius of curvature, as required to withstand the shock pressure generated by heat deposition in the amplifier medium.

2.2.6 Beam-Path Enclosure

The four-beam net-magnification stackers can be so compact that a single beam tube or beam house for each stacker is less expensive and complex than individual beam tubes.

2.2.7 Beam-Path Gas

To maintain an alignment resolution of ± 1 mm over a distance of 400 m for an alignment beam at 820 nm, a sensor with 28-cm-diam optics and an atmospheric thermal structure constant of $C_T^2 < 0.05^\circ\text{C}^2$ for argon and $C_T^2 < 3.0^\circ\text{C}^2$ for helium is required. Therefore helium is completely adequate, but argon might be marginal.

2.2.8 Raman-Cell Windows

Brewster's-angle windows were chosen. The energy to maintain a sheared-flow inert-gas window is prohibitive if the flow is fast enough to prevent the buoyancy differences between CH_4 and argon or helium from producing a lens in the Raman cell. Brewster's-angle windows remove the difficulty of requiring a high-damage-level antireflection coating at both 248 and 266 nm but require the KrF optical train to preserve a linear polarization.

2.3 Description of the Baseline Design

This section describes the baseline design for a 2.45X magnification four-beam stacker and its optical components, alignment system, Raman cell, and support structures.

A 2.45X magnification four-beam stacker was used as a baseline and is similar in layout to the telescope in Figs. 2.1-1 and 2.1-2. The three-spherical-mirror telescope expands each 33.7- x 33.7-cm collimated input beam to fill the 2- x 2-m amplifier aperture and then reduces it back to a collimated output beam at 82.5 x 82.5 cm. The amplifier aperture is determined by both the pumping time and the kinetics of the gain medium, while the beam size in the output end of the stacker is determined by the 5-J/cm² fluence requirement for KrF in the Raman cell. A preliminary design assumed that the tertiary and primary mirrors were single spherical surfaces. Since the fluence levels on the output tertiary mirror become extreme if the beam prints are allowed to overlap, this design required a widely spaced delay mirror array that occupied a prohibitively large volume.

By dividing the primary and tertiary mirrors into segments, the volume occupied by the stacker can be greatly reduced. The individual mirror segments are tilted so that the delay arrays are more closely spaced. This stacker requires a beam tube 120 m in length with a cross section of only 2.1 x 6.2 m. This baseline design has angular optical distortions of less than 10 μ rad in each beam. The image alignment system, with one stacker and the Raman cell, is shown in Fig. 2.1-3.

In its simplest form, an alignment sensor consists of a detector array at the focus of a lens. This sensor is affected by its own angular misalignment, but this type of error can be monitored if the sensor looks directly at a laser diode in the spaceframe. Individual mirrors in the pulse stacker can then be aligned by monitoring the positions of reflected images of fixed laser diode sources in the spaceframe, using the image position of the directly viewed diode as a reference.

The sensors control the steering servos on the first mirror they see down the beam line by imaging the laser diode light sources located on the second mirror down the beam line. For example, sensor S_1 forms an image of the laser diodes on mirror M_2 and compares these point images with a perfect-alignment reference image to generate error signals that are used to drive the servo on M_1 until the images agree. When the images agree, the central ray of the KrF laser beam, which has been aligned adjacent to S_1 by the front-end alignment system, will reflect off the centers of M_1 and M_2 . Similarly, S_2 can align M_2 and M_4 , providing handoff between alignment sensors. The sensor images follow a skew path down the optical train because the sensors are located adjacent to the mirrors, as shown in

Fig. 2.3-1. Thus, the FOV eventually walks off the mirror (after about three reflections) even if the resolution or S/N did not limit the sensor.

Placing the sensors adjacent to the mirrors rather than attempting some form of aperture sharing allows the sensor to be shared by adjacent beam lines and reduces the number of sensors. As shown in Fig. 2.3-1, one sensor can align four beam lines in a stacker when the sensor is located at the center of the primary or tertiary array, or one sensor can align two arrays if the sensor is located at the joints between the arrays on M_8 , M_2 , or M_3 . To calculate the resolution of the sensor, assume that the sensor is a 512- x 512-element array of 20- x 20- μ m diodes with overall dimensions of 1.024 x 1.024 cm. The limiting FOV in the system will be the 87.5- x 87.5-cm delay mirror, located 120 m from the tertiary, that gives the sensor at the tertiary a 7.29-mrad FOV; this corresponds to a 1.97- x 1.97-m area in the object plant 270 m away at the scraper mirrors. We will assume the sensor has a zoom lens that keeps the object-plane area fixed at this value. The longest source-to-sensor distance is 290 m, between S_4 and the closest M_6 , while the shortest distance is approximately 150 m, between S_1 and the closest M_2 . A sensor with an aperture diameter (d) of 28 cm has a diffraction-limited resolution angle $2\theta_{\text{dif}} = 1.22 \lambda/d = 3.57 \mu\text{rad}$ (at $\lambda = 820 \text{ nm}$), which corresponds to 1.04 mm in object space at 290 m. If we assume there is one sensor element per resolution spot (i.e., the sensor array covers a 0.533- x 0.533-m area in object space), then the magnification is $m = -0.0192$, the focal length is $f = 5.69 \text{ m}$ at 290 m and $f = 2.94 \text{ m}$ at 150 m for a zoom ratio of about 2.0. A Questar 12 is a suitable foreoptic for this sensor: $f = 4.572 \text{ m}$, clear aperture = 30.48 cm, FOV = 8.03 mrad, and obscuration ratio = 23.6%. The sensor can cover the whole FOV either by inserting some additional optics to match the 1.97- x 1.97-m object plane to the sensor or by stepping the sensor pointing mirror across the object plane.

The sensitivity of the sensor will be found assuming the source is a laser diode with 2% of its power $P_o = 5 \text{ mW}$ at $\lambda = 820 \text{ nm}$ radiating into a cone with a half-apex angle of $\theta_r = 52.4 \text{ mrad}$. If the high-power mirror has a reflectivity of $R = 0.7$ at $\lambda = 820 \text{ nm}$ and the sensor has a transmission $T = 0.2$, a diameter $d = 28 \text{ cm}$, and an obscuration ratio $r_o = 0.24$, the image-plane power is

$$P = 0.02P_o RT(1 - r_o) \frac{(d/2)^2}{(L\theta_r)^2} = 9.03 \times 10^{-10} \text{ W} ,$$

Fig. 2.3-1. Location of sensors in relation to mirrors.

assuming the diode is the maximum distance ($L = 290$ m) away. Since this power could be spread by system aberrations over, perhaps, 9 sensor elements, the power falling on an element is about 10^{-10} W. For a typical 20-ms integration time and the 20×20 - μm diode area, the energy/area = $0.75 \mu\text{J}/\text{cm}^2$, which is at the low end of the detectable energy density for diode or CCD arrays but which is still easily detectable.

2.4 Cost Scaling

The costs for the four-beam stacker baseline design are divided into categories in Table 2.4-1. The greatest cost sensitivities are in the windows, where small changes in thickness mean large changes in cost, and in areas of technological uncertainty, such as polishing and, particularly, coating.

The approximate costs for a 9-beam stacker can be found from the following scaling arguments. Mirror substrates are not likely to vary significantly in cost because their volumes are similar. The mirror area increases by about 12% to accommodate oversizing, and the coating costs increase proportionately, but polishing and grinding costs should not increase significantly because the increased area and increased mirror quality for the longer beam lines will be offset by the ease of polishing smaller mirrors and the decreased influence of backup-bending distortion. To offset fluorine depletion, the 9-beam amplifier will have a 40% larger aperture, which will increase the fused-silica costs by a corresponding amount. This is the most significant cost driver that favors the four-beam stacker. The larger array for the secondary mirror, and the additional hardware for mounting 9 instead of 4 mirrors per array, would increase the array costs about 10%. The individual mounts for the delay mirrors are less expensive, but 2-1/4 times as many are required, for a net cost increase of 30%. Finally, the 9-beam stacker requires larger sensor foreoptics, which increase the cost by 5% per sensor. Even worse, the 9-beam stacker uses its sensors inefficiently, requiring 117 sensors instead of only 57, because 4 additional sensors are required on the preamp input and 2 more at each primary and tertiary array. However, the sensors at each primary and tertiary array can share a common set of signal-processing electronics, resulting in an overall cost increase of 66% for sensors.

Overall, the cost for a 9-beam stacker is about 30% greater than for a 4-beam stacker when small increases in other items are included for the 9-beam stacker.

Table 2.4-1. Optical-system cost summary (k\$).*

<u>Item</u>	<u>2.45X Telescope</u>
1. Aluminum mirror substrates.	875
2. Fused-silica windows and slumping.	32,100
3. Mirror and window polishing.	11,500
4. Dielectric coatings.	3,500
5. Amplifier and Raman-cell window mounts.	900
6. Delay mirror mounts and servo drivers.	1,100
7. Aligned mirror arrays, mounts, and servo drivers.	7,000
8. Laser diodes and drivers.	400
9. Alignment sensors, signal processing, and controls.	9,300
10. Alignment monitor and display and cable.	200
11. Power and control cables installed.	400
12. Spaceframe installed.	8,000
13. Installation and rough alignment of optics.	1,400
14. Final alignment and test.	<u>300</u>
Total	76,675

*System costs for 14 four-beam 2.45X-magnification stackers pumping a backward-scattering Raman cell. Research and development costs and front-end systems are not included. These are direct costs only: total does not include overhead and profit, capital production, or test equipment but does include special jigs and tooling, in most cases. Most cost estimates are based on the volume required and on the use of typical off-the-shelf components whenever possible, but a few costs are for one-of-a-kind hand-produced items. The above costs are for an unoptimized system and could change if systems assumptions are modified.

2.5 Technology Development

The 10^7 to 10^8 shot lifetimes required for multilayer dielectric reflectors are orders of magnitude beyond the state-of-the-art at 248 nm with 5.86 J/cm^2 and 100-ns pulse length. In addition, the segmented pivot and Raman-cell mirrors have joints that are subject to fluences up to 5.28 J/cm^2 . The best commercial coatings have survived 100 shots at 248 nm with a fluence of 2 J/cm^2 and a pulse length of 20 ns, while bulk-damage levels have been measured above 10 J/cm^2 for single shots at similar wavelengths. The present coatings are all limited by their linear-absorption coefficient and by the large number of defects ($\sim 10^3/\text{mm}$) with diameters of the order of a wavelength. For this report, it was assumed that the coatings could be produced by processing the stock to remove metal ions and trapped gases (which sputter during deposition and increases the roughness) and by using dedicated ultrahigh-vacuum (uhv) deposition chambers. If this procedure is inadequate, it may be necessary to use only materials that can be deposited in atomic layers by molecular-beam epitaxy and to develop this technique for large-area substrates. Another unlikely possibility is the development of two different-index glasses that can be compatibly deposited and annealed. Finally, if the Raman-cell mirror separation is greatly increased, it would be possible to angularly multiplex the pump beams in the Raman cell, an action that would reduce the fluences in the KrF optical line by a factor of two to four.

A second technology problem that carries great cost benefits is to reduce the thickness of the spherical-shell amplifier window to the minimum needed to withstand the amplifier overpressure. Calculations must be done to determine the coupling strength between the amplifier overpressure wave and the radially traveling shear wave that causes fracture. Cost and the convenience of fabrication dictated a four-pane window design for the amplifier, but the additional surfaces may result in reduced fracture resistance, which could drive the design back to a single-pane window. Mounts for these windows have been made for deep-ocean submersibles.

There will be some background photon noise from the afterglow of the windows and mirrors, there will be shot noise in the laser diodes, and there will be scintillation and angle-of-arrival of fluctuations from turbulence in the beam-path gas; consequently, either the detector may have to be modulated to increase the S/N or it will be necessary to develop higher-power diodes with narrower divergence angles. The

angle-of-arrival fluctuations given by

$$\langle a^2 \rangle = 2.91 \left(\frac{3}{8} \right) L d^{-1/3} (1.340 \times 10^{-5}) (\rho_0 k_{GD})^2 C_T^2$$

for spherical waves at STP should dominate the other disturbances. For the maximum viewing distance of $L = 290$ m and a sensor of diameter $d = 0.28$ m, we would like to keep $\langle a^2 \rangle^{1/2}$ less than the resolution of the alignment system, $3.57 \mu\text{rad}$, by specifying a gas of density ρ_0 and Gladstone-Dale constant k_{GD} and by placing a realistic bound on the atmospheric-temperature structure constant C_T^2 . For argon, $\rho_0 = 1.7837 \times 10^{-3} \text{ g/cm}^3$, $k_{GD} = 0.1575 \text{ cm}^3/\text{g}$ at 589 nm , and $\langle a^2 \rangle^{1/2} \sim 3.6 \mu\text{rad}$ if $C_T^2 = 0.025 \text{ K}^2 \text{m}^{-2/3}$, or a temperature fluctuation of about 0.1 K across the sensor aperture dimensions, which might be hard to maintain near mirror edges or around the amplifier.

If helium with $\rho_0 = 0.1785 \times 10^{-3} \text{ g/cm}^3$ and $k_{GD} = 0.2017 \text{ cm}^3/\text{g}$ at 589 nm is used instead of argon, then $\langle a^2 \rangle^{1/2} \sim 3.6 \mu\text{rad}$ if $C_T^2 = 1.54 \text{ K}^2 \text{m}^{-2/3}$, or about 0.8 K across the sensor aperture, which is quite reasonable. Therefore, helium should be used as the beam-path gas.

The servos and two-axis tilting mounts required for the individual delay mirrors need only be modest extensions of off-the-shelf components to handle the $87.5\text{-} \times 87.5\text{-cm}$ mirrors, which have a total mass of 220 kg . These mounts can be driven by available motors that have a stepping rate of 2000 steps/s and stepping accuracies of $0.25 \mu\text{rad/step}$.

The four-mirror arrays present two more difficult problems: can the array be prealigned and held fixed, and can such a large mass be steered with the required accuracy? Calculations show that a highly damped honeycomb optical table can be used as a backup structure that will hold the mirrors to $\pm 5 \mu\text{rad}$ quite easily, even in the face of vibrational impulse loads. The array will weigh about 3000 kg and must be designed so that it has no static friction in its servo driver. It appears that a number of reactionless mirror mounts can handle this weight and that a servo can be designed to accurately drive the array over the required dynamic range; however, the response time may be rather slow. The servos for the alignment sensor itself are all off-the-shelf components. The cycle time of the alignment system is about 40 s , but longer times might be required if the S/N of the sensor requires modulation or if the array servos require longer settling times.

The mirrors and windows in the KrF and Raman optical trains are listed in Table 2.5-1, together with the energy fluence on each optical surface. The loss on reflection from a mirror was assumed to be 4% per bounce, the scattering was assumed to be 1% per bounce, the absorption loss in antireflection-coated fused-silica amplifier windows of 10-cm thickness was assumed to be 1.3% per pass, and the scattering loss was assumed to be 1.7% per pass. The fused-silica Raman-cell windows are tilted in a horizontal plane at Brewster's angle, 56.38° , and the system is assumed to deliver a p-polarized beam to the Raman cell. The optical system delivers the beam from the KrF amplifying medium to the Raman cell with 82% efficiency, including a 1.45% loss to Rayleigh scattering in the helium beam-path gas.

The mirror substrates have investment-cast aluminum backup structures, which include heat exchangers, water manifolds, and lightweight cast honeycomb to provide stiffness, dip brazed to a solid-aluminum faceplate that is 1 to 2 cm in thickness. During the dip-brazing operation, water-manifold rear covers that contain water-pipe connections are also brazed to the investment casting. The overall mirror structure has approximately a 6:1 edge-to-thickness ratio (for square mirrors), which is sufficient to provide stiffness for polishing and to control mounting distortions. The thickness of the faceplate is determined by requiring the heat-exchanger pressure and thermal-mapping distortions to be negligible.

The mirrors must handle a thermal load of up to 0.47 W/cm^2 . Gas cooling is inadequate to handle this load without producing excess backup-bending or overheating the mirror coatings. With a large-channel water-cooled mirror, the water only increases in temperature by 1 K in traversing a 100-cm cooling channel at a velocity of 1 m/s and has a pressure drop of 2300 N/m^2 . Under these conditions, the backup-bending curvature is only 10^{-4} m , which is comfortably large compared to the radius of curvature of the powered mirrors in the system. About 150 litre/s of water are required to cool all the mirrors in the system; this water needs to be cooled about 1 K before return, and the temperature control should be within $\pm 0.1 \text{ K}$.

The fused-silica windows for the amplifier are 10 cm thick with a 6- to 8-m radius of curvature that is convex toward the amplifier to withstand pumping shocks. The 10-cm thickness is the upper limit set by the temperature rise the coatings can withstand from absorption of the KrF beam and the amplifier afterglow at shorter wavelengths. The temperature rise is also

Table 2.5-1 Optical-train component number and
fluence-loading summary.

	Number of mirrors/windows	Number of arrays	Incident fluence	
			248 nm 100 ns <u>J/cm²</u>	268 nm 20 ns <u>J/cm²</u>
M ₁	56	14	2.04*	-
M ₂	56	-	1.92	-
M ₃	56	14	1.80	-
M ₄	56	14	2.13**	-
M ₅	56	14	5.86	-
M ₆	56	-	5.57	-
M ₇	56	14	5.29*	-
M ₈	56	14	4.51	-
M ₁ '	1	-	-	4.00
M ₂ '	7	-	-	0.03
M ₃ '	56	14	-	0.39
W ₁	56	14	4.04**	-
W ₂	21	1	2.72	0.86
W ₃	21	1	2.44	0.01
W ₄	21	1	2.32	2.20
W ₅	<u>21</u>	<u>1</u>	0.55	0.20
Totals	652	116	* 400 ns	
			** Ignoring mirror tilts.	

Number of sensors:

S ₁	8
S ₂	14
S ₃	14
S ₄	7
S ₅	7
S ₁ '	<u>7</u>
Total	57

limited because of the low thermal conductivity of fused-silica and the low heat-transfer coefficient for gas cooling of the window faces.

From an optical standpoint, there are three major uncertainties that might prevent the functioning of this system: dielectric damage, fracture of the amplifier windows, or unacceptable irradiance spread or beam jitter in the Raman beam line. The energy fluences must be quite high for this system to operate efficiently, and it may be difficult to get practical shot lifetimes at efficient fluence levels; hence, the system is very sensitive to the development of coatings. The amplifier windows must be close to the amplifying medium or the gas-cleanup energy requirements will destroy the system efficiency, but, at these close distances, the window coatings could be damaged by the electron pumping beam or the window could be fractured by the overpressure wave. The difficulties with beam quality in the Raman cell are a combination of the typical OPDs for large metal mirrors, the eight glass surfaces it must traverse, the turbulence distortion resulting from energy deposited in the Raman medium itself, and any vibration of the optical elements. These difficulties do not appear to represent an insurmountable obstacle so long as extremely small, uniform focal spots are not required, but their solution might substantially increase the capital cost of the system.

There are also issues about the cycling time of the alignment system and the vibration of the window and mirror at the power amplifier. These issues will probably not affect the system directly in cost or complexity, but solutions to these issues could result in very substantial development costs.

Polishing the mirrors under equilibrium pressure loads is a common procedure, but, to our knowledge, the inclusion of an equilibrium thermal load has not been tested. Computations and tests should be conducted to determine the optical-figure requirements for the unconventional stacker optics and to determine the least costly production method. Diamond turning under thermal load followed by ion polishing or computer-controlled minipad polishing to remove the machining grating might be developed to achieve the required figure accuracies at substantial savings of cost and time. It is possible that the mirror figures required for pellet illumination cannot be achieved on aluminum substrates, and the Raman mirrors M_2 and M_3 might have to be replaced with molybdenum-substrate mirrors. This replacement would increase the cost estimate for the substrates by almost a factor of three.

Finally, the present design assumes that the alignment drift is slow enough compared to the cycle time (40 s) of the alignment system that the beam

prints remain within the mirror oversizing region, $\pm 100 \mu\text{rad}$. Generally, this assumption will work if the optics are mounted directly on the floor and the building is constructed in a quiet environment, but the 2-Hz cycling of the pulsed-power system directly affects both the amplifier window and the secondary mirror and could excite building resonances that could affect the rest of the optical train. The oscillation amplitude and spectrum of the containment building must be measured to determine what isolation of the optics is necessary or if a faster cycling of the alignment system would be sufficient.

2.6 Conclusions

From an optical standpoint, the key issue is the development of high-fluence dielectric coatings. This coating development is a long-lead-time item and must be resolved. Similarly, any issue such as surface quality or mounting distortion that is intrinsic to the large size of the optics is a long-lead-time item because large optics (particularly the fused-silica or molybdenum substrates for the mirrors) are time extensive. When these issues have been resolved, it will be practical to build a small engineering demonstrator to test other issues, such as beam-path conditioning, vibration sensitivity, window shock fracture, alignment and servo performance, and the system's software and signal processing. We believe the inclusion of a Raman cell for beam cleanup and isolation in a fusion pulse-stacker system may offset the disadvantage of developing high-fluence coatings, because the efficiency of pellet implosion may have a strong benefit/penalty trade-off for wave-front quality that would be beyond the capability of pure pulse stackers.

Appendix 3. Process Systems, Facilities, and Capital Cost

J. Caird, W. O. Allen, and H. G. Hipkin
Bechtel National, Inc.

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3.1 Introduction and Summary

To complete the laser system, equipment must be added to properly condition the gas media in the KrF laser amplifiers, the Raman amplifier, and the beam-propagation paths. Electrical power and cooling systems, buildings to house the entire system must be designed. The purpose of this chapter is to define these additional system requirements and to present an overall system capital cost estimate.

One major task in this phase of the study was to examine the feasibility of using aerodynamic windows for the KrF laser amplifiers and the methane Raman amplifier. It was thought that aerodynamic windows would eliminate the requirement for solid windows with high-damage-threshold antireflection coatings. Since the damage threshold of currently available optical coatings at the KrF laser wavelength is considerably lower than that required by this system, this would eliminate the need for an intensive coating development program.

Several approaches to using aerodynamic windows for the KrF amplifiers were examined in depth and are presented in Section 3.2. However, none of these approaches was found sufficiently attractive to incorporate in the final design. The primary reason for this result is that fluorine from the active laser gas mixes with, and must be removed from, the gas in the aero-window. The quantity of fluorine involved is such that its removal is energetically prohibitive (from a laser efficiency point of view) for all methods considered. It was also concluded that a solid window is probably required in any case in order to seal off the active laser region containing highly reactive fluorine and highly expensive krypton gases from the rest of the laser system. Additional potential options for an aero-window system design are suggested for further study, in the event that such a system is ultimately required.

A design for the KrF amplifier gas flow system without an aerodynamic window is presented in Section 3.1. Gas-flow conditioning equipment--including the gas cleanup system, heat exchanger, and blower--is discussed. Systems and procedures for startup and shutdown are included. The major pressure drop around the flow loop, which determines the required blower power, occurs in the heat exchanger. It is assumed that additional flow management for suppression of gas turbulence and acoustic pressure waves can

be accomplished without significant additional pressure drop. This assumption is justified because the Raman amplifier is a very large target: the divergence of the KrF beams can be very large without significant loss of efficiency. An adequate quantitative analysis of the beam divergence created by medium inhomogeneity far above the diffraction limit is needed to establish system requirements in this area.

Flow systems for the methane Raman cell are described in Section 3.3. For this system, it was concluded that antireflection coatings are not required if the laser beams are polarized and the windows oriented at Brewster's angle. The surface damage threshold of clean, highly polished, uncoated fused silica is believed to be adequate for this application. Also, analysis has shown that self-focusing beam distortion due to the nonlinear refractive index of quartz is negligible, given the long pulsewidth assumed in this study and a reasonably thin window. Brewster-angle windows were not considered for the KrF amplifiers in this study because of geometrical constraints of the initial design. However, it appears that there are ways in which they could be incorporated in future designs, and further consideration is suggested.

A conceptual design for the building architecture is presented in Section 3.5. The need for controlled atmospheric conditions in the beam-propagation paths is discussed, and a design approach is described. Additional equipment for cooling the e-beam generator components is discussed, along with other general facility requirements (site work, etc.).

An order-of-magnitude cost estimate for systems based on 400-ns and 900-ns pulsed power is given in Section 3.6. The estimate includes all major mechanical and electrical equipment, building materials, construction labor, indirect field costs, home office services, and 25% contingency.

Several technical issues were identified during the study for which adequate design solutions have not yet been proven. A number of these are discussed in Section 3.7. It is hoped that resolution of these issues will not have a significant impact on overall system costs. Some suggestions for design improvements are also included in this section.

The general design of systems described in this chapter would be applicable for use with KrF amplifiers that have e-beam pump pulse durations from a few hundred nanoseconds to a microsecond or more. The design of a system using 400-ns PFL e-beam generators is discussed in detail to establish a point design. The modifications appropriate for use of 900-ns PFN pulsed power are discussed briefly in Section 3.6.11.

3.2 KrF Amplifier Gas Flow Systems

3.2.1 General Considerations

The basic design parameters for the KrF laser amplifiers were established by LLNL at the outset of this study. Table 3.2-1 lists a number of those parameters that are relevant to the design of the amplifier gas-flow systems. These choices are consistent with the basic design goals, which include an output energy fluence of 4 J/cm^2 , a pulse width of 400 ns, and the largest possible amplifier size consistent with parasitic mode control.

Additional specifications needed to design the gas flow system include the following:

- o Ninety percent of the deposited e-beam energy, or 1.44 MJ per shot, must be removed as waste heat. The actual waste heat will be somewhat less, because some of the energy will be radiated to the walls and out of the window (in the form of nonstimulated KrF^* fluorescence, ArF^* fluorescence, and fluorescence of other excimers and excited atomic species). Therefore, the assumption that 1.44 MJ/shot turns into heat will lead to a conservative design for the required heat exchanger, and for any structural components that must handle the pressure wave resulting from the heat addition.

- o The ambient temperature of the gas prior to e-beam deposition is 50°C to facilitate subsequent heat removal.

- o An active region clearing factor (or flush factor) of 2 is required to reestablish sufficiently quiescent conditions in the amplifier cavity. Given a pulse repetition rate of 2 Hz, this leads to a required flow velocity of 8 m/s through the cavity.

The additional design parameters are also included in Table 3.2-1.

The KrF amplifier flow system design must contend with the temperature rise and pressure wave resulting from the waste heat left in the active region after each shot. The initial temperature rise occurs before the gas has time to expand significantly in volume, thus the increase is given by

$$\Delta T = \frac{\Delta U}{C_v} \quad (3-1)$$

where ΔU is the increase in internal energy, and C_v is the specific heat of the gas at constant volume. Since the laser gas is essentially an ideal monatomic gas, the specific heat is

$$C_v = \frac{3}{2} nR \quad (3-2)$$

Table 3.2-1
KrF amplifier design parameters
(400-ns pulsed power).

Aperture	2 x 2 m
Active length	3 m
Ar/Kr/F ₂ mixture	0.937/0.060/0.003
Pressure	1 atm
Electron energy	1.3 MeV
E-beam energy	1.6 MJ/shot
Intrinsic efficiency	10%
Output energy (optical)	160 kJ
Stacker compression factor	4 X
Output pulse width	100 ns
Repetition rate	2 Hz
Waste heat	1.44 MJ/shot
Gas inlet temperature	50°C
Clearing factor	2
Gas flow rate	8 m/s

where n is the number of moles of gas in the laser cavity, and R is the universal gas constant. Using Eq. (3-2) and the ideal gas equation of state, Eq. (3-1) can be rewritten

$$\frac{\Delta T}{T_0} = \frac{2}{3} \frac{U}{P_0 V_0} \quad , \quad (3-3)$$

where P_0 , V_0 , and T_0 are the pressure, volume, and temperature of the active region prior to the energy deposition. At 1 atm $P_0 V_0 = (1.013 \times 10^5 \text{ nt/m}^2) \cdot (2 \times 2 \times 3 \text{ m}) = 1.22 \times 10^6 \text{ J}$. With $\Delta U = 1.44 \times 10^6 \text{ J}$, Eq. (3-3) yields $\Delta T/T_0 = 0.79$, corresponding to a temperature rise of 255°C , and a corresponding pressure rise of 0.79 atm. As noted above, the actual temperature and pressure rise will be smaller because some of the excess e-beam energy will be radiated away.

Since the pressure outside of the active laser region remains at 1 atm, the increased pressure inside will cause the active region to expand. If the cavity is constructed so that the active region can expand freely, the increase in its volume can be easily estimated. The expansion will continue until the internal pressure becomes equal to the 1-atm pressure of the rest of the plenum (the gas plenum volume is assumed to be very large compared to that of the amplifier cavity, so that the overall pressure rise is negligible). Assuming negligible heat transfer between the expanding gas and the surrounding medium, the internal energy is reduced only by work done against the constant external pressure, hence

$$dU = -P_0 dV = C_v dT \quad . \quad (3-4)$$

Integrating Eq. (3-4) and using the ideal gas equation of state yields

$$\frac{V_f}{V} \approx 1 + \frac{2}{5} \frac{\Delta U}{P_0 V_0} \quad , \quad (3-5)$$

where V_f is the final expanded volume of the active region. In the present system $V_f/V_0 = 1.47$, indicating a 47% increase in the volume of the active laser gas.

It is of interest to determine the increase in the linear dimensions of the active region. For this purpose, it is assumed that the gas expands equal

distances in the dimensions normal to the e-beam (the e-beam foil prevents expansion in its direction). This situation is depicted in Fig. 3.2-1. The final volume is given by

$$V_f = x_f y_f z_f = (x_o + \Delta)(y_o + \Delta)z_o = \alpha V_o \quad (3-6)$$

Solving Eq. (3-6), given the parameters of the current system yields $\Delta = 0.515$ m. This amounts to a 26% expansion in the flow direction and a 17% expansion in the direction of laser beam propagation, as shown in the Fig. 3.2-1. The actual expansion of the active region will be a complex and turbulent process, but these figures give a reasonable estimate on which to base the system design.

The temperature of the active region drops as it expands and does work on the gas in the plenum. The reduction in temperature is given by

$$\Delta T' = -\frac{P \Delta V}{C_v} = \frac{2}{3}(\alpha - 1) T_o \quad (3-7)$$

where α was the volumetric expansion factor. For this design $\Delta T' = 102^\circ\text{C}$, yielding a final temperature in the active region of 203°C . The internal energy of the active region is reduced by $\Delta U' = C_v \Delta T' = 580$ kJ, leaving 860 kJ of excess thermal energy in the active region. The 580 kJ released during the expansion process is assumed to be radiated in the form of sound waves that are dissipated in acoustic absorbers and in the walls of the plenum. This energy must still be removed as heat, but its distribution will depend on the location of the acoustic absorbers.

3.2.2 KrF Amplifier Window

The angularly multiplexed beams require long propagation paths to allow appropriate time delays and amplifier fill factors. The propagation paths cannot contain fluorine because it absorbs light at the laser wavelength, and cannot contain much krypton gas because it is very expensive. The KrF amplifiers must therefore be isolated from the propagation paths by some form of window that transmits the beam and contains the gases.

Fig. 3.2-1 KrF amplifier cavity illustrating the postshot expansion of the active region due to γ -beam heating.

Three major options to the window design were considered:

- o A solid transparent window close to the active region.
- o A purely aerodynamic window.
- o A solid window at a large distance from the active region with an aerodynamic buffer gas separating it from the active region.

3.2.2.1 Considerations for a Solid Window

The solid window close to the active region has the advantage that it eliminates the necessity for coflowing gas streams, the conditioning equipment required for the coflowing window gas, and the energy expenditure required for such conditioning. However, the window (and amplifier mirror) must be separated from the active region by a finite distance so that it is not damaged by the e-beam. In this space, laser energy is absorbed by inactive fluorine molecules in the ground state. The absorption cross section¹ σ_{abs} for F_2 at the KrF laser wavelength (248 nm) is $1.5 \times 10^{-20} \text{ cm}^2$, and the 0.3% of F_2 at 1 atm and 50°C yields a density of $N = 6.9 \times 10^{16} \text{ cm}^{-3}$. The resulting attenuation coefficient is $\alpha = 1.04 \times 10^{-3} \text{ cm}^{-1}$, or about 10%/m. In addition, reflection losses from the window surfaces must be accepted (about 4% per surface if oriented normal to the beam), or the surfaces must be antireflection coated. Presently available antireflection coatings cannot withstand the optical energy density assumed in this design without being damaged. A coating development program is required if normal incidence reflection losses must be eliminated (this may not be necessary for the ETF, or if Brewster windows can be used).

If the window is very close to the active region, there will be little attenuation of the pressure wave generated by the e-beam. Since the window is a stationary surface, the wave will reflect off it, resulting in a local pressure at the surface of nearly twice the initial overpressure. The window must therefore be designed to withstand the stress created by an overpressure of approximately 1.6 atm on its inner surface.

Fused silica (quartz) appears to be the most reasonable window material. If it is used a safe working tensile stress $\sigma = 2000 \text{ psi}$ can be assumed. For a flat square window under static load conditions, the window thickness required to keep the stress down to this level is given by

$$t = 0.048 L \left[P(\text{atm}) \right]^{1/2}, \quad (3-8)$$

where L is the length of a side, and P is the pressure load in atmospheres. In this case, a thickness of 12 cm is calculated for the 2- x 2-m aperture. If the window is curved, a higher static pressure can be tolerated for a given thickness. However, the effects of dynamic loads and repetitive operation have not been analyzed in sufficient detail. These effects are expected to increase the required window thickness.

The intrinsic absorption coefficient for pure fused silica (as might be expected for suprasil) at 248 nm is $1.22 \times 10^{-3} \text{ cm}^{-1}$ (see Ref. 2). At a thickness of 10 cm, the quartz will absorb a little over 1% of the beam in the bulk material, yielding a heat load of 0.1 W/cm^2 for the average beam intensity of 8 W/cm^2 . Additional heat would be generated in the quartz window through absorption of ArF^* fluorescence (193 nm) from the active region. The average intensity of ArF^* fluorescence at the window is estimated to be about 0.2 W/cm^2 . The attenuation coefficient at this wavelength is 0.016 cm^{-1} , yielding an additional heat load of 0.03 W/cm^2 . Additional fluorescence by other species will increase the bulk thermal

loading, especially at shorter wavelengths, where quartz absorption is stronger. It is assumed that the total bulk heating load will be less than 0.2 W/cm^2 for a 10-cm-thick window, corresponding to a volumetric heat deposition rate of $\dot{Q} = 0.02 \text{ W/cm}^3$.

The thermal conductivity of quartz is rather low, $K = 1.4 \times 10^{-2} \text{ W/cm K}$, and the bulk heat deposition will cause the center of the window to be hotter than the surfaces. The hotter interior expands, putting the surfaces under tension and the center under compressive stress. Assuming equal heat flow out of both surfaces it can be shown that the temperature difference between the center and the surfaces is given by

$$\Delta T_c = \frac{\dot{Q}t^2}{8K}, \quad (3-9)$$

where t is the thickness of the window. In this case, a temperature rise of 18°C is calculated. Because the thermal expansion coefficient of quartz is small, this temperature rise is not expected to be a problem; however, because ΔT_c varies with the square of the thickness, a limiting value will eventually be reached if the thickness were substantially increased. Further analysis of the window's thermal stress behavior should be undertaken.

It is assumed that the window is primarily surface-cooled by the gases flowing by it. For a gas velocity of 8 m/s, making conservative assumptions regarding the equivalent duct diameter, a heat transfer coefficient of $h = 1.33 \times 10^{-3} \text{ W/cm}^2 \text{ } ^\circ\text{C}$ is obtained for Argon gas. The 0.02 W/cm^2 of bulk heating leads to a surface heat flux of 0.1 W/cm^2 per surface for a 10-cm-thick window. An antireflection coating that absorbs 10^{-3} of the beam energy at each surface adds another 0.01 W/cm^2 , yielding a total flux of $\phi = 0.11 \text{ W/cm}^2$ per surface. The temperature drop across the solid-gas interface is calculated from

$$\Delta T_s = \frac{\phi}{h} , \quad (3-10)$$

which yields 83°C in this case (assuming equal heat transfer on both sides of the window). Since antireflection coatings are deposited at temperatures in excess of 300°C , this temperature rise should be acceptable. However, if bulk or surface absorption is higher than anticipated, or if a thicker window is required, additional cooling may be necessary. Higher cooling rates could easily be obtained by flowing gas at a higher rate outside the window. If helium gas is used outside the window, the heat transfer coefficient would be increased dramatically. In any case it appears that the temperature rise in the window is not a limiting factor even for a rather thick window, provided the absorption coefficient is held to near the intrinsic limit for fused silica.

The structural integrity of a 10-cm-thick fused silica window is doubtful for a 2- x 2-m aperture, given the repetitive pressure waves incident on it. Doubling the thickness would improve chances of survivability, and might be acceptable from the standpoint of thermal load, but would essentially double the cost of this most expensive optical element. In addition, fabrication problems may be encountered for very thick large-aperture windows. It is felt that a more reasonable design approach would be to segment the window, rather than increase its thickness any further. The final design, therefore, assumes a four-piece window, each 1 x 1 m square, and 10 cm thick, supported by structural steel struts that are about 5 cm thick.

3.2.2.2 Considerations for a Purely Aerodynamic Window

If a purely aerodynamic window with no absorbing gas species is used, the optical attenuation and coating damage problems of the window are eliminated. However, as shown above, the deposition of energy in the active region causes significant mixing of the gas streams, so that fluorine must be removed from the window gas. The energy required for such a separation operation must be compared to the energy that would be lost if a solid window were used. It must also be realized that no separation process could be completely effective, so that some Ar, Kr, and F_2 gas would remain in the window gas stream and would eventually leak out into the propagation paths. This would require further systems for F_2 cleanup and Kr recovery, and might be unacceptable from a safety point of view.

The problem of separating fluorine from the window gas is crucial to the viability of the aerodynamic window. In the following section, a system employing a solid window set at a substantial standoff distance from the active region is considered. The problem of keeping fluorine gas out of the area between the active region and the window also occurs in that system. Further discussion of the fluorine separation systems required in either case appears in Section 3.2.3.

3.2.2.3 Considerations for a Gas Buffered Window

If a solid window is used close enough to the active region to limit fluorine absorption losses, it will have to be rather thick to withstand the pressure wave. Another potential design would reduce the required thickness by placing the window at a large distance from the active region, where the pressure wave is substantially attenuated. However, for reasonable standoff distances, this approach requires use of a gas buffer containing a substantially reduced concentration of fluorine between the active region and the window. In this respect, this approach is similar to that of the pure aerodynamic window. However, the use of a solid window has the advantage that the beam propagation path is physically sealed off from the KrF amplifier region, allowing their atmospheres to be maintained completely independently. Discussion of the fluorine separation systems required to condition the buffer gas is presented in the next section.

3.2.3 Fluorine Separation Systems

In the cases where a pure aerodynamic window or a gas buffered window are considered, the concentration of fluorine in the window gas or buffer gas must be kept very low in order to minimize optical absorption losses. It has been shown that the absorption of fluorine at the KrF laser wavelength is about 10%/m for the F_2 concentration that exists in the active region (0.3% or 3,000 ppm). To reduce this to less than 1%/m, the fluorine concentration must be kept below 300 ppm.

In order to minimize mixing of the gas in the active region with the window or buffer gas, the flow velocity of the two regions must be matched at the boundary between them. However, as is shown above, the release of energy in the amplifier heats and expands the active gas so that substantial mixing of the gas streams is inevitable. The expansion takes place at approximately the velocity of sound in the medium (~ 320 m/s), which is much faster than the transverse flow velocity (~ 8 m/s). It would appear reasonable to assume that all the fluorine that overflows the bounds of the active region must be subsequently removed from the buffer gas. From the previous analysis, this amounts to 17% of the F_2 initially in the active region for the present system design (see Fig. 3.2-1). This amounts to 8.8 g/shot, or 17.6 g/s per amplifier. For the total system of 14 amplifiers, this amounts to 245 g/s or 885 kg/h (almost 1 ton/h). It should be noted that this assumes a buffer gas on both sides of the active region. It may be possible to bring the mirror in close to the active region so that a buffer gas is not necessary on that side; in this case, the amount of fluorine to be recycled would be cut approximately in half.

For the purpose of performing some design calculations, it was assumed that only the buffer gas in the 50-cm region immediately adjacent to the active region (on both sides) needs to be cleaned, while the rest of the buffer gas is simply recycled. Because this region contains mostly buffer gas from between shots and from outside the expanded active region, the average concentration of F_2 in this stream is on the order of 1000 ppm (0.1%). The problem of recovering fluorine at the rate of 1 ton/h from a stream where its concentration is fairly low to begin with is formidable, as discussed below.

The options for removing fluorine from the buffer gas include cryogenic fractionation, absorption, adsorption, permeation, chemical removal, and thermal diffusion. Of these, thermal diffusion, permeation, and adsorption can readily be eliminated from further consideration. Thermal diffusion and

permeation require development programs before they can be utilized. Adsorption is an accepted industrial technique, but fluorine is so reactive that it will react with any common adsorbent. Development of an inert adsorbent would require a lengthy development program. The remaining three techniques are considered in more detail in the following paragraphs.

3.2.3.1 Cryogenic Fractionation

Fractionation at cryogenic temperatures is a well-developed industrial technology used mainly for air separation. The energy required for the separation is input through compression of the feed gas and through refrigeration from an external system (if autorefrigeration is not used). The separation process depends strongly on the assumed composition of the buffer gas. Three cases were considered in this study: an Ar/Kr mixture in ratio 94/6, a pure Kr buffer, and a pure He buffer.

The Ar/Kr buffer mixture has essentially the same specific gravity and viscosity as the active gas and therefore minimizes preshot turbulent shearing between the active and buffer gas regions. However, fluorine and argon boil at temperatures that are only 2.3 K apart, so the separation of fluorine is very difficult. In addition, the freezing points of argon and krypton are within 4 K of their boiling points at atmospheric pressure. In order to keep krypton from solidifying in the equipment, all temperatures need to be kept above 116 K. Pure fluorine does not liquefy at atmospheric pressure until the temperature is reduced to 85 K, and--in order to make this fractionator work properly--the column pressure must be increased until it liquefies above 116 K. This requirement dictates an operating column pressure of about 200 psia.

A lower limit to the power used by the compressor can be obtained by assuming isothermal compression. To the extent that heat is not removed during the compression process, the increase in temperature of the gas results in higher pressure and therefore higher compressive power. From the ideal gas law at constant temperature the work done on the gas is given by

$$W = -\int_i^f P dV = nR^T \int_i^f \frac{dP}{P} = P_i V_i \ln \left[\frac{P_f}{P_i} \right]. \quad (3-11)$$

The compressive power is given by

$$\frac{\dot{W}}{\dot{V}} = P_i \left(\frac{\dot{V}_i}{\dot{V}_f} \right) \ln \left[\frac{P_f}{P_i} \right], \quad (3-12)$$

where $\Delta V_i/\Delta t$ is the volume of feed gas to be processed per unit time. In this case the feed gas stream for each amplifier consists of two ducts 50 cm x 2 m in cross section, with gas flowing at 8 m/s giving $\Delta V_i/\Delta t = 16 \text{ m}^3/\text{s}$. With $P_i = 14.7 \text{ psia}$ ($1.013 \times 10^5 \text{ nt/m}^2$), and $P_f = 200 \text{ psia}$, Eq. (3-12) yields $\Delta W/\Delta t = 4.2 \times 10^6 \text{ W}$ per amplifier. Allowing for some inefficiency and lack of ideal isothermal conditions, the actual compressor load will be somewhat higher. This figure would be cut in half if only one slipstream (the one on the window side) has to be processed. This amount of process energy consumption in itself looks prohibitive from the point of view of laser efficiency because it is comparable to the total 6 MW per amplifier electrical input to the e-beams.

The flow diagram for a heat exchanger-fractionator combination is shown in Fig. 3.2-2. Both of these major units, with their piping, would be built in a "cold box," packed with insulation, and purged with a dry gas. The feed gas (F) is compressed to column pressure before entering the exchanger in order to maintain the proper temperature differences. An external refrigeration system is assumed. The fractionator was calculated to take overhead (D) an amount equal to the amount that expanded from the active gas into the buffer gas, and containing essentially all the fluorine. The overhead is returned to the active gas loop, while the fluorine-depleted bottoms (B) are returned to the buffer gas. Calculations were performed for a number of designs corresponding to various numbers of trays and reflux ratios. The two best designs gave the following results:

	<u>Case I</u>	<u>Case II</u>
Number of Trays	52	52
Feed Tray (from top)	11	11
Reflux Rate (lb moles/h)	20,000	10,000
F_2 in bottoms (ppm)	85	290
Kr in Overhead	0	0
Refrigeration Load (W)	$30.5(10^6)$	$15.8(10^6)$
Refrigeration Temperature (K)	116	116

Neither of these designs appears practical because of the very high refrigeration loads. Case II represents a power input of about 32 MW per amplifier, assuming a refrigeration coefficient of performance of 0.5. The problem with this design is the difficulty of separating the fluorine from the

Fig. 3.2-2 Process-flow diagram for F_2 separation from the window buffer gas (Ar/Kr mixture or pure Kr) by cryogenic fractionation.

majority component, argon. However, the 290-ppm concentration of F_2 in the bottoms (Case II) yields an absorptivity in the buffer gas of 0.1%/m, which should be acceptable for the buffered-window scenario.

Using pure krypton as a buffer gas simplifies the separations. Figure 3.2-2 also serves as a flow diagram for this design. Here the overhead is designed to contain all the fluorine and no more than 6% krypton. The overhead is recycled to the active gas, and the krypton bottoms are recycled to the buffer gas. Calculations were performed for five cases, with the best--but not necessarily optimum--giving the following results:

Number of Trays	22
Feed Tray (from top)	12
Reflux Rate (lb moles/h)	5008
F_2 in bottoms (ppm)	0.22
Kr in Overhead (mole %)	6.4
Refrigeration Load (W)	$5.9(10^6)$
Refrigeration Temperature (K)	131

While the use of a krypton buffer reduces the energy required for the separation significantly, the technique is still unattractive. The column pressure of 200 psia still requires more than 4 MW of compressor power, and the power input to the refrigerator is 12 MW per amplifier, assuming a coefficient of performance of 0.5. This amount of input power would reduce laser efficiency by a factor of almost 4. In addition, the increased Kr inventory used here would be quite expensive. As a result, the pure krypton buffer gas does not appear to be a practical alternative either. It is possible that a fractionation system with a solid Kr or Ar/Kr interface with F_2 vapor could be designed, but this alternative was not investigated here.

If helium is used as a buffer, the capital investment in gas can be reduced significantly from the case of krypton. Also, the helium boiling point is much lower than the other gases, and it cannot be liquefied at normal cryogenic temperatures. Hence a liquid-vapor fractionator is not an appropriate approach. In this case, a simple flash separation was investigated. Figure 3.2-3 shows the flow diagram for this scheme. The feed gas is compressed and refrigerated, so that fluorine, argon, and krypton condense in a single-step process. The flash would be made at pressure to prevent freezing krypton. Analysis of this process has shown that only a

Fig. 3.2-3 Process-flow diagram for F_2 separation from helium buffer gas by flash separation.

negligible amount of liquid is condensed, even at an inlet pressure of 700 psia and a temperature of 113 K (already below the freezing point of krypton). The isothermal compression power input alone at this pressure is 6.3 MW per amplifier. Therefore this approach also appears impractical.

3.2.3.2 Separation by Absorption

Absorption of a component from a gas stream in a higher boiling liquid is a standard industrial separation technique. It is a particularly attractive option in this case for these reasons:

- o Absorption can be done at ambient temperature and atmospheric pressure if a suitable solvent is available for those conditions.
- o Only the minority component, fluorine, is removed. The bulk of the gas need not be condensed.
- o Absorption does not provide sharp separations, which fractionation does provide. It will also remove some of the carrier gas. In this case, the sloppy separation is not harmful.

The disadvantage of absorption for this separation is that fluorine reacts with all normal solvents. About the only class of materials that might be suitable are the totally fluorinated compounds, such as perfluoroheptane or hexafluorobenzene. These two compounds are stable, nontoxic, and nonflammable. Their boiling points are 82.5°C and 80.3°C, respectively, which is lower than desirable but still feasible. Sulfur hexafluoride is also stable, nontoxic, and nonflammable, but it has a vapor pressure over 20 atm at 25°C and is ruled out for that reason.

Unfortunately, solubility data for the noble gases and fluorine in fluorinated solvents are not available. Lawrence Livermore National Laboratory, at Bechtel's request, has conducted a literature search and has found nothing. Without these data, a detailed design could not be made. Figure 3.2-4 is a flow diagram for a typical absorber-stripper combination. Since this type of separation promises to be more economical than fractionation, a suitable solvent should be selected and solubility data obtained experimentally.

3.2.3.3 Chemical Separation

Fluorine is produced commercially by electrolysis of hydrogen fluoride in an anhydrous fused electrolyte, $\text{KF} \cdot 2\text{HF}$ (melting point 71.5°C), at

Fig. 3.2-4 Process-flow diagram for F_2 separation from the window buffer gas by selective absorption in a suitable solvent.

90 to 95°C. A standard production cell operates at a current of 6000 A with a voltage that varies from 8 to 12 V over the life of the cell. The fluorine produced from the cell is contaminated with about 10% hydrogen fluoride and some carbon tetrafluoride. It can be purified by refrigerating to -140°C, or by scrubbing with sodium fluoride. The standard cell described above produces slightly more than 1.0 g of F₂ per second, for an average electrical power input of 60 kW. It was estimated previously that each KrF amplifier will lose 17.6 g of F₂ into the buffer gas per second. At this rate, the power required for electrolysis alone in a chemical separation system would be slightly greater than 1.0 MW per amplifier. It is possible that this figure could be cut in half if no buffer gas is used on the mirror side of the amplifier.

At first glance, this approach looks promising because the impact on overall efficiency would be much smaller than for the fractionation schemes discussed previously. The buffer gas stream to be purified would be mixed with hydrogen from the electrolysis cell to make hydrogen fluoride. The reaction should not be difficult to control at the low concentrations involved here. The boiling point of HF at atmospheric pressure is 19°C, so that separation by condensation at low temperatures is much easier than for F₂ (bp -188°C). However, it is estimated that the initial concentration of HF in the stream to be purified is only about 2000 ppm. Examination of the HF vapor pressure curve shows that at -75°C and 500 psia, only about 30% of the HF would be condensed. The power required for compression of the gas to 500 psia would be at least 5.7 MW per amplifier at room temperature (using Eq. (3-12)). Cooling to lower temperatures would cause additional problems because HF freezes at about -83°C. It is possible that a system based on precipitation of solid HF from the gas at much lower temperatures and atmospheric pressure could be designed. This approach was not examined here and may warrant further investigation. In any case, residual HF in the buffer stream must be removed by other (most likely chemical) means.

Hydrogen fluoride can be removed from the gas by absorption in an aqueous solution of calcium hydroxide (lime water) to precipitate solid calcium fluoride. A process flow diagram based on this approach is shown in Fig. 3.2-5. The calcium fluoride, after filtration and drying, is reacted with sulfuric acid to regenerate hydrogen fluoride, which is then electrolyzed. The buffer gas would also require dehydration before being returned to the amplifier flow system. While the overall process appears

Fig. 3.2-5 Process-flow diagram for chemical separation of F_2 from the window-buffer gas.

feasible, it is complicated and labor-intensive, and requires the handling of some very corrosive chemicals. The additional energy input to the process has not been determined, but is likely to be substantial. Furthermore, a waste stream of impure gypsum is produced in the reaction of calcium fluoride with sulfuric acid, and must be disposed of. For these reasons it is concluded that chemical separation appears unattractive.

3.2.3.4 Conclusion on Fluorine Separation

All types of cryofractionation systems studied were found to require very large power input for compressors and refrigerators. Chemical cleanup was not investigated in significant detail, but also appears to be energetically expensive. The prospect of separating fluorine by absorption in a totally fluorinated liquid appears attractive, but no data on fluorine and rare gas solubility could be obtained, so suitable designs could not be studied in detail. Since no acceptable separation system was identified, the concepts of aerodynamic windows and gas-buffered windows for the KrF amplifiers have been dropped from further consideration.

3.2.4 Other Flow Design Considerations

From the preceding sections it is apparent that the only reasonable design approach identified to date for the KrF amplifier is to use a highly pure fused silica window that stands as close as possible to the active region. Analysis by Physics International (Appendix 1) indicates that at a distance of 20 to 25 cm from the active region, and with a 1-kG magnetic guide field, heating by sidescattering from the e-beam will not damage the window or its coating. If the window and mirror are both placed 25 cm from the active region, then the total amplifier cavity measures 3.5 m x 2 m x 2 m. At a distance of 25 cm, the loss due to absorption of fluorine in the inactive region will be 2.5%. The window at this distance must be thick (~10 cm) and probably segmented (four pieces, 1 x 1 m each is assumed) in order to withstand the pressure wave. If the segments are supported by steel struts 5 cm wide, an additional loss of at least 5% due to their shadows must be accepted. Adding the absorption loss in the window and coating the total window brings optical losses to about 10%. Gas flow systems specific to the Ar/Kr/F₂ active gas mixture are discussed in the next few paragraphs.

3.2.4.1 Construction Materials

At temperatures near ambient, dry fluorine has been handled satisfactorily in steel, stainless steel, nickel, and copper. The surfaces are apparently passivated by oxidation of a thin surface layer. The low concentrations in the laser amplifier should cause no problems, and the preliminary choice of construction material is mild steel. It should be noted that the system must be kept extremely dry because water vapor increases the corrosion of both the metal walls and quartz windows (if used) of the amplifiers.

3.2.4.2 Heat Removal

If the full 1.44 MJ of e-beam energy lost in the gas per shot is assumed to go into gas heating, then the average temperature of gas entering the heat exchanger will be 160°C. The cooling water inlet and outlet temperatures are taken to be 35°C and 50°C, respectively, and the gas outlet temperature is 50°C. The required cooling water flow rate under these conditions is about 800 galls per minute (gpm) per amplifier.

To reduce pressure drop, the exchangers are designed with the same cross-sectional area as the ducts they connect to. The tubes are installed along the larger dimension (3.5 m long) and are finned to improve the heat-transfer coefficient. The cooling water makes an equal number of passes across the duct in each direction to minimize gas-temperature differences across the width of the duct at the exit. Making reasonable assumptions regarding heat transfer coefficients, but without detailed exchanger design, a total heat transfer area of 6600 ft² for each amplifier flow loop is estimated. A preliminary estimate of the pressure drop through the heat exchangers gave approximately 1 psi. It is felt, however, that a detailed design to minimize pressure drop could reduce this to 0.5 psi.

Since the amplifier is firing twice a second, the temperature of the gas at the exchanger inlet will vary with some regular pattern. This temperature pulsation will be damped somewhat by the turbulence in the gas, and the exchanger itself will damp it more for two reasons:

- o The tubes create turbulence and mixing by the alternate contractions and expansions as the gas flows between them.

- o Due to the increased temperature difference, the hotter gas will transfer more heat to the water than the cooler gas, thus leveling out the temperature cycle.

In spite of these damping effects, it appears likely that there will be some temperature cycle at the exchanger outlet. Some of the residual cyclic effects will be removed by flow stream shearing around turns. Hopefully the remainder will be adequately eliminated by the extreme turbulence in the blower.

The control temperature should be measured downstream from the blower. It is possible that temperature uniformity of less than 1°C may be required in the laser cavity to limit optical wavefront distortion by refraction in the medium. This may be difficult to do using existing industrial technology. Further study of the exact process requirements and potential solutions is needed.

3.2.4.3 Pressure-Wave Damping and Flow Management

The pressure wave initiated by the deposition of e-beam energy will reverberate in the ducts of the flow loop for some time after each shot. If significant residual-gas density fluctuations still exist in the laser cavity at the time of the next shot, the wavefronts of the laser pulses will be distorted, and the increased beam divergence may reduce the energy incident on the Raman cell. Previous studies^{3,4} have shown that residual density fluctuations can be a significant problem when a pulsed laser is used to irradiate a small fusion pellet target (on the order of 1 mm in diameter), especially when the time between pulses is short (high repetition rate). Neither of these conditions is obtained in the present study, and no adequate analysis of laser beam divergence under conditions appropriate to this system has yet been performed.

When a 1-mm target is irradiated by a laser from a distance of 100 m the target subtends an angle of $10\text{ }\mu\text{rad}$, as seen from the laser. In order to efficiently couple energy to the target, the beam divergence must be small compared to this angle. In the present system the longest optical path from the amplifier to the Raman cell is 400 m (including optical delays), but the effective target size is on the order of 1 m (the Raman cell aperture). Thus the Raman cell subtends an angle of 2.5 mrad , as seen by the amplifier. Therefore, the allowable KrF beam divergence in the Raman pulse compressed system is 250 times larger than for the previous example. To illustrate, a $10\text{-}\mu\text{rad}$ beam divergence increases the spot size at the Raman cell by only 4 mm (maximum) and reduces the efficiency by less than 1%, whereas a $10\text{-}\mu\text{rad}$ divergence would cause direct target irradiation to be cut by a factor of more than 2.

In addition, the interpulse time is 500 ms for the system under consideration here. The transverse acoustic transit times for the duct with a sound-wave velocity of 325 m/s are 6 ms and 11 ms for the 2-m and 3.5-m dimensions, respectively. Transverse acoustic modes will undergo 80 and 45 reflections in the short and long dimensions, respectively, between shots. If only a 20% reduction in amplitude per bounce is assumed, the attenuation factors would be 10^7 and 10^4 for sound waves rebounding between shots in the short and long dimensions, respectively. These are felt to be quite adequate attenuation factors and should be obtainable with passive sidewall absorbers. On the other hand, the longitudinal acoustic transit time (around the flow circuit) is about 100 ms, indicating only five transits between shots. However, the longitudinal path travels through the blower and heat exchanger, which will provide considerable damping on each pass.

It is likely that some form of acoustic absorbers will be necessary to provide the required transverse-wave attenuation. Provision has been made for vented (perforated) sidewall absorbers on all sides of the duct for a distance of 4 m up and downstream from the laser cavity. If this type of muffler is not adequate, porous materials can be added along the walls and/or in the side-vent cavities. It may also be useful to include some low-pressure drop-flow conditioning elements, such as flow straightening vanes, a honeycomb (an array of longitudinal hexagonal tubes), and perhaps even a screen, upstream from the laser cavity to further reduce any density nonuniformity. None of these devices is expected to add any significant pressure drop in the flow loop, and adequate medium homogeneity is expected. Further theoretical and experimental studies of the exact system requirements in this area, and how to achieve them, are needed.

3.2.4.4 Pressure Drops and Blower Power

The amount of gas circulated in each KrF amplifier gas loop is very large (about 56,000 l/s). To reduce the power required to circulate this amount of gas, it is necessary to keep the pressure drops as low as possible. An estimate of the pressure drops due to various components in the flow channel is given by (see Ref. 3)

$$\Delta P = K_i \rho \frac{v^2}{2}, \quad (3-13)$$

where ρ is the gas density, v is its velocity, and K_i is a constant

characteristic of the i th component. The gas velocity in this system is rather low, so that $\rho v^2/2$ is only 10^{-3} atm. The sum of all coefficients, K_i , for components in this flow loop, outside the heat exchanger (screen, honeycomb, boundary layer friction, flow turns, etc.), is on the order of 10 (see Ref. 3), so that $\Delta p \sim 10^{-2}$ atm is estimated for them.

The major pressure drop will occur in the heat exchanger itself. With careful design, it is felt that this drop can be limited to about 0.035 atm (0.5 psi). With inclusion of the other frictional losses, a total loop-pressure drop of 0.045 atm is estimated. The power dissipated in the flow loop is given by

$$P_F = \Delta p \cdot \frac{\Delta V}{\Delta t}, \quad (3-14)$$

where $\Delta V/\Delta t$ is the volume flow rate. In this system the dissipated power is 260 kW per amplifier loop. If a blower efficiency of 0.7 is assumed, an input power of 370 kW would be required.

The blower can be a standard power-plant design. The only nonstandard item is lubrication. Standard petroleum lubricants cannot be used because they will react with the fluorine gas. Either fluorinated lubricants must be used, or the machine must be run dry (carbon or teflon bearings).

3.2.4.5 Cooling Water Flow Power

Typical industrial cooling tower head pressures run about 50 psi. At 800 gpm through the heat exchanger, the power dissipation is 17.4 kW per amplifier. Twenty-five kilowatts of water pump power will be required for each amplifier, assuming 70% pumping efficiency.

3.2.4.6 Laser Gas Cleanup

The laser gas will inevitably be contaminated by impurities from leaks, material outgassing, and from fluorine reactions. Air leaks introduce carbon dioxide and water vapor into the system, in addition to nitrogen and oxygen. Water is particularly harmful because it increases the corrosivity of the fluorine.

Fluorine reaction products will accumulate in the system with time. Some of these reaction products are metallic fluorides from the duct work, valves, blower, etc., and these will be present as fine particulates. Other common fluoride compounds that may appear include carbon tetrafluoride, hydrogen

fluoride, and the whole range of fluorinated hydrocarbons. Many of these compounds are gases under the operating conditions.

Contaminant gases can be removed by bleeding off a small stream of gas and removing all but the rare gases from it. Fluorine and oxygen can be removed by reacting with a hot metal. Most other molecular impurities (with the exception of nitrogen) can be removed with a cold trap. Finally, N_2 can be removed by reaction with hot magnesium, $3 Mg + N_2 \rightarrow Mg_3N_2$. The rare gases are then returned to the main flow loop with fresh fluorine from an external tank. Continuous monitoring of the gas composition will be necessary. External gas tanks will also be used to readjust the partial pressures of the rare gases. The cost of the gas maintenance system should be relatively small because the feed rate is small. More detailed design of the cleanup system should be undertaken when more is known about the contamination rates and the effects of the various contaminants on laser operation.

3.2.4.7 Startup and Shutdown Operations

A cost saving in the construction of the flow system is realized if it is not required to be evacuated before being charged with the laser gas. In this case, the duct work will not need reinforcement to withstand the inward atmospheric pressure. A procedure for filling the laser flow loop that avoids vacuum pump down is then required.

The filling procedure can start with a purge of the system by argon gas. This should be done by introducing the heavier argon at the bottom of a flow loop and venting the lighter atmosphere (mostly N_2 and O_2) from the top. The vent from one flow loop should be connected to the inlet of the next. In this way, the total amount of argon vented to the atmosphere will be minimized. Krypton gas should then be introduced in proper proportion to each amplifier through the bottom inlet, while venting argon from the top. Residual impurities in the gas system should be removed chemically before the fluorine is added. This could be done by the systems designed for cleanup of the laser gas if the impurity concentrations remaining after purging are sufficiently low. The small fraction of fluorine required would be introduced as a last step before operation begins.

When maintenance on the amplifier system is required, it will sometimes be necessary to remove the laser gas and reintroduce a normal atmosphere to the flow loop. Fluorine should be chemically stripped from the flow system as a first step. Argon and krypton could then be vented to the atmosphere.

However, the cost of these gases will probably dictate that they be pumped into storage for reuse (each amplifier system will contain approximately \$30,000 worth of Kr and as much as \$3,000 worth of Ar, depending on its purity). If the inert gases are to be stored, they should be reasonably well separated so that the subsequent filling procedure can be performed as indicated above. Krypton should be removed by a small cryogenic fractionator designed for this purpose. Argon or helium can be introduced to maintain atmospheric pressure as the krypton is removed. The argon can then be displaced with helium, from which it is separated cryogenically and pumped into storage tanks. Finally, the helium would be vented while it is displaced by the normal atmosphere (the helium gas lost by venting would be valued at less than \$500 per amplifier). Allowances for the necessary gas handling and storage systems have been included in the cost estimates for mechanical equipment.

3.2.4.8 Flow System Layout

Figure 3.2-6 is a layout of the KrF amplifier flow loop as envisioned at the end of this study. No provision is made for buffering the amplifier window or mirror with a fluorine-free gas. Gas handling systems for startup, shutdown, and cleanup are not shown. The heat exchanger is divided into two parts, one to remove heat added by the e-beam, and the other to remove heat added by the blower.

3.3 Methane Raman Cell Gas Flow Systems

The active region of the backward Raman pulse compression cell must be 15 m long, corresponding to half the length of the 100-ns KrF pump pulse. Further general design parameters for the Raman compressor established at the beginning of the study are given in Table 3.3-1. A backward first Stokes gain of 10^3 is obtained by double passing the pump and Stokes beams through the cell. The geometry of the optical system shows that, with a reasonable distance between Raman cell mirrors (180 m end-to-end), the clear aperture must be approximately twice the output aperture. The final design, therefore, allows for two separate cells side-by-side (one for each pass of the pump and Stokes pulse), each with an aperture of 4 x 12 m.

High-purity uncoated quartz (e.g., suprasil) windows oriented at Brewster's angle are used to enclose the methane. The optical pulses are assumed to be linearly polarized to minimize reflection losses. The

Fig. 3.2-6 KrF amplifier gas-flow system.

Table 3.3-1
Methane Raman compressor design parameters.

Stokes pulse length	20 ns
Extraction efficiency	80%
Compression factor	5x
Pump pulse length (cell length)	100 ns (15 m)
Cell pressure	1 atm
Stokes output fluence	4 J/cm ²
KrF pump fluence	5 J/cm ²
Output energy	1.5 MJ (est.)
KrF pump energy	1.9 MJ (est.)
Output aperture (2 x 7 beam array)	3.3 x 11.6 m

Brewster-angle orientation also reduces the energy fluence on the optical surfaces by the cosine of the angle. In this case, the output window sees the maximum fluence of approximately 2.3 J/cm^2 at 248 nm in 100 ns, followed by 2.2 J/cm^2 at 268 nm in 20 ns.

The vibrational energy deposited in the methane in the process of Raman scattering raises the temperature and pressure of the medium only very slightly. Therefore, little acoustic damping is required, and the windows need not be thick (a 1-cm thickness is assumed). The amount of energy deposited in the methane, E_d , is given by

$$E_d = E_s \frac{\nu_r}{\nu_s}, \quad (3-15)$$

where E_s is the output Stokes pulse energy, and ν_s and ν_r are the Stokes and Raman frequencies, respectively. Here $\nu_s/\nu_r = 9.08$, so with $E_s = 1.5 \text{ MJ}$, only 120 kJ is deposited in the methane. Approximately 85%, or 100 kJ of this total is deposited on the second pass. For methane, $C_v = 3.2 \text{ nR}$, so the temperature rise is given by the following (compare Eqs. (3-2) and (3-3))

$$\frac{\Delta T}{T_0} = \frac{\Delta U}{3.2 P_0 V_0}. \quad (3-16)$$

The active volume of the second Raman cell is approximately 600 m^3 , which at a pressure of 1 atm yields $P_0 V_0 = 60 \text{ MJ}$. Using Eq. (3-16), with $T_0 = 300 \text{ K}$, the average temperature rise in the second Raman active region is found to be less than 0.2°C , and the corresponding pressure rise is only 0.4 Torr.

If necessary, it is felt that the small pressure wave generated by the Raman scattering process can be adequately damped out by passive porous acoustic absorbing material on the inside walls of the Raman cell. Since the temperature rise is very small on each shot, the gas can be allowed to flow longitudinally along the cell. At a flow rate of 1 m/s, 30 shots will be fired at 2 Hz during the passage of the gas through the 15-m-long active region, with a net temperature rise of less than 5°C in the second cell ($\leq 1^\circ\text{C}$ in the first). The resulting longitudinal temperature gradient in the methane is not expected to degrade beam quality significantly (a lateral gradient would cause some beam steering).

In the second Raman cell, a heat exchanger must be provided in the return gas flow loop to remove 200 kW of heat. This can be done with the equivalent of a 700,000-Btu/h air conditioning system. Approximately another 100,000 Btu/h is required in the first Raman cell. The total heat exchanger surface area will be small, as will the corresponding pressure drop through it. This, combined with the slow gas flow velocity, will result in a rather small required input power to the gas circulation blowers. It is felt that a few kilowatts of blower power will be adequate, which is a negligible addition to the overall system input power. Variations in the design of the methane flow system, including higher velocity transverse flow, would not increase the required blower power to a point where an impact on overall system efficiency would be felt.

Gas purity is not a significant issue in the Raman amplifier, because most commonly expected contaminants will not interact with the laser pulses. If natural gas is used as a source of methane, it may be necessary to remove heavier hydrocarbons cryogenically before filling the cell (ethane concentrations of several percent would be anticipated). The cell can be filled by purging until the concentration of impurities is sufficiently low. During the purge, excess methane can be vented to the atmosphere, or burned off as appropriate. Similarly, during operation a bleed stream may be vented or burned externally, while fresh gas is added to maintain adequate purity. The simple gas-handling systems required will have little impact on system cost and negligible impact on overall energy-conversion efficiency.

3.4 Overall System Energy Output and Efficiency

The system has been designed with the goal of 160-kJ output energy from each final amplifier. At 2 Hz the total average power out of the 14 amplifiers is 4.48 MW. Assuming an intrinsic efficiency of 10% and an e-beam deposition efficiency of 57%, the input power to the dc power supplies must be 78.6 MW. The final amplifier output is degraded by the window losses (including free F_2 absorption) and amplifier fill factors (shadowing), in addition to output mirror reflectivities before pulse compression in the Raman cell. Overall losses--estimated in Table 3.4-1--result in an output beam after Raman compression with an average power of 2.63 MW, and a laser electrical efficiency of $2.63/78.6 = 3.3\%$. The output energy per shot is 1.31 MJ.

The output energy is considerably less than the design goal of 1.5 MJ. The primary reason is the inclusion of window losses due to F_2 absorption

and the reduced fill factors resulting from the strut shadows in the faceted windows and amplifier housing shadows. Designs that occlude less of the active region with physical structures could improve this situation. At the same time, the input power is considerably higher than anticipated because of the low e-beam generation efficiency. It appears likely that innovation in the e-beam generating system could improve on its efficiency.

To estimate the overall system efficiency, the power used in auxiliary equipment must be added to that input to the power supplies. The KrF amplifier blowers will consume approximately 5.6 MW at 400 kW apiece. The e-beam magnetic guide field systems use up 2.8 MW, assuming 15% loss of energy in the resonant circuit per shot. Finally, the cooling tower water pumps will use 0.7 MW if a 50-psi head pressure is assumed. The total system input power is therefore 87.7 MW, and the overall efficiency is $2.63/87.7 = 3.0\%$. The above estimates are also shown in Table 3.4-1. While this is considerably less than the 5% efficiency desired, it is hoped that improvements in the design can substantially increase the efficiency.

3.5 Structures and Auxiliary Equipment

Synchronization of the pulses from each set of seven final amplifiers is ensured by scraping input pulses spatially from the output of a single preamplifier. The scraped pulses are then distributed radially outward to the final amplifier modules and recombined spatially after amplification at the central location.

3.5.1 Stacker Beam Channel Design

The layout of an individual stacker channel for a single final amplifier is shown in Fig. 3.5-1. Input and output rays are shown. Detailed ray tracing for the stacker optics was shown in Figs. 2.1-1 and 2.1-2.

The segmented primary and tertiary telescope mirrors are set side by side in order to minimize the look angles into the amplifier and thereby maximize the amplifier fill factors. The distance from the amplifier secondary mirror to the primary/tertiary arrays is set by the requirement of >95% amplifier fill factors for all beams (neglecting window strut shadows). Here, a distance of 120 m was chosen, and should give >95% fill for the outer beams and >98% fill for the inner beams.

The delay-generating and delay-removal mirrors are placed on opposite sides of the propagation channel. The unit magnification of the telescope

Fig. 3.5-1 Individual stacker beam channel.

Table 3.4-1
Laser system output and efficiency.

Laser electrical efficiency

<u>Source</u>	<u>Efficiency(%)</u>	<u>Power (MW)</u>
Wall plug input	100	78.6
E-beam deposition	57	44.8
Intrinsic KrF medium	10	4.48
Windows and fill factors	90	4.03
Mirrors	82	3.28
Raman conversion	80	2.63
<hr/>		
Total laser output	3.3%	2.63 MW (1.3 MJ/shot)

Auxiliary equipment input power

Gas-flow blowers	5.6 MW
Magnetic guide fields	2.8 MW
Cooling water pumps	0.7 MW
<hr/>	
Total auxiliary input	9.1 MW
E-beam wall plug input	78.6 MW
<hr/>	
Total system input power	87.7 MW

Overall system efficiency $\frac{2.63 \text{ MW}}{87.7 \text{ MW}} = 3.0\%$

requires rectangular beam-channel dimensions of 2 x 6 m. Some optical aberration results from using the spherical mirrors off-axis. This is minimized by minimizing off-axis angles and therefore requires that the delay mirrors (input and output) be as close to the amplifier end of the channel as possible. The separation between delay mirrors is 15 m in order to generate the required 100-ns time delays.

The most compact beam channel was obtained by allowing the input and output beams to cross each other at the input/output aperture of the channel. The distance from the input scrapers and output mirrors to the beam channel entrance is defined so that clipping of the input beams by the channel aperture is avoided. In this case a distance of 30 m is acceptable. Between the channel entrance and the perimeter building that houses the final amplifier systems, the channel is supported by steel I-beams rising from concrete pylons. Allowance is made in the area of the stacker delay optics for platforms with increased stability.

The channel walls are 1-cm-thick steel plate, welded leak-tight, with insulated siding. External steel ribs are included for cross-sectional rigidity. A ventilation system is included to circulate the atmosphere in the propagation path. Piping is included to transport cooling water to the mirrors. Allowance has also been made for electrical lighting and instrumentation.

3.5.2 Perimeter Amplifier System Housing

The major components of the final amplifier systems are also shown in Fig. 3.5-1. The Marx-bank-driven PFL e-beam generators for 400 ns, discussed in Appendix 1, are shown on either side of the amplifier cavity. The gas-circulation system described in Section 3.2 is also shown. Power supplies for the Marx bank charging at ± 50 kV dc are shown with appropriate scale, as are the capacitor banks for energy transfer to the magnetic guide fields. A reasonable lateral spacing of the equipment dictates a building width of 20 m.

The length of the PFLs and e-beam output tubes would necessitate a large angular separation between adjacent final amplifiers if they were situated in the same plane. Since this would lead to an excessive length for the perimeter building, it was decided to stack the pulse-forming systems, as shown in Fig. 3.5-2. A vertical separation of about 10 ft between the top of the PFLs and adjacent Marx banks is required for maintenance accessibility. The distance from the bottom of the lower-module blowers to the top of the

Fig. 3.5-2 Perimeter building elevation.

upper-module ductwork is 30 m, and the enclosing building is designed to be 35 m high to allow space for overhead cranes. With this design the angular separation between beam channels is 10° , as shown in Fig. 3.5-3.

The perimeter building is assumed to be a simple industrial metal frame structure. Sufficient structural steel for equipment support and some interior finish has been allowed for. Additional equipment required in the building includes the following:

- o A power distribution system for approximately 90 MWe (78.6 MWe of which is at 13.8 kVAc).
- o Cooling units for the PFL dielectric water (4,000 cooling tons total system capacity).
- o Heat exchangers for cooling the Marx bank oil.
- o Other cooling water systems (total cooling water requirement is about 25,000 gpm).
- o Marx oil piping to oil storage tanks.
- o Safety gas purification system (carbon filter vent).
- o Laser gas input, processing, and storage equipment.
- o Miscellaneous - monorail hoists, sewer system, lighting, fire protection, process instrumentation, air conditioning and heating systems, etc.

No provision has been made for noise suppression, or for shielding of the x rays generated by the e-beam in the amplifier. These issues require further investigation.

3.5.3 Hub Building Design

For this study it was assumed that the building that houses the input scrapers and output mirrors (the "hub" building) extends radially outward to the channel entrances. This is a conservative design assumption because beam tubes could be extended inward behind the primary and tertiary mirror arrays to enclose the input/output beams and thereby reduce the building's radius. Further investigation of this possibility would require a more detailed design of the input optical train, which is beyond the scope of this study.

The output mirror array is designed to combine the beams from the 14 amplifiers in a 2 x 7 stack, yielding an output beam 3.3 m wide x 11.6 m high (see Fig. 2.3-1(a)). The stacker channels must connect to the hub at different heights to accomplish this, and are therefore slanted at different angles between the hub and perimeter buildings. The final amplifiers themselves must be correspondingly slanted. In this design the primary and

Fig. 3.5-3 Fusion laser building plan.

tertiary stacker telescope mirrors are mounted at the entrance to the stacker channels at the outer wall of the hub. The height of the building was conservatively taken to be 15 m to allow reasonable clearance above the various mirror arrays.

This building also contains the equipment for control of the atmosphere in the beam-propagation paths. In this case, the atmosphere has been assumed to be helium so that Rayleigh scattering of the short-wavelength laser light is kept to a minimum. The purity of the helium need not be high. Contamination with constituents of the normal atmosphere (primarily N_2 and O_2) will not produce significant losses until they reach about 10% concentration. For this reason the pressure in the beam paths may be kept slightly below atmospheric to minimize leakage of helium to the atmosphere. A system for maintaining adequately low impurity levels has been allowed for.

The structure consists of 1-cm-thick steel plate welded leak-tight, with insulated siding supported by internal steel framework. A welded steel floor is also included. Allowances have been made for piping of cooling water for the mirrors, circulation of the atmosphere (ventilation), electrical lighting, and instrumentation.

3.5.4 Raman: Compressor Building Design

The Raman compressor building extends outward between the two sets of seven amplifier channels. The length of the channel is determined by the requirement of adequate fill factors in the central methane cells. An overall length of 180 m has been assumed for this design. The two methane cells have a combined width of 8 m at the center, but the width of the channel at the ends must be 12 m. This accommodates the pump input, Stokes turning-mirror array, and beam dump at the hub end; and the Stokes input optics, pump-turning mirror array, and output window array at the other end. As a conservative assumption, the channel is taken to be 12 m wide throughout its length. The height of the channel is 15 m to allow some clearance for the optics and the beams.

The structure consists of 1-cm-thick steel welded leak-tight, including the floor. External steel supporting ribs are assumed for cross-sectional rigidity. The details of the Raman cell system are discussed in Section 3.3. A cooling system for the beam dump (1.6×10^6 Btu/h, or 400 kW) is included to remove the heat generated by absorption of the remnants of the pump beam. Allowances have also been made for circulation of the atmosphere in the beam

paths (ventilation), piping for cooling water to the mirrors, and beam dump, electrical power to methane blowers, lighting, and process instrumentation.

3.5.5 Sitework

The cost estimate includes development of the external site. This includes 200,000 cubic yards of grading, 100,000 ft² of roads and paved areas, yard piping, and electrical lighting. The estimate also includes a cooling tower with 700 kW of pump power to handle the total 25,000 gpm of cooling water.

3.6 Facility Construction Cost Estimate

3.6.1 General

The project consists of construction of a KrF laser system suitable for use as a target ignitor in an experimental inertial fusion test facility. This KrF fusion laser system consists of the following:

- o Twenty-eight e-beam generator systems, each depositing 0.8 MJ of energy in the active laser gas in a pulse width of 400 ns. The e-beam systems include suitable Marx capacitor banks, PFLs, output switches, output lines, vacuum diodes (including anode foils), magnetic guide field generators, and appropriate power supplies.

- o Optical systems consisting of mirrors, windows, mounts, alignment systems, and mirror-cooling systems

- o The laser front end, producing a 100-ns preamplifier pulse of 140 kJ total energy, for input to the final amplifier systems.

- o Perimeter buildings, 20 m wide, 35 m high, with effective total length of 420 m. The building houses the 14 KrF final amplifier systems. The building is industrial-type steel frame construction with insulated metal siding and roofing on concrete mat foundations. Other equipment included in this structure is discussed in the previous section.

- o No provision for personnel x-ray protection and noise suppression. It is assumed that personnel need not be present in the structure during operation. Since the laser system is part of a test facility, it is assumed that complete shutdown is permitted for any required maintenance.

- o Fourteen beam channels, each 110 m long x 2 m high and 6 m wide. Channels were constructed of carbon steel plate with structural steel reinforcing and insulated siding. Channels are supported on steel supports and concrete footings.

- o Hub structure consisting of a carbon steel semicircular tank type structure on concrete foundations with insulated siding. Its radius is 30 m, and height is 15 m. The structure houses the central mirror assemblies.

- o The Raman compressor building, 180 m long, 12 m wide, and 15 m high. Construction is carbon steel plate with steel reinforcing, insulated siding, and concrete slab foundation. A Raman module with a methane gas handling and cooling system is included, as discussed in a previous section.

- o Site work consisting of grading an area of approximately 450 x 300 m; construction of approximately 10,000 m² of paved area for roads; a 25,000-gpm cooling tower; site piping utility distribution for cooling water, fire water, potable water, and sanitary sewer; incoming electrical power distribution; and yard lighting and grounding.

3.6.2 Pricing Levels

The estimate is at price and wage levels for the fourth quarter of 1979; no allowance has been made for future escalation.

3.6.3 Direct Field Construction Costs

The direct field construction costs of permanent plant equipment, materials, subcontracts, and construction labor have been included in the estimate on the basis of the following discussion.

3.6.3.1 Mechanical Equipment

The cost of installed electron beam generator systems was furnished by Physics International, as indicated in Appendix 1.

The cost of optical equipment, including the installation of that equipment, was furnished by Hughes Aircraft Company, as indicated in Appendix 2. The 76.7 M\$ cost indicated in Table 2.4-1 does not include an allowance for general and administrative expenses and vendor fee. An estimated 25%--or 19.2 M\$--has been added to account for these costs, bringing the total to 95.9 M\$.

The balance of the civil/structural and mechanical equipment estimate is based on the equipment description furnished by Bechtel Engineering, as discussed in preceding sections of this chapter.

3.6.3.2 Materials

Civil/structural material costs are based on building areas and volumes, as applicable. Other direct material costs were factored from the civil/structural and mechanical equipment costs as appropriate.

3.6.3.3 Construction Labor

The manual labor rate was estimated at \$16.00 per job hour, including an allowance for casual overtime and craft-furnished supervision.

3.6.4 Indirect Field Costs

The indirect field costs that consist of temporary facilities, miscellaneous construction services, construction equipment and supplies, field office, preliminary check-out and acceptance testing, project insurance, taxes, and permits were included as a percentage of the direct labor costs; for this study, 85% was used. A summary of estimated field costs for buildings and ancillary equipment is given in Table 3.6-1.

3.6.5 Front End Costs

The laser system front end provides the input pulses to the final amplifiers. The total energy output of the front-end subsystem, 140 kJ, is approximately equal to the output of a single final amplifier pulse stacker (i.e., one-fourteenth of the output of all the stackers combined). To allow for the expected additional complexity of the front end, its cost has been estimated to be twice that of a single final amplifier, or, approximately one-seventh (14%) of the total cost of pulsed power, optics, buildings, and auxiliary equipment for the final amplifiers.

3.6.6 Home Office Services

The home office services include engineering costs, other home office costs, and fee. Engineering includes preliminary engineering, optimization studies, specifications, detailed engineering, vendor drawing review, site investigation, and support to vendors. Other home office costs comprise procurement, estimating and scheduling services, quality assurance, construction and acceptance testing, and project management. Fee is included as a function of the total project cost.

Table 3.6-1
Buildings and ancillary equipment costs (M\$)
(400-nb pulsed power).

Civil/structural

Perimeter buildings	21.3
Propagation channels	10.4
Hub building	2.8
Raman channel	4.0

38.5

Mechanical equipment	14.7
Piping and instrumentation	8.1
Electrical	4.1
Sitework (grading, paving, cooling tower, ward lighting, and piping) direct	4.0

Total direct field costs	69.4
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Indirect field costs	17.8
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Total field costs	87.2
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The sum of these three categories falls into historically consistent percentages in the range of 10% to 20%, depending on the complexity of the project. For this study, a figure of 18% of total buildings and auxiliary equipment, plus approximately 6% of vendor-installed equipment (e-beam and optical systems) has been used. A figure of 30 M\$ rounds off the total system cost before contingency.

3.6.7 Contingency

Included in the estimate is a contingency that exists within the conceptual design in quantity, pricing, or productivity, and that is under the control of the constructor and within the scope of the project as defined. Implicitly, the allowance will be expended during the design and construction of the project, and it cannot be considered as a source of funds for overruns or additions to the project scope. However, experience shows that it is quite difficult to assess the degree to which future processes are understood in the hardware sense. Thus, if the conceptual arrangement of the plant components contains major uncertainties, or the design duty of plant components proves to be more severe than anticipated, or if additional major subsystems are ultimately found to be necessary, then the scope of the project is deemed to have been inadequately defined, and this then would not be covered by the allowance.

The contingency for this study has been estimated at 25%.

3.6.8 Design Assumptions

Spread-footing type foundations can be used to support the structures and equipment.

A 100-MW power source is available for start-up.

3.6.9 Exclusions

The following items have been excluded:

- o Research and development costs for the laser system.
- o Client engineering, financing, and other similar costs.
- o Financing and interest charges during construction.
- o Site investigation and land acquisition.
- o Training of plant operators.
- o Plant start-up and operation.
- o Utilities and roads outside the site boundary.

- o Mobile equipment.
- o Personnel radiation protection around e-beam generators.
- o Noise-suppression construction around the e-beam generators.
- o Common experimental test site facilities, such as site fencing, offices, warehouses, shops, central control room, power substations, etc.
- o Argon, krypton, fluorine, helium, and methane gases required for operation.

3.6.10 Estimate Summary (400-ns Pulsed Power)

A summary of the overall construction costs based on the preceding discussion is given in Table 3.6-2.

3.6.11 900-ns System Costs

A similar laser system based on 900-ns-duration pulsed power was investigated as a variation on the 400-ns system discussed above. An underlying assumption in this work has been that the total energy output per aperture remained the same, as did the number of final amplifiers. The major differences for the 900-ns system are that a PFN e-beam generator is used and that nine beams are multiplexed to yield the 100-ns output pulse of the KrF stackers.

However, the underlying assumption of equal energy per aperture is quite unreasonable. The allowable size of a single KrF amplifier aperture is limited by parasitic-mode-control requirements, which depend in turn on the optical gain in the medium, and hence on the rate at which the medium is pumped. If the energy output of an amplifier were fixed, the pump rate would be reduced as the pump pulse is increased in length. The lower gain in the medium would then allow larger apertures to be built with adequate parasitic-mode control. Therefore, it is expected that a system with longer pump pulse width should allow a larger energy output per aperture, and hence a lower number of final amplifier units to produce the same total system output energy.

Nevertheless, a cost estimate has been made that assumes 14 final amplifiers are used. The major design changes for the buildings result from the required increase in optical delay times and the decrease in the size of the PFN e-beam generator unit (relative to the PFL). Five additional delay-generating and delay-removal mirrors are required in each stacker channel. If one is taken to be 15 m closer to the hub building, with the other four farther away than the four mirrors of the 400-ns design, then the length of the stacker channels is increased by 60 m. Taking account of an

Table 3.6-2
KrF fusion laser system costs (M\$)
(400-ns pulsed power).

E-beam generator systems	98.7
Optical systems	95.9
Buildings and auxiliary equipment	87.2
Front end (14% of above)	39.4

Total field	321
Home office	30

Total	351
Contingency 25%	88

Construction cost, 4th quarter 1979	439
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increased requirement for structural support of the additional mirror mounts, the increase in civil/structural cost of the channels is estimated to be 6.4 M\$. Proportional increases are seen in the costs of mechanical, piping and instrumentation, and electrical systems for the channels. The reduction in size of the PFN e-beam generator results in a perimeter building reduced in length to 300 m (from 420 m). Assuming the same height and width for the perimeter building, the net civil/structural cost savings is estimated to be 5.7 M\$. Piping and instrumentation in the perimeter building are also reduced substantially because of the reduced size of the building. In addition, some reduction in indirect field costs results from reduced labor charges. The sitework estimate remains the same because the total area of ground covered by the facility remains essentially unchanged. A summary of costs for buildings and ancillary equipment for the 900-ns system is shown in Table 3.6-3. The overall cost is seen to be slightly reduced (1.5 M\$) by the indicated design changes.

With regard to the overall system costs, it was seen in Appendix 1 that going to a 900-ns PFN system saves a net 12.8 M\$ in pulsed power. Analysis of the 900-ns optical system in Appendix 2 indicates a net increase in cost of approximately 20%, or 19.2 M\$, in optical systems is required because of the increased number of components and system complexity. Front-end and home office costs change very little because of the small net change in costs from which they are factored. A summary of the overall costs for the system based on 900-ns pulsed power is shown in Table 3.6-4. A net increase of almost 10 M\$ is seen in the total.

Again, however, it should be noted that the actual design of a system based on 900-ns pulsed power would probably be based on fewer KrF amplifier modules of larger size. A net savings in all categories would then be realized, and the overall cost would likely be reduced from the 400-ns case. Further investigation of the amplifier scaling relationships is required before such savings can be quantified.

3.7 Summary of Technology Development Issues

This study has been a detailed assessment of a particular initial point design that is not considered to be optimized. Further innovation is considered highly probable. Perhaps the most significant result of this study has been the identification of important technical issues that must be addressed before a workable system can be built. A number of these issues are summarized in this section, along with some prospects for improvements in system design.

Table 3.6-3
Buildings and ancillary equipment costs (M\$)
(900-ns pulsed power).

Civil/structural	
Perimeter buildings	15.6
Propagation channels	17.8
Hub building	2.8
Raman channel	4.0
	<hr/>
	39.2
Mechanical equipment	14.8
Piping and instrumentation	6.5
Electrical	4.1
Sicework	4.0
	<hr/>
Total direct field costs	68.6
Indirect field costs	17.1
	<hr/>
Total field costs	85.7

Table 3.6-4
KrF fusion laser system costs (M\$)
(900-ns pulsed power).

R-beam generator systems	85.9
Optical systems	115.1
Buildings and ancillary equipment	85.7
Front end (14% of above)	40.1

Total field	327
Home office	30

Total	357
Contingency 25%	89

Construction cost, 4th quarter 1979	446
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3.7.1 ETF Design Philosophy

It has been assumed that the laser system under consideration here is designed for use in an experimental test facility (ETF). This assumption is primarily evident in the Marx bank capacitor shot life (10^7 shots). However, it is important to note that the ETF design philosophy has not been rigorously applied in all areas.

A potential tradeoff between economy and efficiency exists that has received little attention to date. That is, for an ETF system, we will not be interested as much in the ultimate laser system efficiency as in the cost per unit of output energy. For example, the design allows for helium gas in the propagation channels, including steel walls welded leak-tight and atmosphere circulation and maintenance systems. If the channels were filled with air, the system could be built more cheaply, but Rayleigh scattering would reduce the efficiency by somewhat less than 10%, and the system alignment might be less accurate, resulting in added inefficiency. However, it might be more economically effective to build additional amplifiers to make up for the lost energy and accept the additional inefficiency.

The same philosophy might be applied to the look angle and fill factors for the stacked beams in the final amplifiers. If the propagation channels were shortened, the fill factors would be reduced, resulting in lower system efficiency. However, the construction cost per unit of energy output will be a function of the stacker channel length and will be a minimum for some finite length that has not been determined. If efficiency is not the most critical issue (and it may not be in an ETF), shorter channels might be used to reduce the cost.

A design study aimed at minimizing the system cost per unit of output energy would be useful. Such a study should be undertaken concurrent with work aimed at technical improvement of the baseline design.

3.7.2 KrF Final Amplifier Design

The final KrF amplifiers have been designed with 10-cm-thick, segmented fused silica windows in order to withstand the pressure wave generated by the e-beam energy deposition. Analysis has shown that this design would be adequate under static pressure conditions, but the effects of dynamic loading and repetitive operation have not been investigated in detail. Further analysis of the window's structural integrity and lifetime is needed. Such work would

also serve to define more accurately the required fused silica window thickness, which has a strong impact on the optical system costs (see Table 2.5-1).

The segmenting of the amplifier window leads to additional optical losses due to the shadows of the window-supporting struts. New amplifier designs should be sought that minimize problems with the windows. It is evident that the amplifier aperture need not be square. The distance between e-beam foils is limited by requirements on parasitic-mode control, as is the amplifier length. However, the amplifier width in the flow direction could be considerably longer because there are virtually no reflective elements on the flow sides of the cavity. A 1- x 4-m clear aperture could produce the same amount of output energy as the 2- x 2-m aperture, but a segmented window could be designed for less optical loss in the former case. Designs which scale the amplifier up to a maximum allowable length in the flow direction while reducing the e-beam foil separation should be investigated. It would also be useful to investigate designs in which the beams pass through the amplifier windows at Brewster's angle, thereby eliminating the necessity for damage-resistant antireflection coatings on those windows.

Further investigation of aerodynamic windows may be warranted if flow geometries or concepts can be found that substantially reduce the anticipated mixing of the active-medium gas with the window gas. The separation of fluorine from the window gas by selective absorption in a totally fluorinated liquid appears to be an attractive approach. Further investigation of the relative solubility of F_2 and rare gases in solvents such as perfluoroheptane and hexafluorobenzene is necessary in order to evaluate such a separation process.

The potential for e-beam-induced damage to the amplifier's window and mirror needs further study. This determines the required standoff distance between the optics and the active medium, which in turn affects the losses due to F_2 absorption in the inactive region. The effect of magnetic-field fringing on electron trajectories at the ends of the amplifier cavity must be included in this analysis.

The effectiveness of pressure-wave attenuation by vented sidewall mufflers proposed in Section 3.2.4.3 requires further analysis. When a shot is fired, residual ordered-density inhomogeneities created by the previous shot may limit the beam quality and efficiency of coupling to the Raman cell. Previous analysis done at TRW³ is inadequate because it does not deal effectively

with targets as large as the Raman cell. The assumption in the present work has been that the large size of the Raman cell as a target, combined with the long interpulse time (500 ns), makes the vented sidewall muffler a viable approach.

The effects of going to longer pump pulses to take advantage of cheaper PFN pulsed-power technology are not adequately represented by this study. The principal reason for this is that the variation of optimum amplifier size as a function of the pump pulse duration has been neglected. It is likely that the permissible total energy per aperture will increase with increased pulse width because of relaxed requirements for suppression of parasitic modes. Therefore, fewer amplifiers would be required to produce the same output energy. Future studies must take this into account.

3.7.3 Optical System Design

It has been assumed in this study that losses due to Rayleigh scattering and reduced alignment accuracy prohibits the use of a normal atmosphere in the beam-propagation channels. The use of helium gas as a beam-propagation medium requires construction of channels that are welded leak-tight. A cursory examination of the alignment system indicates that it may be overdesigned. That is, significantly more misalignment of the Rf beams can probably be tolerated without a significant reduction in system efficiency. Therefore the argument that helium must be used to achieve adequate alignment accuracy is questionable.

It has been noted previously that the losses due to Rayleigh scattering may be tolerable when considered from an economic point of view (i.e., cost per unit of output energy). Furthermore, the contributions of separate atmospheric components (N_2 , O_2 , and Ar) to the Rayleigh-scattering attenuation in air⁵ have not been investigated. It is possible that one or more of these or other gases has acceptable low absorption and scattering cross sections and would be suitable as a propagation medium. The use of any gas other than helium would reduce facility construction costs because of relaxed requirements on leakage. The use of dry nitrogen is likely to yield the least expensive system.

Considerable improvements in the optical system design may be expected through further innovation. One possibility within the framework of this design is to generate the stacker-pulse time delays in the preamplifier. This would allow elimination of the input time-delay generating mirrors and the

tertiary telescope mirrors in each stacker channel. The final amplifiers would then be illuminated directly from a set of mirrors in the vicinity of the input scrapers. The number of mirrors would be reduced considerably, as would the beam-channel dimensions.

Passing the entire pump beam through the Raman module twice does not appear to be an optimum design. The 5% attenuation of the pump beam at the pump turning mirrors (M_8 in Fig. 2.1-3) is unnecessary. A better design would probably result from amplification of the Stokes beam in separate stages with expanding optics in between, followed by a single pass through the final backward Raman amplifier. It also appears that little if anything is saved in the present system design by combining all the final Raman amplifiers in one unit, because this necessitates the construction of an additional long propagation channel. Designs should be considered in which individual final backward Raman amplifiers are situated in each stacker channel. The output of all the channels would then be recombined at the center of the hub building for final direction to the target. The reduction in the number of mirrors in the optical train would result in lower cost and higher system efficiency. A conceptual layout of a single amplifier channel incorporating some of these ideas is shown in Fig. 3.7-1.

Finally, a mirror reflectivity of 95% has been assumed in this study. The possibility of attaining higher reflectivities with dielectric coatings having adequate damage resistance deserves considerable attention.

3.7.4 Pulsed-Power System Design

The efficiency of energy conversion from "wall plug" to e-beam deposition in the laser gas medium is projected to be 57% for the present design, as indicated in Fig. 1.2-2. The large inefficiency in this system suggests that innovative technology could result in significant improvements.

For example, a major source of energy loss (about 5-6%) occurs in the shunt conductance of the dielectric water in the PFLs. The water has been assumed to be at room temperature. If the temperature of the water is dropped, its resistivity increases, and losses can be reduced to perhaps 1 or 2% (see Ref. 6) at temperatures near the freezing point. Because of the resistive losses in the dielectric water, the water must be cooled to allow repetitive operation. Simple heat exchangers will not be acceptable because this would allow the dielectric water to run above ambient temperature and increase the losses. Hence cooling units (refrigeration units) for the

Fig. 3.7-1 Alternate stacker design using pre-delayed front-end input and individual Raman amplifiers for each stacker module.

dielectric water have been included in the plant design to keep the water down to ambient temperature. If the cooling units are permitted to reduce the water temperature to well below ambient (perhaps to near freezing), then the overall system efficiency can be increased. In fact, because this reduces the shunt-resistive losses, it may well have the effect of reducing the load on the cooling units themselves.

Looking beyond the ETF, it may also be possible to gain in energy-conversion efficiency between the reactor and the storage capacitors. Here the normal conversion sequence goes as follows: thermal energy $\rightarrow$ mechanical energy $\rightarrow$ ac electricity $\rightarrow$ dc electricity $\rightarrow$ capacitive storage. In Fig. 1.2-2 it is estimated that a 6% loss occurs in ac $\rightarrow$ dc conversion, plus another 2% loss arises in capacitor charging. If the reactor output is to be used to generate electricity, the question arises: Why not generate dc electricity directly to eliminate the required power supplies? If part of the reactor's thermal energy were used to drive a separate high-voltage dc turbine, the "wall plug" to capacitor loss might be substantially reduced.

Along the same lines, the dc machine could be a homopolar generator. Such a pulsed dc machine might be combined with an inductive intermediate-energy-storage system (instead of the Marx bank) that could then be used for PFL charging. This radically different design would require significant technical development, including the development of high-voltage opening switches, but major reductions in system cost and increases in system efficiency might be obtained.

3.7.5 Other Facility Issues

There appears to be no other significant issue associated with the construction of the facility as it has been designed. It has been previously mentioned, however, that no provision has been made in the perimeter building for shielding of personnel from x rays generated in the e-beam pumped amplifier. In addition, no acoustic noise suppression has been allowed for outside of the laser gas ducts. The rationale for this approach is that personnel will not be present in the structure during operation of the ETF. A complete shutdown of the facility is assumed for any required maintenance. For future commercial applications these assumptions may not be valid, and the issue deserves further scrutiny.

3.8 Conclusions

A joint design for a laser fusion driver suitable for use in an ETF has been established and evaluated. The general concept is that of a hybrid KrF pulse stacker-backward Raman pulse compressor. The design is not considered optimized and, in fact, several suggestions for improvements are made in the previous section. A few technical advancements or design innovations such as the development of long-shot-life switches and high-damage-threshold optical coatings are needed before the system can be built as described. It is possible that design innovations such as the use of Brewster angle transmission throughout could eliminate the optical damage issue in the long run.

The possibility of using aerodynamic or inert gas-buffered windows for the KrF amplifiers was studied in detail. However, it was found that considerable mixing of the active and buffer gas streams will result from the e-beam-generated overpressure. Furthermore, no economical or energetically efficient way of removing fluorine from the window gas was found. The final design therefore uses solid fused silica windows close enough to the active region to reduce F_2 absorption losses to reasonable levels. In the present design, the window must be thick (about 10 cm) and faceted to give it the strength required to withstand the e-beam-generated pressure wave. The large thickness makes fused silica the most expensive line item in the optical system costs. Antireflection-coating technology for this window must be developed.

A conceptual design for the KrF gas-flow system was presented, including startup, shutdown, and gas-cleanup systems. Provision has been made for passive pressure-wave suppression by vented sidewall mufflers with acoustic absorbing devices outside the vents. It is felt that this approach is adequate because a rather large beam divergence is tolerable without significant loss of efficiency and because the interpulse time to 500 ms is sufficiently long. The largest pressure drop in the flow loop will occur in the heat exchanger and may be kept as low as 0.5 psi. The blower power required to circulate the gas in each amplifier would then be about 400 kW.

Brewster-angle windows are used for the methane Raman compression module so that optical-coating technology is not an issue. The pressure drop in the methane gas flow loop is low because only small heat exchangers are necessary, and the gas can be circulated at a low velocity. Blower power for this flow loop makes a negligible impact on total system efficiency. Methane gas

cleanup is not an issue because most impurities do not interact with the beam. A small bleed stream can be burned off or vented so that fresh gas can be input, if necessary.

The total energy output in the Stokes beam is 1.3 MJ, with an average power of 2.63 MW. The overall system efficiency is estimated to be 3%. Innovations in the pulsed-power and optical systems design may improve this performance significantly in the future.

Buildings to house the 400-ns pulsed-power laser system have been designed (conceptually), and a cost estimate for construction was made. The channels for beam propagation contain helium gas and are made of steel plate welded leak-tight. Construction costs could probably be reduced significantly if it is found that another gas can be substituted for the helium. When the costs for the pulsed power, optical systems, other process equipment, and buildings are added, and allowances are made for construction of the laser front end, home office costs, and contingency, the total system cost is estimated to be 439 M\$ (last quarter 1979 dollars). It should be noted that the design has not been optimized in terms of cost per unit of energy output.

A system based on 900-ns pulsed power was considered as an alternative, and costs were estimated. It was found that increases in the cost of the optical system are likely to be larger than the reduction of costs for pulsed power and buildings, so that the overall system cost is slightly higher. However, this assumes that the same number of KrF amplifiers is needed in the 900-ns system. This is probably not true because requirements for the control of parasitic modes in the amplifier are relaxed, and larger single amplifier units can be built at 900 ns. Thus it appears likely that further cost reductions in optical systems and buildings would result in lower overall system costs for the 900-ns case. This tradeoff requires further study.

A summary of technical issues needing resolution before the system can be built was given in the preceding section. Considerable work remains in evaluation of suggested design improvements and in system optimization.

3.9 References

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