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TITLE DEVELOPMENT OF CO_2 AND KrF GAS LASERS AS DRIVERS FOR INERTIAL CONFINEMENT FUSION

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DEVELOPMENT OF CO_2 AND KrF GAS LASERS AS DRIVERS FOR INERTIAL CONFINEMENT FUSION

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I. Introduction

On the basis of data obtained in inertial confinement fusion (ICF) experiments over the last five years it is now apparent that successful energy production from inertial fusion targets will require drivers capable of delivering several megajoules of energy to a target at power densities in excess of 100 TW/cm^2. This represents an increase in required energy over earlier projections and has contributed to what might be termed a cost barrier to the further development of ICF. This cost barrier is created by the fact that improvements in target performance are progressing as the cube or fourth root of the driver energy while the cost of the driver continues to scale nearly linearly with output energy. Thus, continued progress toward energy production from ICF depends on a breakthrough in the cost vs energy scaling of fusion drivers.

Several different driver systems are currently under development in the national ICF program. Los Alamos has traditionally emphasized gas laser systems because of their intrinsic high average power capability and ease of operation. This paper will review the status of activities in both carbon dioxide (CO_2) and krypton fluoride (KrF) development at the Laboratory.

II. Antares Laser Facility

By far the greatest effort to date has been given to the CO_2 laser. This development has culminated in the Antares facility, which began experimental operation in November 1983.

The Antares laser system is designed to provide 40 kJ of on-target energy from 24 beams in a nanosecond pulse. The system, shown schematically in Fig. 1, has the basic master-oscillator, power-amplifier configuration of all existing high-energy, short-pulse fusion lasers.

Two power amplifiers provide the 40 kJ output. Each power amplifier is annular in geometry and segmented into 12 beams. At the target chamber an array of fold and focus mirrors bundle the 24 beams into 6 groups of 4 to irradiate the target symmetrically. The 6 beam bundles are brought to focus as if through the sides of a cube with the target at its center.

Figure 2 presents a cut-away view of the power amplifier. A cylindrical geometry houses the central coaxial cold cathode electron gun, which supplies four axial discharge sections, each discharge section being azimuthally segmented into 12 sectors. The design specifications for the power amplifier are given in Table I. The electron gun is a triode with a tubular grid structure. The mechanical design of the grid was a key element in obtaining reliable operation of the electron gun. With a total electron window area of 9 m^2 this is the world's largest known triode tube!

In the construction of large fusion lasers optical components and controls are a significant portion of the system's costs. One of the substantial cost savings possible with CO_2 lasers such as Antares is the use of diamond-turned metal mirrors. The large (35- to 70-cm) optical flats, spheres and off-axis parobolas used in Antares were prepared by Union Carbide's Y-12 facility at Oak Ridge and have surface finishes of about 200 Å and surface figures of one wave in the visible. Because this finish and figure was achieved by machine cut without any subsequent hand polishing the finished costs ranged from $4000 for flats and spheres to $7000 for off-axis parabolas. Greater cost reduction could be realized in mass production of optics for even larger systems.

The Antares optical system delivers 80% of the output energy into a target spot diameter of 300 μm with a pointing accuracy of 25 μm. The alignment system is fully automated. A schematic for this system is shown in Fig. 3. Alignment is performed from a single station for each beam line. Bright, visible light sources are positioned at the needed alignment points along the beam path and viewed by a telescope/TV camera from the alignment station. The centroids of the light spots are determined by a video tracker that generates error signals used by the computer to move appropriate mirrors and bring all beams into congruence. The final alignment is accomplished using a CO_2 laser beam originating at the alignment station and detected by energy transmission through an aperture at the final target position. The target chamber mirrors are adjusted by the computer to maximize the energy through the aperture. The final alignment is accomplished with 10.6 μm light, which removes all sources of dispersion error in elements such as the salt windows. This alignment system has demonstrated a pointing accuracy of 5 μm.

The technology for CO_2 is well developed and could be confidently scaled to megajoule energy levels with costs of about $300 per joule output. However, while CO_2 possesses all of the desirable attributes of a fusion driver from the laser system standpoint, the ICF program has not been successful in developing target designs that lead to high gain (>50) when illuminated by this laser's 10.6 μm radiation. Recent low-energy experiments with short wavelength light have shown favorable trends in both increased coupling to the target and a reduced quantity of hot electrons. Given these trends in target physics Los Alamos has initiated a technology demonstration test of a KrF laser. The remainder of this paper will describe this development activity.

III. KrF Laser Development

The KrF laser has two outstanding attributes for fusion applications: a short, 0.25-μm, output wavelength; and the advantage of a gaseous medium for low-cost, high-power operation. Not as attractive are the facts that its efficiency appears to be limited to 5% or less,[1] which is marginally low, and the laser medium does not store energy. It is this latter fact, namely a KrF* lifetime of under 10 ns, that dominates all aspects of the design of a large KrF laser.

The KrF laser action is most efficiently initiated by deposition of high energy electrons in a few atmospheres of gas containing Ar, Kr, and F_2. Because the laser medium does not store energy for longer than roughly 10 ns, conventional techniques of pulsed power and e-beam excitation fail to input energy rapidly enough to yield the desired laser output. Even if the energy could be input rapidly, a second effect comes to play that significantly affects the amplifier design. The KrF laser gain is proportional to the pumping power. Thus, for a specified energy, the gain g varies inversely with electrical pulse length, i.e., $g \sim t_e^{-1}$. To avoid energy loss through amplification of spontaneous emission (ASE) along paths other than that of the principal optical axis, laser designers typically limit the transverse aperture size d of an amplifier to values such that $gd \simeq 1$. Since the output fluence of a KrF laser saturates at a few joules/cm^2 we observe from the preceeding arguments that the output per aperture, E_{out}, scales as

$$E_{out} \sim d^2 \sim 1/g^2 \sim t_e^2 \quad .$$

Thus, the output of any amplifier unit increases quadratically with the electrical pulse time. In practical systems the pulse length may be several hundred nanoseconds.

The question for fusion applications is then how to decrease the long optical pulse length from an efficiently run amplifier to the few nanoseconds commensurate with target disassembly time. There are currently two approaches to achieving the nominal factor of 100 pulse compression: Raman compression and angular multiplexing. The first approach uses the nonlinear saturation property of backward Raman scattering to achieve pulse compression.[2] While offering optical simplicity this technique has not yet achieved both acceptable [illegible]ession and conversion efficiency. The alternate approach, called optical multiplexing, was first proposed by R. D. Hunter, Western Research Corporation, Inc., and is depicted schematically in Fig. 4. An excimer amplifier is pumped by a long electrical pulse while a number of short optical pulses pass through it at slightly different angles and staggered in time to create a long optical pulse train. The individual pulses are then delivered to the target along paths of different length so that all the individual, short pulses arrive on target at the same time. Although complicated optically this technique works with high efficiency. One of the principal objectives of the Los Alamos development program is to construct, test, and cost this optical concept in a real laser system, not simply a paper system.

If the optical pulse length is t_0 and the electrical pulse length is t_e, then the number of compression channels is $N = t_e/t_0$. The reduction of complexity dictates decreasing N and hence t_e, but recall that because of ASE and KrF kinetics $E_{out} \sim t_e^2$ so an optimum in t_e must exist for any desired energy. This value is found by noting the number of controls c will be proportional to the number of amplifiers $n \approx E_{total}/E_{out}$, and the number of adjustments per multiplexing channel $N = t_e/t_0$. If all amplifiers are driven by a common multiplexing system then n and N are independent and hence

$$c = n + N \sim \frac{1}{t_e^2} + \frac{t_e}{t_0} .$$

A minimization of this function with t_e has been performed and is presented in Fig. 5 parametric in the damage threshold for optics. This number often dictates the optical area required in any laser system. A weak minimum in the pumping pulse length is observed in the range of 300 to 500 ns for a 0.5-MJ, 10-ns system. The minimum shifts to shorter electrical pulses with a decrease in energy and/or optical pulse length.

On the basis of such arguments Los Alamos has chosen a 1 m x 1 m x 2 m power amplifier as the basic building block to be tested for future KrF development. This amplifier, known as the LAM for large aperture module, is excited by a 500-ns electrical pulse delivered by a Marx/water-line driven, cold-cathode diode. The emitting surface of the diode is carbon felt. Other specifications of the LAM are provided in Table II. Construction of the LAM is complete, and it is now involved in electrical and lasing tests. Construction of a front end system to provide the 96-element input pulse train is in progress and should be completed by October 1984. The front end system contains a master oscillator and two intermediate amplifiers to generate enough power to drive the LAM to saturation. The two intermediate amplifiers are smaller than the LAM but otherwise very similar in mechanical and electrical design. They are predicted to have a small signal gain of about 3%/cm and stage energy gains of 150 and 70, respectively. Thus, with a master oscillator output of a few tenths of a joule the energy will be about 30 J after the first intermediate amplifier and 2 kJ after the second. This energy is calculated to be adequate to saturate the LAM in a double pass configuration. The entire system is named Aurora and is predicted to have an energy output of greater than 20 kJ.

It must be emphasized that Aurora is an experiment in low-cost laser technology and is not an ICF target shooter. As such, the Aurora design is not conservative. The choice of a stage gain of 150 for the first intermediate amplifier is admittedly high risk. This choice has been made to reduce systems cost and simplify the optical train. If the high gain operation cannot be achieved (due most probably to ASE), then another intermediate amplifier will be added to keep stage gains in the range of 50 or below. The operation of Aurora is intended to provide data on low-cost, innovative laser system designs and as such will be successful even if the projected 20 kJ is not achieved.

An integral subsystem of Aurora is the optical train linking the master oscillator, intermediate amplifiers, and the LAM. This subsystem consists of an encoder, a relay optical train, two 96 element (8 x 12) mirror arrays, LAM optics and alignment controls. This is a major subsystem of Aurora in which cost control is vitally important. Cost control in this major subsystem is very important. The basic approach to optical multiplexing is to generate a 5-ns input pulse and slice this beam spatially into an 8 x 12 element array. Each of the resulting 96 beamlets are then separate by 5 ns by time of flight to form an optical pulse train 480 ns long. The beams are relayed individually through an entrance pupil and then through the intermediate amplifiers to the LAM along a common optical axis as shown in Fig. 6.

The channel-to-channel beam angles determine the extent and complexity of the optical systems. The angles and entrance and exit pupil size of the system are related by the invariant, $\Delta\theta d$, where $\Delta\theta$ is the angle between beamlets and d is the aperture diameter. In the Aurora design $\Delta\theta$ is 17.5 mrad at the entrance pupil and 1.8 mrad at the exit of the second intermediate amplifier, which defines the exit pupil. The system uses square beams to improve geometric filling of the LAM. Out of plane turns have been avoided because they produce footprint rotation.

The Aurora system is scheduled to be fully integrated and operational at the 20 kJ level by about August 1985. This system will provide a real engineering data base for any future KrF system using the angular multiplexing technique for pulse compression. It may also be used to examine backward Raman scattering in conjunction with multiplexing for pulse length agility. Critical engineering questions to be addressed with Aurora include:

1. LAM - Can reliably uniform emission of large area cold cathode diodes be achieved? Can efficient extraction of optical energy be achieved in large aperture amplifiers with control of ASE?
2. Staging - What is the best technique for achieving high stage gain in KrF sytems?
3. Energy Extraction - Does angular multiplexing lead to efficient energy extraction with little channel-to-channel cross talk as predicted?
4. Cost - What are the actual costs and cost scalings for a KrF system of this design for future applications?

Answers to all of these questions are crucial in determining the potential of KrF to meet the future driver needs of ICF. By far the most critical factor at this time is cost -- a clever set of engineering choices is needed that will allow the ICF program to lower the cost barrier now impeding further development.

Credit for the work summarized in this paper belongs to the entire ICF laser team at Los Alamos. Specific acknowledgement is made of the outstanding contributions of: Jorg Jansen as the Antares Project Manager; Greg Canavan and Allen Hunter for leading the conceptual design of Aurora; and Jack Hanlon for the detailed design of the optical multiplexing system.

References.

1. "Physics of the Krypton Fluoride Laser," T. H. Johnson, A. M. Hunter, J. Appl. Phys. 51 (2606) 1980.

2. "An Efficient, Double Pass Raman Amplifier with Pump Intensity Averaging in a Light Guide," J. Goldhar, M. Taylor, and J. R. Murray, submitted to IEEE-JQE, July 1983.

TABLE I
ANTARES POWER AMPLIFIER DESIGN SPECIFICATIONS

Electrical	
Main Discharge Voltage	550 kV
Current Density	7.5 A/cm^2
Total Current (48 sectors)	960 kA
Electric Field	18 kV/cm
Pressure	1800 torr
E/p	10 kV/cm-torr
Pulse Width	3 μs
Optical	
Gain-length, g_0l	8
Gain Uniformity over Aperture	±15%
Output Energy/Amplifier	20 kJ
Mechanical	
Dimensions	17 m long x 3.7 m diam
Weight	125,000 kg
Anodes	0.75 m x 2.36 m
Discharge Volume Total	3700 liters
Electron Gun	
Voltage	525 kV
Current Density into Gas	50 mA/cm^2
Current Density Uniformity	±20%
Pulse Width	4 μs
Dimensions	11.2 m long x 1.7 m diam
Weight	20,000 kg
Cathode-Grid Spacing	10 cm
Grid-Anode Spacing	15 cm
Total Foil E-Beam Transmission	50%
Pressure	10^{-6} torr
Cold Cathode	48 blades, 80-cm long, 0.5 mil Ta
Foil Area Each Window	25 x 75 cm^2
Total Foil Area	9 m^2
Foil Material	Kapton/Al, 2/2 mil

TABLE II
LAM SPECIFICATION SUMMARY

Marx	
Marx Energy	720 kJ
Pulse Length	500 ns
Laser	
Input Light Energy	2000 J
Output Light Energy	15-20 kJ
$g_0 l$	7-9
Stage Gain	10
Intrinsic Efficiency	~11%
Laser Clear Aperture	1 m x 1 m
Gas Pressure	~1.5 atm
Electron Gun	
Voltage	700 kV
Area (100 cm x 200 cm)	20×10^3 cm^2
Current Density (into Gas)	20 A/cm^2

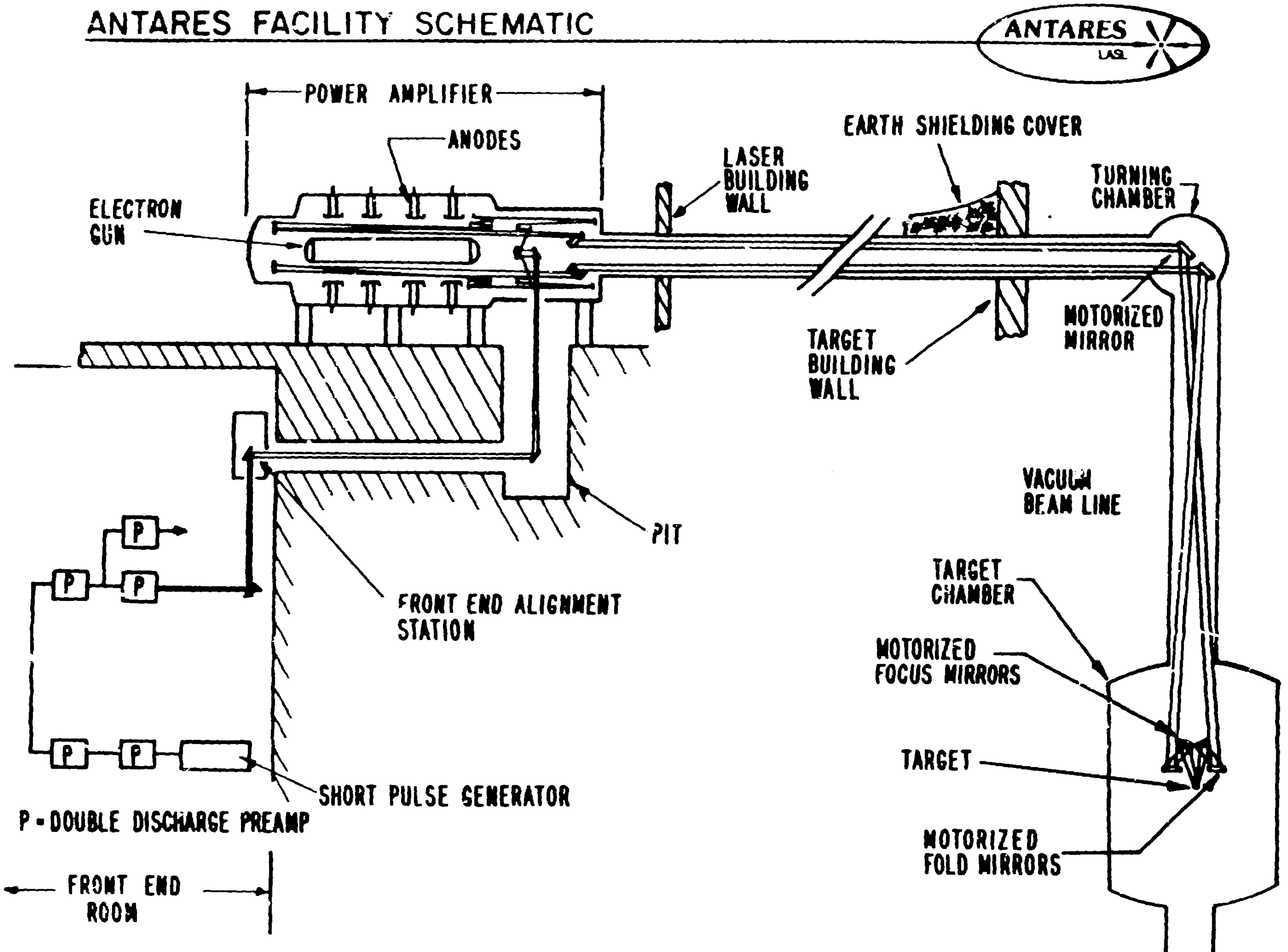
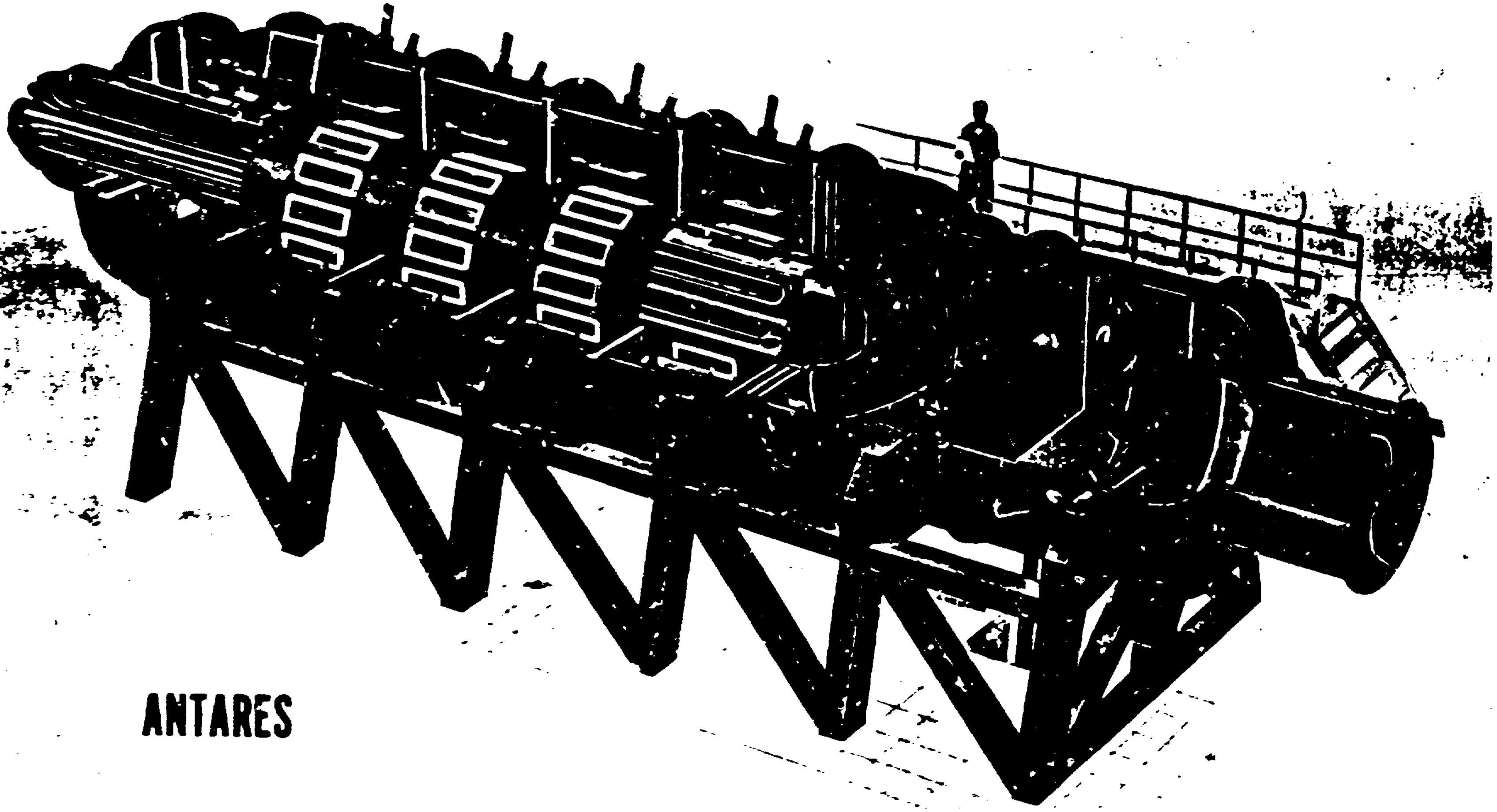

ANTARES FACILITY SCHEMATIC
ANTARES
LASL
POWER AMPLIFIER
ANODES
ELECTRON GUN
LASER BUILDING WALL
EARTH SHIELDING COVER
TURNING CHAMBER
MOTORIZED MIRROR
TARGET BUILDING WALL
VACUUM BEAM LINE
PIT
FRONT END ALIGNMENT STATION
P
P
P
P
P
TARGET CHAMBER
MOTORIZED FOCUS MIRRORS
TARGET
MOTORIZED FOLD MIRRORS
SHORT PULSE GENERATOR
P - DOUBLE DISCHARGE PREAMP
FRONT END ROOM

Fig. 1.2



ANTARES

ANTARES AUTOMATIC ALIGNMENT SYSTEM SCHEMATIC

ANTARES

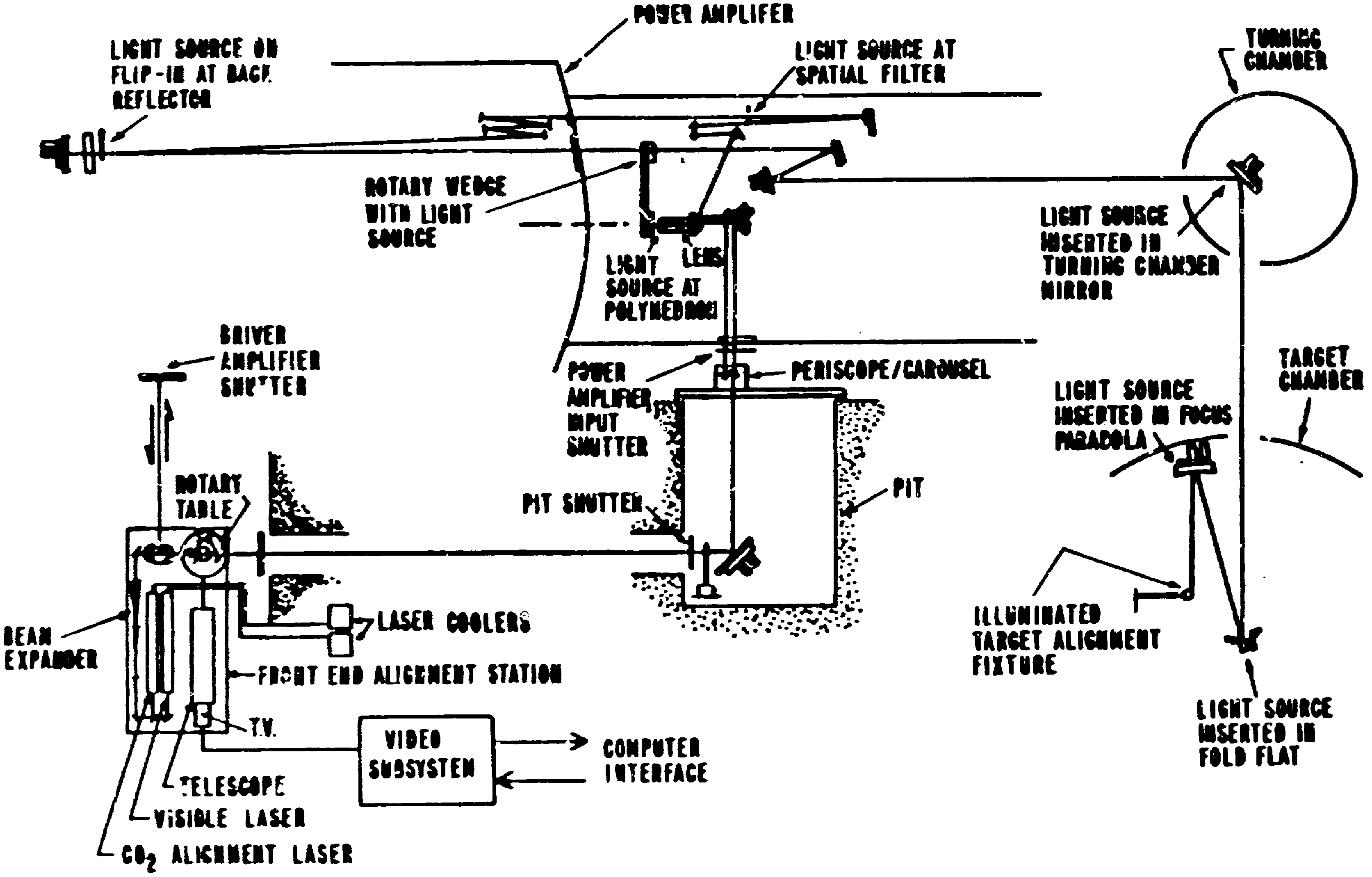
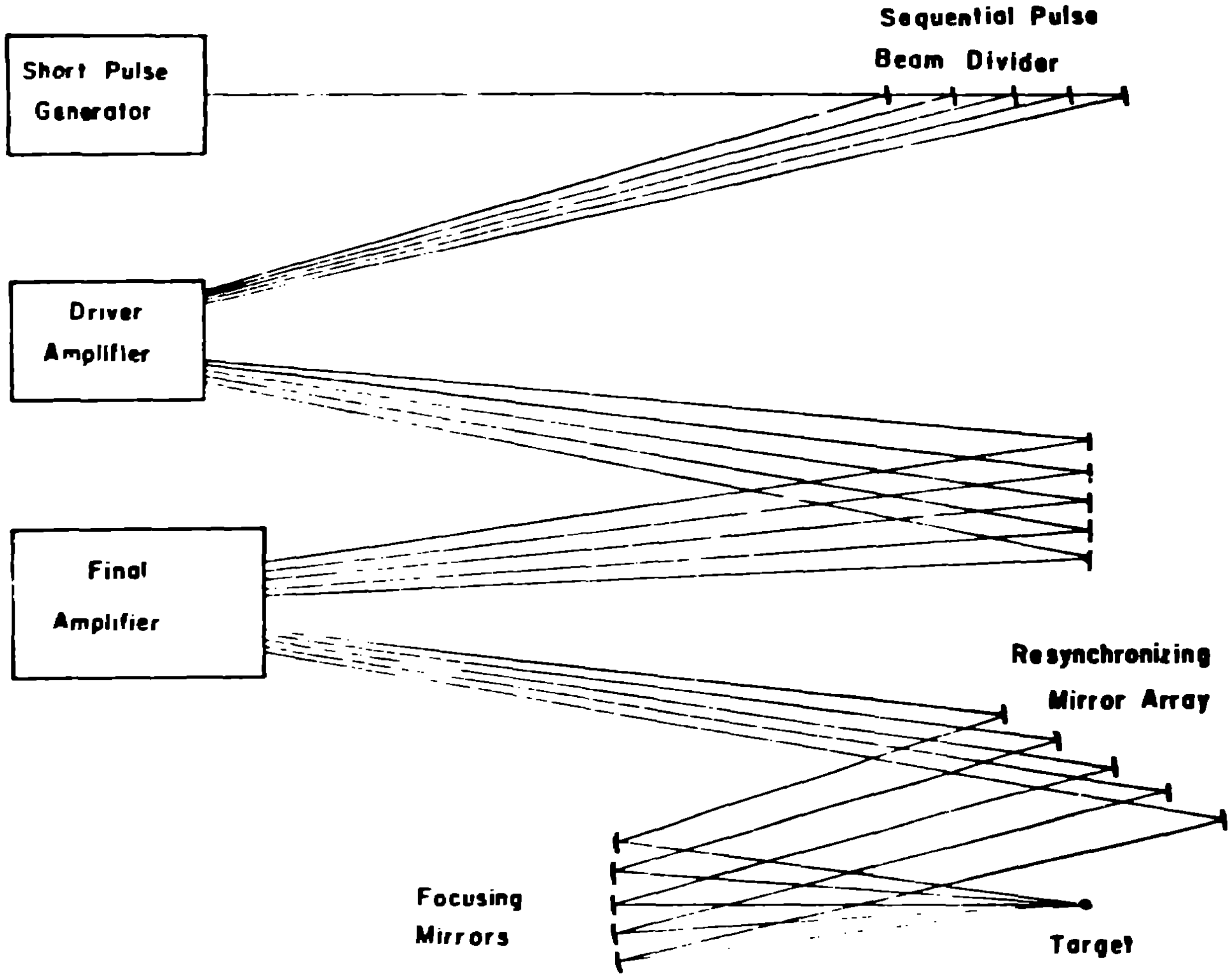
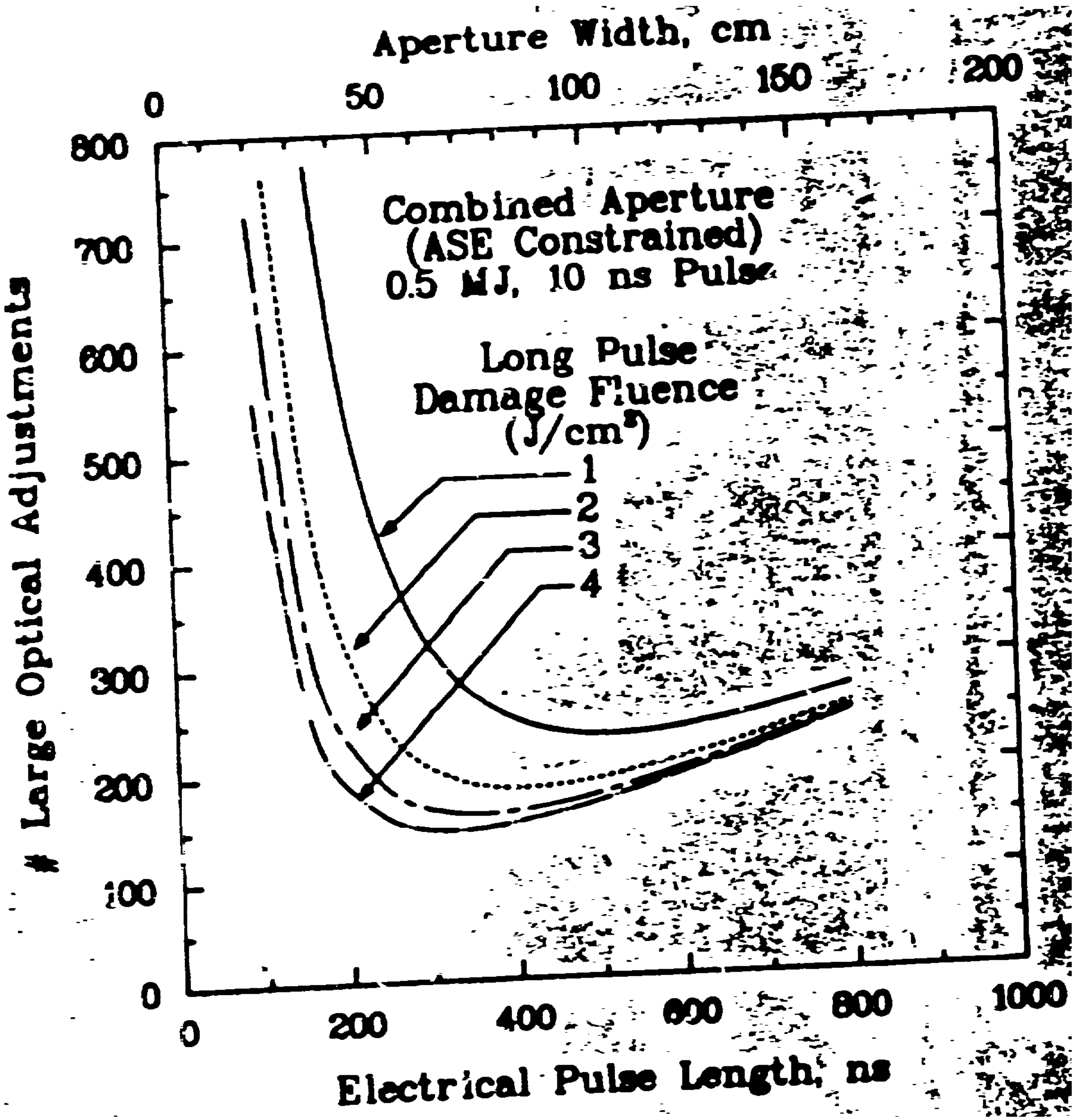


Fig. 1.6

Fig 8

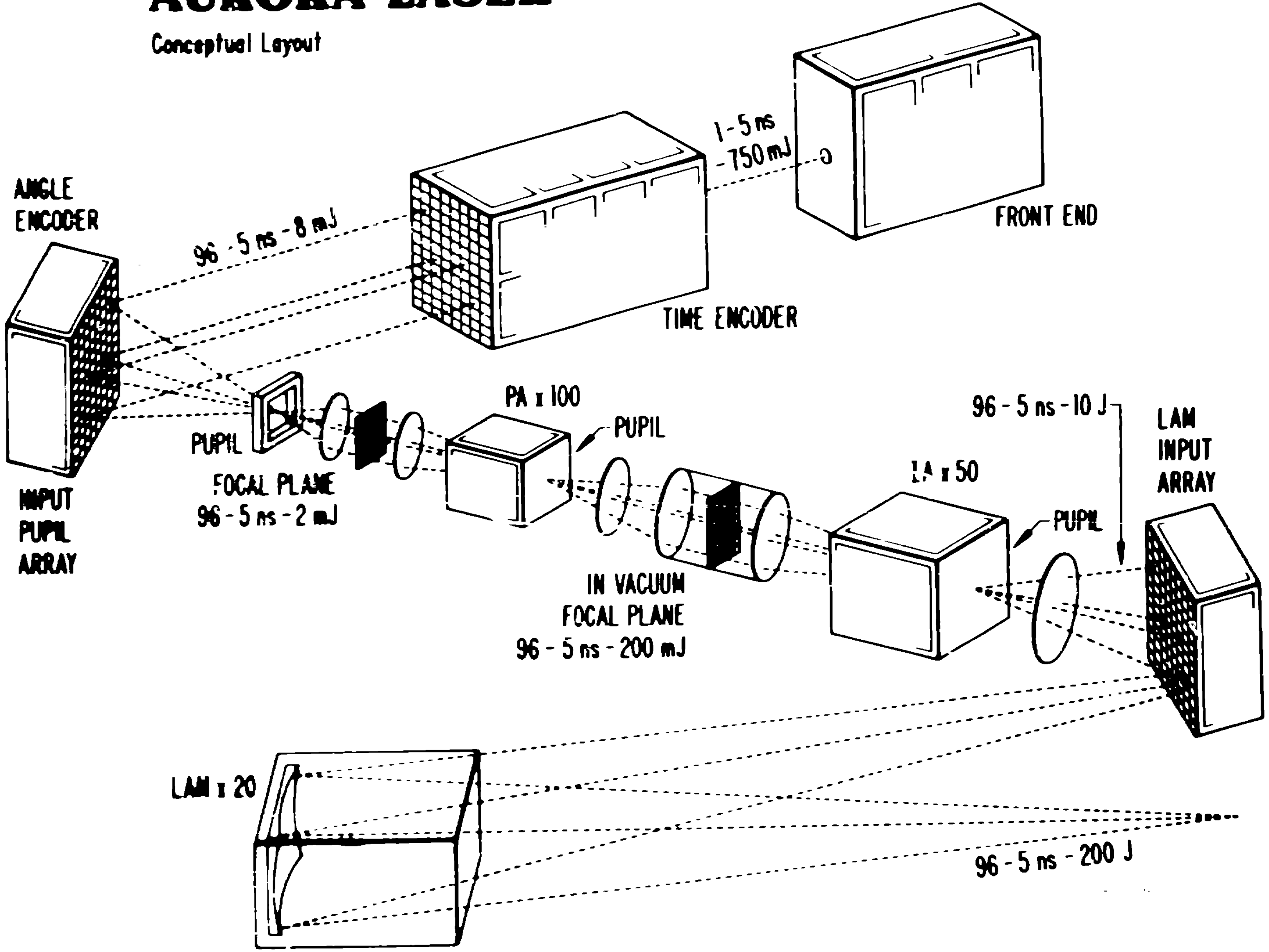


Schematic of angular multiplexing demonstration system.


Aperture Width, cm
0
50
100
150
200
800
700
600
500
400
300
200
100
0
Large Optical Adjustments
Combined Aperture
(ASE Constrained)
0.5 MJ, 10 ns Pulse
Long Pulse
Damage Fluence
(J/cm^2)
1
2
3
4
0
200
400
600
800
1000
Electrical Pulse Length, ns

AURORA LASER

Conceptual Layout



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