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LASERS FOR FUSION*

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Summary

A brief review of the theory of absorption of laser light by plasmas and of the necessary requirements for the production of controlled thermonuclear fusion is given. The implications of this theory in regard to the requirements on the laser to be used for fusion are discussed. The three types of lasers being considered for use (electrically pumped gas lasers, chemical, and solid state lasers) are each described with discussion of their relative advantages and disadvantages. The Nd:glass system is described in greater detail since that system is now being used to study the basic light-matter interactions at a number of laboratories around the world. Finally, mention is made of the present status of, and future plans for, large laser systems now being built at some of those laboratories.

Introduction

Ever since the first laser was operated in 1960 scientists have been considering the possibility that a laser could be used to initiate a controlled thermonuclear reaction. Until recent years, however, this goal has seemed most elusive. Early estimates of the required laser energy to achieve "breakeven" were 10^8 to 10^9 J. With more careful calculations and the advent of shorter (< 1 nsec) pulses by means of modelocking, this number became 10^6 to 10^8 J. It now appears that, with compression of the fuel droplet and careful shaping of the laser pulse, 10^3 to 10^4 J of laser energy may be sufficient to produce "breakeven". As used herein, "breakeven" refers to the condition where thermonuclear energy produced equals the laser energy absorbed by the target. It is in quotation marks because it is an artificial number, not accounting for the efficiency of the laser, the energy reflected by the target and other loss processes. With all of these processes considered, however, the laser energy required for commercial (i.e., economical) power production may be as low as 10^5 to 10^6 J. This is only a factor of 10 to 100 above present technology, a not unreasonable factor considering the current rate of growth of laser technology.

Over the last few years the tremendous possibilities of laser initiated fusion for power production have been recognized by scientists at many laboratories around the world. Laser fusion research is currently being conducted at the Lebedev Institute in the USSR, at Limeil in France, and in Italy, West Germany, Japan and Great Britain. Here in the USA work is being done at the Los Alamos Scientific Laboratory, at Lawrence Livermore Laboratory, at the Sandia Corporation, and at the Naval Research Laboratory, all under the auspices of the Atomic Energy Commission. Many universities and private industries have laser fusion programs including the University of Rochester, the General Electric Company, KMS Industries, and United Aircraft Corporation.

The physics of the interaction between the laser beam and fuel pellet is discussed only briefly here, having been dealt with in greater detail elsewhere.[1,2] It is the intent of this paper to concentrate on the lasers that will be required and on the problems to be overcome in extending present laser technology. The required characteristics of a laser for fusion studies are described. The three major types of lasers now being considered are reviewed. A more detailed description is given of the Nd:glass laser system, since this is the device that is now being used to study the physics of the laser-matter interaction. The inherent inefficiency of a solid state laser system may prevent Nd:glass from being applicable to an economical reactor. However, this is the most advanced type of system at the moment for producing large energies in short times. Finally, a review of the current status of major laser systems is presented, along with some discussion of plans and schedules for the future.

Rationale for Laser Fusion

Controlled thermonuclear reactions will occur if one is able to raise the temperature of the fuel to a sufficiently high value while at the same time maintaining the fuel at a high density. The efficiency with which the fuel "burns" is determined by the temperature, density and length of time which these conditions last.

The most interesting fuel for laser fusion is a sphere of solid (frozen) deuterium-tritium mixture (DT). For DT the ignition temperature, i.e., that temperature at which the production of fusion energy exceeds the energy loss due to radiation, is a few kev. Once this temperature is reached, the DT fuel will burn with an efficiency determined by the product of the density n and the containment time τ. The containment time is determined primarily by hydrodynamics. When the laser beam strikes the fuel target, a shock wave moves into the target followed by a rarefaction wave. The rarefaction wave lowers the density and cools the reaction. Also, as the plasma blowoff from the target expands, it cools rapidly.

The shock wave is beneficial, however, in that it compresses the fuel to higher densities. The energy input required for ignition is inversely proportional to the square of the density. Thus the required input energy decreases rapidly with compression. If one carefully shapes the laser pulse, a series of shock waves can be created in the DT fuel pellet, multiplying the compression.[3] It is precisely this effect which has lowered the predicted energy required to produce thermonuclear breakeven. If compressions of 10^3 to 10^4 can be achieved, then scientific feasibility might be shown with as little as 10^3 to 10^4 J.

Absorption of the Laser Energy

When the laser light is focused onto the target fuel, the light can be absorbed, reflected, scattered, or transmitted. The extent to which the light is absorbed depends on the plasma density n.[4] Almost total reflection occurs at the point where the laser frequency ω equals the plasma frequency ω_p, where

$$\omega_p = \left(\frac{4\pi n e^2}{m}\right)^{1/2} \qquad (1)$$

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In (1) m and e refer to the electronic mass and charge, respectively. For higher frequencies (shorter wavelengths) of laser light the energy is absorbed or transmitted. Longer wavelengths should be reflected. The critical density for a particular wavelength of light is that density n_c for which $\omega = \omega_p$. For solid DT densities the corresponding wavelength is 0.15 μm, in the ultraviolet. If this were the entire story then laser fusion would not look very promising.

By vaporizing the fuel pellet surface first, either with a separate low-energy, longer-time-scale laser pulse or with the leading edge of the main pulse, a density gradient can be established, as shown in Fig. 1. Now a laser beam of wavelength λ will penetrate the plasma until it finds its own critical density, at which point it will be reflected. If we assume that no significant absorption occurs below a density n_a, then the absorbing layer or thickness of the plasma is distance X between densities n_a and n_c. It should be noted that the reflected light passes through the absorbing layer a second time before leaving the plasma.

Fig. 1
50%

Fig. 1. Density gradient for partially vaporized DT pellet. Below critical density n_c the laser light is absorbed. Above n_c, laser light is reflected, according to theory of the inverse bremsstrahlung effect.

The absorption described above is due to inverse bremsstrahlung. In this process, almost all of the absorbed energy appears as increased electron temperature. This energy is then transferred in part to the ions by way of coulomb collisions. It is, of course, the ions which must be heated for the thermonuclear reaction to take place.

There are in addition many other absorption mechanisms which may occur. These include resonance absorption,[5] plasma instabilities[6] and relativistic effects.[7] These mechanisms are being studied using computer simulation techniques, and provide a great deal of hope for the success of laser fusion. The actual amount of their contribution can only be assessed when the experiments are conducted. It now appears theoretically, at least, that the absorption due to these anomalous effects may be as much or more than that of the inverse bremsstrahlung, depending upon the pulse wavelength, intensity and time scale.

Approach to the Problem

Having convinced ourselves that laser fusion is a worthy goal and that there is a reasonable chance of success, we then ask "What approach shall we take in solving the problem?" First, very little is actually known in regard to the many absorption phenomena. These processes have been and are being studied theoretically, but experimental confirmation is needed. Very early experiments, then, are being concentrated on studying the basic interactions of the intense laser beams with matter. This work is in progress in most of the laboratories mentioned earlier. However, many of the phenomena are intensity dependent, requiring more intense beams than are now available. These experiments must await the completion of larger laser systems.

The second phase of experiments will be directed toward the achievement of "scientific breakeven". As described earlier, this is the condition that thermonuclear energy produced equals laser energy input. While such a system would not be practical for power production, this achievement represents a major milestone for the laser fusion effort. Its accomplishment is simplified by the fact that requirements on laser efficiency and repetition rate are not severe. There are at least four laboratories actively building systems for this purpose.

The final step along the road to laser fusion is that of proving economic feasibility. Having shown scientifically that one can produce thermonuclear-yield-to-laser-input ratios greater than 1, the problems of overall efficiency (including the laser) and of repetition rate must be solved. This final phase also includes the design of the power plant itself and the means for extracting the nuclear energy and converting it to usable electrical energy. While work is being done on this part of the problem, it clearly will depend strongly on the results of the first two phases.

Laser Requirements

Using the information developed above one can now determine some of the characteristics desired in a laser to be used for fusion. First of all, an output energy greater than 10^5 J is required for breakeven. How much greater is uncertain. Energies of 10^5 to 10^6 J may be required to prove economic feasibility.

If inverse bremsstrahlung is the primary absorption mechanism, the laser should have a wavelength as short as possible, preferably in the ultraviolet. If some of the anomalous absorption effects mentioned earlier predominate, then this requirement may not hold.

In order to obtain the shock compression desired, most of the energy should be contained in a pulse length of 10^{-10} seconds or less.[8] This final fast-rising portion of the pulse should be preceded by a low power part lasting one or more nanoseconds.

In order to get the power densities required for proper heating, the laser beam must be focused to a small area. This is also necessary because only a small mass of fuel can be heated with a given input energy. On the other hand, the more fuel one is able to heat, the more energy output one can obtain. These factors lead to a minimum DT sphere size of the order of 100 to 200 μm in diameter. This size will increase as laser energies increase. The laser beam divergence must be no greater than a few hundred microradians in order to achieve this spot diameter when focusing.

To obtain compressions of 10^3 to 10^4, the uniformity and symmetry of the shock waves must be very good, of the order of one percent. This requires that the target be irradiated from many directions at once, implying multiple laser beams.

It is obvious that the efficiency of the laser is an important consideration for the final objective. Efficiency is not important, however, for the achievement of breakeven, provided the required laser is technically and economically feasible. The same is true of repetition rate.

There are three types of lasers being studied and built for use in laser fusion work. Each has its own advantages and disadvantages. Each type will be discussed in turn, with comments regarding energies now available and larger systems being built.

Electrically Pumped Gas Lasers

It is well known that CO_2 lasers are among the most efficient types of lasers. Efficiencies as high as 40% have been reported. These efficiencies were for CW and long (many microsecond) pulses, however. For pulses 1 nsec and shorter, the efficiency drops to values nearer 10%. For these short pulses, the rotational relaxation time is not fast enough to allow the stored energy in adjacent rotational lines to contribute to the amplification process. As a result, energy extraction is not as efficient as for longer pulses. Nevertheless, efficiencies of 10% are sufficient for use in a fusion reactor.

Another major advantage of CO_2 is that the active medium is not subject to permanent damage. As the energy output is increased in any system, the problem of component damage becomes more severe. All systems have a common problem of damage to beam optics, but in the case of CO_2 the laser medium, being a gas, does not damage.

A further advantage of this type of laser is the ability to scale the output energy with aperture size. Amplifiers with apertures of 300 cm² have been built, and larger ones can be built if required. These large apertures are not without problems, however. Producing a uniform arc-free electrical discharge over a large volume is difficult, and amplified spontaneous emission may become a serious loss.

The CO_2 wavelength, 10.6 μm in the infrared, is not ideal. It is much longer than that corresponding to the critical density of solid DT, and it is inconvenient to work with in regard to detectors and transmission optics. One method of increasing the plasma absorption is to convert the wavelength to a shorter one at the output of the laser, using nonlinear optics techniques. Schemes for doing this are under active investigation.

One limit to the energy density which can be generated in a CO_2 amplifier is optical breakdown.[illegible] The intensity of the laser pulse is sufficient to cause breakdown of the CO_2 gas mixture. The breakdown threshold varies with parameters of the amplifier, but is typically of the order of magnitude of 10 to 20 J/cm².

At the pressures at which most CO_2 lasers operate, the gain-bandwidth is not sufficient to support the very short pulses required for laser fusion. It is necessary to increase the pressure in order to broaden the bandwidth. Increasing the pressure also increases the energy storage in an amplifier. At Los Alamos a mode-locked CO_2 oscillator has produced pulses of 1 nsec duration.[11] Single pulses have been switched out of the mode-locked train and fed to a chain of amplifiers.

Figure 2 shows the CO_2 system now under construction at Los Alamos.[11] This system consists of the mode-locked oscillator, an extraction switch to select a single pulse, and a chain of amplifiers. The first amplifier is a standard commercial design. The remainder are of LASL design and construction. These amplifiers operate at 1 to 3 atm pressure, and are of similar construction except for scale. The design is based on the generation of a controlled discharge through the application of an external electron beam as the ionizing agent.[12] The electron beam produces a uniform background ionization in the gas prior to and during the main excitation discharge. The excitation of the lasing molecules is accomplished by a second, nonsustaining discharge. Separating the source of ionization from the excitation process avoids the problem of arc formation. The electric field applied to the gas for the main discharge can be used to tailor the electron-velocity distribution, thus improving the pumping efficiency. This process produces more uniform pumping over larger volumes than other techniques and can be scaled to different geometries.

Figure 3 is a cross sectional view of one of the e-beam-controlled discharge CO_2 laser amplifiers. The electron gun and main discharge electrodes are all part of the same structure. The amplifier is shown in perspective in Fig. 4. A part of the system of Fig. 2 is running now, producing 11 J in 1 nsec. It is expected that by the end of 1973 this system will be producing 10^3 J in a single pulse of 1 nsec or less. An even larger system to produce 10^4 J is now being designed at Los Alamos, scheduled for completion in mid 1975. The latter system will have 8 beams converging on the target as shown in Fig. 5.

Another electrically pumped gas laser of interest is CO. Most of the previous comments made concerning CO_2 also apply to CO. Similar pumping schemes can be used. This system is being investigated at several laboratories.

Molecular Xe is also of interest. This system has the advantage of broad bandwidth, so that it can in principle support very short pulses (tens of picoseconds). The wavelength is in the ultraviolet at 1770 Å, both an advantage and a disadvantage. The wavelength is a good match to the target plasma and should be readily absorbed, but is very difficult to handle. Very few

Fig. 2. 1 kJ CO_2 laser system under construction at Los Alamos.

Fig. 3. Cross section of electron-beam-controlled CO_2 laser amplifier.

Fig 4

50%

Fig. 4. Perspective view of electron-beam-controlled CO_2 laser amplifier.

Fig. 5. Scale model of 10^4 J CO_2 laser system, showing 8 beams converging on target.

50%

Fig. 6. HF laser system using SF_6 and ethane. This system at Los Alamos has produced 11 J in 100 nsec.

window materials or optical components are available for this short wavelength. Such items as target chamber vacuum windows and beam turning and focusing optics are difficult problems. The expected efficiency of 50% makes Xe a very attractive laser system. This system is not yet well developed, but is being studied actively.

Chemical Lasers

If efficiency were the only criterion, then chemical lasers would be the obvious choice. Chemical lasers can be greater than 100% efficient in converting electrical energy to laser energy, since they release the energy stored in chemical bonds.[13] The main problems with chemical lasers are the large gains and the long pulse lengths. These lasers typically have gains so large that amplified spontaneous emission tends to drain most of the stored energy in amplifiers before the main pulse arrives. Most chemical lasers also have longer pulse lengths, of the order of tens or hundreds of nanoseconds. While the wavelengths range all the way from the ultraviolet to the far infrared, most of the systems of interest are concentrated in the 2 to 3 μm region and many are based on HF as the lasing molecule.

It is uncertain at this time whether many-nanosecond pulses are applicable to fusion, but the enormous efficiencies may well compensate for the longer pulse lengths. Chemical lasers also tend to be small in size and fairly inexpensive to build. One system based on HF uses SF_6 and ethane. Such a system at Los Alamos is now producing 11 J in 100 nsec.[14] This laser is shown in Fig. 6. Plans are underway to scale this system up to 200 J by the end of 1973. An electrical-input-to-laser-output efficiency of about 200% is expected.

A recent result reported by Suchard of Aerospace Corporation is the operation of an H_2-F_2 laser with 160% efficiency.[15] This system was diluted with He which produced long pulses, but shorter pulses could be obtained if the He were removed from the system.

The chemical laser field is still young and much remains to be learned. Whether or not these lasers are applicable to laser fusion is uncertain, but the efficiencies are such that one can think of laser systems that produce orders of magnitude more energy than other systems.

Nd:Glass Lasers

Of all the laser systems discussed here, the Nd:glass laser technology is the best developed. The most powerful laser beams produced to date were accomplished in Nd:glass laser systems. Pulses as short as a few picoseconds can be generated and amplified. The wavelength of 1.06 μm in the near infrared is better than CO_2 and chemical laser wavelengths, but still a long way from matching the plasma density. This wavelength is quite convenient from the standpoint of optical components and detectors.

A major disadvantage of Nd:glass lasers is the inefficiency. Typical efficiencies are 0.1 to 0.2 percent. These systems are also limited by damage to the laser glass and other components, and by the difficulty in obtaining large pieces of high quality glass for larger aperture systems.

The net effect of all these considerations is that it is unlikely that a Nd:glass laser will be used in a fusion reactor. It is possible however, that such a laser will be used to achieve breakeven and thus prove scientific feasibility for the laser fusion process. As a result, almost every laboratory working in this area is building some form of high energy, short pulse Nd:glass laser. These include a 10^4-J system at Livermore to be completed in 1976,[16] a 400-J system at NRL to be on target in mid-1973,[17] and a 400-J (25-psec) or 1000-J (1-nsec) system at Sandia, also to be finished in mid-1973.[18] Professor Basov at the Lebedev Institute has a 9-beam 600-J (2-nsec) system,[19] and there are systems at the University of Rochester,[20] in France at Limeil,[21] and in Japan.[22]

At Los Alamos a system is being built to produce 1400 J in 4 beams, with a pulse width variable from 100 psec to 10 nsec.[23] A reduced output will be available at 25 psec. This system is scheduled for completion by the end of 1973.

The early stages of this system are shown in Fig. 7 and the complete system in Fig. 8. The oscillator and first two amplifiers are Nd:YAG rather than glass. YAG is used in the oscillator because it produces more stable mode-locking. Because of a higher specific gain and a larger thermal conductivity, less pump energy is required and lower thermally induced strain is observed. This results in improved beam quality and the capability of a faster repetition rate. The YAG oscillator and amplifiers can be fired at a rate of 1 pps. The basic mode-locked pulse in a Nd:YAG oscillator is 25 psec, but bandwidth-limiting Fabry-Perot etalons can be inserted into the cavity to produce any pulsewidth up to 400 psec. For longer pulses, a Q-switched oscillator is used, and Pockels cell switches are used to reduce the pulsewidth to values as small as 1 nsec. The Pockels cell switches in Fig. 7 extract a single pulse from the mode-locked train, the single pulse then being fed to the chain of amplifiers.

Fig. 7. Early stages of Nd:glass laser system, showing details of oscillator, pulse extraction switch, and Nd:YAG amplifiers.

Fig. 8. 1400 J Nd:glass laser system under construction at Los Alamos.

Following the two YAG amplifiers are three 51-mm diameter glass-rod amplifiers. The maximum energy output from the rod amplifiers is determined by self-focusing and consequent damage to the glass rods. Self-focusing[24] is a phenomenon whereby the electric field strength of the laser beam causes the index of refraction n of the material to be changed locally, according to the equation

$$n = n_0 + n_2 E^2, \qquad (2)$$

where n_0 is the ordinary index of refraction and n_2 is the second order nonlinear coefficient. The sign of n_2 is such as to produce a positive lens effect in the material, focusing the laser beam. As the beam focuses, the effect becomes stronger, thus the beam collapses into a tiny filament and leaves a damage track in the glass rod. The occurrence of self-focusing can be forestalled somewhat by expanding the system aperture thus reducing the energy density in the beam, and by maintaining the beam profile as uniform as possible. Sharp spatial gradients in beam intensity, such as hot spots and nulls, cause self-focusing to occur more quickly. It is therefore necessary to be very careful to avoid diffraction patterns produced by aperturing the beam or by defects in rods or other components.

To avoid self-focusing and other damage effects, the aperture of the system must be enlarged to keep the energy density as low as possible. Rods larger than 51-mm diameter are difficult to make with good optical quality, and are almost impossible to pump uniformly. One tends to get high gain at the edges and low gain

Fig. 9. Principle of the disk amplifier.

at the center. One solution that avoids this problem is the disk amplifier.[25] As shown in Fig. 9, the laser glass is formed in disks tilted with respect to the laser beam (usually at Brewster's angle). The pump light from the flashlamps now has only to penetrate the thickness of the disk to produce uniform pumping. The aperture has also been increased considerably, and the piece of glass is of a size that it can be made of very high optical quality. Disk amplifiers are currently operating at NRL, University of Rochester, Livermore and Los Alamos.

The LASL system, shown in Fig. 8, has two sizes of disk amplifiers, 51-mm and 86-mm diameter.[26] These numbers refer to the apertures normal to the beam path, so that the actual apertures in the glass are larger due to the tilt of the disks. The design is modular, so that each pair of disks is contained in its own independent module with flashlamps (helical). A disk amplifier is then formed by combining several modules as one unit. Figure 10 is a photograph of a single disk module and Fig. 11 is a photograph of a complete disk amplifier. In Fig. 8, each box labelled "51-mm Disk Amp" contains 12 disks and each box labelled "86-mm Disk Amp" contains 8 disks. After the first 51-mm disk amplifier, the beam is split four ways, each fourth following an independent but identical beam path. The output of each of the four arms is expected to be 350 J in 100 psec, for a total of 1400 J. The four beams will simultaneously irradiate a target from a tetrahedral symmetry. One of the four beam paths is complete and ready for testing. The entire system is scheduled for completion by the end of 1973.

Isolation

One problem shared by almost all of the laser systems considered here is isolation from target reflections. Since the amplifier pump mechanism is typically slow (microseconds) the amplifiers still have gain long after the laser pulse has gone through. Depending on the conditions, the target plasma may reflect substantial percentages of the incident light. This reflected light gets recollimated by the focusing lens and sent backward through the amplifier chain. The beam is amplified until it becomes intense enough to damage some component.

One method of providing isolation, a Faraday-effect isolator, is shown in Fig. 12.[27,28] An initial polariser agrees with the polarisation of the incoming laser beam. A piece of glass exhibiting the Faraday effect is located inside an axially directed magnetic field. The field intensity and glass length are adjusted so that the polarisation of the beam is rotated 45°. The beam then passes through a second polariser and travels on to the target, is reflected and returns. Any component whose polarisation has been rotated 90° at the target is rejected by the second polariser. The rest of the

Fig. 10. Photograph of a disk amplifier module. The module shown contains one disk and its flashlamps. Double modules, containing two disks and their flashlamps, are also used.

Fig 11

Fig. 11. A complete disk amplifier from the Los Alamos system. This unit contains 12 disks of 51-mm aperture. A similar unit contains 8 disks of the 86-mm aperture.

Fig. 12. Faraday effect isolator.

beam is rotated an additional 45° by the Faraday glass, and is now crossed to the first polarizer and thus rejected. These systems work quite well, but are not without their problems. They are large and bulky (because of the apertures), and require large, precision magnetic fields to obtain good rejection ratios. The Faraday glass and the polarizers are subject to damage by the laser beam. In some cases stacked-plate polarizers must be used, since polarizing crystals and dielectric films are subject to damage. At Los Alamos a Faraday-effect isolator has produced an extinction ratio of 200:1 over an aperture of 51 mm. Based on this ratio, several isolators are required as shown in Fig. 8.

Another method of isolation is to use part of the laser beam to essentially remove a mirror from the path by blasting it after the primary laser pulse has passed.[29] A variant of this method is to use a blast shutter which blocks the return beam.[30]

Perhaps the best scheme for isolation is that of frequency conversion. A nonlinear optical device placed in the beam at the output of the system changes the wavelength of the laser light, preferably to a shorter one. Any light reflected from the target is then no longer in the gain bandwidth of the system, is not amplified, and therefore is not a problem. This method has the further advantage that a better wavelength match is made to the plasma if the conversion is to a shorter wavelength. The major difficulties are damage to the nonlinear optical medium and the efficiency of conversion. Conversion efficiencies of 50% or better are required to make this system applicable. Several methods of frequency conversion are presently being examined for this purpose, including second and third harmonic generation, Raman shifting, and parametric amplification. One method that looks encouraging is third harmonic generation in metal vapors. High efficiencies are possible and the nonlinear optical medium is not damageable.

Conclusions

Laser fusion for power generation is a goal that is being actively pursued by many research laboratories today. The type of laser that will be used to achieve this goal is still uncertain. As a result, several high-energy, short-pulse laser systems of different types are being constructed for research in this area. These systems will be used to conduct experiments over the next several years with the aim of producing scientific breakeven. Following that achievement, the goal will be to show economic and technical feasibility for a laser fusion power plant. Whatever the results, the research into these areas promises to be most interesting.

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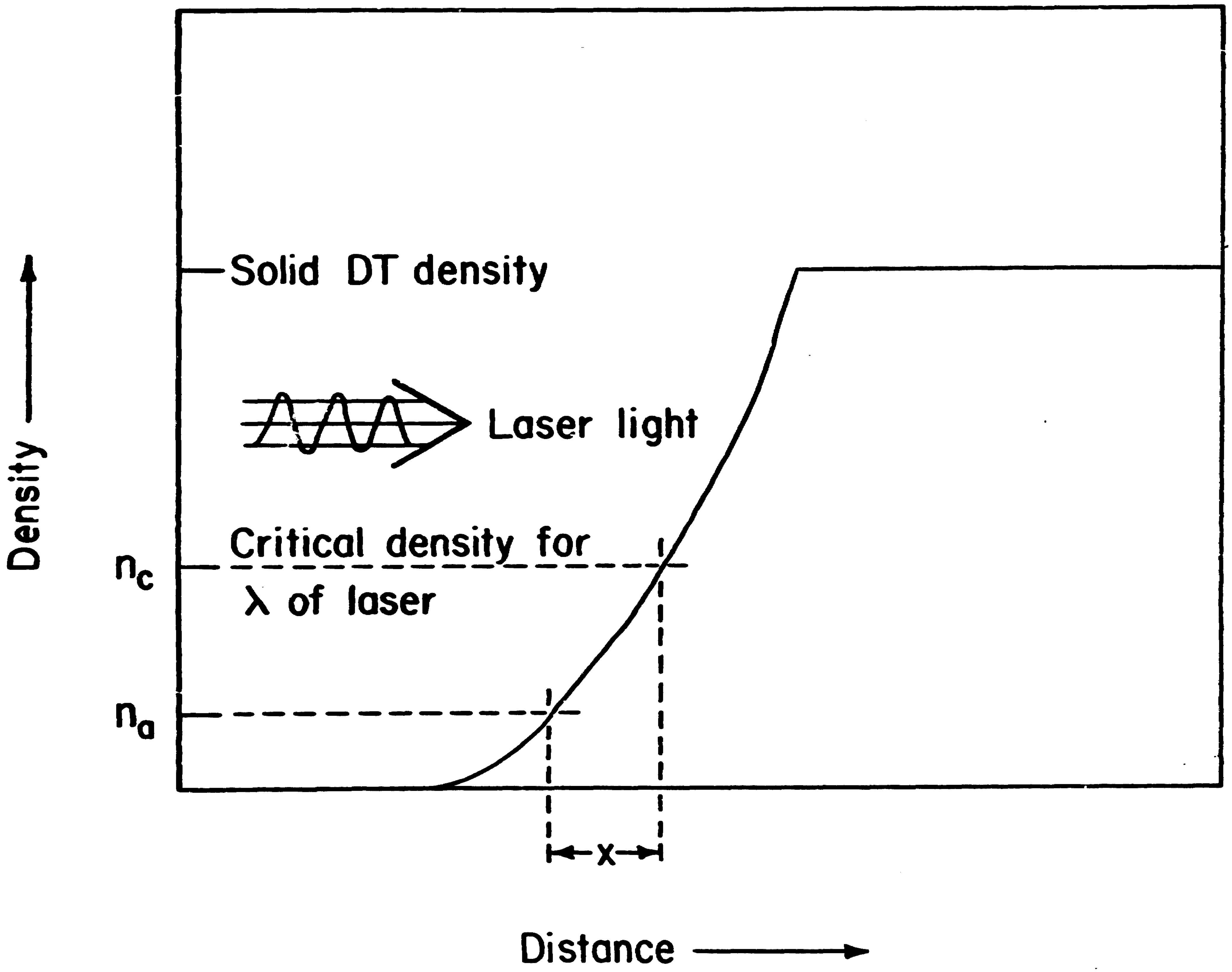
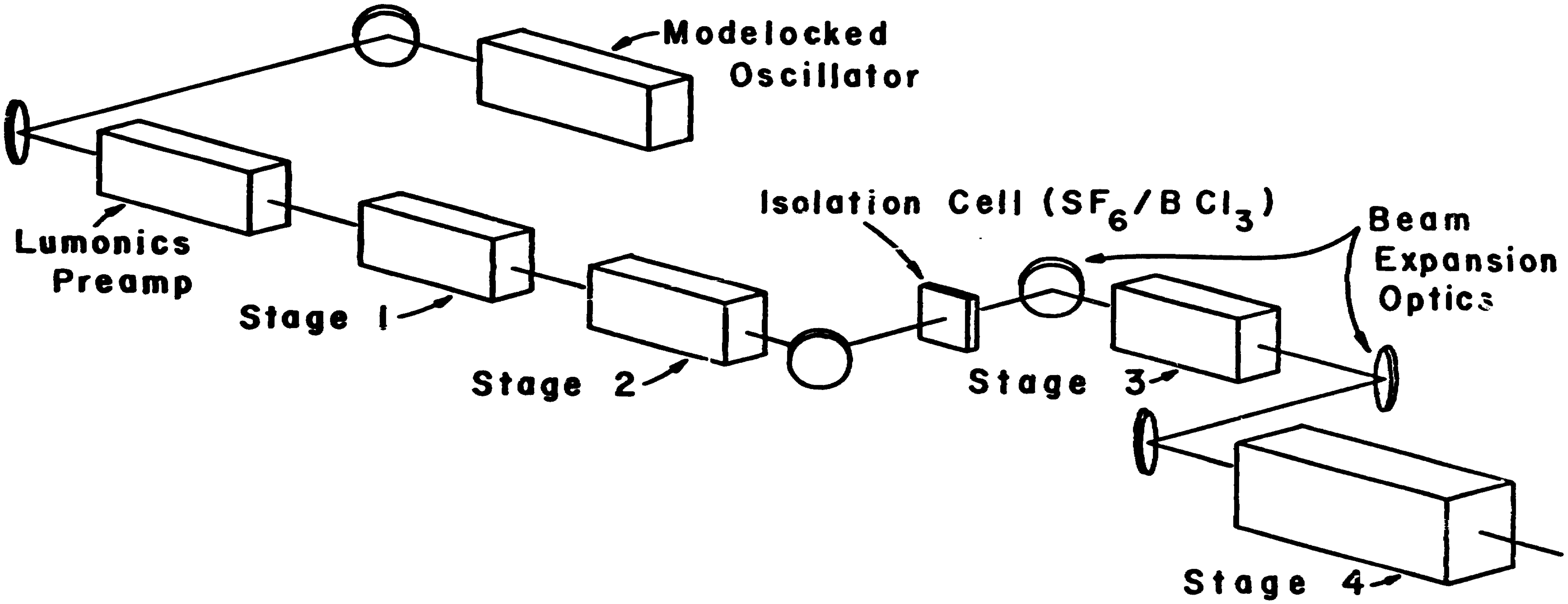
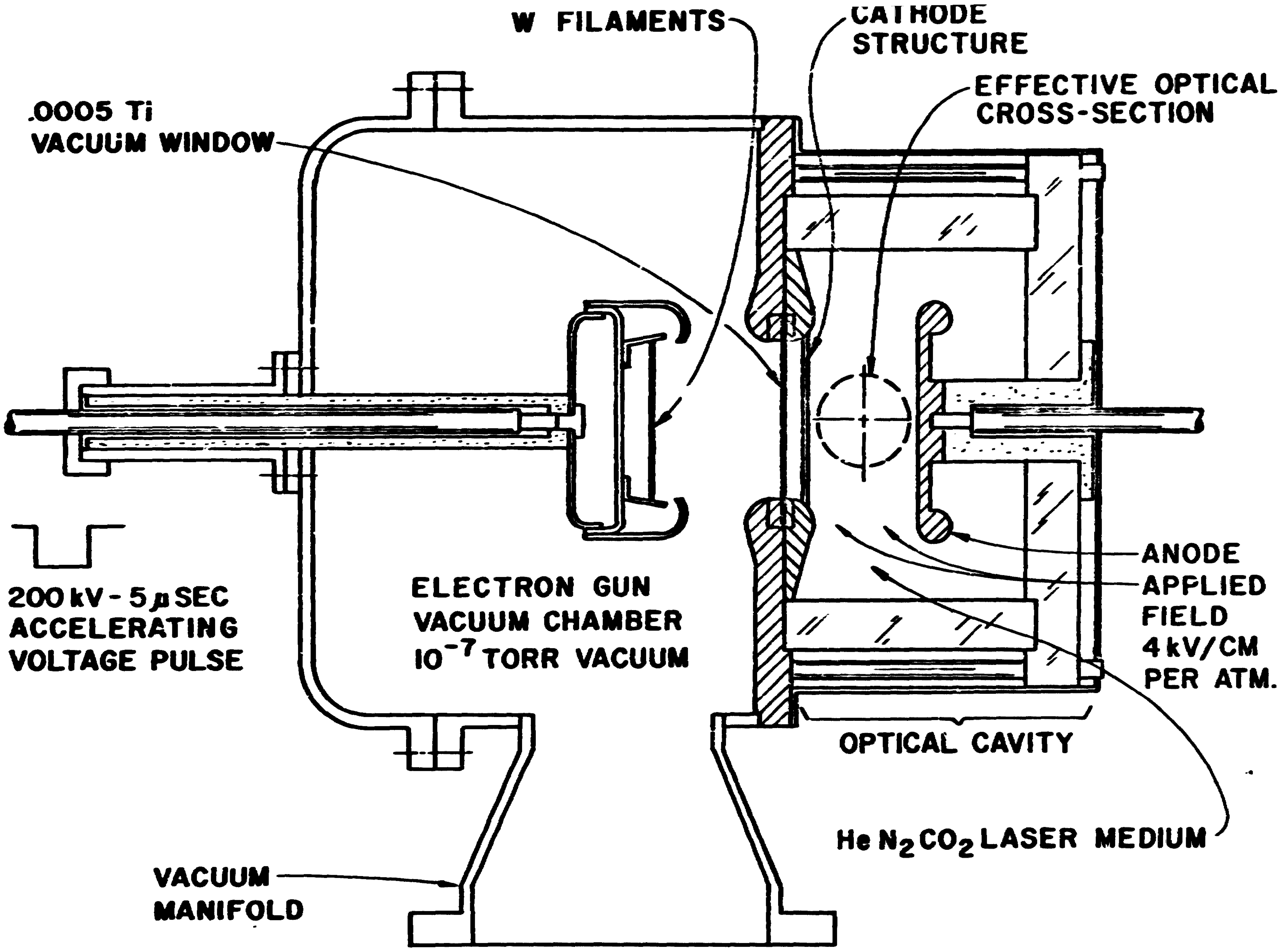

Solid DT density
Laser light
Critical density for
λ of laser
n_c
n_a
x
Density
Distance

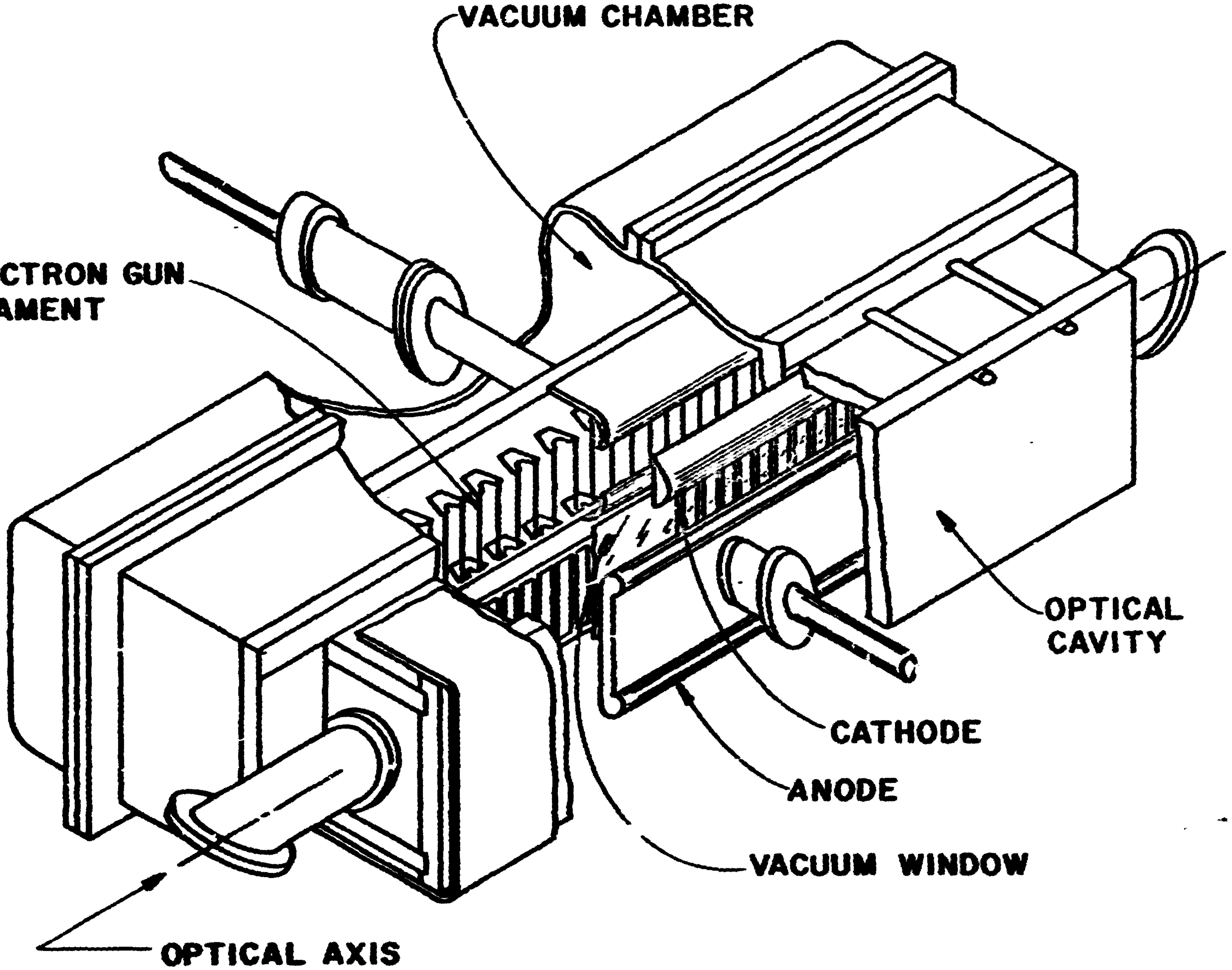
1000 J CO_2 Oscillator/Amplifier System



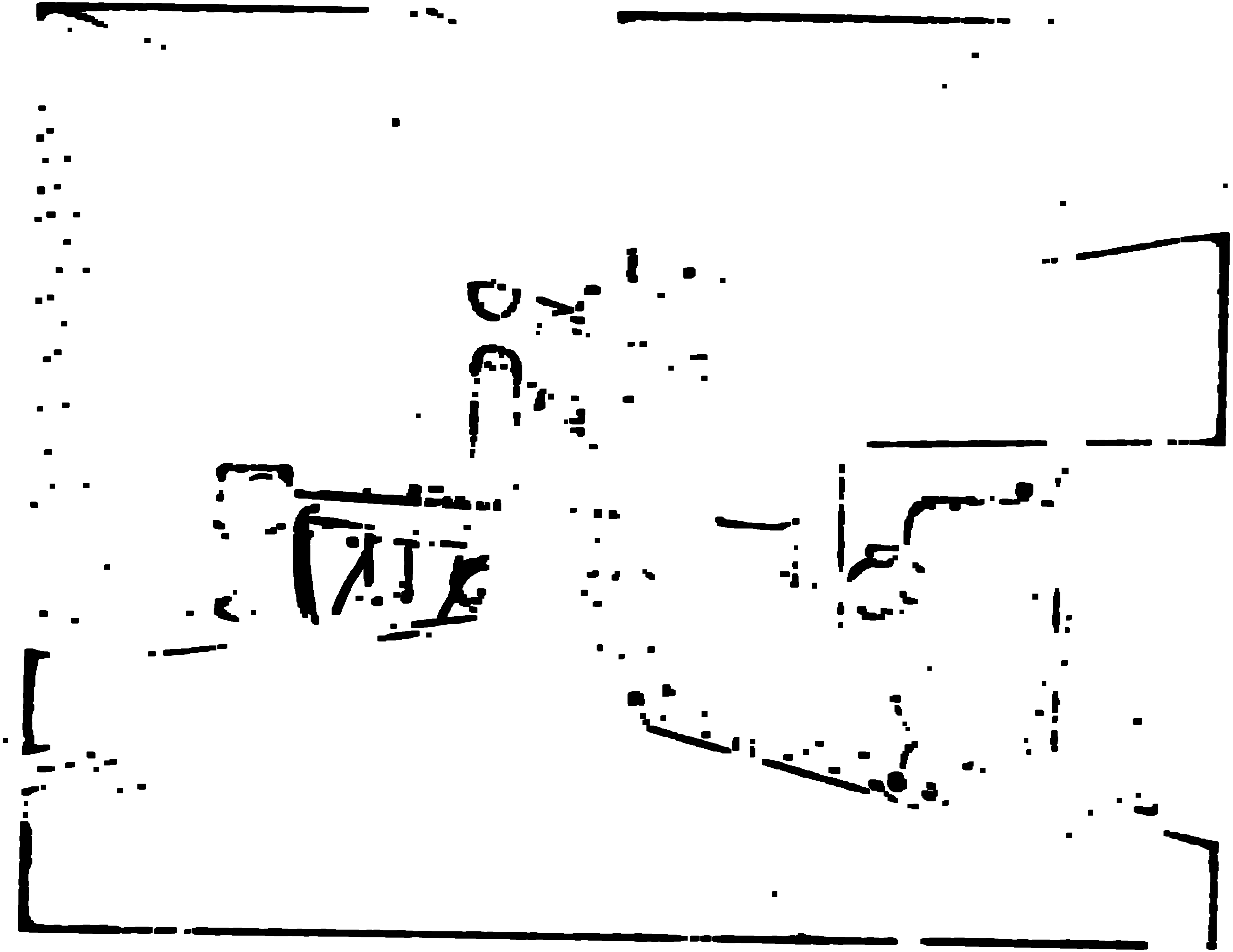
Component	Area	L	Gain	Pressure	ε_{stored} (total)
Preamp	10 cm^2	150 cm	50	600 mm	—
Stage 1	15 cm^2	100 cm	165	600 mm	9 Joules
Stage 2	15 cm^2	100 cm	165	600 mm	9 Joules
Stage 3	40 cm^2	100 cm	80	1200 mm	40 Joules
			(100)	(2280)	(70)
Stage 4	500 cm^2	200 cm	(10^4)	(2280)	(1900)

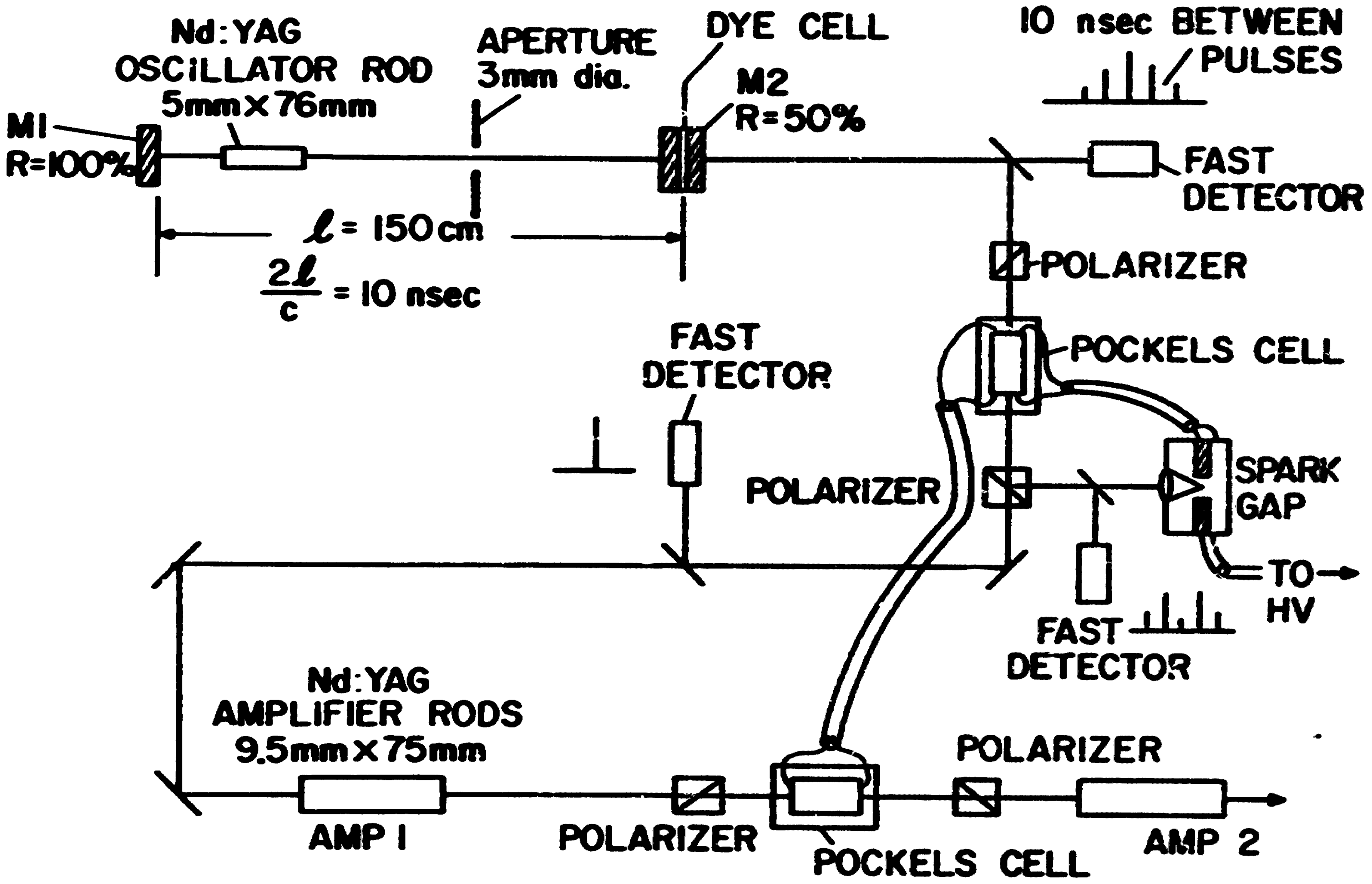


ELECTRON BEAM CONTROLLED CO_2 LASER AMPLIFIER

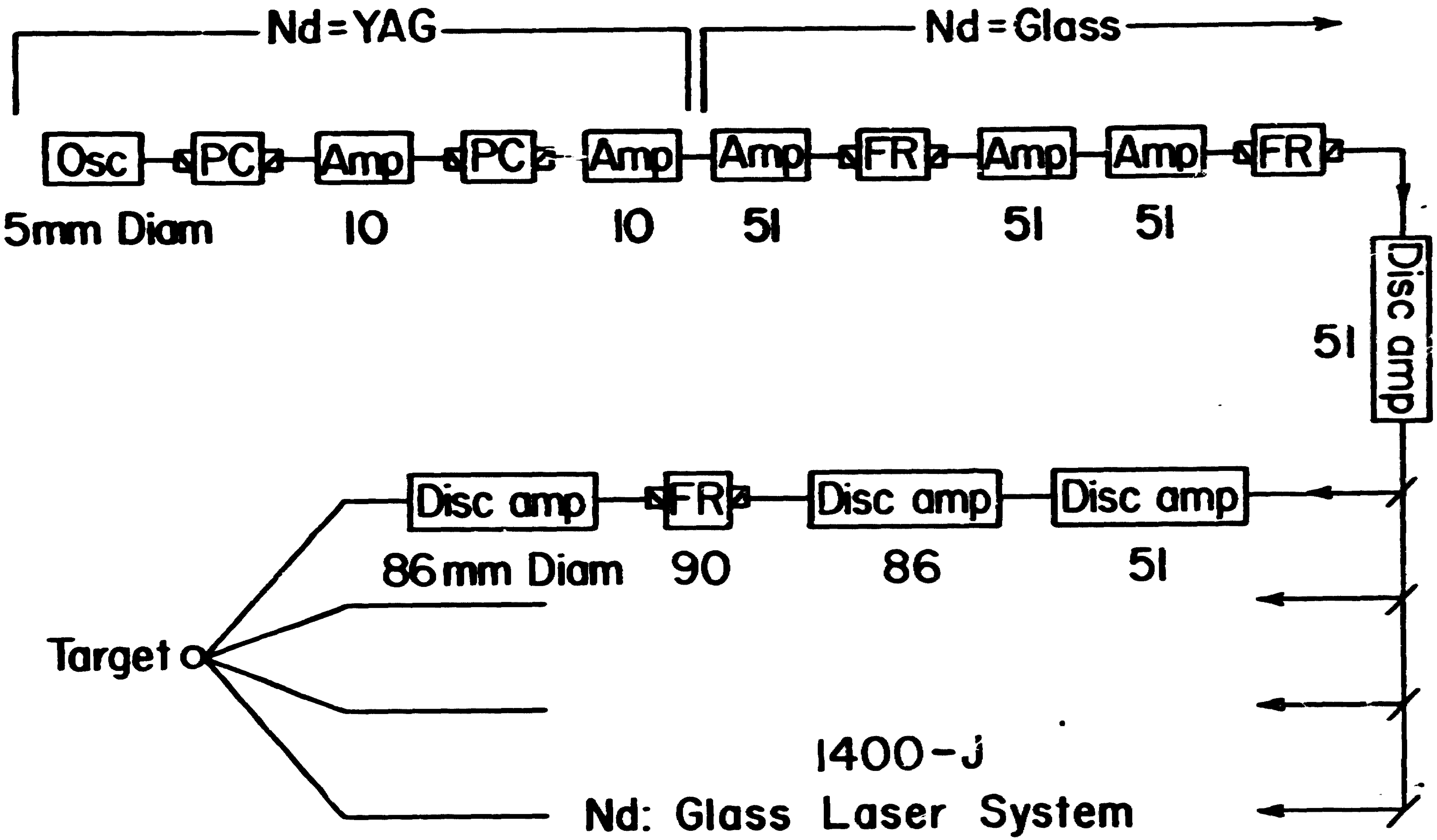


ELECTRON BEAM CONTROLLED CO_2 LASER AMPLIFIER





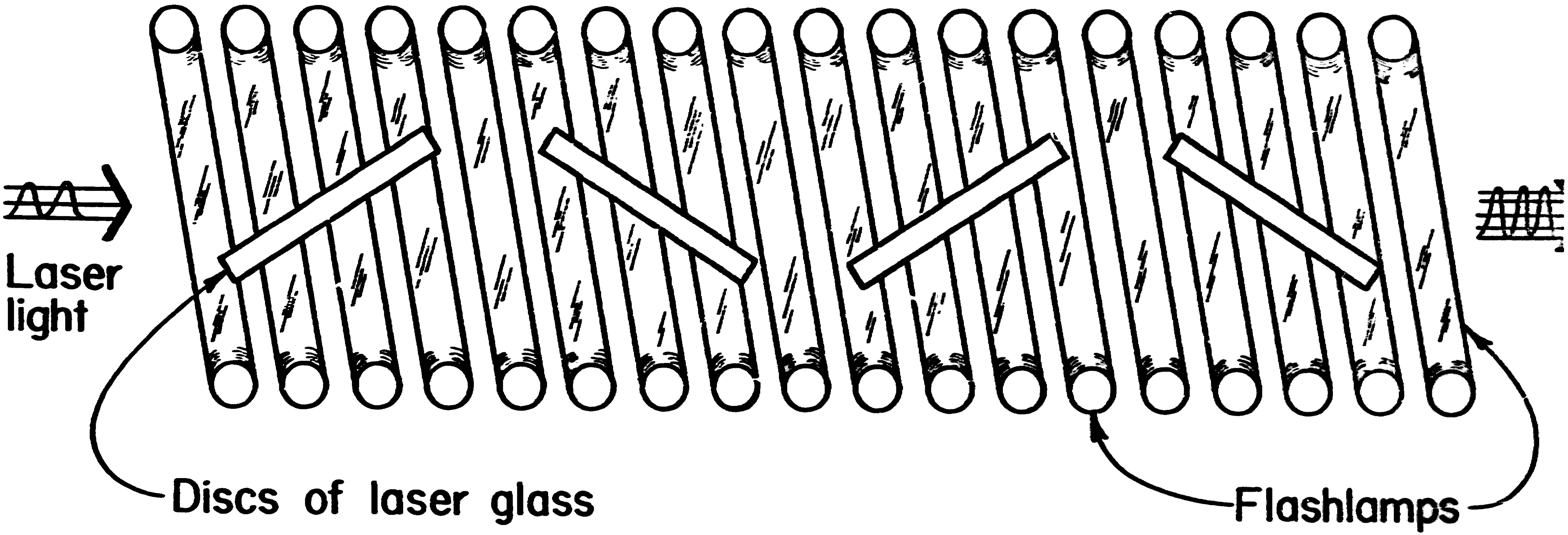
OSCILLATOR, FIRST AMPLIFIERS, AND POCKELS CELL SWITCHES



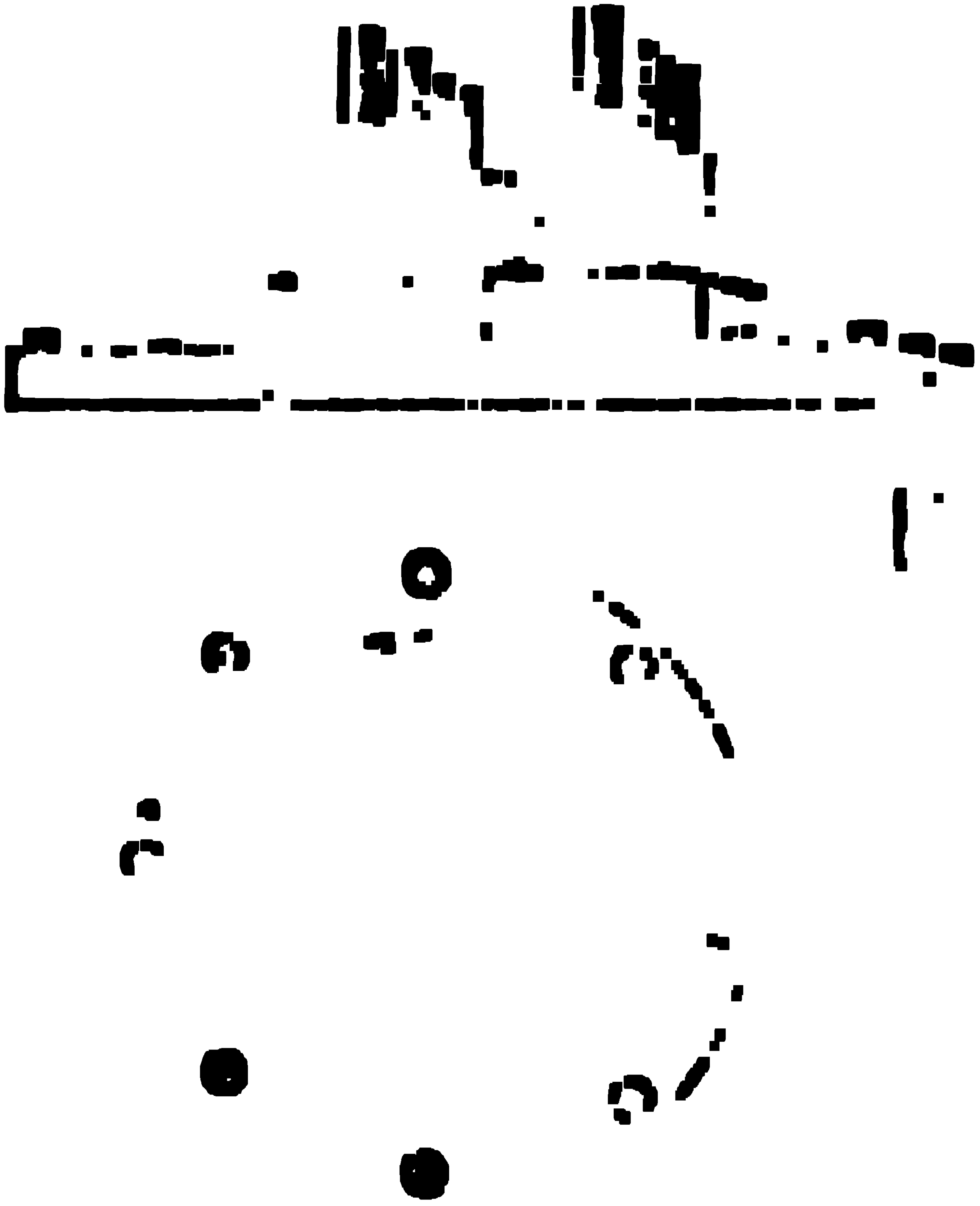
1400-J
Nd: Glass Laser System

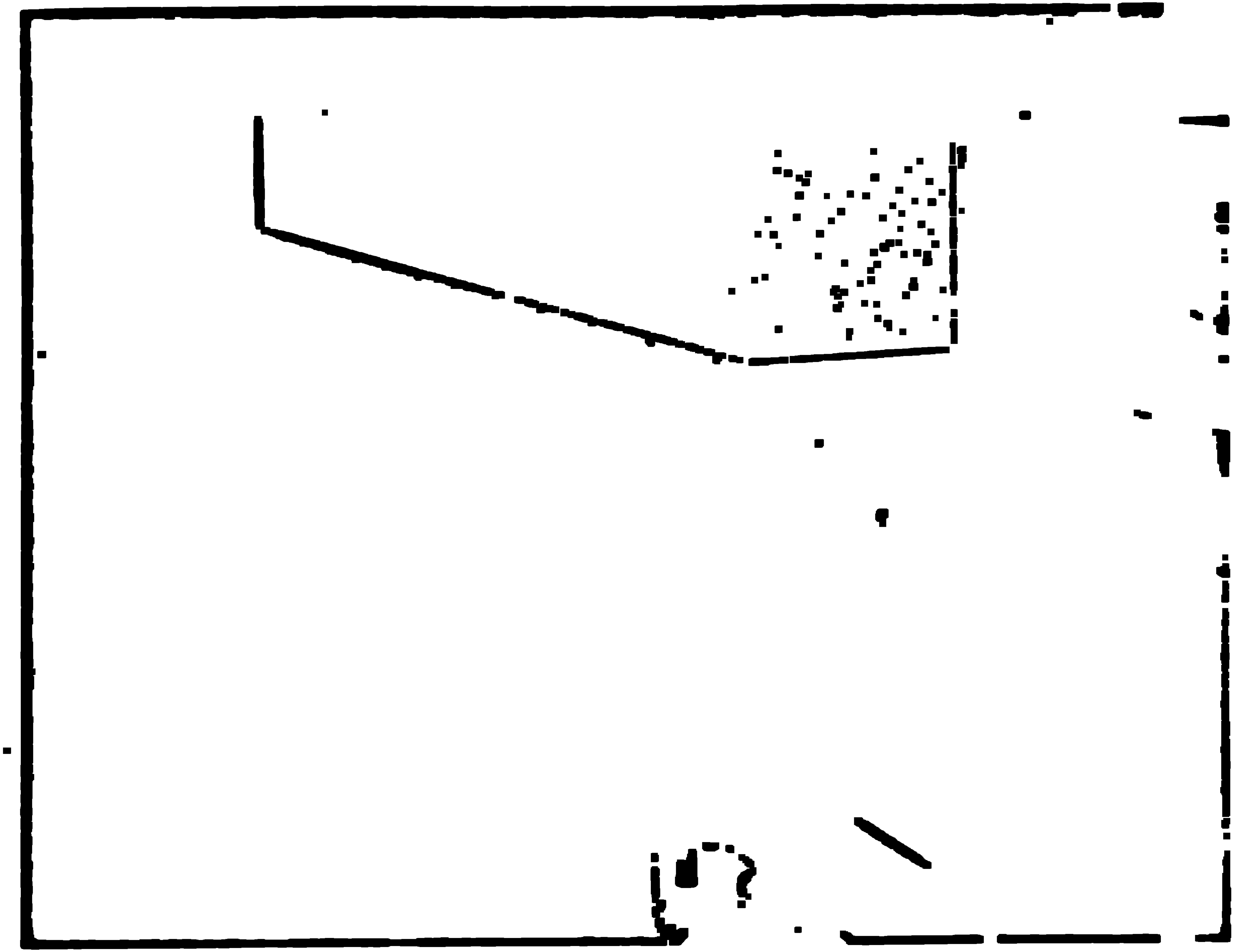
PC = Pockels cell
FR = Faraday-effect rotator

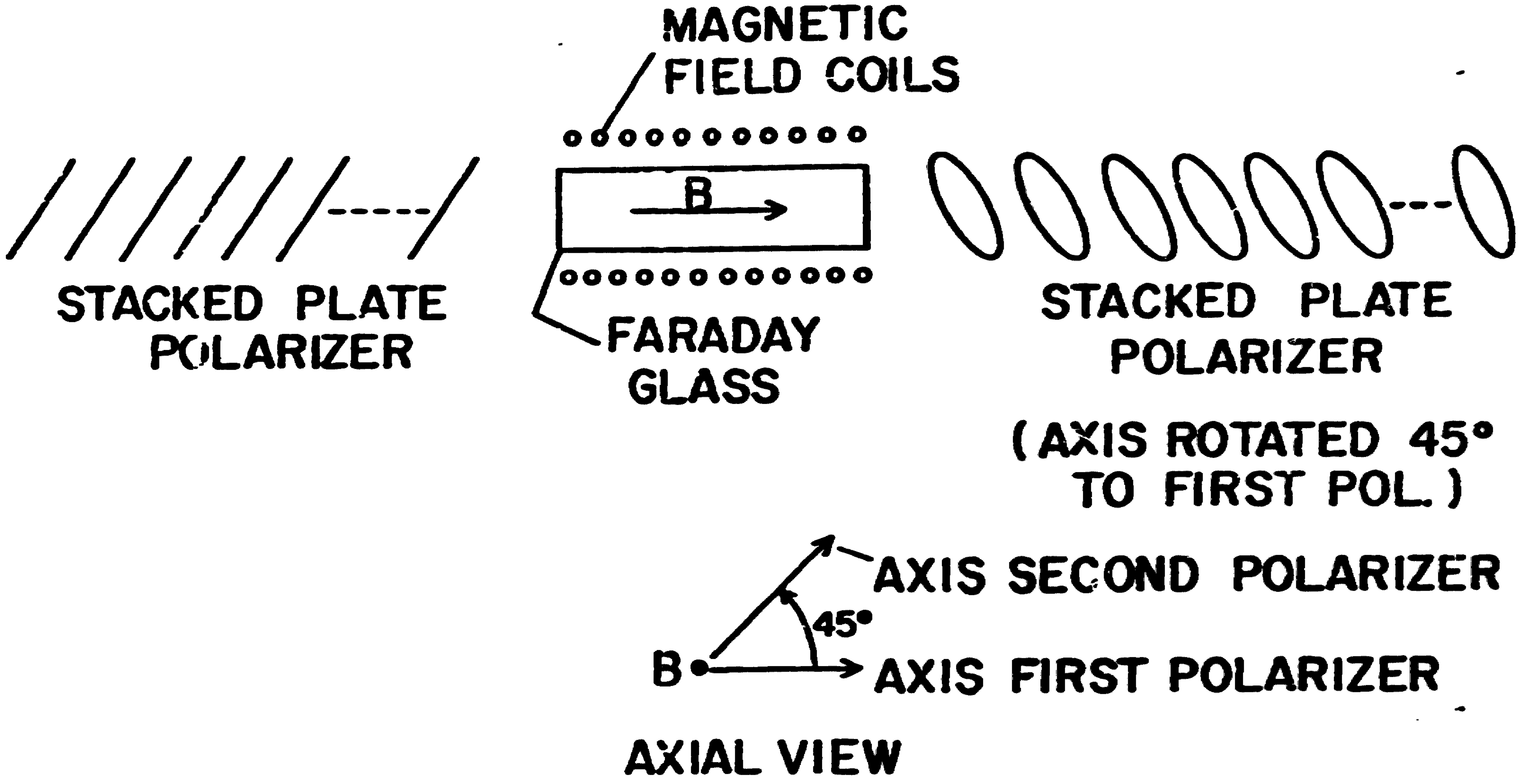
⧄ Polarizer –
Glan prisms, stacked plates,
multilayer dielectric



Principle of Disc Amplifier







FARADAY EFFECT ISOLATOR