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ELECTRON-BEAM-CONTROLLED LASERS: DISCUSSION FROM THE ENGINEERING VIEWPOINT

PART I. DESIGN OF THE 1 kJ and 10 kJ CO_2 LASERS*

R. E. Stapleton, K. B. Riepe, E. L. Jolly, Jr., J. Weinbrecht, J. J. Hayden, E. O. Ferdinand and T. A. Carroll

Los Alamos Scientific Laboratory
University of California
Los Alamos, NM 87544

Abstract

The Los Alamos Scientific Laboratory (LASL) CO_2 laser program was organized to design, fabricate, and evaluate high-energy, short-pulse CO_2 lasers for use in fusion studies. A general discussion of electron-beam-controlled lasers is included, along with details of component designs. This includes a discussion of the high voltage pulsers, electron guns, pumping chamber vessels, timing, and operational experience with the 1 kJ CO_2 laser system components. In addition, the general design o. the 10 kJ CO_2 laser system is presented.

Introduction

An electron-beam-controlled laser[1,2] is one where the ionization production mechanism in the gas media is controlled by an external ionizing source, namely a high-energy electron beam. A typical arrangement is shown in Fig. 1. The energy and quantity of the electrons must be sufficiently high in order to uniformly ionize the complete lasing volume, which then may be readily pumped by an applied voltage less than the breakdown voltage of the lasing gas. This type of system may be operated as an oscillator, long pulse or short pulse amplifier.

The CO_2 laser program at LASL is devoted toward development of short pulse systems, i.e., 10^{-9} seconds. Therefore, all further discussion will be devoted to this area.

Parametric studies were made on small scale models to determine a range of design parameters for larger systems. These data indicated that large laser amplifiers should have a small signal gain of 0.04 to 0.05 cm^{-1}, an applied electric field of 4 kV/cm-atm (STP) and an energy input of 100 to 200 J/ℓ-atm in 3 to 6 μsec. Based on these criteria, an estimate of the required electron density in the lasing gas media is obtained by solving for N_e in the following expression[2]

$$J_s = N_e q_e v_D \tag{1}$$

where J_s is the current density (A/cm²), N_e is the number of electrons/cm³, q_e is the electron charge, and v_D is the electron drift velocity.

The electron density is controlled by the secondary ionization of the external electron beam.[2]

$$\frac{dN_e}{dt} = S_0 - \alpha N_e N_i \tag{2}$$

where S_0 is the source term due to the electron beam and a loss term due to two body recombination, N_i is the gas ion density and α is 2×10^{-7} cm³/s.

For a high pressure system of 1 to 10 atm and mixtures of gas under consideration, diffusion and attachment losses are small and can be neglected. Therefore, S_0 is directly proportional to the electron beam current density and energy loss per unit length, and inversely proportional to the energy loss per ion pair. Then the steady state conditions are[2]

$$N_e = \left(\frac{S_0}{\alpha}\right)^{1/2} \tag{3}$$

Therefore, a typical set of design parameters would be the following:

laser volume	= 8 x 8 x 100 cm
gas mixture	= 3:¼:1::He:N_2:CO_2
gas pressure	= 2.4 atm
electron beam voltage	= 175 kV*
electron beam current density	= 200 mA/cm²*
gas chamber voltage	= 4 kV/cm-atm
gas current density	= 15 A/cm²
gas pumping time	= 5 μsec.

*Incident on the electron beam window foil.

1 kJ CO_2 Laser System

MASTER

General

A short pulse laser system consists of a laser oscillator,[3] which generates a low-energy, short-pulse, and an amplifier or amplifiers to increase the energy in the pulse (see Fig. 2).

Oscillator

The oscillator is a double-discharge type.[4] It is

*Work performed under the auspices of the U. S. Atomic Energy Commission.

actively modelocked, with a system for selecting and switching out a single, 1.2 nsec pulse from the mode-locked train. The amplifier train consists of two 580 Torr modules (A-1 and A-2), a 1800 Torr module (A-3) and final 1800 Torr module.

Amplifier Design

Electron Beam Source. The first consideration was the type of cathode that would supply 100 to 500 mA/cm^2 with a uniformity of plus or minus a few percent. These sources were divided into thermionic (hot) cathode, "cold cathode," field emission cathode, and plasma cathode. At the time, "cold cathode" and plasma cathode systems were in an embryonic state, while the field emission cathode had many disadvantages for long pulse applications of 5 to 10 μsec, such as reproducibility, large area (several hundred or thousand cm^2), uniformity, extreme cleanliness and conditioning. It became apparent that the thermionic cathode was the best approach.

The diode, triode, tetrode, and pentode types of construction were considered. The planar diode, being the simplest form, was chosen for the reduced complexity of the external circuitry and internal construction. A major concern was the reproducibility of output current when the diode was operated emission limited, output. This has not been a problem in the present amplifiers. In addition, an advantage is that the output current density is independent of voltage fluctuations above a critical value for a constant temperature.

The next consideration was the cathode material and was based on operating temperature, electron emission, and susceptibility to cathode poisoning. Pure tungsten, thoriated tungsten, barium-impregnated tungsten and oxide-coated filaments were considered. The selection of thoriated tungsten was made based on the aforementioned criteria.

The cathode tray filaments and support springs are shown in Fig. 3.

The hot filament cathodes of amplifiers 1, 2, 3 and 4 (A-1, A-2, A-3 and A-4) are all similarly constructed. In A-1, A-2 and A-3, the filaments are spaced one cm apart and the overall cathode area is 8 x 100 cm. In A-4, the filaments are spaced one cm apart and the overall cathode area is 28 x 200 cm. The assembly of A-4 is shown in Fig. 4.

Electron Beam Window Studies

In order to determine the optimum design for a vacuum-pressure barrier with a maximum electron beam transmissivity, several parametric studies were done. The approach taken to solve this problem was to use a thin membrane as a gas seal with a slotted support structure backing the membrane to carry the load. Several foil materials and grid structures were subjected to pressure rupture tests. The strongest foil material with the maximum electron transmission was titanium.

Electrical

General. Each of the four amplifiers has a power supply which provides filament heating power. These power supplies are all similar in that they use saturable core reactors to drive the high voltage isolation transformers which deliver power to the filaments. In normal operation, power is delivered to the filaments for only 8 to 10 seconds prior to pulsing, because damage could result to the foil window if filament power were left on continuously. Each power supply has interlocked timing circuits to prevent this from occurring. These circuits are a part of the saturable reactor DC control circuit.

Amplifier 1 and 2 (A-1 and A-2). The quite similar A-1 and A-2 are connected in parallel to the electron beam and pumping chamber pulsers. The electron beam pulser uses a three-stage Marx unit generating voltages from 100 to 140 kV. Each of the three capacitors is .75 μF. A 50 Ω resistor, common with both of the electron beam currents, and a 40 Ω resistor in each of the electron beam current legs limit the short circuit current. A crowbar gap is used to remove the high voltage after firing.

Because of the lower voltage requirement of the pumping chamber pulser, ignitrons are used both for connecting the energy storage capacitors to the pumping chamber and for crowbarring after firing.

Amplifier 3 (A-3). The electron beam power supply for A-3 is a seven-stage Marx generator. Each stage consists of a Maxwell Laboratories Type S, 0.75 μF capacitor rated at 50 kV. Each stage is switched by a three-electrode, pressurized spark gap. The power supply is routinely operated at 160 kV.

The output of the power supply is crowbarred by means of a point-to-plane spark gap in which the insulating medium is water. The time required for electrical breakdown of the water-insulating medium of this unusual switch is dependent upon the electrode spacing. The breakdown vs electrode spacing relationship is linear and is approximately 2.54 cm/μsec. The switch requires no triggering and works well with voltages greater than 110 kV and spacings less than 20.3 cm for the present geometry. The pointed electrode is made of tungsten, the plane of stainless steel.

The pumping chamber power supply for A-3 is a three-stage Marx generator. Each stage consists of two 4.9 μF, 30 kV capacitors connected in parallel. The maximum output voltage is 90 kV and the maximum available energy, 13.2 kJ. The three pressurized, three-electrode spark gaps are triggered simultaneously in order to erect the Marx. The output is crowbarred by means of a pressurized, trigatron spark gap which is triggered after the desired output pulse width has been obtained. The power supply is connected to the pumping chamber by means of six paralleled, 4.3 m long, RG-19 A/U coaxial cables. A typical output current waveform is shown in Fig. 5. The time relationship between the electron beam and the pumping chamber currents is also illustrated in Fig. 5. The timing of the turn-on and turn-off of the electron beam with respect to the pumping chamber voltage has been found to be a factor in pumping chamber breakdown. Applying a fast-rising voltage to a pumping chamber in the absence of an electron beam results in a transient voltage pulse which may produce breakdown in the chamber. This transient pulse is due to the impedance mismatch at the end of the coaxial cable and may result in voltage doubling. Therefore, it is best to insure that the electron beam is present and the conductivity of the chamber is high before applying voltage to the pumping chamber. Turning off the electron beam with high pumping currents present may also lead to breakdown due to transient voltages produced by the inductance of the pumping chamber circuit. Thus, as in Fig. 5, the electron beam is turned on approximately 2 μsec before the pumping voltage and remains on for a few microseconds after pumping chamber current shutdown.

A-3 is fully operational, operating with electron beam voltages (anode-to-cathode) of 160 kV, pumping voltages (anode-to-cathode) of up to 75 kV, and pumping gas pressures to 1800 Torr absolute. Used in conjunction with the oscillator and A-1 and A-2, it has produced single short pulses (~ 1.2 nsec FWHM) of up to 17 J. A measured small signal gain of 4.78 ± .08%/cm was made with the following test conditions: chamber filled to 1800 Torr with a 3:¼:1: :$He:N_2:CO_2$ gas mixture; pumping chamber voltage (anode-to-cathode) of 72 kV; and an electron beam voltage (anode-to-cathode) of 178 kV. The maximum gain appeared 3.3 µsec after the start of pumping current.

Amplifier 4 (A-4). The filament power supply for A-4 consists of a saturable core reactor and an isolation transformer. The circuit diagram is shown in Fig. 6. With the power supply shown, the filaments reach their normal operating temperature of 1750°C in approximately 10 seconds. The power input at this temperature is 36 kW.

The electron beam power supply is a seven-stage, oil-insulated Marx generator. Each stage consists of a 1.8 µF capacitor, with a rated lifetime of 10,000 shots at 60 kV charging voltage. Midplane-triggered, pressurized gas switches are used to connect the Marx stages.

Maximum pulse width is 10 µsec. With a 200 Ω load connected to the power supply, the maximum output voltage is 325 kV. The inductance of the power supply is 1.1 µH.

For a typical operation, the electron beam power supply is pulsed on for 10 µsec producing a peak anode-to-cathode voltage of 244 kV and a current of approximately 1000 A or 166 mA/cm² of window area (30 x 200 cm). A typical current trace is shown in Fig. 7. The cathode is operated emission-limited under these conditions.

The pumping chamber power supply for A-4 is a four-stage LC generator and has a voltage output ranging from 60 to 320 kV. At voltages below 160 kV, it is used as a two-stage LC generator with an effective capacitance of 3.75 µF. At higher voltages, all four stages are used, the effective capacitance being 1.875 µF and the maximum stored energy is 96 kJ.

A-4 is presently in the electrical checkout stage. The electron beam is routinely operating at an anode-to-cathode voltage of 240 kV with a current of 166 mA/cm² of window area. The pumping chamber has been satisfactorily operated with voltages as high as 200 kV. Figure 7 shows the pumping chamber current waveform obtained with a power supply output voltage of 164 kV. The pumping chamber was filled with a 3:¼:1: : $He:N_2:CO_2$. Gas pressure was 1200 Torr absolute. Small signal gain has been measured with these test conditions and a center line gain of ~ 2.7%/cm obtained with gain maximum occurring ~ 5 µsec after the start of pumping current. The electrical energy delivered prior to gain maximum is ~ 132 J/ℓ.

Using the same test conditions, a short pulse (~ 1.2 nsec FWHM) was amplified by A-4 to an energy of 168 J as measured by an SF_6 calorimeter. Increasing the voltage to 200 kV and the pressure to 1300 Torr resulted in a small signal gain of ~ 3.1%/cm.

Mechanical

Electron Beam Chamber (A-1, A-2 and A-3). The electron beam chamber is a rectangular, welded, stainless steel enclosure with inside dimensions approximately 28 cm high, 34 cm deep and 126 cm long. Flanged longitudinally, it can be taken apart to form two long half-shells, the rear of which is ported in five places to receive the insulator supports and cable fittings for the cathode. The forward wall of the front half interfaces with the pumping chamber and so is a relatively massive member (~ 2½ cm thick) with the 8 x 126 cm window and tapped holes to support the window foil assembly, grid and pumping chamber. The front portion also contains the pump-out port leading to the vacuum system. Both ends of both halves of this chamber are fitted with 5 cm diameter viewports. The interior surfaces were electro-finished to a condition of a number 4 finish or better.

Pumping Chamber (A-1 and A-2). The pumping chamber for A-1 and A-2 has a geometry compatible with the 5 x 5 x 100 cm active gas volume. Inside dimensions are approximately 16 cm high, 12 cm deep and 120 cm long and was fabricated from 2.5 cm thick acrylic sheet stock to form a rectangular structure with one side open to the electron beam chamber interface. The acrylic members were glued with tongue and groove joints to make a chamber suitable for the one atmosphere requirement. Optical ports, aligned with the active area, are in both ends of the chamber. Suitable ports exist on the longitudinal member to receive the five insulator feedthrough supports for the anode. The outboard side of the box overhangs the top and bottom by 3 cm and is drilled for 26 permali threaded rods with nuts to secure the pumping chamber to the interface.

Pumping Chamber (A-3). This system evolved from A-1 and A-2 (A-1 and A-2 are identical) and resulted from the need to operate at higher pumping chamber pressures, and a larger pumping volume (8 x 8 x 100 cm). The acrylic structure was replaced in A-3 with an epoxy chamber. Its material composition is as follows:

Epon 8208	- 75 pps/100 by weight
Adiprene L100	- 25 pps/100 by weight
Moca	- 39 pps/100 by weight .

The finished chamber was machined from the rough casting of the box proper and two smaller, cylindrical castings which were taper-fitted and glued in the ends to form optic ports. The chamber was hydrostatically tested to 74 psig. In assembly, permali studs used on A-1 and A-2 were replaced on A-3 by G-10 fiberglass. Achieving an interface seal at 3 to 5 atmospheres involves torquing the nuts to about 70 in-#.

Vacuum system (A-1, A-2 and A-3). The vacuum systems on these amplifiers are electrically isolated from the electron beam chamber by dielectric spacers and bushings for fasteners of the valve, cold trap, diffusion or ion pump and a roughing line. Some He poisoning of the ion pumps was caused by the diffusion through the o-rings in the pumping chamber-electron gun interface. The o-rings were replaced by new ones made of Hydrin 100 which reduced the He leakage by a factor of ten. In addition, the ion pumps have been replaced with cold-trapped oil diffusion pumps on A-1, A-2 and A-3.

Electron Beam Chamber (A-4). The development of a 1 kJ amplifier system posed more problems than merely "scaling up" previous models.

The electron beam chamber is a stainless steel weldment with interior dimensions approximately 64 cm deep, 80 cm high and 250 cm long (see Fig. 8). It is basically a cylinder with two opposite sides truncated to form flat surfaces, one to contain the window and

Achieving an interface seal at 3 to 5 atmospheres involves torquing the nuts to about 70 in/#.

4) Vacuum system. (A-1, A-2 and A-3)

The vacuum systems on these amplifiers are electrically isolated from the e-beam chamber by dielectric spacers and bushings for fasteners of the valve, cold trap, diffusion or ion pump and a roughing line. Some He poisoning of the ion pumps was caused by the diffusion through the o-rings in the pumping chamber-electron gun interface. The o-rings were replaced by new ones made of Hydrin 100 which reduced the helium leakage by a factor of 10. In addition, the ion pumps have been replaced with cold-trapped oil diffusion pumps on A-1, A-2 and A-3.

5) E-Beam Chamber (A-4)

The development of a 1 kJ amplifier system posed more problems than merely "scaling up" previous models.

The e-beam chamber is a stainless steel weldment with interior dimensions approximately 64 cm deep, 80 cm high and 250 cm long. (Fig 8) It is basically a cylinder with two opposite sides truncated to form flat surfaces, one to contain the window and interface with the pumping chamber, the other to mate with a flat flange mounting the cathode and six insulated feed supports. Top and bottom cylindrical walls are well-reinforced to enhance stability under vacuum. Thirty-five cm diameter pump-out lines project at an angle from both ends which are an integral part of the chamber. A manifold fitting on each of these lines runs through a bellows coupling to two ion pumps (four total).

6) Pumping Chamber (A-4)

The pumping chamber for A-4 presented most of the problems. The required pumping volume was 25 x 25 x 200 cm. The very size of the box seemed to preclude attempts to make a successful casting within reasonable cost and so, the decision was made to design a chamber fabricated with stock sheets of G-10 fiberglass-epoxy laminate. The resulting rectangular box has interior dimensions approximately 62 cm high, 44 cm deep and 236 cm long (see Fig. 9).

The box is mounted to the e-beam chamber interface with long, 3/4" diameter G-10 rods, threaded at both ends and extending through the entire length of the box to be capped with phenolic washers and permali nuts.

7) Lasing Gas

All of the amplifiers use a 3:1/4:1::He:N_2:CO_2 mixture. A-1 and A-2 operate at 580 Torr and use a flow-mixing arrangement. A-3 and A-4 are operated up to 1800 Torr and use pre-mixed gas from high pressure gas bottles. Analysis before and after long term operation (several ten's of hours) have revealed no degradation or contamination of the lasing mixture. Temperature rise of the gas is a very critical item and future large systems will ~~contain~~ require a gas cooling recycling system.

8) Optics

Presently, all optical ports use NaCl windows. The sizes range up to 12 (30 cm) inches in diameter and 1-1/4 (3.2 cm) inches thick. Other possible candidates are KCl, Ge ~~IV~~, GaAs ~~III-V~~, CdTe ~~II-VI~~, and ~~some of the alkalihalides.~~ ZnSe. There are still many unanswered questions, such as physical strength, quality and costs of fabrication, transmission quality at 10.6 μ and maximum energy density handling capability.

The large reflective optics ~~are generally made from copper and gold by turning with a diamond knife.~~ are metal mirrors with copper or gold surfaces for maximum reflectivity. Mirrors have been obtained from commercial optical houses in addition. The Y-12 plant of Union Carbide at Oak Ridge has fabricated ~~these units up to 10-inch diameter for LASL.~~ flat mirrors up to 12" diameter by direct micromachining with a diamond knife.

Reflectivity of 6 Inch Micromachined Mirrors*

Material	Center	4 cm from center	1 cm from edge
copper	--	0.9918	0.9927
gold	0.9918	0.9906	0.9902

*measured at 10 μm at AFWL.

10 KJ CO_2 LASER SYSTEM

A. General

The 10 kJ system will consist of an oscillator, preamplifier(s), ~~a~~ beam-splitters and 8 ~~beams of 1250 J each~~ power amplifiers producing 1250 J each. A conceptual drawing is shown in Fig. 10. A cross section of the double-sided ~~(JANUS)~~ amplifier is shown in Fig. 11.

B. Mechanical

1) E-Beam Chamber

Similar in size to the A-4 unit, the ~~JANUS I~~ double sided e-beam chamber design is somewhat more complex. Overall dimensions are similar (50 x 100 x 270 cm). Two 30 cm diameter pump-out ports project from the bottom to connect to the vacuum systems. The two end plates will be removable to allow installation of the cathode which hangs from and through one bushing mounted on a flange at the top and center of the tank. Each end plate is fitted with two 12 cm viewports. Two smaller viewports are at the tank ends, top and bottom.

The tank is ~~again~~ a stainless steel weldment, basically a cylinder made up of ~~[illegible]~~ 3.6 mm thick wall ~~LADISH~~ commercial Tee fittings joined end to end and truncated by two identical flat plates forming sides that mate with the two pumping chamber.

The curved top and bottom are reinforced. The side plates approximate 1" thick support the 36 x 200 cm window structure and related assemblies.

2) Pumping Chamber

Pumping chambers for the LASL gas laser program have presented considerable design problems as laser size has increased. Early boxes were of modest size and relatively easy to build by machining a piece of acrylic to the desired geometry.

Original pumping chamber design for the 10 kJ system approximates that of A-4. Beam path opening is larger (36 x 45 cm). The rectangular, glued-up design is shorter but deeper and higher. It was after this design was essentially complete that problems with A-4 led to an appraisal of other geometries.

Based on the experience with the 1 kJ system, new design approaches are being considered for the pumping chamber geometry. Logic, ~~of course,~~ points to the need for a cylindrical shape and two types are in the conceptual developmental stage. One is a glass epoxy combination filament-wound layup. This chamber would be ~ 90 cm inside diameter, 380 cm long overall with dished ends and 51 cm diameter optic ports. Nominal wall thickness of this chamber is 1.6 cm. Interface flange and insulator ports to be installed with reinforcing ribs.

The other design is an aluminum tank of approximately the same dimensions of the filament wound tank but with flat ends, one of which is removable. This allows a plastic liner to be fabricated and then inserted in the metal case. The plastic lines is ~ 1.6 cm thick virginal polyethylene bonded to a thin layer of conducting polyethylene that makes contact with the metal tank interior. At present the merits and disadvantages of the three pumping chamber designs are being evaluated as to cost and workability.

It is becoming obvious that pumping chamber sizes and weights for larger laser systems will require adherence to pressure vessel codes in design. Consideration also needs to be given to mounting these chamber in such methods as to make operational handling easier. It is planned to mount future boxes on low-friction bearings and ways for moving the box when disassembly is required.

3- Support Stand 3)

It is apparent that increased size and weight of amplifier components point the need for support and mounting structures that allow maintenance and repair, handling and accessibility to be done with maximum ease and minimum downtime. The Janus support stand is a weldment of structural steel members. Round ways are mounted to take roll-type bearings secured to the bottom of the pumping chambers to be moved away from the electron-beam interface for maintenance and eliminate the need for hoists and lifts.

Also in design is a stand with adjustments for height and two directional translation with screw adjustments. This type stand will be used for the close aligning needed in the eight-beam array.

C. Electrical

As discussed previously, the double-sided system will consist of four double-sided laser amplifiers, putting out eight beams of 1250 J each. These will operate at an E/P ratio of 4 kV/cm-atm, pressure of 1800 Torr, and have 35 cm spacing, which require a peak voltage of 330 kV. It is required to deposit 100 kJ in the gas in 3 μsec, with 20% voltage droop. The peak load current is 113 kA. A series resistor of 0.9 Ω is required for current limiting, so the bank voltage will be 420 kV, and the stored energy will be 325 kJ. The total energy in the eight banks will be 2.6 MJ.

The load parameters are shown below:

Output Voltage (kV)	Output Current (kA)	Pulse Length (μsec)
111	35	10
222	69	5
280	84	4
333	113	3

The electron beam power supply will be a 4-stage Marx generator with the following loaded characteristics:

V_{output} = 300 kV

I_{output} = 7 kA

pulse width = 3 - 10 μsec.

D. Computer Control

Due to the complexity, the 10 kJ system will be primarily operated with a computer. This will especially be necessary for the alignment and focusing of eight beams in a 4 π configuration on to a target.

E. Optics

In order to extract the optimum amount of energy from the final amplifier with a minimum energy input, a double- or triple-pass system will be used. These concepts are shown in Fig. 12.

ACKNOWLEDGEMENTS

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FIGURE 1. Electron-beam-controlled CO_2 laser amplifier.

FIGURE 2. 1 kJ short pulse CO_2 laser.

FIGURE 3. Thermionic cathode parts showing filament support springs, insulators and thoriated filaments.

FIGURE 4. A-4 cathode assembly.

FIGURE 5. Typical A-3 current waveforms.

FIGURE 6. Filament power supply, A-4.

FIGURE 7. Electron beam current waveform and gas current waveform.

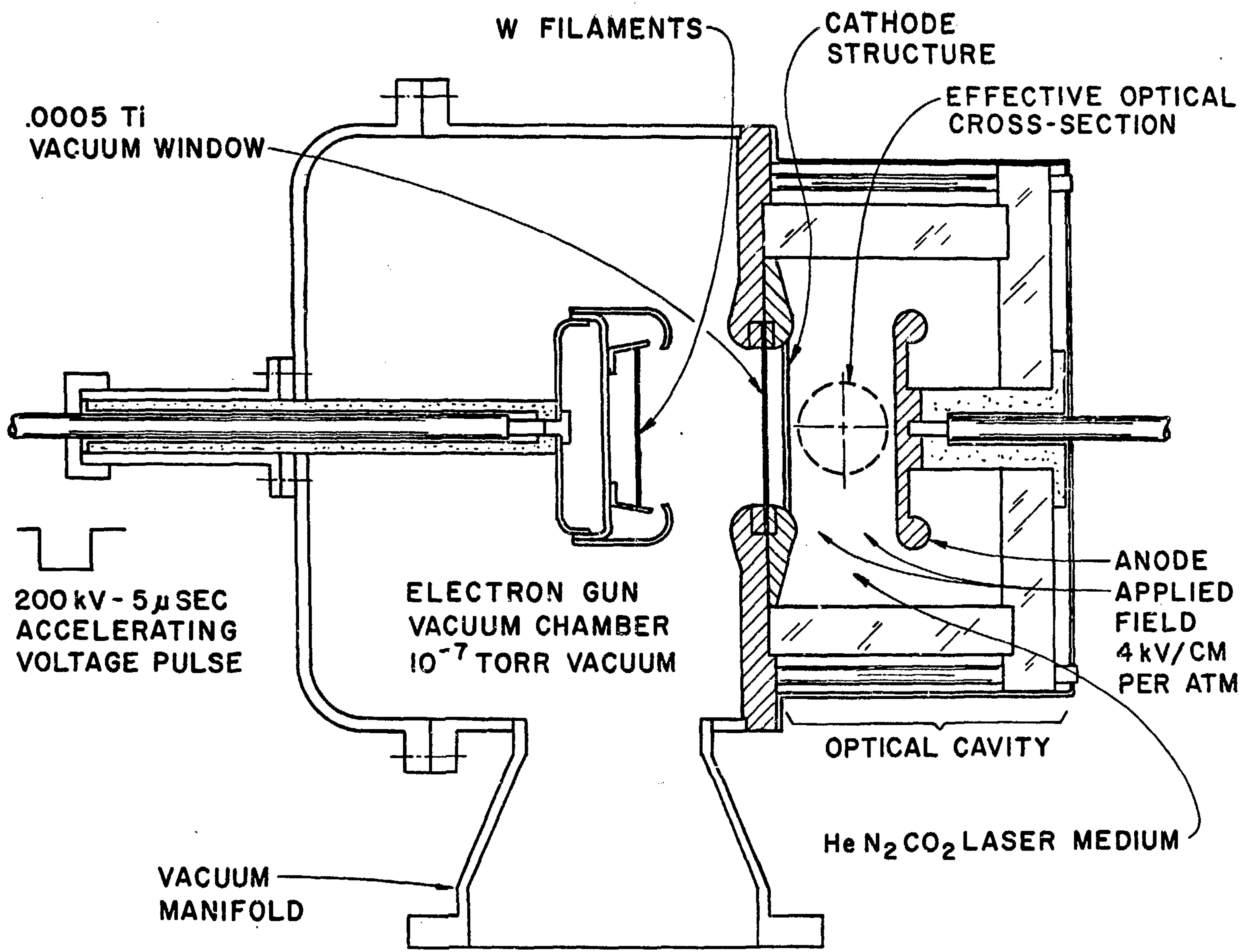
FIGURE 8. A-4 electron beam vacuum chamber.

FIGURE 9. A-4 pumping chamber box.

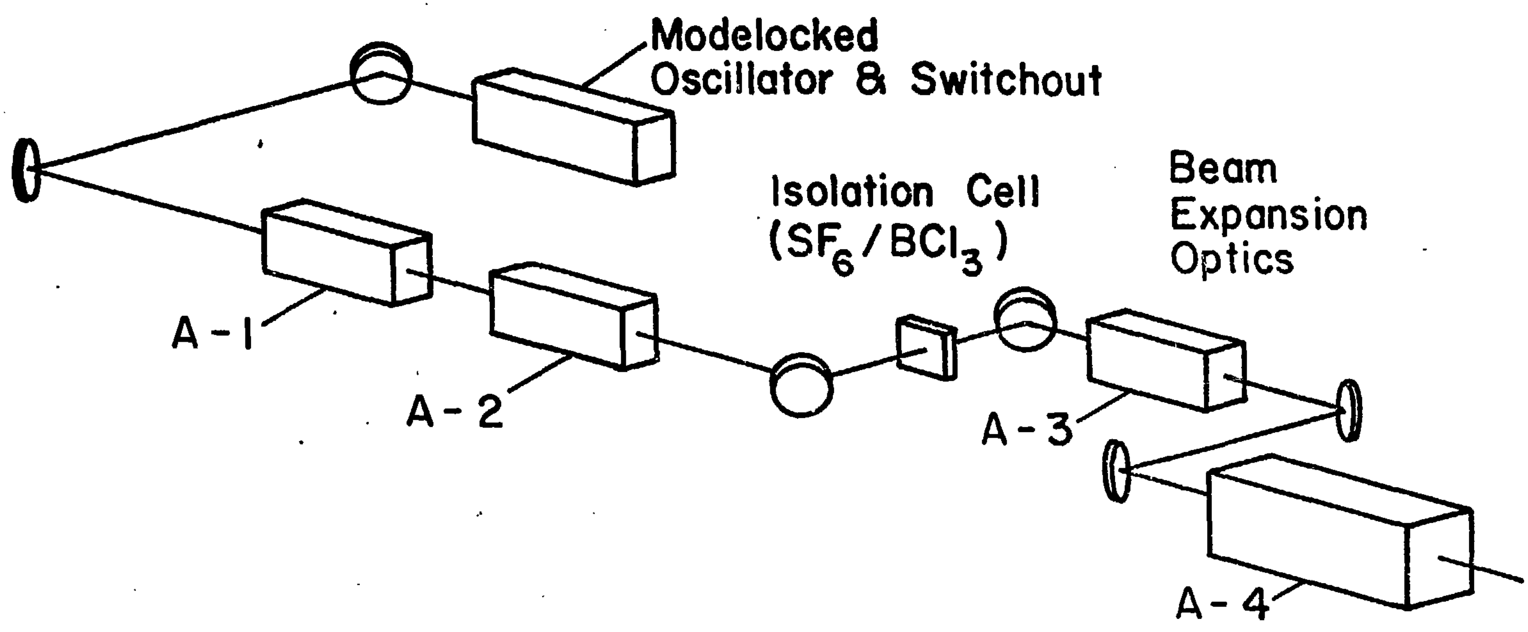
FIGURE 10. Conceptual drawing of 10 kJ, 8-beam, CO_2 laser system.

FIGURE 11. Double-sided CO_2, electron-beam-controlled laser amplifier.

FIGURE 12. Multipass systems.

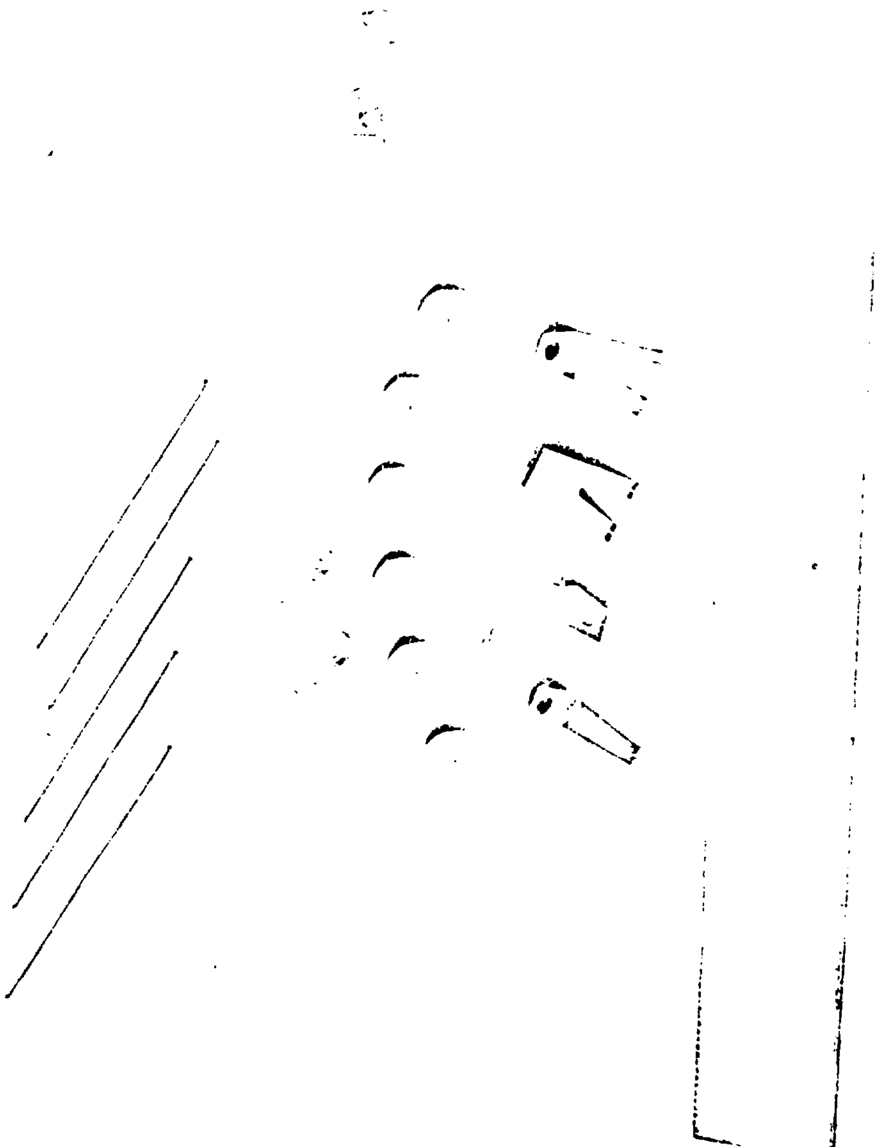


ELECTRON BEAM CONTROLLED CO_2 LASER AMPLIFIER



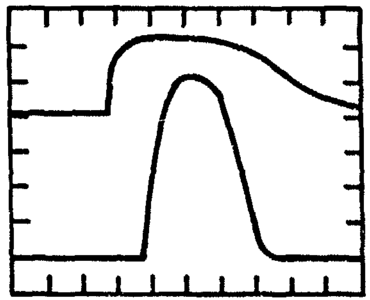
Component	Area, cm^2	L, cm	Gain	Pressure, Torr	Energy Out (Joules)
Oscillator					0.001
Stage 1	15	100	165	600	0.1
Stage 2	15	100	165	600	1.1
Stage 3	40	100	125	1800	17
Stage 4	500	200	10^4	1800	500-700*

* Depends on final operating parameter and configuration.



Upper trace = electron beam current 200 A/div

Lower trace = pumping chamber current 4000 A/div



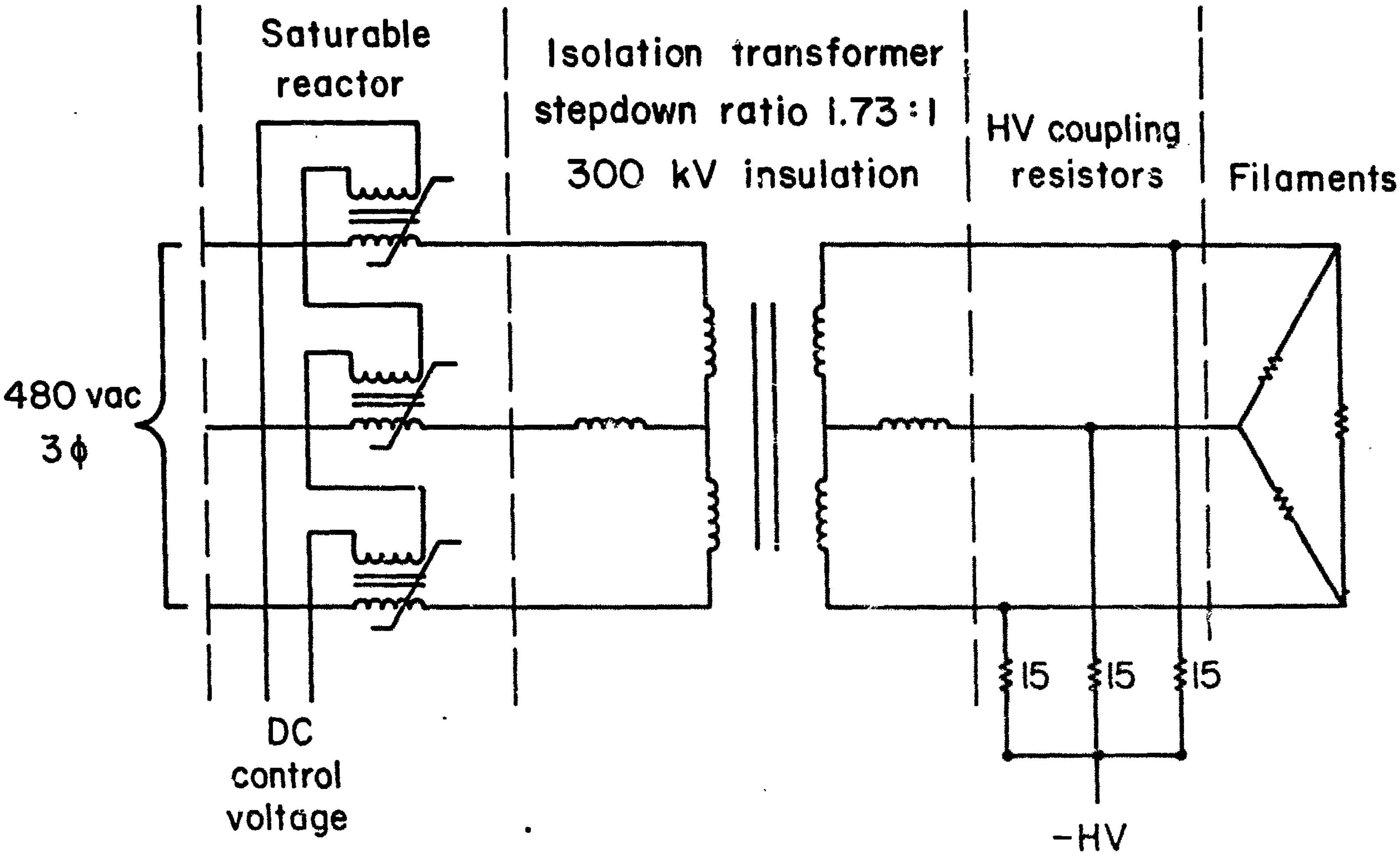
Time, 2 μsec/div

Electron beam voltage (anode to cathode) = 160 kV

Pumping chamber pressure = 1500 Torr abs

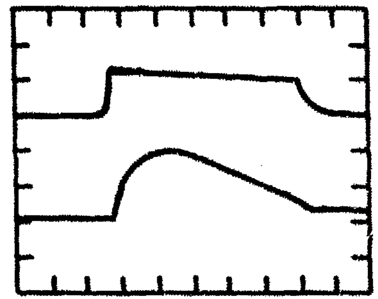
gas mixture = $3 : \frac{1}{4} : 1 :: He : N : CO_2$

Pumping chamber voltage (anode to cathode) = 63 kV


Saturable
reactor
Isolation transformer
stepdown ratio 1.73:1
300 kV insulation
HV coupling
resistors
Filaments
480 vac
3ϕ
15
15
15
DC
control
voltage
−HV

Upper trace =
electron beam
current 800 A/div

Lower trace =
pumping chamber
current 20 kA/div

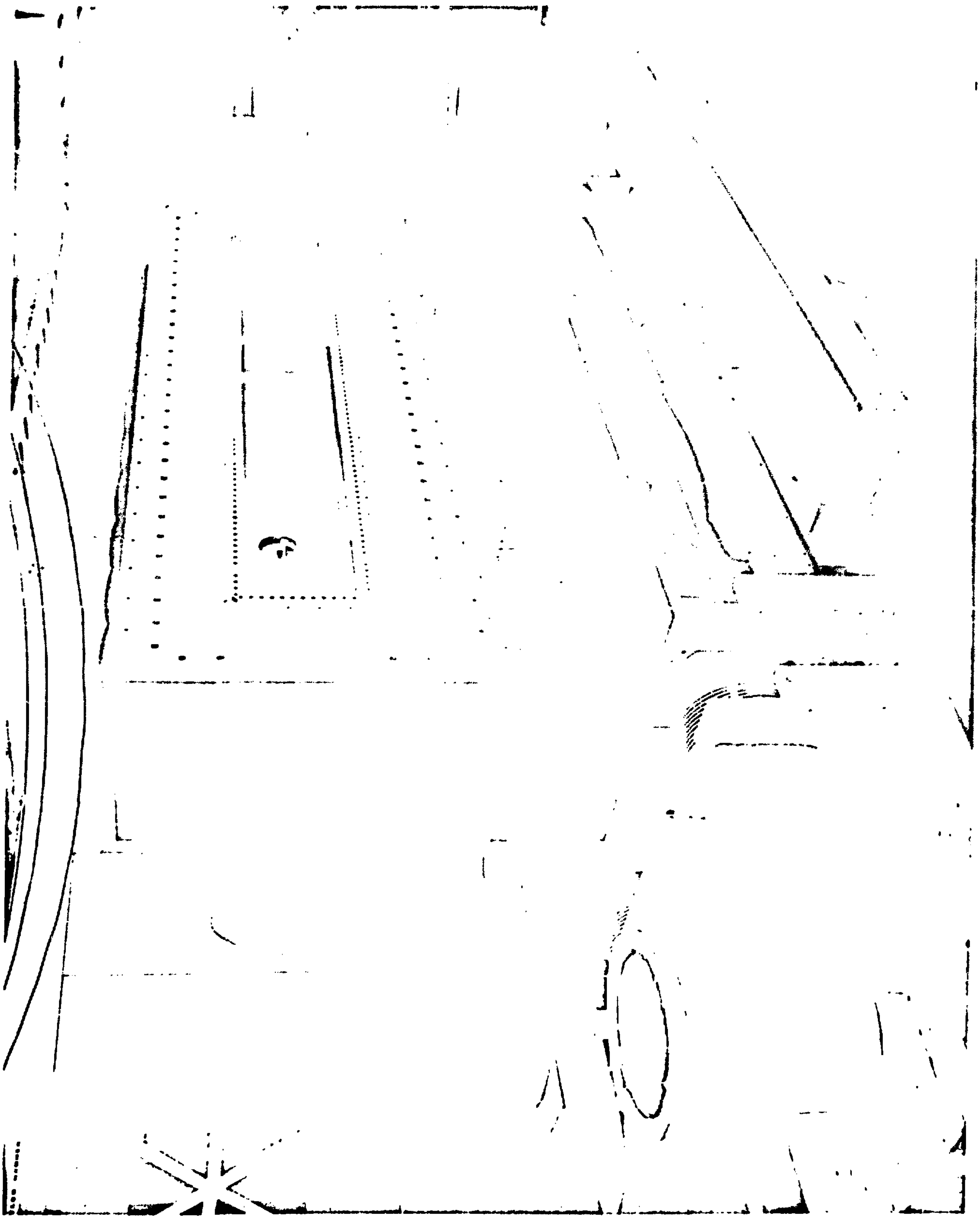


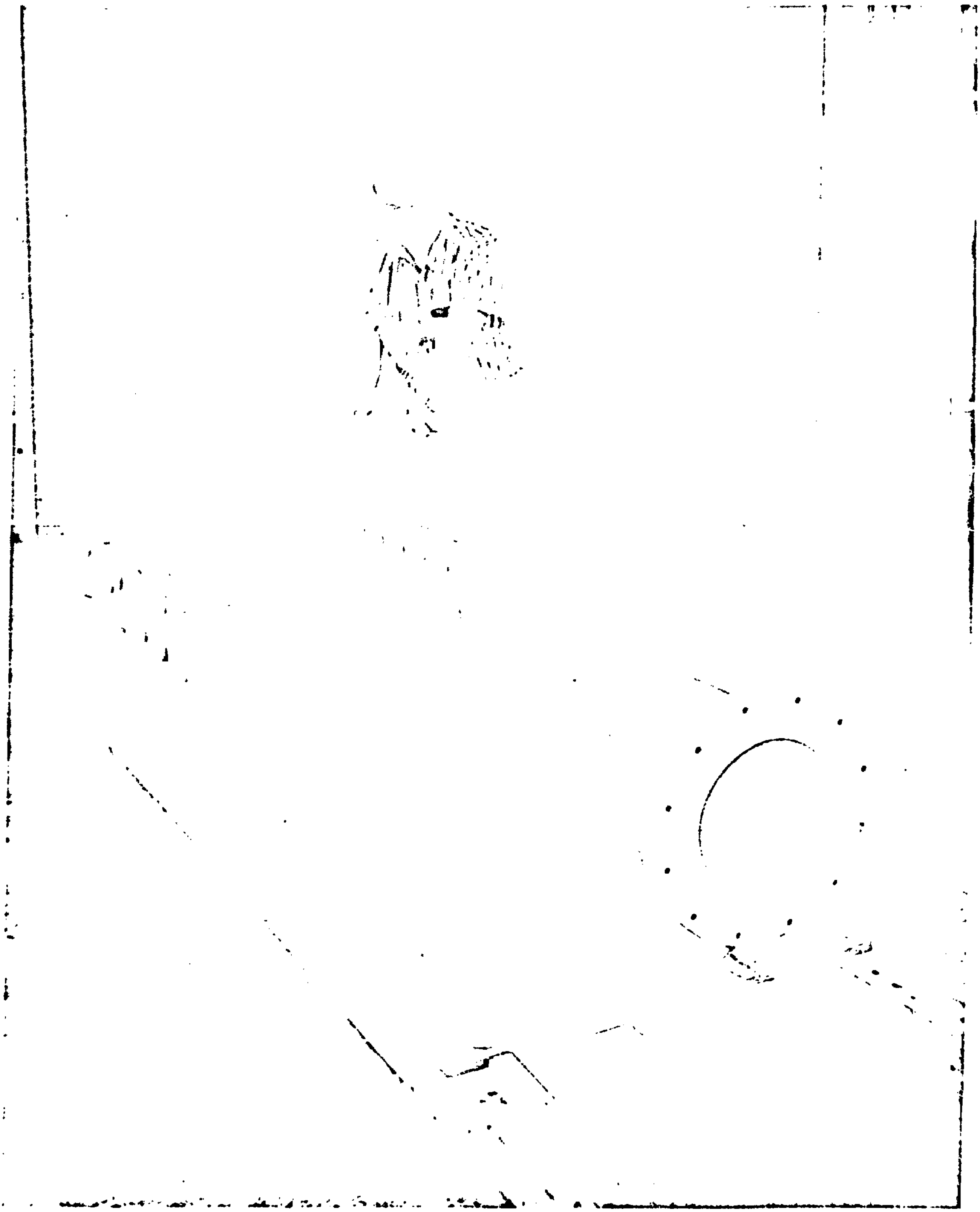
Time, 2 μsec/div

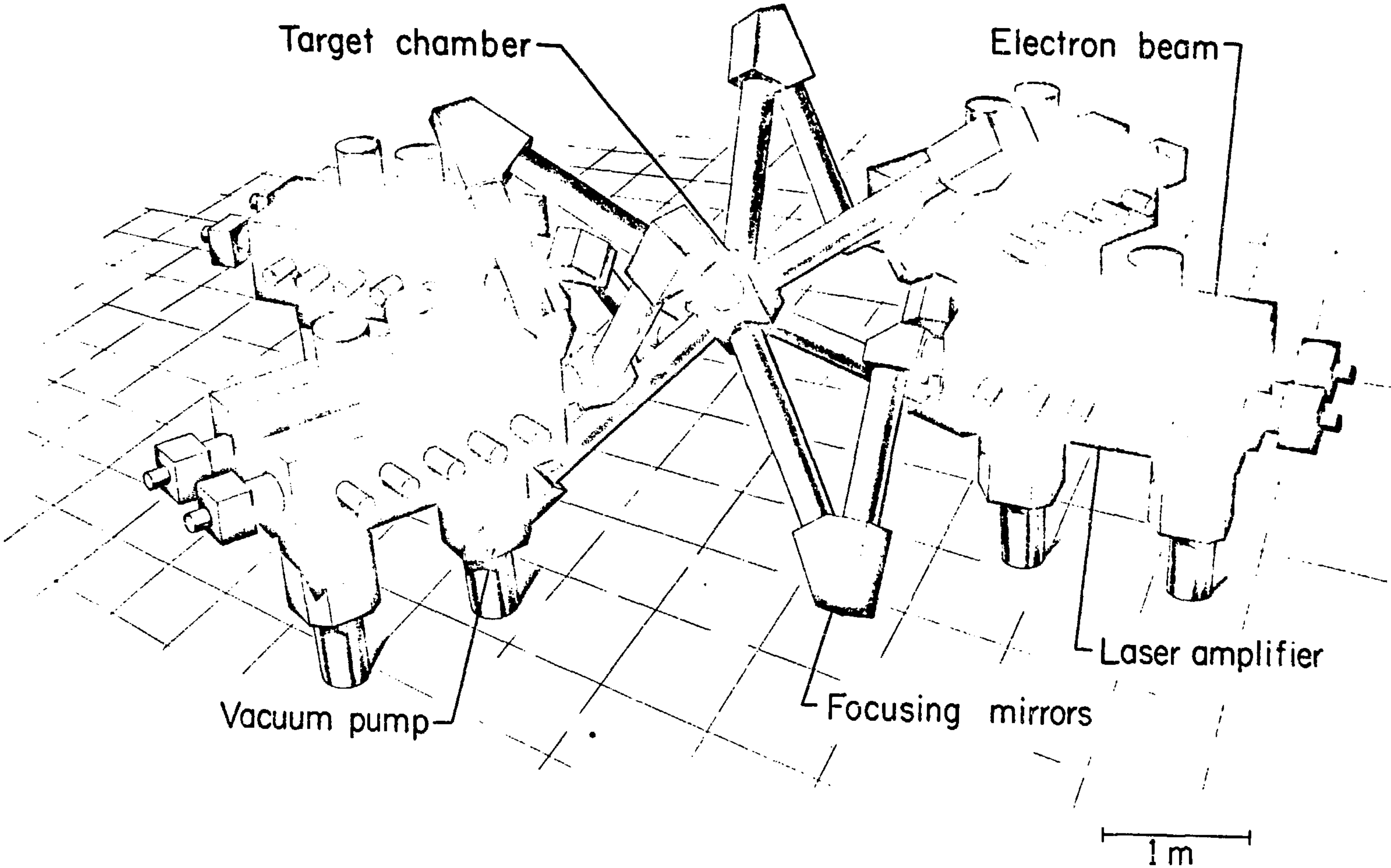
Electron beam
voltage (anode to cathode)
= 244 kV

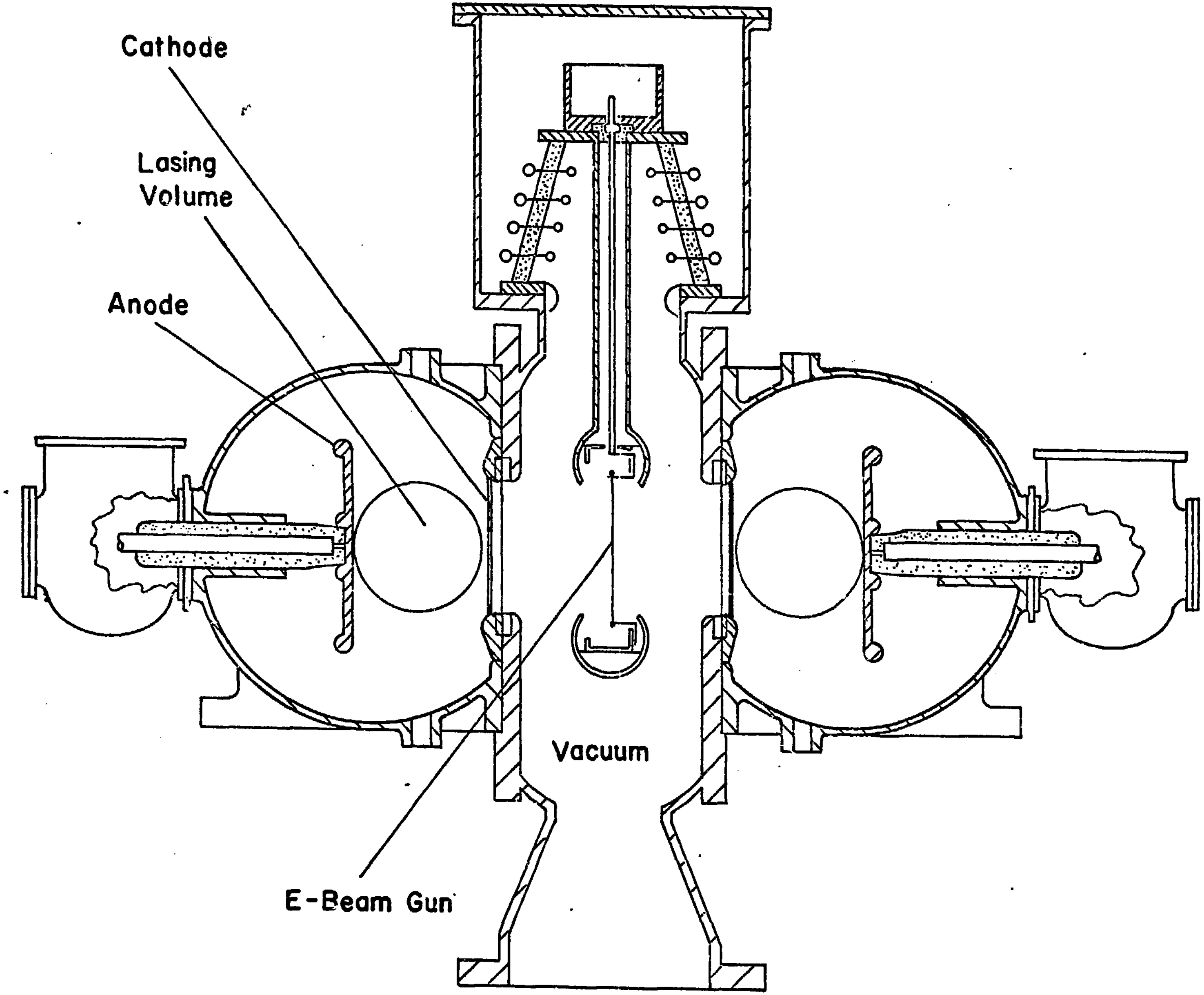
Pumping chamber
pressure = 1300 Torr abs
gas mixture =
$3 : \frac{1}{4} : 1 :: He : N : CO_2$

Pumping chamber
voltage (anode to cathode)
= 200 kV

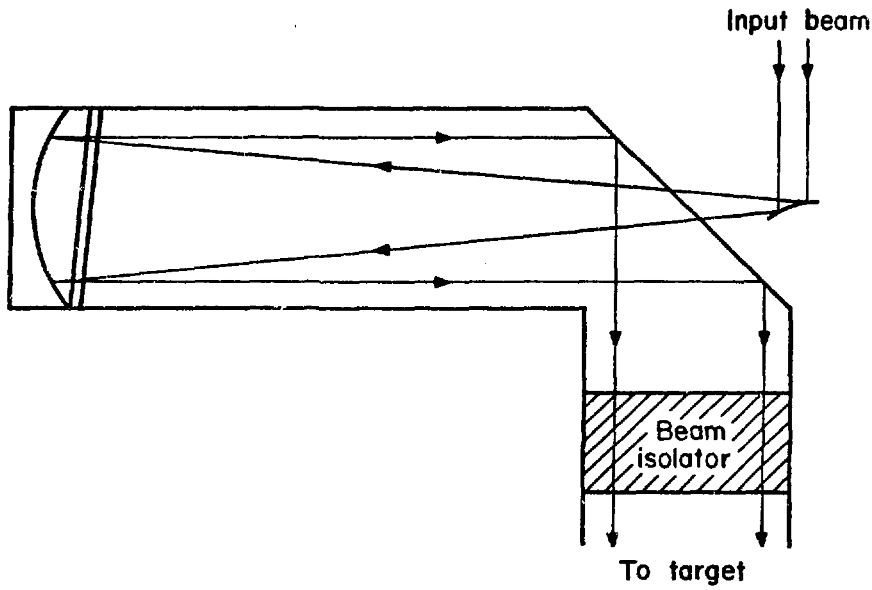




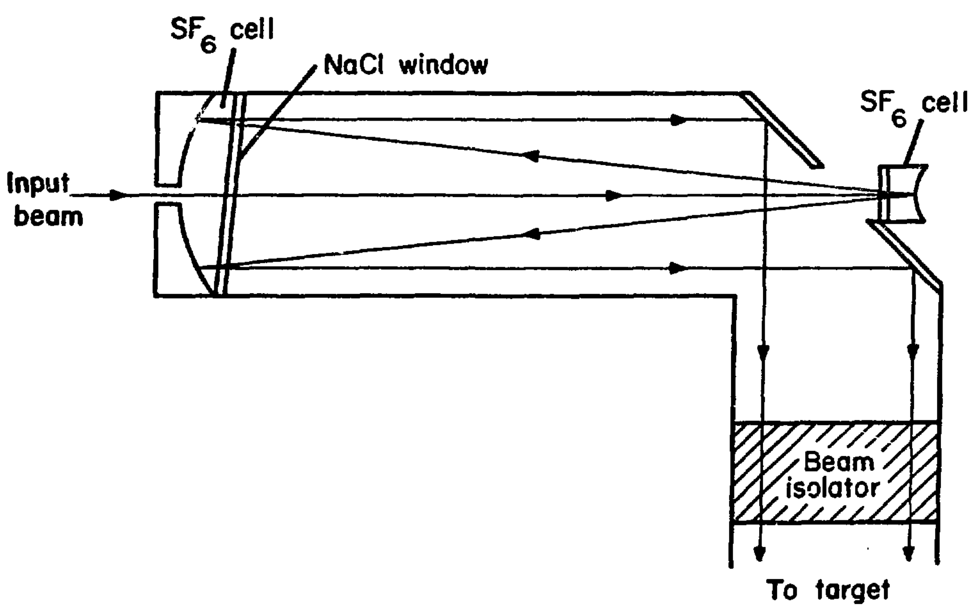

Target chamber
Electron beam
Laser amplifier
Focusing mirrors
Vacuum pump
1 m



Cathode
Lasing
Volume
Anode
Vacuum
E-Beam Gun



Two-pass



Three-pass