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λ -3, Sandia's 100-J HF Laser System

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λ -3, SANDIA'S 100-J HF LASER SYSTEM

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ABSTRACT

Sandia's λ -geometry intermediate electron-beam-initiated HF amplifier is described in sufficient detail such that a similar system could be designed, constructed and characterized. Items included are the design of the laser cell, magnetic field design and measurements, electron-beam calorimetry, and typical laser results.

NOTICE
This report was prepared as part of the work performed by Sandia Laboratories for the United States Government under contract number DT-79-01-0001. The views and opinions contained herein are those of the author and do not necessarily represent those of the United States Government.

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INTRODUCTION

The λ -geometry HF laser (λ -3) was developed to be used as an intermediate amplifier to drive Sandia's Phoenix I final amplifier. In the λ -geometry, electrons produced in the accelerator are magnetically guided into the laser cell at an angle which provides an unobstructed optical axis. This geometry, originally developed by E. L. Patterson and R. A. Gerber at Sandia Laboratories, has been used to axially excite both HF¹⁻³ and other gas lasers.⁴⁻⁶ The present laser is initiated by an intense electron beam from a Physics International⁷ Pulserad 110A accelerator. This laser system operates with a gas mixture of H₂, F₂ and O₂ and produces laser energies in excess of 100 J in the wavelength region between 2.6 and 3.5 μ m.

The purpose of this report is to describe the laser system in sufficient detail such that a similar laser system could be designed, constructed and characterized. One of the motivations for preparing this report was a suggestion from the Office of Inertial Fusion of the Department of Energy that this information be made available to industry. Items that will be covered in this report are: a general description of the system, the electron-beam accelerator together with modifications, the design and construction of the laser cell, design of the magnetic field coils, magnetic field measurements, electron-beam calorimetry including beam steering and deposition, and, finally, some typical laser output results. Although this system was designed with the HF laser in mind, it can be used to produce many gas lasers requiring electron-beam initiation.

GENERAL DESCRIPTION

A schematic drawing of the laser system is shown in Fig. 1. Not shown in the figure is the vacuum and gas handling systems. They are described

Figure 1. Schematic of the λ -3 laser system.

in detail in a recent Sandia memorandum.⁸ The peak electron energy is 1.2 MeV with a beam current of 35 kA and a pulse width of 20 nsec (FWHM). The electron-beam machine is capable of delivering approximately 400 J at the anode foil. The machine has a diode extension which allows the diode to be immersed in a guiding magnetic field. The electrons, produced by a cold cathode, pass through a 0.076-mm thick-titanium anode foil into the drift section. The drift section is used to extend the laser cell away from the machine to facilitate placement of the windows and optics. There is a 0.076-mm-thick stainless-steel foil between the drift section and the laser cell. This foil separates the gas in the laser cell from the gas in the drift section which is normally air at a pressure of 1.75 Torr, which provides good electron-beam transport to the laser cell.

The electron beam is guided along the 6.35 cm-diameter stainless steel laser cell by the axial B-field coils shown in Fig. 1. B-field smoothing coils are added in two locations to compensate for the effects of mounting flanges. An electron-beam turning coil is used to turn the electron beam from the drift section into the laser cell. To prevent damage to the window at the end of the laser cell, the remaining electrons are deflected into the cell wall by a pair of magnetic coils.

The laser cell, shown in Fig. 1, has an active medium length of 91.4 cm and an active volume of 2.9 liters, where the active volume is taken to be the region initiated by the electron beam. The total length of the cell is 148 cm. The laser cell can be fitted with either Brewster angle windows (shown in Fig. 1) or windows with a wedge angle of 15° . Burst diaphragms which rupture during the latter part of the chemical reaction discharge the gases into a pressure relief tank to reduce the total pressure

and thus prevent the laser cell from rupturing. The gases (F_2 , H_2 , O_2) required for the operation of the HF laser are mixed in the cell just prior to firing the electron-beam machine. The fluorine is added first, followed by oxygen. Finally, the hydrogen is turbulently injected to facilitate mixing. Normally the ratio of $F_2:O_2:H_2$ is 1:0.3:0.25 at total pressures less than 2 atmospheres. A photograph of the A-3 laser system is shown in Fig. 2.

ELECTRON-BEAM ACCELERATOR

The electron-beam accelerator is a commercial device; therefore, only a brief description will be given of its operation. The modifications to the accelerator will be given in somewhat more detail.

Basically, the Pulserad system consists of five subassemblies: the dc power supply, the trigger amplifier, the Marx generator, the coaxial-Blumlein pulse forming line and the electron accelerator diode. The operation is as follows: first the Marx generator is charged to the desired level by the dc power supply. When charged, the system is triggered by a fast-rising trigger pulse and begins to charge the Blumlein. After approximately 0.25 μ sec, the Blumlein reaches peak charge, at which time the output switch and prepulse switch close and the charge is transferred to the diode. This particular machine has the low jitter option which gives an overall jitter of about 10 nsec. A photograph of the Marx generator and a schematic of its assembly are shown in Fig. 3.

The diode was modified to accept the laser cell and to permit easy anode foil changes. The laser cell adapter shown in Dwg. 1 (drawings are located at the end of this report) replaces the anode holder supplied with the machine. The anode is a 0.076-mm-thick titanium foil and is held in position between the laser cell adapter and the laser cell

Figure 2. Photograph of A-3 laser system.

Model 110A Marx Generator

Marx Generator Circuit

Figure 2 Photograph and schematic drawing of the PI Model 110A Marx generator.

drift section shown in Dwg. 2.

The cathode tip shown in Dwg. 3 replaces the cathode tip supplied with the electron-beam machine. The anode-cathode spacing is 1.77 cm. Typical Marx generator output voltage, diode voltage and diode current traces after the machine fires are shown in Fig. 4. For a charge voltage of + and -50 kV, the peak Marx voltage is 1.02 MV and the peak diode voltage and current were 1.2 MV and 38.1 kA, respectively.

DESIGN AND CONSTRUCTION OF THE LASER CELL

The first requirement on the laser cell was that it be long enough so that a significant portion of the electron-beam energy be deposited at the highest operating pressure. The range (R) for a 1.2 MeV electron in fluorine is approximately 0.66 g/cm².⁹ At a pressure of 2 atm, the density (ρ) of F₂ is 0.0035 g/cm³ yielding a length, (L), of 1.9 m. Because of foil losses, scattering of electrons to the wall, and the observation that the effective linear range is only about 70% of the tabulated range, the beam path in the cell was made 1.2 m long.

The second requirement on the cell was that it should allow the applied magnetic field to diffuse through the wall in a time period short compared to the quarter-period of the magnetic-field circuit and yet be strong enough to withstand the reaction pressures. Field penetration requirements dictate that the cell wall must be thin with respect to the skin depth. The penetration depth is given approximately by $\delta = (\pi f \mu \sigma)^{-1/2}$, where f is the frequency of the magnetic field, μ is the permeability and σ is the conductivity of the cell wall. It is clear that the cell should be made out of a material with a low electrical conductivity. It is also important that the capacitor bank current have as long a period as possible. In this particular case, the cell

Tri-Phase 115 V 60 Hz 1.0 A peak
 500 psec 10 A Current and 10 A peak
 1000 V/div

Marx Generator Voltage 1.00 MV peak
 1000 V/div

Figure 4. Electron-beam accelerator output waveforms.

is made from stainless steel which has a conductivity of 1.1×10^6 mho/m, and the magnetic field has a quarter-period of ≈ 1.2 msec or an frequency of 208 Hz. When these values are substituted into the formula, one finds a penetration depth of 1.7 cm. The cell was made of tubing with a wall thickness of approximately 1.27 mm which gives a ratio of skin depth to thickness of about 10. Besides the wall thickness, care must also be taken such that the magnetic field will diffuse through the flanges. The flanges are also made of stainless steel and were made as small in diameter as possible (10.16 cm) and as thin as possible (0.64 cm). As will be described, whenever the B-field was decreased because of the thickness of the metal, B-field smoothing coils (Fig. 1) were added to increase the interior magnetic field at these locations.

A detailed drawing of the cell is shown in subassembly B, Dwg. 4. The gas feed lines are as small as possible to allow the magnetic field to diffuse through them. All components and flanges on the cell must be next to the cell to allow the magnetic field coils to slip over the cell. In all the experiments to date, only the single section has been used.

Drawing 5 shows details of the various flanges on the laser cell. The flanges for the pressure relief diaphragms, shown in detail Z, were made so that a V-grooved clamp and a single bolt can be used to hold the flanges together and allows rapid changing of the diaphragms between each laser shot. Captive o-rings were used for ease of assembly.

Drawings 6 and 7 show the design of the window holders for the laser. One at Brewster angle for sapphire and the other at a wedge angle of 15° . In both cases the o-ring grooves were made such that windows from 14 cm to 17.78 cm in diameter could be used. The window clamp is shown in Dwg. 8.

DESCRIPTION OF THE MAGNETIC FIELD COILS

When trying to control an electron beam with a magnetic field it is desirable to have the applied magnetic field strength about equal to that of the self magnetic field of the electron beam. This is just a rough estimate since propagation of the electron beam depends on beam current and electron voltage as well as gas concentration and pressure. Any design should have the flexibility to exceed this value by at least a factor of two. Only detailed electron-beam propagation studies will allow the determination of the optimum magnetic field conditions.

An approximation for the self field at the edges of a cylindrical electron beam is given by $B_{e-beam} \approx \mu_0 I / 2 r$, where r is the beam radius in meters and I is the total beam current in amperes. In this particular case, $r = 0.013$ m, $I = 38.1$ kA, so $B_{e-beam} \approx 0.59$ T or 5.9 kG.

The coils shown in Fig. 1 are all connected in series, therefore, the current through each coil is the same. The magnetic field calculated in each of these coils is such that the magnetic fields on axis and in the center of each coil are equal. The magnetic field is given by $B_z \approx \mu_0 I (N/L) [1 + (2R/L)^2]^{-1/2}$, where N/L is the number of turns per meter, L is the length of the solenoid and R is the radius. The construction of the center solenoid is shown in Fig. 5. In this case $L \gg 2R$ so $B_z \approx \mu_0 I (N/L)$. This 91.4 cm long coil existed in our laboratory so that the rest of the coils (diode coil, drift section coils, turning coils and beam deflection coils) were designed to match the magnetic field of the center solenoid. The diode coil and drift section coil are not shown but are similar to that shown in Fig. 5. The smoothing coils, constructed after the initial magnetic field measurements, provided the necessary additional field at various locations. The construction of

Figure 5. Construction details of the center conductor used to generate the guiding magnetic field.

the beam deflection coils and the electron-beam turning coil is shown in Fig. 6. The diameter of these coils was chosen so that the electron-beam turning coil would fit over the junction where the electron beam enters the cell, as shown in Fig. 1.

The 91.4 cm long solenoid is held in position by 5.0 cm Lucite clamps at each end and mounted to a phenolic base. This base has a series of 1/4-inch-diameter screws so that the laser cell can be aligned with the electron-beam machine. Styrofoam inserts, at each end of the solenoid, are used to center the laser cell in the solenoid. The turning coil is held in position with two gimbaled clamps mounted on the laser cell flange that connects to the drift section. This allows the coil to be moved in the horizontal direction and with adjustable screws so it can be tilted in the vertical direction.

MAGNETIC FIELD MEASUREMENTS

The current is supplied to the magnetic field coils by a commercially available capacitor bank.¹¹ The total capacity of this bank is 250 μ fds. The charge voltage is variable from 1 to 20 kV. The total inductance of that magnetic field coils connected in series is 2.24×10^{-3} h giving a total period of the current of 4.8 msec or a quarter-period of 1.2 msec. The magnetic field can be varied from 800G (charge voltage of 1 kV, $I = 320$ A) to 16 kG (charge voltage of 20 kV, $I = 6.4$ kA).

The magnetic field inside the cell was measured as a function of distance to determine uniformity. A dB/dt probe having a cross sectional area of 0.71 cm^2 was used to infer the magnetic field values. The probe was made by wrapping 40 turns of #29 copper wire on a 0.95-cm-diameter core. The bank current was also monitored by measuring the voltage with a low inductance resistor whose value is $2.5 \text{ m}\Omega$. After normalization, the

Figure 6. Construction details of the beam deflection and electron-beam turning coils.

current could be used to monitor the magnetic field on the axis of the long solenoid. For the magnetic field measurements, the bank was charged to a voltage of 1 kV. Typical capacitor bank current and dB/dt traces are shown in Fig. 7. The magnetic field was determined by integrating the dB/dt curve to the time of peak current, since the electron beam normally was fired at the time of peak current.

The magnetic field as a function of distance is shown in Fig. 8. At the location at which the beam entered the cell, the magnetic field probe was positioned such that only the magnetic field in the direction of the beam travel was measured. The magnetic field, shown in Fig. 8, is 750 G to within about $\pm 20\%$. A few points near the 45° bend were somewhat higher than this value. The points at distances less than 0 (anode position) were obtained by removing the cathode and the cathode shank. These data were taken to ensure there was sufficient magnetic field in the diode.

ELECTRON-BEAM CALORIMETRY

Electron-beam calorimetry is important in the λ -geometry for two reasons. First, the correct position of the turning coil can be determined to maximize beam propagation around the corner into the laser cell, and, secondly, it permits an estimate of the amount of energy deposited in the gas as a function of distance and gas pressure by measuring the transmitted energy at various distances and pressures.

The calorimeter designed for this experiment is shown in Fig. 9. This 31 element, totally stopping, segmented carbon calorimeter facilitates the measurement of the radial energy distribution and transmitted energy. The calorimeter has an outside diameter of 5.72 cm with an element thickness of 0.64 cm. The calorimeter was designed to

SWEEP RATE: 0.2 msec / div

Figure 7. Magnetic field current and time rate of change of the magnetic field as a function of time.

Figure 8. Magnetic field measurements as a function of distance along the linear cell.

31 ELEMENT CALORIMETER

Figure 9. Geometry of the segmented 31 element carbon calorimeter.

provide good magnetic field penetration. The calorimeter voltage output versus deposited electron energy depends on the volume of the individual elements, density of the material and the type of thermocouple used. In this case, all the elements have a volume of 0.37 cm^3 . The thermocouples are made of chromel-constantan and are glued to a pumice base to reduce heat loss. The calibration of each element is 0.0856 mV/J . This Sandia designed calorimeter is now commercially available.¹²

The output voltage from each thermocouple (normally 1 to 10 mV) is recorded with one of Sandia's calorimeter systems¹³ with a bank of strip-chart recorders. In some instances, after beam steering experiments were completed, some elements at the same radius were connected in series so that four chart recorders were used to measure transmitted electron-beam energy, as a function of radius.

A first set of experiments were done to determine the effect of varying the magnetic field. These measurements were done at a distance of 16.5 cm from the anode, which is at the far end of the electron-beam drift section (see Figs. 1 and 8). For these measurements the pressure in the drift section was normally 1.75 Torr of air. Figure 10 shows the radial electron-beam profiles at magnetic fields of 2, 4, 6, and 8 kG. The data points (except for the element in the center) were averages of the individual elements at the same radius. The number in parenthesis on each curve is the total energy measured and was obtained by adding the energy from each individual element. Figure 10 shows that for low magnetic fields (2 and 4 kG), the profile remains nearly constant and the applied field does not really alter the profile. At 6 and 8 kG, the transmitted energies are approximately equal and are about 10% higher than the low field conditions. The profile at 8 kG shows a depression in the center

Figure 10. Radial electron-beam profiles and total transmitted energy as a function of optical magnetic field.

of the beam, which is probably indicative of emission from the cathode. At this magnetic field level, collective effects in the diode as well as scattering in the anode are nearly eliminated. Since the energy did not increase significantly at 8 kG and the profile was dipped in the center, a magnetic field of 6 kG was chosen for the rest of the experiments. The energy stored in the capacitor bank for a 6 kG field is 4.5 kJ.

Electron-Beam Steering

Once the operating magnetic field was selected, the calorimeter was used to determine the optimum position of the turning coil. When the electrons are turned by a magnetic field, they will experience an $\vec{v} \times \vec{B}$ curvature drift,¹⁴ causing the electron beam to be deflected either to the top or bottom of the laser cell. In order to compensate for this drift, the turning coil must be tilted to obtain beam propagation along the axis of the cell. The procedure used to obtain the correct position for the turning coil is essentially a trial and error process. Normally, the calorimeter is placed at a point beyond where the electrons enter the cell. In this particular cell, a distance of 41 cm from the anode was selected (see Fig. 8). The pressure in the cell should be approximately the same as that anticipated for laser operation. In our case, nitrogen was used in place of fluorine since fluorine would chemically react with the carbon calorimeter. The coil is adjusted so that the beam is symmetrical about the axis. When adjusting the turning coil both the angle and the tilt must be changed since they are coupled. Thus, correct centering of the electron beam may take many shots (100 or so) before the beam is positioned correctly. When this position has been determined, the gas pressure should be varied to ensure that the beam remains on axis. In our case, the pressure was varied from 20 Torr to 1433 Torr. If the

beam varies significantly, the coil should be adjusted slightly. When this had been accomplished, the calorimeter was positioned near the end of the cell and beam profiles were checked for a few pressures. After the final setting, drift tube pressures, foil thickness, magnetic field values, etc., should not be varied. If any of these are changed, the coil may have to be readjusted.

Electron-Beam Deposition

After determining the optimum position for the turning coil, electron-beam deposition in the gas was inferred at various pressures. Energy deposition is required to determine beam propagation and to obtain intrinsic laser efficiency (laser energy/deposited electron-beam energy). As was previously stated, nitrogen at the same density as a F_2 , H_2 , O_2 mixture was used for the deposition studies. Nitrogen was used at pressures of 179, 354, 537, 716, 895, 1074, 1253 and 1432 Torr. These pressures correspond to laser mixtures ($F_2:O_2:H_2 = 1:0.3:0.25$) for partial pressures of Fluorine of 100, 200, 300, 400, 500, 600, 700 and 800 Torr. In addition, transmitted energy was obtained at a nitrogen pressure of 20 Torr, which should give an indication of the minimum amount of energy scattered to the wall, since at this pressure electron deposition in the gas should be negligible. Transmitted energy was obtained at distances from the anode of 41 cm, 85 cm and 116 cm. The deposition was estimated by subtracting the amount of energy transmitted at a given pressure from that transmitted at a pressure of 20 Torr. This gives an upper bound to the deposition since there is additional scatter at higher pressures, which is shown in Fig. 11. This figure shows the electron-beam profiles at 716 Torr N_2 and 1432 Torr N_2 at three different axial positions. A higher percentage of transmitted energy was measured at a large radius for the higher pressure which

Figure 11. Electron-beam energy profiles at various distances and at two different gas pressures.

suggests scattering in the wall.

The total energy transmitted, at the various pressures as a function of distance from the anode, is shown in Fig. 12. The data for distances greater than 17 cm has been smoothed by using a linear approximation to the data with pressure at a given distance. The energy of the beam through the 0.076-mm-thick Ti anode is approximately 400 J. The dashed line at a distance of 17 cm represents the end of the drift section. The measured loss through the 0.076 mm stainless steel was about 8% of the incident energy. The second dashed line at 32 cm represents the point at which the electron beam enters the laser cell. The total energy deposited at a given pressure was determined by the difference between the transmitted energy at 20 Torr and transmitter energy at the desired pressures over the length of the cell (124 cm - 32 cm). The deposited energy for each given N_2 pressure is given in Table I.

Table I. Deposited Energy as a Function of Pressure

<u>N_2 Pressure (Torr)</u>	<u>Equivalent $F_2/O_2/H_2$ Pressure (Torr)</u>	<u>Energy Deposited in Cell (Joules)</u>
179	100/30/25	10
358	200/60/50	35
537	300/90/75	51
716	400/120/100	68
895	500/150/125	86
1074	600/180/150	103
1253	700/210/175	121
1432	800/240/200	139

The raw data that was used to obtain the curves in Fig. 12 was also compared to Sandia's one-dimensional Monte Carlo deposition code.¹⁵ A comparison of the measured beam energy lost to the calculations is shown

Figure 12. Electron-beam energy transmitted at various locations at different N₂ gas pressures.

in Fig. 13. The initial beam energy (entering the laser chamber) was approximately 250 J, and it was assumed that the energy of each electron was 1.2 MeV. Figure 13 shows that the measured beam energy lost is larger than the calculations would predict. As previously mentioned, some of this loss is due to scattering. The lower calculated energy deposition could be due to the entering electron's energy actually being considerably less than 1.2 MeV.

TYPICAL LASER RESULTS

The laser system described here was first characterized as an HF oscillator using both gas mixtures of $\text{SF}_6\text{-C}_2\text{H}_6$ and $\text{F}_2\text{-O}_2\text{-H}_2$.¹⁶ Laser measurements included energy, pulse width, and spectral identification as a function of gas pressure and concentration. This laser was then used as the oscillator in an oscillator-amplifier experiment to determine energy extraction of the Phoenix I amplifier.¹⁷ Recently the laser system was used as an intermediate amplifier in the saturated amplifier experiments using the Phoenix I final amplifier.¹⁸ Only one set of typical results will be given for this system.

Figure 14 shows the energy and pulse width of the laser when operated as an oscillator. The optical cavity was of the stable configuration and consisted of a calcium-fluoride flat output coupler and a 10 m radius-of-curvature copper mirror. The cavity separation was 2.1 m. The laser was fitted with sapphire (Al_2O_3) Brewster angle windows for these measurements. The laser energy increases with increasing F_2 pressure reaching a value of 90 J at an F_2 pressure of 200 Torr. The pulse width decreased from about 70 nsec at an F_2 pressure of 200 Torr to a pulse width of approximately 20 nsec at a pressure of 700 Torr F_2 . The energy of the laser has been increased

Figure 13. Measured electron-beam energy loss and calculated beam deposition as a function of density-length product.

Figure 14. 3-3 HF laser oscillator characteristics.

to approximately 180 J by operating at higher pressures.

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Drawing 2. Drift Section

Drawing 2A. Drift Flange Modification

Drawing 3. Cathode Tip

Drawing 5. Laser Cell Subassemblies

Drawing 7. 15° Window Holder