Early History of High Power Lasers

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ABSTRACT

This paper gives the history of the invention and development of early high power lasers, to which the author contributed and had personal knowledge. The earliest hint that a high power laser could be built came from the electric CO_2-N_2-He laser of Javan. It happened that the director of the Avco-Everett Research Laboratory had written his Ph.D. dissertation on the deactivation of the vibrational excitation of N_2 in an expanding flow under Edward Teller, then at Columbia University. The director then started an in-house project to determine if gain could be achieved in a mixture similar to Javan's by means of a shock tunnel where a shock heated mixture of N_2, CO_2, and He gas was expanded through a supersonic nozzle into a cavity. This concept was named by the author as the "gasdynamic laser" (GDL). The paper traces the history of the initial gain measurements, the Mark II laser, the RASTA laser, the Tri-Service laser, its troubles and solutions, the United Technology's XLD gasdynamic laser, and their ALL laser. The history of the coastal Crusader will also be mentioned. Also discussed are the early experiments on a combustion-driven chemical laser, and its subsequent rejection by the director.

Keywords: high power lasers; gasdynamic laser; CO_2 gas laser

1. INTRODUCTION

In the 1950's, Professor Robert Leighton of Caltech taught a course in modern physics. It covered the Boltzman distribution of energy states; what stated in thermal equilibrium each higher quantum energy state had a lower population than a lower state, at normal temperatures. He asked the question: if the upper state has a greater population, would that constitute a negative temperature? It was apparent that he had not read Einstein's earlier paper on photon absorption[1]. In that paper, Einstein not only considered the energy conservation of photon absorption by a gas atom, but also momentum conservation. Out of that, he concluded that the absorption coefficient of a gas α was related by:

$$\alpha \propto \left(\frac{n_L}{g_L} - \frac{n_U}{g_U} \right) \tag{1}$$

where n_L and n_U are the number density in the lower and upper quantum states respectively and g refers to the degeneracy of the state. Thus, if $n_U/g_L > n_L/g_U$ there should be gain. Townsend and others won the Nobel Prize for using this principle in a microwave amplifier and postulated that this could be achieved in the optical regime. An optical laser was then invented by Ted Maiman at Hughes Research Laboratory, in which a flash lamp optically pumped the upper state of ruby. This was very exciting to weapons designers at the time, and indeed was used to melt tiny holes in a razor blade. Shortly afterward, electrically pumped lasing was demonstrated in a gas, HeNe [2]. This prompted the first idea of a flowing gas laser with expansion to create a visible laser[3], which never worked, because electronic stimulated emission times were too short to be of use.

A further breakthrough occurred in 1964, when Patel reported his development of an electric discharge CO_2 laser[4]. Shortly after, it was scaled up in power. This news was brought back by Dr. Morton Camac, a physical chemist, to the Avco-Everett Research Laboratory, which I had just joined, . It created immediate excitement, because it was known that the first vibrational energy level of N_2 was very close to a higher vibrational energy level of CO_2, and that heated nitrogen, in an expansion, say through a supersonic nozzle could not radiate because it is homonuclear, and lost its vibrational energy through collisions only slowly[5]. This lead to the first effort, of thinking about a mixing laser, in which heated N_2 would be rapidly expanded through a nozzle and mixed with cold CO_2. To refresh everyone's memory, the energy level diagrams for the N2=CO2 system is shown in Fig. 1

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It is necessary to understand the importance of flow for high power lasers. The waste heat caused by the energy cascade from the lower state to the ground state heats the lasing medium. As the lasing medium heats up, the lower laser state fills, just due to the Boltzmann distribution. So this heat must be removed. The principle method for heat removal prior to the gasdynamic laser (GDL), was by heat conduction to the exterior walls of the lasing medium, where the heat could be further transferred into a coolant. Thus the time to remove heat by conduction is given roughly by[6]:

$$\tau_{cond} = \frac{D^2}{\kappa} \tag{2}$$

where D is a typical dimension of the lasing medium, and κ is the thermal diffusivity. On the other hand, if flow of velocity u is used to remove heat, then the time to remove the waste heat is just D/u. So the ratio of the heat removal times is:

$$\frac{\tau_{flow}}{\tau_{cond}} \approx \frac{\kappa}{uD} \tag{3}$$

Since the thermal diffusivity in gases is roughly equal to the kinematic viscosity, the heat removal times are inversely proportion to the Reynolds number. And since flows can achieve very high Reynolds number, for example, 10^6, the route to high power was through flow. This is shown in Fig. 2.

We were interested in scaling to higher power for industrial and military use, I envisaged a long row of nozzles through which heated N_2 would flow, and at the nozzle tips, cold CO_2 would be injected. I did some analyses, based on my working on wakes and mixing, but it was never built because of a better idea. But such mixing nozzles are currently used in HF and DF chemical lasers.

2. A BETTER IDEA

It is important to understand the role of the lower state deactivator. After the CO_2 lases, it enters the lower laser quantum state. If this population increases to equal that of the upper state, then lasing will cease. So a selective deactivator is needed. The original experiments used helium for this role; later about 1% water vapor was used. When we were all discussing the parameters for a mixing laser, Dr. Kurt Wray of AERL said, "You could try premixing all of the ingredients, heat them somehow, then expand the mixture through a [supersonic] nozzle, and who knows? You might be lucky and the deactivator will selectively deactivate the lower laser level preferentially over the upper laser level." This is what was tried and it succeeded[7]. An important parameter for the success of this concept was the radiative lifetime of the CO_2. This was measured by Gerry and Leonard[8].

2.1 Initial Shock Tube Measurements of Gain

AERL had a number of shock tubes for studying chemical kinetics and other physical phenomena. Dr. Jack Wilson adapted one into a shock tunnel. In such a shock tunnel, the shock wave is reflected from an end wall, and the shock wave heats the mixture, pretty much to equilibrium. In the endwall, however, is a supersonic nozzle, so the gas which was compressed and heated by the shock wave expands through this nozzle in quasi-steady flow until the shock-heated gases are exhausted, or the rarefaction wave from the diaphragm that separates the driver gas from the driven gas reaches the end wall. Figure 2 shows how it was supposed to work, except that helium was initially used instead of water vapor. However, Wilson had trouble measuring any gain downstream of the nozzle. Dr. Robert Greenberg approached me and suggested that there may be something wrong with the nozzle of Dr. Wilson's shock tube. My response was to immediately go into the laboratory and examine it. Dr. Greenberg then told me that no one was allowed in his laboratory. So we waited until D. Wilson was away on a trip, then went into his laboratory, and requested the technician to disassemble the nozzle. We found there was a lip between the end of the nozzle and the downstream straight section. It was filed down and the shock tunnel was reassembled. Lo and behold: when Dr. Wilson returned from his trip, gain was measured. Based on that success, the first combustion-driven laser was built. Similar work was proceeding in the Soviet Union, which we learned about later[9].

We were also concerned about what kind of nozzles to build, so a number of experiments were performed. The variants included a gradually converging nozzle with a straight downstream supersonic expansion section, a sharp upstream section followed by a gradual expansion, and a flat-faced upstream section followed by a gradual expansion section. Inteferograms were taken in of each, shown in Figs 3a, 3b, and 3c. A gradual upstream section followed by a curved downstream section calculated by means of the method of characteristics by Dr. Robert Greenberg was finally adopted as creating the smallest downstream index-of-refraction disturbances.

2.2 Combustion-Driven Gas Dynamic Laser

As I recall, the design of the first one was similar to that schematically shown in Fig. 4. I believe it generated about 1 kW of laser power. To scale the concept to higher power, more flow area was needed. But there was a restriction on the height of the nozzle throat due to the competition between expansion time and collisional deactivation time of the N_2. for reasonable combustor pressures. That meant that the cavity would have to be very long to achieve high power, or multiple nozzles would be needed. The latter is shown in Fig. 4. There are several interesting features in these early GDLs:

- The fuel was cyanogen, C_2N_2; I had heard about this from Prof. A.V. Grosse at Temple University. He had used it to make high temperature flames to test potential ablation materials while I worked at G.E. It was burned with oxygen, but we used air. Later GDLs used CO as the fuel, since cyanogen was much more than CO, with oxygen as the oxidant.
- The split diffuser. Ordinarily, the diffuser would be between the top and bottom walls; but then this could not be scaled in height. I believe the idea for the split diffuser was mine.
- The strange looking resonator. At that time, low power lasers used stable cavities with partially transmitting mirrors at one end. This was AERL's method of making a resonator, since we did not know of a material that was partially reflecting and partially transparent to 10.6 μm that could stand the high power that we were generating. This "holey" design carried over into the RASTA laser described later. Note the power level achieved was 6 kW. This was not quite a record, because Raytheon had built a very large electric discharge laser based on Patel's design which generated about 10 kW.

2.3 Opposition and Redemption

After the shock tube experiments, AERL's work on GDLs was funded by DARPA and was classified and compartmented as "Eighth Card." We wanted to scale this to much higher power, but were frustrated by the number of committees that were examining the feasibility high power. I remember in particular Dr. John Walsh, then at IDA, who questioned the technical feasibility of achieving good beam quality at high power. He was worried about unsteady combustion and turbulence, soot, etc. He proved to be a major barrier to our developing a GDL for higher power.

About this time, Mr. Peter Rose, deputy director of AERL had heard about an opportunity to build a larger GDL. The part of the Air Force that develops ballistic missiles was having a thermal problem with the nose tip of a reentry vehicle (RV), and they needed to simulate the heating, at about 10,000 W/cm^2. He suggested that I go see them and see if they would fund the next step, to achieve 100 kW. It happened that I knew the RV branch chief from when we worked together at Air Force Headquarters in the Pentagon, Col. John Anderson. I called him and told him that we may have a way of providing this heat flux. He invited me to give a presentation and I travelled to see him. I met with him in his office and explained the concept of the GDL, and that we could probably scale it to the power level he needed. I stated that this was proprietary information, but he asked me if I could share it with his scientific and engineering assistance team from Aerospace Corporation . I agreed, and to my surprise, eight members of Aerospace were in the next room. AERL was invited to submit a proposal, which was delivered a few days after my return. The laser was to be called the Radiation Augmented Special Test Apparatus (RASTA), and a sketch of it from the proposal is shown in Fig. 5. We were under contract in 10 days, for a total cost of $500,000. It was built and tested in 5 months by Arne Mattson, who previously had been working on MHD power generation. It aborted on the first try; but ran successfully on the second start. I believe that it was the RASTA which first indicated the possibility of high power lasers to the technical community. It also had a stable resonator and a holey output mirror. The output of each of the 360 holes had to be separately aimed at the focal point. But it was successful. A sketch of it with its holey output mirror is shown in Fig. 6,

and a photograph of it in Fig. 8. Unfortunately, it was later scrapped and no parts of it were ever found. A copy was built for AERL's use, and an unstable resonator was installed, but it never developed the power of the RASTA, and its beam quality was also not very good, as shown in Fig. 9.

2.4 Revelation

In this time period, there was an interesting incident. I was a member of a committee looking at the military applications of space. Abe Hertzberg was also a member of this committee. At one of our meetings, Alex Glass, then at IDA, gave a presentation of AERL's work on the GDL, which he was not supposed to do because of the special access required for the Eighth Card program. Mr. Hertzberg was livid, saying "They stole my idea" Of course it was not, because Mr. Herztberg's idea was for electronic states, and the GDL operated on vibrational states. But that event exacerbated the existing bad relation between him and the director of AERL. It turns out that Mr. Hertzberg had been a graduate student of the director of AERL when the latter was still a professor prior to his forming AERL, but Mr. Hertzberg never received his Ph.D. from that school. Mr. Hertzberg went on to a successful career at what was then the Cornell Aeronautical Laboratory in Buffalo, N.Y., and had built a shock tunnel for hypersonic aerodynamic studies. That activity has continued through today, while AERL has disappeared. Mr. Hertzberg also became active in Mathematical Sciences Northwest, hired Peter Rose from AERL, and which also became active in laser development.

2.5 Competition

Competition also warmed up, from the United Technologies Research Laboratory. They built a GDL larger than the RASTA in Florida, named the eXperimental Laser Device (XLD), which generated 210 kW[10]. It is shown in Fig. 10. It did not have good beam quality, which gave Lincoln Laboratory a chance to try adaptive optics for beam cleanup. It also had a moving target on a train about 2 miles away, to test such things as wind speed effects on thermal blooming.

3. THE TRI-SERVICE LASERS (TSL)

3.1 Problems

The three services decided that they each needed their own GDL for test purposes. It was named TSL. To the director of AERL this looked more like an engineering task, so he transferred it to Avco's System Division to build, with Ed Gerry and Arne Mattson acting as advisors. Lincoln Laboratory helped the services write the specifications to fit their desires. Lincoln wanted to use it as a MOPA, with a very long gain length. So the cavity height was only 10 cm, and 5 meters long, with multiple passes. The first pass was to be parallel to the shock wave. I would not have accepted these specifications for reasons that will be soon become apparent. Its power was to be over 100 kW with a beam quality of 1.5.

Three lasers were built and installed; one at the Air Force Starfire Optical Range, then called the Sandia Optical Range (SOR). Avco had a crew out there getting it to run. The Army's was at the AERL laboratory in Haverhill, MA, and the Navy elected to assemble it themselves on the banks of Chesapeake Bay. A photo of it is shown in Fig. 11 and a close up in Fig. 12.

The problem was that is was far over schedule, over cost, and under performing. The laboratory director called together his senior people to decide what to do about it. The overwhelming decision was to take the management of it back to AERL. Dr. Edward Gerry was then the manager of laser projects, so it was assumed that he would direct the project, with Mr. Mattson as his chief engineer. But it did not happen that way. Two weeks later, Dr. Gerry resigned to go to Darpa as their head of high energy laser projects. Although I had worked on the early GDLs, I had been assigned to other projects that used passive optics. But the director of the laboratory called me into his office and asked me to give up my current responsibilities and take over the completion of the TSL. He said that sometimes "you have to stoop to conquer." I agreed, although I did not have a clue as to how to solve its technical problems.

3.2 Low Power Fixed

The first problem was low power, both at the SOR and Haverhill lasers. The problem with the latter was a little simpler – it was to have been a MOPA, with a 100 W CO_2 electric laser from Hughes. A sketch of the optical layout is shown in Fig. 13. But the output was less than 10 W. It was subsequently changed into an unstable resonator.

The SOR laser already had an unstable resonatory, but its power was also low and the near field intensity was extremely uneven. The engineer aligning the resonator was using a narrow beam HeNe laser for the alignment, but reflecting it off a very small area of the resonator mirrors. It seemed to me that this was the wrong way to align a resonator, so I sent him back to Avco. I worked out a different alignment scheme – I sent Richard Frosh down range with the HeNe and a large white board with a hole cut out of the center for the HeNe. The HeNe beam was shown back into the resonator (through Hughes' Field Test Telescope) and the optics aligned until the beam reflected by the resonator was centered on the board around the hole. This solved the resonator alignment problem and the required power was achieved.

It should also be mentioned that initially, there was vibration of the nozzle blades. This was alleviated by putting small tabs on them on the upstream side of the nozzles that kept their separation distant constant.

3.3 Beam Quality Fixed

The other problem was that the beam quality was bad and became worse after about ½ sec. At this stage, the Air Force, under then Col Lamberson, decided that the Air Force Weapons Laboratory should take it over from Avco.

The output beam was in a "dog-leg" in which the beam was focused through a small output port. Dr. Glen Zieders thought that this could be causing thermal blooming. I tried to obtain information on the local atmospheric CO_2 content, but was frustrated. This once had been recorded by the local environmental monitoring station, but a few years previously, Congress had prohibited its further measurement. So it was difficult to make calculations of potential thermal blooming at the exit of the dogleg. Dr. Robert Greenberg proposed eliminating the dogleg, and substituting a supersonic aerowindow, which would not have the thermal blooming problem. A model was built and tested satisfactorily[11], and with the Army's permission, one was built and installed on the Haverhill TSL.

The beam quality was now steady, but still unacceptable. I began to think that the problem was caused by 2 of the optical passes being parallel to the weak shock-wave structure from the end of the nozzles. Interferograms of the flow had been taken on "Little Herbie." I took the one with flow and overlaid it on the one with no flow. It was difficult to align them, but it appeared that in one orientation the optical aberrations would be acceptable, but in another orientation that I thought more likely, the shock waves stood out. I did some crude calculations of what the far field would look like, and it was poor.

I suggested that we shine a visible laser through the cavity with a Hartmann plate at the exit and see if there was wavefront tilts. The tests went well, and there were major organized wavefront tilts from the shock waves in the cavity, which I though could account for the poor beam quality. On this basis, Dr. Zeiders reoriented the resonator mirrors so that the beam went through the shock fronts at an angle. With these changes, acceptable power and beam quality was achieved, and the Army accepted their TSL.

The Air Force followed suit. They adapted an aerodynamic window, made by United Technolgies, and realigned the resonator following consultation with Dr. Zeiders. Although they showed a beam profile which met the beam quality requirements, I was told that this was only on one axis, that it was more spread out in the other axis. This history has been coorborated by Dr. Zeiders, and contradicts a published account of how the Air Force solved its TSL problem[12].

4. THE COASTAL CRUSADER

The Navy had a great interest in countering antishipping cruise missiles, and to them, a high power laser could be just the right answer. They released a request for proposals to build a shipboard GDL. A sketch of Avco's version is shown in Fig. 14. It was never funded. The competition was chemical lasers (CL), namely DF. It had lower atmospheric absorption and in principle could be focused to s smaller spot size on the target because of its shorter wavelength (3.8 μm instead of 10.6 μm). But it was more affected by atmospheric turbulence: the shorter the wavelength, the greater the blurring due to atmospheric turbulence. Atmospheric turbulence is strongest at low altitude, and one can hardly get to a lower altitude than sea level where ships operate. I did a survey of temperature, turbulence, and relative humidity over oceans, and made a probability distribution chart that showed that the kill probability was about the same for both the GDL and the CL. But that did not help sustain GDLs, for reasons suggested below. The Navy contracted with TRW for the Navy Chemical Laser (NACL). It was to incapacitate an antishipping missile a few kilometers away. I did a few calculations that showed that even if the wings were shot off, it would still have enough momentum to hit the ship. I

brought this to the attention of the Navy, but they were not interested in my pessimism. Subsequently the issue of lethality sunk the Navy high energy laser effort.

5. THE EPLIGUE TO CO_2 GAS DYNAMIC LASERS

5.1The Design Confirmation Segment

DARPA continued to fund GDLs for a while at AERL with the emphasis on higher efficiency and improved beam quality. Mattson built the Design Confirmation Segment (DCS). The cavity was 20 cm high and about 80 cm long. It operated at a higher temperature and Mach number than the TSL. Dr. Greenberg designed the nozzles and side walls, taking into account boundary layer growth. The optical layout is shown in Fig. 15. Its beam quality was about 1.2, based on the first Airy ring, as shown in Fig. 16. This design was later used for the Airborne Laser, discussed next.

5.2 The Airborne Laser Laboratory

The Air Force at this point wanted to put a high energy laser, mainly a GDL on an airplane, and shoot down air-to-air missiles. A competition was held, and United Technology won the contract for the laser. We were later told that they used the nozzle design of the DCS. It eventually did its job and downed air-to-air missiles[11].

5.3 The Cylinderical GDL

One of the problems of the GDL is that the cavity height was limited by the bending stress level in the nozzle blades. The length of the cavity was limited by the product of zero-flux gain and the length of the cavity, to an amount less than about 12 to avoid amplified stimulated emission. This limited the power that could even be achieved by a linear CO_2 GDL. The laboratory director had previously suggested an assembly of nozzle rings, with each one having a diameter smaller than the previous, so that the assembly resembled a cone. At the apex would be the feedback mirror, and at the base the total reflector. The entire assembly would be mounted on a gimbal and pointed at the target, thus removing the necessity for a separate beam director. This was never built, but it pointed out the advantage of rings over straight nozzle blades: the former were subject to tension stresses while the latter to bending stresses, which are more severe. So a truly cylindrical GDL was proposed, but it also was never built. A sketch is shown in Fig. 17. Note the similarity to cylindrical chemical lasers which were evolved later.

5.4 AERL Shift to Electric Lasers

It was recognized that the GDL had poor chemical efficiency of a few percent and a low specific energy, perhaps 10 kJ/kg. It also did not fit the director's ambition of a having a space-based laser using electricity from a nuclear reactor, so that refueling would be unnecessary. So he placed his further investments into electric CO_2 lasers, discussed below.

5.5 Shift to Chemical Lasers

Shortly after the GDL was invented, Dr. Richard Airey, who nominally worked in my group at AERL, made a flowing chemical laser with HCl (virtually simultaneously with two others). He wanted to continue this work, but the director felt that because of the in-space chemical lasant replenishment problem, it would not satisfy his goal. The result is that Dr. Airy left AERL and became the high energy laser czar at DARPA. Needless to say, he emphasized chemical lasers. Also, Dr. Greenberg was told by the associate director that there was no inclination to promote him, so he also left for Washington and also emphasized chemical lasers.

5.6 Patent Suit

Long after all this, the Air Force threatened Avco with a patent suit over the CO_2 GDL. They claimed that uch of the work was done through Air Force funding, and were demanding a royalty-free license. Our contracts administrators were very upset. I suggested that they call the trial officer and state that we would be willing to give the Air Force a license for $1,000,000. The Air Force eventually paid $100,000 for what was by now a license for a useless invention, as no other GDL was ever built for the military, or for any commercial application (to my knowledge).

6. ELECTRIC CO_2 LASERS

AERL had a group of physicists under the direction of Dr. Richard Patrick, which had been working on electron beams, having to do with energy storage for fusion. But they had the idea that they could use a wide-area electron beam to pre-

ionize the gas mixture and then send a discharge through it to create the population inversion; it would be CW. The idea was developed into a CO_2 laser welder.

6.1 The Army Mobile Test Unit (MTU)

About that time, Dr. John Foster, head of DDR&E, visited AERL. I prepared a presentation for him showing power level vs. range for a number of applications, from an Army application to shoot down missiles in support of the Army front line, to ballistic missile defense. He chose the smallest on the list, the first one. Subsequently we were under contract to built the Mobile Test Unit, which was a scale up of the CO_2 laser welder. It is shown in Fig. 18 and a mockup of the MTU in Fig. 19. It involved a large piece of insulating, reeinforced plastic. It was not manufactured in that size, so the program manager had the systems division of Avco join two pieces with epoxy. I remember seeing the piece and asking why the joint was gray color. He stated that experts had done it, and I did not pursue it. It turns out it was loaded with aluminum, so that when 50 kV was put across it, instead of acting as an insulator, it shorted out. The Army subsequently took it away from AERL, I was relieved of my responsibility, and it was completed by a group o technical personnel who left Avco. After it was fixed, it successfully downed a BQM34 drown and a helicopter. It was later given to the NASA Marchall Space Flight Center. I was told their support contractor dismantled it, took it apart, and it never ran again

6.2 More Powerful Electric CO2 Lasers

AERL developed even more powerful electric CO_2 electric lasers, both CW and pulsed, under the direction of Dr. Jack Daugherty. The first was the Humdinger, which was e-beam prionized. It ran at 250 pulses per second and developed considerable power, very much higher than had been achieved before. It was funded by the Air Force, who became convinced that they wanted a CW electric version. This was built by Dr. David Ahouse, but it immediately ran into a beam quality problem. He and I made high speed interferograms of the cavity and discovered a transverse acoustic wave, caused by mode-media interaction. He solved that problem by placeing an acoustic absorber on one wall of the cavity, but the long wavelength of CO_2 was no longer attractive to the Air Force.

The Navy also wanted a very large energy per pulse electric CO_2 laser. It was the Thumper, also at AERL. While it demonstrated pulsed structural damage to thin panels, the Navy lost interest in favor of DF chemical lasers. The Army became interested in an even more powerful rep-pulse electric CO_2 laser. That was built by Mr. Robert Feinberg but ran into cavity arcing and severe mode-medium disturbances. That was the last of the high power CO_2 lasers[13].

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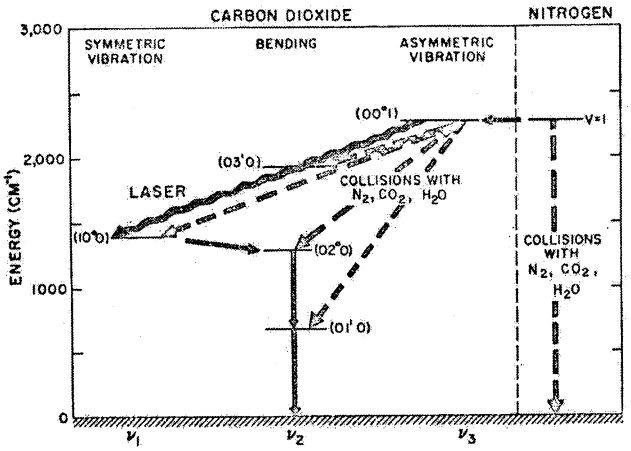


Fig. 1. N_2 and CO_2 vibrational energy levels. The 00°1 is the upper laser vibrational energy state and 00°0 is the lower. It is necessary to deactivate the lower state by collisions.

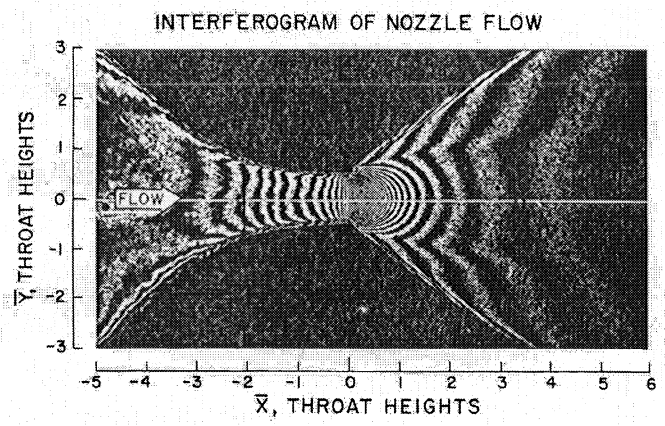


Fig. 3a. Interferogram of GDL nozzle flow with straight downstream walls.

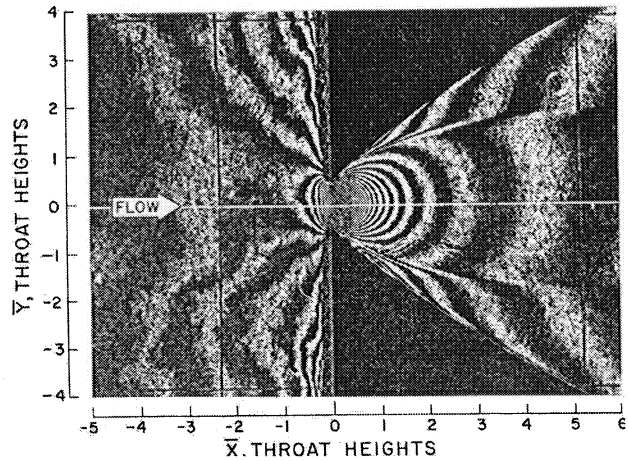


Fig. 3c. Interferogram of GDL nozzle with flat upstrea wall and straight downstream walls. Note excessive disturbances.

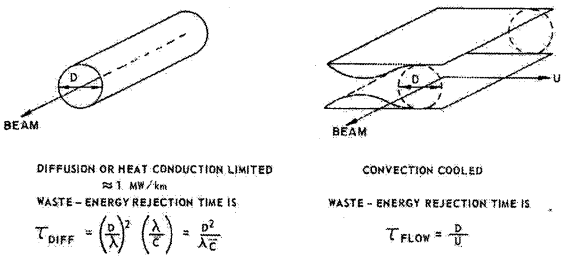


Fig. 2. Illustrates the difference between waste removal by heat conduction and flow; the latter is many orders of magnitude greater than the former and allows for high power lasers.

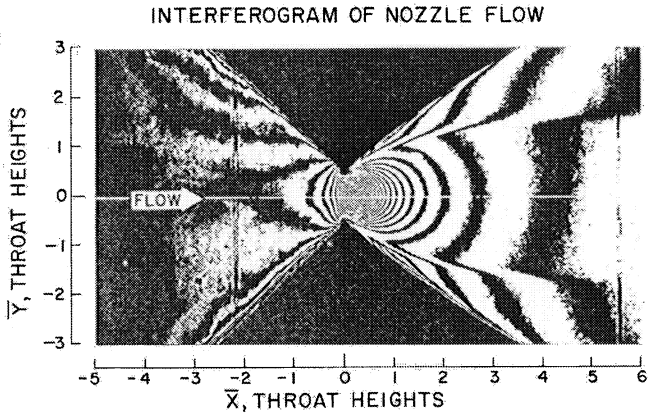
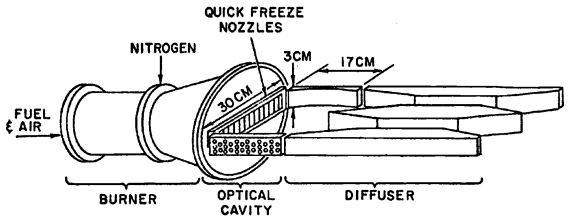


Fig. 3b. Interferogram of GDL nozzle flow with straight upstream and downstream walls; note exessive disturbances.



TYPICAL OPERATING CONDITIONS	
STAGNATION PRESSURE	17 ATM
MASS FLOW RATE	3 LB/SEC
STAGNATION TEMPERATURE	1300°K
MACH NUMBER	4.0
GAS COMPOSITION	
CARBON DIOXIDE	8%
CARBON MONOXIDE	0.2%
NITROGEN	91%
WATER	0.8%
MIRROR COUPLING	2%
PERFORMANCE	
POWER OUTPUT	6 KW
INTRA-CAVITY FLUX	1 KW/CM²

Fig. 4. Parameters of the AERL Mk 2 GDL. Note multiple nozzles, dual diffusor, and holey output mirror.

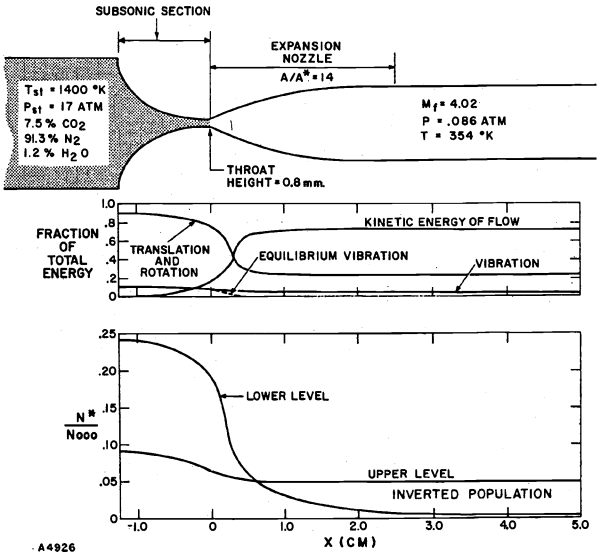


Fig. 5. Energy states in a CO_2 GDL.

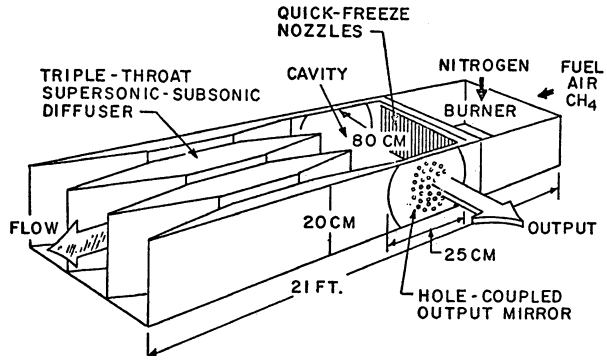


Fig. 7. RASTA laser with triple diffuser and holey output mirror.

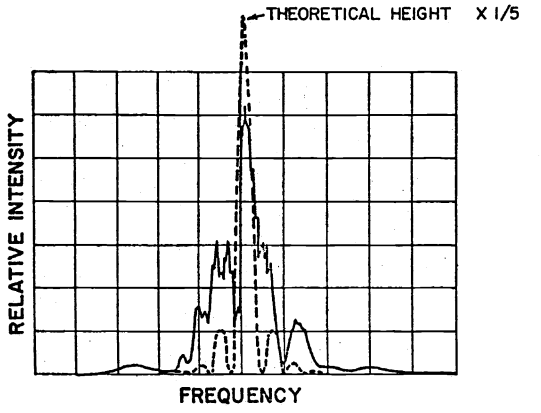


Fig. 9. Far field irradiance of the Mark V with an unstable resonator, showing poor beam quality

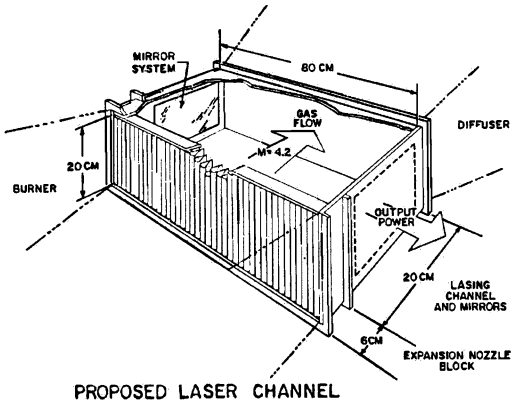


Fig. 6. Sketch of the RASTA laser from 1968 proposal.

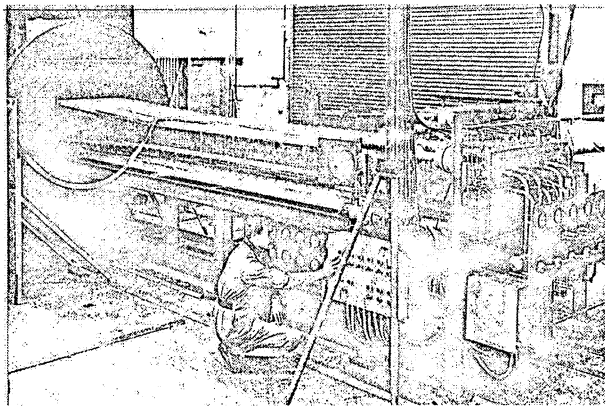


Fig. 8. Photograph of the RASTA laser.

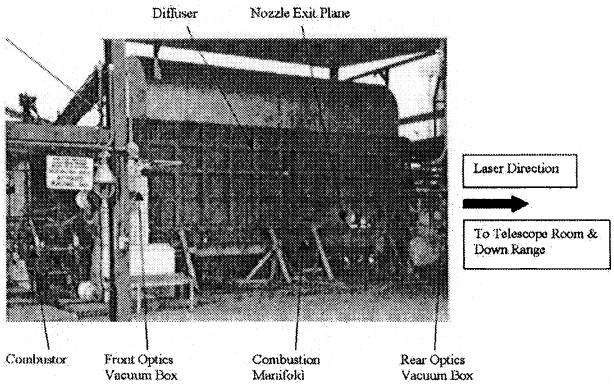


Fig. 10. Photograph of the United Technology XLD GDL

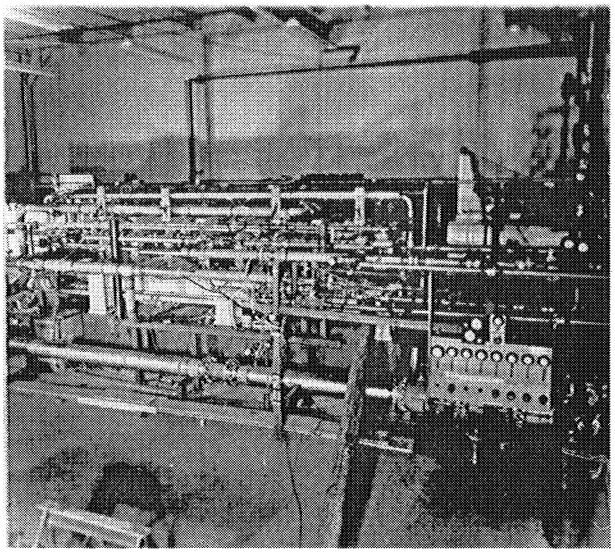


Fig. 11. Tri-Service Laser, probably at Haverhill, MA. Note maze of cooling and lasant gas plumbing.

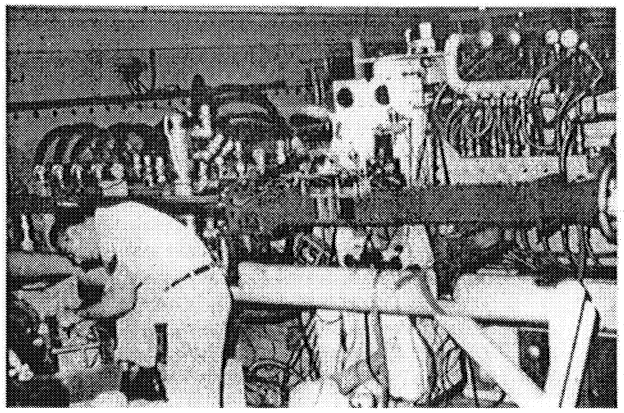


Fig. 12. Close-up of the TSL.

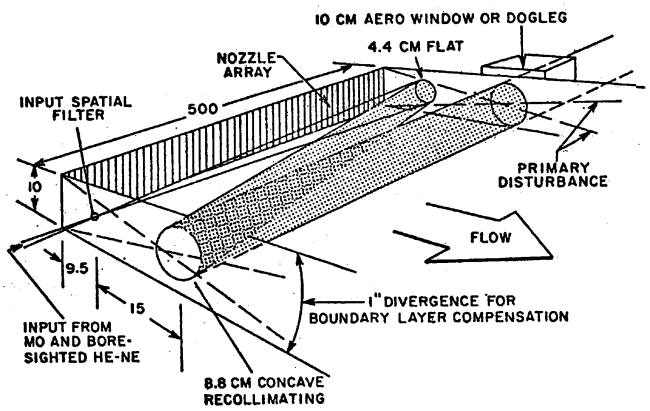


Fig. 13. Optical layout of the TSL in the MOPA configuration.

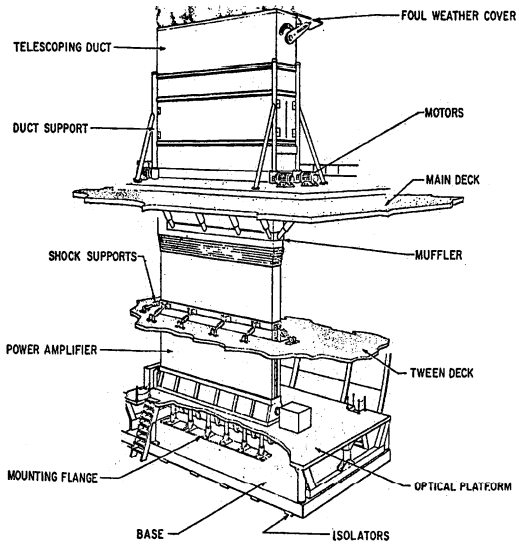


Fig. 14. Sketch of the GDL for the Coastal Crusader, never built.

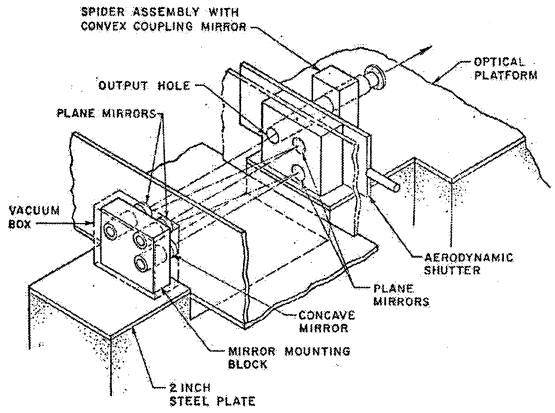


Fig. 15. Optical layout of the DCS GDL, last built by AERL.

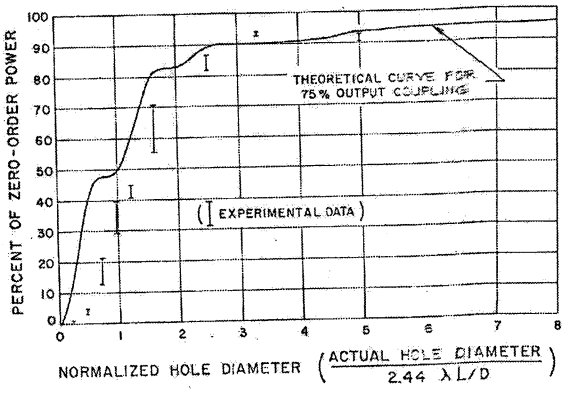


Fig. 16. Encircled energy produced by the DCS GDL, showing excellent beam quality; 1.2 at the first Airy ring.

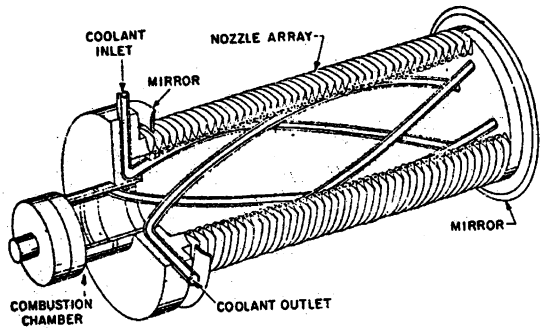


Fig. 17. Concept for a cylindrical GDL to overcome cavity height limitations of a linear geometry. Never built.

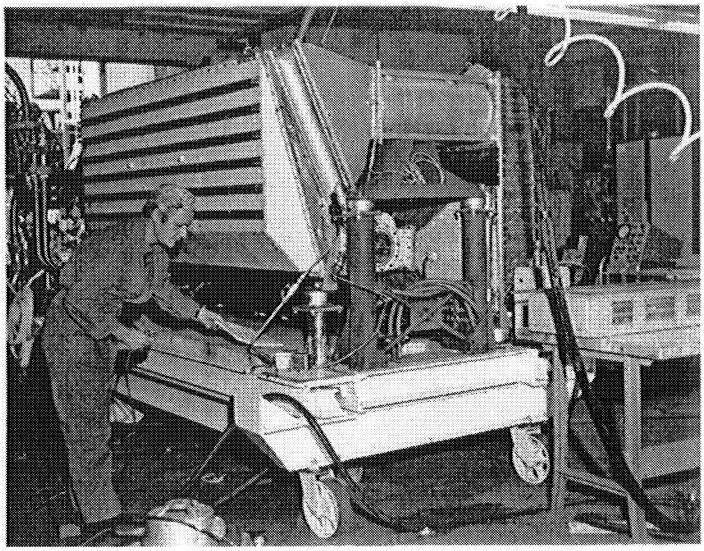


Fig. 18. Mr. Bernard Wasserman, program manager of the MTU electric CW CO_2 laser with it. Notice ever present coffee cup. Shot down a BQM34 and a helicopter before being transferred to NASA, where it never ran again.

The vehicle is a Marine vehicle, which caused the Army some heartburn.

Fig. 19. MTU vehicle with mockup of the beam director turret and heat exchangers. The vehicle is a Marine vehicle, which caused the Army some heartburn.