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Technical Progress Report

Contract Title And Number: **Date:** August 18, 1989
A Compact, High-Powered
Far-Infrared (FIR) Laser **Report Period:** 1-22-88 to
DE-AC-03-87SF17128 present

Contractor Name: Connecticut College
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Contract Period: 9-30-87 through 7-31-89

Project Objective:

A compact CO₂-¹³CH₃F laser system where the FIR laser cavity is inserted in a pump, three-mirror CO₂ laser cavity, with optically-switched semiconductor cavity-dumping, will be designed and tested. The 1.207 mm cavity-dumped oscillator is expected to be characterized by predominantly single longitudinal mode, narrow linewidth operation and to produce peak powers of order 100 kW in pulses of order 10 ns duration. The 1.2mm wavelength lies in an atmospheric transmission window (1 dB/km at sea level [1]), which opens up the

1. J. Gallagher, M. Blue, B. Bean, and S. Perkowitz, Infrared Physics 17, 52 (1977).

MASTER *JMB*

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possibility of millimeter-wave space- or ground-based radar and communications systems [2]. The laser can also be used as a FIR spectroscopic source to investigate dynamic properties of elementary excitations of the solid state [3].

Although much progress has been made, the project is behind schedule due to a malfunctioning pump CO₂ laser. An extension has been requested and it is anticipated that testing of the laser system can begin shortly.

Concept Description:

The key features of the laser design are the zigzag, three-mirror pump CO₂ cavity [4], and the semiconductor-switched cavity-dumper. These offer the following advantages:

- (1) Compact and simple geometry
- (2) Enhanced pumping efficiency

2. R.J. Temkin, K.E. Kreisler, W.J. Mulligan, S. MacCabe, and H.R. Fetterman, "A 100 kW, 140 GHz pulsed gyatron", Int. J. IR and MM Waves 3, 427 (1982).

3. T.E. Wilson, "A Proposal for the Direct Electromagnetic Generation of Coherent Terahertz Acoustic Phonons in Semiconductor Superlattices at the UCSB-FEL Facility", JOSA B 6, 1058 (1989).

4. H. Hirose and S. Kon, Int. J. IR. and MM. Waves 5, 1571 (1984).



(3) Decoupling of FIR and the pump CO₂ laser powers

(4) Substantial increase in the peak power with a corresponding decrease in the pulsewidth of the FIR output

The circulating FIR energy in the high-Q, near-hemispherical resonator will be cavity-dumped by optically-switching an intracavity, high resistivity (8500 Ω-cm) silicon wafer placed on-axis at the Brewster angle near the beam waist.

The maximum expected circulating FIR energy can be estimated under the assumptions of saturating pump and FIR intensities [5]. The first condition is well satisfied as the pump transition for our system saturates at 2.5×10^3 W/cm² and our pump intensity is at least an order of magnitude above this value. The rate of FIR energy generation under these conditions is proportional to the rate of pump absorption from the ground state rotational levels. For intense pumping, this process is limited by the collisional refilling of the ground absorbing states and the emptying of the upper laser states, both of which proceed at the rotational collision rate $\tau_{\Delta J}^{-1} \sim 10^8 \text{ sec}^{-1} \text{ torr}^{-1}$. If f_i is the equi-

5. D.T. Hodges, *Infrared Physics* **18**, 375 (1978).



librium fraction of molecules in the ground absorbing states and N_o is the total molecular density, then the pumping rate to the ($J=5, K=3$) ν_3 level of $^{13}\text{CH}_3\text{F}$ will be limited to $f_i N_o \tau_{\Delta J}^{-1}$ and the maximum volumetric power generation is given by:

$$\frac{P_{FIR}}{V} = \frac{1}{2} h \nu_{FIR} f_i N_o \tau_{\Delta J}^{-1}. \quad (1)$$

As Temkin [6] shows, one cannot pump more than a total of $\frac{1}{2} N_o$ molecules into the ν_3 level, so the pump laser pulse-length t_{lp} should satisfy the relation:

$$t_{lp} \leq \tau_{\Delta J} / f_i. \quad (2)$$

For example, for the 1.2 mm $^{13}\text{CH}_3\text{F}$ laser, $f_i = 7.6 \times 10^{-3}$, and at a pressure of .5 torr, $t_{lp} \sim 2 \mu\text{sec}$. The pulse width of our pumping CO_2 laser is 200 ns so that condition (2) will be satisfied for operating pressures as high as 5 torr. The maximum circulating FIR energy in the cavity of volume V and pressure p after the pumping has taken place can be written:

$$E_{FIR} = (2.4E+3) p^2 V t_{lp} \frac{J}{\text{torr}^2 \cdot \text{liter} \cdot \text{sec}}. \quad (3)$$

6. R.J. Temkin, IEEE QE-13, 450 (1977).



For example, Hacker et al. [7] measured the energy output from a 1.2 mm $^{13}\text{CH}_3\text{F}$ 2-pass mirrorless laser cavity containing 3.4l at .5 torr, pumped by a CO_2 laser with a pulsewidth of 300ns. They measured .26mJ, consistent with the maximum energy expected to be developed in the cavity, .66mJ, given by (3). With our cavity of much higher Q but similar volume, we expect to be able to generate nearly the maximum amount of the circulating energy, and, by coupling out all of the energy by cavity-dumping, expect the peak power output to be of order 100 kW as mentioned above.

The power absorption coefficient for high-resistivity Si at 1.2mm is .131 neper/cm [8] resulting in greater than 99% transmission of the FIR radiation per pass. The switching radiation is supplied by the 1.06 μm output from a Laser Photonics MYL-100 miniature pulsed YAG laser providing $\sim 1\text{mJ}/\text{cm}^2$ at the Si surface. The YAG laser is pulsed at a slight delay with respect to the pumping CO_2 laser in order to maximize the FIR output power. The free carrier density

7. M.P. Hacker, Z. Drozdowicz, D.R. Cohn, K. Isobe & R.J. Temkin, Phys. Lett. 57A, 328 (1976).

8. Personal communication from Prof. Mohammad Nurul Afsar, Department of Electrical Engineering, Tufts University, Medford, MA 02155.



rapidly (<1 ns) produced in the Si by the infrared pulse exceeds the plasma cut-off density for FIR wavelengths with a resultant large increase in the reflectivity [9].

Discussion of the Experimental Apparatus

I. Optics

Since project initiation in September of 1987, the design and construction of the laser and a metal-mesh scanning Fabry-Perot interferometer (FPI) have been completed (please see Status Report #1 for construction details of the FPI). The FPI, shown in photograph 1, is constructed from commercially available components, and has a finesse of 25 with a 50 mm clear aperture. A mount was made which allows it to be fastened directly to the laser cavity for alignment convenience. A TPX lens is used to focus the transmitted energy onto a fast pyroelectric detector, Molelectron P5-00, backed by a 400 MHz amplifier, a Molelectron P5-AMP. The lens and detector may also replace W1 if desired.

Photograph 1 also shows the crossed cylindrical lenses (focal lengths of 25.4 and 6.35 mm) used to enlarge the 3 mm

9. R.F. Leheny, R.E. Nahory and M.A. Pollack, Phys. Rev B **8**, 620 (1973); H. Salzmann, T. Vogel, and G. Dodel, Optics Comm. **47**, 340 (1983).



diameter YAG laser beam to an area approximately 1.5" x 4" centered on the silicon wafer.

Figure 1 illustrates the FIR laser design. Both the resonator mirrors and the long rectangular mirrors are held in mounts which provide two rotational degrees of freedom for alignment convenience. The majority of the work on the FPI and the millimeter-wave laser design was done prior to 1989. The machining of the laser itself was done at the machine shop at Wesleyan University in Middletown, CT and was not completed until February of 1989. The machining costs were significantly underestimated and a cost overrun incurred which was the dominant factor for the previously requested funding increase. Nearly all of the optics were custom made by either Janos Technology, BiOptical, Melles-Griot, or Laser Power Optics. The intrinsic silicon wafer was donated by Wacker-Siltronix. Mirrors 1, 2, and 4 are bare-gold coated. The two long rectangular flat (approximately 5" x 20" x 3/4") mirrors have an enhanced silver coating. M1 and M4 are held in gimbals, one of which is on a precision translation stage. The gimbals and translation stage are oil-free and vacuum-compatible and obtained from Newport. All adjustments are made through vacuum feed-throughs. W1 is 75 x 6 mm and is sometimes replaced with a



75 mm focal length TPX lens. W2 is 50 mm x 4 mm. All of these were obtained from Specac. M5, obtained from Infrared Optics, completes the 4.9m long external CO₂ cavity and the radius of curvature, 8.8m, was chosen to match the wavefront curvature of the diverging CO₂ beam there. M5 is housed in a Newport gimbal attached to a Newport translation stage for fine tuning the external cavity. Not shown is a CO₂ spectrum analyzer by Lasercraft which can be inserted in the CO₂ beampath for line verification.

The FIR Gaussian beam radius at the round flat mirror near the cavity-dumping Si wafer is 1.7cm, at the round concave mirror it is 3.3cm. The Fresnel number for the cavity is approximately .8, corresponding to .2dB loss/bounce due to diffractive spillover for the TEM₀₀ mode. The Brewster angle for silicon at 250 GHz is 73.69°. For the 4" wafer to be used as the cavity dumper, this results in an effective horizontal width of 2.9cm facing the beam, slightly less than the 3.4cm beam waist. The laser gain medium has a volume of approximately 3.8 liters pumped by the 1.93m long CO₂ zigzag path.

An automotive battery-backup circuit was constructed to supply power to the heating tape surrounding the salt windows, BW, (required to prevent damage from the ambient



humidity) in the event of a power outage.

II. Vacuum System

The laser cavity can be evacuated by a Danielson oil-free Tribodyn 150 molecular-drag pump and the expensive isotopic gas may be recycled via a cryogenic pump as indicated in figure 2 and photograph 2. The cryopumps are old Varian VacSorb pumps and were donated by General Electric. Most of the valves and fittings are either Swagelok, Nor-Cal or Huntington. Recycling of inexpensive ammonia gas has been successfully tested with the system and it is expected to also work for isotopic methyl fluoride. The laser cavity gas pressure is monitored by two MKS Baratron capacitance manometers, either type 220B for 0-1 Torr or type 122A for 1-1000 Torr, and displayed on an MKS model PDR-C-1B control module. The entire system has been helium leak-checked.

One of the outstanding concerns here is that the laser chamber is presently outgassing at the rate of .06mT/min and that the outgassing will degrade the laser output with time as the gas is recycled over many uses. Union Carbide type 3A molecular sieve with a pore size of 3 Angstroms has been ordered for the cryopumps. It is hoped that the outgassing is primarily water vapor whose effective molecular diameter



of 2.65 A will be trapped by the sieve while allowing $^{13}\text{CH}_3\text{F}$ with an effective diameter of 3.36 A to be unaffected by the presence of the sieve material in the recycling cryopump when the pump reaches room temperature. Should this approach fail, the laser chamber will be subjected to a low temperature bake (approximately 200°F) to clean the walls of the cavity (200 feet of 3 W/ft heating tape has already been installed around the laser). However, the PI is hesitant to bake the laser chamber for fear of resulting optical misalignment. An attempt is also being made to obtain more of the expensive isotopic gas from the Los Alamos and Livermore National Laboratories at no cost.

III. Data Acquisition System and Associated Electronics

The output from the P5-00 pyroelectric detector is input to an SRC model SR250 gated integrator and boxcar averager. An SRC265 software package allows an IBM PS/2 computer, via a SR245 Computer Interface Module, to acquire, display and manipulate the data from the SR250. The Principal Investigator has modified the software package in order that time scans may be performed using the SRC model DG535 Digital Delay Generator controlled through a National Instruments MC-GPIB card installed in the computer.



Some explanation is needed here. The DG535 acts as the master clock. The DG535 can generate, relative to either an internal or external clock, up to four precisely timed logic transitions, with high accuracy (1 ppm), precision (5 ps), wide range (0 to 1000s), and low jitter (50 ps RMS). Two of these are needed to trigger the CO₂ laser (see below) while the third is used to trigger the YAG laser to initiate the cavity-dumping. The SRC265 FORTRAN routines "boscn" (beginning of scans), "eachpt" (each data point), and "eoscn" (end of scan) have been modified to send appropriate commands to the DG535 via the subroutine "mcgpib" which allows for talking to MC-GPIB devices. Before a scan begins, the display menu prompts the user for the appropriate DG535 commands. In our case, after a data point has been collected, the DG535 is instructed to increment its Channel A delay (used for the YAG laser) at the next clock pulse. Channel A's logic transition is then used to trigger the SR250 whose gate is set over the pyroelectric detector output for acquisition. This system allows for the cavity-dumping to be initiated, and the resulting output acquired, digitized, and displayed in a precise time scan relative to the firing of the CO₂ laser by use of the DG535. Alternatively, a FPI wavelength scan of the cavity-dumped output, at fixed delay relative to



the CO₂ laser, can be obtained. In this mode, the SR265 pauses after each data point to prompt the user to increment the FPI intermesh spacing before data collection recommences. The SR265 software package's modified routines were recompiled and relinked and for this it was necessary to purchase Microsoft FORTRAN 4.1 and Macro Assembler 5.1. The timing is set up and viewed on a Tektronix 2465A 350 MHz oscilloscope. The signals to the CO₂ laser are sent over edge-triggered TTL-compatible fiberoptic lines (in-house construction employing T&B 92910 Series PCB Data Links) to the Faraday cage housing the CO₂ laser. The modified software package can correctly operate at up to a 33 Hz pulse repetition rate and is available upon request.

IV. CO₂ Laser

The CO₂ laser has been responsible for the delay in project completion. The unit was purchased used prior to the contract award from Gentec where it had been used for testing their IR detectors. In the spring of 1989, a new Ge output coupler and a grating were installed. The unit functioned very well when internally triggered, producing over .6J/pulse (~3 MW) with less than 5% amplitude fluctuation, multi-mode output on the 10R20 line. However, undocu-



mented modifications to the unit triggering circuitry by Gentec engineers were found by the PI to result in the unit not meeting its external triggering specifications. Unfortunately, local problems with the installation of a water chiller delayed the discovery of this problem. The unit was found not to be externally triggerable by a TTL logic pulse as the PI was informed; furthermore, when the unit was successfully triggered, the jitter was a horrendous $\pm 1\text{ms}$. Since Gentec no longer manufactures the laser, support was minimal. After much effort (primarily due to a lack of correct circuit schematics) it was discovered that the external trigger essentially only enabled the output of a 555 timer to trigger the thyatron firing circuitry. Since the external trigger and the 555 timer had no phase relationship, this resulted in a completely unacceptable jitter for the purposes of the experiment at hand.

The trigger generator circuitry was changed to correct the jitter problem and tested in mid-June; however, upon testing, the changes were found to be only partially successful in the following manner. The laser did fire correctly but for only a few minutes before going into a latch-up mode. The PI suspected either the ALE high voltage supply interface card or the thyatron to have been damaged



since a subsequent bench test of the trigger generator was found to be successful. Also the grid pulses to the thyatron were fine. The HV unit was sent back to the factory for repairs which took several weeks. Upon return, the PI was informed that the HV unit was not damaged after all. Therefore, the PI suspects that feedback from the HV laser discharge damaged some of the trigger generator integrated circuits in such a manner that malfunctions only become manifest in a noisy RF environment such as during the laser discharge and not during a bench test. Currently the trigger generator circuitry is being rebuilt on a new card. Handshake cables to the ALE HV unit are being shielded in copper screen and diode clamps are being used on the inputs of the optocouplers for protection against large voltage spikes which exceed the peak reverse voltage of the npn transistors. The PI is optimistic that these modifications will be in place in September and will remedy the problem. Also, requests to Lawrence Livermore National Laboratory for spare CX-1159 EEV thyratrons have been made and two spares are being sent, courtesy of Dr. Hugh Kirbie. Photograph 3 shows the Gentec DD250 TEA CO₂ laser.

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Summary

Although much progress has been made towards the testing of the FIR laser system, delays due to a malfunctioning CO₂ pump laser have pushed the anticipated date for project completion beyond the contract period. Teaching demands upon the PI's time may preclude an earlier project completion date than the summer of 1990 although it is certainly hoped that system testing will commence shortly. Project funds are depleted although this should not be a problem provided requests to Livermore and Los Alamos National Laboratories for the expensive isotopic methyl fluoride and a miniature pulsed Laser Photonics MYL-100 YAG laser (instead of leasing one for \$1000/month) are successful.

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Millimeter-wave Laser

M1, M2, M3 - flat mirrors

M4 - radius curvature = 1.7m

M5 - radius curvature = 8.8m

Si - Silicon wafer $\rho = 8500 \Omega \cdot \text{cm}$

BW - NaCl Brewster window

W1 - TPX window

W2 - Spectrosil window

L1 - Spectrosil lens

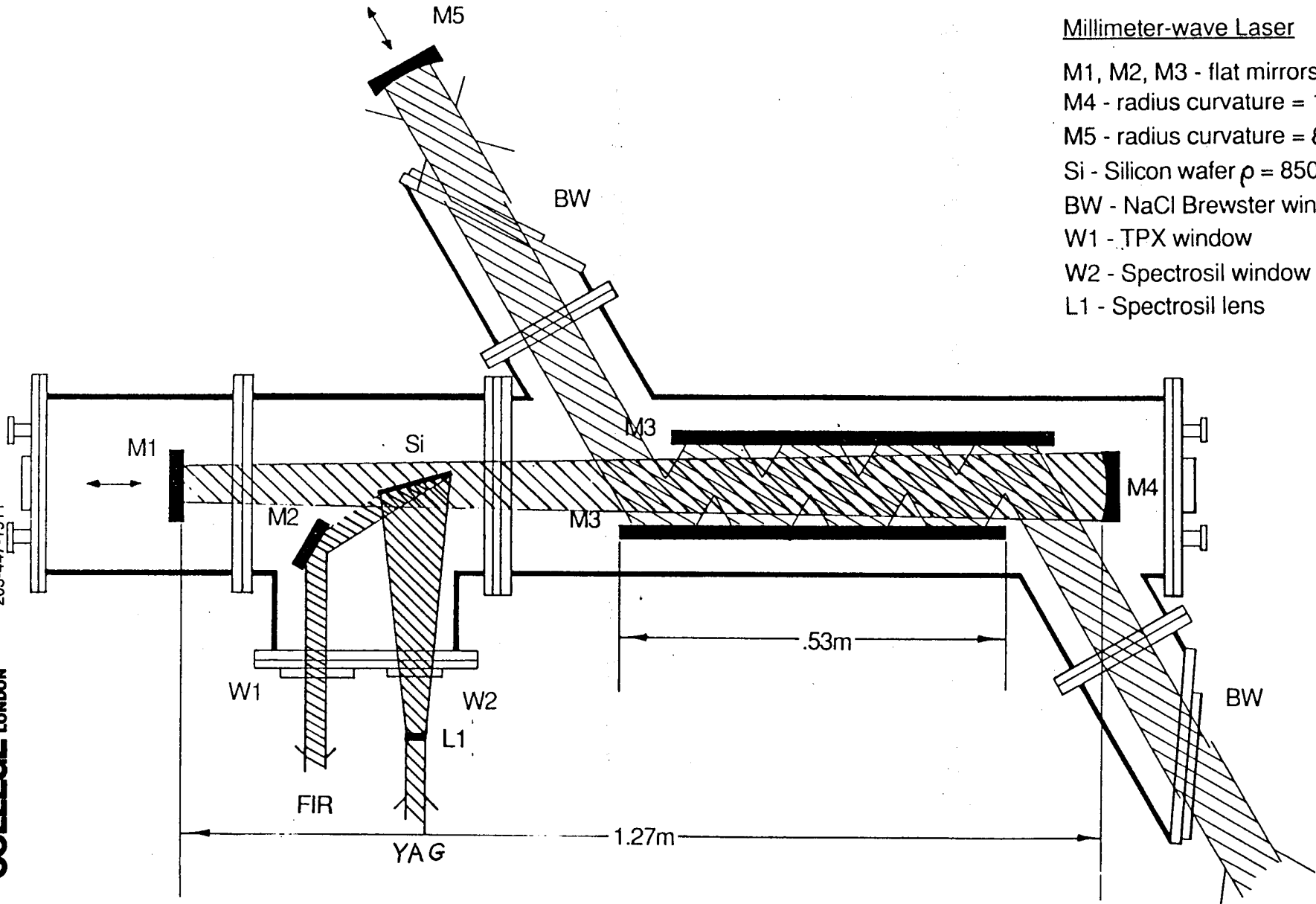


Figure 1 - Millimeter Wave Oscillator

CO₂

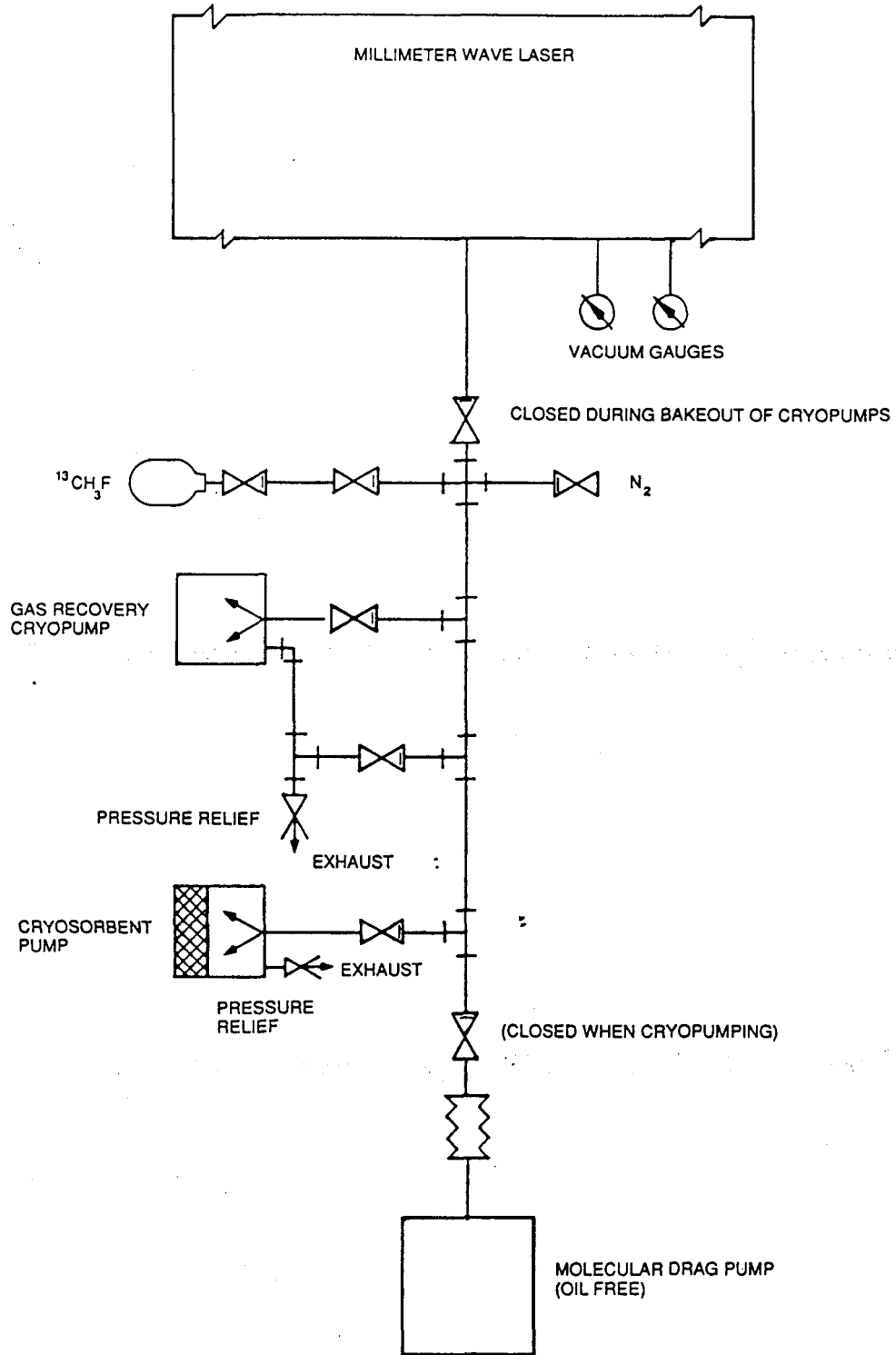
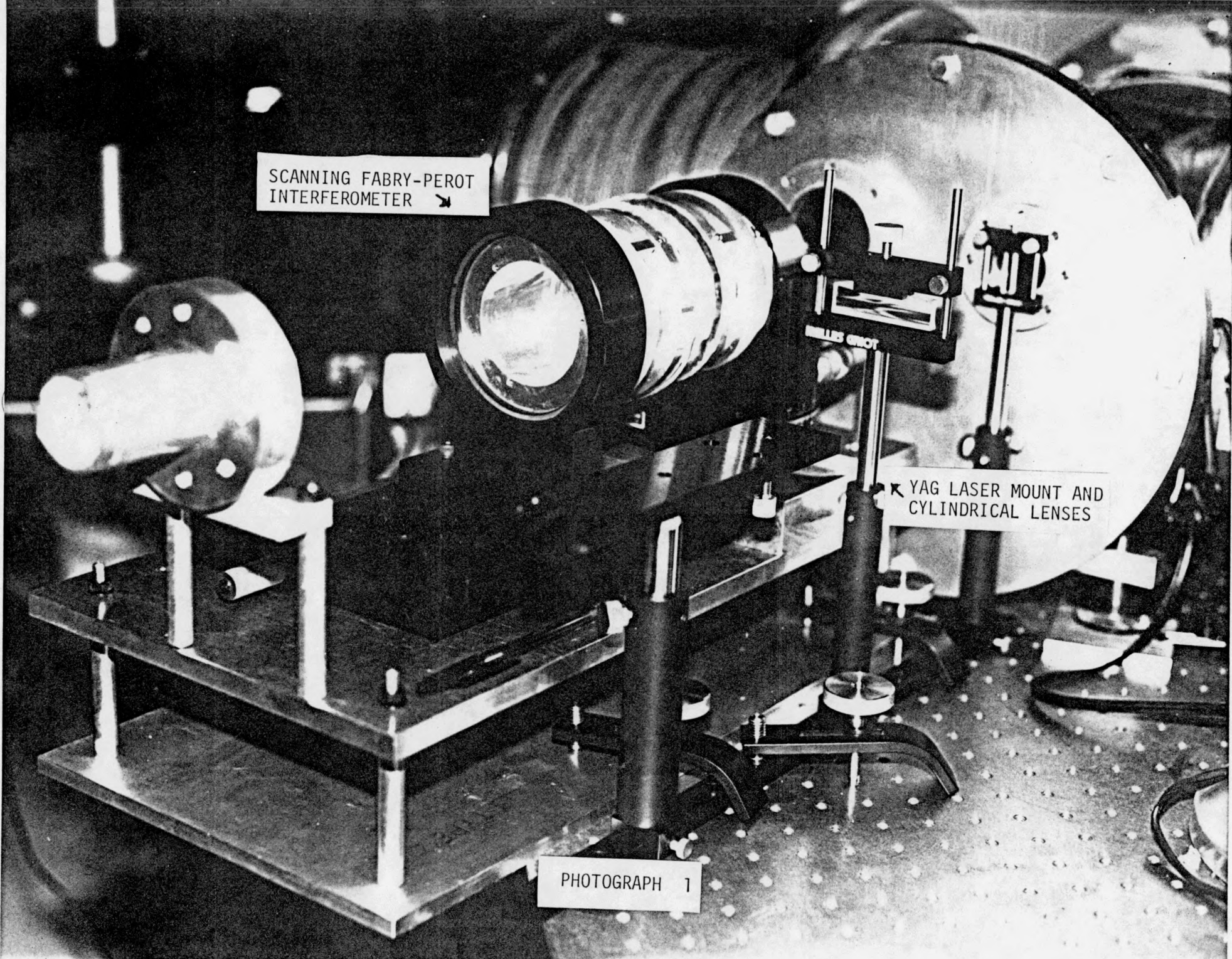


Figure 2 - Vacuum System

SCANNING FABRY-PEROT
INTERFEROMETER

YAG LASER MOUNT AND
CYLINDRICAL LENSES

PHOTOGRAPH 1

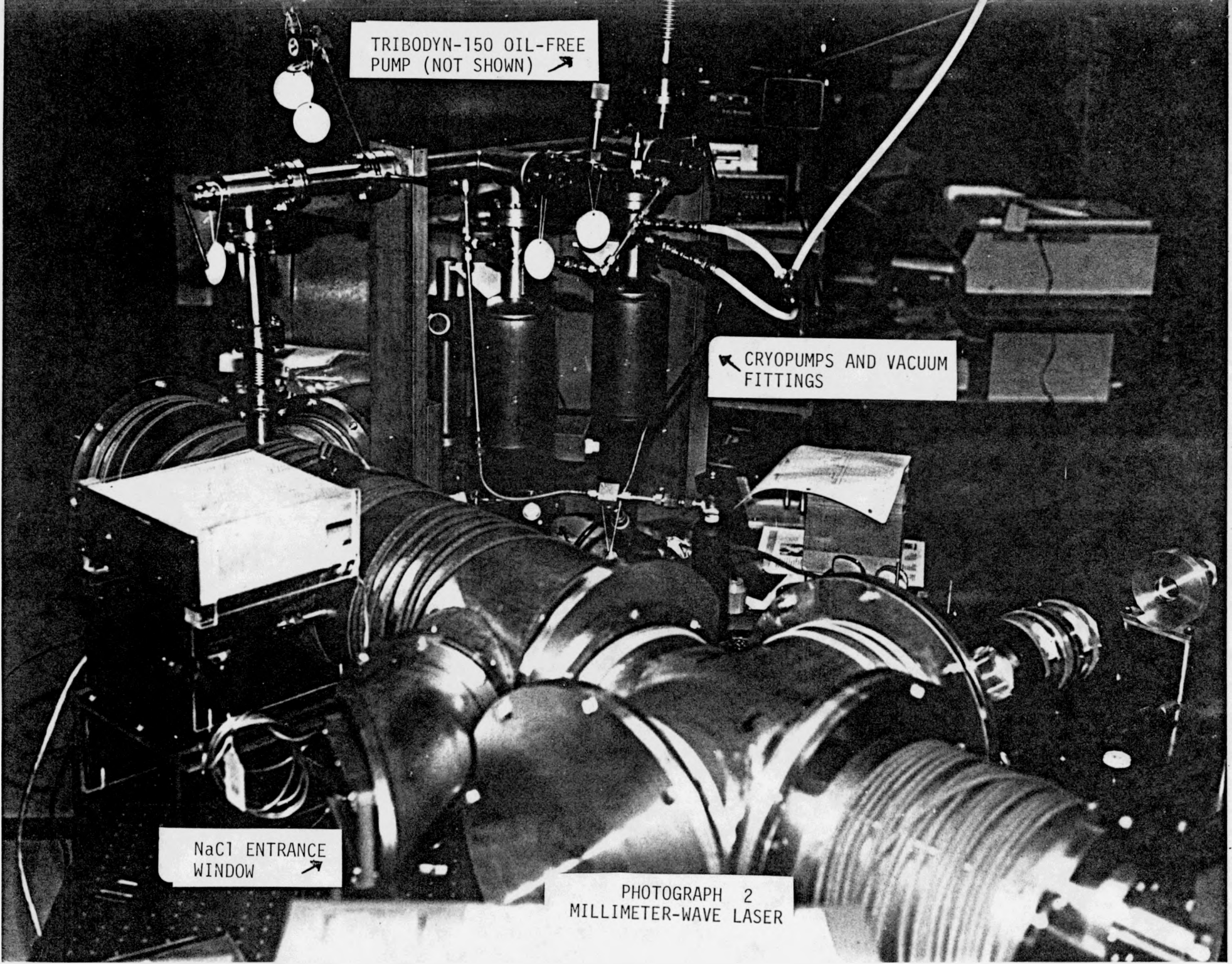



TRIBODYN-150 OIL-FREE
PUMP (NOT SHOWN) ↗

↖ CRYOPUMPS AND VACUUM
FITTINGS

NaCl ENTRANCE
WINDOW ↗

PHOTOGRAPH 2
MILLIMETER-WAVE LASER





TRIGGER GENERATOR

PHOTOGRAPH 3
GENTEC DD-250 PULSED CO₂
TEA LASER (IN SHIELDED
ROOM)