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Final Technical Report

Contract Title And Number:	A Compact, High-Powered Far-Infrared (FIR) Laser, DE-AC-03-87SF17128
Contractor Name:	Connecticut College Mohegan Avenue New London, CT
Contract Period:	9-30-87 through 1-31-90
Principal Investigator:	Thomas E. Wilson, Ph.D. Thom E. Wil
Date:	April 21, 1990

Project Objective:

A compact CO_2-$^{13}CH_3F$ laser system where the FIR laser cavity is inserted in a pump, three-mirror CO_2 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 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].

Concept Description:

The key features of the laser design are the zigzag, three-mirror pump CO_2 cavity [4], and the semiconductor-switched cavity-dumper. These offer the following advantages:

- Compact and simple geometry
- Enhanced pumping efficiency
- Decoupling of FIR and the pump CO_2 laser powers

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- 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 2.5x10^3 W/cm^2 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 $\tau_{\Delta J}^{-1} \sim 10^8 \sec^{-1} torr^{-1}$. If f_i is the equilibrium 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 $^{13}CH_3F$ will be limited to $f_i N_o \tau_{\Delta J}^{-1}$ and the maximum volumetric power generation is given by:

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

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 pulselength t_{lp} should satisfy the relation:

$$t_{lp} \leq \tau_{\Delta J} / f_i. \tag{2}$$

For example, for the 1.2 mm $^{13}CH_3F$ laser, $f_i = 7.6 \times 10^{-3}$, and at a pressure of .5 torr, $t_{lp} \sim 2 \mu \sec$. 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:

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

For example, Hacker et al. [7] measured the energy output from a 1.2 mm $^{13}CH_3F$ 2-pass mirrorless laser cavity containing 3.4l at .5 torr, pumped by a TEA CO_2 laser providing .6J/pulse in 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, pumped by a TEA CO_2 laser with similar output characteristics, we expect to be able to generate nearly the maximum amount of the circulating energy. By coupling the energy out via cavity-dumping, we 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 1.06μm output from a pulsed electro-optic Q-switched YAG laser, Laser Photonics model YQL-102, providing ~10mJ/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 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].

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 pyroelectric detector. 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 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 overun 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 feedthroughs. 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 CO_2 cavity and the radius of curvature, 7.5m, was chosen to insure that the external resonator is stable. M5 is housed in a Newport gimbal attached to a Newport translation stage for fine tuning the external cavity. Not shown is a CO_2 spectrum analyzer by Lasercraft which can be inserted in the CO_2 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 TEM_{00} 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 CO_2 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 Varian VacSorb pumps donated to the physics department by General Electric. Most of the valves and fittings are either Swagelok, Nor-Cal or Huntington. Recycling of the expensive isotopic methyl fluoride gas has been successfully tested. The laser cavity gas pressure is monitored by two MKS Baratron capacitance manometers, either type 220B for 0-1 Torr or type 122A for 1-10 Torr, and displayed on an MKS model PDR-C-1B control module. The entire system has been helium leak-checked using an Edwards leak detector.

III. Data Acquisition System and Associated Electronics:

The output from the 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 CO_2 laser (see below) while the third is used to trigger the YAG laser to initiate the cavity-dumping. The SRC265 FORTRAN routines "boscns" (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 than 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 CO_2 laser by use of the DG535. Alternatively, a FPI wavelength scan of the cavity-dumped output, at fixed delay relative to the CO_2 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 CO_2 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 CO_2 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 CO_2 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, undocumented 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 ±1ms. 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 thyratron 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 rebuilt on a new card. Handshake cables to the ALE HV unit were shielded in copper screen and diode clamps used on the inputs of the optocouplers for protection against large voltage spikes which exceed the peak reverse voltage of the npn transistor junctions. These modifications have succeeded in that the laser can now be externally triggered by TTL logic, at pulse repetition rates of up to 30pps, and with a measured jitter of less than +/- 10ns. Also, requests to Lawrence Livermore National Laboratory for spare CX-1159 EEV thyratrons resulted in six spares being sent, courtesy of Dr. Hugh Kirbie. Photograph 3 shows the Gentec DD250 TEA CO_2 laser.

Results:

The laser system has been successfully tested and weak, far-infrared output has been obtained from CH_3F and $^{13}CH_3F$. Cavity-dumping has not been attempted as yet; presently conventional output is obtained using a Ni mesh reflector at M1 in figure 1.

Graph 1 shows the temporal evolution of the CO_2 9P20 line, in reflection from the NaCl Brewster window of the millimeter-wave resonator. The FWHM is seen to be approximately 200ns as expected. The measured energy/pulse is typically .3-.6 Joules.

Graphs 2 and 3 show boxcar scans taken of far-infrared output using CH_3F and $^{13}CH_3F$, respectively. The measured peak power at 496μm is only 400W and the peak power at 1.2mm is even worse, 100W. In the former case, this is much less than the power levels obtained by Cohn et al. [10] at the MIT Magnet Laboratory using a very similar zigzag pumped system. Dr. Cohn is currently studying the differences between our two systems and will advise the PI shortly on ways in which to increase the efficiency. Meanwhile, a close study of the paper of Hirose and Kon, indicates that the polarization of the pump CO_2 laser's electric field is critical in obtaining strong FIR output. It is clear that for our laser system, the present orientation is not correct. Hence, the PI is currently in the process of remounting the diffraction grating of the CO_2 laser, and rotating the NaCl Brewster windows of the millimeter-wave laser (see figure 1). These modifications are necessary to allow the CO_2 laser output to enter the millimeter-wave resonator vertically polarized. This modification is expected to dramatically increase the output power and will be tested very soon.

After we obtain much stronger conventional output through the metal-mesh mirror M1, we will use the Fabry-Perot Interferometer (see Status Report #1) to measure the linewidth of the 1.2mm wavelength output. Furthermore, studies will be made of the output power as a function of CH_3F gas pressure, CO_2 laser gas mixture and flow rate, and output mesh reflectivity. After the completion of these studies, cavity-dumping will be attempted; the metal-mesh mirror will be replaced by a solid, flat total reflector at M1 and the output taken through W1, as shown in figure 1.

The PI has been very fortunate in obtaining a high-power, electro-optic Q-switched YAG laser on a long-term loan from Dr. George York of the Los Alamos National Laboratory. The laser, a Laser Photonics model YQL-102, is ideal due to its small size, large pulse energy (150mJ), narrow pulsewidth (16ns), high repetition rate (20Hz) and small time-jitter from an external trigger (+/-.5ns). An earlier plan to lease a much less expensive Laser Photonics model MYL-100 was scrapped when it was determined that it had a completely unacceptable time jitter of > 3 μs from an external trigger. The demonstration of high-peak power, cavity-dumped operation is expected to take place during the early summer.

Although much progress has been made, delays due to the malfunctioning CO_2 pump laser during the summer of 1989 pushed the anticipated date for project completion beyond the contract period. However, new funding for the project has been obtained under the National Science Foundation's Small Grants for Exploratory Research (SGER) program. The SGER grant, to commence in June of 1990, provides support for materials and supplies for an additional year.

Endnotes

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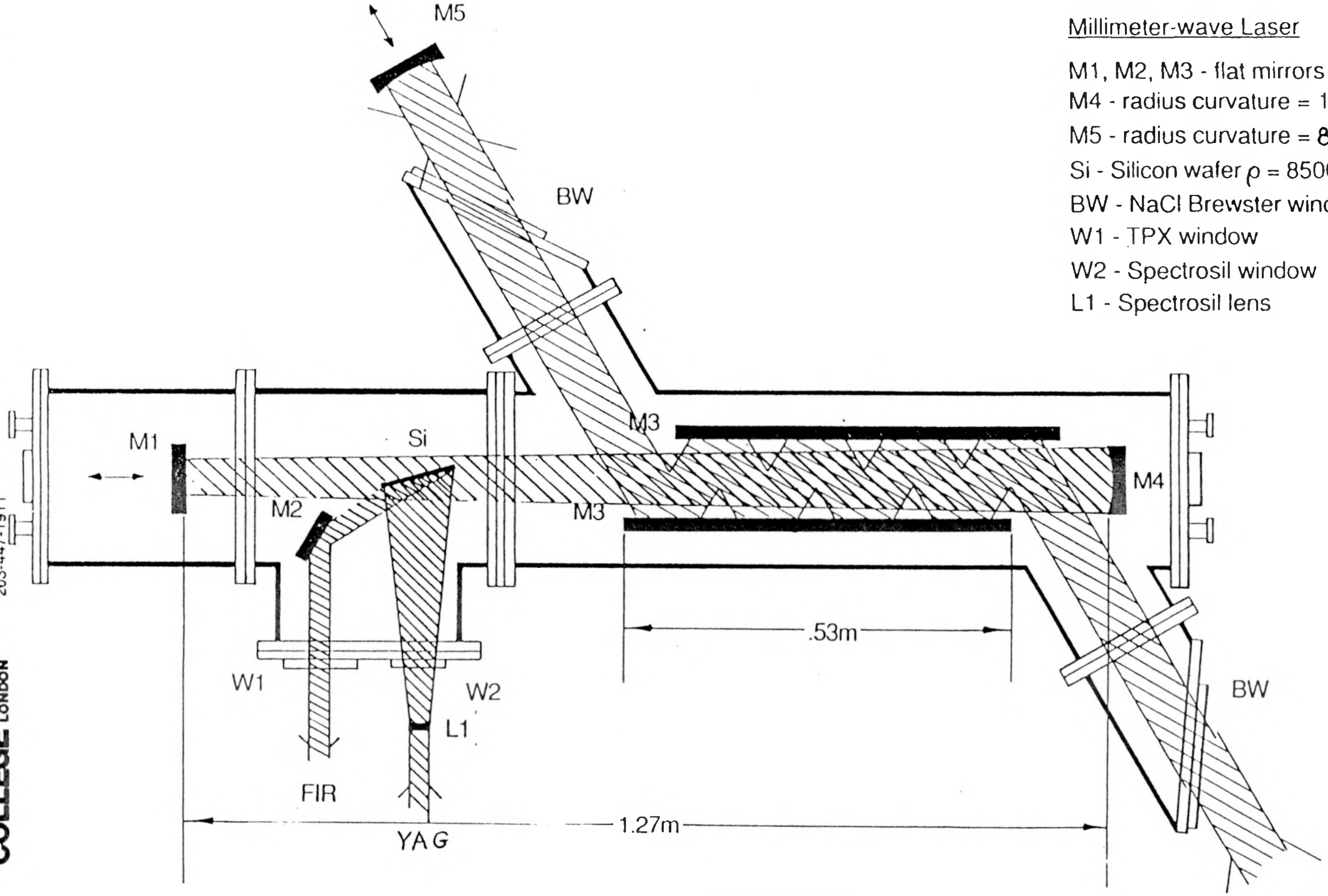
10. D.R. Cohn, T. Fuse, K.J. Button, B. Lax, and Z. Drozdowicz, "Development of an efficient 9-kW 496-µm CH_3F laser oscillator", Appl. Phys. Lett. **27**, 280 (1975); Z. Drozdowicz, R.J. Temkin, K.J. Button, and D.R. Cohn, "Efficient high-power CH_3F amplifier for a 496-µm cavity laser", Appl. Phys. Lett. **28**, 328 (1976).



<u>Millimeter-wave Laser</u>

M1, M2, M3 - flat mirrors
M4 - radius curvature = 1.7m
M5 - radius curvature = 8.8m
Si - Silicon wafer ρ = 8500 Ω·cm
BW - NaCl Brewster window
W1 - TPX window
W2 - Spectrosil window
L1 - Spectrosil lens

Figure 1 - Millimeter Wave Oscillator

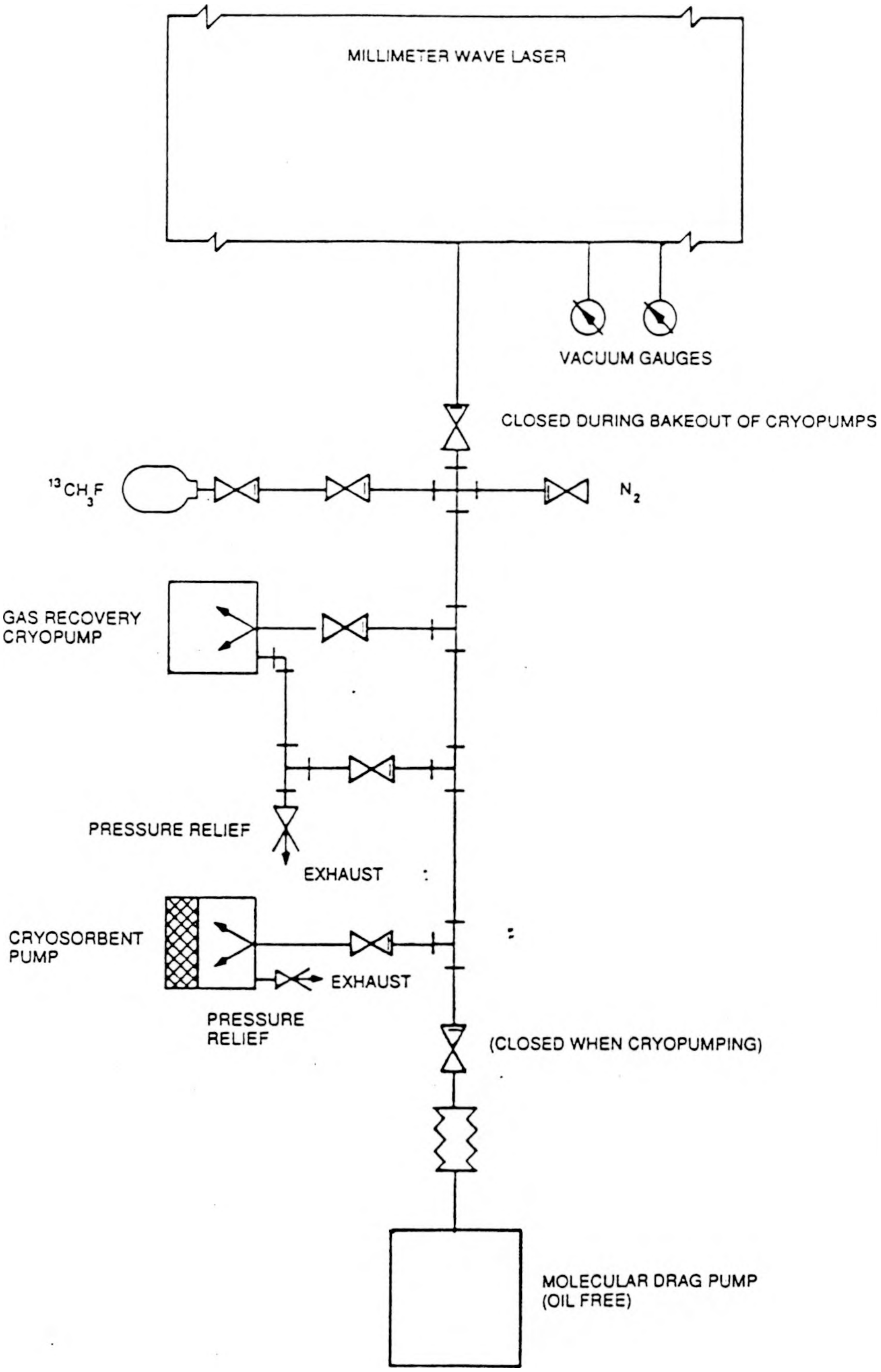
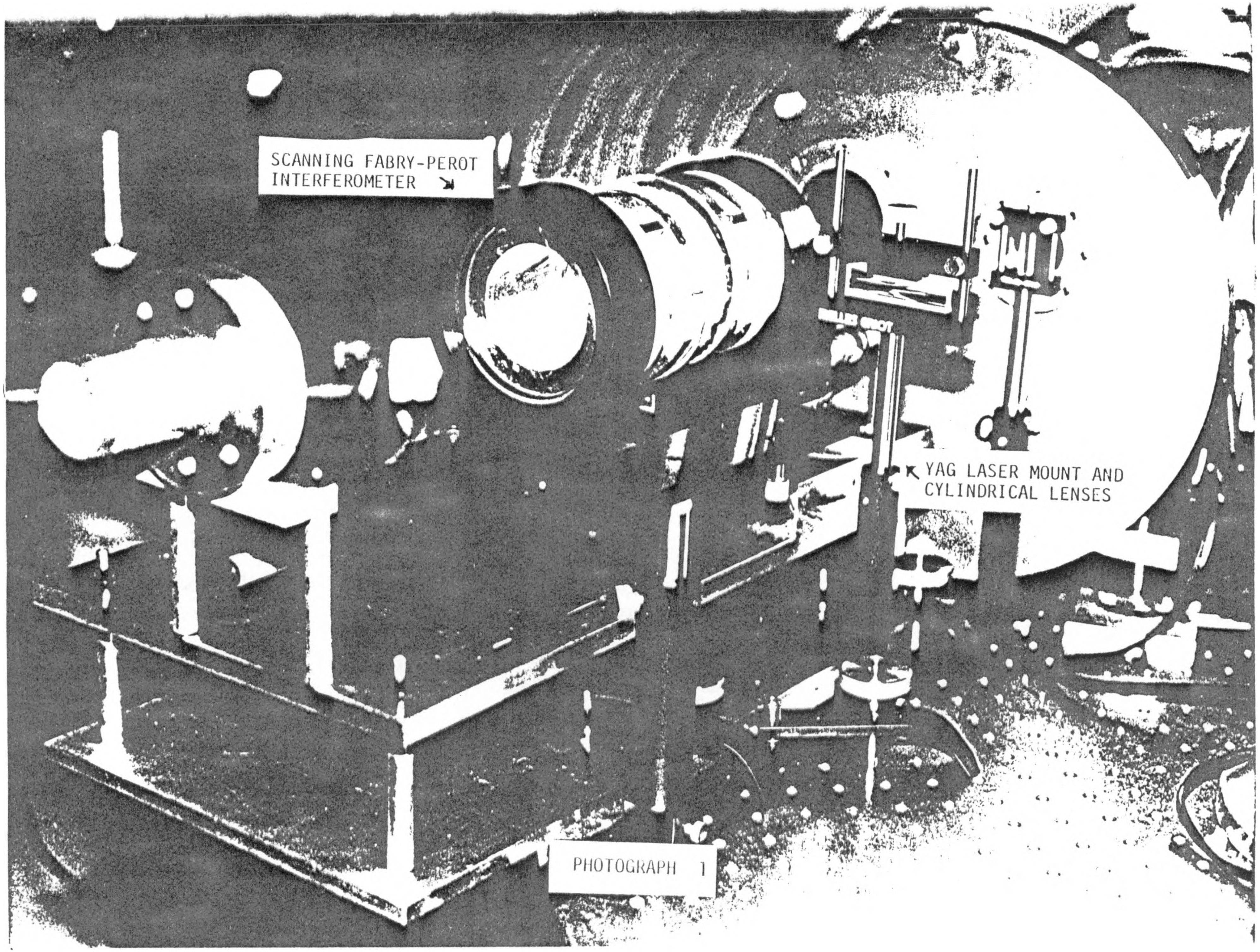


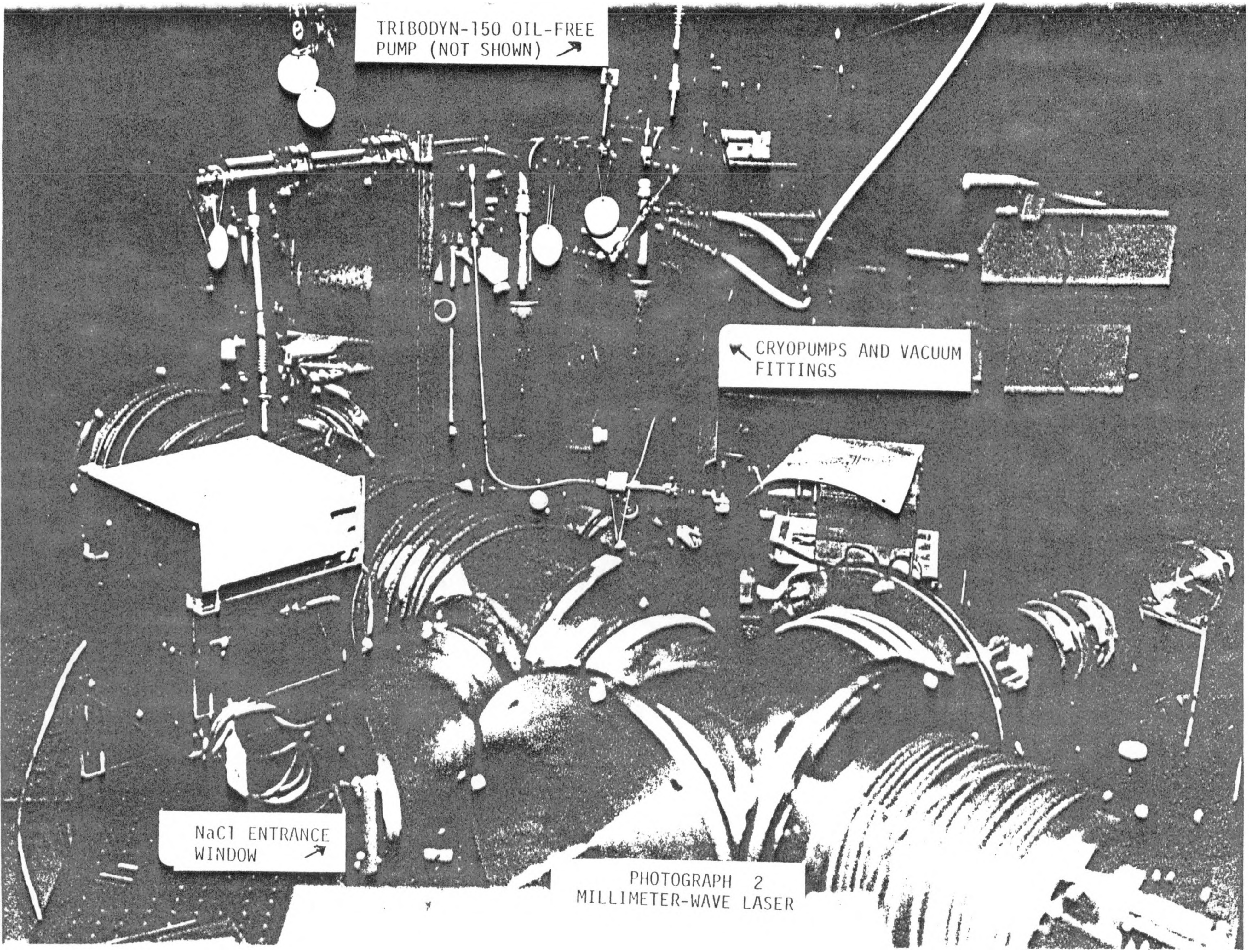
Figure 2 - Vacuum System



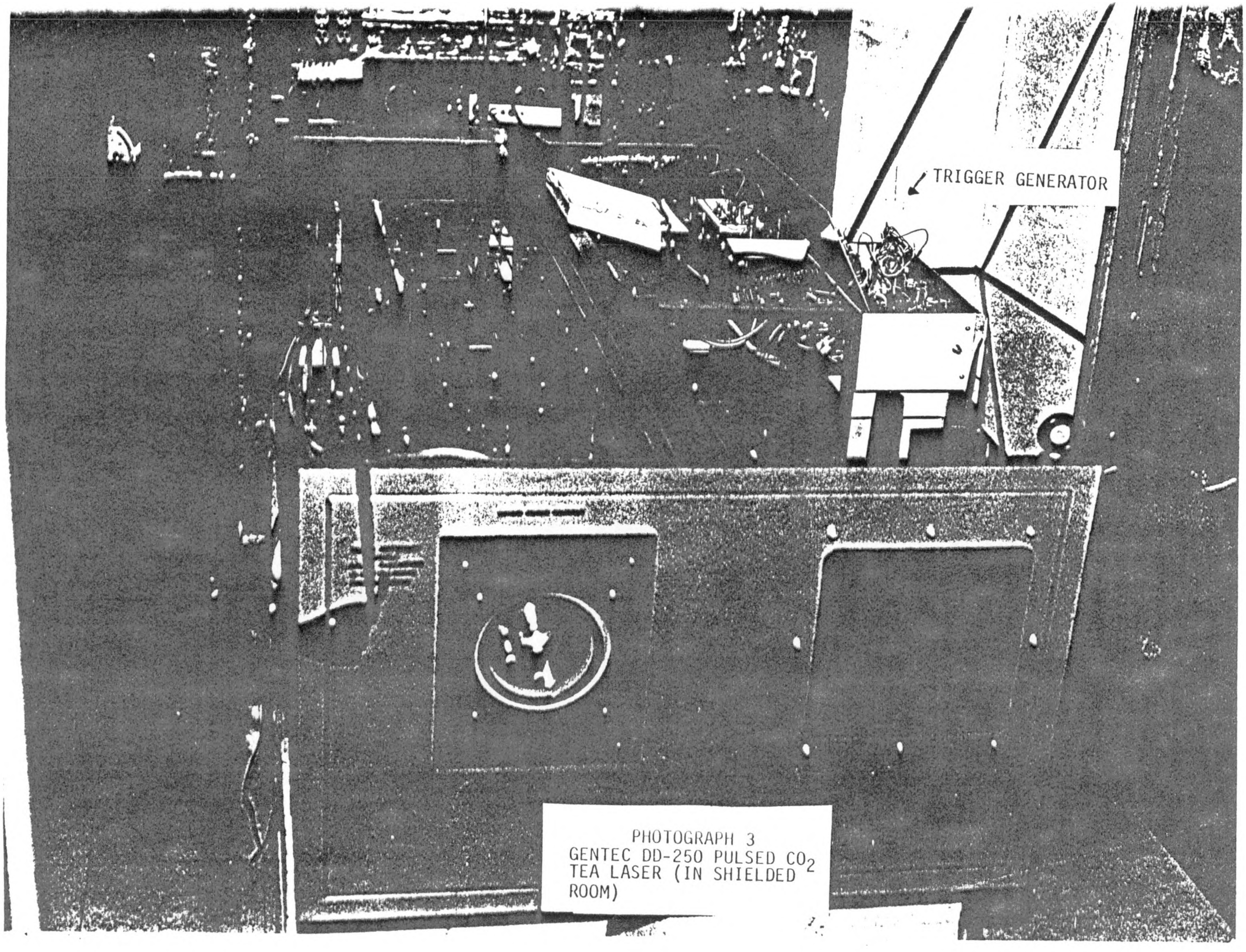
SCANNING FABRY-PEROT INTERFEROMETER

YAG LASER MOUNT AND CYLINDRICAL LENSES

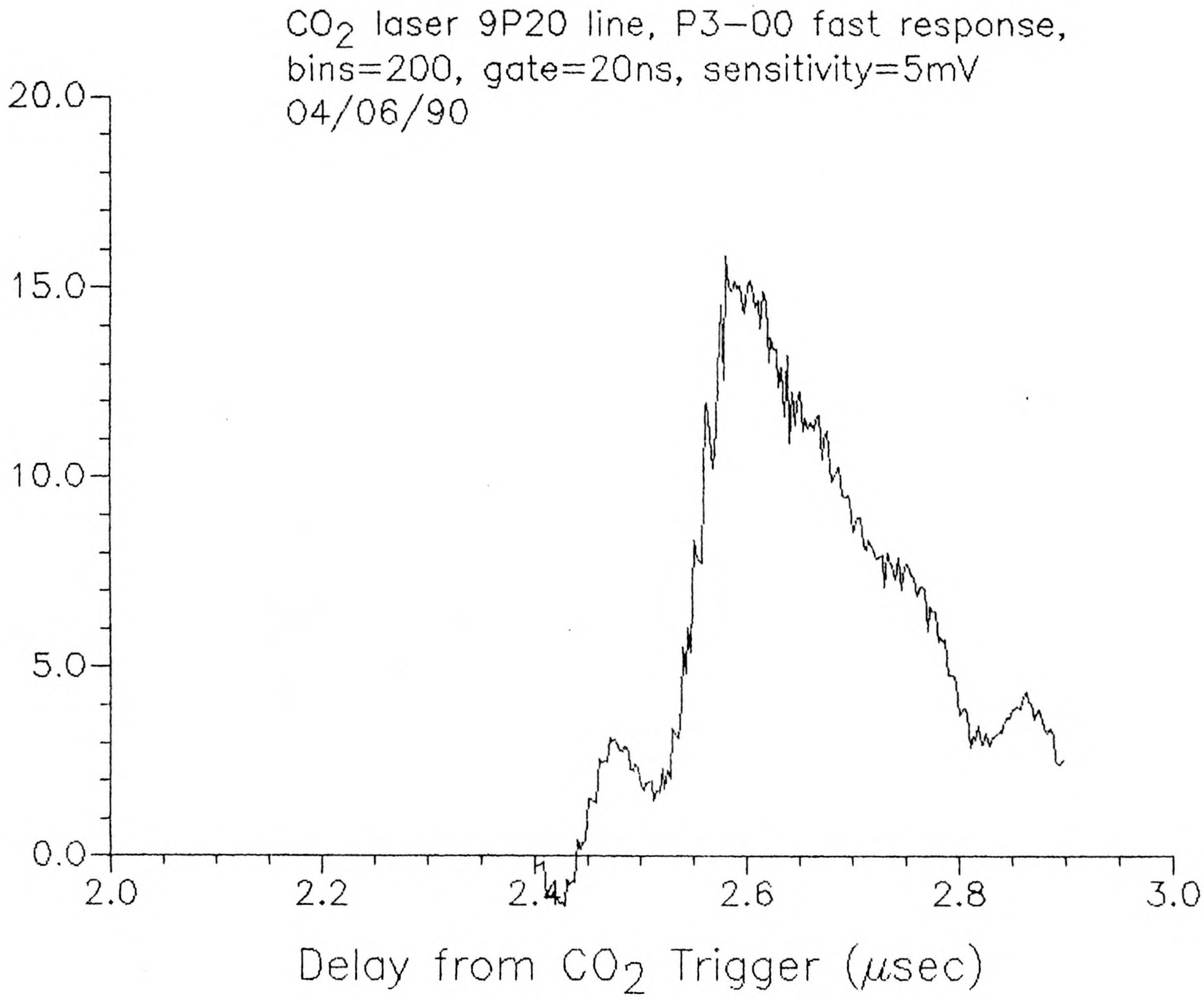
PHOTOGRAPH 1



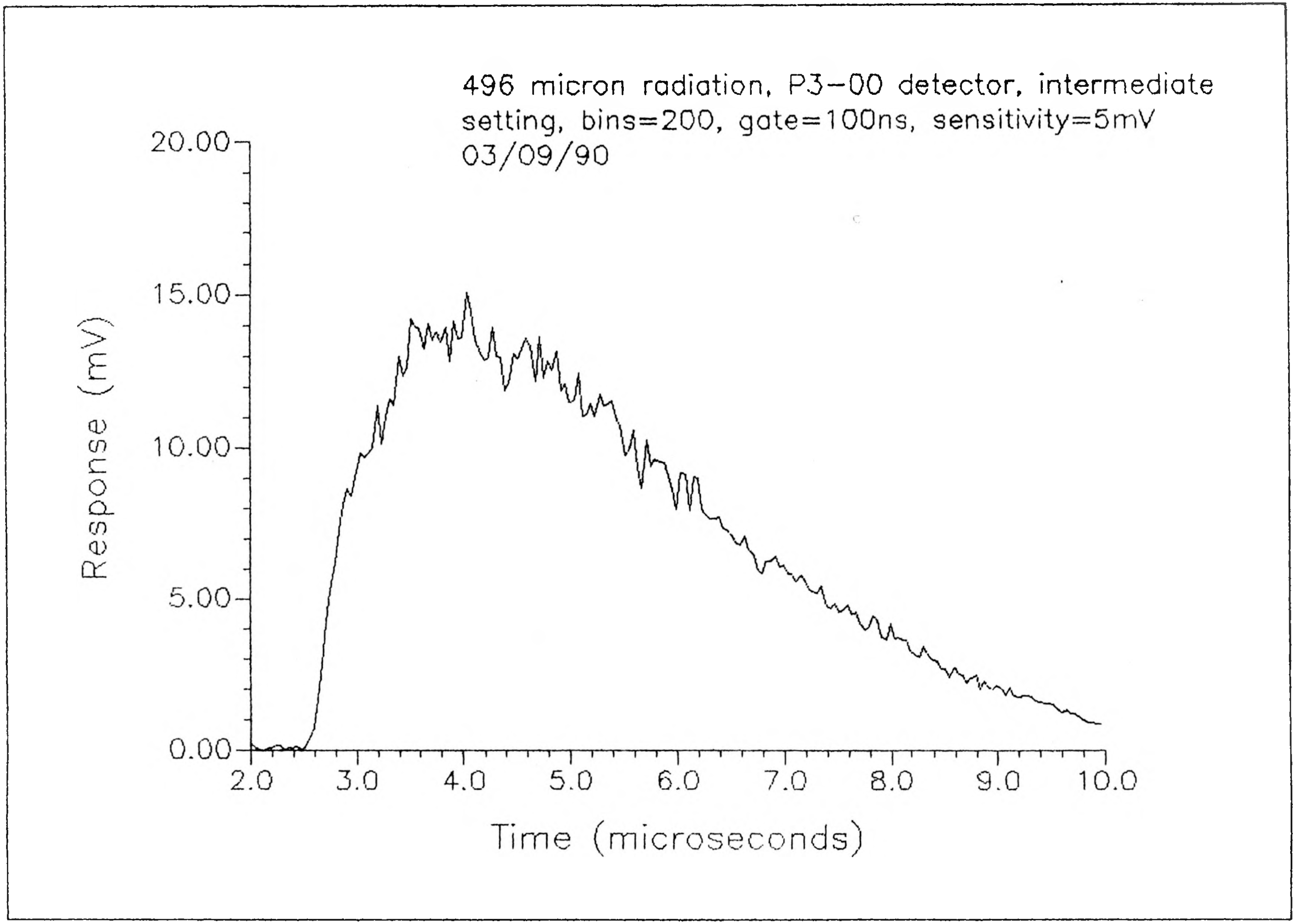
PHOTOGRAPH 2
MILLIMETER-WAVE LASER



PHOTOGRAPH 3
GENTEC DD-250 PULSED CO_2
TEA LASER (IN SHIELDED ROOM)

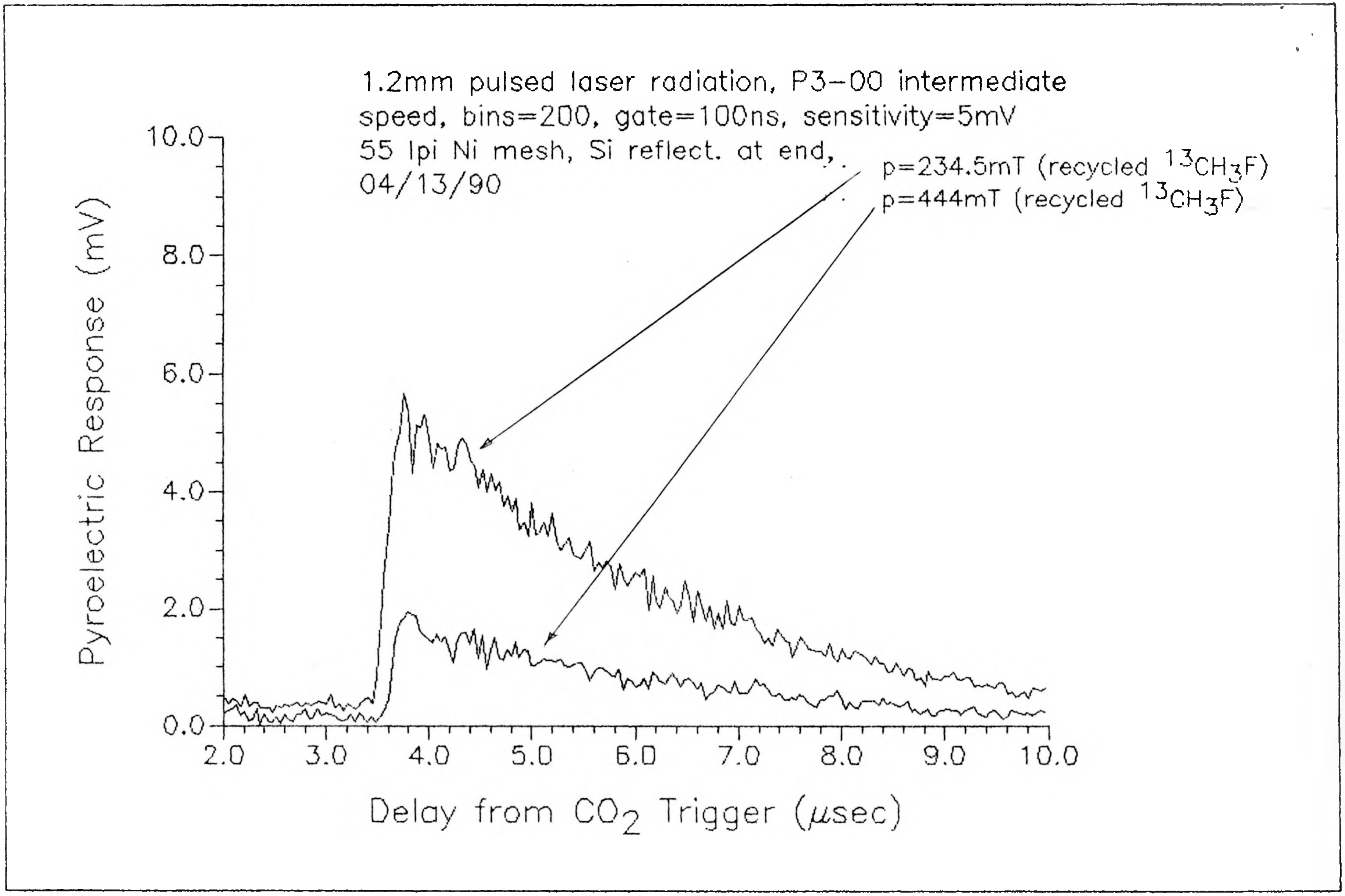

CO$_2$ laser 9P20 line, P3–00 fast response,
bins=200, gate=20ns, sensitivity=5mV
04/06/90
Pyroelectric Response (mV)
20.0
15.0
10.0
5.0
0.0
2.0
2.2
2.4
2.6
2.8
3.0
Delay from CO$_2$ Trigger (μsec)

Graph 1



496 micron radiation, P3-00 detector, intermediate
setting, bins=200, gate=100ns, sensitivity=5mV
03/09/90
Response (mV)
20.00
15.00
10.00
5.00
0.00
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Time (microseconds)

Graph 2


1.2mm pulsed laser radiation, P3–00 intermediate
speed, bins=200, gate=100ns, sensitivity=5mV
55 lpi Ni mesh, Si reflect. at end,
04/13/90
p=234.5mT (recycled $^{13}CH_3F$)
p=444mT (recycled $^{13}CH_3F$)
Pyroelectric Response (mV)
0.0
2.0
4.0
6.0
8.0
10.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
Delay from CO_2 Trigger (μsec)

Graph 3