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A HIGH-ENERGY D_2O SUBMILLIMETER LASER FOR PLASMA DIAGNOSTICS

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A narrow line optically pumped D_2O laser operating at 385 μm has delivered more than 5 J in pulses longer than 3 μsec using a large aperture unstable resonator cavity design. Pulse levels which are > 1 J and 1 μsec are necessary for a single shot ion temperature measurement by Thomson scattering in large tokamaks. Experiments have, for the most part, been conducted at a 360 J, 5 μsec CO_2 laser pump level where high efficiency (~ 2.5 J at 385 μm) has been obtained. These are the highest energies reported to date in the far infrared. In addition, the pulse length has been extended beyond the vibrational relaxation time.

Key words: D_2O, Submillimeter laser, Far infrared Laser, Plasma Diagnostics, Pulsed, Thomson scattering.

I. INTRODUCTION

The need for coherent radiation in the far infrared (FIR) for plasma diagnostics has often been the primary reason for developing high power laser systems in this region of the spectrum. Most widespread has been the development and use of CW FIR systems for use in plasma interferometry, Faraday rotation, and coherent scattering from superthermal fluctuations. The development of a pulsed FIR laser system to be used to determine the ion temperature via Thomson scattering from thermal level fluctuations has been much slower owing to the size and complexity of the system necessary to achieve this. Because of its efficiency and relatively narrow bandwidth, the optically pumped D_2O laser operating at 385 μm has shown promise[1] as a source for this diagnostic. This wavelength represents a good compromise between refraction effects, plasma noise background, spatial resolution, and mechanical complexity. It is generally recognized[2,3] that for a plasma of interest for fusion, a laser source producing more than 1 J in a pulse longer the 1 μsec and a power level of about 1 MW would be necessary to provide a sufficient signal to noise ratio for a single shot measurement. We have developed a laser fulfilling these requirements using a system which is relatively simple for its size. This system has produced the highest energy (~ 5 J) in the FIR reported to date as well as the highest efficiency.

II. LASER CONFIGURATION

The FIR laser system, which is shown in Fig. 1, consists of a CO_2 pump laser, a CO_2 injection laser used to lock the pulsed pump laser to a single frequency, an FIR laser, and the instrumentation necessary for diagnostic purposes.

A. The CO_2 Pump Laser

The pump laser consists of four Lumonics 620, UV preionized (flashboard type), CO_2 TEA laser units (20-cm x 25-cm aperture). Two of these units are used in a grating tuned unstable ring resonator,[4] set to operate on the R22 (9.26 μm) transition. The remaining two units are used as amplifiers. The unstable ring resonator cavity, which has a magnification M=5, is comprised of a concave (CC) spherical copper mirror (R=10 m) with a 10-mm central hole, a 50-mm diameter flat 135 ℓ/mm master grating (G), a plane copper relay (R) mirror and a convex (CX) spherical copper mirror (R=2 m) placed 4 m from mirror CC in a confocal arrangement. A 25-cm NaCl window is used to pass the output beam. The output energy is uniform across a 22-cm diameter × 20-cm wide "race track" beam shape, with the exception of the shadows of the grating (5-cm diameter) and its three narrow "spider arms" support structure. The effective beam area is ~ 400 cm^2. Each unit could be fired independently to optimize the gain history and produce pulses close to the desired shape.

B. The CO_2 Injection Laser

Because more than enough pump energy was available, peak efficiency was not required. Hence, for simplicity, a CW injection laser was used rather than a tunable pulsed laser which has the potential of pumping the FIR laser more efficiently.[1] The injection laser was an Apollo Lasers #560 fitted with a flat 65% reflectivity ZnSe output coupler and a flat 135 ℓ/mm master grating mounted on a piezoelectric translator. An aperture was placed on a microscope translation stage between the ZnSe Brewster window and the grating. These improvements were necessary to ensure single line operation on 9R22 as well as fundamental mode operation and pointing stability. The output of the laser immediately impinges on a near-Brewster-angle CdTe plate used as a beam combiner for a HeNe alignment beam and as a beam splitter to provide a signal from a room temperature epitaxial HgCdTe fast detector (Labimex). This signal was used to ensure single mode operation before a laser shot. A high purity output of 16-19 W was obtained with this laser. This power was marginally adequate to ensure that the pump pulses were reliably frequency locked during their entire pulse (see Fig. 7a, right). Pulsing the injection laser (50-sec pulse) using a capacitor/step-up transformer supply[5] had an adverse effect in the large volume system presumably due to the low lying modes allowed to come slightly above threshold when the laser is pumped this way.

C. The Far Infrared Laser

The pump beam is directed by two 12" diameter diamond machined flat mirrors into the FIR cavity. Located directly behind the NaCl pump input window is the rear element of the 3.6 m FIR unstable cavity. This consists of a 25.5-cm x 36.5-cm free standing wire grid, composed of 25-μm diameter tungsten wires spaced 100 μm apart. This grid acts as plane reflector (95% reflectivity) for 385-μm radiation and as a 75% transmitting input coupler for the pump beam (Fig. 2). The grid transmission at the pump wavelength is dictated only by geometrical effects and is the same for all polarization orientations relative to the wires. Since the D_2O laser at 385 μm shows a larger gain for polarization perpendicular to that of the pump, the grid was placed with the wires perpendicular to the pump polarization.

The feedback element is a 12-cm diameter, convex copper mirror (R=15 m). With a geometrical magnification of 2.2 and a 30-cm free aperture, this cavity produces a diverging output. A 0.75-mm thick Teflon™ CO_2 beam dump is placed in front of the convex mirror at a slight angle in order to eliminate pump beam feedback which would have an adverse effect on the pump pulse shape. A biconvex polyethylene lens serves as the output window and focuses the divergent beam at a distance of 1.2 m.

An unstable ring resonator geometry similar to that of the pump oscillator was tried because it has the potential of reduced linewidth and eliminates the necessity for a dump. However, because of the limited space available for the extra mirrors, the output mode and energy were degraded with only a slight improvement in bandwidth. This configuration was not investigated fully and will not be further discussed.

D. Instrumentation

The portion of the CO_2 laser output reflected by the NaCl window is used to monitor the pump laser. Power and energy are measured simultaneously with a photon drag detector (D) and a thermopile (T), respectively.

The focused FIR output beam first impinges on a wire grid (25 μm W wire, 75-μm spacing) beam splitter (BS) which directs most of the FIR energy to a thermopile (T). The remaining output is collimated by a negative lens to form a 4-cm diameter beam which impinges on a grating (G) and concave mirror (0.5 m F.L.) placed in a Czery-Turner spectrograph configuration. This arrangement separates the individual laser lines which can be monitored with individual point contact detectors or thermopiles for quantitative measurements, or with steel wool or encapsulated liquid crystal for alignment (without beam splitter in this case). The point contact detectors are standard encapsulated W-Si diodes placed in 4-mm microwave mounts. They provided sufficient sensitivity when biased, so that the radiation needed to be attenuated further with approximately 20 layers of manilla folder material.

The FIR thermopile is a Scientech 3600 head. An efficiency of 0.5 was assumed[6] in determining absolute energies. All other thermopiles were Melcor

Peltier cells. A large thermopile was constructed to determine the total energy in the CO_2 pump beam. The CO_2 laser pump monitor was calibrated with respect to the large one. The energy signals were directed to a chart recorder. Absolute calibration of these signals was done by electrical substitution in the pulsed mode (i.e., a known capacitor was discharged through a small heater wire glued on the thermopile).

The fast signals (photon drag and point contact) are transported to a screen room through ~ 15 m of RG 253/U low loss semi-rigid cable which is very effective in reducing noise pickup. The signals are monitored with two Tektronix R7912 transient digitizers. The system risetime as evidenced in Fig. 7(e) and similar traces is less than 1 nsec (CO_2 laser not injection locked, FIR laser "superradiant," i.e., mirrors grossly misaligned) which is consistent with the 500 MHz bandwidth of the system.

Most of the time evolution of the signals are displayed in the "scope mode" (familiar to most readers) rather than the digitized mode, as the appearance of the digitized signal is very dependent on software parameters. The digitally reduced time signal can yield a cleaner looking trace than the corresponding oscilloscope trace. The digitized traces, however, can be Fourier analyzed and give precise information as to the frequency content of the laser pulses (for beat signals larger than ~ - 20 dB).

III. EXPERIMENTAL RESULTS

Experiments were originally conducted with the CO_2 pump laser operating in the usual gain switched spike/low power tail fashion (power spike >> 10 x power tail) with the hope that injection locking and delayed firing of the multiple CO_2 laser units would stretch the pulse. These pulses were produced with a laser gas mix typically consisting of 70% He%, 23% CO_2, and 7% N_2.

This method did not give satisfactory results. Not much widening (from 150 nsec to ~ 200 nsec) of the spike occurred as the two oscillator units were delayed by up to ~ 1 μsec. Delaying by more than that or delaying the amplifiers resulted in pulses that were not reproducible.

In this first phase of the experiment, FIR pulses such as shown in Fig. 3a were obtained. Although they evidenced a fairly narrow band, compared with a superradiant pulse shape,[7] the modulations were not reproducible from shot to shot and did not correspond to longitudinal mode beating. These 1 J ~ 5 MW pulses obtained with a 250 J pump pulse (2 units CO_2 oscillator only, 3 MW/cm^2) and D_2O pressure in the range of 4 to 8 Torr produced occasional air sparks (Fig. 4) at the focus of the output window lens. It is presumed that since the FIR laser power and energy were quite reproducible, these sparks were initiated by ionization around dust particles. Raising the pump energy (up to 450 J) and varying the D_2O pressure did not significantly increase the FIR energy for these "short" high intensity pump pulses. By reducing the pump energy to 60 J (1 CO_2 oscillator unit, 0.72 MW/cm^2), almost single mode 250 mJ, 385 μm pulses were obtained (Fig. 3b) for D_2O pressures ~ 1 T. The remaining oscillations at 39 MHz were very coherent, due to an additional longitudinal mode. This shows that frequency pulling existed[8] as the empty cavity mode spacing is 41.7 MHz. In the following experiments, whenever mode beating occurred, it was observed at 39 MHz or at multiples of this frequency independently of FIR laser parameters such as pressure and pump intensity.

Interesting pulse shapes for Thomson scattering were obtained when the CO_2 concentration in the pump laser was reduced to 1-2% (e.g., 89% He, 2% CO_2, and 9% N_2). Under these conditions, direct pumping of the CO_2 was minimal so that the gain switched spike can almost be suppressed. Also, the pulse can be stretched because the stored energy in the N_2 molecules can only "trickle" to the CO_2 molecules. It was critical that the CO_2 concentration be quite low, as a slight increase of concentration caused pronounced relaxation oscillation throughout the pulse. Also, with increasing concentration one quickly obtained the usual gain switched spike.

As the gain was sharply reduced by this method (although not the stored energy), laser oscillation did not take place when only one unit was fired. A compromise between reduction of the gain switched spike and lengthening of pulse was found when the firing of the two oscillator units was delayed by 1 μsec. The amplifiers were fired at the same time as the second oscillator unit to produce pulses similar in shape to those of the oscillator. A typical oscillator-only (360 J) pulse is shown in Fig. 7a (right). The general pulse shape was very reproducible within a run but less so from day-to-day, as the peak of the spike (1 to 2 x peak of tail) was very dependent on CO_2 concentration. These pulses were single frequency except that generally an extra mode (beat freqency ~ 19 MHz corresponding to round trip time of cavity) appeared for ~ 1.5 μsec, 2-3 μsec after the beginning of the pulse or later. We believe that this could be completely eliminated either by increasing the injected single mode power or by adjusting the pulsed cavity length.[9] This is because this effect could be eliminated when the grating was detuned, thus changing the effective cavity length. However, this method of adjusting the equivalent Fresnel number of the pulsed cavity in order to match the injected beam had the adverse effect of reducing the energy output of the laser.

The FIR laser energy and efficiency were greatly enhanced when pumping took place with these lower intensities and longer pulses. Figure 5 shows the dependence on pressure of the FIR energy output at 385 μm for various pump levels corresponding to oscillator alone, oscillator + 1 amplifer, and oscillator + 2 amplifier units. To produce these curves, we took 75% as the percentage of 385 μm emission in the FIR output pulse. This was measured to be ~ 70-75% regardless of the pump energy and power for the range investigated with the balance of the energy being emitted at the 359 μm cascade transition exclusively.

Assuming 69% of the CO_2 laser energy was transmitted into the FIR laser (NaCl window T=92%, pump input coupler T=75%), then the maximum efficiency of the FIR laser has been measured to be 42% at 3 Torr, 360 J pump, and 51.5% at 4 Torr 530 J. The maximum efficiency E_{max} obtainable (100%) is given by the Manley-Rowe limit of $E_{max} = \nu_{FIR}/\nu_p$ for a Raman laser. Considering the excited volume (144 ℓ), at 3 Torr (4 Torr), 2.5 J (4.5 J) out of a possible 7.5 J (10.2 J) is emitted while these molecules are pumped with 248 J (366 J) out of 320 J (426 J) which can at most be absorbed by the number of molecules present. These numbers are valid if the molecules are excited only once during a pulse. However, the characteristic pulse shape (Fig. 7a) of the FIR laser where, after an initial peak, the power reaches a plateau even though the CO_2 laser power drops, is a sign that this power is limited by vibrational relaxation and that the molecules are indeed recylced. The time evolution of the tail of the pulse also agrees well with the 1 μsec Torr relaxation time constant measured for several (000) - (010) transitions.[10]

The far field beam profile of the D_2O laser was measured at the focus of the output window/lens when the laser was pumped at the 360 J level. A Molectron 32 element pyroelectric array gave single shot profiles (Fig. 6a). The tctal energy inside a given radius, "energy in the bucket" was measured with a thermopile apertured by an iris diaphragm (Fig. 6b). The smooth curves are ideal Airy functions for the oscillator magnification with their scaling adjusted to fit the data. It must be noted that since the D_2O laser is not pumped uniformally and that the pumped area does not correspond to the output area, a disparity between the ideal Airy pattern and the actual profile is expected.[11]

Figure 7 shows some typical pulse shapes for the D_2O laser and the 360 J pump laser. The shorter sweep times were triggered 4 μsec into the pulse. The smoothness of the traces, especially those at the shortest sweep times (Fig. 7d), shows that the pulse bandwidth is very much reduced over that of an uncontrolled laser (Fig. 7e). The signals of Fig. 7b are shown in the digitized mode in Fig. 8 along with the Fourier transform of the signals. Often an additional longitudinal mode at 78 MHz is observed, and occasionally at very low level, another at 117 MHz. A 19 MHz beat signal is also observed, together with the usual 39 MHz beat when that oscillation is present in the CO_2 laser.

From these video signals, one can observe that the spectral width is much smaller than 100 MHz FWHM. The modulation which can be observed on the FIR signals are similar to those observed from the 385μm D_2O laser used for Thomson scattering on Alcator C.[12] It must be noted, however, that the linewidth much below the peak cannot be estimated by video methods. These components of the spectrum falling outside a ~ 100 MHz band can mask the scattered signal unless stray light is eliminated. In this case as the D_2O laser is pumped by a CO_2 laser operating at its line center (low pressure injection laser) which corresponds to an offset of 320 MHz with respect to the D_2O absorption line center, the FIR radiation at 385 μm is expected, for these pump intensities, to originate principally from the stimulated Raman transition.[1] A line center component of the FIR laser, ~ 320 MHz beat signal,[13] was actively looked for on short sweep times but never observed, thus placing an upper limit of -20 dB on this component. At these low pump intensities, the low level linewidth (-60 dB) is expected to be within acceptable limits[14] for a scattering geometry which includes reasonable light dumps.

IV. SUMMARY AND CONCLUSIONS

We have described an experiment which has produced narrow line FIR laser pulses with energy up to 5 J. For the first time, energies > 1 J and pulsed FIR laser operations for times longer than the vibrational relaxation time have been observed.

When pumped at the 360 J level, the complexity of the laser system is greatly reduced and the FIR laser produced reliable 2.5 J pulses of adequate bandwidth for Thomson scattering. The system performance can probably be enhanced by using a more uniform pump illumination, using the full volume available in the FIR laser, and using a tunable injection laser. This last point might increase the complexity of the system but would prove useful in a particular scattering system, if the stray light needs to be reduced by an N_2O notch filter.[14]

V. ACKNOWLEDGMENT

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FIGURE CAPTIONS

FIG. 1 FIR laser system. BS-Beamsplitter, BD-beam dump CC-concave mirror, CX convex mirror, D-fast detector, G-Grating, MG-metal grid, R-relay mirror, T-thermopile, W window/lens.

FIG. 2 FIR laser back mirror made of wound tungsten wire.

FIG. 3 Pulse shapes. FIR-left; CO_2-right. a) 250 J CO_2 laser pump; b) 60 J CO_2 laser pump

FIG. 4 Air spark produced by ~ 1 J pulses as in Fig. 3a.

FIG. 5 FIR laser energy vs pressure for lon pump pulses (> 3 μsec).

FIG. 6 D_2O laser beam profiles in the far field a) profile vs radius; b) "Energy in the bucket." Smooth curves are Airy functions for oscillator magnification.

FIG. 7 FIR (left) and CO_2 (right) pulse shapes a) - d) normal injection locked pump pulses, e) "superradiant" FIR pulse.

FIG. 8 Digitized and Fourier analyzed signals as shown in Fig. 7b.

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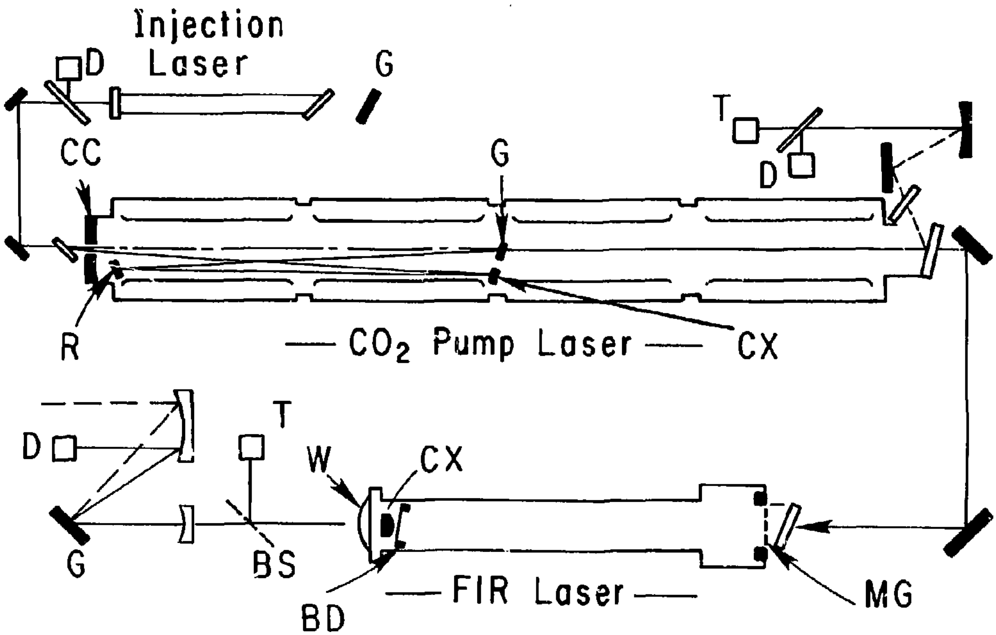

Fig. 1

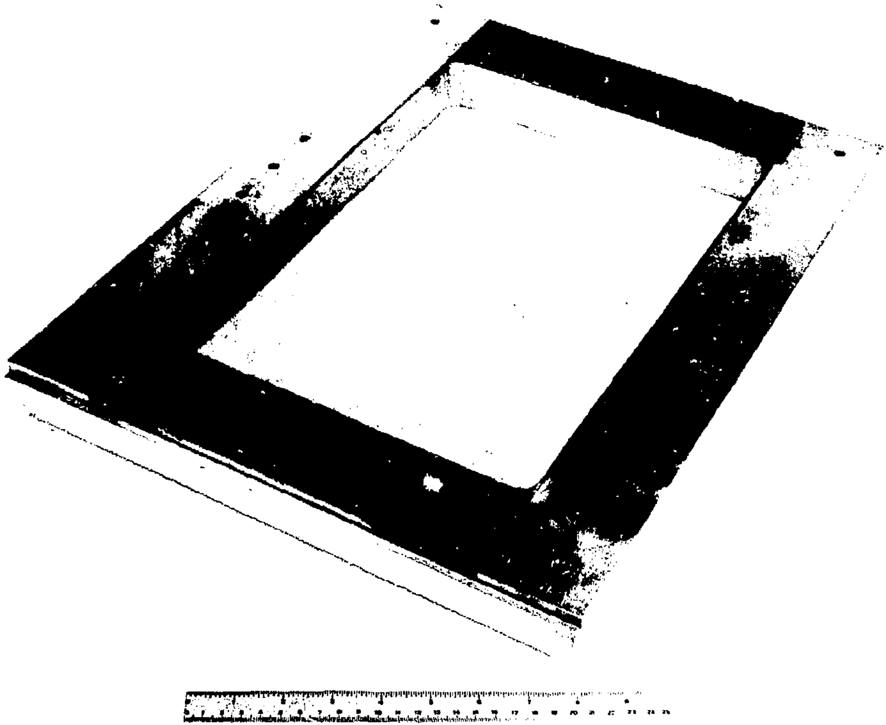

Fig. 2

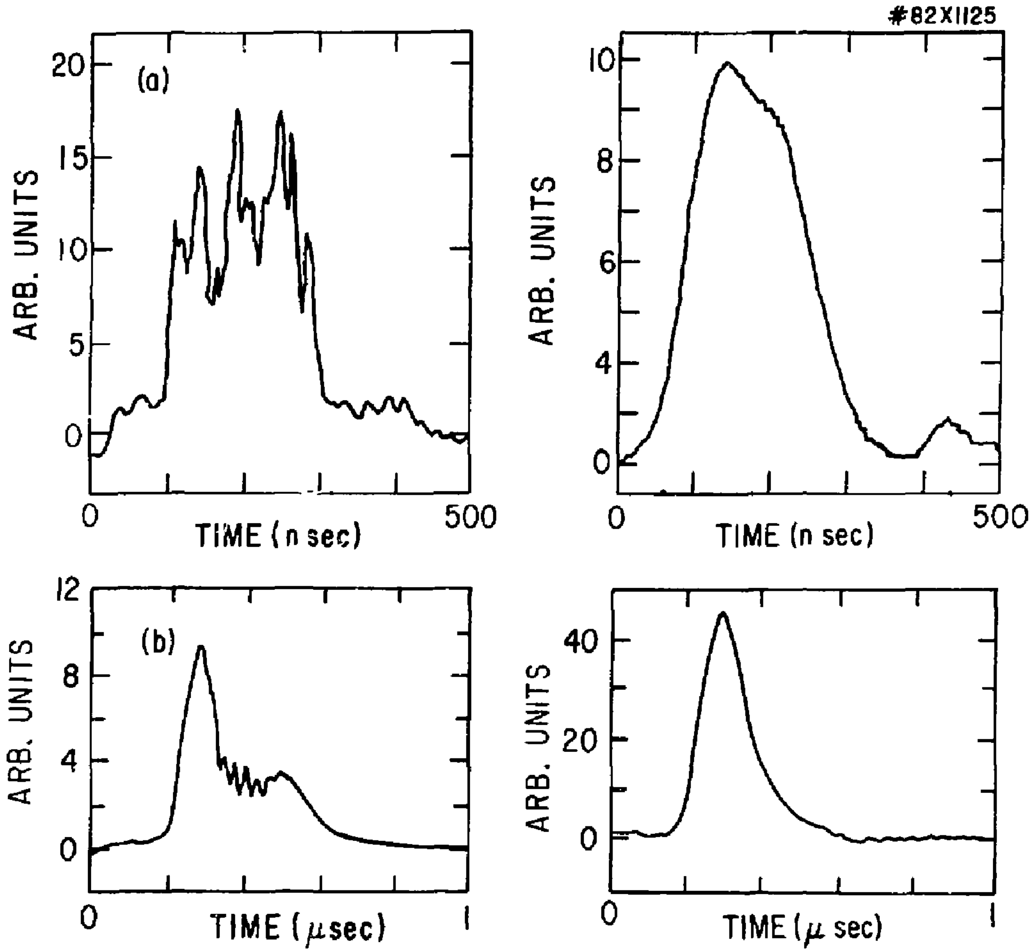
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Fig. 3

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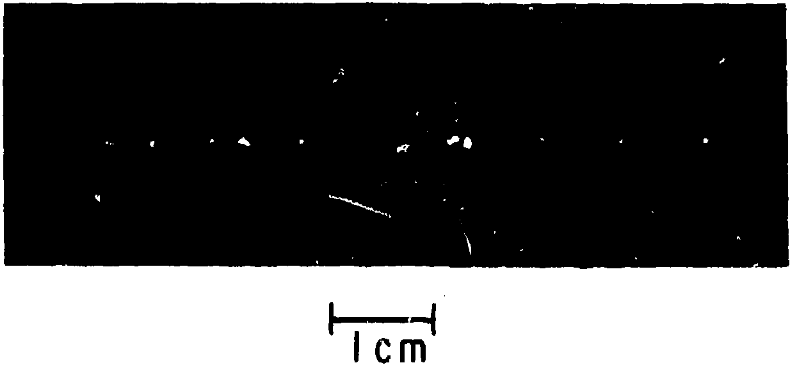
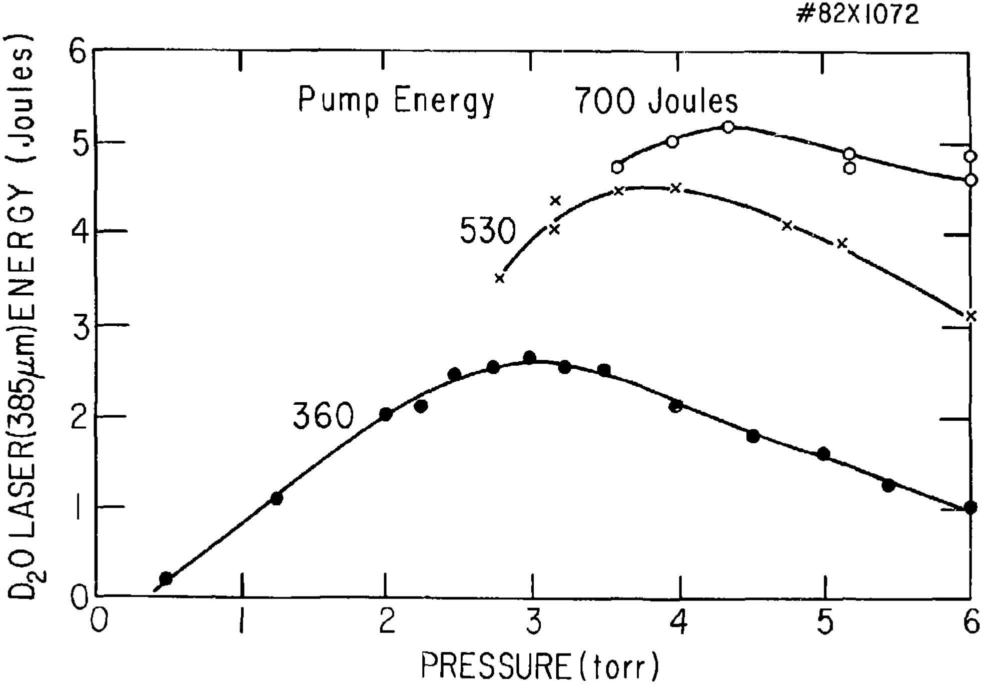


Fig. 4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6

Fig. 5

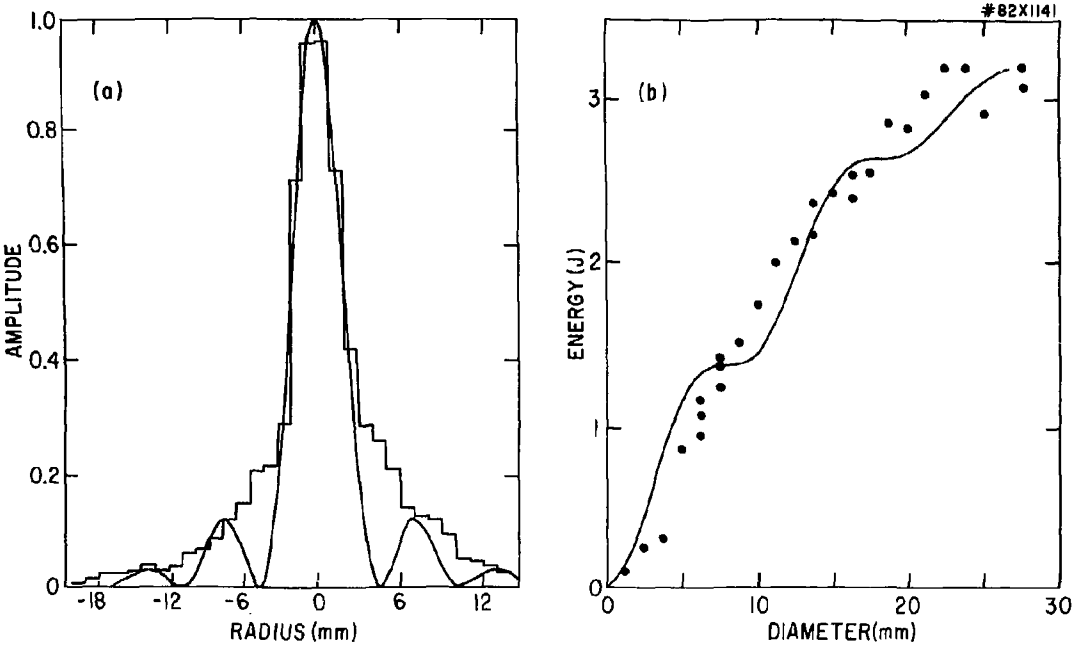

Fig. 6

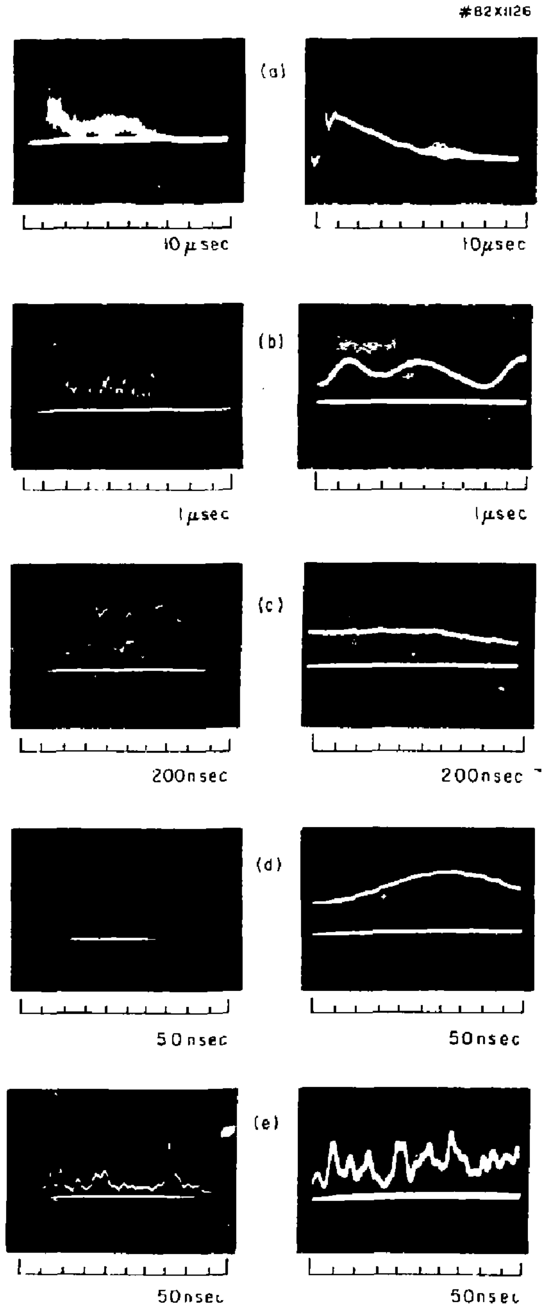
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Fig. 7

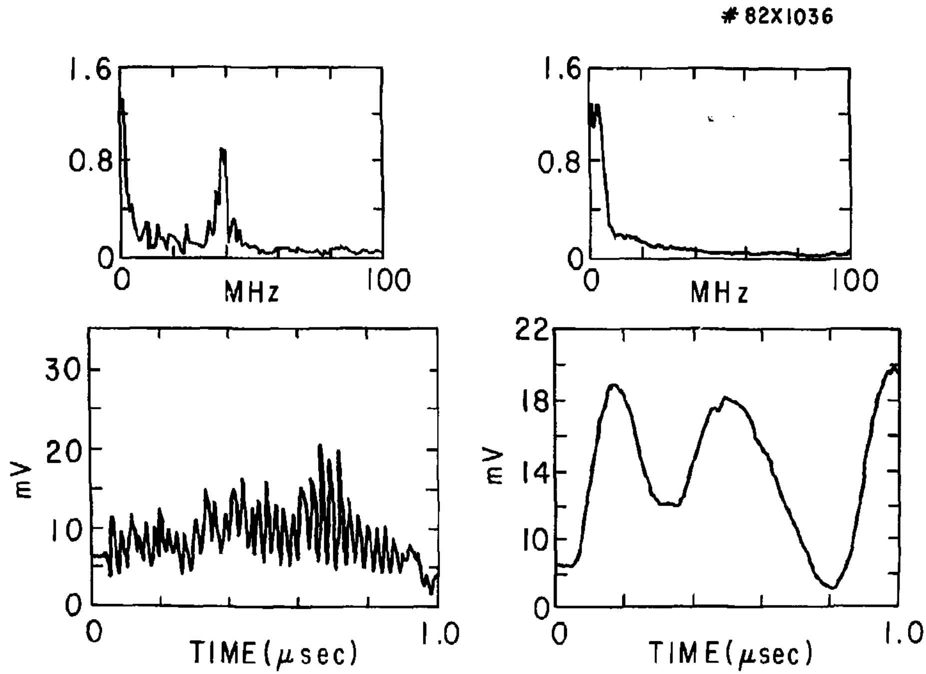
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Fig. 8