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ABSTRACT

The generation of single-mode pulses of far-infrared (FIR) radiation of duration up to 700 nsec at 385 μm has been achieved using a confocal unstable resonator with $D_2O$ as active medium. Future volumetric scaling to the power levels necessary for measuring ion temperature in tokamak plasmas by Thomson scattering appears encouraging. A comparison between the performance of the unstable resonator and two hemispherical resonators is reported.

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* killed in a mountaineering accident on 30/4/1981.

## INTRODUCTION

The determination of plasma ion temperature in tokamaks by collective Thomson scattering at FIR wavelengths will require lasers with the following characteristics: wavelength ~ 100 - 400 µm, power ⩾ 1 MW, pulse duration ⩾ 1 µsec and linewidth ⩽ 50 MHz [1].

It is generally recognized that unless new, powerful FIR lines are found the optically-pumped $D_2O$ laser at $\lambda$ = 385 µm is presently the most promising candidate. To achieve the required power levels a powerful $CO_2$ pump laser chain is necessary and the $D_2O$ laser has to be scaled to large volumes. The line width requirement can only be met by single-mode operation. The unstable resonator is of great interest as it can be used to extract energy from a large excited volume whilst preserving good mode control.

Long pulse operation is important for signal statistical reasons in the detection process of the scattered radiation.

In this paper we compare the performance of an unstable resonator with that of two hemispherical resonators. We report the production of single-mode pulses of duration up to 700 nsec FWHM, at 385 µm.

# APPARATUS

## The $CO_2$ Laser

The $CO_2$ laser system used to optically pump the $D_2O$ has been described in detail elsewhere [2],[3],[4], and is shown schematically in Fig. 1. It comprises a hybrid oscillator and an amplifier chain. The half-symmetric resonator is tuned by means of a plane diffraction grating and the cavity length, 225 cm, is stabilised against temperature changes by opposed invar and stainless steel rods [5]. Two gain sections are employed, a TEA section of dimensions 50 x 5 x 5 cm and a low-pressure pulsed section working at a pressure of 10 torr.

The oscillator output, ~130 mJ in a beam of diameter 0.7 cm, has only one longitudinal and one transverse mode. This is amplified by a single pass through 3 TEA sections, each twice as long as the oscillator section but otherwise the same. Two gas cells, each of length 20 cm, are used to prevent the occurrence of parasitic oscillations in the 10 μm bands. In each cell equal concentrations of $SF_6$ and $C_4F_8$ are used at pressures of about 10 torr. The transmission spectrum of this gas mixture is given in Fig. 2.

The maximum output measured on the 9R(22) line was ~20 J in a beam of diameter 4.5 cm. The output was plane polarised to better than 95% with the E vector horizontal. Pulse durations within the range 100 to 700 nsec could be chosen by varying the delay between the firing of the oscillator and the amplifier stages - in this way amplifying the gain-switched spike only, or progressively more and more of the tail of the oscillator pulse. Fig. 3 shows typical oscilloscope traces of the pump pulse. The two traces show single-mode outputs of different pulse length. The bandwidth of the recording system was 400 MHz.

## The FIR Oscillator

The unstable resonator is particularly attractive for use at FIR wavelengths as it provides a large uniformly-filled mode volume, excellent transverse-mode control and variable output coupling with all reflecting optics [6].

Figure 4 shows the unstable confocal FIR resonator. The $CO_2$ laser radiation is coupled into the cavity through a free-standing wire grid inclined at 45°, the wires running in the vertical direction. The construction of the grid, wires of thickness 10 μm and periodicity 25 μm, results in a measured reflectivity of better than 95% at 385 μm for an incident beam plane polarised parallel to the direction of the wires. However, the transmission of the grid for the $CO_2$ laser pump beam was only 20%. Taking other losses into account, this resulted in a mean energy-density of 0.12 J/cm$^2$ being dumped into the FIR laser cavity, over an area of diameter 4.5 cm. A glass tube is used as beam guide to collect a maximum of the diffracted or scattered $CO_2$ pump radiation which has passed through the grid. The folded FIR laser cavity is defined by a concave mirror (radius of curvature 300 cm) and as output coupler a convex mirror (radius of curvature 100 cm).

The characteristics of FIR emission from a stable cavity could be studied by replacing the convex output coupler with a plane mesh or mylar film. At 385 μm, the transmission of the mesh (200 lines per inch) has been measured to be 39 ± 5% whilst that of the 0.2 mm thick mylar film was found to be 85 ± 5%. In calculating the reflectivity of these elements it is assumed that absorption is negligible.

For all cavity configurations the length of the FIR laser resonator was 100 cm, its thermal stability being assured by using invar steel rods. Superradiant emission could also be studied by the removal of the output coupler altogether.

## RESULTS

### Energy Measurements

Using a 0.25 m Jarrell-Ash spectrometer, employing a grating ruled at 1.6 grooves/mm, the various emission lines of $D_2O$ when pumped by the 9R(22) $CO_2$ laser line could be identified. With reference to the partial energy level diagram for $D_2O$, Fig. 5, the energy ratio between the 385 μm line and the cascade line et 359 μm was measured to be 10 : 1, for the case of the unstable resonator. No other lines were observed. The polarisation of the FIR laser output was found to be better than 90 :1, in a direction perpendicular to the polarisation of the $CO_2$ laser beam.

In Fig. 6 the FIR energy output is plotted as a function of the $D_2O$ vapour pressure, for different cavity configurations and pump pulse lengths. The FIR energies were measured using a pyroelectric detector (Laser Precision RjP 736 RF) with an extended spectral response. Careful cross checking with other energy detectors enables the uncertainty in the absolute energy values to be quoted as not exceeding ± 25%, while the uncertainty in the relative measurements is better than ± 15%.

The mean pump energy density deposited in the FIR laser cavity was 0.12 J/cm$^2$ at most, in a single-mode pulse of duration between 100 and 700 nsec FWHM. The cavity configurations were either a confocal unstable resonator (Fig. 6a), with 11% feedback, or a hemispherical resonator with 15% or 61% feedback (mylar film, Fig. 6b, and mesh, Fig. 6d, respectively). Also shown, in Fig. 6c, is the case without feedback (superradiant emission). For all resonator configurations, maximum energy outputs were recorded at vapour pressures between 2.5 and 5.5 torr.

In Fig. 7 the variation of FIR laser output with the pump energy is plotted for the unstable resonator. From this plot it is possible to obtain the conversion efficiency, which we define as the FIR laser energy produced per Joule of $CO_2$ laser energy. For the 385 µm line a conversion ratio of 1.2 mJ/J was measured. This agrees well with the values obtained at 66 µm from an unstable resonator using $D_2O$ [4], if the energy is scaled according to the Manley-Rowe relation. No saturation behaviour is observed in the relationship between FIR laser energy and pump energy.

## Temporal Profiles

Figures 8 to 11 are a series of time resolved pulses of the FIR laser emission and the pump output. The oscilloscope traces representing the $CO_2$ pump pulses are on the left of each figure while the corresponding FIR pulses are on the right. The square pulse at the beginning of each trace is a digital marker which provides a common time reference for both oscilloscopes. A Rofin photon drag detector was used for the $CO_2$ laser pulses while a Molectron P5-01 pyroelectric detector was used for the FIR pulses. Both devices had risetimes of less than a nanosecond and both were used with oscilloscopes of bandwidth 400 MHz at a sensitivity of 10 mV/cm. Under some conditions it wasnecessary to use a preamplifier (gain 26 dB, bandpass 0.1 to 1300 MHz) with one or other of the detectors to achieve adequate sensitivity. The temporal profile of all FIR pulses was obtained after the FIR laser output had been passed through the grating spectrometer. Consequently, only the contribution due to the 385 μm transition was recorded.

The oscilloscope traces of FIR radiation shown in Figs 8 and 9 were obtained using the hemispherical resonator with mesh output coupler and a $D_2O$ vapour pressure of 10 torr. In Fig. 8, for the case of a single-mode pump pulse of duration 100 nsec, the presence of several longitudinal modes in the FIR laser cavity can be inferred from the beating in the FIR emission. The time separation of 6.7 nsec between the peaks corresponds to the cavity round-trip time, c/2L, for the metre-long FIR resonator. This is particularly evident in the trace obtained at a sweep speed of 20 nsec/cm.

However, for a single-mode pump pulse of duration ~700 nsec. the FIR laser emission exhibits no beating and indicates the presence of only one longitudinal mode in the cavity, upper half of Fig. 9. When pumping with a $CO_2$ laser pulse, of duration ~700 nsec, which exhibits mode beating with a separation of ~15 nsec between peaks, corresponding to the cavity round-trip time in the 225 cm long $CO_2$ resonator, the FIR emission also exhibits the same modulation. However, there is no structure which indicates the beating of FIR laser modes, lower half of Fig. 9 which shows part of a pulse only.

For pressures of less than 5 torr, the output of the FIR stable resonator always exhibits modulation irrespective of the pump pulse duration. When using a single-mode pump pulse, the FIR emission displays beating due to several longitudinal modes in the FIR laser cavity. For pumping using a multi-mode pulse, the FIR output exhibits structure identifiable with both cavities.

In Figs. 10 and 11 we present pulse shapes obtained using the unstable FIR resonator. The traces in Fig. 10 were obtained using a pump pulse of duration ~100 nsec and a $D_2O$ vapour pressure of 5 torr. When the pump pulse is single mode, the resulting FIR pulse also exhibits only one mode; upper half of Fig. 10. However, when the pump pulse shows amplitude modulation due to the presence of two longitudinal cavity modes, Fig. 10 lower traces, the FIR pulse is also modulated at the same frequency. In Fig. 11 the output from the FIR laser when using a pump pulse of duration ~700 nsec is shown. The upper traces show a single-mode pulse for both the pump and FIR laser, while the lower traces show multi-mode operation for both lasers. Within the pressure range 1-12 torr the performance of the FIR laser was found to be insensitive to pressure, with respect to the pulse shape.

Temporal profiles were also obtained in the case of superradiant emission. It was found that the output exhibited strong irregular fluctuations in amplitude irrespective of the pulse duration of the pump or the vapour pressure employed. No structure was observed in these fluctuations which could be associated with modes in either of the lasers.

## DISCUSSION

From the energy measurements, it is apparent that all of the FIR cavity configurations give approximately the same output for a given pump energy. Furthermore, within the range of pump intensities explored (170 kW/cm$^2$ to 1.2 MW/cm$^2$) there is no significant variation in energy output with pump pulse duration, for constant pump energy. The best efficiency $\varepsilon$ obtained is about 4.7% of the theoretical maximum for a stimulated Raman process, i.e. it is assumed that each photon of $CO_2$ laser energy can produce one photon of FIR radiation. The efficiency may then be calculated since $\varepsilon = E_{FIR} \times \lambda_{FIR} / (E_{CO_2} \times \lambda_{CO_2})$.

The maximum output achieved, ~2.3 mJ, was produced using 2 J of useful pump energy in a volume of 1.6 litres at a pressure of 3 torr. Thus the volume extraction is 0.47 mJ/litre torr and the energy produced is ~1.1 mJ/J of $CO_2$ laser energy. These figures compare with 0.80 mJ/litre torr and 2.2 mJ/J from the Princeton group [7] and 0.95 mJ/litre torr and 2.0 mJ/J from the MIT group [8], respectively.

For all three experiments, the pumping energy density was ~0.4 J/litre torr. However, in the work currently being reported the cavity length used was 1 m compared with 4 m in the other two experiments. Hence, absorption of the $CO_2$ laser radiation would be increased for the latter, resulting in an improved conversion efficiency and volume extraction.

The implication of these values is that to scale up to FIR laser energies of ~ 1 J $CO_2$ pump lasers will be required capable of delivering energies in the range of ~ 450 to 900 J. Furthermore, from the volume extraction, it is seen that a volume of between ~200 and 700 litres will be required, for pressures of a few torr, to scale up to the required energy. However, the maximum energy that can in principle be extracted from a number, $n_m$, of molecules in the case of laser emission by a stimulated Raman process is $0.5\ n_m\ hc/\lambda$. It has been assumed that none of the molecules excited to the $\nu_2 = 1$ vibrational level relax back into the $\nu_2 = 0$ ground level during the duration of the pumping pulse. Consequently, for $\lambda = 385\mu m$ the maximum volume extraction is ~ 17 mJ/litre torr, which is considerably higher than any of the values quoted and which indicates some room for improvement. Also, in the event of the pumping pulse being much longer than the time for vibrational equilibration of the $\nu_2 = 0$ level, an even greater volume extraction could be expected. Consequently, it is reasonable to anticipate that energies of ~ 1 J could be extracted from volumes of the order 100 litres for pump pulses of duration ~ 1 μsec.

It is interesting to note the change in the temporal behaviour of the FIR emission from the stable resonator, with both pulse duration and working pressure. At high pressure (10 torr) and for long pulse duration (700 nsec) single mode output is obtained when the pumping pulse is itself single mode. However, for short pump pulse duration (100 nsec) or at low pressure (1.5 torr, for example) the output of the hemispherical resonator is always multi mode, always exhibiting modulation indicative of several longitudinal FIR cavity modes beating, irrespective of the form of the pump pulse. These changes in the form of the FIR emission may be explained by saturation effects.

According to DeTemple [9] for the 385 μm line of $D_2O$ the saturation intensity, $I_{sp}$, for the pump transition is ~ 7.1 kW $cm^{-2}$ $torr^{-2}$. Consequently, at 10 torr pressure $I_{sp}$ ~ 710 kW $cm^{-2}$ and at 1.5 torr pressure $I_{sp}$ ~ 16 kW $cm^{-2}$. In comparison, the pump intensity is ~ 1.2 MW $cm^{-2}$ and ~ 170 kW $cm^{-2}$, for 100 and 700 nsec pulses, respectively. Likewise, the saturation intensity, $I_{sf}$, for the FIR lasing transition is given [9] as ~ 18 W $cm^{-2}$ $torr^{-2}$. Hence, at a pressure of 10 torr $I_{sf}$ ~ 1.8 kW $cm^{-2}$, while at a pressure of 1.5 torr the value is ~ 40 W $cm^{-2}$. At 10 torr pressure the intensity of FIR emission is ~ 410 W/$cm^2$ and ~ 40W/$cm^2$, for pump pulses of duration 100 and 700 nsec, respectively, while at a pressure of 1.5 torr the corresponding intensities are ~ 1.3 kW/$cm^2$ and ~ 170 W/$cm^2$.

For pump intensities which are in excess of the saturation intensity, $I_{sp}$, the gain profile is modified due to the a.c., or dynamic, Stark effect [10]. With increasing pump intensity, and for low levels of FIR emission, the profile splits into two components which move further apart in frequency as the intensity increases - Rabi splitting. In addition, as the intensity of FIR emission increases above the saturation intensity, $I_{sf}$, the frequency band over which emission occurs becomes progressively broader. This effect is termed power broadening. At sufficiently high intensities the effect of power broadening is to fill in the trough in the emission due to Rabi splitting. This qualitative description is strictly only true for resonance pumping, i.e. when the frequency of the pump radiation coincides exactly with the line centre of the absorption transition. For off-resonance pumping, the Rabi splitting and power broadening develop asymmetrically - the degree of asymmetry varying with the frequency offset [10].

The work of Temkin [10] has been followed in obtaining the emission profiles particular to the conditions under which the results reported herein were obtained. Turning to the results obtained using the stable resonator, the 1-metre-long cavity has a longitudinal mode spacing of 150 MHz. At a pressure of 10 torr, and in the absence of pump saturation, the width of the pressure-broadened gain profile would be ~ 400 MHz FWHM (broadening ~ 40 MHz/torr). Consequently, a mode which coincided with the profile maximum would experience a gain which was ~ 50% greater than that for adjacent modes and would dominate, i.e. single-mode output would be expected. This is indeed what is observed for pump pulses of duration ~ 700 nsec, even though the gain difference mentioned is reduced to ~ 31% because of a small role played by the a.c. Stark effect. However, for pulses of duration ~ 100 nsec, the a.c. Stark effect would result in a gain profile which is broader by a factor of 2.7 than in the simple pressure-broadened case

- the pump intensity not being sufficient to produce distinct splitting into 2 components. In this case, the maximum difference in relative gain between adjacent modes would be only ~ 8%. No single mode would dominate and multi-mode FIR emission could be expected, as is observed experimentally. In neither of the cases considered is the intensity of the FIR emission sufficient to lead to power broadening.

At a pressure of 1.5 torr, however, the situation is quite different. For both short and long pump pulses the pump and FIR transitions are well saturated. Consequently, both Rabi splitting and power broadening play a role. Typically, for the ranges of intensities encountered in the present work, the width of the FIR emission profile can be up to about 20 times greater than the width of the gain profile due to pressure broadening. Consequently, there is not a sufficiently great difference in gain between adjacent FIR cavity modes to ensure single mode operation, and the FIR emission is always multi mode irrespective of whether or not the pump pulse is multi mode.

Strangely, for a single mode pump pulse, within the ranges explored, the FIR output from the unstable resonator is always single mode, irrespective of the pressure of the active medium or the duration of the pump pulse. However, the feedback of the output coupler of the unstable resonator is much lower than in the case of the stable resonator, 11% compared with 61%. A likely explanation of the persistent single-mode operation is that, in spite of Rabi splitting and power broadening at lower pressures, the cavity losses are so high that only the longitudinal mode closest to gain maximum is well above the threshold for oscillation.

## CONCLUSIONS

We have demonstrated the generation of FIR laser pulses of duration up to 700 nsec FWHM at 385 µm. Single longitudinal and transverse mode control were achieved using a confocal unstable resonator with $D_2O$ as the active medium and optically pumped using a $CO_2$ laser. The results are an encouragement to scaling up the system volumetrically and to extending the pulse duration, in an attempt to achieve the MW power level and µsec pulse length necessary to perform a scattering measurement of ion temperature in a tokamak plasma.

For a given cavity length and volume, as much energy can be extracted from $D_2O$ using an unstable resonator as using stable resonators. However, much larger beam diameters can be accommodated with unstable resonators than with stable ones, whilst preserving a single transverse mode. Also, provided that the equivalent Fresnel number [11] is correctly chosen for the unstable resonator good longitudinal mode control can be achieved. In the case of the stable resonator either the cavity length must be limited so that the inter-mode spacing is greater than the gain width of the lasing transition or extra elements must be incorporated into the cavity to achieve mode selection. The latter approach can lead to substantial losses.

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## FIGURE CAPTIONS

Figure 1: $CO_2$ laser system for optical pumping

Figure 2: IR spectrum of the isolation gas mixture

Figure 3: Typical oscilloscope traces of the pump pulse (a: 50ns/div; b: 200 ns/div.)

Figure 4: The folded, unstable, confocal FIR resonator

Figure 5: Partial energy level diagram of the $D_2O$ molecule (spacings of levels not to scale)

Figure 6: The FIR output energy as function of $D_2O$ vapour pressure, for different cavity configurations and pump pulse length

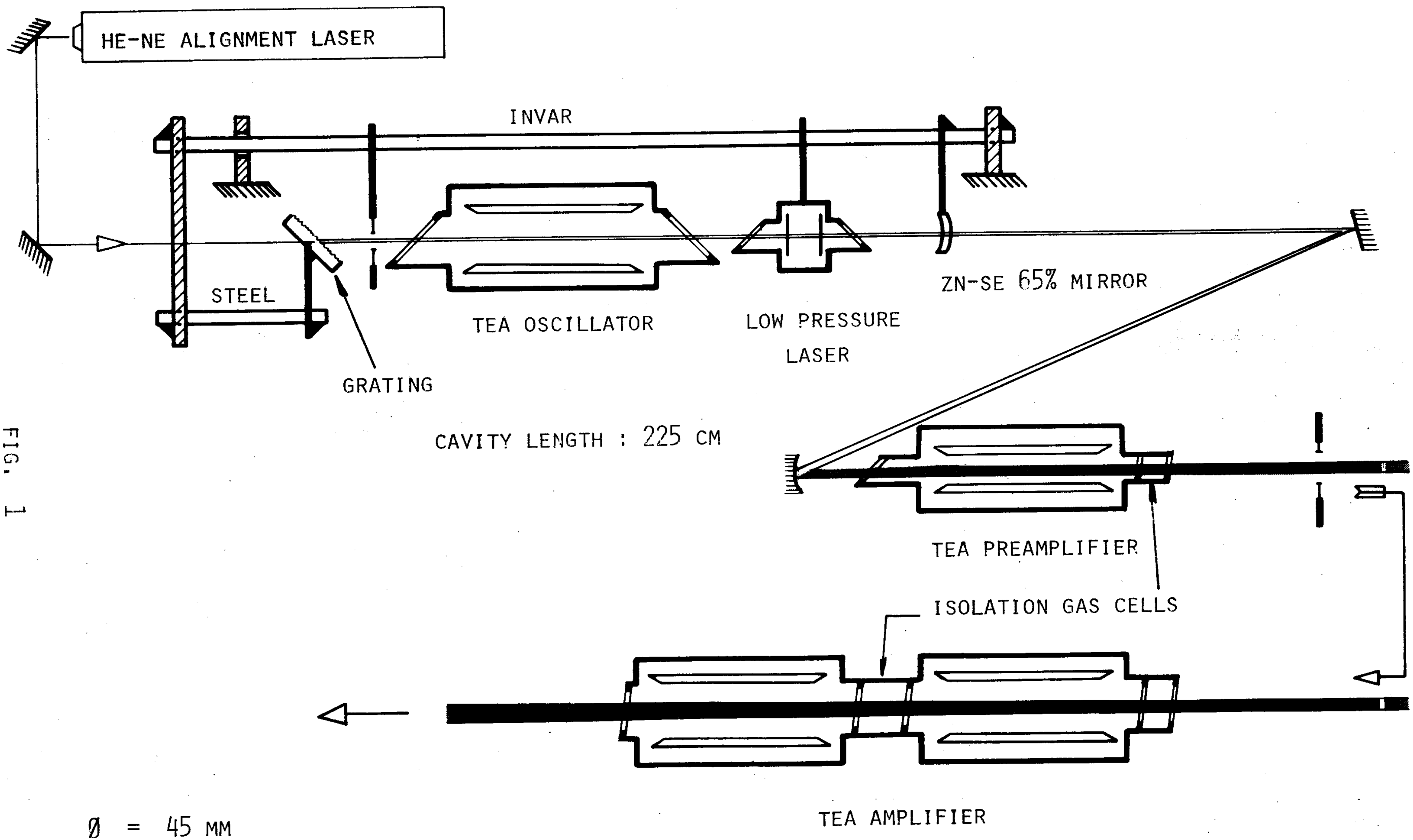
Figure 7: The FIR output energy vs. pump energy for the confocal unstable resonator

Figure 8: Time resolved pulses

Figure 9: idem

Figure 10: idem

Figure 11: idem

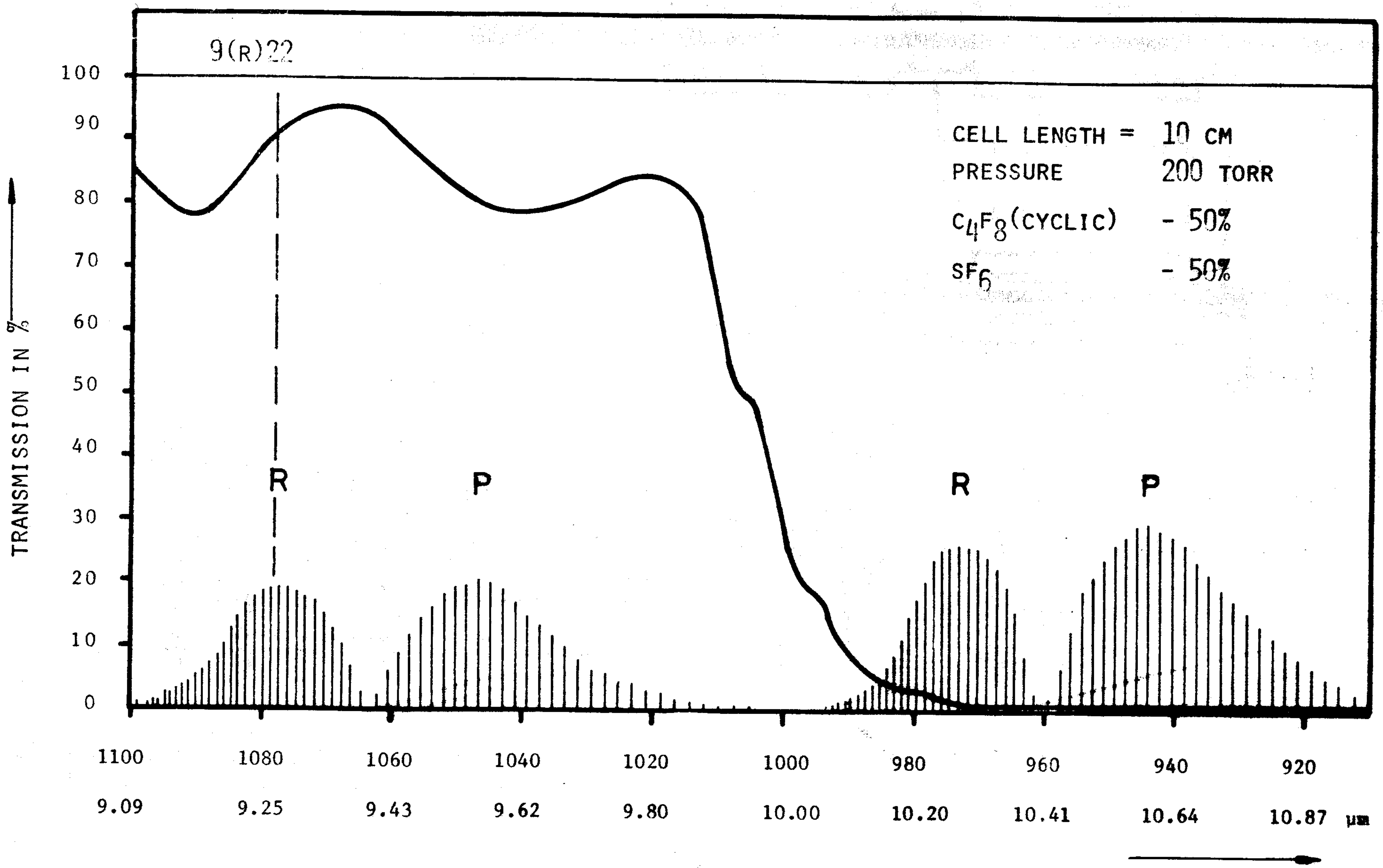



Ø = 45 MM

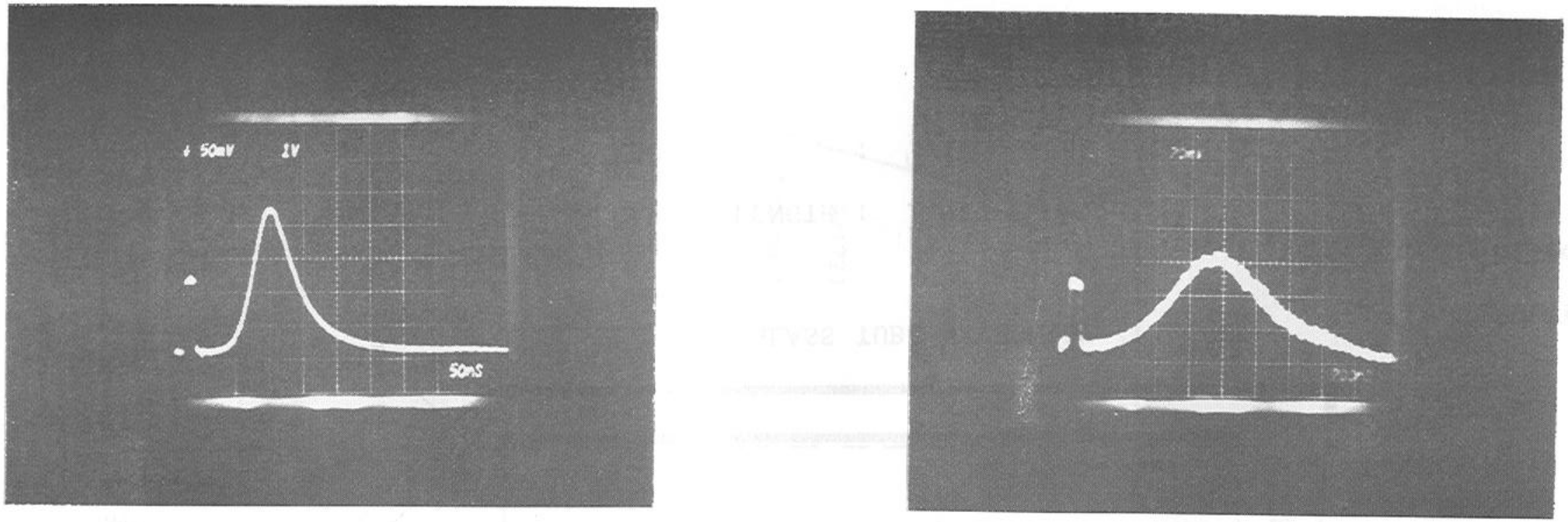
E = 20 J AT 9R22

FIG. 1

FIG. 2

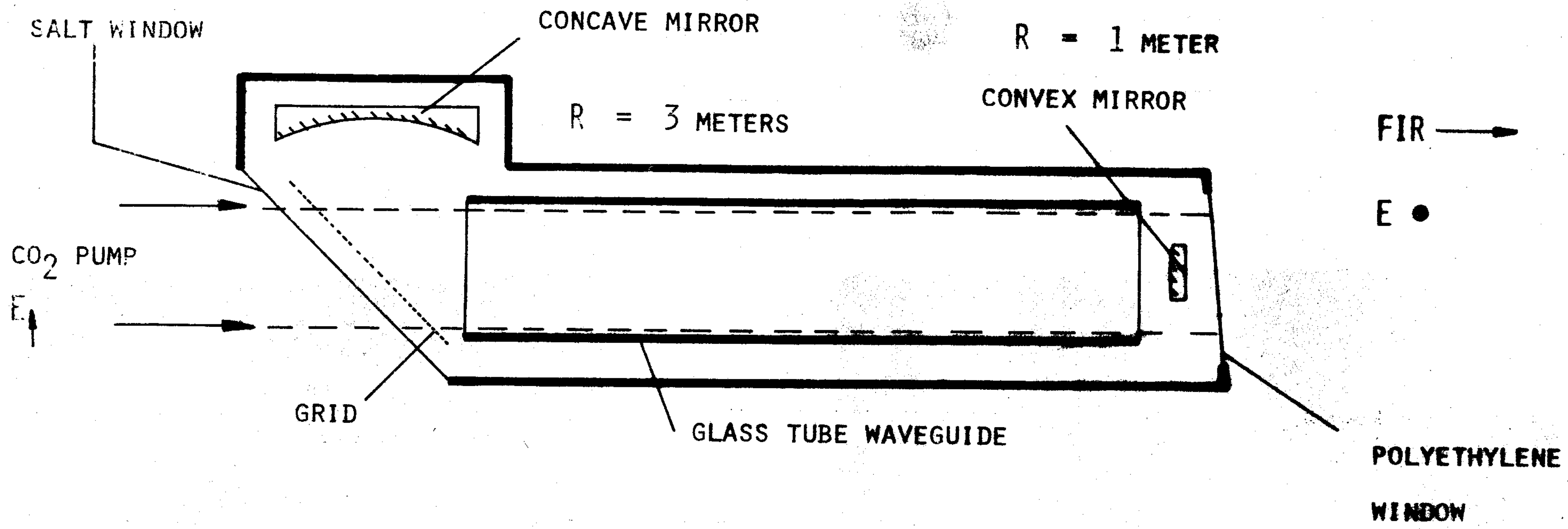



IR SPECTRUM OF THE ISOLATION GAS MIXTURE




a) b)

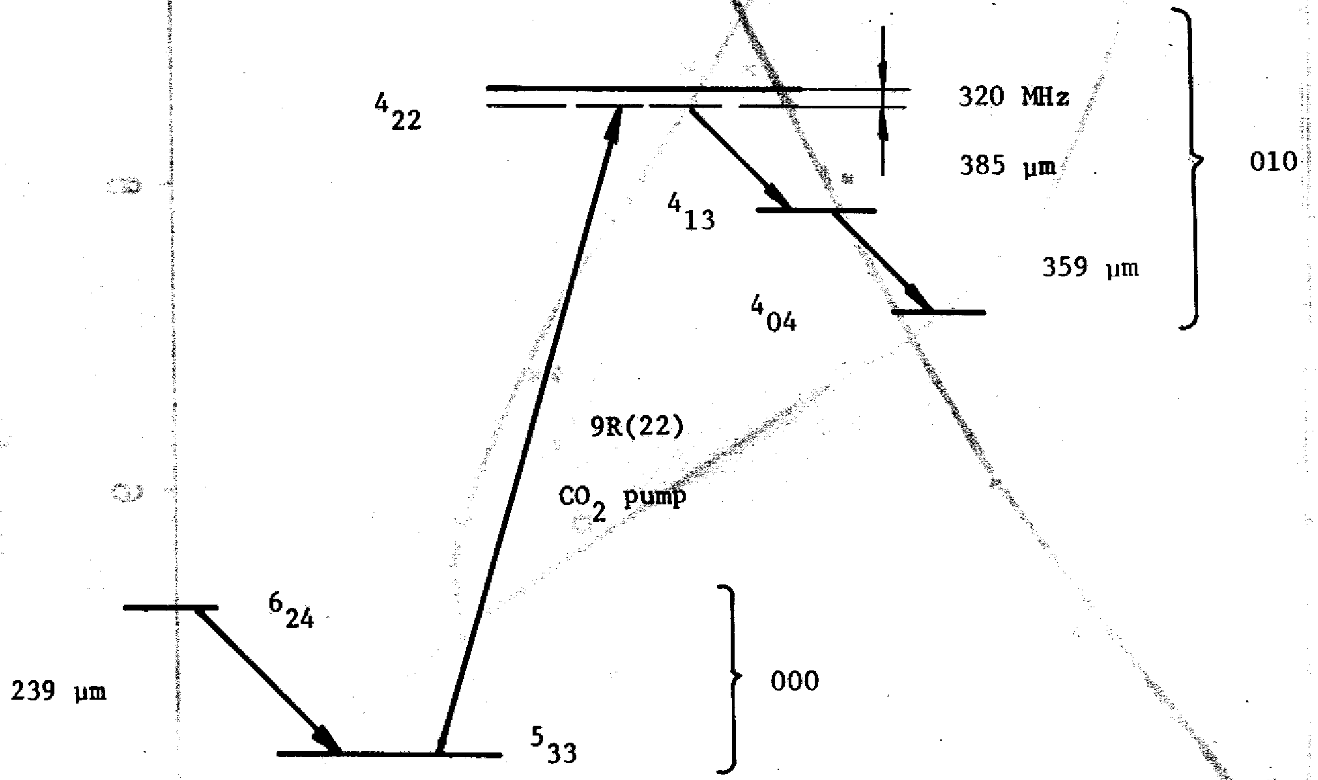
FIG. 3




CAVITY LENGTH : 1 METER

NEQ : 0.1 FEED BACK : 11%

FIG. 4



$4_{22}$
320 MHz
385 μm
010
$4_{13}$
359 μm
$4_{04}$
9R(22)
$CO_2$ pump
$6_{24}$
239 μm
000
$5_{33}$


FIG. 5

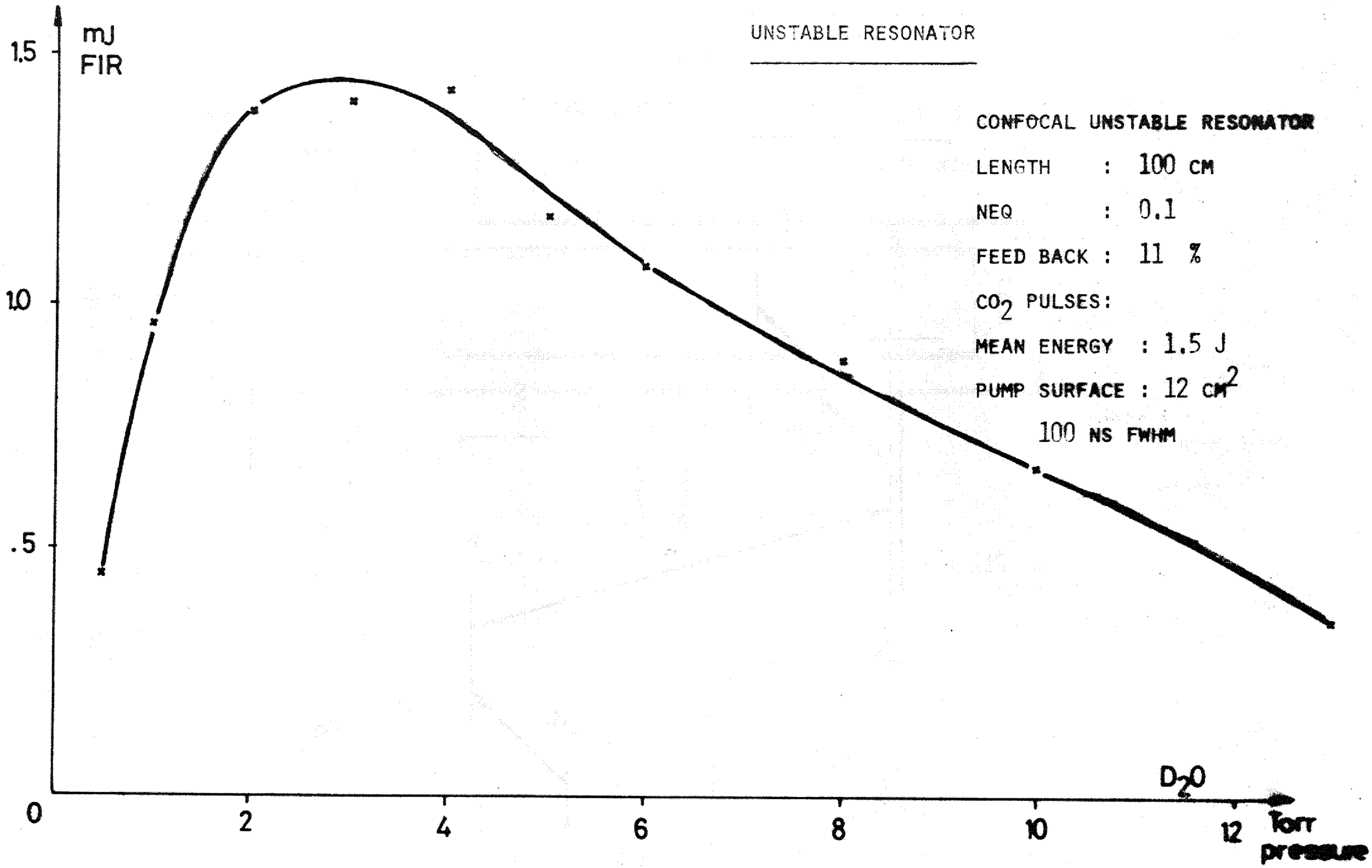
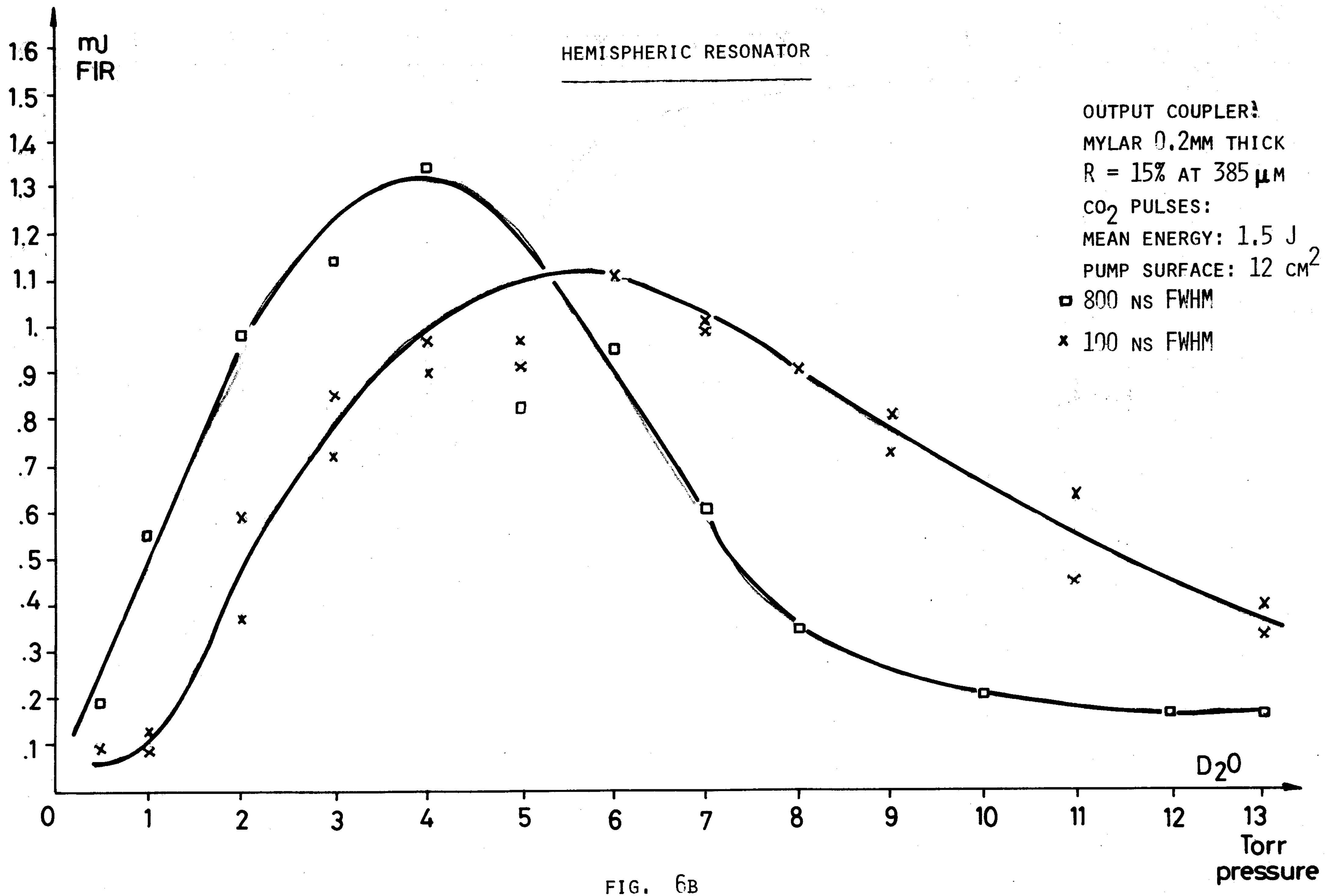
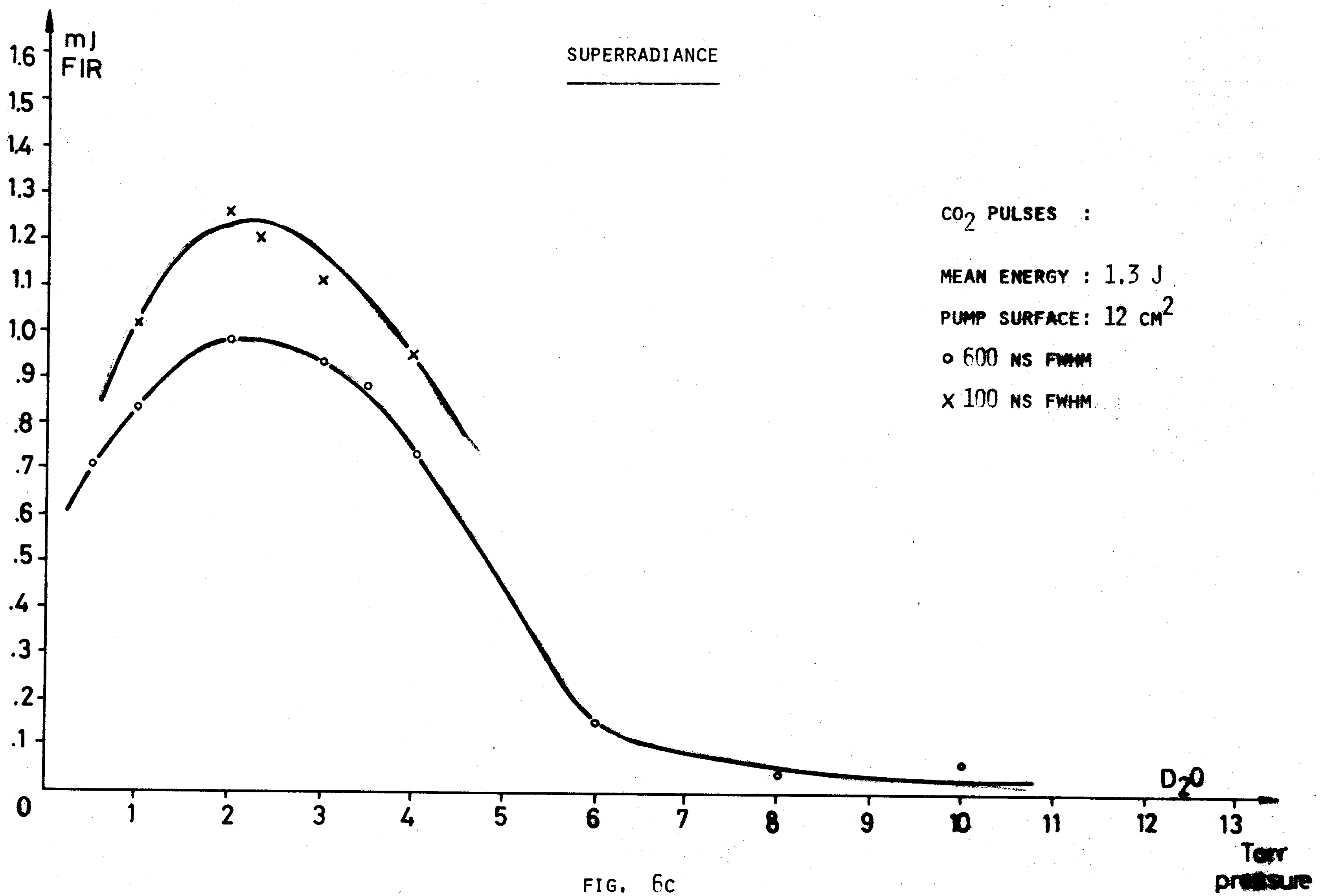

UNSTABLE RESONATOR
CONFOCAL UNSTABLE RESONATOR
LENGTH : 100 CM
NEQ : 0.1
FEED BACK : 11 %
$CO_2$ PULSES:
MEAN ENERGY : 1.5 J
PUMP SURFACE : 12 $CM^2$
100 NS FWHM
mJ
FIR
1.5
1.0
.5
0
2
4
6
8
10
12
$D_2O$
Torr
pressure

FIG. 6A



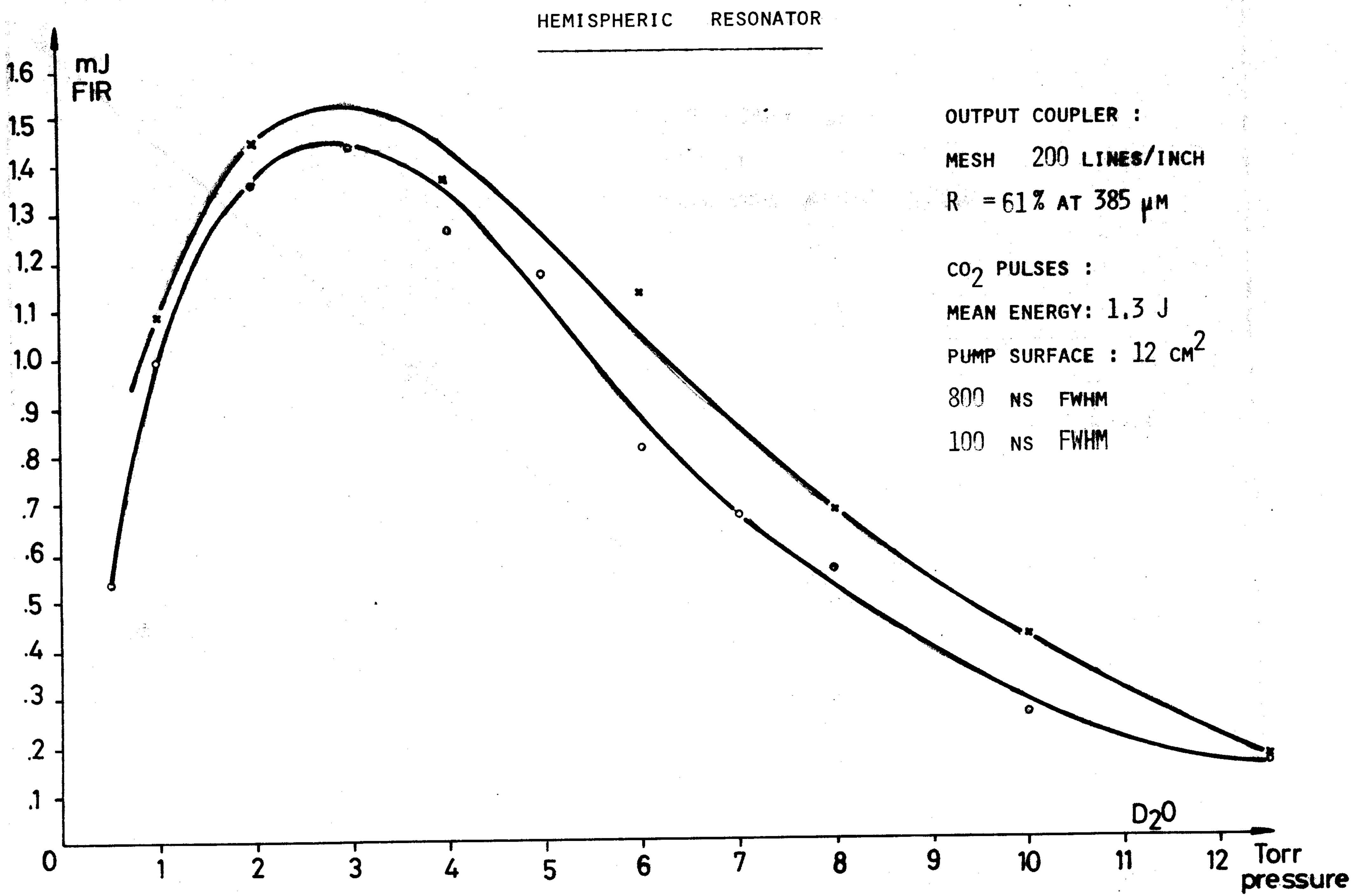
mJ
FIR
HEMISPHERIC RESONATOR
OUTPUT COUPLER:
MYLAR 0.2MM THICK
R = 15% AT 385 μM
CO2 PULSES:
MEAN ENERGY: 1.5 J
PUMP SURFACE: 12 CM2
800 NS FWHM
100 NS FWHM
D2O
Torr
pressure
1.6
1.5
1.4
1.3
1.2
1.1
1.
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1
2
3
4
5
6
7
8
9
10
11
12
13


FIG. 6B



SUPERRADIANCE
mJ
FIR
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Torr
pressure
D2O
CO2 PULSES :
MEAN ENERGY : 1.3 J
PUMP SURFACE: 12 CM2
o 600 NS FWHM
x 100 NS FWHM

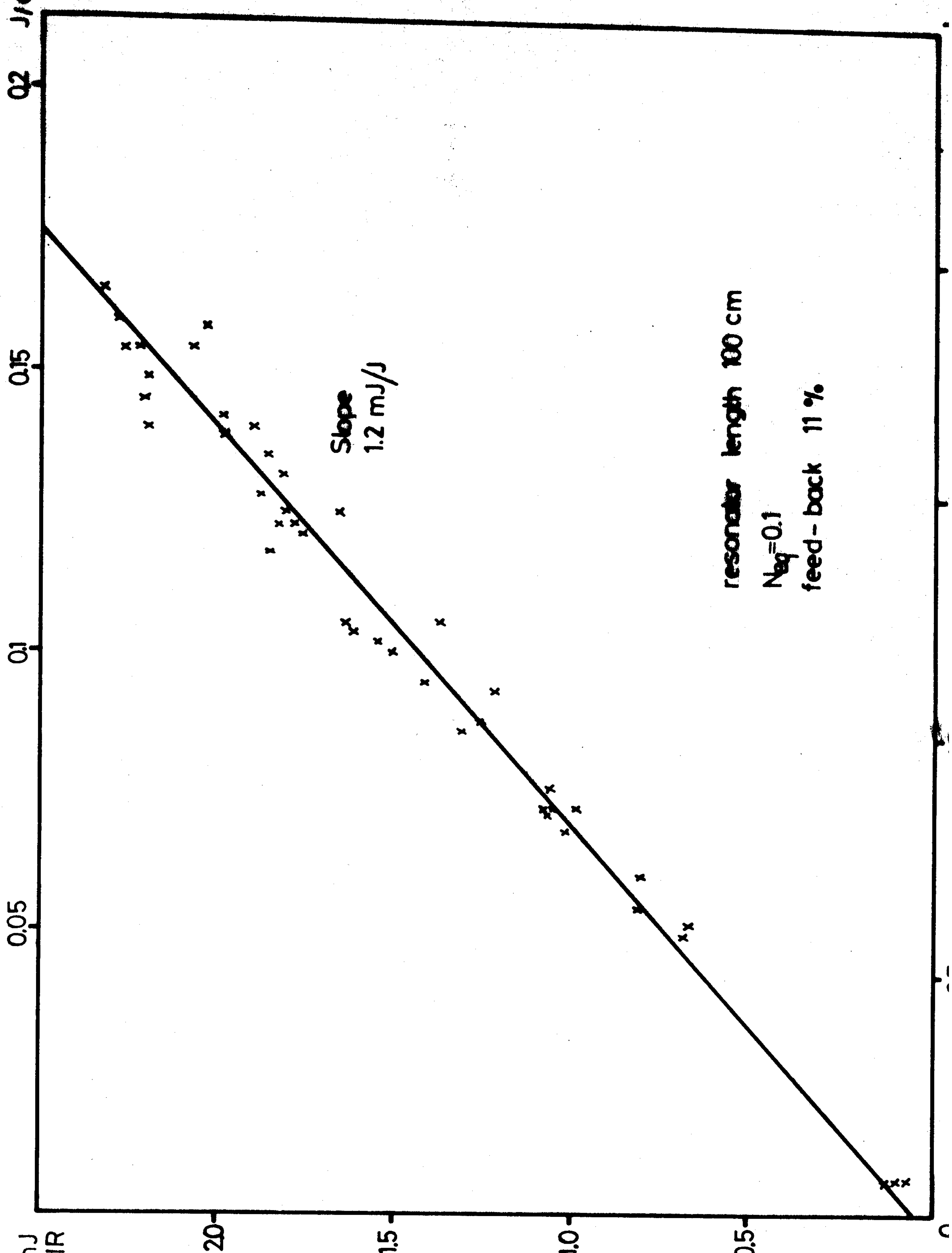

FIG. 6C



HEMISPHERIC RESONATOR
mJ
FIR
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1
2
3
4
5
6
7
8
9
10
11
12
Torr
pressure
D2O
OUTPUT COUPLER :
MESH 200 LINES/INCH
R = 61% AT 385 μM
CO2 PULSES :
MEAN ENERGY: 1.3 J
PUMP SURFACE : 12 CM2
800 NS FWHM
100 NS FWHM


FIG. 6D

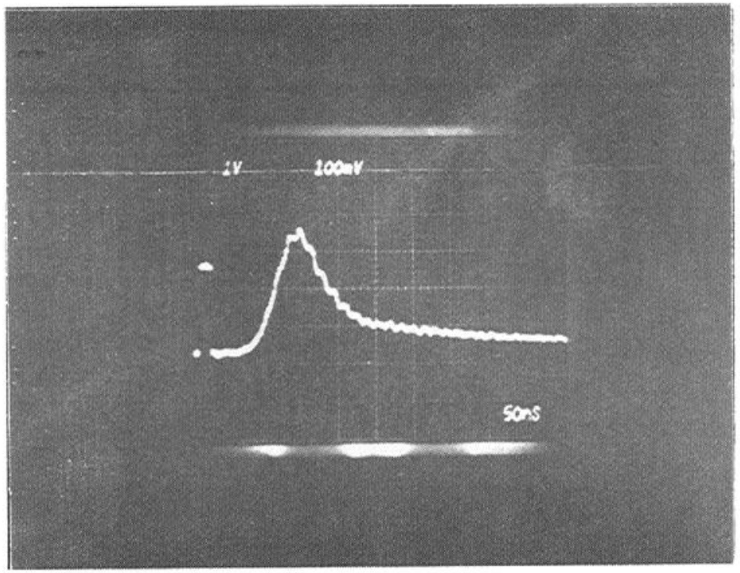
FIG. 7



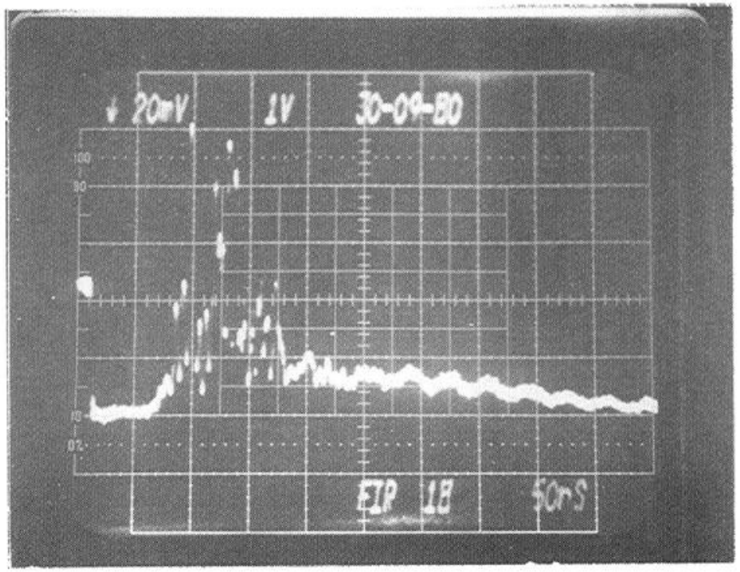
J/cm² CO₂
0.2
0.15
0.1
0.05
mJ IR
2.0
1.5
1.0
0.5
Slope
1.2 mJ/J
resonator length 100 cm
Neq=0.1
feed-back 11 %

HEMISPHERIC RESONATOR

$CO_2$



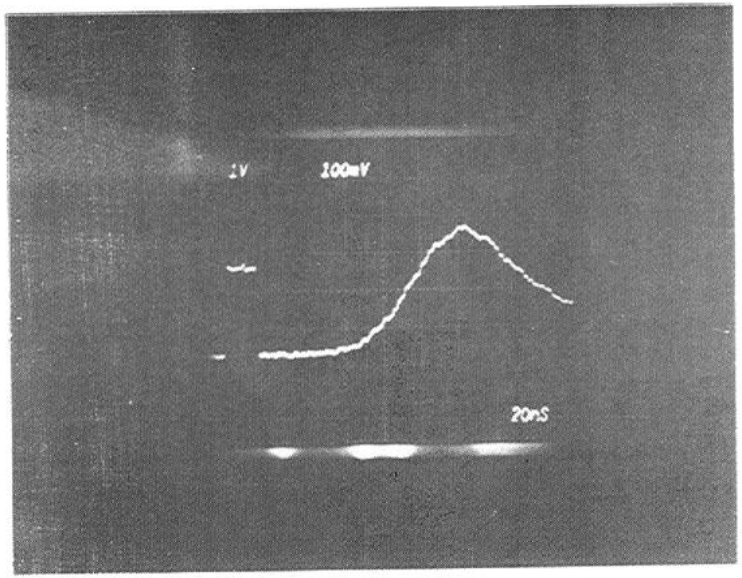

FIR



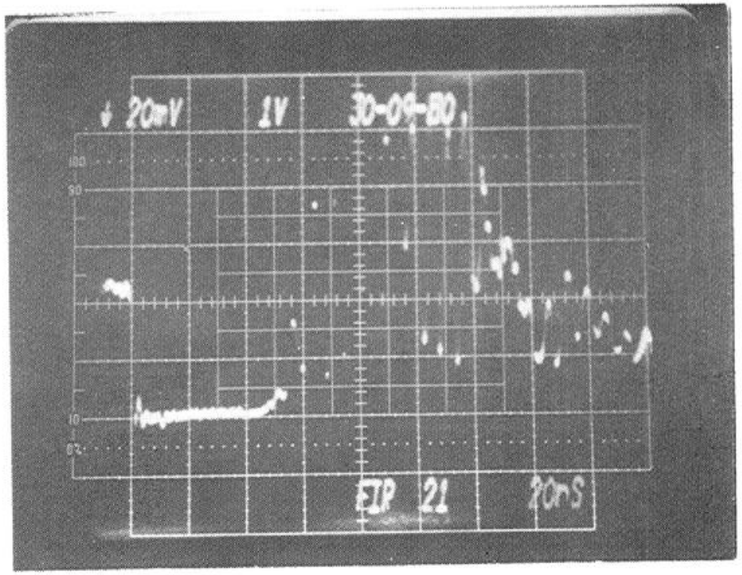

50 NS/DIV

$D_2O$ : 10 TORR

$CO_2$



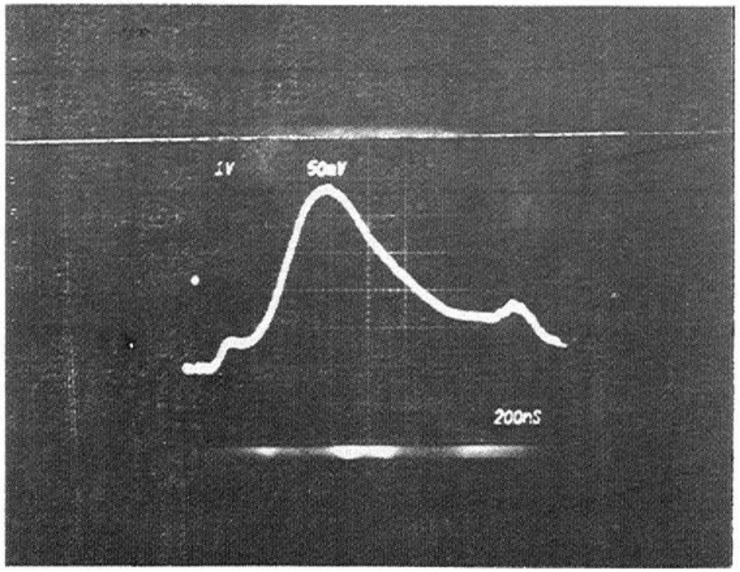

FIR




20 NS/DIV

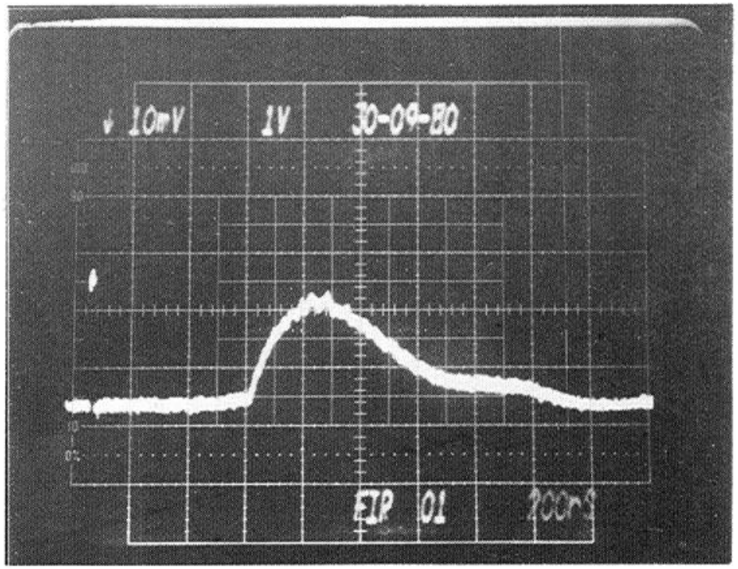
Fig. 8

## HEMISPHERIC RESONATOR




$CO_2$

FIR

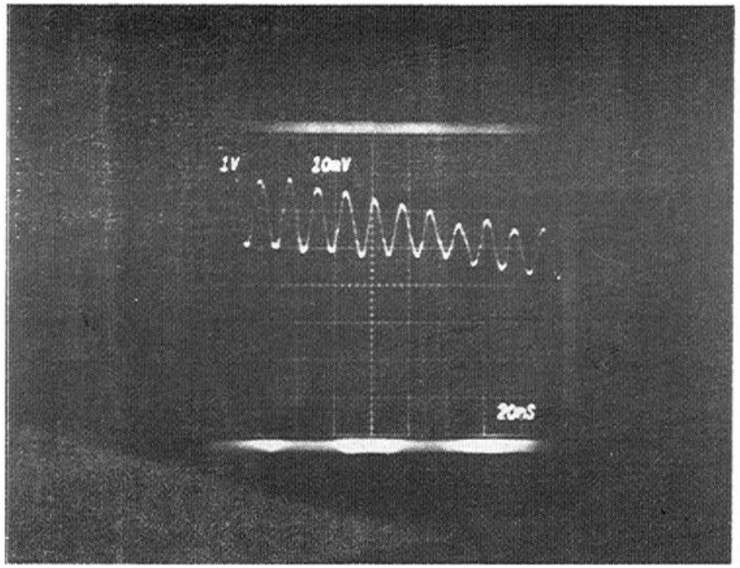



$D_2O$ : 11 TORR

200 NS/DIV

20 NS/DIV

$D_2O$ : 10 TORR




$CO_2$

FIR

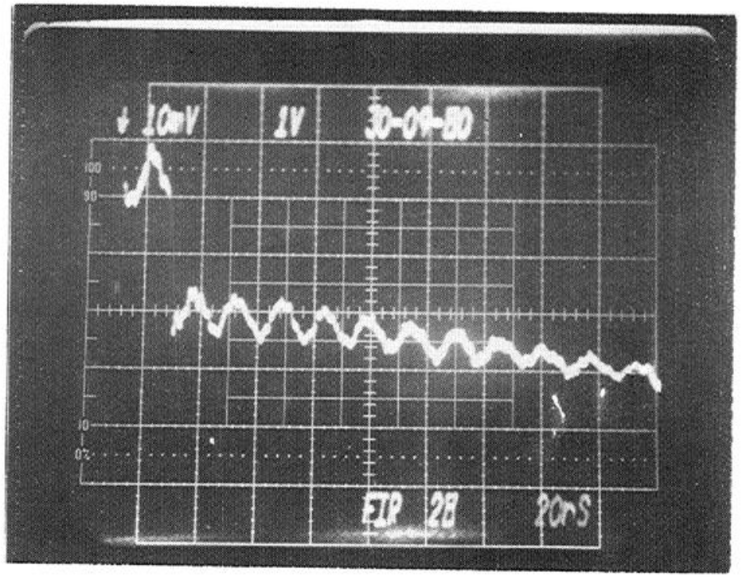
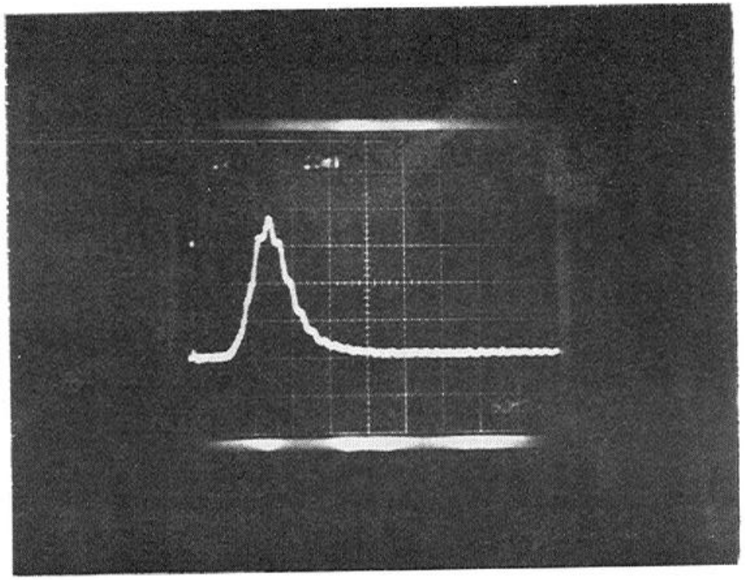


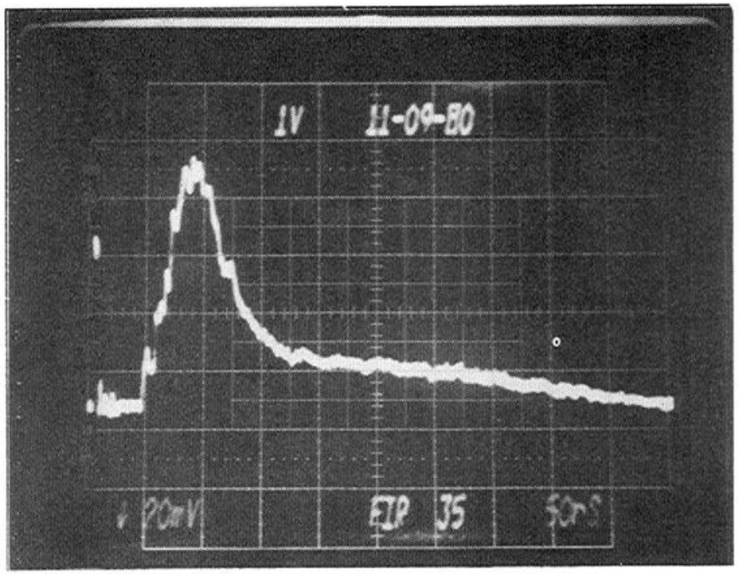

Fig. 9

UNSTABLE RESONATOR

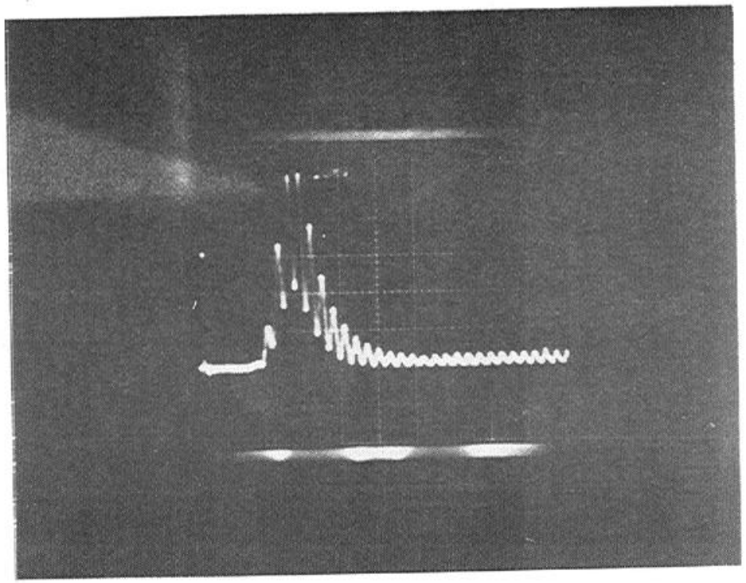


$CO_2$

FIR




50 NS/DIV $D_2O$ : 5 TORR



$CO_2$

FIR

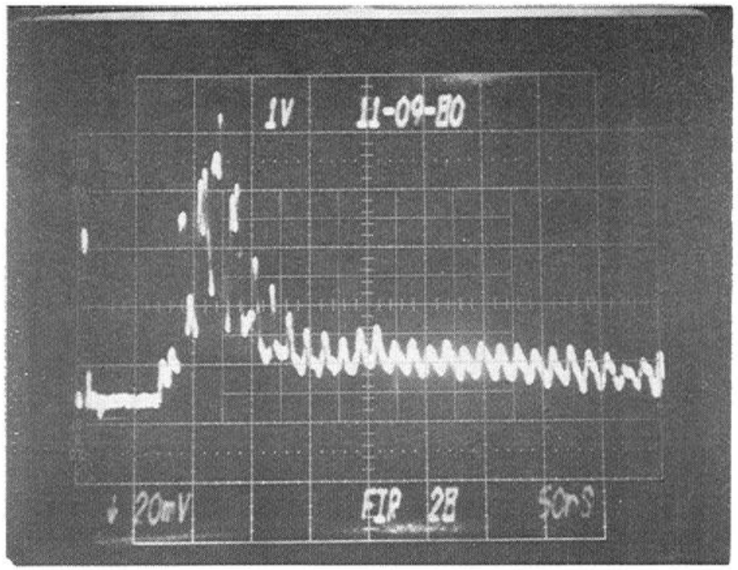
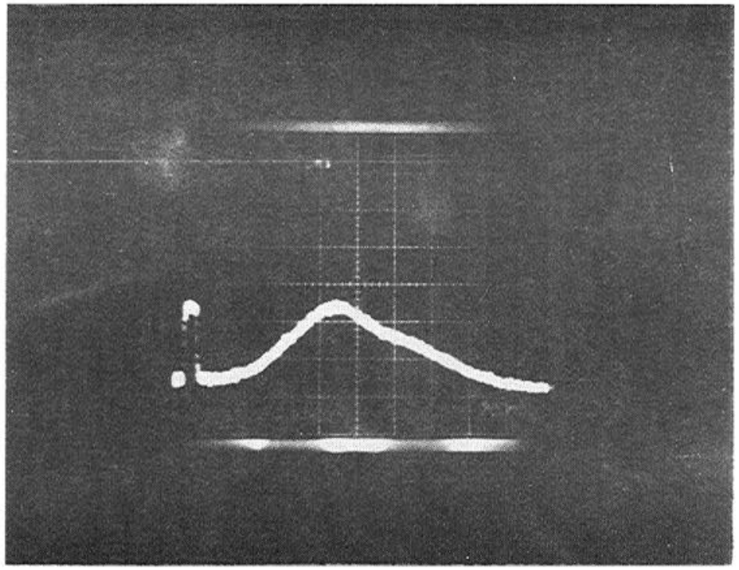


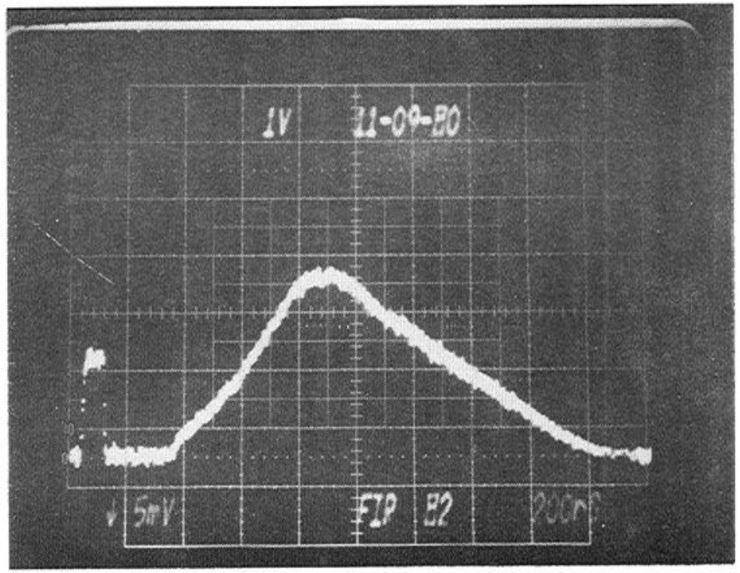

Fig. 10

## UNSTABLE RESONATOR

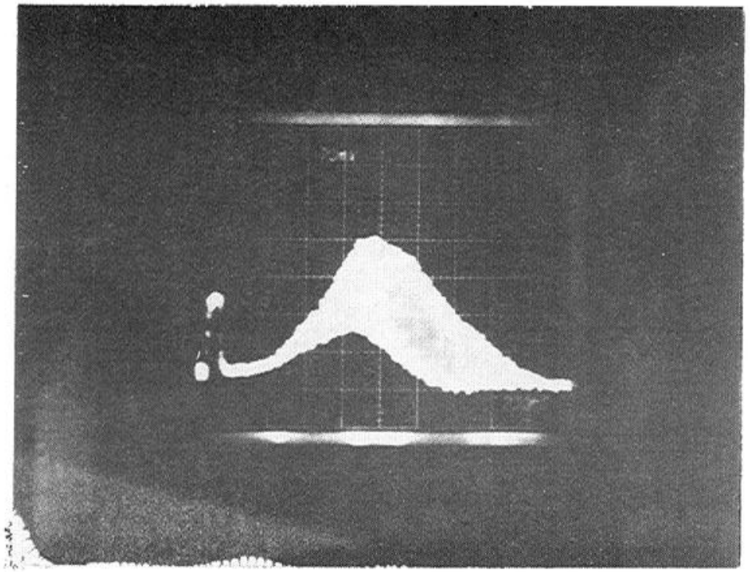


$CO_2$

FIR




200 NS/DIV $D_2O$ : 3,5 TORR



$CO_2$

FIR

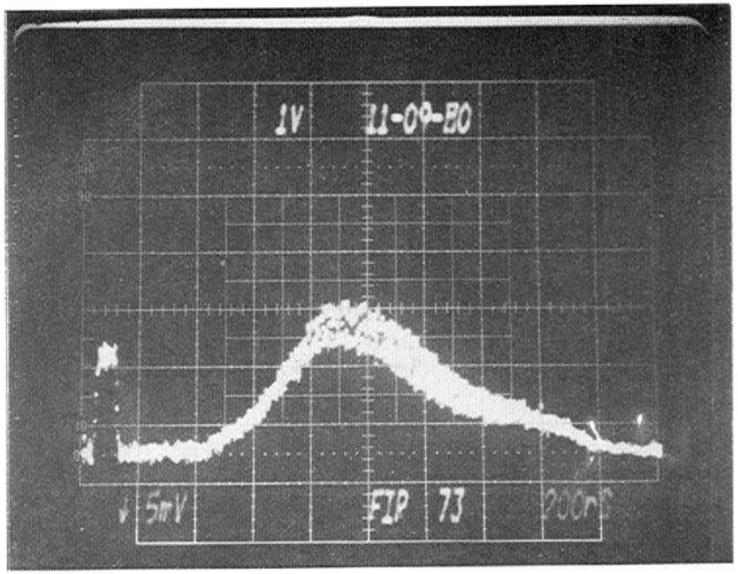



Fig. 11