N 72 16559

3rd SEMI-ANNUAL STATUS REPORT

to

CASE FILE
COPY

National Aeronautics & Space Administration

Period covered: April 1, 1971 to Sept. 30, 1971

N.G.R. : 52-133-001

Rubidium Gas Cell Studies

Quantum Electronics Laboratory
Dept. of Electrical Engineering
Laval University
Quebec 10, P.Q.
CANADA

October 1971

3rd SEMI-ANNUAL STATUS REPORT

to

National Aeronautics & Space Administration

Period covered: April 1, 1971 to Sept. 30, 1971

N.G.R. : 52-133-001

Rubidium Gas Cell Studies

Quantum Electronics Laboratory
Dept. of Electrical Engineering
Laval University
Quebec 10, P.Q.
CANADA

October 1971

FOREWORD

This is the 3rd semi-annual report relative to studies on rubidium gas cells, made for NASA (N.G.R. 53-133-001). We include in this report only information which is considered new, relative to our previous report (2nd semi-annual report, April 1971). The present report, covering the period starting April 1, 1971 and ending September 30, 1971, concerns the two following projects:

I. Stability of rubidium 87 optically pumped masers.

II. Stability of rubidium gas cells.

Progress on both projects is reported, with emphasis on the maser stability study. It describes A) the significant steps that have been accomplished during the last six months period on both projects (status of work) B) the significant changes which we have done in our technical approach C) what remains to be done to achieve our goals in both projects.

The scientists working on the various aspects of the projects are: M. Têtu, G. Missout and G. Busca.

Jacques Vanier, Ph.D.
Principal investigator
Laboratoire d'Electronique Quantique
Dépt. de Génie électrique
Université Laval

October 1971

A. PRESENT STATUS OF THE PROJECTS

I - Rubidium 87 Masers

a) The masers

Our technical approach to the construction of the masers has not been changed since our last report(1), except that we have added the task of building a new vacuum tight stainless steel cavity, in order to be able to investigate the stability of this other type of maser(2). Our approach then has been to build the masers according to the drawing of figure 1 and the description of the following sections:

1) The Cavity and Bulb. The cavity is made of a quartz cylinder. The top which is used for coarse tuning is made of copper, and is transparent to the pumping light. The bottom which is also made of copper is not transparent. The arrangement provides a certain amount of compensation against temperature variations although no efforts have been made to design the system such as to provide uptimum characteristics relative to long term frequency stability. Rough measurements however have shown that the cavity tuning was not too sensitive to temperature, and it was found that for the present task the results obtained were satisfactory.

The cavity itself is surrounded by a copper jacket on which is mounted the heater elements. This arrangement is necessary, in order to avoid as much as possible the gradients that would exist, if the heaters were mounted directly on the quartz cavity, which has a poor thermal conductivity. The jacket is in good contact with the copper ends of the cavity.

After a systematic investigation of various bulbs and quartz cavities, we have found some combinations which allowed us first the possibility of tuning the maser to the rubidium 87 hyperfine frequency and furthermore obtaining a Q high enough to permit continuous oscillation(3,4). We have obtained the results shown on Table 1.

Table 1

	NAS 1 Rb 87 Maser	LEQ 1 Rb 87 Maser
Cavity	Quartz cylinder	Quartz cylinder
Top	Transparent Wrinkled Foil	Perforated copper plate
Bottom	Opaque	Opaque
Bulb	Quartz 04	Quartz 05
Q_u	34,700	38,000
Q_ℓ	31,500	35,800
β	0.1	0.06

The second NAS 2 Rb 87 Maser has not yet been mounted.

2) The Lamp. The lamp-filter cell arrangements has not been changed from the original design. We are still using a combination of a single bulb 1" in diameter and single reflector 3" in diameter; the power to excite the electrodeless discharge at a frequency of the order of 80 M Hz is supplied by a vacuum tube 3E 29. As analyzed on the Fabry Perot interferometer, the lamps are very stable, either in their temperature or

intensity characteristics. In the section on experimental results, we give some explanations on these characteristics.

We have had some problems with the filter cells. Due to temperature gradients mostly caused by the large size of the cells used, we have observed condensation of rubidium on the face of the cells, inhibiting maximum transmission of useful light. We have tried various solutions to this problem on another type of maser (rubidium 85 maser) and have found that the best solution is to purposely create a gradient in the filter cell, in order to keep on the outside of the cylinder a ring which is colder than the front and back ends of the cells. This is being applied to the rubidium maser lamp filter cell arrangement used in connection with the rubidium 87 masers. There should be no need to redistribute the rubidium periodically in the filter cell if this solution is adopted.

3) The Solenoid and Shield. One unique shield is used in the present maser design. It is made of molly permalloy material. A solenoid fitting closely to the shield permits the application of a small orienting field along the main axis of the maser and the selection of $\Delta M_F = 0$ transitions only. The single shield arrangement is sufficient in the present study, since we are interested in the short stability of the masers.

4) The Electronics. The detection system at 6.8 G Hz is completed and operates satisfactorily. It consists of a superheterodyne receiver with an i.f. frequency of 30 M Hz.

The electronics proper to the maser is also completed, including the magnetic field control and the thermal control for eight separate control points. Thus, in principle, we have the possibility of controlling four points at each maser i.e., two filter cells, the cavity and the bulb tip. Testing of the stability on these proportional thermal controls, in order to know their exact possibilities, is under way.

b) Experimental results and theoretical calculations.

1) <u>Stability Measurements</u>. Maser NAS 1 has been operating continuously for several months. Maser LEQ 1 has been put in operation recently. The simultaneous operation of these two masers has made possible the measurement of their short term stability. The two masers have been found to differ in frequency by approximately 640 Hz. This is due mainly to the difference in buffer gas pressure in the two storage bulbs. Nitrogen used in the maser, at a nominal pressure of approximately 10 Torr, has a shift of approximately 520 Hz per Torr. No efforts have been made to adjust the pressure to equal values in the two bulbs, during their filling. In fact, the difference in frequency is desirable for measurement of stability in the short term region.

The signals of the two masers were sent to the same receiver and the beat frequency was detected. As illustrated in figure 2, this frequency was counted in an HP 5060A computing counter, programmed to give the fractional frequency stability $\sigma\ (N,\ T,\ \tau)^{(5)}$. We have set $N = 2$ and, due to counter characteristics, T was found to be τ + 4.5 m sec. The preliminary results of our analysis are shown on figure 3. These results are rather encouraging, due to the fact that no care was taken in the experiment to optimize the maser parameters. A very significant characteristic is the rather low power output that we have measured, i.e., approximately 10^{-12} watt with one maser about twice as powerful as the second one. This relatively low power can be increased by adjusting the various maser parameters. For example we know that, in those experiments, one maser was not set at optimum temperature for maximum power output relative to the light intensity available. In fact, a diagram was placed in front of the light beam, and the maser oscillation could be quenched when the diaphragm was set at its maximum opening. The cavity coupling was not optimum either.* Thus, we are hoping to improve on power output and on short term stability proportionally.

2) Light Shift Measurements. During the second maser (LEQ 1) assembling, light shift experiments were done with NAS 1 maser. The latter is equiped with a variable iris diaphragm, and light intensity can be varied either by a combination of neutral density filters or iris openings. The maser is also equiped with a fine tuner which permits the measurements of maser frequency against cavity tuning.

---

* Recent adjustment of the coupling parameter has increased the maser power output to approximately 3×10^{-11} watt on one maser.

The combined effect of light intensity variation and cavity tuning can be expressed by assuming an expression as in the hydrogen maser:

$$\nu_m = \nu_o + (\nu_c - \nu_o)\,\frac{Q_c}{Q_\ell} \qquad (1)$$

where ν_m is the maser output frequency, ν_o is the resonance frequency of the rubidium atoms including the buffer gas, the magnetic field shifts and the light shifts, ν_c is the cavity resonance frequency, Q_c is the quality factor of the cavity and Q_ℓ is the quality factor of the atomic resonance line. If I is the intensity of the incident pumping radiation, we can assume that

$$\nu_o = \nu_{oo} + \alpha I \qquad (2)$$

$$\Delta\nu_\ell = \Delta\nu_{\ell o} + \beta I \qquad (3)$$

where ν_{oo} and $\Delta\nu_{\ell o}$ are respectively the rubidium frequency and the width of the hyperfine transition line without the effect of the light. The values given in equations (2) and (3) may be replaced in equation (1) to give the following equation:

$$\nu_m \cong \nu_{oo} + \alpha I + (\nu_c - \nu_{oo})\,\frac{Q_c}{Q_{\ell o}}\left(1 + \frac{\beta I}{\Delta\nu_{\ell o}}\right) \qquad (4)$$

In the previous expressions, α and β may be determined experimentally, and calculations are also presently made on a computer to obtain their values from basic principles which are encountered in the theory of optical pumping(6,7). From equations 2 and 3, it is seen that α is related to the light shift, and ρ to the line broadening. Both parameters are functions of the light spectrum and consequently of the filter cell temperature. A similar approach has been used by E.N. Bazarov and V.P. Gubin(8) and our solution differs only in minor details of notation. However, our experimental data are not in agreement with the conclusions of these authors.

Since the light shift is introduced by the non-coincidence of the pumping line and absorption line, a thorough study of the filter cell temperature effect on the shape of the lamp spectrum has been initiated on a Fabry Perot interferometer built specially for this kind of study(10). For the present experiment, one lamp with its filter cell is placed directly in front of the Fabry Perot, while a reference lamp is placed at right angle to the axis of the Fabry Perot interferometer. An alternating mirror permits the chopping from one lamp to the other, while an order of the spectrum is traced. On figure 4, which is a recording of the light spectra obtained through this technique, it can readily be observed that coincidence of the spectra exists when the filter cell is cold. There are obvious shifts that can be measured precisely in the light spectrum of the filtered lamp when the filter is hot. A study is presently made on the 7947Å line.

Initial study has been made on the maser itself, in order to determine the parameters of equation 1. However, it was soon found that, although some of the parameters could be obtained from the measurements, an absolute tuning of the maser could not be achieved since in our present set-up there is no way to tune the maser by a method which does not produce a systematic shift of the maser frequency at the same time. Consequently, we are planning to perform the experiment in the following way:

- we will study the maser characteristics under the influence of the D_1 line only;
- we will tune the maser by an independent method while the lamp intensity is maintained constant. This will be done by producing transitions in the Zeeman levels at a low frequency. This has the effect of broadening the maser line allowing a simple way of tuning the maser. The method is similar to the one that can be used in the hydrogen maser(9).

3) Maser Theory. The theory of the operation of the maser has been completed, and the results will be published in a future issue of the Canadian Journal of Physics(11). The abstract of this theoretical paper is given in Appendix A. The main conclusion is that we understand well the principles which governs the oscillation conditions of the rubidium 87 maser.

II - Rubidium Gas Cells Studies

Our program on rubidium gas cells studies has been progressing rather rapidly during the last six months period. It is recalled that the idea is to build a bridge system of such a design as to make frequency comparison between two cells pumped by the same lamp or alternately, comparing the output of one cell pumped in alternance by two different lamps. The overall design of the system is shown on figure 5, which is similar to the figure shown in our first semi-annual report.

The whole arrangement thus consists of two complete electronic systems driven by a bridge type of optical package. Up to now, we have one complete branch of the system with its electronics and crystal oscillator, operating. Preliminary stability measurements against a HP Rubidium clock 5065A are under way, and the results are very promissing.

However, some undesirable characteristics have appeared in our first design of the optical package as well as in our electronic systems. We are presently correcting these defects, and the second branch of the system is being constructed according to these findings.

B. SIGNIFICANT CHANGES IN THE APPROACH TO PROBLEMS

No major changes have been done in our approach to the tasks proposed in both projects.

I. Rubidium Masers

In this project, we have kept to the main lines suggested at the beginning, which are:

a) complete the assembly of one NASA Rubidium maser operating with a quartz bulb and a quartz cavity, and study its inherent characteristics;

b) compare it to our own LEQ 1 rubidium maser of a similar design and study the relative stability of both units.

Both these tasks were accomplished.

The only significant changes introduced in our program is the construction of a new maser made entirely of stainless steel which will operate without quartz storage bulb. With this design, a higher cavity Q will be obtained which will permit a higher power output level. This, in principle, should produce better short term stability. Its design is achieved and its construction is completed to about 50%. Its design is shown on figure 6, and figure 7 is a photography of its present state of construction.

II. Rubidium Gas Cells

There are no major changes in our rubidium gas cells program, except for electronic components location, in order to minimize interference between the two branches of the bridge arrangement. At a later date, if necessary, it is possible that we add two synthesizers in our systems such as to be able to use slave oscillators at a nominal frequency of 5 M Hz instead of a sub-multiple of the rubidium frequency as is done presently. However, this is not an essential point in our project, since our frequency comparator has a band pass large enough to allow the use of our present crystal oscillators locked to a sub-harmonic of the rubidium frequency. Nevertheless, it would be preferable to have crystal oscillators at 5 M Hz, in order to compare with other available stable frequencies such as a slave oscillator locked to our hydrogen maser.

C. PROJECTS FOR THE PERIOD ENDING APRIL 1, 1972

I. Rubidium Maser

On the Rubidium Maser program, we are planning to do the following work during the next six months period.

a) We will optimize various parameters of the present operating masers, in order to increase the power output. These parameters are filter temperature, lamp temperature, maser bulb temperature, cavity coupling parameter.

Measurement of stability against averaging time will be made for various power output levels, and comparison with theory will be made (12,13). Long term stability of the maser will also be investigated.

b) We will also complete the study of the light effects on one of the maser and develop at the same time our magnetic quenching method of cavity tuning. The results will be compared with the theory.

c) We will finish the construction of our vacuum tight cavity and put it into operation. We should then be in a position to obtain stability comparison with our present storage bulb type maser.

II. Rubidium Gas Cells

In this project we hope to have solved most of the problems concerning the electronics within the next six months. Effectively, by the end of that period, the two electronic systems should be completed, and measurements of stability and frequency shifts, as a function of various parameters, should start. And it is then, that the real work starts. The question is which, in the arrangement lamp-filter-absorption cell, is the most critical parameter and causes long term drift. We hope to solve this problem in our bridge set-up by studying various combinations of glass cells, buffer gas mixtures and lamp spectra.

REFERENCES

(1) Jacques Vanier, 2nd semi-annual report to National Aeronautics and Space Administration (NGR 52-133-001), April 1971.

(2) P. Davidovits, W.A. Stern, Appl. Phys. Letters, 6, 20, 1965.

(3) Jacques Vanier, Phys. Rev. 168, 129, 1968.

(4) M. Tessier, J. Vanier, Can. J. Phys. 40, 1482, 1971.

(5) Hewlett Packard Application Note 116. "Precision Frequency Measurements."

(6) J.P. Barrat and C. Cohen Tannoudji, J. Phys. Radium, 22, 329, 1961.

(7) Jacques Vanier, Can. J. Phys. 47, 1461, 1968.

(8) E.N. Bazarov and V.P. Gubin, Radio Engineering and Electronics Physics, Vol. 13, No. 8, 1968.

(9) Jacques Vanier, Patent No. 3, 435, 369. "Tuning of atomic masers by magnetic quenching using transverse magnetic fields" (1969).

(10) G. Missout, R. Vaillancourt, M. Têtu, J. Vanier, Revue de Physique Appliquée (Sept. 1971).

(11) M. Tessier, J. Vanier, Can. J. Phys. To be published in a future issue.

(12) L.S. Cutler, C.L. Searle, Proc. IEEE. 54, 136, 1966.

(13) R. Vessot, L. Mueller, J. Vanier. Proc. IEEE 54, 199, 1966.

Figure Captions

Figure 1 -	Design of the "Storage bulb - quartz cavity" type rubidium 87 maser.
Figure 2 -	Block diagram of experimental set-up to study the relative stability of two rubidium masers. The computing counter is a Hewlett Packard 5060A model with its keyboard. It is programmed to give the relative stability directly.
Figure 3 -	Stability of a rubidium 87 maser as measured with the system shown on figure 2.
Figure 4 -	Typical spectra observed on the Fabry Perot interferometer. The trace is alternated between the filtered lamp and a reference lamp by a rotating chopper. Figure 4a is for a lamp without filter, while figure 4b is for a hot filter. In figure 4a the lines coincide, while in figure 4b one line is absorbed by the isotopic filter and the other is shifted.
Figure 5 -	"Double lamp - double cell" bridge system which is used to study the medium and long term stabilities of gas cells.
Figure 6 -	Design of the stainless steel vacuum tight cavity.
Figure 7 -	Vacuum tight cavity: construction stage.

Rb 87 MASER SCHEMATIC DIAGRAM

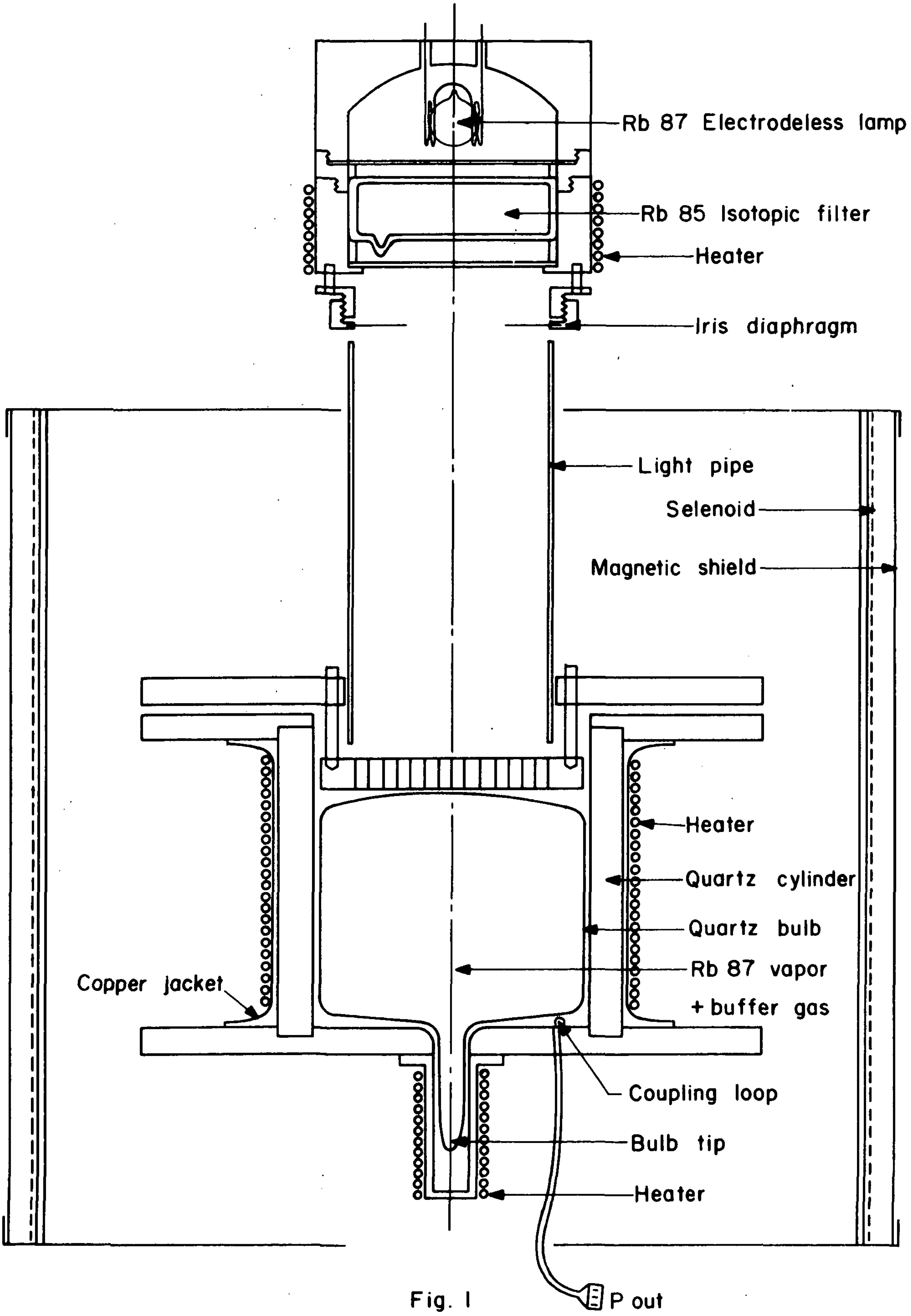

Fig. 1

EXPERIMENTAL SETUP

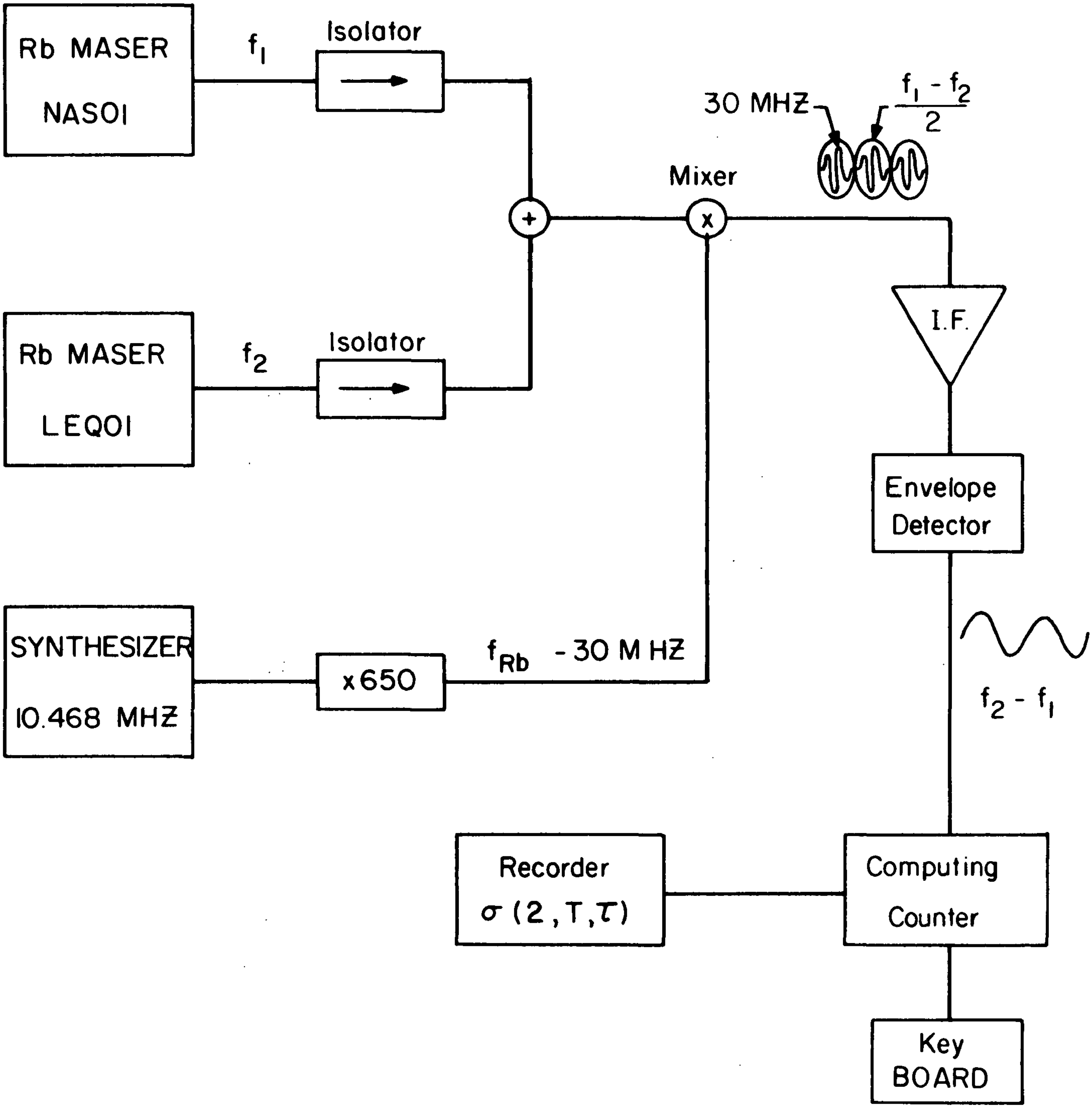

Fig. 2

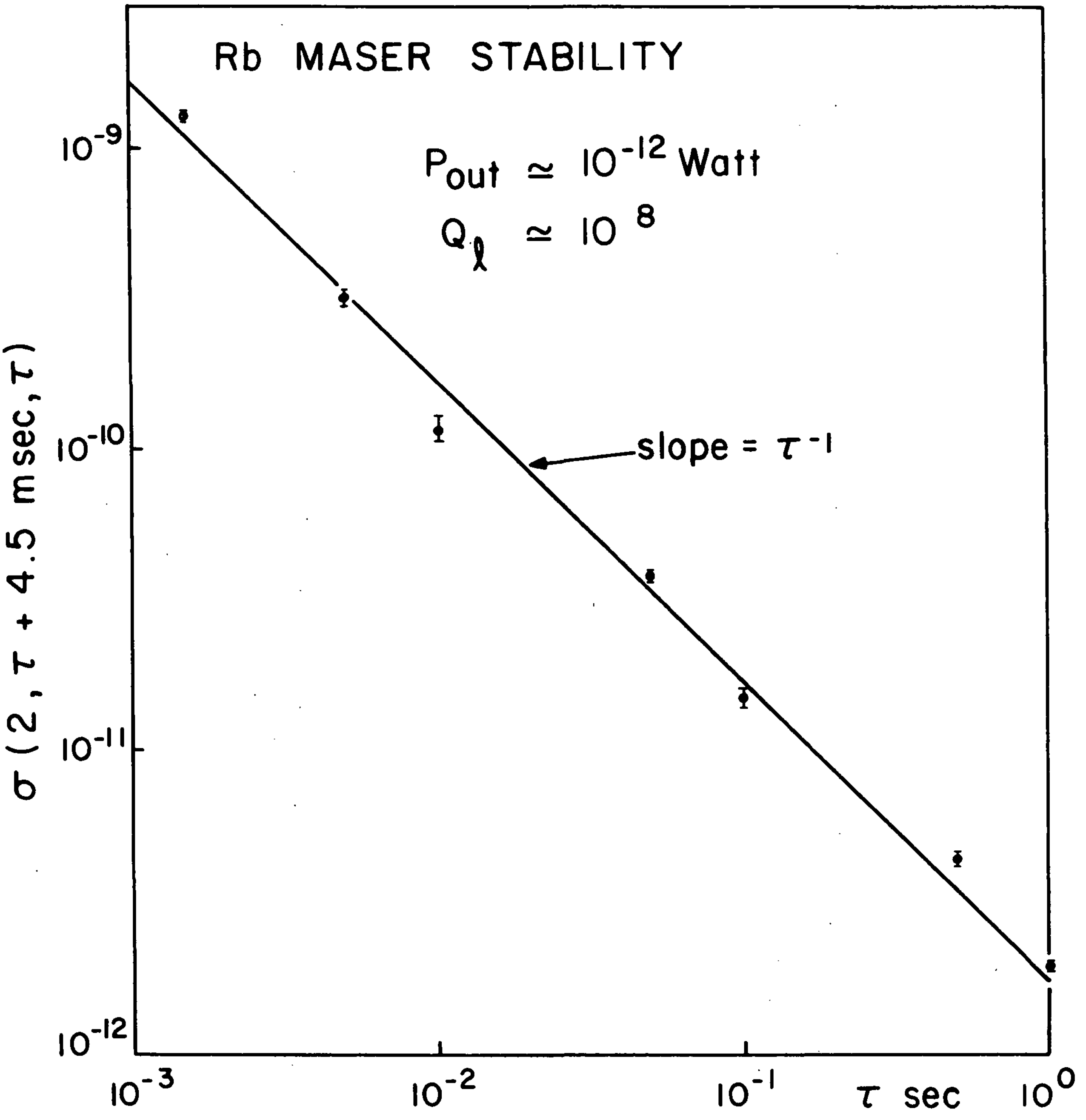
Rb MASER STABILITY
$P_{out} \simeq 10^{-12}$ Watt
$Q_l \simeq 10^{8}$
slope = τ^{-1}
$\sigma(2, \tau + 4.5 \text{ msec}, \tau)$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-3}
10^{-2}
10^{-1}
τ sec
10^{0}

Fig. 3

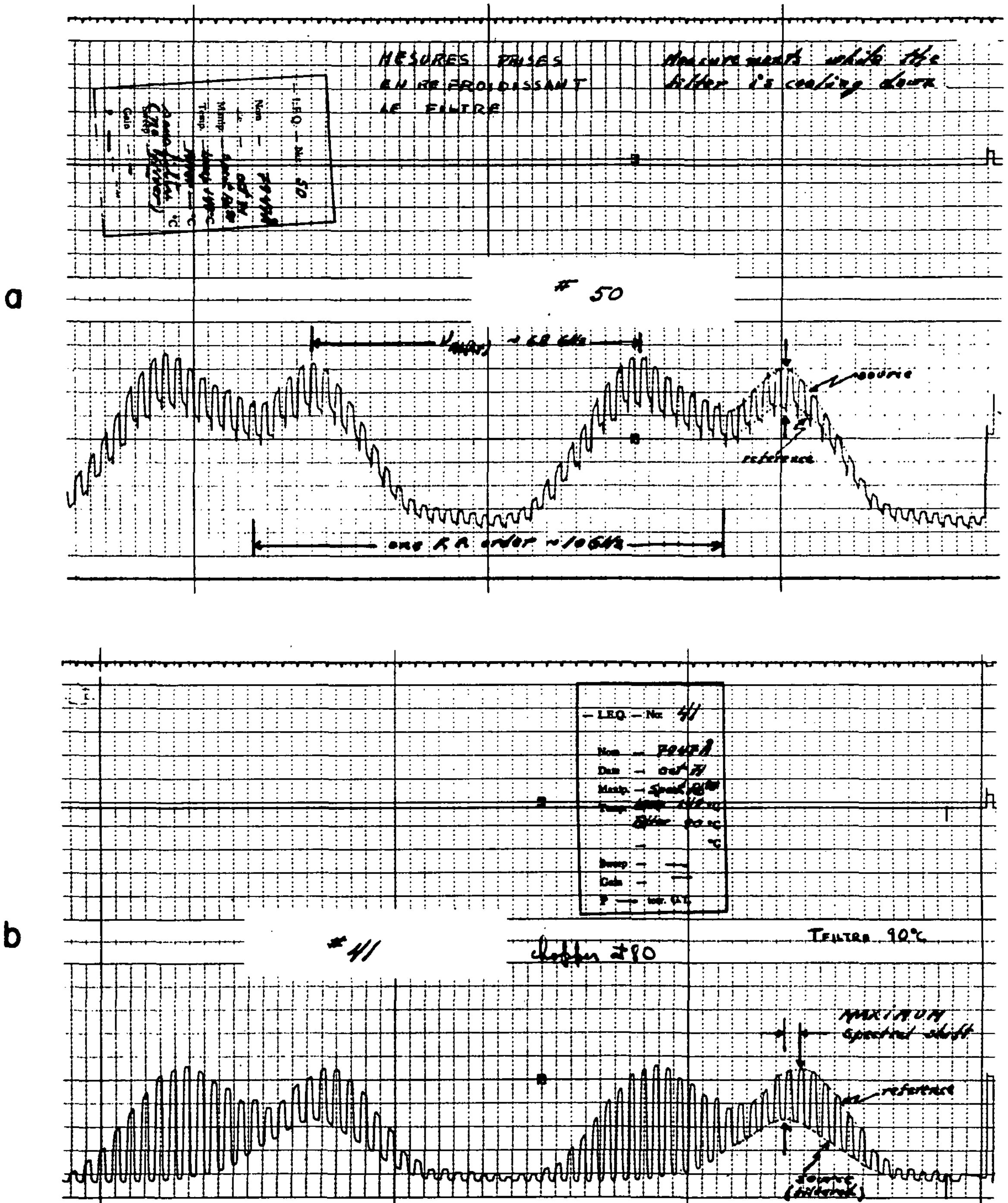a
MESURES PRISES
EN REFROIDISSANT
LE FILTRE
Measurements while the filter is cooling down
L.E.Q. — No 50
Nom
Manip
Temp.
Gain
50
one F.R. order ~10 GHz
source
reference
b
L.E.Q. — No 41
Nom
Date
Manip.
Temp.
filter 90 °C
°C
Sweep
Gain
P
41
chopper ≠ 80
TFILTRE 90°C
MAXIMUM
spectral shift
reference
source
(filtered)

figure 4

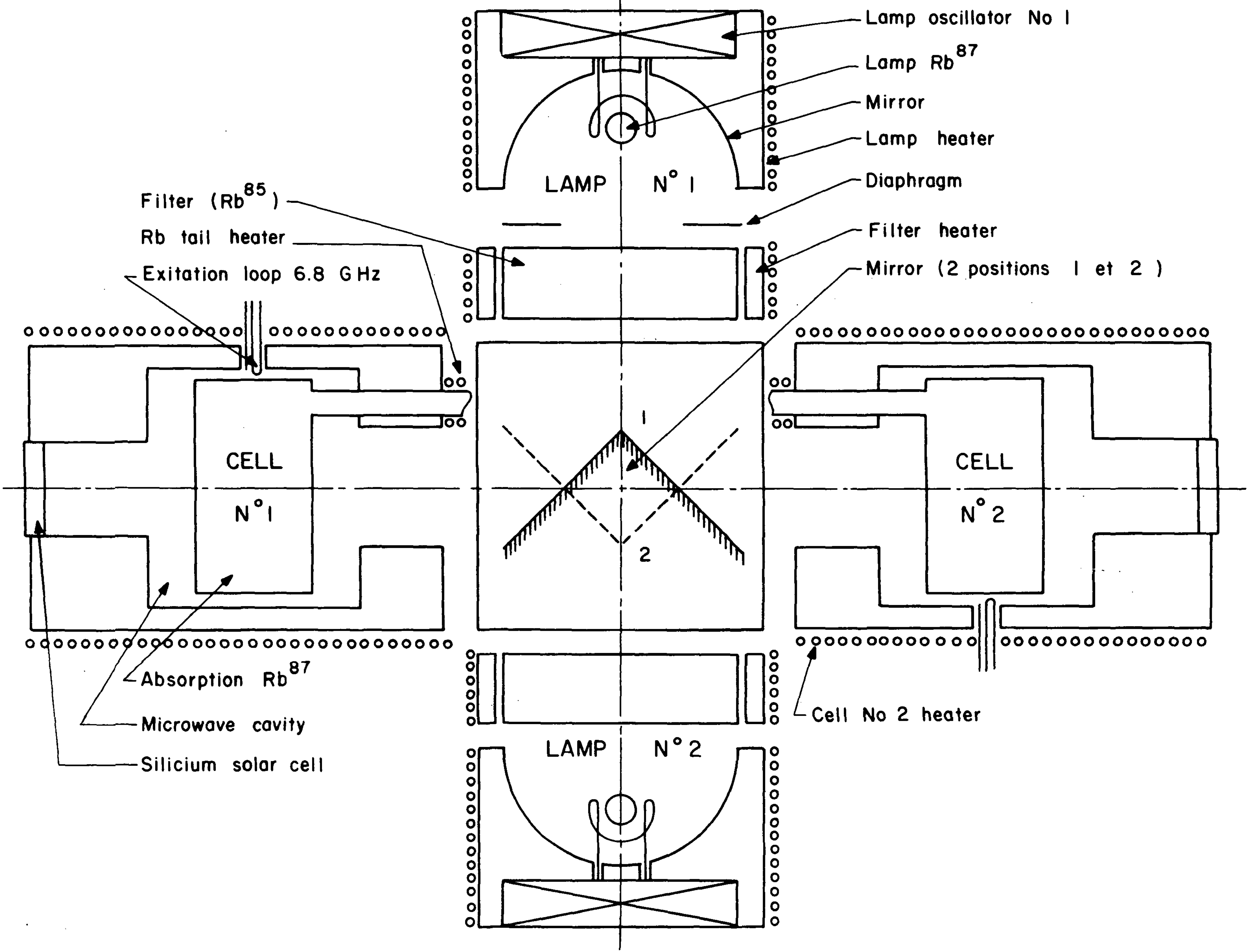
Lamp oscillator No 1
Lamp Rb^{87}
Mirror
Lamp heater
LAMP N° 1
Diaphragm
Filter (Rb^{85})
Rb tail heater
Filter heater
Exitation loop 6.8 GHz
Mirror (2 positions 1 et 2)
1
2
CELL N° 1
CELL N° 2
Absorption Rb^{87}
Microwave cavity
Silicium solar cell
Cell No 2 heater
LAMP N° 2

Figure 5

Rb87 MASER

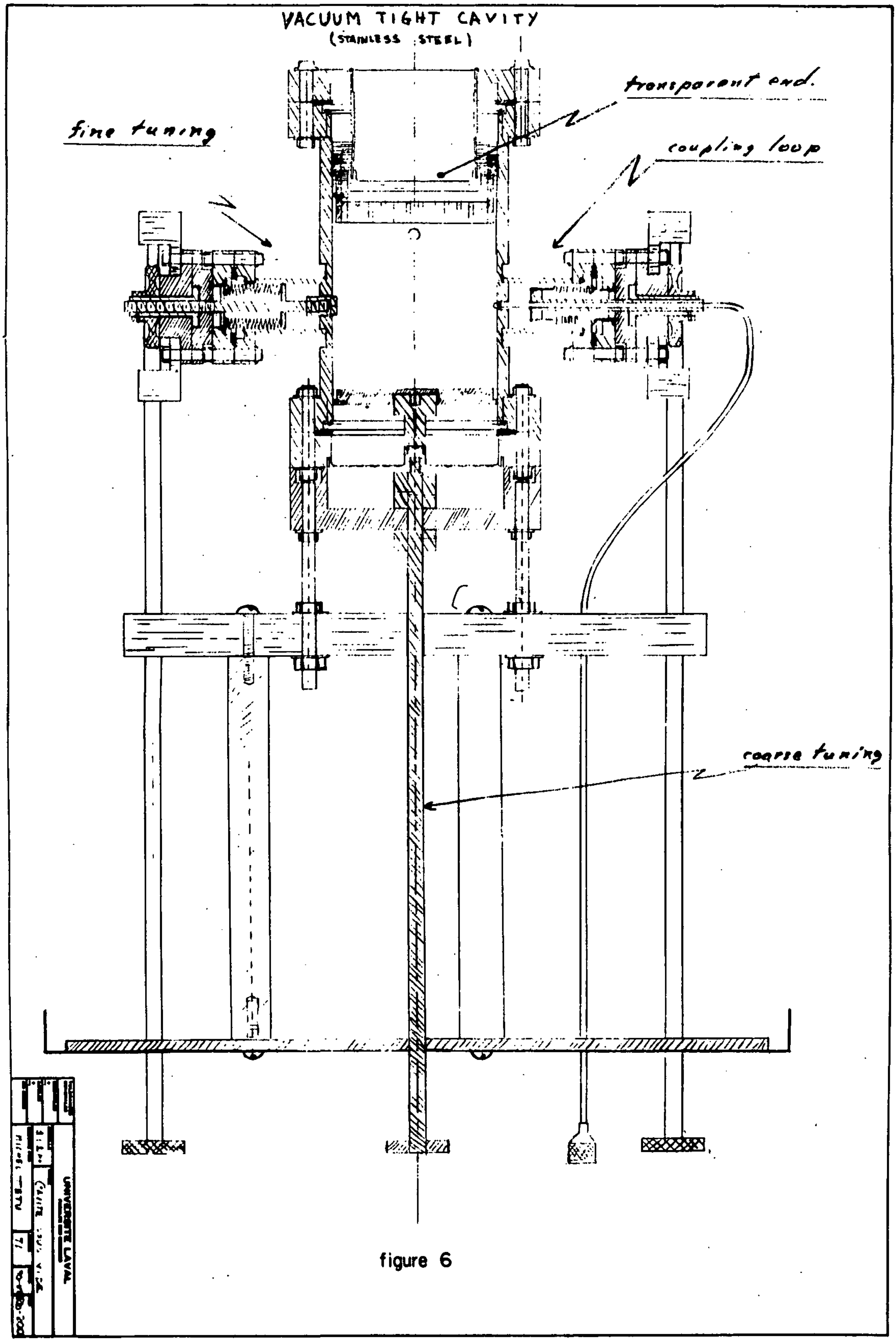

figure 6

Figure 7

APPENDIX A

Rubidium 87 Maser Theory

M. Tessier et J. Vanier
C.R.A.M. Laboratoire d'Electronique Quantique
Département de Génie électrique
Université Laval, Québec 10, CANADA

ABSTRACT:

The paper describes calculations made on the power output of the rubidium 87 maser, taking into account local variations of the optical pumping rate and of the density matrix elements associated with the problem. The results obtained agree well with published experimental data.

Théorie du maser au rubidium 87*

RESUME:

On effectue le calcul de la puissance de sortie du Maser à rubidium 87 en tenant compte des variations locales du taux de pompage et des termes de la matrice densité associée au problème. Les résultats obtenus confirment assez bien les résultats expérimentaux obtenus à ce jour.

---

* This paper is being published in French and will appear in a future issue of the Canadian Journal of Physics. In our final report, we will present an English version of the calculations.