HYDROGEN MASER DESIGN AT THE LABORATOIRE DE L'HORLOGE ATOMIQUE

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ABSTRACT

A description is given of some specific features of the Laboratoire de l'Horloge Atomique masers, together with a discussion of the reasons of their choice. The performances achieved are given, with and without action of a classical autotuning system. Some possible improvements are also described.

INTRODUCTION

Besides two experimental hydrogen masers, two reference hydrogen masers are in operation at the Laboratoire de l'Horloge Atomique since 1972. Fig. 1 shows a schematic drawing of these masers, designed for operation in laboratory conditions. We describe their specific features and the performances obtained. The technical choices are discussed, as well as possible improvements.

SPECIFIC FEATURES OF THE REFERENCE MASER

Three major points will be considered : the production of the beam of atomic hydrogen, with a difference of population between the levels involved in the maser transition, the storage of the atoms in the microwave cavity, and the maser signal processing.

PALLADIUM PURIFIER

It is designed to give a fast response time to the hydrogen flow regulator, so that the dead time while the cavity is tuned by varying the beam intensity is very small.

a. Low thermal inertia palladium purifier

The palladium-silver alloy, shaped as a glove finger, is heated directly (Fig. 2) [1]. The hydrogen gas under high pressure (3 x 10^5 Pa (3 bars)) is located inside the palladium tube, so that the heat transfer to the surrounding is minimized. The working pressure of 7 Pa (5 x 10^{-2} torr) is obtained with a current of 2.5 A in the glove finger. The corresponding heating power is 0.4 W only ; the measured thermal inertia of the palladium leak equals 4 s.

b. Source pressure regulator

A pressure gauge is made with a thermistor, with a small thermal inertia. A simple electronic system maintains constant the value of its electrical resistance, and therefore the value of its temperature for all the useful values of the hydrogen pressure. This electronic system provides to the thermistor the electric power which compensates its thermal losses. The heating current is alternating, with a frequency of 15 kHz, in order to avoid the drifts associated with the operation of a DC current pressure gauge. The emf of the source providing the power to the thermistor, which is a function of the hydrogen pressure, is detected at a high signal level and compared to an adjustable reference voltage in order to servo the heating current of the palladium leak and to maintain the source pressure at the desired level.

The time constants in the servo loop are the time constant of the palladium (4 s), the time constant of the pressure gauge (10^{-2} s), the pumping time of the gas in the source (1.5 s) and the transit time of the gas between the palladium and the gauge (0.5 s).

c. Performances

Fig. 3 shows the response of this pressure regulator to steps of the reference voltage. The pressure, measured by the gauge, is established within 20 s. This time could be reduced by a factor of 2 by decreasing the transit time of the hydrogen gas between the palladium leak and the discharge tube [1].

The stability of the pressure source is quite good : the drift is smaller than 1 % per day for a working pressure of 13 Pa (0.1 torr).

HYDROGEN DISSOCIATOR

Molecular hydrogen is dissociated in a cylindrical discharge tube, 2 cm in diameter and 20 cm long. The mean time spent by a molecule in the discharge is long, so that its dissociation probability is very high.

The atomic beam is issued from a single cylindrical tube, coaxial with the discharge tube. This design is easy to implement, and does not significantly affect the directivity of the beam and the efficiency of the dissociation : the measured atomic concentration in the beam is of the order of 0.6 for a working pressure of 13 Pa (0.1 torr) [2].

STATE SELECTOR

The pole tips of the hexapole are shaped in order to fit the theoretical equipotentiel curves [3]. The measured field repartition in the magnet is very close to the theoretical field repartition, as shown in fig. 4. Consequently, the effective diameter of the magnetic lens is very close to the physical diameter of the magnet, allowing an efficient use of the atomic flux issued from the source, and the optical properties of the magnetic lens can be calculated for a given velocity distribution in the beam [4].

CAVITY PULLING

In order to lower the cavity pulling effects, it is necessary, for a given atomic line width, to reduce the thermal coefficient of the cavity, to control its temperature, and to tune it properly.

a. Thermal compensation of the cavity

The cavity is made of quartz, with metallic compensation rods. The compensation is adjusted in order to be effective for the cavity loaded by the storage bulb. The cavity is enclosed in a thermal shield situated inside the vacuum tank. In a recent realization, the measured thermal coefficient is of the order of 0.1 kHz K^{-1}.

b. Thermal control of the cavity

The temperature of the cavity is regulated within 10^{-3} K for 20 days and 10^{-2} K for four years.

The thermal control is provided by three concentric ovens ; each of them being divided into three independently regulated parts :

- the magnetic shield n° 2 (the two end caps and the lateral wall). Its temperature is maintained at about 28° C.

- the magnetic shield n° 5 (the two end caps and the lateral wall). Its temperature is maintained at about 43° C.

- the copper tank enclosing the cavity. The lateral part of the tank and the upper part of the pumping tube are maintained at 48° C. The lower part of the pumping tube, made of stainless steel, is maintained at 35° C at the level of shield n° 2.

The separation between each magnetic shield is filled with a thermal insulator.

The microwave cavity itself and the storage bulb are thermally insulated from their enclosure, being supported by quartz posts. A cupper cup is set at the top of the pumping tube, in good thermal contact with the copper vacuum tank. It prevents, as much as possible, thermal radiation exchanges with lower parts of the maser. The time constant of the temperature variations of the cavity is 15 hours about.

The temperature sensors are thermistors, which are maintained in two opposite arms of a Wheatstone bridge.

The voltage produced by temperature fluctuations is amplified by a low drift operational amplifier and determines the duty cycle of a multivibrator. The period of the pulses is about 1 ms. Their width determine the heating power.

The output transistor of the circuit is used as a switch, and the power efficiency is very good.

The heating current feeds a resistive coaxial cable. The inner conductor is a thin copper wire. The outer conductor, also made of copper, is externaly insulated with teflon. The cable is glued to the wall which is to be controlled. The thermistors are in good thermal contact with the wall, and as close as possible to the heating cable, in order to reduce the delay due to the heat propagation time.

We never observed any trouble in the maser operation due to the use of pulsed heating current when every conductor inside the magnetic shields is coaxial.

The performances obtained have been measured by the cavity pulling, using a cavity with a large thermal coefficient (1.5 kHz K^{-1}), for the 1 mK stability over 20 days, and by a direct measurement of the cavity temperature, via a platinum resistance temperature transducer for the 10 mK stability over 4 years.

MAGNETIC FIELD

The atoms are shielded from spurious magnetic field variations by six magnetic shields, all made of mumetal, with a thickness of 2 mm. The fluctuations of the magnetic field which is applied to the hydrogen atoms, due to magnetic noise in the laboratory has been measured on an experimental maser equipped with similar shields. The measurement of the frequency stability of the field dependent $\Delta F = 1$, $\Delta m = 1$ transition [5] showed that the fluctuations are of the order of 10^{-11} T (0.1 microgauss) only.

COLLISIONS WITH RESIDUAL GASES AND WITH THE WALL OF THE STORAGE BULB

Collisions with paramagnetic gases may have important effects on the atomic frequency and relaxation times [6].

The best way to get rid of these spurious effects is to maintain as good as possible a vacuum. This is the reason why we use two vacuum pumps and two separate vacuum chambers, made of stainless steel or copper (inside the magnetic shields). Only metallic gaskets are used.

MICROWAVE SIGNAL PROCESSING : ELECTRONIC CIRCUITS WITH NO SPURIOUS PHASE SHIFT ASSOCIATED WITH VARIATIONS OF THE SIGNAL LEVEL

When a hydrogen maser is used as a frequency or time standard, its cavity is tuned by the classical "frequency method" tuning. In this method, the atomic linewidth is modulated and the cavity is tuned in order to cancel any frequency modulation associated with the linewidth modulation. The level of the oscillation varies with the atomic linewidth. If the receiver introduces phase shifts related to the level of the signal, these phase shifts affect the short term frequency stability of the frequency standard.

Furthermore, the application of an alternative method for the cavity tuning critically depends on the use of electronic circuits showing, as far as possible, a level independent phase shift. In this application, the level correlated spurious phase shift must be smaller than a few 10^{-3} degree for amplitude variation of 3 dB.

These phase shifts are due to non linearities in bipolar transistors parameters and to thermal effects.

It has been shown [7] that the non linearities of the transistor parameters are proportional to the square of the voltage amplitude and to the phase lag in the considered circuit.

In low frequencies amplifiers, the thermal effects result of the variation of the electrical parameters of the transistors which are induced by the variations of the power dissipated in the transistors. This variation has a component in quadrature with the collector current, owing to the thermal inertia of the device. An amplitude dependent phase shift may result.

This effect can be avoided if the transistor is polarized for an extremum (maximum) power dissipation : the fundamental of the parameters variations then disappears.

We have built 5.75 kHz amplifiers (Fig. 5) according to the following design rules :

- transistors with a large transition frequency are used
- the collector to base voltages are high enough to reduce the voltage dependence of the collector to base capacitor
- the high frequency cut-off is as large as possible, and the low frequency cut-off as small as possible
- the collector is polarized for the maximum value of the dissipated power
- feedback in the emitter circuit reduces the distorsion rate and linearizes the input impedance
- the output voltage must not be too large : the maximum amplitude is 1 V at 5 kHz and 0.1 V at 500 kHz.

On the other hand, it is known that phase comparators are not ideal devices and that a modulation of the amplitude of the signal induces a modulation in the D.C. output, even when the signal and the reference are very close to the quadrature condition. Consequently, the use in the phase-lock loop of an amplitude limiter showing a level independent phase shift is of prime importance when the maser oscillation level is modulated.

Such amplitude limiters, at a working frequency of 5.75 kHz, have been built (Fig. 6), according to the Franck's [8] analysis of the wave form dependent phase shift.

Various tests on amplifiers and amplitude limiters give confidence that the achieved amplitude correlated phase shift is much smaller than 10^{-2} degree for amplitude variations of 3 dB.

PERFORMANCES OF THE TWO REFERENCE MASERS

We have not yet performed a direct precise measurement of the wall shift in our reference masers. Such a measurement will be possible in a near future, using the double bulb device described later.

FREQUENCY STABILITY WITHOUT AUTOTUNING SYSTEM

The signals delivered at the output of the 1420 MHz low noise amplifier of the two reference masers are mixed and applied to the input stage of an electronic heterodyne receiver. After detection, the beat note is filtered in a low pass filter, with a bandwidth of 6 Hz. The difference in frequency between the two masers is set between 0.1 and 1 Hz by adjusting the magnetic field.

Fig. 7 shows a plot of the root mean square of the Allan variance of each maser, the statistical properties of which being assumed to be identical.

For each value of the averaging time τ, ($\tau < 10^4$ s) each experimental point is determined from a series of more than 100 samples. The uncertainty in the estimation of the Allan variance is then less than 10 % [9].

The fractional frequency stability is $4 \times 10^{-13}/\tau$ for $1\ s < \tau < 40\ s$ and 3×10^{-15} for $\tau = 1000$ s (for that last figure, 600 non selected data points of a continuous run have been used to compute the Allan variance). The daily frequency fluctuations equal a few parts in 10^{14}.

FREQUENCY STABILITY WITH AN AUTOTUNING SYSTEM

A classical autotuning system has been built and tested. The frequency of the 5 MHz quartz crystal, phase locked to the maser under tuning, is measured for high flux and low flux.

The difference between the two results is used to tune the cavity. In this device, the frequency is not measured while the flux changes (the dead time equals 30 s, which is longer than the time needed for the pressure change in the source).

Fig. 7 shows the frequency stability of the phase locked 5 MHz quartz crystal oscillators multiplied up to 400 MHz. The frequency stability measurement data are taken continuously, even when the flux is varying, and without correlation with the atomic flux modulation. The short term frequency stability could be improved by using better frequency multipliers in the phase lock loop.

POSSIBLE IMPROVEMENTS

ADIABATIC RAPID PASSAGE

This device, which reduces the spin exchange relaxation rate without affecting the density of useful atoms in the bulb has been successfully tested in the past in an experimental maser [10]

PHASE METHOD FOR THE TUNING OF THE CAVITY

It has been shown [5] that if the level of the maser oscillation is varied, without affecting the atomic linewidth (for instance, by varying the beam composition without affecting the total beam flux), the phase of the maser oscillation varies, unless the cavity is tuned to a particular value.

For this particular value, the maser angular frequency $\omega_{(\Delta\phi=0)}$ differs from the atomic angular frequency by the quantity

$$\Delta\omega_{(\Delta\phi=0)} = 2\ \varepsilon_H\ \gamma_{2e} \tag{1}$$

where $\varepsilon_H = (4.04 \pm 0.35)\ 10^{-4}$ at room temperature [6]. ε_H is the parameter describing the effect of the duration of hydrogen-hydrogen spin exchange collisions [6], and γ_{2e} is the transverse relaxation rate associated with spin exchange.

On the other hand, the classical linewidth method tuning leads to an oscillation angular frequency $\omega_{(\Delta F=0)}$ which differs from the atomic angular frequency by the quantity :

$$\Delta\omega_{(\Delta F=0)} = -2\ \varepsilon_H\ \gamma_{20} \tag{2}$$

where γ_{20} is the transverse relaxation rate not depending on the atomic density in the storage bulb.

The values $\Delta\omega_{(\Delta F=0)}$ and $\Delta\omega_{(\Delta\phi=0)}$ can be measured within 10 % since ε_H is known within this error [6] and γ_{20} and γ_{2e} can be measured with an uncertainty of a few percents [11]. This uncertainty on the value of $\Delta\omega_{(\Delta F=0)}$ and $\Delta\omega_{(\Delta\phi=0)}$ leads to a relative uncertainty of a few parts in 10^{14} on the maser frequency.

Consequently, the phase method can be used as well as the classical method. One must keep in mind that the oscillation frequency of the maser tuned by the phase method slightly depends on the density in the bulb : a γ_{2e} fluctuation of 0.1 s^{-1} leads to a fractional frequency fluctuation smaller than 1 part in 10^{14} at room temperature.

The difference between the two frequencies $\omega_{(\Delta\phi=0)}$ and $\omega_{(\Delta F=0)}$ is :

$$\omega_{(\Delta\phi=0)} - \omega_{(\Delta F=0)} = 2\,\varepsilon_H\,\gamma_2 \qquad (3)$$

(it is worth noticing that this formula could be used for a measurement of the ε_H parameter).

The phase method has been successfully tested : the modulation of the level of oscillation was obtained by modulating the beam composition. This was accomplished by switching on and off a DC current in a coil, coaxial to the beam, and located between the state selector and the storage bulb entrance. The period of the modulation was 4 s.

The experiment was made possible by the use of the electronic circuits described in the previous section.

The experimental results are shown in Fig. 8 where the phase variation $\Delta\phi$ is referred to the maser oscillation frequency of 1.42 GHz.

The origin of the horizontal axis is set at the frequency $\omega_{(\Delta F=0)}$ delivered by the maser tuned according to the classical method. The errors bars are determined from the level of residual noise affecting the measured voltage.

The line crosses the horizontal axis for $\Delta f/f_o = (0.25 \pm 0.8) \times 10^{-13}$ whereas the fractional frequency shift should be 2.8×10^{-13} as given by equation (3). This apparent smal discrepancy is likely connected to the joint effect of inhomogeneïties in the static magnetic field and the microwave field [6] as already observed for the classical method of tuning of the cavity [12].

The fundamental advantage of the phase method should be a large reduction of the period of modulation (i.e. 4 s instead of 300 s when the beam intensity is modulated). Consequently, the flicker noise of frequency of a crystal frequency source, if used as a frequency reference in the autotuning system, would contribute to a smaller extent to the noise in the error signal which is used to tune the cavity.

DOUBLE STORAGE BULB DESIGN

The standard method for measuring the frequency shift due to the atomic collisions on the wall of the storage bulb consists in measuring the maser oscillation frequency as a function of the collision frequency by using bulbs of various diameters. It is also possible to vary the collision frequency by using a single bulb with a variable shape[13].
These last devices imply the use of a flexible teflon sheet which is submitted to different stresses for the different configurations.
We are studying a double configuration bulb without any flexible sheet and which allows a large variation of the collision frequency. Fig. 9 shows the principle of this bulb. The two collision frequencies are obtained, for a given temperature, for the two positions of the valve. They differ by a factor of 1.85.
The oscillation is maintained for the two positions of the plate, and for bulb and cavity temperature between 293 and 393 K with a good frequency stability.

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FIGURE CAPTIONS

Fig. 1 - Simplified representation of the structure of the masers

Fig. 2 - Mechanical assembly of the palladium-silver leak

Fig. 3 - Response of the pressure regulator to steps of the reference voltage

Fig. 4 - Measured magnetic field variations as a function of the distance to the axis of the hexapole magnet

Fig. 5 - Amplifier at 5.75 kHz with a gain of 40 dB

Fig. 6 - Basic circuit for amplitude limiter

Fig. 7 - Plot of the root mean square of the Allan variance

1 for the reference masers without autotuning

2 for the reference masers with an autotuning system

Fig. 8 - Experimental results for the test of the phase method for the cavity tuning

Fig. 9 - Double storage bulb set-up

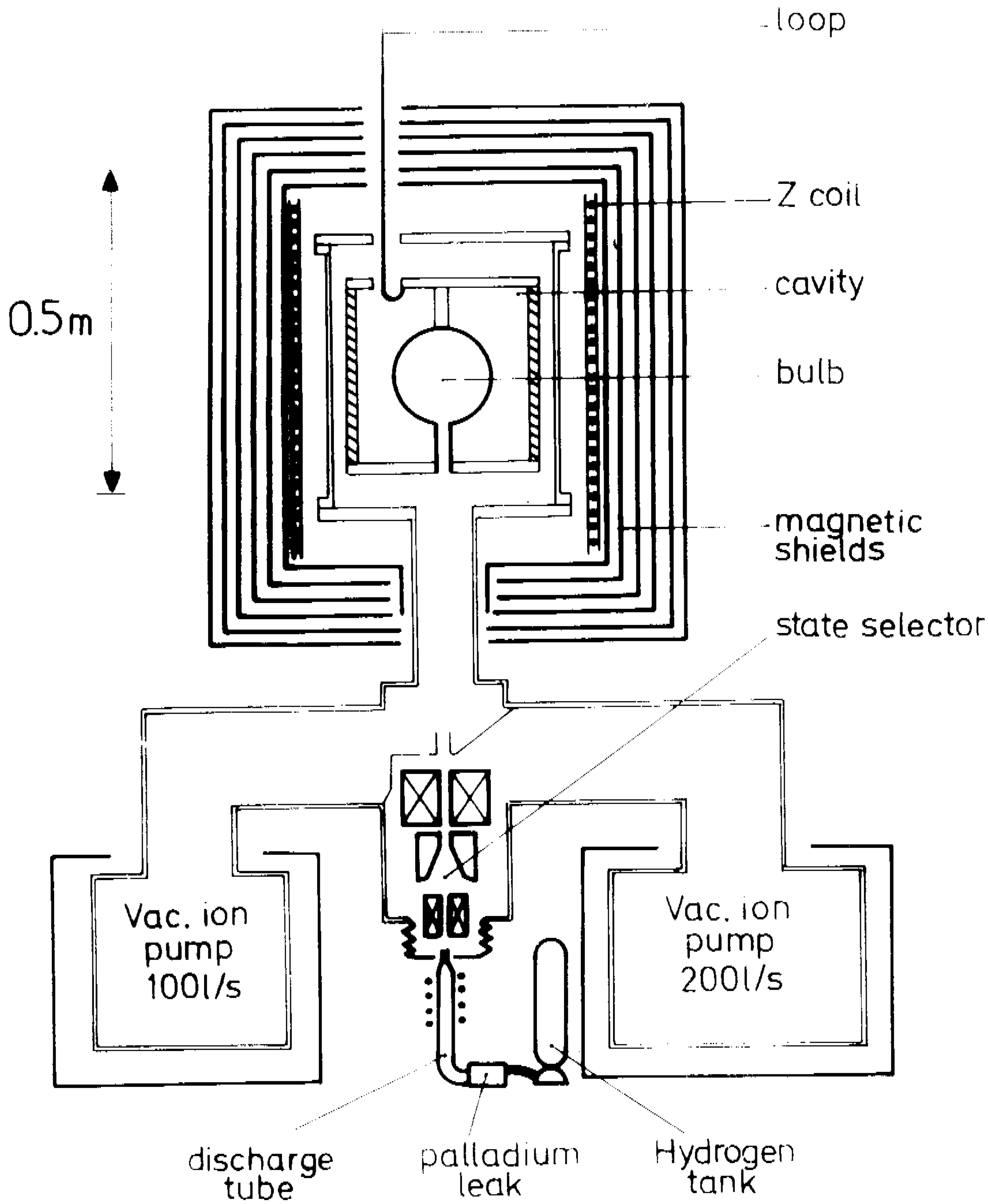

Fig.1_Simplified representation of the structure of the masers

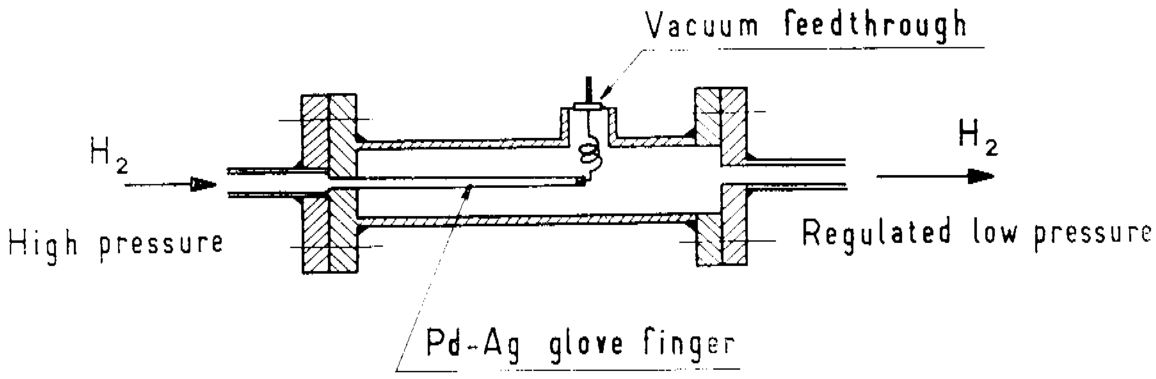

Fig. 2 _ Mechanical assembly of the palladium-silver leak

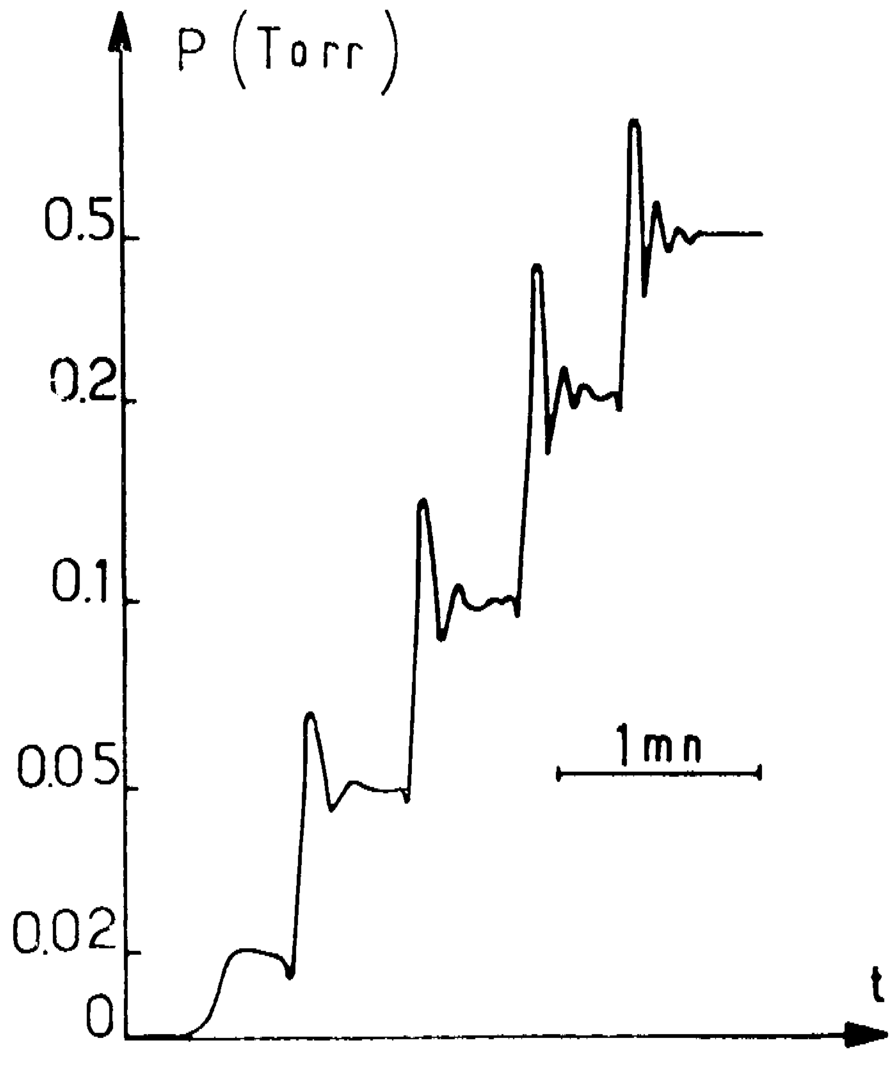

Fig. 3-Response of the pressure regulator to steps of the reference voltage

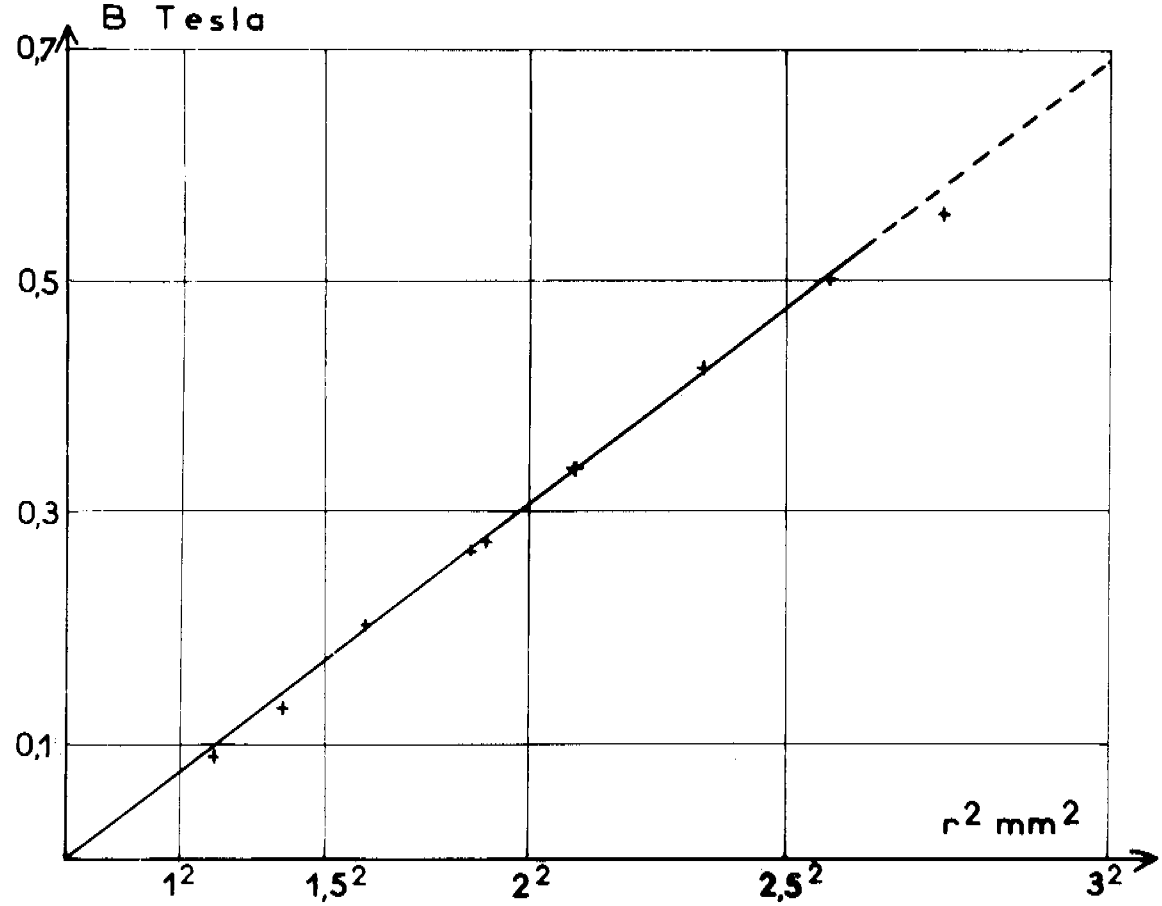

Fig.4 _ Measured magnetic field variations as a fonction of the distance to the axis of the hexapole magnet

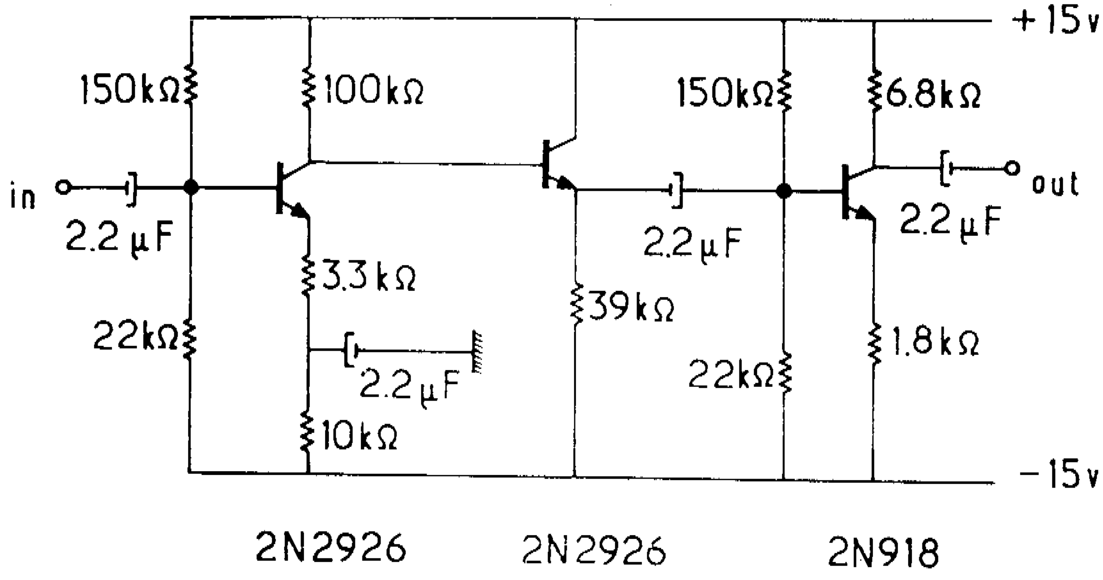

Fig.5 — Amplifier at 5.75kHz with a gain of 40dB

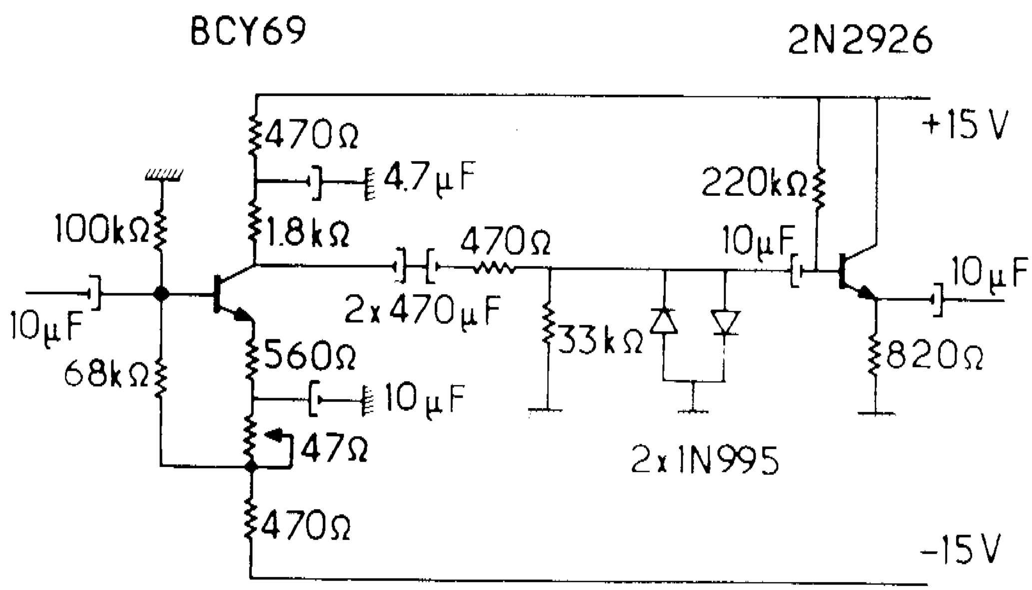

Fig.6 — Basic circuit for amplitude limiter

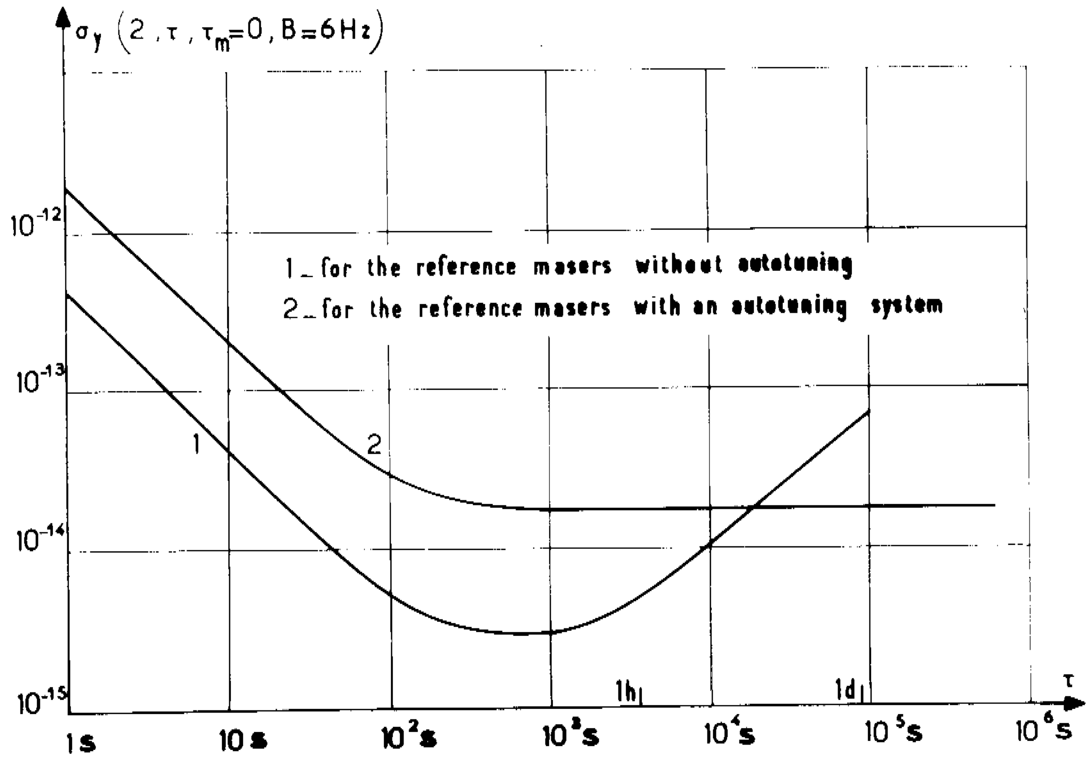

Fig.7 _ Plot of the root mean square of the Allan variance

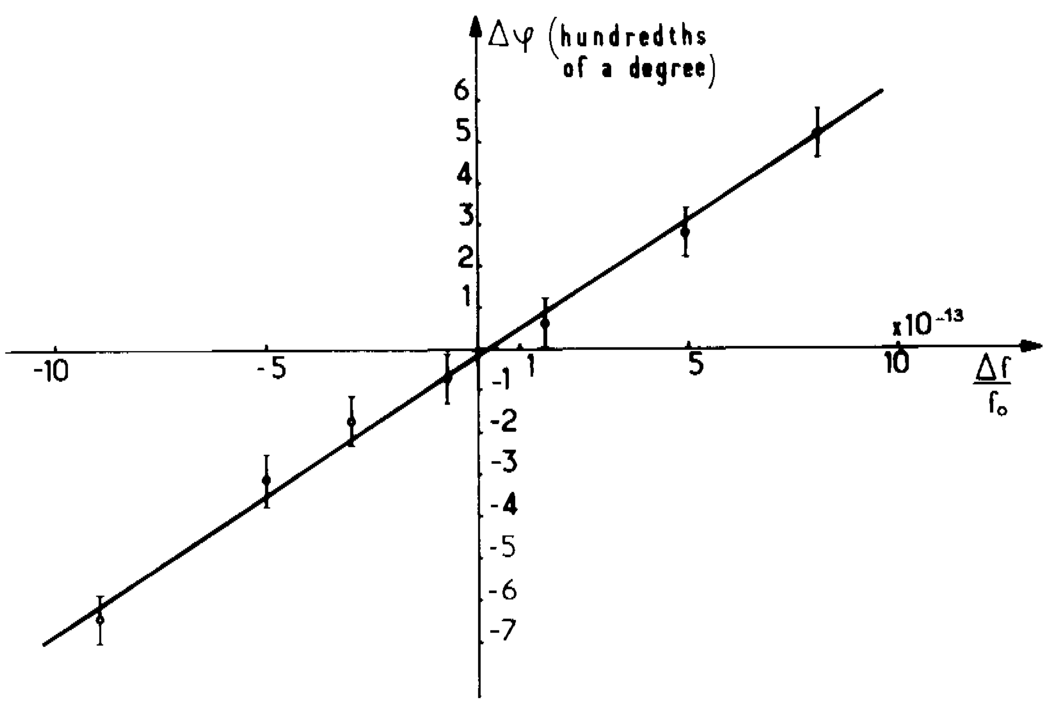

Fig.8 _ Experimental results for the test of the phase method for the cavity tuning

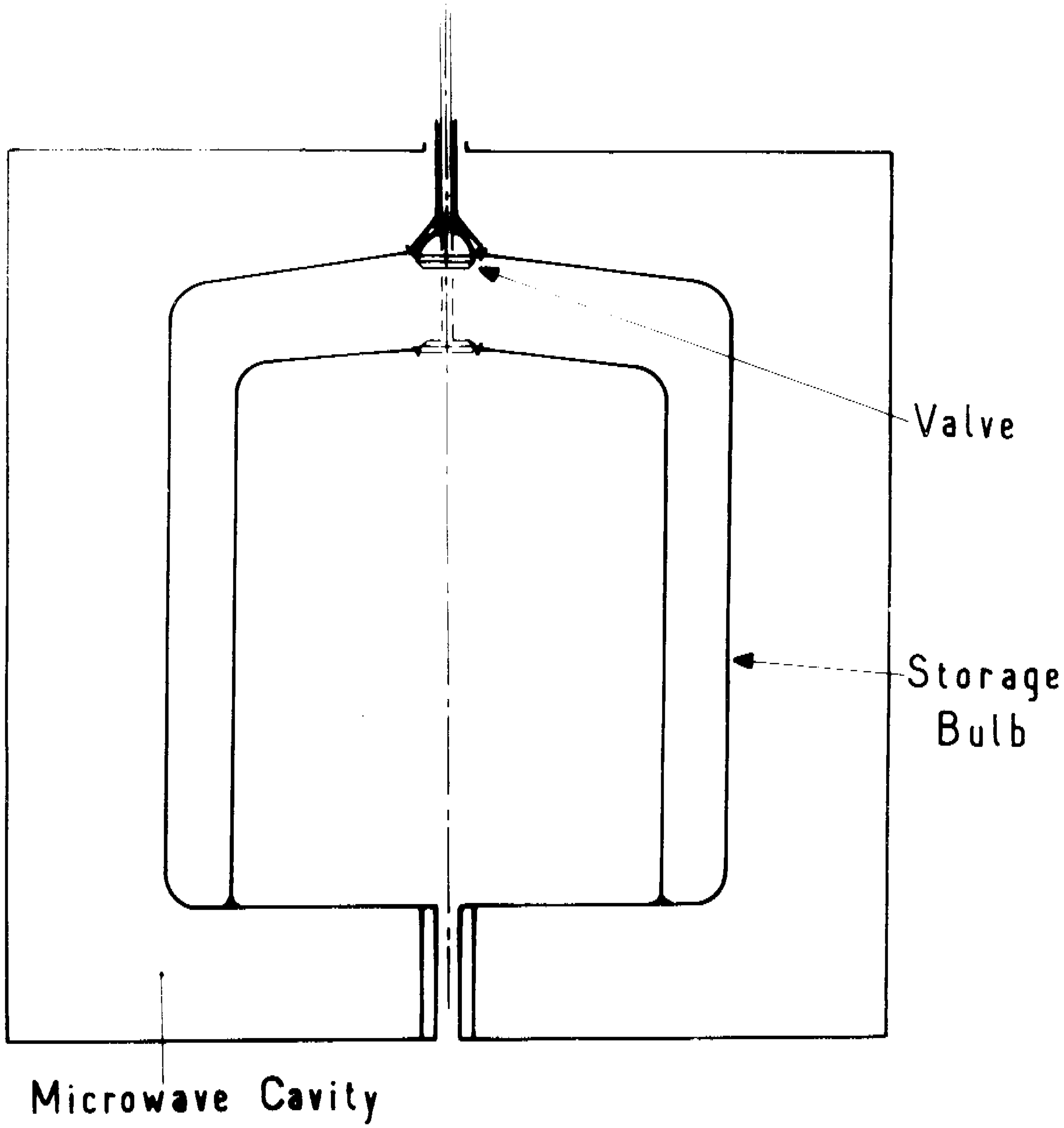

Fig.9 — Double storage bulb set-up