PROGRESS IN THE DEVELOPMENT OF IEM KVARZ PASSIVE HYDROGEN MASERS

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Abstract

This paper presents progress in development of the passive hydrogen masers at IEM KVARZ. The passive hydrogen maser physics package and electronic systems are described and the results of measurements of the passive maser's frequency stability and its immunity to variations in external temperature and magnetic field are reported.

1. INTRODUCTION

Passive hydrogen masers, developed during the last fifteen years, combine the highest short-and long-term stability with small dimensions of a top-bench instrument. A passive hydrogen maser frequency stability is typically better than 1×10^{-12} per sec and 1×10^{-14} per day. This is much better than in cesium standards.

The high stability of a passive hydrogen maser depends primarily on the physics package having a very high Q_l (quality hydrogen emission line) . The main sources of passive maser frequency instability are the same as in an active hydrogen maser, namely: cavity frequency detuning, aging of the wall shift, magnetic field, and beam flux system instability.

At present IEM KVARZ is producing the passive hydrogen maser CH1-76, which is successfully in use in various laboratories in Russia and many other countries. Some results of its study were reported earlier [1,2].

This paper reports on the development and some resulting studies of the new passive hydrogen maser featuring smaller dimensions, weight, power consumption that can work in more severe environmental conditions than the previous model.

2. PHYSICS PACKAGE

The design of the physics package of the passive hydrogen maser is given in Fig.1.

The "magnetronic" cavity constitutes the basis of the physics package of the passive hydrogen maser [3]. In this cavity metal plates are fixed to the lateral surface of the cavity, manufactured from a monolithic aluminium block (Fig.2). The cavity length is 200 mm and diameter 120 mm. Such cavity construction ensures high mechanical rigidity and reliability. High Q_c –factor ($Q_c=10^4$) and high value of filling factor η (η=2,5), defined as $\eta=\langle B_z\rangle^2_{bulb}/\langle B^2\rangle_{cavity}$ (where $\langle B_z\rangle^2_{bulb}$ is the mean value of the axial component of the amplitude of the magnetic field averaged over the storage bulb volume), provide the passive maser amplification of over 6 – 8 dB.

The storage bulb is made of quartz glass in the form of a cylinder of 0.45 l volume. The inner surface of the bulb is coated with 3 layers of fluroplastic, type F-4 MD.
The atomic hydrogen source is made of quartz glass in the form of cylinder of 30 mm diameter and 40 mm height. The source is connected to the vacuum pump by an indium gasket. The output source channel (collimator) is a set of 200-250 channels of 13 µm diameter and 0.65 mm length each. This provides the hydrogen atom beam flux.

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Hydrogen dissociation is performed by molecular impact ionization in the electromagnetic field of the RF-generator-coil. RF-generator power is typically 12W. The magnetic state selection is performed by means of a quadrupole magnet. The bore diameter of the magnet is 1.6 mm, its length is 75 mm,and outer diameter is 30 mm. The magnetic induction at the pole tips is 1T.

The compound $LaNi_5H_x$ (about 250g), placed into the metal bulb, is used as molecular hydrogen source. It consists of 20-25 liters of hydrogen at normal pressure that is sufficient for more than 15 years of continuous maser operation. The bulb with molecular hydrogen has a vacuum-tight connection to the purifier. Nickel tube of 0.4 mm diameter and 0.05 mm wall-thickness coiled for compactness is used as purifier. The hydrogen flux is controlled by purifier temperature. Purifier power consumption is about 1 W.

Thermal cavity stabilization is ensured by the two-zone oven placed in vacuum. The temperature is controlled to 0.01°C over the environmental temperature range. Oven power consumption is typically < 1 W.

The maser has a four layer permalloy magnetic shield system. Three of them are located in vacuum and made of 81 NMA permalloy of 0.5 mm thickness. The fourth shield made of 79 NMA permalloy covers all discriminator construction with vacuum pumps and hydrogen beam source. To prevent undesirable mixing of Zeeman sub-levels in the drift region, a ring magnet is placed on the discharge bulb of the hydrogen beam source to assure a smooth transition between the quadrupole magnet and the apertures of the magnetic shields.

The maser has two separated vacuum chambers. The first one includes the storage bulb, state selector magnet, and atomic hydrogen source, whilst the second one includes cavity ovens and magnetic shields. Such a construction achieves excellent vacuum conditions in the storage bulb. Hydrogen pumping is performed by means of an absorption pump with titanium as getter material. The getter is activated at 800°C by an internal tungsten heater. The weight of the getter is 0.7 kg,which is sufficient for more than 15 years of continuous operation. Residual gases are pumped in both vacuum chambers by 1 l/s ion pumps. The physics package weight of the new hydrogen maser is 13.5 kg, diameter – 180 mm, length – 490 mm.

3. ELECTRONICS

Block diagram of electronics of the passive hydrogen maser is given in Fig.3

It consists of two frequency lock-loops: The 5 MHz crystal oscillator lock to the hydrogen emission line and discriminator RF-cavity frequency adjustment loop to the crystal oscillator frequency. The frequency modulation auto-tuning method with high modulation frequency in both loops was used in passive hydrogen maser [4]. The 5 MHz crystal oscillator signal phase is modulated by the 12.5 kHz signal, multiplied up to 1400 MHz,mixed with the synthesized 20.4057 MHz signal,and fed to the RF cavity. The power of this test signal is $\sim 1 \times 10^{-12}$ W and the frequency modulation factor is 1.5.

Error signals (information about the test signal frequency detuning relative to the hydrogen emission line and RF cavity) are formed as a result of test signal spectrum linear distortions which appear as a result of interaction of the emission line, RF cavity, and test signal. Error signals are contained in the 12.5 kHz amplitude modulation of the output signal. A low noise (NF~1.5 dB) RF converter (receiver) provides sufficient signal amplification for amplitude detection and the 1440 MHz local oscillator eliminates the influence of synchronous disturbances (5 MHz harmonics and 20.405 MHz signal) in the intermediate frequency amplifier [5]. Error signals from the crystal oscillator and RF cavity are divided two ways by the phase-shifters set at 90° angle and entered into the frequency control circuits.

Open-loop proportional –action coefficients are 1×10^7 for the crystal oscillator loop and 1×10^4 for the RF-cavity loop. Total frequency static tuning error for 5 MHz output signal is less than 1×10^{-15}.

4. FREQUENCY STABILITY AND ACCURACY OF PASSIVE HYDROGEN MASER

The physical effects causing hydrogen discriminator frequency variations are the same as in an active hydrogen maser and well-known [6,7]. They are: cavity pulling, magnetic fields, aging of the wall shift, second –order Doppler shift, and spin-exchange shift. Frequency shift values and their instabilities are shown in Table 1.

Table 1

Physical effect	Shift value	Shift instability	Note
1. Cavity pulling	$-(2\text{-}5)\times10^{-12}$	2×10^{-15}	Due to method of tuning and spin –exchange shift
2. Magnetic fields	2.5×10^{-13}	$1\text{-}2\times10^{-14}$ 1/Oe	
3 Wall shift of storage bulb coating	$3\text{-}4\times10^{-11}$	$3\text{-}5\times10^{-13}/^{0}C$	Possible changing up to 3×10^{-13}/year
4.Second order Doppler-shift	-4.46×10^{-11}	$-1.4\times10^{-13}/^{0}C$	

The passive hydrogen maser phenomenon is a relatively large cavity pulling frequency shift due to the method of tuning used and the spin-exchange emission line shift.

Short-term frequency stability of a passive hydrogen maser depends on the quantum discriminator characteristic steepness and the noise figure of the preamplifier in the receiver. These define the low-frequency (<10 Hz) white-noise level of the output 5 MHz signal phase-noise spectrum.

In practice it is very convenient to estimate discriminator quality in combination with electronics. A normal FM test signal is fed to the discriminator. The amplitude detector output voltage change is measured at the calibrated test signal carrier frequency shift by half of the hydrogen emission line width. For the passive hydrogen maser the measured quality factor value is within 300....400 and ensures the 5 MHz output signal 1 s frequency stability is between $(5 \ldots 8)\times10^{-13}$.

The long–term stability and accuracy of a passive hydrogen maser depends greatly on the electronics, FM test signal spectrum distortions caused by changing temperature,and also as a result of component aging.

The basic units are modulator, frequency multiplier,and receiver.

Using an automatic output voltage control system in the frequency multiplier and a varactor with very high linearity in the modulator, spurious modulation has been reduced to a level of –110 dB.The Butterworth passband filter (of the 3rd order)with a passband of 25 MHz and with high-passband flatness is used in the receiver. All this has allowed considerably reduced frequency shifts due to electronics and a low-temperature frequency coefficient, which is 1×10^{-14} / ° C.

5. EXPERIMENTAL DATA

Figure 4 presents the results of the passive hydrogen maser short-term stability measurements. The active hydrogen maser operating in the cavity autotuning mode was used as a reference standard. The frequency drift of the reference standard was $<3\text{x}10^{-16}$ / day. The bandwidth of the frequency comparator is 10 Hz and the frequency instability introduced by the comparator is expressed as $8\ \text{x}10^{-14}/\ \tau + 3\text{x}10^{-16}$.

Short-term stability of the passive hydrogen maser is well expressed by $\sigma_y(\tau) = 8\ \text{x}\ 10^{-13}/\tau^{1/2}$.

Figures 5 and 6 present the results of the frequency stability measurements for 1-hour and 1-day measuring time, respectively.

Figure 7 presents the results of the passive hydrogen maser frequency measurements over the temperature change. In Figure 7 we can see the temperature coefficient of the passive hydrogen maser frequency is less than $1\text{x}10^{-14}$ /°C.

Figure 8 shows the results of the passive hydrogen maser frequency measurements over the magnetic field change. We can see from Fig. 8 that magnetic field sensitivity of the passive hydrogen maser is at least less than $2\text{x}10^{-14}$ 1/Oe.

6. CONCLUSIONS

IEM KVARZ has created a new model passive hydrogen maser, which is significantly smaller in size and lighter in weight than the previous model passive maser CH1-76. Weight of the maser is 38 kg, including the internal batteries providing the device operation during 1 hour; height is 200 mm (Fig.9).

This maser has the same frequency stability as the previous model, but its physics package is considerably smaller in size.

In our opinion, there are some ways of further reducing the size of the physics package without significantly changing the signal/noise ratio and, as a result, frequency stability degradation. Ruggedness of the maser allows use as transportable clocks for synchronization of time scales.

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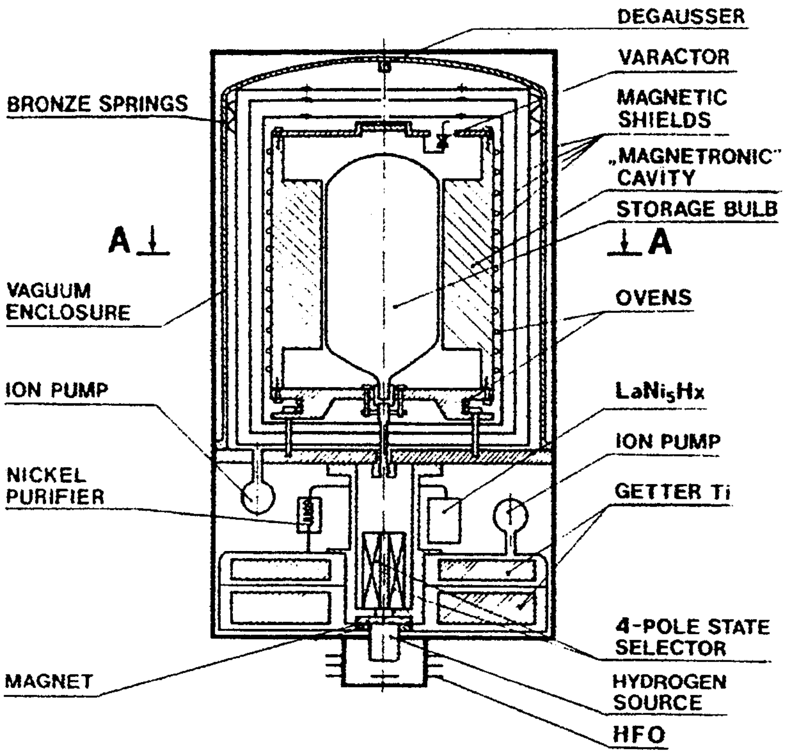


Fig. 1.The passive hydrogen maser physics package.

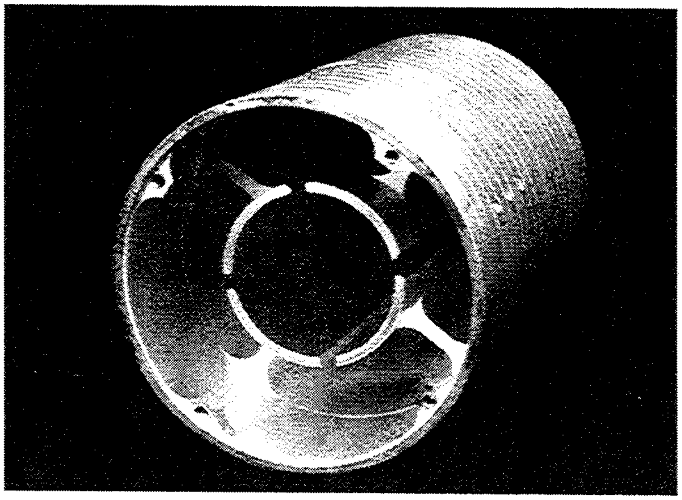


Fig. 2. The "magnetronic" cavity.

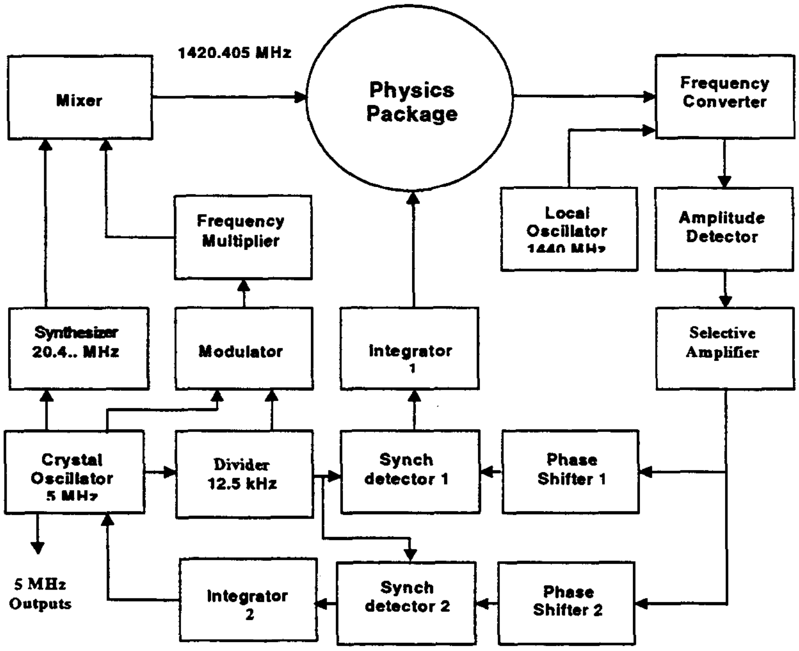


Fig.3. Block diagram of the passive hydrogen maser.

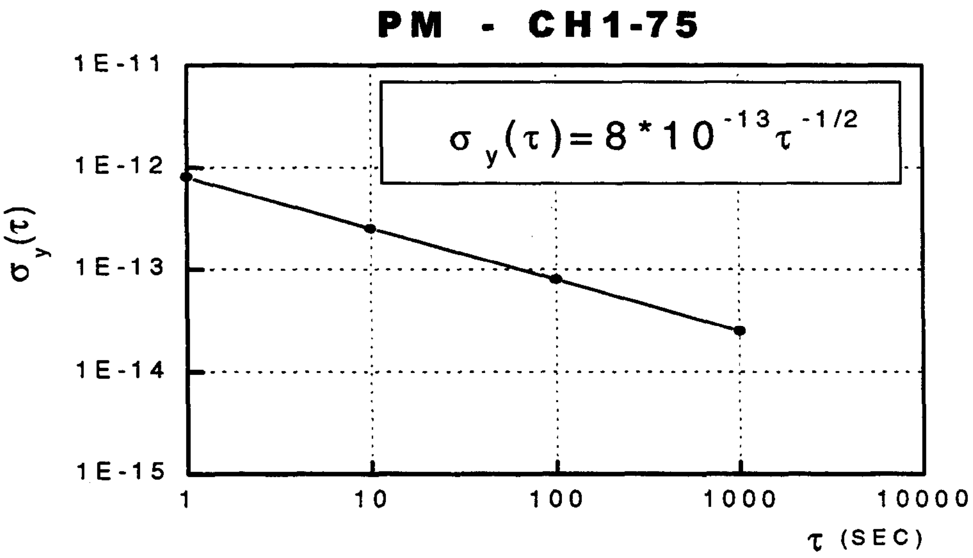
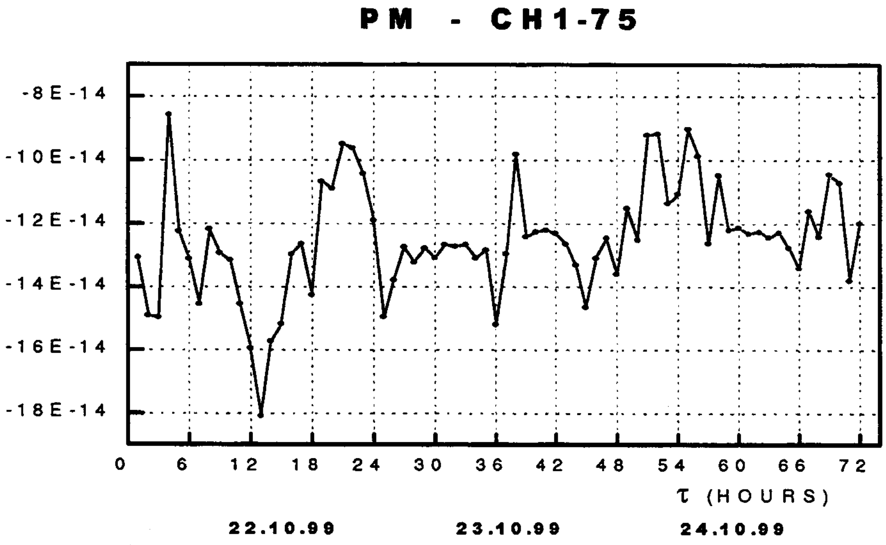


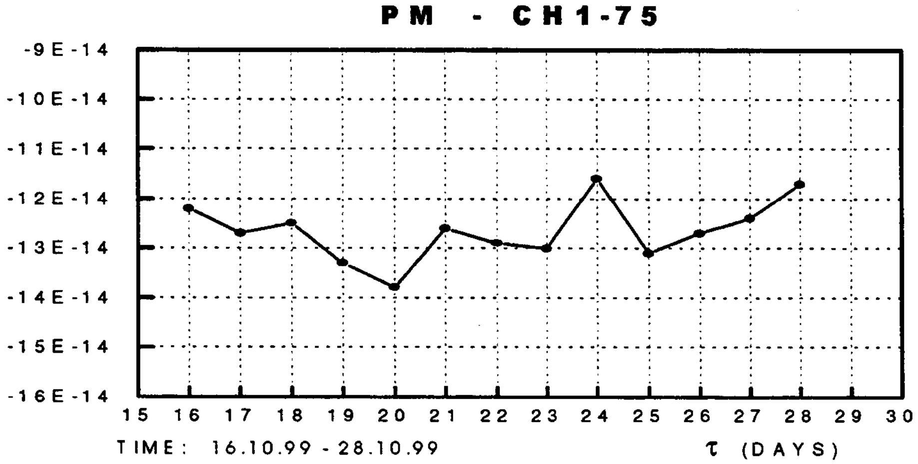
Fig.4. Short-term stability of the passive hydrogen maser.


PM - CH1-75

MEAN FREQ. = -1.25E-13 σ = 1.76E-14

$\sigma_y(\tau)$ = 1.25E-14

Fig.5.Frequency stability of the passive hydrogen maser at τ =1 hour.


PM - CH1-75

TIME: 16.10.99 - 28.10.99

MEAN FREQ. = -1.26E-13 σ = 6.49E-15

DRIFT : NO $\sigma_y(\tau)$ = 6.16E-15

Fig.6.Frequency stability of the passive hydrogen maser at τ =1 day.

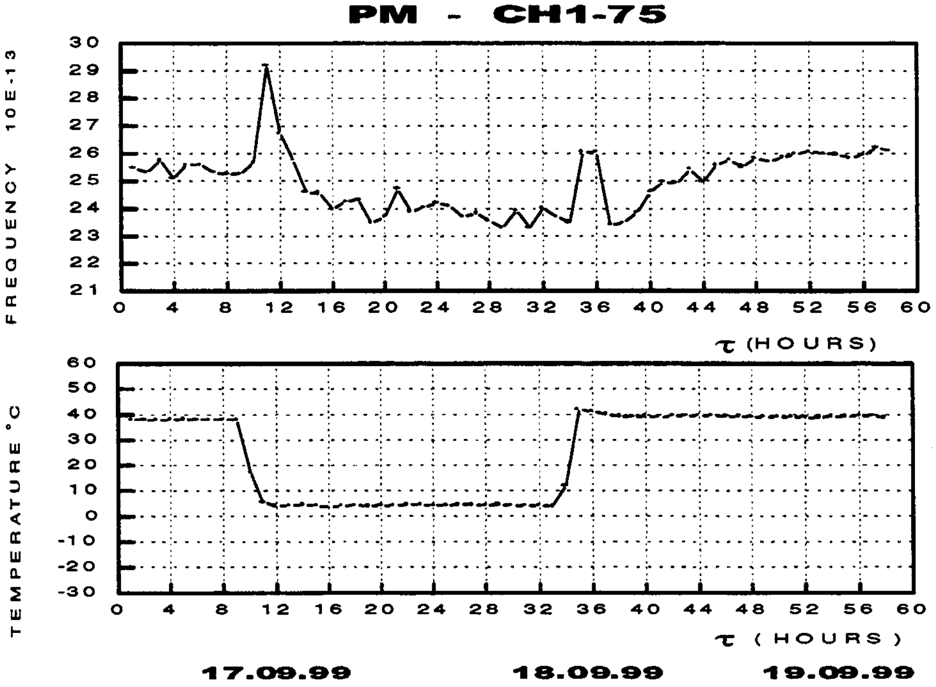


Fig.7. Frequency stability of the passive maser at temperature change.

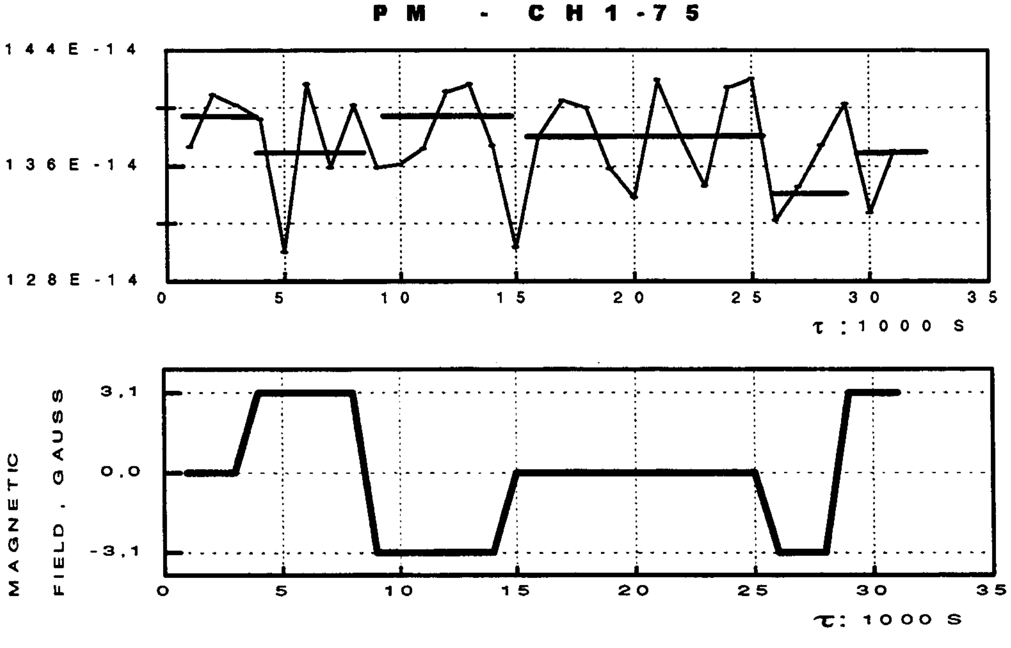


Fig 8. The frequency stability of the passive maser at magnetic field change.

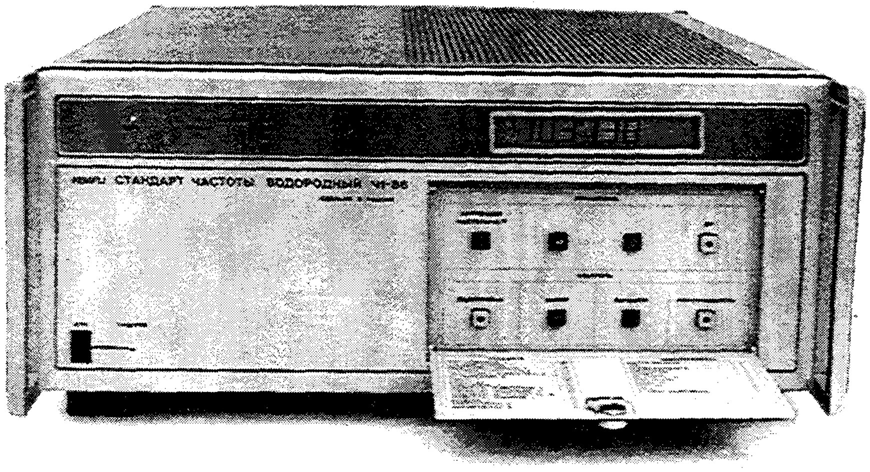


Fig.9. The passive hydrogen maser.