UDC 621.528.6

Hydrogen maser, recovery and performance life extension of magnetic discharge pumps

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Abstract

The paper considers the aspects of functioning, improvement, and performance life extension of the hydrogen maser, Ch1-70 measure, and measures to maintain its metrological characteristics at a high level. When using quantum generators, there is a need for complex maintenance of one of the key elements of the maser – the magnetic discharge ion-getter pump. Practical aspects of technical maintenance of one of the key elements of the hydrogen maser, Ch1-70 measure, which uses magnetic discharge ion-getter pumps, are considered. The design, principle of operation, and main technical characteristics of this type of pumps are described. The condition of the pumps after long-term operation is analysed, typical defects such as the formation of titanium powder, cathode production, and deterioration of dielectric properties of insulators are identified. Measures to restore the pumps have been developed and implemented, including cleaning and replacing the damaged components and checking the vacuum parameters. The results of experimental studies have confirmed the restoration of short-term instability of frequency and other metrological characteristics of the Ch1-70 measure. Ways to further improving the equipment to extend the term of its use and optimize metrological parameters are proposed, in particular, a magnetic discharge ion-heterodyne pump of the Ch1-70 measure. The design and principle of operation of the magnetic discharge ion-heterodyne pump, as well as the design and principle of operation of this type of pumps, as part of the Ch1-70 measure, are presented.

The condition of the equipment has been analysed, measures to restore metrological characteristics of the Ch1-70 measure and other time and frequency measurement standards of this type have been proposed and implemented.

Ways to further improving the metrological characteristics and extending the performance life of the hydrogen maser, Ch1-70 measure, are presented.

Keywords: magnetic discharge ion-heterodyne pump; accuracy; frequency; time; measurement standards; Ch1-70 measure; measurement; measurement uncertainty; hydrogen maser; quantum generator.

Received: 17.02.2025 Edited: 11.03.2025 Approved for publication: 14.03.2025

Introduction

The development of quantum generators (masers and lasers) is truly considered one of the most outstanding achievements of physics of the 20th century. Not only did this discovery enrich fundamental science, but also led to the emergence of countless technologies that are now an integral part of our lives.

The first quantum generators – masers – were designed in the mid-1950s. They were based on the phenomenon of the stimulated emission, predicted by Albert Einstein at the beginning of the 20th century. Soon, in 1960, the first laser operating in the optical range was designed. A maser means amplification of microwaves by stimulated emission. A hydrogen maser is an active generator with a natural output obtained from a quantum transition between two hyperfine levels [1] ($F=1$, $M_F=0$ to $F=0$, $M_F=0$). This corresponds to a well-known 21 cm line (Fig. 1).

The hydrogen maser uses the physical property of atomic hydrogen as a reference frequency source, which is stable up to 2×10^{-16} seconds per day. Molecular hydrogen, coming from a storage tank, is dissociated into atoms by a high-frequency plasma discharge in the hydrogen source. Leaving the hydrogen source, the atoms enter a state selector, which directs a beam of atoms in the appropriate quantum state ($F=1$, $M_F=0$ and $F=1$, $M_F=1$) into a quartz flask covered with Teflon to minimize the interaction

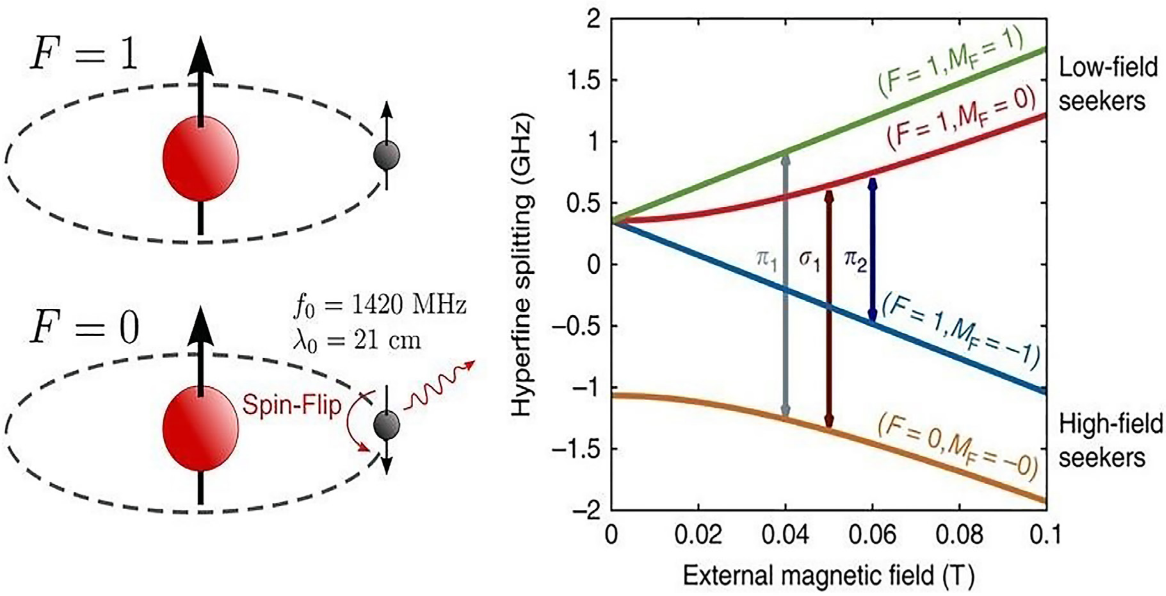

Fig. 1. Transition between two hyperfine levels

of the hydrogen atoms with the walls of the flask (Fig. 2).

The bulb is placed in the centre of a microwave cavity. The cavity is tuned and close to the transition of the hyperfine structure of the hydrogen atom [2]. The tuning of the cavity is controlled by the cavity temperature (coarse tuning) and a varicap diode. A coupling loop installed in the cavity extracts some of the maser energy to a low-noise receiver and a phase-locked loop (PLL).

When using a hydrogen maser, Ch1-70 measure, there is a need for complex maintenance of one of the key elements of the hydrogen maser, a magnetic discharge ion-heterodyne pump, characteristics of which, as a result of long-term use, deteriorate, which in turn deteriorates metrological characteristics of the Ch1-70 measure when it is used as a reference. The vacuum deteriorates and the consumption current increases, by which it is possible to observe and draw conclusions about the quality of the vacuum. The level of residual vacuum is critical for ensuring the accuracy of the operation of the standard measure, since it affects the signal-to-noise ratio and the spectral width of the atomic radiation line, the worse the vacuum is, the wider the spectral line of hydrogen radiation is, and in some cells (Fig. 3), the consumption current is so large that the instructions for use prohibit the use of this standard and require sending it to the manufacturer. The level of residual vacuum is one of the key factors for achieving high metrological characteristics of the standard, since it affects both the signal-to-noise ratio and the extension of the atomic line due to collisional effects.

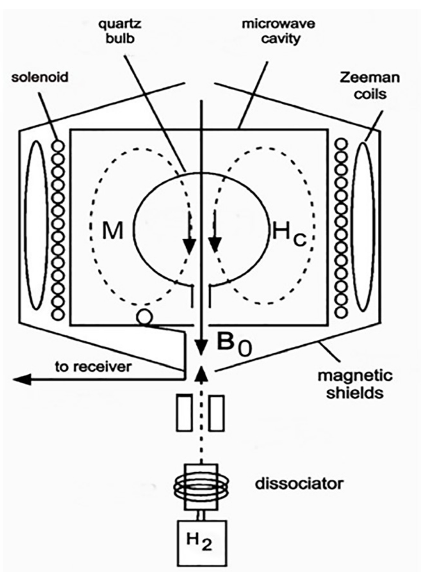

Fig. 2. Schematic representation of a hydrogen maser

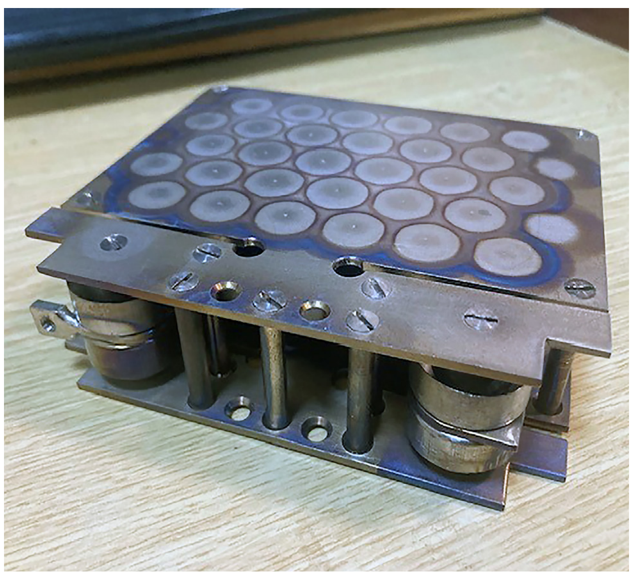
Fig. 3. Magnetic discharge ion-heterodyne pump cell

Design and operating principle of a magnetic discharge ion-heterodyne pump

Magnetic discharge pumps belong to the category of oil-free high-vacuum heterodyne pumps [3]. According to the principle of operation, there are two types of magnetic discharge pumps, diode pumps and triode pumps, diode pumps are used as part of the Ch1-70 measure (Fig. 4), with the use of which the ultimate pressure of residual gases can be achieved, up to 1×10^{-9} – 1×10^{-10} Torr.

These pumps are well suited for high vacuum and ultra-high vacuum applications due to their design.

Advantages and disadvantages of magnetic discharge vacuum pumps

Disadvantages:

• high selectivity of pumping by gas type: magnetic discharge pumps pump inert gases poorly, which affects the composition of the residual atmosphere in the vacuum chamber;

• unable to withstand high gas load;

• difficult to warm up the pump for degassing due to the presence of permanent magnets;

• high supply voltage (5–7 kV);

• long start after the atmosphere is introduced into the pump;

• sensitivity to contaminants, including hydrocarbons (oils).

Advantages:

• no moving parts – no wearing parts in the pump chamber;

• no noise and vibration during operation;

• the discharge current is approximately proportional to the pressure in the chamber volume – in fact, the magnetic discharge pump is a magnetic discharge sensor with a cold cathode, and the discharge current allows one to estimate the pressure in the vacuum system;

• reliability, long-term performance life, with proper operation, practically does not require maintenance [4].

The design of the magnetic discharge pump consists of a housing in which the electrode blocks are located Fig. 4. The composition of the Ch1-70 measure uses 7 open cells (Fig. 3) and one closed cell.

The design of the magnetic discharge pump consists of a housing in which the electrode blocks are placed. The structure of the Ch1-70 measure uses 7 open cells and one closed cell, the electrode block of the diode magnetic discharge pump consists of a parallel anode and two cathodes made of titanium. The anode has a cellular structure, each cell is a tube that is assembled into a package that acts as an anode, the cathode is a monolithic titanium plate.

A high (5–7 kV) voltage is applied between the cathode and the anode, which is supplied to the pump cavity through a high-voltage water seal. Permanent magnets are placed on the outside of the magnetic discharge pump housing in such a way that the magnetic field is perpendicular to the plane of the anode (cathodes). The principle of operation of the diode magnetic discharge pump is as follows. In a vacuum, electrons are always present in the pump cavity. In electric and magnetic field, electrons move along spiral trajectories in the direction from the cathode to the anode until a collision (collision) of the electron with atoms of the gaseous medium occurs.

As a result of such collisions, the neutral atom is ionized. Before the electron hits the anode, several such ionizing collisions occur (higher the pressure, the more collisions). The ions formed as a result of such collisions move to the cathodes, participating in the formation of current through the anode-cathode discharge gaps. Moving from the anode to the cathode, the ions are accelerated under the influence

Fig. 4. Magnetic discharge ion-heterodyne pump of Ch1-70 time and frequency measure consisting of 7 open and one closed cell

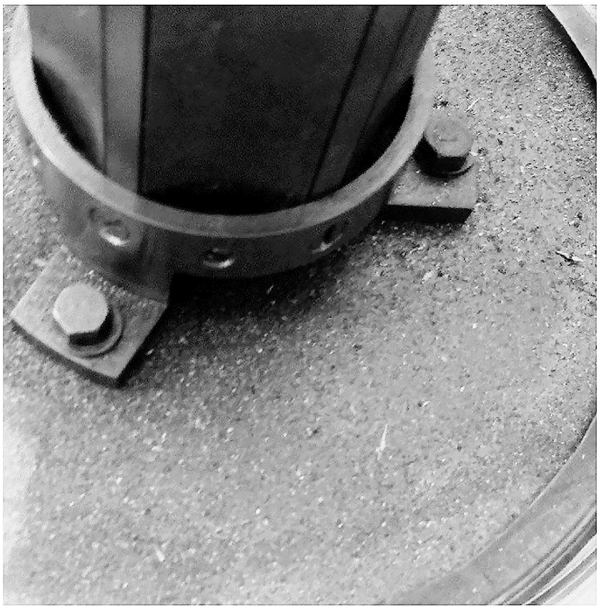

Fig. 5. Titanium powder

Fig. 6. Production of material, cathode

of the electric field. By the time of collision with the cathode, the ions acquire energy sufficient to knock out titanium atoms from the cathode surface – the cathode surface is constantly sprayed during pump operation. Atoms (molecules) of the pumped gas can bind on the surfaces of materials as a result of the following processes (titanium is an active heterodyne):

- when a gas atom (molecule) hits the cathode surface, adsorption and dissolution with the formation of chemical compounds can occur;
- ions can be introduced to the cathode, in some cases diffusion of ions into the cathode material is possible;
- titanium atoms knocked out from the cathode surface are deposited on the anode and pump housing; the films formed in this way are capable of absorbing atoms (molecules) of the gas medium. The implementation of a particular mechanism depends on the type of gas. Other active gases are absorbed with the participation of all of the above mechanisms, but the main one is chemisorption of gases by the titanium film, the molecules are continuously deposited on the anode. For hydrogen, the second of the above mechanisms is significant because it easily diffuses into the volume of titanium plates with the formation of various compounds and solid solutions.

Restoration and extension of the performance life of magnetic discharge pumps

During the use of the Ch1-70 time and frequency measure, the magnetic discharge ion-getter pump (Fig. 4) was maintained, which, as a result of long-term use, had deteriorated characteristics. The design and principle of operation of this type of pumps are well described in the literature, although such maintenance is not included in the list of works performed during their maintenance. To maintain the equipment in proper condition, it was decided to evacuate the Ch1-70 time and frequency measure and to perform defecting of the cells, during which the following shortcomings were identified.

A large amount of titanium powder, which is shown in Fig. 5.

Production of the material, cathode, which is shown in Fig. 6.

Deterioration of dielectric properties of insulators

During the maintenance and defecting, the cells and internal cavities were cleaned of titanium residues, the cathodes were turned over to the other side that did not have defects, the anode was washed and cleaned of titanium sputtering residues.

Deterioration of dielectric properties of insulators turned out to be the most difficult factor, constructively the cell is windowed so that the insulator is protected from titanium evaporation, if this still happens, then the porous structure of the insulator is well covered with titanium and becomes a conductor and fails to fulfil its purpose, attempts to clean it were in vain – titanium resists both mechanical and chemical treatment well. The only way out was to perform cleaning with a laser beam or replace a bad insulator with this service, for which available insulators from stocks were used.

After defecting, cleaning, and other necessary steps, the cells were degassed, and the standard was evacuated to the so-called starting pressure of the magnetic discharge pump. Depending on the model, the starting pressure can be $(5–10) \times 10^{-4}$ Torr. From a pressure of 1×10^{-3} Torr, the magnetic discharge pump starts extremely reluctantly, usually several attempts are required.

It is highly desirable to perform preliminary pumping with oil-free fore vacuum pumps: an oil film on the electrode blocks of the magnetic discharge pump leads to a significant deterioration in its efficiency.

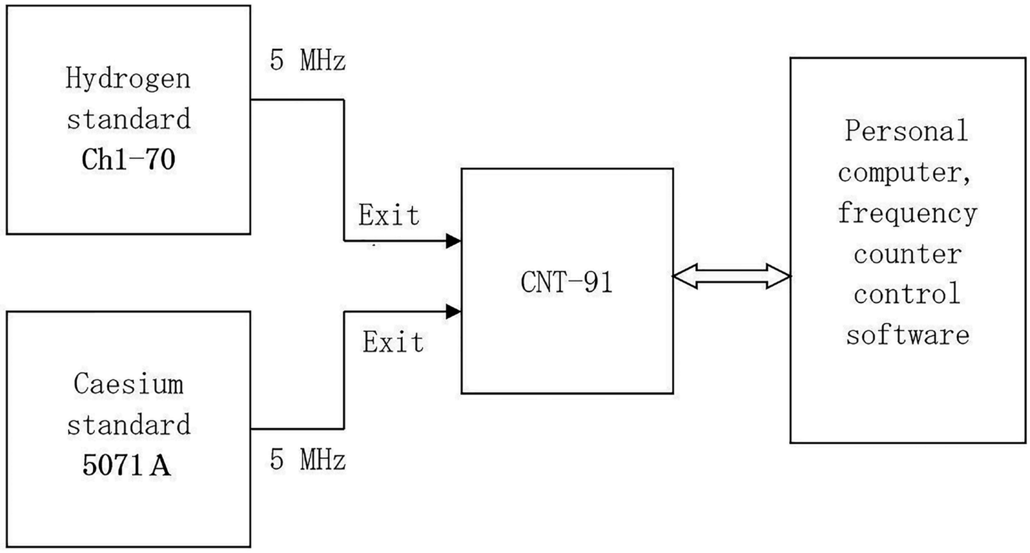

Fig. 7. Flowchart for conducting a study of short-term instability

At the moment of start, the magnetic discharge pump consumes a fairly large amount of power and, as a result, heats up actively. Therefore, there may be a need for several start attempts, but subsequent attempts should be started no earlier than after the pump cools down. When operating at pressures up to ~1×10^{-3} Torr, the pump also heats up.

After maintenance, the metrological characteristics of the Ch1-70 standard were checked for a month. The metrological characteristics of the standard were studied after maintenance regarding its short-term and long-term instability. First of all, the characteristics of short-term instability were experimentally studied. At the same time, measurements of the output frequency of the Ch1-70 standard were performed – 5 MHz relative to the output frequency of 5 MHz of the standard (measure 1), which is part of the group and forms the working scale of the standard.

The structural diagram of the study is shown in Fig. 7. The figure shows the diagram that was used to measure the output frequency of the Ch1-70 standard relative to the caesium frequency standard (5071A).

The main elements of the scheme:

Ch1-70 hydrogen standard;

5071A caesium standard;

CNT-91 frequency meter;

Personal computer with software for data recording.

The short-term instability of the standard was studied applying a phase-time method, CPU 07-21:2015, service TF2.1.1 in the Classifier of Calibration and Measurement Capabilities of NDETU TF-01-2021 (CMC) KCDB [5]. The measurement results were recorded for 3 days with a recording rate of 1 second. Based on the measurement results, the relative frequency differences of the Ch1-70 hydrogen generator against the caesium standard (measure1) were calculated.

The actual frequency value f_∂ of the measure being calibrated was calculated by formula (1) from the calibration procedure CPU 07-21:2015:

$$f_\partial = f_{nom}[1-\frac{1}{J}\cdot\sum_{j=1}^{J}(\Delta T_{cp(j+1)}-\Delta T_{cpj})/\tau_в], \quad (1)$$

where f_{nom} is the nominal value of the frequency being calibrated.

The result obtained was entered into the protocol. The measurement uncertainty was evaluated.

The expanded calibration uncertainty U at a coverage factor $k=2$ with a confidence probability $p=0.95$ according to DSTU-N RMG 43 [6] was calculated by formula (2) from the calibration procedure CPU 07-21:2015:

$$U = 2\cdot\sqrt{u_A^2+u_B^2}, \quad (2)$$

where u_A is the standard uncertainty of Type A, u_B is the standard uncertainty of Type B.

The standard uncertainty of Type A was calculated using the following formula (3) on the calibration procedure CPU 07-21:2015:

$$u_A = \sqrt{\frac{\sum_{n=1}^{J-1}\left(f_{\partial n}-f_\partial\right)^2}{(J-1)\cdot(J-2)}}, \quad (3)$$

where $f_{\partial n} = f_{nom}[1-(\Delta T_{cp(j+1)}-\Delta T_{cpj})/\tau_в]$.

The standard uncertainty of Type B, u_B, was calculated using formula (4) on the calibration procedure CPU 07-21:2015:

$$u_B = f_{nom}\cdot\left(\sqrt{\left|\Delta_{ef}\right|^2+\left(\frac{\delta_T}{I\cdot\tau_в}\right)^2}\right)/\sqrt{3}, \quad (4)$$

where δ_T is the resolution of the comparator (for measuring time intervals CNT-91 $\delta_T = 1\times10^{-10}$ s);

Δ_{ef} is a relative error in frequency, which is determined for the leading standard measure at the time of measurement according to the Bulletin E2

Table 1

Dependence of Alan deviation on averaging time, obtained experimentally

τ, s	1	10	100	1000	10000	100000
	6.9×10^{-12}	5.3×10^{-12}	1.0×10^{-12}	2.1×10^{-13}	9.3×10^{-14}	2.6×10^{-14}

on the website of the National Science Centre “Institute of Metrology”.

The result obtained, calculated by formula (2), was entered into the protocol.

The main parameter used to assess a short-term frequency instability is Alan deviation. Therefore, using the results of the time series of studies, the Alan deviation [7] value was calculated for the averaging time of 1s, 10s, 100s, 1000s, 10000s, and 100000s. The results are given in Table 1.

The analysis of the data proves a fairly high level of convergence between real and passport data after maintenance.

Conclusions

The results obtained during the maintenance of quantum generators make it possible to significantly extend the performance life of the Ch1-70 time and frequency measure while maintaining metrological parameters, which in its turn contributes to the rational use and saving of state funds, compared to the purchase of new equipment, which is quite expensive, or performing this maintenance at a production facility located abroad. In addition, this type of equipment, Ch1-70 time and frequency measure, is no longer manufactured at this time, and the performance life has already expired, while the vacuum part has all the great potential for long-term use and improvement of metrological characteristics of the standard when replacing electronic equipment. Estimates of this type of improvement when improving will allow enhancing the metrological characteristics of the Ch1-70 time and frequency measure by one or two orders of magnitude, which will correspond to characteristics of new and modern equipment of this type of time and frequency measurement standards.

Водневі зберігачі частоти, відновлення та продовження терміну використання магніторозрядних насосів

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Анотація

Розглянуто практичні аспекти технічного догляду, обслуговування та продовження терміну використання одного із ключових елементів водневого зберігача частоти, міри Ч1-70, у складі якої використовуються магніторозрядні іонно-гетерні насоси, та заходи щодо підтримання його метрологічних характеристик на високому рівні. Під час використання квантових генераторів виникає потреба в складному обслуговуванні одного із ключових елементів водневого зберігача – магніторозрядного іонно-гетерного насоса. Описано конструкцію, принцип роботи та основні технічні характеристики цього типу насосів. Проаналізовано стан насосів після тривалої експлуатації, виявлено типові дефекти, такі як утворення порошку титану, виробка катодів та погіршення діелектричних властивостей ізоляторів. Розроблено та реалізовано заходи з відновлення насосів, включаючи очищення, заміну пошкоджених компонентів та перевірку параметрів вакууму. Результати експериментальних досліджень підтвердили відновлення короткочасної нестабільності частоти та інших метрологічних характеристик міри Ч1-70. Запропоновано шляхи подальшого вдосконалення обладнання для продовження терміну його використання та оптимізації метрологічних показників, зокрема магніторозрядного іонно-гетерного насоса міри Ч1-70.

Проаналізовано стан устаткування, запропоновано та виконано заходи з відновлення метрологічних характеристик міри Ч1-70 та інших еталонів часу та частоти даного типу.

Ключові слова: магніторозрядний іонно-гетерний насос; точність; частота; час; еталони; міра Ч1-70; вимірювання; невизначеність; водневий зберігач; квантовий генератор.

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