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Design of a vacuum system for space active hydrogen maser

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With the high precision and stability of its frequency signal outputs, active hydrogen maser plays an important role in such fields as timing, satellite navigation, and communication. However, it needs to be lighter so as to be applied in space. We made a research, based on the calculation of the hydrogen flow and the adsorption efficiency of the adsorption unit, on the parameters of the vacuum system and the structural requirements, and designed a combined vacuum pump for the Space Active Hydrogen Maser (SAHM). This vacuum pump consists of a getter pump and a small ion pump, the total mass of which is about 5 kg. The pumping speed will be about 474 L/s by computation, when an amount, 2.5 MPa L, of hydrogen has been adsorbed by getters. Theoretically, the total source hydrogen inflow in lifetime is not higher than 20% of the total capacity getter pump, thus the design should amply meet the requirements of the SAHM vacuum system, and is of great significance for future SAHM applications.

KEYWORDS

hydrogen maser, space, active, vacuum system, getter pump, design

1 Introduction

The hydrogen maser, which uses the hyperfine energy level transition signal of the hydrogen atoms for precise timing, has excellent measurement accuracy and stability. It has developed rapidly since the advent of the first hydrogen maser in 1960 [1]. Many companies and organizations, such as Chinese Shanghai Observatory, Beijing Institute of Radio Metrology and Measurement, American Symmetricomg Company, Switzerland Spectratime, T4Science Company, Russia KVARZ, Vremya-CH Company and the Russian-British joint venture Quartzlock Company, have offered various kinds of high-performance hydrogen maser products which were widely applied in timing, navigation, communications, space exploration and other fields [2–5].

With the continuous development of space science experimental projects, new requirements are put forward for hydrogen masers applied in space. It not only needs better frequency stability and reliability, but also needs to meet the requirements of space applications such as light weight, small size and low power consumption. The performance of the active hydrogen maser is better than that of the passive hydrogen

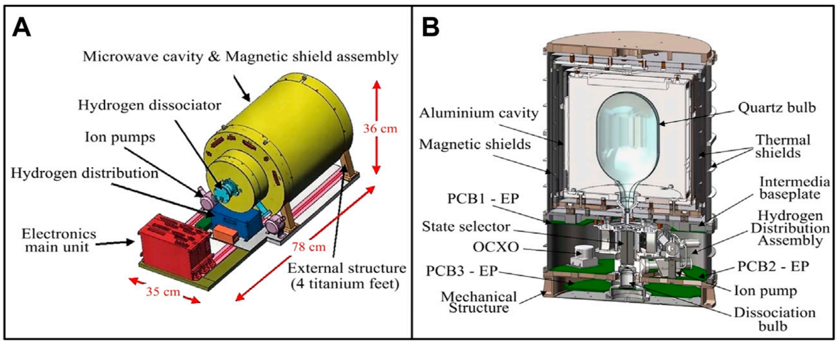

FIGURE 1
35 kg space active hydrogen maser **(A)**; 40 kg space active hydrogen maser **(B)**.

maser, thus the before is a better choice for the frequency standard in space. However, it is currently too bulky to be applied in space.

At present, the countries that carry out the research and development of space active hydrogen masers mainly include Europe [5–8], Russia [9–11], and China [12–14]. The Neuchatel Observatory in Switzerland used a high-Q sapphire microwave resonator to replace the traditional resonator in space active hydrogen maser, which greatly reduced the mass of the entire system to about 35 kg (Figure 1A), and the frequency stability could reach 1.5×10^{-13}/s and $1.5 \times 10^{-15}/10^5$ s [6, 7]. SpectraTime (SpT) developed a 40 kg lightweight active Space Hydrogen Maser (Figure 1B) for the European Space Atomic Clock Ensemble in Space (ACES) mission which would be flown on the International Space Station (ISS) in 2013 [5]. The Russian Vremya-CH company uses a glass-ceramic resonator to reduce the total mass of the active hydrogen maser to 60 kg. It could achieve a long-term stability 2×10^{-14}/day, and was launched in 2011 [10, 11]. Beijing Institute of Radio Metrology and Measurement has also developed a space active hydrogen maser with a mass of about 45 kg, its stability could reach 2.3×10^{-15}/day and might be launched with satellites in 2022. Meanwhile, it is still continuing to optimize its performance, and it will be applied in Chinese space station projects in the future [13].

The space hydrogen maser has high requirements on vacuum system, generally about 10^{-5} Pa [15]. The poor vacuum environment will lead to broadening of transition spectral lines and weakening of signals, which will significantly affect the overall performance. Therefore, a vacuum system that can maintain working conditions for a long time is particularly important. As a comparison, the ground active hydrogen maser uses a sputtering ion pump, equipped with two large magnets of about 50 kg, to maintain the vacuum state of the system. This type of vacuum pump has good stability, high reliability and long service life, whereas it is so bulky that cannot be used in SAHM.

The spaceborne passive hydrogen maser adopts a scheme of combined pump system to meet the vacuum requirements of space applications [16]. The combined pump consists of a getter pump and a small ion pump, in which the getter pump mainly absorbs reactive gases (mainly hydrogen), and the ion pump absorbs the inert gas in the system. This type of combined pump system turned out to have the high stability and reliability, the large capacity and particularly the small volume and light mass while, which is very consistent with the development trend of the hydrogen maser. Compared with the passive hydrogen maser, the active ones have better stability and accuracy. However, the active hydrogen maser also has larger hydrogen load flow rate, for which the vacuum system needs to be redesigned to meet the needs of the space active hydrogen maser.

Space active hydrogen masers are mainly used for space station punctuality, space high-precision scientific experiments and large scientific installations such as space telescopes and space VLBI (Very Long Baseline Interferometry) projects. Active hydrogen maser has not yet had space applications in China. The Shanghai Astronomical Observatory Space VLBI Project requires higher time-frequency accuracy and stability, which promotes the space application process of active hydrogen masers.

This work aims to design a lightweight vacuum combined pump for space application of active hydrogen masers. The combined pump combines a zirconium iron vanadium alloy getter pump and a small ion pump, with a total mass of about 5 kg, which is 90% lighter than that of the ground active hydrogen masers. In terms of performance, the theoretical pumping rate and total pumping volume of the design's 10-year service period (according to the requirements of the national research task) far exceeded the expectations, which reflect the excellent gas adsorption and vacuum retention capabilities. This design amply satisfies the vacuum degree and life requirements of

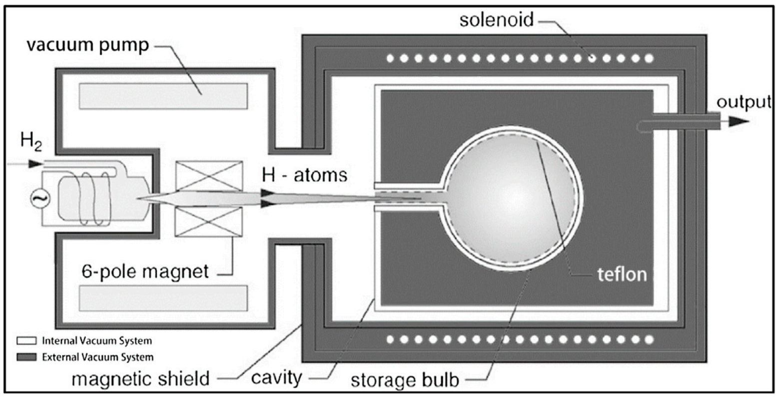

FIGURE 2
Basic structure of the physical part of the hydrogen maser.

the vacuum system, and provides significant reference for the active hydrogen maser application in space.

2 Theory and method

2.1 Vacuum system of hydrogen maser

Figure 2 shows the basic physical structure of the hydrogen maser. After purification, ionization, and state selection, the hydrogen gas enters the storage bubble, where the energy level transition occurs and a microwave signal of a specific frequency is generated. Finally, it will be collected by the vacuum pump. The storage time of hydrogen atoms in the atomic storage bubble is about 1 s. In order to avoid collisions between high-energy hydrogen atoms ($F = 1$, $m_F = 0$) and other atoms, which will cause collision broadening and lead to a decrease in the signal-to-noise ratio of hydrogen atom transition signals, this process generally needs to be carried out in a high vacuum environment.

In a high vacuum environment, the particle density in the atomic storage bubble is at a low level, which increases the average free path of high-energy hydrogen atoms, and reduces the collision probability between hydrogen atoms or with other particles, thereby prolonging their interaction time. At present, the space hydrogen maser mainly adopts a double vacuum system [17]. The background vacuum degree of the internal vacuum system during operation is about 10^{-5} Pa. The stable system vacuum degree is one of the important influence factors affecting the long-term stability of the hydrogen maser. The vacuum pump system turns out to be the most critical part that affects the vacuum degree of hydrogen masers.

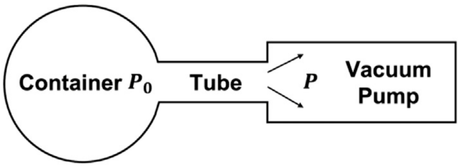

FIGURE 3
Brief schematic diagram of vacuum system.

2.2 Basic parameters of hydrogen maser vacuum system

2.2.1 Gas flow Q_G

The temperature is almost constant in the vacuum system of hydrogen maser. According to The Boyle's law, the product of the gas volume V and the pressure P is constant if only the pressure changes. Therefore, in a vacuum system, the product $P \times V$ is generally used to represent the amount of gas, we can obtain the expression of flow after differentiating time:

$$Q_G = V\frac{d_p}{d_t} + P\frac{d_V}{d_t} \tag{1}$$

The pressure everywhere remains generally constant when the system is stable, and the pressure changes little in a short time interval. At this time, Formula 1 can be written as:

$$Q_G = P\frac{d_V}{d_t} \tag{2}$$

This is the constant pressure expression of flow, unit for Pa·m^3·s^{-1} or Pa·m^3·s^{-1}.

2.2.2 Pumping rate S_p and effective pumping rate S_0

Figure 3 is a brief schematic diagram of the vacuum system. When the vacuum pump starts pumping, the pressure P at the inlet of the vacuum pump is less than the pressure P_0 in the container, thus the gas flows to the vacuum pump and is collected or discharged out of there. The pumping speed S_p of a vacuum pump is the ratio of the gas flow $\boldsymbol{Q_G}$ to the pressure P at the pump port:

$$\boldsymbol{S_p = \frac{Q_G}{P}} \tag{3}$$

The unit is $m^3{\cdot}s^{-1}$ or $L{\cdot}s^{-1}$. Compared with Formula 2, when the pressure P is constant, S_p is approximately equal to $\frac{d_V}{d_t}$.

Due to the pressure difference between the pumped container and the vacuum pump, there is also a difference between the pumping rate of the vacuum pump and the pumping rate of the gas in the container. To distinguish between them, the pumping speed of the gas in the container is usually called the effective pumping speed, represented by S_0, it can be obtained by dividing the gas flow Q_G by the pressure P_0 in the container:

$$\boldsymbol{S_0 = \frac{Q_G}{P_0}} \tag{4}$$

2.2.3 Flow conductance U of connecting tube

Hydrogen pressure and flow rate are both small while in the high vacuum state of the hydrogen maser, which make the probability of collision between molecules is much less than with the tube wall. After each collision, molecules will move forward or backward in different directions. Therefore, the flow of hydrogen in the connecting tube is molecular flow.

The calculation of flow conductance is closely related to the shape of the tube. The structure of hydrogen maser is very compact, and short tubes (tube length L/diameter $d < 20$) are usually used in vacuum systems. The flow conductance calculation formula of air in molecular flow state in a short tube at 20°C can be expressed as follows:

$$\boldsymbol{U_{f.20^\circ\mathrm{C}} = \alpha \cdot 116 A_0} \tag{5}$$

Where the α is the Clausing coefficient, which is related to the value of L/d; A_0 is the cross-sectional area of the tube. Under the same conditions, the conductance of hydrogen and air has the following relationship:

$$\boldsymbol{U_{H_2} = 3.78\, U_{Air}} \tag{6}$$

The conversion formula for flow conductance at different temperatures is:

$$\boldsymbol{U_T = U_{20^\circ\mathrm{C}} \sqrt{\frac{T}{293.15}}} \tag{7}$$

Based on Formulas 5ormulas –Formulas 7, we can obtain the relationship between the flow conductance of hydrogen in the short tube and the temperature:

$$\boldsymbol{U_{H_2} = 438.48 \cdot A_0 \cdot \alpha \cdot \sqrt{\frac{T}{293.15}}} \tag{8}$$

2.2.4 Basic equation of vacuum system

When the gas flows in the tube, the pressure decreases gradually along the direction of the gas flow, so there is a dynamic pressure difference $(P_1 - P_2)$, P_1, and P_2 respectively represents the upstream and downstream gas pressure in the tube. The pressure difference is proportional to the gas flow, the formula is as follows:

$$\boldsymbol{Q_G = U(P_1 - P_2)} \tag{9}$$

In the vacuum system, assuming that there is no air leakage or air source and the air flow is in a stable state, according to the law of conservation of mass, the flow $P \cdot S_P$ at the right end of the conduit (vacuum pump inlet), the flow $P_0 \cdot S_0$ at the left end of the conduit (container outlet) and the flow $U(P_1 - P_2)$ at any section in the conduit are equal, that is:

$$\boldsymbol{U(P_1 - P_2) = U(P_0 - P)} \tag{10}$$

$$\boldsymbol{P_0 S_0 = U(P_0 - P) = P S_P} \tag{11}$$

After the convention of Formula 11, the following equation can be obtained:

$$\boldsymbol{\frac{1}{S_0} - \frac{1}{S_P} = \frac{1}{U}} \tag{12}$$

Formula 12 is the basic equation of the vacuum system when the air flow reaches a stable state. It relates the flow conductance U of connecting tube, the pumping rate $\boldsymbol{S_p}$ and the effective pumping rate $\boldsymbol{S_0}$, and plays an important role in the design of the vacuum system.

2.2.5 Effective suction area F

As the absorption of hydrogen content in the getter increases, hydrogen atoms at the surface will spread inward at a slower rate, which results in a reduced inspiratory rate. In order to ensure that the suction rate can maintain a good vacuum state of the system after absorbing a certain amount of gas during the required working life, it is necessary to ensure a certain effective suction area. The calculation formula of the effective suction area is as follows:

$$\boldsymbol{F = \frac{Q_i}{m_i q_i K_i}} \tag{13}$$

Where the Q_i is the required one-time inspiratory volume; m_i is the mass of getter per unit area; q_i is the suction amount of getter when the pump pumping speed tends to be stable; K_i is a

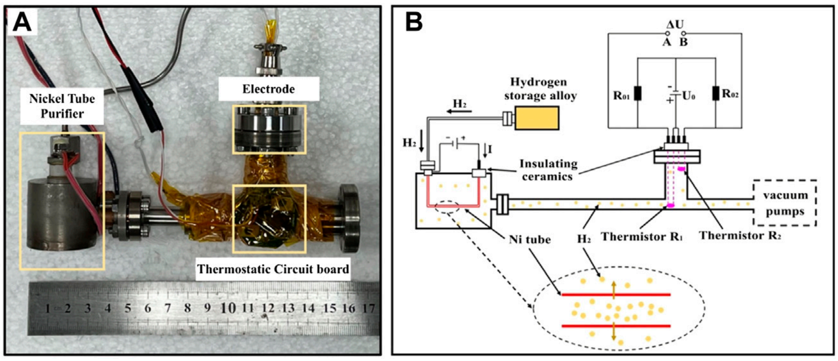

FIGURE 4
Hydrogen flow measurement experimental device **(A)**; hydrogen flow measurement experimental principle diagram **(B)**.

constant, when only one side is working, the value is 0.9, and when both sides are working, the value is 0.55.

2.2.6 Hydrogen evolution flow *q* of nickel purifier

The hydrogen evolution flow rate in hydrogen maser is mainly determined by the nickel tube purifier. We designed a measuring device for hydrogen permeability under different operating currents of nickel tube purifier. As shown in Figure 4A, it is mainly composed of nickel tube purifier, electrode flange, thermostatic circuit board and measuring tube. The right side of the measuring tube is connected with a vacuum pump to maintain the vacuum environment of measuring. The measuring principle is described as follows.

Under certain conditions, the heat conduction capacity of gas molecules is related to the number of gas molecules per unit volume. According to this principle, hydrogen is released from the hydrogen storage alloy bottle into the nickel tube; when the nickel tube is connected to the direct current, the joule temperature rises, and hydrogen diffuses outward into the measuring tube, where the heat exchange with the thermistor and changes the thermistor temperature. The temperature of thermistor corresponds to the resistance value, thus the voltage difference ΔU between A and B in the bridge also changes accordingly. Therefore, ΔU can be used to reflect the change in hydrogen flow rate.

In Figure 4B, R_{01} and R_{02} are standard resistors with resistance values of $100\,\mathrm{k\Omega}$. R_1 and R_2 are the same thermistors. The resistance value is $100\,\mathrm{k\Omega}$ at 25°C, B value is 3950 K. Hydrogen will take away part of the heat from thermistor R_1 while exchanging heat with it in the measuring tube. The heat loss per unit time can be obtained by the following formula:

$$\Delta P_{Loss} = C_P \cdot (T_0 - T_H) \cdot q \tag{14}$$

Where the C_P is the hydrogen constant pressure specific heat capacity, the T_0 is the initial temperature of the deprecated thermistor R_1 without hydrogen gas flow, the T_H is the temperature of hydrogen; and q is the hydrogen flow. Meanwhile, the heat generated by the thermistor R_1 due to the inflow current in unit time is:

$$\begin{aligned}\Delta P_e &= \left(\frac{U_0}{R_{02} + R_2}\right)^2 \cdot R_2 - \left(\frac{U_0}{R_{01} + R_1}\right)^2 \cdot R_1 \\ &= \frac{\Delta U^2 (R_{01}R_{02} - R_1R_2)}{R_{01}R_{02}(R_2 - R_1)}\end{aligned} \tag{15}$$

Where the U_0 is the voltage of the direct current supply. It was done experimentally to determine the optimal value as 1.2 V (for details, see Section 1.1 of the Supplementary Materials). According to the law of energy conservation, the heat loss ΔP_{Loss} between thermistor R_1 and hydrogen is equal to the heat ΔP_e generated by thermistor R_1. Thus, the calculation formula of hydrogen penetration q can be written as follows:

$$q = \frac{\Delta U^2 (R_{01}R_{02} - R_1R_2)}{R_{01}R_{02}(R_2 - R_1)C_p \cdot (T_0 - T_H)} \tag{16}$$

3 Design and discussion

3.1 Requirements of vacuum system design

In the vacuum system of hydrogen maser, the nickel tube purifier continuously permeates hydrogen into the system, and the vacuum state of the container needs to be maintained by the vacuum pump, which belongs to the dynamic vacuum system. In normal operation, the vacuum degree of the system should be kept at about 10^{-5} Pa, and the working life should be more than 10 years. Based on these two requirements, we calculate the required performance parameters of the vacuum pump design in the vacuum system.

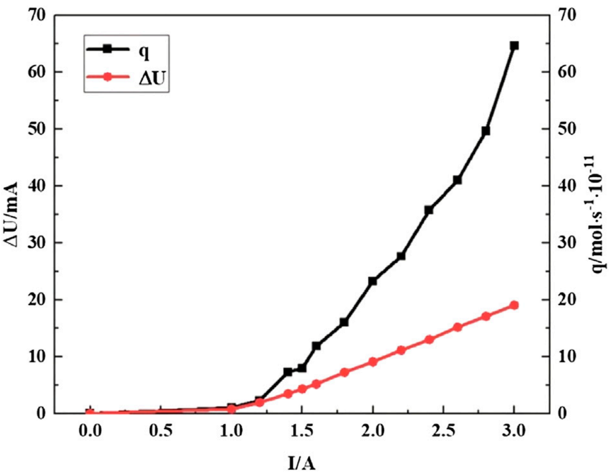

FIGURE 5
Relation curve of operating current of nickel tube and ΔU and flow of hydrogen.

3.1.1 Calculation of gas flow Q_G

In a vacuum system, the suction capacity and suction rate are the two most important parameters. In order to calculate the specific values of these two parameters, the total gas flow Q_G in the system needs to be calculated first. In general, Q_G consists of the following parts [17]:

$$\mathbf{Q_G = Q_l + Q_d + Q_p + Q_b + Q_r} \tag{17}$$

Where, Q_l is the hydrogen permeation amount in the vacuum system; Q_d is the amount of adsorbed gas desorption on the surface of the internal vacuum system; Q_p is the amount of gas discharged by diffusion or infiltration of the internal material in vacuum system; Q_b is the reflux volume of vacuum pump; Q_r is the air emission of the structural components assembled in the inner vacuum system. In the vacuum system of the hydrogen maser, the gas mainly comes from the hydrogen, which is permeated through the nickel tube during the operation, the other items are relatively little that can be ignored, thus $Q \cong Q_l$.

According to the hydrogen evolution rate experiment of the nickel purifier under different current (in Section 2.2.6), the result (shown in Figure 5) shows that the hydrogen permeability increases with the increase of the working current of the nickel tube purifier. When $I = 1.0–3.0$ A, the flow increases greatly, until when $I = 3.0$ A, $q = 1.58 \times 10^{-8}$ L s^{-1}. Considering the hydrogen maser signal and the impairment to the vacuum pump, the current of the nickel tube purifier is generally set to 3.0 A to get an optimal value of hydrogen flow (for details, see Section 1.2 of the Supplementary Materials).

Based on the hydrogen permeation amount q under this current flow, we can get the total hydrogen flow of the vacuum system $Q_G = 1.60 \times 10^{-3}$ Pa·L·s^{-1} from Formula 2 and the ideal gas equation. The total suction amount Q_A can be obtained by multiplying Q_G with working life. For 10 years, the total inspiration Q_A is about 0.5 MPa L.

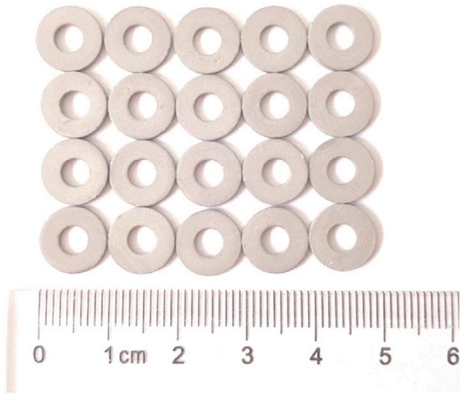

FIGURE 6
Getter tablets of vacuum pump.

3.1.2 Calculation of conduit conductivity U_{H_2}

In the vacuum system, it is a cylindrical stainless-steel tube between the pumped container and the vacuum pump, which is 70 mm in length and 60 mm in diameter. The cross-sectional area $A_0 = 2{,}827.43$ mm^2, $L/d = 1.167$, according to the table, Clausing coefficient a is 0.488. According to Formula 8, the flow conductance of hydrogen in the tube at 20°C can be calculated: $U_{H_2} = 6050$ L s^{-1}.

3.1.3 Calculation of pumping rate S_0 and effective pumping rate S_p

According to the requirement of hydrogen maser vacuum system, the gas pressure in the pumped container $P_0 = 1 \times 10^{-5}$ Pa, gas flow $Q_G = 1.60 \times 10^{-3}$ Pa L s^{-1} and the effective pumping velocity $S_0 = 160$ L s^{-1} can be calculated by Formula 4.

According to effective pumping rate $S_0 = 160$ L s^{-1} and flow conductance $U_{H_2} = 6050$ L s^{-1}, The pump speed $S_p = 164$ L S^{-1} can be calculated from the basic equation of vacuum system (Section 2.2.4).

Due to the short and large diameter of the tube, the change of gas pressure at both ends is very small, thus the calculated values of S_0 and S_p are almost equal, which to some extent reduces the requirement of vacuum pump on pumping speed.

3.1.4 Calculation of effective suction area F

In this work, Zr-V-Fe alloy getter tablets (as shown in Figure 6) is used as the basic material of the getter pump. At the beginning of the operation, there is little internal hydrogen content and the getter tablet has a high pumping rate of hydrogen. With the increase of suction volume, the pumping rate decreases gradually. Under 20° Cand 10^{-5} Pa vacuum, the initial inspiration rate of the carrier is over 2,500 cm^3·s^{-1}·g^{-1};

when the inspiratory capacity reaches 5,000 Pa·L·g^{-1}, the inspiration rate tends to stabilize at about 900 cm^{3}· s^{-1}·g^{-1}.

The inner diameter of the single getter tablet is 4.0 mm, the outer diameter is 10.0 mm, the thickness is 1.3 mm, and the mass is 273.8 mg. The calculated effective suction surface area (the upper, lower and outer wall surfaces) of the single tablet is 172.9 mm^2. Therefore, the mass of getter per unit area m_i = 1.59 mg/mm^2.

According to the one-time inspiratory volume requirement, Q_i = Q_A = 0.5 MPa L, the suction capacity as the suction rate tends to be stable is taken as the value of q_i = 5,000 Pa·L·g^{-1}, K_i = 0.55 for double-sided suction, thus we obtained the suction surface area $F = 1.16 \times 10^5$ mm^2 for 10 years from Formula 13.

3.2 Design of getter pump

In the design of getter pump, the main considerations are the suction amount and suction speed. The suction amount is to ensure that the working life of the getter can meet the required number of years after one activation, and the suction rate is to ensure that the getter can maintain the vacuum state requirements until the whole service life. Generally, the more the amount of getter in the pump, the larger the maximum suction amount and suction rate will be. However, its mass and volume are limited for the space hydrogen maser, thus it is necessary to combine the actual situation to calculate the proper amount of getter and get the corresponding getter pump structure design.

3.2.1 Performance design of getter pump

According to the previous calculation, the total inspiratory Q_A of service hydrogen maser is 0.5 MPa L for 10 years. In order to prevent the getter material from embrittle, it is necessary to retain a certain amount of allowance for use [18]. Meanwhile, for maintaining the required vacuum state, the vacuum pumping rate should be faster than 164 L/s, and the effective area of the getter should be larger than 1.16×10^5 mm^2.

Considering the balance of cost, performance, weight and allowance reserve, we design a vacuum system for space active hydrogen maser based on the above research and calculations. The pump contains 527 g getter materials with a total number of 1925 getters. The single effective suction surface area is 172.9 mm^2 and the total effective suction area of about 3.3×10^5 mm^2.

The inspiratory capacity of single tablet is not less than 5,000 Pa·L·g^{-1}, thus the capacity of the total getter pump is not less than 2.5 MPa·L, meanwhile, the suction rate is about 474 L/s, and the theoretical gas consumption is less than 20% of the full capacity, which fully meets the above performance requirements and can meet the engineering application needs of space active hydrogen maser for more than 10 years.

3.2.2 Structural design of getter pump

Based on the performance requirements and our previous work [19], the getter pump structure designed as follows.

The overall structure of the getter pump is shown in Figure 7A, which is mainly composed of a shell, getter tablet and its bracket, and heating devices. The shape of the pump and its overall size is determined by the internal requirements of the active hydrogen maser. The outer diameter is 196.0 mm, the inner diameter is 90.0 mm, and the height is 40.0 mm. The shell of the pump is composed of a Ti metal plate, which is 1.5 mm in thick, to reduce the influence of magnetic field on the performance of the hydrogen maser.

Figure 7B is the schematic diagram of the internal getter structure. There are altogether 175 getter units assembled in six layers, with 25 in the innermost layer and 30 in the outer five layers.

Figure 8A shows the structure of getter unit, which is mainly composed of base, getter tablets, Ti gasket, fixed nut, heating wire, and Ti support. Each getter unit contains 11 getter tablets, as described above, its inner diameter is 4.0 mm, outer diameter is 10.0 mm, thickness is 1.3 mm, and single mass is 273.8 mg (Figure 8B).

Each getter is separated by Ti metal gasket to increase the suction area; The bracket is a hollow structure, with an inner diameter of 3.0 mm, an outer diameter of 3.5 mm and a length of 35.0 mm (Figure 8C). Nickel-chromium alloy hot wire is installed inside the bracket to facilitate the activation of getter.

After the getter is exposed to the atmosphere or used for a long time, a passivation layer will be formed on its surface, which will reduce the rate of hydrogen absorption. Therefore, the getter pump needs to be equipped with a heating device for high temperature treatment to remove the passivation layer and obtain the fresh active surface, this process is called the getter pump activation.

The heating device uses nickel-chromium alloy heating wire with diameter of 1.0 mm and resistivity of 0.832 μΩ m. It has strong corrosion resistance, non-magnetic, and the operating temperature can up to 1,200°C. In the getter pump, the heating wires inside each getter unit are connected in series with a total length of 4.5 m and a resistance of 4.7 Ω. One end is connected with the pump shell as a negative pole, and the other end is connected with the ceramic electrode insulated with the pump shell as a positive pole. The total mass of the getter pump is approximately 4.5 kg, containing 527 g getter materials.

3.3 Lectotype of small ion pump

In the combined pump of small ion pump and getter pump, hydrogen absorption is mainly accomplished by the getter pump, and the small ion pump plays the role of eliminating trace impurities. The trace impurity gas in the vacuum system

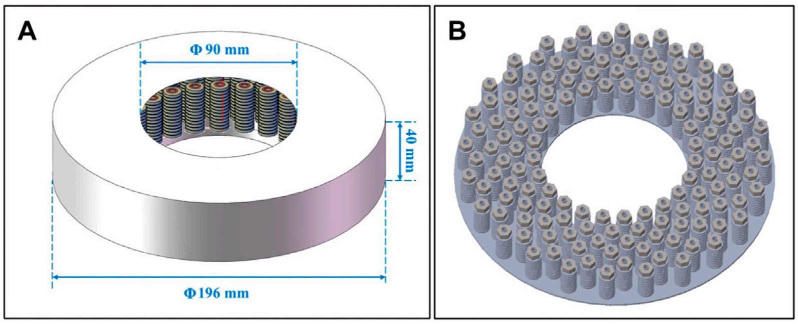

FIGURE 7
(A) External structure size of getter pump; **(B)** Schematic diagram of internal structure.

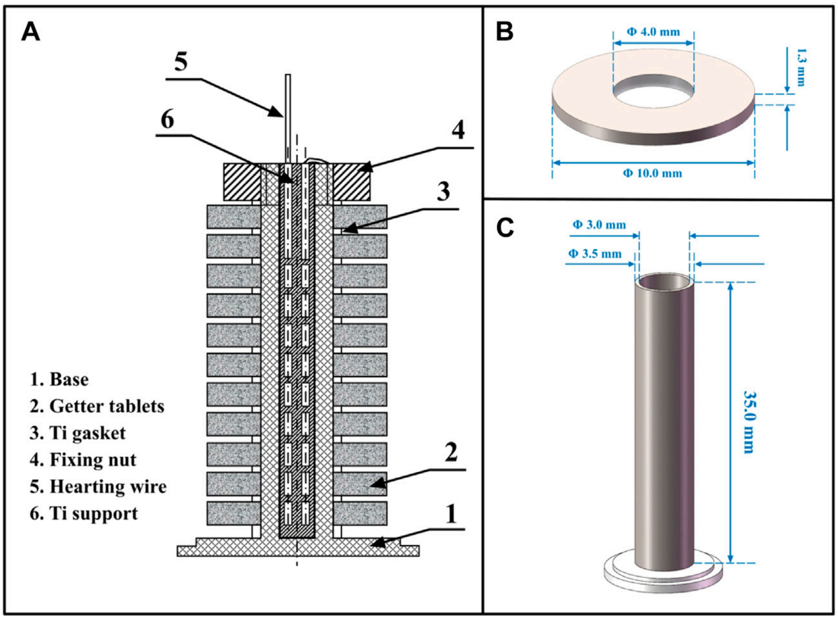

FIGURE 8
(A) Structure of getter unit; **(B)** Structural size of getter tablet; **(C)** Ti support structure size.

mainly comes from the gas leakage of the wall material, which is mainly determined by the outgassing rate of the wall material. As the outgassing rate decreases slowly with time during the service life, the maximum outgassing rate at the beginning is used for calculation to maximize the reliability requirements.

According to the existing data of the outgassing rate of the space-borne passive hydrogen maser [20], considering a larger hydrogen flow that the active hydrogen maser has than passive ones, we selected the Agilent 5 L/s small ion pump as the composite pump in this work. The pumping rate has a large surplus, which can be further optimized according to the requirements of practical application. Additionally, remote vacuum level monitoring can be achieved with ion pump current readings. The weight of this small ion pump is about 0.5 kg and the service life exceeds 10 h under above operating conditions [21], which fully meet the 10-year engineering application requirements.

4 Conclusion

The active hydrogen maser with excellent timing accuracy and wide amplitude stability plays an important role in the fields of timing and navigation. In order to meet the lighter requirements of the Shanghai Astronomical Observatory for SAHM in the space VLBI project, we designed a combined vacuum pump composed of a getter pump and an ion pump. The getter pump plays the main role of hydrogen adsorption. It is in the shape of a ring, with an outer diameter of 196 mm, an inner diameter of 91 mm, and a height of 40 mm. Among it there are 1,925 getter tablets, the mass of which is 527 g and the getter pump is about 4.5 kg. Agilent Diode small ion pump is adopted as the combined ion pump to deal with trace amounts of inert gas impurities. The total mass of the composite pump is about 5 kg. Under conditions with a background vacuum of 10^{-5} Pa for the active hydrogen maser, the effective suction area of this pump is about 3.3×10^5 mm^2, which is higher than the required value (1.16×10^5 mm^2). When the suction volume of the getter pump reaches 2.5 MPa·L, the pumping speed of is about 474 L/s, those are much higher than the total hydrogen flow rate (0.5 MPa·L) of the hydrogen maser life requirements for 10 years and the pumping speed requirements (more than 164 L/s), This design amply satisfies the vacuum degree and life requirements of the vacuum system, and provides significant reference for the active hydrogen maser application in space.

In order to avoid embrittlement of the aspirant material, it should be retained a certain suction margin during the 10-year operating time. Generally, there is only 10%–25% of the full capacity is used. The aspirator tablets selected in this design have not appeared embrittlement after a long period of hydrogen absorption in the engineering test, thus we set the 10-year theoretical suction capacity is at about 20% of the full capacity. The suction pump design still retains a large free space to balance the performance and mass of the vacuum system, and to ensure the adequate flow of gas in the suction pump and improve the effective contact area. If higher reliability requirements need to be met in future work, the use of aspirated tablets can be appropriately increased to increase capacity redundancy. Meanwhile, since there is no securable working data of the active hydrogen maser or other relevant data, we selected a large redundancy suction speed to make the lectotype of small ion pump, and remain a large space for lighter design, it can be further optimized after future data support. Otherwise, for verifying the adaptability and reliability of the designed combined pump in the extreme space environment, it should also be simulated in the space environment experiments, potential problems should be actively optimized to ensure the realization of all relevant functions expected.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

HQ contributed majorly to this work. All authors participated in the writing of the manuscript.

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Conflict of interest

Authors JX and TL were employed by Shanghai Kingv Material Technology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphy.2022.970705/full#supplementary-material

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