Updates of SHAO Active H Maser and Design of the Space Principle Prototype

Jiayu Dai*, Yong Cai*, Xueling Hou†, Tiexin Liu*, Zhengkai Li*, Di Zhuang*, Wujiabei Xu*†,

Haohui Que*†, Yueqiang Liu*†, Mingzhou Yu*‡, Lei Yang*§

daijy@shao.ac.cn, cy@shao.ac.cn, flybird1656@163.com, tiexinl@shao.ac.cn, zkai@shao.ac.cn, zd@shao.ac.cn, xwjb@shao.ac.cn, hh@shao.ac.cn, liuyueqiang@shao.ac.cn, yumingzhou22@shao.ac.cn, yanglei@shao.ac.cn

*Time & Frequency Research Laboratory, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China
†School of Materials Science and Engineering, Shanghai University, Shanghai, China
‡School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing, China
§Department of Physics, Shanghai University, Shanghai, China

***Abstract*—Shanghai Astronomical Observatory (SHAO) is now researching a space active hydrogen maser by upgrading the ground active maser. In addition to the relevant materials and crafts development, the vacuum and the magnetic field shielding system of the physical package have been optimized for a compact space H maser. For the moment a 60 kg physical package has been achieved with the standard size TE011 microwave cavity.**

Keywords—hydrogen maser, H plasma, vacuum, ambient magnetic field shielding, simulations, material science, space active H maser, Chinese Space Station

I. INTRODUCTION

Since the Time & Frequency (**TF**) researching and broadcasting program started in the 1970's in Shanghai Astronomical Observatory (**SHAO**), hydrogen masers, as one of the **TF** relevant projects in **SHAO**, has experienced a half century development up to now. From the ground based traditional active design (of more than 200 kg) to the satellite compact passive version (of no more than 23 kg), and now to the research of a space active one (with a goal of 50 kg or below) for the Chinese Space Station (**CSS**) purpose, focus has gradually been turned onto a compromise between its instability performance of the frequency output signals and its volume as well as the mass reduction, for the restrictions proposed by the space application circumstances.

Meanwhile, **SHAO** is taking part in astronomical observation and researching, such as the Very Long Baseline Interferometry (**VLBI**), and Square Kilometre Array telescope (**SKA**), etc., which are closely connected to the performance of active hydrogen masers. Working on the space maser research will contribute to the development of the precise astronomy subjects in the near future.

II. OVERVIEW OF THE ACTIVE HYDROGEN MASERS

As shown in **Table I**, instability performance of the **SHAO** Ground Active H Maser (**GAHM**) is about 2×10^{-15} per day. Apparently it's too heavy for the space application with the mass and volume being 300 kg and 900 mm (in length) × 500 mm (in diameter), respectively. On the other hand, the **SHAO** Satellite Passive H Maser (**SPHM**) has its instability performance not good enough for the **CSS** application, of which 5×10^{-15} per day should be satisfied. In the light of this, **SHAO** started the Space Active H Maser (**SAHM**) project years before.

In principle the **SAHM** prototype should be 50 kg below, and it is going to be realized by the combination of a Physical Part (**PP**) of 35 kg, and an Electronics Package (**EP**) of 15 kg. Virtually, the work on **PP** prototype is now carried out in steps for the assurance of maser's instability performance. For example, although the quartz microwave resonant cavity of the **GAHM PP** has limited the volume reduction to a large extent, still it is preferred to for the reason of its good performance. So realization of a 35 kg **PP** with the volume being 700 mm (in length) × 400 mm (in diameter) is completely a tough work. **Fig. 1 (a)** shows a **PP** with the sputtering ion pump of **GAHM** only for the performance verification experiment. All components apart from the sputtering pump weights up to about 55 kg in total.

For the moment, preliminary design of a 60 kg **PP** prototype has been accomplished, as shown in **Fig. 1 (b)**, and it had originally been conceived as a 70 kg one from a conservative point of view. Main work on the **PP** prototype will be presented in the following sections.

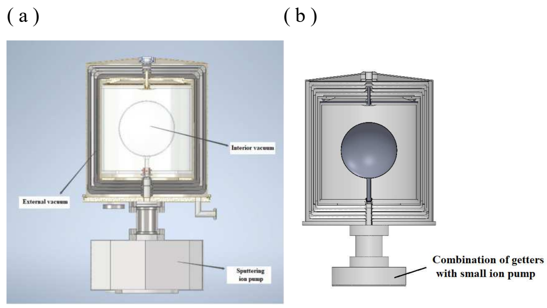

Fig. 1. Schematic overview of the preliminary designed **SAHM PP** prototype. (a) a **PP** with the sputtering ion pump of **GAHM**, for performance verification experiments; (b) 60 kg **PP** with a combination of getters with a small ion pump.

TABLE I. SPECIFICATIONS OF **SHAO GAHM**

Time	Performance of GAHM			
	Allan deviation standard $\sigma_y(\tau)$	*Accuracy*	*Temperature sensitivity*	*Mass*
1 sec.	3×10^{-13}	$\pm 3 \times 10^{-13}$	1×10^{-14}	300 kg
10 sec.	5×10^{-14}			
100 sec.	9×10^{-15}			

The work on getters research was supported by **NSFC** (U1531120) from 2016 to 2018. And further improvement is now supported by **NSFC** (12373078) till December of 2027.

Time	Performance of GAHM			
	Allan deviation standard $\sigma_y(\tau)$	*Accuracy*	*Temperature sensitivity*	*Mass*
1000 sec.	5×10^{-15}			
10000 sec.	1.5×10^{-15}			
1 day	1×10^{-15}			

III. DESIGN OF THE 60 KG **PP** PROTOTYPE

Compared with the **GAHM**, subjects such as the vacuum system and the magnetic shielding system of the **SAHM PP** have been optimized to ensure mass reduction being valid. For example, the vacuum pump has been replaced to realize a mass reduction from 70 kg to 6 kg. And the microwave resonant cavity has been moved out of the interior vacuum to improve the background vacuum, by reducing gases sourcing from the surface of the components, so as to make the combination of getters with a small ion pump applicable. Getters has been developed as a result of the collaboration with Shanghai University (**SU**) and of the support by the National Scientific Funding of China (**NSFC**). Combination of getters with a small ion pump, weighting only 6 kg, has been designed according to the practical getters performance measurements which had been carried out in terms of the testing criteria **ASTM F798**, and it will be applied to the next generation of **PP** prototype too. The standard size TE_{011} microwave cavity with its length and diameter being 250 ~ 270 mm has been employed, although it obviously restricts the whole **PP** mass reduction. Finally, the ambient magnetic field shielding system has been optimized in the thickness, the space between each two adjacent layers, and the alloys applied. The mass distribution of the 60 kg **PP** prototype is given in **Table II**.

TABLE II. MASS DISTRIBUTION OF THE 60 KG **PP**

Mass	Components			
	Vacuum pump	*Microwave resonant cavity*	*Magnetic shielding system*	*Others*
Design	6	9	25	30
Practical	≈ 6	≈ 9	≈ 13	≈ 32

A. Vacuum design and hydrogen gas load

Corresponding to the current **GAHM PP**, relevant vacuum demands should be satisfied for the **SAHM PP** at least. In fact, the 12 years continuous working period proposed a more stringent restriction for the following reason. The **SHAO GAHM PP** employs a sputtering ion pump with the pumping speed of being 250 liters per second. And rarely was the full-time operation of more than 10 years required. Usually the vacuum was manually restored by replacing the pumping cell. In the light of this, a more robust design is needed for the space application. Obviously, compound of getters and a small ion pump seems to be the best solution to the question, since hydrogen is the main gas load.

So, first we made an estimate of the practical hydrogen flux. This work was done by a theoretical and experimental study of the properties of hydrogen diffusion through the Ni purifier. A testing bed in **Fig. 2** [1] was designed in terms of the Pirani Gauge, to simulate the practical **GAHM** vacuum system (with its vacuum background of being $\leq 10^{-5}$ Pa), for measuring the relationship between the electric current *I* applied through the thin film Ni tube, of 300 ×1 × 0.1 (length × diameter × thickness) in mm, and its temperature, as well as the flux $(H_2)_{out}$ entering the discharging bulb, respectively.

Normally, **GAHM PP** operates at 3.0 ampere for the applied electric current setting, which corresponding to a $(H_2)_{out}$ flux of 6.47×10^{-10} mols per second, or 1.60×10^{-3} Pa·L/sec. It is an order greater than the flux of H atoms entering the storage bulb, which being $10^{12} \sim 10^{13}$/sec [2]. Accordingly, a 5 kg combination of getters with an ion pump had been developed by the year 2022 [3], for a 10 years operation period. Then, for a conservative design a larger $(H_2)_{out}$ flux, with the applied electric current of being 3.5 ampere, was taken for the **SAHM PP** vacuum design. The $(H_2)_{out}$ flux entering the discharging bulb will be 9.18×10^{-10} mols per second, or 2.27×10^{-3} Pa·L/sec., corresponding to 5.5×10^{14} per second on average. Accordingly, an amount of 0.85 MPa·L hydrogen gas load in total for the 12-years operating will only consume 34% of the whole getters capacity of the same combined pump. It still leaves a margin.

Getters should be good both at the hydrogen absorption performance and its reliability. A getter pump, in **Fig. 3**, was developed for **SAHM PP** prototype on the basis of sample experiments, which had been done to investigate the practical performance of getter disks, such as hydrogen absorption speed, hydrogen capacity, and brittleness of the shaped compound, etc.. Each getter disk is 20 mm (diameter of outside edge) × 6 mm (diameter of inside edge) × 2 mm (thickness) in appearance, weighting 2.5 g on average. An amount of 6 MPa·L H_2 can be absorbed in 5 minutes by the getter pump after activation with 500℃ for 30 minutes, according to the sample experiments. It could be taken for granted that a much better performance should be expected, since the practical H atom flux is much smaller.

On the other hand, an external vacuum system has been designed for a better thermal frequency sensitivity. Simulations of time it takes to arrive at the thermal equilibrium is given in **Fig. 4**, with the condition of an initial environmental temperature being 1 K higher than the microwave cavity. Comparison has been made in terms of the background vacuum ranging from 10^{-5} to 10^{-3} Pa. The longer it takes to arrive at the equilibrium, the better the thermal insulation is. Finally, leakage and outgassing have been measured or calculated, before a small ion pump of 5 liters per second being applied to maintain the external vacuum. Normally, a background of $\leq 10^{-3}$ Pa is handily realized, and a 10^{-5} Pa below background vacuum can be achieved by a sophisticated outgassing craft.

Fig. 2. Experiment of the (H_2) flux measurement.

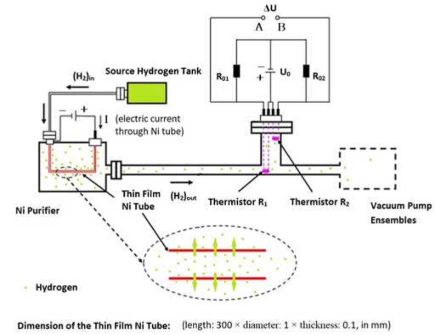

Fig. 3. Assembly of getters developed.

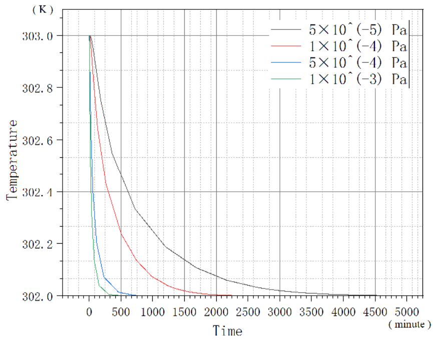

Fig. 4. Curves of the temperature variation versus time for the microwave cavity to arrive at thermal equilibrium with the background vacuum ranging from 10^{-5} to 10^{-3} Pa.

B. *Microwave resonant cavity*

- The hydrogen atoms storage bulb has been strengthened to realize the assembly via its entrance tube for the interior vacuum sealing.
- Then a slight adjustment in the geometric dimension of the microwave resonant cavity was done on the basis of simulation to avoid the conversion of the magnetic component of the RF field inside of the storage bulb, as shown in **Fig. 5**.
- The measured quality factor is greater than 35,000.

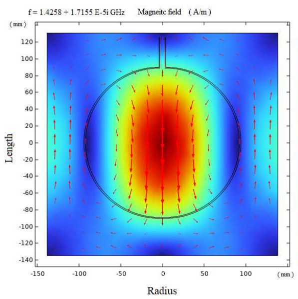

Fig. 5. Distribution of the magnetic component of the TE_{011} mode **RF** field, inside the standard size microwave resonant cavity.

C. *The magnetic field shielding system*

Magnetic field shielding system is critical to stabilize the frequency of emission by the transition of the hydrogen atoms ensemble, from the state (F=1, m_F=0) to (F=0, m_F=0), since the hyperfine energy levels vary with the magnetic field. A stable, very small, and uniform magnetic field of the order 10^{-7} tesla [4] for the H atoms transition, is usually realized by a solenoid enclosed by four or five layers of thin cylindrical shielding shells. To reduce the perturbation of atomic energy levels, the amplitude of background magnetic field in the region of microwave cavity should be an order less than 10^{-7} T at least. Gradient and the fluctuation of the field should be strictly restricted too. Shielding factor of the system is required to be greater than 10^5 for the maser to arrive at a magnetic sensitivity being no more than $1.0 \times 10^{-14}/10^{-4}$ T [5]—[7].

A four layer shielding system similar to those of the **PP** of **GAHM** is hired in this stage of development, as shown in **Fig. 1**. Distribution of the background magnetic field inside the shielding system and variation of its amplitude with the permeability performance of the layers are given in **Fig. 6 (a)** and **(b)**, respectively, suppose the ambient field is 5×10^{-5} T. The volume of the shielding system has been slightly optimized for the mass reduction although the contribution is tiny. And the thickness of each layer has been reduced to about 0.5 mm. The shielding factor is 10^5 by simulation, with the application of the combination of two best domestic permalloy 1j85, whose permeability being given in **Table III**. Hence, the magnetic sensitivity of frequency will be $\leq 10^{-14}/10^{-4}$ T.

TABLE III. COMPARISON OF THE PERMEABILITY PERFORMANCE

Samples	Permeability Measurements	
	Initial permeability, μ_i (mH/M)	***Maximum permeability, μ_{max} (mH/M)***
1j85-1	≈ 25	≈ 220
1j85-2	≈ 30	≈ 200

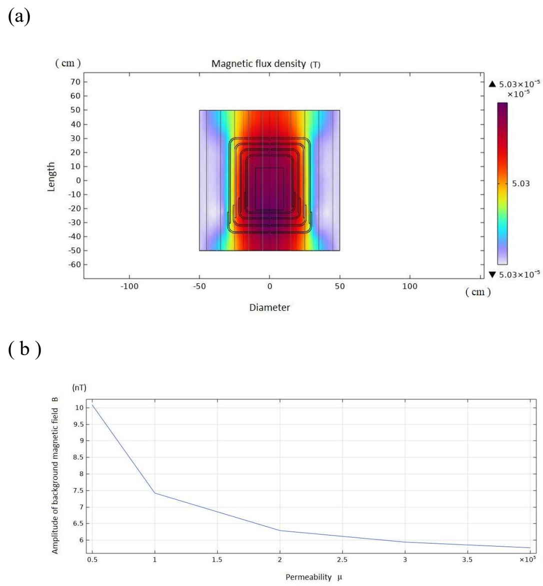

Fig. 6. Distribution of the magnetic field inside a four-layer shielding system, with the environmental magnetic field being 5×10^{-5} T along the vertical axis.

IV. CONCLUSION AND DISCUSSION

A 60 kg **PP** prototype of **SAHM** has been designed, with its vacuum system finely prepared for the 12 years operation. The magnetic shielding system is qualified to arrive at a magnetic sensitivity of $10^{-14}/10^{-4}$ T. Finally, the frequency instability should be of the same level as the **GAHM** since most of the design has been inherited.

On the other hand, working on the following subjects is necessary to the next generation 35 kg **PP**.

A. A Compact Microwave Cavity

The 35 kg **PP** requires a more compact microwave cavity design. Performance of a dielectric material was compared with the sapphire when applied to H masers [8]. Also, the $Ba(Mg_{1/3}Ta_{2/3})O_3$ (**BMT**) [9] ceramics could be another promising material, with the quality factor of the empty cavity being 51,000 according to the simulations in **Fig. 7**.

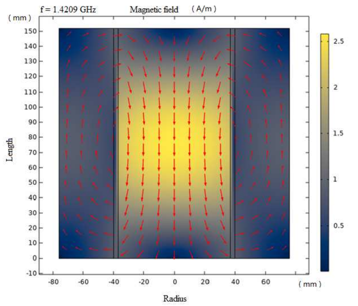

Fig. 7. Simulation of microwave resonant cavity with ceramics **BMT**.

B. Hydrogen Dissociator

More survey of the dissociator malfunction is necessary to the H maser reliability improvement. For example, contaminants in white normally appears on the inner surface of the discharging bulb after months of operation. They are supposed to be the deposits of small silica particles sputtered from the surface of the bulb according to the chemical component analyses by Energy Dispersive Spectrometer (**EDS**) as shown in **Fig. 8 (a)**, and to the observation of the inner surface of discharge bulb by Scanning Electron Microscope (**SEM**) as given in **Fig. 8 (b)**, which is in agree with the work by L. Maleki [10]. More work on the evaluation of hydrogen discharging degradation is ongoing.

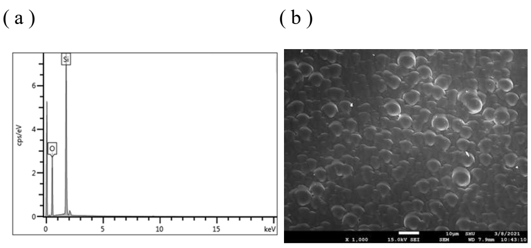

Fig. 8. Experimental analyses of the discharging bulb.

C. Some Other Work

a) Upgrade of the Magnetic Field Shielding System: Developing a higher permeability performance material will contribute both to the instability performance and the **PP** mass reduction either of space masers or ground masers. Updates from the laboratory of permalloy researching has brought the measured permeability of samples being double of our best current industrial products, which will make the next **PP** development delightful, supposing the practical massive production of this new alloy can be realized soon. Theoretically, 10^5 of the shielding factor by a 3-layer magnetic shielding system will be possible by simulations.

b) Comparison of State Selectors: In the 35 kg **PP**, the hexapole magnetic state selector is going to be subsituted by the quadrupole design for the advantage of a shorter distance between the exit of state slecetor and the entrance of storage bulb. It seems that more atoms of (F = 1, m_F = 0) could enter the storage bulb, but the deflection amount of atoms (F = 1, m_F = -1) and (F = 0, m_F = 0) will decrease according to the simulations of the same input H flux.

ACKNOWLEDGMENT

We thank Mr. Tao Lu, Jie Xiang, Shui-ming Huang, and some others, unknow their names, of Shanghai King Material Technology Ltd.. Their kindly sharing of their devices and experiences speeds up the getters development for the **PP** of **SAHM**. We appreciate their contributions.

REFERENCES

[1] Qi Li, Xueling Hou, Jiayu Dai, et al., "Research on a material for hydrogen purifying and flux controlling with application to space active hydrogen – masers," AIP Advances 12, 035207 (2022); https://doi.org/10.1063/5.0084176.

[2] Jacques Vanier, Claude Audoin, "The Quantum Physics of Atomic Frequency Standards," Chpater 6, (1989) IOP publishing, Ltd.

[3] Haohui Que, Wujiabei Xu, Qi Li, Jie Xiang, Tao Lu, Tiexin Liu, Yong Cai, Jiayu Dai, and Xueling Hou, "Design of a vacuum system for space active hydrogen maser," Frontiers in Physics, August 2022, doi: 10.3389/fphy.2022.970705.

[4] Daniel Kleppner, H. Mark Goldenberg, and Norman F. Ramsey, "Theory of the Hydrogen Maser," Physical Review, Vol. 126, No. 2, April 15, pp. 603-615, 1962.

[5] D. U. Gubser, S. A. Wolf, J. E. Cox, "Shielding of longitudinal magnetic fields with thin, closely spaced, concentric cylinders of high permeability material," Rev. Sci. Instrum. 50, 751-756 (1979), https://doi.org/10.1063/1.1135915.

[6] D. Gingras, J. Vanier, "Comment on magnetic shielding in hydrogen masers," Journal of Physics E Scientific Instruments, Vol. 18, 1985 doi: 10.1088/0022-3735/18/11/019.

[7] Demidov NA. "The development and futrue of hydrogen maser clock technology," J Astronomical Metrology Meas (2007) 6. doi:10.3969/j.issn.1000-7202.2007.z1.002.

[8] Zhou, T. et al. (2020). "New Research Progress in Active Hydrogen Maser in BIRMM," In: Sun, J., Yang, C., Xie, J. (eds) China Satellite Navigation Conference (CSNC) 2020 Proceedings: Volume II. CSNC 2020. Lecture Notes in Electrical Engineering, vol 651. Springer, Singapore. https://doi.org/10.1007/978-981-15-3711-0_41.

[9] K. Matsumoto, T. Hiuga, K. Takada, H. Ichimura, "Ba (Mg1/3Ta2/3)O3 Ceramics with Ultra-Low Loss at Microwave Frequencies," Sixth IEEE International Symposium on Applications of Ferroelectrics, Bethlehem, PA, USA, 1986, pp. 118-121, doi: 10.1109/ISAF.1986.201108.

[10] L. Maleki, "The development of a magnetically enhanced hydrogen gas dissociator," 36th Annual Frequency Control Symposium, 1982.