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Development of an ultra-high vacuum system for space cold atom clock

Wei Ren, Jingfeng Xiang, Yuantao Zhang, Bin Wang, Qiuzhi Qu, Jianbo Zhao, Meifeng Ye, Desheng Lü*, Liang Liu*

Key Laboratory of Quantum Optics and Center of Cold Atom Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

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ABSTRACT

Space cold atom clock (SCAC) is developed for a series of experiments related to laser cooling of atoms and cold atom clock in space microgravity environment. An ultra-high vacuum (UHV) system is the key element for SCAC. This paper presents the design of the UHV system and also shows the status of an initial UHV system prototype with the design and a series of special vacuum treatments whose pressure distribution satisfies the special requirements for SCAC. A dual pumping system, including ion pump and getter, is introduced, and pressures of different positions have been calculated. Experiments have been carried out to acquire the performances of the initial prototype. It is proved that the initial prototype can not only self-sustain an equilibrium pressure for more than 2 months without power but also withstand the mechanical vibration test and space environment simulation test. Furthermore, an optimization design is used to get pressures which are much lower than the desired pressure (~$\times 10^{-8}$ Pa) in the interaction zone of the system has been demonstrated.

1. Introduction

The Space Cold Atom Clocks (SCAC) using cold atoms as frequency reference have some special advantages over ground cold atom clocks due to microgravity and will play an important role in the field of metrology, precision measurement and fundamental physics [1,2]. Typically a SCAC is composed of a vacuum system, an optical system, a control system, and a microwave system. The ^{87}Rb atoms are cooled, launched, selected, interrogated with microwave, detected in the vacuum system. The requirements of the SCAC for the vacuum system involve magnetic field intensity and pressures at different positions in the system as following:

- The magnetic field along flight route of the cold atoms provides a quantization axis whose aim is to purify the cold atoms especially when the cold atoms are interrogated and detected [3]. It must be with a constant direction and its fluctuation must be less than a few nano-Tesla in the region where the cold atoms are interrogated and detected [4].
- The pressure of the vacuum system reflects the density of the background gas which is directly related to the number and life of the cold atoms due to the collision between them, and the collision reduces the coherence time of the cold atoms [3]. It is especially important for a SCAC because of longer interrogation time compared to a fountain clock. Hence, the pressure is crucial for SCAC, and the UHV system is needed. The estimated pressure in the interragation region for a SCAC needs to be lower than ~$\times 10^{-8}$ Pa, and lower than ~$\times 10^{-7}$ Pa in the cooling region [3].

Besides, the UHV system of a SCAC must satisfy the restrictions:

- The UHV system should be lightsome and must be able to withstand the rigorous mechanical test due to the harsh mechanical environment during the rocket launch [4].
- The storage temperature of the UHV system should be in the range of 0 °C–40 °C according to the internal environment of the spacecraft.
- The pressure in the UHV system should be maintained for more than 2 months without power supply to prevent the accident power fault and meet the requirement of low electric power during the rocket launch [4].

* Corresponding authors.
E-mail addresses: dslv@siom.ac.cn (D. Lü), liang.liu@siom.ac.cn (L. Liu).

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This paper presents the design of the UHV system for a SCAC and the solutions we choose to match the requirements of the space application.

2. Design of the vacuum system

In order to satisfy the restrictions of space application and match the specific requirements for space application, we have designed a UHV system for the SCAC. Based on the basic structure of the Rubidium atom fountain [5,6] and the early designs in our group [7], the design includes a vacuum tube, a rubidium base, and a dual-pump system. And the vacuum tube includes cooling, selection, interaction and detection zone as shown in Fig. 1. The ^{87}Rb atoms stored in a glass cell, not rubidium dispenser, which located in the rubidium base diffuse into the cooling zone. Then some of them are cooled and captured by magneto-optical trap. The cold atoms are launched and fly along the axis of the vacuum tube. The selection cavity and chamber are located in the selection zone and the Ramsey cavity lies in the interaction zone. The design also involves the selection of the material and pumps and the method of sealing as following.

2.1. Material selection

In order to satisfy the first requirement of the SCAC, that is the fluctuation of the magnetic field along the Ramsey cavity axial is less than a few nano-Tesla and to match the restriction of the space application about mechanical strength and the weight limitation, we have chosen the material TC4 as the major material of the vacuum system for the SCAC. The TC4 has the specifications such as low density, high strength, non-magnetic, low outgassing rate, which is one kind titanium alloy material composed of Ti-6Al-4V, as shown in Table 1. TC4 is lightsome (density of 4.43 g/cc) with high specific ultimate tensile strength and a low thermal and electrical conductivity which can also match the demand about the large storage temperature range for space application [8]. The specifications of the TC4 make the vacuum system more stable and resistible for corrosion and stress-corrosion. Besides, the TC4 is nonmagnetic. Hence, TC4 is suitable for the SCAC's space application.

2.2. Pumps selection

A dual-pump system is introduced to keep the vacuum system at around 5×10^{-8} Pa. We use two ion pumps as the main pumping system to obtain pressures in the UHV. And the 2 ion pumps connected with the vacuum tube by flange as shown in Fig. 1. We also set 2 groups of getters at the two ends of the interaction zone and each group contains 4 getters. The pumping speed of the interaction zone which results from the getters is higher than that in other zones in the vacuum system, hence the pressure in the interaction zone is much lower than other zones. Moreover, the getters with lager pumping speed are passive device which do not need power supply and can be activation repeatedly. Thus the dual-pump not only can guarantee the desired pressure distribution in the UHV system of SCAC but also can insure that the UHV system can maintain ultra-high vacuum for a long time without power supply.

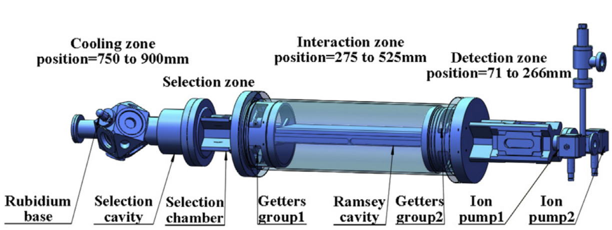

Fig. 1. The design of the ultra-high vacuum system of an SCAC.

Table 1
Physical and mechanical properties of the TC4.

Physical properties	Metric	Mechanical properties	Metric
Density	4.43 g/cc	Hardness, vickers	349
Electric resistivity	17.8 Ω/cm	Tensile strength, ultimate	950 MPa
Magnetic permeability	100.005	Elongation at break	14%
CTE, linear 20 °C	8.6 μm/(m °C)	Modulus of elasticity	113.8 GPa
CTE, linear 250 °C	9.2 μm/(m °C)	Shear modulus	44 GPa
Thermal conductivity	6.7 W/m/K	Fatigue strength (10,000,000 cycles)	510 MPa

2.3. Sealing method

The vacuum system has four parts connected by flanges with each other. For decreasing the leak of the system, all the flanges are sealed by Delta seals (Garlock Helicoflex) and indium as shown in Fig. 2a. The fluctuation of the magnetization induced by the Delta seals is not more than ±1 nT in the magnetic shield. And the indium that has superior ductility is used to reinforces the sealing together with the Delta seals so that any defect on the sealing surface can be smoothed. It is important that same force moment which is used on all the fasteners is needed according to the size and the distribution of the screws on a same flange. In order to satisfy the mechanical requirements, it is also very important to tight the flanges without any gap between flanges.

Windows' sealing is crucial for the vacuum system not only because it directly affects the leak of the system but also they are fragile. We choose viton o-ring and indium to seal the windows as Fig. 2b. The viton o-ring provides a restoring force to prevent the leak and fragmentation due to the thermal deformation during the environment temperature changing. As well as, we choose the same force moment to symmetrically fix the fasteners to prevent the windows from being broken.

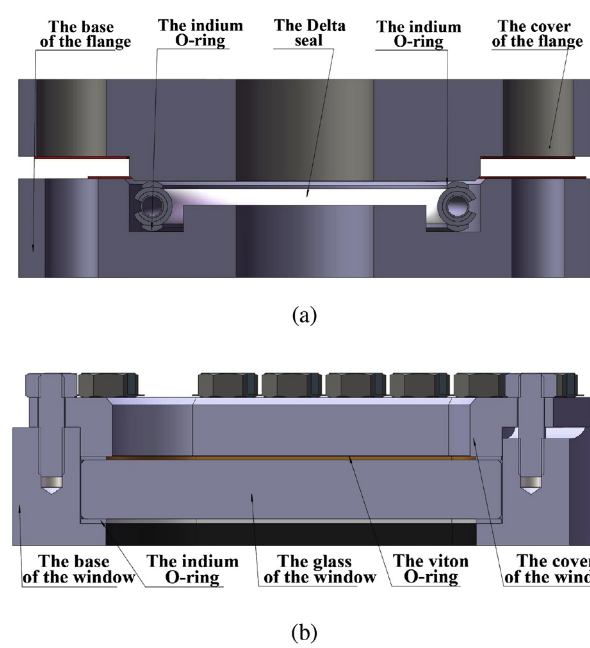

Fig. 2. The sealing method of the flanges and the windows. (a): sealing method of the flanges. (b): sealing method of the windows.