Physics package of the 35kg space active hydrogen maser for the ACES space mission of ESA

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***Abstract*—The 35kg space active Space Hydrogen Maser (SHM) is part of the Atomic Clocks Ensemble in Space (ACES) mission of ESA. The Physics Package (PP) of the Engineering Model (EM) of the SHM is currently developed at the Observatoire de Neuchatel and for the nominal operational parameters has the long-term frequency stability of 1.5x10^{-15}@10'000s. In this article we report the latest developments on the PP of the EM.**

I. INTRODUCTION

The ACES mission of ESA [1] is aimed at demonstrating the superior performance of a new generation of atomic clocks in microgravity space environment and enable a number of fundamental physics experiments on board of the International Space Station (ISS). Its objective is based on the merged performances of two high-performance clocks. The primary on-board clock, PHARAO [2], based on the laser-cooled cesium atoms, holds the potential of up to now unprecedented long-term ($\tau \geq 3000$s) frequency stability and the active Space Hydrogen Maser (SHM) with its superior frequency stability in the mid-range ($3\text{s} \leq \tau \geq 3000$s) as a reference compile into the system with outstanding characteristics for each interrogation time.

The SHM is currently being developed at the Observatoire de Neuchâtel (ON). To accommodate the maser within the ACES payload a rigorous miniaturization of the Physics Package (PP) was necessary leading to an overall mass of the complete instrument of only 35 kg, the lightest ever built active hydrogen maser.

The PP development is presently at Engineering Model (EM) level. The EP is manufactured, assembled and in the advance stage of testing. Currently functioning with the laboratory electronics developed at ON it has successfully completed a series of functional and performance tests which will be reported in these proceedings. In Chap. II after the recapitulation of the SHM instrument overview we discuss the details of the operation and design and present some results of the performed functionality test. Chapter III summarizes the status and presents the forthcoming steps of the SHM development towards the Proto-Flight Model.

II. PHYSICS PACKAGE DESCRIPTION

The PP of the SHM is presented in Fig. 1. It provides the actual atomic oscillator and consists of the microwave cavity, the magnetic shield assembly and several peripherals like the hydrogen distribution assembly and the ion pumps.

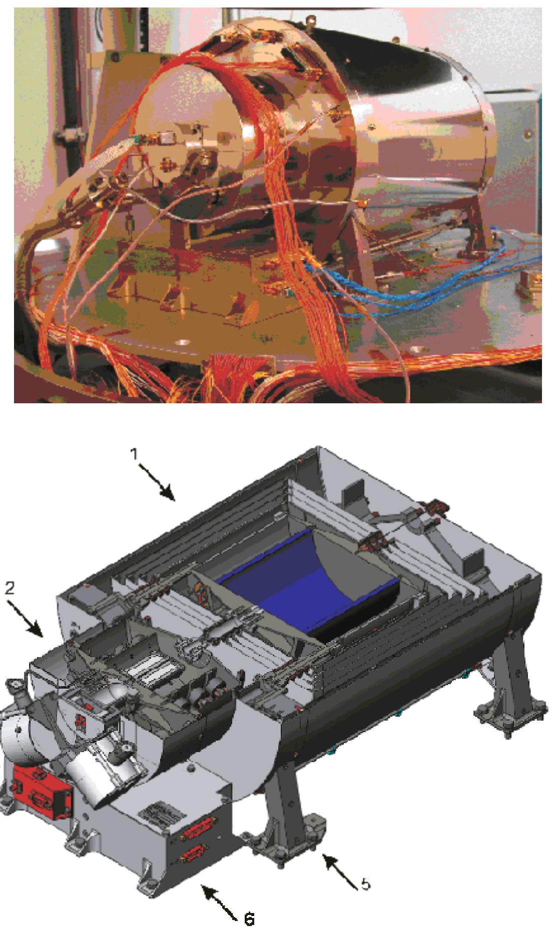

Figure 1. The photo of the Engineering Model and cross-section schematics view of the Physics Package of the SHM instrument: 1: Microwave cavity and shields assembly; 2: Hydrogen-vacuum assembly; 3: Ions pumps; 4: Low noise RF amplifier 5: External fixation structure; 6: Hydrogen distribution assembly.

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The upper part of the Fig.1 is a photograph of the PP-EM sitting on the baseplate of the Thermal Vacuum Chamber (TVC), while the horizontal-cut view in the lower part indicates the various functional subassemblies

A. Mircrowave cavity and storage bulb

Considering that typical ground masers weight more than 100 kg, to reach a mass reduction by factor of three was quite a challenge. In order to fulfill the SHM design requirement of 35 kg, the cylindrical microwave resonator is loaded with a coaxial sapphire cylinder. The high dielectric constant of sapphire allowed a significant size reduction. The cylinder is made of a single crystal to limit losses. Table 1 gives the design parameters and theoretical sensitivities of the TEM_{011} mode to dimensions and temperatures. Note that the main contribution to the thermal coefficient of – 69 kHz/K is not the thermal expansion but the variation of the dielectric constant of sapphire with temperature. These design assumptions, based on a theoretical basis given in [2], have been experimentally confirmed in [3]. The internal volume of the microwave cavity is 4.4 liter. This is to be compared with the 20 liter of a conventional unloaded cavity tuned to the hydrogen hyperfine frequency. The storage volume for hydrogen is 1.7 liter which is comparable to a conventional design based on a full size cavity.

TABLE I. DESIGN PARAMETERS OF MICROWAVE CAVITY

D_1 [mm] inner diameter of sapphire cylinder	125
D_2 [mm] outer diameter of sapphire cylinder	137
D_3 [mm] diameter of metallic cavity	200
h [mm] length of sapphire cylinder & metallic cavity	140
f_0 [MHz] resonant frequency of TE_{011} mode	1420.405
unloaded quality factor Q of TE_{011} mode	40'000
mass of sapphire resonator [kg]	1.4
mass of complete Ti/sapphire cavity [kg]	4.3
V [cm^3] storage volume for hydrogen	1'720

$d\nu_0/dD_1$ [MHz/mm]	-35
$d\nu_0/dD_2$ [MHz/mm]	-33
$d\nu_0/dD_3$ [MHz/mm]	-4.9
$d\nu_0/dh$ [MHz/mm]	-2.3
$d\nu_0/dT$ [kHz/K]	-69

sapphire, E normal to c	
tan(δ)	1.7e-5
ε	9.36

The cavity cylinder is made of titanium with the inner surface coated with copper and an overlayer of gold. The unique feature of the present design is that the sapphire cylinder is vacuum-tightly bonded to the titanium end faces of the cavity and serves at the same time as the storage container for the atomic hydrogen (Fig. 2). The seal is achieved by a thermal diffusion bonding technique, whereby the similar thermal expansion coefficients of the brittle sapphire and titanium assure a stress-free connection [4].

The interior of the sapphire/Ti envelope is coated with FEP to prevent spin depolarization of hydrogen atoms during their emission of radiation. Developments at ON have led to a coating that yields a very low wall relaxation rate that is very stable with time [5][6]. In view of operation in space the effect of proton irradiation on the Teflon coating was studied experimentally. The test showed that the shielding of the outer metallic layers of the PP is sufficient to protect the Teflon coating from proton radiation damage. Further analysis showed that this shielding also blocks completely the electrons of the radiation belts.

The microwave cavity is tuned mechanically, thermally and electrically to the hydrogen hyperfine frequency. The coarse adjustment is performed during the machining of the cavity, the intermediate adjustment is realized through the temperature coefficient of the cavity (-69kHz/K) and the fine-tuning (0.1Hz level) is controlled by a varactor diode. The loaded cavity factor has been measured at 35'000. The second step towards the miniaturization is based on the fact that SHM will operate in the space environment, *i.e.* that the thermal isolation of the microwave cavity will be achieved directly by the vacuum of the space environment. That allowed the removal of the external vacuum enclosure and leading to a further decrease of the total mass.

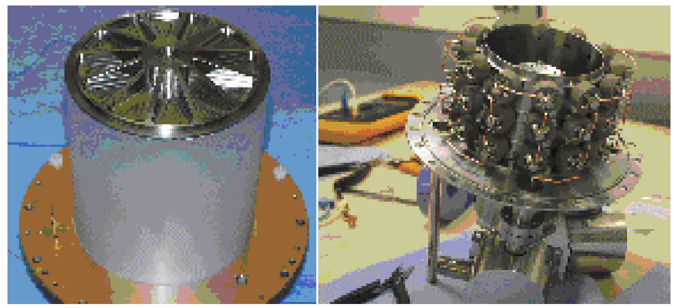

Figure 2. Photos of the sapphire bulb bonded to the microwave cavity end faces and the and mounted getter assembly

B. Hydrogen supply system

Hydrogen is supplied from a solid-state metal alloy (rare-earth pentanickel). The storage metal is contained in granular form in a small metal container (BL20-M of Hydrogen Components Inc., USA), which holds also a sintermetal filter to prevent contamination of the gas line by metal hydride particles. The hydrogen desorption pressure is temperature dependent.

Fig. 3 shows the pressure evolution for two fixed container temperatures as function of the amount of hydrogen (bar*l) stored in the alloy. Over a wide range of concentrations the pressure is essentially stable for a given temperature. For the maser operation this temperature is fixed to 45°C by a thermistor controlled feedback loop, which acts on a transistor heater. At this temperature desorption pressure stays around 10 bar.

The high-pressurized hydrogen flows through stainless steel tubes towards the Nickel Diffusion Control Device (NDCD). The NDCD acts as a purifying membrane and reduces the high to low pressurized hydrogen needed for the maser operation. It includes a thin-walled Ni tube through which hydrogen permeates as function of its temperature.

Downstream of the NDCD the hydrogen flows into the hydrogen dissociator. The dissociator pressure is controlled by a Pirani-thermistor gauge, whose set-pressure is fed back to the NDCD heater. This control loop forms the last stage of the Hydrogen Distribution Assembly (HDA), an external building block outside the actual maser assembly.

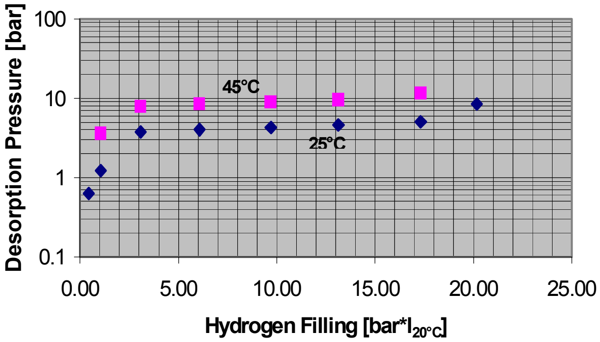

Figure 3. Measured pressure-concentration isotherms of the metal hydride M in BL-20 container for two desorption temperatures, 25°C and 45°C

Fig. 4 shows the configuration of the HDA, which has undergone extensive functional and acceptance testing to determine operational parameters and safety limits. The Maximum Design Pressure (MDP) of the high-pressure system is determined by the desorption pressure generated above the fully filled hydride at the maximum allowed storage temperature, 27.5 bar @ 75°C. The strength of the hydride container was tested at a design burst pressure of 2.5 x MDP = 67.5 bar, and the fully assembled high-pressure region was proof pressure tested at 1.5 x MDP = 41.25 bar.

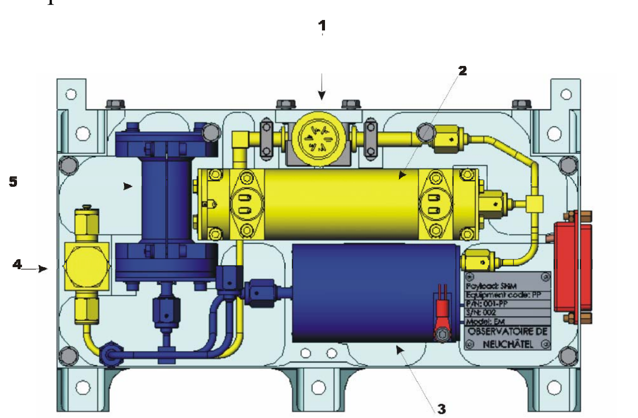

Figure 4. Overview of the hydrogen distribution assembly: 1: High pressure gauge; 2: Hydrogen supply container; 3: Nickel purifier; 4: Filling valve; 5: Pirani vacuum pressure gauge.

C. Hydrogen Dissociator Assembly

The molecular hydrogen gas supplied by the HDA enters into a low-pressure gas-bulb (0.1 bar) where an rf-plasma discharge of 10 W maximum is sustained, which produces atomic hydrogen with an efficiency of about 50%. Dissociated atomic hydrogen leaves the bulb through a single-hole collimator (0.15 mm diameter x 1.5mm length) and forms collimated beam entering the vacuum chamber. In first approximation the atomic hydrogen beam flux is determined by the fixed conductance of the collimator and the controlled pressure in the dissociation bulb. However the dissociation efficiency decreases slightly over extensive operation times. The nominal hydrogen fill of 17 bar*l in the hydride container at nominal flux of 2.7 bar*l/year allows a continuous operation of the maser over 6 years.

D. Vacuum system

The hydrogen atomic beam and storage bulb are maintained under high vacuum. Passive pumping of the hydrogen relies on the use of 30 ST-172 (Zr-Va-Fe) [SAES, Italy] non-evaparable bulk getters. One getter unit weighs 11g and has a theoretical hydrogen pump capacity of 1.4 bar*l when activated at 450°C for 20 min. However in order to avoid embrittlement of the charged getter material only 15% of the full capacity will be used over an operation time of 6 years. The getter array (Fig. 2) allows a vacuum autonomy of 10 days without electrical power. The internal vacuum is further supported by the use two miniature ion pumps of 2 l/s in order to absorb the other background gases.

E. Magnetic controls

The trajectories of the atomic beam are guided by the presence of the high magnetic field gradient (1.8 T/mm) of a quadrupole state selector. Atoms in undesired states are deflected off the beam trajectory whereas those reaching the hydrogen storage bulb create the necessary population inversion in the atomic ensemble within the bulb for the detection of the atomic oscillations. Since the clock transition of the maser runs between selected magnetic sublevels of the hydrogen hyperfine levels of the atomic ground states, a weak static magnetic field (360 µOe) parallel to the microwave cavity axis is created by a solenoid to separate these levels.

As the clock transition frequency is highly sensitive to any external magnetic field, the cavity is enclosed by four concentric magnetic shields (0.5 mm thickness layers of special alloy mumetal) and a fifth external magnetic shield around the whole assembly, with a total shielding factor of 200'000. Magnetic field compensation is further enhanced by an additional external magnetic sensor servicing an active compensation feed-forward control loop. The output signal of the sensor is amplified to drive the current in a compensation coil wired between the two most external SHM shields. The addition of this external sensor enhances the compensation by a factor of 10, *i.e.* the combined shielding factor amounts to 2x106 for external field variations of ± 0.5 Oersted.

F. Temperature Control and Power Consumption

To avoid frequency instability due to thermal perturbations the microwave cavity is temperature stabilized by a three-stage temperature control system. The design is based on three pairs of concentric heaters regulating the nominal cavity temperature of 48°C within 1 mK. In orbit the instrument is covered by multi-layer thermal insulation blanket. All thermal exchanges are performed by conduction to a temperature-controlled baseplate, which is part of the space platform. The maximum temperature changes of this plate over one orbit are specified to 1.5°C. A special challenge of the thermal design was the horizontal position of the instrument axis with respect to the baseplate, resulting in asymmetric heat dissipation.

A set of tests was performed under vacuum to verify that the thermal control system of the SHM is able to ensure the temperature stability within 1 mK. The PP-EM was mounted on the TVC baseplate, which is thermally controlled by a fluid circulator. The baseplate temperature variations were programmed to follow a sinusoidal function around 25 °C with 1.5 °C pp with a period of 90 min, mimicking the orbital period of the international space station. The temperature of the baseplate was monitored by 40 sensors, evenly distributed over its bottom side. Fig. 5 demonstrates that the PP-EM cavity temperature is actually controlled within 1 mK.

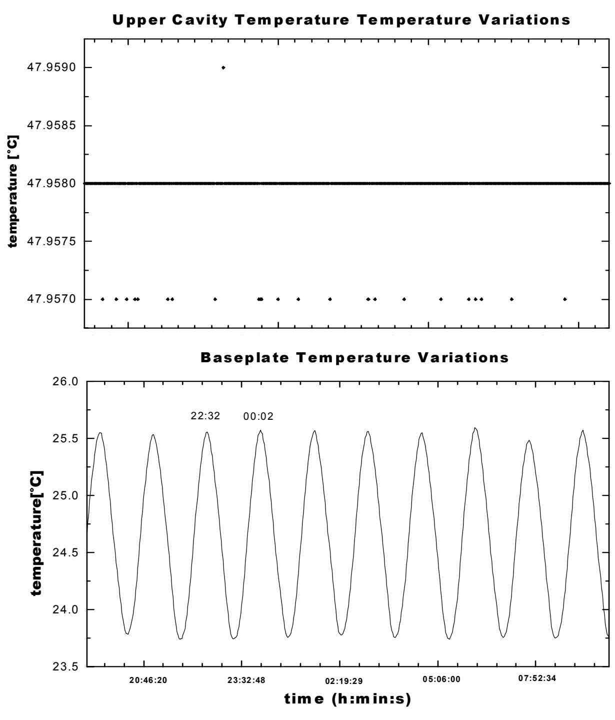

Figure 5. Upper cavity temperature as function of cyclic baseplate temperature variations with a period of 90 min

The thermal sensitivity of the maser output frequency is determined by the cavity pulling effect, which is proportional to the ratio of the loaded quality factor of the cavity and the atomic line quality factor, which is about $2x10^{-5}$. In order to fulfill the frequency stability requirement for the ACES mission σ_y (τ =10000 s) = $1.5x10^{-15}$ [1], the cavity frequency has to be stabilized within 0.1 Hz., With a thermal coefficient of the cavity TE_{011} of –39 kHz/K this cannot be achieved by thermal control only. An Automatic Cavity Tuning (ACT) system is needed to reduce the cavity pulling by an additional electronic feedback system. Details of the ACT system developed at ON and used in the SHM are given in an accompanying paper [7].

Power consumption is an important issue for the ISS for each of its sub-system units that imperatively have to be in the frame of the given specifications. Furthermore, since the development of the SHM space electronics has been transferred to a subcontractor (Oerlikon Space AG, Zurich) well specified power consumptions are needed for the detailed development. Ten power (heater) sources that are part of the SHM structure, cavity and HDA thermal regulations together with ion pumps power supply were submitted to the detailed power measuring campaign under maser working condition with the variations of the base plate temperature in the range from 0 °C to 48 °C (the temperature when the cavity heaters turn off). Table II lists the sum of powers dissipated in the principal parts of the PP, the MSCA and the HDA, at three different baseplate temperatures.

TABLE II. PP POWER CONSUMPTIONS

Base plate temperature [°C]	10	20	40
Cavity and Shields Assembly [W]	11.63	9.91	4.96
Hydrogen Distribution Ass. [W]	9.59	8.42	6.43
Total Physics Package [W]	21.22	18.33	11.39

III. STATUS AND OUTLOOK

After the first assembly of the PP it was found that stray magnetic fields deteriorated the stability performance. It was found that one cause originated from residual thermoelectric currents. Although the original design avoided carefully dissimilar metal interfaces in the sensitive areas near the cavity, it was found that thermo-electric powers are generated even between different alloys of the same metal (Ti grd.2 and grd.5). To resolve the problem all 12 the cavity feet had to be axially insulated by Kapton layers. For the PFM both the cavity and the external structure will be built of the same material (Ti grd.5)

The SHM EM Physics Package is now fully re-assembled (Fig. 1) and outgassed. However, the vacuum pumping devices (ion pumps and getters) are only installed but not yet operating. Temporarily the vacuum is sustained by an external 40 l/s ion pump. This configuration was chosen, since analysis has shown that during activation, when the getter are heated to 450°C for an extended period of time excessive heat might be generated in sensitive areas (indium seals). A dedicated cooling jig to limit the external temperatures is under development.

Performance tests of the PP under vacuum have provided results, which meet the specifications:

- the maser output signal at 1.42 GHz is -103.5dBm (spec: -105 dBm);
- the atomic line quality factor is $1.51x10^9$(spec: $1.5x10^9$);
- the required static magnetic C-field is nominal (400 μG);
- the magnetic shielding factor is 200'000 (spec: ≥ 100'000)
- the cavity temperature is stable within 1mK during baseplate temperature variation within 1.5°K.
- the hydrogen distribution assembly showed that it operates within design goals and specifications.

The full evaluation of the complete Engineering Model (PP+EP) will be the next step.

ACKNOWLEDGEMENT

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