

THE DEVELOPMENT OF A PASSIVE HYDROGEN MASER CLOCK FOR THE GALILEO NAVIGATION SYSTEM

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Abstract

Galileo Avionica S.p.A. (GA), Italy, is industrializing under the European Space Agency supervision a passive hydrogen maser (PHM), to be used in the GalileoSat constellation as master onboard clock.

The Engineering Model (EM) phase is being completed under the lead of the Observatory of Neuchâtel (ON, Switzerland) with the cooperation of GA and Temex Neuchâtel Time (TNT, Switzerland). Current activity regards integration at ON of the EM electronics with the EM physics package. Tuning is in progress and preliminary results are good. Test completion is planned by the end of this year.

The parallel industrialization activity, with GA leading the industrial consortium of the above-mentioned companies, is aimed at PHM design consolidation for future flight production. While GA produces the electronics and integrates the PHM, TNT with ON support produces the physics package. In this frame the EM design is being thoroughly reviewed in the scope of performance optimization and cost reduction, while keeping the critical performances unchanged (e.g. Allan deviation $\sigma_y(\tau) \leq 1 \times 10^{-12} \times \tau^{1/2}$, for $1 \text{ s} \leq \tau \leq 10000 \text{ s}$).

INTRODUCTION

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DEVELOPMENT BACKGROUND

An active hydrogen maser (AHM) was the original candidate onboard master clock for Galileo. As a result of previous developments at the Observatory of Neuchâtel, the AHM mass could be reduced down to the limit of 35 kg. However, following the Galileo definition phase, it became evident that the accommodation of an AHM on board was too penalizing in terms of mass and volume. Moreover, it was recognized that the excellent stability performances of the AHM were not required.

For the above reasons the development activities in beginning of 2002 were redirected towards the development of a passive hydrogen maser (PHM), that better fulfills the requirements of the Galileo mission.

PHM DESIGN CONCEPT

The PHM architecture is shown in Figure 1. The design includes the following special features:

- *Magnetron-type microwave cavity.* This choice reduces mass and size not only of the cavity, but also of the surrounding magnetic shields, as well as the relevant heating power need. A two-stage active thermal control and a triple magnetic shielding are implemented.
- *No thermal vacuum pumping.* The in-orbit space vacuum is exploited for thermal isolation of the cavity. The GSE provides pumping during ground test.
- *Bulk getter-pumped hydrogen vacuum system.* Bulk getters avoid the heavy ion pumps used in conventional ground masers for hydrogen pumping; only a lightweight miniature ion pump is used to pump non-getterable gases.
- *Solid-state hydrogen storage.* This solution avoids the pressure tank, a potential fracture critical item, and saves volume and mass. The pressure is stabilized over life via an active control.
- *Hydrogen dissociation.* It is obtained via radiation of a VHF field to the dissociator bulb.
- *Automatic Cavity Tuning system (ACT).* Although the cavity temperature is already stabilized by a two-stage thermal control, an additional electronic ACT system is used to optimize the cavity frequency pulling effect caused by the residual thermal drift.
- *Single modulation frequency lock.* This patented double servo system uses a single modulation tone for both the cavity frequency (ACT) and the atomic interrogation frequency tuning.
- *Start-up power control.* An automatic sequence is implemented that enables the various PHM internal loads in sequence after switch-on, so that the warm-up time is minimized, while keeping the power drain inside the specified limits.

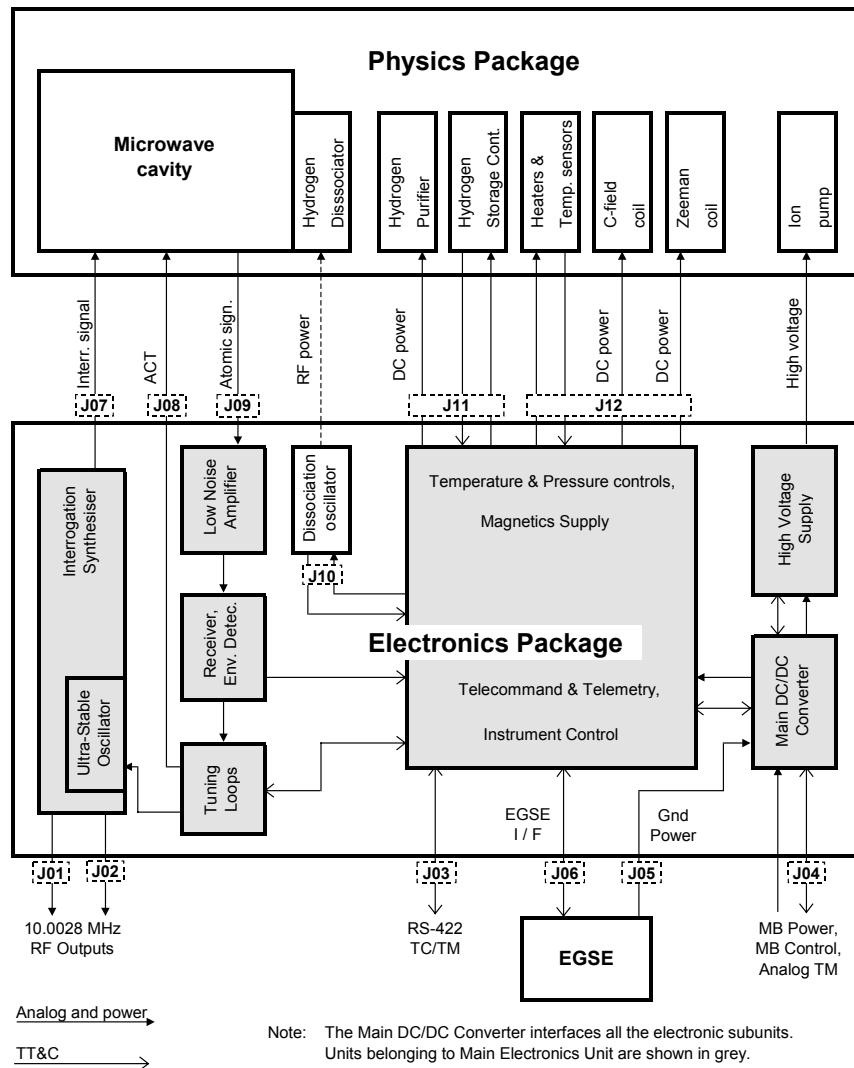


Figure 1. PHM architecture.

Figure 2 shows the single modulation tuning system. The cavity interrogation signal is obtained from a 10.0028 MHz ultra-stable crystal oscillator (USO) after $\times 142$ multiplication and phase modulation with a 12.5 kHz tone ($f_{USO} = f_H/142$, no DDS is used). The error components for USO and ACT loops are separated by a dedicated phase shifter after envelope detection.

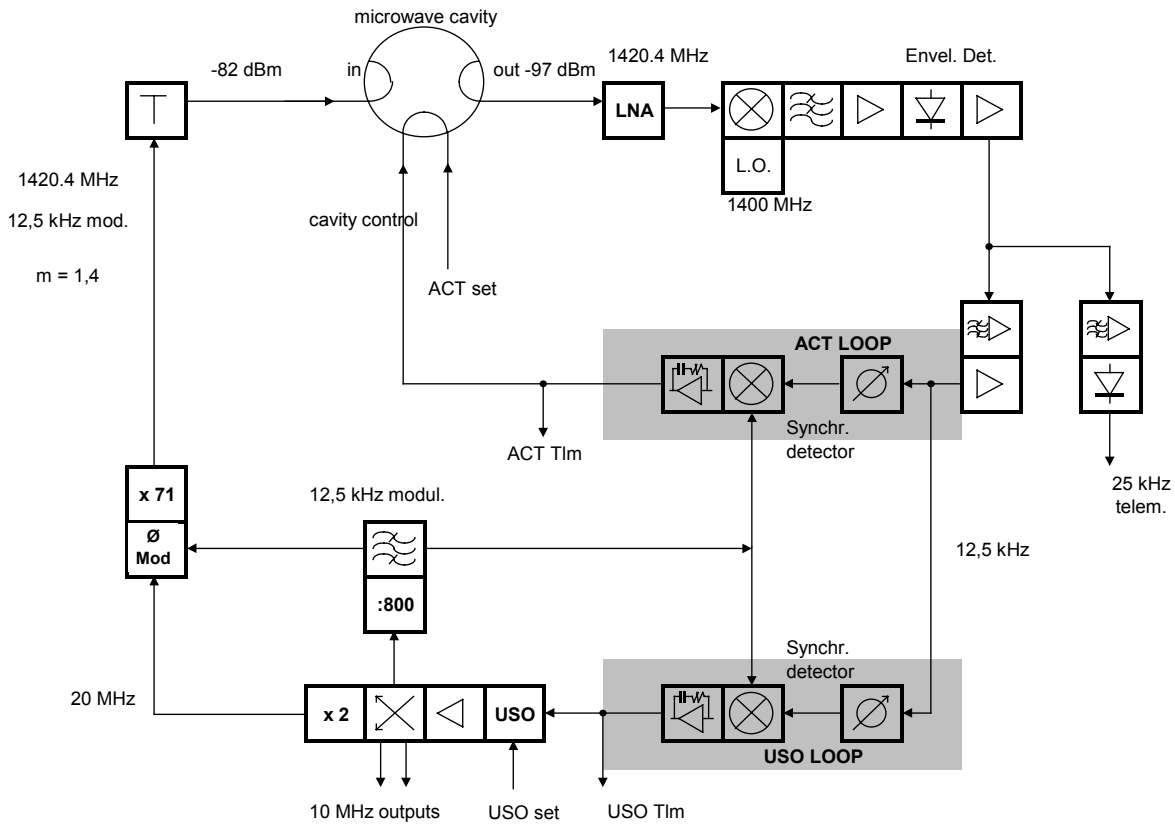


Figure 2. RF architecture.

PHM DESIGN VERIFICATION APPROACH AND PERFORMANCES

The PHM design verification approach was based first on performance analysis at the main functional level, like cavity thermal control stability, evaluation of mechanical loads, displacements and mechanical

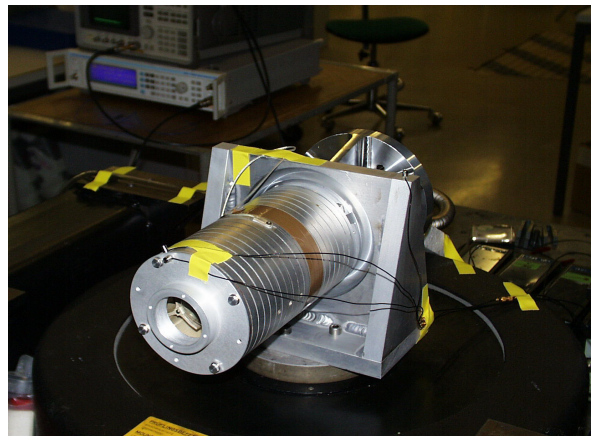
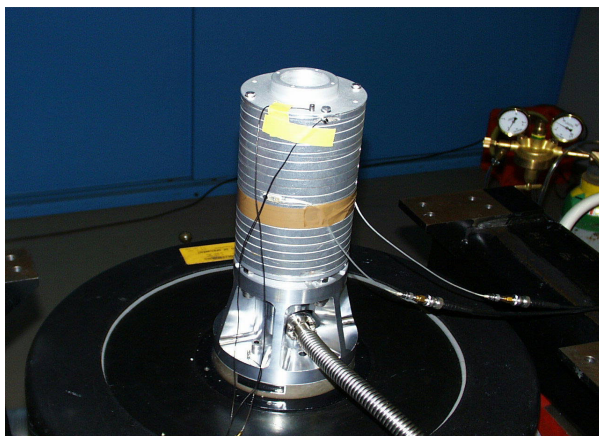


Figure 3. Microwave cavity and storage bulb under vacuum and vibration testing.

resonance frequencies, and RF tuning loops stability. Some functional items identified as potentially critical (microwave cavity and storage bulb assembly, ion pump, Ni purifier valve, hydrogen dissociator) were also submitted to random vibration and thermal vacuum testing (see Figure 3). Critical electronics were breadboard-tested.

A preliminary optimization of the PHM space design was carried out at the physics package and the electronics package Engineering Model level, after integration of each PP and EP with complementary ground equipment. Individual full characterization of EP and PP was carried out, obtaining performances in line with GalileoSat requirements. Figure 4 shows the EM PP under testing; Figures 5 and 6 show some PP performance data.

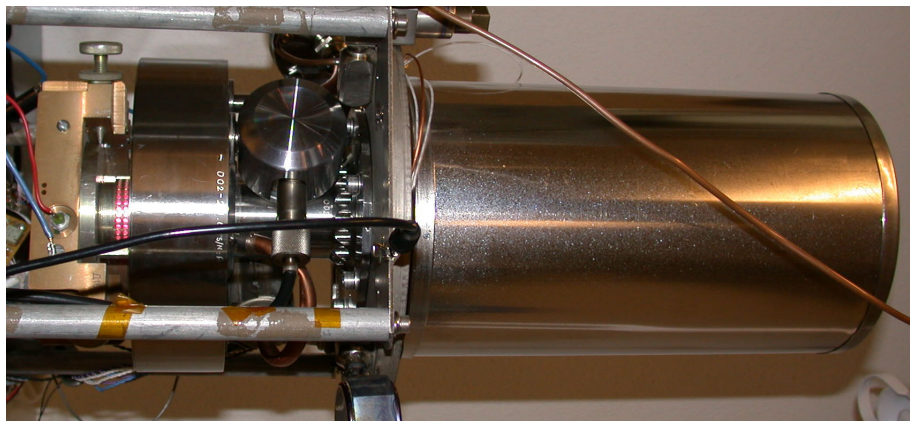


Figure 4. EM physics package under testing.

The PHM design, resulting from the Development Phase at the Engineering Model stage of definition, is of self-standing equipment composed of a Physics Package (PP) and an Electronics Package (EP), assembled on a common interface base-plate. This base-plate provides the mechanical and thermal interface with the S/C (see Figure 7).

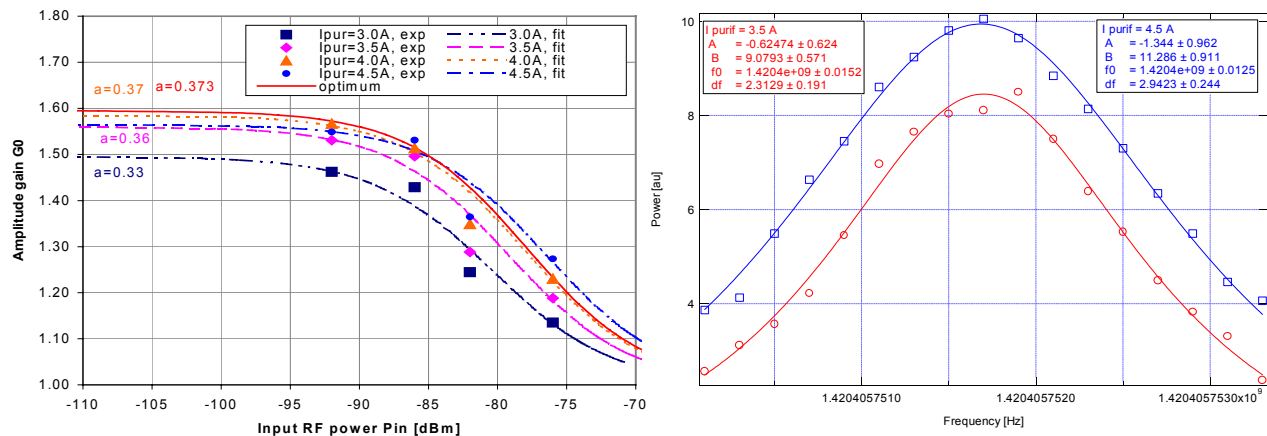


Figure 5. EM PP main performances, atomic gain, and line width.

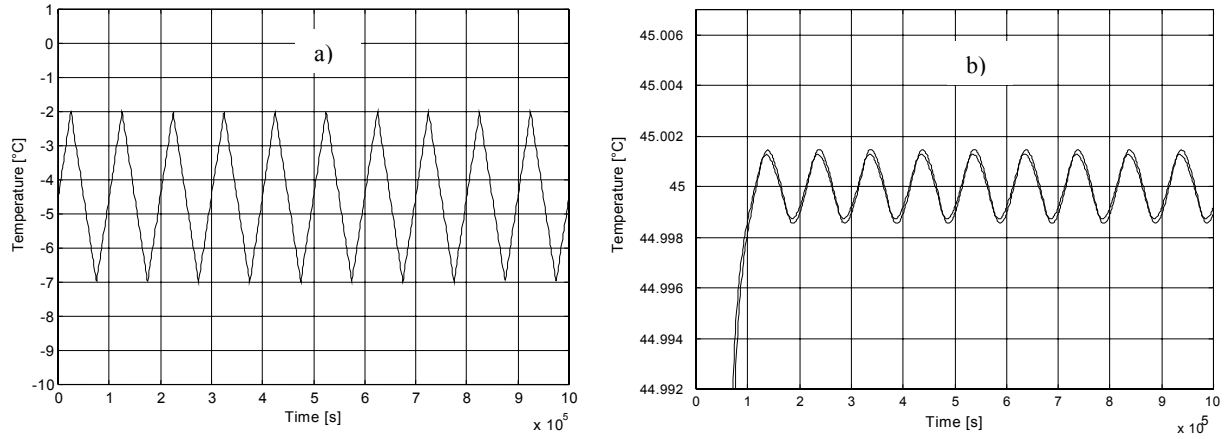


Figure 6. Microwave cavity thermal control: a) platform temperature, b) cavity temperature.

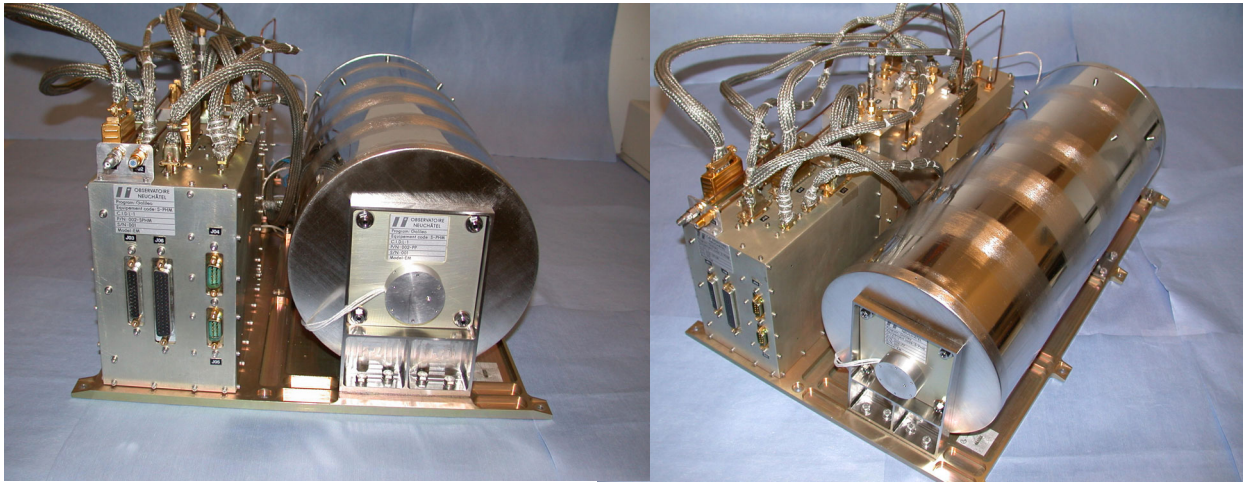


Figure 7. Integrated EM, MLI removed from PP.

The EM instrument characterization is running. Results are shown onwards. The frequency stability is similar to that measured previously on space EP and PP, each integrated with ground hardware (see Figure 8). The frequency drift is only $1.9 \cdot 10^{-14}/d$, 1 week after switch-on. Long-term stability tests are running.

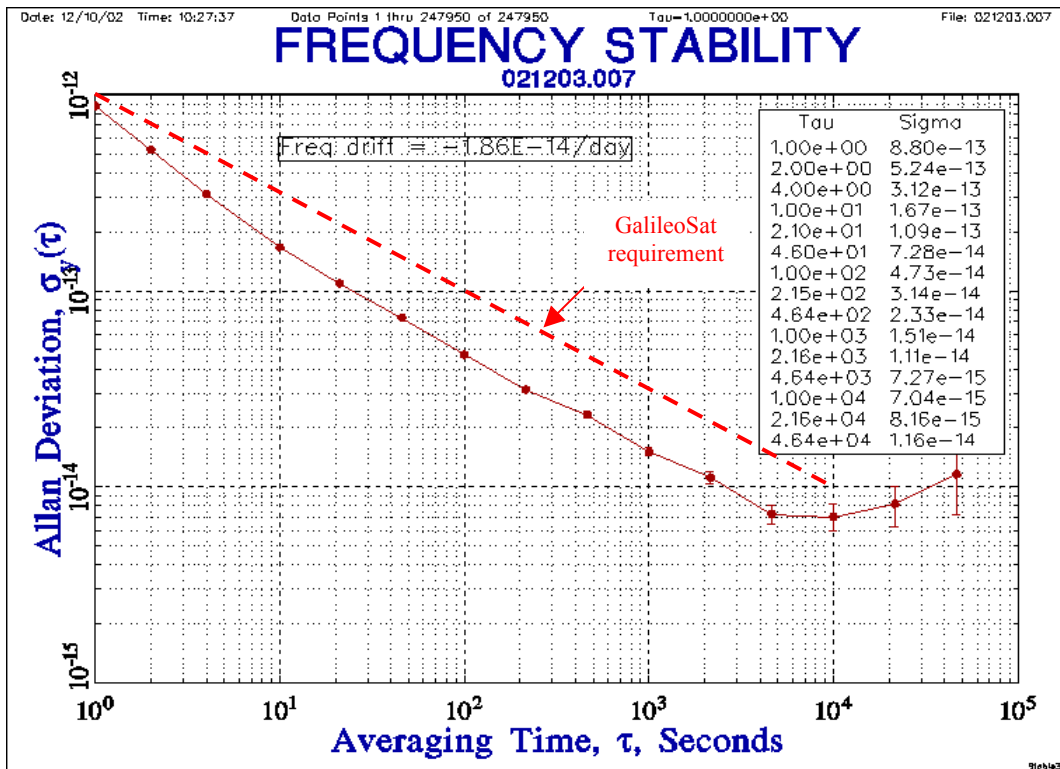


Figure 8. Frequency stability of the integrated EM.

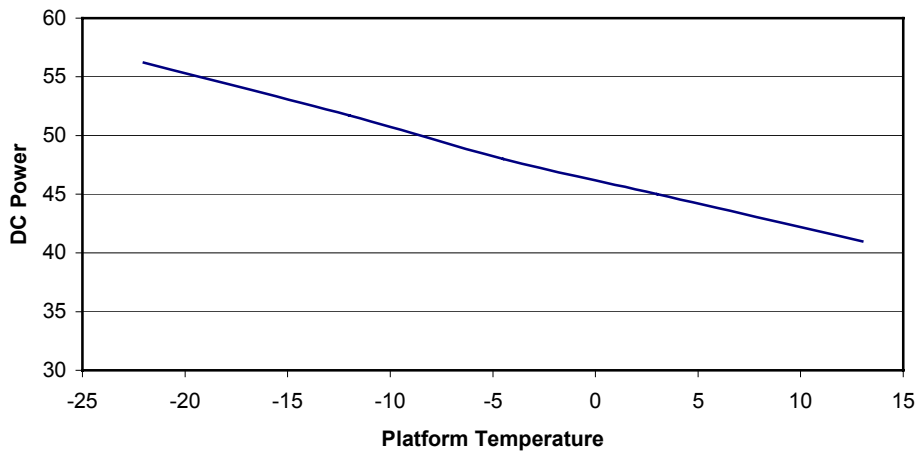


Figure 9. Power consumption of the integrated EM vs. temperature.

DESIGN IMPROVEMENTS FOR INDUSTRIALIZATION

- *On-ground operation.* The cavity temperature shall be kept in the millidegree range to achieve the required frequency stability. A vacuum is needed to guarantee this challenging thermal stability with

a minimum of heating power, and the PHM in EM configuration cannot perform at ambient pressure. On the contrary, the PHM user community strongly pushes for having the PHM perform at ambient conditions, which allows easier testing at P/L level. The solution, presently being implemented for PHM Industrialization and Galileo System Test Bed (GSTB), consists of enclosing the microwave cavity and shield assembly (MCSA) into a hermetic canister, to be connected to GSE during ground test, for pumping. The pump shall be removed (and its connection left open) after ground test completion.

- *Footprint and volume reduction.* A different PHM configuration is being analyzed, with the PP mounted over the EP (see Figure 10). The preliminary thermal and mechanical analyses do not evidence major criticality. This is possible, thanks to the special stiffness of the EP Main Electronics Unit.
- *Improvement of ionizing radiation shielding.* The required hardness for 12 years' life in MEO orbit imposes, besides use of adequate components, a special radiation shielding for the electronics. The thickness and materials of the EP main electronics unit box are being selected on purpose. The PP has inherent shielding and includes only passive parts.
- *Operability.* The power bus interface is being adapted to accept both regulated and non-regulated voltages. The TT&C interface will include additional provision for PHM switch-on/off.

Notwithstanding the above, the industrialization phase will be dedicated to master the critical technologies, in particular of the PP, by building a technological model. It will serve to ensure repeatable and reliable processes and tests fixtures for:

- Teflonization of the quartz storage bulb
- Getters assembly
- H2 purifier assembly
- State selector assembly
- Hydrogen beam assembly
- Tuning of the microwave cavity
- Magnetic shield assembly
- Hydrogen supply and dissociator

The industrialization phase includes manufacturing of one engineering qualification model plus five QM's, the latter for life testing. In addition, accelerated life tests will be conducted on critical items (hydrogen dissociator, hydrogen purifier, beam collimator, getter pumping).

PHM MAIN PERFORMANCES (AFTER INDUSTRIALIZATION)

Main performances of the PHM, to be guaranteed over the FM production, are the following:

- Output frequency: 10.002857407 MHz ($f_H / 142$)
- Frequency accuracy: better than $1 \cdot 10^{-10}$
- Output level: +7 dBm (two outputs)
- Frequency drift, per year: $\leq 3 \times 10^{-12}$
- Allan deviation, $1s \leq \tau \leq 10^4s$: $\leq 1 \times 10^{-12} \times \tau^{-1/2}$
- Temperature sensitivity: $\leq 3 \times 10^{-15}/^\circ\text{C}$
- Magnetic sensitivity: $\leq 2 \times 10^{-14}/\text{Gauss}$
- Main Bus voltage sensitivity: $\leq 3 \times 10^{-15}/\text{V}$
- Power consumption: $\leq 60\text{W}$ (over operating temperature range)
- Stay-alive power: $\leq 5\text{W}$
- Total mass: 15 kg goal
- Size (w x l x h): 210 x 500 x 250 mm³
- Qualification temperature range: -15 to +20°C
- Orbit (MEO) life: 12 years

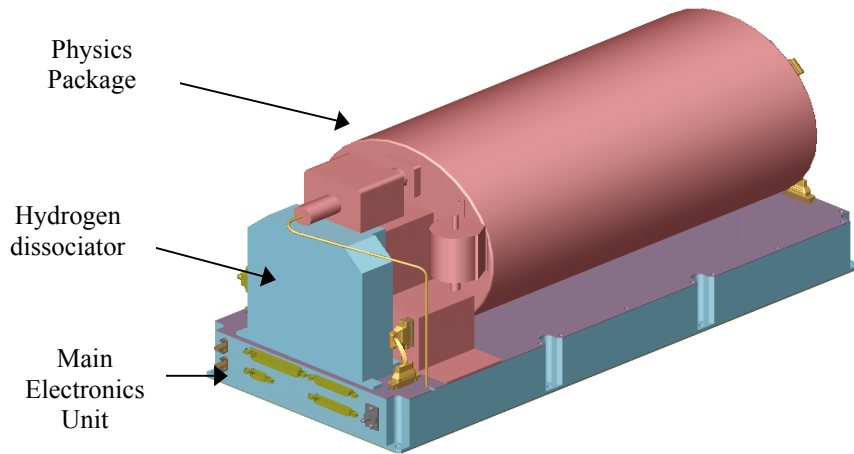


Figure 10. PHM concept for industrialization and GSTB.

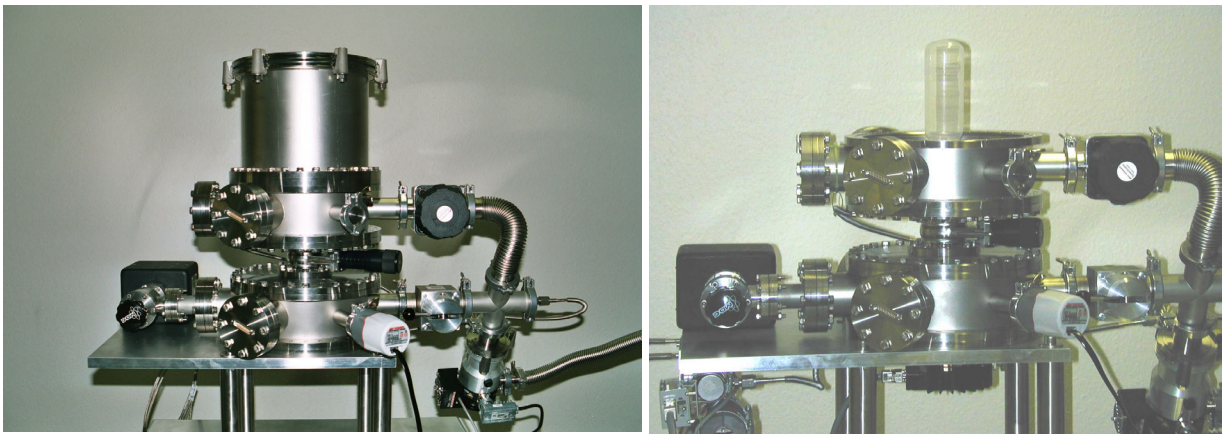
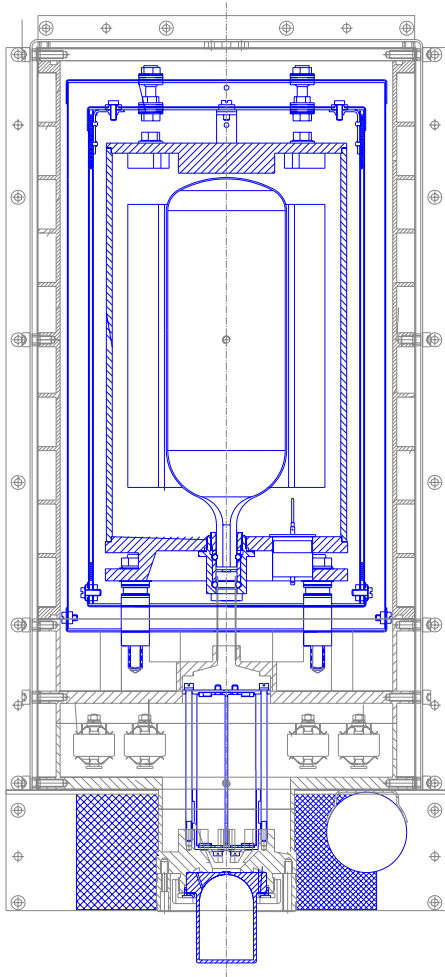


Figure 11. Technological model with/without cover.

PP MAIN PERFORMANCES (AFTER INDUSTRIALIZATION)



Overall:

- Power gain at resonance: > 2 dB
- Operational line width: < 3.5 Hz
- Magnetic sensitivity: $< 2E-14$ /Gauss
- Sensitivity to temp. With ACT: $< 3E-15$ /°C
- Vacuum operations or with external pump for ground tests

Microwave cavity:

- Quality factor: > 7000
- Storage bulb volume: 0.4 liter
- Frequency change after vibration: < 30 kHz
- Electrical tuning range: > 60 kHz

Hydrogen/vacuum system:

- Hydride storage tank capacity: > 18 bar*ltr
- Getter pumping capacity: > 28 bar*ltr
- Hydrogen flux: < 1.5 bar*ltr/year

Figure 12. Industrialized Physics Package drawing (definition in progress).