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THE 35KG SPACE ACTIVE HYDROGEN MASER (SHM-35) FOR ACES

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Abstract- A 35-kg active hydrogen maser is in an advanced stage of development at the Observatory of Neuchâtel (ON) for the European mission ACES (Atomic Clock Ensemble in Space).

The miniaturization of the instrument is based on a sapphire loaded microwave cavity. A frequency stability of $1.5x10^{-15}$ over averaging time of 10'000 s is made possible by the use of an Automatic Cavity Tuning System.

A prototype model of the sapphire loaded microwave cavity has been operated continuously for more than two years. The engineering (EM) and the flight (FM) models of the microwave cavity assembly have already been manufactured.

In this paper, the design of the instrument is presented. The overall expected performances as well as measurement results are reported.

I. INTRODUCTION

The 35-kg active Space Hydrogen Maser (SHM-35) is essential to reach the objectives of the ACES mission [1] to be flown on the ISS. Fig. 1 shows the frequency stabilities of each ACES clock: the SHM-35 and the cold atom cesium clock PHARAO [2].

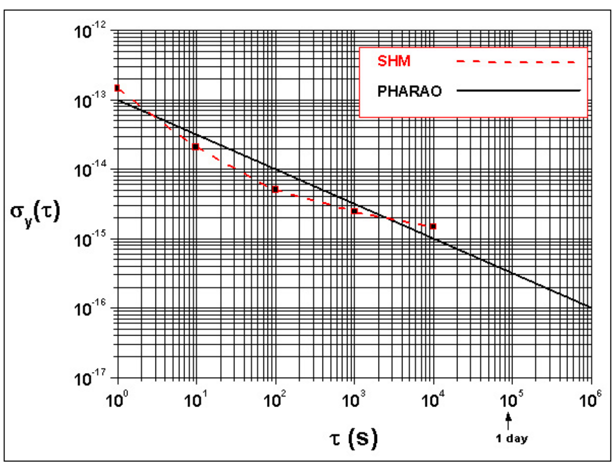

Fig. 1. Expected Allan deviations of the SHM-35 and PHARAO in ACES

To take advantage of the high performances of the SHM-35 for the medium term stability and PHARAO for the long term stability, the two clocks will operate in a two-loops configuration. In a fast servo-loop (time constant < 10 s), PHARAO will be locked to the SHM-35 and in the slow servo-loop (time constant > 1000 s), the SHM-35 will be steered by the cold atom cesium clock. The medium term stability of the SHM-35 will be particularly important because of the 300 s mean duration of an ISS pass over the ground stations. In a first phase of the mission, the SHM-35 will also be used as the reference for the evaluation and optimization of the PHARAO operating parameters.

II. CONCEPT OF THE SHM-35 DESIGN

The SHM-35 instrument is made of the microwave cavity and magnetic shield assembly, the electronics unit and several peripherals like the hydrogen distribution assembly and the ion pumps (Fig. 2).

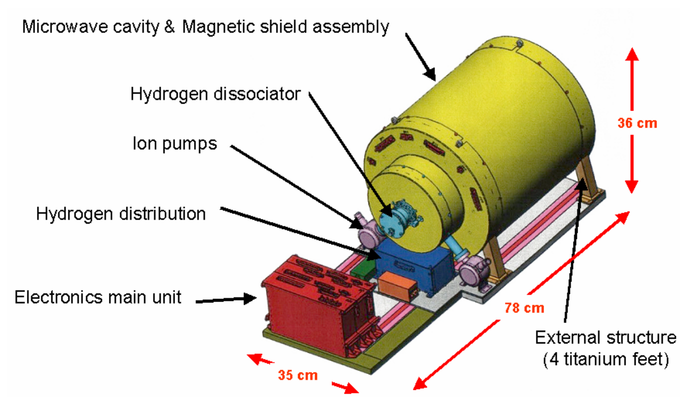

Fig. 2. SHM-35 instrument overview

The miniaturization of the instrument is based on a sapphire loaded microwave cavity of 4.4 liters already used in a previous development [3].

The microwave cavity, made of titanium, is tuned mechanically, thermally and electrically at the hydrogen hyperfine frequency: the coarse adjustment is realized during the machining of the cavity, the intermediate adjustment is done through the temperature coefficient of the cavity (70 kHz/K) and the fine tuning (0.1 Hz level) is controlled by a varactor diode.

The atomic storage bulb is a sapphire cylinder of 1.7 liter bonded to the titanium cavity covers and Teflon coated. This volume, comparable to a full size maser design, and the Teflon coating technology developed at ON allow to reach a high atomic signal and operating quality factor. Fig. 3 shows the titanium microwave cavity with the sapphire cylinder. The top annular cover, a removable part of the cavity, is not shown on the figure.

The thermal design is based on three pairs of concentric heaters regulating the microwave cavity temperature with a stability of 1 mK. The heat is evacuated by conductance through the mechanical structure only, the instrument

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operating under low pressure environment. The thermal losses by radiation are made negligible with the MLI (Multi Layer Insulation) covering the instrument.

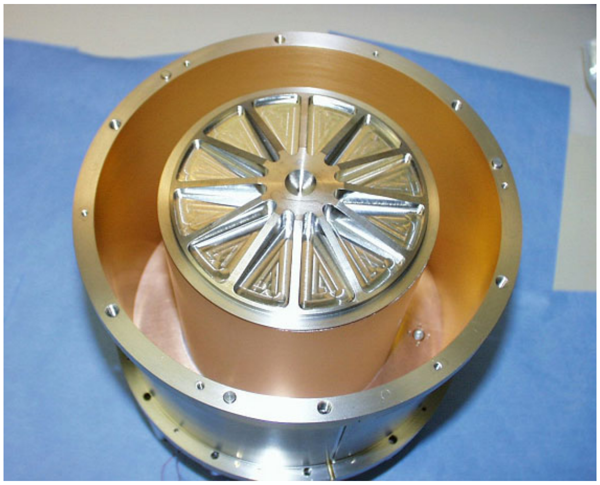

Fig. 3. Sapphire loaded cavity (without the top annular cover)

The hydrogen atomic beam and storage bulb are maintained under high vacuum with an ensemble of getters and ion pumps. The getter ensemble allows a vacuum autonomy of 10 days without electrical power and an instrument life time of more than 5 years.

An Automatic Cavity System (ACT), based on a sampled interrogation scheme, prevents the SHM-35 drift due to the cavity pulling.

The magnetic shielding, based on five layers of 0.5 mm of special type of mumetal, is enhanced with an active compensation control loop.

A new scheme for the hydrogen molecular discharge has been introduced to improve the dissociation efficiency and to insure the RF plasma ignition.

III. SHM-35 INSTRUMENT SPECIFICATIONS

Weight: 35 kg
Power consumption: 77 W
Frequency stability:

Table I: Allan deviation

τ [s]	$\sigma(\tau)$
1	1.5×10^{-13}
10	2.1×10^{-14}
100	5.1×10^{-15}
1'000	2.1×10^{-15}
10'000	1.5×10^{-15}

Operating temperature range: +10°C to +35°C
Temperature coefficient of the frequency: 3×10^{-15} /K
Magnetic coefficient of the frequency: 1×10^{-10} /Tesla
Operating pressure range: < 10^{-4} hPa
Nominal cavity quality factor: 30'000
Nominal operating quality factor: 1.5×10^{9}
Nominal atomic signal power: -105 dBm

IV. AUTOMATIC CAVITY TUNING

The long term stability of the SHM-35 is dominated by the cavity pulling effect. With the nominal cavity and operating quality factors, the pulling factor is $K=2 \times 10^{-5}$.

To reach an ultimate stability of 1.5×10^{-15}, the cavity frequency must then be continuously tuned within 0.1 Hz of the hydrogen hyperfine frequency (1.42 GHz).

The cavity resonance (Fig. 4) is alternately interrogated with two signals synthesized at several kHz bellow (F1) and above (F2) the atomic frequency (F0). The difference between the responses of the cavity to these two signals generates a correction voltage sent to the cavity varactor. In terms of differential F2-F1 amplitude, a stability of 1 ppm is necessary to reach a detection error of 0.1 Hz.

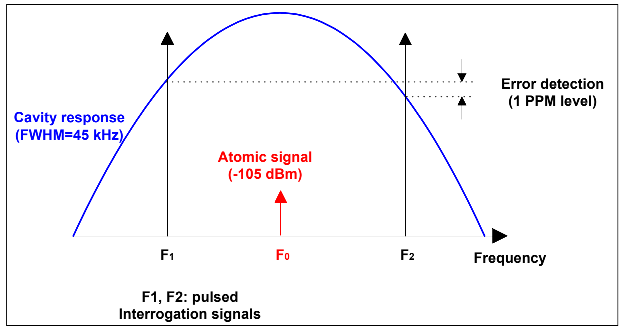

Fig. 4. Cavity response to ACT interrogation signals

The sampled interrogation scheme is time multiplexed with the atomic signal detection: typically 50% of the time is used for the ACT and 50% for the main PLL where the local quartz oscillator is controlled by the atomic signal.

Fig. 5 shows the measured stabilities of the SHM-35 prototype with the ACT breadboard switched-on and switched-off. The specified stability is also represented.

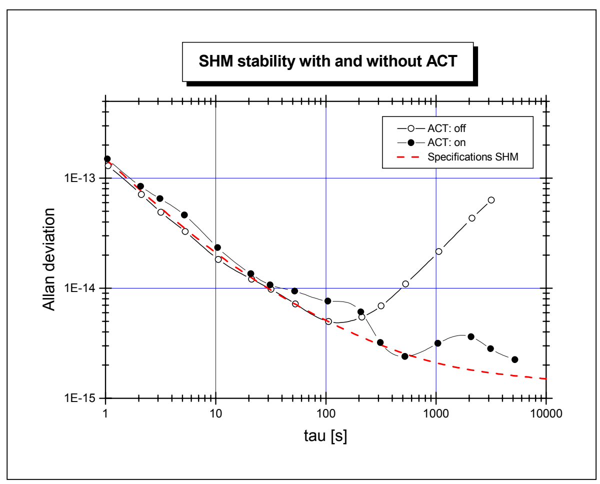

Fig. 5. SHM-35 frequency stability with and without ACT

Above an averaging time of 100 s, the ACT breadboard improves clearly the SHM-35 behavior. Residual perturbations are still visible; they are attributed to the way the error signal is treated before sending the correction to the cavity varactor. The ACT breadboard is presently under further development to reach the specifications.

V. ENHANCED MAGNETIC SHIELDING

The magnetic shielding factors (typically 100'000) obtained with the mumetal material is enhanced by a factor of 10 with an active feed-forward compensation.

A magnetic sensor is installed externally, but close to the SHM-35. The output signal is amplified to drive the current in a compensation coil wired between the two most external magnetic shields (Fig. 6). The amplification gain can be adjusted by telecommand and will be optimized experimentally.

The main advantage of this method, by comparison to a feed-back closed loop scheme requiring an internal sensor, is the reduction of the magnetic perturbations generated by the sensor itself.

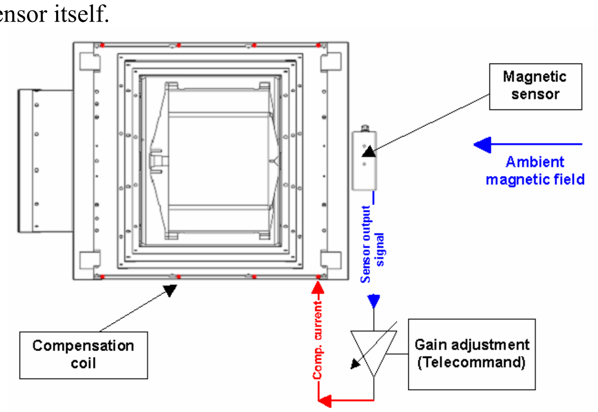

Fig. 6. Feed-forward active magnetic compensation

VI. HYDROGEN MOLECULAR DISSOCIATOR

The atomic beam of the SHM-35 is realized by dissociation of the hydrogen molecules in a plasma discharge induced by RF power.

It is well known that the ignition of the plasma discharge is often problematic due to the difference in the electrical impedance seen by the RF excitation signal when the plasma is present or not. Moreover, the environmental conditions, or the aging of the dissociator itself, change the ignition conditions.

Experimentally, it was observed that plasma ignition can be practically insured in all cases by changing the RF frequency and RF power.

The new scheme, introduced for the SHM-35, is based on an oscillator with programmable frequency (120 to 150 MHz) coupled to an adjustable amplifier (1 to 10 W). The amplifier drives an RF antenna mounted close to the hydrogen dissociator bulb. An optical sensor detects the light emitted by the plasma discharge.

To start the discharge, the oscillator frequency is swept upward from 120 MHz until optical detection of the ignition. After discharge ignition, the RF frequency and power can be adjusted by telecommand to optimize the dissociation efficiency for obtaining the highest atomic signal level.

VII. DEVELOPMENT STATUS

The complete SHM-35 prototype has been operated and tested continuously for more than two years. This prototype has been used to validate the SHM-35 technology and design of the EM and the FM.

The engineering model of the microwave sapphire loaded cavity has been manufactured, teflonised and integrated in a ground maser for the evaluation of the atomic quality factor. The measured quality factor at nominal atomic signal (-105 dBm) is shown on Fig. 7 for the first five months of operation. The quality factor is better than specified and shows no measurable aging of the Teflon coating.

The flight model of the sapphire loaded microwave cavity has been manufactured and is ready for the Teflon coating.

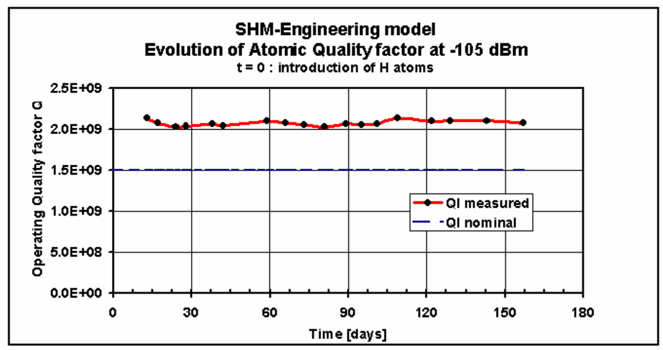

Fig. 7. Evolution of the atomic quality factor

The thermal and structural mathematical models are under progress. A 400'000 nodes finite element model (Fig. 8) is available and shows a margin of 45 Hz for the lowest resonance mode at 145 Hz and a 45% margin in the maximum stress of the titanium structure. A microwave cavity and magnetic shield assembly has been successfully tested under random vibration at 14 g_{rms}.

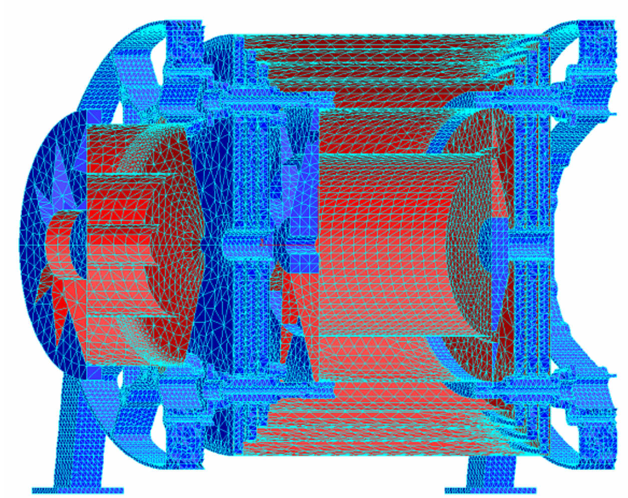

Fig. 8. SHM-35 Finite Element Model (400'000 nodes)

The active magnetic compensation principle has been validated in a set of mumetal shields.

The excitation scheme of the molecular dissociation has been validated with the SHM-35 prototype.

The ACT is under its final phase of development.

VIII. CONCLUSION

The key technologies of the SHM-35 instrument has been validated. The design of the physics package is nearly completed and under validation by analyses. The critical elements have been successfully tested under vibrations.

The physics package technology has been validated by extensive evaluation during more than two years.

The thermal, magnetic and hydrogen controllers as well as the low noise receiver parts of the electronics package have been validated and the Automatic Cavity Tuning is under its final phase of development.

The next important phases are the final validation of the ACT and the completion, integration and test of the engineering model of the SHM-35 instrument.

The finalization program of the FM instrument is compatible with the ACES flight foreseen end 2006.

ACKNOWLEDGMENT

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