Design of a stabilised environment for an ultra-stable optical resonator

Tuan M. Pham[1], Martin Čížek[1], Petr Jedlička[1], Lukáš Slodička[2], Ondřej Číp[1]

[1]Depatent of Coherent Optics, Institute of Scientific Instruments of the CAS, Brno, Czechia
[2]Depatment of Optics, Palacky University, Olomouc, Czechia

Email: tuan@isibrno.cz

Abstract— **This paper outlines our realisation of the key insulation and stabilisation stages used for the high-finesse cavity, which is used for stabilising the frequency of the spectroscopy laser used in cold ion experiments. It mainly covers the mechanical structure of the insulation, including vibration isolation, acoustic shielding and a home-made water-cooling system using the gravity effect. The resulting effective suppression of vibration in the spectral range from 0.1 Hz to 150 Hz is by a factor of 20.**

Keywords—temperature stability, vibrational isolation, high-finesse cavity, water cooling system, insulation materials

I. Introduction

For decades atomic frequency standards played a critical role in basic science and precision measurement. During this period, the increasing need for more precise timing and synchronisation for a wide range of applications, including navigation, synchronisation, or tests of fundamental physics, has demanded oscillators with higher frequencies and higher performance. To excite those oscillators coherently, high spectral purity of the laser source is a crucial feature, and stabilisation techniques have constantly been renewed and developed over time. The general approach thus far involves stabilizing the laser frequency to a passive high-finesse Fabry–Perot cavity [1,2,3]. Additionally, by well-engineered servo electronics, the laser's fractional frequency instability aligns with the fractional optical-path-length instability of the cavity. Consequently, environmental disturbances like temperature fluctuations or vibrations, which can vary the optical path length, must be effectively minimized [4,5].

This paper introduces the mechanical and electrical design of an insulation platform that is currently built in our setup. The mechanical part surrounding the stable cavity can be divided into two sections. The inner section surrounds the cavity and consists of a vacuum chamber, where the HF-cavity is placed, including a passive thermal shield and thermistor. This will minimize the fluctuation of the refractive index and environmental vibrations of the inner part of the chamber and thus allow the cavity to reach a low-level thermal noise. provide the cavity with a stable operating condition and isolate it from thermal radiation that could affect the cavity dimensions.

The outer section consists of a wooden box embedded with insulation foams and elements for insulation of environmental perturbations such as acoustic vibration and temperature noises.

II. The inner section

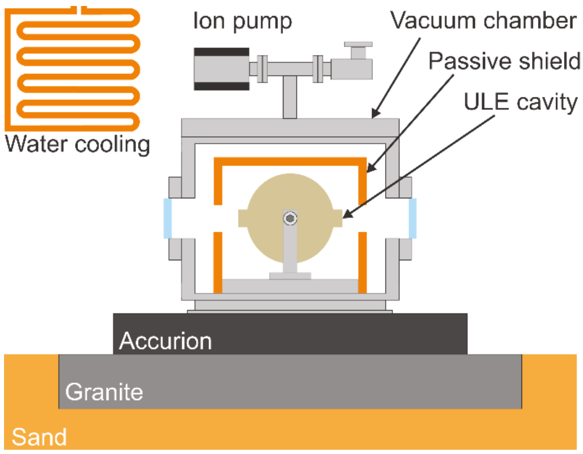

Fig. 1. Schematic of the vibration and thermal isolation platform, including the vacuum chamber and the gold, plated aluminium passive heat shield centred around the ULE cavity (The shield is temperature controlled with a Peltier element). The whole setup is then enclosed in a wooden box with thick layers of thermal isolation material.

To minimise the fluctuation of the refractive index of the inner part of the HF-cavity, environmental vibrations on the optical cavity and thus reach a low-level thermal noise, the cavity is sealed in the vacuum chamber[1]. A high-level vacuum inside the chamber is reached with the 3 l/s ion pump[2]. The pump provides a stable pressure of 5.3 x 10^{-8}, which is enough to isolate the cavity from thermal convection and pressure fluctuation. In order to suppress cavity length variations due to temperature changes, the temperature of the cavity needs to be stabilised. The optimal temperature for operating the cavity is the so-called zero-crossing temperature at which the thermal expansion coefficient crosses the zero level [5]. In the present case, the zero-crossing temperature of our cavity is 13 ± 3 °C, as was verified by the manufacturer via speed of sound measurement.

The stabilization of the cavity temperature is solved as a two-stage, in order to optimize the temperature gradient of

[1] Thermally insulated Stainless Steel Vacuum VH630-Can, Stable laser systems.
[2] 3S Titan Ion Pump, Gamma Vacuum.

the cavity to the laboratory where the resonator is located. The first stage is its own vacuum chamber.

The chamber contains a Peltier element[3] and a thermistor with an impedance of 10 kΩ at 25 °C[4]. The thermistor is placed under the cavity holder and thus measures the temperature at very close proximity to the cavity. The PID-controller for temperature control of the cavity holder keeps the cavity at the required temperature. The Peltier controls current so that the temperature of the cavity holder is in 1 mK stability range at the set temperature 13.5 °C. Furthermore, the cavity is enclosed inside the gold-coated aluminium passive heat shield centred around the cavity. This shield prevents the temperature exchange via radiation between the cavity and chamber walls. The whole setup with individual isolation aspects can be seen in Fig. 1.

III. THE OUTER SECTION

To prevent the temperature gradient between the laboratory environment and the vacuum chamber. The whole optical setup with the necessary locking electronics is enclosed into a 10 mm thick wooden box. The box is inside coated with 76 mm thick foam made from compressed fibre glass[5] with 96 kgm^{-3} density, which serves as a second temperature stabilising stage. The temperature inside of the box is stabilised by a water-cooling system made from copper pipes surrounding the box walls (the helical evaporator) (Fig. 2).

The design of the water-cooling system is based on transferring the heat obtained inside the wooden insulating box with the helical evaporator to the external radiator, which is located under the laboratory's ceiling. The transfer medium is distilled water with an additional solutions preventing the degradation of the pipes. The external radiator is connected to the water circuit via an aluminium heater equipped with a Peltier element. The water circuit contains a water pump, but it is used only for the initialisation phase of cooling and is switched off during regular operation. The system thus works entirely on the self-gravity principle. Therefore, the liquid flow in the cooling circuit is exclusively laminar and does not generate significant acoustic interference that would be transmitted to the HF cavity.

The water circuit is equipped with three temperature sensors - thermistors. One thermistor is placed on the outlet pipe from the evaporator and the other on its inlet. The third sensor is placed in a heater fitted with the Peltier element. The temperature stabilisation inside the wooden box is based on the temperature control of the liquid that enters the evaporator in the wooden box. This temperature is monitored by the appropriate thermistor and is fed to the PID1 controller, which subsequently determines the temperature of the aluminium heater with the Peltier element. This required value is sent to the PID2 controller, which then controls the current to the aluminium cooler's Peltier element and ensures its required temperature. This system makes it possible to stabilise the temperature of the inlet liquid in the evaporator in a wooden box very robustly even when the temperature in the laboratory changes by several degrees Celsius.

[3] TE Technology HP-127-1.0-1.3-71R.
[4] General Electric MC65F103B.
[5] Prima acoustic Broadband 3"

The Fig. 2 indicates the current scheme for the water-cooling system designed for temperature stabilisation of the high-finesse cavity and its surroundings. The desired temperature is sent from a computer to each PIDs. They then regulate the temperature by driving the Peltier element. The temperature is measured as close to the element as possible. The temperature sensors are placed as follows. TS1 - on the aluminium cooler, TS2 - on the outlet end of the pipe, TS3 - on the inlet end of the pipe, TS4 - on the vacuum chamber, TS5 - placed in the air, TS6 - measure the temperature of the optical table, TS7 – measure the temperature of the cavity.

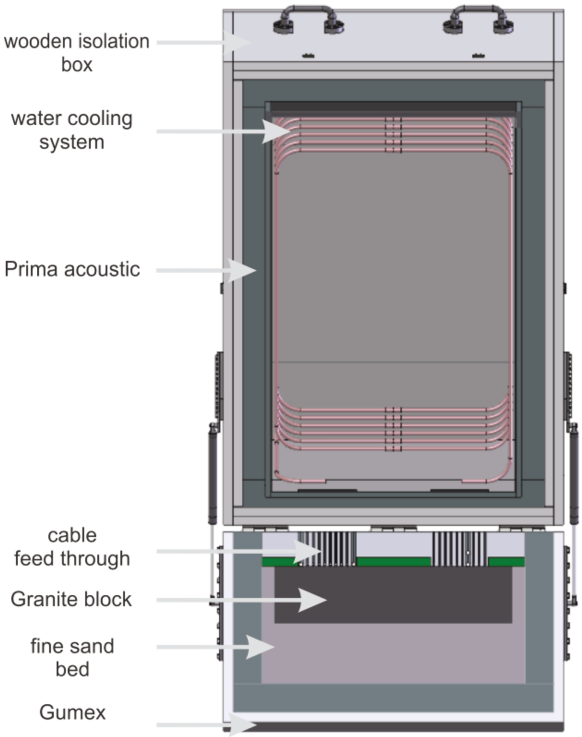

Fig. 2: The view of a wooden box equipped with insulation elements for isolation the HF-cavity from the acoustic vibrations. The temperature inside the box is kept at stable 16 °C by a water cooling system.

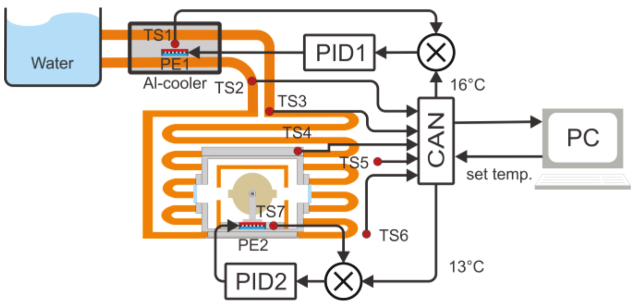

Fig. 3: The schematic of temperature monitoring and control. PE: Peltier element, CAN: Controller Area Network, TS: Temperature sensor, PID1, PID2: Proportional-Integral-Derivative controllers. Temperature sensors: TS1 - on the aluminium cooler, TS2 - on the outlet part of the pipe, TS3 - on the inlet part of the pipe, TS4 - on the vacuum chamber, TS5 - placed in the air, TS6 - measure the temperature of the optical table, TS7 - measure the temperature of the C729 holder.

IV. VIBRATION ISOLATION AND ACOUSTIC SHIELDING

The vacuum chamber lies in the actively controlled vibration isolation table[6], with active bandwidth from 0.6 - 200 Hz. The isolation performance is min. 25 dB at 5 Hz and 40 dB at frequencies beyond 10 Hz. As the cavity is mounted the way that the axis of the spacer is horizontally oriented, I have decided to minimise the sensitivity of the spacers for vertical vibrations by placing the whole setup on a 250 kg block of granite. The granite block lies on a fine sand bed, and a thermal isolation box then encloses the whole setup. The block of sand is insulated from the floor by a rubber ELASTON-ELTEC FS 700[7], which can absorb mechanical energy between the floor and the sand block. Acoustic insulation consists of a 10 mm thick wooden box, which serves as the first acoustic noise isolation. The inside of the wall is laid with 76 mm thick foam made from compressed fibreglass[8] with 96 kgm^{-3} density suppressing noise from 100 Hz to 5 kHz. The followed 2 mm thick lead sheet also serves as an excellent acoustic insulation.

V. MEASUREMENT OF ACOUSTIC AND VIBRATION INSULATION

After completing the cavity insulation platform. The measurements of its performance of the acoustic insulation is provided by a seismic accelerometer Model 731A[9]. The accelerometer was placed inside the box and lies on the actively isolating platform next to the cavity. For the second measurement the accelerometer is placed on the optical table next to the insulation box. The record of this measurements can be seen in Fig. 4 and Fig. 5. There is clearly a visible effect of suppression of vibrations in the spectral range from 0.1Hz to 150Hz by a factor of 20.

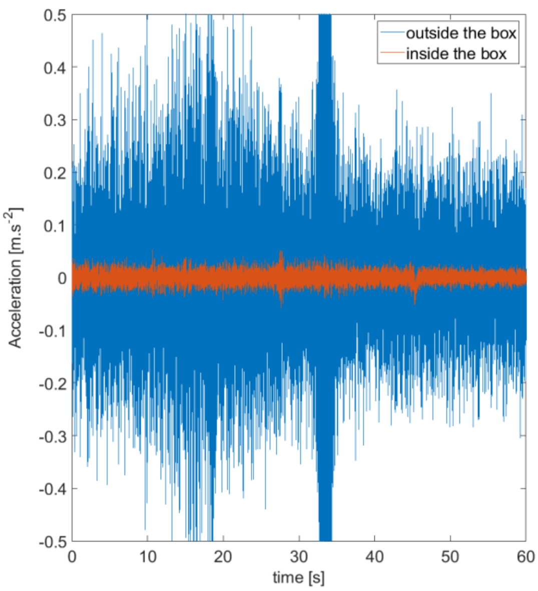

Fig. 4: Measured acoustic vibration by the seismic accelerometer. Model 731A placed inside (red) and outside the insulation box.

[6] Active vibration isolation system, Accurion halcyonics i4large M6/25.
[7] GUMEX company.
[8] Prima acoustic Broadband 3"
[9] Wilcoxon Sensing Technologies.

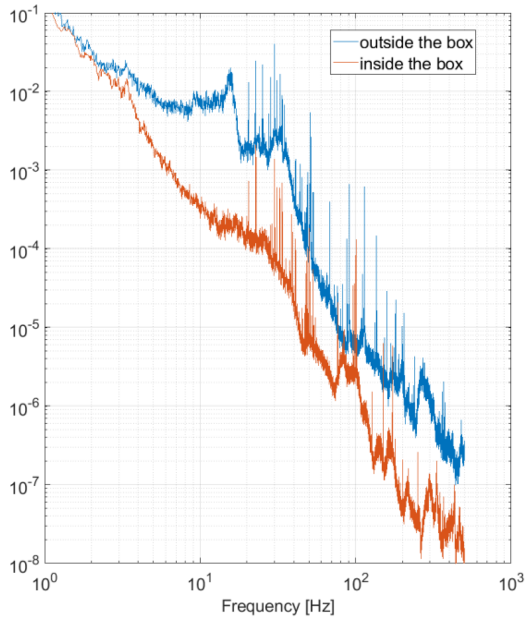

Fig. 5: Measured frequency noise density of the vibrations by the seismic accelerometer. Model 731A placed inside (red) and outside the insulation box.

ACKNOWLEDGMENT

The authors wish to express thanks for support to: Horizon Europe, European Partnership in Metrology 22IEM01 TOCK and 23FUN03 HIOC, Ministry of Education, Youth and Sports of the Czech Republic: Quantum Engineering and N a n o t e c h n o l o g y (Q U E E N T E C) CZ.02.01.01/00/22_008/0004649, co-funded by European Union.

REFERENCES

[1] YOUNG, B. C.; CRUZ, F. C.; ITANO, W. M.; BERGQUIST, J. C. Visible Laserswith Subhertz Linewidths. Physical Review Letters [online]. 1999, vol. 82, no. 19, pp. 3799–3802 [visited on 2022-05-20]. issn 0031-9007, issn 1079-7114.

[2] STERR, U.; LEGERO, T.; KESSLER, T.; SCHNATZ, H.; GROSCHE, G.; TERRA, O.; RIEHLE, F. Ultrastable lasers: new developments and applications. In: IDO, Tetsuya; REID, Derryck T. (eds.) [online]. San Diego, CA, 2009, 74310A.

[3] LEIBRANDT, David R.; THORPE, Michael J.; NOTCUTT, Mark; DRULLINGER, Robert E.; ROSENBAND, Till; BERGQUIST, James C. Spherical reference cavities for frequency stabilization of lasers in non-laboratory environments. Optics Express [online]. 2011, vol. 19, no. 4, p. 3471 [visited on 2022-05-20]. issn 1094-4087.

[4] DREVER, R. W. P.; HALL, J. L.; KOWALSKI, F. V.; HOUGH, J.; FORD, G. M.; MUNLEY, A. J.; WARD, H. Laser phase and frequency stabilization using an optical resonator. Applied Physics B Photophysics and Laser Chemistry [online]. 1983, vol. 31, no. 2, pp. 97–105 [visited on 2022-05-20]. issn 0721-7269, issn 1432-0649.

[5] KELLER, Jonas. Spectroscopic characterization of ion motion for an optical clock based on Coulomb crystals. [N.d.], p. 135.

[6] OX, Richard W. Temperature analysis of low-expansion Fabry-Perot cavities [online]. 2009, vol. 17, no. 17, pp. 15023–15031 [visited on 2022-06-16]. fabry-perot-cavities. Last Modified: 2017-02-19T20:02-05:00. M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.