Radiative cooling of the PVLAS Fabry-Perot cavity mirrors

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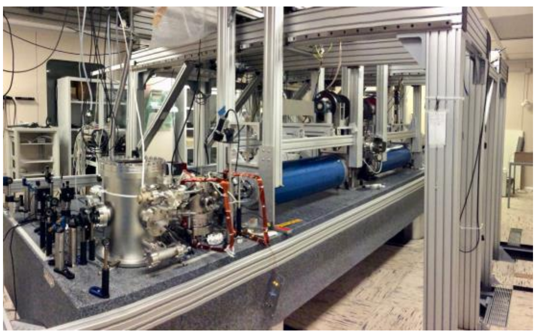
Abstract. The experiment PVLAS (Polarizzazione del Vuoto con LASer) aims at the measurement of the vacuum polarization as predicted by the QED (Quantum Electro Dynamics).In the new experimental set-up at INFN Ferrara two mirrors, 3.5 meter apart, constitute an optical cavity (with finesse=700 000) for a 1.064 micrometer Laser. Between the two mirrors two independent high field permanent dipole magnets (Halbach type) are installed, which can rotate up to 10 Hz around their longitudinal axis. In order to reduce the thermal noise of the mirrors their temperature will be lowered through a "cold finger" immersed in liquid Nitrogen (LN2). The mirrors must have the possibility to rotate of 360 degrees and to be tilted of about one degree. As a consequence the mirrors are cooled by radiation without any physical contact to the cold finger. A test set-up has been constructed at the INFN Laboratori Nazionali di Legnaro in order to measure the ultimate temperature that the mirrors can achieve.

1. Introduction

The PVLAS experiment [1] aims at measuring the magnetic birefringence of vacuum predicted by QED.A sensitive polarimeter, based on a high finesse Fabry-Perot, is running in Ferrara since 2014. The instrument has at present a sensitivity of $5\times10^{-7}/\sqrt{\text{Hz}}$ in ellipticity at about 10 Hz. Recently it has been observed that a substantial limitation to the sensitivity could come from thermal noise [2].

To verify this hypothesis, a test set-up employing liquid nitrogen has been designed and installed at the Laboratori Nazionali di Legnaro (LNL) to verify the possibility of cooling the mirrors only by radiation, since any contact would contribute to increase the vibrational background. Each of the two mirrors which form the PVLAS Fabry-Perot interferometer is fixed to three cascaded independent room temperature motors: the last one allows the azimuthal 360° rotation, the other two the tilting around two orthogonal axes (see Figure 1).



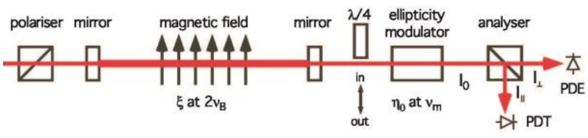


Figure 1. On the left-hand side is a photograph of the experiment PVLAS at INFN-Ferrara. Above is depicted a simplified scheme of the experiment (see Ref. [1], [2].

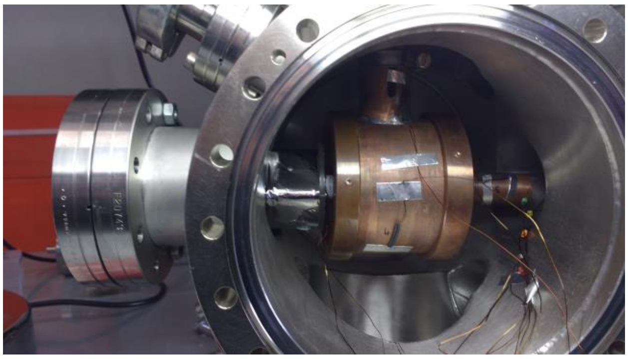


Figure 2. The test set-up at INFN-LNL. The dummy mirror, inside the LN2 thermal shield, is cooled by radiation only.

The movement of the mirror is necessary for aligning the cavity.

A test set-up has been constructed at the INFN Laboratori Nazionali di Legnaro (see Figure 2) in order to measure the ultimate temperature that the mirrors can achieve. In the LNL test set-up, a dummy mirror is clamped between two aluminum rings fastened to a low thermal conductivity support made of two coaxial tubes to maximize the conduction length. In the final installation, the thermal insulator will be mounted on the 360° rotation motor. As low thermal conductivity material, we used both Plexiglas and PEEK (Polyether ether ketone). The mirror is surrounded by a 2 mm thick copper sheet held by a cold finger at liquid nitrogen (LN2) temperature.

The foil is shaped in such a way to shield the mirror from thermal radiation coming from the surrounding room temperature objects (motors, vacuum chambers...). The outside of the copper shield is electrochemically polished, while its inner surface is blackened with Aquadag. The aluminum rings, which clamp the mirror, are also blackened. Five cryogenic Pt100 temperature sensors are fixed to the cold finger, to the shield, to the aluminum rings, to the mirror and to the "nose" respectively.

2. Experimental set-up and results

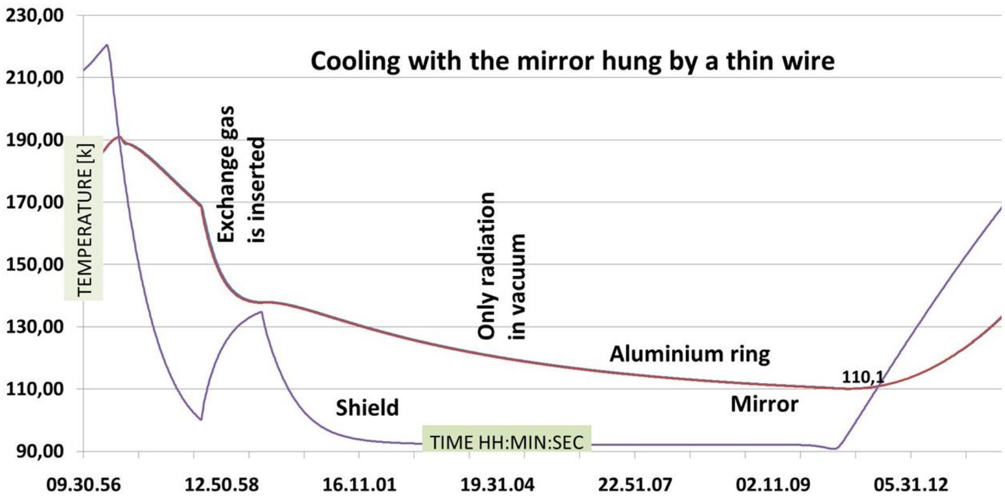


Figure 3. Cooldown graph of the mirror hung by a thin stainless steel wire. In order to increase the cooling speed 1 mbar of dry nitrogen is introduced until the temperature of the thermal shield and the one of the mirror approaches. Then chamber is evacuated to allow the further cooling only by radiation. The minimum temperature acquired in this condition by the mirror is 110 K.

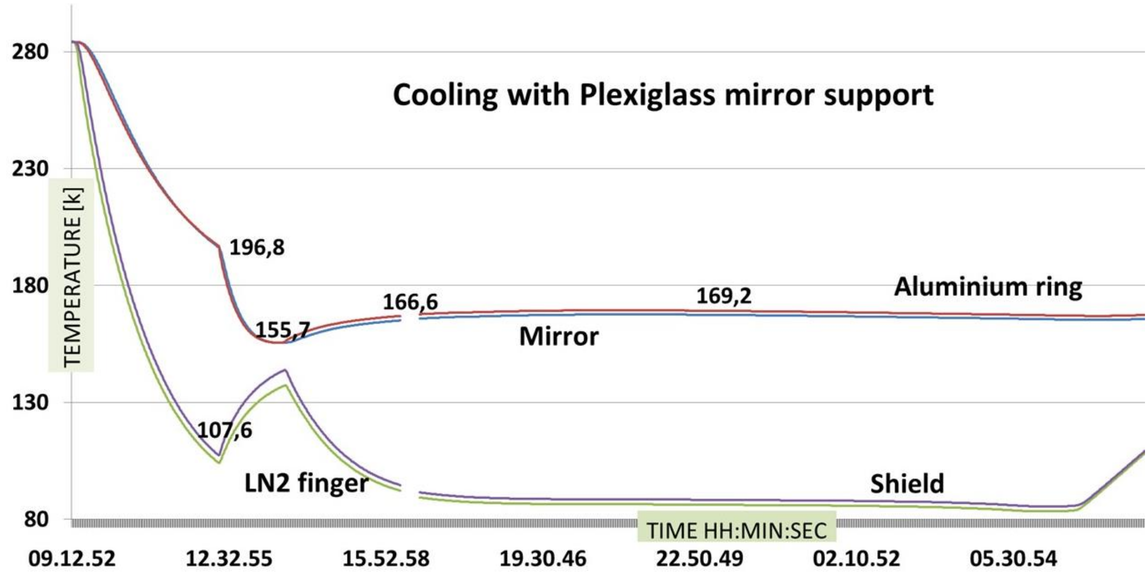


Figure 4. Cooldown graph of the mirror when supported by a coaxial Plexiglas tube anchored to the 300 K outside chamber, in order to simulate the conditions of the PVLAS experiment, where the mirrors are attached to motors at 300 K. The minimum temperature reached by the mirror in this conditions is 169 K.

Once everything is installed (see Figure 2) and the vacuum chamber is evacuated to the 10^{-6} mbar level, the LN2 reservoir is filled and the time evolution of the temperatures recorded. Many cooldowns have

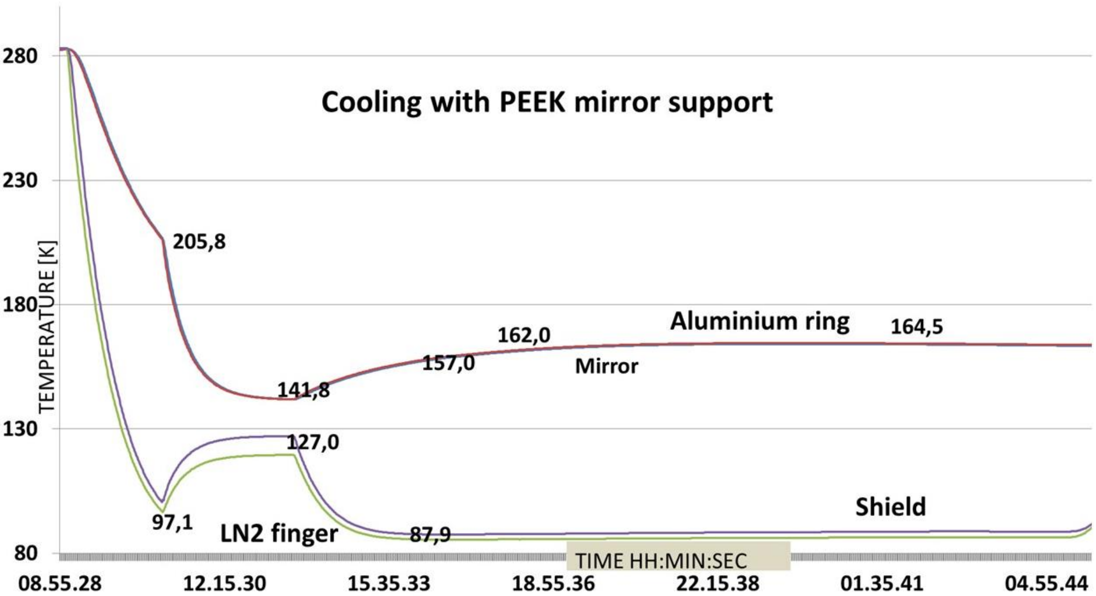


Figure 5. Cooldown graph of the mirror when supported by a coaxial PEEK tube anchored to the 300 K outside chamber, in order to simulate the conditions of the PVLAS experiment, where the mirrors are attached to motors at 300 K. The minimum temperature reached by the mirror in this conditions is 164 K.

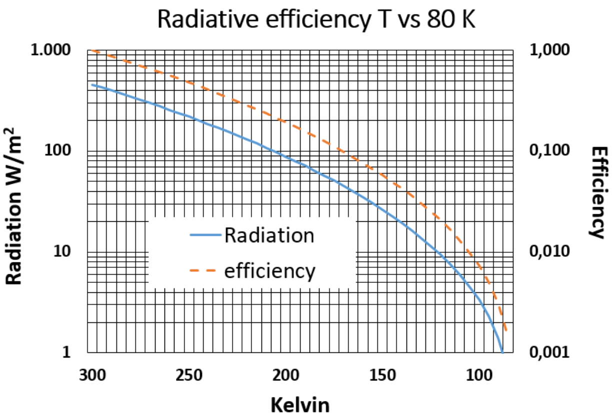


Figure 6. The solid line represents (values on the left) the specific radiation power in W/m^2, the dotted line (values on the right) the ratio between the specific radiation at 300 versus 80 K and the value at T versus 80 K. It can be seen that the power exchanged is reduced of an order of magnitude when the temperature goes down to 170 K.

been carried out in order to optimize the results.

Radiative cooling is a very slow process (see Figure 6) with an efficiency rapidly decreasing with decreasing temperature difference. To reduce the cooldown time, about 1 mbar of dry nitrogen has been introduced as a thermal exchange medium. The gas is removed when the temperatures of the mirror approaches the one of the shield. The mirror final temperature is given by the equilibrium between the radiation power and the thermal conduction through the insulating support of the mirror.

In another test, the mirror, instead of being fixed to the support, was suspended in the middle of the shield by means of a thin stainless steel wire. To this configuration, which is not suitable for the final set-up, corresponds the lowest temperature of the mirrors achievable with LN2 radiation cooling. In Figure 4 and 5 two sets of graphs are shown, with the support in Plexiglas and PEEK respectively: the results are comparable. When the copper shield is connected to the cold finger, both the shield and the mirror start to cool down, the cooling speed of the mirror given by radiation being much smaller than that of the shield, due to conduction.

When the dry nitrogen is introduced, the shield temperature increases due to the convection, but the mirror cools down much faster. As soon as the two temperatures are close, the exchange gas is pumped out and high vacuum is re-established in the chamber. In the conditions described above the mirror is cooled down to about 160 K. With the suspended mirror the final temperature is about 110 K. If the thermal noise in the optics of the PVLAS experiment is a linear function of the temperature, almost a factor two could be gained in sensitivity.

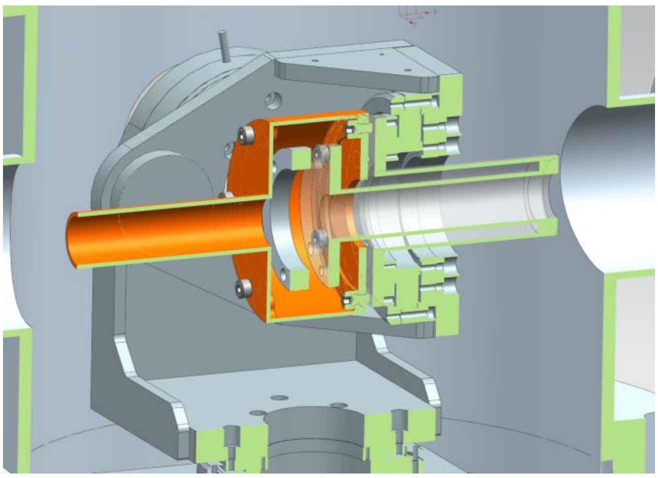


Figure 7. The final configuration for the cooling of the PVLAS mirrors is shown. Each mirror is clamped between two Aluminum rings screwed on a PEEK coaxial tube, which act as support and also as thermal connection to 300 K. The design allows the mirror to rotate 360 degrees around its perpendicular axis as required by the necessary optical cavity adjustment.

On the basis of the results obtained at LNL, we designed (see Fig.7) the radiative shield to be installed in the Fabry-Perot cavity of INFN Ferrara. The goal is to obtain the cooling of each of the two mirrors of the optical cavity maintaining the capability to move them along three axes with motors, which are at room temperature. As in the test set-up, the mirror support will be made of PEEK, the copper will be polished on the outside and chemically blackened on the inside.

In a test set-up simulating the conditions of the PVLAS optical cavity, we have demonstrated that a mirror connected to room temperature motors can be cooled down to about 160 K only by radiative cooling. The final set-up is under construction and it will be installed in the experiment site at INFN Ferrara. This should allow the study of the contribution to total noise arising from the thermal noise

3. Conclusions

A possible reason for the limited sensitivity of the PVLAS elipsometer is the thermal noise of the Fabry-Perot cavity mirrors, which are kept at room temperature. In order to verify the hypothesis, the mirrors will be cooled down at first at the lowest achievable temperature when only cooled by radiation. An experimental set-up has been designed and installed at the Laboratories of Legnaro which has demonstrated that the minimum temperature that the mirror can reach is 110 K, when hung by a thin stainless steel wire, and about 160 K when connected to the room temperature through a low thermal conductivity medium as PEEK.

References

[1] F. Della Valle et al. (PVLAS collaboration), Eur. Phys. J. C 76 (2016) 24.
[2] G. Zavattini et al., Eur. Phys. J. C 76 (2016) 294.