ELSEVIER Nuclear Instruments and Methods in Physics Research A 461 (2001) 297–299

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Thermal noise limit in the Virgo mirror suspension

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Abstract

The expected current limit to the Virgo sensitivity is presented. New materials to realize a low thermal noise suspension for the Virgo optics are investigated. A promising fused silica suspension for the Virgo mirrors is presented.

Keywords: Gravitational wave detection; Thermal noise; Virgo project; Suspension of interferometer mirrors

1. Introduction

Virgo is the French–Italian project for the construction of a 3 km interferometer for the detection of gravitational waves (GW). The interferometer is currently under construction in the Cascina site, near Pisa, and the civil works are scheduled to finish before the end of the 2001. The Virgo interferometer is a Michelson interferometer, containing a 3 km Fabry–Perot cavity of finesse $F = 50$ in each arm. The laser will be a 20 W Nd–YAG laser, with a power recycling factor of about 50($\simeq 1$ kW of stored power). The interferometer optic is seismically isolated by a cascade of mechanical filters named Superattenuator (SA). Because of the performances of the SA, the seismic noise at frequencies higher that 4–5 Hz is negligible. Neglecting the so-called *gravity gradient noise*, the main limit to the Virgo sensitivity between 5 and 500 Hz is the thermal noise, due to the pendulum thermal fluctuation (dominant in the 5–50 Hz range) and the mirror internal mode vibration (dominant in the 50–500 Hz range). At frequencies larger than 500 Hz the main limit to the Virgo sensitivity is due to the photon shot noise.

2. The pendulum thermal noise

The low frequency region is very important for the coalescing binaries GW detection. Big efforts are performed by several research groups in the world to improve the sensitivity of the interferometric GW detectors at frequencies below few hundreds Hertz. The pendulum thermal noise is composed of three different contributions: clamping losses, material internal loss angle and geometrical dilution factor. It has been shown [1] that the clamping losses can be reduced by using special clamps with high clamping pressure, to minimize the *stick and slip* process between suspension wire and clamp, and using some *spacer*

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in the suspension wire–mirror contact point, but the best solution is to use a large head (the so-called *monolithic*) wire suspension. The large head of the wire makes possible a clamping with very low frictional loss. The remaining two contributions to the pendulum thermal noise power spectrum are summarized in the following formula:

$$X^2(\omega) \approx 4k_B T \frac{g}{\omega^5} \frac{1}{L^2} \sqrt{\frac{Eg}{4\pi Nm}} \frac{\phi_w}{T_b C_S} \quad (1)$$

where only the pendulum horizontal mode has been considered. ϕ_w is the material loss angle, T_b

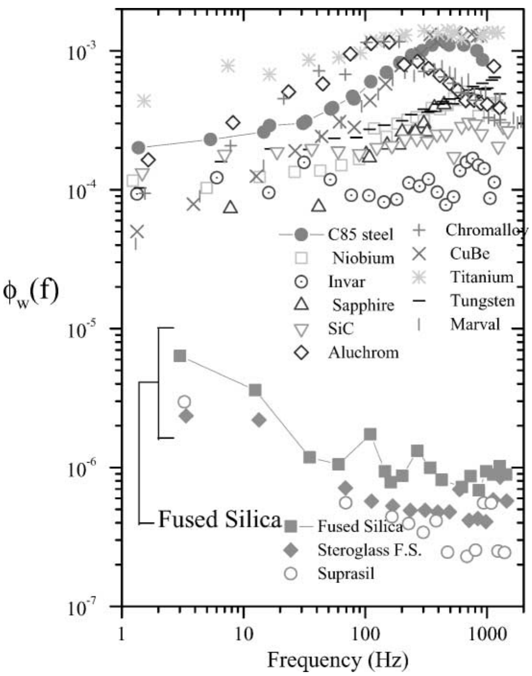

Fig. 1. Loss angle vs. frequency for several materials.

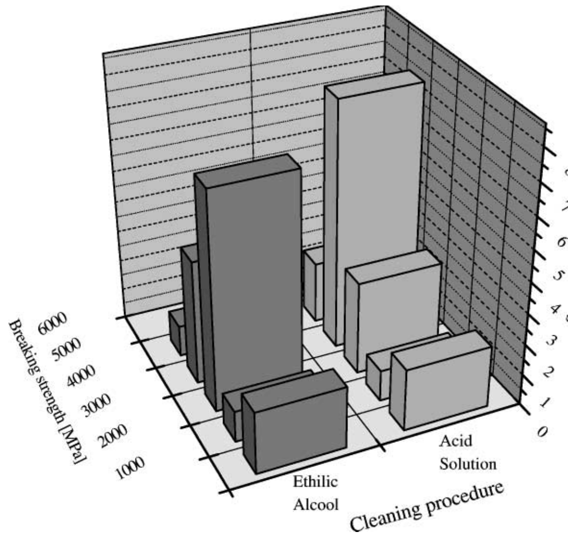

Fig. 3. Breaking strength for fused silica fibers.

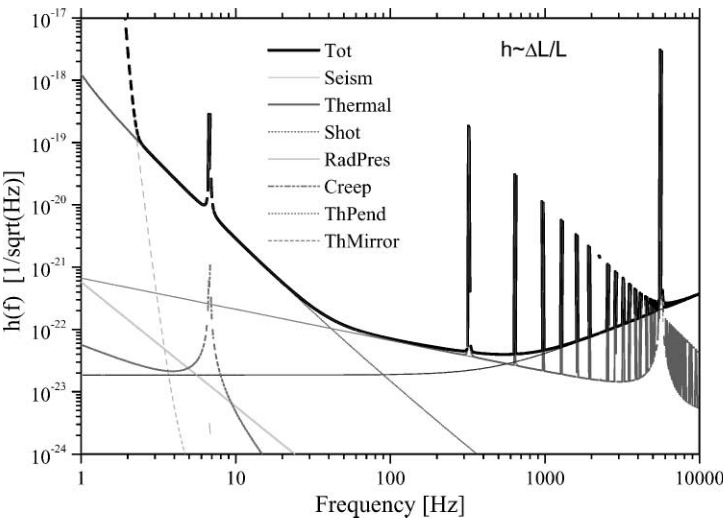

Fig. 2. Expected Virgo sensitivity.

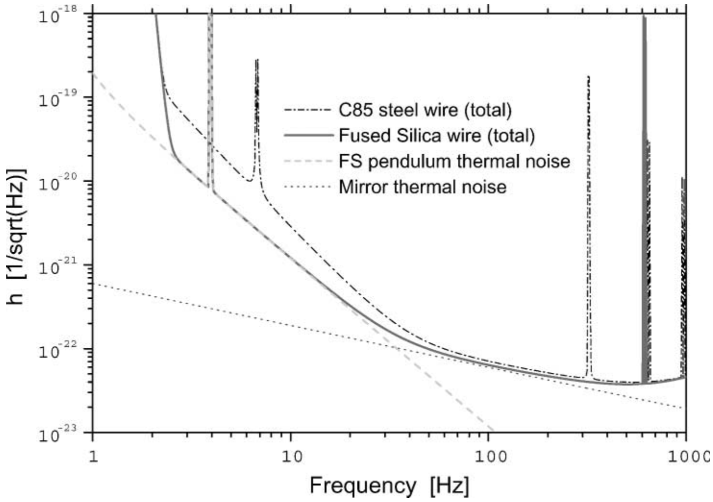

Fig. 4. Comparison of the Virgo sensitivity with C85 steel suspension wires and with fused silica suspension fibers.

the wire breaking strength in Pa and C_s is a *confidence factor* ($0 < C_s < 1$) related to the reliability of the suspension wire. C_s represents the load on the single suspension wire in T_b units. The optimization of the pendulum thermal noise is performed through the minimization of the ratio $\phi_w / T_b C_S$. In the current solution the suspension of the Virgo mirrors is realized using a double loop of C85 steel wires. C85 steel shows a low loss angle ($\phi_w \simeq 2 \times 10^{-4}$, see Fig. 1), very high breaking strength ($T_b \simeq 2.9$ GPa) and an excellent confidence factor ($C_s \simeq 0.65$). The expected sensitivity for the Virgo detector using the current mirror suspension solution is reported in Fig. 2. The most promising candidate (see Fig. 1) for a low loss suspension is based on fused silica (FS) fibers. FS shows a very low ϕ_w [2] and a very high breaking strength ($\simeq 3.9$ GPa, see Fig. 3), in average larger than C85 steel. This result has been reached producing the fibers by pulling FS rods with a particular O_2–H_2 flame. The standard deviation of the T_b values measured for FS is large ($\simeq 0.7$ GPa) and T_b strongly depends on the handling and cleaning procedure adopted to prepare the suspension wire.

3. Conclusions

Fused silica is the best candidate to build the new generation of mirror suspension for interferometric GW detectors. The comparison of the Virgo sensitivity with standard C85 steel suspension wires and with FS suspension fibers is shown in Fig. 4. The strong variability of its breaking strength limits the use of FS in current interferometric GW detectors. Improvements of the production technique are needed to solve this problem. Another possible problem is currently under investigation. Creep noise (mechanical shot noise) is a possible source of noise in the steel suspensions of interferometric GW detectors and it is cured through thermal treatment of the suspension wires [3] or choosing special steels [4]. No conclusive answer is available for FS fibers.

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