Thermal and mechanical noise in gravitational wave detectors

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I. INTRODUCTION

Gravitational Waves detectors based on laser interferometry like Advanced Virgo, Advanced LIGO and KAGRA, are expected to be limited by mechanical thermal noise in the frequency band where the sensitivity is the highest. A first series of detectors, based on mechanical resonators, have been developed in the forty years after the pioneering work of Josef Weber in 1960. The current generation is based on the laser interferometry used to monitor the length changes on a Michelson interferometer arms. These detectors have an optical readout able to measure displacements of the order of 10^{-20} m/$\sqrt{\text{Hz}}$ from 10 Hz to 10 kHz. With such performance they can be seen as gigantic amplifiers of mechanical and thermal noises and actually these noises are thought to be limiting the detection of GW in the advanced detectors. During the 30 years of interferometric detector developments many sources of noises have been studied, some of them have led to other questions, some other have not completely explained or investigated yet. A view on these standing challenges on GW detector noise will be given.

II. THE MECHANICAL NOISES

The Seismic Noise is the first of all the mechanical noises to cure in a GW detector. It's typical amplitude is 10^{-7} m/$\sqrt{\text{Hz}}$ at 1 Hz and falls roughly as $1/f^2$ up to few tens of Hz. The seismic noise is able to shortcut the suspension system designed to filter the Earth vibrations before they reach the mirrors: the density fluctuations of the soil are directly coupled to the mirrors through the Newtonian law of gravity. The effect is irrelevant in most of the experiments but in future GW detectors which are designed to work at frequencies as low as 1 Hz. Following some models, this noise could be detected even by the present generation of detectors. What is still under discussion is how to mitigate the effect of this noise: will the measurement of the seismic motion by an array of accelerometers be a solution good enough to mitigate this noise or the underground operation is an avoidable caveat for the third generation of GW detectors?

One of the most long standing question in the mechanical noise domain is whether or not stress in structures can trigger sudden relaxations of elastic energy that can be seen as either burst signals or a continuous shot noise on the GW detectors. In the GW community such noise is called *creep noise* or *cracking noise*. Relatively high stress that is able to trigger relaxations close enough to the test masses (i.e. the mirrors) is present on the metal cantilever blades used to vertically filter the seismic noise, on the mirror suspension fibres made of silica and on the silicate bonding layer used to attach the connecting elements between the thin fibres and the large mirrors. In the latter the stress is not particularly high (few MPa) but the bonding layer is thought to have plenty of relaxation centres. An overview of the investigations conducted and ongoing around this subject will be given.

III. THE THERMAL NOISES

Thermal noise is indeed the most reach source of "troubles", and hence of research interest, among all the fundamental noises in GW detectors all along the history of their development. In the first generation of GW detectors suspension thermal noise was the most severe limit to the instrument sensitivity but in the last 15 years, since the technology of fused silica suspension replaced the one based on steel wires, the focus has moved onto the mirror coatings thermal noise: any tiny reduction of this noise level is translated in an equivalent increase of the maximum distance at which a GW detection can be made.

The observable, whose fluctuations are picked up by the interferometer output, is the phase of the laser beam reflected by the Bragg structure of coatings deposited on each mirror. This fact together with the uncorrelated fluctuations of temperature and density make the study of coating thermal noise rather complicated and at the same time reach of phenomena.

The materials used so far are amorphous (glasses) in both the forms of bulk and thin films. The greatest unsolved problem in this subject is to understand the origin of structural relaxations that represent the highest source of thermal noise in coatings. A review of the structural studies and modeling of glasses will be given.

In recent years people have started to develop Bragg reflectors made of III-V semiconductors. These materials have shown a considerable reduction of thermal noise level as compared to the amorphous counterpart. A brief description of the new type of thermal noise mechanisms affecting these devices will be presented.

IV. OTHER WELL KNOWN UNSOLVED PROBLEMS

As a possible way to reduce thermal noise, a design of a detector operated at cryogenic temperatures has been made[1]. In this design the mirror suspension fibres work with a large thermal gradient. The mirrors itself have a thermal gradient due to the laser power dissipated in the mirror substrates or on the coatings. These facts triggered the interest on studying the thermal noise under steady state heat flux. No theory has been made that is able to treat systems like those and only very few people in the GW community have done an investigation on that. In the near future the situation might change.

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[1] The ET Science Team, technical note ET-0106C-10, http://www.et-gw.eu/etdsdocument This large document contains the majority of the relevant publications in the field of GW detectors development.