R&D on thermal noise in Europe: the Strega Project

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Abstract. The design of cryogenic interferometers and quantum limited ultra-cryogenic resonators (3rd generation Advanced Gravitational Wave Detectors) is driving the R&D activities in the area of thermal noise reduction at low temperature. The project Strega coordinates the R&D activities of 18 labs in Europe involved in Interferometric, Resonant and Electromagnetic Detectors. The aim of the collaboration is to develop a technology that will reduce the thermal noise in the third generation detectors 10 times with respect to the second generation (advanced resonators and advanced room temperature interferometers). The work carried out in Strega, in the areas of Materials, Cryogenics and Thermal Noise Specific Studies after 14 months since the project started, will be reviewed.

1. Introduction

As B. Barish said in the concluding remarks at this Amaldi 6 Conference, the interferometric detectors are finishing the “noise hunting” phase of their developments and they are becoming gravitational wave detectors ready to pick up the first direct signal from cosmic sources. This status has already been achieved by the resonant detectors and it is possible to identify all the detectors operating now, regardless whether interferometric (TAMA300, Ligo, GEO600 and Virgo) or resonant (ALLEGRO, Auriga, Explorer, Nautilus and Niobe), as First Generation detectors.

Despite the success of these projects the probability of detecting gravitational waves within the working life of an experiment is very low due to the event rate of the typical gravitational wave sources [1]. The only solution to this problem is to design and build detectors with better sensitivity that have a detection volume much larger than the one at present.

Following this idea a number of projects has been started aiming at the design and construction of Advanced Detectors. The resonant detectors have identified their breakthrough steps in a different geometry of their test masses, going from bars to spheres, and in the attainability of the Standard Quantum Limit in their capacitive readouts. Projects like MiniGRAIL [2, 3] and Mario Schenberg [4] have been successfully started as a first step toward the construction of a much bigger sphere. People working on interferometers have also started R&D projects on new detectors. In this case there are two main leading ideas on how the future detectors should be designed: a) exploiting as much as possible the performances of materials and technologies at room temperature like in the Advanced LIGO Project [5, 6], GEO-HF [7]
and the next upgrade of Virgo [8]; b) operating the interferometer at low temperature mainly
to reduce the thermal noise. Pioneers of the latter solution are indeed the Projects LCGT [9]
and the associated R&D CLIO [10].

The cryogenic technology applied to the interferometric detectors represents a solution that
is not just an upgrade of existing detectors. Therefore it is convenient to separate the future
detectors into two different Detector Generations.

The Second Generation includes the interferometers that will work at room temperature
(Advanced LIGO, Advanced Virgo, GEO-HF) and resonant detectors like MiniGRAIL, Mario
Schenberg and their possible upgrades that have a completion date around the year 2010.

The Third Generation includes instead the interferometers that will work at cryogenic
temperatures (LCGT is the only project that has started) and the resonant detectors of
novel concept like DUAL [11]. This generation should be complementary to the space based
interferometer LISA and hopefully one day they will belong to a worldwide array of gravitational
wave detectors.

It is in this context that several groups in Europe have decided to coordinate their research
activities on the reduction of thermal noise in the Third Generation detectors. At low as much
as at room temperatures, thermal noise is the ultimate sensitivity limit to the detection of
gravitational waves in the frequency band from 10 Hz to few hundreds Hz, once all the technical
noises are under control. It happens that groups belonging to different projects share the same
interest in some materials or have the same kind of facilities to use in their investigation. It was
of common interest then to coordinate the efforts of each group and that was possible once the
project STREGA was approved under the Framework Program 6 of the European Commission.

2. The STREGA Project
The Second Generation of interferometric detectors has a planned sensitivity limit that is about
a factor of 15 better than the First Generation ones [1]. The detection range for three kinds of
binaries are listed in table 1. From some preliminary study on the thermo-mechanical properties
of silicon [12], it seems possible to have a further increase by a factor of 10 on the detection
range for a cryogenic interferometer.

STREGA is a Joint Research Activity that aims at reduce by a factor of 10 the thermal noise
in the 3rd Generation detectors with respect to the 2nd Generation ones. STREGA stands for
Study for Thermal noise Reduction in Gravitational wave Antennas.

STREGA coordinates the efforts that a number of laboratories of different experiments spend
on the thermal noise research for 3rd generation detectors and possibly it will represent the
nucleus of a much larger collaboration for the design and realization of a European Gravita-
tional Observatory. In order to fulfil the STREGA mission three Objectives have been identified:
Study on Advanced Materials; Development of Advanced Cryogenics; Specific Investigations on
Thermal Noise. Each of these objectives have been divided in Tasks listed below. The aims
of the tasks as they have been approved at the end of the first year of activity are now briefly
described.

M1 – Mirror substrates. Silicon (Si) and Calcium Fluoride (CaF2) have been considered
the best candidates as mirror substrates for advanced interferometers. In this task thermal
expansion, thermal conduction and mechanical losses of these two materials will be measured,
varying the temperature from 300 K down to 4 K. In the case of silicon, the alteration of thermo-
mechanical properties as a function of quantity and nature of dopants is investigated. Prototypes
will be realized and tested in connection with the tasks M4 and M5.

M2 – Materials for Resonant Detectors. This task aims at developing knowledge of the
material properties and innovative technology for the production of test masses and transducers
Table 1. Detection ranges and event rates for three types of coalescing binaries. The symbols stand for: NS-NS, neutron star binary with 1.4 solar mass components; NS-BH, binary with a neutron star and a 10 solar mass black hole; BH-BH, black hole binary with 10 solar masses each. For the 1st and 2nd Generations the data are coming from reference [1] assuming the LIGO and Advanced LIGO as typical detectors for the 1st and 2nd Generations respectively and considering that the detector range for single detector is about 1.5 times lower than the range for 3 detectors. For the 3rd Generation the ranges and rates have been extrapolated considering the sensitivity curve of EGO [13] shown in figure 1.

|                  | 1st Generation Detectors | 2nd Generation Detectors | 3rd Generation Detectors |
|------------------|--------------------------|--------------------------|--------------------------|
| NS-NS            | 14 Mpc                   | 240 Mpc                  | 1 Gpc                    |
|                  | 1/3000 yr to 1/3 yr      | 3/yr to 4/d              | 2/month to 2/h           |
| NS-BH            | 29 Mpc                   | 500 Mpc                  | 2.4 Gpc                  |
|                  | 1/2500 yr to 1/2 yr      | 1/yr to 6/d              | 1/month to 3/h           |
| BH-BH            | 67 Mpc                   | $z \sim 0.3$             | $z \sim 1$               |
|                  | 1/600 yr to 3/yr         | 1/month to 30/d          | 1/3 d to 1/5 min         |

Figure 1. Comparison between the theoretical sensitivity curves of a number of detectors of the 3 Generations. For details on the European Gravitational Observatory (EGO) design study proposal please see the reference [13].

made of new materials like Molybdenum, Silicon-Carbide (SiC), Beryllium, Copper Aluminium (CuAl), Niobium. Thermal expansion, thermal conduction and mechanical losses will be measured varying the temperature from 300 K down to 0.1 K. Fabrication processes to be investigated are silicate bonding for SiC, and electron beam welding, explosion welding and cold welding for metals. In order to reduce the cool-down time, an investigation will be carried out on the various metal production processes as well as low temperature calorimetric studies to choose metals with the smallest Hydrogen contamination.
M3 – **Superconducting materials.** An innovative detector based on superconducting resonant cavities has recently been proposed [14]. The interesting feature of this detection scheme is the very high electromagnetic quality factor that can be obtained in superconducting structures. It is proposed to build cavities using the technique of niobium sputtering on a substrate having high thermal conductivity and low intrinsic mechanical dissipations. Such a facility will be essential for the development of advanced superconducting RF detectors with better sensitivity.

M4 – **Mirror coatings.** It is proposed to develop an innovative technology for low loss dielectric coatings, starting from an investigation of the specific loss reduction of SiO$_2$/Ta$_2$O$_5$ and SiO$_2$/Al$_2$O$_3$. Another possibility is to decrease the number of layers and investigation on SiO$_2$/XX, where XX is a high index of refraction material like Zinc Selenide (ZnSe), are considered here. Measurement of mechanical losses, optical losses and index of refraction have to be performed at room and low temperatures. Prototypes will be realized and tested in connection with the tasks M1 and M5.

M5 – **Test mass suspensions.** An investigation of low temperature properties of and fabrication processes for fibres made of Silicon, Calcium Fluoride, Molybdenum and Ruthenium is planned. These materials have excellent low temperature properties and they are compatible with the mirror and test mass materials developed in M1 and M2. A very innovative technology that has to be fully investigated is based on a localized cooling process through the inverse fluorescence mechanism [15]. Prototypes will be realized and tested in connection with the tasks M1 and M4.

M6 – **Cosmic ray acoustic effects.** In a low temperature detector the energy released by cosmic rays represents a significant contribution to the thermal energy of the test masses [16, 17]. In addition to the increase in the average energy in the test masses, the absorption of cosmic rays produces bursts of acoustic emission through a thermoelastic process that could be confused with gravitational wave bursts by the detector. A theoretical investigation of the thermoelastic mechanism that generates the acoustic emission and a series of tests on different materials are proposed.

C1 – **Last-stage suspension cryogenics.** The design of low noise and high thermal conductive suspension elements can be achieved through the investigation of suitable materials (task M5) as well as through the design of new suspension elements (such as cantilever blades or flexural joints) to be located on the final stage. A low-noise remote control of the mirror position has to be achieved, using sensors and actuators compatible with the cryogenic environment. A full prototype of cryogenic final stage will be assembled and tested.

C2 – **Ultra-cryogenic suspensions for resonant detectors.** Although the ultra-cryogenic detectors have been successfully operated, further advances in cooling and/or isolating the antenna can be achieved via finite element modelling and experimental tests. Two 1.2 ton spheres of MiniGRAIL [2] with their cryogenic suspension will be assembled and measurements of mechanical quality factor and thermal noise at low temperatures performed.

C3 – **Cryogenic suspension system for interferometers.** The aim is to demonstrate the capacity to remove a sufficient amount of heat from the cryogenic payload while preserving the suspension seismic isolation performance, namely its “softness” in all degrees of freedom. This result can be achieved by connecting suspension attenuation stages with high compliance and high thermal conductivity elements, exhibiting, at the same time, low stiffness. A low noise cryo-generator is also studied.

T1 – **Thermoelastic noise measurements.** Using a very high sensitivity interferometer with a small spot size (about 100 µm) on the optical elements it should be possible to observe the thermoelastic noise in sapphire, YAG, Silicon and CaF$_2$ masses. Some existing facilities like the interferometers in Glasgow and in Perugia have to be converted and upgraded. After this substantial change has been completed, the possibility of the direct measurement of thermoelastic noise will be investigated.
**T2 – Photoelastic effect measurements.** Theories on thermal conduction inside mirrors and coatings [18] can be experimentally verified using the photoelastic effect induced by a low frequency intensity modulation of the light entering a Fabry-Perot cavity [19]. This measurement can be performed with the temperature ranging between tenths of Kelvin up to room temperature. Low optical loss coatings will be tested.

**T3 – Selective readouts.** The effect of thermal noise depends on the size of the read-out area that for the interferometers is determined by the laser spot on the mirrors whereas in the case of the resonant masses it is determined by the used displacement transducer. The study of read-out configurations, in which only the contributions coming from modes strongly coupled to the signal of interest are selected, is proposed. At this end developments on the Fabry-Perot cavities and on capacitive transducers are implemented.

Further details on the project can be found in reference [20].

2.1. **ILIAS and the managing structures of STREGA**

In order to understand how STREGA is funded and managed it is essential to explain first that since 1984 the European Commission has been supporting the development of the European Research Area with Framework Programs, lasting typically 5 years. In the last one, the FP6, the Astroparticle Physics European Coordination (ApPEC) supported and submitted a proposal called Ilias (Integrated Large Infrastructures for Astroparticle Science [21]). The gravitational waves community joined the ApPEC initiative as well as the other communities working on Dark Matter, Double $\beta$-decay and the theorists working more generally on Astroparticle. The Ilias mission is to strengthen the coordination in the three scientific poles of: i) Physics in the Deep Underground Laboratories; ii) Gravitational Wave Detection; iii) Theoretical Astroparticle Physics.

The instruments that Ilias has to fulfil its mission are: three Joint Research Activity projects (STREGA is one of them); five Networking projects designed to facilitate the mobility of people between laboratories (the gravitational wave community has one Networking, called Gravitational Wave Antennas); one Transnational Access project to increment the availability of the large infrastructures and facilities in Europe for scientist from all over the world.

STREGA started on the 1st of April 2004 and it lasts for 5 years, the total funding is 1.39 million Euro. Each year a scientific program is approved and a pre-financing is given to the participants. At the end of the year a report is submitted and depending on the achievement of milestones and deliverables declared at the beginning of the year the expenses are reimbursed and another pre-financing is issued.

The institutions participating in Ilias sign a contract (Consortium Agreement) where they commit themselves to achieving milestones and deliverables and to the approved managing rules of Ilias. The institutions participating in STREGA and their laboratories are listed in below:

- **CNRS:** ESPCI (Paris), LKB (Paris), LMA (Lyon)
- **INFN:** Sez. Firenze, Sez. Genova, LNF (Frascati), LNL (Legnaro), Sez. Napoli, Sez. Perugia, Sez. Pisa, Sez. Padova, Sez. Roma 1, Sez. Roma 2
- **IFN:** Trento
- **Uni. of Leiden:** MiniGRAIL
- **Uni. of Glasgow:** IGR

The institutions are represented in the Governing Council of Ilias. The STREGA managing structure is based on the Task Supervisors that are responsible for the milestones and the deliverables in their respective tasks. They are nominated by the coordinators of the groups.
working on the same task. The Task Supervisors nominate the three Objective Supervisors (one for each Strega objective) that form, with the STREGA and GWA Coordinators, the top managing body of STREGA: the STREGA Steering Committee.

3. Status of the project
A short description of the results achieved in the first year of the project activity is given below. A detailed description can be found in reference [22].

M1 Preparation of large samples of Si and CaF$_2$ for Q measurements; optical measurements at room temperature on Si and CaF$_2$ small samples.

M2 Construction of SiC, Mo and Be resonators for low temperature Q measurements; test of 1-mode and 2-modes CuAl transducers on MiniGRAIL; achievement of $2.5 \times 10^6$ V/m electric field in the 1-mode transducers.

M3 Test of the electron-welded copper cavity; production of a seamless aluminium cavity.

M4 Development of a Q measurement facility on membranes at LMA; procurement of SiO$_2$/Al$_2$O$_3$ coatings on sapphire substrates; optical measurements at room temperature.

M5 Production of silicon fibre with the $\mu$-pulling technique; loss measurements at various temperatures on cantilever blades and on fibres; upgrade of the facilities.

M6 Measurements on small scale Aluminium and Niobium resonant bars; for the Niobium agreement with the model using the superconducting parameters for temperature below the transition.

C1 Production of cryogenic low-frequency accelerometers; development of a noise filtering device for the pulse tube refrigerator;

C2 Cooling of MiniGRAIL down to 68 mK and measurements of mechanical transfer function and thermal conductance; test of the new design of SQUID amplifiers.

C3 Thermal analysis with FEA model of the last stage suspension; structural works at the EGO site for the cryogenic test facility.

T1 Locking of the laser to the 10 m cavity; installation of the measuring cavity in progress; first measurements of thermal noise close to the resonances of a silicon membrane.

T2 New measurements of the photoelastic effect showing finite size and coatings effects; room temperature measurements on a cavity with finesse higher than $2 \times 10^5$ and preparation of the set-up for cryogenic measurements.

T3 Theoretical analysis on the folded Fabry-Perot cavity, on the Concave-Convex cavity and on the mechanical amplifier eventually used in a dual-detector.

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