Contribution aux exercices de prospective nationale 2020-2030

*Détecteurs et instrumentation associée*

# Low loss signal detection

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1. **Informations générales**

**Titre: Low loss signal detection**

**Résumé** *(max. 600 caractères espaces compris)*

Among the challenges for the advanced and third generation gravitational waves detectors, the losses of the detection system must be minimized so as not to degrade the sensitivity of the instrument. For this purpose, output filtering cavities (required for a good contrast defect of the detector), must be realized with very low optical losses. In addition, a very low noise electronics chain must be developed for the high quantum efficiency photodiodes involved in the readout of the laser beam carrying the information on the gravitational wave signal.

***Préciser le domaine technologique*** *(plusieurs choix possibles)*

* Photo-détecteurs (photodiodes à haute efficacité quantique)
* Micro-électronique, Electronique Front End
* Mécanique, integration
* Optique

***Préciser la motivation principale de recherche visée par la contribution :***

* R&D Détection d’ondes gravitationnelles

1. **Description des objectifs scientifiques et techniques   
   *(1 page max incl. figures)***

Quantum noises, which include shot noise and radiation pressure noise, are among the fundamental limits of the sensitivity of gravitational wave detectors. The shot noise is limiting the sensitivity at high frequency (typically above ~100 Hz), while the radiation pressure noise impacts the sensitivity at low frequency.

In order to minimize the impact of shot noise on their sensitivity, gravitational wave detectors are operated at dark fringe. One consequence of this approach is that the power reaching the detection port of the detector is several orders of magnitude smaller (4 orders with Virgo at present time) than the power injected in the interferometer, which makes the detector sensitivity strongly impacted by the contrast defect of the interferometer. Indeed any spurious light induced by optical imperfections in the interferometer can easily overshadow the much dimmer beam containing the gravitational wave signal. In order to tackle this issue, filtering optical cavities, called output mode cleaner (OMC), are placed at the detection port of gravitational wave detectors to improve their contrast defect. To this purpose, the OMC cavities are made resonant on the fundamental mode of the laser beam, which allows the rejection of the high order modes of the laser as well as the rejection of the control side bands which do not contain the imprint of gravitational wave signals.

Shot noise can be reduced by injecting a squeezed vacuum state through the detection port of the interferometer. This technique, also known as « squeezing », is already implemented on the gravitational wave detectors. Moreover frequency dependent squeezing is being prepared for Advanced Virgo+ and will allow a reduction of both shot noise at high frequency and radiation pressure noise at low frequency. The noise reduction obtained with squeezing is however limited by the amount of losses present in the interferometer and at the detection port. It is therefore crucial to reduce as much as possible optical losses induced by the components of the detection system, such as the OMC cavity mentioned above. For the same reason, the readout of the dark fringe beam involves high quantum efficiency photodiodes. As the noise of the electronic chain of these photodiodes has a similar impact as losses on the squeezing performances, the front-end electronics must be designed for an electronic noise much smaller than the shot noise level. Moreover, as the optimization of the preamplifier noise strongly depends on the amount of power reaching the photodiodes, this electronics will undergo several adaptations during the commissioning phases of Advanced Virgo+ and towards the path of Einstein Telescope. Another specificity of these photodiodes comes from the fact that their front-end electronics is entirely integrated to a suspended bench located inside a vacuum chamber, which puts constraints on the compactness of the electronic boards and their thermal dissipation.

The OMC implemented in the Advanced Virgo detection system is made of two monolithic cavities in series. The beam propagates inside the cavity medium (i.e. fused silica). Each cavity has a finesse of about 125. About 7.5% losses are currently associated to the OMC cavities, which stands for about half of the overall losses of the detection system. In order to reduce the OMC losses in view of Advanced Virgo+ and Einstein Telescope, several improvements are proposed :

* The current OMC system made of two cavities in series will be replaced by a single OMC cavity of higher finesse (about 1000). This will allow to get rid of the relative mismatching losses between the two OMC cavities, while the higher finesse should make it possible to obtain the required filtering of high order modes and control side bands. One potential drawback of a larger finesse is the increase of the coupling of the OMC length noise [1] to the detector sensitivity. This sets stringent requirements on the OMC lock precision which will have to be kept below 6 x 10-13 m. Although the experience acquired with the Virgo and Advanced Virgo OMC control system should help reaching this goal, an optimization of the control loop parameters will be required. Moreover experimental tests of a high finesse cavity will be performed in order to check that the controllability of the cavity and its optical performances are not degraded by thermal effects that could be induced by the increased finesse.
* With a larger finesse, internal losses of the OMC cavity are expected to increase. Past measurements have shown that the OMC cavity internal losses are presently dominated by scattering on the cavity surfaces. These losses will be mitigated thanks to a more stringent requirement on the polishing of these surfaces. Indeed cavity substrates recently polished exhibit a micro-roughness which is more than 3 times better than the one of the Advanced Virgo OMC cavities. This should translate into a reduction of the scattering losses by at least a factor 10. More generally a further loss reduction can be achieved by replacing all the optics placed along the dark fringe beam path (which includes 10 mirrors, 4 lenses, and 1 viewport) with super-polished optics.
* Mismatching losses between the interferometer beam and the OMC cavity include mode mismatch, polarization mismatch and misalignment. One of the difficulties faced during the commissioning of Advanced Virgo was the lack of actuators enabling a remote tuning of the polarization and mode matching while the bench hosting the OMC was suspended and under vacuum. In order to address this problem, appropriate actuators will be implemented in order to be able to use all the degrees of freedom of the mode matching telescope, and to adjust the polarization of the interferometer beam. An automatic alignment of the OMC, involving new sensors, will also be implemented in order to follow the interferometer alignment drifts and avoid misalignment losses.
* On a longer time scale, as the state of the art evolves, new materials for the OMC substrate should be explored, with the goal of finding materials with very low absorption to reduce further internal losses, and very good homogeneity and isotropy to minimize optical aberrations and birefringence which contribute to polarization and mode mismatch.
* An evolution of the OMC cavity design towards an empty cavity (where the beam propagates in vacuum) should also be explored. This approach would have the benefit of removing losses due to the absorption of light in the substrate and remove birefringence effects.

1. **Livrables associés, calendrier et budget indicatifs (1 page max. incl. figures)**

A lower losses OMC system made of a single cavity of high finesse is being developed and will be installed in the detection system of Advanced Virgo+ and commissioned in the years 2020-2021. The targeted losses with this new design are about 3%, which is less than half of the current OMC losses in Advanced Virgo.

Depending on the performances of this new OMC system, a further evolution in the design may be envisaged for the 2023/2025 upgrade break of Advanced Virgo +.

On the longer term (2025-2030), the OMC design should be revised according to the new state of the art concerning the polishing quality of optical surfaces and the best materials for cavity substrates (low absorption, low birefringence). Moreover the impact of potential new beam geometries on the OMC design should also be studied in preparation of Einstein Telescope.

In parallel to the evolution of the OMC design, a constant effort will be made throughout these years to improve the precision of the alignment and mode matching tuning.

A new preamplifier board will be developed in 2020 for the high quantum efficiency photodiodes involved in the readout of the beam carrying the imprint of gravitational wave signals. The goal of this development is to bring the level of electronic noise at least a factor 10 below the shot noise, in order to keep the equivalent losses lower than 1%. These new boards will be installed on Advanced Virgo+ in 2021.

Depending on the evolution of the dark fringe power, further adaptations will be made to the photodiodes front-end electronics in the following years. In order to improve the flexibility of the photodiodes electronics during the commissioning phases of gravitational wave detectors, the possibility to have a low noise front-end electronics which can easily be adjusted to different incident powers will be studied.

The choice of the photodiodes technology will also be revised in view of Einstein Telescope, in particular for the adaptation to new laser wavelengths.

1. **Impact *(1/2 page max.) (optionnel)***

*Décrire les retombées envisageables par le développement pour des applications sociétales.*

*Le cas échéant, préciser les partenariats industriels envisageables.*

1. **Références**

[1] R. Bonnand, M. Ducrot, R. Gouaty, F. Marion, A. Masserot, B. Mours, E. Pacaud, L. Rolland and M. Was, Upper−limit on the Advanced Virgo output mode cleaner cavity length noise, Classical and Quantum Gravity, 2017, 34, 17