Contribution aux exercices de prospective nationale 2020-2030

Détecteurs et instrumentation associée

IMPROVING THE QUANTUM LIMIT IN GRAVITATIONAL WAVE DETECTORS

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1. Informations générales

Titre : Squeezing technics in gravitational wave detectors

Acronyme : *(optionnel)*

Résumé *(max. 600 caractères espaces compris)*

Quantum noise dominates present gravitational wave interferometers across a large fraction of their target sensitivity bandwidth. Therefore, a significant sensitivity enhancement could be achieved by reducing the quantum noise contribution. Different techniques for reducing quantum noise with squeezed vacuum state injection are under development in IN2P3 laboratories in collaboration with INP and INSIS laboratories.

Préciser le domaine technologique *(plusieurs choix possibles)*

- Optics
- Quantum mechanics

Préciser la motivation principale de recherche visée par la contribution :

- R&D Détection d'ondes gravitationnelles

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

Quantum noise arises from vacuum quadrature fluctuations entering into the interferometer dark port [1]. In a Michelson interferometer each of the two vacuum quadrature contributes exclusively to shot or radiation pressure noise. Therefore, the ratio between the vacuum quadrature variances (the product is fixed by the uncertainty principle) determines the relative weighting of shot and radiation noise contributions in the total quantum noise. Under normal conditions, the variances of the two vacuum quadratures are equal. However, non-linear processes can be used to produce a squeezed vacuum state characterized by an unbalanced quadrature uncertainty. Squeezed states are represented in quadrature space by an uncertainty ellipse, whose magnitude and phase is encapsulated by the ellipse axis ratio and rotation angle. The standard interferometer quantum noise can be reduced by injecting into the dark port a squeezed vacuum field with a suitable choice of the squeezing ellipse angle. In practice the quadrature variances ratio is tuned to reduce the dominant noise component at the expense of the other, until a minimum (optimum) of the total noise is reached. Since shot noise and radiation pressure noise have a different dependence on frequency, the optimal angle of the squeezing ellipse also depends on frequency. In current detectors, Frequency Independent Squeezed (FIS) vacuum states are injected in the dark port to reduce the shot noise contribution, which dominates the high frequency sensitivity at the expense of an increase of the Quantum Radiation Pressure (QRP) noise at low frequencies. This technique is clearly suboptimal because the improvement in high frequency sensitivity is accompanied by a possible deterioration in the low frequency region. A Frequency Dependent Squeezed (FDS) source is thus required to produce a broad-band quantum noise reduction.

An FDS field can be produced through the mature technique of non-linear optical effects using optical parametric oscillator (OPO) associated with a filter cavity, or with a newly developing technique using an optical parametric amplifier (OPA) and Einstein–Podolsky–Rosen (EPR) entanglement.

Different aspects will need to be studied related to this important improvement:

- work on in-vacuum squeezing source to reduce optical losses in the system,
- R&D on reducing the optical losses working on coatings or optical defects controls
- new R&D on the EPR entanglement technique

The different groups of IN2P3 currently involved in the Virgo experiment are working on theses techniques to improve the sensitivity of the Advanced Virgo detector but also in preparation of the next generation of ground-based instruments like Einstein Telescope (see contributions in GT04). This work can only be done with strong contributions with the INP and INSIS Virgo groups.

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

In-vacuum squeezed source: We are presently working on a setup called Exsqueez (financed by ANR) where we are testing a new scheme for in-vacuum squeezed to obtain one of the best squeezed sources in the world. A first test will be done with a micro-resonator and then we will move the system to test frequency dependent squeezing by using a 50 m long cavity installed at LAL. This program is done in collaboration between LKB, LAL, IP2I and LAPP. A second step is under preparation (International ANR Qfilter) to allow a better tuning of the frequency rotation by adding a coupled cavity to the first one. This type of system could be used in future generation of detectors. It involved the LKB, LAL and IP2I. Such development will be done in the next 5 years. An adding cost is estimated around 100 keuros for equipment and maintenance of the present setup. Having one thesis and one postdoc is important to cover the need in manpower on the planned studies.

Defect corrections: Defect in the different optics used can introduce losses on the optical path of the squeezed beam. A possible system to correct dynamically such defect is to use thermally deformable mirrors without introducing actuation noise which could spoil the squeezed beams. A prototype of such system is under test at LAL with 3 mirrors equipped with an array of resistors and a short (~cm) cavity to measure the defects and test the feedback control.

Very low loss optics: the quality of the squeezed light is easily degraded by optical losses. In collaboration with LMA, we aim to develop a new generation of very low loss optics. In particular, polarising beamsplitters which separate the light between the 2 polarisations s and p are a known source of loss, of the order of percent. We propose to investigate and test new coating design to guarantee losses 10 times smaller. Faraday isolator bought off the shelves could also be improved by better coating and choice of the crystal materials.

EPR entanglement: This method promises to achieve a frequency-dependent optimization of the injected squeezed light fields without the need for an external filter cavity. EPR-squeezing offers an attractive solution by harnessing the quantum correlations generated between a pair of EPR entangled beams and effectively exploiting the interferometer itself as a filter cavity, thereby achieving a similar response with minimal additional optical components and the relative costs for infrastructure. A setup is under construction on the Virgo site with a collaboration between INFN groups and APC.