EPR experiment for a broadband quantum noise reduction in gravitational wave detectors

Valeria Sequino[1], Matteo Barsuglia[2], Mateusz Bawaj[3], Marco Bazzan[4,5],
Giacomo Ciani[4,5], Livia Conti[5], Beatrice D'Angelo[1,6], Martina De Laurentis[7,8],
Sibilla Di Pace[9,10], Viviana Fafone[11,12,13], Barbara Garaventa[1,6], Alberto Gennai[14],
Laura Giacoppo[9,10], Jan Harms [13], Imran Khan[12,13], Luca Naticchioni [10],
Catherine Nguyen[2], Diego Passuello[14], Alessio Rocchi[12], Fiodor Sorrentino[1],
Marco Vardaro[15,16], Jean-Pierre Zendri[5]

[1] INFN sez. di Genova, via Dodecaneso 33, 16146 Genova, Italy
[2] APC, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris
[3] INFN, Sezione di Perugia, I-06123 Perugia, Italy
[4] Università di Padova, Dipartimento di Fisica, I-35131 Padova, Italy
[5] INFN, Sezione di Padova, I-35131 Padova, Italy
[6] Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
[7] Università di Napoli Federico II, Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy
[8] INFN, Sezione di Napoli, Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy
[9] Università di Roma La Sapienza, I-00185 Roma, Italy
[10] INFN, Sezione di Roma, I-00185 Roma, Italy
[11] Università di Roma Tor Vergata, I-00133 Roma, Italy
[12] INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
[13] Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy
[14] INFN, Sezione di Pisa, I-56127 Pisa, Italy
[15] Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
[16] Institute for High-Energy Physics, University of Amsterdam, Amsterdam, The Netherlands

valeria.sequino@na.infn.it

December 15, 2019

Abstract

Squeezed states of light contribute to the reduction of quantum noise in gravitational-wave interferometers. This result, predicted by Caves in 1981, has been demonstrated by the main gravitational-wave detectors. The injection of phase-squeezed light only decreases quantum shot noise fluctuations, improving the detector sensitivity in high-frequency band; the corresponding anti-squeezing, indeed, induces radiation pressure noise, increasing quantum noise in low-frequency band. This becomes important for near detector generation, where current low frequency noises, that cover the radiation pressure noise, will be reduced. To face this problem, the use of frequency dependent squeezing, obtained using a long external filter cavity, is planned. An alternative method, based on EPR experiment, can be used for the same purpose. It has the advantage to avoid further complex infrastructures required for the filter cavity. We propose a table-top experiment to test the broadband quantum noise reduction that can be obtained injecting entangled beams through the interferometer dark port. The conceptual design and the possible implementation in a small-scale suspended interferometer will be presented.

DOI: 10.5281/zenodo.3554320

Introduction

Vacuum fluctuations entering the dark port of an interferometric Gravitational Wave (GW) detector are the origin of the Quantum Noise (QN). The high-frequency component of QN is Shot Noise (SHN), while the low-frequency one is Radiation Pressure Noise (RPN). The sensitivity of the present detectors is only affected by the first, the RPN being covered by technical noises. SHN reduction, by injecting Frequency Independent Squeezing (FIS) from the dark port of the interferometer, has been already demonstrated in GEO, LIGO and, recently, also in Advanced Virgo [1, 2, 3]. In the near future, once low-frequency technical noises are reduced and the laser power is increased, RPN will limit the detector sensitivity, then a broadband QN reduction will be needed. Since RPN noise is related to the vacuum amplitude fluctuations, two different squeezing angles are necessary for low and high frequencies.

Squeezed vacuum, produced by a degenerate Optical Parametric Oscillator (OPO), can be kept in a fixed squeezed quadrature by controlling the squeezing angle. In particular, in order to reduce SHN, phase-squeezed quadrature is needed. The squeezing process, obtained in this way does not depend on the observation frequency, for this reason it is referred to as Frequency Independent Squeezing (FIS). The injection of frequency independent squeezed vacuum in an external Filter Cavity (FC), as we can see in the following, makes the squeezing angle dependent on observation frequency and a Frequency Dependent Squeezing (FDS) will be obtained.

The required squeezing angle rotation must occur around the frequency of the interferometer pole (i.e. around 100 Hz). The additional requirement to limit intra-cavity losses to a few percent implies that the FC must be hundreds meters long. Injecting Einsten-Podolsky-Rosen (EPR) entangled vacuum fields into the interferometer can be a valid alternative to the use of a FC [4]. It will allow to obtain the frequency-dependent rotation angle with a more compact system, avoiding the expensive infrastructure needed for the Filter Cavity, including all the related control systems and the interface optics between the filter cavity and the interferometer. A table-top demonstration of the squeezing angle rotation using EPR has been already obtained [5, 6]. The encouraging results are a good starting point towards the optimization of this technique for GW detectors. The frequency-dependent squeezing produced with the table-top experiment we planned to build at the Advanced Virgo site, will be used to test the radiation pressure noise suppression in a small-scale interferometer with suspended test masses [7].

Need for a Frequency-Dependent Squeezing in GW detectors

Quantum noise reduction using squeezed state of light was mathematically demonstrated in 1981 [8]. The challenge for GW detection was to have a quantum noise reduction in the audio-band (from 10 Hz to 10 kHz) that is the band of interest for interferometric gravitational-wave detectors. This result was achieved in 2007 by the quantum optics group of the Albert Einstein Institute in Hannover [9]. Currently, the main GW detectors experienced a shot noise reduction using squeezed vacuum states, with a consequent improvement of their sensitivity [1, 2, 3].

In the near future, technical noises that, at present, cover radiation pressure noise will be reduced, hence low-frequency quantum noise reduction will be also needed. Quantum noise will then dominate the target Advanced Virgo sensitivity above 30 Hz.

To reach this target, FDS is needed. The squeezing angle must be rotated in order to have amplitude squeezing below the cross-over frequency where the interferometer passes from being RPN limited to being SHN limited.

In a double-recycled interferometer [10], where power recycling mirror and signal recycling mirror are installed, the cross-over frequency depends on interferometer parameters and it is given by

$$\Omega_{\mathrm{SQL}} = \left(\frac{t_{\mathrm{sr}}}{1+r_{\mathrm{sr}}}\right)\frac{8}{c}\sqrt{\frac{P_{\mathrm{arm}}\omega_0}{mT_{\mathrm{arm}}}} \tag{1}$$

where t_{sr} and r_{sr} are, respectively, the amplitude transmittivity and reflectivity of the signal recycling mirror, P_{arm} the power circulating in the arm cavities, m the mirror mass, T_{arm} the transmittivity of the input mirror of the arm cavity, ω_0 the angular frequency of the laser field and c is the speed of light [11].

A proposed solution is to produce FDS by rotating a squeezing angle rotation of a phase-squeezed beam by using an external cavity by means of its frequency dispersion in reflection. Theoretical studies about this can be found in [11]. The first experimental demonstration has been obtained by Chelkowski et al. [12] in 2005 using a cavity 0.5 m long with a squeezing angle rotation in the MHz region. Ten years later, in 2015, the first rotation in the kHz region has been obtained using a cavity 2 m long. In order to obtain a squeezing angle rotation at the frequencies of interest for GW detectors, the ratio between the round trip losses and the cavity length must be optimized, hence the cavity must be hundred of meters long.

At the National Astronomical Observatory of Japan (NAOJ), using a FC 300 m long, a first rotation angle below 100 Hz has been demonstrated, obtaining a FDS vacuum source able to reduce quantum noise in the whole GW detection band [13]. This long cavity has been realized using the infrastructure of the former TAMA detector [14]. LIGO also planned to use this technique, combining it with an in-vacuum squeezed light source, to achieve the squeezing ellipse rotation at 50 Hz. Finally Advanced Virgo planned to join the fourth observation run O4 with FDS implemented with a target of improving the interferometer high frequency sensitivity by a factor of 7 dB to 8 dB without degrading the low frequency region sensitivity where, quantum noise, due to RPN, will instead dominate. Considering that the interferometer will work in a double-recycled configuration, one FC will be used. In particular, this will have a linear geometry in order to minimize possible sources of scattering and losses, due to the minimum number of reflection surfaces [15].

Filter Cavity (FC) working principle

Vacuum fluctuations, entering the interferometer output port, experience an opto-mechanical coupling that induces amplitude and phase correlations. The interferometer transfer matrix depends on the detection frequency Ω [11]:

$$T_{\mathrm{ITF}} = \begin{bmatrix} 1 & 0 \\ -K(\Omega) & 1 \end{bmatrix} \tag{2}$$

with

$$K(\Omega) = \left(\frac{\Omega_{\mathrm{SQL}}}{\Omega}\right)^2 \frac{\gamma_{\mathrm{ITF}}^2}{\Omega^2+\gamma_{\mathrm{ITF}}^2}. \tag{3}$$

where γ_{ITF} is the interferometer bandwidth. The rotation induced by the interferometer is $\Theta_{\mathrm{ITF}} = \arctan(K(\Omega))$. Being $\Omega \ll \gamma_{\mathrm{ITF}}$, it becomes

$$\Theta_{\mathrm{ITF}} = \arctan\left(\frac{\Omega_{\mathrm{SQL}}}{\Omega}\right)^2. \tag{4}$$

Considering that the light, circulating in a detuned filter cavity experiences the following angle rotation

$$\theta_{\mathrm{fc}}(\Omega) = \arctan\left(\frac{2\gamma_{\mathrm{fc}}\Delta\omega_{\mathrm{fc}}}{\gamma_{\mathrm{fc}}^2 - \Delta\omega_{\mathrm{fc}}^2 + \Omega^2}\right) \tag{5}$$

where γ_{fc} is the filter cavity linewidth and $\Delta\omega_{\mathrm{fc}}$ is the filter cavity detuning, in order to compensate the rotation induced by the interferometer the cavity parameter must be chosen such that

$$\Delta\omega_{\mathrm{fc}} = \gamma_{\mathrm{fc}} = \frac{\Omega_{\mathrm{SQL}}}{\sqrt{2}}. \tag{6}$$

Frequency-Dependent Squeezing via EPR entanglement

In [4], a solution that allow to avoid to setting up an additional low-loss and long filter cavity has been proposed. This method consists into the injection of EPR entangled signal and idler beams, where the first is resonant inside the interferometer while the idler is slightly detuned and experiences the interferometer as it was a filter cavity. The measurement of frequency-dependent rotation acquired by the idler, conditionally squeezes the signal in the same frequency-dependent way.

Being ω_0 the interferometer carrier frequency, the OPO pump beam must be detuned by a frequency shift Δ with respect to the second harmonic frequency $2\omega_0$; the pump beam frequency will be then:

$$\omega_{\mathrm{p}} = 2\omega_0 + \Delta \tag{7}$$

where Δ is of the order of few MHz. This beam frequency shift will be achieved by phase-locking an external laser to the interferometer main laser, in order to keep this frequency difference constant. The signal will have the same frequency of the interferometer carrier frequency $\omega_{\mathrm{s}} = \omega_0$, while the idler will have a frequency $\omega_{\mathrm{i}} = \omega_0 + \Delta$, due to the energy conservation law (see figure 1). Signal and idler beams are correlated being their upper and lower sidebands correlated, as we can see in figure 2. These two collinear beams will enter the interferometer and will recombine at the output port; then, they will arrive to the interferometer output mode-cleaner cavities that will separate and filter them. Each beam will beat with a local oscillator (LO) at a frequency ω_0 and $\omega_0 + \Delta$, respectively. These LO beams will be provided by two other external lasers, phase-locked between each other. In order to obtain practical benefits from the signal conditional squeezing, a Wiener filter must be applied to the photocurrent of the idler and it must be subtracted from the signal photocurrent. In this way, a broadband quantum noise reduction of the interferometer will be obtained.

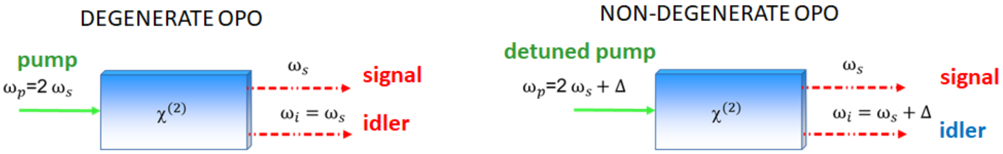

Figure 1: In standard squeezers for GW detectors, OPO is used in degenerate configuration, where signal and idler have the same frequency. For the EPR squeezer, we need squeezed beams with different frequencies, where one of them must have the same frequency of the GW interferometer carrier field.

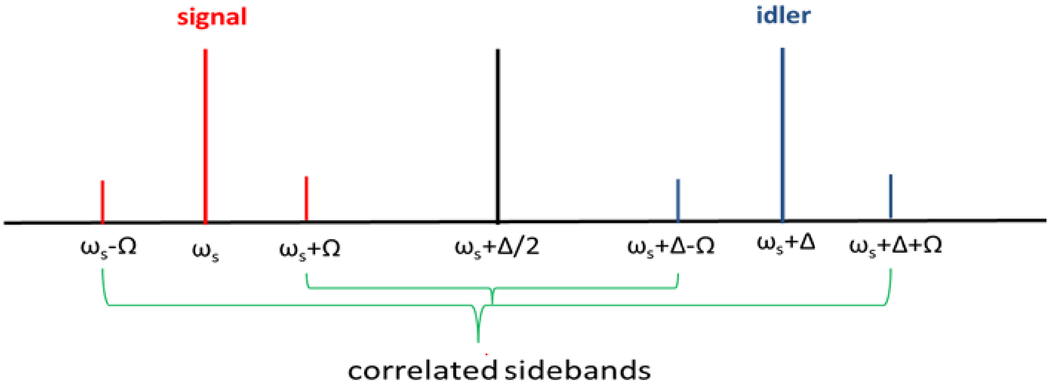

Figure 2: This is a representation of the upper and lower sidebands for signal and idler beams. In the center, there is the frequency whose second harmonic beam, at a frequency $2\omega_0 + \Delta$, is used as pump beam for the OPO. Upper and lower sidebands of each beam are respectively correlated to the lower and upper sideband of the other beam, the sum of their frequency is indeed equal to the OPO pump beam frequency.

Proposal for a table-top demonstrator

In this paper, we want to report the state of the art of the table-top experiment, already proposed in [16], in which a test cavity is planned to be used instead of the interferometer. The first step will be the production of the two entangled beams and their injection in this cavity, that will be suitably detuned for the idler beam. The two beams, reflected back from the test cavity, will be separate and separately sent to a homodyne detector where they will beat with LO beams at the same frequencies. The homodyne measurement of the idler will conditionally squeeze the signal beam, as we mentioned before.

A preliminary study on the feasibility of this experiment and the its optical design has been performed; most of the components we will use have been already tested for a long time, being part of a squeezing facility, located at the Advanced Virgo site, used to test a fully automated squeezed vacuum source. The control software, based on Finite State Machine, tested on this facility gave good results and it is ready to be used for the planned EPR table-top experiment [17].

As it is shown in figure 3, three lasers must be used. One of these will be our reference and its frequency must be equal to signal beam one. Another laser, phase locked to this, with a frequency shift of $\Delta/2$, will pump a second harmonic generator (SHG) cavity that will provide the pump beam for our OPO. This pump beam will have a frequency of $2\omega_0 + \Delta$. The two entangled beams, at ω_0 and $\omega_0 + \Delta$ will be our signal and idler beam, respectively. They will be reflected back by this cavity and will be separate using an etalon, designed to transmit the signal and reflect back the idler beam. Being the chosen frequency shift between these two beams, equal to the Free Spectral Range (FSR) of the OPO cavity, the FSR of the etalon must be double with respect to that of the OPO. Etalon length will be controlled by acting on the temperature; in order to ensure thermal stability, a suitable mechanical holder has been designed and manifactured at the AstroParticule & Cosmology (APC) laboratory in Paris (France), where some tests on etalon have been performed. These tests show that the thermal control meets the stability requirements (±0.03 °C). Once separated, each beam will reach an homodyne detector where they will beat with a LO beam, at the same frequency. The local oscillators, for signal and idler beams, will be provided by two different lasers.

All the auxiliary beams, including the beam used to implement the *coherent control technique* [9], in the following referred to as "coherent control beam" (CCB), will be provided by frequency shifting the laser beams by means of acousto-optic modulators (AOM) in double-pass configuration. Tests on the AOM have been performed in the Quantum Optics laboratory located in Genova (Italy) [18]. As we can see in figure 3, for each coherent control beam, we planned to use two AOMs, the reason is that, since the CCB must experience the nonlinearity of the OPO, that has a cavity pole equal to 25 MHz, we need a frequency shift of few MHz, that the commercial AOM are not able to provide. The idea is to use them in cascade in order to subtract the frequency shifts.

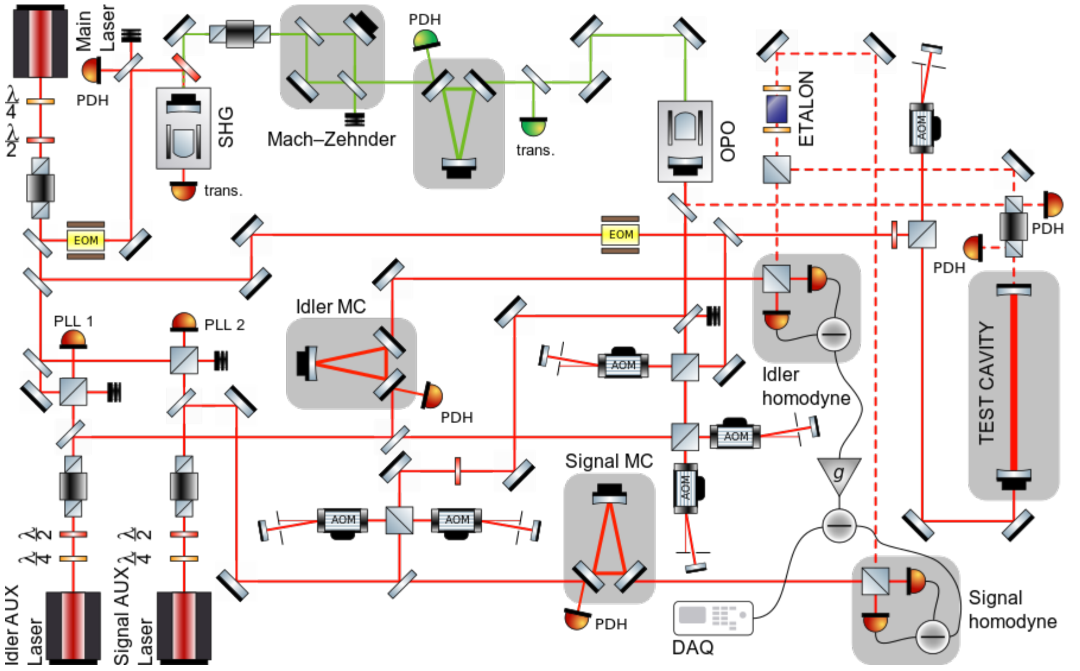

Figure 3: Conceptual scheme for the proposed EPR table-top experiment. The first laser is doubled in frequency by a Second Harmonic Generator (SHG). This beam, after being power-stabilized by a Mach Zehnder interferometer and mode-cleaned by a triangular cavity, is injected inside a degenerate OPO that produces the two entangled beams. This two beams will be both injected in a test cavity, the reflected squeezed beams will be separated and their squeezing level will be measured using the homodyne detection technique, using two local oscillators beams provided by the other two lasers. Auxiliary beams for length and phase control will be frequency-shifted using acousto-optic modulators.

Conclusions

We have proposed a table-top experiment to test the conditional squeezing provided by a couple of EPR-entangled beams. This two beams will be injected in a test cavity that will mimic an interferometer. The second step will be to test the effect of the obtained frequency-dependent squeezing by injecting the squeezed beams in a small-scale interferometer with suspended test masses that is under construction at the University La Sapienza in Rome (Italy) [7].

References

[1] J. Abadie, B. Abbott, R. Abbott, T. Abbott, M. Abernathy, C. Adams, R. Adhikari, C. Affeldt, B. Allen, G. Allen, *et al.*, “A gravitational wave observatory operating beyond the quantum shot-noise limit,” *Nature Physics*, vol. 7, no. 12, p. 962, 2011.

[2] F. Acernese, M. Agathos, L. Aiello, A. Allocca, A. Amato, S. Ansoldi, S. Antier, M. Arène, N. Arnaud, S. Ascenzi, *et al.*, “Increasing the astrophysical reach of the advanced virgo detector via the application of squeezed vacuum states of light,” *Physical Review Letters*, vol. 123, no. 23, p. 231108, 2019.

[3] M. Tse, H. Yu, N. Kijbunchoo, A. Fernandez-Galiana, P. Dupej, L. Barsotti, C. Blair, D. Brown, S. Dwyer, A. Effler, *et al.*, “Quantum-enhanced advanced ligo detectors in the era of gravitational-wave astronomy,” *Physical Review Letters*, vol. 123, no. 23, p. 231107, 2019.

[4] Y. Ma, H. Miao, B. H. Pang, M. Evans, C. Zhao, J. Harms, R. Schnabel, and Y. Chen, “Proposal for gravitational-wave detection beyond the standard quantum limit through epr entanglement,” *Nature Physics*, vol. 13, no. 8, p. 776, 2017.

[5] W. Li, Y. Jin, X. Yu, and J. Zhang, “Enhanced detection of a low-frequency signal by using broad squeezed light and a bichromatic local oscillator,” *Physical Review A*, vol. 96, no. 2, p. 023808, 2017.

[6] J. Gniesmer, M. Korobko, S. Steinlecher, and R. Schnabel, “Frequency-dependent squeezed states for gravitational-wave detection through epr entanglement,” in *Quantum Information and Measurement*, pp. S2B–4, Optical Society of America, 2019.

[7] S. Di Pace *et al.*, *Small scale Suspended Interferometer for Ponderomotive Squeezing (SIPS) as test bench for EPR squeezer integration in Advanced Virgo.* Available at `http://dx.doi.org/10.5281/zenodo.3569196`, GRASS 2019 conference proceeding.

[8] C. M. Caves, “Quantum-mechanical noise in an interferometer,” *Physical Review D*, vol. 23, no. 8, p. 1693, 1981.

[9] H. Vahlbruch, S. Chelkowski, B. Hage, A. Franzen, K. Danzmann, and R. Schnabel, “Coherent control of vacuum squeezing in the gravitational-wave detection band,” *Physical review letters*, vol. 97, no. 1, p. 011101, 2006.

[10] K. Strain and B. Meers, “Experimental demonstration of dual recycling for interferometric gravitational-wave detectors,” *Physical review letters*, vol. 66, no. 11, p. 1391, 1991.

[11] P. Kwee, J. Miller, T. Isogai, L. Barsotti, and M. Evans, “Decoherence and degradation of squeezed states in quantum filter cavities,” *Physical Review D*, vol. 90, no. 6, p. 062006, 2014.

[12] S. Chelkowski, H. Vahlbruch, B. Hage, A. Franzen, N. Lastzka, K. Danzmann, and R. Schnabel, “Experimental characterization of frequency-dependent squeezed light,” *Physical Review A*, vol. 71, no. 1, p. 013806, 2005.

[13] Y. Zhao, N. Aritomi, E. Capocasa, M. Leonardi, M. Eisenmann, Y. Guo, E. Polini, A. Tomura, K. Arai, Y. Aso, *et al.*, “A frequency-dependent squeezed vacuum source for broadband quantum noise reduction in advanced gravitational-wave detectors,” *arXiv preprint arXiv:2003.10672*, 2020.

[14] E. Capocasa, M. Barsuglia, J. Degallaix, L. Pinard, N. Straniero, R. Schnabel, K. Somiya, Y. Aso, D. Tatsumi, and R. Flaminio, “Estimation of losses in a 300 m filter cavity and quantum noise reduction in the kagra gravitational-wave detector,” *Physical Review D*, vol. 93, no. 8, p. 082004, 2016.

[15] M. Evans, L. Barsotti, P. Kwee, J. Harms, and H. Miao, “Realistic filter cavities for advanced gravitational wave detectors,” *Physical Review D*, vol. 88, no. 2, p. 022002, 2013.

[16] M. Bawaj, M. Barsuglia, M. Bazzan, E. Calloni, G. Ciani, L. Conti, B. D’Angelo, M. D. Laurentis, R. D. Rosa, S. D. Pace, V. Fafone, B. Garaventa, G. Gemme, A. Gennai, L. Giacoppo, J. Harms, I. Khan, E. Majorana, L. Naticchioni, C. Nguyen, D. Passuello, G. Prodi, F. Ricci, A. Rocchi, V. Sequino, F. Sorrentino, M. Vardaro, and J. Zendri, “Study and experiment on the alternative technique of frequency–dependent squeezing generation with EPR entanglement for virgo,” *Journal of Physics: Conference Series*, vol. 1468, p. 012215, feb 2020.

[17] M. Bawaj, V. Sequino, C. Nguyen, M. Vardaro, S. D. Pace, I. Khan, D. Passuello, A. Gennai, M. D. Laurentis, J.-P. Zendri, and F. Sorrentino, “Finite state machine controls for a source of optical squeezed vacuum,” *arXiv preprint arXiv:2004.00316*, 2020.

[18] B. Garaventa, “Towards an einstein-podolsky-rosen experiment for quantumnoise reduction in gravitationalwave detectors,” m.S. thesis, Università degli Studi di Genova, 2019.