frontiers | Frontiers in Quantum Science and Technology

TYPE Original Research
PUBLISHED 28 February 2024
DOI 10.3389/frqst.2024.1363409

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OPEN ACCESS

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RECEIVED 30 December 2023
ACCEPTED 12 February 2024
PUBLISHED 28 February 2024

CITATION
Giovinetti F, Altucci C, Bajardi F, Basti A, Beverini N, Capozziello S, Carelli G, Castellano S, Ciampini D, Di Somma G, Di Virgilio ADV, Fuso F, Lambiase G, Maccioni E, Marsili P, Ortolan A, Porzio A and Velotta R (2024), GINGERINO: a high sensitivity ring laser gyroscope for fundamental and quantum physics investigation.
Front. Quantum Sci. Technol. 3:1363409.
doi: 10.3389/frqst.2024.1363409

GINGERINO: a high sensitivity ring laser gyroscope for fundamental and quantum physics investigation

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Ring Laser Gyroscopes, based on the Sagnac effect, are currently the most sensitive rotation sensors. GINGERINO, a RLG installed underground, shows a proved sensitivity that enters the few frad/s regime in about 2.5 days of integration time. On one hand, this sensitivity is well below the shot−noise−level as predicted applying to GINGERINO the so called independent beam model. On the other hand, it paves the way to the use of RLG in fundamental and quantum physics research. Indeed, high sensitivity rotation measurement opens to test general relativity and alternative theory of gravity. Moreover, it make possible to study the interplay between quantum effects in the optical domain and non-inertial reference frames.

KEYWORDS
quantum optic, general relativity (GR), sagnac beat frequency, sagnac and fabry-pérot interferometers, quantum noise (QN)

1 Introduction

The Sagnac effect [Sagnac 1913b; Sagnac (1913a)] was intended by Sagnac itself to disprove the validity of Einstein Special Relativity (SR) [Pascoli (2017)] and, in particular, to prove the existence of the luminiferous aether. More than 100 years later, Sagnac gyroscopes have reached sensitivity levels high enough to test some General Relativity (GR) effect (Di Virgilio et al., 2020; Di Virgilio et al., 2021; Di Virgilio et al., 2022), like De Sitter and Lense–Thirring ones, and to set upper bounds to the validity of alternative theories of gravity [Capozziello et al. (2021)].

A Sagnac Ring Laser Gyroscope (RLG) is a ring optical cavity that includes an active laser medium volume. This is intrinsically a quantum mechanical system where two laser emissions, travelling in opposite directions, are emitted with different frequencies as they experience two optical cavities of effective different length due to the rotation of the ring. The RLG, then, is a quantum device where the measured quantity is the difference in frequency of the two counter–propagating optical waves. The latter is the so called Sagnac frequency, proportional to the rotation rate of the RLG. If the rotation is described in the GR frame it is possible to evidence the role of GR in the measured frequency. The Sagnac effect can be easily understood in term of wave-optic while a detailed description of the system would require a quantum optical approach that takes into account the presence of the gain medium and all the possible mechanisms, like back–scattering, that may couple the two beams. A complete quantum mechanical model may also enlighten the use of RLGs for investigating the interplay between rotation, and in general non–inertial reference frames, and quantum optical effects like entanglement and superposition.

The role of RLGs in Fundamental Physics Research has been established since the early days of these devices (Scully et al., 1981; Stedman 1997), while only recently the interplay between quantum effects in the optical domain and rotation has gained some interest (Restuccia et al., 2019; Toroš et al., 2020; Toroš et al., 2022; Kish and Ralph 2022; Cromb et al., 2023).

Both types of effect, GR and quantum, are tiny and require high sensitivity device.

We found, recently, that the sensitivity of GINGERINO [Di Virgilio et al. (2023)], an active RLG installed at the INFN Gran Sasso National Laboratory, shows an experimental upper limiting noise close to 2×10^{-15} rad/sec for $\sim 2 \times 10^{5}$ s of integration time. This value is surprisingly almost one order of magnitude below the value calculated following the quantum model of RLG, developed under the so called independent beams concept (Dorschner et al., 1980; Cresser et al., 1982b,Cresser et al., 1982a; Cresser 1982).

GINGERINO is a prototype RLG in view of the on-going construction of the GINGER (Gyroscopes IN General Relativity) experiment: an array of independently oriented RLGs. Based on the sensitivity observed for GINGERINO, GINGER should reach a sensitivity of 1 part in 10^{11} of the Earth rotation rate, two orders of magnitude better than the one required to measure GR effects.

In this paper we recap the so far published result in the use of RLGs in GR and beyond tests. Before presenting the last experimental results in term of GINGERINO sensitivity we briefly discuss the physical mechanisms that may give rise to theoretically unexplored correlation causing the above mentioned inconsistency. Looking at GINGERINO data, we also discuss the impact of data analysis on noise estimation.

2 Lorentz invariance and theories of gravity

Measuring the Earth rotation with high accuracy would pave the way to testing some gravitational effects predicted by GR. Prerequisite to this goal is having at disposal a rotation sensor that reaches a sensitivity better than 10^{-9} times the Earth rotation rate. As mentioned, a RLG can play this role and, actually, GINGERINO has reached this highly demanding sensitivity.

Despite its extraordinary predictive power, GR suffers from some difficulties in describing Nature at the ultraviolet (UV) and far-infrared (IR) scales. Concerning the UV (high-energy) regime, where the quantum nature of matter cannot be ignored, there is currently no known coherent and self-consistent reformulation of GR as a standard Quantum Field Theory (QFT) [Goroff and Sagnotti (1986)]. On the other hand, the formation and dynamics of cosmic structures and the evolution of the observable Universe require the addition of dark matter and dark energy, whose fundamental nature is currently unknown (Peebles and Ratra 2003; Frieman et al., 2008).

In order to overcome GR shortcomings, several alternative theories have been proposed (Stelle 1977; Capozziello and De Laurentis 2011; Clifton et al., 2012), but their ever-increasing number makes it necessary to develop very precise experiments aimed at constraining their free parameters and discarding non-viable models. This is where a RLG array, as planned for the GINGER experiment [Altucci et al. (2023)], fits in. In fact, some features of gravitational theories, including violation of Lorentz symmetry, may be detected as non-reciprocal effects experienced by counter-propagating light beams inside a ring optical cavity. In the following, we will illustrate how this is possible from a theoretical point of view.

To this end, we adopt the geometrical optics approximation on curved spacetimes (Misner et al., 1973; Santana et al., 2017), valid in both GR and generic metric-affine theories [Capozziello and De Laurentis (2011)] (i.e. theories in which gravitation is described by a Lorentzian metric and/or by a linear connection defined on a spacetime manifold). In particular, we will assume that a Sagnac interferometer consists of an appropriate set of mirrors that force two light rays to circulate on two null geodesics whose spatial projection is the same closed path $\mathcal{S}$ travelled in opposite directions, as seen from an observer at rest on $\mathcal{S}$. We also assume, for simplicity, that the spacetime is endowed with a stationary symmetric Lorentzian metric that, in the coordinates adopted, can be written in the form $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$, where the components $g_{\mu\nu}$ are independent of the time coordinate. The difference between the roundtrip (proper) time of the counter-propagating beams inside the optical cavity, as measured from the observer mentioned before, is given by Kajari et al. (2009):

$$\Delta\tau = -\frac{2}{c}\sqrt{g_{00}(q^r)}\int_{\mathcal{S}} \frac{g_{0i}}{g_{00}} ds^i \tag{1}$$

where q^i are the spatial coordinates of the point (on $\mathcal{S}$) in which the observer is located.

Restricting to the case of metric theories, adopting a proper reference system, i.e. one in which the observer is at rest in the origin of coordinates, metric components assume the following form:

$$g_{(00)} = 1 - \frac{2}{c^2} a_{(i)} x^{(i)} + O(|\mathbf{x}|^2) \tag{2}$$

$$g_{(0j)} = \frac{1}{c}\epsilon_{(jkl)} x^{(k)} \Omega^{(l)} + O(|\mathbf{x}|^2) \tag{3}$$

$$g_{(ij)} = \eta_{(ij)} + O(|\mathbf{x}|^2) \tag{4}$$

where $x^{(\mu)}$ are the coordinates in the proper reference system and $\eta_{(\mu\nu)}$ the components of the Minkowski tensor. The worldline of the observer is described by the set of equations $x^{(i)} = 0$. In Eq. (2), $a^{(i)}$ are the spatial components of the 4-acceleration of the observer, while in Eq. (3) $\Omega^{(i)}$ are the spatial components of the angular velocity 4-vector of the orthonormal tetrad carried by the observer relative to Fermi-Walker transported tetrads, i.e. relative to ideal test gyroscopes carried by the observer along its world line. Terms quadratic in the distance from the world line are proportional to the components of the Riemann tensor. Physical effects we are interested in are encoded in the spatial part of the angular velocity 4-vector, and, as we will see in a moment, they can be derived when confronting the local angular rotation rate measured by the RLG and those measured relative to distant inertial observes. We remark on the fact that, given the construction of the proper reference frame [as reported for example in Misner et al. (1973)], Eqs 2, 3 are valid for a general metric theory of gravity provided that the details of the theory (e.g. parameters of the PPN formalism) are encoded in the relations between metric components and the matter sources via $\vec{\Omega}$, for example.

For a sufficiently small planar Sagnac interferometer, Eq. 1 can be rewritten in the following form:

$$\Delta\tau = \frac{4}{c^2}\vec{\Omega}\cdot\vec{A} \tag{5}$$

where $\vec{A}$ is the area vector associated to the cavity.

The quantity given by Eq. 5 is the *Sagnac time delay*. However, the quantity measured by an actual RLG is the *Sagnac frequency*, that is the frequency difference between the counter-propagating beams, given by:

$$\omega_s = 8\pi\frac{\vec{\Omega}\cdot\vec{A}}{\lambda P} \tag{6}$$

where P is the perimeter of the cavity and λ is the (mean) wavelength of the beams. Eq. 6 can be derived from Eq. 5 taking into account resonance condition for the cavity.

Sagnac frequency is proportional to $\vec{\Omega}$, the angular velocity of the rest frame of the observer (so also of the interferometer) relative to local inertial frames. This vector provides information on both the motion of the observer in spacetime and the structure of the spacetime itself.

The components of $\vec{\Omega}$ can be read off from time-space components of the metric once they have explicitly written it in appropriate coordinates, as Eq. 3 suggests. Adopting a linear perturbation approach, it can be shown that for a Sagnac interferometer at rest on Earth's surface $\vec{\Omega}$ is given by:

$$\vec{\Omega} = \vec{\Omega}_\oplus + \vec{\Omega}_I + \vec{\Omega}_{loc} + \vec{\Omega}_{Th} + \vec{\Omega}_{dS} + \vec{\Omega}_{LT} \tag{7}$$

Here $\vec{\Omega}_\oplus$ is the Earth angular velocity (with contributions from tides and polar motion) and $\vec{\Omega}_{loc}$ provides information on local deformations. These terms are derived from geophysics and geodesy. They are usually provided by the International Earth Rotation System (IERS) through VLBI (Very Long Baseline Interferometry) technique, so they represent rotation rates relative to distant stars (asymptotic inertial frame).

The term $\vec{\Omega}_I$ is the contribution coming from spurious rotation of the device (relative to the laboratory frame) due to external perturbation.

The last three terms in Eq. 7 derive from the relativistic nature of gravitational theories and they all represent the rotation rates of ideal test gyroscopes carried by the observer (at rest in the laboratory frame) relative to the frame of distant stars. $\vec{\Omega}_{Th}$ is the *Thomas precession angular velocity* and it affects gyroscopes in non-linear accelerated motion. It can be derived from SR alone and it essentially encodes the non-group nature of Lorentz boosts in different directions. $\vec{\Omega}_{dS}$ is the *De Sitter precession* angular velocity and it is due to the coupling between the velocity of a gyroscope and the static part of the gravitational field due to the presence of a central mass. $\vec{\Omega}_{LT}$ is the *Lense-Thirring precession* term and is a manifestation of the dragging of (local) inertial frames due to spinning masses.

De Sitter and Lense-Thirring effects are known as *gravitoelectric* and *gravitomagnetic* terms, respectively, as they can be derived adopting a linear perturbation approach to Einstein field equations and solving equations of motion for a test gyroscope in analogy with those for a spinning electric charge in electromagnetic field (Thorne 1988; Ciufolini and Wheeler 1995; Mashhoon 2007). In more detail, restricting to the GR case and provided a suitable choice of coordinates and reasonable properties of the matter sources, metric components can be related to the gravitoelectric Φ and gravitomagnetic potentials $\vec{A}$. The first is the Newtonian potential in the weak field limit, while the latter has components proportional to the time-space elements of the metric g_{0i}. Given Φ and $\vec{A}$, in the same way as in electromagnetism, the so called gravitoelectromagnetic fields $\vec{E}$ and $\vec{B}$ can be defined. In terms of $\vec{E}$ and $\vec{B}$, Einstein equations are rewritten in a form very similar to Maxwell equation, so precession effects for a test gyroscope in the gravitational field are derived in exact analogy with precession terms for a spinning charge moving in the electromagnetic field. In particular, $\vec{\Omega}_{LT}$ is the analogous of the Larmor precession angular velocity, so it is proportional to $\vec{B}$, while $\vec{\Omega}_{DS}$ is due to the (gravito) magnetic field induced in the rest frame of the spinning charge moving in a static external (gravito) electric field, so it is proportional to $\vec{v}\times\vec{E}$ Thorne (1988).

Sagnac time delay has been calculated in the context of various alternative theories of gravity Capozziello et al. (2021). For instance, retaining only the lowest order corrections to GR, a generic metric theory of gravity in PPN formalism predicts the following Sagnac time delay Bosi et al. (2011):

$$\Delta\tau_{(PPN)} = \frac{4A}{c^2}\Omega_\oplus\left[\cos(\theta+\alpha) - (1+\gamma)\frac{G_N M}{c^2 R_\oplus}\sin\theta\sin\alpha - \frac{C}{4}\frac{G_N I_\oplus}{c^2 R_\oplus^3}(2\cos\theta\cos\alpha + \sin\theta\sin\alpha)\right] \tag{8}$$

where γ and $C = -\frac{1}{2}(4+4\gamma+\alpha_1)$ are parameters to be constrained. In Eq. 8, θ is the colatitude and α denotes the angle between the radial direction and the normal vector of the cavity $\hat{u}_n$, defined as $\hat{u}_n = \cos\alpha\ \hat{u}_r + \sin\alpha\ \hat{u}_\theta$. In deriving Eq. 8 we have assumed the Earth as an isolated spherical spinning body of radius $R_\oplus$ and mass $M_\oplus$ and we have discarded the contribution coming from $\vec{\Omega}_I$ and $\vec{\Omega}_{loc}$. The first term is the kinematic term given by Earth rotation, the second is the total contribution of Thomas and De Sitter precessions, the latter is the Lense-Thirring one.

GR is recovered for $\gamma = 1$, $C = -4$. In this case, it can be shown that each relativistic contribution to 8 is roughly 1 part in $10^{(9\div10)}$ of the Earth's rotation term ($\Omega_\oplus \approx 7.29\times10^{-5}\ rad/s$).

Gravitomagnetic effects generated by isolated spinning Earth have also been derived in the context of the low energy limit of a specific Horava–Lifshitz gravity model Radicella et al. (2014), $f(R)$ scalar-tensor gravity (Capozziello et al., 2015; Capozziello et al., 2021) and Standard Model Extension Moseley et al. (2019). Moreover, some authors have derived the gravitoelectric contribution generated by the Sun in the case of light scalars coupled conformally and disformally to matter Benisty et al. (2023). It is interesting to note that Horava-Lifshitz gravity and the Standard Model Extension are theories with broken local Lorentz invariance. For both theories, non-reciprocal effects entering the Sagnac frequency arise from Lorentz violating terms in the Lagrangian. So, a measure of $\vec{\Omega}$ could provide insight into the local symmetries of the spacetime.

It has been demonstrated that the expected performances of GINGER Altucci et al. (2023) will allow to test all theories listed above at a sensitivity level comparable, if not better, to present satellite tests. Moreover, the measurements are not averaged and do not require a map of Earth's gravity, since the RLG is located at a fixed latitude.

According to studies conducted on GINGERINO, GINGER will be able to measure the De Sitter and Lense-Thirring effects with a precision of 1 part in 10^4 and in 10^3 of their general relativistic values, respectively Capozziello et al. (2021). Details on how the above precision levels translate into constraints on the free parameters of the theories listed above can be found in Moseley et al., 2019; Capozziello et al., 2021; Benisty et al., 2023.

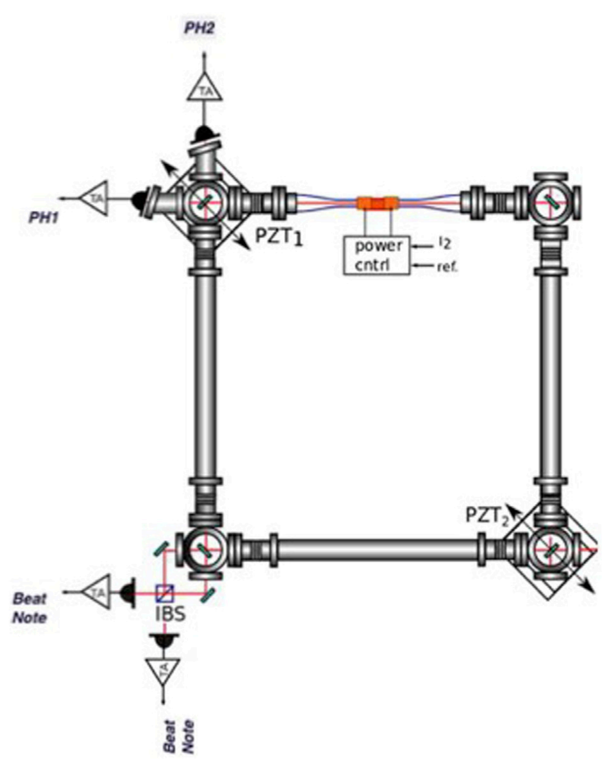

FIGURE 1
Sketch of the GINGERINO lay-out. The square optical cavity is defined by four super−mirrors contained in vacuum tanks connected by stainless pipes filled with a isotopic mixture of Helium Neon. In the middle of the top side the mixture is excited by a radio frequency signal applied to a pyrex capillary. The laser emission is around 633 nm. Although the mirrors are equipped with piezoelectric actuators (two of them shown as PZT1 and PZT2). To control the geometry presented measurement are made with the control switched off. On the bottom left mirror the transmitted light beams are interfere at a cube beam-splitter, the resulting beat−note is recorded by the photodiodes and stored to be analysed. On the top left corner the two counter−propagating output beams (called monobeams, PH1 and PH2) are recorded by photodiodes. The Sagnac frequency is reconstructed using the beat note signal. The mono−beams, are used to correct backscattering and null−shift. Reprinted from: "Carlo Altucci *et al.*, AVS Quantum Science, Vol.5, article ID 045001, 2023; licensed under a Creative Commons Attribution (CC BY) license".

3 The quantum limit to the sensitivity of a ring laser gyroscope

The sensitivity of any measurement based on the detection of photons is limited by an intrinsic limit: the shot−noise level (SNL). This limit comes from the quantum nature of light and is often referred as standard quantum limit (SQL). The inherent fluctuations in the number of photons that stochastically are converted in photo-electrons set an intrisic limit to the precision of the measurement. This limit depends on the effective description of the measurement in a quantum model. While rarely SQL becomes an effective limit to the precision one can achieve in an optical apparatus, it is well known that it limits interferometric measurements Caves (1981)) and methods exist to overcome it Aasi et al. (2013).

Generally the limit to the sensitivity, is assumed to be the one obtained for a coherent beam optical probe, i.e. with all the involved light beams in a coherent state of the quantum field. If there are more than one beam involved in the measurement, they are assumed mutually independent so that the noise is the squared sum of the SNL relative to each of the beam.

As it is now clear, a RLG relies on the interference of two beams of slightly different frequency. In the hypothesis of two independent beams, the shot noise has been calculated by Cresser et al. (1982b). There, the two beams phase noise Langevin equations are uncoupled and driven by two commuting and delta correlated Langevin forces coupled independently one to each mode. This amounts to have two independent phase (Wiener) diffusion processed inside the laser medium (Stedman, 1997, Section 4).

At the same is widely accepted that the classical amplitude of the two beams are governed by coupled equations (Wilkinson, 1987, Section 4). This happens because in the RLG dynamics there are more than one physical mechanisms that, already at the classical level, may couple the two counter−propagating modes. Two of them, passive back−scattering from cavity mirrors and scattering mediated by the gain medium, have been recently studied by A. Mecozzi from a quantum perspective Mecozzi (2023) in the frame of a full quantum model where both cavity field and laser emitters, in terms of atomic transitions, are represented by quantum operators while the optical cavity is modeled in the standard input−output formalism that gives reason of the cavity linewidth. This approach leads to a modification of the noise behavior of the Sagnac signal and, in particular, modifies the Allan variance for the frequency difference. The latter deviates from the one calculated by the uncoupled modes model in function of the coupling parameter between the two modes. This model is not easily applicable to our

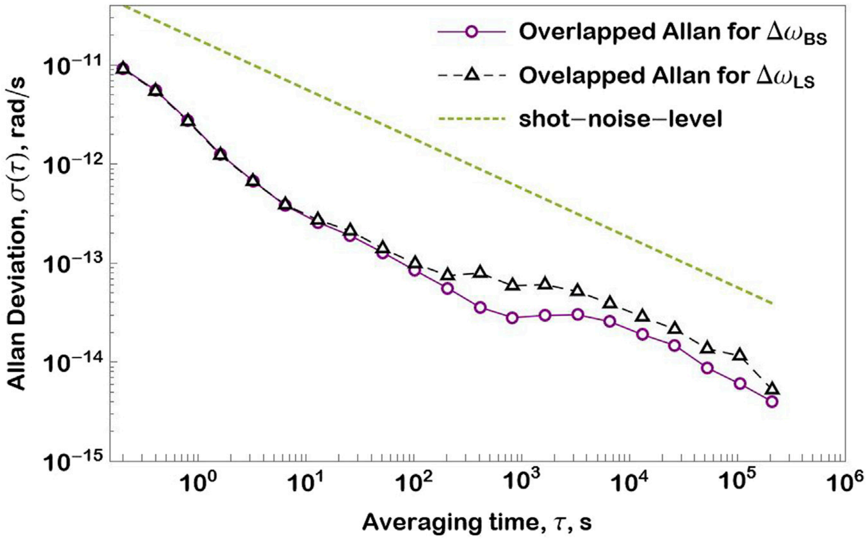

FIGURE 2
Allan Deviations obtained by STABLE32, a statistical routine freely available from http://www.stable32.com/ using $\Delta\omega_{BS}$ (Hilbert transform of data corrected only for the backscattering) and $\Delta\omega_{LS}$ (data corrected also for laser dynamics). The green-dashed line represent the expected level of shot−noise as obtained by the independent beam model.

system where the laser medium is an isotopic mixture of He-Ne whose effect is to favorite decoupling of the two counter-propagating emission. In this case to calculate the weight of the coupling requires a precise model of the gain profile and of the laser threshold values for the two isotopes.

4 The sensitivity of GINGERINO

GINGERINO is a RLG with a square optical cavity (see Figure 1). Its sensitivity limit, in the frame of the independent beam model, is expected to be 18 prad/(s Hz$^{1/2}$) [(Schreiber and Wells, 2013, Table 2)] (GINGERINO parameters p = 14.4 m, A = 12.96 m^2, $Q = 1.8 \times 10^{12}$ (corresponding to a cavity decay time of ≈600 μs), a power ouput p = 40 nW, $\omega_l = 2\pi \times 4.74 \cdot 10^{15}$ Hz). It operates rigidly attached to the ground through a granite basement directly installed on the bed rock of one of the LNGS tunnel.

Four vacuum chambers are located at the corner of a square. Each chamber hosts a super-mirrors (R = 99.999%) so to define a square high finesse optical cavity. The corner boxes are connected by pipes, vacuum tight. The whole tank is filled with an isotopic mixture of Helium Neon gas. At the midpoint middle of one of the side is the pyrex capillary provided with external electrodes, used to excite the laser medium by radio frequency. The laser emits around 632.8 nm. Mirrors are equipped with piezoelectric actuators to control the geometry, but in general the RLG can run uncontrolled. Outside one of the mirror the transmitted light beams interferes at a cube beam-splitter, the interference contains the beat−note. At another corner two photodiodes monitor single beam intensities and are used, then, for analysing the back-scattering signal that appears as a modulation of the single beam intensity. This modulation is at the Sagnac frequency, implicitly confirming that this type of coupling impacts on the Sagnac signal itself. The Sagnac frequency is, then, reconstructed using the beat note signal and the mono−beams, in order to correct the typical systematic of the laser: backscatter and null−shift.

The interference signal is acquired in a differential scheme. Two photodiodes measure the two interference signal outing the two ports of the mixing beam−splitter. This configuration allows to have two distinct Sagnac measurements that, if summed, give a SNR $\sqrt{2}$ higher than a single one, if used in a differential configuration permit detailed noise floor analysis.

Since 2020 (Di Virgilio et al., 2020; Di Virgilio et al., 2021) we had experimental evidence that the ultimate sensitivity of the GINGERINO prototype is not fully consistent with the shot−noise calculated by the above mentioned independent beams model.

4.1 Experimental noise measurement

In a recent letter Di Virgilio et al. (2023) we have firstly reported differential measurements giving a conclusive proof that the experimentally measured noise limit of the instrument is well below that shot−noise−level.

The instrument noise floor is obtained by subtracting measured frequency data obtained from the two equivalent beat notes. The optical signals are acquired at 5 kHz sampling rate and then each time series undergo to a discrete Hilbert transform. The reconstruction of the Sagnac signal proceeds by steps as described in Di Virgilio et al. (2019); Di Virgilio et al. (2021).

The differential measurement has been implemented to rule−out any unwanted noise under−estimation caused by filtering and data manipulation. Subtracting two statistically independent signals implies to cancel any common mode signature so leaving, by principle, the stochastic noise floor as the unique contribution to the noise. This amounts to evaluate the ultimate noise level of the instrument. Looking this procedure from a quantum optical perspective it allows the estimation of the quantum noise level being that classical noise, i.e. technical, environmental and anthropic noises, in the two output are correlated. In order to better understand the role of the different steps of data manipulation we have also evaluated the Allan deviation at the different point of true rotational signal identification.

In Figure 2 we report the result obtained for $\Delta\omega_{BS}$ (Hilbert transform of data corrected only for the backscattering) and $\Delta\omega_{LS}$ (data corrected also for laser dynamics). At high frequency, short times, the two perfectly overlap demonstrating that any effect of deeper data analysis is confined at low frequency. Moreover, as expected for any faithful manipulation of data, the noise level is slightly increased. The Allan Deviation, calculated with the overlapped routine, reaches the value of 4.00 ± 0.01 frad/s in 2.5 days of integration time, well below what predicted by the independent beam model.

From the quantum optical and noise analysis point of view, it makes sense to have an evaluation of the noise slope with frequency. It is well known that a slope of $-\frac{1}{2}$ corresponds to a Poissonian statistics and so represent the shot–noise while steeper slopes indicate the presence of correlation. If the steeper slope runs beneath the SNL then the system would enter the quantum metrology regime Giovannetti et al. (2006).

Applying to data plotted in Figure 2 the linear fit routine LinearFitModel of © Mathematica one gets the linear coefficient $b = -0.50 \pm 0.03$ with $R^2 = 0.944$ for ω_s and $b = -0.46 \pm 0.03$ with $R^2 = 0.937$ for ω_m. From the graph it is possible to see that this average slope is indeed made of three or may be four different intervals showing different slopes. Selecting the first six data (up to $\tau = 6.4$ s) of the ω_s set the evaluated slope became: $b = -0.95 \pm 0.03$, $R^2 = 0.996$. Adding data up to $\tau \simeq 1{,}000$ s, where the change in the slope is quite evident, gives $b = -0.70 \pm 0.03$ with $R^2 = 0.978$. We also note that the slope increases for longer times. We have $b = -0.62 \pm 0.03$ for the last four points ($\tau > 2.6 \times 10^4$), $b = -0.58 \pm 0.03$ for the last five, ($\tau > 1.3 \times 10^4$ s). This experimental findings indicates that some sort of correlation, classical and/or quantum, in the system dynamics exist. A complete and a deeper understanding of its nature cannot avoid a complete quantum model.

5 Conclusion

The experimental noise limit of GINGERINO, a square RLG operating underground at the INFN National Gran Sasso Laboratory has been measured by a dual signal scheme. The measured noise is below what has been thought so far as the SQL for a an active RLG. The theoretical expectation come from the stringent assumption of two independently generated and counter–propagating laser beams inside the ring cavity. Renouncing to this hypothesis implies including in the fully quantum system equations all possible physical mechanisms that may couple the two beams. The noise behavior of GINGERINO is a conclusive experimental proof that its noise floor is not consistent with the independent beam models. The slope of its frequency dependent Allan variance, in some frequency ranges, is not permitted by delta correlated noise sources. These two results require a complete quantum model where all the possible couplings among the two optical modes are taken into account for understanding the nature of the evident correlation. Eventually, the sensitivity reached by GINGERINO is a jumping–off point for the use of RLG for fundamental physics research including the study of optical quantum effect in non-inertial frames.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

FG: Writing–original draft, Writing–review and editing, Formal Analysis. CA: Supervision, Writing–review and editing. FBa: Formal Analysis, Writing–review and editing. AB: Writing–review and editing, Validation. NB: Conceptualization, Supervision, Validation, Writing–review and editing. SaC: Writing–review and editing, Conceptualization, Formal Analysis, Supervision, Validation. GC: Data curation, Investigation, Writing–review and editing, Project administration. SiC: Writing–review and editing, Data curation, Investigation. DC: Writing–review and editing, Supervision. GS: Investigation, Writing–review and editing, Data curation. AD: Validation, Writing–review and editing, Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing–original draft. FF: Formal Analysis, Writing–review and editing, Conceptualization, Validation. GL: Writing–review and editing, Formal Analysis. EM: Data curation, Investigation, Writing–review and editing. PM: Writing–review and editing, Data curation, Investigation. AO: Conceptualization, Formal Analysis, Supervision, Writing–review and editing. AP: Supervision, Writing–review and editing, Conceptualization, Formal Analysis, Validation, Writing–original draft. RV: Supervision, Writing–review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. INFN has funded the whole experiment.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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