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GINGER Status Report

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Abstract. The GINGER project is based on ring lasers and is under construction at the underground Gran Sasso laboratories, as part of the underground geophysical observatory of Gran Sasso (UGGS). Large frame ring lasers are top sensitivity instruments to measure angular rotation rate, in particular when attached to the Earth crust they can measure with very high precision the Earth angular velocity. This kind of measurements when the precision is of the order of 1 part in 10^9, are certainly relevant for geophysics and geodesy, for instance to measure the fast variation of the length of Day (LoD), but are also relevant for fundamental physics, since are affected by de Sitter and Lense-Thirring effects and can be used to investigate Lorentz's violations. Ring lasers ensure long-term continuous operation with record sensitivity. The limit of 1 part in 10^9 of the Earth's rotation rate has already been demonstrated, and recent sensitivity study has shown that the ring laser shot noise limit is at least a factor 10 better than expected. GINGER and its status report will be described.

Introduction

GINGER is an experiment based on an array of large frame ring laser gyroscopes, top sensitivity instruments to measure absolute angular rotation on Earth. Ring laser gyroscope (RLG) is based on a closed path interferometer, usually a square defined by 4 mirrors at the vertices of the square, and defining a high finesse optical cavity. An active medium is contained in the square ring cavity, two counter-propagating laser beams are generated. The interference of the beams transmitted by each mirror brings information on the non reciprocal effects experienced by the two counter-propagating beams. Since the two beams share the same path, the differences due to these non reciprocity effects are extremely small. However, if the optical cavity is rotating, an asymmetry is generated between the two propagation directions, producing a difference between the beams proportional to the rotational rate, a well known effect since more than 100 years, known as Sagnac effect, which largely dominates all other effects and is generally exploited in devices for inertial navigation[1, 2]. The active large frame Sagnac interferometer is by far the most sensitive instrument; prad/s sensitivity and continuous operation has been extensively demonstrated[3, 4, 5]. However, there are other non reciprocal effects related to the space time structure or to fundamental asymmetries, and so RLGs are suitable for fundamental physics investigations. The experimental set up plays a big role, since the response depends on the geometry and it is necessary to avoid spurious rotation of the apparatus induced by environmental disturbances. The first working RLGs were based on monolithic structures made of very low thermal expansion ceramic materials, and most of the small size gyroscopes are monolithic. However, for large very high performance apparatus, this choice is quite challenging in terms of cost and space, and it poses severe limitations in its use in an array. A hetero-lithic (HL) cavity is composed of different mechanical components, whose relative orientation can be modified. Therefore, rigidity and geometrical stability must be ensured by using active controls by piezoelectric actuators (PZT). Two HL prototypes have been built and extensively studied by our group: GINGERINO [6], placed in the Gran Sasso underground INFN laboratories, and GP2 [7], located in Pisa INFN laboratories. Our experimental work has indicated that GINGER can be realized using a HL structure, and that a deep underground location is particularly recommended, since it takes advantage of the natural thermal stability and of reduced environmental noise. Unattended continuous operation for months, a typical sub-nrad/s sensitivity in 1 second of measurement time, large bandwidth, fast response, in principle as fast as milliseconds, have been proven in the experiments carried out so far.

In the following the impact on fundamental physics, the RLG and GINGER will be outlined.

1 GINGER and Fundamental Physics tests

It is known that General Relativity currently constitutes the theory with the widest consensus in the scientific community for describing gravitational phenomena at all experimentally accessible scales. Still the theory is not perfectly adequate in describing nature at the ultraviolet (UV) and far-infrared (IR) scales. Alternative theories have been proposed. In general metric-affine theories are considered, i.e. theories in which gravitation is described by a (Lorentzian) metric and by a linear connection defined on a spacetime manifold. Other theories of gravity, instead, explicitly break some basic assumptions of GR, eventually inspired by other fundamental theories, as for instance Horava–Lifschitz theory and the Standard Model Extension; in both cases local Lorentz symmetry is broken. It is necessary to develop experiments aimed at constraining their free parameters and discarding non viable models. A more detailed overview (although not exhaustive) of these theories can be found from recent papers [8, 9, 10, 11, 12, 13, 14]. GINGER experiment will provide data for the direct measurement of the Lense–Thirring effect. The major differences with data coming from space experiments [15, 16][17, 18] are: GINGER does not require the the global Earth gravitational map, as the measurement is not based on the orbits reconstruction; and it is at a fixed latitude. Also violations of Lorentz symmetry can be revealed by GINGER as additional contributions to the rotation rate. GINGER is strategically positioned within this framework, as its anticipated sensitivity can be harnessed to achieve various scientific goals, for a detailed description, interested reader are invited to read our most recent papers [13, 14], and the large literature on the subject [19, 20, 21, 12, 22, 25, 26, 29, 32].

Ring Laser

Large frame RLG is based on a square optical cavity, above 3-4 m sides, and operates rigidly attached to the ground. The rigidity of the cavity plays a big role, and the first prototypes were composed of a large single piece of ultra low expansion material with mirrors optically contacted to the frame. Since the beginning of our experimental research we have developed and studied prototypes based on a modular mechanical design (HL). Fig. 1 shows the general scheme of our HL RLG prototypes with a 4 mirrors optical cavity under vacuum. In general the cavity is attached to a granite monument attached to the ground, and can be oriented at will with respect to the Earth rotation axis. So far we have successfully operated prototypes with different orientations: horizontal, vertical and inclined at the maximum signal.

An RLG senses the component of the angular velocity vector $\vec{\Omega}$ along the axis of the closed polygonal cavity, defined by the area vector. The relationship between the Sagnac frequency ω_s and the angular rotation rate Ω reads:

$$\omega_s = 4\frac{A}{\lambda L}\Omega\cos\theta \tag{1}$$

where A is the area enclosed by the optical path, L is its perimeter, λ is the wavelength of the light, and θ is the angle between the area vector $\vec{A}$ and $\vec{\Omega}$, and eq. 1 can be interpreted as the scalar product between $\vec{A}$ and $\vec{\Omega}$. In general $\vec{\Omega}$ is the sum of several different components:

$$\vec{\Omega} = \vec{\Omega}_{\oplus} + \vec{\Omega}_{loc} + \vec{\Omega}_{FP} + \vec{\Omega}_{I} \tag{2}$$

where $\vec{\Omega}_{\oplus}$ indicates the Earth rotation rates with all known contribution from tides and polar motions, $\vec{\Omega}_{FP}$ [35, 36] indicates General relativity terms of due to fundamental physics effects able to cause non reciprocity among the two counter-propagating beams, $\vec{\Omega}_{loc}$ takes account of local deformations [34], and $\vec{\Omega}_{I}$ instrumental rotation due to the fact that external perturbation causes spurious rotation of the apparatus (this term should be reduced as much as possible improving the mechanical design and by offline analysis).

GINGER and its near future plan

The main objective of the instrument is to reconstruct the total angular velocity vector $\vec{\Omega}$. The kinematic local and global contributions are derived from geophysics and geodesy, as polar motion and tides [37], and due to their very high sensitivity it is expected to measure the sub-daily component of the Length of Day (LOD). These kinematic terms are continuously monitored by the International Earth Rotation System (IERS) with very high accuracy, and so gravitational theories can be tested by comparing the independent measurements of RLGs and IERS [38, 39].

The effectiveness of GINGER for fundamental physics investigations depends on its sensitivity, which quite often is expressed as relative precision in the measurement of the Earth angular rotation rate, and 1 part in 10^9 is the target to be meaningful for fundamental physics, accordingly any sensitivity improvement will be an improvements for fundamental physics tests. At this point it is important to say that the dynamical range of the RLG signal has a huge dynamical range, since it is based on frequency reconstruction.

At present, beside our RLGs, several other high sensitivity instruments are in operation: in Germany, G [37] of the geodetic observatory of Wettzell, and ROMY, an array of four triangular rings at the geophysical observatory of Bavaria[40], ER1 at the University of Canterbury,[41] in New Zealand, and HUST-1 [42] a passive gyroscope built at Huazhong University of Science and Technology in Wuhan (China) as part of the TianQin project. Collaboration with all these groups is already active.

The GINGER project foresees the construction of 2 equal RLGs[36], square cavity with 3m side . The first one, called RLX, oriented at the maximum Sagnac frequency, with axis parallel to Earth rotational axis, will provide the absolute value of the angular velocity; the second, RLO, will be oriented outside the meridian plane by approximatelu 30 degrees. This installation will be in the tunnel between Node A and Node B at LNGS, few meters far from GINGERINO, closer to node A. GINGERINO will remain operative, and will be upgraded later on replacing the mechanical parts with the new ones, becoming RLH, the third component with the vertical area vector. The sensitivity is such that very small variations in the orientation of RLH and RLO will affect the measurement, in general with a single device it is impossible to separate the angular rotation and the effect of change of angle between the area vector and the rotation axis; RLX allows a precise determination of the orientation of the other two gyros with respect to the rotation axis [36], allowing the identification of the angular rotation.

Sensitivity is a key point. The limiting noise is determined by the shot noise of the apparatus, which is a function of the cavity losses.

GINGERINO has 3.6m side, while GINGER will be 3m, this will reduce by 20% the scale factor and the sensitivity. However the first target of 1 part il 10^9 should be feasible in any case. The first proposal was to have 5m side cavities, but the proposed location inside the tunnel is not large enough. For this reason the RLG have been scaled down to 3m side; in this way there is room to have enough space in the back of each mirror for checks and fine tuning of the cavity. Based on the experience gained with our RLG prototypes, we have developed a new HL RLG design, called GP3. It is important to remark that

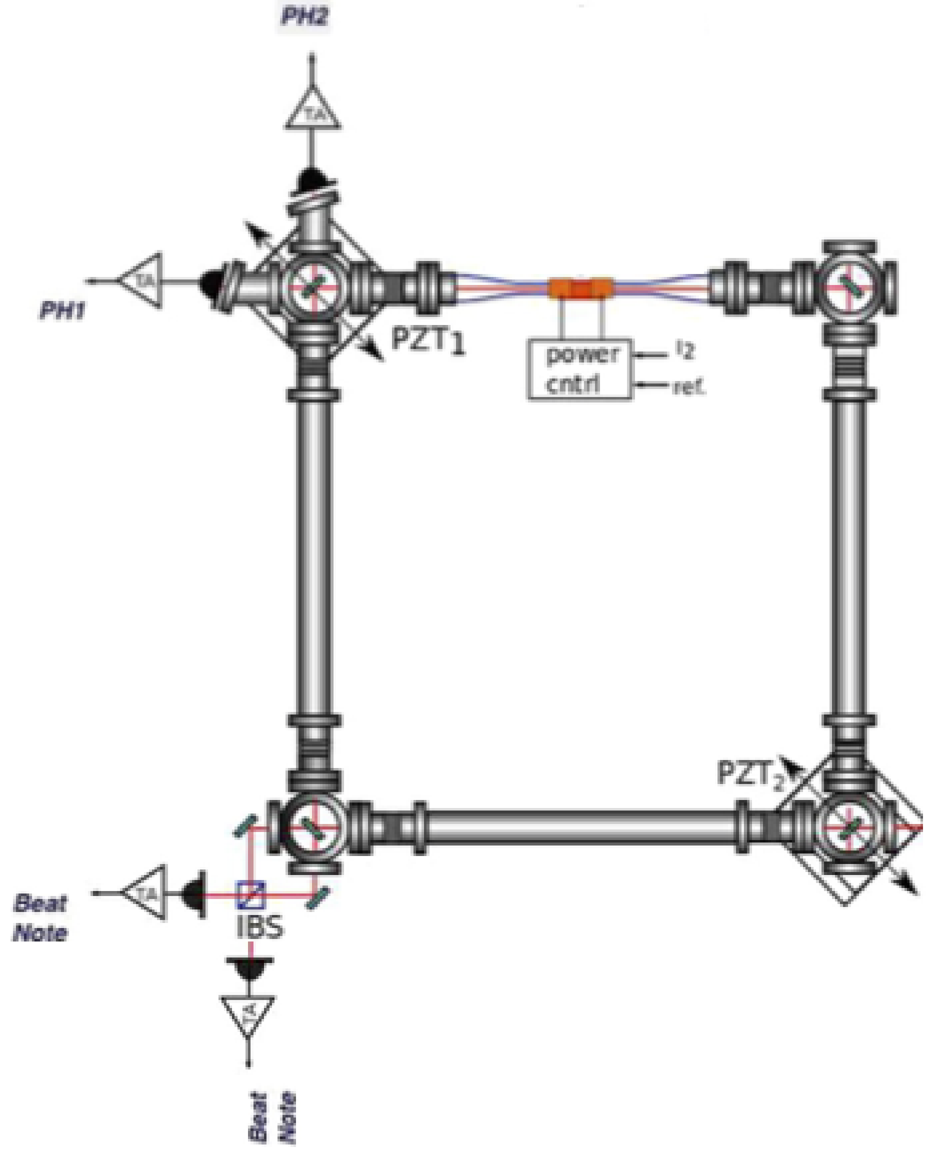

Figure 1: Schematic lay-out of our RLG prototypes. Four vacuum tank boxes are located at the corner of a square. The boxes host the four super-mirrors that are aligned in order to define a square optical cavity. The boxes are connected by pipes, vacuum tight, and is filled with a mixture of Helium Neon gases. In the middle of one of the side is located the pyrex capillary with external electrodes, used to power the laser by radio frequency excitation. The laser emission has wavelength 633nm, red lines indicate the light beams. The mirrors are equipped with piezoelectric actuators, two are shown in figure (PZT1 and PZT2). They are used to control the geometry, but in general the RLG can be operated uncontrolled. On the bottom left mirrors the transmitter light beams are over–imposed at a cube beam-splitter, the interference is the beat–note recorded by the photodiodes and stored to be analysed. On the top left corner the two output beams (called monobeams, PH1 and PH2) are recorded by photodiodes. The Sagnac frequency is 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 GP3 model is modular and the size of the cavity can be tuned changing the size of the spacers, so in principle in the future the apparatus can be rebuilt in a larger area increasing the size with the only change of the spacers. We have been able to evaluate directly the limiting noise of the GINGERINO prototype, demonstrating that the limiting noise floor is in the prad/s $\mathrm{Hz}^{-1/2}$ range (in the frequency range < 0.1 Hz), more than a factor 10 below the expected one[5].

This experimental noise level limit indicates that a realistic final sensitivity target of GINGER should be around 1 part in 10^{10} of the Earth rotation rate.

The whole experimental set up has been developed based on the experience acquired on the GINGERINO apparatus and details of the experimental layout can be found in the literature [8]. The preparatory work inside the tunnel to prepare the installation has started and the orders of the different parts are proceeding. The constructions of the apparatus is expected to start at the end of 2024, the commissioning will take 6 months and the data taking should start immediately after. Figure 2 shows the two components of GINGER (RLX and RLO) inside the tunnel between nodes A and B, of the Gran Sasso laboratory. The installation will be few meters far from the GINGERINO location. As already said, GINGER will be part of the underground seismic station of the Gran Sasso montain, composed of a large seismometer array, high sensitive gravimeter, water pressure probes an tilt-meters. This new installation in one side will provide unique information on the Gran Sasso area, which is one of the most important seismically active area in Europe, and in the other side the comparison of different apparatus will provide the validation for GINGER data analysis in the lower frequency range, allowing as well accuracy studies. GINGERINO has been working on a continuous basis and unattended for more than 6 years, and all the tools to operate remotely have been developed and already tested. All tools developed and tested with GINGERINO will be used for GINGER.The expectation is to start the GINGER construction sometime in 2025, but before installation it is necessary to prepare the infrastructure inside the tunnel, see fig. 2. At present the expectation is to have GINGER in operation between the end of 2025 and the beginning of 2026. The operations to upgrade GINGERINO in order to become the third component of GINGER, RLV, will start after the construction of the first two components. GINGERINO is based on a hetero-lithic mechanical structure, one of the first prototype of this kind, in which the optical cavity is not rigid enough; and angular rotations of instrumental origin are present (Ω_I), problem which has so far limited the performances of GINGERINO to fractions of nano-rad/s. For this reason the GINGERINO's upgrading will be necessary.

GINGER is intended as an interdisciplinary project, with significant results not only in the field of fundamental physics, but also in geodesy and in geophysics. It should give information complementary with the GNNS and VLBI networks about the Length Of the Day and the Earth polar motion. For geophysical applications, it will provide the rotational seismic information to the multi-components geophysical observatory UGGS. GINGER is an interdisciplinary project, which brings together physicists and geoiphysicists, and it co-funded by INFN and INGV.

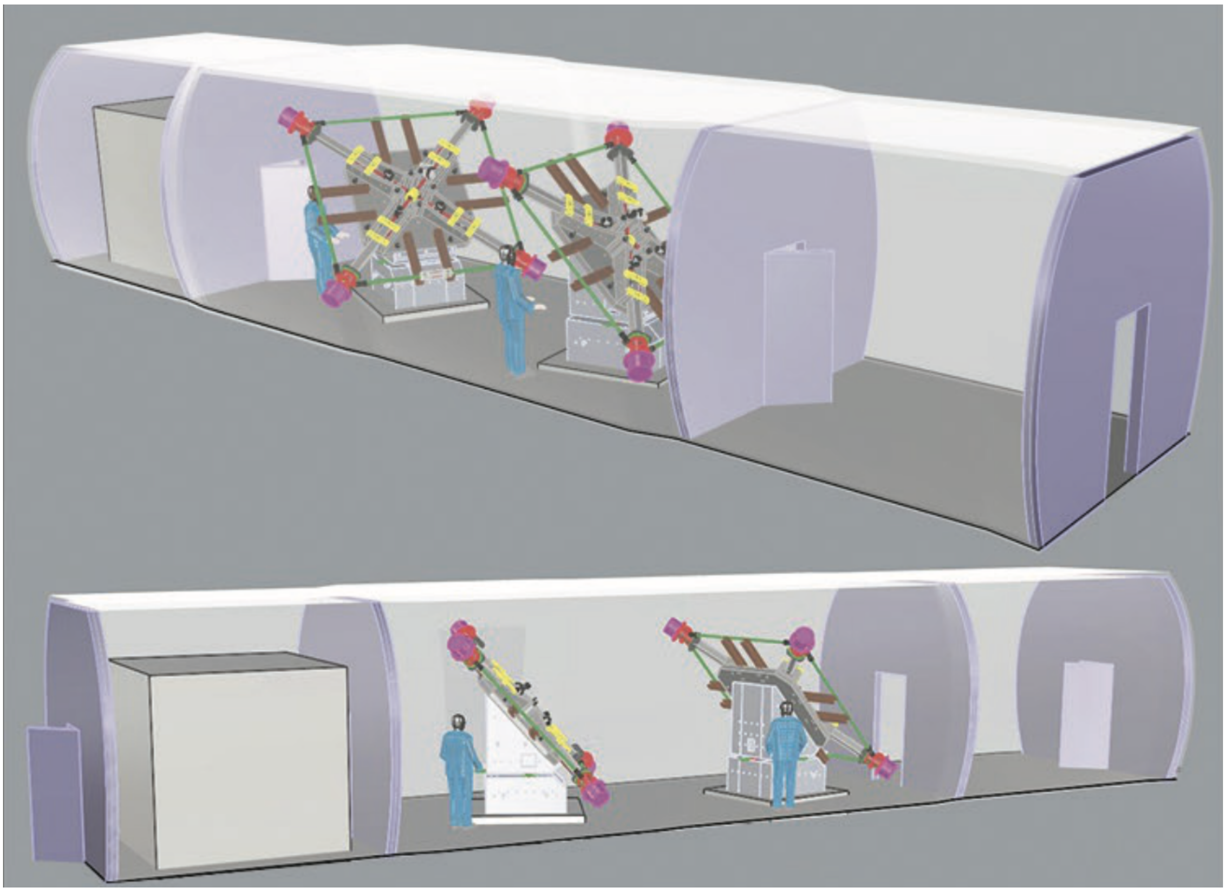

Figure 2: Two view of the GINGER apparatus, contained in the tunnel between nodes A and B, it is composed of three different rooms, the two RLGs RLX and RLO are located in the central room. The first room on the right will contain the electronics, and the box evident inside the room on the left is a clean cabinet, necessary for mirrors handling during installation The RLGs are based on the GP3 mechanical design, which is composed of different pieces; a central element in granite, spacers which can allow to change the size from 2 up to 5m side, the four elements colored in opal blue, and the mirror boxed. In the present set up the spacers are in silicon carbide and the size of the squared cavity will be 3m. The silicon carbide guarantee a very low thermal expansion and high uniformity during the expansion, in this way rotation due to deformation of the components will be minimised.

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