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The Sagnac effect: 100 years later / L'effet Sagnac : 100 ans après

A ring lasers array for fundamental physics

Un réseau de lasers en anneaux pour la physique fondamentale

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ABSTRACT

After reviewing the importance of light as a probe for testing the structure of space-time, we describe the GINGER project. GINGER will be a three-dimensional array of large-size ring-lasers able to measure the de Sitter and Lense–Thirring effects. The instrument will be located at the underground laboratory of Gran Sasso, in Italy. We describe the preliminary actions and measurements already under way and present the full road map to GINGER. The intermediate apparatuses GP2 and GINGERino are described. GINGER is expected to be fully operating in few years.

RÉSUMÉ

Après avoir passé en revue l'importance de la lumière comme sonde pour évaluer la structure de l'espace-temps, nous décrivons le projet GINGER. GINGER sera un réseau tridimensionnel de lasers en anneaux de grandes tailles capable de mesurer les effets de Sitter et Lense–Thirring. Cet instrument sera localisé dans le laboratoire souterrain du Gran Sasso, en Italie. Nous décrivons les actions préliminaires et les mesures déjà en cours, puis nous présentons la feuille de route complète de GINGER. Les équipements intermédiaires GP2 et GINGERino sont décrits. GINGER devrait être complètement opérationnel d'ici quelques années.

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1. Introduction

One of the pillars of the contemporary understanding of matter, energy and space-time is general relativity (GR). Its successes in explaining the behavior of the world around us and of the whole universe are well known as well as its so far unresolved conflict with quantum mechanics in the high-energy domain. It is however true that also in the very low-energy sector of the gravitational interaction, there are predictions of GR that have not been fully explored up to these days.

A typical example is the so-called gravito-magnetic component of the gravitational field, whose direct verification relies for the moment on only three experiments in space: Gravity Probe B (GP-B) that took data from 2004 to 2005 concluded in 2011 and the results were published in the same year [1]; the two LAGEOS satellites orbital nodes analysis, published in 2004 [2] and, with an improved modeling of the gravitational field of the Earth, in 2011 [3]; the LARES mission, under way and gathering data, launched in February 2012 [4].

GP-B verified the geodetic effect in the gravitational field of the Earth with an accuracy of 0.28% and the Lense–Thirring (LT) drag with an accuracy of 19%; the analysis of the precession of the nodes of the LAGEOS satellites verified the LT effect with the accuracy of 10%; finally LARES is working to determine the LT drag with an accuracy of a few percents (possibly 1%). Other evidence of gravito-magnetic effects may be found in the laser ranging of the orbit of the moon and in the study of the dynamics of binary systems composed of at least one compact massive object (neutron star).

Another example of a weak effect predicted by GR are gravitational waves. No direct measurement has been performed so far, but very strong indirect evidence for their existence is obtained from the observation of double star systems including a pulsar [5].

Besides pure GR effects, the observation of the universe on the widest scale provides also facts that can be consistent with GR, assuming that otherwise unseen entities exist, such as dark matter and dark energy. The former would produce the additional gravity required to explain the rotation curves of galaxies and the speeds of the components of star or galaxy clusters. The latter would be necessary to generate the push required by the accelerated expansion of the universe. These facts, partly going back to the thirties of the last century (dark matter) [6], partly quite recent (dark energy) [7], have stimulated ideas implying that GR might need some extension if not a complete change of paradigm. What matters here is that the phenomenology to look for and to analyze in search for differences from GR is in the domain of low and ultralow energies. The above remarks present reasonable motivations for working experimentally on the gravitational interaction in the weak domain looking for post-Newtonian effects and Parameterized Post Newtonian (PPN) descriptions that could evidence deviations from classical GR. Can such an investigation be conducted in a laboratory, besides relying on large-scale observations of the sky? The answer is yes and, among various possible experimental approaches, a perfect tool is represented by light. Light is indeed intrinsically relativistic and is affected in various ways by the gravitational field. In the classical domain and, as far as a theory is considered treating space-time as a continuous four-dimensional Riemannian manifold, light completely covers the manifold with a network of null geodesics. If we find the way of reading the local and global configuration of the null geodesics tissue, we can reconstruct the “shape” of space-time, i.e. the gravitational field, and see whether it fully corresponds to the GR description or maybe there is something missing.

While considering how to exploit light in order to explore the gravitational field, we should add that the advancement of the laser technologies has pushed the possibilities of such devices to unprecedented values of accuracy and precision. All in all, a laser, and in particular a ring laser, appears today as a most interesting apparatus to probe the structure of space-time at the laboratory scale.

These are the main motivations for the design and implementation of an experiment based on the use of ring lasers for fundamental physics. The main purpose is to explore the asymmetric propagation of light along a closed space path in the gravitational field of a rotating body. In a sense, the prototype of this type of experiments is the old Sagnac interferential measurement of what we can now call the *kinematic* asymmetry of the propagation of light along a closed space contour, as seen by a rotating observer in a flat space-time (no gravitational field) [8]. So far ring lasers have been built as Sagnac sensors of absolute rotations (which means with respect to the “fixed stars”) for practical purposes, as compact and sensible devices replacing mechanical gyroscopes (this is the reason why ring lasers are also called gyrolasers) for navigation or, in the case of the most refined instruments, for geodesy or even for determining the length of the day in competition with VLBI (Very Long Base Interferometry). The latter application, which is fundamental, is already in the reach of the G Ring in Wettzell [9]. The latter facility is by now on the verge of being able to detect not only the kinematical rotations of the laboratory, but also the physical effects of the gravitational field due to the rotation of the source and of the laboratory.

Our experiment, named GINGER (Gyroscopes IN GEneral Relativity), is intended to further improve the technology beyond G. The rest of the paper will describe both the theoretical framework and the final configuration of GINGER, and the steps that are under way in order to test the innovative technologies we are going to use and in order to build the final laboratory which will be located in the LNGS (Gran Sasso National Laboratories) of the Italian INFN. The ring laser appears today as a most interesting apparatus to probe the structure of space-time at the laboratory scale. At his early stage, the expected sensitivity of GINGER will not be competitive with space measurements to test PPN theories, but being the apparatus on Earth, improvements will be feasible with time.

2. Light in the gravitational field of a rotating body

Assuming that space-time can be described by a metric theory on a four-dimensional Riemannian manifold with Lorentzian signature, the central geometric object containing the essence of the gravitational field will be the line element. If the source of curvature (i.e. gravity) is a steadily and freely rotating object, the line element is given by:

$$ds^2 = g_{00}c^2\,dt^2 + g_{rr}\,dr^2 + g_{\theta\theta}r^2\,d\theta^2 + g_{\phi\phi}r^2\sin^2\theta\,d\phi^2 + 2g_{0\phi}cr\sin\theta\,d\phi\,dt \tag{1}$$

The coordinates used in (1) are spherical in space with the radial coordinate measured from the barycenter of the central mass, assumed to be in free fall, the θ angle (colatitude) measured from the rotation axis of the source and ϕ (longitude) measured from a fixed direction (with respect to the "fixed stars") in space; time t is measured by clocks located in a remote region not influenced by the gravitational field. The not fully standard notation used in (1) insures the dimensionlessness of the $g_{\mu\nu}$ functions; the speed of light c is here essentially a conversion factor transforming time into a length. The $g_{\mu\nu}$'s (the components of the metric tensor) depend on the variables r and θ only, because of the symmetry. If the central mass is indeed rotating, no global coordinate transformation exists converting the metric in (1) into the Minkowski metric.

The underlying assumptions so far are:

- the source of gravity is isolated and in steady rotation with respect to the 'fixed stars';
- the central object is rigid or at least it keeps its shape and mass distribution fixed in time, and it is axially symmetric with respect to the rotation axis;
- space-time is asymptotically flat and Minkowskian.

If we consider a real system, such as the terrestrial gravitational field, none of the above conditions, strictly speaking, is satisfied. The Earth is influenced by the other bodies in the Solar System so that its axis does not keep a fixed orientation with respect to the quasars ("fixed stars"). The gravitational perturbations induced by the surrounding bodies and the differential heating of the surface cause changes in the shape and mass distribution because of the non-rigidity of the planet. Space-time is not flat anywhere in the universe because no empty asymptotic region exists.

If we are interested in tiny relativistic effects we shall be very careful while using the simple symmetries implied in (1), because they are all imperfect.

In any case, working with light and assuming that in free space its speed is the same c for all inertial freely falling observers (which is the essence of relativity), the corresponding line element will be equal to 0, and we will be able to write the coordinated time span along the world line of a light ray as:

$$dt = \frac{-g_{0\phi}r\sin\theta\,d\phi \pm \sqrt{g_{0\phi}^2 r^2\sin^2\theta\,d\phi^2 - g_{00}(g_{rr}\,dr^2 + g_{\theta\theta}r^2\,d\theta^2 + g_{\phi\phi}r^2\sin^2\theta\,d\phi^2)}}{cg_{00}} \tag{2}$$

To ensure in any case an evolution towards the future ($dt > 0$) the + sign must be chosen.

Eq. (2) permits to evaluate the coordinated time of flight of an electromagnetic signal between two successive events in vacuo. Let us consider a closed path (in space); of course, excluding the horizon of a black hole, a closed path may be followed by light only in presence of some technical expedient (mirrors, optical fiber).

Integrating over the path, both on the right and on the left, two different results are obtained because of the off diagonal $g_{0\phi}$ component of the metric tensor. Let us use the angular velocity of the central body as a reference for the direction of rotation: the so-defined anticlockwise sense will correspond to $d\phi > 0$, the clockwise will correspond to $d\phi < 0$. Finally we see that the difference between the corotating time of flight, t_+, and the counter-rotating one, t_-, will be:

$$\delta t = t_+ - t_- = -\frac{2}{c}\oint \frac{g_{0\phi}}{g_{00}} r\sin\theta\,d\phi \tag{3}$$

If at the start and arrival point, imagined as being fixed in the chosen reference frame, there is a device sensible to (3) its proper time τ difference will be:

$$\delta\tau = -\frac{2}{c}\sqrt{g_{00}}\oint \frac{g_{0\phi}}{g_{00}} r\sin\theta\,d\phi \tag{4}$$

The $\delta\tau$ difference is the basis of the way a ring laser works. $\delta\tau$ may be measured letting the two counter-rotating beams interfere and this is the typical Sagnac technique; the way of a ring laser is however different. Since the emission of light is continuous and steady, two standing waves, associated with the two directions of rotations, are formed and co-exist in the annular cavity of the laser. The time of flight difference is converted into different frequencies of the two waves, and in turn the frequency difference gives rise to a beat note. The frequency of the beat can be read analysing the power spectrum of the signal extracted at any point of the ring. The beat frequency f_b is

$$f_b = c^2\frac{\delta\tau}{2P\lambda} = -\frac{c}{P\lambda}\sqrt{g_{00}}\oint \frac{g_{0\phi}}{g_{00}} r\sin\theta\,d\phi \tag{5}$$

where P is the length of the perimeter of the ring and λ is the wavelength of the radiation.

2.1. A laboratory on Earth

So far we have assumed an observer at rest with respect to the fixed stars, which is a quite unphysical situation. In practice, the experiment we want to perform will be located within a laboratory fixed to the solid body of the Earth. If so, we should update our choice of the coordinate system. There are various possibilities; the simplest, probably, is to still choose a global reference frame, but let its axes rotate together with the Earth. In this way, basically, the coordinates remain the same, but colatitude and longitude are terrestrial rather than celestial.

Now, from the viewpoint of the fixed stars, the paths followed by the light beams we want to use are no longer closed in space, because of the motion of the laboratory, but they still turn out to be closed in the corotating terrestrial reference frame. The general form of the line element still is like Eq. (1), but now the functions have different forms. Under the same assumptions as before we may work out the new metric elements applying first a kinematical rotation of the axes at the angular speed of the Earth Ω, then a physical Lorentz boost at the peripheral speed of the Earth in correspondence of the location of the laboratory [10].

The formal result of these two steps is a bit complicated, but for practical purposes, we may approximate the result considering that:

$$\begin{aligned} &\frac{\Omega R}{c} \sim 10^{-6} \\ &G\frac{M}{c^2 R} = \frac{\mu}{R} \sim 10^{-9} \\ &G\frac{J}{c^3 R^2} = \frac{j}{R^2} \sim 10^{-15} \end{aligned} \tag{6}$$

G is Newton's constant; M is the mass of the Earth; R is its radius at the location of the laboratory and J is the angular momentum of our planet.

The highest order to which we are interested is the lowest non-zero term containing j/R^2. Under this condition the final beat frequency f_b turns out to be:

$$f_b \simeq 2\frac{A}{\lambda P}\Omega(\hat{u}_a \cdot \hat{u}_n) + \frac{cA}{\lambda P R}\left(2\left(\frac{\Omega\mu}{c}\sin\theta - \frac{j}{R^2}\cos\theta\right)(\hat{u}_r \cdot \hat{u}_n) - \frac{j}{R^2}(\hat{u}_\theta \cdot \hat{u}_n)\sin\theta\right) \tag{7}$$

where A is the area of the ring; the $\hat{u}$'s are unit vectors in the directions, respectively, of the axis of the Earth ($_a$), the normal to the ring ($_n$), the direction of the local meridian ($_\theta$). The ratio $\frac{A}{\lambda P}$ is called the *scale factor* S of the instrument. The second term on the right of the formula is approximately 10^{-9} times the first one.

3. The GINGER project: Gyrolasers for fundamental relativity

Considering the orders of magnitude (6) and formula (7), we see that, in order to reveal general relativistic effects depending on the mass and the angular momentum of the Earth, we need a device endowed with a sensitivity at least nine orders of magnitude better than the one required for measuring the only angular velocity of the Earth, through the classical Sagnac effect. In fact, in formula (7), the first term is the classical Sagnac term, whereas the second one contains both the Lense–Thirring drag, depending on the angular momentum $\bar{J}$ (whose norm appears in the equation in its geometrized form j), and the de Sitter or geodetic term expressing the interaction of the local Newtonian force with the angular velocity of the Earth. The latter two contributions turn out to have the same order of magnitude on the surface of the planet.

Is the needed sensitivity available or attainable today? Commonly, in navigation applications, ring lasers are based on single longitudinal mode He–Ne lasers operating at a wavelength of 632.8 nm. Inertial navigation devices usually have an area $< 0.02\ \text{m}^2$ corresponding to a perimeter of 30 cm or less. The typical sensitivity of such devices is around $5 \times 10^{-7}\ \text{rad/s}/\sqrt{\text{Hz}}$ and the drift is as low as 0.0001 deg/h. This performance level is fully sufficient for navigational demands, but falls short by several orders of magnitude for most geophysical applications; even more for fundamental physics.

The Gross Ring (G) in Wettzell is a square ring, 4 m in side, mounted on an extremely rigid and thermally stable monolithic Zerodur slab, located under an artificial 35-m thick mound. The most recent performance of G, expressed in terms of measured equivalent angular velocity, has a lower boundary below 1 prad/s (picoradian/second) at 1000-s integration time [11]. This sensitivity is above the requirement for the measurement of the GR effects, but various improvements in technologies, global design and signal cleaning should fill the remaining gap.

Actually at the level of prad/s and less, many delicate problems arise, besides the ones already mentioned, concerning the stability and behavior of the laser and the mirrors. Formula (7) has been obtained under the hypothesis that the rotational speed of the Earth is a constant, but this is not the case because of the coupling of the moment of inertia of the planet with the gravitational influence of the moon and the sun, which in turn changes with the configuration of the two celestial bodies. Furthermore, the non-rigidity of the Earth appears, influencing the instantaneous moment of inertia of the planet. Even the angles appearing in (7) are not stable at the required accuracy of the nrad or less, because of the non-rigidity of the crust of the Earth and because of mechanical and thermal instabilities of the measuring device.

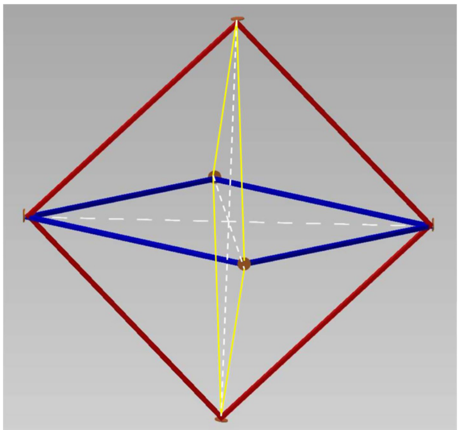

Fig. 1. (Color online.) Octahedral configuration of GINGER. Six mirrors give rise to three mutually perpendicular square rings. The active control of the geometry may be achieved by laser cavities along the three diagonals connecting the mirrors.

A specific difficulty that has to be faced in the LT measurement is that the sought-after effect is a tiny time independent quantity superposed to a comparatively huge signal (the kinematical Sagnac term), so that the calibration is quite demanding. For this reason, an accurate investigation of the systematics of the laser is needed, and different techniques for extracting the signal need to be considered and evaluated. The result could in principle be validated repeating the measurement with different techniques and operating the laser at a different working point. In fact, one could also use a passive cavity, i.e. the measurement could be repeated with the same apparatus, but using an external laser source to interrogate the array of cavities. The technique of the passive cavity Sagnac is however not as mature as the active one, but in general a ring-laser system allows one to repeat the measurement with two different methods, having different systematics thus making the detection of a small constant effect easier.

G has reached remarkable sensitivity and stability, which makes the goal of using this kind of instrumentation for fundamental physics experiments a demanding but reasonable objective.

However, the different contributions to the beat frequency correspond to effective rotations along different directions. In practice, in order to discriminate the various terms, it is necessary to have a three-dimensional device able to measure the three components of the rotation vectors. The monolithic design cannot easily be extended to such a three-axial ring-laser system. Not considering mechanical difficulties, the monolithic solution would have prohibitive costs.

To overcome the above weaknesses and difficulties, we have conceived the idea of a three-dimensional array of square rings (each of which bigger than the present G ring), mounted on a heterolitic structure. Since the control of the shape of the rings is vital at the level of accuracy required, the rigidity of the 'monument' carrying the mirrors and cavities would be replaced by a dynamical control of each perimeter (like, at a smaller scale, for G-Pisa). In practice, the size and shape of any loop can be stabilized by piezoelectric actuators applied to the holders of the mirrors. The control loop, that will drive the piezos, will also exploit the passive optical cavities installed along the square diagonals. In order to develop and test the above-said controlled ringlaser, GP2, a new prototype, has been realized; it is equipped with six piezos. The GP2 experimental set-up has been recently completed in the laboratory of S. Piero a Grado, close to Pisa.

In addition, the final location of the laboratory could not be as close to the surface of the Earth as in Wettzell, because of the limits imposed by the top soil slow motion due to atmospheric pressure changes, rain, wind, etc. The location could be underground at the Gran Sasso laboratory (LNGS) facility in Italy, in a cavern under an average rock coverage 1400 m thick. This arrangement will insure a very good shielding against all kinds of surface noise.

A possible configuration for GINGER is shown in Fig. 1. Actually the octahedral structure is the most compact, and, in principle, easy to control, configuration; being the control obtained by means of laser cavities along the three main diagonals of the octahedron. The side of each of the three square loops would be not less than 6 m.

4. The GINGER roadmap

The actual building of GINGER requires a number of preliminary steps and phases related to the technologies and measurement strategies to be deployed. For this reason we have devised a *roadmap* to GINGER.

4.1. Goals and needs

We assume G as a benchmark for our project. Its intrinsic structural stability and a careful work to control the cavity length and laser discharge parameter made it possible to obtain a stability performance very close to the shot noise limit up to $\approx 10^4$ s integration time. This corresponds to a statistical error in the angular velocity evaluation at a level of $10^{-8} \times$

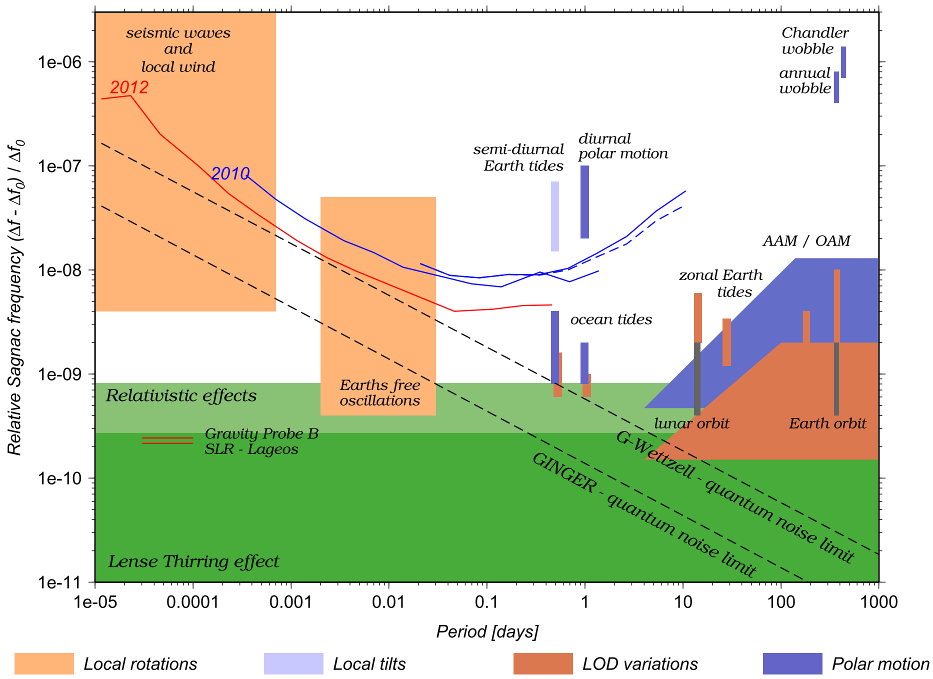

Fig. 2. (Color online.) The picture compares the Allan deviation of G in Wettzell (years 2012 and 2010, courtesy of K.U. Schreiber) with the most relevant geodetic signals. The green parts show the region of interest for the geodetic precession and the Lense–Thirring effect; on the left of the picture it is possible to see the present level of test obtained by Gravity Probe B and Lageos. The two dotted lines show the shot noise of the G (16-m perimeter), and of a ring with perimeter 24 m.

Ω_{Earth}, a factor of 5 above Ω_{LT} (the Lense–Thirring contribution to the Earth's rotation); Fig. 2 compares the results of G in Wettzell with what is necessary in order to be sensitive to the relativistic signals.

Such an impressive long-term stability has been obtained by an accurate modelling of all the environmental effects of geodetic, geophysical, or meteorological origin. G lacks, however, absolute accuracy: it is sensitive to one component of the angular velocity vector, and the absolute orientation of the laser cavity with respect to the fixed stars inertial frame cannot be measured with the required degree of precision. In order to arrive to a measurement of the Lense–Thirring effect, we need to improve the instrumental apparatus with respect to the following issues.

1. The signal-to-noise ratio (SNR), where noise is the shot noise of the instrument, should be increased. This can be obtained by:
   a increasing the size (the increase in SNR is more than quadratic with the size);
   b improving as much as possible the quality of the mirrors, and with a careful choice of the reflectivity and transmission;
   c investigating new techniques of laser operation (multimode locked operation, split mode, etc.);
   d increasing as much as possible the integration time with a suitable location of the apparatus.
2. The laser's long-term stability has to be improved in order to allow longer integration times. This can be accomplished by actively controlling its operative parameters.
3. The scale factor stability and the accuracy with which it is known, for each ring of the array, must be improved. This requires:
   a active control of the geometry of the rings;
   b active control of the relative size of the different rings and of their relative orientation.

The main research activities and tasks can be grouped in five major areas.

i) The scale factor of each ring must be known and kept constant at the level of 10^{-10}. This can be achieved by controlling the geometry of each ring and the wavelength of the laser, by metrology techniques. "Heterolithic" ring lasers, i.e. based on a mechanical design, are cheaper, the mirrors support can be implemented with suitable translators (usually piezoelectric), and they are flexible enough to develop complex structures to support rings with different orientations. We are developing a method that uses information from the ring itself and the length of its diagonals (which are as well-resonant optical cavities), in order to drive the actuators of the mirrors and keep the ring, from a geometrical point of view, stable at the required level of 10^{-10}. To this aim, the heterolithic prototype GP2 has been developed. It has six piezoeletric actuators, and will be the test bench for the above-mentioned control strategy. At present this work is in progress [12].

ii) The Lense–Thirring measurement requires to recover the angular velocity vector, with errors in the relative alignment of the planes of the rings of the order of 1 nrad. Large-frame ring lasers have been working with different orientations with respect to the Earth's axis, but a multi-axis system of this size has not been implemented so far. As explained above, the heterolithic ring laser can "easily" be expanded to hold rings with different orientations in order to recover the full angular velocity vector; the very demanding issue is the nrad relative accuracy between different rings. The octahedron arrangement, in principle a very elegant design, could be a solution, since the cavities and diagonals can effectively provide information on the relative angles. The three diagonals of the octahedron are resonant Fabry–Pérot linear cavities that can monitor the relative angle between two different rings of the octahedron. Alternative configurations, other than octahedral, and different strategies for the relative angle monitoring must be investigated, as for example the use of interferometry with 3D retro-reflectors, which has reached prad-level accuracy [13].

iii) Identify and refine the estimate of the Lamb parameters that regulate the non-linear dynamics of the ring-laser itself [14]. The identification procedure will consist of two parts: i) identification and monitoring of cavity losses from mono-beam amplitudes and phase; ii) estimation and monitoring of the laser single pass gain and the remaining Lamb parameters from the measured plasma dispersion function of the He–Ne mixture. The scale associated with the non-linear dynamics permits to perform the absolute calibration of the instrument. To this aim, it is important to select the most convenient working point of the ring laser. In addition, the knowledge of laser dynamics enables us to run a non-linear Kalman filter that, *a posteriori*, can remove a large fraction of the backscattering contributions from the rotation rate measurements. In this way, we can improve the long-term stability of our rings, which represent a key issue of the GINGER project.

iv) Top-quality mirrors are adequate for ring lasers; however, mirrors will always be a point of concern. The mirrors used for ring-lasers are standard 1–2 inches substrate, but the quality of the substrate, the uniformity and quality of the coating are important issues, so that the mirror birefringence at the sub-ppm level and the possible related problems must be investigated as well. Any non-reciprocal effect induced by the mirrors has repercussions in unbalance in the two counter-propagating beams. There are few factories in the world able to provide this kind of mirrors; we are in touch with all of them.

v) Quantify environmental disturbances in order to have a proper assessment of the experimental site. This is of paramount importance, since the ring-laser is an inertial sensor, which is operated to deduce a global measurement quantity. Therefore the properties of the monument connecting the ring lasers to the Earth are critical. The operation of the G ring laser has shown that a near-Earth's surface installation is subject to seasonal changes and noise generated by local wind patterns [15,16]. Therefore deep underground locations such as the LNGS have inherent advantages. In general, a deep underground installation within solid rock is almost insensitive to external environmental perturbations. This suggests that LNGS is potentially a good site for installing an array of actively stabilized large ring lasers, but dedicated measurements are necessary for site validation.

4.2. Work-plan

At the time of writing, two experimental areas are under construction: GP2, which will be used to develop the geometry control, has just been completed, and GINGERino, the 3.6-m-side ringlaser which will qualify the LNGS site for GINGER, is under construction. GINGERino will be located in a part of the laboratory away from daily activity, it will be acoustically protected and mounted on top of a granite structure well connected to the ground; it should start taking data in the second half of 2014.

Further steps will be taken to complete the characterization of the site, to test the technologies, and to collect information for geophysics.

The scientific work-plan toward the GINGER operation can be summarized as follows.

1) 2014: 3.6 m horizontal ring (in principle we should have an improvement of a factor 7.8 in sensitivity with respect to our first prototype) obtained using the mirror holders of our first prototype and longer tubes. The size is limited by the room presently available in the specific location within LNGS. A different positioning will allow a larger ring. In any case, as long as the present mirrors will be used, the side of the ring cannot exceed 6 m, because the mirrors have a 4-m curvature radius.
With GINGERino, the systematics of the laser will be reduced, in particular backscattering noise should be reduced. In fact, we expect larger biases from the Earth's rotation, the larger distance between mirrors and gas discharge, higher Q of the optical cavity (keeping the quality of the mirror constant). Acoustic shielding and a high-quality reference laser for the perimeter control are required. The task for GINGERino will be to observe the Allan deviation of the measurement, in order to understand the environmental disturbances. We expect to record some relevant seismic events, and, because of the improvement in sensitivity, also geodetic signals should be detected. Correlation with G Wettzell measurements should be possible (common tele-seismic events etc.).

2) 2015: One or two smaller rings should be added to GINGERino in order to reconstruct the angular velocity vector, with μrad precision (at least) in the vector direction. In particular, with a ring aligned with the Earth's axis, a good measurement of the Length of the Day can be pursued.

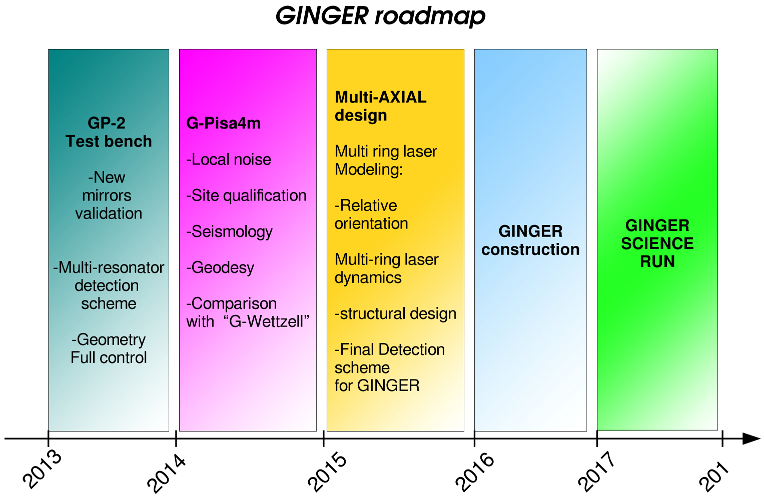

Fig. 3. (Color online.) Workplan for the GINGER roadmap.

3) 2015–2016: The geometry and relative orientations of the rings should be defined, and it should as well be defined how to monitor the relative angle between the different rings.
4) 2015–2016: Construction of the octahedral arrangement of the full GINGER experiment.
5) 2017–2018: GINGER in operation.

At the end of 2015, it should be possible to qualify the LNGS installation, and to understand at which level of precision the full installation of GINGER can be qualified. Fig. 3 shows the above outlined roadmap.

5. Discussion and conclusions

Summing up, we have started a number of practical steps towards the implementation of an experiment of fundamental physics based on a three-dimensional array of advanced ring lasers, named GINGER. The first objective of the experiment is to measure general relativistic effects due to the rotation of the Earth. In order to overcome the difficulties — implicit in the extreme sensitivity required by the measurement — we have built an international collaboration, involving two more laboratories in the world. A framework agreement is being signed between INFN, the University of Canterbury (Christchurch, New Zealand), the Technische Universität and the Maximilian University of Munich, Germany. We have also designed a roadmap (which we have already started to follow) aimed at testing and solving many technological and methodological problems. Step-by-step various intermediate facilities are in use and will be built: GP2 to develop the control of the geometry, and GINGERino, based on our first prototype G-Pisa, to qualify the possible installation inside the underground laboratory of LNGS. In 2015, after the first set of measurements taken inside LNGS, the feasibility of GINGER will be clearer, and its time schedule as well; the construction of the GINGER apparatus *per se* is rather simple, it should not take more than one or two years. The use of a facility as LNGS, which is a very large and well-equipped laboratory, will facilitate the construction and the start up as well.

We should mention that techniques similar to the ones using lasers could be envisaged, such as atomic beams interferometry [17], or long fibers loops [18]. Atoms would have an advantage with respect to light due to the fact that, for equal rings, the phase difference between the clockwise and the counter-clockwise circulation turns out to be proportional to the rest mass of an atom, whereas for light it is proportional to the energy of a photon. The former can easily be bigger than the latter. For the moment, this type of approach has very high potential for atomic 'gyroscopes', but it cannot (as yet) compete with advanced, large-scale ring laser technology, because the areas of atomic gyrometers are much smaller than those of ring lasers; furthermore in the atomic devices the signal-to-noise ratio is generally more unfavorable than with light.

The terrestrial detection of the Lense–Thirring effect is the main, but not the only purpose of GINGER. The main difficulty of the Lense–Thirring measurement is that it corresponds to a constant signal and the calibration is quite demanding. This is the reason why we are investigating as deeply as possible the systematics of the laser, and different techniques to extract the signal: the result could be validated repeating the measurement with different techniques and operating the laser at a different working point. The Sagnac effect works as well for a passive cavity, i.e. the measurement could be repeated with the same apparatus, but using an external laser source to interrogate the array of cavities. The technique of the passive cavity Sagnac, however, is not as mature as the active one. In summary: any measurement of constant effects is in principle difficult, but a ring-laser system allows one to repeat the measurement with two different methods, which have different systematics.

Beyond LT, we should mention that measurement methods from modern *Space Geodesy* perform at about the 10^{-9} error level. Lunar Laser Ranging for example provides precise round trip optical travel times between a geodetic observatory and cube corner retro-reflectors placed on the moon by the American APOLLO and the Russian LUNA landers [19]. With a long time-series of observations and continuous technical improvements, which reached a range precision of several millimeters in recent years, the error margin has reached a level of $10^{-9} \div 10^{-11}$. As one of many results according to [19], this led to improved constraints for the gravitational constant and its spatial and temporal variation of $\dot{G}/G = (2 \pm 7) \times 10^{-13}\ \mathrm{yr}^{-1}$ and $\ddot{G}/G = (4 \pm 5) \times 10^{-15}\ \mathrm{yr}^{-2}$.

Apart from actually measuring the Lense–Thirring effect with a ground-based gyroscope, also high-precision tests of metric theories of gravity in the framework of the PPN formalism come within reach. With $\hat{J} = I_\oplus \hat{\Omega}_\oplus$ according to [20], one obtains

$$\hat{\Omega}_\mathrm{G} = -(1+\gamma)\frac{GM}{c^2 R}\Omega_\oplus \sin\vartheta\, \hat{u}_\vartheta \tag{8}$$

for the geodetic (de Sitter, index G) precession rate and

$$\hat{\Omega}_\mathrm{B} = -\frac{1+\gamma+\frac{\alpha_1}{4}}{2}\frac{GI_\oplus}{c^2 R^3}\big[\hat{\Omega}_\oplus - 3(\hat{\Omega}_\oplus \cdot \hat{u}_\mathrm{r})\hat{u}_\mathrm{r}\big] \tag{9}$$

for the gravitomagnetic (Lense–Thirring, index B) precession rate; the sum of the two terms gives the contribution of the gravitational field to the angular velocity. Then there is the dominant kinematical term which is the classical Sagnac precession rate. In Eqs. (8) and (9), α_1 and γ represent the PPN parameters that account for the effect of a preferred reference frame and the amount of space curvature produced by a unit rest mass. So, high-precision ring laser measurements performed by GINGER should be able to access α_1 and γ. As already stated, being the apparatus on Earth, it should be possible in the future to envisage improvements and upgrading. With improvements of the order of 100–1000, it will be possible to set constraints on the PPN parameters competitive with space experiments.

Georges Sagnac would be surprised to see how far his method has gone after one century from his initial experiment. His purpose was to prove Special Relativity wrong now; under his name, we are preparing the most accurate verification of one of the effects of General Relativity. Maybe we shall not prove it wrong but insufficient. We shall know in few years.

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