GRAvitational-waves Science&technology Symposium (GRASS 2024)

Report of Contributions

Contribution ID: **1** Type: **Contributed talk**

Resonant behavior of linear three-mirror cavities in the context of quantum noise reduction

Tuesday, 1 October 2024 09:40 (20 minutes)

The implementation of Fabry-Perot cavities in gravitational-wave detectors has been pivotal to improving their sensitivity, allowing the observation of an increasing number of cosmological events with higher signal-to-noise ratio. Notably, Fabry-Perot cavities play a key role in the frequency-dependent squeezing technique, which provides a reduction of quantum noise over the whole observation frequency spectrum. The next generation of detectors such as Einstein Telescope – Low Frequency will need different filtering systems to meet their own quantum noise targets. For this purpose, different configurations of filter cavity are currently studied. Among these, linear three-mirror cavities could be particularly interesting because of their variable finesse which could offer additional control for frequency-dependent squeezing. The adaptability of linear three-mirror cavity optical properties also leads to one of their key features, the doubling of their resonant frequency. I will present simulations we performed to explore how the resonant behavior and stability of this system vary with its configuration.

Primary author: STEVENS, Paul (CNRS / IJCLab)

Presenter: STEVENS, Paul (CNRS / IJCLab)

Session Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Track Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Contribution ID: **2** Type: **Contributed talk**

Mirrors Design for Future Gravitational-Wave Detectors

Monday, 30 September 2024 14:20 (20 minutes)

Alex Amato, on behalf of the GWFP group of Maastricht University.

While current gravitational-wave detectors allow for successful detections, there is a need to increase their sensitivity by trying to enlarge their frequency band to observe additional types of gravitational waves sources. Future cryogenic detectors such as the Einstein Telescope aim for this improvement. Improved operating conditions, such as cryogenic temperature, will help reduce the mirror's Brownian thermal noise, one of the limiting noises in the detector. Meanwhile, low temperature applications are driving technological development towards the study of new materials and coating design for the mirrors of these large interferometers.
Material candidates such as amorphous silicon (aSi) and silicon nitrides (SiN) show low thermal noise but their high optical absorption reduces the power in the interferometer and hence the signal-to-noise ratio. In Maastricht University, we are testing a crystalline-silicon top-layer design, based on the industrially established silicon-on-insulator (SOI) technique, which will allow the use of low thermal-noise but highly-absorbing materials such as aSi and SiN. In addition, this new design will potentially reduce the defect density in the upper coating layers, where the high laser power may induce damages, and solve a mismatch in tolerable heat-treatment temperatures of the coating and the mirror substrate.

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **3** Type: **Contributed talk**

Estimation of joint detection probabilities of Gamma-Ray Burst and Gravitational Waves produced by NSBH binary mergers

Tuesday, 1 October 2024 11:30 (20 minutes)

Black hole-neutron star (NSBH) coalescence events are regarded as highly significant phenomena within the current multimessenger framework of gravitational waves,
and they are poised to assume an increasingly prominent role in the foreseeable future. To date, only a handful of such events have been observed,
with GW200105 and GW200115 being the most noteworthy among them. However, with the forthcoming upgrades to the LIGO-Virgo-Kagra (LVK) interferometers,
and particularly with the prospective implementation of next-generation instruments such as the Einstein Telescope (ET), we anticipate a substantial increase
in the detection rate of these events, potentially by orders of magnitude.

The study of NSBH coalescences, alongside neutron star binary (BNS) mergers, is pivotal due to their status as prime multimessenger candidates capable of producing
a wide range of electromagnetic counterparts, including Gamma-ray Bursts (GRBs) and Kilonovae. By conducting joint analyses of both the gravitational and electromagnetic signals,
it becomes feasible to derive more precise insights into the properties of the involved celestial objects and the myriad processes occurring during and subsequent to the merger,
including the neutron star's stiffness and the mechanisms underlying GRB generation and beam structure.

This work provides an estimation of the combined detection capability for gravitational signals and GRBs originating from NSBH events,
considering the anticipated upgrades to existing instruments and the deployment of next-generation facilities. In assessing the gravitational wave detectors,
we compare the LVK interferometers with ET employing the GWFish software, while for evaluating the detectability of GRBs, particularly focusing on the afterglow component,
we primarily reference Fermi and the prospective CTA array telescope. By utilizing state-of-the-art models for beam formation and propagation, we investigate how the goodness
of information derived from these events is contingent upon the instruments utilized and the inherent characteristics of the coalescence itself.

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Session Classification: GW and multi-messenger observational science

Track Classification: GW and multi-messenger observational science

Contribution ID: **4** Type: **Contributed talk**

Measurement and Analysis of Backscattered Light for Advanced Virgo+

Tuesday, 1 October 2024 16:30 (20 minutes)

The sensitivity of the gravitational wave detectors interferometer are impacted by backscattered light in the cavities, which can be recombined and interferes with the main beam creating unwanted background noise. This risk of interference is particularly acute when the light is backscattered along the direction of propagation of the incident beam. Backscattered light can originate from defects on optical components such as surface imperfections, optical coatings or interference with other opticals components. An experiment called the backscatter meter [1] has been set up at LAPP to measure backscattered light from optics intended to be deployed on the optical benches used to extract the Virgo interferometer beams. In the context of the installation of new stable recycling cavities foreseen for the next Advanced Virgo+ phase 2 upgrade scheduled to start in 2026-2027, a new telescope will be developed and installed on the optical bench used to detect the interferometer output beam. In order to help identifying the best design for this telescope, a test campaign is being carried out on the scatter meter at LAPP to test refractive and reflective optics and quantify the contribution to back-scattered light of each type of considered telescope configurations - those with low-incidence curved mirrors or a simple telescope with lenses. In this talk we will introduce this backscatter meter, show preliminary results obtained with this experiment and give some perspectives for the backscatter meter experiment.
[1] M. Wąs and E. Polini, "High-angular-resolution interferometric backscatter meter," Opt. Lett. 47, 2334-2337 (2022)

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Presenter: SAYAH, Sihem (LAPP-CNRS)

Session Classification: Stray light mitigation

Track Classification: Stray light mitigation

Contribution ID: **5** Type: **Contributed talk**

State of the art of crystalline test mass suspensions

Wednesday, 2 October 2024 09:40 (20 minutes)

Crystalline materials are playing a major role in determining the design, thermal and structural behavior of suspensions for the test masses of future gravitational wave interferometers that will use cryogenic payloads. The talk will present the state of the art of the joint research between various laboratories, research centers and private companies regarding the development of cryogenic test mass suspensions capable of suspending 200 kg substrates with excellent thermal and mechanical performances.

Primary author: TRAVASSO, Flavio (Istituto Nazionale di Fisica Nucleare)

Presenter: TRAVASSO, Flavio (Istituto Nazionale di Fisica Nucleare)

Session Classification: Other challenges for future GW detectors

Track Classification: Other challenges for future GW detectors

Contribution ID: **6** Type: **Contributed talk**

Demonstrating optical cavity functionality and 40 dB of straylight suppression with tunable coherence in a Michelson

Tuesday, 1 October 2024 14:50 (20 minutes)

As straylight is an important limitation for the sensitivity of gravitational wave detectors, we investigate new laser operation concepts and interferometer topologies for a more straylight-resilient detector configuration.
Our main focus is the use of tunable coherence realized by phase modulation following a pseudo-random-sequence on the interferometer laser. This breaks the coherence of the delayed straylight reducing its intrusive impact with the remaining coherence length only depending on the modulation frequency. Thus, effectively realizing a pseudo white-light interferometer with tunable coherence length. We demonstrate this in a Michelson and a Sagnac-topology with a remaining coherence length of roughly 30 cm. Additionally, we investigate the use of tunable coherence in optical resonators, demonstrating the functionality of cavities with the PRN-modulated laser.
Here, we present our recent results, achieving more than 40 dB of straylight suppression in a table top Michelson-interferometer using tunable coherence and the full functionality of an optical cavity with a matched PRN-sequence.

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Session Classification: Stray light mitigation

Track Classification: Stray light mitigation

Contribution ID: **7** Type: **Contributed talk**

Scattered light noise mitigation for the AEI 10m Protytype

Tuesday, 1 October 2024 15:30 (20 minutes)

The AEI 10m Prototype will operate a Fabry Perot Michelson interferometer with 10m long arm cavities limited by the standard quantum limit (SQL). It will be a test-bed for testing and developing technologies improving the sensitivity of gravitational wave detectors beyond SQL. In order to achieve SQL-limited sensitivity, we need to suppress all other classical and technical noise sources. Among them, scattered light noise presents a big challenge. In this talk, I present the current work being done towards developing the scattered light noise mitigation strategy by testing and characterizing suitable baffle materials, designing and optimizing baffles, optical simulations of the scattered light in the cavities, and calculation of the scattered light noise budget for the prototype.

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Session Classification: Stray light mitigation

Track Classification: Stray light mitigation

Contribution ID: **8** Type: **Contributed talk**

Investigating Crystalline Corundum Coatings for Low-Noise Cryogenic Interferometers

Monday, 30 September 2024 17:30 (20 minutes)

To further reduce the mirror coating thermal noise for the Einstein Telescope (ET) and other third-generation gravitational wave detectors, a substantial improvement in the coating technology and material is necessary. Employing crystalline coatings is one of the new promising directions of the scientific endeavor to replace SiO₂ and Ti:Ta₂O₅ for interferometric measurements at cryogenic temperatures. So far, the most promising epitaxial coatings taken into consideration are III-V compounds multilayers, such as GaAs/Al_{1-x}Ga_xAs on a GaAs substrate. Despite these coatings' high optical and mechanical performance, significant concerns involve their upscaling to the desired mirror size for the ET.
In this study, we propose crystalline corundum materials (crystal structure X₂O₃ as sapphire) as an upscalable alternative to III-V compounds for high-reflectivity multilayer coatings in cryogenic detectors. As proof of concept, we started studying Cr₂O₃ coatings deposited epitaxially via oxygen-assisted MBE on Al₂O₃ substrates. Mechanical losses measurements via GeNS system show losses of the chromia coating as low as 5·10⁻⁶ between 5K and 55K, 1-2 orders of magnitude lower compared to the losses of SiO₂ and Ti:Ta₂O₅ at the same temperatures. Nonetheless, the optical absorption of this material is still 2 to 3 orders of magnitude higher than the specifications required for the ET at different working wavelengths. This work still proves to be useful, as it shows the potential of crystalline materials in cryogenic optical applications. Furthermore, a wide range of compounds (Ga₂O₃, Fe₂O₃, Ti₂O₃⋯) is epitaxially compatible with sapphire, i.e. presents the same corundum structure, so there is a wide margin for optimization and choice for the most suitable pair of materials to employ in the multilayer.

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **9** Type: **Contributed talk**

Growth of monocrystalline silicon fibers for mirror suspension in gravitational-wave detectors

Monday, 30 September 2024 18:30 (20 minutes)

Monocrystalline silicon fibers are a promising candidate to be used in gravitational-wave detectors for suspension of silicon test masses. High thermal conductivity and mechanical quality factor Q, very low thermal expansion coefficient, large strength-to-weight factor and compatibility with test masses enable stable support of heavy silicon mirrors and effective extraction of laser beam heat deposited therein. In addition, excellent material properties of silicon at cryogenic temperatures perfectly fit requirements of future third generation gravitational-wave detectors, such as the Einstein Telescope (ET), which will operate at cryogenic temperatures in order to reduce thermal noise and increase the detection-sensitivity at intermediate frequencies. As-grown monocrystalline silicon fibers have a particular interest for suspension application since they are both in bulk and surface free from cracks and defects (e.g. dislocations) that ensures high tensile strength.

In the frame of our research, we investigated crucible-free crystal growth methods for fabrication of fibers that can be suitable for application as mirror suspensions in ET. As the result, two growth set-ups, float zone (FZ) and pedestal, were developed and successfully utilized for fabrication of thin silicon fibers with monocrystalline structure and circular cross section. After thorough step-to-step process adjustment, the growth conditions were significantly improved, ensuring the stable and reproducible growth of 0.5 m to 1.0 m long silicon fibers, by both pedestal and FZ techniques, with uniform diameter along the entire length of the crystal, measured to be 3.0 mm, with maximum deviation of less than 0.1 mm. The structural analysis of as-grown fibers shows that the developed technique ensures the growth of dislocation-free monocrystalline silicon, which is highly preferable for mirror suspensions

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Session Classification: Coating and Materials

Track Classification: Other challenges for future GW detectors

Contribution ID: **10** Type: **Contributed talk**

Balanced homodyne detection design and application at the 10m Prototype sub-SQL interferometer

Tuesday, 1 October 2024 10:00 (20 minutes)

Quantum noise fundamentally limits the performance of ground-based interferometric gravitational wave detectors (GWDs).
The quantum nature of the light and its interaction with the interferometer defines the so-called interferometric standard quantum limit (SQL).
To further upgrade the GWDs sensitivities, as in the planned A+, VIRGO_nEXT, Einstein Telescope, and Cosmic Explorer, more complex, better-performing techniques will be required. In general, the SQL can be overcome with the application of quantum non-demolition techniques (QND).
One of the realizations of QND is known as Balanced Homodyne Detection (BHD).
In the context of GWDs, this technique requires suspended optical components.
This detail increases the technical challenges, such as the creation of a very stable local oscillator signal and the design of a more complex scheme to lock the interferometer at the dark fringe.
This adds to the requirements of the BHD, such as having strict BHD beamsplitter parameters and the further reduction of optical losses.
This presentation focuses on an overview of the relevant issues and solutions found for the implementation of a BHD using the Albert Einstein Institute (AEI) 10m Prototype sub-SQL interferometer. An optimal facility to study novel technologies for reaching and surpassing the SQL.
This will also include a report on the current progress towards realizing the interferometer and the current work in the application of a BHD scheme to achieve a direct sub-SQL measurement.

Primary author: CARLASSARA, Matteo (Max Plank Institute for Gravitational Physics - AEI Hannover - 10 m Prototype)

Presenter: CARLASSARA, Matteo (Max Plank Institute for Gravitational Physics - AEI Hannover - 10 m Prototype)

Session Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Track Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Contribution ID: **11** Type: **Contributed talk**

Towards quantum-enhanced gravitational wave detection using entangled light and atomic spin oscillator

Tuesday, 1 October 2024 09:20 (20 minutes)

We explore the idea of quantum noise reduction in contemporary gravitational wave detectors (GWDs), outlined in [1,2]. In that theoretical proposal, the measurement on the GWD should be performed in a reference frame of the auxiliary quantum system, which has the same response to the quantum noise. If the reference quantum system acts as a harmonic oscillator with an effective negative mass and approaches the dynamics of a free mass, the broadband reduction of the quantum noise in the hybrid system is possible. To implement the "parallel" measurement on the GWD and the reference oscillator, these two systems should be probed using an entangled state of light.

The talk will present progress towards the experimental realization of this protocol. We have built and characterized the hybrid quantum system, comprising an EPR-entangled state of two optical modes at different wavelengths, one of which is coupled to the atomic spin ensemble. The two entangled modes are chosen to match the wavelengths required for an efficient interaction with the GWD interferometer and the Cs atomic ensemble, respectively [3]. In turn, the spin system is prepared in the regime of the quantum oscillator [4] with the possibility to switch the sign of the effective mass. In particular, we demonstrate that the measurement performed on one of the entangled modes probing the spin ensemble creates a *frequency-dependent conditional squeezing* in the second entangled mode.

The non-classical state of the hybrid system, presented here, exhibits high tunability and, in particular, preserves the quantum features in the frequency range approaching the upper part of the audio band. Further optimization of the low-frequency performance can make our source of frequency-dependent squeezing practically compatible with state-of-the-art GWDs in the interferometric configuration. More generally, we envision potential applications in a broad field of quantum metrology, where the quantum noise of light needs to be manipulated or reduced.

[1] F. Ya. Khalili and E. S. Polzik. Phys. Rev. Lett. 121, 031101 (2018).
[2] E. Zeuthen, F. Ya. Khalili and E. S. Polzik. Phys. Rev. D100, 062004 (2019).
[3] T. B. Brasil et al.. Nature Comm. 13, 4815 (2022).
[4] J. Jia et al. Nature Comm. 14, 6396 (2023).

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Presenter: NOVIKOV, Valeriy (University of Copenhagen)

Session Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Track Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Contribution ID: **12** Type: **Invited talk**

GW detections from neutron star mergers in the ET era

Tuesday, 1 October 2024 12:30 (30 minutes)

The advent of third generation GW detectors, including the Einstein Telescope, will enable the detection of GW signals not only from the inspiral phase, but also from the post-merger phase of two coalescing neutron stars. The post-merger signal is potentially extremely rich and can shed light on the fate of the remnant, as well as on properties of matter at the highest densities reached in nature. In this talk, I will present some of the most recent results obtained by detailed simulations in Numerical Relativity including detailed microphysics, focusing on the impact and scientific outcome of GW as well as multimessenger detections. I will in particular focus on the so-called prompt collapse scenario, discussing the ring-down signal, as well as the possibility of measuring nuclear properties at the highest densities. In addition, I will also discuss the most urgent issues in merger modelling and multimessenger signal analysis.

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Session Classification: GW and multi-messenger observational science

Track Classification: GW and multi-messenger observational science

Contribution ID: **13** Type: **Contributed talk**

Birefringence measurements of substrate materials and coatings for Einstein Telescope

Wednesday, 2 October 2024 10:20 (20 minutes)

The birefringence that can occur in the optics that will be used in the Einstein Telescope (ET) interferometer is an essential phenomenon to be considered to ensure the desired sensitivity for gravitational wave (GW) detection.
The birefringence of the optics directly depends on the substrate and coating materials and is mainly induced by stress in these materials (residual internal stress, externally induced stress, intrinsic stress fluctuations).
Being experienced in sensitive birefringence measurements, the Ferrara ET Reasearch Unit (University of Ferrara and INFN - Ferrara) has been working on birefringence 2D mapping of different samples both in transmission and in reflection at 532nm and 1064nm.
Results of such measurements will be presented at the Symposium.

A medium of thickness D with birefringence Δn will induce a time dependent ellipticity $\psi(t)$ on a rotating linearly polarized beam given by
$\psi(t) = \frac{\pi}{\lambda} \int_{\text{light path}} \Delta n \, dl \sin 2\vartheta(t) \simeq \frac{\pi}{\lambda}\Delta n D \sin 2\vartheta(t) \qquad (1) where, here, \vartheta(t)$ is the time dependent angle between the polarization and the birefringence axis.

The scheme of the polarimeter for transmission measurements is based on a linearly polarized beam (either 532 nm or 1064 nm wavelength) passing through two half-wave plates co-rotating at ν_w. Between them is the sample whose birefringence is to be measured and a 2.5 T magnetic field rotating at ν_B, for calibration purposes. Together these will generated a time dependent ellipticity $\psi(t)$. After the two half-wave plates an ellipticity time dependent photo-elastic modulator adds a known ellipticity $\eta(t)$ to $\psi(t)$ followed by an analyser placed at maximum extinction. The modulator ellipticity linearises $\psi(t)$ in the output power, $P_{\text{out}}(t)$, after the analyser. The precisely known sinusoidal time dependence of $\psi(t)$ also allows its separation from spurious harmonics generated by the two rotating half-wave plates and from slowly varying $1/\nu$ spurious ellipticity noise, always present due to the various optical elements, all contained in the ellipticity $\Gamma(t)$.

Finally, the output power $I_{\text{out}}(t)$ detected at the diode PDE will be $\text{P}_{\text{out}} = P_0 \left[\eta(t) + \psi(t) + \Gamma(t)\right]^2 \simeq P_0 \left[\eta^2(t) + 2\eta(t)\psi(t) + 2\eta(t)\Gamma(t) + ...\right]$.

The total ellipticity $\psi(t) + \Gamma(t)$ is extracted by demodulating $I_{\text{out}}(t)$ at the modulator frequency. The main two harmonics of interest to us in the demodulated signal will be: the sample ellipticity at $4\nu_w$; the Cotton-Mouton effect of air at $4\nu_w \pm 2\nu_B$. Zero measurements can be made without the sample to minimize the contribution of spurious ellipticities generated by the half-wave plates at, in particular, the frequency of interest $4\nu_w$. The sample is mounted on a horizontal-vertical manual positioning system so as to acquire a 2D ellipticity map which can be converted to a birefringence (average Δn over the thickness) map through Equation (1).

Measurements are also feasible in reflection to study mirrors and coatings with a minor modification of the transmission scheme. The beam enters through the output port of the analyzer. The beam then passes through the modulator, through the 'second' half-wave plate, the magnetic field and is then reflected by the sample and returns back along its path. The extinguished beam is then collected and analysed in the same way as in transmission measurements.

In this scheme a position sensitive detector (PSD) was introduced to ensure that during the mapping of the reflective surface, the reflected beam always returns through the same point on the half-wave plate. Given that no real zero measurements are possible (sample cannot be removed) in this configuration, for each position of the sample, two measurements were taken with the sample rotated by 90°. In this way the ellipticity of the sample changes sign whereas the spurious ellipticity induced by the rotating half-wave plate does not. By adding and subtracting the two measurements, the sample ellipticity can be extracted.

In both the transmission and reflection configurations the sensitivity to optical path difference is $calD = \int \Delta n \; dl \approx 5 \times 10^{-13}$ m, limited by the spurious ellipticity generated by the half-wave plates and not by noise.

We will present transmission maps for a 1 mm thick silicon plates in transmission measured at 1064 nm and reflection map measurements of various reflecting surfaces (silver mirror, coating, dielectric mirror, pure dielectric surface) at both 532 nm and 1064 nm.

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Session Classification: Other challenges for future GW detectors

Track Classification: Coatings and Materials

Contribution ID: **14** Type: **Contributed talk**

Stray light mitigation in KAGRA

Tuesday, 1 October 2024 16:10 (20 minutes)

In this presentation, I will review the stray-light mitigation activities for the KAGRA interferometer since its construction began. The stray light, including ghost beams and scattered light generated within the interferometer, is unwanted, as it somehow recombines with the main beam path and eventually becomes noise, which practically limits the interferometer sensitivity. To suppress the noise, optical baffles, dumps, or shields in (or out of) vacuum chambers need to be designed under a good connection with those of mechanical stuff, such as vibration-isolation systems or cryogenic systems, in the very first place, while the seriousness of this fact is not always shared among the relevant subsystems. In addition to simulations, careful engineering is necessary. Summarizing our activities so far would be useful for the detailed design of future interferometers.

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Session Classification: Stray light mitigation

Track Classification: Stray light mitigation

Contribution ID: **15** Type: **Contributed talk**

Real-time monitoring of thermal annealing as a tool to enhance the properties of coatings for GWD mirrors.

Monday, 30 September 2024 15:00 (20 minutes)

Enhancing the performance of GWD mirrors is a complex endeavor which entails several key steps, including the selection of a suitable mirror design, the choice of the most appropriate chemical composition of coatings and the protocol for post-deposition treatments –i.e., thermal annealing.
During more than two decades of continuous research and development [1,2], a lot of effort has been dedicated to understand and optimize the first two steps, while thermal annealing has remained a mandatory yet somewhat poorly-understood process. Indeed, the beneficial effects of thermal annealing have been studied mostly by ex-post analysis, that is, by probing the coatings before and after the annealing [3]. The lack of information about the real-time evolution of the coatings during the annealing means that the parameters used in the annealing protocol used to produce the current GWD mirrors might not be optimized, potentially leading to sub-optimal performance.
In this work, we present the real-time monitoring of the coatings during thermal annealing as a valuable tool to deepen the understanding of the annealing process, and most importantly, to provide guidelines for the optimization of the annealing protocol [4]. In this presentation, the real-time monitoring of the annealing of Ti:Ta2O5 - the high-index material currently used in GWD mirrors - will be presented and discussed. The ultimate goal is to apply this real-time analysis to each of the materials that are currently under evaluation as possible substitutes for Ti:Ta2O5, to make sure that their properties after the annealing are the best attainable for GWD applications.

References

[1] Penn S. D. et al., Class. Quant. Grav. 20, 2917 (2003)
[2] Harry G. M. et al., Class Quant Grav 27, 205 (2007)
[3] Amato A., Magnozzi M. et al., ACS Appl. Opt. Mater. 1, 395 (2023)
[4] Colace S., Samandari S., Granata M., Amato A., Caminale M., Michel C., Gemme G., Pinard L., Canepa M. and Magnozzi M. Class. Quant. Grav. 41, 175016 (2024)

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **16** Type: **Contributed talk**

Study of the optical losses as a function of beam position on the mirrors in a 285 m suspended Fabry-Perot cavity

Tuesday, 1 October 2024 10:20 (20 minutes)

Optical losses introduce noise, impair noise reduction techniques, and degrade signal gain in gravitational wave detectors. The squeezed vacuum state of light is a well-established method for quantum noise reduction. An optical cavity, often called a filter cavity, is essential to impose a frequency-dependent phase rotation on the squeezed vacuum. In the Virgo gravitational wave detector, the filter cavity is 284.9 meters long with a finesse of about 10,000.

In this talk, we report on the characterization of optical losses within the Virgo filter cavity. By using cavity angle information, we reconstructed the beam position inside the cavity and conducted an in-situ optical loss mapping. Our findings indicate that optical losses depend significantly on the beam's position on the input mirror, while losses are more uniform on the end mirror. The lowest measured losses are comparable to those expected from pre-installation mirror characterizations. The larger discrepancies observed for certain beam positions are likely due to contamination. Additionally, this methodology enabled the regulated identification of an optimal cavity axis position within half an hour, achieving some of the lowest round trip losses ever recorded. This work contributes to meeting the stringent loss requirements for the optical cavities of future gravitational wave detectors, such as the Einstein Telescope and Cosmic Explorer.

Primary author: ZHAO, Yuhang

Presenter: ZHAO, Yuhang

Session Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Track Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Contribution ID: **17** Type: **Contributed talk**

Molecular dynamics study of the formation of porous films by room-temperature physical vapor deposition of silica

Monday, 30 September 2024 16:30 (20 minutes)

Low-temperature physical vapor deposition is studied by means of molecular dynamics (MD) simulations using the reactive force field (ReaxFF) potential. In contrast with prior MD studies of this process, which employed non-reactive, rigid ion force fields, our approach allows for accurate modeling of the reactive incorporation of impinging particles, generated by the vaporization process, into the growing film. The use of the ReaxFF force field also enables us to properly model the charges of impinging particles and their electrostatic interactions with the atoms forming the topmost layers of the growing film. In order to better evidence the associated effects, we focus on the conditions of growth when the impinging particles have moderate kinetic energies (below a couple of electron-volts). We thus evidence that, in these conditions, impacting particles tend to be strongly deflected during the last stages of their approach to the film, and all the more so that they are slow. As a result, they tend to be captured by denser regions, leading to the formation of porous microstructures. This phenomenon results from the polarization of \ce{Si-O} bonds, and the tendency of silicon atoms to surround themselves with oxygen atoms, leading to an overall polarization of the interface between dense matter and pores.

Primary authors: Prof. LEMAITRE, Anael (Laboratoire Navier – ENPC); Prof. LÉONARD, Céline; Dr POVARNITSYN, Mikhail; SHCHEBLANOV, Nikita (MSME & NAVIER, UNIVERSITE GUSTAVE EIFFEL); Mr TO, Quy-Dong

Presenter: Prof. LEMAITRE, Anael (Laboratoire Navier – ENPC)

Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **18** Type: **Contributed talk**

Raman spectra of a-Ta_2O_5: a first-principles analysis

Monday, 30 September 2024 15:20 (20 minutes)

We present a first-principles study of the vibrational spectra, i.e. vibrational density of states (v-DOS), infrared (IR), and Raman spectra, in amorphous tantala (a-Ta_2O_5). Model structures of upto three-hundreds atoms have been generated by means of classical and *ab-initio* molecular dynamics. An unprecedented series of *ab-initio* test calculations of the v-DOS and the IR dielectric function, with different kinds of exchange-correlation functionals and pseudopotentials, have been performed by using the Quantum Espresso package. Comparisons with available experimental data have then been carried out to select the optimal DFT setup for further investigations. Our study confirms that the vibrational modes above ~550 cm^{-1} consist mainly of Ta-O stretching motion of oxygen (O) atoms, meanwhile Ta motion gives a major contribution to the v-DOS only below ~200 cm^{-1}. In particular, the vibrational modes underlying the main Raman peak at 670 cm^{-1} are related to Ta–O bond stretching motions, and a major contribution to the peak appears to come from twofold O atoms. Finally, by means of projectional analysis we infer that vibrational modes with frequencies above 550 cm^{-1}, arise mostly from the asymmetric and symmetric stretching modes of TaO_n ($n = 5, 6, 7$) polyhedra. The latter analysis, in particular, allows to explain the origin of the experimental Raman doublet at ~830-840 and ~935-945 cm^{-1}.

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **19** Type: **Invited talk**

Machine-learning enhanced quantum state tomography and its applications to the gravitational wave detectors

Tuesday, 1 October 2024 08:30 (30 minutes)

With this talk, I will first illustrate the implementation of our machine-learning (ML) enhanced quantum state tomography (QST) for continuous variables, through the experimentally measured data generated from squeezed vacuum states, as an example of quantum machine learning. Our recent progress in applying such a ML-QST as a crucial diagnostic toolbox for applications with squeezed states, from Wigner currents, optical cat state generation, and Bayesian estimation for GWD will be reported.

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Session Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Track Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Contribution ID: **20** Type: **Contributed talk**

Two-color Einstein-Podolsky-Rosen entangled state in the sub-kHz regime

Tuesday, 1 October 2024 09:00 (20 minutes)

Since the third observation run, Quantum Noise Reduction (QNR) techniques have become fundamental for Gravitational Wave Detectors (GWDs). Various alternatives to broadband QNR are currently being investigated. Specifically, we are exploring the measurement of a GWD signal in the reference frame of an auxiliary quantum system that mimics the dynamics of a free mass and exhibits the same response to the quantum noise of light [1,2]. The scheme requires the GWD to be coupled to the quantum reference via two-color Einstein-Podolsky-Rosen (EPR) entangled beams [3], establishing a quantum channel between the detector and a cesium atomic ensemble. The atomic ensemble has the special propriety of acting as an effective negative mass oscillator, essential for the QNR [4]. In this presentation, I will describe the first generation of a two-color EPR entangled state in the sub-kHz regime. The performance improvement is obtained by generalising the coherent control scheme currently implemented in single-mode squeezing sources to the control of a two-color EPR state. This represents a significant step towards enabling the negative mass reference system approach for broadband noise reduction in GWDs.

[1] F. Ya. Khalili and E. S. Polzik. Phys. Rev. Lett. 121, 031101 (2018).
[2] E. Zeuthen, F. Ya. Khalili and E. S. Polzik. Phys. Rev. D100, 062004 (2019).
[3] T. B. Brasil et al. Nature Comm. 13, 4815 (2022).
[4] J. Jia et al. Nature Comm. 14, 6396 (2023).

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Session Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Track Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Contribution ID: **21** Type: **Contributed talk**

Contribution of the contrast defect and control sidebands to the phase noise in Advanced Virgo Plus

Tuesday, 1 October 2024 10:40 (20 minutes)

Phase noise consists into the oscillation of the squeezing angle and it is one of the mechanisms that can degrade the level of squeezing injected in gravitational wave detectors used to reduce quantum noise. This jitter can be due to several reasons. In this talk, we want to show the analysis done to evaluate the contribution given to this noise by the interferometer contrast defect and control sidebands in Advanced Virgo Plus.

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Presenter: SEQUINO, Valeria (INFN sez. Napoli, Università degli Studi di Napoli "Federico II")

Session Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Track Classification: Reduction of quantum noise in interferometric gravitational wave detectors

Contribution ID: **22** Type: **Contributed talk**

A futuristic hill-contained vertically positioned gravity decelerator spanning 2,300 meters for detection of dark matter and gravitational waves

In this paper, we delineate the engineering hurdles and envisaged an infrastructure of a newly proposed hill-contained, vertically positioned Gravity Decelerator. This decelerator possesses several attributes, specifically: (a) a 2,300 meters-long vertical vacuum tube designed for decelerating a low-energy beam of heavy ions and protons, facilitated by gravity; (b) a 12 meter diameter, Dark Matter and Gravitational Waves detectors situated at the top end of the vacuum tube; and (c) a low-energy linear accelerator for accelerating heavy ions and protons, respectively, positioned at the bottom end of the vertical vacuum tube. This newly envisioned facility aims to achieve the following objectives: (i) detection of Dark Matter; (ii) identification of low-energy Gravitational Waves; and (iii) investigation of Ordinary Matter-Dark Matter interactions.

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Session Classification: Other challenges for future GW detectors

Track Classification: Other challenges for future GW detectors

Contribution ID: **23** Type: **Contributed talk**

Theoretical modeling and experimental characterization of the light retro-reflected and/or backscattered by optical components

Tuesday, 1 October 2024 15:10 (20 minutes)

The performance of a giant interferometric detector such as Virgo or LISA can be affected by the presence of coherent stray light. In particular, it can be generated by the scattering of laser beams at the various interfaces of the instrument. It is therefore particularly important to be able to characterize in amplitude and phase the fraction of this scattered light that interacts coherently with the incident beam.
This is made possible by the BARRITON (for Back-scattering And Retro-Reflection by InterferometTry with lOw coherence) bench developed by the Light Scattering group at the Institut Fresnel. As the acronym suggests, it is a balanced detection interferometer used in white light. The white light source here is a superluminescent diode covering the spectral band between 1000 nm and 1100 nm, while the balanced detector was developed specifically for our application by the Light Detection and Analysis group at THORLABS Germany. A motorized delay line, using a hollow cube corner as a moving element, allows the optical path difference inside the interferometer to be varied, providing sequential access to the different scattering interfaces of the component under test (remember that the interferometric signal is only visible near zero path difference). The difference between the currents supplied by each of the photodiodes of the balanced receiver is converted into a voltage by a transimpedance amplifier with adjustable gain and then digitized at high speed (1 Msamples/s) by a 16-bit analog-to-digital converter. A discrete Fourier transform applied to the signals recorded near each zero optical path difference provides access to the spectrum of the corresponding backscattered light in amplitude and phase. The angular orientation and lateral position of the device under test can be changed with very high resolution movements (µm and milli-degrees).
In this paper, we present a detailed theoretical modeling of the operation of this test bench based on the use of artificial surfaces whose waviness and roughness can be independently adjusted, showing the fast variations in amplitude and phase of the signal induced by tiny changes in the position of the surface. The main conclusions of this modeling are confirmed by experimental results obtained with BARRITON on various elementary components (antireflective coated windows, silver coated mirrors, photodiodes or beam dumps).
The authors thank the AMIdex Talents Management Program, the University of Aix Marseille, and the French National Space Center (CNES) for financial support, and the Virgo Collaboration for fruitful discussions.The authors would like to thank the AMIdex Talents Management Program, Aix Marseille University, and the French National Space Center (CNES) for their financial support, and the Virgo Collaboration for fruitful discussions.

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Presenter: LEQUIME, Michel (Institut Fresnel)

Session Classification: Stray light mitigation

Track Classification: Stray light mitigation

Contribution ID: **24** Type: **Invited talk**

Measurement and identification of coherent stray light in complex interferometers

Tuesday, 1 October 2024 14:20 (30 minutes)

Stray light is an issue in any optical interference measurement, particularly in interferometric gravitational wave detectors, where stringent limits are placed on the noise floor: the control and mitigation of stray light are critical. After general considerations about stray light, this presentation will address the development underway of an instrumentation for stray light measurement at system level, where a frequency-swept laser beam is injected into the system under test, and the signals from the photoreceivers are recorded and processed. This allows to measure, and identify, the different contributions to stray light, each contribution being given by
- the optical path length difference (OPD) of stray light, with respect to the nominal beam
- its fractionnal optical amplitude, with respect to the nominal beam.

The performance of our prototype, in terms of OPD resolution, measurement floor etc., has been checked in measurements of stray light in two interferometric demonstrators, in view of its use with the Interferometric Detection System (IDS) of the LISA project.

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Presenter: LINTZ, Michel (Observatoire de la Côte d'Azur, laboratoire ARTEMIS)

Session Classification: Stray light mitigation

Track Classification: Stray light mitigation

Contribution ID: **25** Type: **Contributed talk**

The verification strategy for the LISA Gravitational Reference System

Wednesday, 2 October 2024 12:20 (20 minutes)

The Gravitational Reference System proved exceptional acceleration noise performance during the LISA Pathfinder mission. Indeed, the LISA Pathfinder mission demonstrated a performance that was better than the LISA requirements at all frequencies.

Building on the success of the LISA Pathfinder, the LISA Gravitational Reference System is being upgraded to meet the unique demands of the LISA mission. These upgrades, which span the GRS design, hardware, and on-ground verification strategies, are crucial for ensuring the system's performance and reliability in the new mission context.

We will present progress in the GRS verification plan strategy definition, focusing in particular on the characterization of the performance of capacitive sensor electrode housing (which is the hardware closer to the test mass) and the integrated tests on representative prototypes of the front-end electronics and charge management system developed for LISA.

In this regard, torsion pendulums are invaluable tools, as they can measure small forces acting on test masses along the torsional degree of freedom to a level almost comparable with the LISA requirements.

The four-test mass torsion pendulum at the University of Trento will test the newly built electrode housing for LISA. We will give an overview of the apparatus's capability regarding its sensitivity to the various classes of measurements it can perform and describe the improvements we plan to implement before the testing campaign.

Primary authors: DAL BOSCO, Davide (Istituto Nazionale di Fisica Nucleare); DOLESI, Rita (Istituto Nazionale di Fisica Nucleare); WEBER, William (Istituto Nazionale di Fisica Nucleare)

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Presenter: DAL BOSCO, Davide (Istituto Nazionale di Fisica Nucleare)

Session Classification: Other challenges for future GW detectors

Track Classification: Other challenges for future GW detectors

Contribution ID: **26** Type: **Invited talk**

Gravitational Wave space-based detectors in the post-LISA era

While LISA was entering its implementation phase, the European Space Agency identified a post-LISA gravitational wave detector as one of the possible probes for their exploration of the early universe in the 2050 time frame.

Triggered by that, a group of members of the LISA community has initiated a study, called GWSpace2050, on the possible science case and on the required technology, for such a LISA follow-on mission.

The study is exploring potential missions in all frequency ranges that are inaccessible from ground, from deep in the micro-Hz range up to the deci-Hz one.

The talk will report on the progress of these studies.

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Presenter: VITALE, Stefano (University of Trento)

Session Classification: Other challenges for future GW detectors

Track Classification: Other challenges for future GW detectors

Contribution ID: **27** Type: **Contributed talk**

Measurement of Polarization of GWs by 3G Detectors as a Test of Gravity

Tuesday, 1 October 2024 11:50 (20 minutes)

In this contribution I present the capabilities of ground-based third generation detectors to constrain the presence of non-tensor polarization modes in gravitational wave (GW) signals. These capabilities are assessed with mathematically simple figures of merit that discriminate between different theories of gravity. Different theories predict different polarization modes for GW emission by a Compact Binary Coalescence (CBC). In addition to the two tensor modes predicted by General Relativity, called $+$ and $\times$, several modified theories of gravity predict the existence of additional modes, that can be either vector or scalar. The formalism of null-streams can be used for the direct detection of such exotic polarization modes.

A null-stream is a linear combination of the measured signals, displayed as S_a for the a-th detector: $S_a = \sum_{\text{pol}} F_a^{\text{pol}} h_{\text{pol}}$, where F_a^{pol} is the detector's antenna pattern for the pol polarization mode at the location of the source. A simple null-stream is, for instance: $\text{NS} = \epsilon^{lmn} F_m^{+} F_n^{\times} S_l$, where the antenna patterns are now computed at the $estimated$ location of the source. One can easily prove that such a quantity is identically zero when only tensor modes are present, as in General Relativity, since it is given by the contraction of an antisymmetric tensor (the Levi Civita symbol) and a symmetric part; conversely, it can be non-zero when the detected strain contains non-tensor polarization modes.

We have tested the performance of the null stream as a figure of merit in the detection of non-tensor modes using a simulated population of 10^5 Binary Black Hole events. We compared the null-streams in the case of a completely GR-like signal (thus containing tensor modes only) and in the case of a deviation from GR (adding a scalar or vector mode contribution). This test has been performed both for a network of current detectors and for a network of third generation ground-based facilities, in order to investigate the enhancement future detectors would provide to this subject.

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Co-authors: Dr DHANI, Arnab (Albert Einstein Institute - Potsdam); Prof. SATHYAPRAKASH, Bangalore (Penn State University)

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Session Classification: GW and multi-messenger observational science

Track Classification: GW and multi-messenger observational science

Contribution ID: **28** Type: **Contributed talk**

Assessing the impact of metallic adhesion on the injection function of a proof mass into a geodesic trajectory

Wednesday, 2 October 2024 12:00 (20 minutes)

The design of Gravitational Reference Systems (GRS) heavily hinges on the technologies developed, such as the mechanisms in charge of securing a reference test mass (TM) during the mission launch and then releasing it into free fall.
Such mechanisms need to be tested to ensure they minimize friction, adhesion, and fretting at the contacting surfaces, since space environment provides critical conditions for cold-welding phenomena, especially with the requirements of gravitational wave science.

The case of study here dealt with analyzes the quick separation of two gold surfaces in the frame of the LISA Pathfinder (LPF) flight-tested GRS.
The mission initialization depends on the performance of a mechanism in the release of a TM into a geodesic trajectory, minimizing the residual velocity with respect to the spacecraft.
The presence of adhesion between the metallic surfaces of the release mechanism end-effector and the TM constitutes a limiting factor for the injection function, proving to be a key factor influencing the TM net residual velocity.

The experimental characterization of the momentum produced by the rupture of adhesive bonds at the separation of two metallic surfaces is a complex research activity involving system dynamics, experimental design, measurement techniques, and the modeling and measurement of mechanical vibrations. Moreover, the accurate prediction of the adhesion momentum poses a significant technological challenge since existing models in the literature fall short of providing a dependable prediction.

Therefore, at the University of Trento, a dedicated experimental facility has been developed to assess the impact of adhesion on the injection function.
The testing facility is based on a sensing body suspended in a nearly free-fall condition as a pendulum inside a vacuum chamber.
Usually, the pendulum swing mode response constitutes the main observable for the estimation of the impulse, i.e. the time integral of the adhesion force time history up to the rupture of the bonds.
In this research, the observable quantities correlated to the adhesion impulse characteristics are extended to the vibration modes of the suspended body of the pendulum, where the impulse is applied.
The proposed approach aims at developing a novel techniques based on analytical and experimental methods to measure the adhesion momentum transferred to the TM at the release.
The technique combines a numeric finite element model of the suspended pendulum, a dedicated symbolic dynamic model of its motion and a fitting procedure, improving the overall estimation performance. The multiplicity of the outputs (amplitudes of vibration) produced by the same input (adhesion impulse) is exploited to characterize additional properties of the impulse, i.e. not only the adhesion force time integral but also the impulse time duration.
This enhanced characterization approach provides valuable insights into the influence of adhesion on the injection function of a proof mass into geodesy, facilitating a deeper understanding of the adhesive bonds dynamical properties.

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Presenter: DALLA RICCA, Edoardo (Università di Trento)

Session Classification: Other challenges for future GW detectors

Track Classification: Other challenges for future GW detectors

Contribution ID: **29** Type: **Contributed talk**

Studying binary neutron star systems with future ground-based gravitational-wave detectors

Wednesday, 2 October 2024 08:30 (20 minutes)

Gravitational waves offer us a unique tool to study binary neutron star (BNS) systems and the supranuclear-dense matter that comprises these objects. The gravitational-wave signal emitted during a BNS coalescence depends on the neutron stars'properties, including their masses, spins, and tidal deformabilities. The increased sensitivity of future-generation detectors, such as the Einstein Telescope, will allow us to measure these parameters with unprecedented accuracy. I will discuss how precisely we expect to determine the properties of neutron stars with the Einstein Telescope, compare results for different proposed designs of the detector, and show how we can use this information to place constraints on the underlying equation of state of dense matter. Additionally, I will present a new tool, based on machine learning techniques, that allows us to predict the postmerger remnant of a BNS system—e.g., whether it undergoes a prompt collapse or not—based on the binary system's parameters inferred from gravitational-wave inspiral signals.

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Presenter: PUECHER, Anna (University Potsdam)

Session Classification: GW and multi-messenger observational science

Track Classification: GW and multi-messenger observational science

Contribution ID: **33** Type: **Contributed talk**

Prospects for kilonovae detections with the next generation multi-messenger observatories

Wednesday, 2 October 2024 08:50 (20 minutes)

The detection of the gravitational wave (GW) signal GW170817 and the electromagnetic (EM) signal AT2017gfo confirmed the association between binary neutron star (BNS) mergers and kilonovae (KNe) and showed the potential of joint detection to unveil the nature of neutron stars and the nucleosynthesis of heavy elements in the Universe. The next-generation GW interferometers, such as the Einstein Telescope (ET), are unprecedented resources to enhance the chances of detecting EM counterparts significantly enlarging the horizon of detectable BNS mergers, and dramatically improving the source parameter estimation. Starting from BNS merger populations based on population synthesis codes, we compute the number of detected mergers and estimate the source parameters for different configurations of ET operating alone or in a network of present or next-generation GW detectors. We compute the KN emission associated with the BNS merger population for two different nuclear equations of state, considering the influence of black hole prompt collapse on the kilonova signal. Furthermore, we include the emission from the afterglows of short gamma-ray bursts. In the talk, I will discuss the perspectives for KNe detections with ET observing in synergy with the Vera Rubin Observatory, taking into account the present uncertainties on the rate of BNS mergers, neutron star mass distribution, and nuclear equation of state.

Primary authors: LOFFREDO, Eleonora (INAF-OAAB); LOFFREDO, Eleonora

Presenter: LOFFREDO, Eleonora

Session Classification: GW and multi-messenger observational science

Track Classification: GW and multi-messenger observational science

Contribution ID: **34** Type: **Contributed talk**

Surface properties of gold coated surfaces used in the discharge system of LISA.

Monday, 30 September 2024 18:10 (20 minutes)

LISA will integrate in the gravitational reference system (GRS) an ultra-violet (UV) illumination device that will avoid excessive charge build-up on the test masses (TM) by producing appropriate photoelectron currents.
The properties of the gold-coated surfaces of the TM, and of the electrode housing that surrounds it, play a crucial role in determining the performance of this discharge system: surface work function, roughness, polycrystal orientation, adsorbed contaminants on surface etc… are examples of parameters relevant for the photoemission process. Equally important are their variability as a consequence of manufacturing, manipulations during the inevitable assembly phases in air, the exposure to desorbed molecular species during bake-out processes, and during the planned storage for many years, until exposure to vacuum in flight.
Understanding if surfaces during these processes maintain the same characteristics regarding photo emissivity, as well between on ground test and flight model, is of importance and in case determinate the principal surface parameters responsible of photo emissivity change.
We present here the ongoing investigation of the information offered by several surface characterization techniques that we are considering, with the aim of improving the reliability of the surface monitoring strategies to be implemented from the initial GRS manufacturing phases of the first prototypes, up to the flight models.

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Presenter: KLASER, Teodoro (Università degli studi di Trento)

Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **35** Type: **Contributed talk**

FemtoNewton forces and their origin: understanding the LISA Pathfinder performance

Wednesday, 2 October 2024 11:40 (20 minutes)

One of the key elements for LISA to achieve the required sensitivity for gravitational wave detection is the nearly geodesic free-fall of the test masses, down to a sub-femto-g performance at milliHertz frequencies. LISA Pathfinder, which surpassed its requirements and achieved the LISA ones, represents an important benchmark in this context.
We will review the latest advances in the understanding of the physics behind the LISA Pathfinder acceleration performance: its stability during the mission, the impact of the identified noise sources, and their evolution in time.

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Presenter: SALA, Lorenzo (UniTrento/INFN/TIFPA)

Session Classification: Other challenges for future GW detectors

Track Classification: Other challenges for future GW detectors

Contribution ID: **36** Type: **Contributed talk**

Stray light noise from dust particles in GW interferometers

Tuesday, 1 October 2024 15:50 (20 minutes)

High cleanliness levels are a prerequisite for GW detectors with laser interferometers: this can guarantee that light scattering is minimized and under control as being limited by the quality of the optical components. Assessing the cleanliness requirements involves sizing the stray light noise added by dust particles deposited on the optical components or floating and crossing the light beams. We report about the work we have done towards this goal for the case of the Einstein Telescope. We discuss the relevant parameters determining the scattering properties of dust particles; then we describe both the analytical and numerical work to predict the dust-originated stray light noise in the detector, as well as the experimental work to verify our studies. Finally we report about the work we carry out for the Virgo interferometer to monitor the evolution in time of the cleanliness in several of its environments.

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Presenter: CONTI, Livia (Istituto Nazionale di Fisica Nucleare)

Session Classification: Stray light mitigation

Track Classification: Stray light mitigation

Contribution ID: **37** Type: **Contributed talk**

Internal friction of silica membranes at high frequencies

Monday, 30 September 2024 16:50 (20 minutes)

Knowledge of the frequency-dependence of the acoustic attenuation in structural glasses is necessary to understand their universal low temperature thermal properties. However, very little experimental information is currently available on the vibrational properties of glasses in the frequency range between 100 GHz and 1 THz, corresponding to the temperature range relevant for these thermal anomalies. I will present recent results on the sound attenuation of vitreous silica probed by the extreme ultraviolet transient grating technique now available at the Fermi free electron laser [1]. The recently developed method is based on a four-wave mixing scheme, where two pump beams generate a transient grating, whose decay is detected by the appropriately delayed probe pulse. The technique allowed us to investigate the propagation and damping of sound waves in silica membranes 100 nm thick, in a large frequency interval between 50 and 400 GHz [2]. The method can be applied to other thin films of interest for gravitational wave detectors, both in the form of freestanding membranes or deposited on a substrate. We will show some preliminary results on films of pure tantala and present ideas for future developments.

[1] L. Foglia *et al.*, Photoacoustics **29**, 100453 (2023).
[2] D. Fainozzi *et al.*, APL Mater. **12**, 051122 (2024).

Primary author: BALDI, Giacomo (Istituto Nazionale di Fisica Nucleare)

Presenter: BALDI, Giacomo (Istituto Nazionale di Fisica Nucleare)

Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **38** Type: **Contributed talk**

Characterization of Amorphous Silica Coatings for Gravitational Wave Detectors: A Multitechnique Spectroscopic Approach

Monday, 30 September 2024 15:40 (20 minutes)

Amorphous silica coatings play a crucial role as mirror components in gravitational wave detectors, such as those used in the Virgo experiment at the European Observatory in Cascina (PI, Italy). Exceptionally high sensitivity is required for the detection of gravitational waves and thermal noise from mirror coatings is one of the main limiting factors in the spectral region where the detector is most sensitive [1]. The main challenge is to identify new materials and define the deposition and post-deposition procedures that ensure thermal noise reduction. In this context, silica is one of the most advantageous materials, and a thorough characterization of its properties would be highly advantageous. Possible tools to obtain structural information and detect the presence of impurities on thin films are specular reflection (SR) and attenuated total reflection (ATR) IR spectroscopic techniques [2]. In our work, these two approaches are employed to analyse amorphous silica coatings produced by ion-beam spattering on a silicon and SiO2 substrates, and treated after deposition at different annealing temperatures, from 500℃ to 1000℃. We highlight how such techniques can be applied to the structural analysis of thin films of nanometric thickness. In particular, we demonstrate how spectroscopic techniques are powerful tools to detect impurities and inhomogeneities. In addition, they provide estimates of effects induced by annealing on the complex refractive index and the effective thickness of the film. To this end, the results of IR measurements are discussed and compared to those obtained by Brillouin scattering, Scanning Electron Microscopy and Spectroscopic Ellipsometry. A multitechnique approach allowed us to provide a comprehensive overview of the properties of silica coatings, highlighting new points for discussion.

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **39** Type: **Invited talk**

Gravitational-wave astronomy in the 2030s: prospects and challenges for data analysis

Wednesday, 2 October 2024 09:10 (30 minutes)

The fourth observing run of the LIGO-Virgo-KAGRA network of gravitational-wave (GW) detectors is ongoing and will add a significant number of compact binary mergers to the catalogs of GW transient observations. This is expected to further advance our understanding of astrophysics, cosmology and fundamental physics. The current network of interferometers is expected to reach design sensitivity in the late 2020s, with future directions of GW astronomy from the ground and in space already in advanced planning stages. In this talk, I will give an overview of state-of-the-art techniques currently employed for the analysis of LIGO-Virgo-KAGRA data, and provide an outlook on the significant challenges that still need to be overcome on the road to data analysis with third-generation GW instruments like LISA and the Einstein Telescope.

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Session Classification: GW and multi-messenger observational science

Track Classification: GW and multi-messenger observational science

Contribution ID: **40** Type: **Contributed talk**

A Deep Learning Powered Numerical Relativity Surrogate for Binary Black Hole Waveforms

Tuesday, 1 October 2024 12:10 (20 minutes)

Gravitational wave approximants are extremely useful tools in gravitational wave astronomy. By skipping the full evolution of numerical relativity waveforms, their usage allows for dense coverage of the parameter space of binary black hole (BBH) mergers for purposes of parameter inference, or, more generally, match filtering tasks. However, these benefits come at a slight cost to accuracy when compared to numerical relativity waveforms, depending on the approach. One way to minimize this is by constructing so-called \textit{surrogate models} which, instead of using approximate physics or phenomenological formulae, rather interpolate within the space of numerical relativity waveforms. In this work, we introduce NRSurNN3dq4, a surrogate model for non-precessing BBH merger waveforms powered by neural networks. This approximant is extremely fast and competitively accurate: it can generate to the order of tens of thousands of waveforms in a tenth of a second, and mismatches with numerical relativity waveforms are restrained below 10^{-3}. We implement this approximant within the \texttt{bilby} framework for gravitational wave parameter inference, and show that it obtains good performance for parameter estimation tasks.

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Session Classification: GW and multi-messenger observational science

Track Classification: GW and multi-messenger observational science

Contribution ID: **41** Type: **Contributed talk**

High Power is Nothing Without Control: Tackling Thermal Aberrations in Future GW Detectors

Wednesday, 2 October 2024 10:00 (20 minutes)

Almost all future plans for gravitational wave detectors foresee operation at increasingly higher power levels to reduce shot noise, making residual aberrations from thermal effects more critical, potentially becoming a limiting factor despite the effectiveness of current correction methods.
Since the beginning of the Virgo project, we made significant strides in mitigating thermally-induced aberrations, which pose a key challenge for maintaining interferometric stability and sensitivity. These aberrations, primarily caused by thermal effects in the optics, affect the main laser beam and degrade detector performance. By analyzing the techniques employed to correct these aberrations during O4 and the long commissioning experience, we can identify potential critical elements for future operations.
To address these challenges, we are actively refining thermal compensation systems, improving real-time monitoring and control of non-axisymmetric or non-spherical residual aberrations, and developing more advanced adaptive optics. These innovations aim to enhance the detector's resilience to thermal disturbances, ensuring that future runs, such as O5 and beyond, operate at peak sensitivity. We present the landscape of hints gathered from current experience that point to possible future issues, providing a picture of the status of developing solutions.

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Session Classification: Other challenges for future GW detectors

Track Classification: Other challenges for future GW detectors

Contribution ID: **42** Type: **Contributed talk**

Development of femtoAmpere photo-current measurement facility in preparation of LISA Charge Management System end-to-end discharge test

Monday, 30 September 2024 17:50 (20 minutes)

We are developing and tuning a facility to support the end-to-end discharge test campaign, part of the LISA Gravitational Reference System(GRS) test campaign, which probes directly the photo-current produced by UV illumination of the Test Mass and Electrode Housing via an electrometer. LISA Test Masses will be subject to collisions from charged space particles with energies >100 MeV, which penetrate into the spacecraft. These produce a net positive charging rate on each Test Mass λ = 1-100 e/s(1-100 aA), depending on solar activity. LISA acceleration noise budget requires |QTM| $<$ 2.4 pC, assuming as a baseline the measured net charging rate of LPF λ = 25 e/s(4 aA). A Test Mass will reach this limit in 14 days, so discharging the Test Masses is fundamental to assure the success of the mission. The Charge Management System(CMS) consist of UV leds at ~4.9 eV, that shining the AU-coated surface frees low energy electrons, produce a negative charge flux which counters the effect of the Test Mass positive charging rate. The facility consists of a LPF Electrode Housing replica and an hollow Test Mass, kept in vacuum and connected to an electrical interface that controls the Electrode Housing end electrodes voltage biases and to the electrometer. Here I show how this facility can probe directly the discharge current with resolution at ~1 fA and how this kind of setup can replicate the in-flight electrical conditions. The technique developed with this facility will become the guideline for the end to end tests that will be part of the LISA GRS testing campaign from the engineering model to the integrated flight model of the GRS Head.

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **43** Type: **Contributed talk**

Design and testing of an improved LISA grabbing, positioning and release mechanism

Wednesday, 2 October 2024 12:40 (20 minutes)

LISA will be the first gravitational waves observer in space, consisting of three spacecraft in a triangular formation trailing the Earth along its orbit. Within each spacecraft, two gravitational reference sensors (GRSs) enclose cubic test masses (TMs), which are free-falling during the science phase. Besides providing a safe environment for the TM, shielding it from non-gravitational forces, the GRS includes the mechatronic system responsible for the TM handling during non-science phases.
The grabbing, positioning, and release mechanism (GPRM) is responsible for the TM injection into its geodesic trajectory, which is pivotal for the start of the science phase. It is composed of two symmetric units located at two opposite sides of the GRS, actuating two cylindrical-shaped end effectors (fingers) designed to grab and center the TM inside its housing. Starting from the grabbed configuration, in which the two fingers hold the TM, two small tips, coaxial to the fingers, are extended towards the TM, while the fingers are retracted, maintaining an ideally constant preload on the TM. Thanks to this procedure, called handover, the TM is held by the GPRM tips with a reduced contact area and holding force prior to the release. The TM release to the geodesic trajectory is performed by means of a simultaneous and rapid retraction of the two tips, followed by the retraction of the fingers.
The GPRM flown in LISA Pathfinder (LPF) showed an unexpected performance, consisting in a large TM velocity, non-compliant with the requirements. Analyzing the LPF telemetry data, the most consolidated hypothesis for the non-compliance of the mechanism is associated to unexpected impacts between the mechanism fingers and the TM at the release. Indeed, at the end of the handover, the nominal gap between the fingers and the TM is equal to 10 μm only. Moreover, alignment tolerances, mechanism vibrations and anomalous motion of the end effector easily reduce the available gap and dramatically increase the risk of impacts. An intense research activity is focused on the identification of the main parameters which concur in the gap erosion and on the exploration of possible strategies to mitigate the non-compliance.
Possible improvements of the GPRM for LISA are focused on increasing the nominal gap and on limiting the non-ideal motion of the fingers. As a first step in this direction, the improving strategies are embedded in a breadboard of the mechanism, which has been tested at the University of Trento. The results of the testing gave important guidelines to increase the mechanism performance in view of LISA.

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Session Classification: Other challenges for future GW detectors

Track Classification: Other challenges for future GW detectors

Contribution ID: **44** Type: **Contributed talk**

Measuring coating loss angle in thermoelsatic-dominated crystalline substrates for new generation gravitational wave detectors

Monday, 30 September 2024 17:10 (20 minutes)

Coatings of materials with low optical and mechanical losses find prominent application in present terrestrial interferometric gravitational-wave detectors. The mirrors of the interferometers currently consist of fused silica substrates coated with stacks of alternating layers of amorphous silica and titania-tantala mixing. Research and development of novel materials is very active, since a major limitation to the sensitivity of the detectors in the middle-frequency range (40 - 400 Hz) is due to thermal noise within the coating, which is directly related to its mechanical loss angle. For the new generation of detectors, operating at cryogenic temperatures, crystalline substrates and coatings are also being explored; they present unique challenges with respect to the metrology of mechanical loss angle, since the loss in the sample substrates is dominated by thermoelastic dissipation.

The usual method of loss angle measurement in a coating is based on the stationarity of the substrate: the characteristics of the substrate do not depend on the presence of the film. However, the thermoelastic contribution to the dissipation in a substrate, after coating deposition, is influenced by the thermo-mechanical parameters of the film, which are generally unknown. Therefore, whenever thermoelastic loss is dominant, the loss measurements are significantly affected.

We develop a model that helps to understand the role of each material property in the thermoelasticity of layered plates, and based on this we identify three possible cases in which any coating-substrate combination could be classified. This allows an estimation of the expected change in thermoelastic loss after coating deposition, and enables the careful choice of the best sample geometry in order to minimize it, a choice that can be tailored for each specific material combination.

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **45** Type: **Contributed talk**

Reduction of mirror coating thermal noise via thermal treatment and material optimization.

Monday, 30 September 2024 14:40 (20 minutes)

Reducing coating thermal noise (CTN) in mirrors for gravitational wave (GW) interferometers is pivotal to improve sensitivity in the mid-frequency range. Mirror coatings are Bragg's mirrors alternating between high and low refractive index layers.
Commonly, amorphous coatings are heat-treated post-deposition in order to both reduce their internal strains and improve their optical quality. The current standard treatment for GW coatings consists in a 10 hours thermal annealing at 500℃. Treating the samples at higher temperatures and/or for longer annealing times may lower the mechanical losses of the samples but it may also lead to the formation of crystalline regions inside the coating, which are generally considered detrimental from the optical point of view. It is however not clear to what point the annealing procedure can be pushed in order to achieve the best performances, eventually allowing for the presence of a small amount of crystallized material.
In this work we present two examples of two different approaches used to reduce CTN.
The first case consists in performing controlled thermal annealing treatments on amorphous tantalum oxide (tantala, Ta2O5) thin films in order to achieve varying degrees of crystallized fraction. After thermal treatment, the amorphous films comprise randomly distributed crystalline grains, whose density and average size depends on the duration of thermal treatment. When assessing mechanical losses via a Gentle Nodal Suspension (GeNS) system, we detect a substantial reduction in the coating's mechanical loss angle with respect to unannealed amorphous coatings. This reduction in mechanical losses however, comes at the expense of a strong increase in optical scattering.
The second approach consists in test-annealing amorphous HfO2:Ta2O5 thin films with different HfO2 concentrations. The inclusion of HfO2 increases the material's crystallization temperature, allowing us to push further the annealing temperature without experiencing crystallization. We found an optimal HfO2 molar concentration for our material at the 60% concentration allowing the film to be treated at 800℃ for 10 hours. We then used this material to deposit a multilayer mirror and measure its CTN as a function of annealing temperature. We observe a dramatic decrease in CTN due to annealing, showing the potential of HfO2:Ta2O5 as candidate for future GW mirrors coatings.

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **46** Type: **Invited talk**

Mirror coatings for next-generation detectors: what do we need

Monday, 30 September 2024 13:50 (30 minutes)

US-based next-generation gravitational wave detectors can currently be divided in two implementations: A# will feature 100 kg test masses and should operate at room temperature (RT), while Cosmic Explorer (CE) should feature even 320 kg test masses, and laser power reaching 1.5 MW in the arms, with its first incarnation operating at RT. In the former, sensitivity limits in the most sensitive frequency range will be dominated by coating thermal noise (CTN) if the dielectric Bragg reflectors (DBRs) consist of the amorphous materials used in current detectors, so solutions to radically decrease that noise must be identified. Various amorphous mixtures and treatments have been attempted, with some success, together with a deeper understanding of the features of a good material at the atomic scale, but improvements to the CTN by almost an order of magnitude are required to make it insignificant compared to other noises. We will discuss two approaches: the GaAs-based approach, and the one based on silicon-on-insulator (SOI). Then, because of its characteristics, especially the arm's length, the DBRs for the CE could consist of the current materials, but also because of its size, tolerances on mirror deformation will be much more stringent, and materials featuring absorption below 0.1 ppm might be needed, with very few defects, on mirrors that may have more than 800 mm in diameter. The question therefore arises: how to achieve that, how to measure low absorption and achieve it on such a large area without defects.

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Session Classification: Coating and Materials

Track Classification: Coatings and Materials

Contribution ID: **47** Type: **Invited talk**

Quantum superfluids as analog models of gravity: a fruitful synergy of gravity and quantum optics

Wednesday, 2 October 2024 11:10 (30 minutes)

In this talk, I will present the state of the art and the new perspectives in the theoretical and experimental study of analog models of quantum field theories in flat, curved, or time-dependent backgrounds using condensed matter and optical systems.

I will start with a brief presentation of the general concept of analog mode and a review of milestone theoretical and experimental works on Hawkingemission of phonons from acoustic horizons in trans-sonic flows of ultracold atoms.

I will proceed by reviewing the on-going investigations in the direction of observing back-reaction effects of the quantum field onto the background, both in single-mode circuit-QED configurations simulating Dynamical Casimir Effect and in multi-mode cold-atom platforms simulating the so-called preheating state of the early Universe at the end of inflation. New decoherence processes will be highlighted, also in connection with the outstanding problem of black hole evaporation.

I will conclude with an outline of a joint theoretical-experimental effort that is on-going at the BECCenter on false vacuum decay processes: I will present experimental evidence of the decay of an extended metastable state via the nucleation of spatially localized bubbles in a two-component atomic superfluid and I will review a numerical MonteCarlo wavefunction study of the role of coupling to the environment in speeding up the false vacuum decay in monitored quantum systems.

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Session Classification: Other challenges for future GW detectors

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