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Semiannual report of MSU group
January 2003 — June 2003

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The researches were supported by NSF grant PHY0098715
"Low noise suspensions and readout systems for LIGO"
(July 2001 – June 2004)

Moscow 2003

Contents

1	Experimental researches	2
1.1	Measurements of variation of electric charge on a prototype of fused silica test mass of gravitational wave antenna	2
1.2	Measurement of thermal and excess noise in high-Q modes of all fused silica suspension	2
1.3	Investigations of the mirror coating properties	3
1.4	Thermorefractive noise in microspheres	4
2	Theoretical researches	4
2.1	Thermoelastic noise in the mirror coating	4
2.2	Low pumping energy mode of the “optical bars”/“optical lever” topologies of gravitational-wave antennae	4
3	Collaboration with LIGO	5
3.1	The results of collaboration between the MSU group and Kip Thorne’s group	5
3.2	Interaction of the MSU group and the LIGO team	6

1 Experimental researches

1.1 Measurements of variation of electric charge on a prototype of fused silica test mass of gravitational wave antenna

V.P. Mitrofanov, K.V. Tokmakov and postgraduate student L.G. Prokhorov in the collaboration with Phil Williams (Caltech) continued long-term measurements of variations of electric charge located on the fused silica test mass prototype. Electric charges located on the test masses may vary in part due to adsorption-desorption processes that occur on their surface, due to cosmic and background radiation and other processes. Variation of electric charge can produce the additional fluctuating force acting on the test mass due to electrostatic interaction with surrounding surfaces. In this way variation of electric charge could be potential source of excess noise. In this experiment they have carried out the investigation of correlations between the changes of the electric charge and the flux of cosmic rays. The measurement of electric charge was realized using the capacitive probe connected with high impedance electrometric amplifier. The detectors of cosmic rays (11 scintillation paddles supplied by photomultipliers) were installed around the vacuum tank.

Four new runs of measurements (each run had duration of about one month) have been carried out. During one run the amplitude of free torsion oscillation of the suspended cylinder (the relaxation time $\tau^* \approx 2.2 \times 10^7$ s) decreased by about 15%. This allowed the long-term continuous monitoring of the charge after initial excitation of the oscillation amplitude. The signal from the probe showed the slow change of the charge corresponding to the negative charging of the test mass surface with average approximate rate of the order of 10^4 e/cm²/day.

In one of the new runs they have observed cascades of jumps of the signal from the capacitive probe, which were synchronous with jumps of the test mass oscillation amplitude. Before observing the jumps (between the runs) DC electric voltage $U = 1.5$ kV was applied to the electrodes of the probe. It was routine procedure to control the state of surface of silica test mass according to results [1]. It was supposed that the exposition of fused silica test mass in electric field influent on the state of the system "fused silica pendulum and nearby electrodes". Observing jumps appear as a result of the change of state of the system. It is likely that surface properties of the suspended fused silica sample play a crucial role. Application of electric field is only one of the factors which might change the state of the system.

They have not found statistically significant coincidences between bursts of signals of the cosmic ray detectors and jumps of charge and amplitude in this state of the test mass. This fact does not prove that cosmic rays were not related to jumps of charge at all.

This work is in progress now.

The results of this work will be reported at 5-th Amaldi conference [2].

1.2 Measurement of thermal and excess noise in high-Q modes of all fused silica suspension

Different kind of random mechanical oscillations in violin modes of the suspension may give substantial contribution to the total noise budget because these oscillations act directly on the test masses. In previous grants this kind of noise in steel wires (used in initial LIGO) were registered and analyzed in-depth. Those measurements have shown

the existence of ordinary Brownian component and also of the excess noise additional to Brownian. The last one depends sharply on the stress in wires. The violin Q's in those experiments were of order 5×10^4 , the sensitivity of optical readout meter (based on Michelson interferometer scheme) was 2×10^{-11} cm/ $\sqrt{\text{Hz}}$ near the frequency of observation ~ 2 KHz.

During the first part of the year 2003 I.A.Bilenko and his postgraduate student N.Yu.Markova completed several improvements of the Fabry-Perot cavity based installation, prepared for the measurement of thermal and excess noise in high-Q modes of all fused silica suspension prototypes. The anti-seismic filter now includes multispring stage for vertical degree of freedom (eigen frequency is about 2 Hz) and vibration damper used samarium-cobalt magnets. New ultra low noise preamplifier was placed inside the vacuum chamber, nearby the photodetector. Some modifications of the mechanical parts were made in order to reduce stress in junctions. As a result, the sensitivity reached value $S_x = 3 \times 10^{-13}$ cm/ $\sqrt{\text{Hz}}$ near the frequency 1 kHz and $S_x < 9 \times 10^{-14}$ cm/ $\sqrt{\text{Hz}}$ at frequencies higher than 2 kHz. These values even slightly exceed requirements declared in the grant proposal.

In order to check the measurement system for presence of internal excess noise sources series of test records have been done. For these tests sample fiber with a small mirror was replaced by a large fixed mirror. The analysis of the obtained data shows absence of any significant excess noise.

In the April 2003 the recording of mechanical noise in the high quality modes of the fused silica fibers was started. To date 10 different samples have been tested, about 40 hours of records obtained. Applied strain varies from 3% to 15% of breaking point. Signal-to-noise ratio in the 10 Hz bandwidth (near the mode frequency) varies from 10 to 100 depending on the applied stress. Measured quality factors varied from 5×10^6 to 2×10^7 . After the application of vetoing procedure based on the seismic and other control channels information, the distribution of the amplitude variation appeared to be pure exponential. All data at these measurements were sampled with $\tau = 0.2$ s rate, that allows to resolve the amplitude variations $\delta A \simeq A \times \sqrt{2\tau/\tau^*} = 2 \times 10^{-2} A$ (here A is a mean value of amplitude of thermal fluctuations). Value of the variation shows that only Brownian noise was observed till now.

1.3 Investigations of the mirror coating properties

The analysis of the thermoelastic noise in the mirror coating has shown (see details in part 2.1 of the proposal) that the value of thermal expansion coefficient α of Ta_2O_5 which is used in the multilayer coating is crucially important. At the same time the measured values of $\alpha_{\text{Ta}_2\text{O}_5}$ published by independent experimentalists are very contradictory (from $-4 \times 10^{-5} \text{ K}^{-1}$ to $+3.6 \times 10^{-6} \text{ K}^{-1}$). This circumstance forced direct measurement $\alpha_{\text{Ta}_2\text{O}_5}$ value in the multilayer coating identical to one planned to be in use for Advanced LIGO mirrors (19 pairs of quarter-wavelength Ta_2O_5 - SiO_2 layers). This measurement was carried out by postgraduate student A.A.Samoilenko. The bend of $100 \mu\text{m}$ thick plate, one side of which was covered with this coating, was measured while the plate was heated. The obtained value $\alpha_{\text{Ta}_2\text{O}_5} = +(5 \pm 1) \times 10^{-6} \text{ K}^{-1}$ permits to expect, that in advanced LIGO project the value of sensitivity which corresponds to SQL may be reached (see details in [3]).

1.4 Thermorefractive noise in microspheres

Michael L. Gorodetsky has reported his results with a student I. Grudin on the measurement of thermorefractive noise in a test system - optical microspheres on the conference Photonics West-2003 in San-Jose CA. The manuscript that was attached to the previous report will be published in Proc. of SPIE 4969 [4]. Full scale article is prepared for publication.

2 Theoretical researches

2.1 Thermoelastic noise in the mirror coating

During the previous grant members of MSU group M. L. Gorodetsky and S. P. Vyatchanin carried out an in-depth analysis of the role of thermoelastic and thermorefractive noises in the mirrors [5, 6]. The practical consequence of this analysis was the reconsideration of the appropriate value of the laser spot diameter on the mirror: instead of 3 cm the diameter of the spot will be $10 \div 15$ cm. In this analysis the thermoelastic noise in the mirror coating was ignored. During last year of the current grant S. P. Vyatchanin analyzed the contribution of the thermoelastic noise in the coating into the total noise budget. This analysis shown that the numerical value of the thermal expansion coefficient of Ta_2O_5 (material used in the coating) is playing a crucial role. This circumstance stimulates an experiment performed by A. A. Samoilenko which is briefly described in section 1.3 of this proposal. The value of thermal expansion coefficient $\alpha_{Ta_2O_5}$ obtained by A. A. Samoilenko and the formulas derived by S. P. Vyatchanin permit to predict that thermoelastic noise in the coatings used today will limit that sensitivity of Advanced LIGO (in units of metric variation) between $0.6 \times 10^{-24} \text{ Hz}^{-1/2}$ and $1.4 \times 10^{-24} \text{ Hz}^{-1/2}$. These values indicate that taking into account only this type of noise the SQL may be reached in LIGO-II (see details in [7]). At the same time higher sensitivity (better than SQL) may be obtained only with substantial changes in the coating technology.

2.2 Low pumping energy mode of the “optical bars”/“optical lever” topologies of gravitational-wave antennae

The “optical bars”/“optical lever” intracavity topologies of gravitational-wave antennae [8, 9, 10, 11] allow to obtain sensitivity better that the Standard Quantum Limit while keeping the optical pumping energy in the antenna relatively low. In particular, they allow to overcome the Energetic Quantum Limit

$$\mathcal{E} = \frac{\mathcal{E}_{\text{SQL}} \zeta^2}{2\xi^2}. \quad (1)$$

Here \mathcal{E} is the minimal optical energy which have to be stored in the interferometer arms in order to obtain given sensitivity, ξ is the ratio of the signal amplitude which can be detected to the amplitude corresponding to the Standard Quantum Limit (the smaller is ξ the better is the sensitivity), and ζ is the squeezing factor ($\zeta = 1$ for the optical field coherent quantum state and $\zeta < 1$ for the squeezed state), \mathcal{E}_{SQL} is the optimal energy for the SQL-limited interferometric antenna. In the case of the Advanced LIGO values of the antenna parameters $\mathcal{E}_{\text{SQL}} \approx 40$ J. Corresponding circulating optical pumping power

is equal to $W_{\text{SQL}} \approx 0.75 \text{ MW}$. In the intracavity topologies the necessary non-classical quantum state of the optical field [factor ζ in the formula (1)] is generated automatically and therefore the pumping energy does not depend directly on the required sensitivity.

In the “optical bars”/“optical lever” schemes the optical field acts as a two rigid springs located between of the antenna end mirrors and additional local mirror placed between them. It was shown that if optical energy exceeds some threshold value of $\mathcal{E}_{\text{thres}}$ then these springs are rigid enough to provide the signal displacement of the local mirror equal to the displacement of the end mirrors (see [9]). In this case the sensitivity does not depend on the optical energy and is defined by the sensitivity of the local meter which monitors the local mirrors position. However, it was concluded that the threshold energy have to be rather large and close to \mathcal{E}_{SQL} (see [9]). At the same time if a local meter with cross-correlated measurement noise and back-action noise is used then the threshold energy can be substantially lower than the \mathcal{E}_{SQL} (see [10]).

This cross-correlation regime is analyzed in detail in the article [12]

It was shown that if SQL-limited local meter is used, then sensitivity of the antenna will be limited by the Standard Quantum Limit for the heavy end mirrors. Pumping energy in this case have to be several times smaller than \mathcal{E}_{SQL} . Typical energy (for the Advanced LIGO values of parameters) can be equal to

$$\mathcal{E} \approx 0.25 \mathcal{E}_{\text{SQL}}. \quad (2)$$

The local mirror mass in this case have to be equal to $m \approx 0.25 \text{ g}$.

Substantially better results can be obtained if QND local meter, for example Stroboscopic-Variation meter [13] is used. In this case the pumping energy is limited by internal losses in the optical cavities only, and sensitivity can be several times better than the SQL.

Estimates show that for values of parameters available for contemporary and planned gravitational-wave antennae, sensitivity about one order of magnitude better than the Standard Quantum Limit can be obtained using the pumping energy about one order of magnitude smaller energy than is required in the traditional topology in order to obtain the Standard Quantum Limit level of sensitivity. Values of the local mirror mass in this case can vary in wide range ($\approx 10\text{g} \div 10\text{Kg}$) and should be chosen considering technological reasons.

3 Collaboration with LIGO

3.1 The results of collaboration between the MSU group and Kip Thorne’s group

Members of MSU group together with Kip Thorne have done a detailed analysis of quantum classical-force measurement. It was shown that photon shot noise and radiation-pressure back-action noise are the sole forms of quantum noise in interferometric gravitational wave detectors that operate near or below the Standard Quantum Limit, if one filters the interferometer output appropriately. No additional noise arises from the test masses’ initial quantum state or from reduction of the test-mass state due to measurement of the interferometer output or from the uncertainty principle associated with the test-mass state. See details in [14].

3.2 Interaction of the MSU group and the LIGO team

The members of MSU group in the collaboration with member of LIGO Lab P. Williems (Caltech) continued long-term measurements of variations of electric charge located on the fused silica test mass prototype.

The members of MSU group together with members of LIGO Lab W. Kells and E. D'Ambrosio formulated recommendations for experimental program in LIGO-I which might detect the precursors of parametric instability.

The member of MSU group with members of LIGO Lab M.M. Fejer and S. Rowan have analyzed thermoelastic noises in mirror's coating. The joined paper is submitted for publication [15].

During his stay in California M.L.Gorodetsky met with P.Willems from LIGO Lab and they were working on the joined new paper (M.L.Gorodetsky, S.P.Vyatchanin, P.Willems) on thermorefractive noise and electrocaloric effect.

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