Appendix 1

Form No. 24

THE PRECISION LASER METROLOGY
FOR ACCELERATORS AND DETECTOR COMPLEXES

THEME **02-0-1127-2016/2021**

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DATE OF SUBMISSION OF PROPOSAL OF PROJECT TO SOD _________

DATE OF THE LABORATORY STC _________ DOCUMENT NUMBER _________

STARTING DATE OF PROJECT _________

(FOR EXTENSION OF PROJECT — DATE OF ITS FIRST APPROVAL) _________

Appendix 2

Form No. 25

PROJECT ENDORSEMENT LIST

FULL TITLE OF PROJECT

CODE NAME OF PROJECT OR COLLABORATION

CODE OF THEME

NAME OF PROJECT LEADER

APPROVED BY JINR DIRECTOR	SIGNATURE	DATE
ENDORSED BY		
JINR VICE-DIRECTOR	SIGNATURE	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	DATE
CHIEF ENGINEER	SIGNATURE	DATE
HEAD OF SCIENCE ORGANIZATION DEPARTMENT	SIGNATURE	DATE
LABORATORY DIRECTOR	SIGNATURE	DATE
LABORATORY CHIEF ENGINEER	SIGNATURE	DATE
PROJECT LEADER	SIGNATURE	DATE
PROJECT DEPUTY LEADERS	SIGNATURE	DATE
ENDORSED		
RESPECTIVE PAC	SIGNATURE	DATE

Appendix 3

Form No. 26

Schedule proposal and resources required for the implementation of the Project

THE PRECISION LASER METROLOGY

FOR ACCELERATORS AND DETECTOR COMPLEXES

<table>
<tr><th colspan="3" rowspan="2">Expenditures, resources, financing sources</th><th rowspan="2">Costs (k$)
Resource requirements</th><th colspan="3">Proposals of the Laboratory on the distribution of finances and resources</th></tr>
<tr><th>1st year
2019</th><th>2nd year
2020</th><th>3rd year
2021</th></tr>
<tr><td colspan="2">Expenditures</td><td>1. Precision Laser Inclinometer (PLI)
2. Interferometric Distance Meter (IDM)
3. Laser Fiducial Line (LFL)
4. Seismically-stabilized Research Platform (SRP)</td><td>68
106
139
34</td><td>24
36
48
12</td><td>23
34
45
11</td><td>21
36
46
11</td></tr>
<tr><td>Required resources</td><td>Standard hour</td><td>Resources of
– Laboratory design bureau;
– JINR Experimental Workshop;
– Laboratory experimental facilities division;
– accelerator;
– computer.
Operating costs.</td><td>998</td><td>358</td><td>319</td><td>321</td></tr>
<tr><td rowspan="2">Financing sources</td><td>Budgetary resources</td><td>Budget expenditures including foreign-currency resources from BMBF.</td><td>347</td><td>120</td><td>113</td><td>114</td></tr>
<tr><td>External resources</td><td>Contributions by collaborators.
Grants.
Contributions by sponsors.
Contracts.
Other financial resources, etc.</td><td></td><td></td><td></td><td></td></tr>
</table>

PROJECT LEADER Julian Budagov

Appendix 4

Form No. 29

Estimated expenditures for the Project

THE PRECISION LASER METROLOGY

FOR ACCELERATORS AND DETECTOR COMPLEXES

	Expenditure items	Full cost	1st year 2019	2nd year 2020	3rd year 2021
	Direct expenses for the Project				
1.	Accelerator, reactor	h			
2.	Computers	h			
3.	Computer connection	k$			
4.	Design bureau	standard hour			
5.	Experimental Workshop	998 standard hour	358	319	321
6.	**Materials**	**104 k$**	39	32	33
7.	**Equipment**	**201 k$**	67	67	67
8.	Construction/repair of premises	k$			
9.	Payments for agreement-based research	k$			
10.	**Travel allowance, including:**	**42 k$**	14	14	14
	a) non-rouble zone countries	36 k$	12	12	12
	b) rouble zone countries	6 k$	2	2	2
	c) protocol-based				
	Total direct expenses	**347**	**120**	**113**	**114**
	Including:				
	DLNP budget	84	28	28	28
	BMBF funding	263	92	85	86

PROJECT LEADER Julian Budagov

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST

THE PRECISION LASER METROLOGY FOR ACCELERATORS AND DETECTOR COMPLEXES

ABSTRACT

Prolongation of the Project “The Precision Laser Metrology for Accelerators and Detector Complexes” for 2019-2021 involves the development of new metrological instruments and upgrading of the existing ones, i.e.:

- distributed network of six Precision Laser Inclinometers;
- the Interferometric Distance Meter on the basis of high-frequency amplitude modulation of the laser beam power;
- The 130 m Laser Fiducial Line adapted to the conditions of the DLNP Metrological Laboratory.
- an additional activity: the operating prototype of the Research Platform in the DLNP Metrological Laboratory, seismologically-stabilized from angular oscillations of the Earth surface;

The proposed new concept metrological devices, as it is supposed, will make the new generation basis of the future elemental robotic measuring system in experiments at the Large Hadron Collider.

ПРЕЦИЗИОННАЯ ЛАЗЕРНАЯ МЕТРОЛОГИЯ ДЛЯ УСКОРИТЕЛЕЙ И ДЕТЕКТОРНЫХ КОМПЛЕКСОВ

АННОТАЦИЯ

Продление Проекта «Прецизионная лазерная метрология для ускорителей и детекторных комплексов» на 2019-2021 гг. предусматривает создание высокоточных новых метрологических инструментов и развитие ранее созданных авторами, а именно:

- распределённая сеть (Network) из шести Прецизионных Лазерных Инклинометров;
- Интерферометрический Измеритель Расстояний на основе высокочастотной амплитудной модуляции мощности лазерного луча;
- Лазерная Реперная Линия длиной 130 м адаптированная к условиям метрологической лаборатории ЛЯП;
- Дополнительная активность: действующий прототип сейсмостабилизированной от угловых колебаний поверхности Земли исследовательской платформы в Метрологической Лаборатории ЛЯП.

Предлагаемые метрологические устройства, как предполагается, составят основу элементной базы нового поколения для будущей роботизированной измерительной системы в экспериментах на Большом Адронном Коллайдере.

INTRODUCTION

Urgent issues of modern high energy physics and progress in accelerator technology resulted in the development of a unique research complex: the collider LHC with spectrometric systems ATLAS, CMS, ALICE. At present the diameter of the beams focused in the zone of their collisions in these experiments is 20 μm. This value defines the "precision scale" of metrological instruments applied in collider experiments. In the increased radiation conditions at the LHC, metrological measurements are supposed to be possible if remote-controlled robotic complexes are available.

Taking into account the collider dimensions (8.5 km), the spectrometer dimensions (ATLAS – 46 m long, diameter 25 m), tough radiation conditions we can suppose that, probably, the laser beam will be the only "measuring instrument" that will allow the necessary precision.

On the basis of completed R&D's and achieved experimental results of 2016-2018 [1-8], in the extension (2019-2021) of the Project we propose three metrological instruments: the Precision Laser Inclinometer (PLI), the Interferometric Distance Meter (IDM), the Laser Fiducial Line (LFL). These new instruments are supposed to form the elemental basis of the remote-controlled Robotic Measuring Complex (RMC).

Measurement of the dimensional stability of the wall and floor position in the ATLAS measurement hall showed their high instability [9]: for the floor – 150 μm per year, for walls 500 μm per year. Practically, less than in a month such considerable geodesic change takes place in the experiment net that need renovation. In short periods when the collider experiments shut down the measurements are impossible or very difficult; RMC proposed in the Project can improve the situation.

The Precision Laser Inclinometer developed at DLNP is the *world first angular seismograph* that registers microseismic oscillations of the Earth surface with the accuracy of $2.4 \cdot 10^{-11}$ rad/Hz$^{1/2}$ in the frequency range [10^{-6} Hz;4 Hz], that provides registration of all known microseismic phenomena. Two inclinometers have been launched and measure steadily angular inclinations of the Earth surface in tunnel TT1 at CERN (Geneva, Switzerland) and in the International Geophysical Observatory (Garni, Armenia). In 2018 the development of working samples of six PLI will be finished that will make the basis of the first in the world Distributed Network of Detector of angular oscillations of the Earth surface.

In the activities on the IDM the measurements on the short-distances about 10 micron have been realized with achieved measurement accuracy of 0.03 μm. We introduced this method into the practically used procedure of the PLI calibration. As for today, a prototype of 5 m IDM has been developed in the thermo-isolated laboratory; the full scale scientific research cycle will be finished in the DLNP Metrological Laboratory which is under completion.

The LFL measurements showed full possibility to integrate of this method in existing theodolitic measurements. The accomplished experiments in the 50 m length in aerial environment showed coincidence of data with the theodolitic system in the error limit of theodolitic measurements of 30 μm [10].

In DLNP the development of a metrological laboratory is coming to its finish; it is equipped with a precision climate system of aerial environment in the volume of $23 \times 6 \times 3$ m^3.

Thus, the prolongation of the Project for 2019-2021 envisages:

- The development of a network of 6 PLI for visualization of deformation of the Earth surface caused by seismic waves.
- To accomplish work of ILM development with the 16 m length.
- To accomplish work of the vacuumed LFL prototype development with the length of 150 m.
- Additional activity: On the PLI basis to develop a laboratory prototype of a research platform seismically isolated from angular oscillations of the Earth surface.

1. PLI NETWORK FOR VISUALIZATION OF DEFORMATION OF THE EARTH SURFACE CAUSED BY SEISMIC WAVES

One of the most important tasks in metrology of modern collider experiments is to provide their seismic stability. In fact, when Rayleigh waves occur (sinusoidal surface seismic wave) the Earth surface is deformed, particle beam trajectories are distorted that may cause divergence in the focus position in the collision zone. To be exact, we demonstrated the data we obtained on the dependence of the luminosity on angular oscillations of the Earth surface at the RUPAC2016 conference [11].

We propose *as a first step*, for preparation – in the prospect – of a decision of the full scale problem of the luminosity control, to develop a distributed network of six PLI in the LHC situation zone. The obtained data on the deformation of the Earth surface can be used by the feedback system to correct online the operation parameters of the collider and to stabilize spatial position of the beam focus in the collision zone.

1.1. The approach to register deformation of the Earth surface caused by seismic waves with the complex "PLI-Network"

Let us regard the case when it is necessary to visualize the passage of the sinusoidal wave along one horizontal coordinate X (axis X coincides with the direction of the wave movement). We install inclinometer along one line with coinciding directions of registration of angular oscillations of the Earth surface in vertical and horizontal planes. Fig.1 shows six inclinometers along the axis X at approximately equal distances L_i.

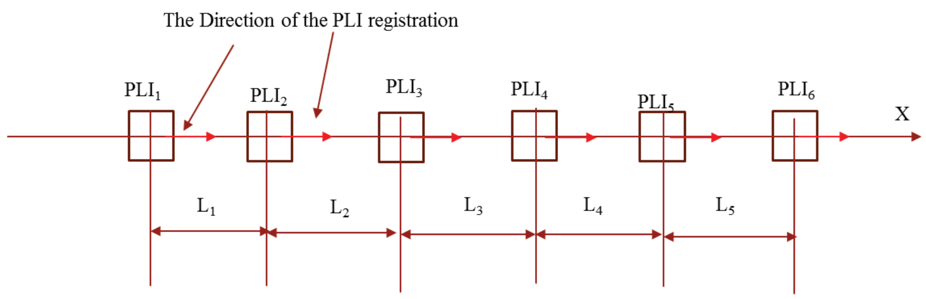

Fig.1 Position of PLI inclinometers from one another in registration of the angular deformation of the Earth surface along horizontal coordinate X

The average distance between the inclinometers is chosen with account of the surface wave length. For Rayleigh waves of the "Microseismic Peak" the average frequency of the registered events is $f = 0.3$ Hz. With the rate of the Rayleigh wave of $V = 2$ km/sec the wave length is $\lambda = V/f = 6.7$ km. In registration of such waves with six inclinometers the average distance between them is 2 km.

Fig.2 shows the position of inclinometers in the vertical plane with the passage of the Rayleigh wave at the time moment t_0.

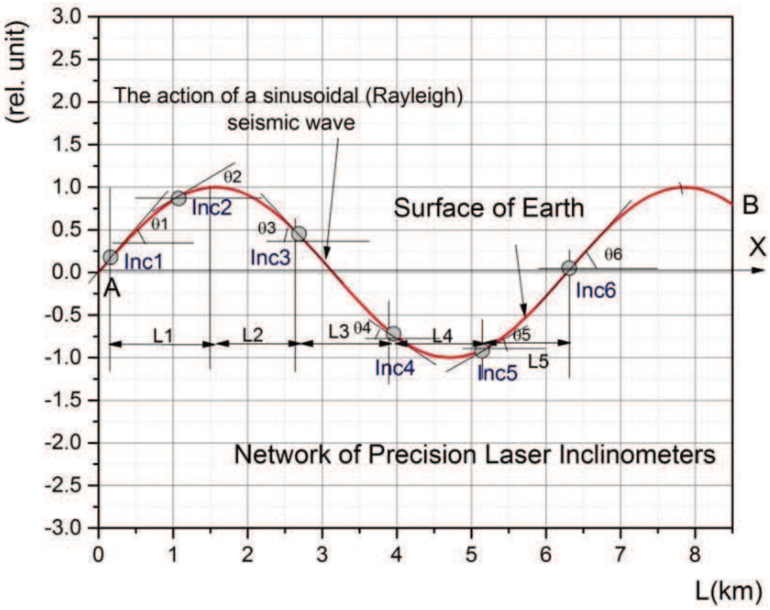

Fig.2 NETWORK registration of oriented inclinometers of the line profile on the Earth surface in the passage of the Rayleigh wave

The inclinometers along the line AB at one moment of time t_0 register the deflection angle of the Earth surface. Knowing the distance between the inclinometers $L_1, \dots, L_5$ and the measured angles $\theta_1, \dots, \theta_6$ of deflection of the Earth surface we determine the gain of height $h_1, \dots, h_5$ with the formula

$$h_i \approx \frac{tg(\theta_i)+tg(\theta_{i+1})}{2} L_i \qquad \{1\}$$

As the angles $\theta_1, \dots, \theta_6 \ll 1$ this expression is written in the form

$$h_i \approx \frac{\theta_i+\theta_{i+1}}{2} L_i \qquad \{2\}$$

Then we gradually determine the height of the location of the measured points along line AB on the Earth surface:

$$H = \{H_1=h_1;\ H_2=h_1+h_2;\ H_3=h_1+h_2+h_3; \dots \} \qquad \{3\}$$

With sequence {3} we transform the measured angle of the inclinometer into vertical shift of the Earth surface.

At the next moment of time t_1 the Rayleigh wave shifts for the distance

$$\Delta l = V * (t_1 - t_0)$$

and the inclinometers will register new angle values that will be calculated in the frames of sequence {3}. Finally, we determine the vertical shift of the measured points on the Earth surface in the passage of the surface wave in time. In other words, we visualize the change of the landscape of the Earth surface in the passage of the surface seismic wave.

In NETWORK registration in the plane (two orthogonal horizontal coordinates *X* and *Y*) (see Fig.3) the inclinometers are located in the intersection nodes of mutually perpendicular lines. The direction of the angular oscillations registration in vertical and horizontal planes of all PLI coincide and their directions are parallel to axes *X* and *Y*.

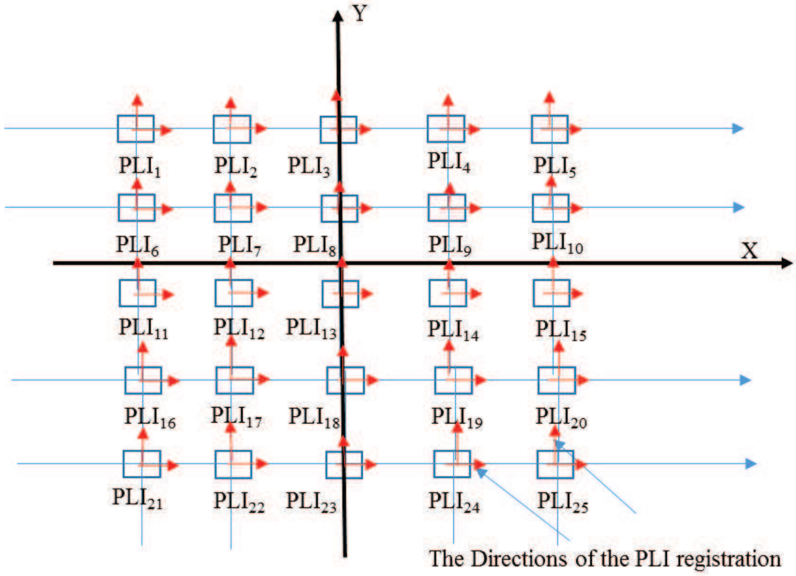

Fig.3. Registration of the Rayleigh wave passage in the plane by PLI NETWORK

In this case registration is conducted of the height change along the line with sequence {3} with further restoration of the surface heights in the passage of the surface wave.

Regarding the situation in the plane, it should be taken into account that in reality, generally, there are several waves of different directions of the "Microseismic peak" from different sources with various frequencies. Therefore, the real picture of seismic waves requires a more complex mathematical model to describe them.

1.2. Technical specifications and tasks of 6-PLI NETWORK

The accuracy of the inclinometer in online registration of the surface wave is 10 nrad. The average amplitude of the deflection angle of the Earth surface from the Rayleigh waves of the Microseismic peak $\approx 2\cdot10^{-7}$ rad. Thus the accuracy of registration of the Earth surface deformation by the Rayleigh waves of the "Microseismic Peak" is about 5 %.

We evaluate the time for registration, processing and visualization of information that comes from the system of six PLI as 0.1 sec. It will allow us to describe well (20 points for a period) the oscillations of the Earth surface at the frequency of the "Microseismic Peak" as 0.2 Hz.

The first stage tasks for the NETWORK:

• to register and demonstrate the fact Earth's surface spatial deformation in the passage of Rayleigh wave.

• to determine the necessary quantity of inclinometers for efficient visualization of the Earth surface deformation caused by seismic waves.

• to work out efficient processing algorithms for information from PLI NETWORK.

To implement these we need:

1. to manufacture six PLI samples
2. to locate them in the LHC tunnel
3. to design software for synchronous registration of angular oscillations of the Earth surface
4. to conduct online processing of the arriving data
5. to online visualize the oscillations of the Earth surface in the passage of seismic waves

1.3. Terms of the project implementation

Stage	Beginning	End
Provision of record of data from PLI to TIMBER – the system of data acquisition in CERN	March 2018	December 2018
Production in LNP JINR workshop of 6 sets of mechanical PLI elements in the frames of the agreement	February 2018	June 2018
Delivery to CERN and installation of 5 PLI sets in places determined beforehand and provision of storing synchronous angular microseismic information in CERN –TIMBER	May 2018	February 2019
During the installation of 5 PLI sets designing of service NETWORK of 6 PLI programme with the capacity of 3D visualization of angular and dimensional (change in height, length and width) of microseismic activity of the Earth surface	May 2018	September 2019
Holding experiments with a test NETWORK to determine optimal quantity and PLI location in the tunnel system of CERN	September 2019	December 2020

2. INTERFEROMETRIC DISTANCE METER WITH THE MEASUREMENT LENGTH OF 16 METERS

A distance meter up to 16 m with a long-term (year) measurement accuracy better than 10 µm is needed for connecting the coordinate systems of two LHC accelerators in the ATLAS experiment.

Specifically, the distance meter connects three geodetic networks (two are the accelerators and one is the detector). The distance meter must periodically measure (monitor) the distance between two reference strings. Three main LHC experiments require 18 distance meters.

In the existing methods, the measurement error (300 µm per year) strongly depends on the environment parameters.

It is proposed to make a length meter on the basis of a laser interferometer, in which the effect of the ambient temperature, pressure, and humidity is insignificant and stays within the necessary measurement accuracy. In the "movable-arm" interferometer, the interferometric pattern variations are continuously recorded using the ADC, and the measured length is found by counting the interference fringes. The fringe counting begins and ends when the auxiliary beam crosses the reference strings connected with the coordinate systems of the accelerators and the detector.

The Interferometric Distance Meter System must work in the robotized regime and continuously monitor the distamce variations between the reference string lines. At the reference line position measurement accuracy of 10 µm the geodetic networks can be united with an accuracy of 15 µm, which almost coincides with the diameters of the focused particle beams (in the ATLAS experiment the particle beam diameter is 17 µm) – the basic position uncertainty of the colliding particles.

Our investigations revealed strong sensitivity of the interference pattern of interfering rays adjustment precision. It turned out that the accuracy of beam alignment over a length of 16 m must be as high as 0.1 mm. Thus, for alignment of the interfering rays over the entire measurement length (16 m) their collinearity must be better than $5 \cdot 10^{-6}$ rad (1 s).

The angular accuracy of the assembly of the components in the Interferometric Meter is better than $5 \cdot 10^{-6}$ rad, which will be achieved in the metrological laboratory to be put into operation by the summer of 2018.

To reduce dependence on the accuracy of laser beam adjustment, a modification of the interferometric distance meter is proposed. For the interferometer, the concept of the "Amplitude Interferometer" is suggested, where the amplitude modulation of the laser beam at the frequencies from 1 to 10 GHz is used. In this case, the amplitude modulation wavelength of 0.3–0.03 m is much larger than the laser source wavelength of 0.63 µm, and thus the dependence of the distance meter operation on the high-precision positioning of the laser beams considerably decreases.

In the Amplitude Interferometer, two signals from the laser beams reflected from the movable arm of the interferometer are detected. Then, after subtraction of the signals by the operational amplifier, the "interferometric signal" is separated, which is recorded by the ADC.

2.1. IDM on the basis of the Amplitude Interferometer

The Amplitude Interferometer used the amplitude modulation of the laser beam. Figure 4 shows an analogue of the Michelson–Morley interferometer.

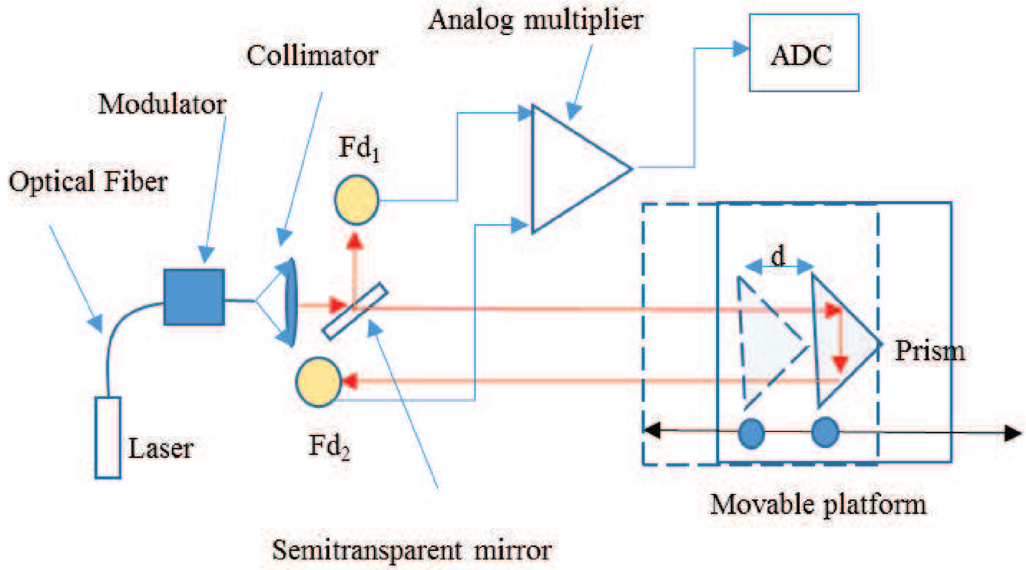

Fig. 4. Amplitude Interferometer of the Michelson–Morley type.

The amplitude modulator modulates the laser beam by a sine function with frequency *ν*. As a result, we obtain time dependence of the laser beam power

$$P = P_0 \sin(2\pi\nu t - \frac{2\pi}{\lambda} x)$$

where *x* is the propagation distance of the laser beam from its modulation point to its observation point *x*, and $\lambda=c/\nu$ (*c* is the speed of light) is the wavelength of the sine amplitude modulation. After modulation, part of the laser beam is sent to the photodetector Fd_1 using a divider plate, and the main part of beam, being reflected from the movable arm, is sent to Fd_2. Voltage signals from Fd_1 and Fd_2 are fed into the differential amplifier, where they are subtracted. As a result, we have the alternative voltage signal

$$S = U_0\,(sin(2\pi\nu t) * U_0\, sin\left(2\pi\nu t - \frac{2\pi}{\lambda}\, x\right)\,) = \frac{U_0^2}{2}(cos\left(\frac{2\pi}{\lambda}\, x\right) - cos\left(4\pi\nu t - \frac{2\pi}{\lambda}\, x\right)\,)$$

Let us consider the case where the prism moves with a constant velocity *V*. This means that a change in the distance covered by the laser beam can be presented as $x = 2Vt$ (considering that the light is reflected from the prism, and the optical distance of the light increases by a factor of two).

$$S = \frac{U_0^2}{2}(cos\left(2\frac{2\pi}{\lambda}Vt\right) - cos\left(4\pi\nu t - 2\frac{2\pi}{\lambda}Vt\right)\,)$$

At the output of the differential amplifier there appears an ac signal with the frequency $\Omega = 2\ V/\lambda$ governed by the prism velocity $V = s/t$

$$S = \frac{U_0^2}{2}(cos(2\pi\,\Omega t) - \cos(4\pi\nu t - 2\pi\Omega t))$$

Actually, at the output of the differential amplifier we have a modulator ac signal at the double frequency 2ν modulated by the low-frequency $\Omega = 2\ V/\lambda$ signal caused by the motion of the prism. subtracting the prism motion signal by the frequency filter, we send it to the detecting ADC. As the useful signal varies from maximum to maximum, the carriage with the prism travels a distance of $\lambda/2$.

Thus, using the differential amplifier, we performed interference separation of the signal based on the amplitude modulation of the laser beam.

The advantage of this method is that it is relatively insensitive to the possible disadjustment of the interferometer.

As the laser beam displaces by ΔX due to its angular rotation, the error in the determination of the distance Δx is found from the relation $\Delta x = \frac{\Delta x^2}{L}$ (Fig. 5).

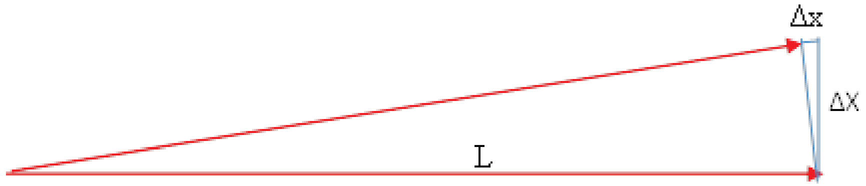

Fig.5. Determination of the error in the distance measurement when the angular disadjustment of the laser beam.

When the laser beam displaces by $\Delta X = 5$ mm due to its inclination over the length $L = 16$ m, the systematic error of measurement will be $\Delta x = 1.6$ µm.

The principle of distance detection remains the same as in the interferometric method (Fig. 6).

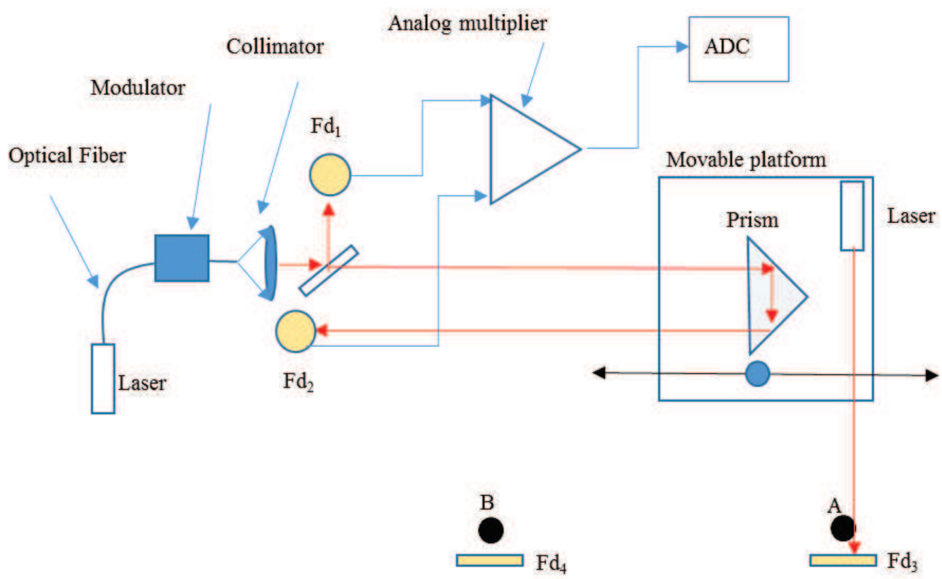

Fig. 6. Measurement of the distance between two strings A and B by the IDM.

The additional laser beam from the second laser source positioned on the movable platform crosses the stretched string at the initial measurement point A. The fixed photodetector Fd3 behind the string detects this crossing. At the final measurement point B a similar signal is detected by the photodetector Fd4. Current signals from the photodetectors Fd1 and Fd2 are summed and converted to voltage, which is applied to the input of the synchronized two-channel ADC. A signal from the differential amplifier is fed into the second channel.

Distances are determined by processing the data recorded by the two-channel ADC. Figure 7 shows variation in signals from two ADC channels.

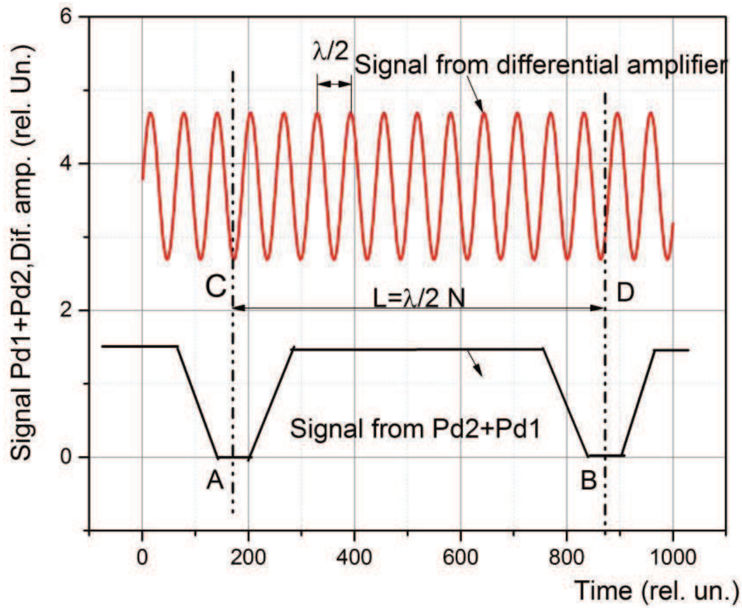

Fig. 7. Measurement of the distance between the strings.

In the first channel there are signals from the crossing of the strings by the laser beam, and in the second channel there is a sine signals from the interferometer. Determining the point in time when the laser beam crosses the center of the strings, we determine the pointes C and D on the time axis and their corresponding values of the interferometer signal. Then the number of interferometer signal peaks is found between the determined points C and D in the interference signal. Having found their number N, we multiply it by the distance $\lambda/2$ and obtain the desired distance.

2.2. Main stages in the development of the IDM:

- Development of software for recording and processing signals and determining distances.
- Testing of the amplitude interferometer usage method.
- Construction of a working prototype for distance registration over a length of 16 m with an accuracy of 10 μm.

2.3. Interferometric Distance Meter project period

Stage	Beginning	End
Assembly of the prototype interferometric distance meter for the distance of 0.5 m. Optimization of the method for counting the number of interference fringes for determining the distance between two strings.	June 2018	December 2018
Transition to the Amplitude Interferometer concept. Construction of a prototype for the length of 2 m.	January 2019	December 2019
Construction of a prototype for the length of 16 m.	January 2019	December 2020

3. LASER FIDUCIAL LINE

The laser fiducial line is used for continuous measurement of NETWORK point coordinates along the laser beam motion line. The origin of the coordinates is the beginning of the laser beam (the point laser source is the optical fiber end) and the final point of the laser beam arrival, the quadrant photodetector center. The laser fiducial line can control the NETWORK points under measurement over the unit length of up to 2 km.

The LFL effectively replaces the sting fiducial line for controlling linear accelerators more than 5 km long.

Position stability of the laser beam depends on the air environment (dust, refraction index fluctuations). Therefore, the tube in which the laser beam moves is subjected to forevacuum pumping.

To have an effectively operating laser fiducial line, it is necessary

• To continuously stabilize the laser beam against the noise effects of laser beam wandering and angular seismic inclination of the Earth surface.

• To develop a nondestructive system for recording the position of the measured point on the object under control relative to the stable position of the laser beam.

• To fabricate high-precision optical plane-parallel plates with surface flatness better than 10^{-8} rad for efficient nondestructive control of the measured points. This technology has been developed and tested.

• To decrease the effect of angular microseismic oscillation of the Earth surface on the laser beam using a seismically insulated platform.

• To control the positions of the NETWORK points using both the LFL and the external theodolite system for integration into the global NETWORK.

3.1. Experimental layout for the construction of the prototype Laser Fiducial Line

In May 2018, a metrological laboratory will be put into operation, which will allow Laser Fiducial Line investigations to be carried out. Under the Metrological Laboratory conditions (length 23 m), the LFL is supposed to be constructed in several stages.

LFL 20 m long:

Tryout of elements of the vacuum system, system for positioning the initial and final LFL points, and system for detecting laser beam oscillation.

LFL 60 m long:

• Tryout of the system for triple laser beam reflection to increase the length of 60 m under vacuum conditions.

• Tryout of the system for stabilization of the laser beam wander.

• Tryout of the system for nondestructive control of the position at the measured point.

LFL 130 m long:

• Seismic insulation of the LFL supports by placing them on a seismically insulated platform (Fig. 8).

• Determination of the LFL measurement accuracy.

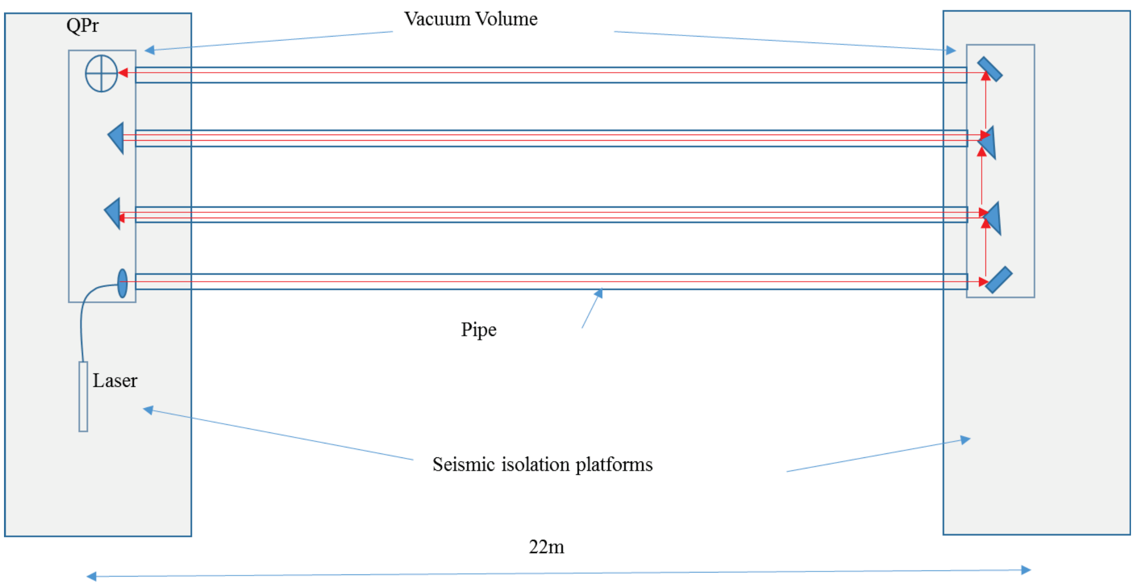

Fig. 8. Arrangement of the 130-m-long Laser Fiducial Line in the metrological laboratory.

3.2. Laser Fiducial Line project period

At the first stage it is planned to construct a vacuum version of the 130-m-long LFL prototype.

Stage	Beginning	End
Construction of the 20-m-long vacuum LFL prototype	June 2018	December 2018
Construction of the 60-m-long vacuum LFL prototype with a system for suppression of laser beam wander noise	January 2019	December 2019
Construction of the 130-m-long vacuum LFL prototype 130 м with a system for suppression of laser beam wander noise using a seismically insulated platform. Determination of LFL noise characteristics.	January 2020	December 2020

4. RESEARCH PLATFORM SEISMICALLY STABILIZED AGAINST ANGULAR OSCILLATIONS (PROTOTIPE, ADDITIONAL ACTIVITY)

Apart from using the PLI to detect microseismic activity of the Earth surface, earthquake prediction, and seismic stabilization of the collider, another line of research important for gaining substantially new physical data is a Seismically-stabilized (against angular oscillations of the Earth surface) Research Platform (SRP).

This is of considerable interest for the ATLAS spectrometric complex, where highly accurate reproduction of the mutual arrangement of the spectrometer subsystems and structures is required.

Moreover, there are a lot of significant physical experiments that require long-term angular stability of the facility foundation:

• In gravitational antennas the mirrors are suspended on quartz threads. Inclination of the Earth surface is followed by inclination of the mirrors, which affects stability of the interference pattern in the gravitational wave detector.

• As the Earth surface becomes inclined, the picture in the focus of a modern telescope with a mirror more than 5 m in diameter is displaced and the image is subsequently smeared.

• In experiments on the determination of the gravitational constant *G* an inclination of the platform affects the position of the proofmasses, which gives rise to an uncontrollable systematic error during the experiment.

• A more sensitive detector of the Earth rotation nonuniformity based on the Zöllner pendulum can be built on the platform seismically stabilized with respect to an angle.

• The study of long-term changes in the landscape to reveal Earth surface areas with accumulation of deformation energy for improving earthquake prediction technique.

The PLI-based technology for making a seismically stabilized platform seems to allow new measurement precision levels to be obtained in physical experiments and methods.

4.1. Seismic stabilization of the research platform

For the experiment, it is proposed to use the available optical table 2.4 m long and 1.6 m wide (Fig. 9).

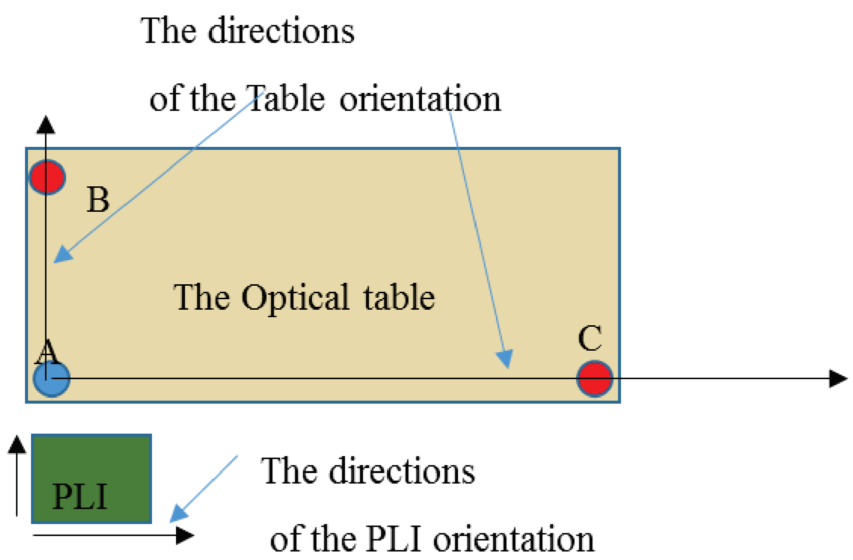

Fig. 9. Scheme of seismo-stabilization of research platform using the PLI.

The optical table has three support points, one fixed A and two movable B and C with their height varied by piezoelectric actuators. The Precision Laser Inclinometer is placed near the optical table on the floor that is in direct contact with the Earth surface. The directions in which the PLI detects angular oscillations of the Earth surface are collinear with the directions determined by lines AB and AC on the optical table.

Signals from the angular oscillations of the Earth surface in the vertical and horizontal planes are processed online in the computer, and the resulting correction signals are supplied to the piezoelectric actuators at points B and C.

The seismic stabilization quality is checked using a vacuum suspension system (Fig. 10).

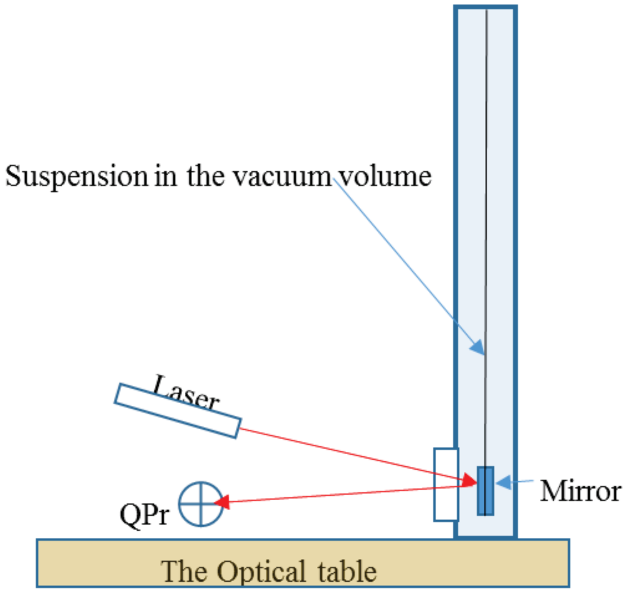

Fig. 10. Quality check of the seismic stabilization against angular oscillations of the Earth surface using vacuum pendulums.

A specific feature of these suspensions is their different length. This allows the seismic stabilization quality to be investigated at different frequencies in two stabilization directions. The minimum oscillation frequency dictated by the distance from the optical table surface to the ceiling $l = 3$ m is $f = \frac{1}{2\pi}\sqrt{\frac{g}{l}} = 0.29$ Hz. Seismic stabilization at the maximum frequency is estimated using the suspension with the length $l = 5$ cm, which corresponds to the frequency of 2.2 Hz.

The suspension oscillation frequency is measured using a laser beam and a quadrant photodetector. When the suspension is inclined relative to the table surface, the reflected laser beam also becomes inclined, which leads to displacement of the laser beam spot on the quadrant photodetector QPr. Recording signals from the quadrant photodetector QPr, one can determine the suspension oscillation amplitude. The ratio between the suspension oscillation amplitudes before A_0 and after seismic insulation A_{SI} determines the seismic stabilization coefficient $K = \frac{A_0}{A_{SI}}$.

Thus, objective data on seismic stabilization can be obtained by finding oscillation amplitudes of suspensions before and after switching on the seismic insulation regime.

4.2. Attainable seismic stabilization against angular oscillations of the Earth surface

The average angular oscillation of the microseismic peak in the frequency range [0.1 Hz; 1 Hz] is estimated at $2\cdot10^{-7}$ rad. The online PLI measurement accuracy is as high as 10 nrad. Consequently, the attainable angular oscillation suppression coefficient for the microseismic peak is $K \approx 20$.

SRP development objectives:

- Creation of a program producing a feedback signal from the PLI readings for the SRP.
- Creation of a wideband system for determining the seismic stabilization quality.

4.3. Seismically-stabilized Research Platform project period

Stage	Beginning	End
Construction of the SRP prototype in the Metrological Laboratory on the basis of the operating production-type Precision Laser Inclinometer	June 2018	July 2019
Experimental estimation of attainable seismic stabilization in the frequency range of 10^{-4} Hz to 4 Hz	August 2019	August 2020

SWOT ANALYSIS

Strengths of the Project

International support: Nowadays the R&D on the creation of PLI as a professional mass-production instrument is completed. Two of our PLIS are already commissioned and performs a continuous monitoring of seismic activity: in CERN for a quantitative study of the contribution of microseismic oscillations to the instability of the orbits of the beams in LHC-machine and in the International Geophysical Observatory in Garni for monitoring of seismic situation in the seismically dangerous area. The international scientific community expresses of the interest in the further development of our Project:

- The activity is carried out with the support of the BMBF Foundation.
- The JINR-CERN Agreement on the creation of additional five inclinometers for the study of the effect of PLI-network application for LHC luminosity increasing program in ATLAS experiment has been signed.
- The JINR-Armenia Agreement for studying the possibility of using the PLI in estimation of seismic hazards and earthquakes predicting has been signed.

Financing: The Project is carried out with the financial support of the BMBF fund, which together with funding from the DLNP budget ensures the opportune execution of all phases of the Project.

Personnel: The Project is carried out by a highly qualified team of scientists with a significant proportion of young employees. Our research can take a relatively long time and it is extremely important to have a balanced age structure in the team to ensure of experience and knowledge succession during the implementation of the Project.

Material base: The creation of a modern thermostabilized Metrology laboratory which is equipped with the modern optical, electronic and mechanical facilities has practically been completed. The presence of such Laboratory will ensure the effective implementation of all directions of the Project.

Own production: DLNP has own workshops for the experimental production of the metrological instruments, which allows the creation of necessary high-technology constructs in a short time.

Weaknesses of the Project

Relatively small team (5 FTE now + 2-3 FTEs in next 2 years). With a possible increasing of the work scope (creation of 50 inclinometers for CERN and/or 20 for Garni), expansion of cooperation with other scientific centers will require an increasing of the staff.

Opportunities

Our new unparalleled metrological technologies and instruments create the conditions for the formation of a previously nonexistent market for unique devices.

Our new metrology technologies and instruments create the conditions of a qualitatively new level of high-precision physical experiments in wide spectra of scientific problems. This guaranties the additional cooperation which will attract of talented physicists and, will be the center of crystallization of the application of our devices in subsequent projects.

Threats

The cuts of the funding from the BMBF foundation and/or from JINR budget will stop the creation of the PLI for CERN and GARNI. The deterioration of the foreign policy environment will not allow the purchasing of necessary electronic and optical equipment, which will slow down the creation of our metrological devices.

CONCLUSIONS

In the project “Precision laser metrology for accelerators and detector complexes” submitted for prolongation, proposals are given for research and development of new laser metrology methods. They all are aimed at obtaining fundamentally important results that will noticeably improve the accuracy of physical experiments.

A network of Precision Laser Inclinometers will make it possible for the first time to visualize variation in the Earth’s surface landscape during the propagation of surface seismic waves. This possibility will allow practically implementing seismic stabilization of large physical facilities (colliders, linear particle accelerators).

The Interferometric Distance Meter will solve the problem of uniting NETWORK coordinate systems in experiments at the Large Hadron Collider.

The Laser Fiducial Line will help control online the positions of the accelerating units of the linear collider, effectively replacing the string fiducial line. It can operate under radiation conditions, which is fundamentally important for linear accelerators.

Development of the above tools, apart from their individual importance, is a milestone in development of a robotized measuring system that ensures a continuous metrological measurement process in underground experimental halls for collider experiments.

A Seismically-stabilized Research Platform insulated against angular oscillations of the Earth surface on the basis of PLI measurements will improve conditions for physical experiments, which will inevitably increase their accuracy.

The SRP will allow seismically stabilized conditions for a number of high-precision technological processes in industry (for example production of microcircuits).

Thus, development of metrological laser technologies is a currently important objective in modern physics, which will allow a new level of accuracy to be achieved in the modern physical experiment.

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