Precision Laser Metrology for Accelerators and Detector Complexes

Prolongation of the Project for 2022-2023

JINR

DLNP

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Introduction

- The Project "Precision Laser Metrology for Accelerators and Detector Complexes" is aimed at creating the necessary metrological instruments for conducting experiments in seismic conditions isolated from angular vibrations of the Earth's surface.
- The Project provides for the creation of a Precision Laser Inclinometer (PLI), a Laser Reference Line (LRL), an Interferometric Distant Meter (IDM) and Research Platform Seismically isolated from angular vibrations of the Earth's surface(SIP) .
- This toolkit makes it possible to implement a new approach to conducting experiments on such large-scale physical installations as LHC, FCS, NIKA and Interferometric Gravitational Antennas (IGA).
- The result of the Project is the achievement of sufficient sensitivity for such control:
- **The Precision Laser Inclinometer will have a on-line measurement accuracy of the order of 10^{-9} radians,**
- **The Laser Fiducial Line must have a measurement accuracy of the order of a few microns at a distance of 130m,**
- **The Interferometric Distance Meter should measure a distance of 16 m with an accuracy of the order 10 microns.**
- **The Seismic Research Platform must be horizontalized to an accuracy of 10^{-8} Rad.**
- The gained results and pace of work in the Project gives us confidence in its successful completion.

Results of work on the Project for a 6-year period

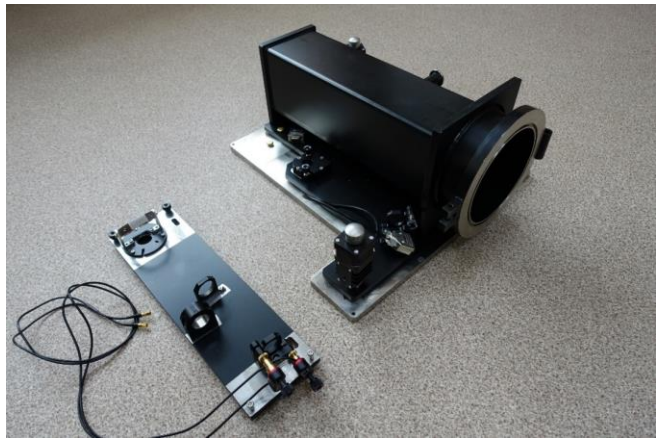
- Creation of the Metrological Laboratory (ML) DLNP is one of the most important achievements of the metrology group during the two Project extensions.

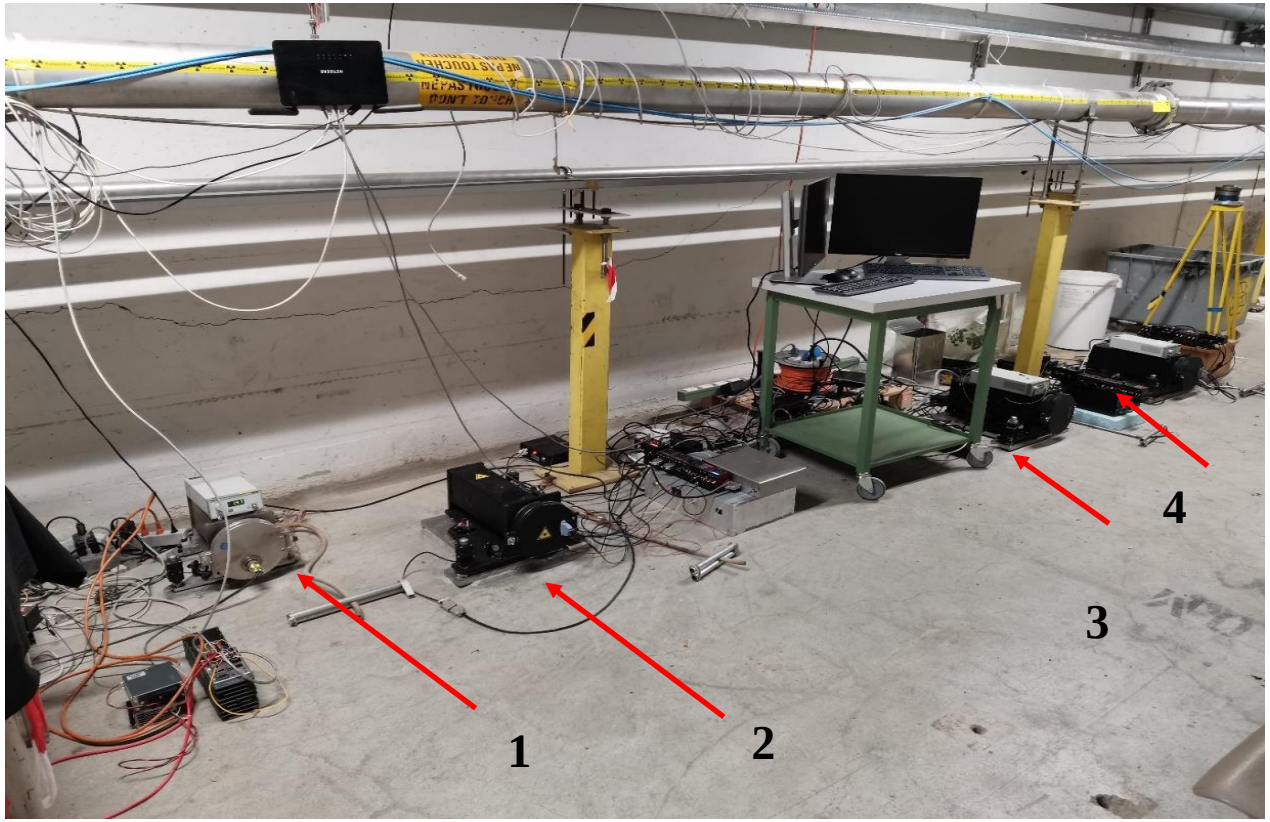
- Within the framework of the Metrological Laboratory, conditions are provided for carrying out all experiments that are currently planned within the extended Project.

- The metrological laboratory is a temperature-stabilized room 24 m long and 6 m wide.

- It is equipped with a professional precision air conditioner that stabilizes the indoor temperature with an accuracy of $\pm 1^0$C. The Laboratory has five optical tables. It has basic optical equipment, also conditions have been created for conducting experiments within the framework of the extended Project.

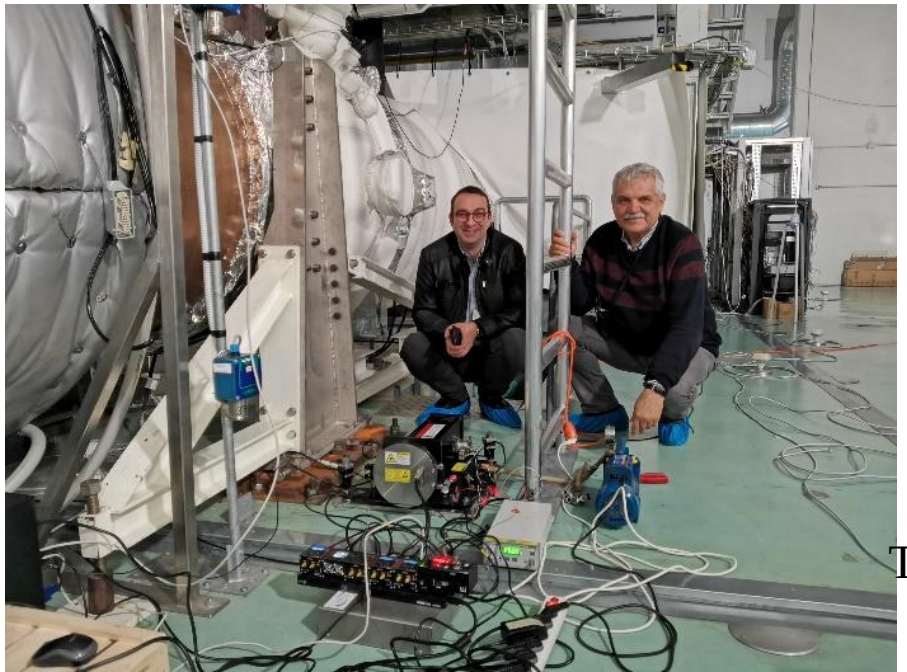
Creation of a network of four PLIs at CERN





- Creation of a network of 4 Precision Laser Inclinometers was an important achievement of the Metrological Group for the specified period (CERN-JINR Agreement).
- A network of four PLIs is designed to measure the deformation of the floor of the LHC Tunnel. Currently, all four PLIs have been tested in the LHC Transport Tunnel No. 1 and in the spring of 2021 four inclinometers (1,2,3,4) have been placed in the LHC tunnel.
- Simultaneous recording of signals from inclinometers will allow visualizing the passage of surface seismic waves under the collider and also registering a slow change in the geometry of the LHC tunnel.
- The data obtained as a result of this experiment will make it possible to take into account the deformations of the collider and, in the future, will be used to stabilize its position in order to increase its luminosity.

Creation of a monitoring system for angular oscillations of the Earth's surface on the territory of the VIRGO Interferometric Gravitational Antenna (IGA)



- One of the remarkable achievements of the Metrological Group is the installation of two Precision Laser Inclinometers [1] on the territory of the VIRGO [2] Interferometric Gravitational Antenna].
- The main task of using the PLI on the VIRGO IGA is stabilization of its sensitive elements from angular microseismic noise.
- The placement and continuous operation of two PLIs for more than one year was a major breakthrough in experiments on the IGA VIRGO.
- They demonstrated the reliability and required accuracy of measurements, which made it possible to proceed to the next stage using a small-sized PLI directly in the vacuum of the IGA.
- Currently, two PLIs are used in the noise reduction system of the IGA VIRGO North Mirror.

[1] Proposal of ac. V.A. Matveev, [2] Agreement INFN-JINR-CERN

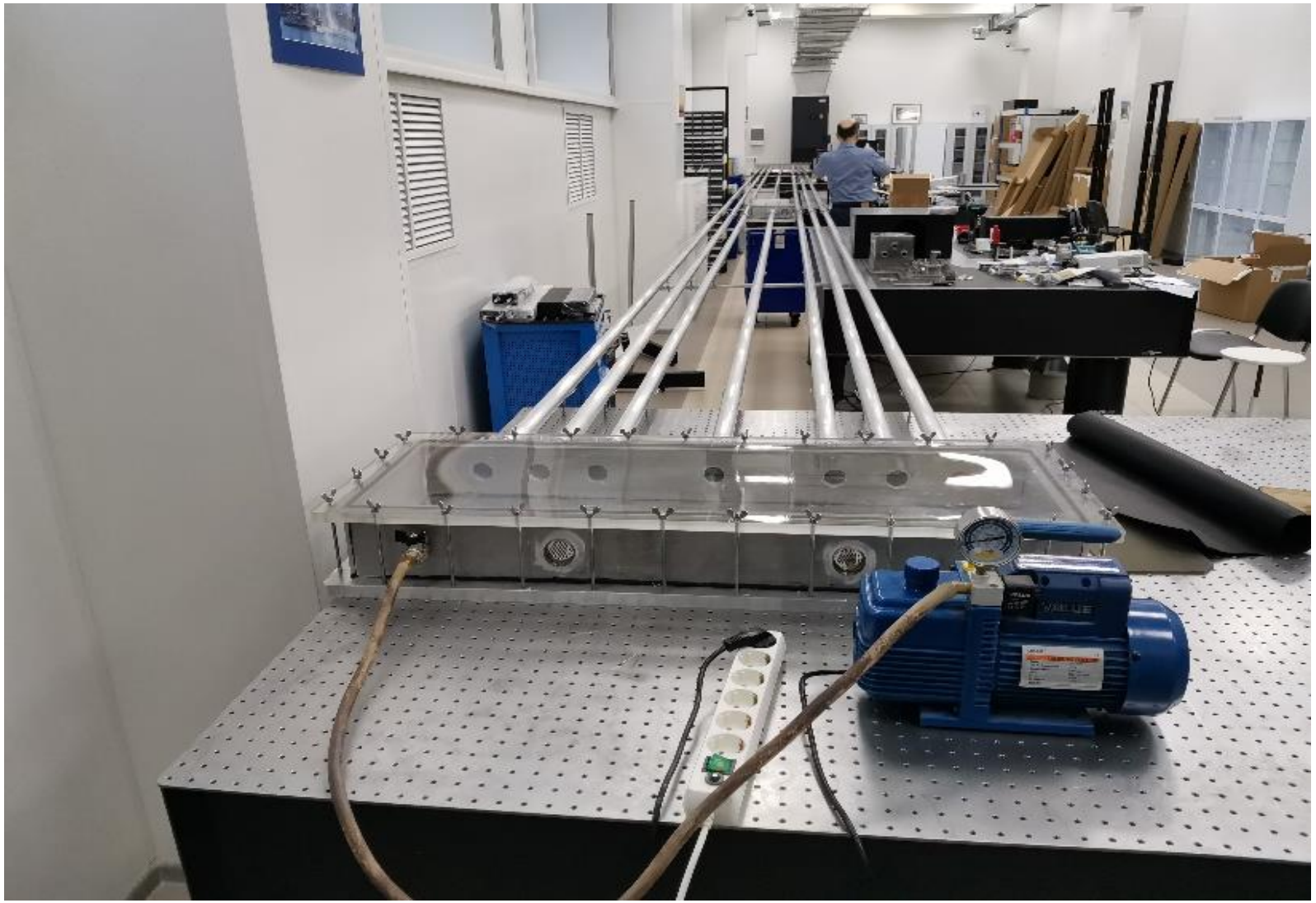
Two PLI JINR housed in the building of the North Mirror IGA VIRGO

Earthquake forecast using PLI network

- Work is underway to use the inclinometer for earthquake prediction tasks at the Garni International Geophysical Observatory (Armenia).
- This observatory hosts one PLI, and work is underway to create a network of four inclinometers in the geophysical centers of Gyumri and Garni.

JINR PLI at the International Garni Geophysical Observatory (Armenia)

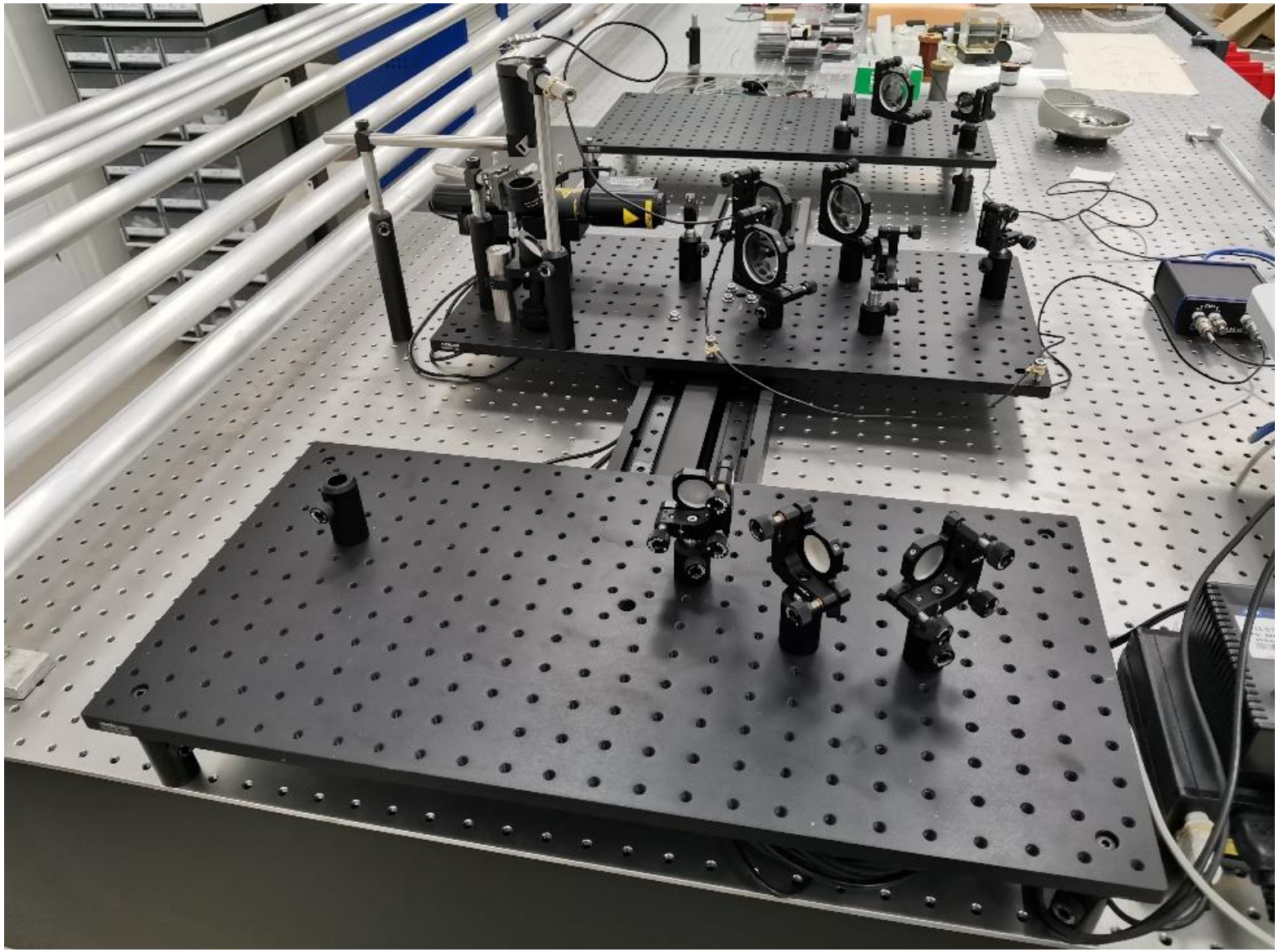
Laser Fiducial Line 130m



- The creation of a 130m long Laser Reference Line is entering its final stage.
- A system of vacuum volumes was created, connected by vacuum tubes with a total laser beam propagation length of 130m.
- Experiments at a length of 18 m revealed a strong dependence of the parameters of a single-mode laser beam on the quality of mirror surfaces in the laser beam collimation system.
- Currently, preparations are underway for the production of such mirrors. It is planned to commission the LRL by the end of 2021.

Laser Vacuum Reference Line 130m long at DLNP Metrological Laboratory

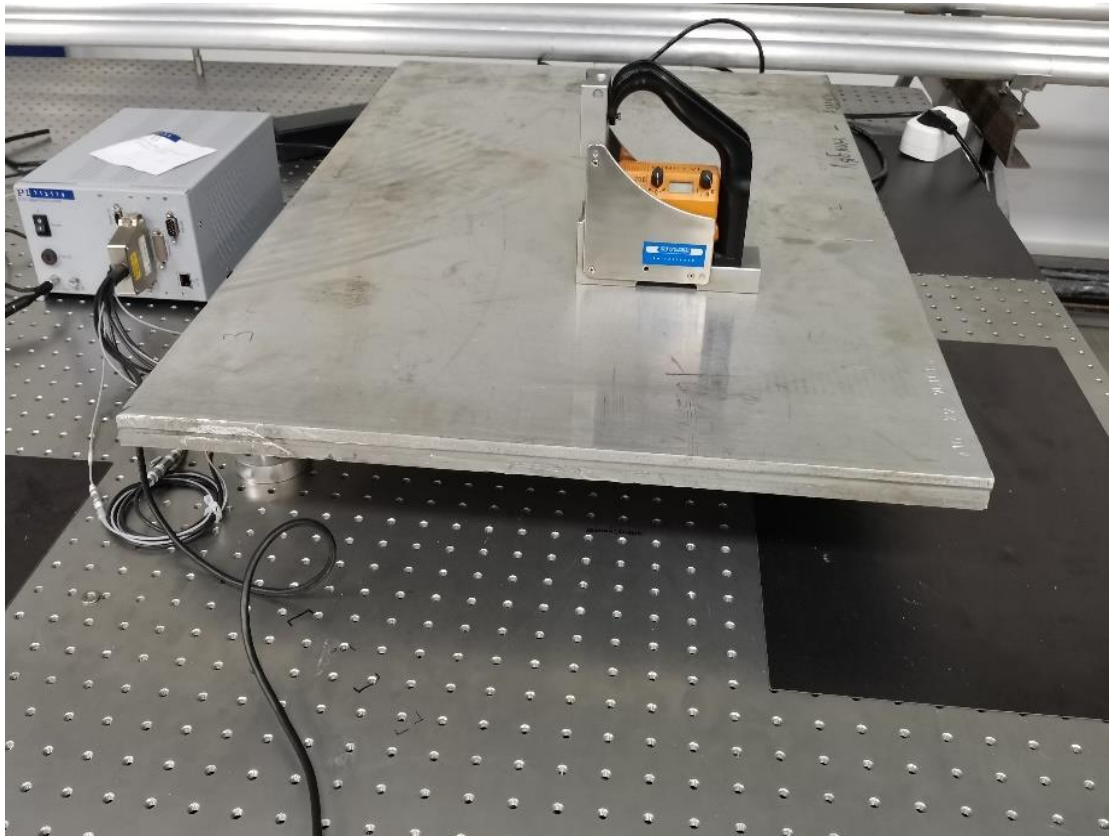
Interferometric Distance Meter



External view of the JINR Interferometric Distance Meter

- Work on the Interferometric Length Gauge showed a strong dependence of the sensitivity of the interferometer on the parameters of the air environment. Experiments were carried out at a length of **0.1m.**
- Accuracy of length measurement was 10 μm. To achieve greater accuracy, length measurement experiments are transferred to a vacuum volume. Experiments under vacuum conditions are planned by the end of the year.

Research seismic-isolated Platform



- A research platform isolated from angular microseismic vibrations is being created.
- The platform is to be kept in a horizontal position by the feedback system with the Precision Laser Inclinometer.
- The creation of such a platform is necessary for carrying out fundamental physical experiments (more accurate measurement of Newton's gravitational constant G, Majoran's experiment on the search for gravitational-like forces, etc.).
- At present, the measurements of the Measuring Platform inclinations by the MINILEVEL have been carried out at calibration inclinations of $\approx 10^{-5}$ rad (Fig. 7). The measured MP slopes are consistent with the Calibration.

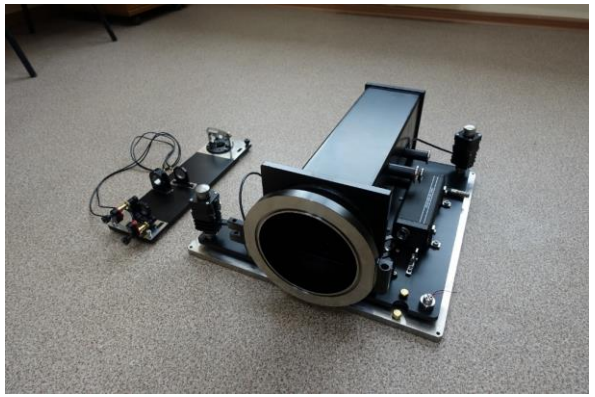
The Research Seismic-isolated Platform at DLNP Metrological Laboratory

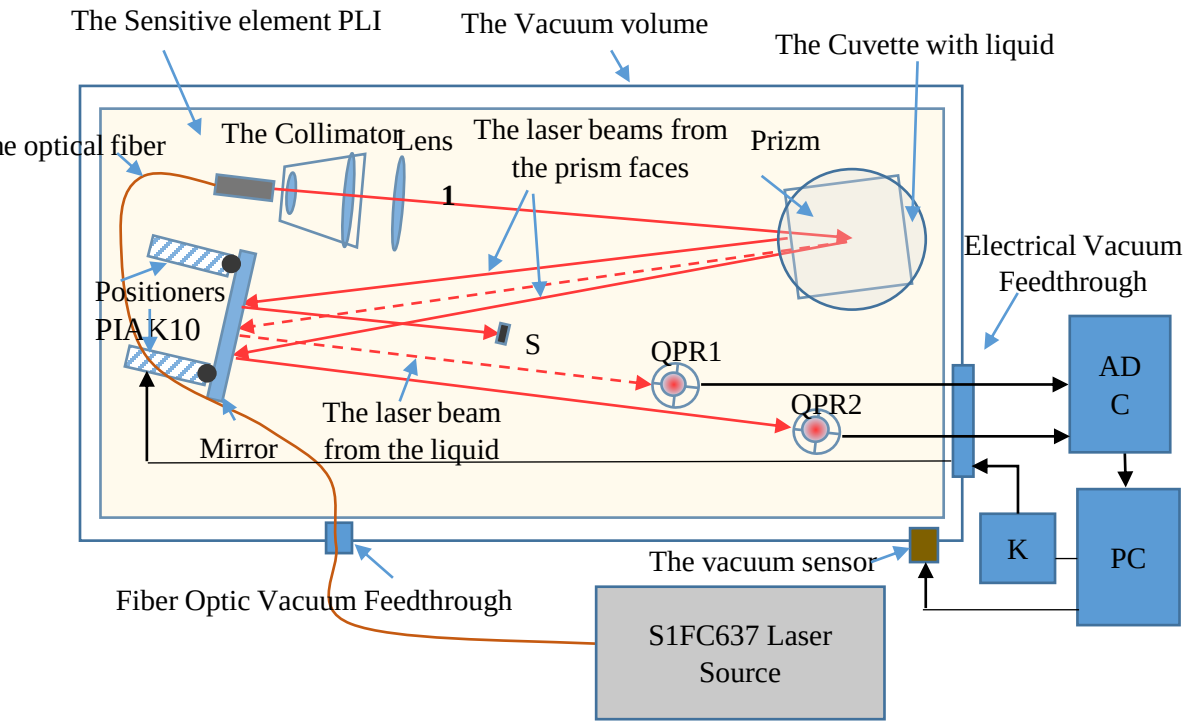
Tasks for the second extension of the Project

Compact Monolithic Precision Laser Inclinometer (CPLI)

- In the second extension of the Project, the creation of a monolithic CPLI is proposed. In this inclinometer the following tasks should be solved:- achieving of a smaller dimensions (less than 20x20x20cm) and small weight (less than 10kg);
- Significant decrease in the dependence of CPLI readings on temperature (introduction of thermoresistive elements)
- Use of the position-sensitive method of dividing plates (a significant reduction in the dimensions of the optical scheme of the PLI, a decrease in the influence of the positional noise of the photodetector);
- Ensuring the solidity of the PLI design (all PLI elements are connected using anaerobic glue, which excludes temperature-dependent changes in the direction of laser beams)
- Use of a new method of PLI calibration, based on interferometric measurement of the piezomodule value of the calibration piezo staker.

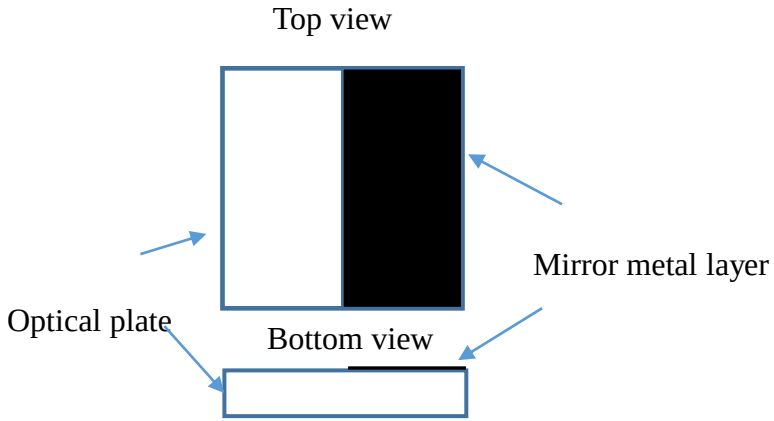
Compact Monolithic Precision Laser Inclinometer 2



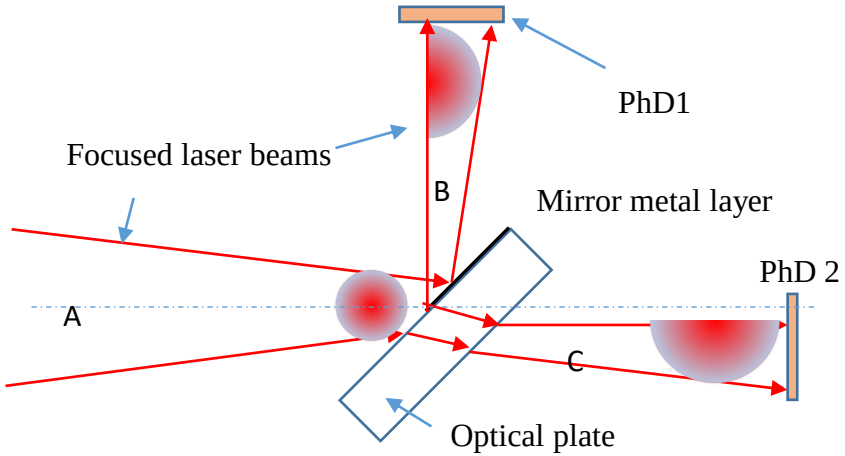


- In a conventional PLI, a quadrant photodetector is used to register the position of the laser beam reflected from the surface of the liquid.
- The presence of a dielectric gap separating the photodetectors with a width of 30 μm requires the organization of focusing the laser beam into a region with a diameter of 100 μm.
- Using the formula for the diameter of a focused laser beam
- $d = \frac{4}{\pi} \lambda \frac{F}{D}$
- where F is of the focal length, D is the diameter of the collimated laser beam in front of the lens. For D = 1cm, we get F = 100cm. It is this circumstance that creates the current dimensions of the PLI (50x40x30cm). Moreover, the weight of such a PLI exceeds 60 kg.
- We propose to radically reduce the overall dimensions and weight of the PLI using a relatively new position-sensitive photometric method of dividing plates . It is based on the use of specially made dividing plates

Compact Monolithic Precision Laser Inclinometer 3



Arrangement of the metallic reflective Layer on a plane-parallel dielectric plate

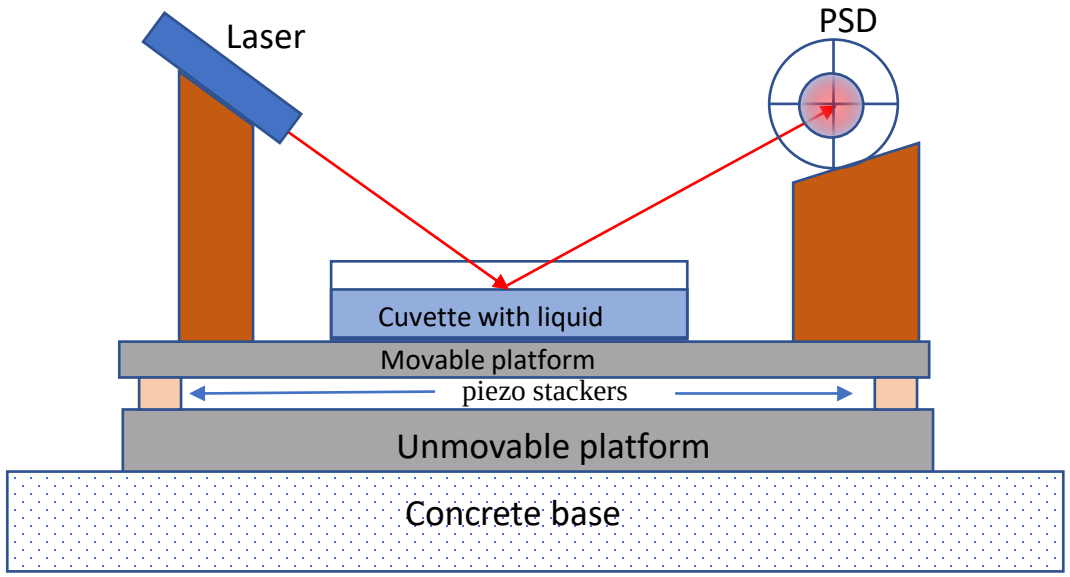


- New method is based on the use of specially made dividing plates. A layer of metal is sprayed onto the surface of a plane-parallel plate so that the line of connection between the metal and the dielectric surface of the plate is straight. By focusing the laser beam on this line, it is possible to divide it into two parts - one passes through the transparent plate, the other part of the laser beam is reflected.

- The lateral displacement of the spot of the laser beam A on the dividing plate changes the intensities of the transmitted C and reflected B laser beams. By measuring the change in the intensity of the separated laser beams, we obtain a position-sensitive photodetector. In this device there is no limitation on the diameter of the laser beam and, accordingly, on the size of the focal length of the laser beam.

- According to preliminary estimates, it is possible to reduce the size of the focal length of the laser beam to 7.5 cm and, accordingly, reduce the dimensions of the PLI to 20x20x20 cm.

Compact Monolithic Precision Laser Inclinometer 4



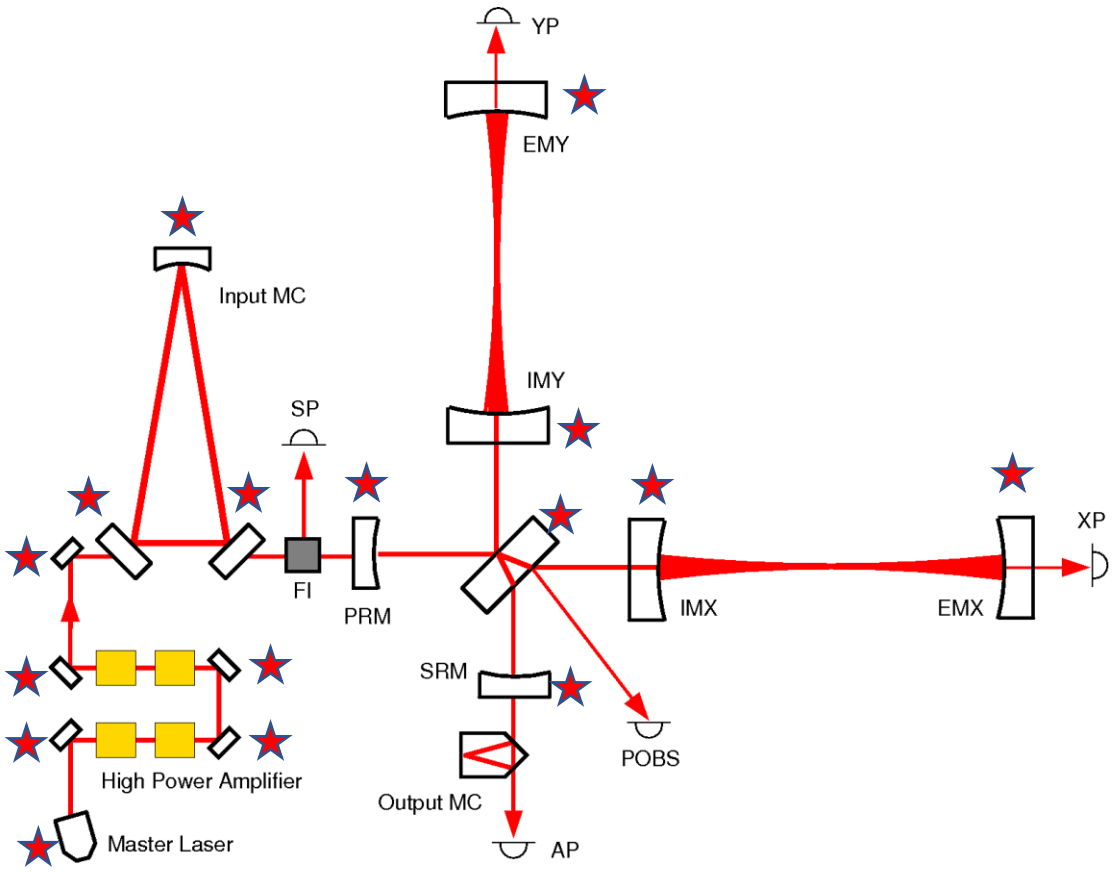
- To achieve the required stability of the position of laser beams in a small-sized PLI, we propose the creation of a monolithic structure with the simultaneous use of thermoresistive elements **(RF State Patent).**

- In this case, all elements of the PLI are held together with aerobic glue on a fixed base. The PLI movable platform is connected to the fixed base using piezo stackers of the same size.

- In this case, a change in temperature changes the dimensions of the piezo stackers, but does not cause parasitic tilts of the PLI.

- Our proposed creation of a monolithic structure using thermal resistance will improve the performance of the PLI and reduce its noise

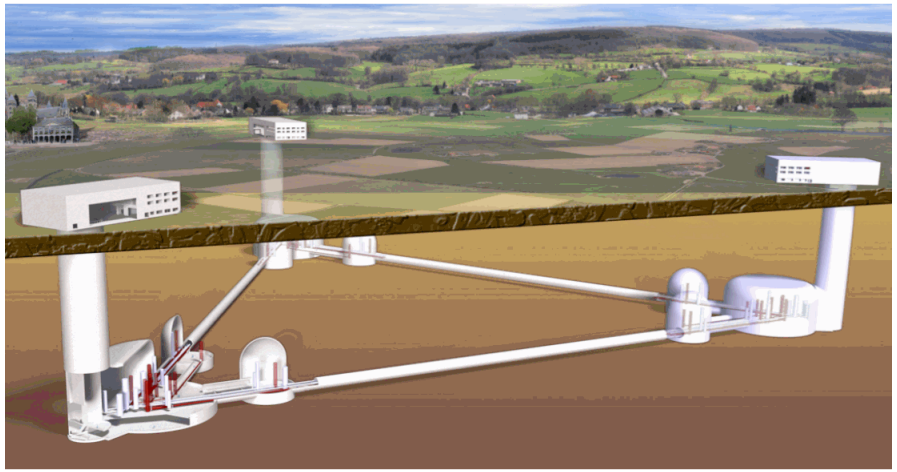
The use of a monolithic CPLI in the operation of the VIRGO Interference Gravitational Antenna

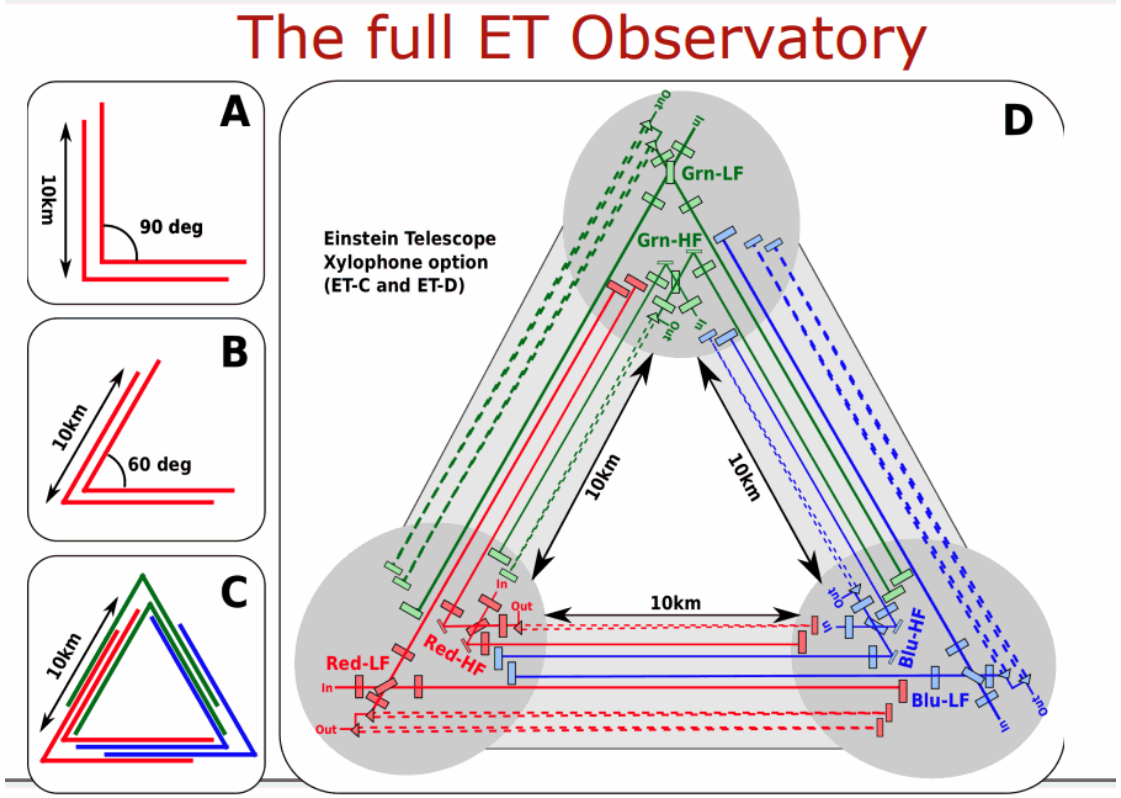


★ Points of the installation CPLI

- To ensure the operation of the IGA VIRGO, ~ 10 units of Compact PLI are required (our estimated).
- The direct operation of the CPLI as part of the IGA VIRGO requires significant adaptation of the CPLI to the conditions of deep vacuum (it is necessary to use special vacuum positioners, create a sealed cuvette with liquid, etc.).
- The necessary work to create an agreed design inclinomrter will begin after preliminary approbation of the CPLI in the area of the IGA VIRGO location.

Development of a cryogenic Compact PLI for the IGA of the third generation "Einstein's Telescope"





- The work of the CPLI as part of the IGA VIRGO is extremely important, but represent only the first stage in the use of the PLI in the IGA of the third generation- “Einstein's Telescope“.

- This gravitational antenna requires operation of the PLI in cryogenic conditions at liquid Ne temperature (23-24^{0}K). Liquid Ne is used as the horizontalizing fluid.

- It is proposed in the extended Project to begin work on the creation of prototypes of CPLI based on liquids and liquefied gases:

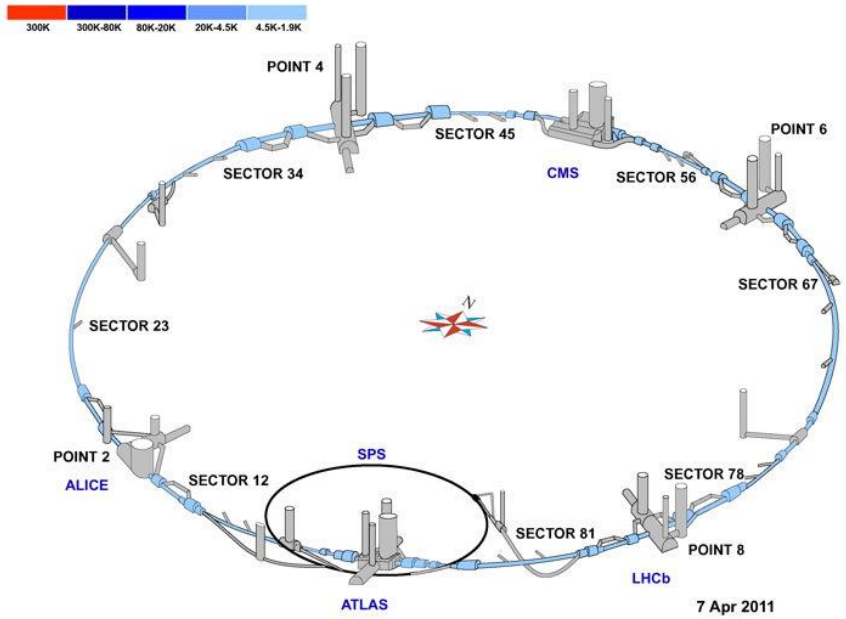
1. Ethanol (room temperature),liquefied carbon dioxide (-58^{0}C),
2. liquid nitrogen (77^{0}K).
3. Further, the transition to liquid neon will be carried out with the ultimate goal of ensuring the operation of the third generation IGA in conditions of isolation from microseismic angular noise.

- For this, it is planned to develop the concept of a cryogenic PLI. Specifically, this is: ensuring the operation of piezo stackers and photodetectors at low temperatures.

Visualization system for angular microseismic tilts of the earth's surface for the NIKA collider and LHC

- Microseismic slopes of the earth's surface exist in a wide frequency range from 10^{-6} Hz to 20 Hz. In fact, two microseismic phenomena dominate in different frequency ranges:

1. high-frequency surface microseismic waves. These are surface waves from the wind load on the surface of the oceans and seas (Microseismic Peak) and industrial noises (the movement of railway and road transport, the operation of a vacuum pump, etc.)
2. low-frequency change in the slopes of the Earth's surface (the influence of the Moon and the Sun), ground subsidence (underground rivers under the LHC), seasonal movement of groundwater (NIKA).



LHC and NIKA location areas

- Visualization of angular microseismic oscillations of surface microseismic waves in the frequency range **10^{-2}-20 Hz** is required.
- In the range of **1-10 Hz**, the conditions for the maximum displacement of beams of colliding particles arise both at the NIKA collider and at the LHC.

Laser Fiducial Line 130 m long.

Planned list of experiments on LFL:

1. Determination of the positioning accuracy of a laser beam in a vacuum at a length from 18m to 130m.

In the experiment, it is planned to investigate the behavior of a laser beam under the action of angular microseismic vibrations.

2. Determination of the accuracy of long-term measurements of LRL at a length of 130m.

In the experiment, it is planned to determine the long-term stability of the LRL at a length of 130 m over a long period (day).

3. Determination of measurement accuracy using seismically isolated platforms.

The experiment will find the maximum positioning accuracy of the LRL in the absence of angular microseismic vibrations.

4. Measurements of the displacement of the test object relative to the stable LRL.

When the maximum stability is reached in the LRL, the displacement of the test object relative to the LRL will be investigated. It is planned to measure the long-term motion of the test object with respect to a stable laser reference line.

5. Comparison of the motion of a laser beam in pipes at atmospheric pressure relative to vacuum.

The experiment will continue the study of the previously found effect of laser beam stabilization in closed tubes. The parameters of such an attenuation of a relatively stable LRL in vacuum will be determined.

Interferometric Distance Meter.

- To overcome the influence of the atmosphere on the measurement accuracy, it is planned to carry out experiments on measuring the length in vacuum in order to obtain the ultimate measurement accuracy. For these purposes, it is proposed to place all the elements of the interferometric length meter in a vacuum box.
- To increase the measurement length, a processing program will be created, which must determine the current coordinate of the carriage movement in the IDM online.
- The use of a processing program will allow you to avoid information overflow in the measurement system and increase the measurement length to a length of 2m. After the IDM has been tested at a length of 2m, it will be placed on the floor of the Metrological laboratory on metrological rails for carrying out full-scale measurements of lengths up to 16m.

Research platform seismically isolated from angular vibrations of the Earth's surface

- After the manufacture of a Compact monolithic PLI, it is planned to conduct experiments on the Seismic Research Platform (SIP) with dimensions of 1 x1 (m).

• The main purpose of such experiments is to demonstrate the angular seismic isolation of the optical table with dimensions of 3x1.5m.

It is planned in future upon Project completion to carry out fundamental physical experiments on an optical table seismically insulated from angular oscillations of the Earth's surface :

✓ measurement of Newton's gravitational constant G with greater accuracy,

✓ Majoran's experiment to search for gravitational-like forces,

✓ experiments with Kibble weights, etc.

Conclusion

- The second extension of the Project is taking place under the conditions of intensive improvement of the parameters of the Precision Laser Inclinometer.

The successes achieved with the help of PLI open up the possibility of using this device in several research areas.

- The most important direction of PLI application is its use for registration of angular microseismic vibrations of large-scale physical setups.
- With a new extension of the Project, it is planned to put into operation a unique new device - a monolithic Compact PLI. This device can investigate angular microseisms in a wider frequency range, which will significantly expand the field of application of the Precision Laser Inclinometer in physics experiments.
- For the NIKA, LHC and FCC colliders, the use of this device will improve the parameters of their spatial stability.
- The use of CPLI for stabilization of interferometric Gravitational Antennas is very promising. Without this device, it is practically impossible to stabilize angular microseisms, both for the existing VIRGO, LIGO, and for the future interferometric gravitational antenna - the Einstein Telescope.
- For the third generation cryogenic IGA, it is planned to develop PLI for operation in cryogenic conditions. In the Project, it is planned to start R&D for PLI, which will operate on cryogenic liquids, and we hope that in the future JINR will take part with the cryogenic Precision Laser Inclinometer method in the third generation IGA Project - the Einstein Telescope.
- The new device will make it possible to start systematic work on the creation of a network in order to predict earthquakes in seismic zones of Armenia and Uzbekistan.