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RECENT ADVANCES AND PERSPECTIVES OF THE HIGH PRECISION LASER METROLOGY

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Последние достижения и перспективы высокоточной лазерной метрологии

Метрология, основанная на использовании лазерного луча, открывает новые возможности в решении задач, где достижение высокой точности измерений является принципиально необходимым требованием.

Протяженная лазерная реперная линия (координатная ось) необходима для прецизионного выстраивания базовых структурных единиц крупномасштабных ускорителей, для тонкой сборки детекторов при монтаже больших спектрометрических комплексов, «он-лайн» контроля относительного пространственного расположения детекторов частиц в рабочий период.

Высокочувствительные лазерные инклинометры открывают новые возможности контроля углового движения поверхности Земли и позволяют стабилизировать пространственное положение пучков ускорителей для достижения высокой интенсивности (светимости) в области их взаимодействия.

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

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Recent Advances and Perspectives of the High Precision Laser Metrology

The laser-based metrology presents new means and opens possibilities in solving tasks where achievement of a high precision survey is of the principal significance necessity.

The extended laser fiducial line (coordinate axis) is necessary for precision alignment of basic structure units of large-scale accelerators, for precision assembly of subdetectors when mounting large spectrometric complexes, for online control of space stability of particle detectors during the data taking period.

The high sensitivity laser inclinometers open the new possibilities for ground motion control and for accelerator (collider) beam space stabilization essential for achievement of stable high intensity (luminosity) at the interaction area.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2014

INTRODUCTION

The next generation of linear colliders and particle detectors are very demanding concerning the alignment tolerances of their components. For the CLIC project, the reference axis of the components will have to be pre-aligned within 10 μm at 1 sigma with respect to a straight line in a sliding window of 200 m.

A new proposal is using a laser beam over 150 m as a straight alignment reference.

Tasks that can be solved using the laser fiducial line: metrological measurements in inaccessible conditions for existing methods, online position control of ATLAS detector and subsystems in data taking period, the online connection of coordinate systems of the LHC and detectors during the runs.

The method is based on the laser beam space stabilization effect when a beam propagates in atmospheric air inside a pipe with standing acoustic wave.

METHOD OF LASER BEAM SPACE STABILIZATION

Observation of the Effect of the Stabilization of the Laser-Ray Space Location Inside the Tube with the Standing Acoustic Waves. Our experimental R&Ds have shown that independent of direct sun rays and of an air heat fluxes we found as a very significant, by an order of magnitude, decrease of the laser beam space noise oscillations.

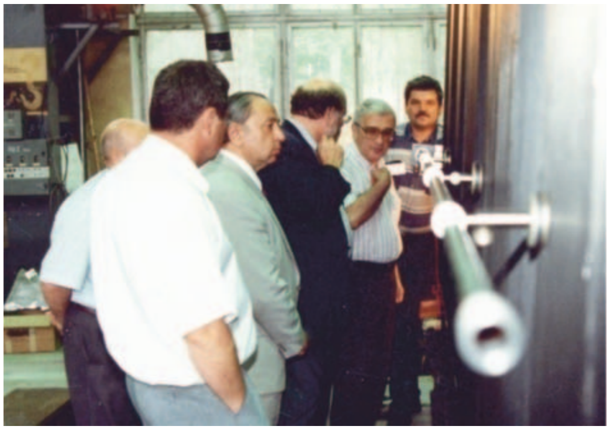

Fig. 1. Demonstration to the CERN and JINR Directorates delegation (R. Cashmore, A. Sissakian, N. Russakovich et al.) of the laser-ray stabilization effect inside the tube. This photo was made in Dubna during the period of laser controlled high precision assembly of 65 MODULES for the ATLAS Hadronic Tile Calorimeter

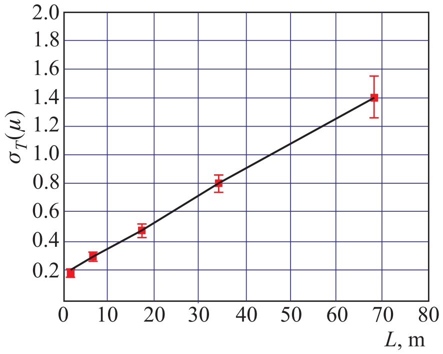

Fig. 2. The σ_T uncertainty for the case «with the tube»

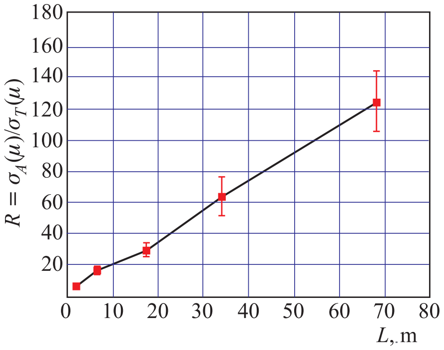

Fig. 3. The $R = \sigma_A/\sigma_T$ ratio with σ_A for the case «without tube»

We found that the laser beam space uncertainty σ is strongly decreased upon ray exits of a tube with the standing acoustic wave in an atmospheric air inside [1–4] (Figs. 1, 2 and 3)

The factor $R \approx 120\,\mathrm{x}$ gain is an impressive result we observed for 70 m tube.

We propose to use as an *extended coordinate axis* the low-σ_T laser beam obtained on the base of the new effect described above.

Laser Fiducial Line: Operation and Design. The Laser Fiducial Line (LFL) measuring system uses a laser beam as a reference of alignment (Fig. 4) with its beginning and end points $\mathrm{A_b}$ and $\mathrm{A_e}$ determined in the global reference frame of the tunnel [5] (Figs. 5 and 6).

Beginning and End Points of the Laser Fiducial Line. The fiber-optic input of the laser radiation into the LFL is needed for thermostabilization of the beginning point.

The two-axis positioner is needed for precise alignment of the centre of the quadrant photodetector with the laser beam axis.

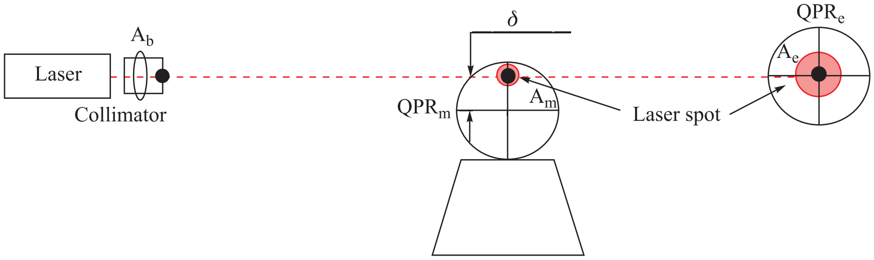

Fig. 4. View of the laser fiducial line

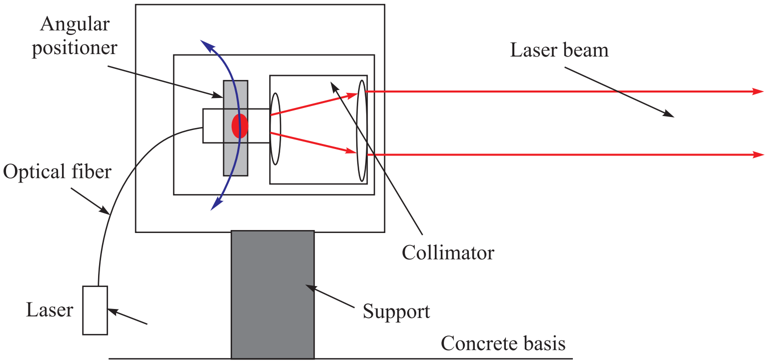

Fig. 5. The beginning point of the LFL

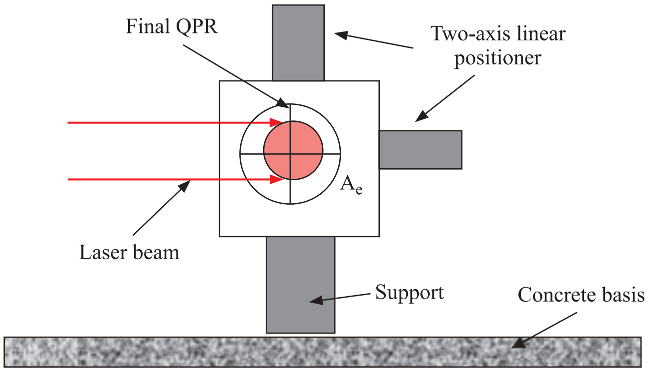

Fig. 6. The end point of the LFL

Intermediate Points of Measurements. The position of the measured point O is shown in Fig. 7.

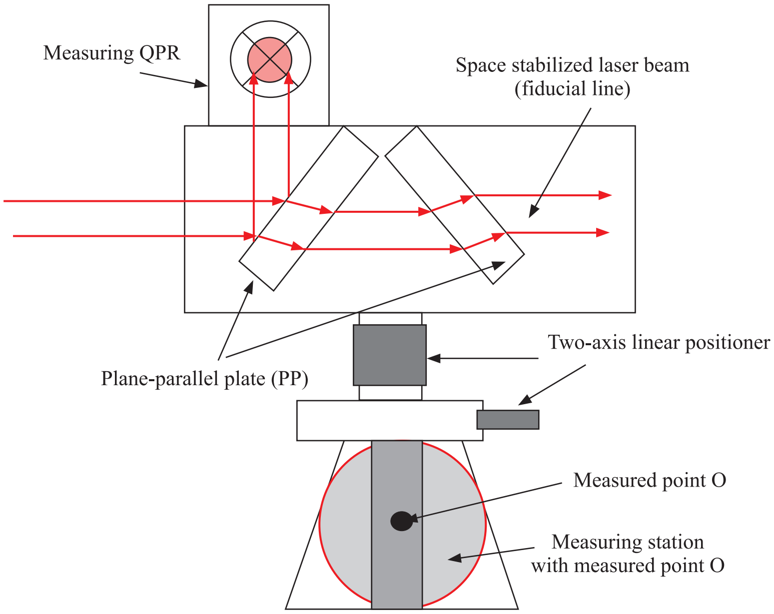

Fig. 7. Nondestructive control system of position of the measured point O

Thermal Stability of the Laser-Ray Position. We use effect of laser beam stabilization when it propagates inside an atmospheric air filled pipe with standing acoustic waves (see Figs. 8 and 9).

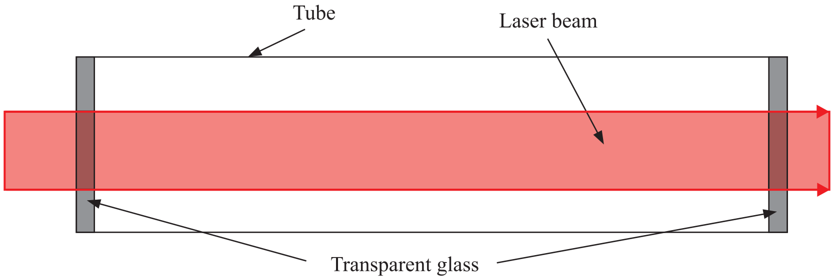

Fig. 8. The short-term system of the stabilization of laser beam location in the tube

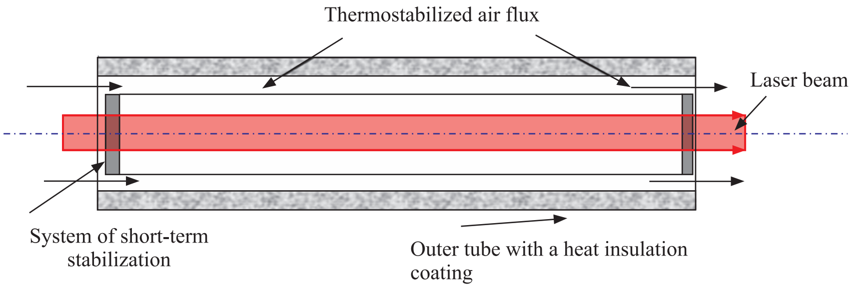

Fig. 9. The long-term system of the stabilization of the laser beam location in the tube

Two tubes set were used. Between tubes the thermal stabilized air flux is propagating. With allowed few microns for the laser-ray displacement from primary direction the long-term temperature stabilization is to be on the level of 0.5 °C.

Precision Long-Term Air Temperature Stabilization in the Thermoisolated Laboratory. The thermal stabilization of air environment has been studied inside 10 m long thermoisolated optical laboratory [6], see Fig. 10.

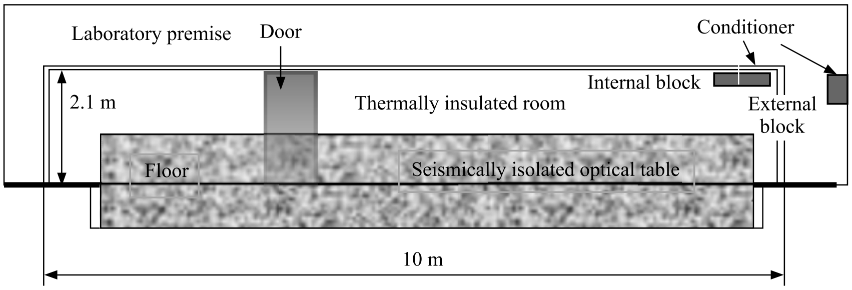

Fig. 10. The schematic view of the thermoisolated laboratory with seismically isolated optical table

Using the air condition in operating in COOL mode, we got the daily value of the temperature instability of 0.05 °C in the whole volume of the thermoisolated room.

During the day we determined the difference in temperature for maximally separated points in thermoisolated room. The magnitude of the difference of temperatures reached 0.03 °C (see Figs. 11 and 12).

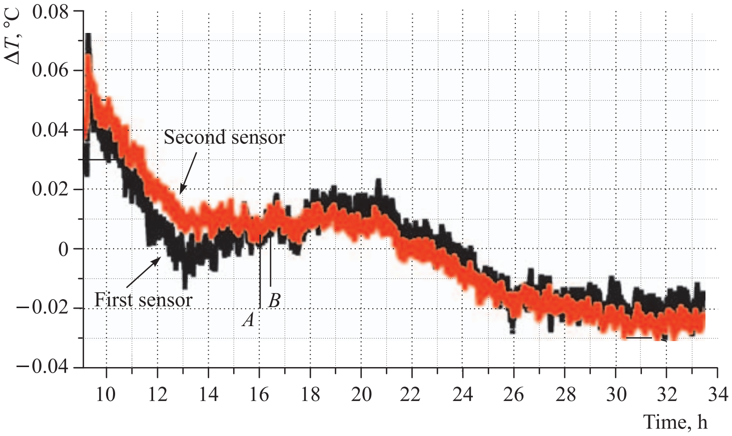

Fig. 11. Temperature difference measurement for points spaced as much as in the thermally insulated room during the day

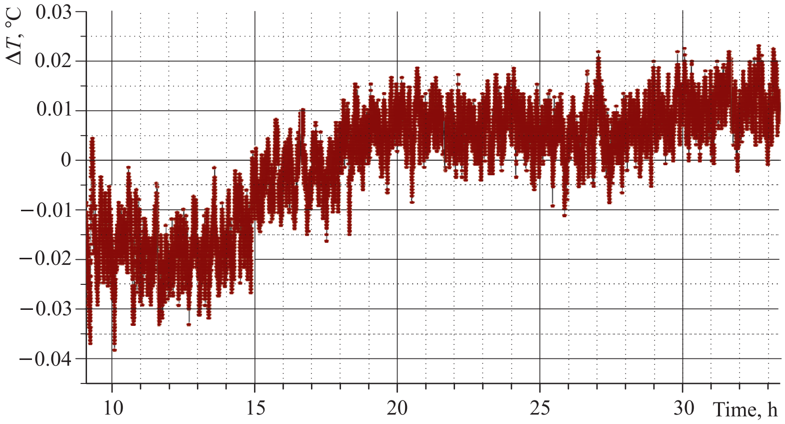

Fig. 12. The difference $\Delta T(^\circ\mathrm{C})$ between the two thermometers data inside thermally isolated room with the conditioner at COOL option (the data of Fig. 11 are used)

Laser Beam Optimal Collimation in LFL. The maximum length of the collimation of the laser beam is achieved in the scheme with prefocusing (Fig. 13) and is determined by the formula

$$L_{\max} = 2Z_{\max} = \frac{\pi}{4}\frac{D_{\max}^2}{\lambda},$$

where $D_{\max}$ — maximum diameter of the laser beam, λ — the laser wavelength (see Fig. 14).

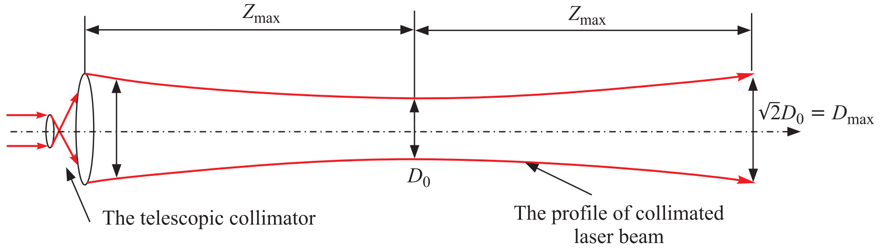

Fig. 13. Profile optimally collimated laser beam in LFL

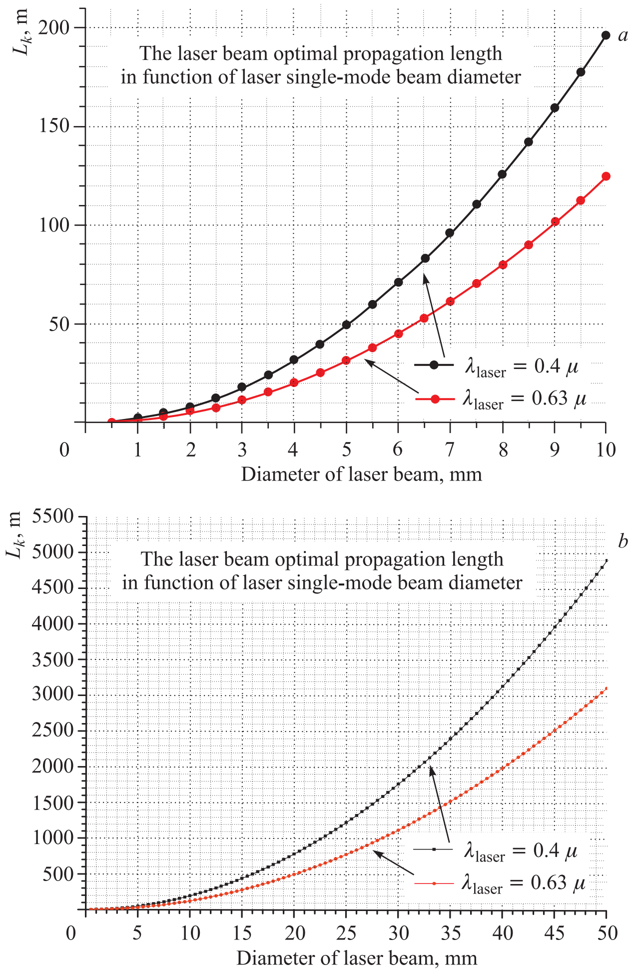

Fig. 14. The collimation length L_k of single-mode laser beam in function of the beam starting diameter: a) for D by 10 mm; b) for D by 50 mm

Including of the Laser Fiducial Line to the Global Coordinate System; LFL Precision Control by Total Station in an Open Air Media. For the 50 m long laser fiducial line and total station measurements, the difference was nearly 100 μm for 16 meters laser–tube T distance [7] (Fig. 15).

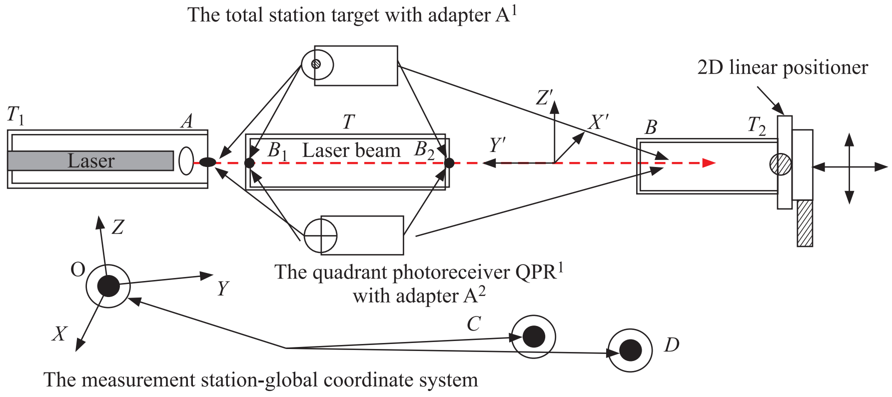

Fig. 15. Scheme of joint coordinate measuring of the tube T ends coordinates using LFL and total station in the global coordinate system $X\,Y\,Z$ and local coordinate system $X'Y'Z'$

The Angular Seismic Isolation of the Laser Source in LFL. We used the essentially new way for measuring of the angular oscillations of the Earth's surface. Main principle: to use a reflected laser beam from horizontal surface of liquid [8, 9] (Fig. 16).

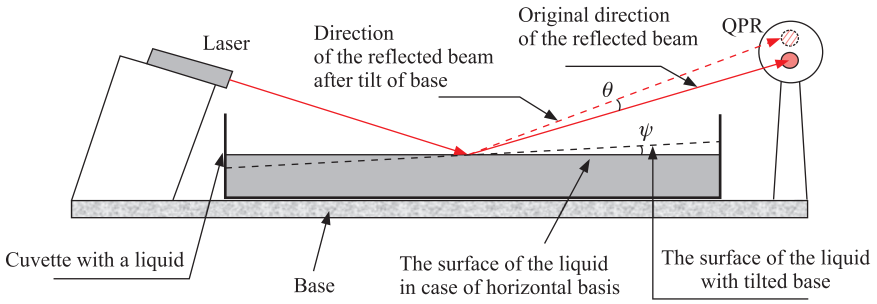

Fig. 16. The principle of construction of the registration device to measure the seismic slope of the Earth's surface

The Experimental Set-Up Inclinometer. The principal view of the inclinometer is shown in Fig. 17

- Frequency internal of the inclinometer: $10^{-4}\text{Hz} \div 1\,\text{Hz}$.
- The achieved inclinometer angular precision: $5 \cdot 10^{-9}$ rad.

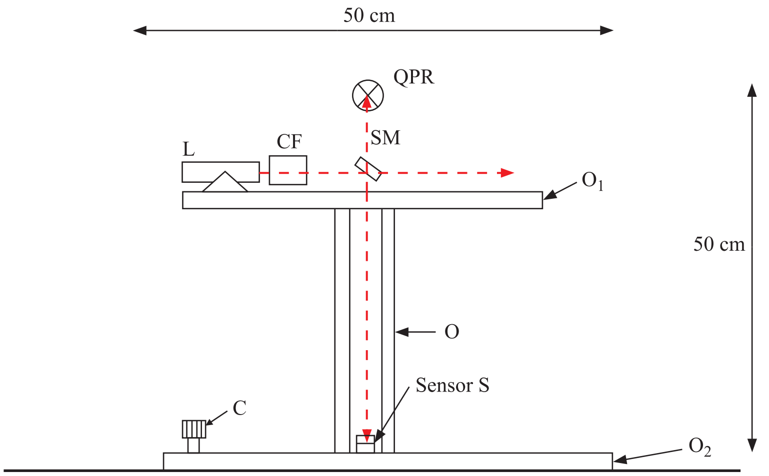

Fig. 17. The principal view of the inclinometer: L — laser, QPR — quadrant photodiode, O, O_1, O_2 — bases, SM — semitransparent mirror, C — calibration screw, CF — collimator with variable focus

THE INCLINOMETER TESTS

The Earthquake in Siberia on February 26, 2011. Physical characteristics of the earthquake: average amplitude of quake in Siberia was 6.5 units; the distance to Geneva $L = 6160$ km; calculated time of earthquake beginning $T_{\text{calc}} =$ 6 h 21 min in Siberia (world time) practically coincides with the published $T_{\text{pub}} =$ 6 h 17 min; amplitude of angular oscillations was $2 \cdot 10^{-6}$ rad (Fig. 18).

The Earth's Surface Single Oscillation. We discovered the phenomenon of the single angular oscillations of the Earth's surface. Amplitude was a few μrad (Fig. 19).

The Earth's Angular Surface Oscillations of an Industrial Noise Origin. The Earth's angular surface industrial noise origins: high activity of auto traffic, works in the neighboring (with our set-up) lab room, people movement close to detecting set-up, etc. The σ values: in work period (CD) 0.3 μrad; in dinner time (AB) 0.04 μrad.

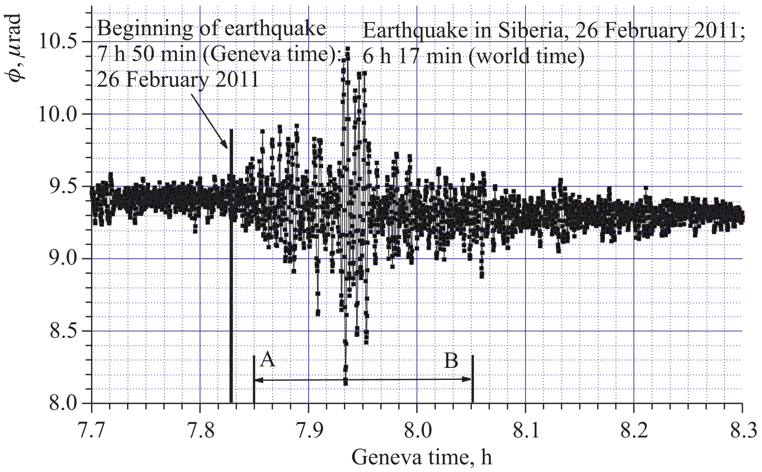

Fig. 18. The seismogram of the angular oscillations of the surface of the Earth as a result of an earthquake in Siberia (registration in the Geneva area)

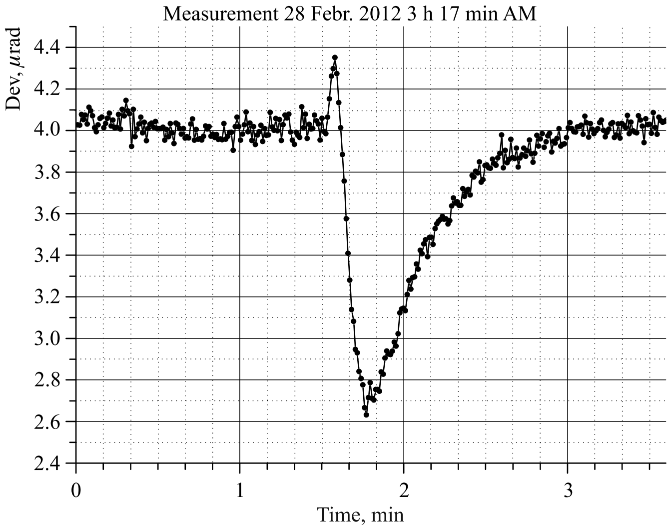

Fig. 19. The seismogram of the single angular oscillation of the Earth's surface

We measured concrete floor inclination due to man presence in 3 meters distance from the experimental set-up. Amplitude was 0.3 μrad (Figs. 20 and 21).

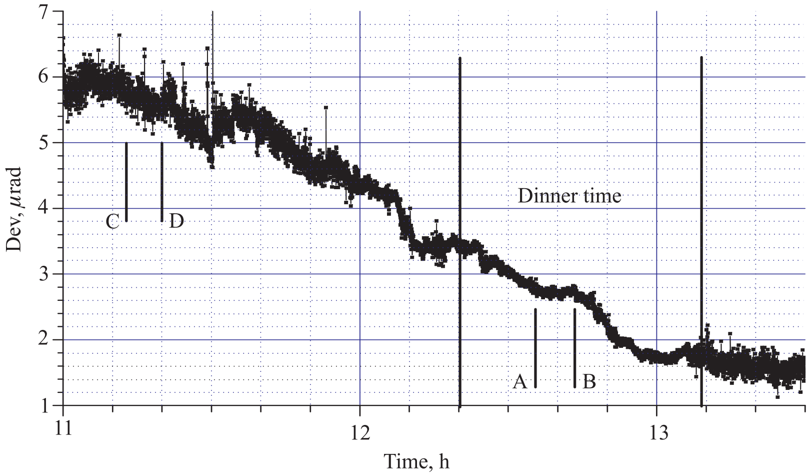

Fig. 20. The day measurement of angular seismic movement of the concrete floor

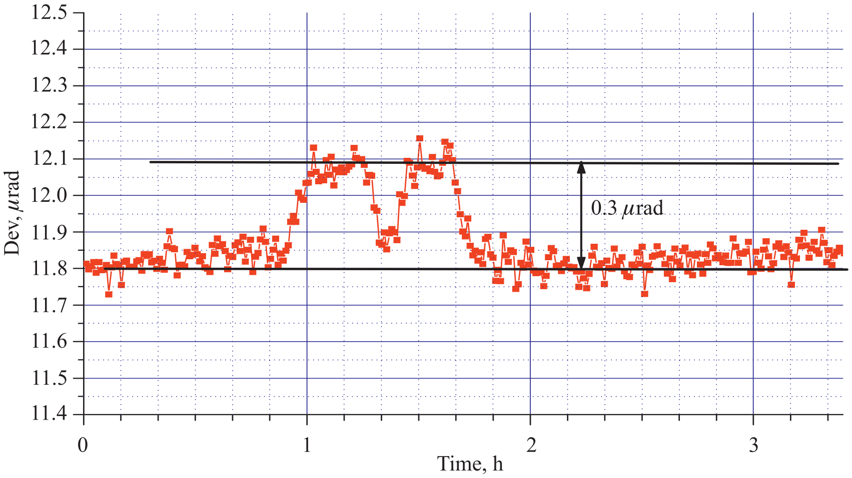

Fig. 21. The measured inclination of the concrete floor due to man presence

The Microseismic Peak Observation by Ground Angular Motion. We first recognized and recorded the angular oscillations of the Earth's surface coinciding with the known phenomenon of «microseismic peak» (Figs. 22 and 23).

Amplitude of the Earth's surface oscillations at the «microseismic peak» frequency was 0.03 μrad with frequency $f_d = 0.13$ Hz. The inclinometer sensitivity estimate gives $\approx 5 \cdot 10^{-9}$ rad.

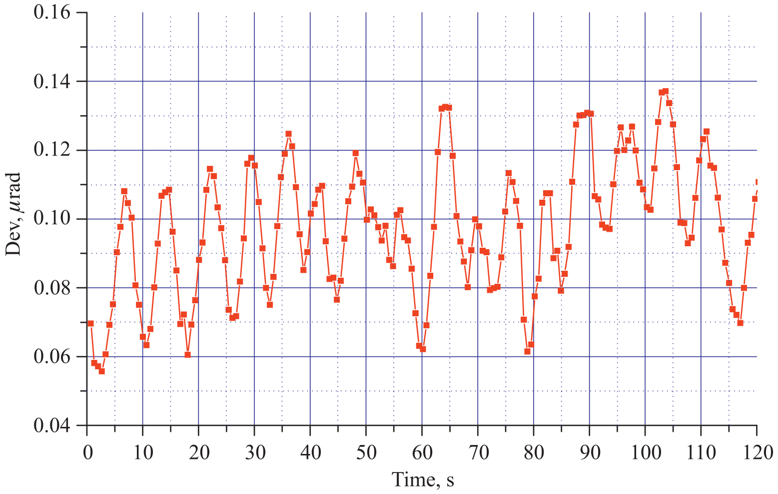

Fig. 22. The seismogram of the angular oscillations of the Earth's surface of the «microseismic peak» frequency

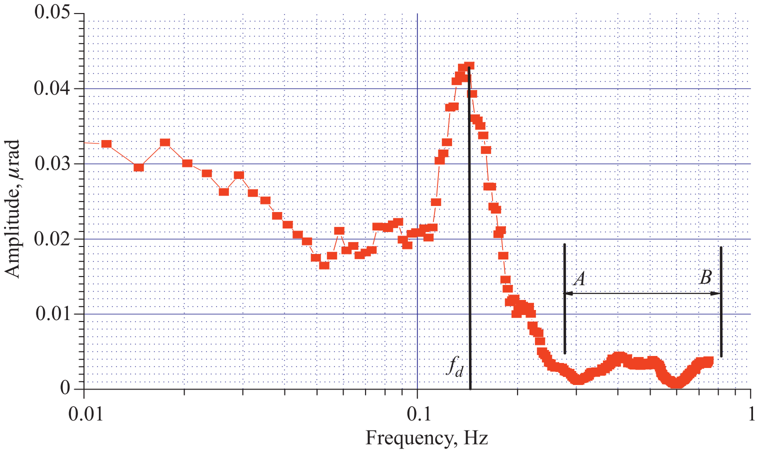

Fig. 23. The fourier analysis of the data of Fig. 21

The Long-Term Experimental Set-Ups Space Location Stability and the Earth's Surface Angular Oscillations. Different accelerator parts are inclined relative to the «basic» horizontal line and consequently particle beams going through the focusing elements leave them with some angular spread θ_{mp} relative to the nominal. As a result, it leads to random motion of position of focuses accelerators (Fig. 24).

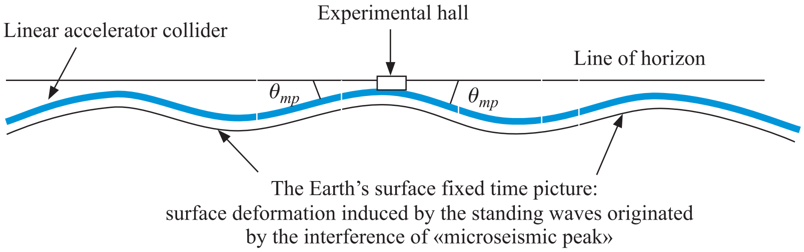

Fig. 24. The accelerator collider positioning on the Earth's surface deformed by the microseismic peak wave

If we can stabilize the angular movements of the accelerator components with an accuracy of 10^{-9} rad, we will be able to stabilize position of its focuses within 50 nm.

CONCLUSIONS

Different technical issues of 150 m and accuracy of 10 μm LFL in atmospheric air were discussed, showing that the combination of

— Single-mode laser associated with a fiber beam coupler for the light emitting point.

— An optimal laser-ray focusing collimation.

— An intermediate sensor having no impact on the straightness of the beam.

— The calibration of each sensor.

— The suppression of air media refraction index and long-term variation of temperature.

— The isolation of the laser source from angular seismic industrial noise can lead to an alignment system providing the location of points within 10 μm.

Such an alignment system opens new perspectives to reach a new precision level of alignment for projects like CLIC and ILC.

An original method for precision measurements when alignment of beam pipe ends on a reference axis has been proposed and tested. The test measurements have been performed using jointly the LFL in a local coordinate system and a total station survey instrument in a global 3D coordinate system. The fiducial marks at the pipe ends have been measured with both instrumentations. A transformation to a common coordinate system has been applied to allow the comparison of the results.

The results of the measurements coincide to an accuracy of approximately $\pm 100\,\mu$m in the directions perpendicular to a common reference line close to the laser beam and for a pipe placed at the middle of 50 m line.

The ground motion was studied by the detection of the Earth's surface angular oscillations. Instrumental method is based on the conceptually new design laser inclinometer using the reflecting surface liquid as a space stable (horizontal) reference level. The achieved inclinometer measurement precision was experimentally proved to be $\approx 5 \cdot 10^{-9}$ rad.

The achieved laser inclinometer sensitivity was proved (in Geneva) by observation of

Ground $2\,\mu$rad oscillation caused by the Siberian earthquake (6160 km).

Single $1 \div 2\,\mu$rad oscillation of origin to be studied.

Industrial origin noise of about $3 \cdot 10^{-7}$ rad amplitude.

Microseismic peak for the first time recognized as a ground $\approx 3 \cdot 10^{-8}$ rad angular oscillation at 0.13 Hz frequency.

The last observed effect, if properly «compensated» by adequate instrumental method, could give significant collider luminosity increase by «compressing» of beams intersection area to about 50 nm level (an estimate) due to some suppression of the lateral focus effect.

The instrument of this sort can probably be useful for modern high precision research equipment stabilization, for example large telescope, to reach an extreme resolution.

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