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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

A LASER-BASED FIDUCIAL LINE FOR HIGH-PRECISION MULTIPOINT ALIGNMENT SYSTEM

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The next generation of linear colliders is 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 solution based on stretched wires with wire positioning sensors has been proposed in order to fulfill the alignment requirements in the Conceptual Design Report of the project. This solution has some drawbacks and laser-based alternative solutions are under study in order to validate the wire solution and possibly replace it.

A new proposal is introduced in this paper, using a laser beam over 150 m as a straight alignment reference, with the objective of having an uncertainty in the determination of its straightness within 10 μm. Sensors coupled to the components to be aligned would provide after calibration the horizontal and vertical offsets with respect to the laser beam, within a few micrometers, in their coordinate system.

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. The principal schemes of corresponding optoelectronics devices and temperature stabilization solutions are also proposed, making probable the extension of the laser fiducial line up to a 500 m length.

Новое поколение линейных коллайдеров весьма критично к соблюдению точности «выстраивания» их структурных элементов. Для проекта CLIC решение основано на применении натянутых струн в качестве референсных линий (координатных осей). Неопределенность в пространственной координате оси должна быть на уровне 10 мкм (сигма) на рабочей длине 200 м. Применение натянутой струны предусмотрено в концептуальном проекте CLIC для достижения необходимой точности «выстраивания» его структур. Это решение имеет некоторые недостатки, и альтернативное решение с развиваемой лазерной методикой послужит либо для выбора «струнной» версии, либо ее замены на лазерную.

В данной работе представлено новое предложение использовать 150-метровой длины луч лазера как прямую референсную линию для «выстраивания» компонентов ускорителя, имеющую неопределенность в пространственной координате не более 10 мкм. Датчики на «выстраиваемых» компонентах после специальной калибровки обеспечат горизонтальные и вертикальные отклонения от лазерного луча с точностью несколько микрон в координатной системе этих датчиков.

Метод основан на эффекте стабилизации пространственного положения луча лазера при его прохождении в атмосферном воздухе внутри трубы со стоячей звуковой волной. Также предложены принципиальные схемы используемых оптоэлектронных устройств и температурной стабилизации, что делает вероятным продление лазерной реперной линии до 500 м.

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INTRODUCTUION

A new method allowing the alignment of accelerators components along a straight line of 150 m is proposed. Contrary to other laser-based alignment solutions under development for such a distance [1–3], the laser beam does not propagate under vacuum, but inside a pipe with standing acoustic waves, allowing an uncertainty in the determination of its straightness of 10 μm. In this paper, the stability in position of the laser beam is discussed, based on results of measurements performed over 70 m. The operation and design of such an alignment system are detailed, as well as the different components of such a system, from the laser beam to the alignment sensors. The impact of temperature and industrial noise on such a system is discussed, and solutions to reduce their effects are proposed.

1. LASER RAY POSITIONAL STABILITY

The principle of a laser beam used as an extended fiducial line is based on the effect of laser beam stabilization when it propagates inside an atmospheric air filled pipe with standing acoustic waves [4–6]. The transversal laser beam fluctuation was reduced by a factor greater than 100 with respect to a beam propagating in open air.

Figure 1 contains the standard deviations $\sigma_{\mathrm{rms}}(L)$ of beam space localization uncertainty, determined experimentally, as a function of beam covered distance L (up to 70 m) [7].

By extrapolation, the expected σ_{rms} for $L = 150$ m could be on the 3–4 μm level.

Experiments [3] performed on a distance $L < 70$ m highlighted the effect of industrial noise, acting on the laser source support and consequently on the inclination of the laser beam. This effect contributes to the linear growth of the standard deviation of the beam axis space localization $\sigma_{\mathrm{rms}}(L)$ in Fig. 1.

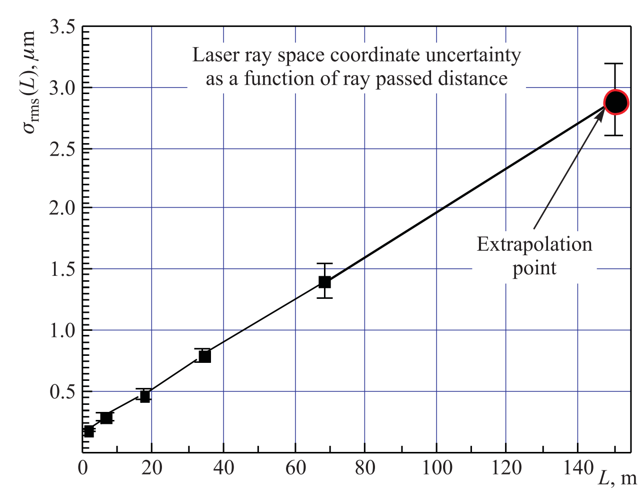

Fig. 1. The $\sigma_{\mathrm{rms}}(L)$ uncertainty in laser ray space coordinate with respect to propagation distance L inside the atmospheric air filled tube with standing acoustic wave

2. LASER FIDUCIAL LINE: OPERATION AND DESIGN

The Laser Fiducial Line (LFL) measuring system uses a laser beam as the reference of alignment, with its beginning and end points O_1 and O_2 determined in the global reference frame of the tunnel. The laser beam source can be precisely adjusted in the azimuthal θ and polar φ angles by using a two-axis angular positioner combined with a position-sensitive quadrant photoreceiver QPr allowing the determination of the beam axis position (Fig. 2).

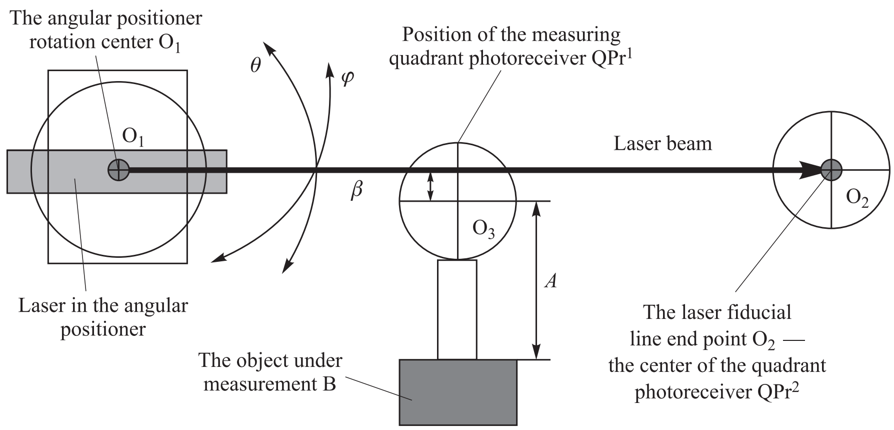

Fig. 2. Block diagram of the Laser Fiducial Line complex

The LFL reference points are:

(a) the beginning point O_1, which is the center of the angular positioner of the laser beam source (determined by direct measurements on the two-axis angular positioner);

(b) the end point O_2, which is the center of the end quadrant photoreceiver QPr^2.

In most of the metrological problems, it is necessary to measure the coordinates of an object in the transverse direction with respect to the laser beam. In the case considered in Fig. 2, the position of the measured object B relative to the LFL is given by the vertical and horizontal readings of QPr. During a calibration process, the center O_3 of the QPr^1 will be determined in the coordinate system of the sensor, materialized by a kinematic mount, allowing a dismounting and mounting of the sensor on the object within a few micrometers. This step allows then one to determine the radial and vertical position of the object B with respect to LFL.

In another calibration process, the center O_3 can be determined with respect to external fiducials, as 0.5″ or 1.5″ Corner Cube Reflector interfaces, allowing one to improve the accuracy in the determination of an underground geodetic network for example [8].

3. THE COMPONENTS OF LFL

The system consists of three components:

— a beginning point;

— an end point of fixation;

— N intermediate points of measurements.

3.1. Beginning Point. A fiber beam coupler, input of the laser emission, provides a stiff mechanical reference to the optical center of the light-emitting point. It is combined with a collimator, positioned into a precision angular positioner which is fixed on a rigid support (Fig. 3).

This configuration has two advantages: the space separation of the laser source itself, and the laser emitting entrance point by an optical fiber. Consequently, the noise coming from the laser angular instability due to the non-uniform heating of the laser-source working body is cut out. Also, using the one-mode optical fiber, a high-quality irradiation source can be obtained, guaranteeing the absence of the positional noise of residual modes [9].

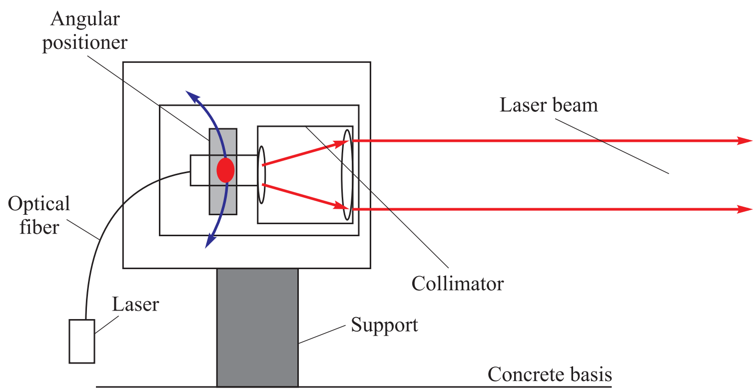

Fig. 3. The fiber-optical input of the laser radiation into the LFL

Collimating devices with variable focus distance are used, allowing one to obtain a beam profile with focusing along the $2Z_{\max}$ length of collimated beam, in such a way that the beam diameter D_0 of the laser line does not exceed $D = \sqrt{2}D_0$ in the first and last points of ray (Fig. 4).

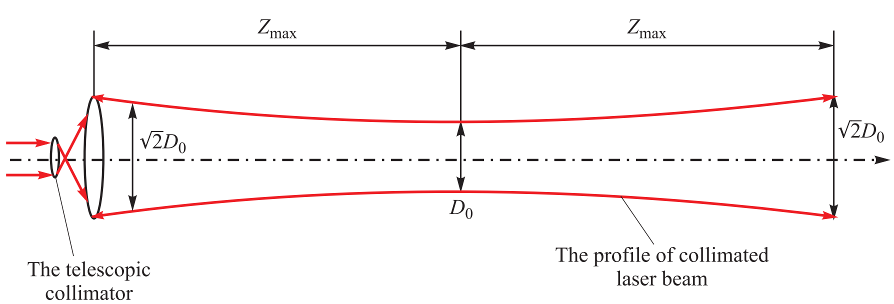

Fig. 4. The laser beam profile with optimal collimation

Figure 5 gives the optimal collimation length L_c (corresponding to $2Z_{\max}$ in Fig. 4) as a function of the beam diameter, considering a single-mode laser ray in the beginning point for wave-lengths of $\lambda = 0.4$ μm and $\lambda = 0.63$ μm.

As an example, for a blue laser source $\lambda = 0.4$ μm, with a starting diameter of 9 mm, the length of LFL can be 150 m.

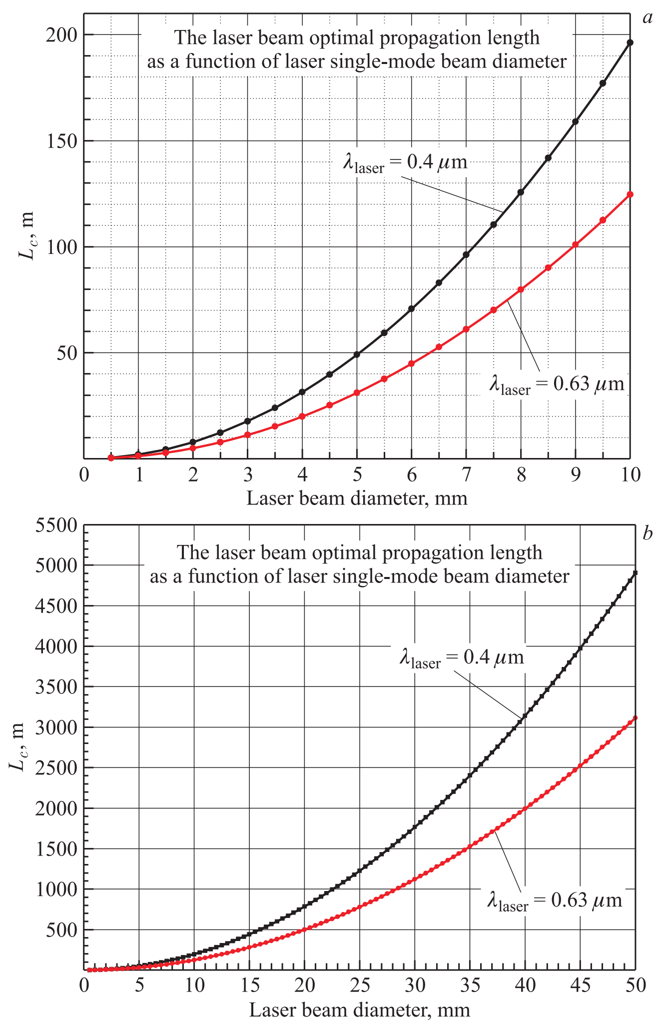

Fig. 5. The collimation length L_c of single-mode laser beam as a function of beam starting diameter: *a*) for D by 10 mm; *b*) for D by 50 mm

3.2. End Point of Fixation. A quadrant photoreceiver is used to fix the laser-ray axis position at the final point O_2 (Fig. 6). It is positioned on a two-axis linear translation stage, adjustable by micrometric screws, which will allow the centering of the QPr center with the laser beam axis. According to the readings performed on the QPr of the final point, on-line corrections are also introduced to the angular positioner of the light-emitting point to stabilize the LFL location.

3.3. Intermediate Points of Measurements. In order to keep the straightness of the laser beam, considered as the reference of alignment, plane-parallel plates are implemented, as shown in Fig. 7.

The plane-parallel plates (PP) are positioned at 45° with respect to the laser ray to allow a partial reflection of ray on the measuring QPr. It is essential that both QPr and PP are part

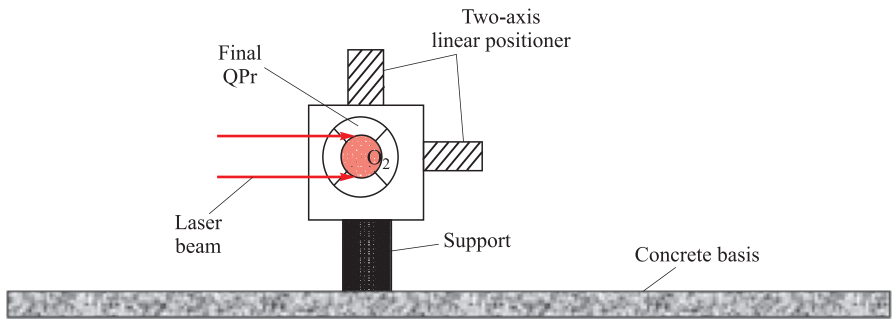

Fig. 6. The final quadrant photoreceiver location on the two-coordinate positioner

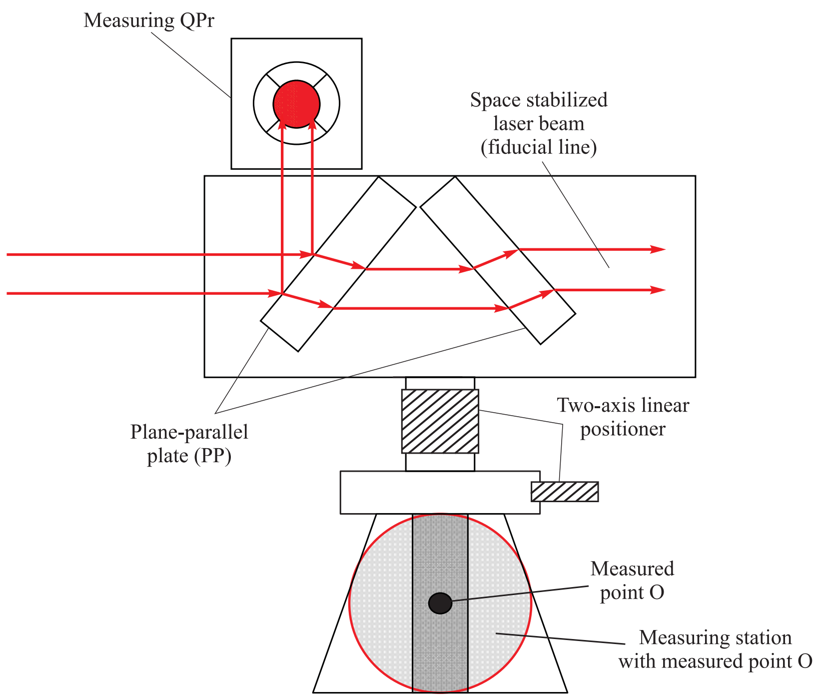

Fig. 7. The intermediate measuring quadrant photoreceiver location on the two-coordinate linear positioner

of the same support, the support being linked to the object O to be measured by means of a two-axis linear translation stage. Using the micrometric screws, the reflected laser beam axis is adjusted on the center of the measuring QPr. The position of the object O can be deduced from the displacements performed by the micrometric screws and the readings of QPr. To compensate the laser beam offset due to the refraction in PP plate, a second correcting PP plate is positioned at 135° to laser ray.

If each intermediate sensor follows a calibration process, the two-axis displacement tables will not be needed anymore.

4. STABILITY OF LASER RAY POSITION

4.1. Short-Term Stability. The laser-beam space stabilization effect with standing acoustic wave, observed in pipes with closed ends, gives an idea of the design needed for short-term stabilization of the beam: it might be a set of pipes surrounding the laser beam, with transparent windows at the starting and ending points of the LFL (Fig. 8).

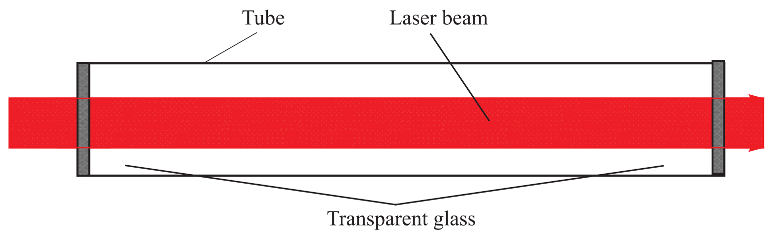

Fig. 8. The short-term laser-ray stabilization scheme

4.2. Long-Term Stability. In case of a slow variation of the temperature gradient in the air media, the index of refraction is changing, and consequently the laser beam position. Below is given an estimate of this effect influence on the laser space stability in the LFL.

Air refraction index variation Δn with the temperature at a stable pressure is given by

$$\Delta n = 0.0003(\Delta t/273^{\circ}\mathrm{C}). \tag{1}$$

The long-term stability of the temperature is $\Delta t = 0.1^{\circ}$C, the refraction index change is $\Delta n = 10^{-7}$.

Considering that laser ray propagation through air-media temperature nonuniformities is similar to ray propagation through inclined parallel-plane plates, the laser ray displacement δL can be computed relative to its primary direction AB (Fig. 9).

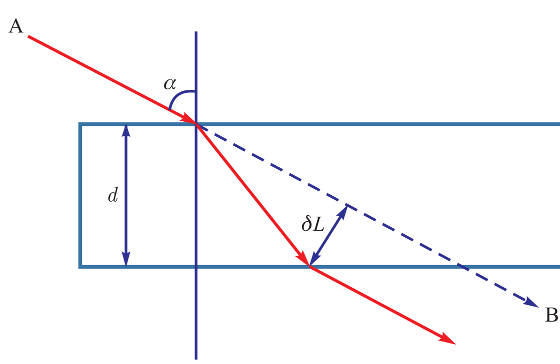

Fig. 9. The laser ray displacement when propagating through PP plate

The laser ray displacement δL in PP plate is

$$\delta L = d \sin\alpha \left(1 - \frac{\cos\alpha}{\sqrt{n^2 - \sin^2\alpha}}\right), \tag{2}$$

where d is the plate thickness, α is the plate inclination angle with respect to the laser ray, $n = 1 + \Delta n$ is the plate refractive index.

Considering $\alpha = 45°$, $d = 10$ m and $\Delta n = 10^{-7}$, one has $\delta L \sim 1$ μm.

The estimate given above is obtained for a thermal stability of $\Delta t = 0.1$°C for the LFL location region, knowing that this level is easily reachable with modern air conditioners.

Long-term stabilization of the LFL will include an additional pipe with a thermal shielding, surrounding the short-term thermal stabilization system.

The conditioned air located between the pipes (outer tube with thermal shielding and inner tube — short-term stabilization system) will be pumped along the whole LFL in order to guarantee thermal isolation from outside temperature gradients (Fig. 10).

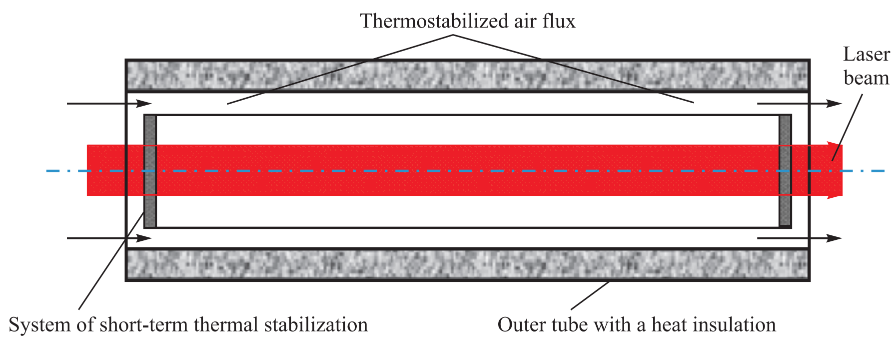

Fig. 10. Long-term thermostabilization system

4.3. Seismic Stability of the LFL Laser Source. As mentioned before, because of the seismic activity and industrial noise, the laser source support must be stabilized.

During the day time, noise is generated, coming from auto-transport movement, works in the neighborhood, people moving in the vicinity of the LFL system, etc. To measure

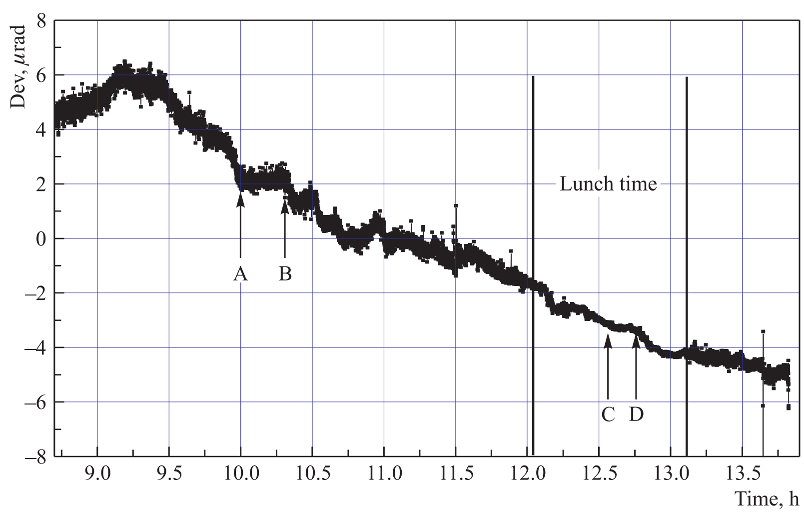

Fig. 11. The earth surface angular oscillations of an industrial noise origin during working hours and at lunch time

the average level of the industrial noise, angular oscillations of the earth surface were monitored [7]. The data presented below comes from the monitoring of the laboratory (CERN B926) concrete floor oscillations Dev (μrad) measured between 11:00 and 13:30 (Fig. 11).

During lunch time, a significant decrease of industrial noise is observed down to the level of $8 \cdot 10^{-8}$ rad — the Dev spread on the CD interval. During the working hours, the earth angular oscillations are characterized by the $5 \cdot 10^{-7}$ rad of Dev spread on the AB part.

Figure 12 presents the tilt angle of concrete floor Dev (μrad) caused by the weight of man at 3 m from the measuring device.

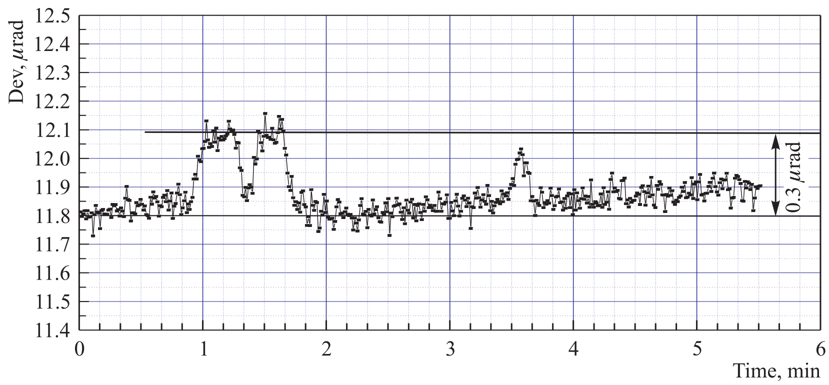

Fig. 12. The concrete floor deformation — tilt angle — as a result of the weight of man present at 3 m distance from the detecting device

The registered tilt angle was $3 \cdot 10^{-7}$ rad. The industrial noise is the source of laser-ray angular instability, which leads to the instability of the laser-ray spot location on the measuring QPr; this instability is increasing with the distance: considering a distance of 100 m, the noise could reach 50 μm. In order to neutralize such a noise, feed-back systems are proposed, based on the signals from very precise inclinometers positioned on the source support.

5. LENGTH OF LFL

The laser-ray optimal collimation length dependence on the initial ray diameter (Fig. 5) shows that the maximal collimation is limited by the diameter of the laser ray used in the LFL. It looks technically possible to use a ray with a diameter of 30 mm. In this case, with a single-mode laser emission, the maximum length of the LFL may be $L_{c\,\max} \sim 2$ km.

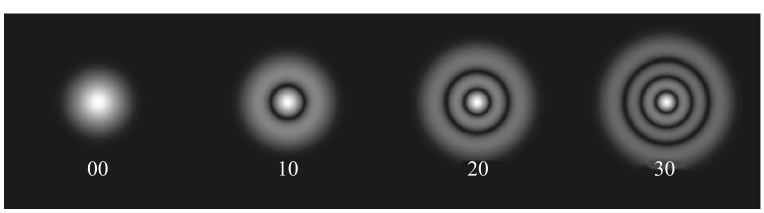

Fig. 13. Irradiated power distribution $I(r, \varphi)$ as a function of radius and azimuthal angle across a multimodes laser ray; case with laser radiation with non-flat mirrors

The laser-ray propagation length could be increased using the so-called Laguerre–Gaussian modes [10].

This case is illustrated in Fig. 13, showing the irradiation power $I(r, \varphi)$ distributions in single mode "00" and multimodes "10", "20", "30" laser rays from the laser source with non-flat mirrors [11]. In the central part of the "10", "20", "30" modes, the r-, φ-symmetric light spots are observed with an angular divergence nearly twice smaller than for single modes. If so, using the indicated modes, the maximal collimation length could be doubled in the LFL.

CONCLUSIONS

As a summary, different technical issues of a 150 m 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 industrial noise

can lead to an alignment system providing the location of points within 10 μm.

The maximum distance is limited to 2 km for a maximal ray diameter of 30 mm. The use of Laguerre–Gaussian modes "10", "20", "30" is an interesting possibility to double this length.

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

This work is the result of the letter-exchange between DG of CERN and DG of JINR with expressing the common wish for both Labs to cooperate in the high-precision laser metrology development for the CLIC components alignment.

REFERENCES

1. *Anastasopoulos M. et al.* Theoretical and Practical Feasibility Demonstration of a Micrometric Remotely Controlled Pre-Alignment System for the CLIC Linear Collider // EuCARD-CON-2011-039. P. 547–549.
2. A Multi-TeV Linear Collider Based on CLIC Technology. CLIC Conceptual Design Report. CERN-2012-007.
3. *Geiger A. et al.* Feasibility Study of Multipoint Based Laser Alignment System for CLIC // Intern. Workshop on Accelerator Alignment, Batavia, USA, Sept. 10–14, 2012.
4. *Batusov V. et al.* On Some New Effect of Laser Ray Propagation in Atmospheric Air // Phys. Part. Nucl. Lett. 2010. V. 7, No. 5. P. 359–363.
5. *Batusov V. et al.* Observation of Specific Features of Laser Beam with Propagation in Air Standing Acoustic Waves // Ibid. No. 1. P. 33–38.
6. *Batusov V. et al.* A Study of an Air Medium Influence on the Rectilinearity of Laser Ray Proliferation towards the Using for Large Distances and High Precision Metrology // Phys. Part. Nucl. Lett. 2007. V. 4, No. 1. P. 92–95.

7. *Batusov V., Budagov J., Lyablin M.* A Laser Sensor of a Seismic Slope of the Earth Surface // Phys. Part. Nucl. Lett. 2013. V. 10, No. 1. P. 43–48.
8. *Batusov V. et al.* On a Laser Beam Fiducial Line Application for Metrological Purposes. JINR Commun. E13-2007-98. Dubna, 2007.
9. *Wallner O., Leeb W. R., Winzer P. J.* Minimum Length of a Single Mode Fiber Spatial Filter // J. Opt. Soc. Am. A. 2002. V. 19, No. 12.
10. *Freise A., Strain K.* Interferometer Techniques for Gravitational Wave Detection // Living Rev. Relativity. 2010. V. 13. P. 1.
11. http://en.wikipedia.org/wiki/Gaussian_beam#Laguerre-Gaussian_modes

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