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Refraction effects on a Structured Laser Beam as a reference line for alignment

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Abstract

A Structured Laser Beam (SLB) is a pseudo-non-diffractive beam characterized by an optical intensity profile resembling a Bessel Beam. SLBs are known for the small divergence of their inner core (i.e., 10 µrad) during long-distance propagation (i.e., 900 m) making them suitable for establishing a reference line for an offset measurement. However, the propagation of laser beams through an inhomogeneous medium causes light path deviation, introducing constraints on reference lines for particle accelerator alignment. Historically, vacuum systems have addressed atmospheric refraction influences, yet their installation poses challenges such as vacuum forces, reflections inside a vacuum pipe and symmetry breaking of an SLB. In addition, the sequential measurement adds other constraints connected to the synchronisation of the multipoint measurement system. This paper investigates atmospheric refraction effects on SLBs in a 140-meter underground laboratory, assessing SLB straightness using the Hydrostatic Levelling System (HLS) and Wire Position Systems (WPS). The results reveal straightness in the horizontal and vertical directions under 400 µm, albeit with the standard deviations reaching 580 µm. These findings provide insights into the feasibility of SLB-based alignment systems for particle accelerators.

Alignment, Laser, Measurement, Positioning

1. Introduction

Particle accelerators impose stringent demands on the alignment of their elements, reaching 20 µm within a length of 200 m [1]. Generally, the techniques used for accelerator alignment refer to either gravity or a straight line.

One of the systems that exploits the gravitational field is the Hydrostatic Levelling System (HLS). The HLS serves as the primary vertical reference at the interaction points for the High Luminosity Large Hadron Collider (HL-LHC). The HLS utilizing capacitive sensors demonstrates a repeatability of 2 µm and an accuracy of 10 µm [2].

Another category of systems involves offset measurement with respect to reference lines in the horizontal or vertical direction, established in space using either a physical object or an optical axis. The Wire Positioning System (WPS) utilizes capacitive sensors for continuous transverse offset measurement relative to a stretched wire, achieving a measurement resolution of 0.1 µm and a sensor accuracy of a few micrometres [3]. The WPS primarily measures the transversal offset but can be used to determine the vertical deviations by combining information acquired by the HLS and the catenary reconstruction [4].

Establishing a straight-line reference for accelerator alignment sometimes involves an optical beam. However, the divergence of light poses limitations on long-distance propagation. To address this, various laser systems have been proposed [5], [6]. The future system based on the Structured Laser Beam (SLB) shows particular advantages in beam divergence.

An SLB represents a pseudo-non-diffracting beam with a transversal intensity profile similar to a Bessel Beam. The transversal intensity profile of an SLB is characterized by a narrow inner core surrounded by concentric rings. The low divergence of the inner core reaching 10 µrad, which was experimentally tested over 900 m is promising for establishing a straight reference line. The generation principle and main properties of an SLB were detailed in the previous work [7].

However, the potential of an SLB for alignment may be limited by the symmetry breaking of the beam. This phenomenon, observed by Polak [8] occurs when the transversal intensity profile is obstructed by an asymmetric obstacle. The influence may be especially detrimental for narrow propagation paths where a large portion of the profile is covered resulting in a transversal change in the inner core position.

Atmospheric refraction is one of the most significant limitations to long-distance optical alignment due to its influence on the alignment reference straightness. In the atmosphere, light bends due to local differences in the refractive index of air. To mitigate the effect of refraction, a vacuum pipe with a pressure of around 0.01 mbar was introduced [5]. Other institutes, inspired by pioneering works at SLAC, installed vacuum systems at KEK [9] and DESY [6].

The objective of this paper is to quantify the influence of refraction on the straightness of the laser beam in the 140 m underground tunnel. The investigation assesses the refraction influence on the SLB in atmospheric pressure based on the WPS and HLS measurements, which was not studied before. In addition, other sources of errors that limit the alignment performance are discussed in the paper together with potential harm reduction measures.

2. Methodology

The long-distance test was conducted in an underground tunnel with a total measurement setup length of 140 m. The setup comprises seven metrological plates made of invar [10].

On each plate, sensors for three different systems (HLS, WPS, and SLB) have been installed, as illustrated in Figure 1.

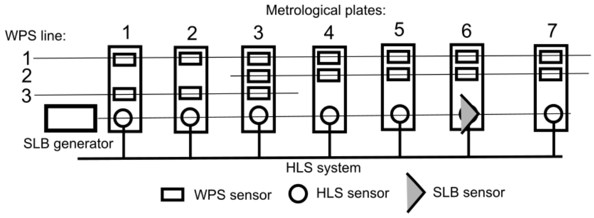

Figure 1. Experimental setup in the 140 m tunnel of HLS, WPS and SLB.

For the free air test, a 3.5-inch modified Taylor-Hobson ball was used as a housing for the camera (Basler a2A5328-15umPRO) with a chip of 14.60 mm x 12.62 mm. The ball was positioned directly on the conical top of the HLS sensors as shown in Figure 2. The perpendicularity of the camera coordinate system with respect to the laser line was ensured using a spirit level mounted on the ball, and a mirror installed in front of the ball was used for autocollimation. The generator for the initial two measurement series was placed at the beginning of the line in front of plate 1, and for the subsequent two measurement series, it was positioned behind plate 7. A single sensor was manually displaced between different metrological plates during the measurement. The typical acquisition period for each position has been 10 minutes with a frequency of 2 Hz. For the analysis, the arithmetic mean has been calculated.

Figure 2. The camera mounted in the Taylor-Hobson ball adapter on the conical top of the HLS sensor (left) and the WPS sensor (right).

The algorithm chosen for the measurement of an SLB in the images was the centre of gravity with gamma correction, as described in [11]. This algorithm enables precise detection of the inner core position while maintaining an appropriate measurement frequency.

3. Results

The transversal intensity profile of an SLB is shown in Figure 2. The two images were acquired using the CMOS chip at the middle plate (number 4) after 70 m and at the last plate (number 7) after 140 m of propagation. In the pictures, the inner core and concentric rings are visible, and the inner core fits well within the camera frame, allowing for the detection of its centre of gravity.

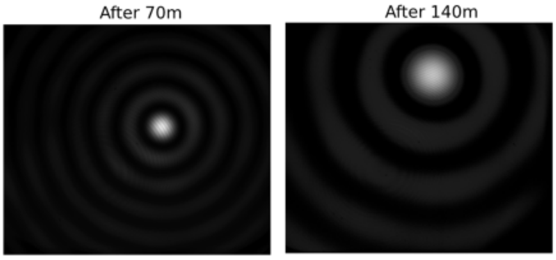

Figure 3. The transversal intensity profiles after 70 m and 140 m of propagation.

In Figure 4, the results of free air propagation along seven metrological plates are presented. The horizontal and vertical offsets of an SLB line with respect to the straight line, measured by WPS and HLS, are displayed. Absolute deviations are comparable in both directions and are smaller than 400 µm. When the distance is limited to 100 m, deviations do not exceed 100 µm. Additionally, the standard deviations of the measured position are provided. The maximum standard deviation of the horizontal position is twice as large as the vertical. The standard deviations across all series of measurements are consistent.

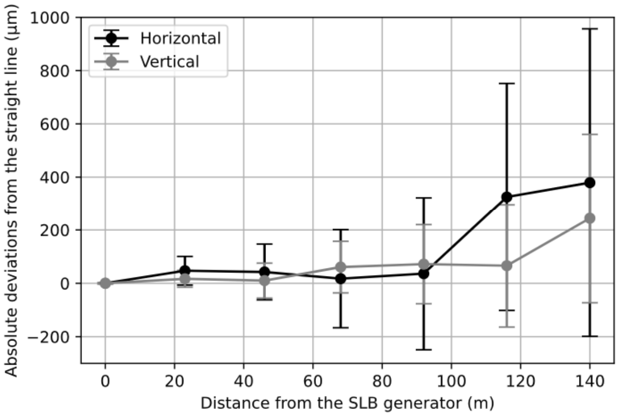

Figure 4. Results of the horizontal and vertical straightness along with the standard deviation of an SLB for 140 m propagation in the tunnel compared to WPS and HLS references.

4. Discussion

The results demonstrate the accuracy of offset measurements based on the SLB laser reference line. An SLB may enable measurements in particle accelerators, depending on a specific alignment task. By leveraging the low divergence of the inner core, the SLB laser line could have various applications, potentially replacing Gaussian beams.

The bending of an SLB propagating in a non-homogeneous medium excludes its exploitation for the most stringent alignment tasks, especially taking into account high standard deviation. The bending of the SLB line is mainly induced by a temperature gradient along the propagation path.

The test tunnel exhibits thermal stability, with a daily temperature variation at 0.005 °C for the base slab and 0.082 °C for the air as reported in previous investigations [12]. Tests conducted at the tunnel during a previous study, using a 2.5 m long rod with six thermometers positioned at 10 locations along the tunnel, suggest air temperature differences reaching up to

3 °C [13], see Figure 5. However, since the gradient was measured using a single rod displaced from one position to another, the results are dynamic in time. The SLB is nearly horizontal as it passes above the HLS conical sockets aligned vertically within a few millimetres. This implies that the effective temperature gradient is even less pronounced.

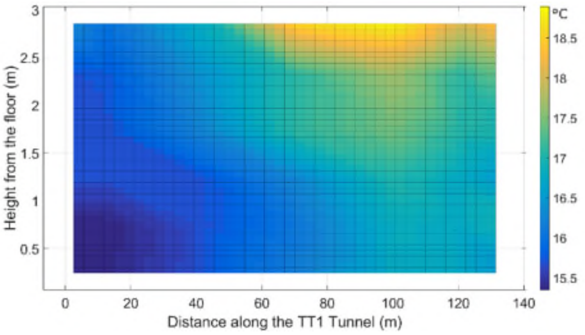

Figure 5. The temperature distribution measured in the test tunnel for another experiment [13].

Despite the excellent thermal stability in the test tunnel, which lacks the active ventilation and electronic systems present in accelerator facilities, it is not sufficient to provide a homogeneous temperature gradient. To utilize an SLB for more challenging tasks, mitigating the effects induced by atmospheric refraction is imperative. While atmospheric modelling seems like an obvious solution, its limited effectiveness has been demonstrated [14]. Refraction dynamically changes over time, and even small deviations can significantly influence the light path, given its considerable length. Monitoring refraction would require a dense grid of temperature sensors along the propagation path, ensuring unbiased readings despite small temperature differences. Ideally, temperature data acquisition would be synchronized with laser data measurements.

The SLB line direction may be unstable over time, potentially due to noise in the power supply or heating of the generator. Similarly, the inclination of the generator, treated as a rigid and constant entity over time, may be induced by vibrations and movements of the Earth's crust. By measuring the position of the inner core at multiple places along the SLB line at the same moment, it becomes possible to mitigate temporal changes in the laser line direction.

Refraction in the tunnel environment presents different characteristics compared to refraction observed in surface measurements. In contrast, as shown in Figure 4, the horizontal deviations are larger than the vertical deviations. The well-known layering of the air, in accordance with the gravitational vector, is recognized as typical behaviour of the temperature gradient in geodetic measurements on the surface. However, in underground tunnels, the effect of layering is not as visible, especially when the laser passes closer to the tunnel walls. Additionally, other air movements exist in the tunnels connected to ventilation that differentiate the atmosphere behaviour underground from that on the surface. Therefore, it cannot be excluded that horizontal errors induced by atmospheric refraction may be more detrimental than vertical ones.

The most well-known solution to reduce refraction in a non-homogeneous medium is to use a vacuum system. While these solutions have proven to be effective, they may face challenges due to the contraction of the vacuum system, impacting the accuracy of the alignment system. The vacuum system shrinks upon reaching operational pressure, posing potential problems for the transfer and stability of relative alignment between the sensor and the measured object. Additionally, vacuum installations must adhere to strict technical conditions of tightness, making them a relatively expensive and fragile part of the alignment system.

The vacuum pipe is typically of limited diameter to reduce costs and avoid reserving large space in the precious underground environment. This limitation brings the problem of symmetry breaking, which can potentially deviate the straight reference line. Moreover, the propagation of an SLB in the steel vacuum pipe may introduce reflections of light, potentially reducing the quality of the detected image due to interference from both direct and reflected light reaching the sensor.

The alternative to the vacuum system may be propagation in a closed pipe under atmospheric pressure. The air inside the pipe can be additionally homogenized using a ventilation system. This approach has the advantage that shrinkage is limited, and expensive equipment is not necessary. However, the problems of symmetry breaking and reflection inside the pipe may still be detrimental to the alignment system. This type of solution has not been used in any accelerator facility yet.

5. Conclusion

The study highlights the straightness of SLB in an underground tunnel of 140 m. The deviations from straightness in the horizontal and vertical directions are under 400 µm, with standard deviations reaching 580 µm, which is considered a large value compared to their magnitude. Although an SLB can be well-suited for diverse applications, challenges arise during free air propagation over hundreds of metres due to atmospheric refraction. To address this issue, the most effective solution appears to be the adoption of a vacuum system. However, potential limitations such as system contractions, symmetry breaking, and light reflections in the vacuum pipe need further investigation, making them crucial areas for subsequent research.

In addition, alternative solutions to the vacuum system should be studied to avoid demanding infrastructure and, in some other way, control the conditions along the propagation path. Such a solution may involve a covered space with additional ventilation to avoid the layering of the air. Another important aspect to increase accuracy is proposing a simultaneous measurement system along the straight line, which would help with laser line drift and changing conditions over time.

The SLB exhibits potential for precise measurements, contingent on the implementation of appropriate strategies to mitigate atmospheric effects.

Acknowledgement

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