# LAYER BEAMS AND THEIR PROSPECT FOR LONG-RANGE ALIGNMENT

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*Abstract*

As part of the study on using structured laser light for alignment, an innovative technique is proposed for generating symmetrical pseudo-non-diffracting layers of caustic optical beams, known as Layer Beams (LB). The state-of-the-art for producing similar beams consists of using spatial light modulators. Our approach is based on the design of a generator with a specific arrangement of cylindrical lenses that shapes the wavefront to create an LB. The intensity distribution of the LB in a plane transversal to the direction of propagation shows parallel lines whose number varies with the distance from the generator. Our experiments, conducted in a 140-meter-long optical laboratory facility, demonstrated successful propagation over the entire available distance, with the thickness of the transversal lines on the order of millimeters. This approach considerably reduces the complexity and cost of such a system compared to LBs generated using spatial light modulators. This paper summarises the main aspects of this research, highlighting the potential of using LBs for aligning accelerator components over long distances.

## INTRODUCTION

### *Multi-point alignment system needs*

Accurate alignment of accelerator components over long distances presents a significant challenge, particularly for achieving transversal positioning accuracy within tens of micrometers over spans of hundreds of meters. At CERN, straight-line reference systems are used to meet these requirements [1]. These systems, including the wire positioning system and the hydrostatic leveling system, rely on physical references of the stretched wire and the water level. Although these methods provide high accuracy, they face challenges related to implementation complexity, component costs, and scalability to larger accelerators. An optical-based system could offer a viable alternative for future colliders, such as the Compact Linear Collider (CLIC) [2] or the Future Circular Collider (FCC) [3], both of which are under study at CERN. These projects demand tight alignment tolerances in the transversal direction, with an accuracy requirement for CLIC of up to 10 $\mu$m ($1\sigma$) over a 200m span [4]. Several optical-based systems have been proposed for aligning structures over long distances [5, 6, 7, 8, 9, 10]. However, the primary limitation of these systems is the relatively high divergence of the optical reference, making it challenging to achieve precise straight-line measurements over extended distances.

A promising solution to this limitation is the Structured Laser Beam (SLB) [11, 12]. The SLB is a pseudo-non-diffracting beam with a transversal intensity distribution similar to that of a zeroth-order Bessel Beam (BB) [13]. Unlike a BB, the SLB maintains a well-defined central core that, with a divergence of less than 0.01 mrad, remains confined within a reasonably sized camera chip, even after propagating over several hundred meters.

To establish a reference line, it is necessary to measure the position of the SLB at multiple distances from the beam generator. The position of the reference line can be determined by detecting the subpixel position of the central core [14]. However, changes in the reference position over time, for example due to the fluctiation of the refractive index, can introduce significant errors in the alignment process [15]. Therefore, it is preferable to measure the reference line simultaneously along the entire distance. A key challenge arises when the central core of the SLB is obscured, preventing further position measurements. This can be partially addressed by introducing fast-moving shutters that briefly cover the beam while sequentially measuring the position. However, since the reference position is not measured simultaneously, any movement of the reference can introduce errors. Beam splitters can also be used to partly mitigate this issue, but any angular inaccuracy between the interface planes of the beam splitter can affect the beam's straightness over long distances.

We propose to address this challenge by moving away from rotationally symmetric beams to beams with reflectional symmetry generated by cylindrical lenses, referred to as Layer Beams (LB). These beams create patterns consisting of different numbers of lines in the transversal intensity distribution. These lines, compared to a laser line generated by a single cylindrical lens, can be tailored for long-distance propagation and be much thinner, due to the structuralization of the transversal intensity distribution and low divergence. This allows for the same type of translational misalignment measurement as in the case of the SLB. Furthermore, the reference plane provides an additional rotational degree of freedom for measurement. This paper will analyze the potential of LBs for alignment applications.

There are additional challenges when using an optical system as a reference. If the beam propagates through an inhomogeneous medium, such as the atmosphere, fluctuations in the refractive index can cause the beam to deviate from a straight trajectory, altering the reference position. To mitigate this issue, it is preferable that the beam propagates within a vacuum pipe. However, introducing a pipe creates an additional aperture, which can cause diffraction-induced trajectory changes. Therefore, the pipe's dimensions must be optimized to minimize these effects. The beam can also reflect from the inside of the pipe, which lowers the signal-to-noise ratio and can complicate the reference detection. Electronics, such as CCD or CMOS chips, are vulnerable to radiation damage over time in the accelerator environment. This paper will introduce concepts to address some of these challenges, facilitating the successful development of an alignment system using the LB.

## METHODOLOGY

### *Generation principle of Layer Beams*

The LB generator utilized in this study comprises three key components: a dimensional lens, a phase lens, and a projection lens. The dimensional lens is oriented at 90 degrees relative to the other two lenses around the optical axis, extending the beam pattern along the y-axis. The phase lens functions as a phase modulator, inducing specific angular spectrum modulation. The projection lens then performs a spatial Fourier transformation of the angular spectrum and influences the spatial dimensions of the beam, leading to the formation of the generating wavefront.

The spacing between these lenses plays a crucial role in determining the beam properties, including whether the beam propagates to infinity, the number of lines in the transversal profile, and the beam's intensity. In addition, the focal length of the projection lens affects the spatial dimensions of the beam.

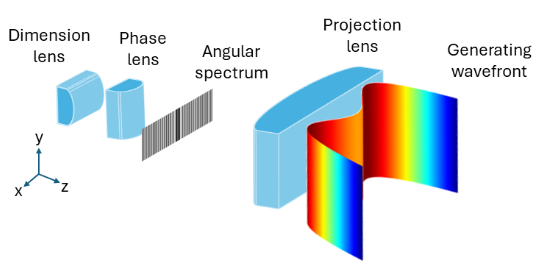



Figure 1: Layer beam generator.

For the simulations and measurements conducted, the generator utilized NBK-7 lenses with focal lengths of 10 mm for the dimensional lens, 5.79 mm for the phase lens, and 100 mm for the projection lens. The distance between the lenses and the focal length of the projection lens was optimized for a propagation distance of 140 m, corresponding to the length of our testing facility.

There were three points at a distance of 1.8, 70, and 140 m away from the generator along the propagation distance, at which the beam was measured. It was ensured that the essential part of the transversal intensity distribution was visible on a camera chip of 14.57 mm × 12.6 mm and allowed for successful detection of the reference plane.

### *Detection algorithm*

To detect the reference plane generated by the LB, a weighted center of gravity algorithm (WCoG) was used to compute the centroid coordinate for each row of pixels. The centroid coordinate $\overline{x}$ of the row intensity vector $I(x)$ is calculated as follows:

$$\overline{x} = \frac{\sum_{x=0}^{x_{max}} I(x)x}{\sum_{x=0}^{x_{max}} I(x)} \tag{1}$$

To enhance detection accuracy, thresholding or gamma correction can be applied as a preprocessing step to the intensity vector. The centroid coordinates obtained using Eq. 1 serve as input for a least-squares fitting algorithm, which fits a line to the data. This fitting process enables the detection of both rotational and translational misalignments.

Alternatively, the columns of the transversal intensity distribution can be summed to produce a single intensity vector. Applying the centroid algorithm to this vector allows for the detection of translational misalignment. Although this approach sacrifices information about rotational misalignment, it offers the advantages of increased calculation speed and an improved signal-to-noise ratio.

## RESULTS

### *Long distance propagation*

The propagation of the LB was simulated using the commercially available software VirtualLab Fusion. The resulting longitudinal and transversal intensity distributions are shown in Figs. 2 and 3, respectively. The transversal intensity was measured at distances of 1.8, 70, and 140 m, corresponding to the positions of our sensors along the propagation pipe.

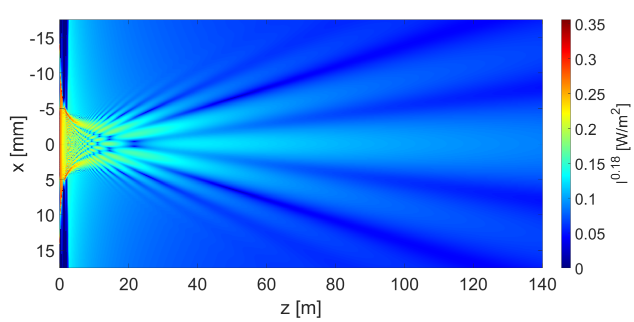
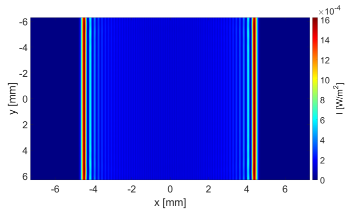
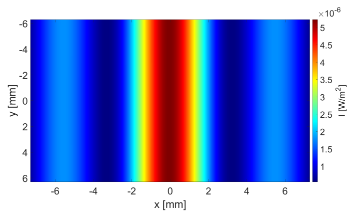



Figure 2: Simulated longitudinal profile (xz plane) of the LB. Contrast enhanced for better visibility.

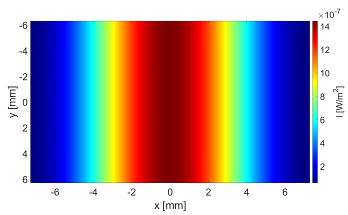
The intensity distribution undergoes rapid changes over the first 20 m, which is evident in the varying number of lines in the transversal intensity distribution. Upon reaching the far zone, at approximately 30 m, the transversal pattern stabilizes, comprising of only three lines that remain unchanged as the beam continues to diverge. By the time the beam reaches 140 m, only the central line of the pattern is visible on the detector.




(a)




(b)




(c)

Figure 3: Simulated transversal intensity distribution (xy plane) at distances of (a) 1.8 m, (b) 70 m, and (c) 140 m

## *Detection of a reference plane*

A generator with the same properties as those used in the simulations was constructed and the resulting beam was propagated over 140 m within a metallic pipe. It should be noted that the pipe was not under vacuum, but it is planned to be so in future experiments. The beam was optimized to ensure that the central symmetrical part of the pattern was visible on the camera, enabling detection of the reference plane.

The measured transversal profiles after 140 m of propagation within the metallic pipe, along with the corresponding row and column intensity summations, are shown in Fig. 4. The highly reflective interior of the pipe resulted in significant speckle and interference fringe noise, which severely degraded the signal-to-noise ratio. This noise made it impossible to detect the reference plane with sufficient accuracy. To mitigate this issue, an additional low-reflectivity plastic pipe was installed along most of the length of the metallic pipe. This was due to time constraints, for a future set-up the vacuum pipe should be coated with an antireflective coating.

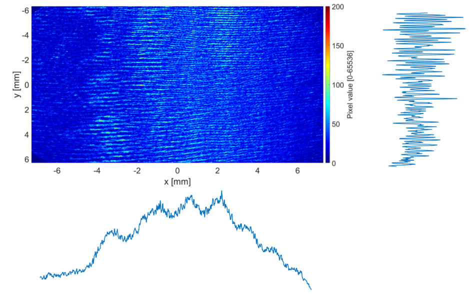
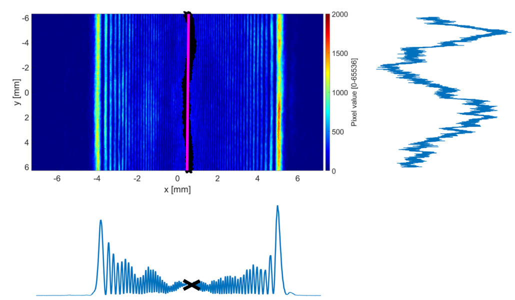
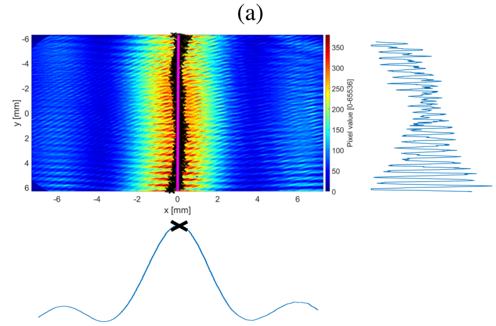


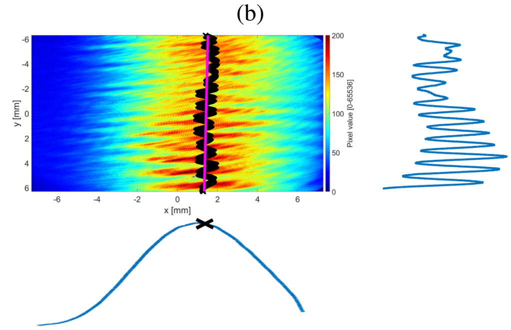

Figure 4: Measured transversal intensity distribution at 140 m after propagating inside a metallic pipe together with column and row intensity summation.




(a)




(b)




(c)

Figure 5: Measured transversal intensity distribution at (a) 1.8 m, (b) 70 m, and (c) 140 m after propagating inside a metallic and non-reflective plastic pipe with column and row intensity summation. The center of gravity coordinates are represented by black crosses and the reference plane by a purple line.

The measured transversal intensity distributions, along with row and column intensity summations, after the introduction of the non-reflective pipe at distances of 1.8, 70, and 140 m are presented in Figs. 5a, 5b, and 5c, respectively. A clear resemblance to the simulation can be seen by comparing the measurements to Fig. 3. The speckle noise was significantly reduced with the introduction of the plastic pipe, as can be seen by comparing Figs. 4 and 5c, however, because the non-reflective pipe did not extend along the entire length of the metallic pipe reflections causing interference fringes were not completely eliminated, as evidenced primarily in the row summation. This indicates that additional non-reflective pipe sections are needed to further reduce this effect. Despite this, the position of the reference plane was successfully detected using the WCoG algorithm at all positions along the beam.

## *Conceptual ideas for an alignment system*

For an eventual alignment system, we propose generating the reference plane using the reflection symmetry of the transversal intensity distribution along the entire path of the beam, as illustrated in Fig. 6.

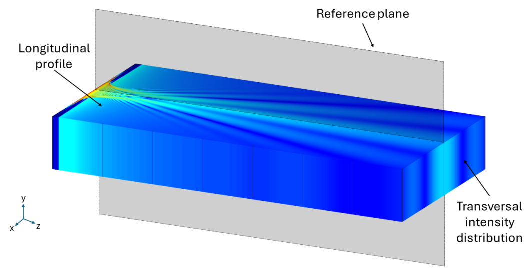



Figure 6: Alignment reference plane created using a Layer beam.

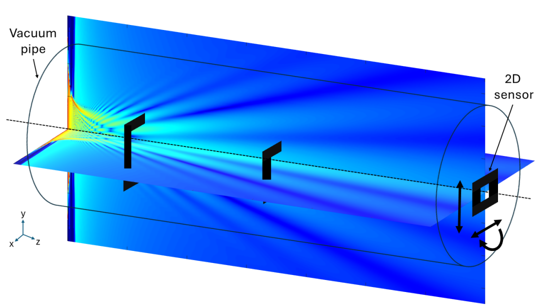



Figure 7: Conceptual design of an alignment system with two-dimensional sensors that can detect translation in x and y together with a roll.

To establish a basis for an orthogonal reference, we propose two LBs rotated by 90 degrees to be employed, as depicted in Fig. 7. The reference plane along both axes is detected using a sensor composed of four linear CCD sensors, as shown in Fig. 8. The sensor width of several pixels in the y-direction is needed to reduce the noise and detect the center coordinate with high enough accuracy. Two points along each axis are detected, which allows the fit of two orthogonal lines that are the orthogonal base of the alignment reference. In this setup, only a portion of the beam is intercepted by the sensors, allowing the majority of the beam to continue propagating forward. This configuration enables the detection of multiple points along the beam at the same point in time. It allows for the detection of translational misalignments in the x and y directions as well as rotational around the z-axis.

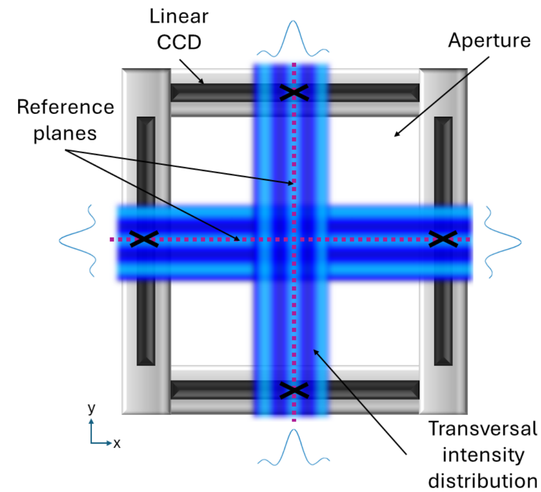



Figure 8: Schematics of a proposed two-dimensional sensor with an aperture.

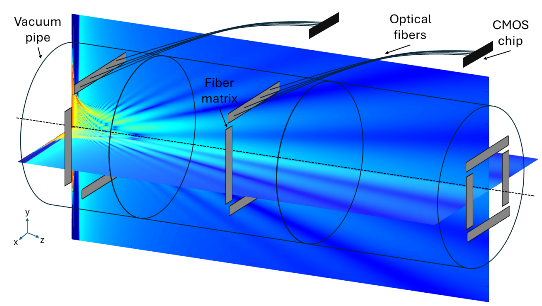



Figure 9: Conceptual design of a sensor integrated in a vacuum pipe resistant to radiation.

It is important to note that the introduction of an aperture can lead to diffraction effects. The aperture must therefore be large enough to minimize these effects. Any aperture restriction should vary in size to prevent overlap, unless sufficiently spaced apart, allowing the beam's divergence to ensure that light reaches the subsequent chip even if partially obscured at the start.

As previously mentioned, the high-radiation environment of the accelerator tunnel can potentially damage the detection electronics. To address this issue, we propose a system based on a fiber matrix that could transmit the image away from the radiation zone, thereby protecting the electronics, as illustrated in Fig. 9. However, it needs to be addressed how the image quality and intensity loss caused by the fiber matrix affects the detection of the reference plane.

## CONCLUSION

In this study, we explored the use of Layer Beams as a novel approach for generating reference planes in precision alignment systems for future particle accelerators. Through both simulations and experimental validation, we demonstrated that the LBs can effectively serve as reference planes over long distances.

During propagation over 140 m inside a metallic pipe, we observed a low signal-to-noise ratio due to the pipe's high reflectivity. To address this, we implemented non-reflective plastic pipe sections inside the metallic pipe, which significantly reduced the speckle noise. This improvement allowed for accurate detection of the reference plane at various points along the beam path.

The proposed setup, utilizing two orthogonally oriented LBs, provides a robust method for detecting both x and y translational misalignments, as well as rotational misalignment around the z-axis. We are also tackling the challenges posed by the high-radiation environment typical of accelerator tunnels by proposing a fiber matrix system to transmit the LB image to electronics located outside the radiation zone.

Future research will focus on prototyping and further optimizing the system, particularly by comparing it to state-of-the-art systems such as the wire positioning system and the hydrostatic leveling system, addressing diffraction effects caused by the apertures of the sensors and pipe, reducing the impact of atmospheric turbulence, and evaluating light attenuation in the fiber matrix.

Our findings suggest that LBs hold significant promise as a scalable and effective solution for meeting the stringent alignment requirements of next-generation particle accelerators, such as the CLIC and the FCC.

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