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THE POTENTIAL CONTRIBUTION OF A STRUCTURED LASER BEAM TO ACCELERATOR ALIGNMENT TECHNOLOGY

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Abstract

The Structured Laser Beam (SLB) is a type of optical beam characterized by an intense, sharply defined, low divergence core at its center, similar in its transverse intensity distribution to a Bessel beam. The SLB can propagate over a theoretically infinite distance, and has recently been tested up to a distance of 900 m. This test confirmed the low divergence of the SLB core, of about 0.01 mrad in this case. Furthermore, a hollow SLB (HSLB) can be created by feeding the generator with vector beams. These properties open the possibility of creating new types of optical alignment systems that could be used over long distances, for example for particle accelerators. Investigations are ongoing to optimize the SLB and fully evaluate its alignment potential. Methods are under development to accurately detect the center of the SLB, based either on the beam intensity distribution or on the measurement of particular polarization states of the HSLB. Moreover, in order to deal with alignment in harsh environment, systems based on passive elements are also of interest. This paper summarizes these studies and includes a discussion of phenomena such as the straightness of the SLB.

INTRODUCTION

The Structured Laser Beam (SLB) is one of the so-called pseudo-non-diffractive optical beams. Its transverse optical intensity profile looks similar to that of a quasi Bessel Beam (BB). It is characterized by a sharply defined core propagating with a low divergence, surrounded by concentric circles. Combined with its ability to propagate over very long distances, theoretically to infinity, this paves the way for its use in the domain of geodetic metrology, for example as an optical reference line for long distance alignment needed for large particle accelerators.

This paper briefly introduces the SLB and summarizes some of the studies on its properties and characteristics related to the alignment field, including a discussion on the SLB straightness.

PRESENTATION OF THE SLB

A method of creating adjustable SLBs has been proposed [1], where the SLB results from the superposition of the waves coming from a wavefront with a special shape obtained after the spherical aberration produced by the generation system, see Fig. 1. This phenomenon generates an SLB with a high intensity central core surrounded by high and low intensity rings.

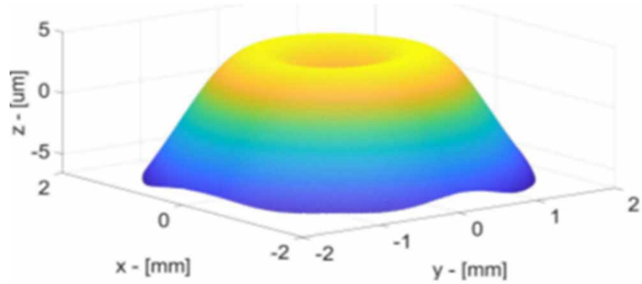

Figure 1: A measured SLB wavefront profile at the generator output, the beam propagates downwards along Z-.

SLB Intensity Distribution

The longitudinal and transverse SLB intensity distribution shows an inner core (IC) surrounded by concentric circles sharply bounded by dark areas whose intensity can be equal to zero, see Fig. 2.

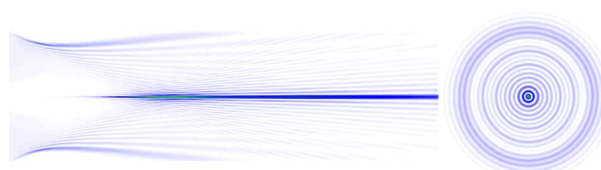

Figure 2: Simulated SLB longitudinal (left) and transverse (right) intensity distributions.

By adjusting the SLB generator, the shape of the wavefront, and thus the intensity distribution and divergence of the SLB, can be changed.

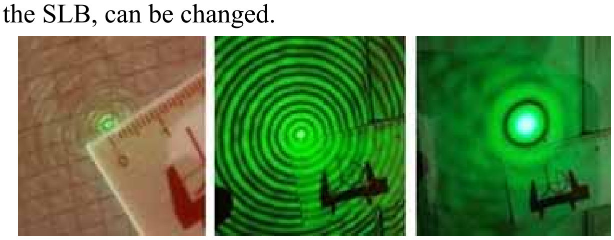

Figure 3: SLB images at 120 m, propagated outdoor, with different generator adjustments. The IC diameter varies from approximately 1 mm with a high number of rings (left) to 15 mm (right) with a low number of rings.

The beam characteristics can change from beams with an intense but divergent IC to beams with a less intense but low divergence IC, see Fig. 3Figure 3. Note that as the divergence of the IC decreases the divergence of the overall SLB beam increases and the number of visible rings also increases.

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SLB Divergence and Long Distance Propagation

The SLB is subject to divergence, but the divergence of the IC can be kept small along very long distances as shown in the simulation of Fig. 2.

So far, the lowest measured divergence of the IC is 9.6 µrad. Figure 4 (left) shows an accurately measured SLB on a CCD sensor at a distance of 140 m from the generator. The IC diameter, which was close to a few µm at 5 m from the generator, increases almost linearly with distance to reach 1.3 mm at 140 m.

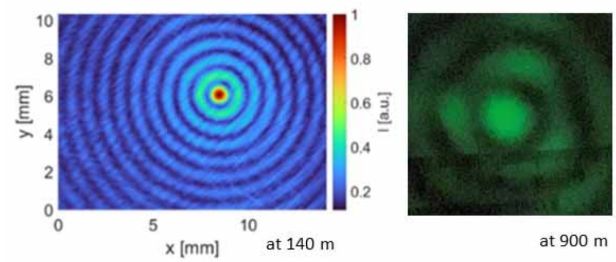

Figure 4: Real SLB measurement at a distance of 140 m from the generator, the optical intensity I is in arbitrary units (left). Picture of an SLB at 900 m distance from the generator, the IC is approximately 1 cm diameter (right).

Experiments have also been carried out at long distance, up to 900 m outdoors, by feeding the generator with a low power laser diode of 0.5 mW. As shown in Fig. 4 (right), the SLB is still visible. An IC diameter of about 1 cm was measured on a ruler, confirming that a divergence of about 0.01 mrad is achievable.

Hollow Structured Laser Beams

When illuminated by an input beam with a spiral polarization, see Fig. 5, a generator produces a Hollow Structured Laser Beam (HSLB) which has a dark central core surrounded by light and dark circles, see Fig. 6Figure 6.

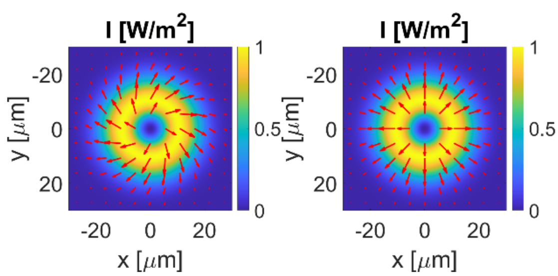

Figure 5: Input Beam with a spiral polarization. General case (left). Particular case with radial polarization (right).

Note that the HSLB contains longitudinally oriented electric and magnetic field vectors in its dark IC. In the case of an input beam with radial (see Fig. 5) or azimuthal polarization only the electric or magnetic field vector is present in the IC.

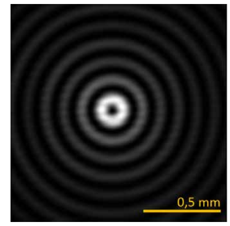

Figure 6: Intensity in the transverse plane of a real HSLB at 2 m from the generator.

SLB CENTRE DETECTION

Different types of SLB centroid detection based on image processing of the transverse intensity distribution have been investigated. In the case of the HSLB, another type of beam center detection based on the polarization in the transverse plane is being investigated.

Centroid Detection from Intensity Distribution

Studies have been conducted with 2 types of intensity data analysis [2]. The first one is based on the calculation of the center of gravity, using either all the raw data, an enhanced procedure with a threshold to cut off the low intensity values, or the application of gamma correction to the image to favor the high intensity values. The second method is based on fitting a Bessel Function of the first kind and zero order to the distribution. In this case, a circular mask was applied to limit the analysis to an area including the core of the beam and the first full rings, where the SLB and BB are similar and the fit is valid.

The results are very similar for all methods. At short distance, with an SLB in a tube at atmospheric pressure, a precision at the micrometer level is obtained. For long distances, the air turbulence affects the stability of the SLB. In the experimental conditions at CERN, a data acquisition of 3 images per second during 1 hour shows that the amplitude of SLB oscillations at atmospheric pressure can reach almost 1 mm at 120 m distance with a sigma of 0.250 mm.

Note that the calculation of the center by the method of the center of gravity is faster by several orders of magnitude than the processing based on the Bessel function fit and allows multiple images per second to be analyzed.

Detection Using Polarization

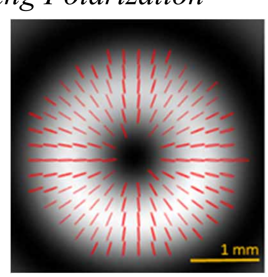

Figure 7: Image of a real HSLB at a distance of 50 m, cropped to the first light ring. The radial polarization in the transverse plane is represented in superposition.

For an HSLB, a new approach based on beam polarization, rather than on intensity analysis, is proposed and is under study at CERN and at TUL. HSLBs created from a

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radially polarized beam also have a radial polarization in the bright rings, see Fig. 7Figure 7. In this case, the center is obtained by intersecting the radial lines defined by the components in the transverse plane of the polarization vectors.

DISCUSSION

BBs have already been used for alignment purposes [3-5] but these beams propagate for only a limited distance of a few tens of meters. In the field of geodetic metrology, the choice of the SLB seems to be a promising approach for the development of long-range alignment systems. However, the straightness of the SLB is of major importance for the creation of an optical reference line. The potentially harsh environment in accelerators also have to be considered for the development of any alignment system.

Symmetry Breaking Effect on Straightness

A study of the effect on SLB straightness of a symmetry breaking in the beam propagation area has been conducted [6] for a linear and a circular cropping in the zone close to the generator and in the far zone.

According to the simulations, a symmetry breaking in the transverse plane results in variations of the position of the beam center calculated with a Bessel function best fit. Nevertheless, when the optical element apertures and the propagation space around the SLB are reasonably large these changes can be reduced to the micrometer level even for long distances.

Propagation in Non-homogenous Media

Another important parameter for alignment applications based on SLB is the influence on the beam straightness of propagation in a medium having a non-homogeneously distributed refractive index. For propagation in the atmosphere, this is usually the result of temperature inhomogeneity.

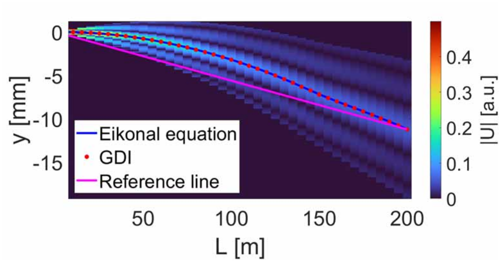

Figure 8: Longitudinal profile of the SLB field amplitude for temperature distribution based on measurement in the LHC tunnel at CERN.

Because of the complexity of the SLB, a study based on a new concept using a Generalized Diffraction Integral (GDI) taking the full field into account has been conducted [7]. For a propagation in the standard conditions of a tunnel at CERN, even if the GDI method shows little differences with the existing Eikonal equation or Ray tracing methods, the effect of refraction on the beam direction is not negligible and can reach the millimeter level, see Fig. 8Figure 8. It indicates that for high precision a dedicated closed space, under vacuum, is preferable.

Next Steps in SLB Studies

In order to face the issues due to propagation in a non-homogeneous medium, a project for the construction of two SLB test facilities equipped with a 50 m and a 140 m long vacuum lines is ongoing at CERN. These facilities will help in the evaluation of new sensors and in the understanding of integration needs for a future alignment system for particle accelerators.

In the meantime, the SLB center detection algorithms are being improved and studies are ongoing to optimize the beam shape i.e. decreasing the number and the divergence of the outer rings of the SLB, while keeping a narrow IC with low divergence.

Due to the potentially harsh conditions in particle accelerators, investigations are also underway to move the active parts of the alignment systems into protected areas that can be located away from the components to be aligned. Several approaches are under investigation, including the production of generators made of passive retroreflectors immersed in a large Gaussian beam and attached to the points to be measured, in order to send an SLB back to a dedicated detection area. The first results at short distances show interesting results.

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