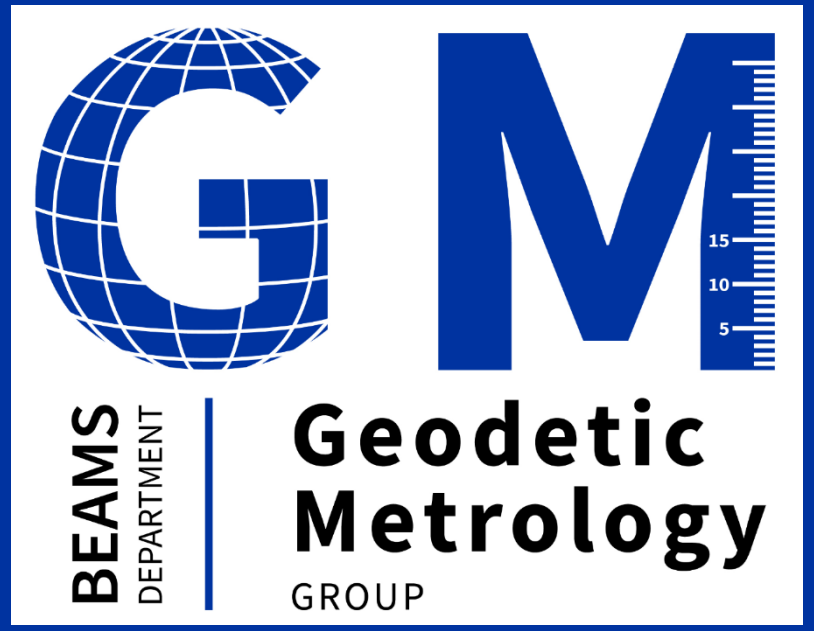


Academic Training
Geodetic Metrology For Future Accelerators
Facing The Future Challenges For Accelerator Alignment

Structured Laser Beam And Large Scale Metrology

Jean-Christophe Gayde (CERN)

17.06.2022

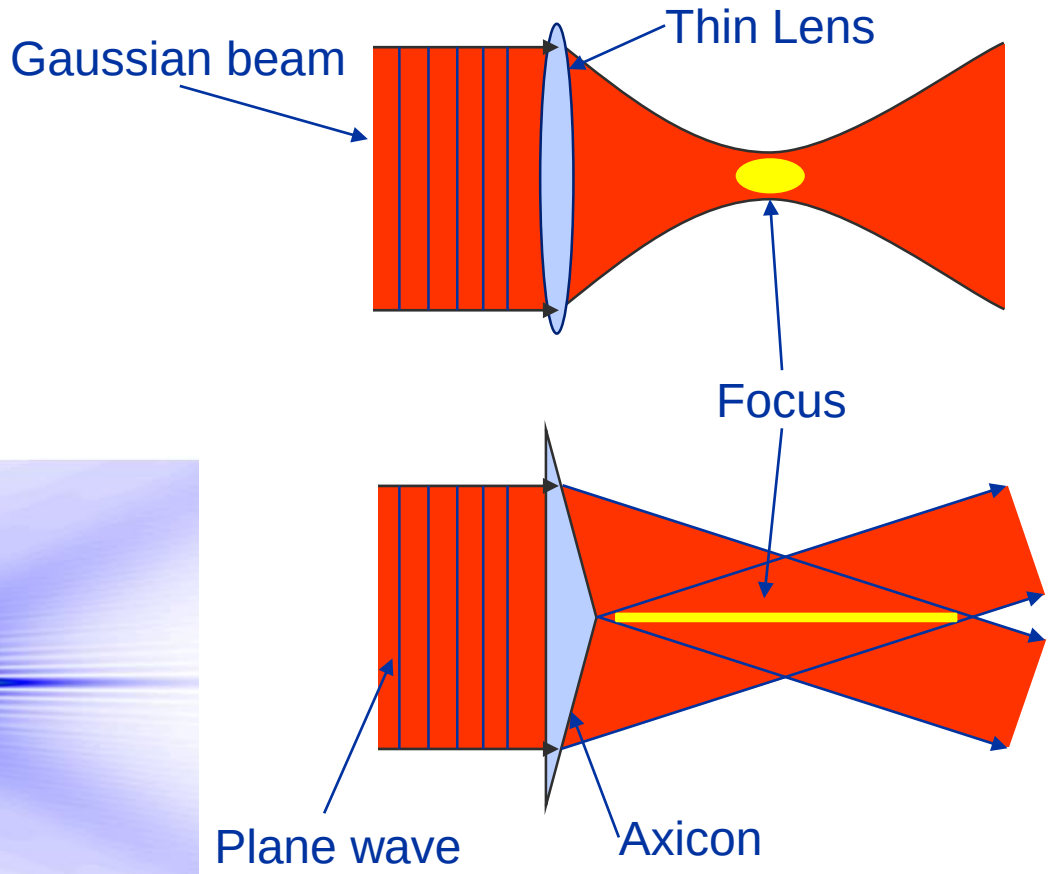
Table of contents

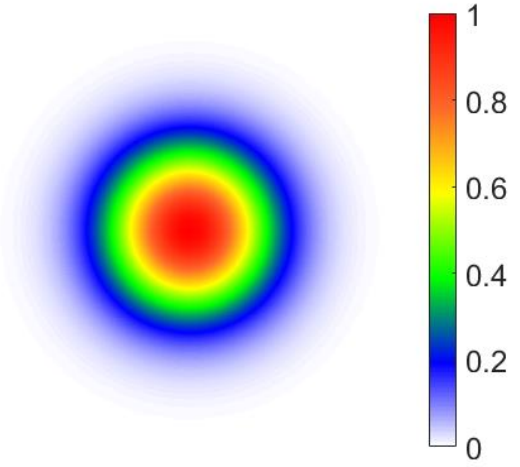
Basics about optical beams

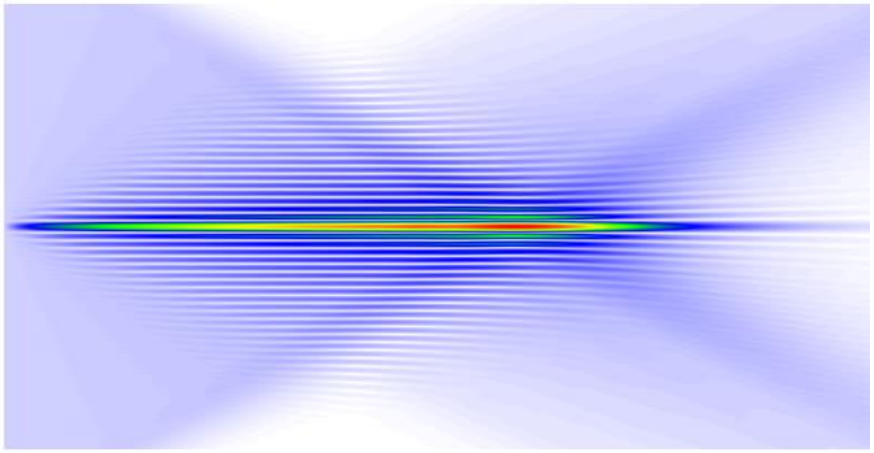
- An optical beam is a special bounded form of the light propagating with a small divergence

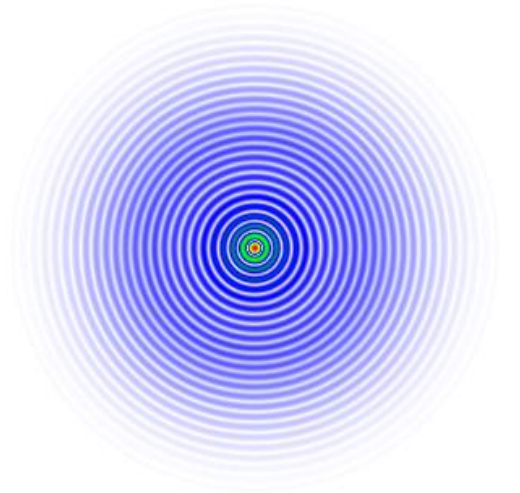
- Gaussian beam
  - Small focus
  - Significantly divergent

- Bessel beam
  - Long longitudinal focus
  - Limited longitudinal range
  - Zero divergence





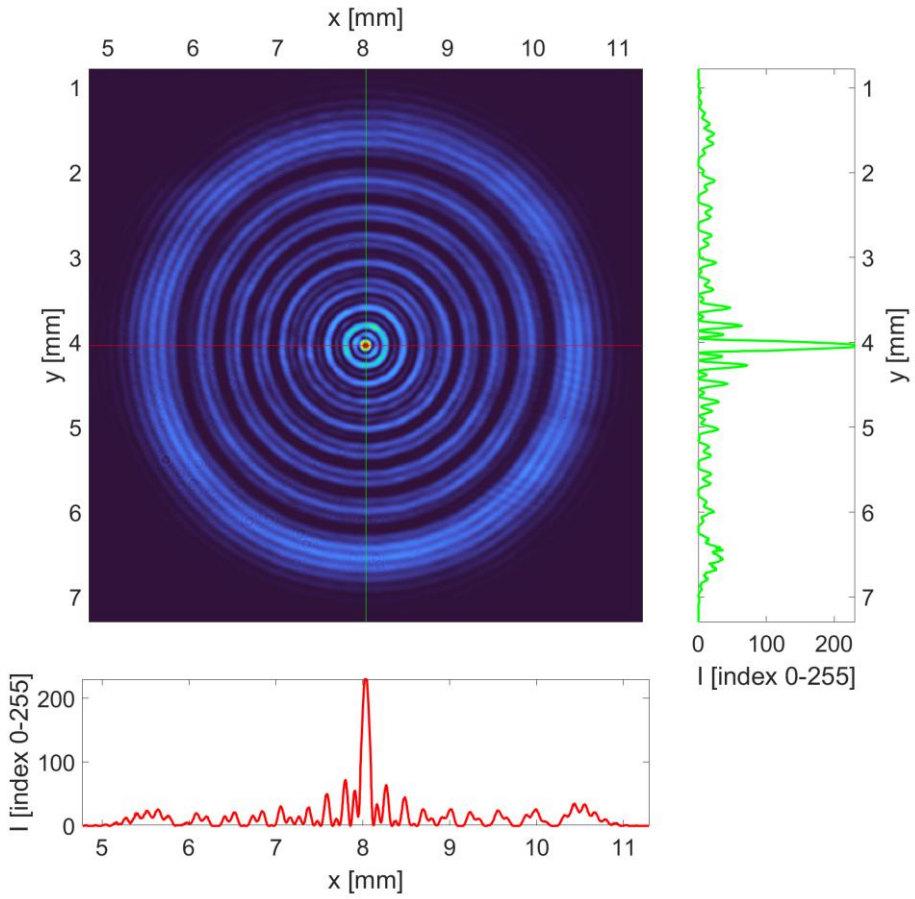




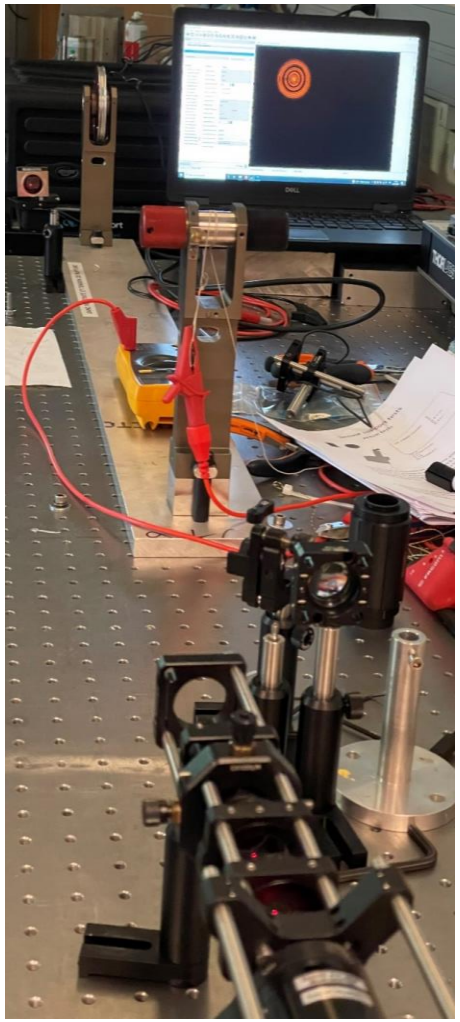
Introduction to SLB

- SLB: Pseudo non-diffractive optical beam
- Structured Laser Beam (SLB) with bright and dark areas
- Propagation over long distances
- Extremely compact central spot size

- Result from a R&D collaboration between CERN and IPP (CZ)
- Research supported by KT
- *https://kt.cern/technologies/structured-laser-beam*
- Patent application on-going for SLB … status “published”



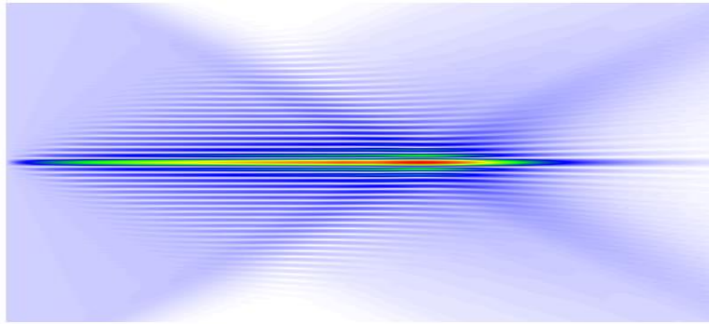
SLB – Real image

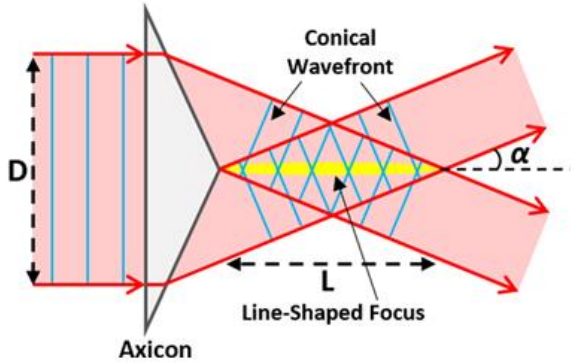


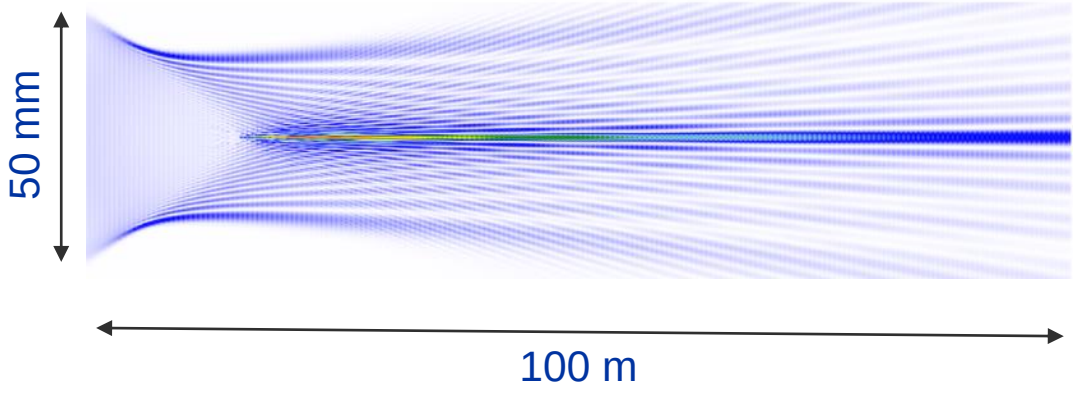
Non diffractive beams – State of the art

Bessel beam

- Long longitudinal focus
- Limited range
- Zero divergence



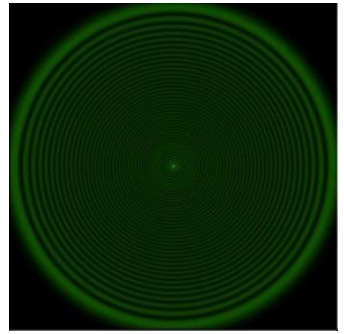


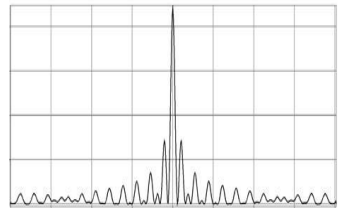


SLB – Simulation of a longitudinal profile

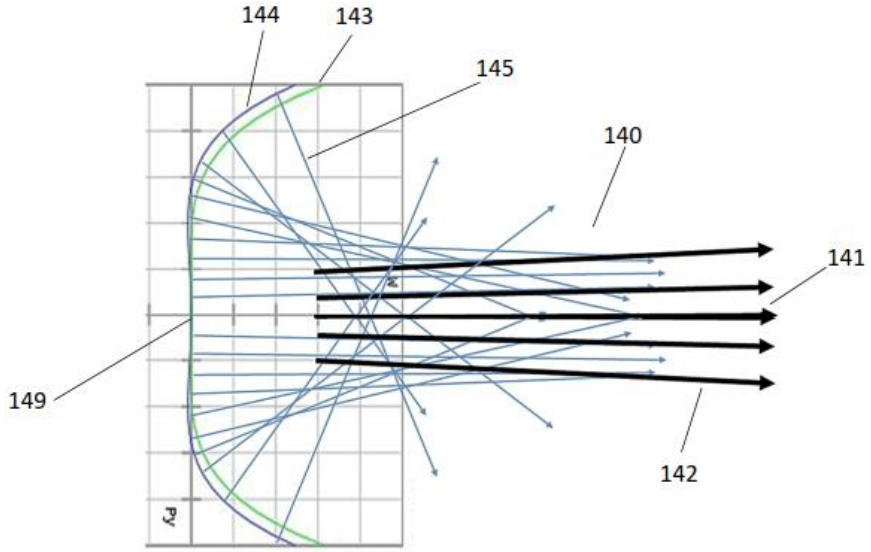
SLB – What is new?

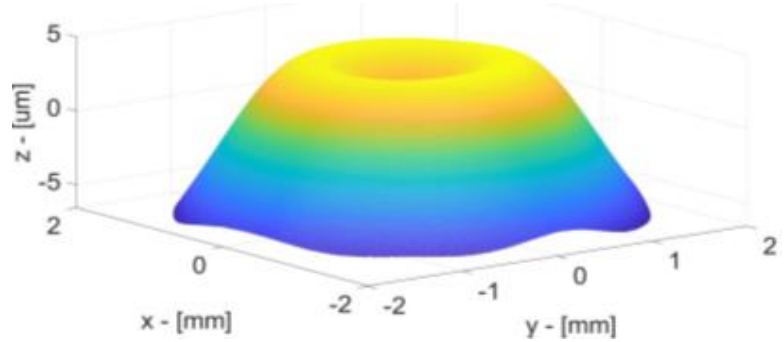
- Creation of a pseudo non diffractive SLB
- Propagation over very long distances
- More than 150m tested, theoretically to infinity
- Focus of the beam adjustable
- Easiness to adapt the setup
- Not exactly described with a Bessel function



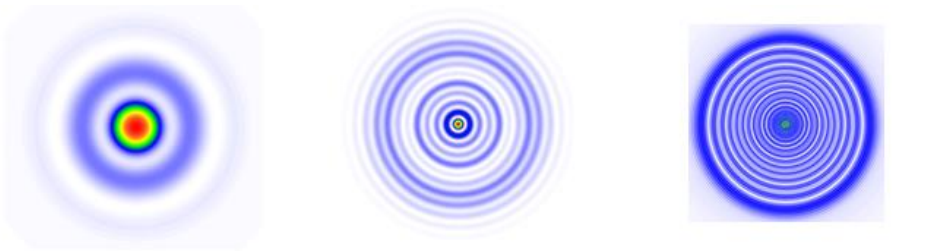


SLB principle of creation





A measured SLB wavefront



- From the creation of a special wavefront shape
- Obtained by different optical paths in very high index optical elements
- Defocus and spherical aberration
- The generator allows to change the shape of the beam

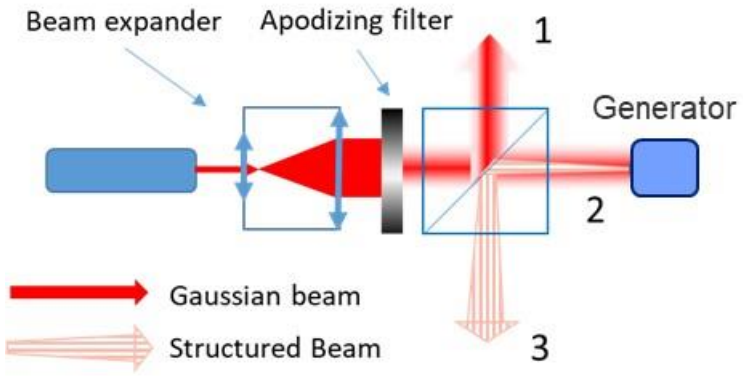
SLB – Structured beam or diffraction pattern?

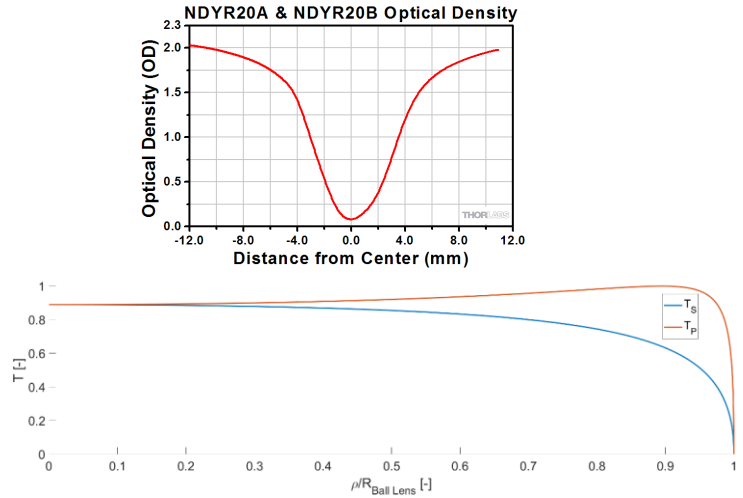
Experiments
- Illumination with significantly smaller beam than the system aperture
- Use of a reverse apodizing filter
- Input beam intensity decreases gradually to zero in the radial direction

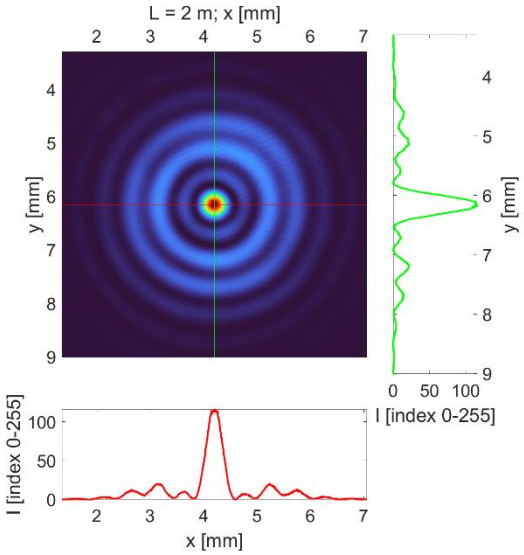
Even if no filter:
- The aperture of the generator will not cut off the optical beam
- No jump in the change of intensity, which would lead to diffraction

For both situations → significant reduction of diffraction phenomena at the circular aperture of the system

- **Confirmation that the shape of the SLB depends on the shape of the wavefront**
- **The beam created with the generator is really a structured laser beam**
- **It is not an image of a diffraction pattern coming from the circular aperture in the generator**

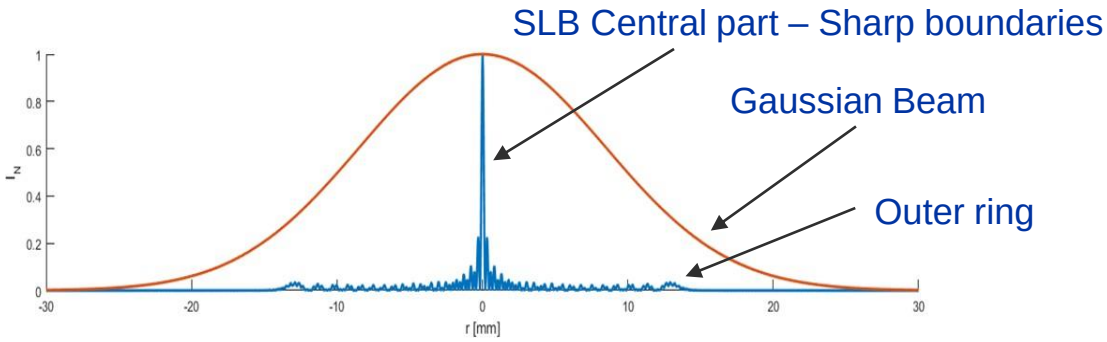




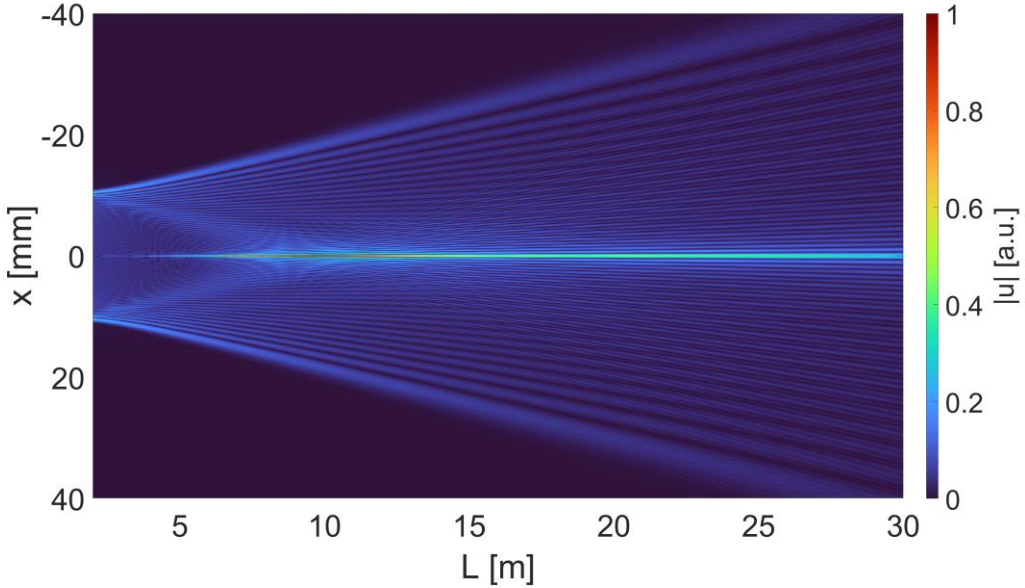


SLB – Some properties

- Beam has an intense central part with black and bright rings in a conical projection
- Low divergence of the central part of the beam linearly increasing (test 1mm at 150m → ~0.007 mrad)
- Very sharp profile of the central peak
- Ring diameter proportional to the distance
- Tuneable symmetrical structure depending on the setup adjustment
- Secondary beam production
- Reconstruction property after obstacles (up to some limits)
- Possible to create in a wide range of wavelength (typically Blue to IR)
- Non standard polarization of the beam



Typical profile comparison SLB – Gaussian Beam

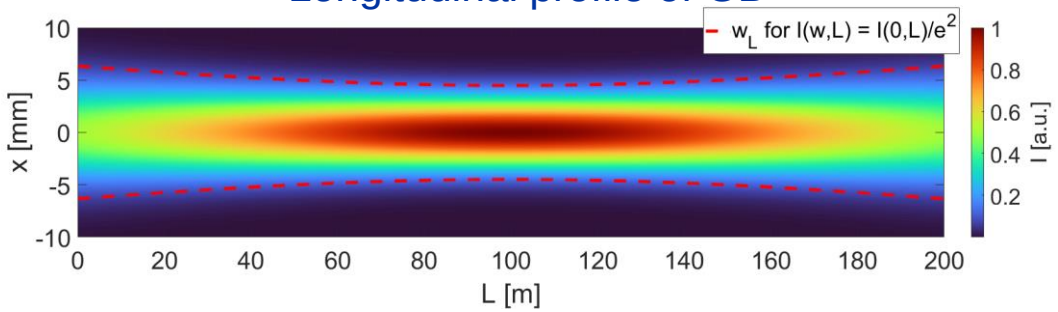


- **Some of these properties look interesting for large scale metrology and alignment applications**

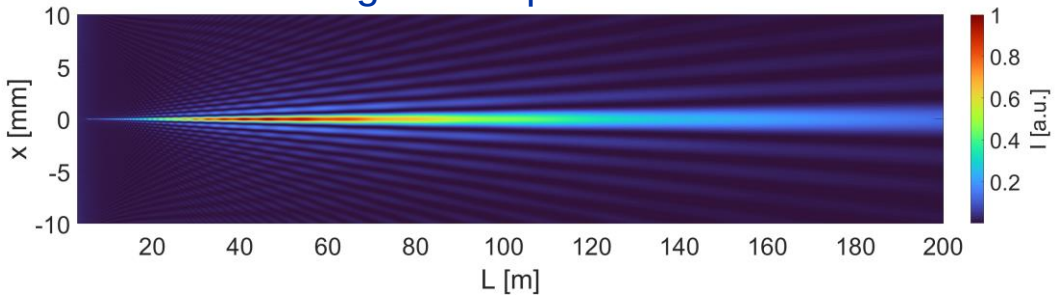
Comparison of SLB and GB

- GB waist size w_0 gives GB radius at any distance
- On a range L, minimum GB radius is obtained with waist at $L/2$
  - Then the GB radius is the same at start and at end
- Example of He-Ne laser along $L = 200\,m$, and w_0 at $L/2$
  - Radius at $L = 200\,m$: $w = 6.347\,mm$
  - To avoid diffraction, circular aperture: $D_A \geq 6w$ $(38.08\,mm)$
- For comparison: SLB simulation (with aperture $D = 38\,mm$)

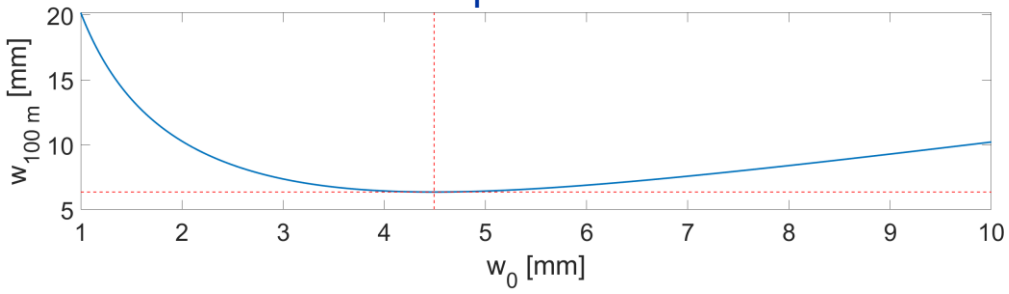
Longitudinal profile of GB



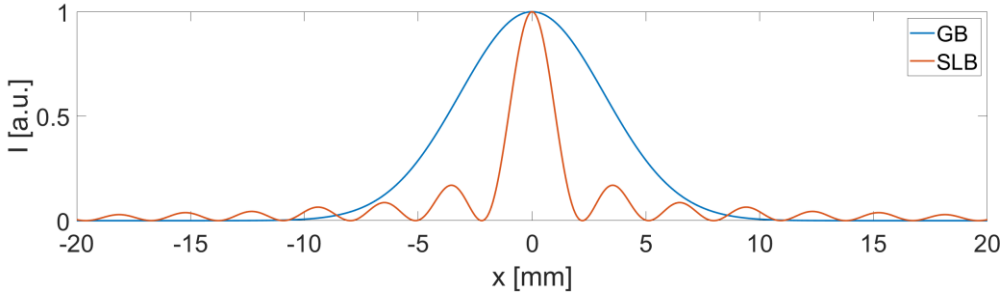
Longitudinal profile of SLB



GB optimization



Comparison of cross sections of SLB and GB at distance $L = 200\,m$

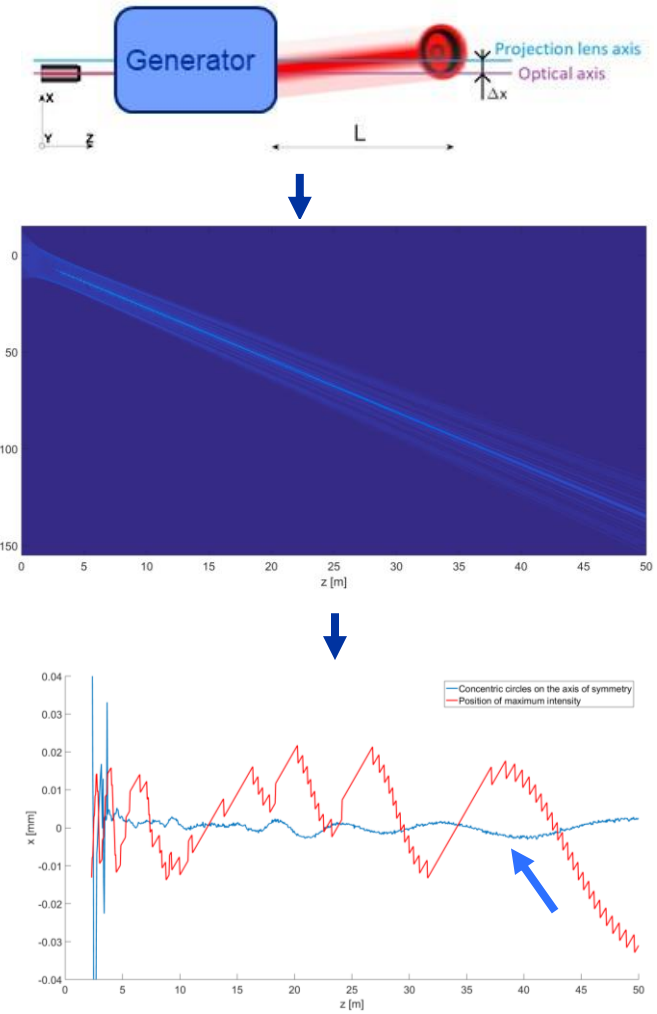


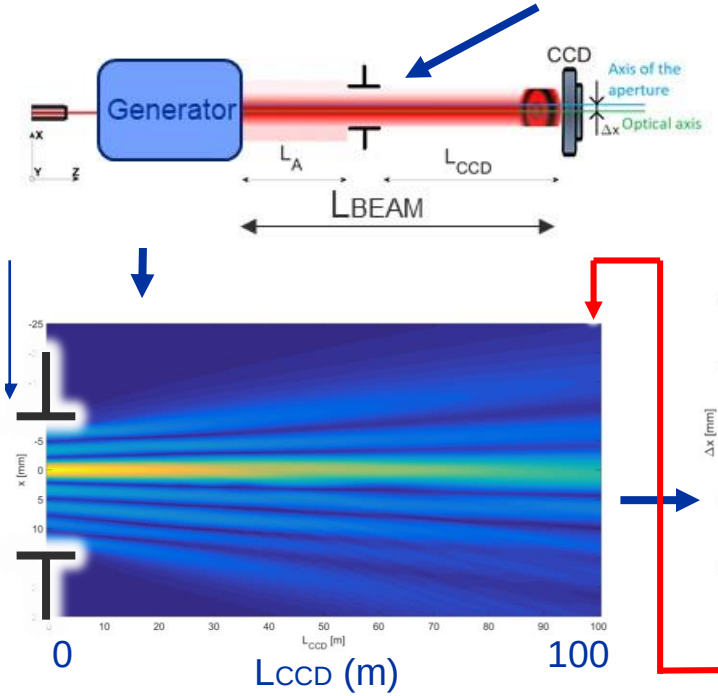
- **SLB - long range propagation and low central core divergence - looks well suited for long range alignment systems**
- **However, its straightness must be considered carefully**

SLB – Study of straightness

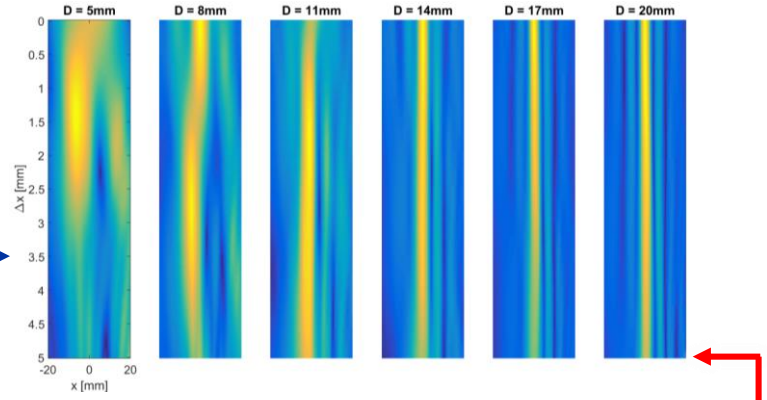
- 2 main factors have an impact on the straightness of the SLB:
  - SLB symmetry breaking
  - Refractive index gradient distribution (refraction in the propagation medium)
- SLB symmetry breaking can be of two kinds:
  - Symmetry breaking of the phase distribution (Aberration of the generator)
  - Symmetry breaking of the amplitude distribution (Cropping of the SLB)

Misalignment in the generator





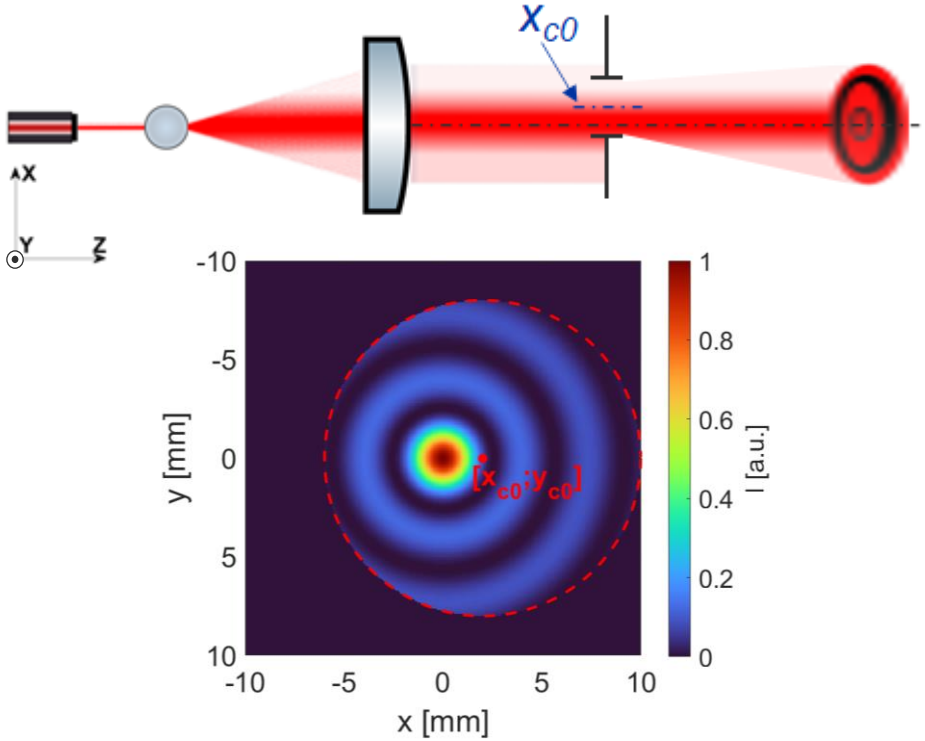
Beam transverse profile at L_{CCD}=100 m and L_{BEAM}=150 m for different apertures and offsets



Straightness study - Asymmetric SLB blocking

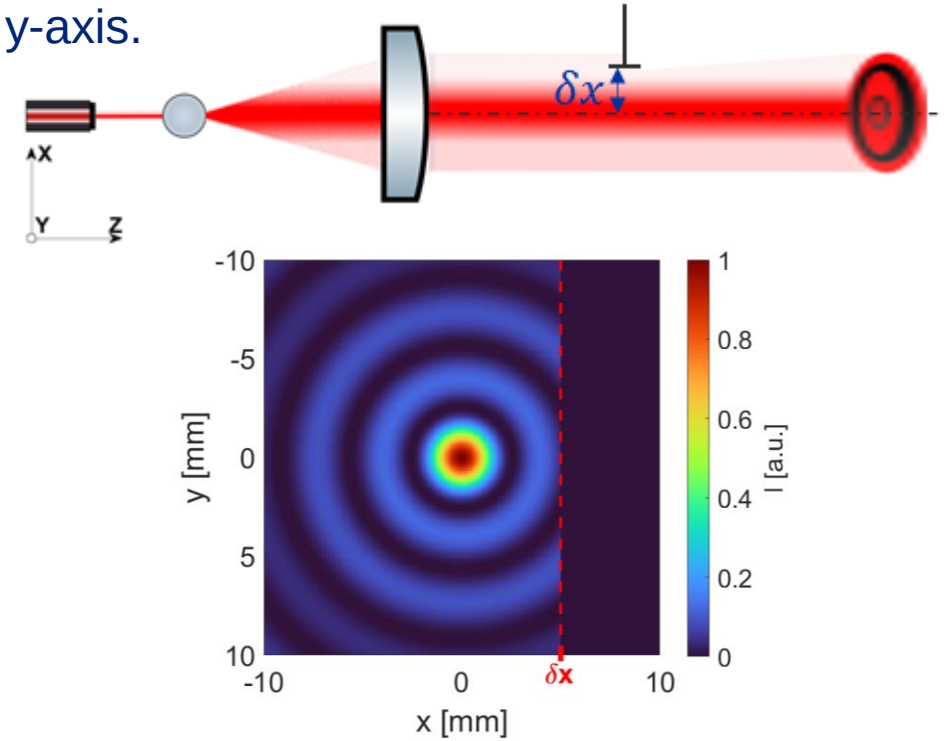
Shifted circular aperture

Points $[x_{c0}; y_{c0}]$ are the coordinates of the circular aperture, in a reference frame defined by the propagation axis. If x_{c0} and $y_{c0} = 0\,mm$, SLB is cropped symmetrically.



One-side SLB blocking

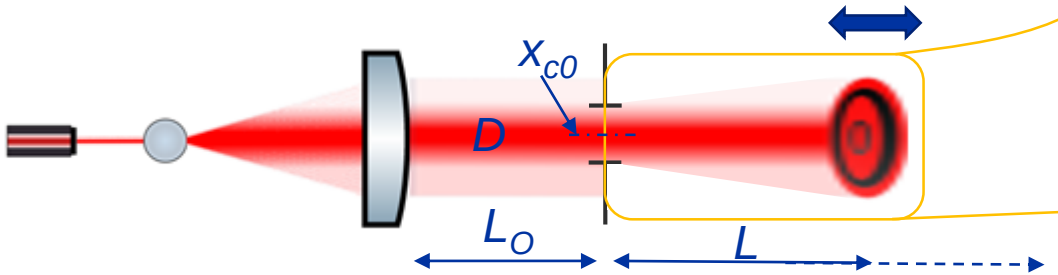
An infinitely large obstacle with a straight edge perpendicular to the x-axis. The position of the obstacle is defined by the δx parameter, which expresses the distance of the obstacle from the y-axis.

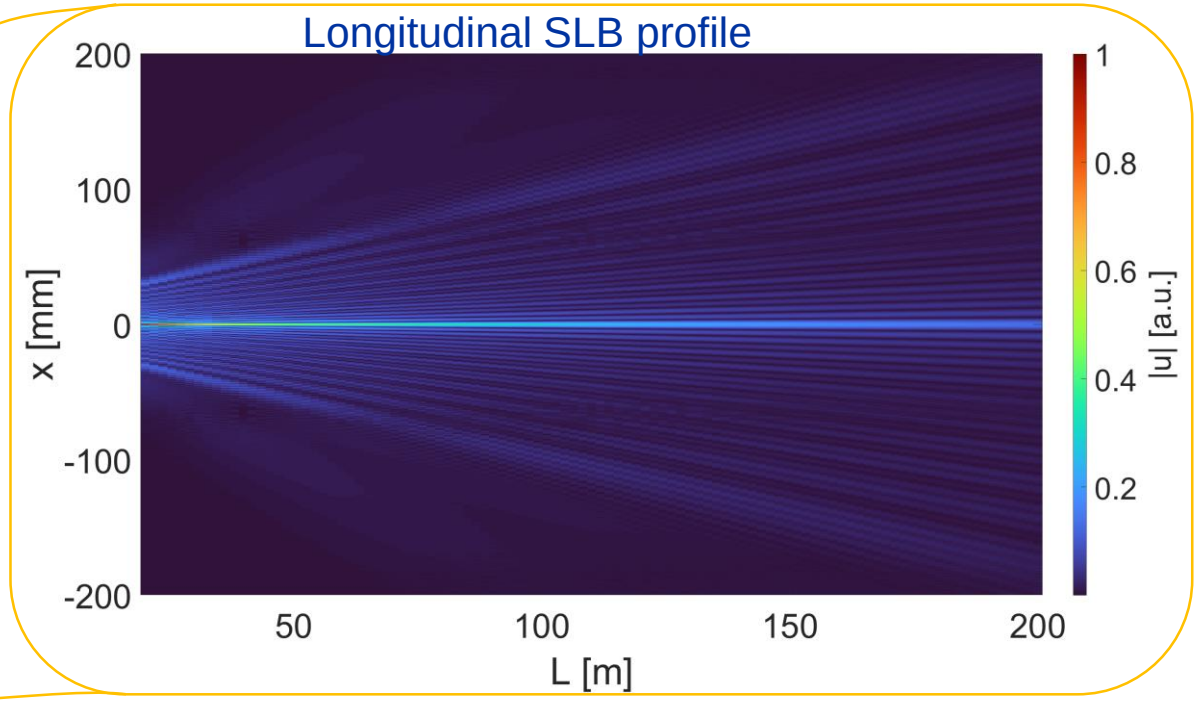


SLB straightness for a given symmetry breaking

One illustrative example:

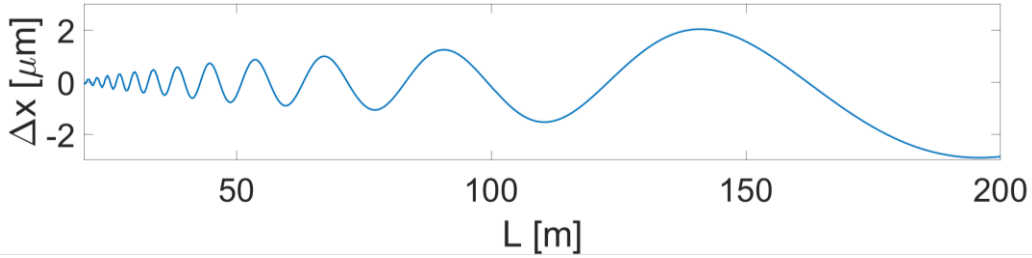
- Obstacle with a circular aperture shape
- Distance of the obstacle $L_O = 10\,m$
- Aperture diameter $D = 40\,mm$
- Obstacle position $x_{c0} = 0.16\,mm$ and $y_{c0} = 0\,mm$
- The plane of observation moves along the z axis





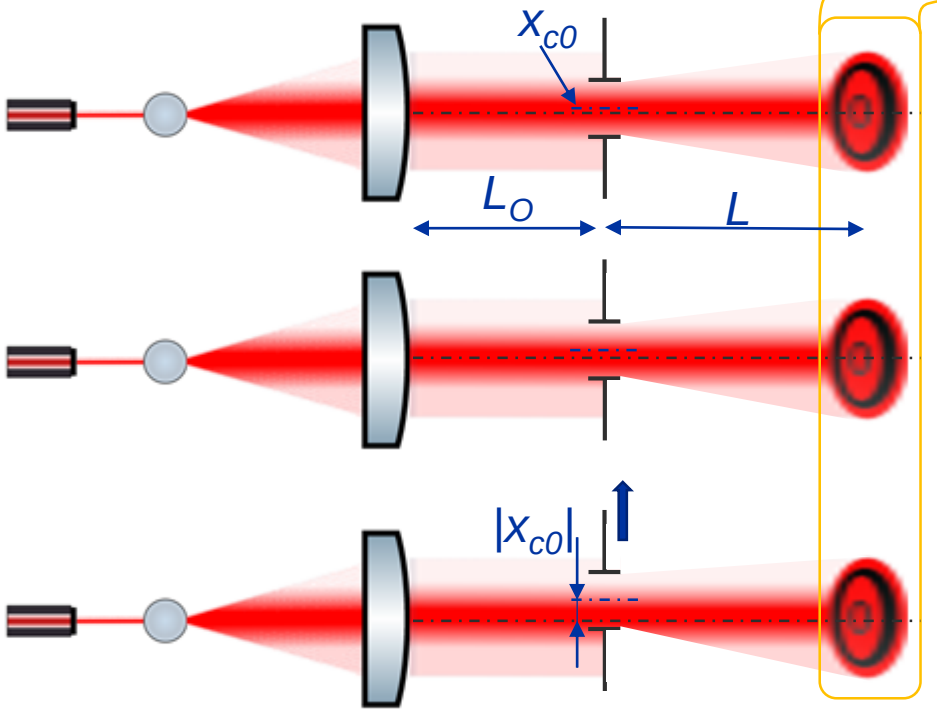
- It is clear, after evaluating the SLB's center position, that SLB does not propagate in a straight line.

SLB centre position for obstacle at $x_{c0} = 0.16\,mm$

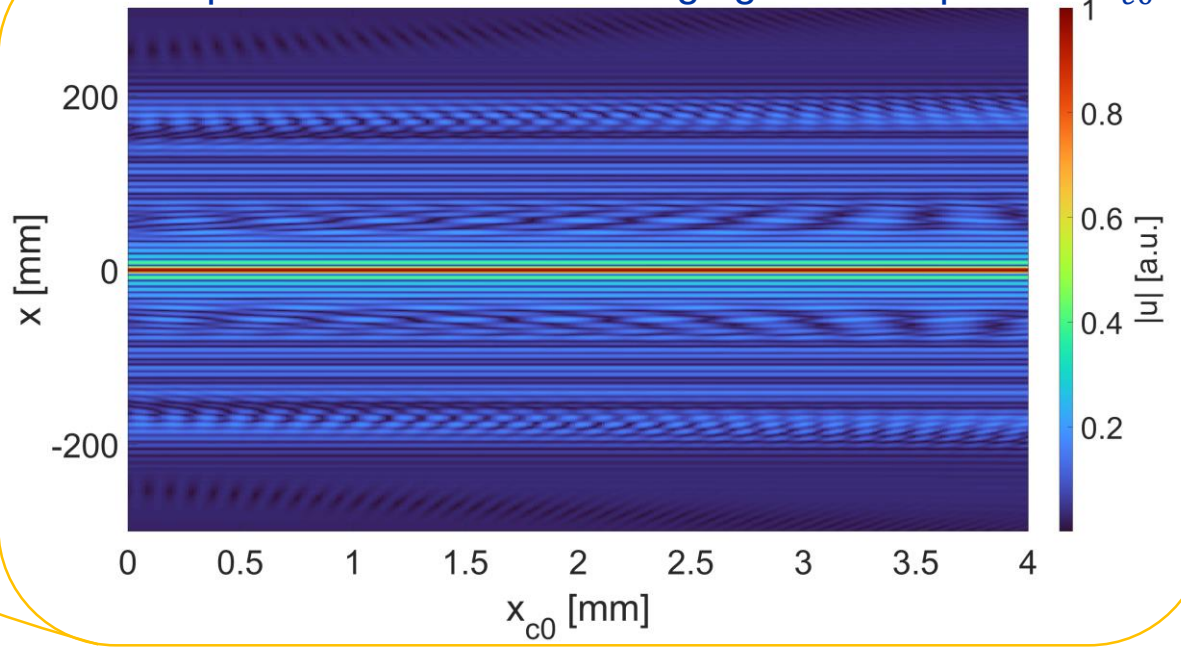


Influence of the obstacle position on straightness

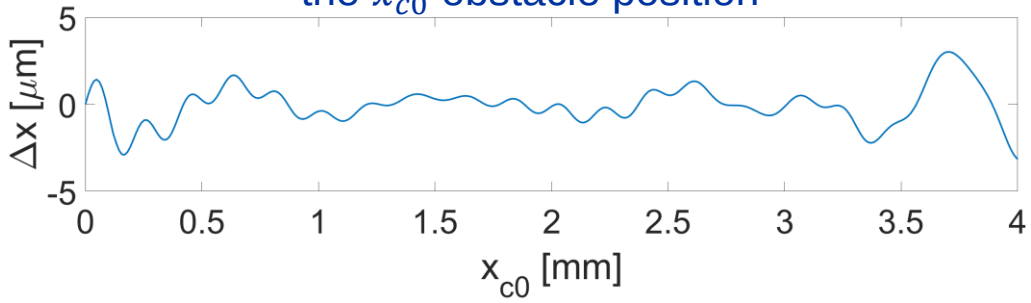
- Example with same circular obstacle as before
- Obstacle position x_{c0} changes in $[0; 2]\ mm$ interval
- The SLB is evaluated at the fixed distance $L = 200\ m$



SLB amplitude at 200 m for changing obstacle position x_{c0}



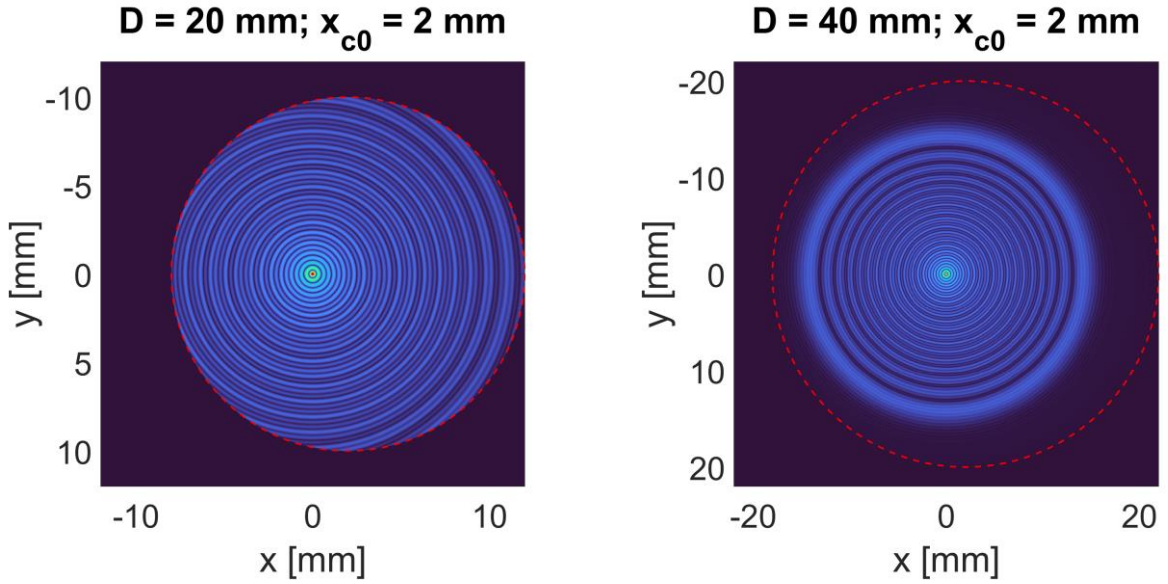
SLB centre at given distance in function of the x_{c0} obstacle position



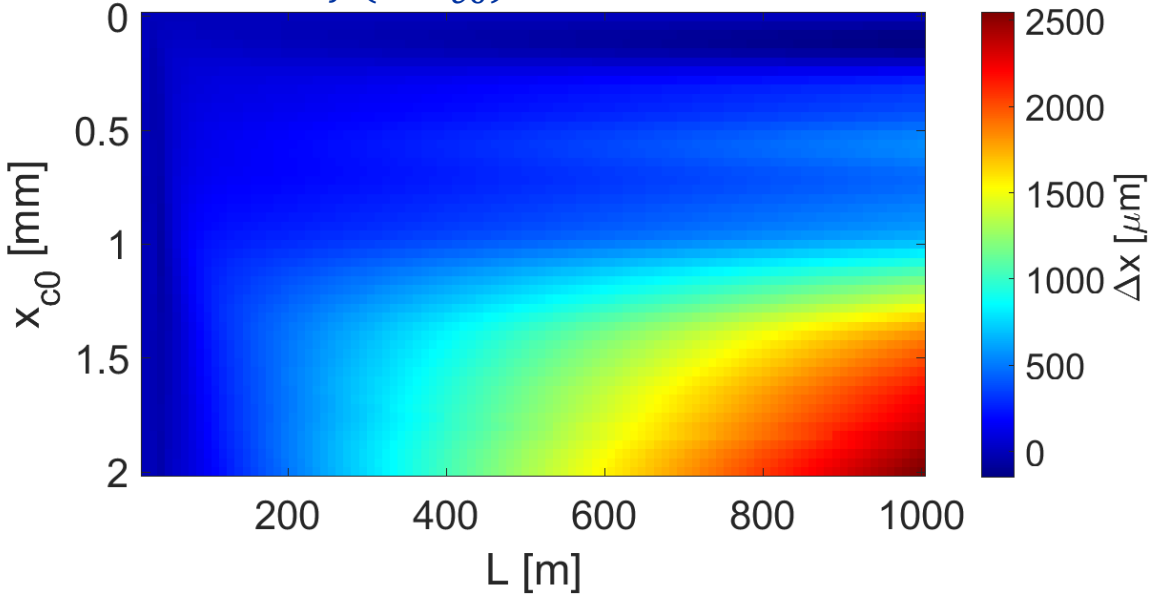
- The evaluated position of the SLB center shows a non-trivial dependence

Circular aperture in the near (Fresnel) zone

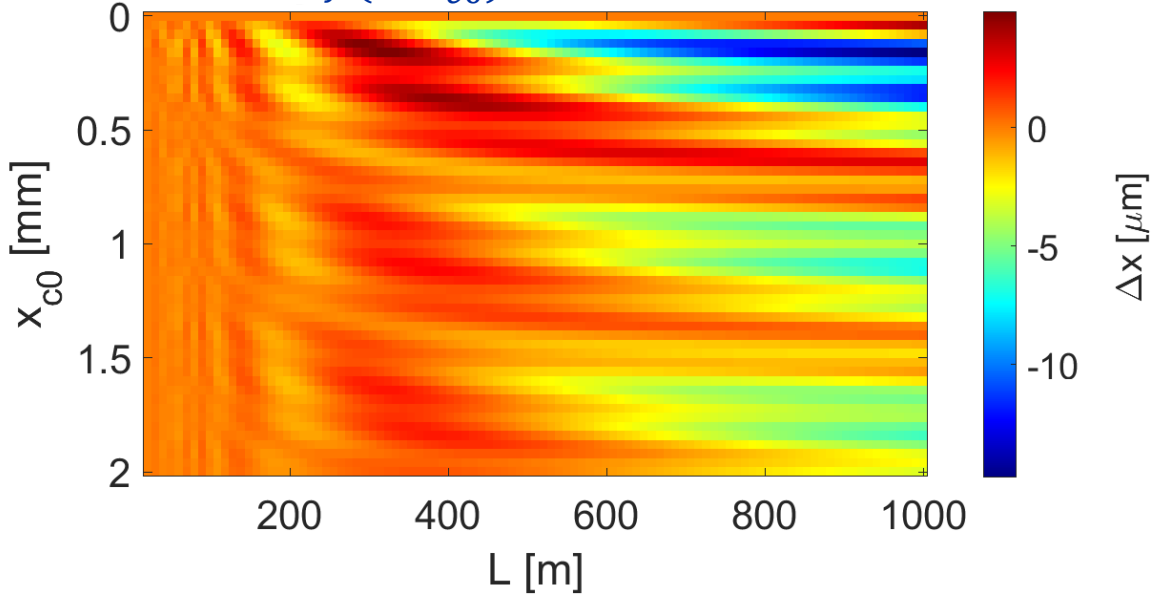
- Distance of the obstacle from the SLB generator $L_O = 10\,m$
- Two different diameters of the circular aperture D
- Δx is the change of SLB centre position
- The two graphs below show Δx in function of the obstacle position x_{c0} at different observation distances L



$\Delta x = f(L; x_{c0})$ for $D = 20\,mm$

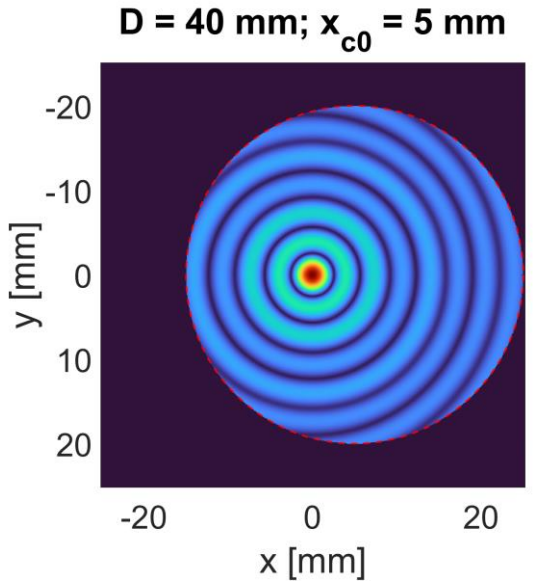


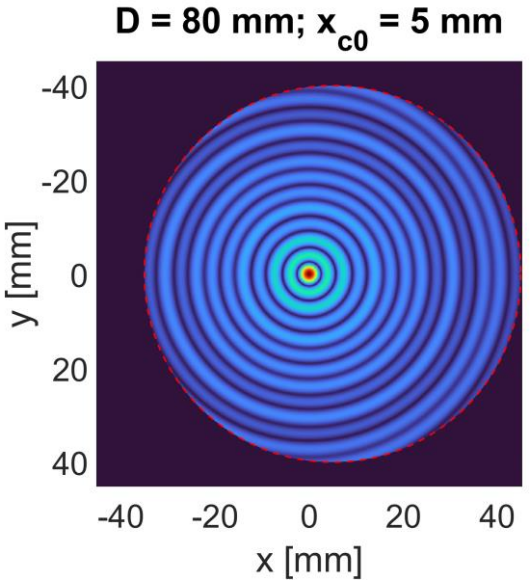
$\Delta x = f(L; x_{c0})$ for $D = 40\,mm$



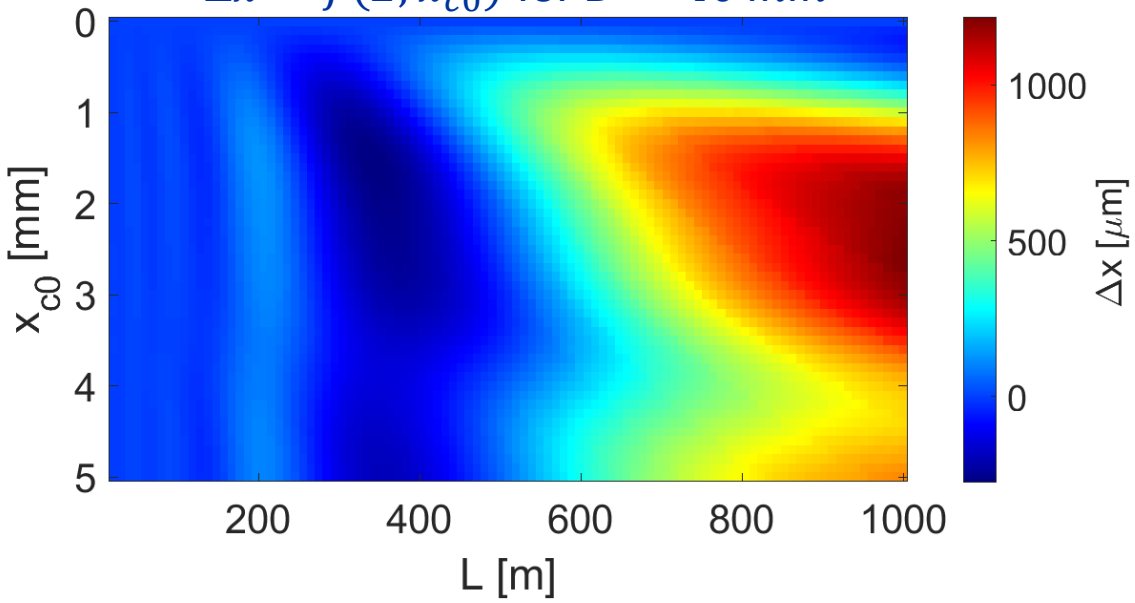
Circular aperture in the far (Fraunhofer) zone

- Distance of the obstacle from the SLB generator $L_O = 100\,m$
- Two different diameters of the circular aperture D
- Δx is the change of SLB centre position
- The two graphs below show Δx in function of the obstacle position x_{c0} at different observation distances L

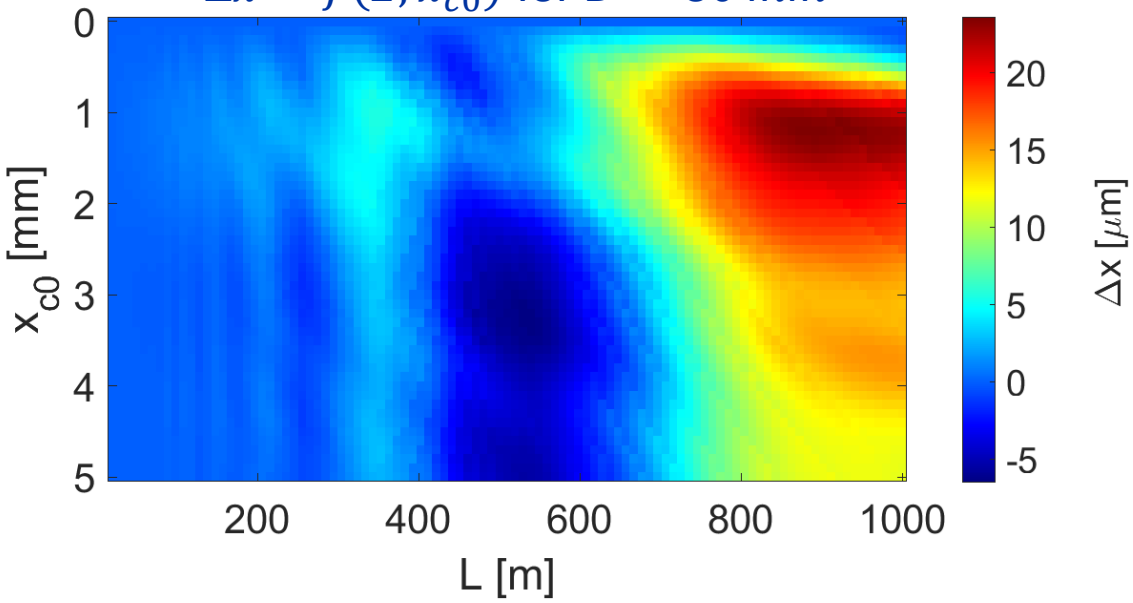




$\Delta x = f(L; x_{c0})$ for $D = 40\,mm$

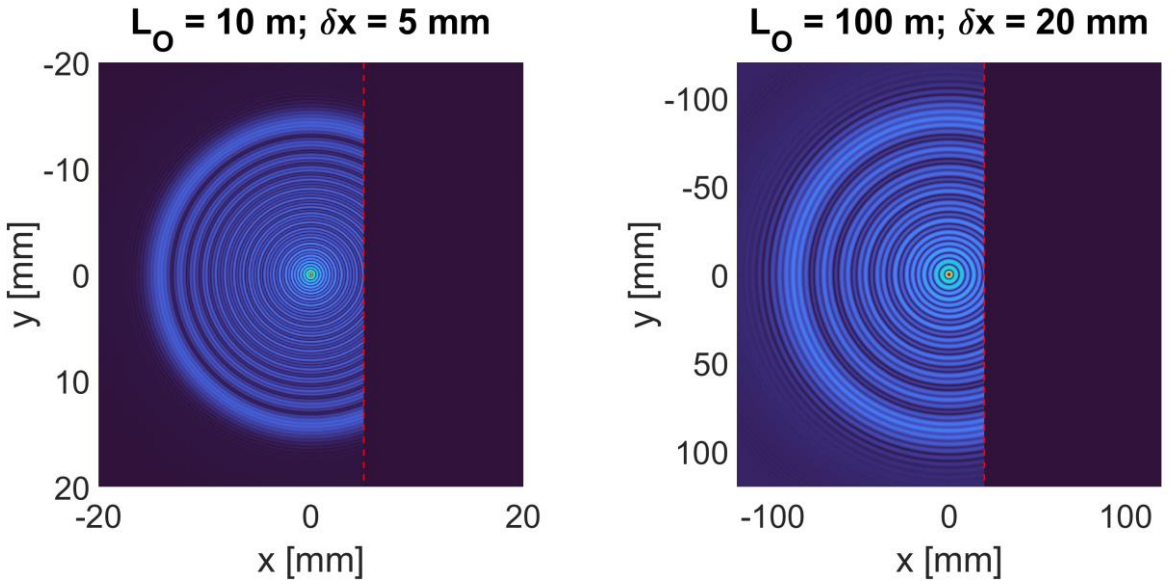


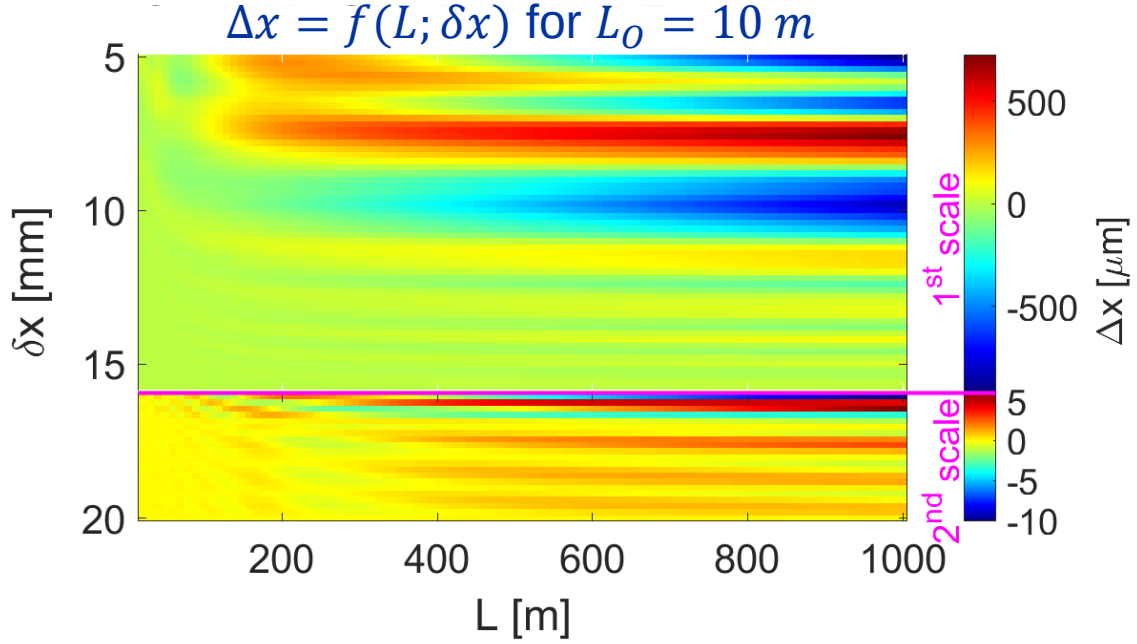
$\Delta x = f(L; x_{c0})$ for $D = 80\,mm$

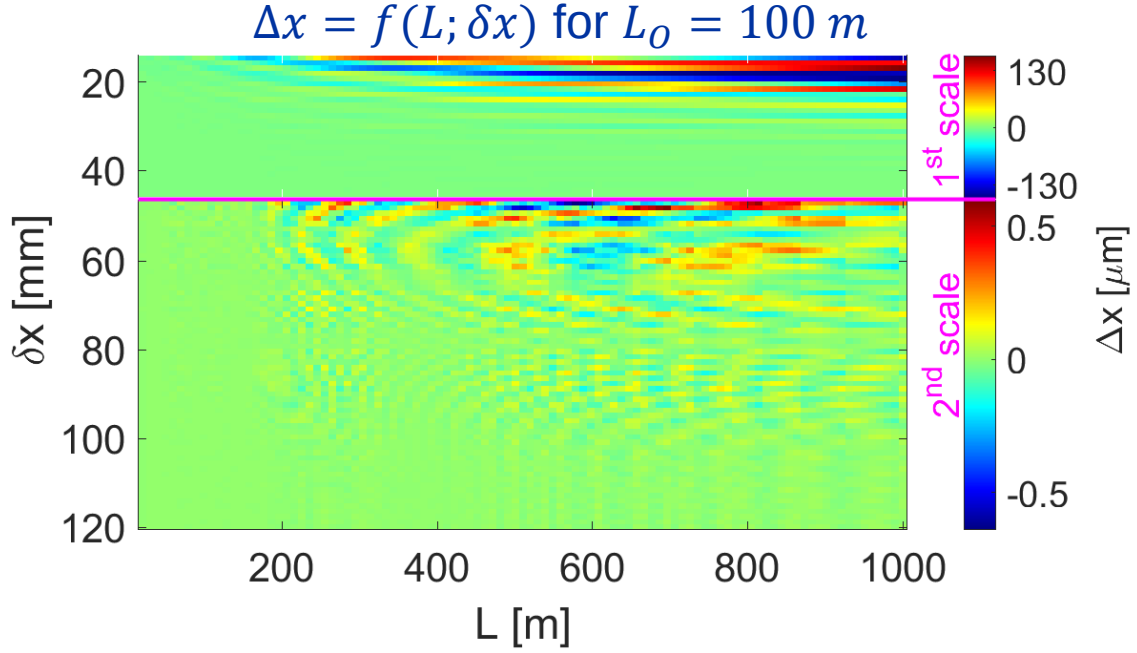


One-side SLB blocking

- Two cases are simulated
- The obstacle is placed at two different L_O distances
- $L_O = 10\,m$ in the Fresnel zone
- $L_O = 100\,m$ in the Fraunhofer zone
- In each graph two color scales are used to increase the visibility of small movements
- The two graphs below show Δx in function of the obstacle position δx at different observation distances L

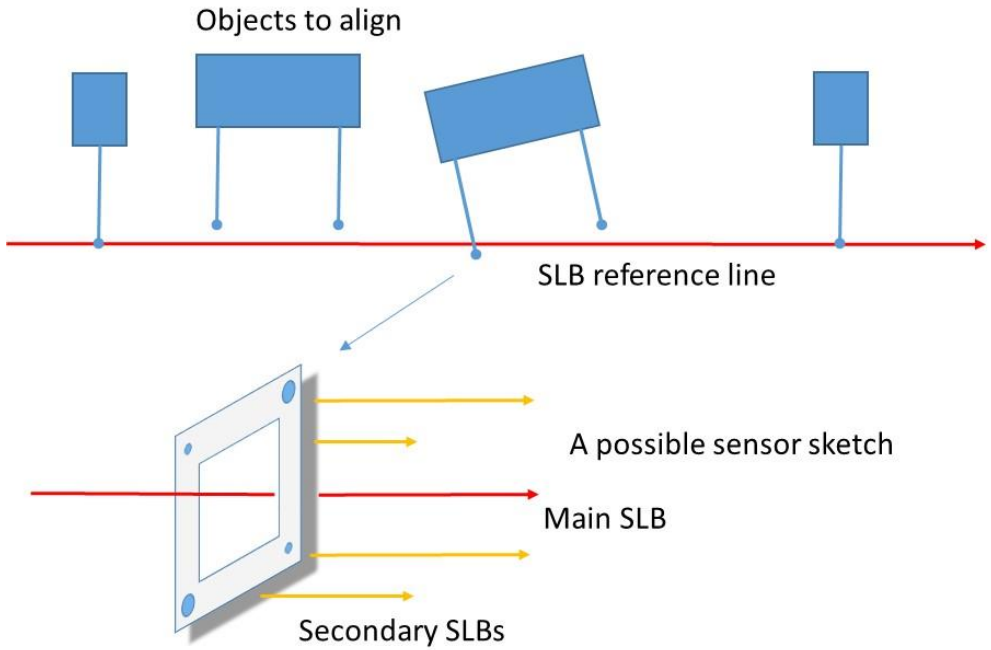


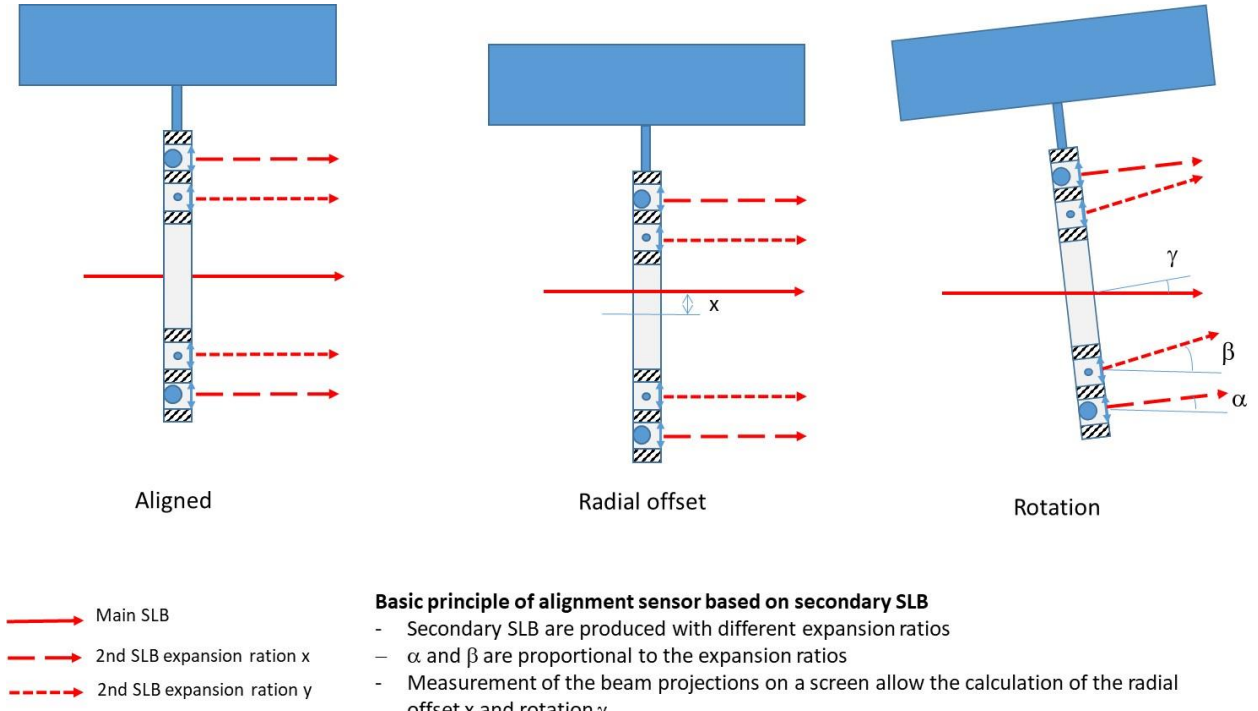




SLB – Towards a multi-point alignment system

- From simple system shining CCD sensors -> the spot size stay compatible with CCD size over long distance (>> 100 m)
- To more sophisticated systems by imaging of spot projection
- With additional degrees of freedom reconstruction using secondary beams generated with different expansion ratios



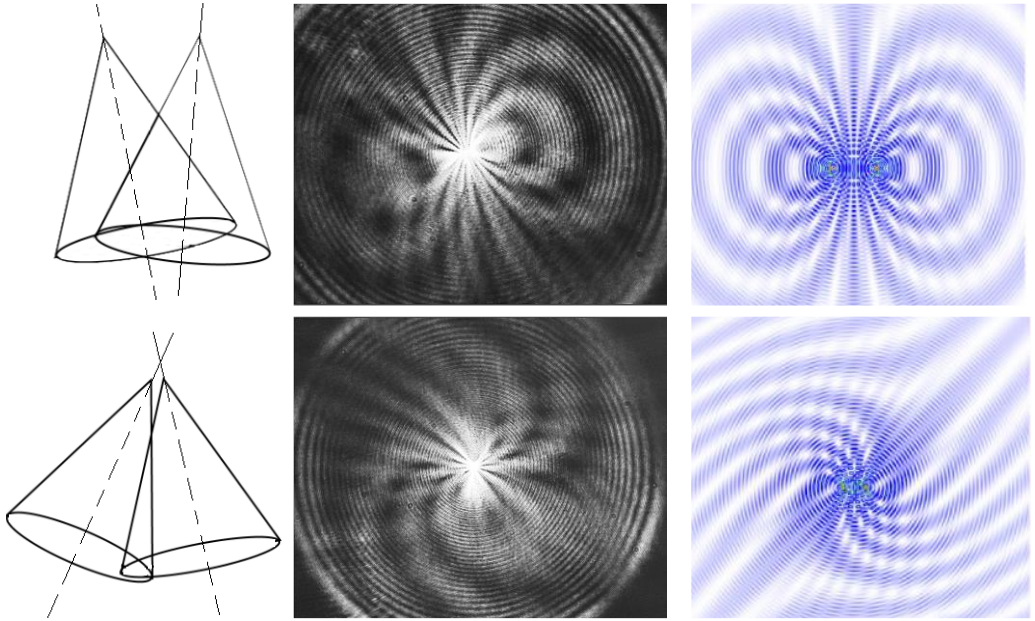


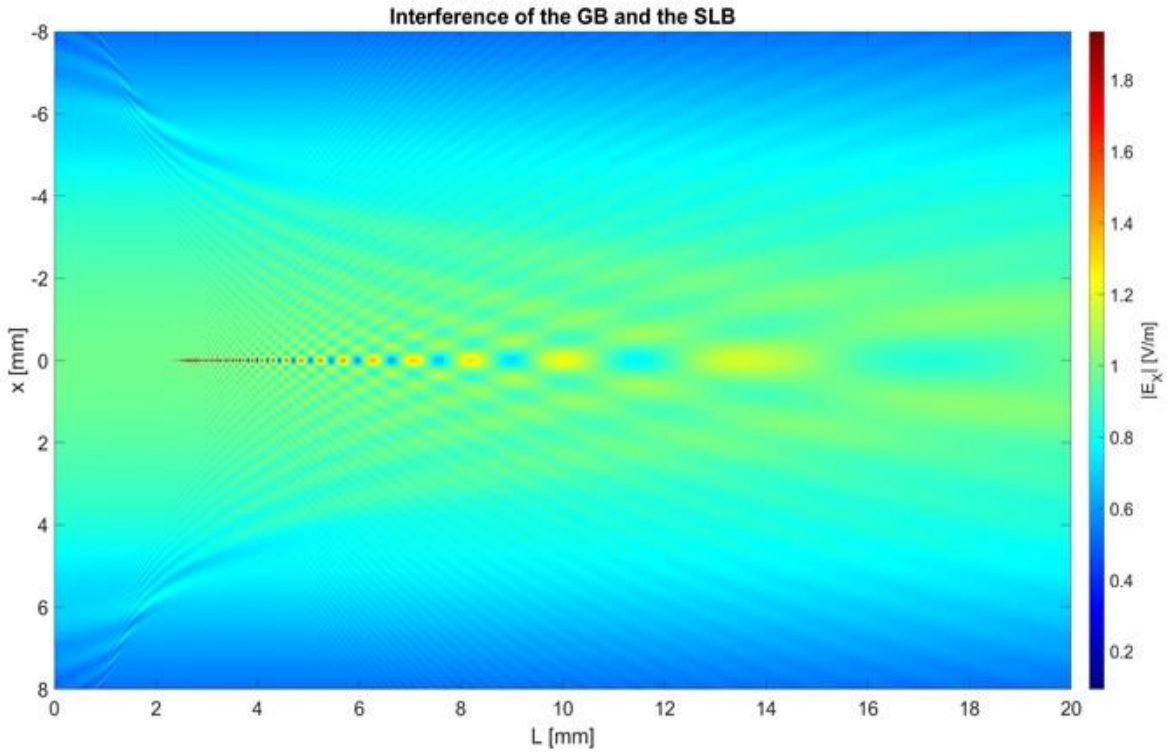
Basic principle of alignment sensor based on secondary SLB

- Secondary SLB are produced with different expansion ratios
- α and β are proportional to the expansion ratios
- Measurement of the beam projections on a screen allow the calculation of the radial offset x and rotation γ

- First tests will start soon

SLB – Interferometry





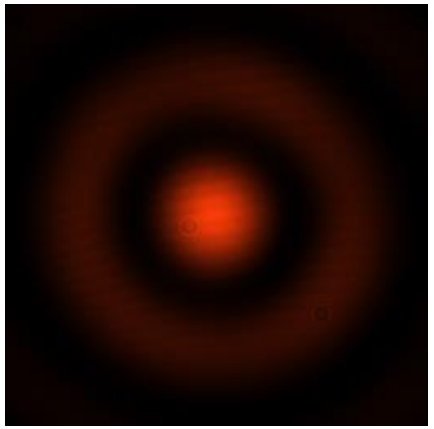
- More degrees of freedom measurements
- Interferograms in good agreement with simulations

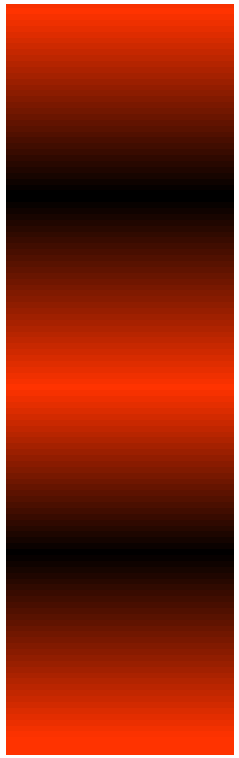
- Absolute distance measurement

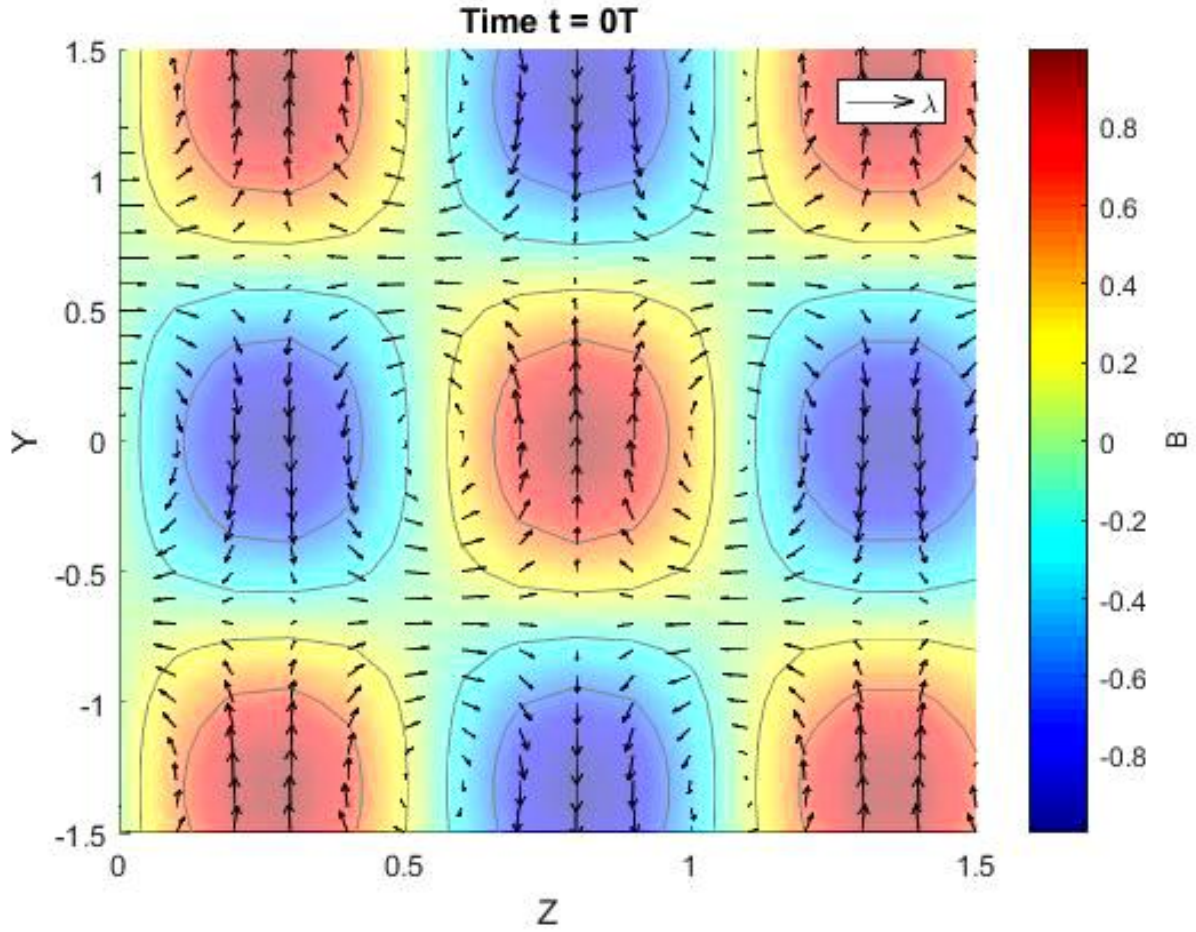
SLB – Polarization

- Input beam with linear classical polarization
- Arrows → E field

SLB real image





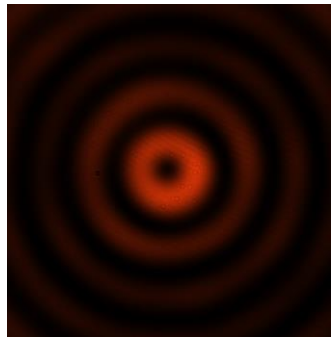


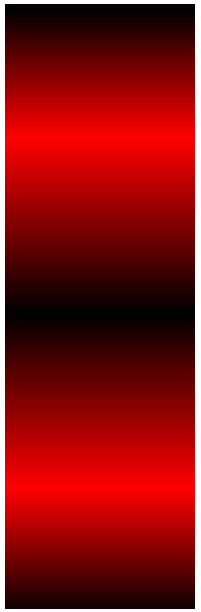
Matlab animation

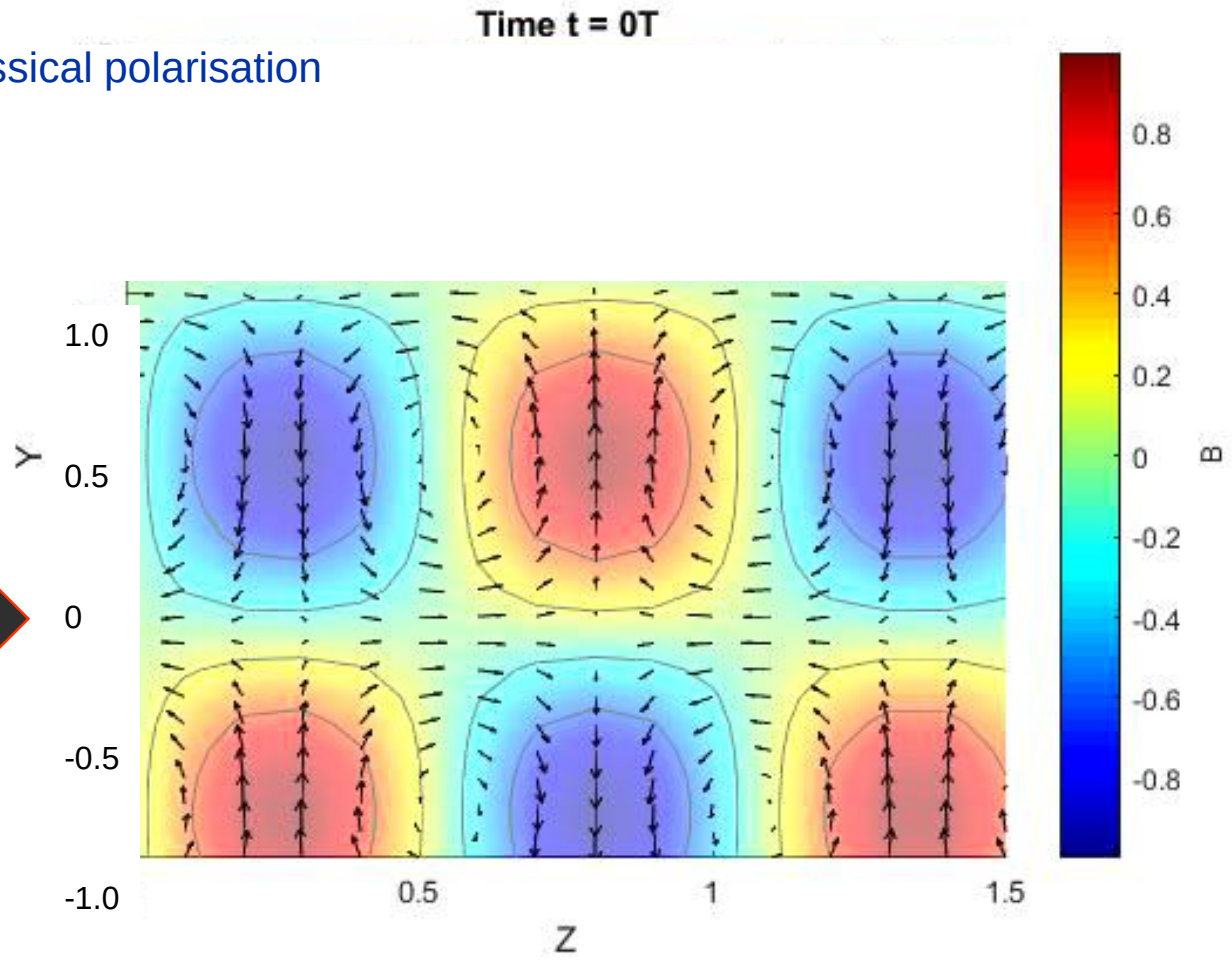
SLB – Hollow beam - Polarization

- Hollow beam from input beam with radial non-classical polarisation
- Arrows → E field

Real image



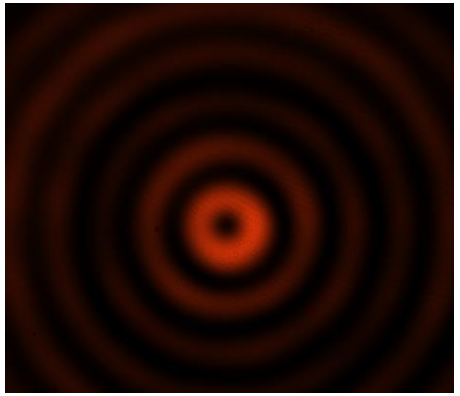


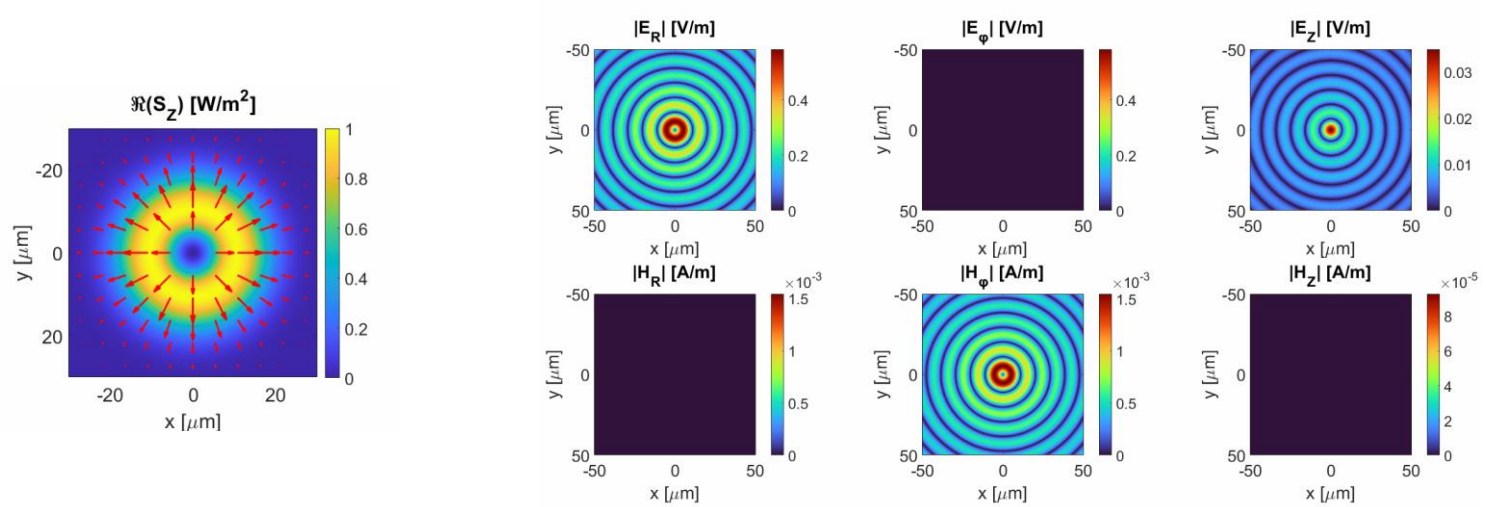


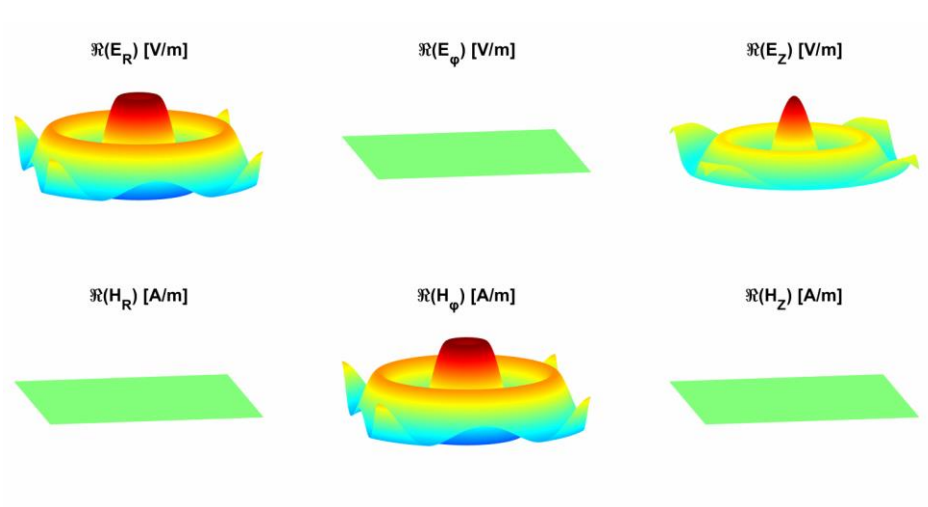
Matlab animation

SLB – Study of non-classical polarization states

- Study on-going
- Interesting polarization states
- Orientation of polarization depend on the transversal position in the optical beam
- Two limit states: radial and azimuthal polarization
- Illumination optical beam with non-classical polarization has singularity in its center.
- Generated SLB contains areas with a non-negligible longitudinally polarized field







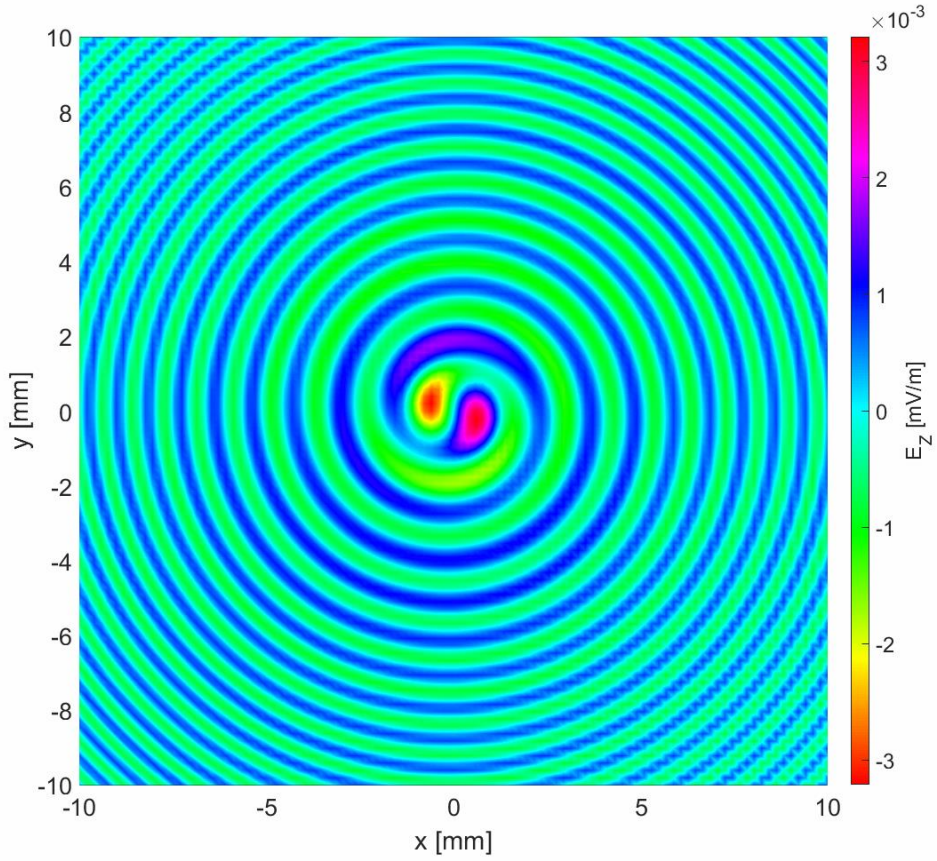
Cylindrical coordinates are more convenient, circular symmetry.

Summary

- SLB: Towards new contactless alignment tools for large scale metrology and surveying
- Potential application to particle accelerator alignments and in industry
- Possible alternative to the currently used techniques
- Could be extended to measure more than 2 degrees of freedom
- Could be combined with interferometry and possibly absolute interferometry for spatial positioning
- Present status of R&D:
  - Several MSc student works have been done
  - A PhD is on-going for the study of the theory and of the main properties of the beam (CERN / TUL)
  - A PhD started last february on the development of position detection including AI for image analysis (CERN / TUL)
  - A PhD for the development and the integration of an accelerator alignment system (FCC) just started (CERN / ETHZ)
  - A PhD student from TUL, presently COAS at CERN, is studying the special polarization states
  - And …
- More R&D could open the development of other potential applications in different domains such as Physics, Communication, Aerospace, Optical tweezing, …

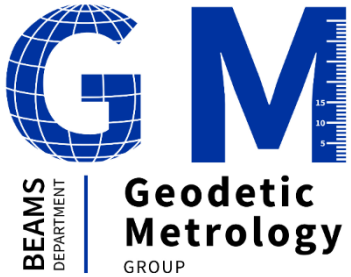
SLB is a fascinating project

As shown by the SLB longitudinal componant of the E field from an input beam with circular polarization



Acknowledgement to whole team working on SLB with a special thanks to Krystof Polak for his contribution to the study and to the presented SLB simulations

Thank you for your attention!



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