

Alignment system based on a Structured Laser Beam

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22/05/2025 Geodetic Metrology group - Future Projects section (BE-GM-FP)

ETH zürich

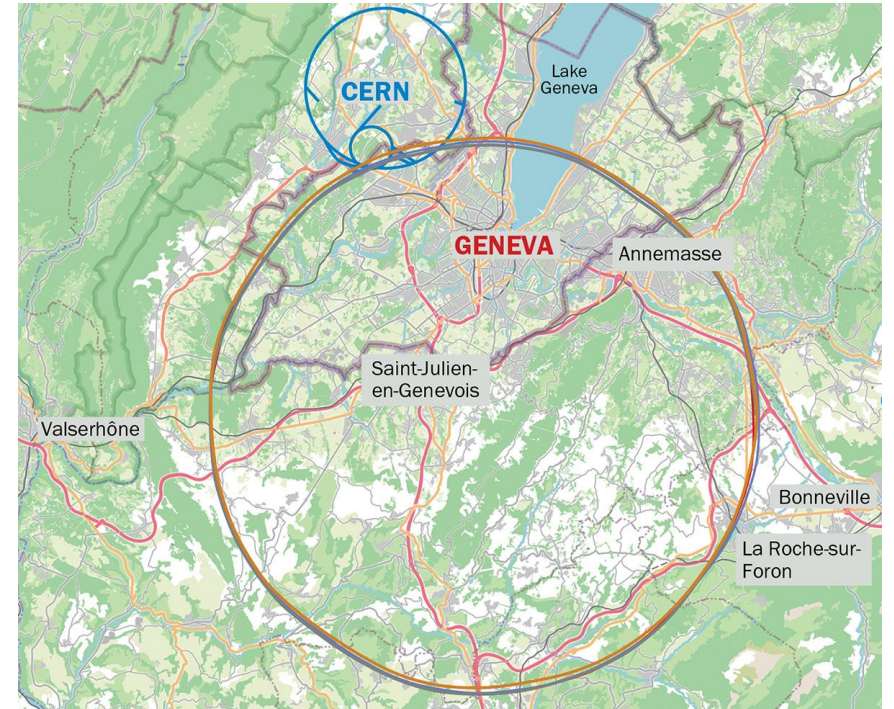
Content

- 1. Alignment of particle accelerators**
- 2. SLB-based reference line**
- 3. Alignment system prototype**

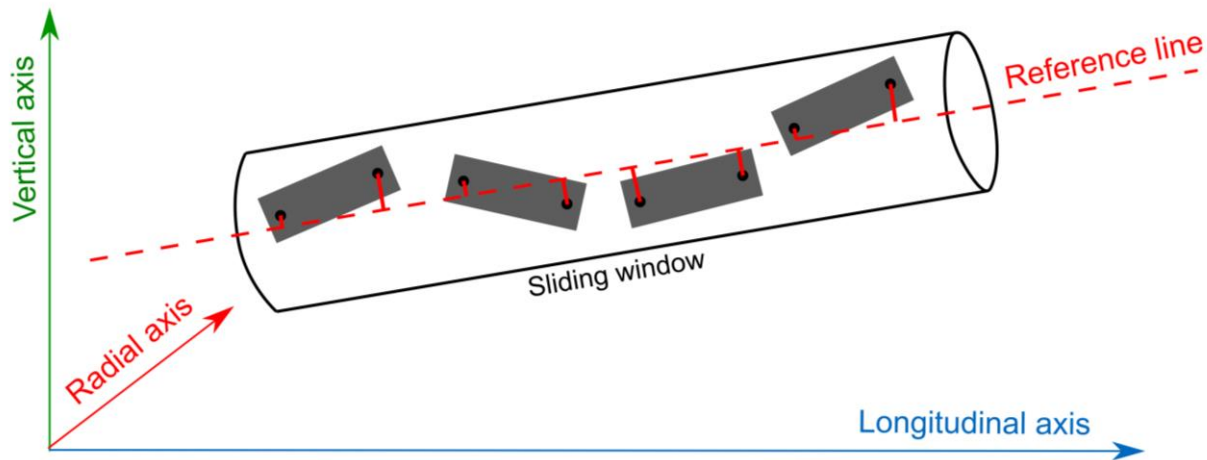
Alignment of particle accelerators



Large Hadron Collider (LHC)



Future Circular Collider (FCC)



Alignment of entire machine:

- Accuracy LHC $200 \mu\text{m} / 150 \text{m}$ (sliding window)

Reference line for alignment

Component I

Component II

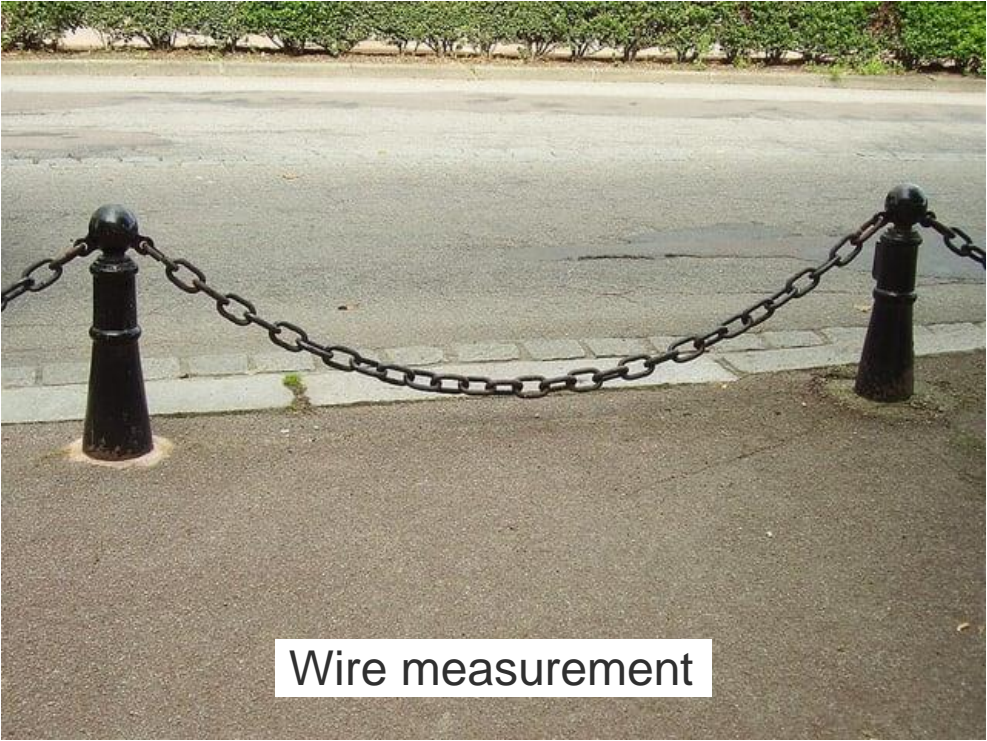
Component III

Reference line

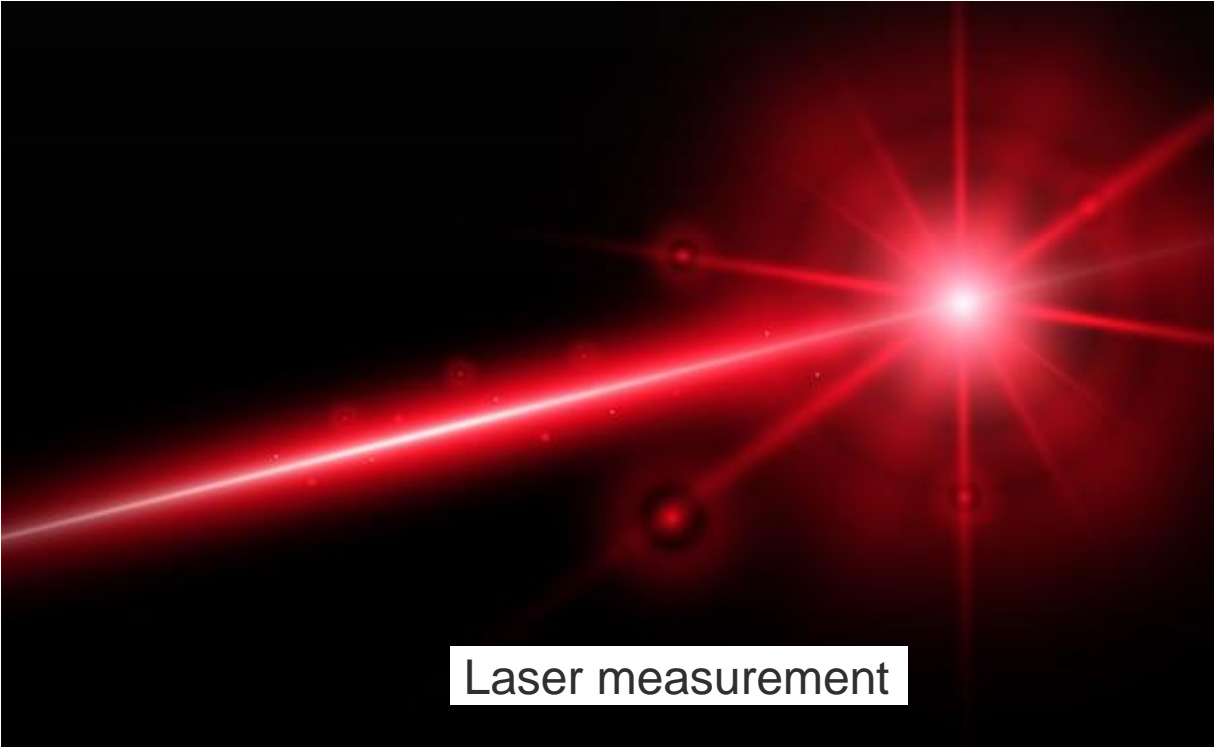


Assumptions:

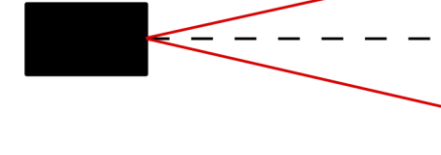
- Line is straight
- Offsets are perpendicular



Wire measurement

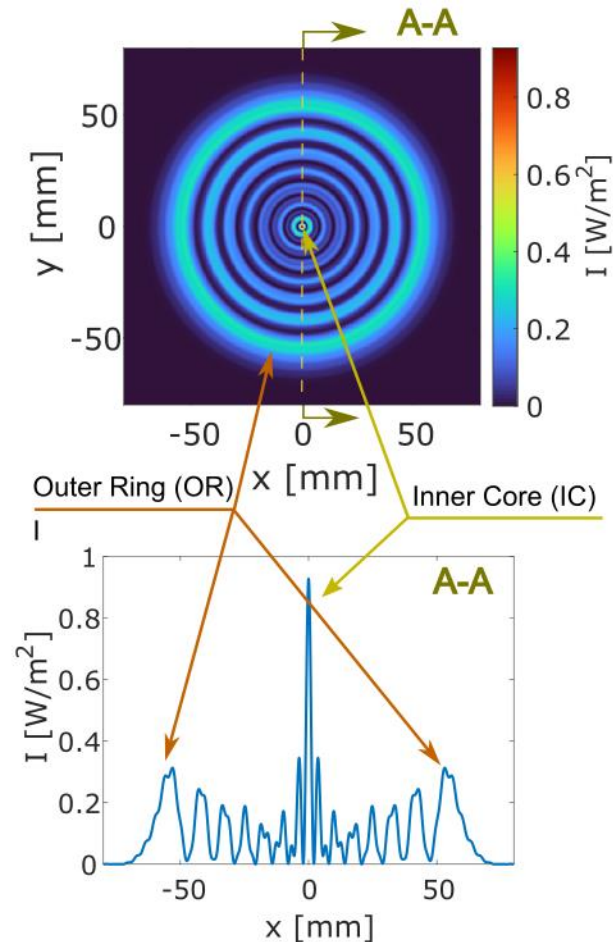


Laser measurement

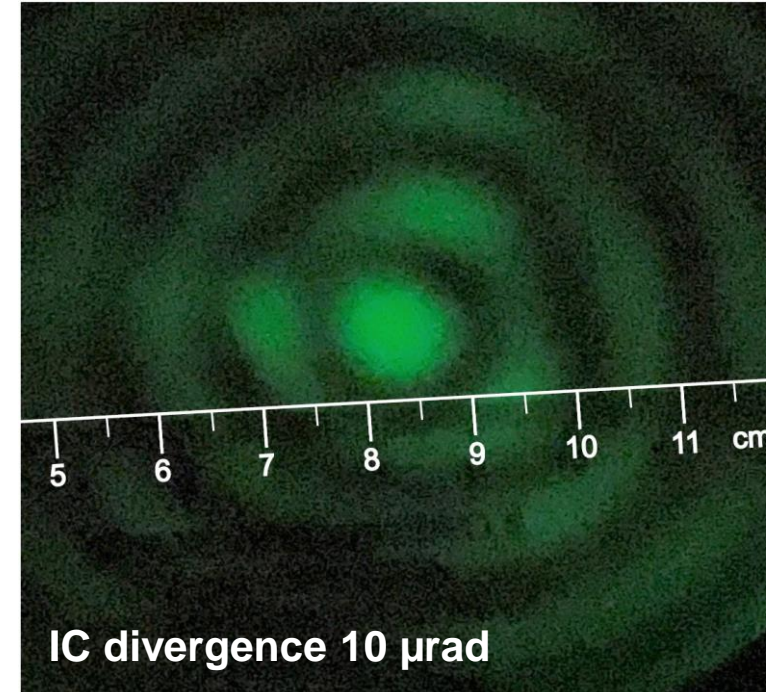


Structured Laser Beam (SLB)

Example of theoretical transverse profile of an SLB at 225 m - Inner core \varnothing 3 mm, Outer ring 100 mm



Acquired transverse profile at 900 m

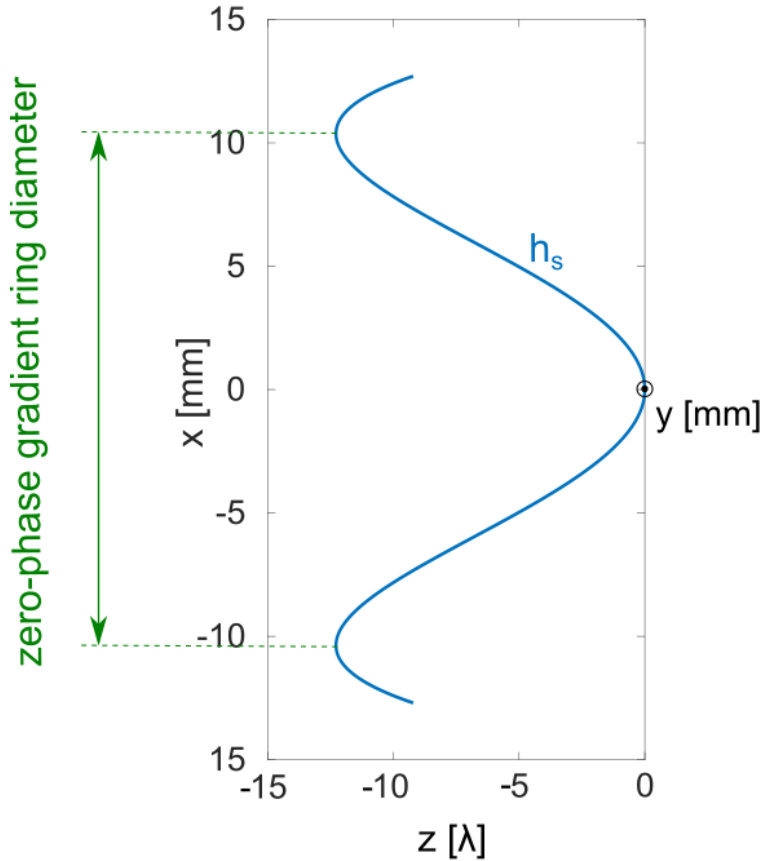
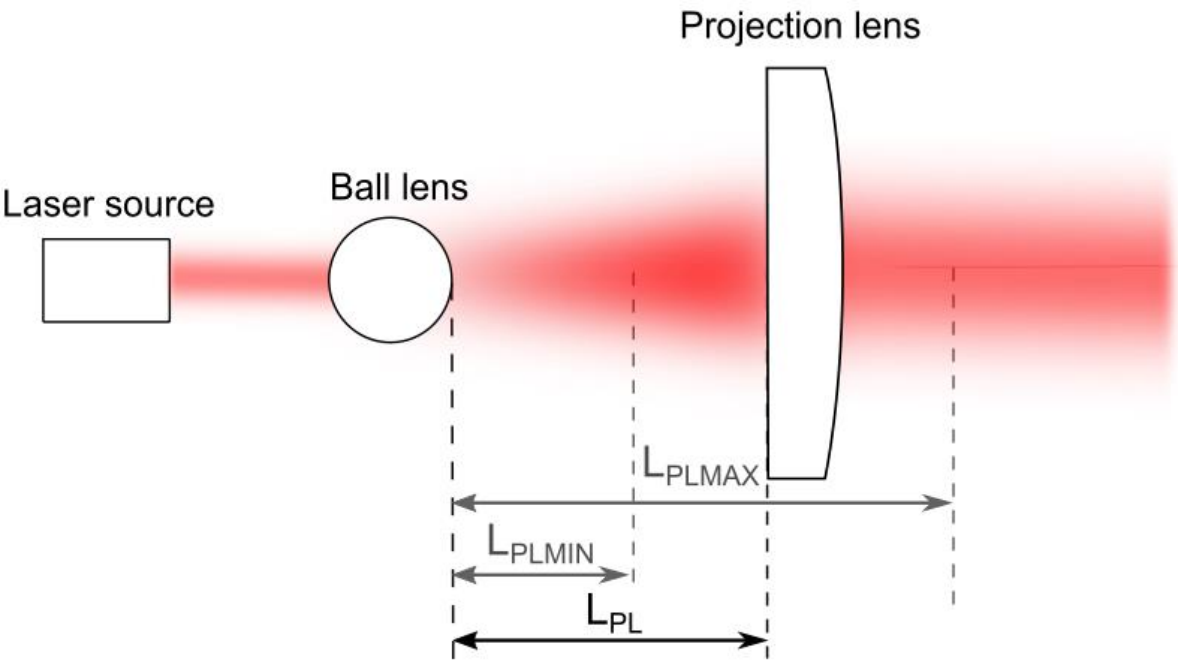
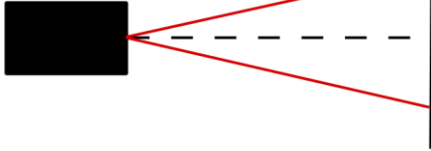


Advantages of SLB for alignment:

- Low divergence of the IC
- Theoretically, propagation to infinity
- Easy-separable IC

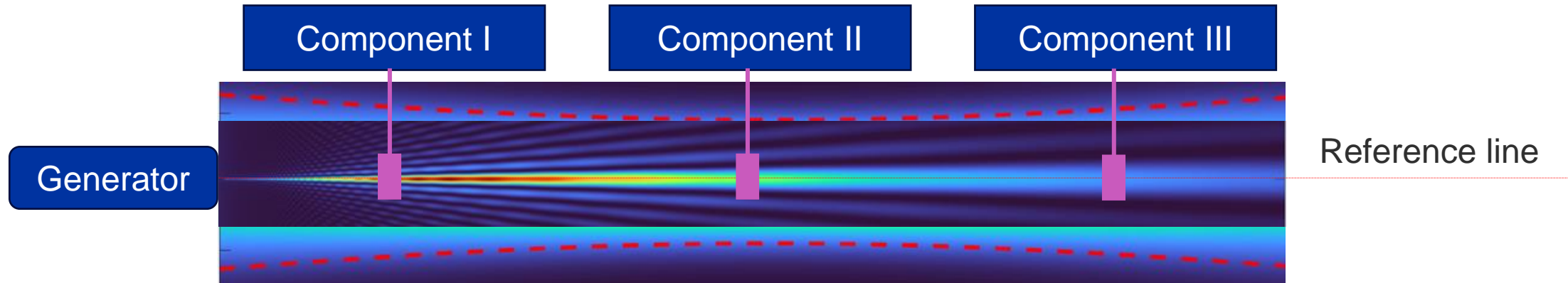
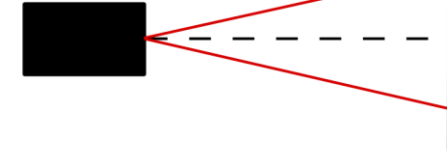
SLB generator and wavefront

Laser divergence

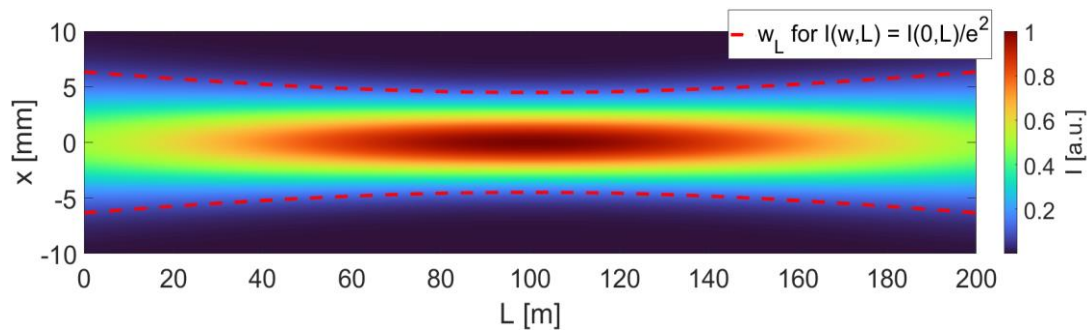


Alignment - SLB inner core reference

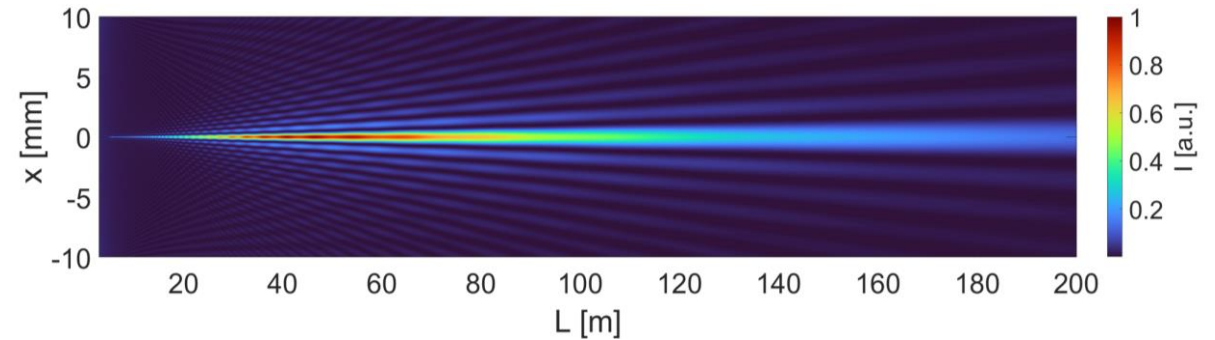
Laser divergence



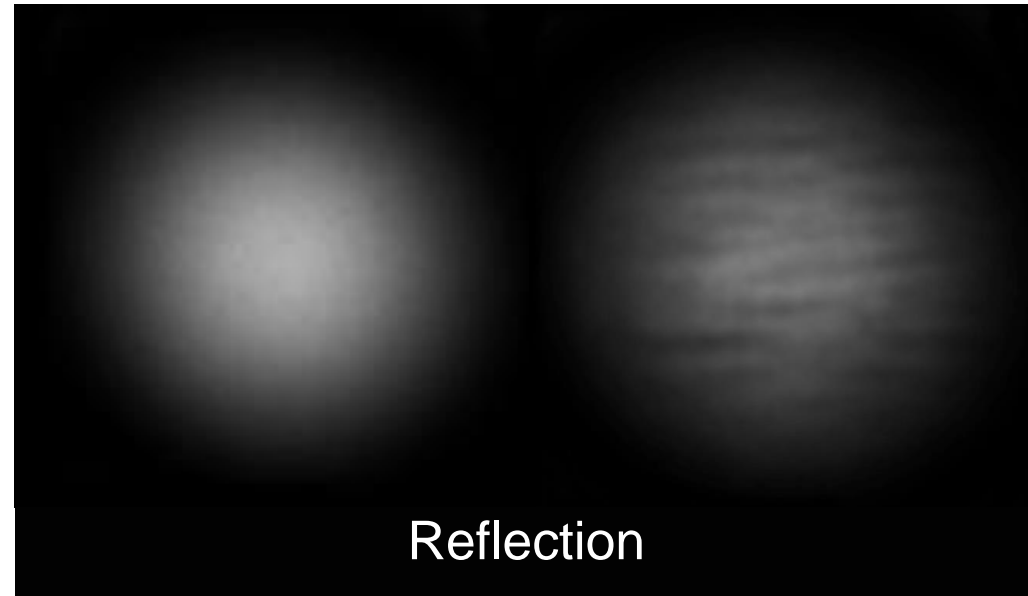
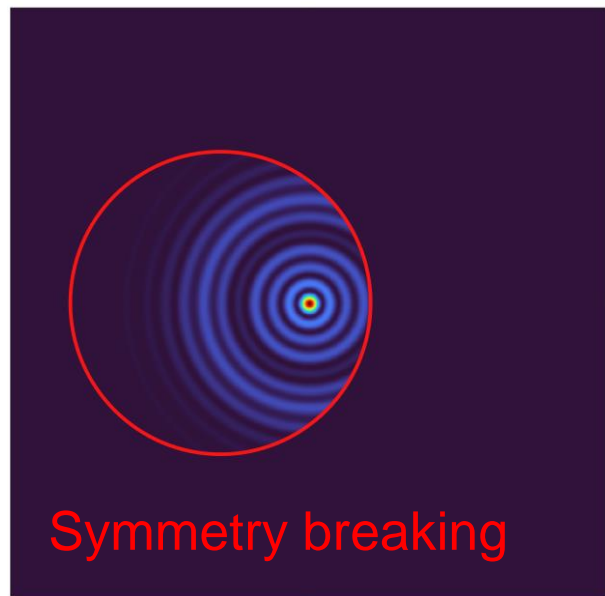
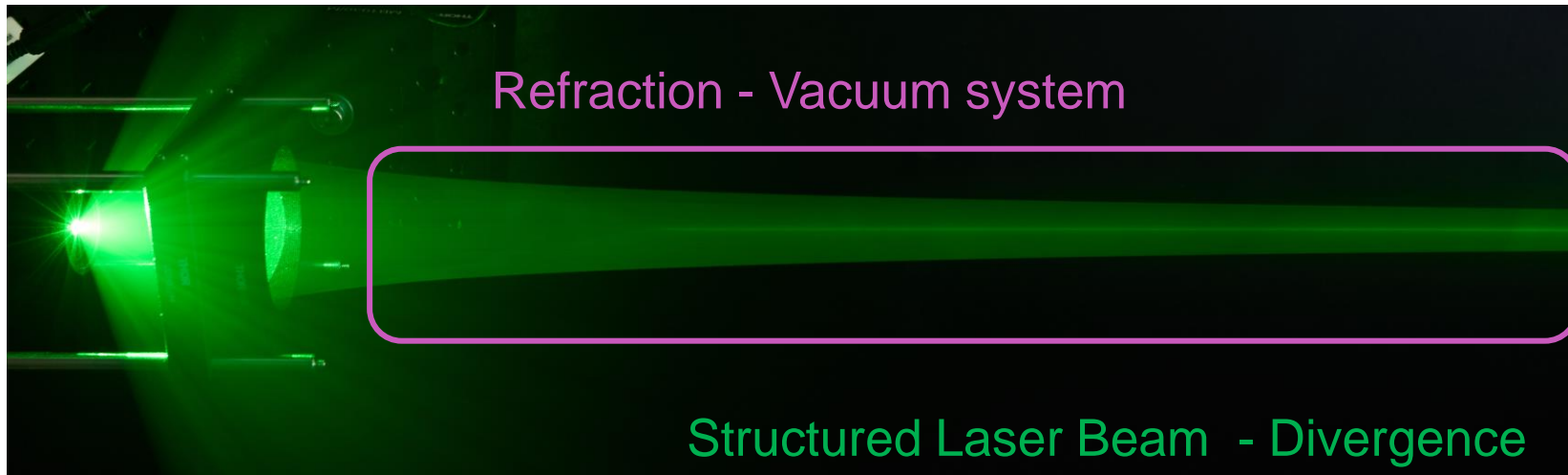
Longitudinal profile of a Gaussian Beam

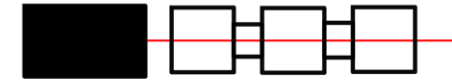


Longitudinal profile of an SLB



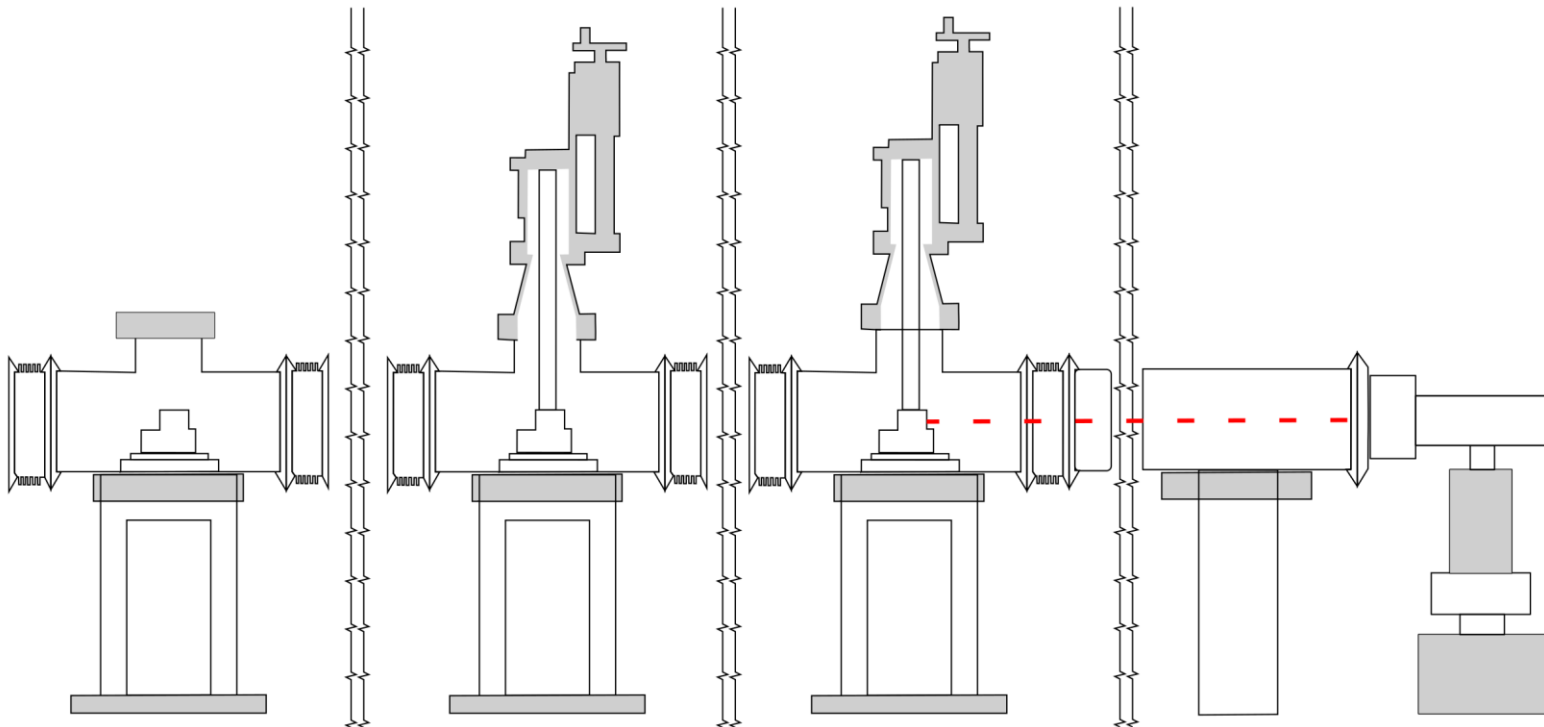
Challenges



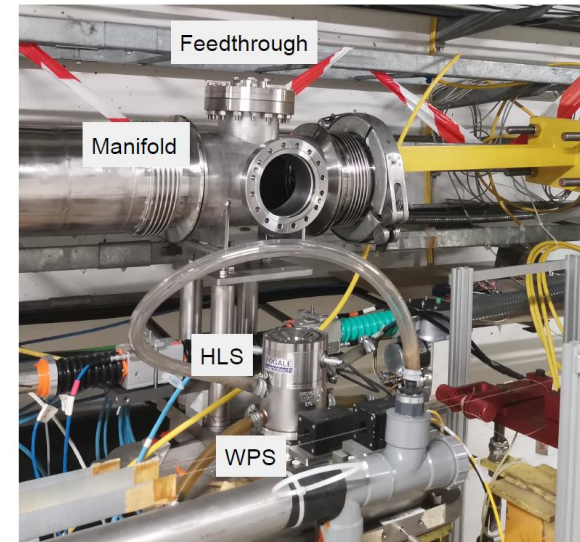


Shutter system - 140 m length

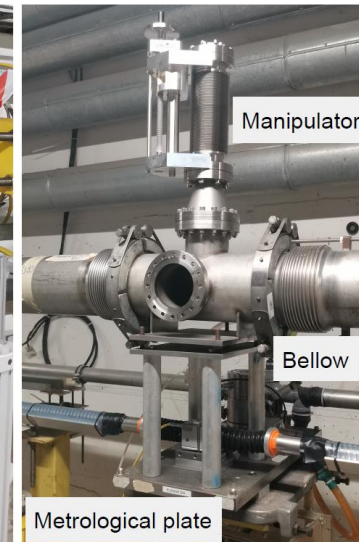
Measurement station 1 Measurement station 4 Measurement station 7 0 250 500 mm



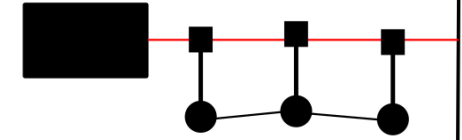
Measurement station 1



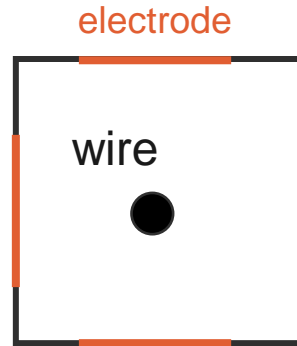
Measurement station 4



Experimental setup - Prototype evaluation

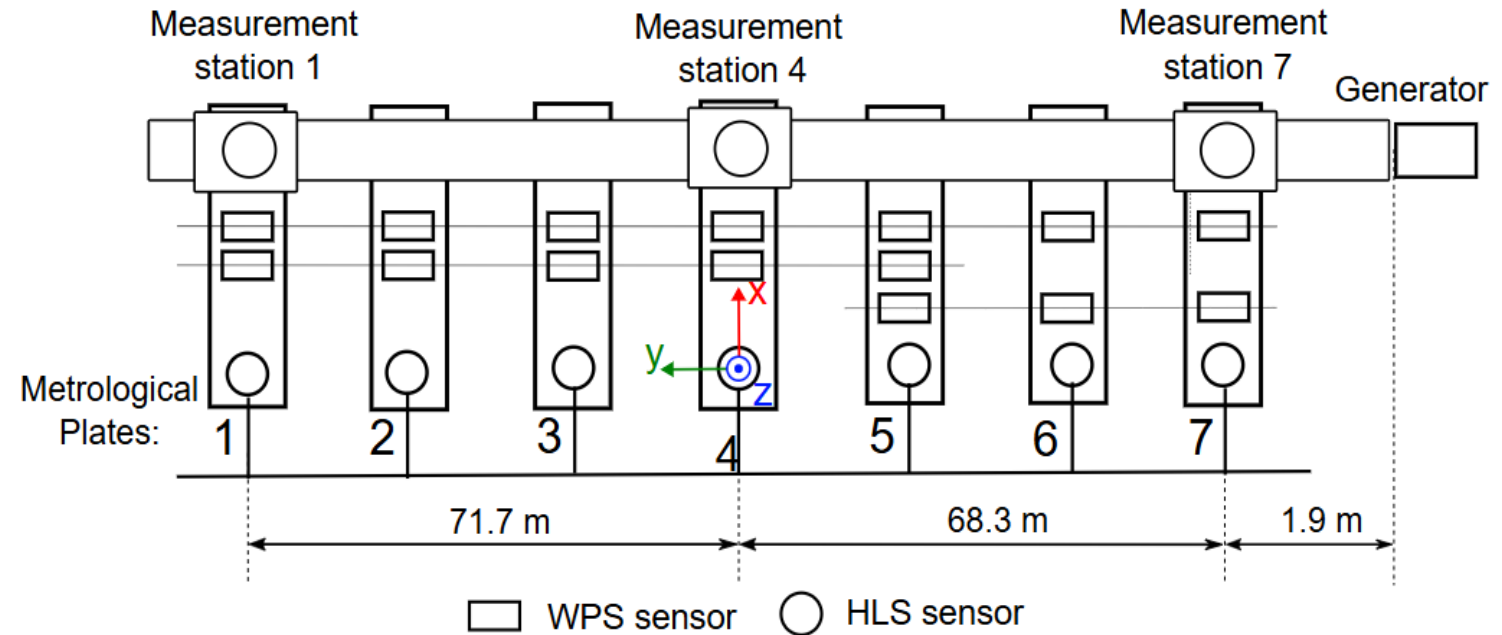


Wire Positioning System (WPS)

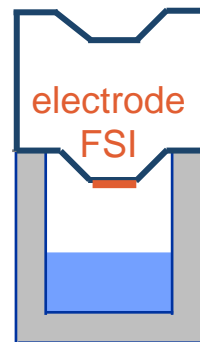
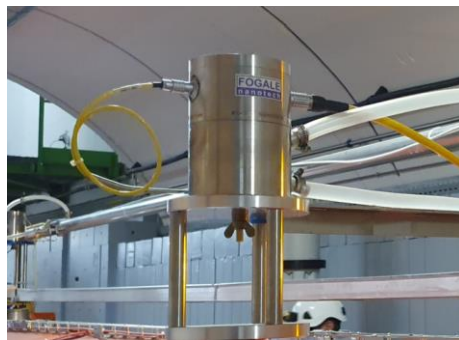


Experimental setup for comparative assessment of the prototype with the WPS and HLS

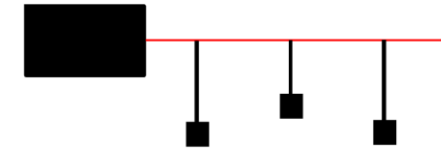
SLB alignment system



Hydrostatic Levelling System (HLS)



Assessment with WPS and HLS network



Offset of Station 4 relative to Stations 1 and 7
Two acquisition series of 3.5 hours each
Error bars based on SLB data variation

Precision

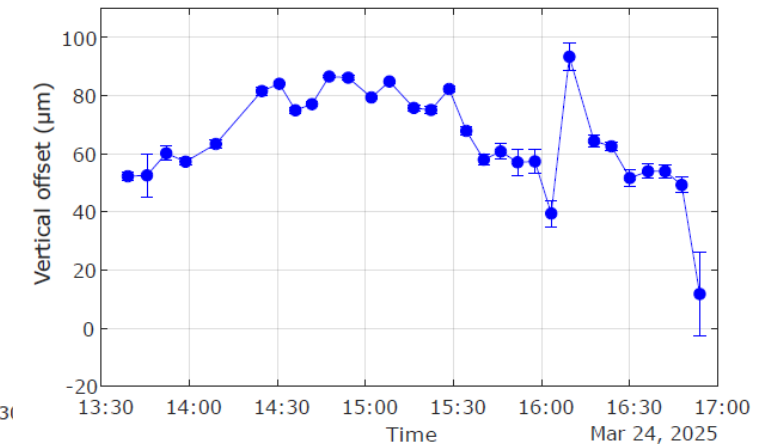
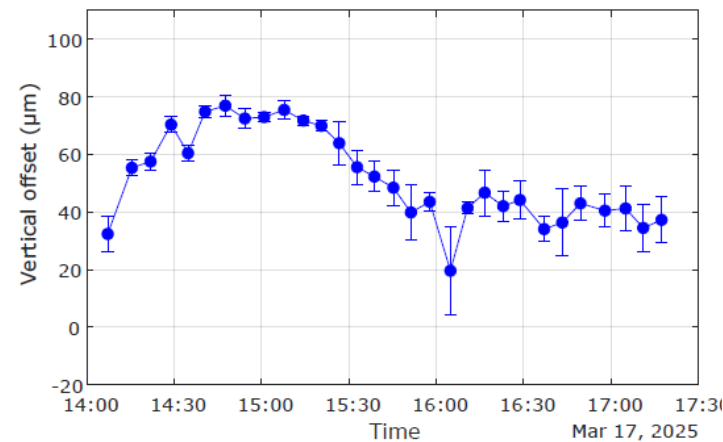
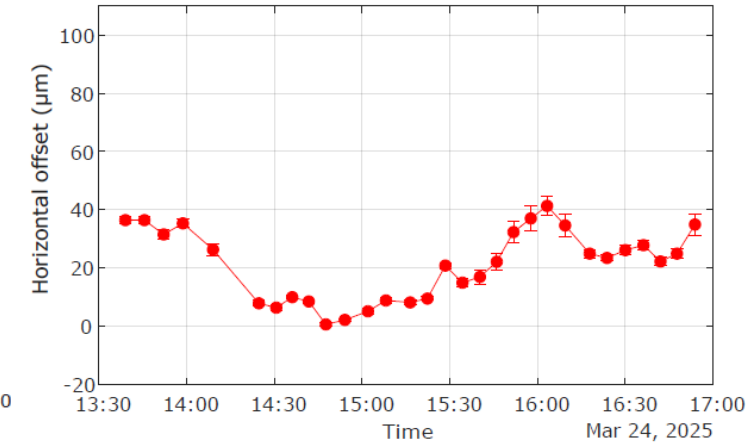
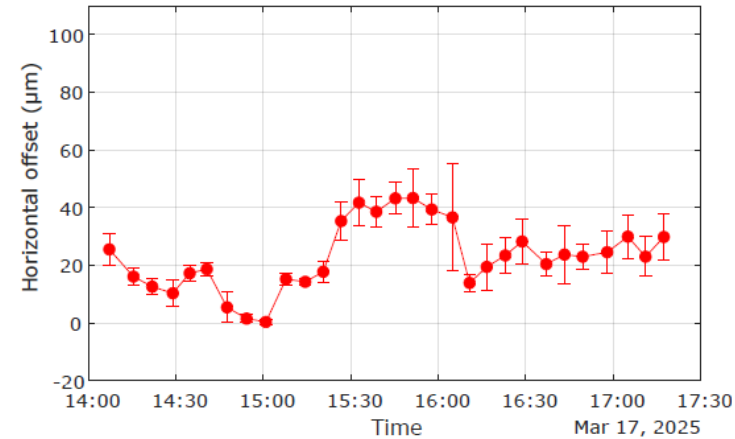
Standard deviation below 20 μm

Improvement: enhanced reference line stability by extended vacuum system, thermal stabilisation, multipoint measurement – Layers Beams.

Accuracy

Absolute bias horizontal 20 μm and vertical 50 μm

Improvement: modified the fiducialisation process by lowering the vacuum system, fiducialisation in the metrology laboratory.



Conclusion

- 1. SLB can be used for alignment thanks to low divergence, high IC contrast, and long beam propagation.**
- 2. Multiple challenges were overcome to construct the prototype using a vacuum system.**
- 3. The prototype achieved high precision, showing strong potential for future systems.**
- 4. Addressing challenges with radiation, multipoint alignment, and multiple lines is a priority for future implementations.**

References:

1. W. Niewiem, K. Polak, M. Dusek, D. Mergelkuhl, J-Ch. Gayde, A. Wieser, M. Sulc, “Variation of structured laser beam pattern and optimization for an alignment reference line creation” Optics Express 31 (2023)
<https://doi.org/10.1364/OE.503016>
2. W. Niewiem, K. Polak, S.Figura, D. Mergelkuhl, J-Ch. Gayde, A. Wieser, “The influence of symmetry breaking on the Inner Core of a Structured Laser Beam”, Express 33 (2025)
<https://doi.org/10.1364/OE.549391>
3. W. Niewiem, S. Figura, D. Mergelkuhl, J-Ch. Gayde, A. Wieser, M. Sulc, “Speckle induced by reflections in pipe propagation of a Structured Laser Beams” Applied Optics 64 (2025), soon available
4. W. Niewiem, S. Figura, D. Mergelkuhl, J-Ch. Gayde, A. Wieser,, “Shutter-type multi-point optical alignment using a Structured Laser Beam in vacuum” JINST (2025), soon available



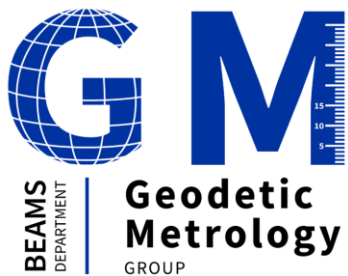
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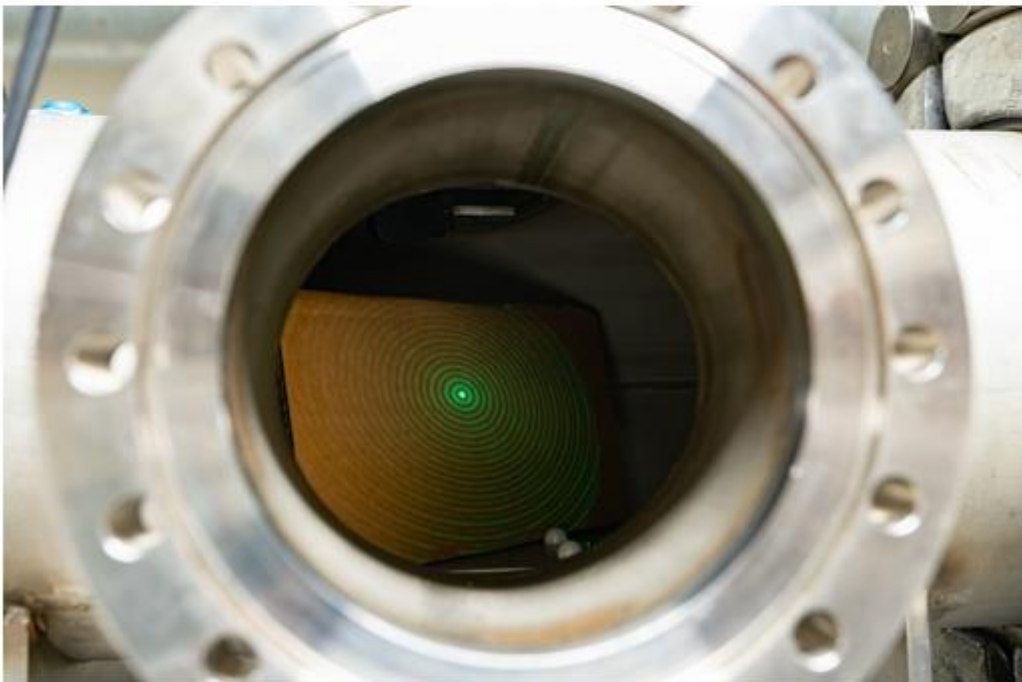
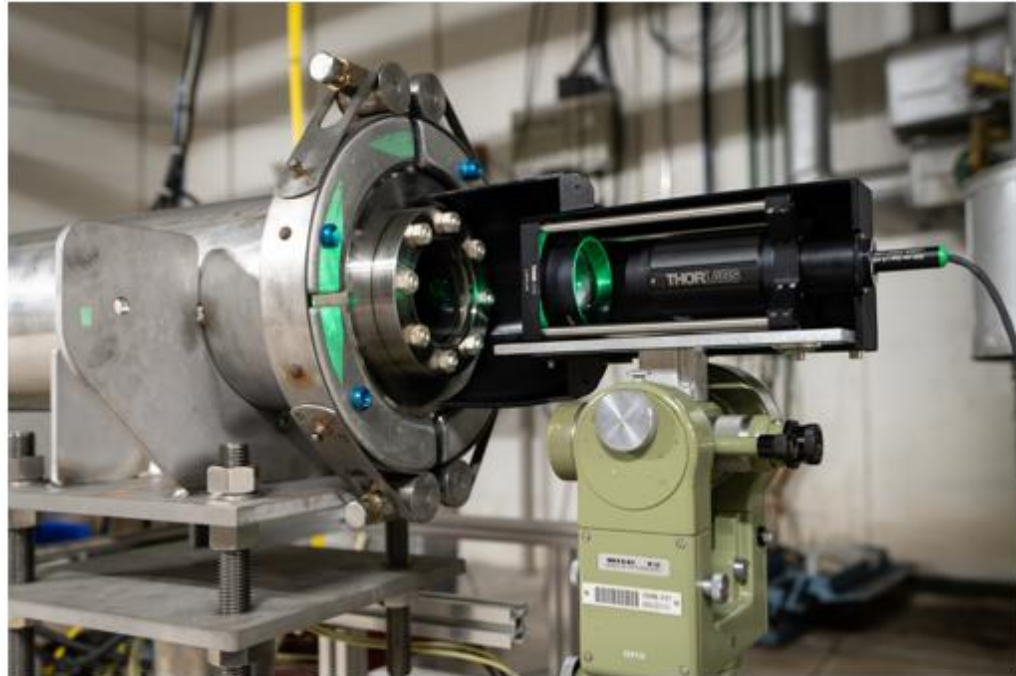
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Precision - Stability of reference



Support and SLB generator

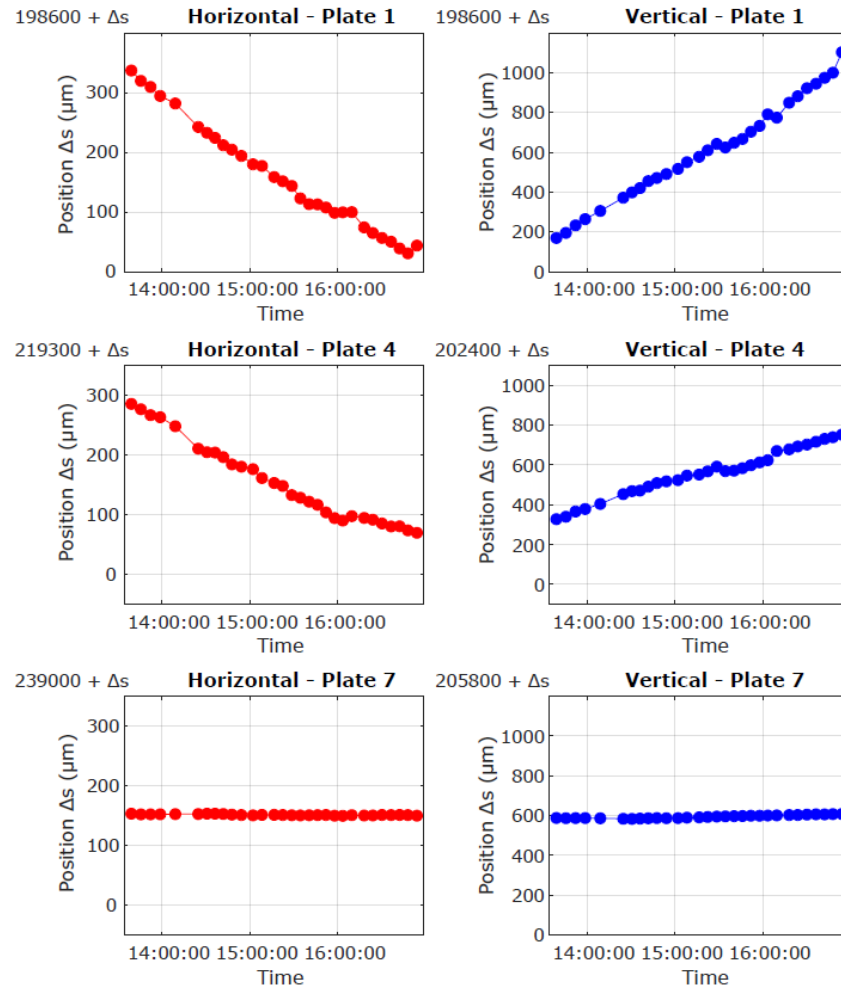
Distance from
the generator

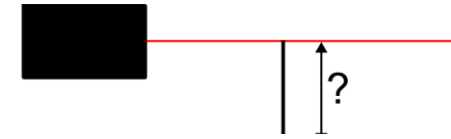
141.9 m

70.2 m

1.9 m

IC position in global CS - drift





Accuracy - Systematic error

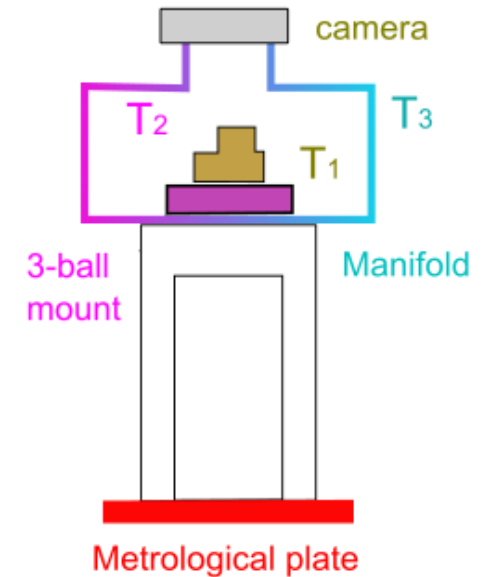
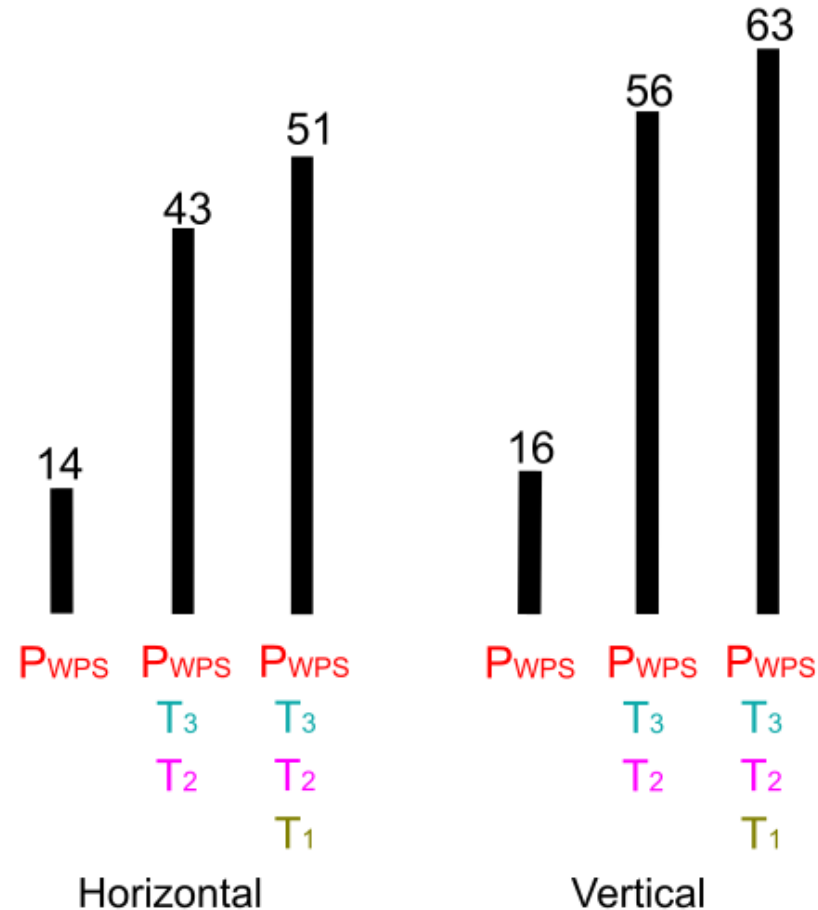
Offset uncertainty (µm)

Position of the IC in global coordinate system
 Uncertainty propagation components

$$IC_{global} = P_{WPS} \cdot T_3 \cdot T_2 \cdot T_1 \cdot IC_{camera}$$

Laser tracker
measurement – two steps

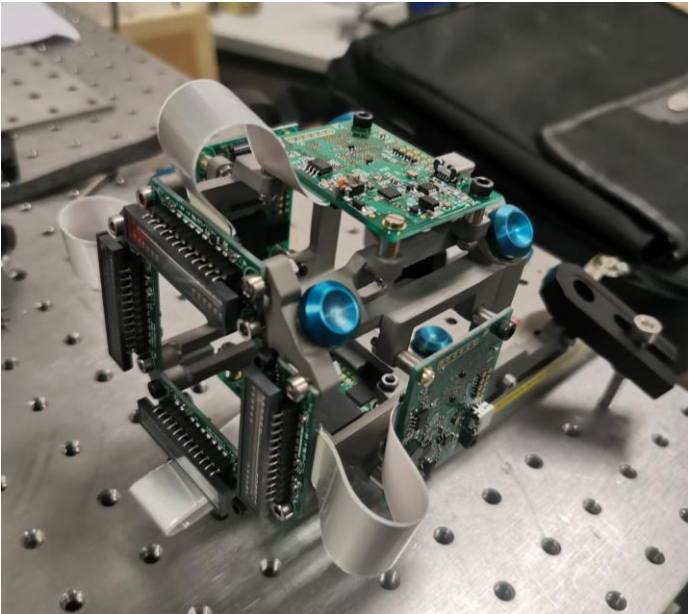
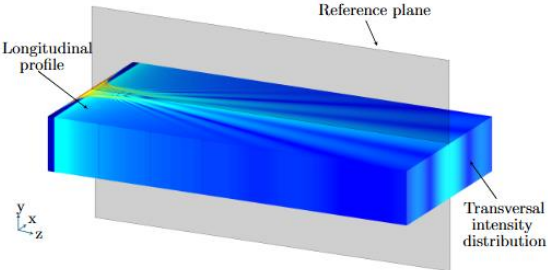
Least-squares (WPS, HLS) network with fiducialisation/calibrations
CMM verified by in-house method



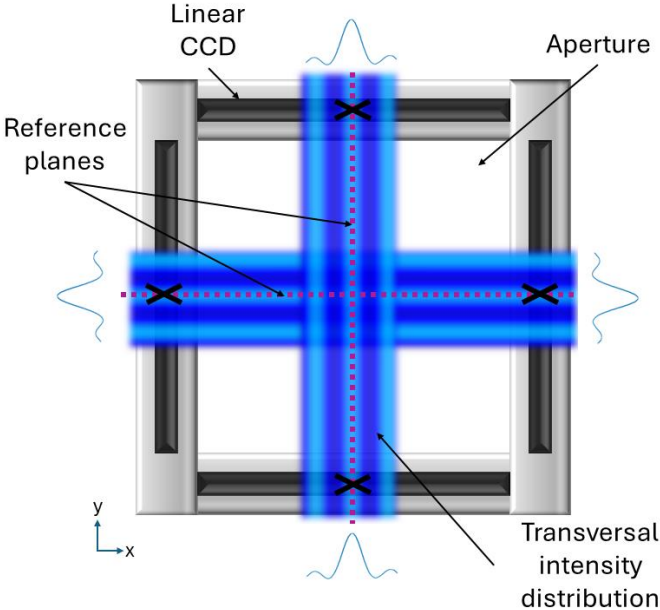
Layer beams – Martin’s Dusek doctorate

- **Layer beams – linear chip sensor**

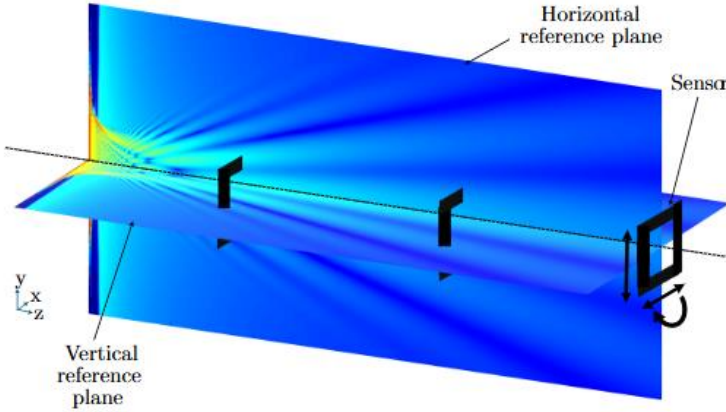
- Prototyping of the sensor with 4 linear CCDs with an aperture (allows for multipoint measurements at one instance in time)
- Position of the CCD sensors will be measured in metrology lab to be ready for future absolute misalignment measurements



Sensor prototype

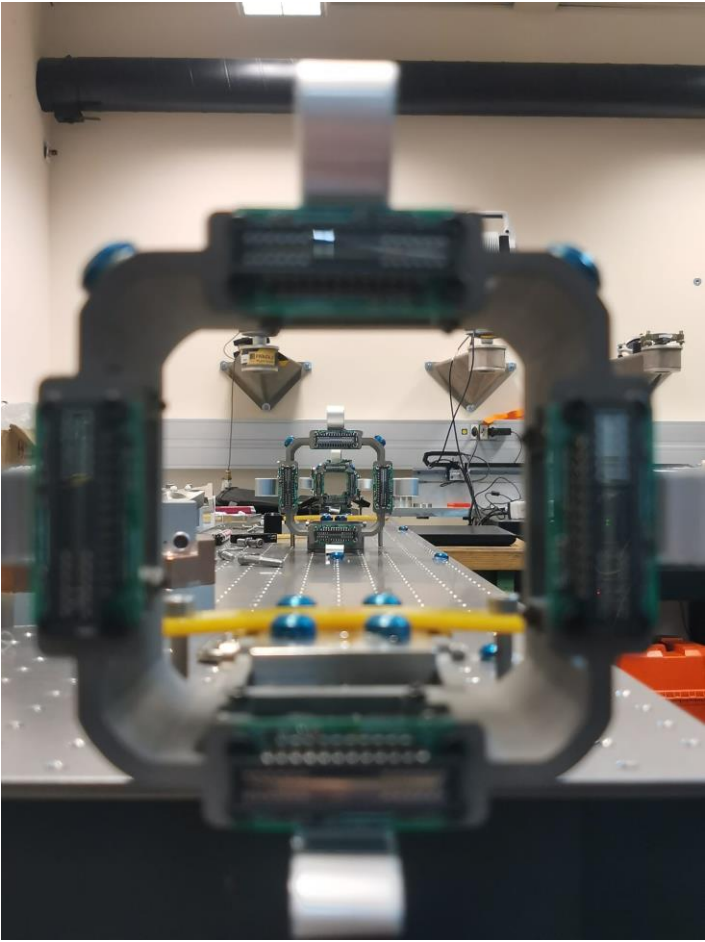


Sensor mockup

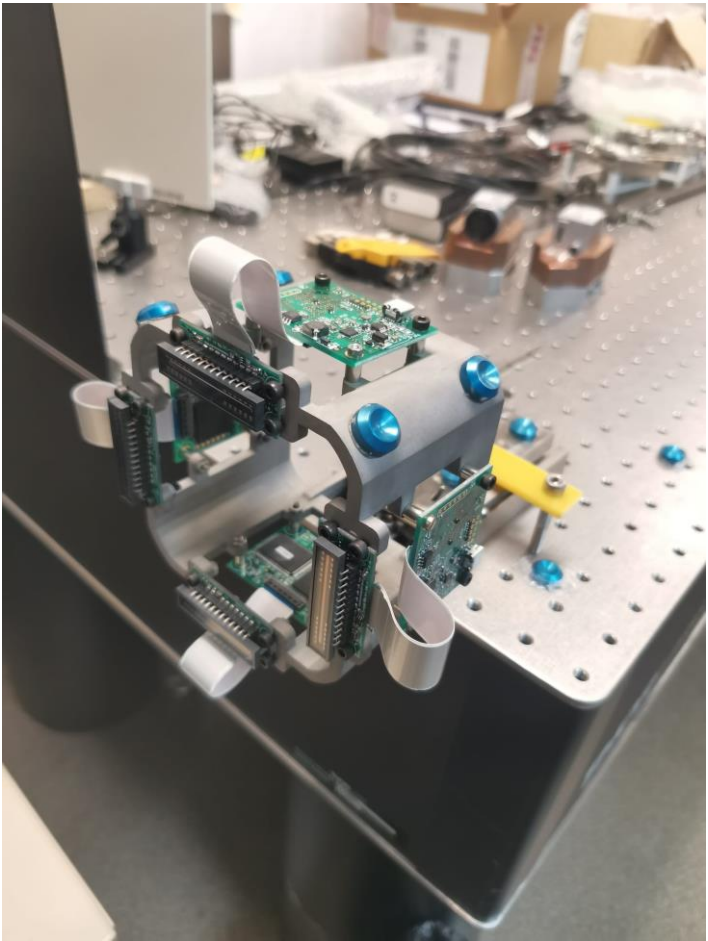


Reference planes created by a Layer Beams

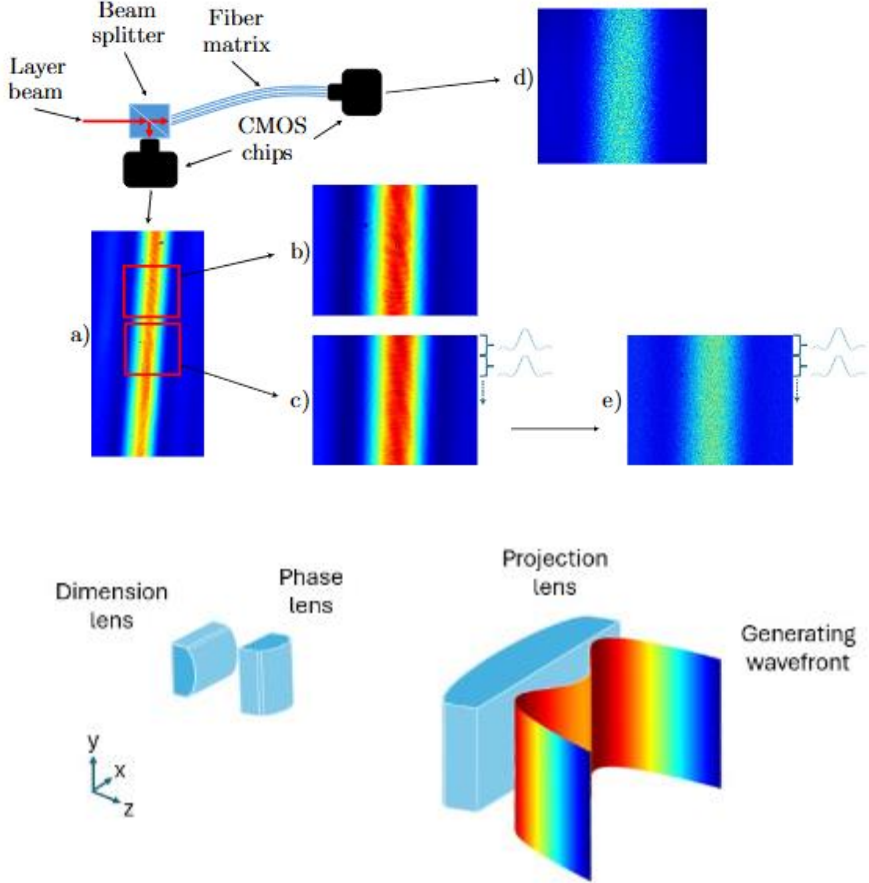
Layer beams – Martin’s Dusek doctorate



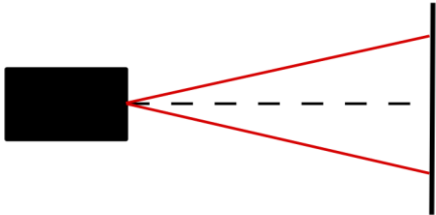
Laboratory setup



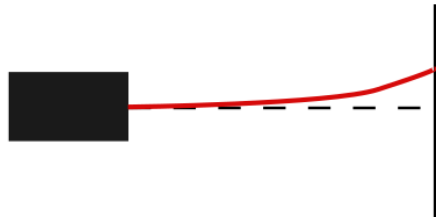
Sensor mockup



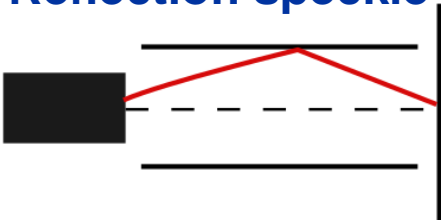
1. Laser divergence



2. Atmospheric refraction

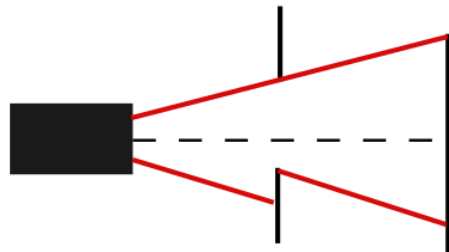


5. Reflection speckle

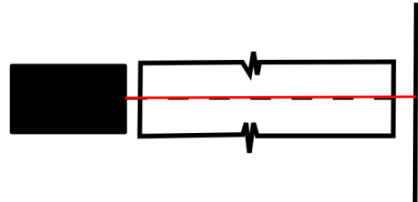


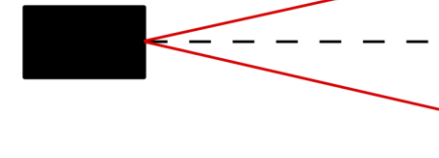
Project challenges and solutions

3. Symmetry breaking

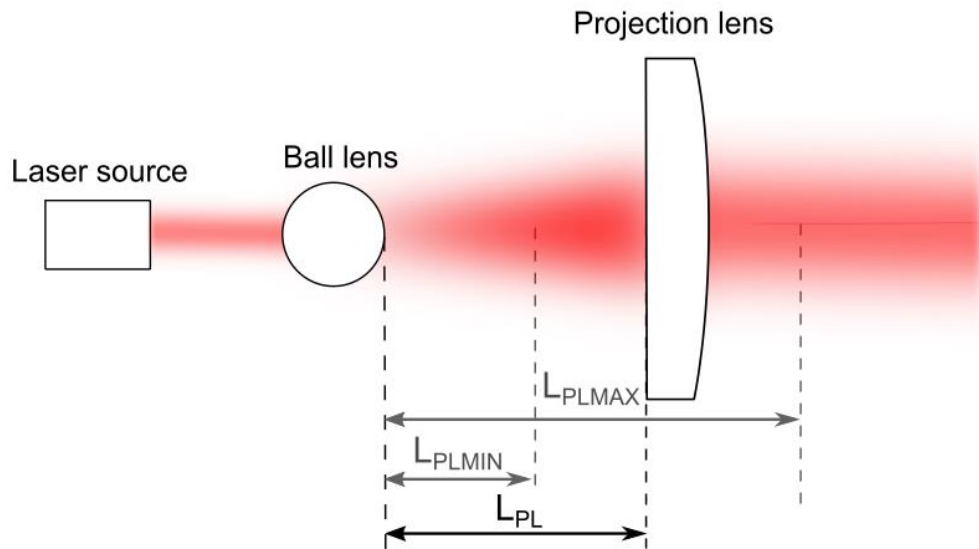


4. Vacuum forces

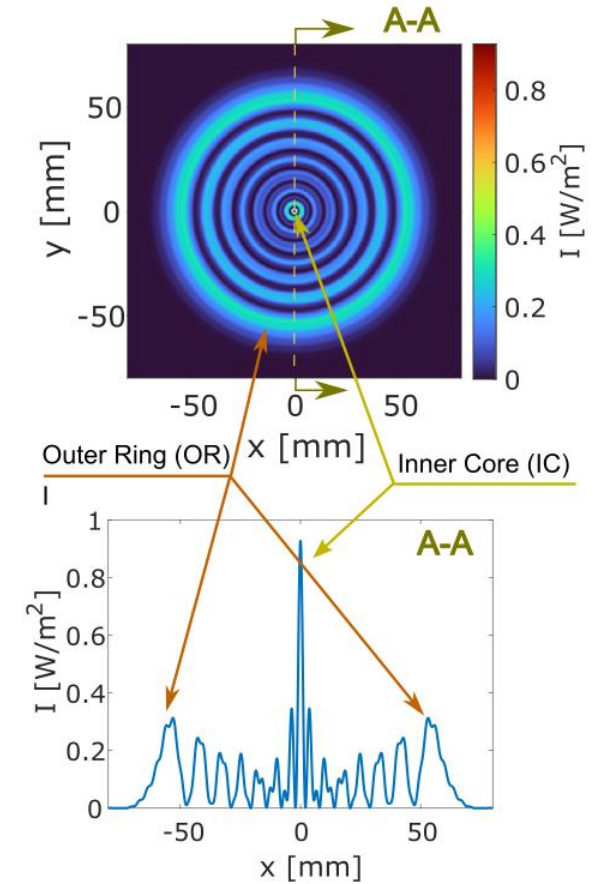
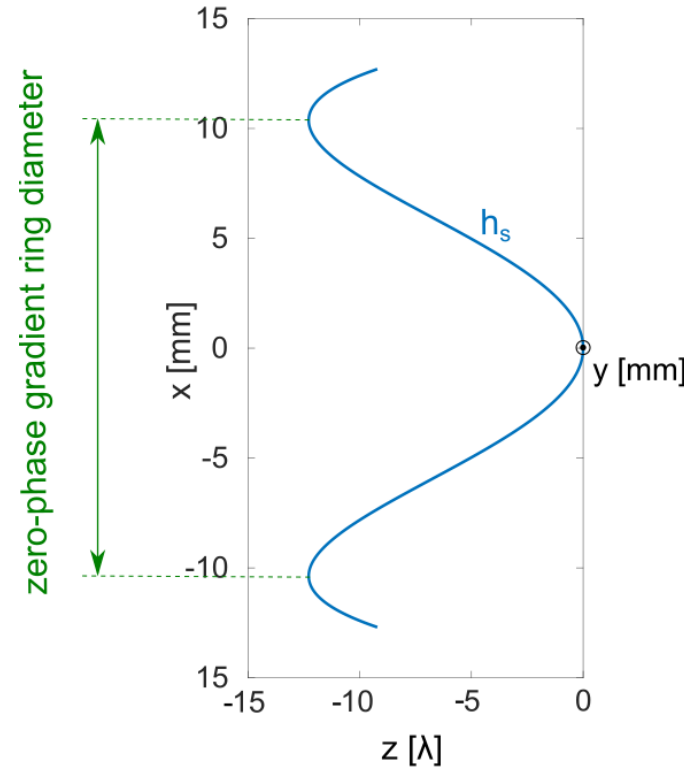


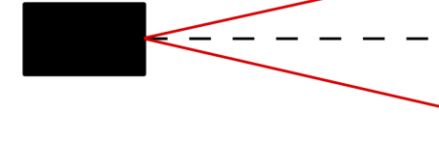


Generator, intensity profile and wavefront

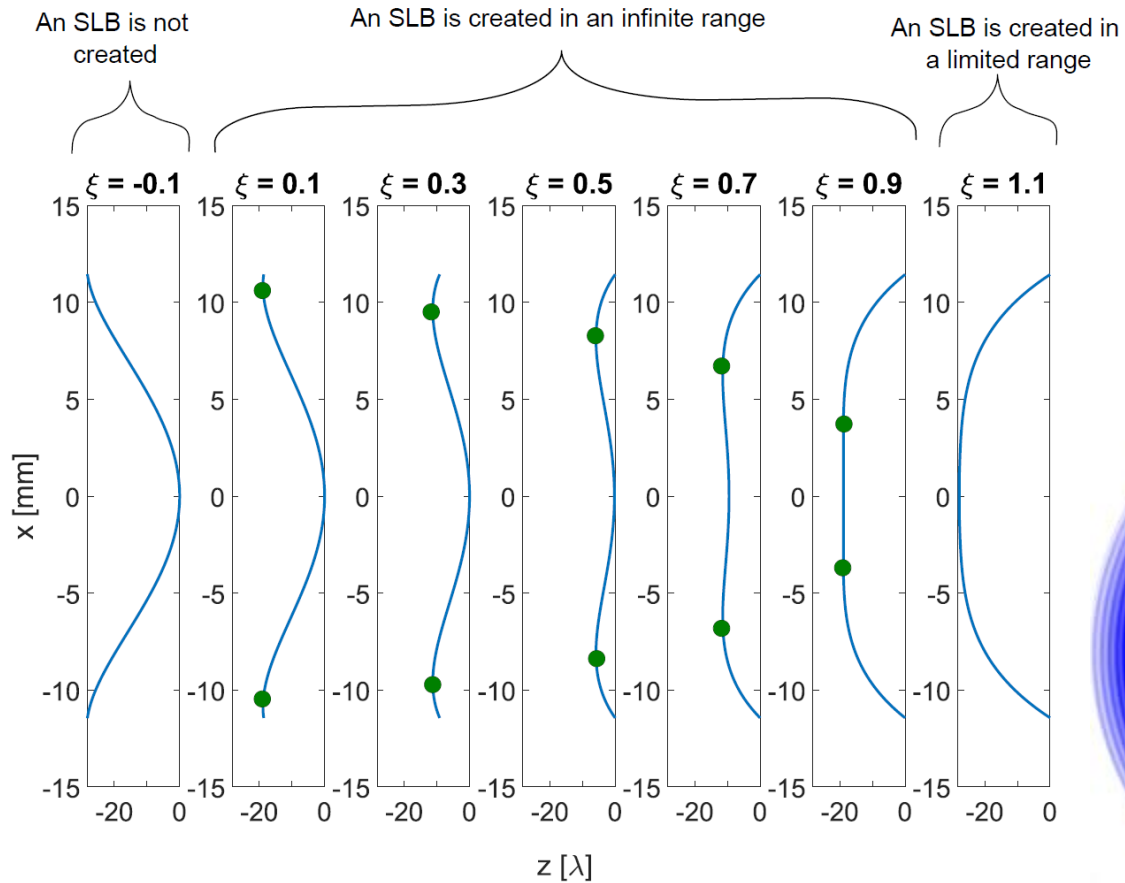


$$L_{PL} = L_{PLmin} + \xi(L_{PLmax} - L_{PLmin})$$



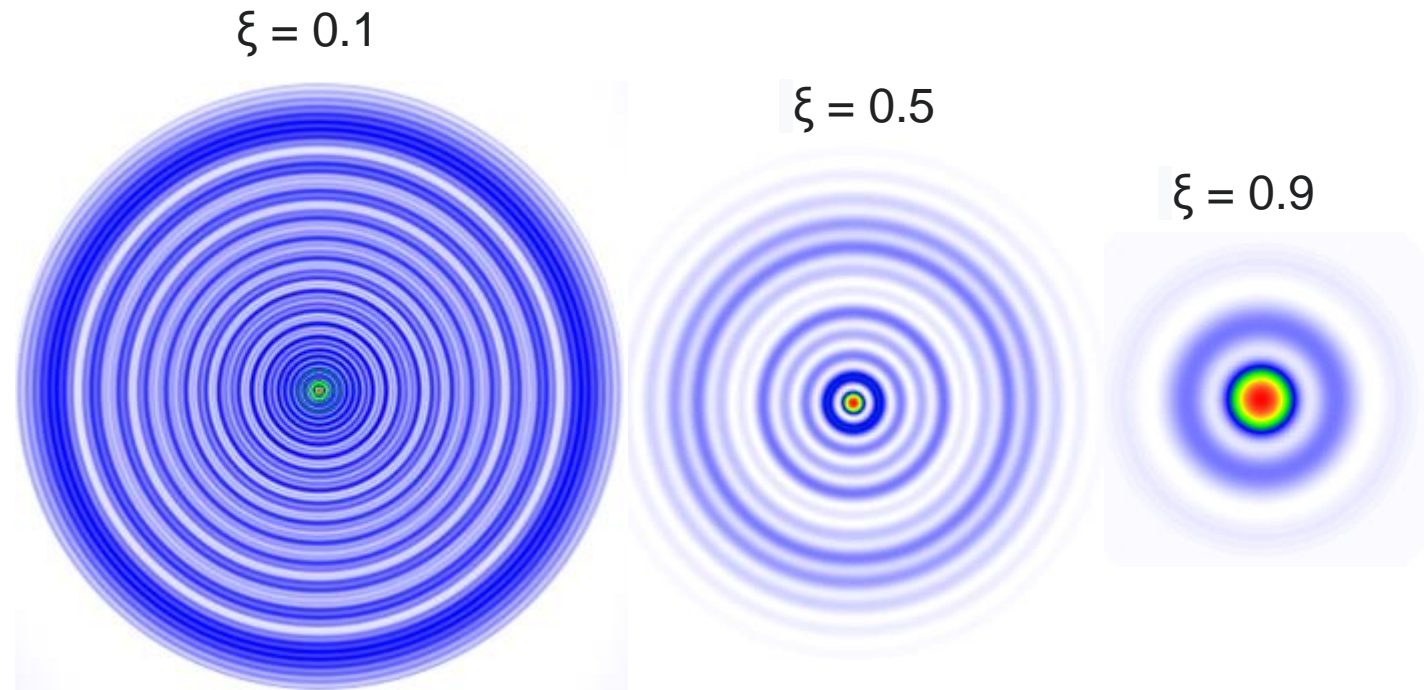


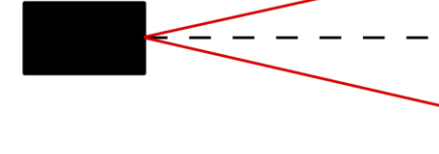
Wavefront and profile



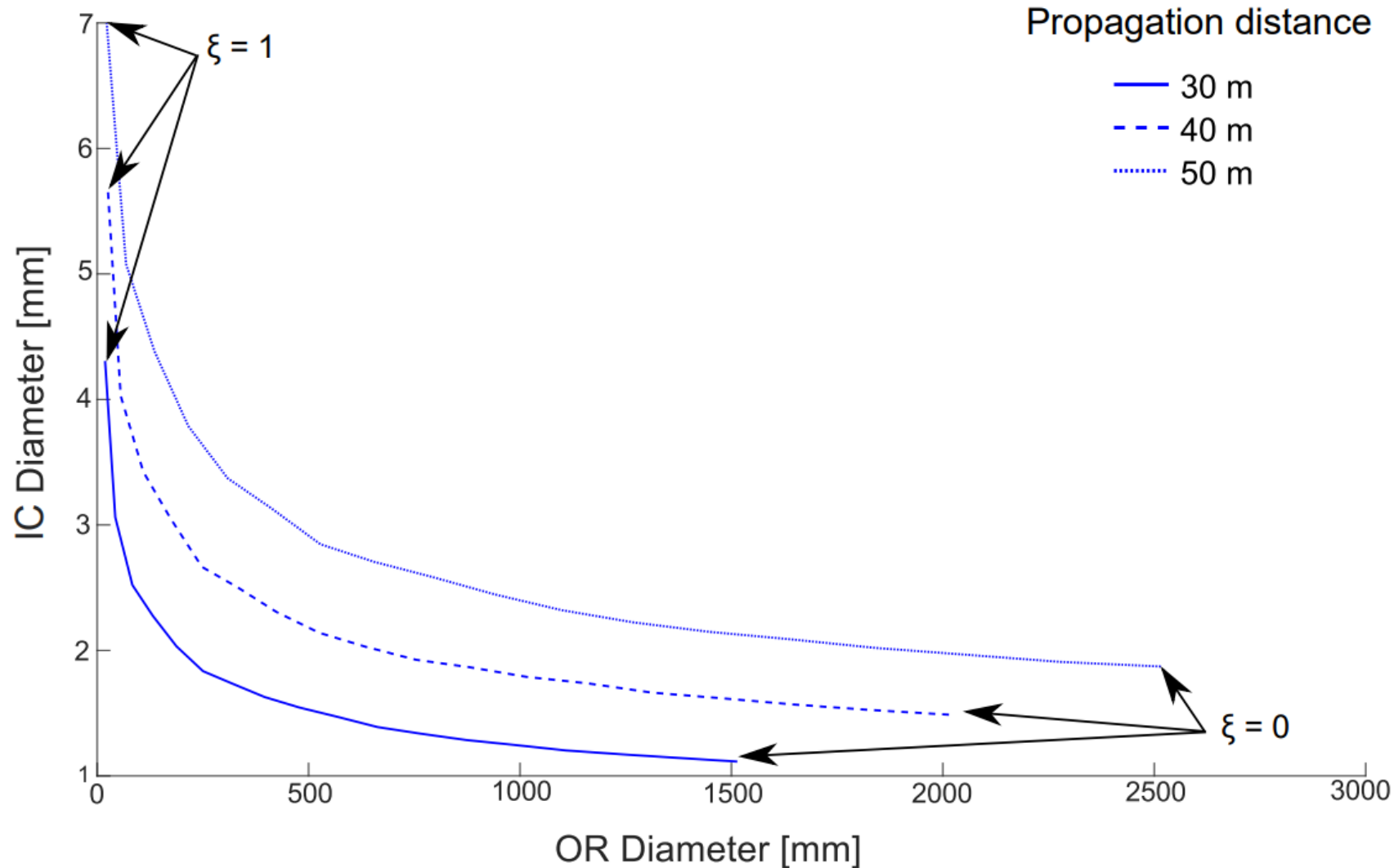
Large zero-phase gradient ring:

- Small IC
- Large OR

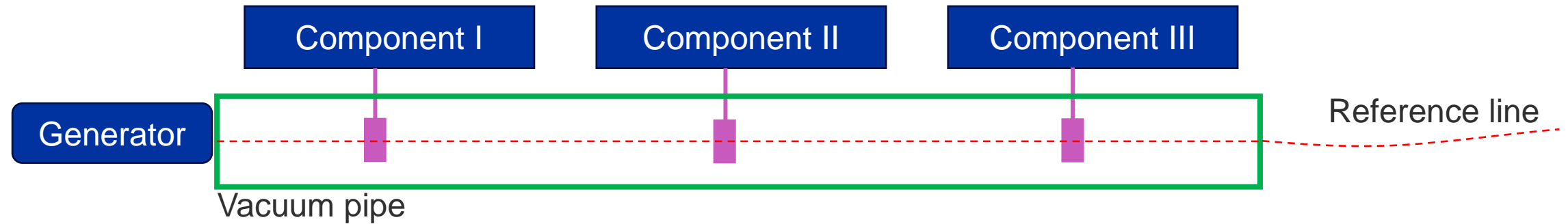
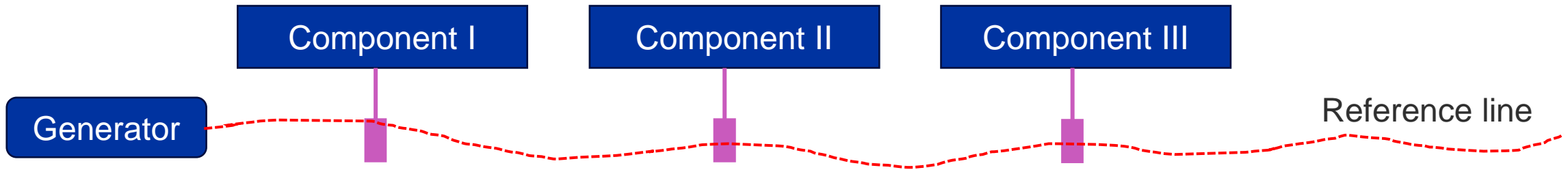
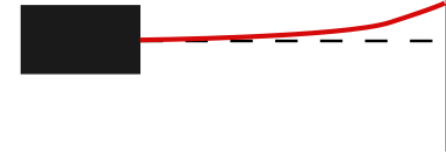




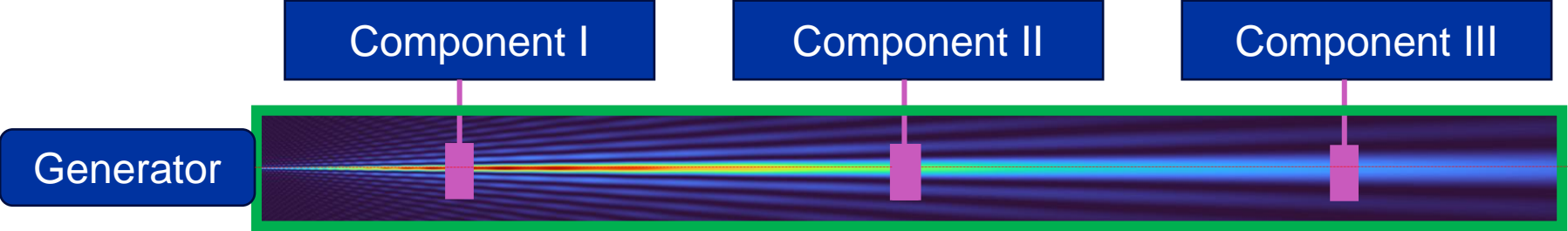
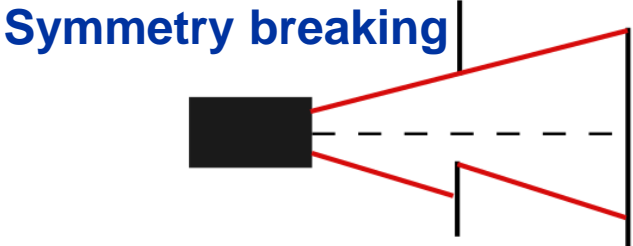
Inner Core and Outer Ring diameters



Refraction and Vacuum

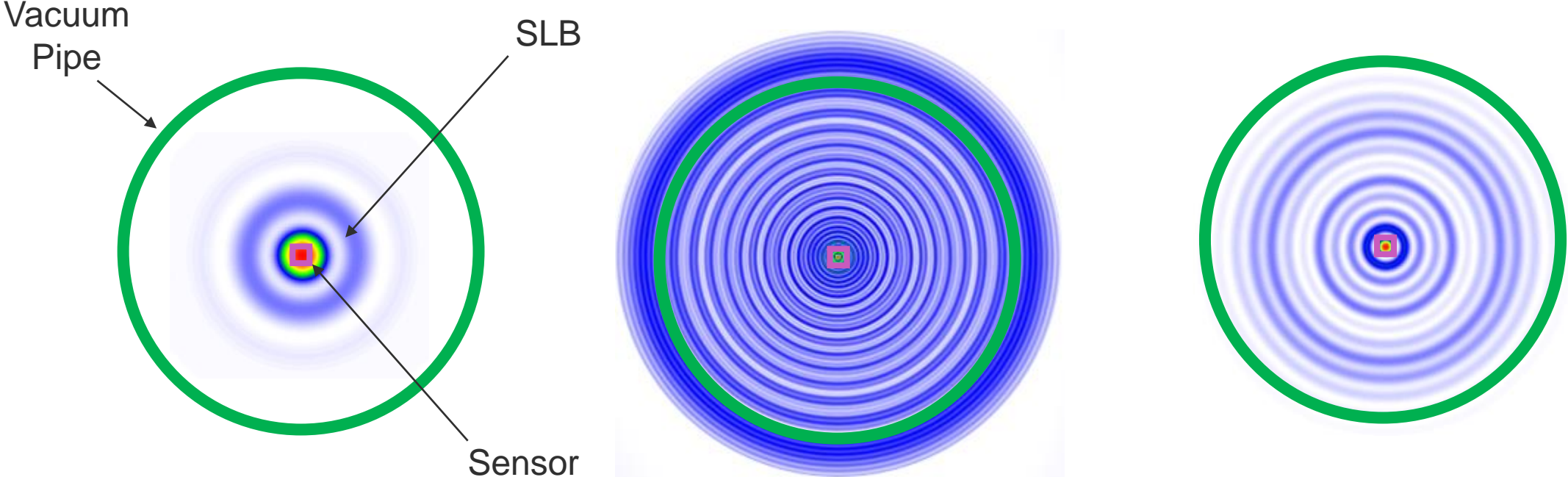


Symmetry breaking - Vacuum pipe



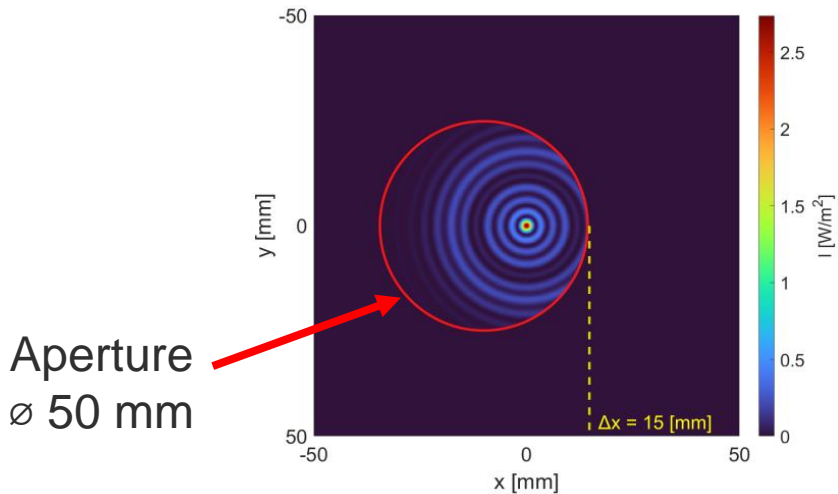
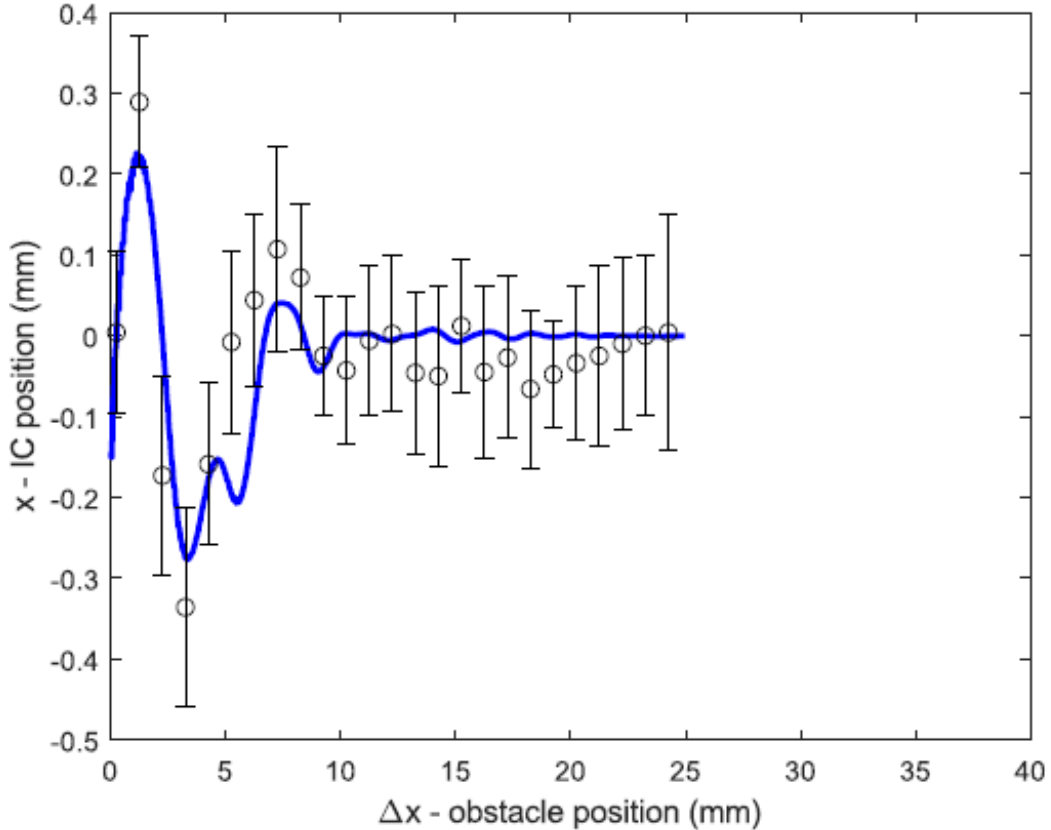
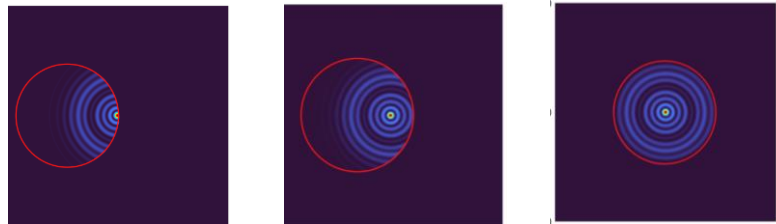
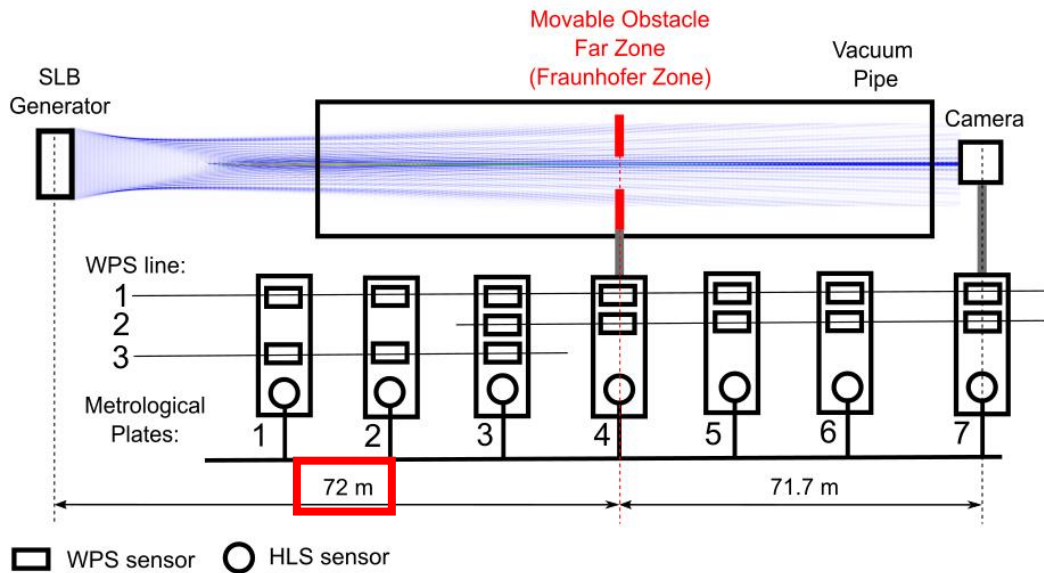
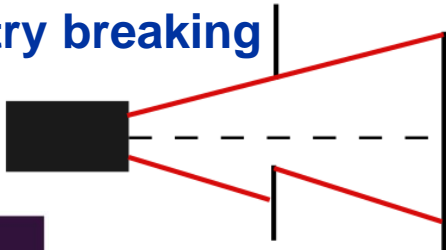
Reference line

Inner Core and Outer ring vs Vacuum Pipe and Sensor size



Symmetry breaking - Far zone

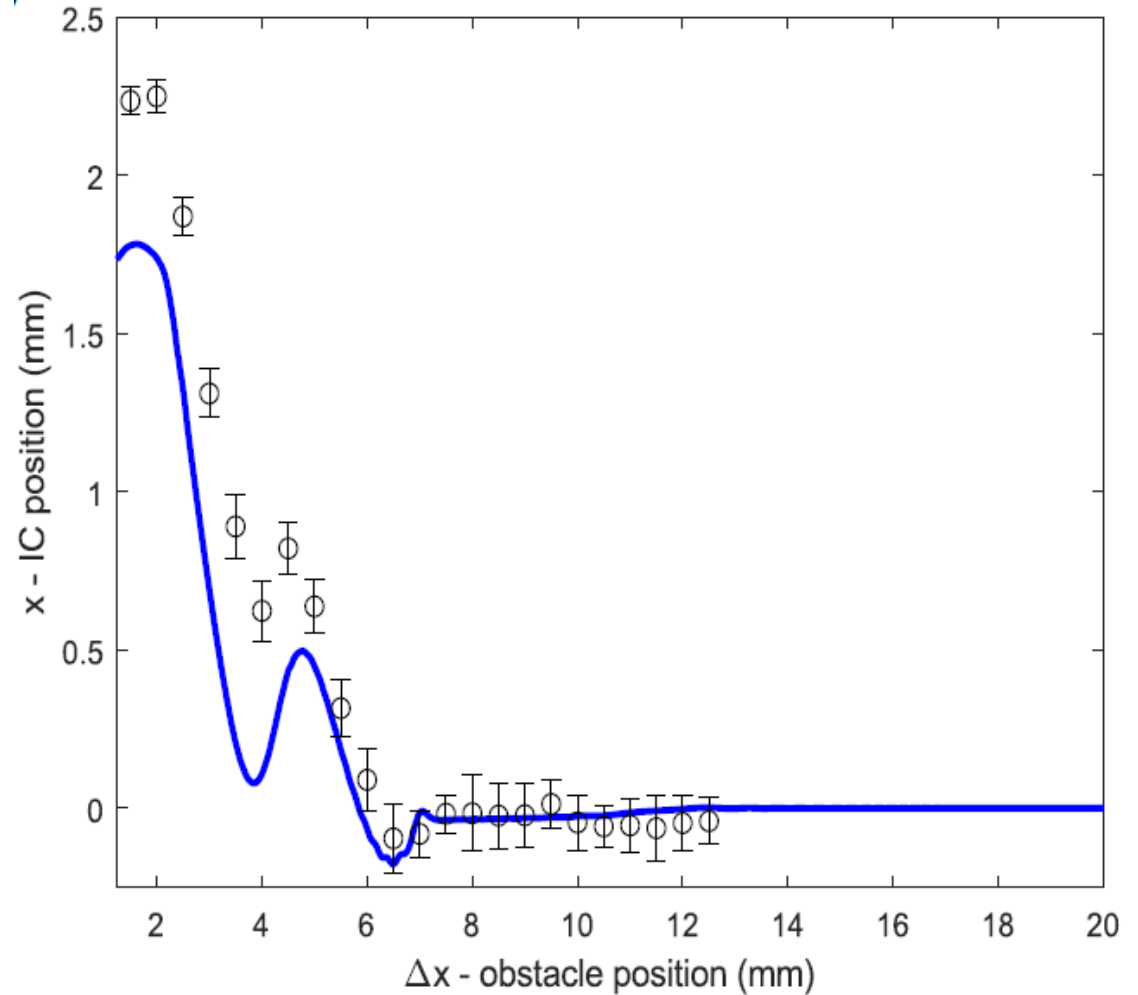
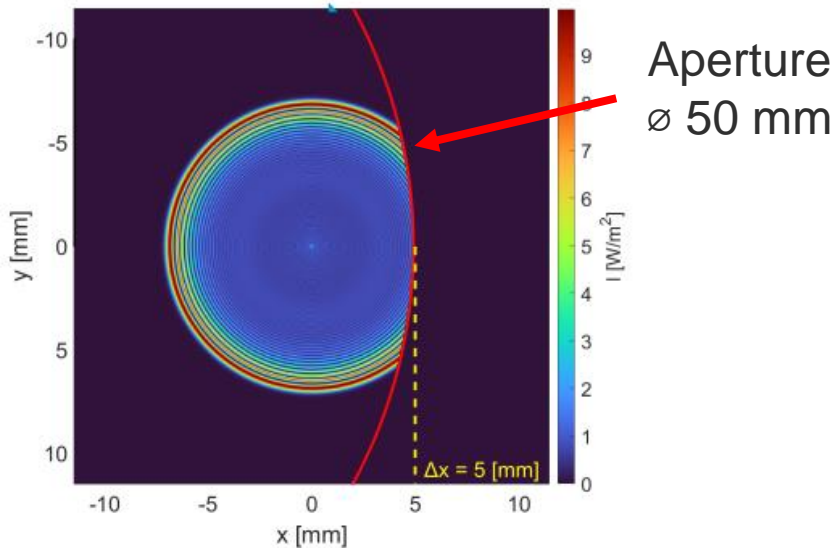
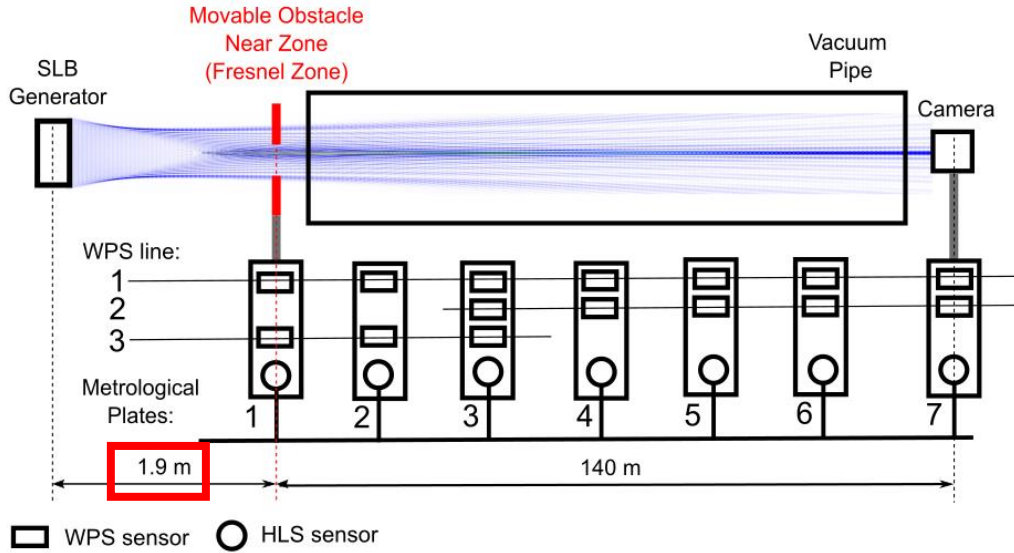
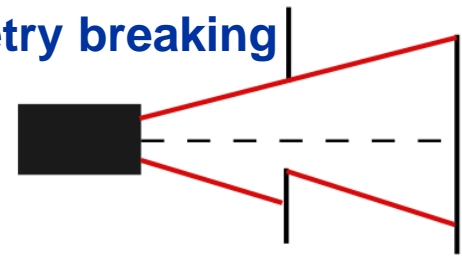
Symmetry breaking



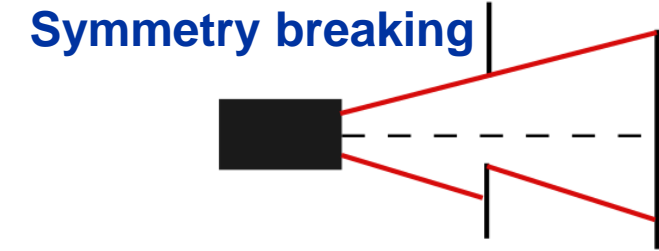
Aperture
∅ 50 mm

Symmetry breaking - Near zone

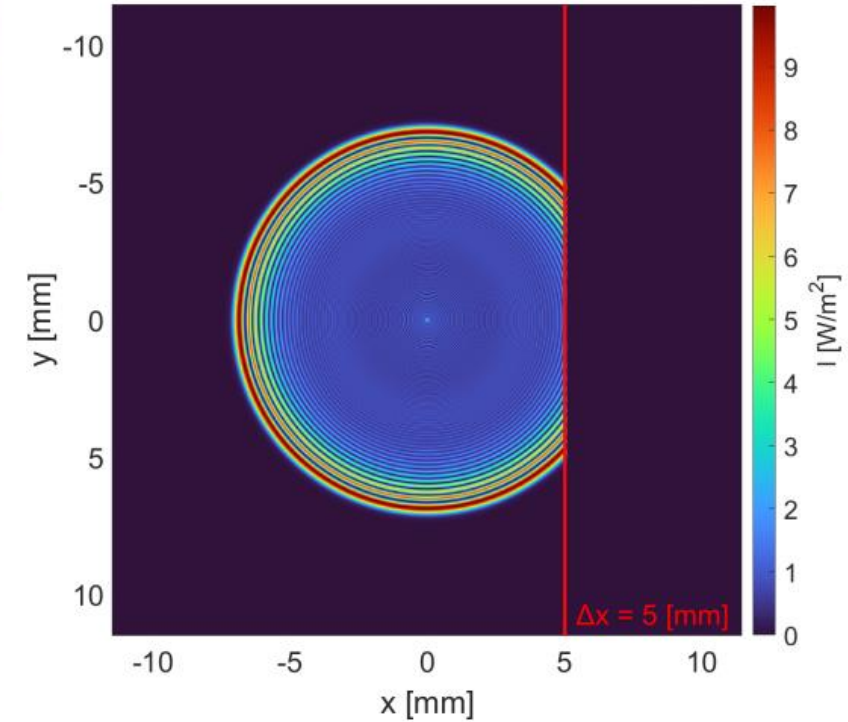
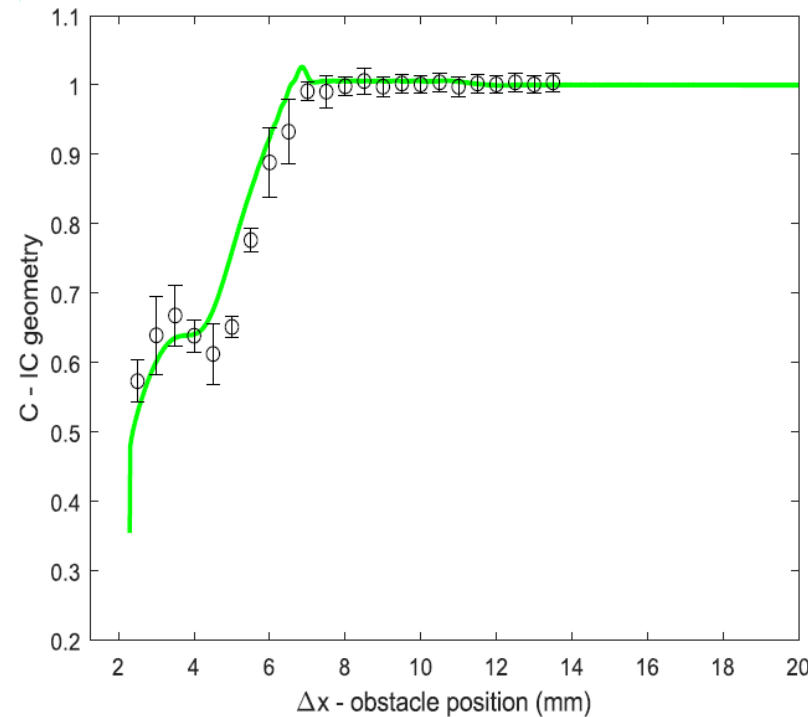
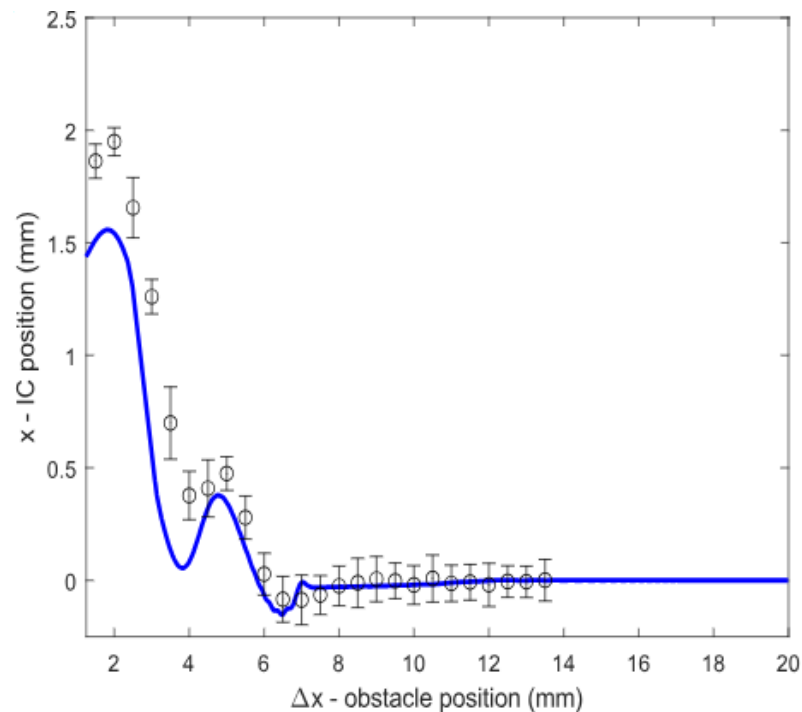
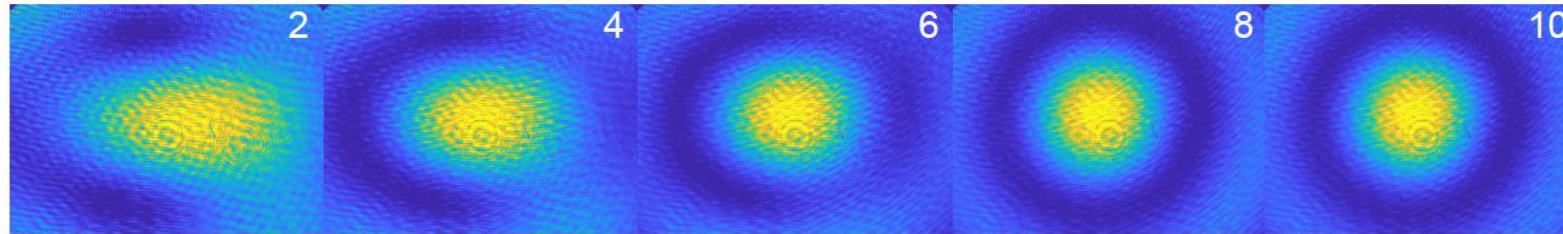
Symmetry breaking



Symmetry breaking - IC deformation

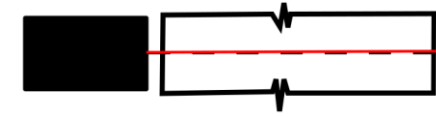


Δx - obstacle position (mm):

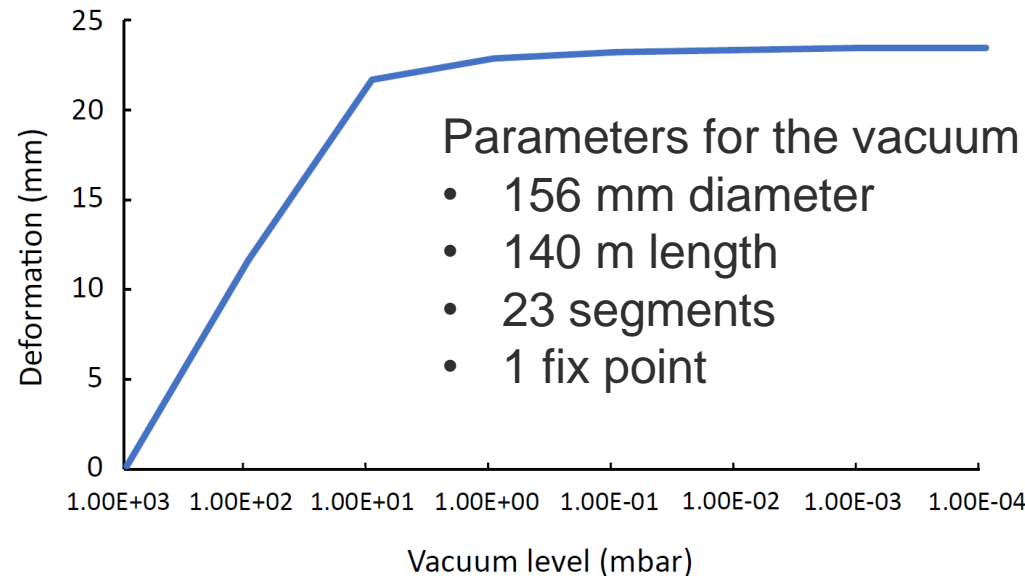
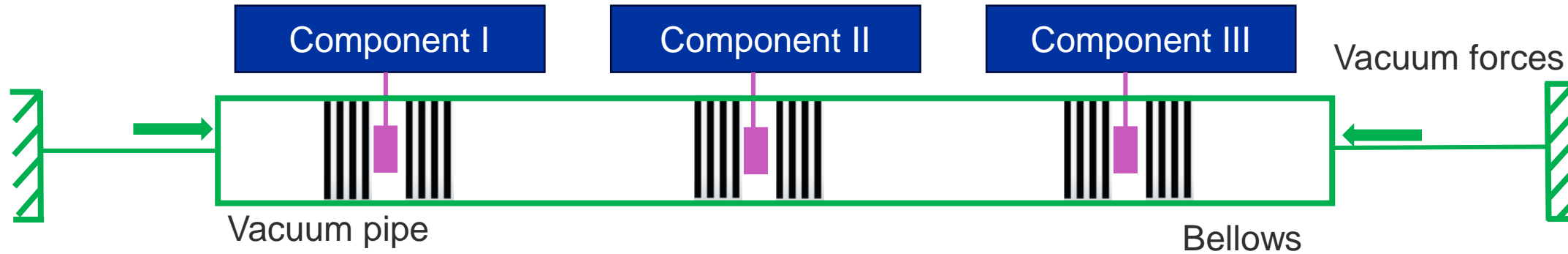


Rectangular obstacle
in the near zone

Vacuum forces - System defromation

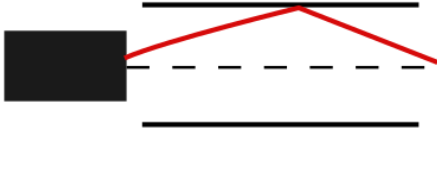


Constraint on the mechanical link between the vacuum system and measured components

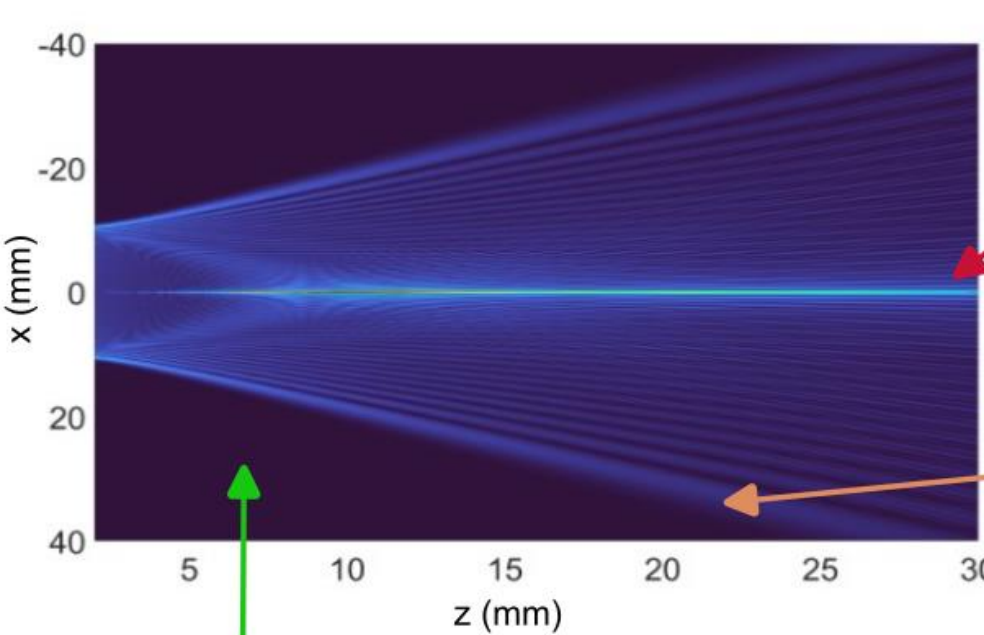


Source of reflection - Speckle

Reflection speckle

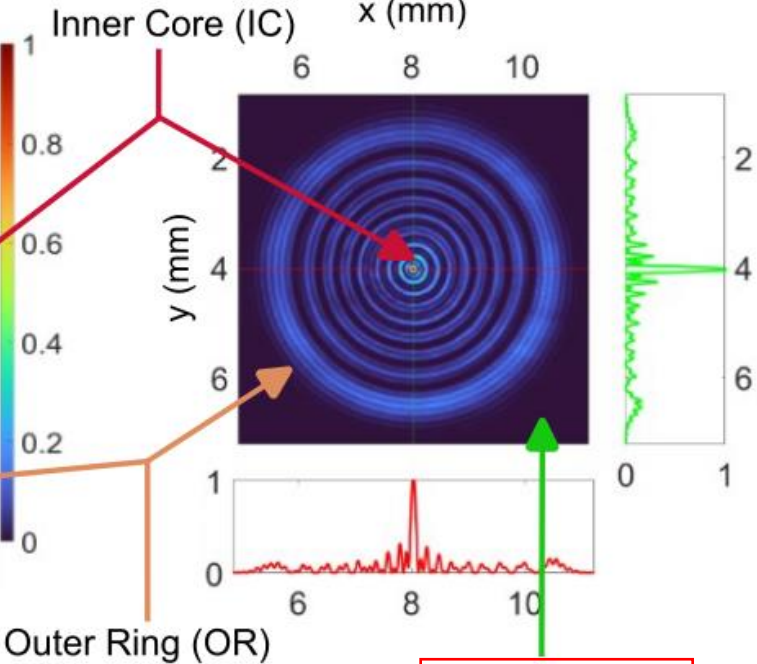


SLB longitudinal intensity profile



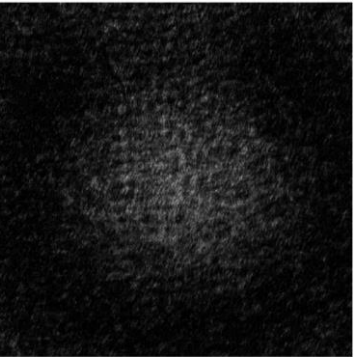
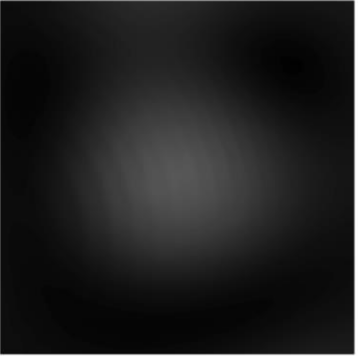
Stray light

SLB transverse intensity profile



Stray light

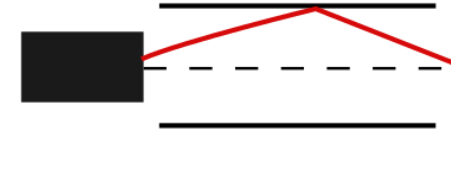
Propagation in free air
140 m



Propagation in vacuum
pipe 140m

Reflection reduction - Methods

Reflection speckle



Pipe

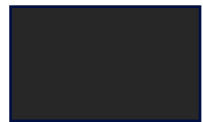
Laser

Color

Structure

Temporal coherence

Spatial coherence



Black



Rough Baffles



Wavefront (t)



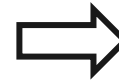
Wavefront (t)



Black undulated



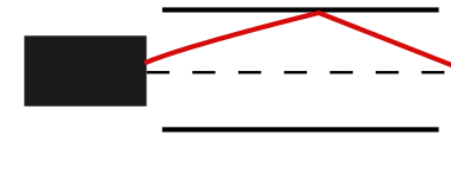
He Ne laser



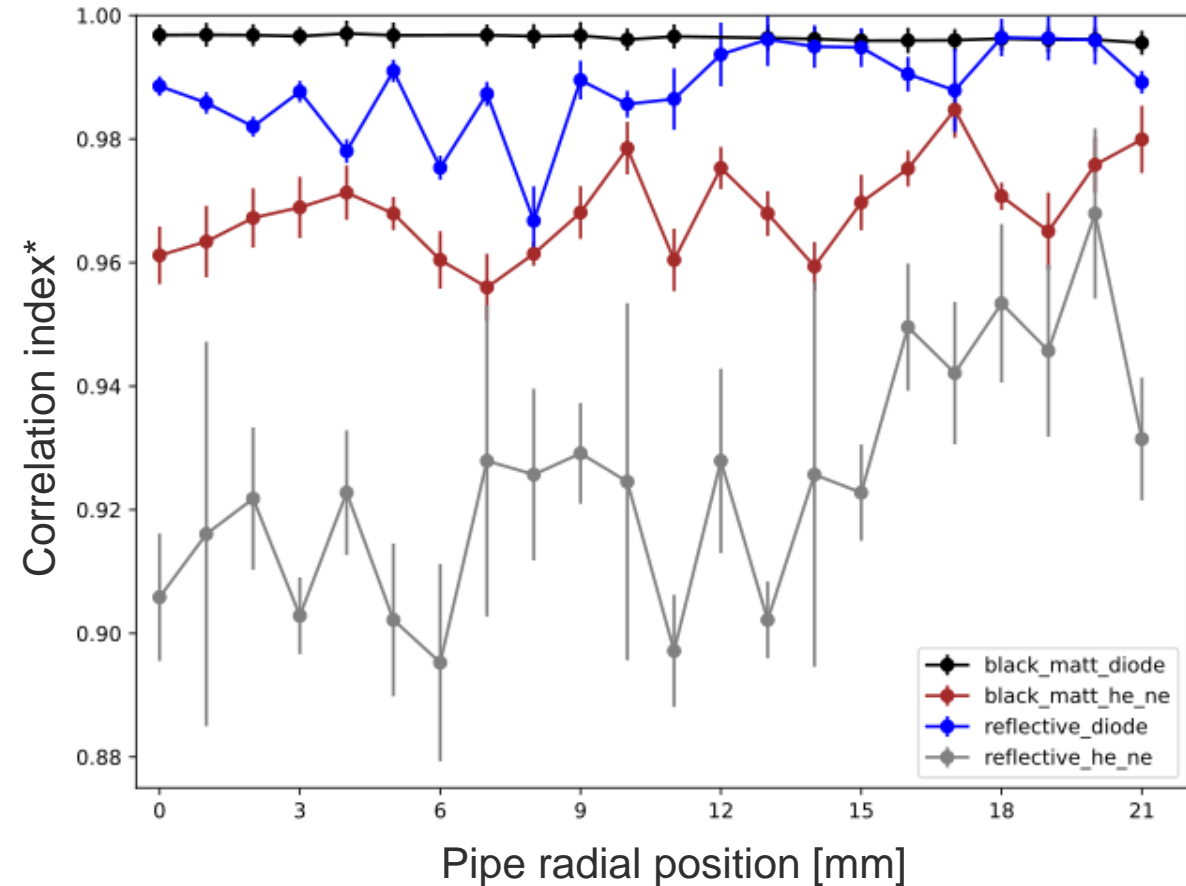
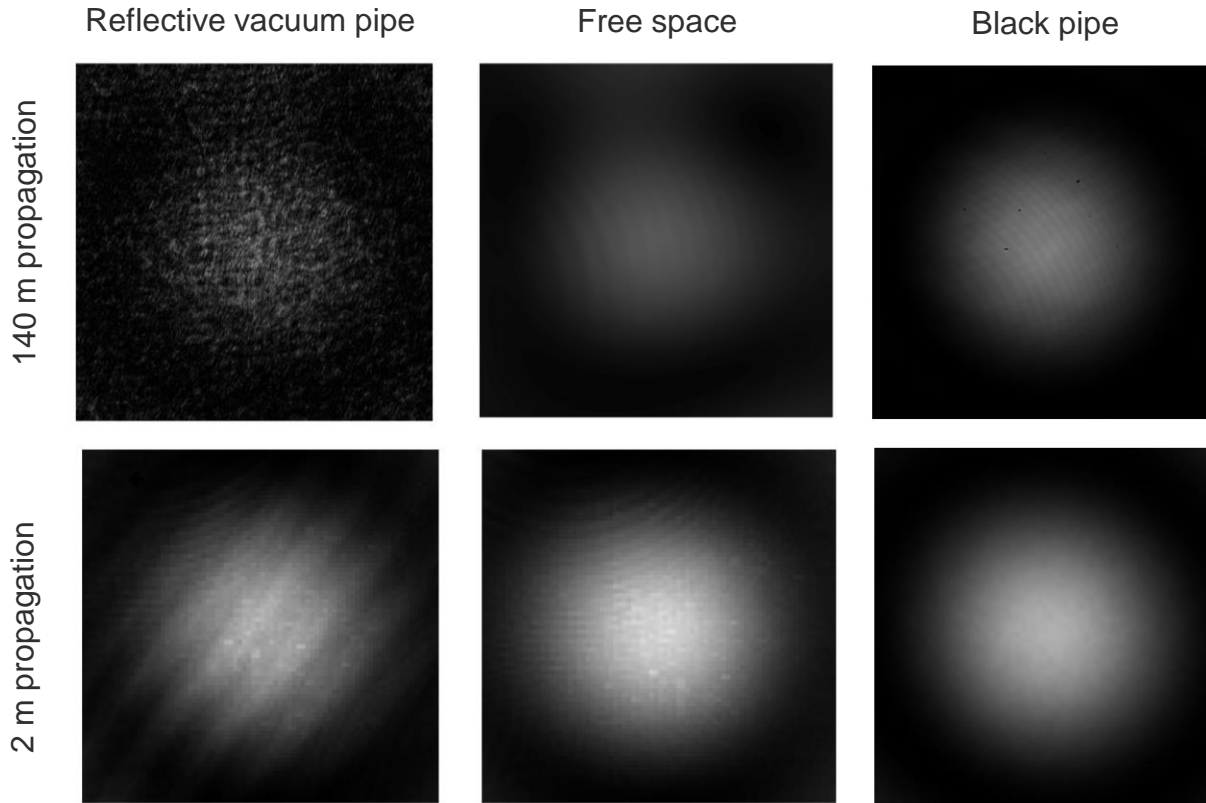
Laser Diode

Reflection reduction - Results

Reflection speckle

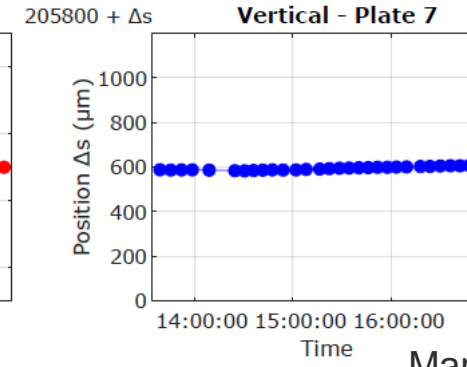
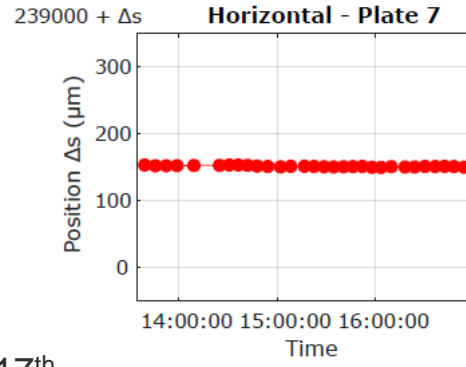
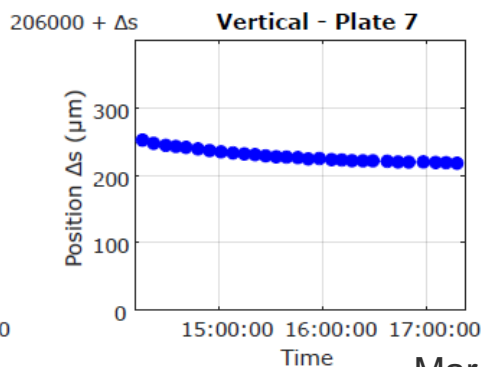
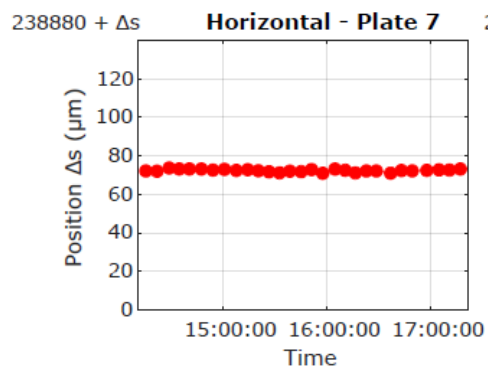
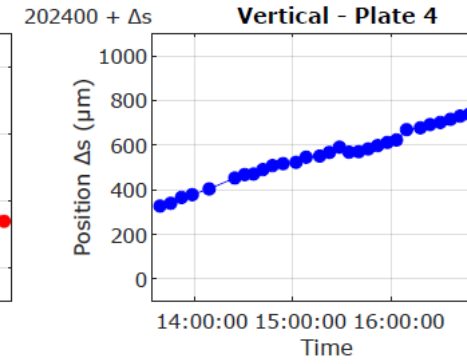
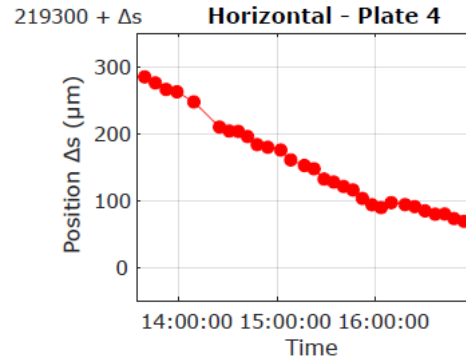
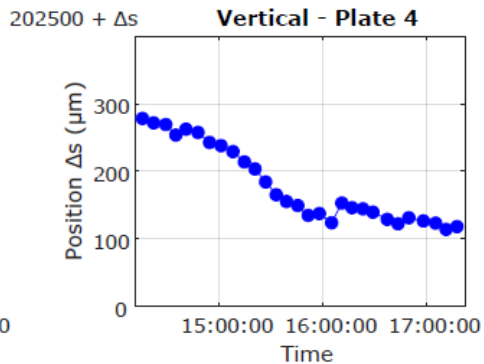
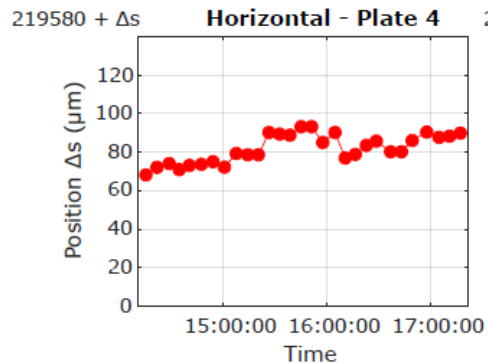
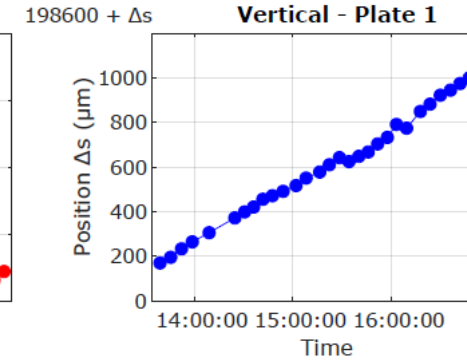
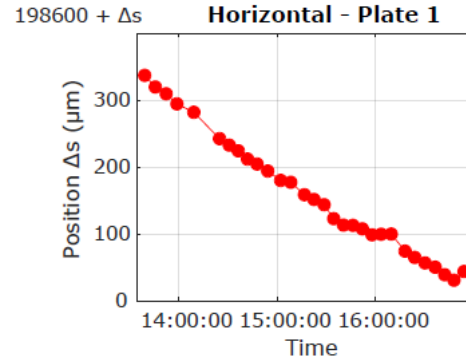
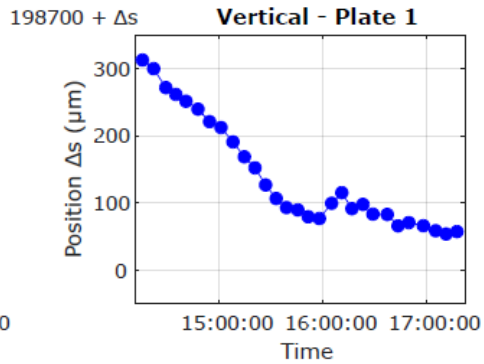
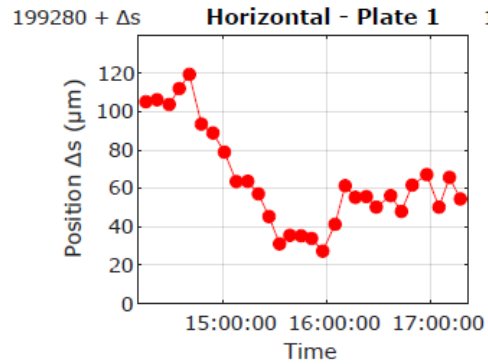
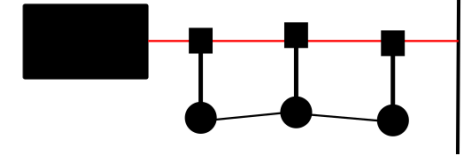


Inner Core



Correlation index* - Structure Similarity Index Measure (SSIM) between photos in free space and in the pipes (test at 2 m)

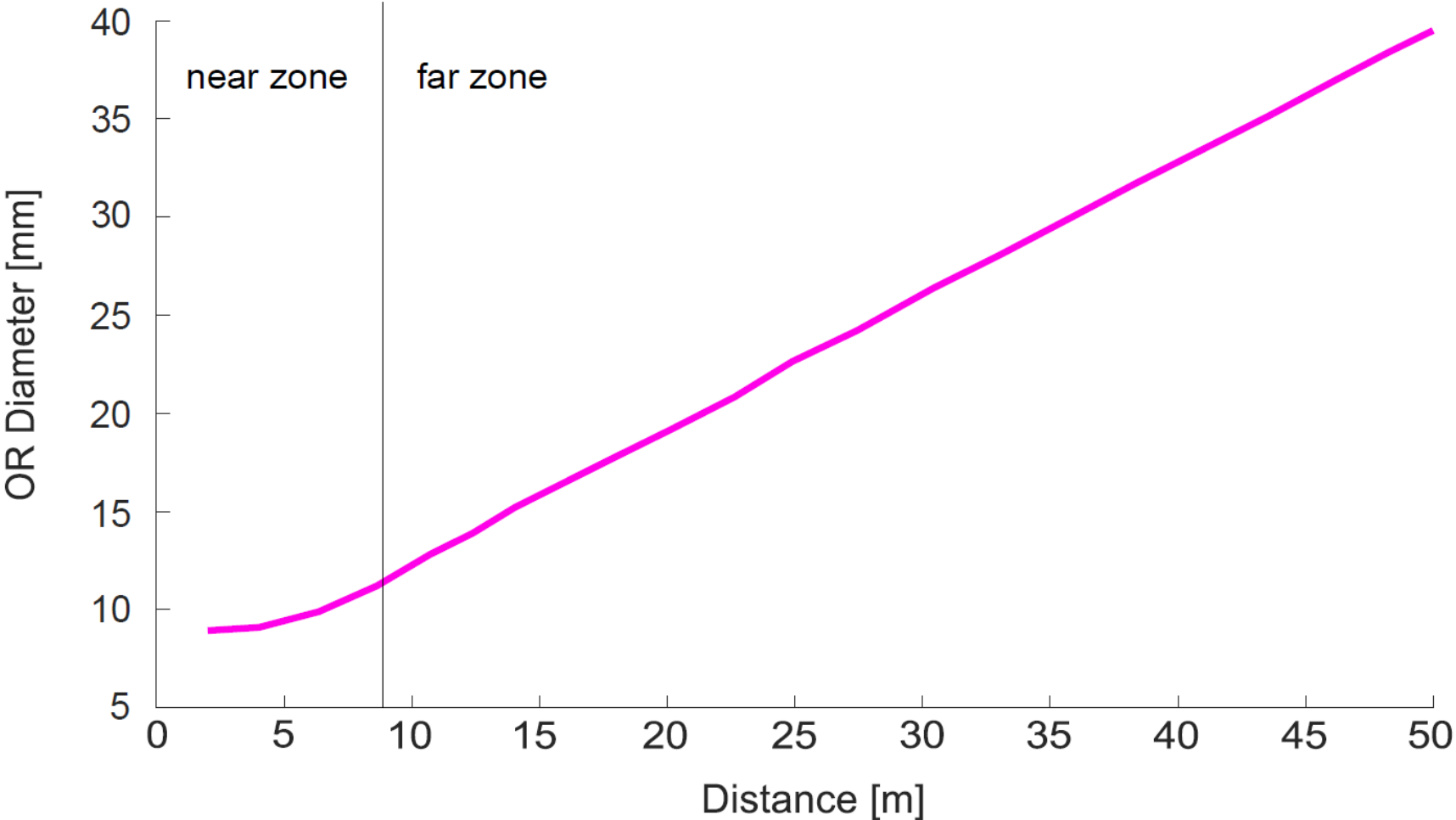
IC position in global CS - drift



Mar 17th

Mar 24th

Near and far optical zones



Add the wavefront

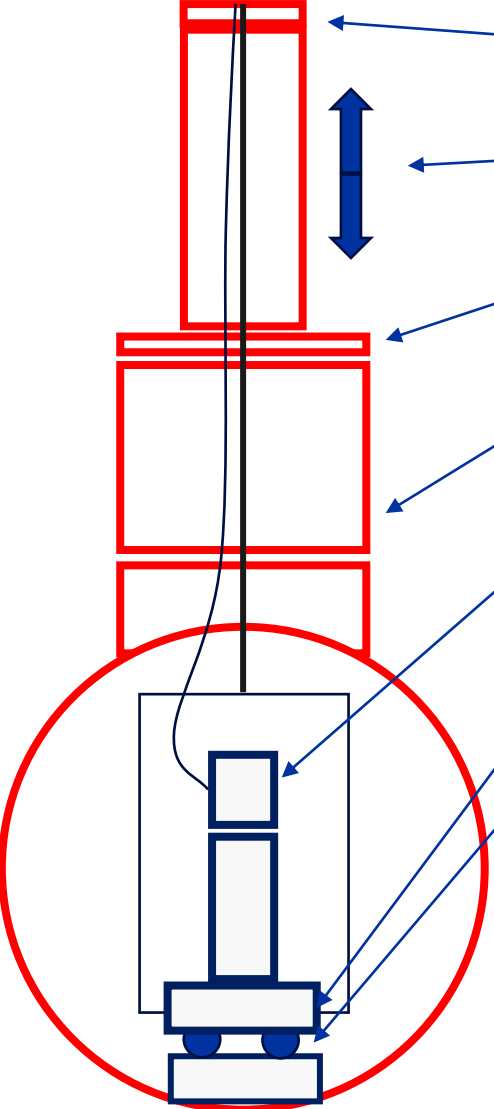
Laser alignment systems - elsewhere

Institute*	Date	Divergence mitigation	Light sensor	Refraction mitigation**	Expected accuracy	Current state	
SLAC	1960 – now partialy	Fresnel plates Poisson pattern	Manual readout	Vacuum 1.333 Pa	250 microns 3,2 km	2/3 of length disassembled	Test with classical methods Accuracy 5mm-3.2km 0.23mm-1.5
KEK	1990 - 2010	Fresnel plates Airy pattern	Quadrant Photodiode	Vacuum 1 Pa	100 microns 500 m	Non-operational	Lack of testing method relative 0.1 on 268 m
DESY	2000 - now	Poisson pattern	CCD camera	Vacuum 10 Pa	200 microns 600 m	Operational	Relative 25 and 50 microns just by moving. Accuracy 0.18mm – 500 m there are 3 systems with differe lenght

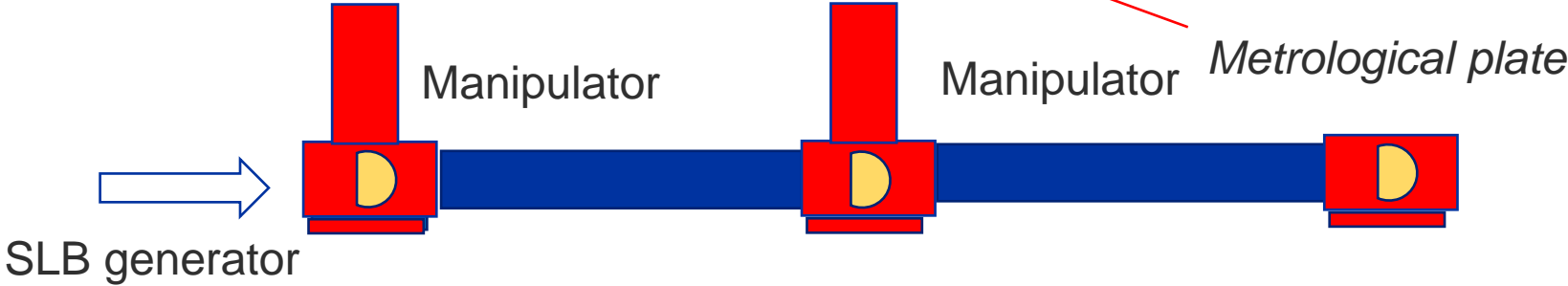
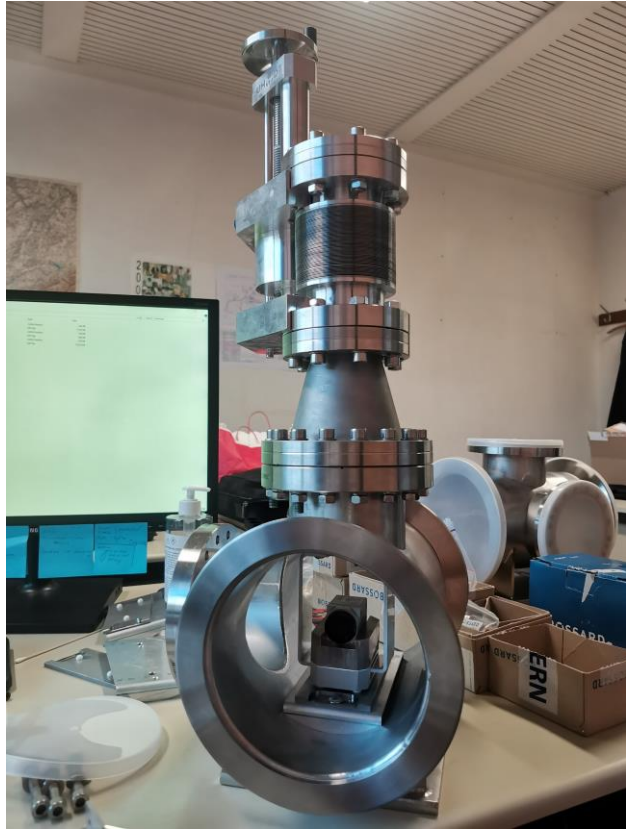
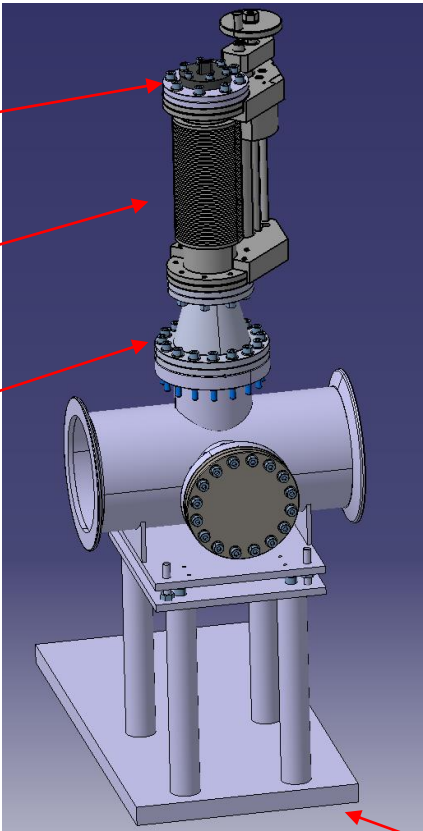
* The works on the laser alignment systems were also conducted at: SPring, CERN, CSNS, Dubna, Argonne and Nikhef

** Standard atmosphere (atm) is defined as 101 325 Pa

Shutter system principle

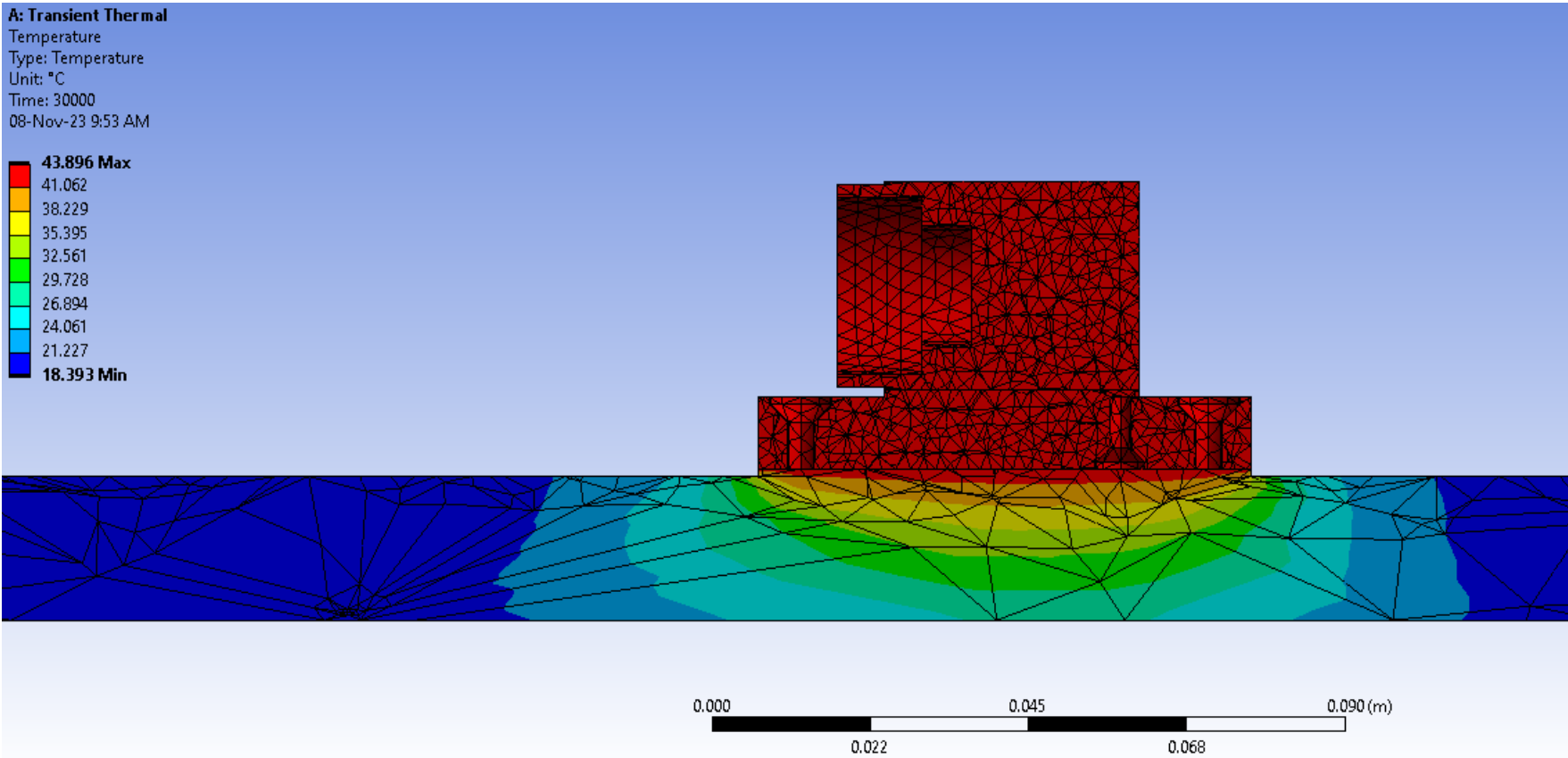


- Feedthrough
- Manipulator
- Adapter flanges
- Extension
- Camera
- Groove
- Kinematic mount



Setup side view

Heat dissipation - simulation



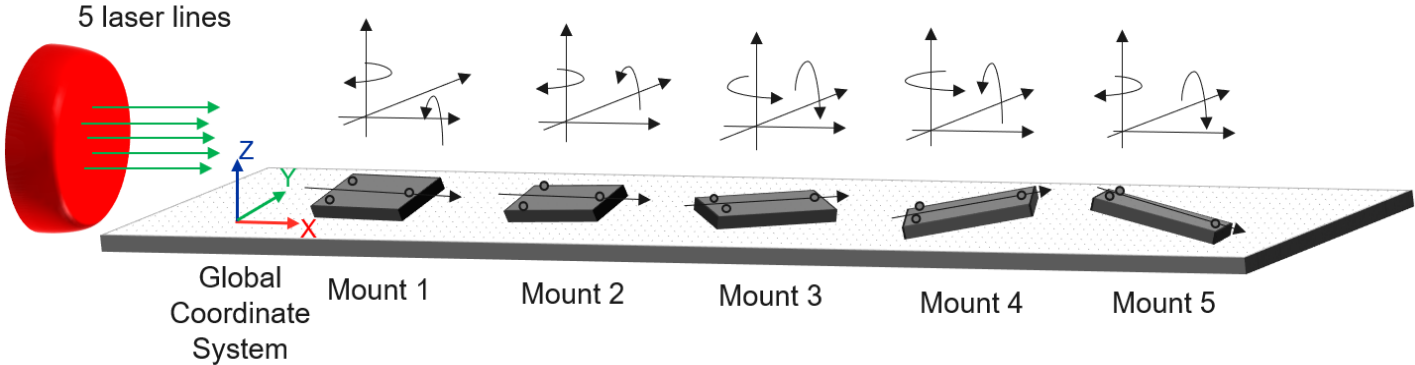
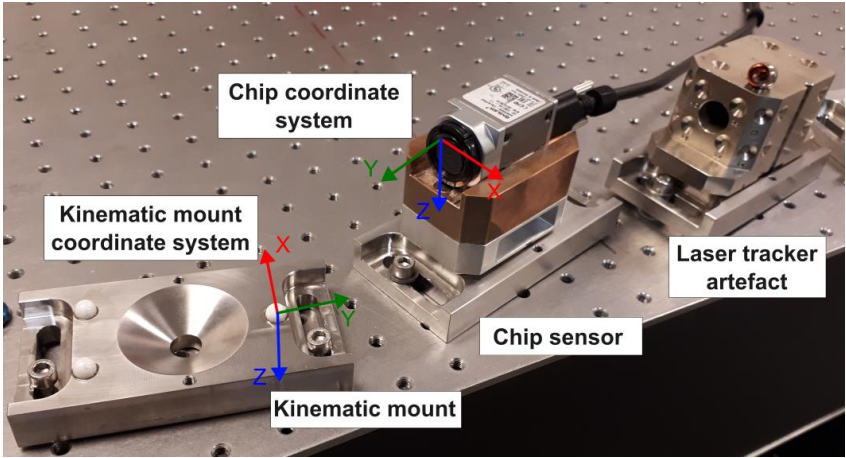
Tabular Data

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2	600.	19.775	28.771	21.187
3	1190.1	19.667	33.503	21.871
4	1780.2	19.511	36.67	22.331
5	2468.5	19.25	39.053	22.68
6	3202.4	18.988	40.679	22.919
7	3978.2	18.781	41.773	23.081
8	4790.7	18.638	42.501	23.19
9	5633.	18.539	42.981	23.262
10	6502.3	18.474	43.297	23.309
11	7393.2	18.434	43.503	23.341
12	8302.5	18.421	43.638	23.361
13	9237.6	18.409	43.728	23.375
14	10175	18.401	43.785	23.384
15	11124	18.396	43.823	23.39
16	12079	18.394	43.848	23.394
17	13043	18.392	43.864	23.397
18	14971	18.393	43.88	23.399
19	17971	18.394	43.89	23.401
20	20971	18.394	43.893	23.401
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22	26971	18.393	43.896	23.402
23	30000	18.393	43.896	23.402

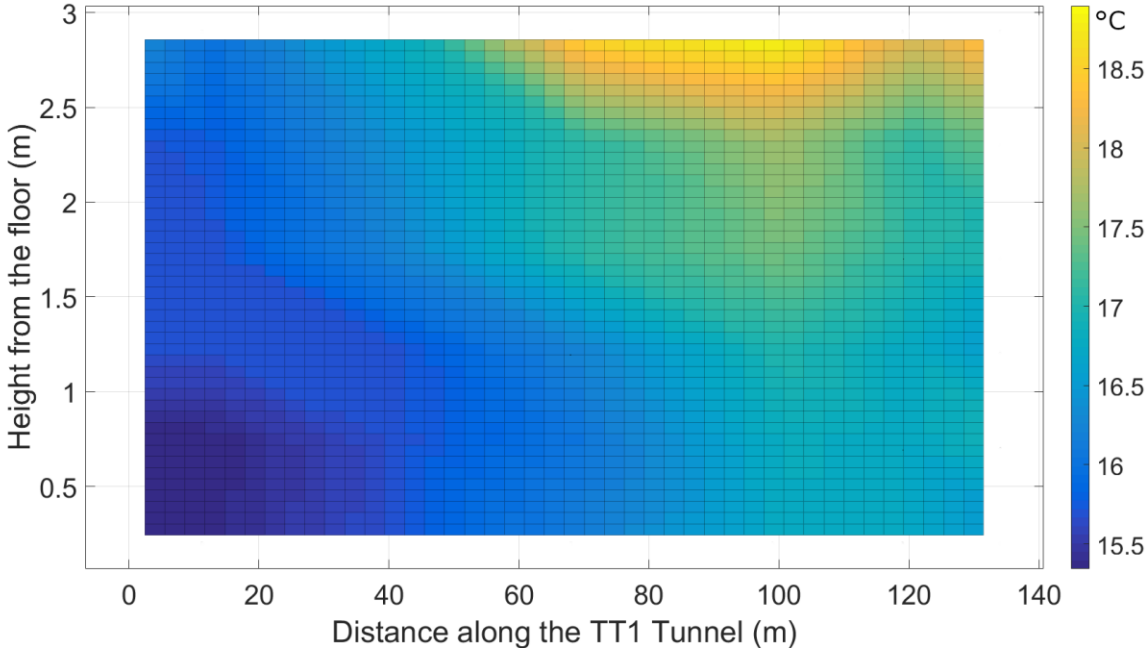
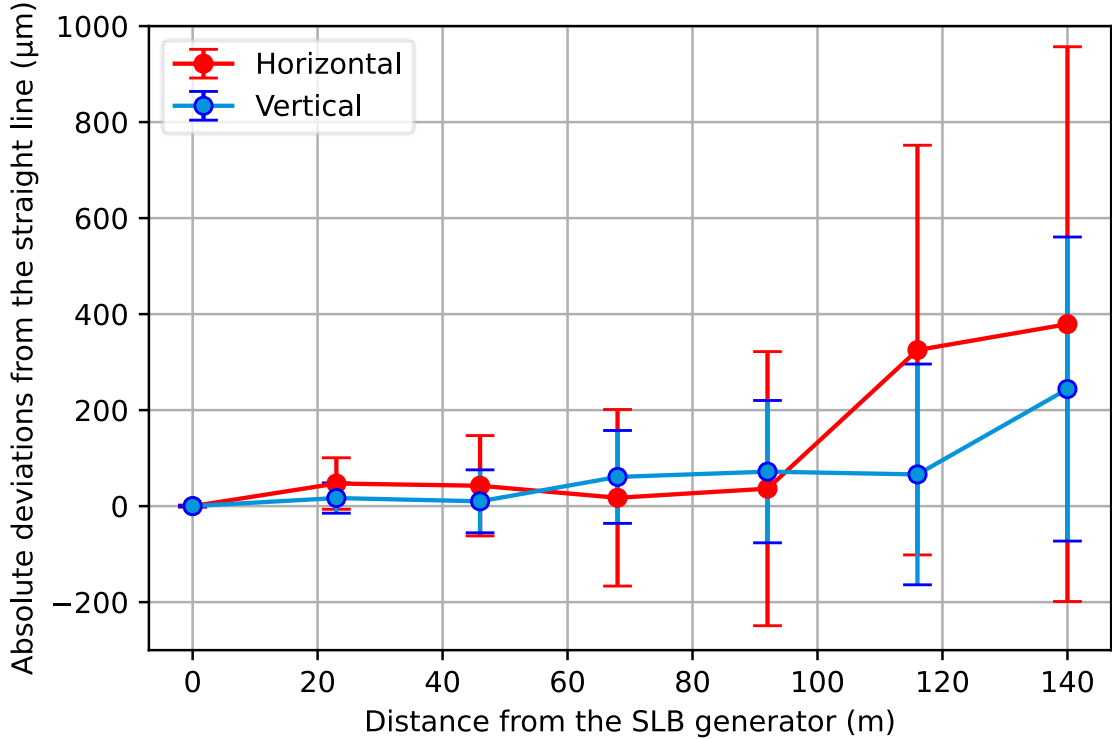
Camera calibration

Differences in-house method and CMM

Corner point name	X difference (μm)	Y difference (μm)	Z difference (μm)
TL	6	11	-4
TR	14	10	-2
BL	8	5	-4
BR	15	5	-2



Free air propagation

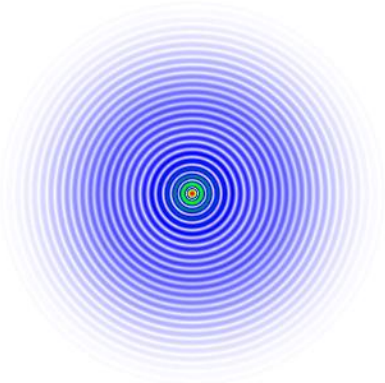
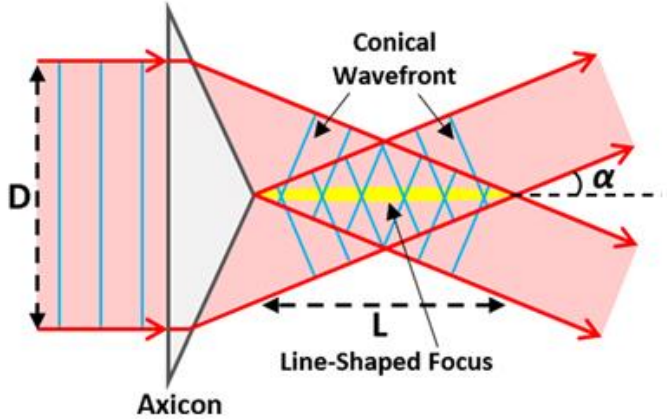
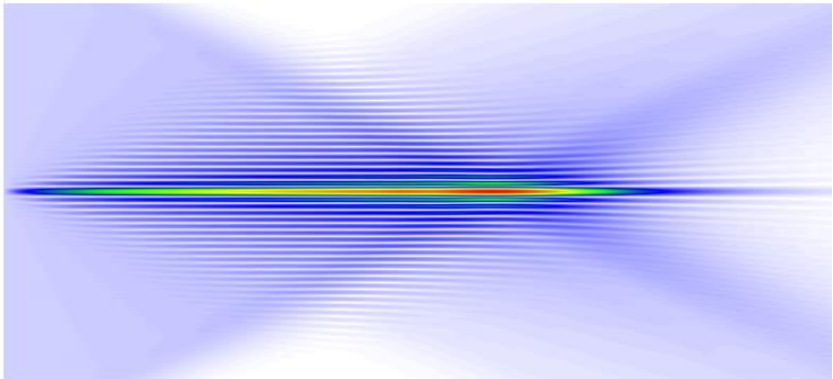
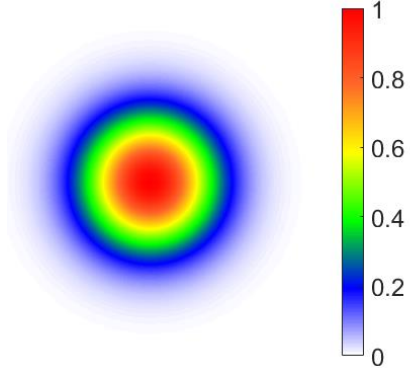
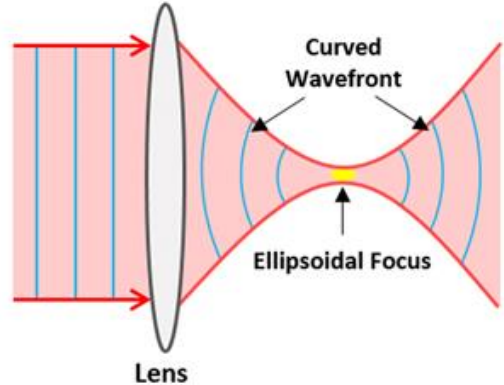


Optical beams GB and Bessel Beam

Forms of light waves propagating with small divergence

Gaussian beam
 small focus
 significantly diverges

Bessel beam
 long longitudinal focus
 limited range
 zero divergence



Field contribution – SLB applications

- Laser pointer in a total station and LiDAR
- Military and civil targeting and follow-up
- Precise rotary level for civil engineering
- Wireless communication
- Precision cutting and engraving

