EOS Topical Meeting on Diffractive Optics, September 2019, Jena, Germany

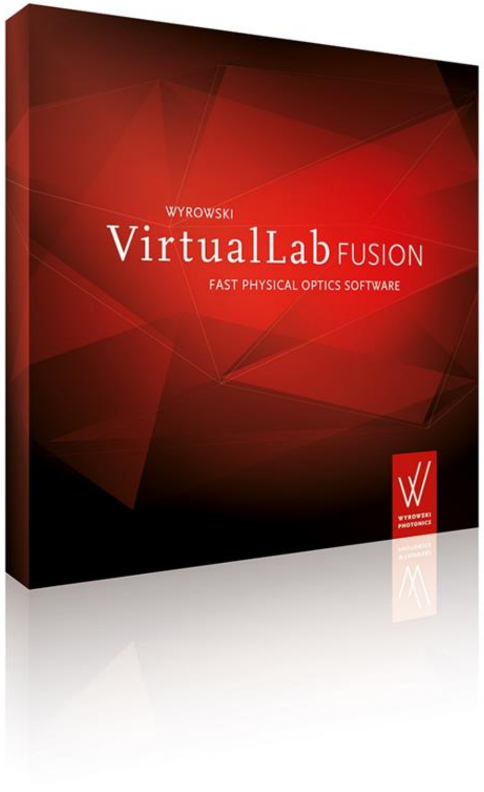
Systematic design concept for AR&MR lightguide devices

S. Steiner*, C. Hellmann**, R. Knoth**, S. Zhang**, and F. Wyrowski***

*LightTrans International UG, **Wyrowski Photonics GmbH, ***University of Jena

Lightguide Modeling and Design

AR&VR in VirtualLab Fusion → System configuration → Lightguide modeling → Lightguide design → Optimization of incoupling grating

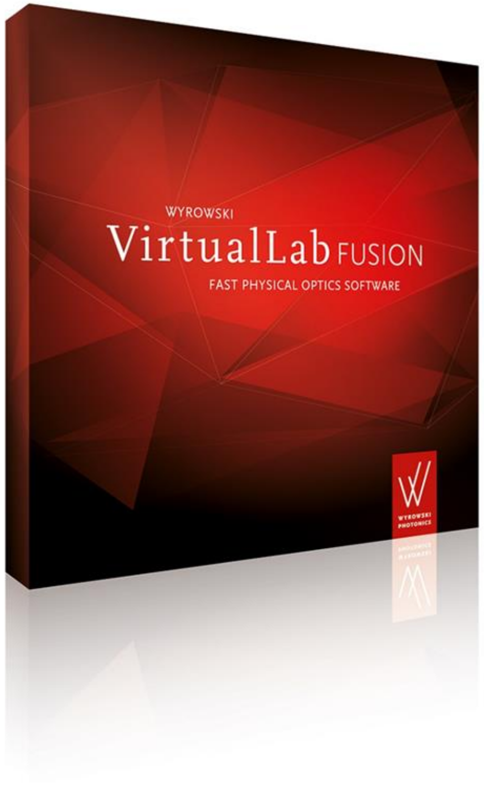


Yesterday: Physical-optics analysis of lightguides for AR&MR glasses, F. Wyrowski, University Jena; C. Hellmann, Wyrowski Photonics UG (Germany); S. Steiner, R. Knoth, S. Zhang, LightTrans International UG (Germany)

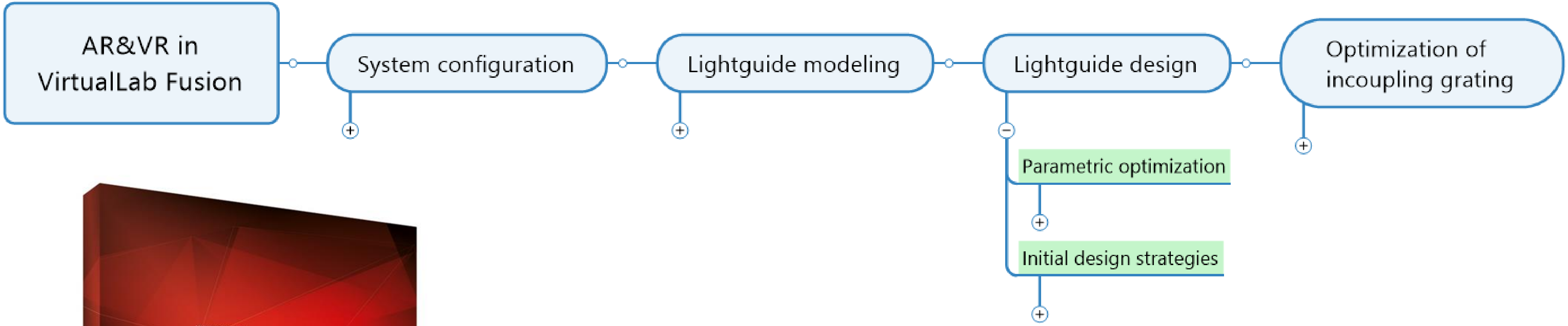
Lightguide Modeling and Design

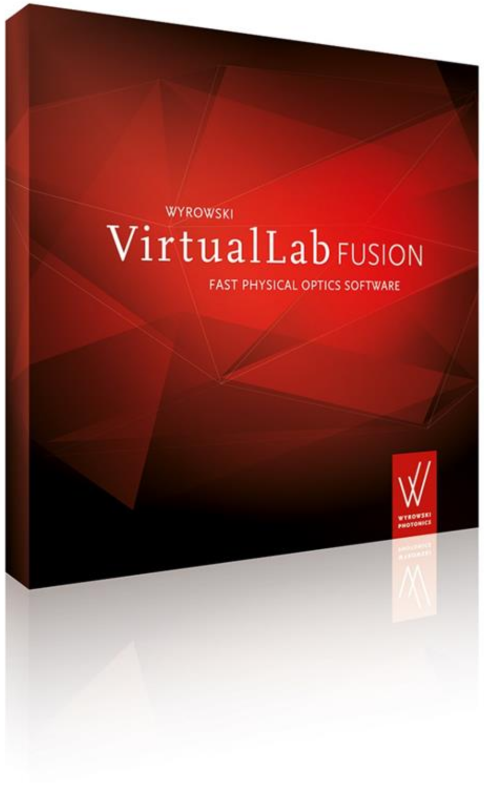
AR&VR in VirtualLab Fusion

- System configuration
- Lightguide modeling
  - Ray tracing
  - Fast physical optics (connecting field solvers)
  - All relevant physical effects included to evaluate detectors
- Lightguide design
- Optimization of incoupling grating



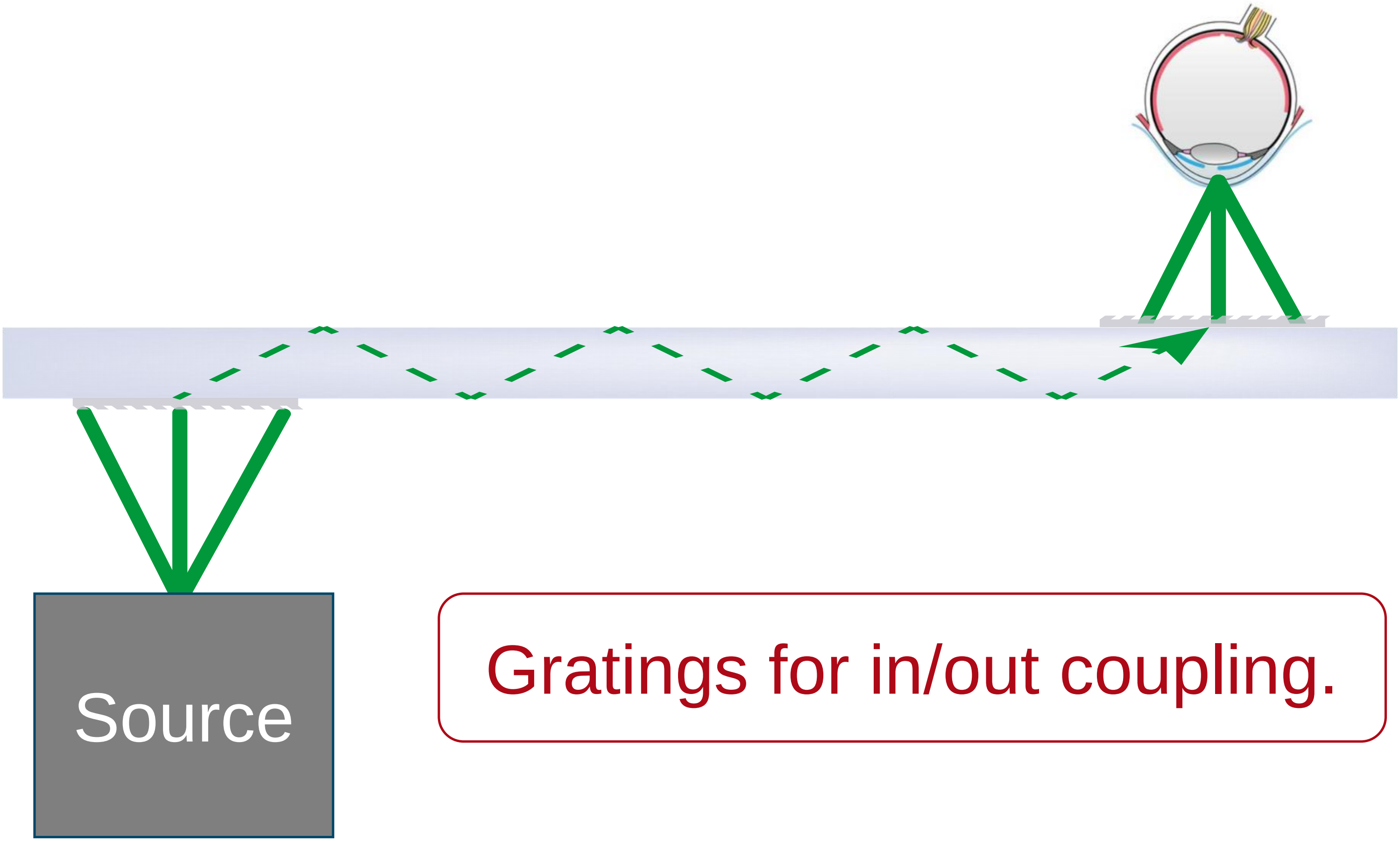
Lightguide Modeling and Design





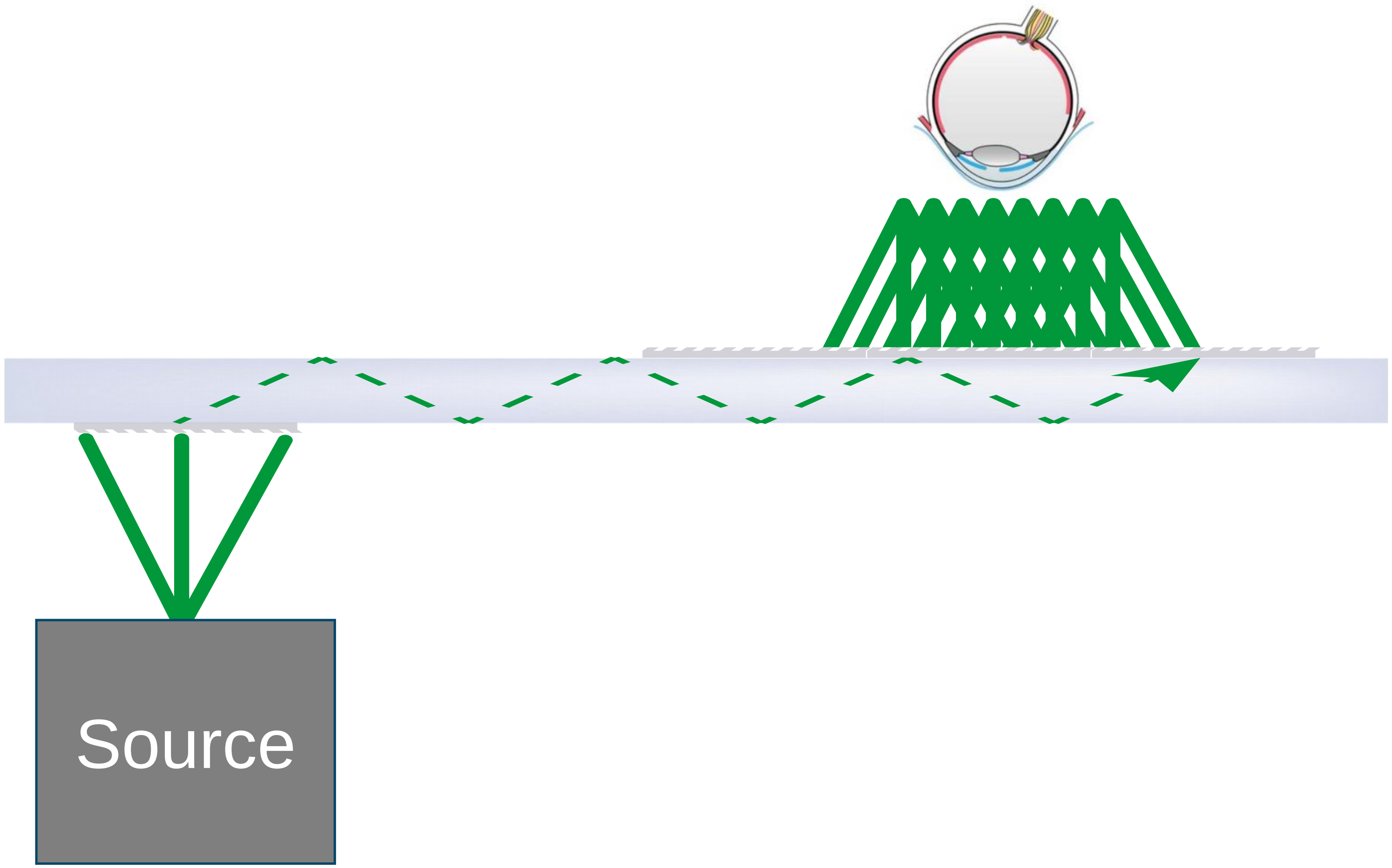
Selection of design criteria?

Lightguide Concept: In/Out Coupling

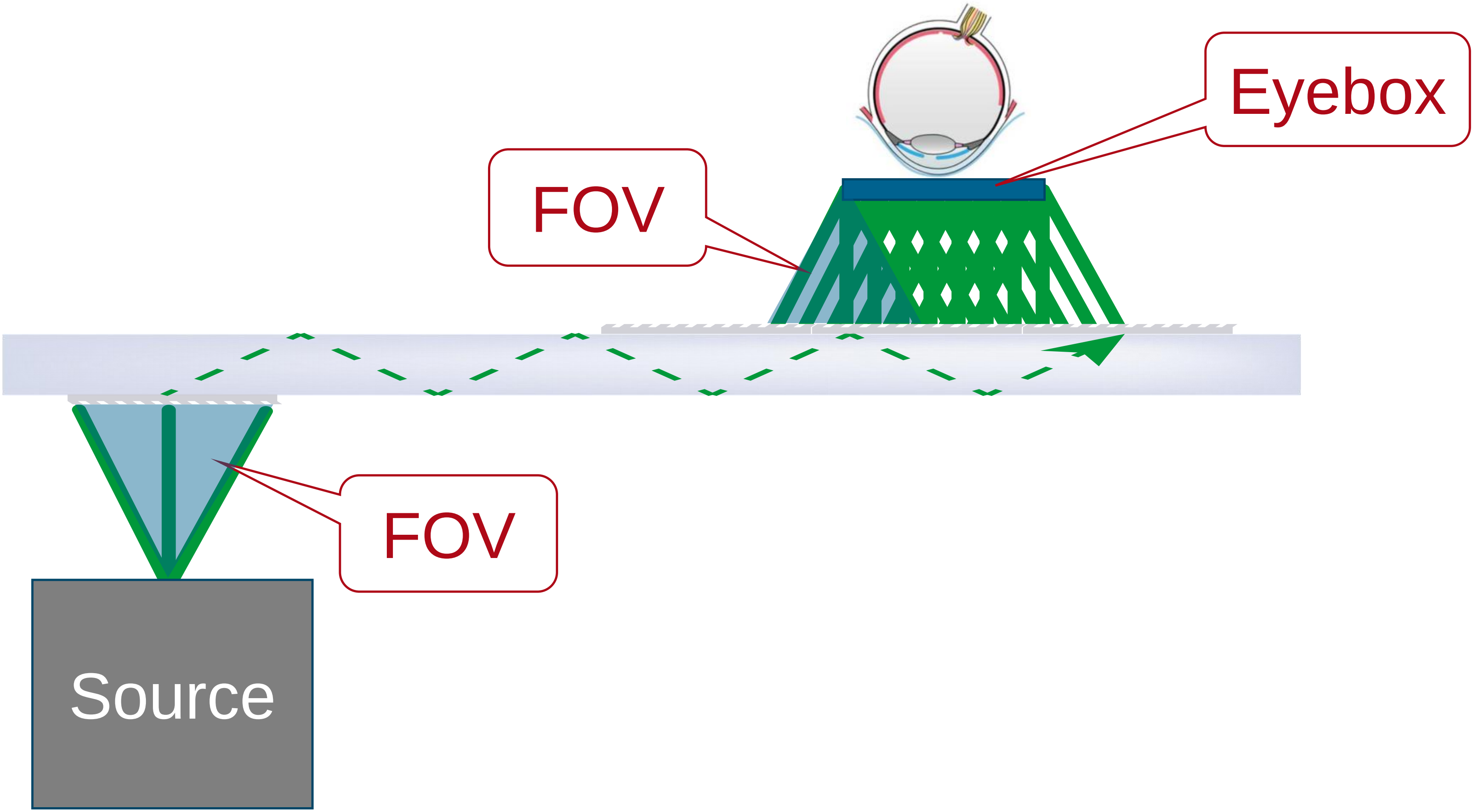


Gratings for in/out coupling.

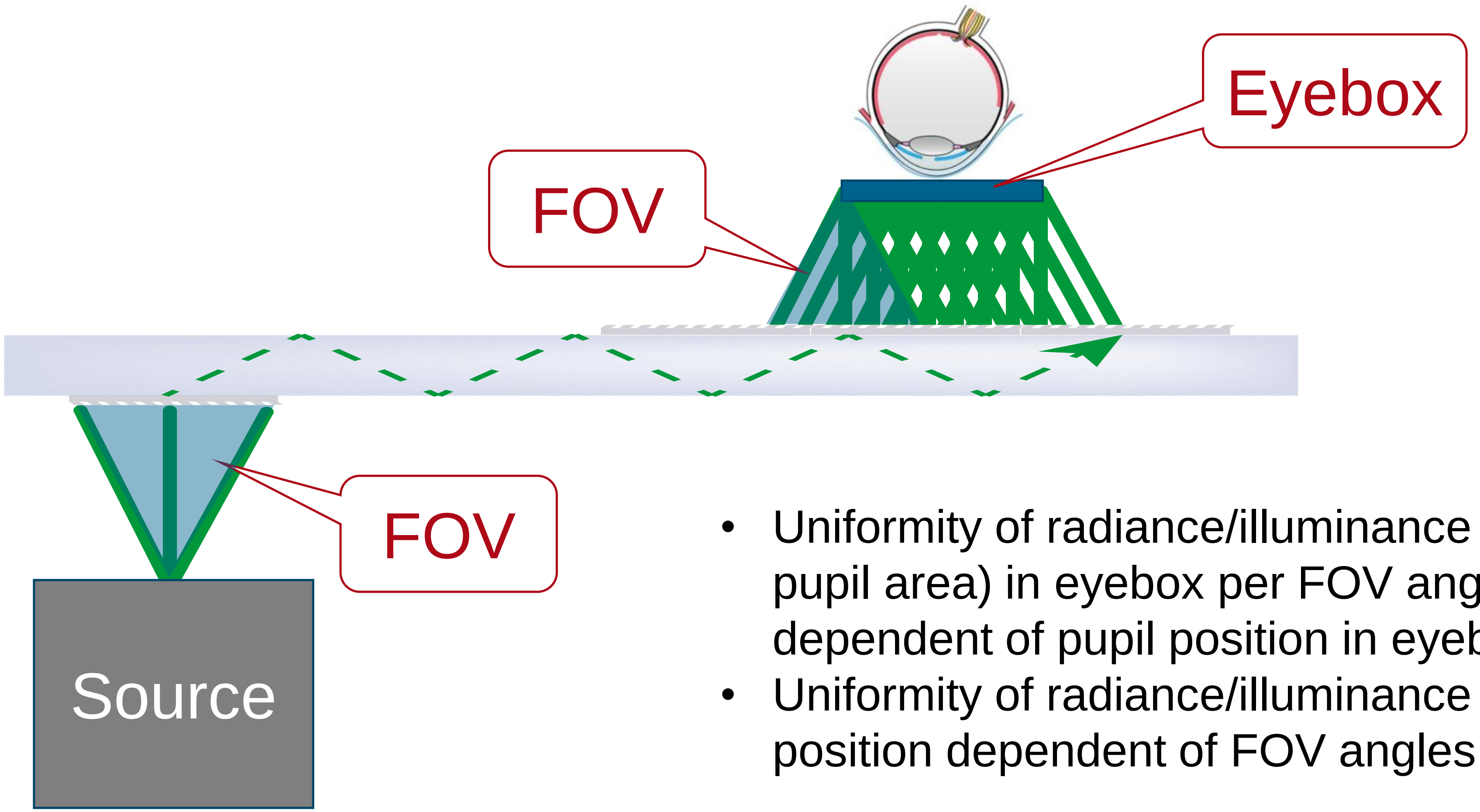
Lightguide Concept: Exit Pupil Expansion



Lightguide Concept: Exit Pupil Expansion

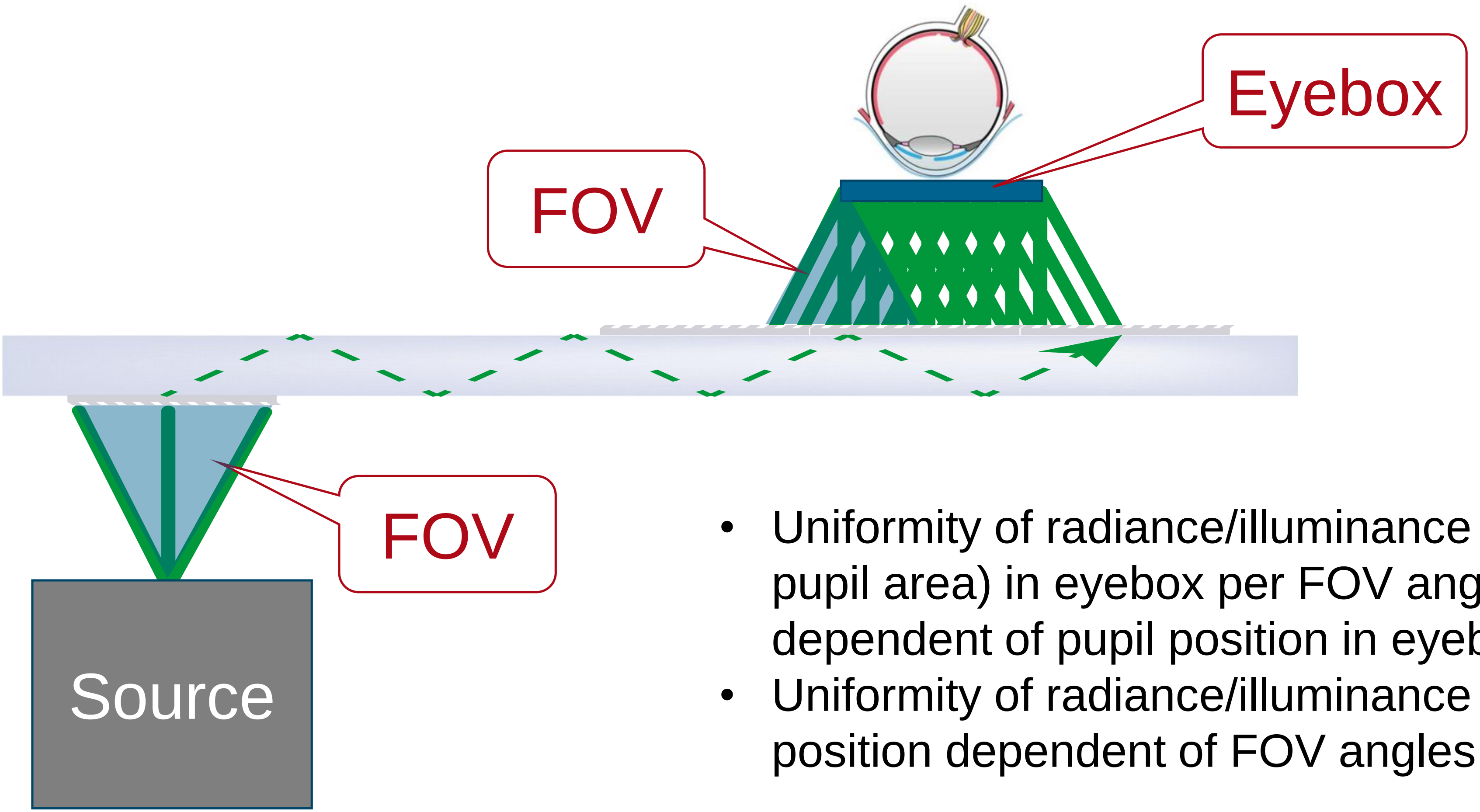


Lightguide Concept: Fundamental Design Criteria



- Uniformity of radiance/illuminance (per pupil area) in eyebox per FOV angle/mode dependent of pupil position in eyebox.
- Uniformity of radiance/illuminance per pupil position dependent of FOV angles.

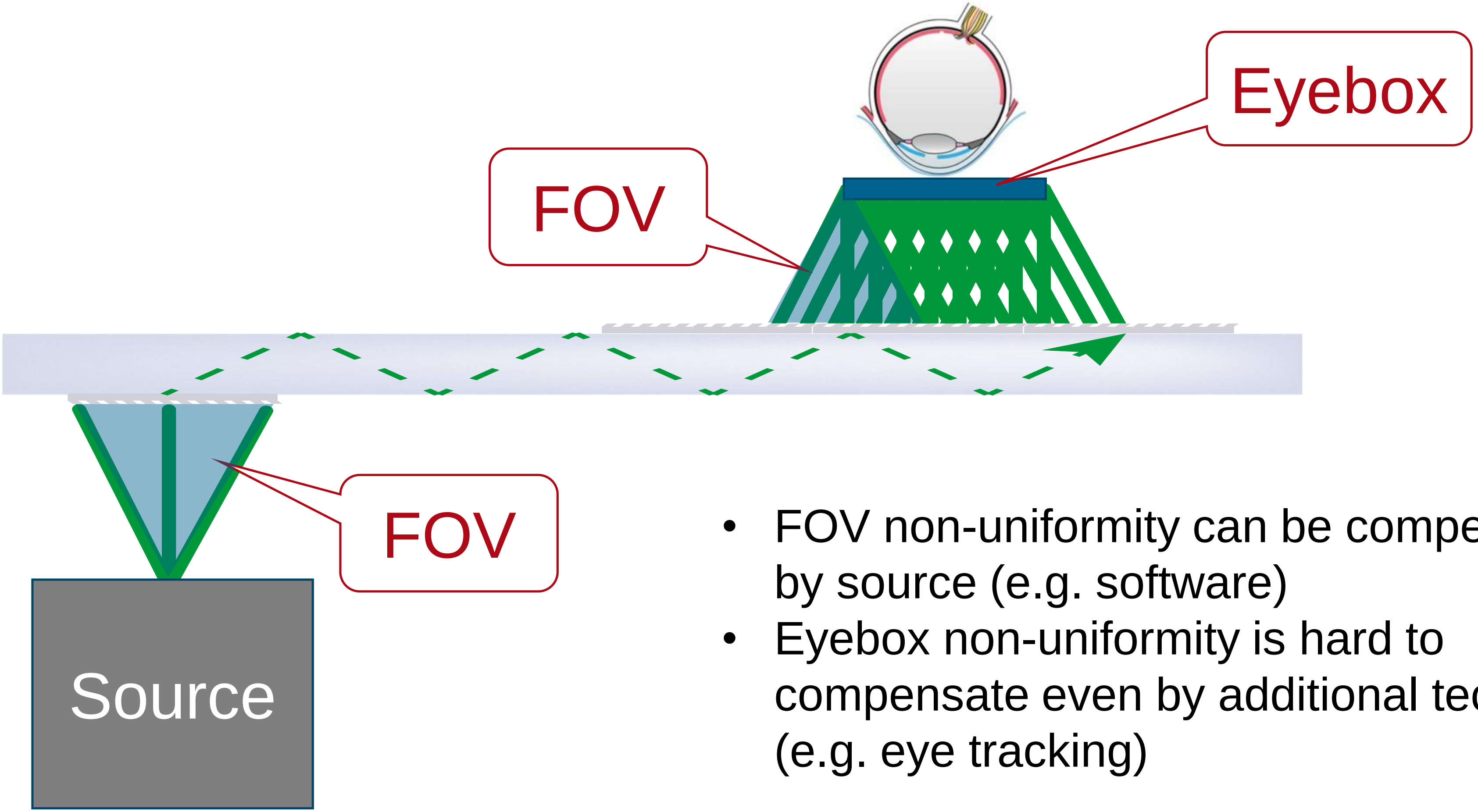
Lightguide Concept: Fundamental Design Criteria



- Uniformity of radiance/illuminance (per pupil area) in eyebox per FOV angle/mode dependent of pupil position in eyebox.
- Uniformity of radiance/illuminance per pupil position dependent of FOV angles.

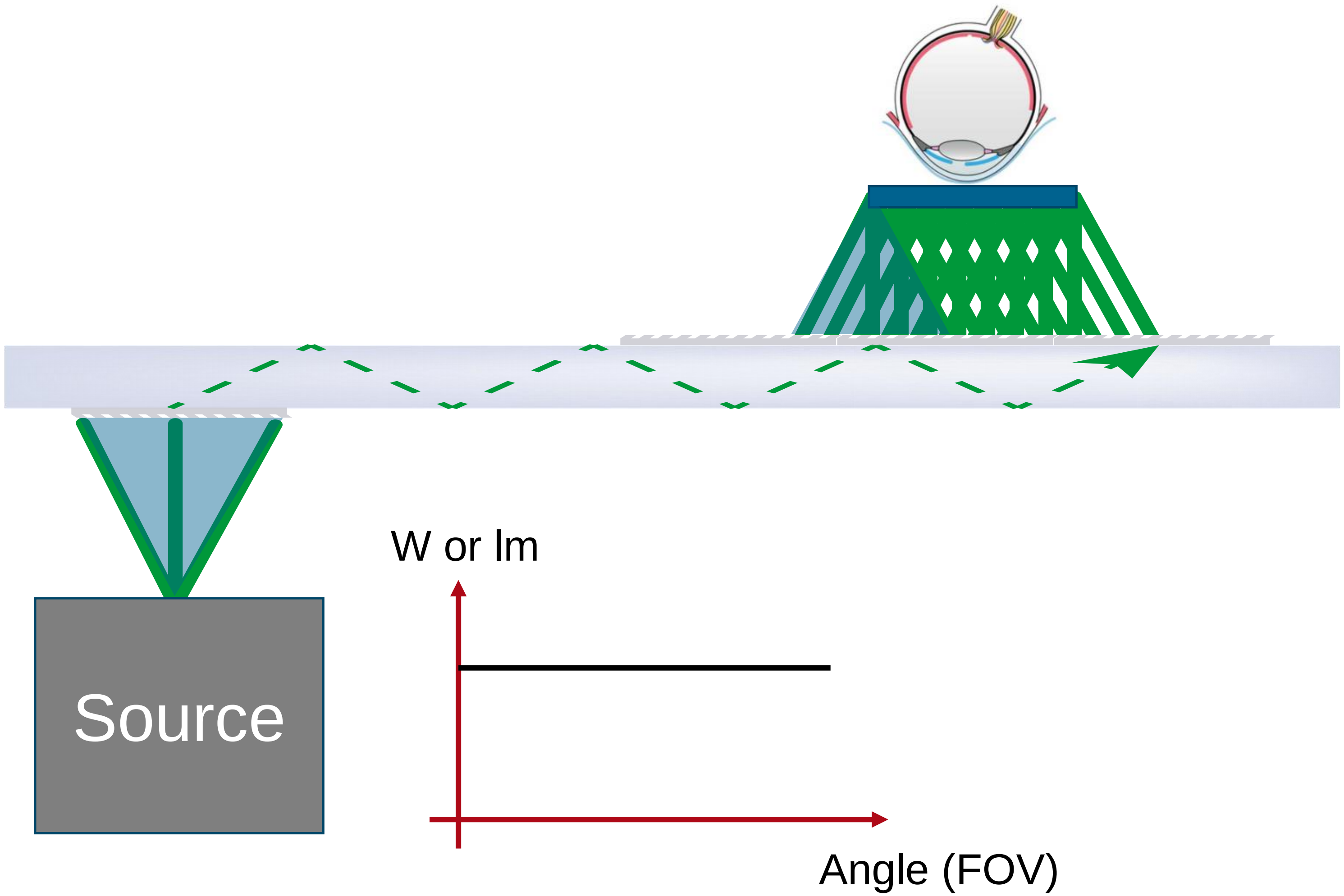
Which one is more critical and should be prioritized?

Lightguide Concept: Fundamental Design Criteria

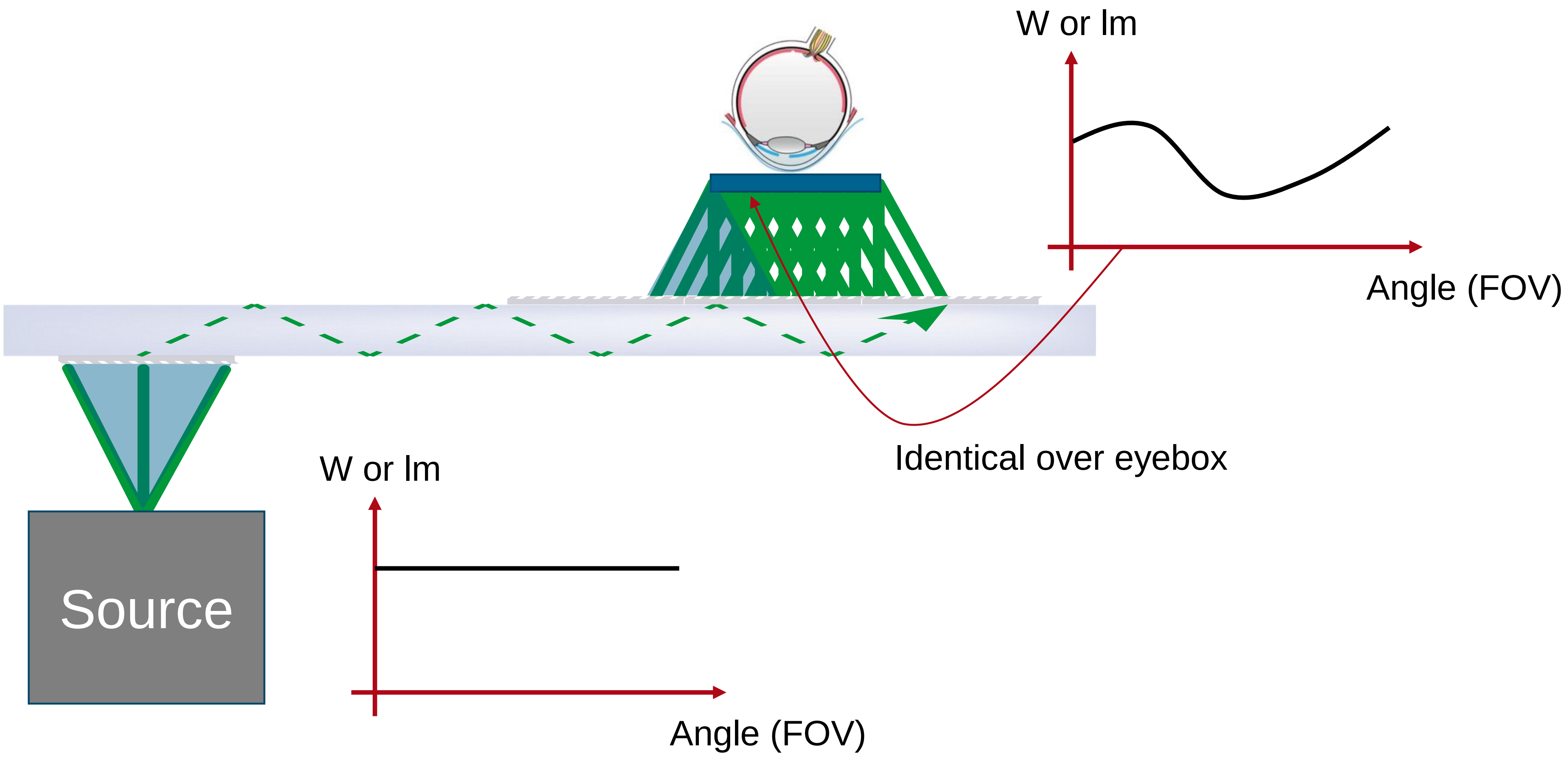


- FOV non-uniformity can be compensated by source (e.g. software)
- Eyebox non-uniformity is hard to compensate even by additional techniques (e.g. eye tracking)

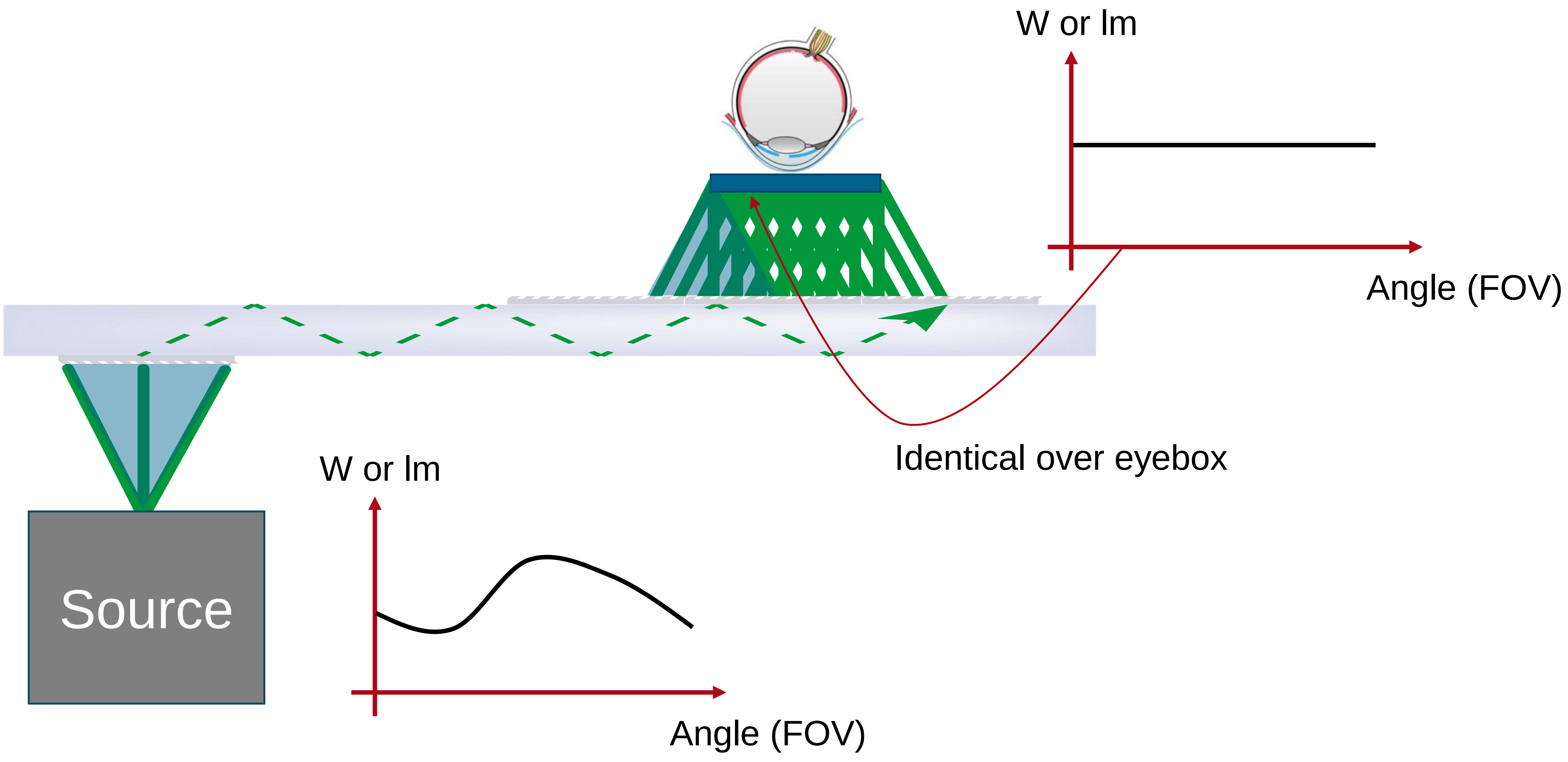
Lightguide Concept: Fundamental Design Criteria



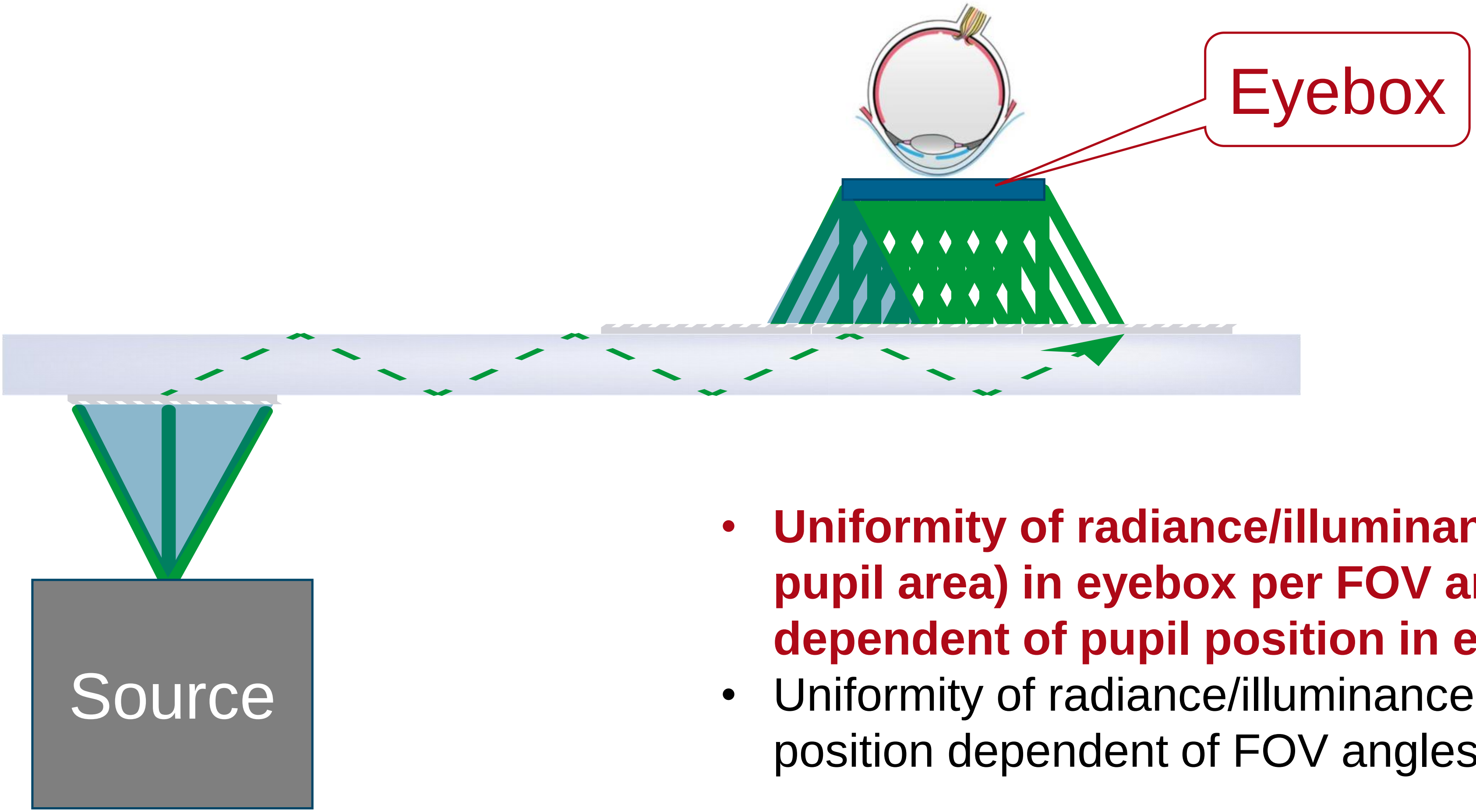
Lightguide Concept: Fundamental Design Criteria



Lightguide Concept: Fundamental Design Criteria

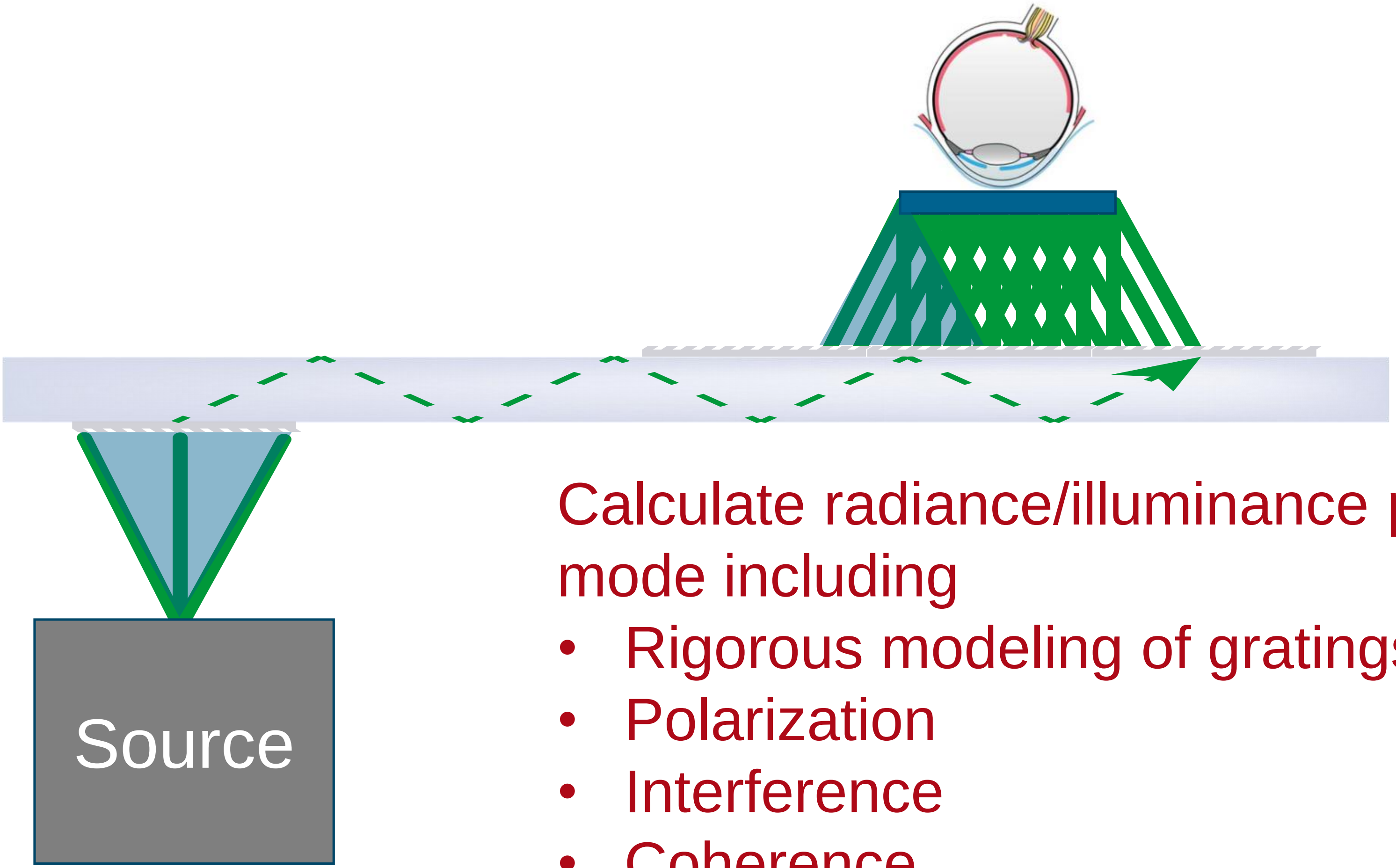


Lightguide Concept: Fundamental Design Criteria



- **Uniformity of radiance/illuminance (per pupil area) in eyebox per FOV angle/mode dependent of pupil position in eyebox.**
- Uniformity of radiance/illuminance per pupil position dependent of FOV angles.

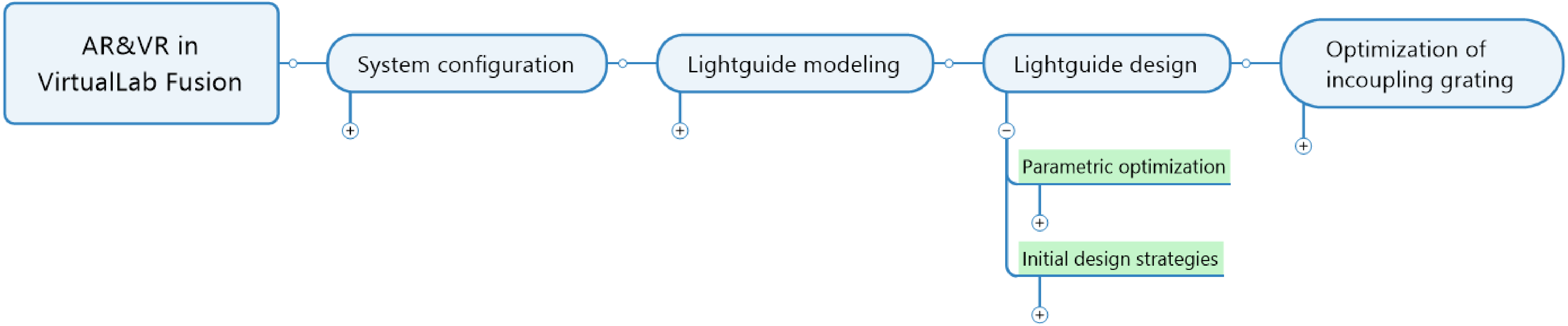
Lightguide Concept: Modeling Task



Calculate radiance/illuminance per FOV mode including

- Rigorous modeling of gratings
- Polarization
- Interference
- Coherence

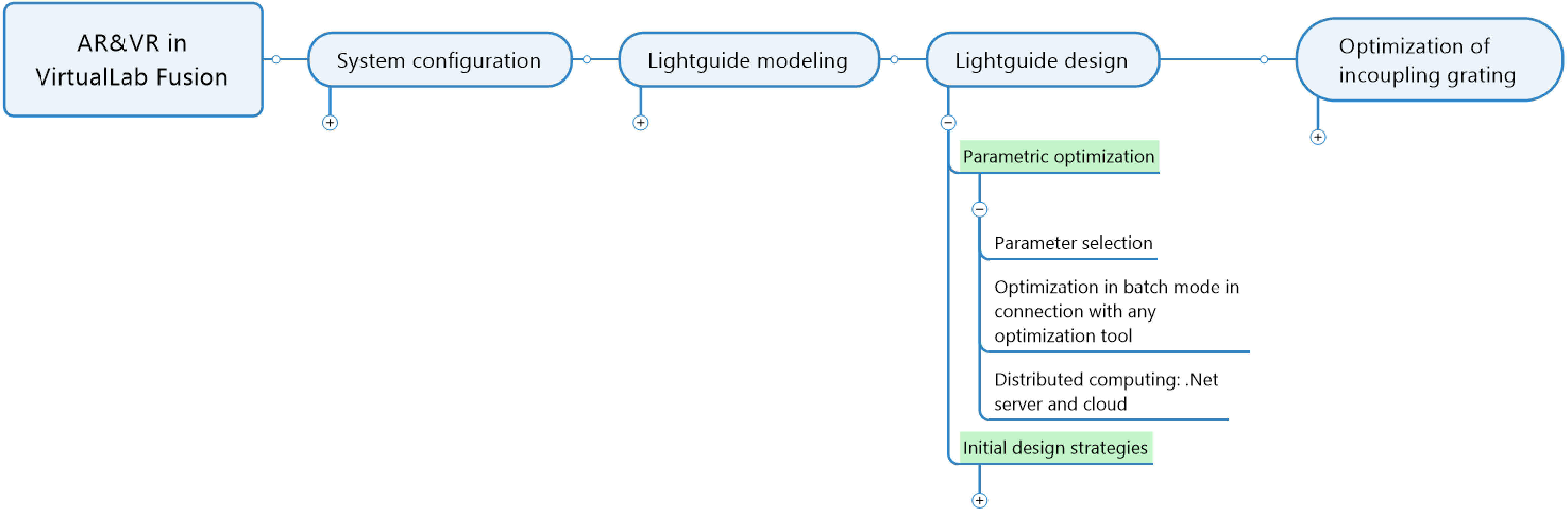
Lightguide Modeling and Design



Parametric Optimization of Lightguide Parameters

Parametric optimization

Lightguide Modeling and Design



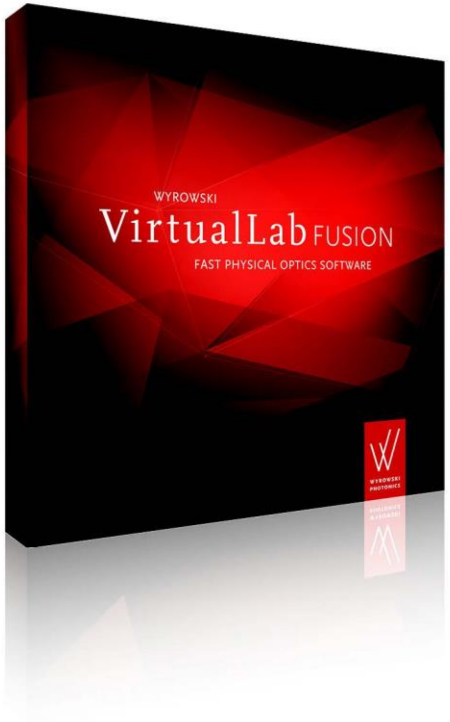
Cross Platform Simulation/Optimization - Python

PYTHON
- interactive access to batch mode files
- external mathematical functions and tools

Batch mode files
- execution of simulations
- optical parameters and simulation result storage

VirtualLab Fusion
- optical setup definition
- kernel simulation engine

batch file
xml files
...



cross-platform simulation

Cross Platform Simulation/Optimization - MATLAB

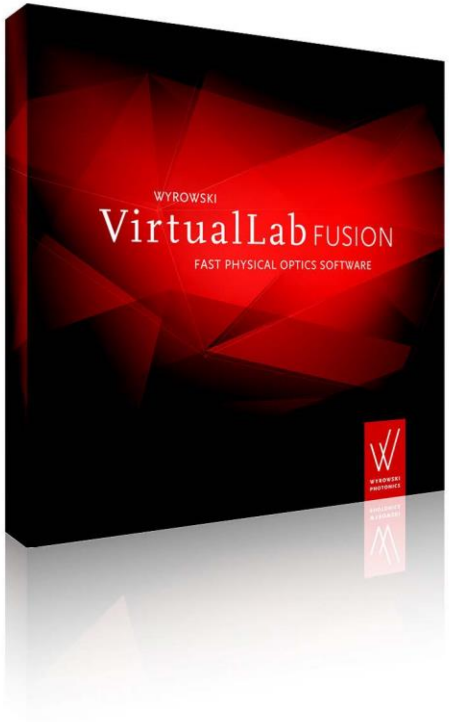
MATLAB
- interactive access to batch mode files
- external mathematical functions and tools

Batch mode files
- execution of simulations
- optical parameters and simulation result storage

VirtualLab Fusion
- optical setup definition
- kernel simulation engine

MATLAB

batch file
xml files
...



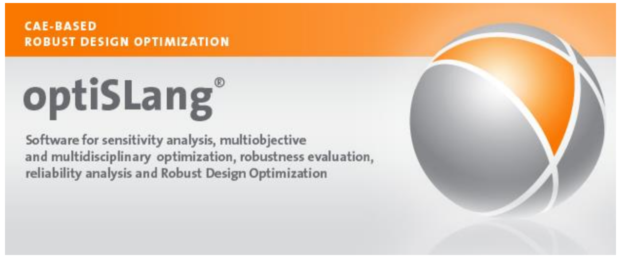
cross-platform simulation

Cross Platform Simulation/Optimization - optiSLang

optiSLang
- interactive access to batch mode files
- internal mathematical functions and tools

Batch mode files
- execution of simulations
- optical parameters and simulation result storage

VirtualLab Fusion
- optical setup definition
- kernel simulation engine



batch file
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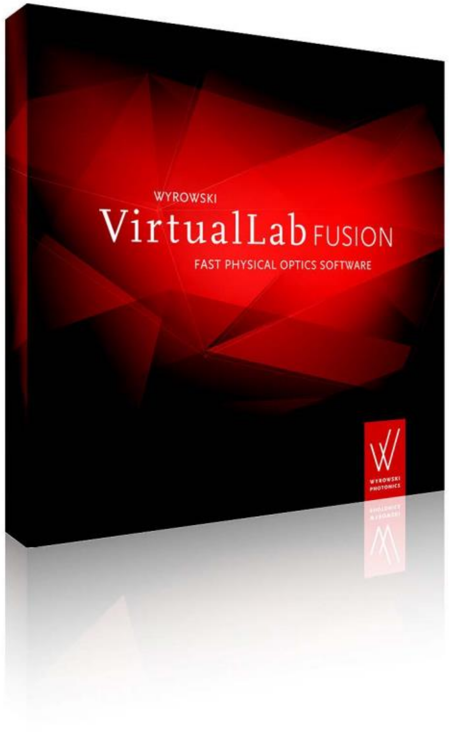
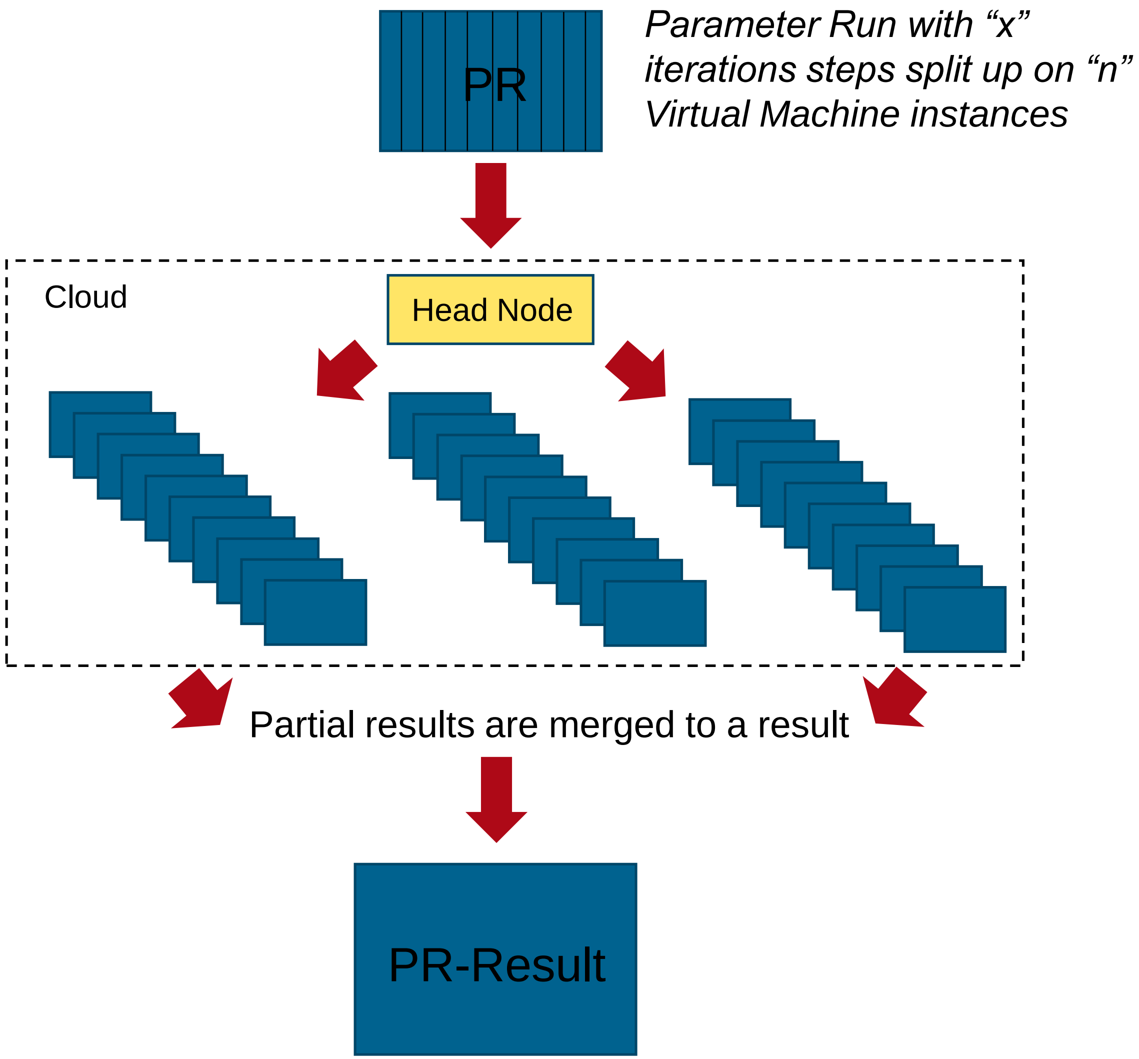
...



cross-platform simulation

Cloud Computing

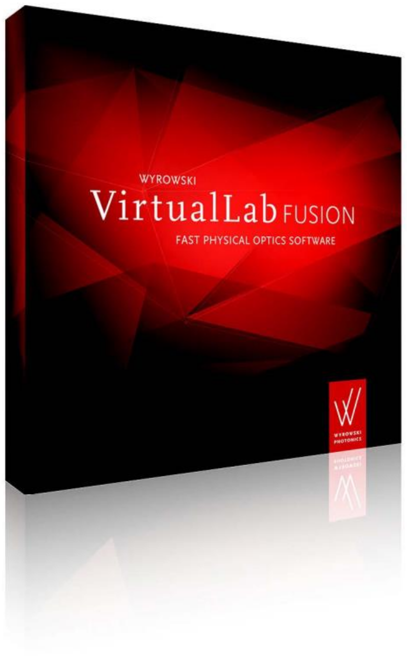


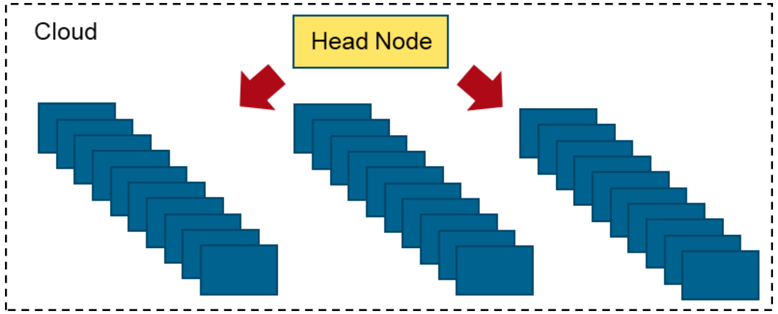
VirtualLab supports cloud computing on Azure cloud:

- Cluster with e.g. 8 or more nodes
- Windows Machines with e.g. Windows Server 2012 R2 OS
- Software: HPC Pack 2012 (Microsoft tool) (High Performance Computing)

The usage of cloud computing enables a speed up of the simulation, which can be scaled by the size of the cluster in use.

Parametric Optimization by VirtualLab & External Tools





Provides full flexibility by a powerful combination of tools to find the best solution for your lightguide architecture

Parametric Optimization of Lightguide Parameters

Parametric optimization

Parametric Optimization and Initial Design

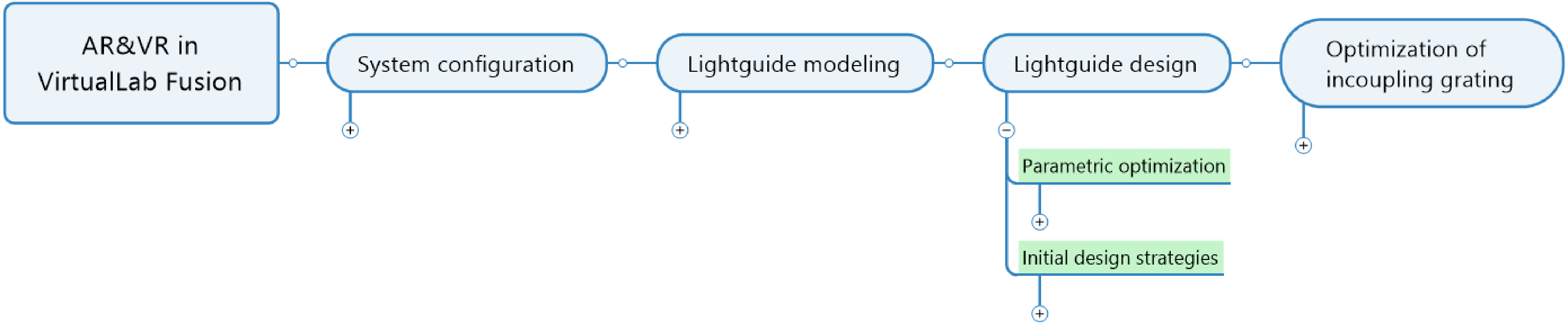
Initial design, e.g.

- Inverse approaches
- Functional design

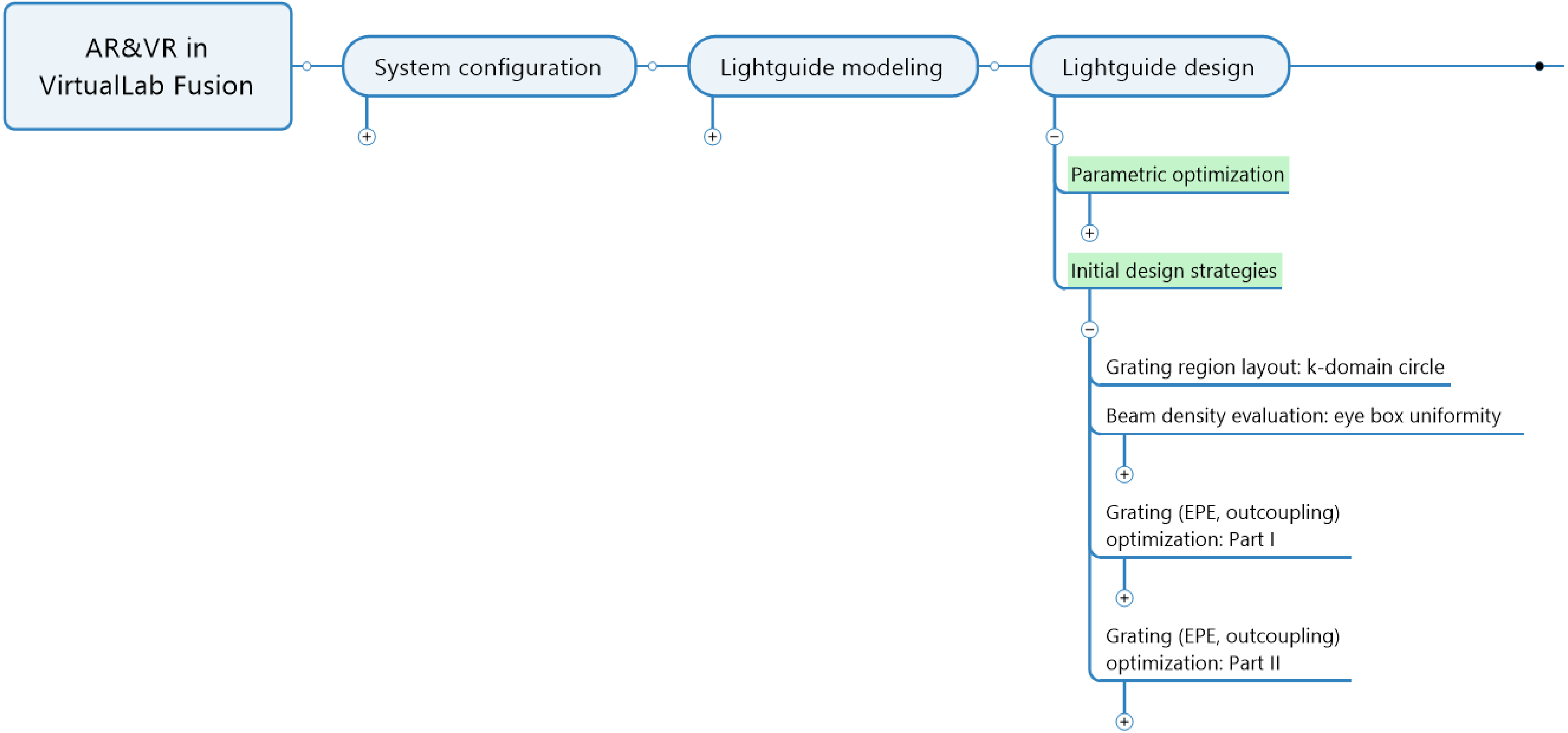
In suitable combination

Parametric optimization

Lightguide Modeling and Design



Lightguide Modeling and Design



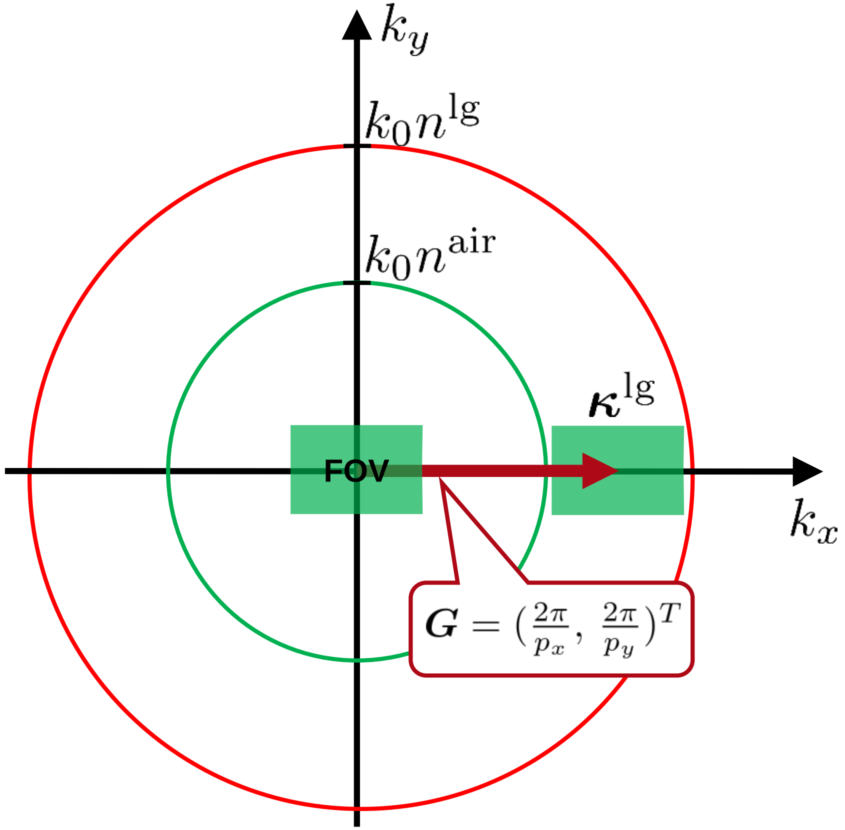
Lightguide Modeling and Design

AR&VR in VirtualLab Fusion

System configuration

Lightguide modeling

Lightguide design



Parametric optimization

Initial design strategies

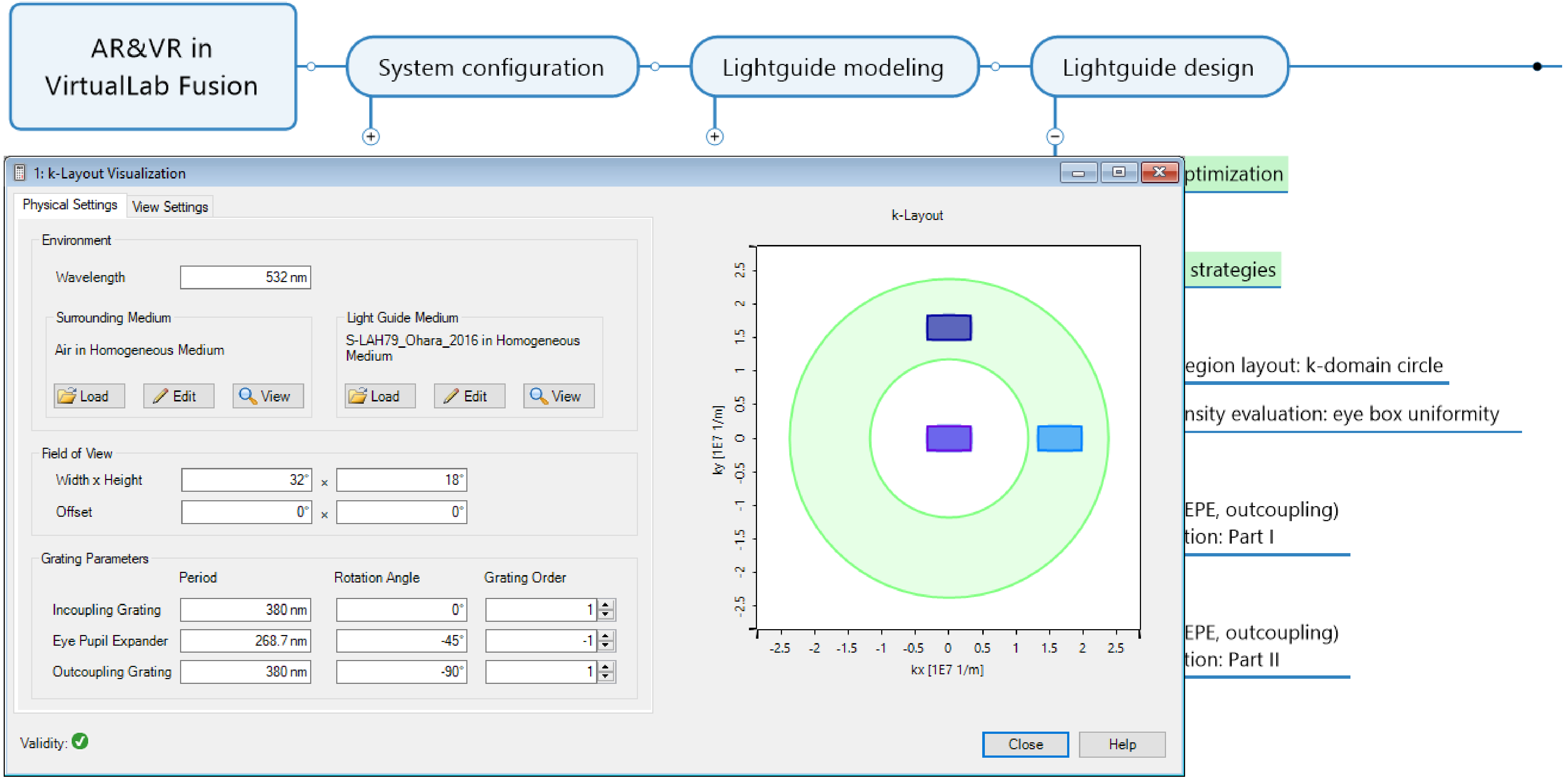
Grating region layout: k-domain circle

Beam density evaluation: eye box uniformity

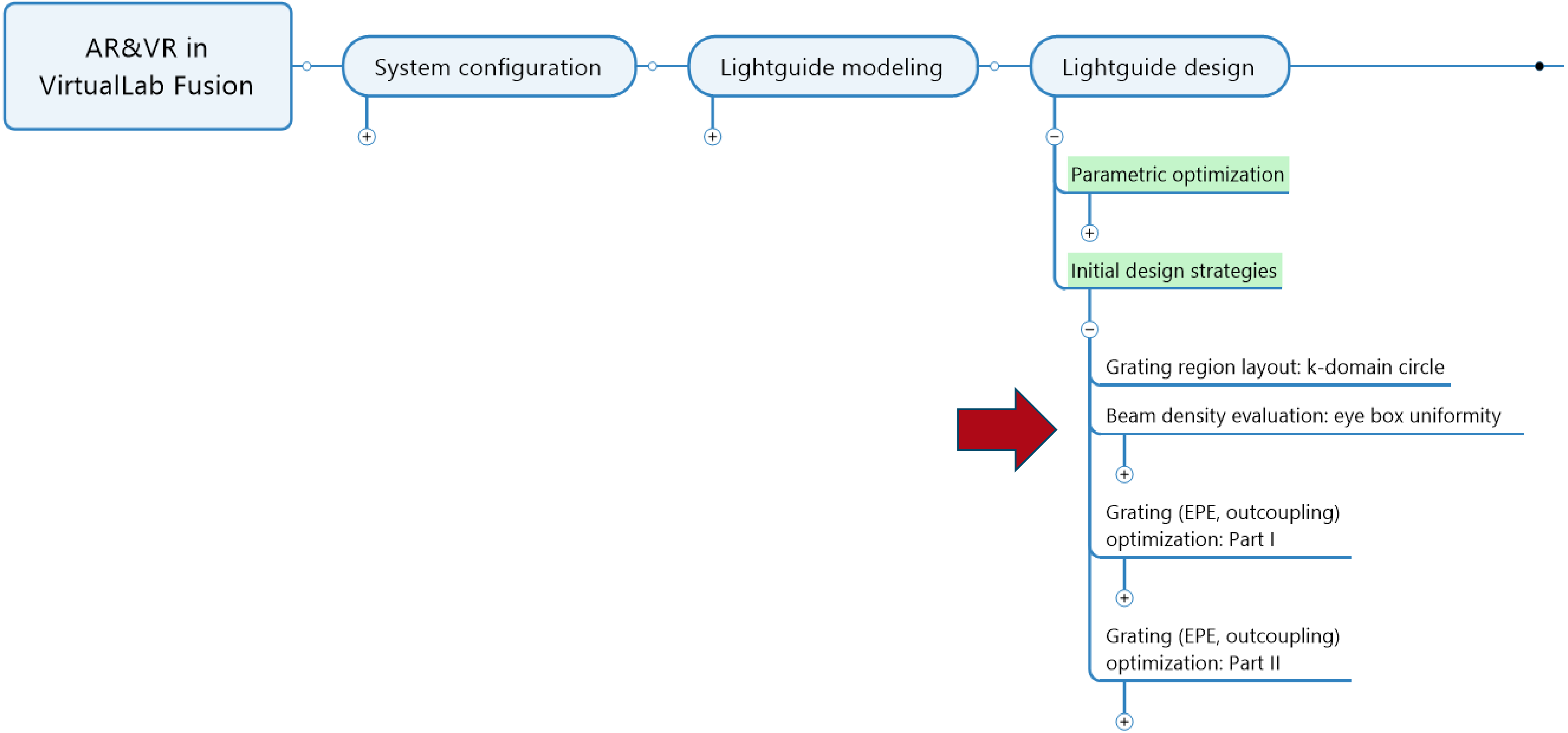
Grating (EPE, outcoupling) optimization: Part I

Grating (EPE, outcoupling) optimization: Part II

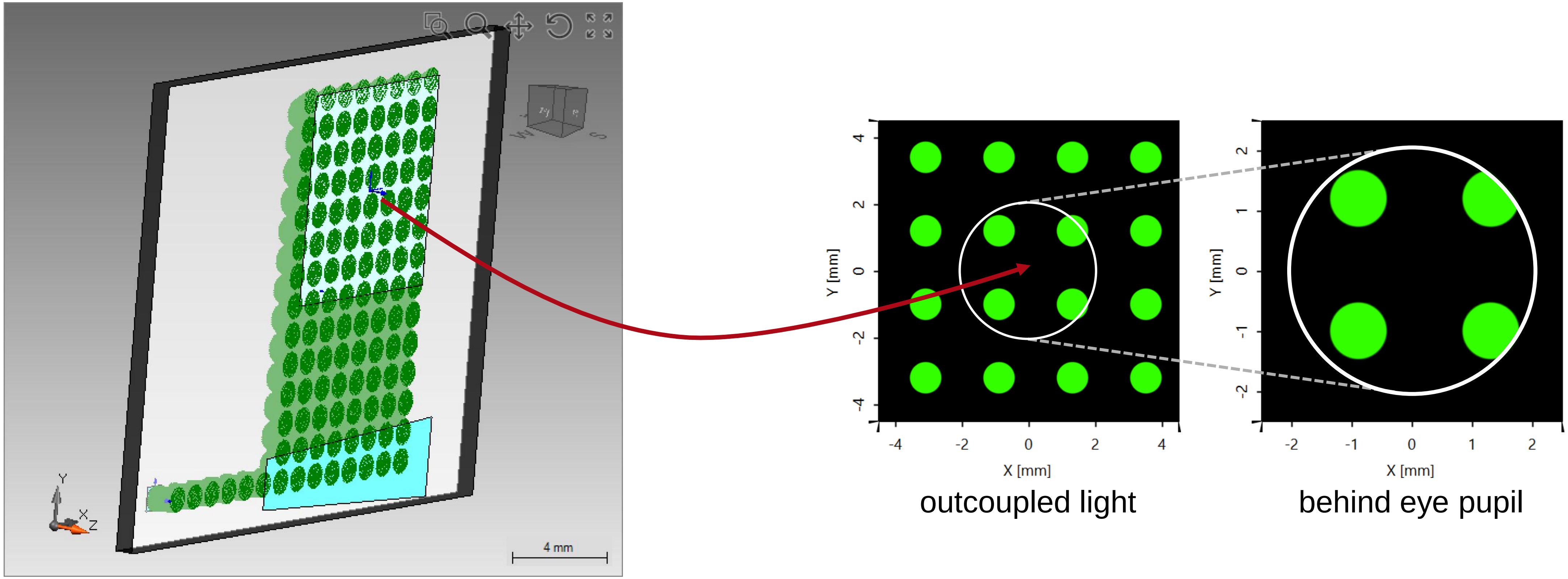
Lightguide Modeling and Design



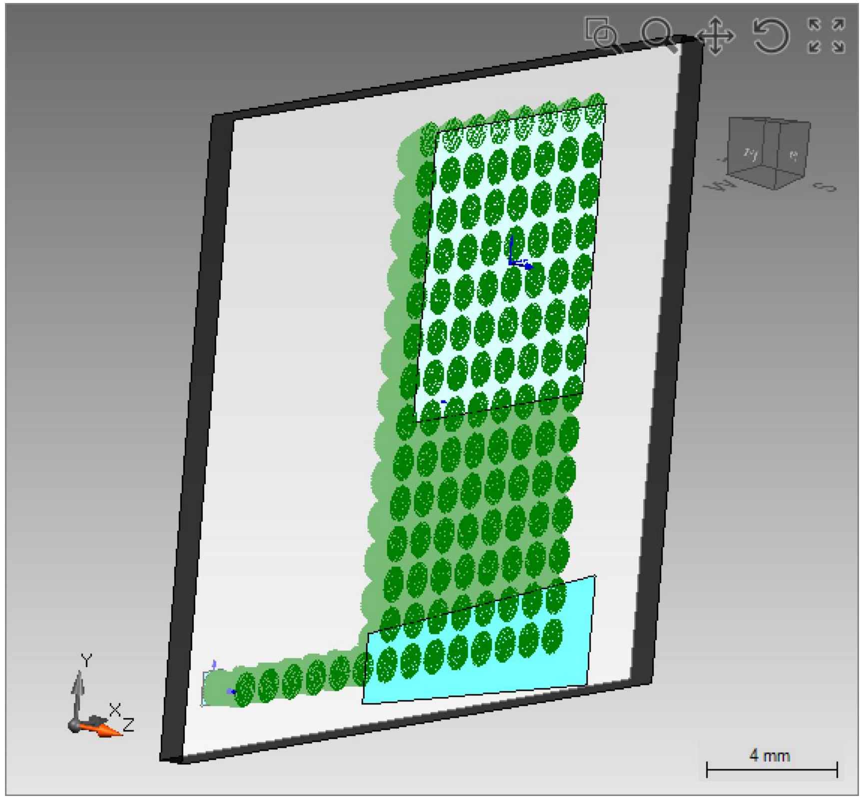
Lightguide Modeling and Design



Eyebox Uniformity vs. Beam Density



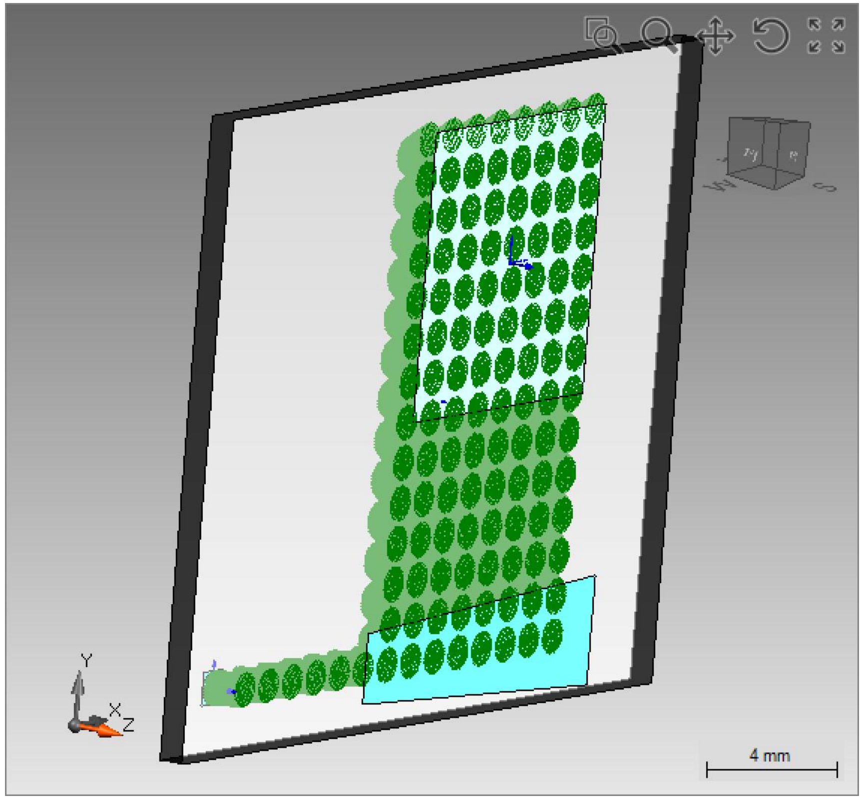
Eyebox Uniformity vs. Beam Density



- Per eye position (x, y) in eyebox the flux into the eye per FOV angle (θ_x, θ_y) is calculated, which represents the radiance L_e.
- The uniformity error $\Omega(\theta_x, \theta_y)$ is defined as the contrast of L_e:

$$\Omega(\theta_x, \theta_y) = \frac{\max_{(x,y)} L_e(\theta_x, \theta_y; x, y) - \min_{(x,y)} L_e(\theta_x, \theta_y; x, y)}{\max_{(x,y)} L_e(\theta_x, \theta_y; x, y) + \min_{(x,y)} L_e(\theta_x, \theta_y; x, y)}$$

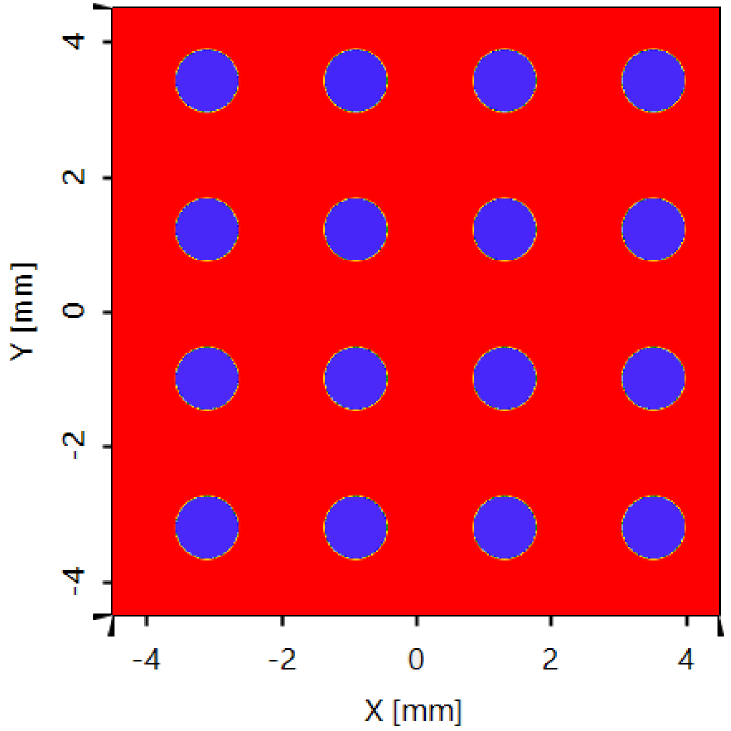
Eyebox Uniformity vs. Beam Density



Initial investigation:

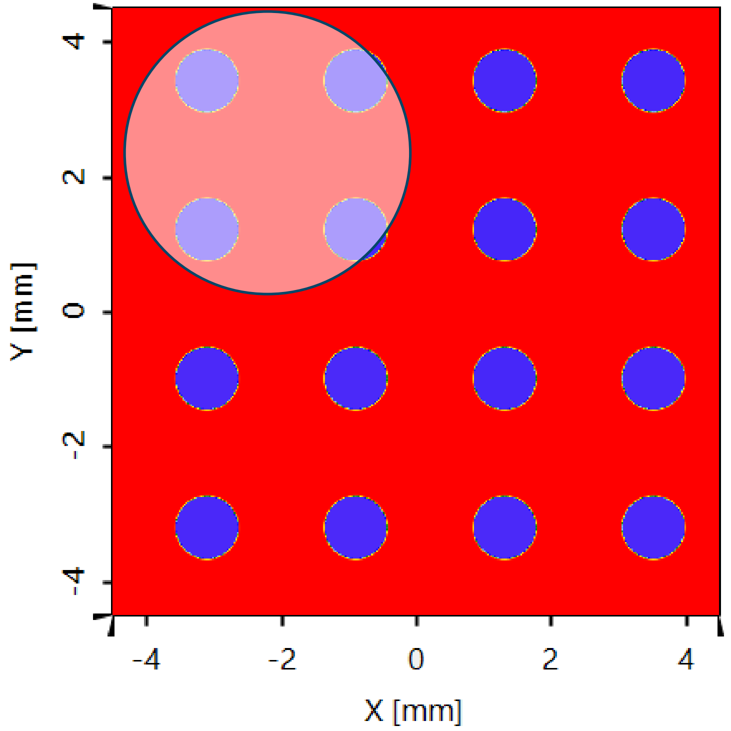
- Assume ideal gratings which provide perfectly uniform beams.
- Concentrate on beam density vs.
    - Thickness of lightguide
    - Beam size (light engine)
    - Off-axis angle incoupling

Eyebox Uniformity vs. Beam Density



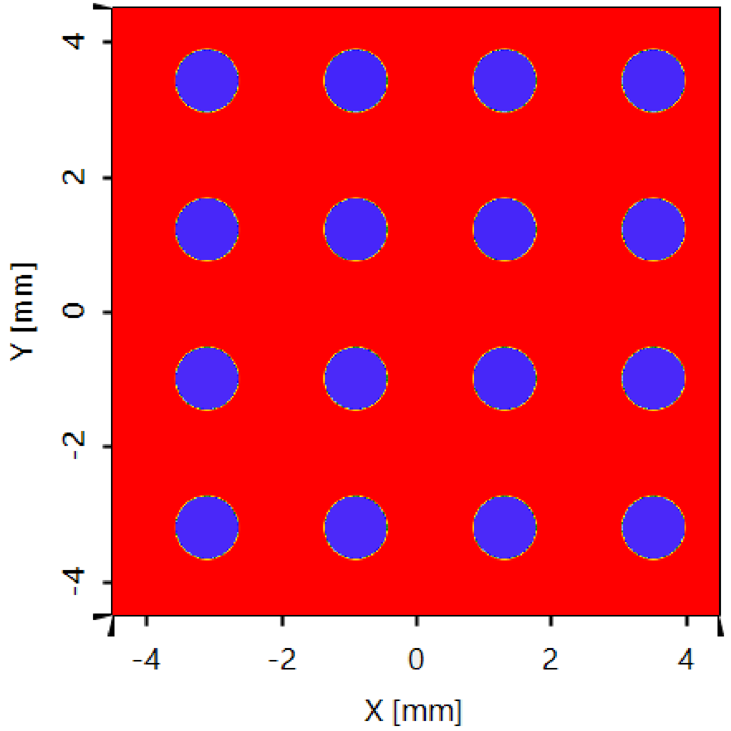
Irradiance in eyebox: FOV (0°, 0°)

Eyebox Uniformity vs. Beam Density

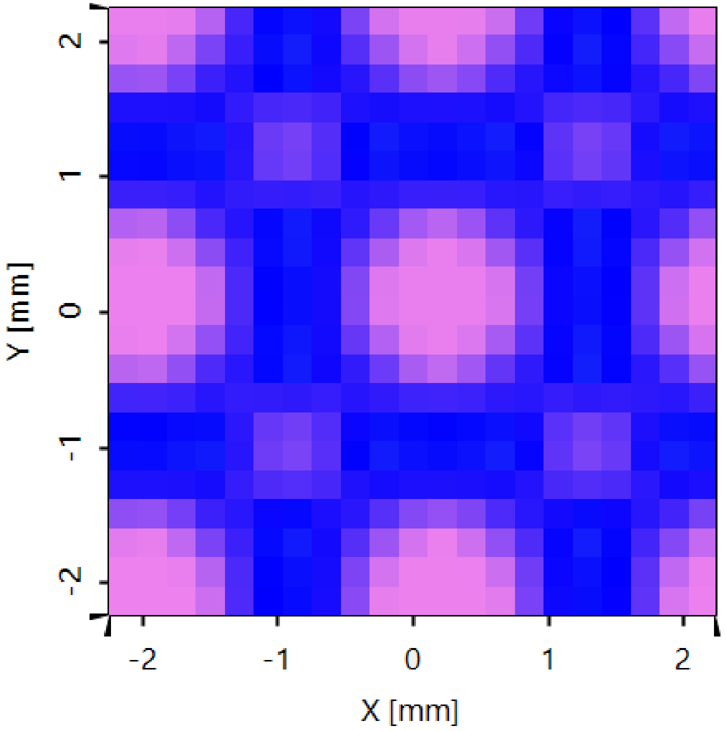


Irradiance in eyebox: FOV (0°, 0°)

Eyebox Uniformity vs. Beam Density



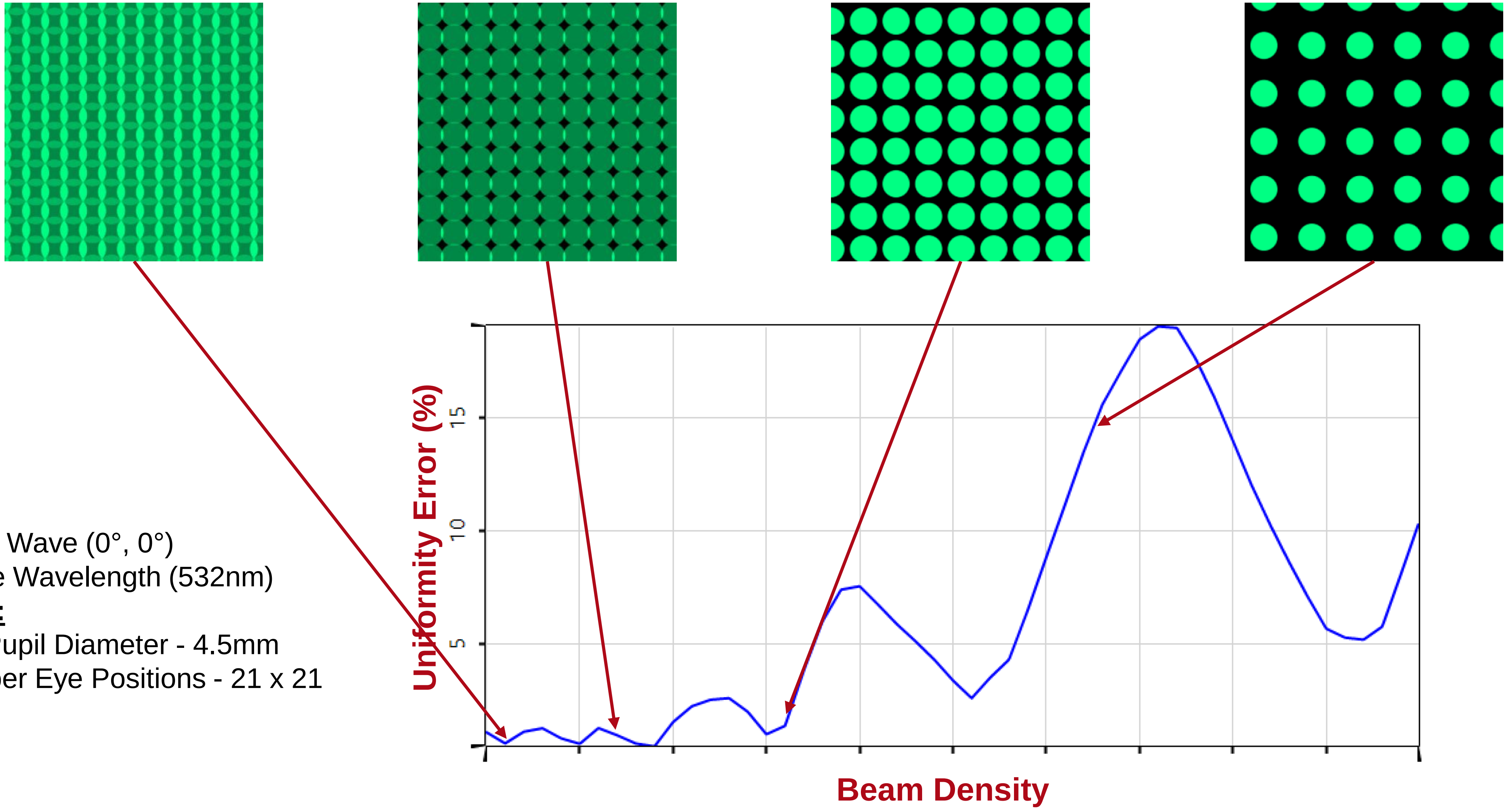
Irradiance in eyebox: FOV (0°, 0°)



Radiance FOV (0°, 0°)

Uniformity: 10.5%

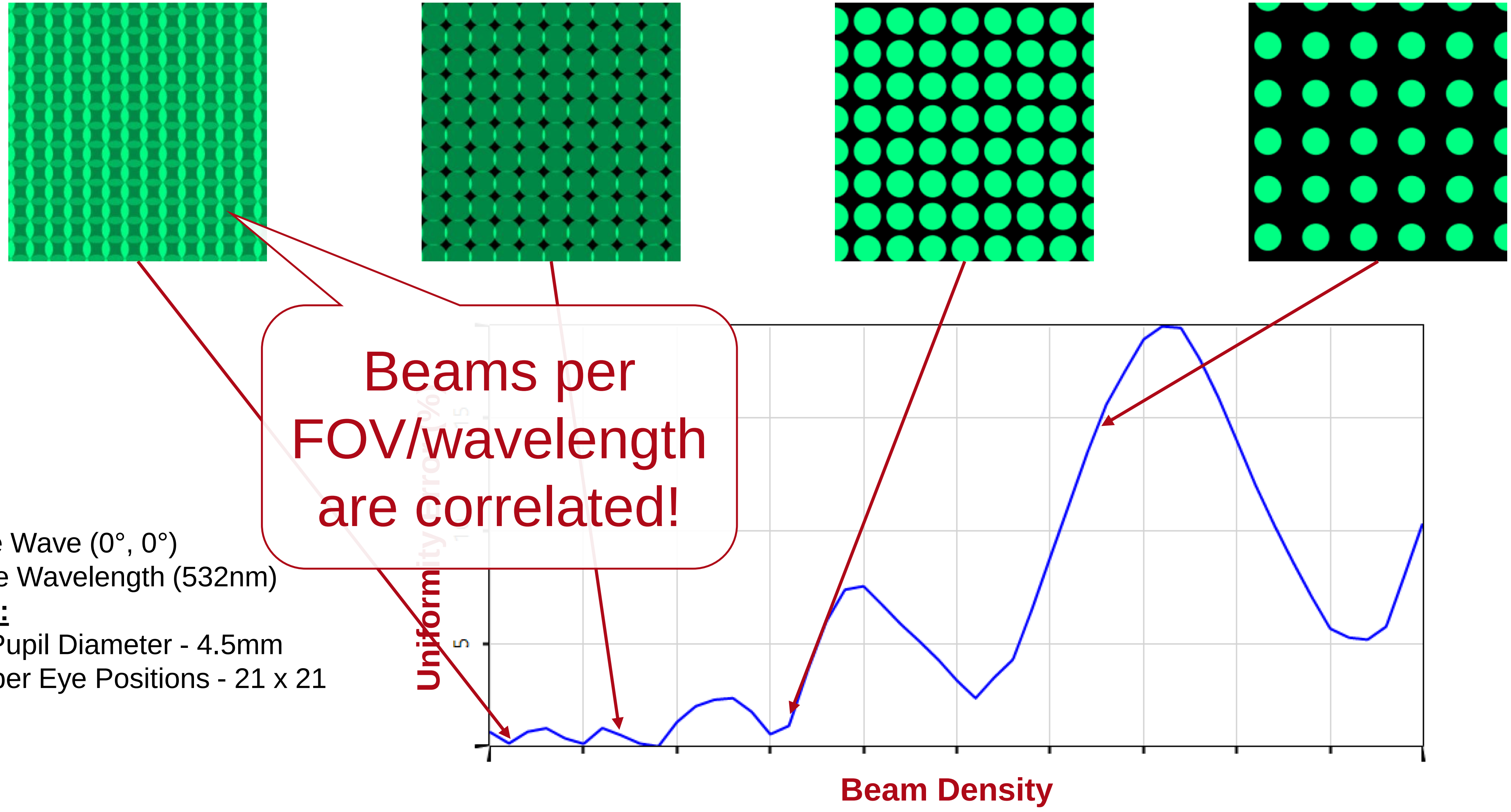
Eyebox Uniformity vs. Beam Density: Single Wavelength



Source
- Plane Wave (0°, 0°)
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

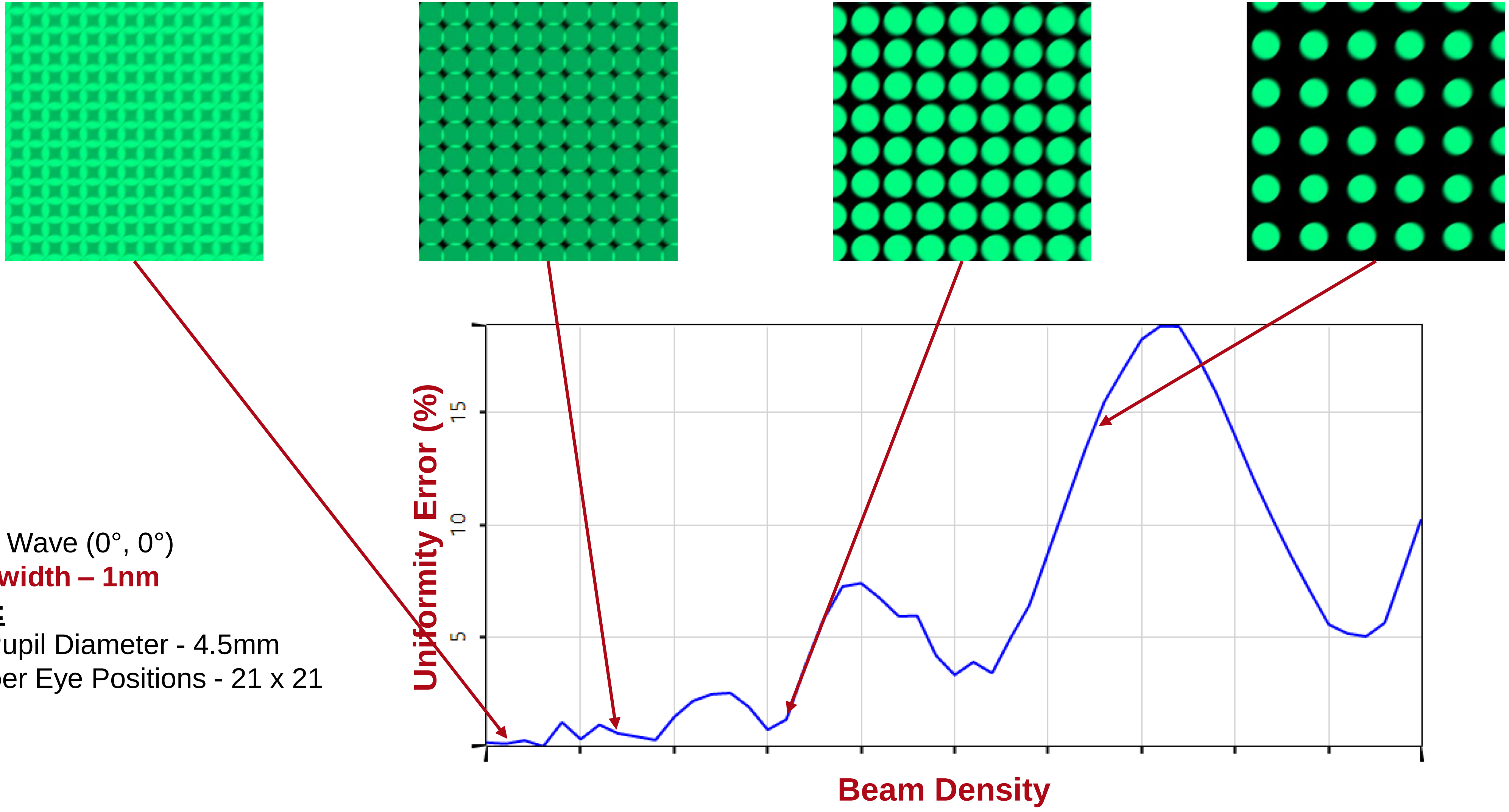
Eyebox Uniformity vs. Beam Density: Single Wavelength



Source
- Plane Wave (0°, 0°)
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Eyebox Uniformity vs. Beam Density: Bandwidth 1nm



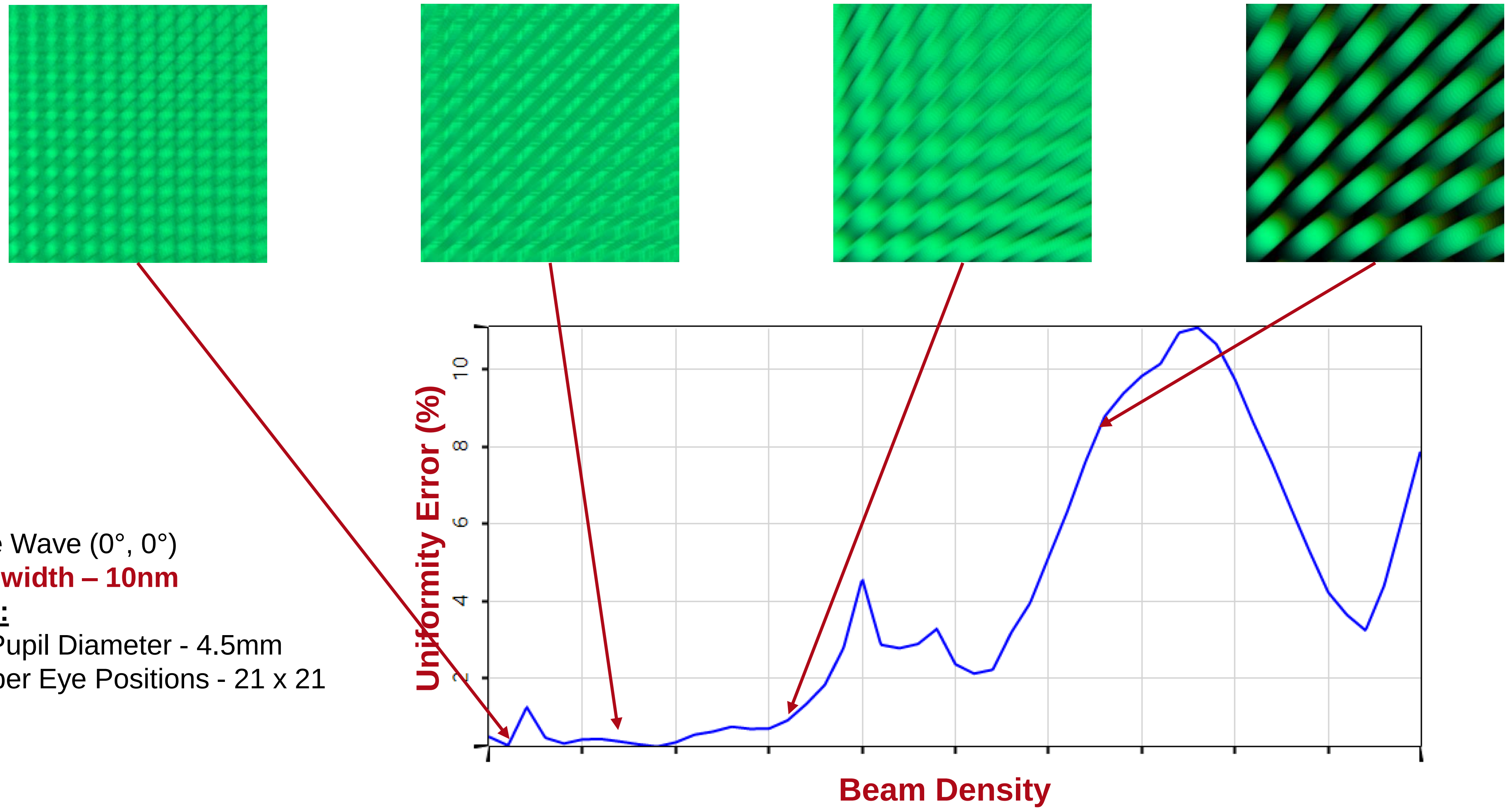
Source

- Plane Wave (0°, 0°)
- **Bandwidth – 1nm**

Detector:

- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

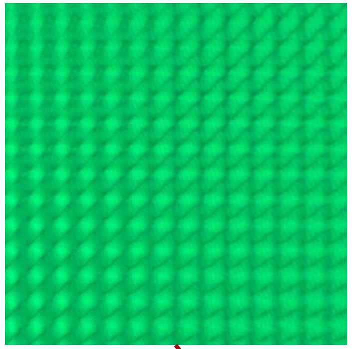
Eyebox Uniformity vs. Beam Density: Bandwidth 10nm

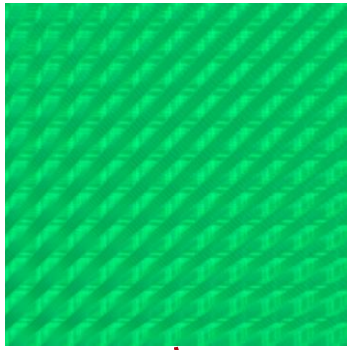


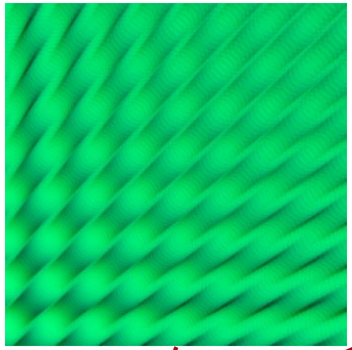
Source
- Plane Wave (0°, 0°)
- **Bandwidth – 10nm**

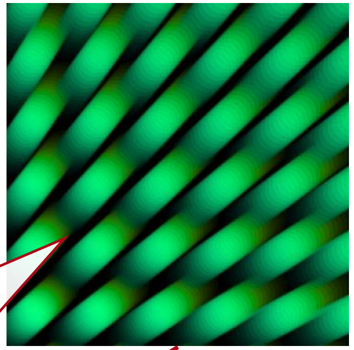
Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

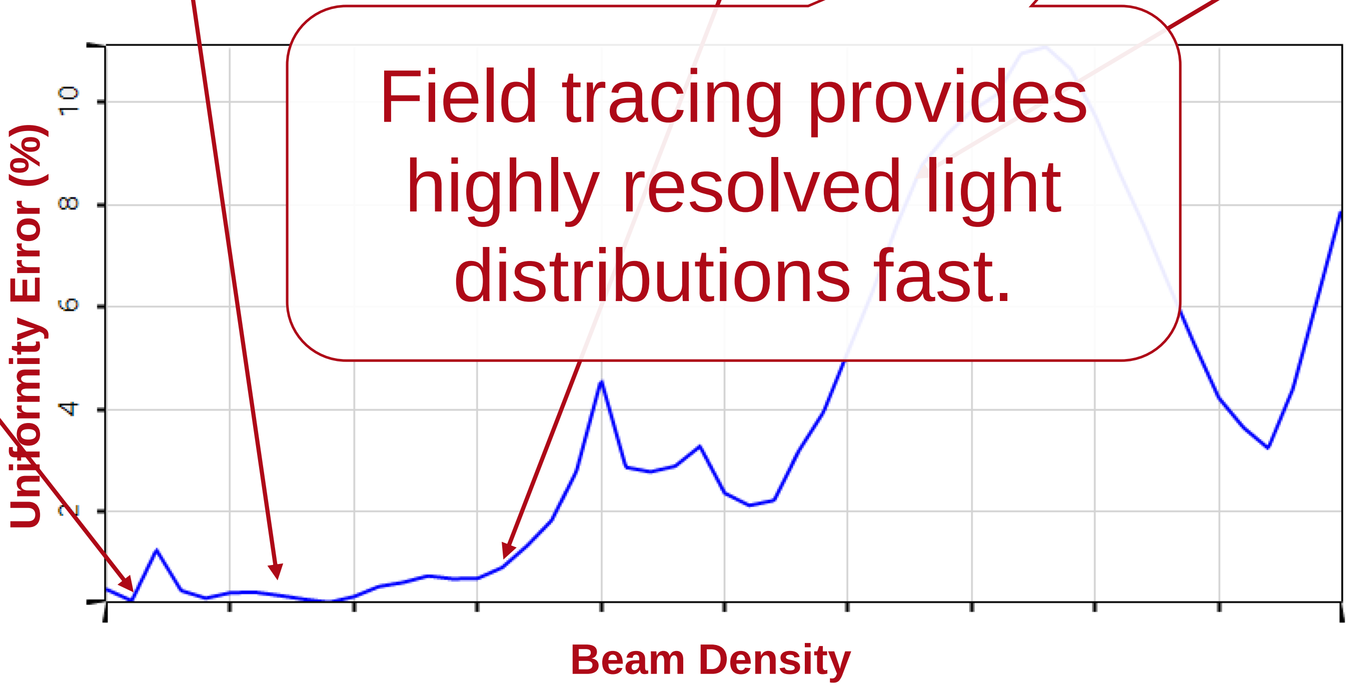
Eyebox Uniformity vs. Beam Density: Bandwidth 10nm







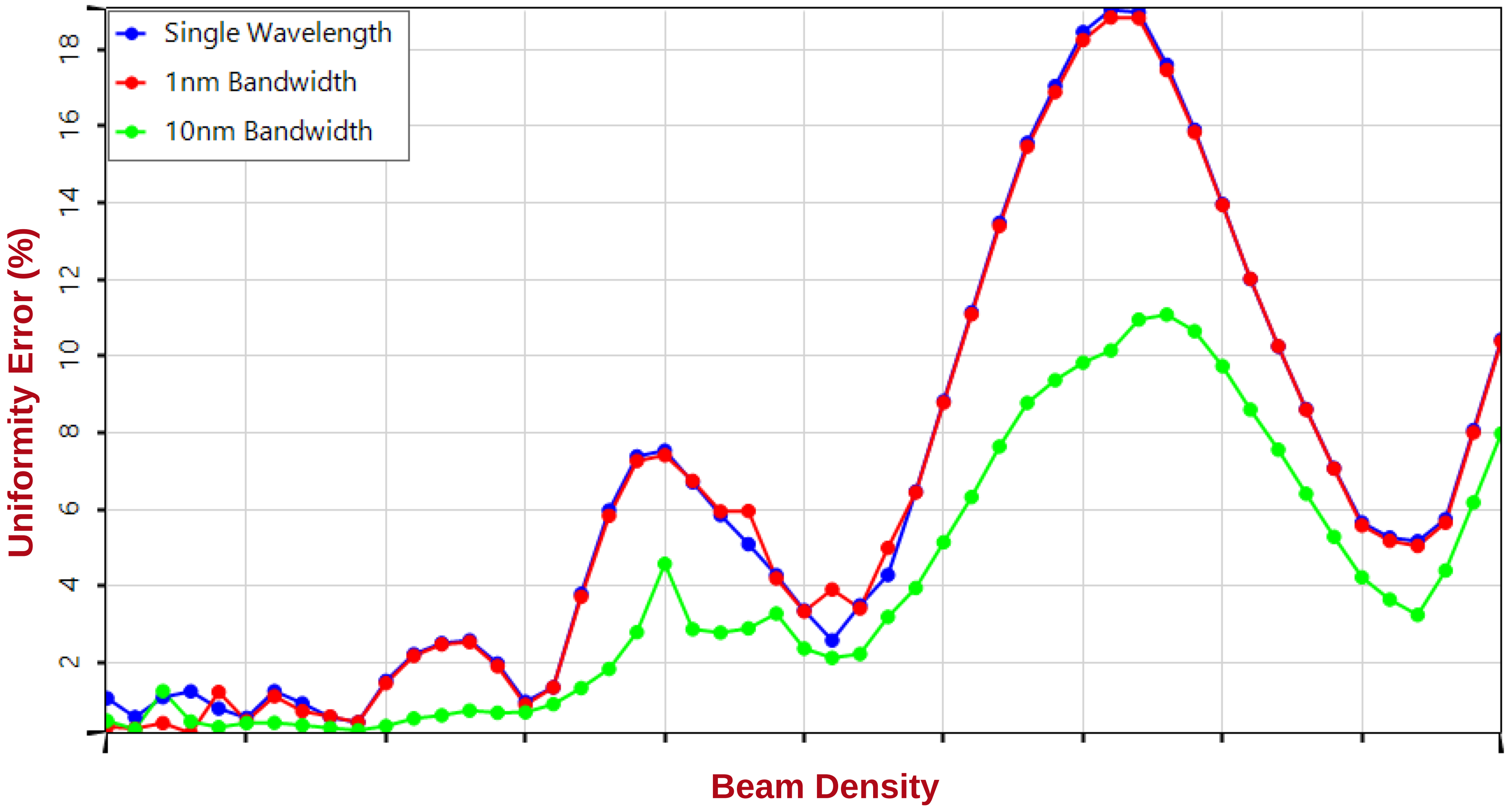




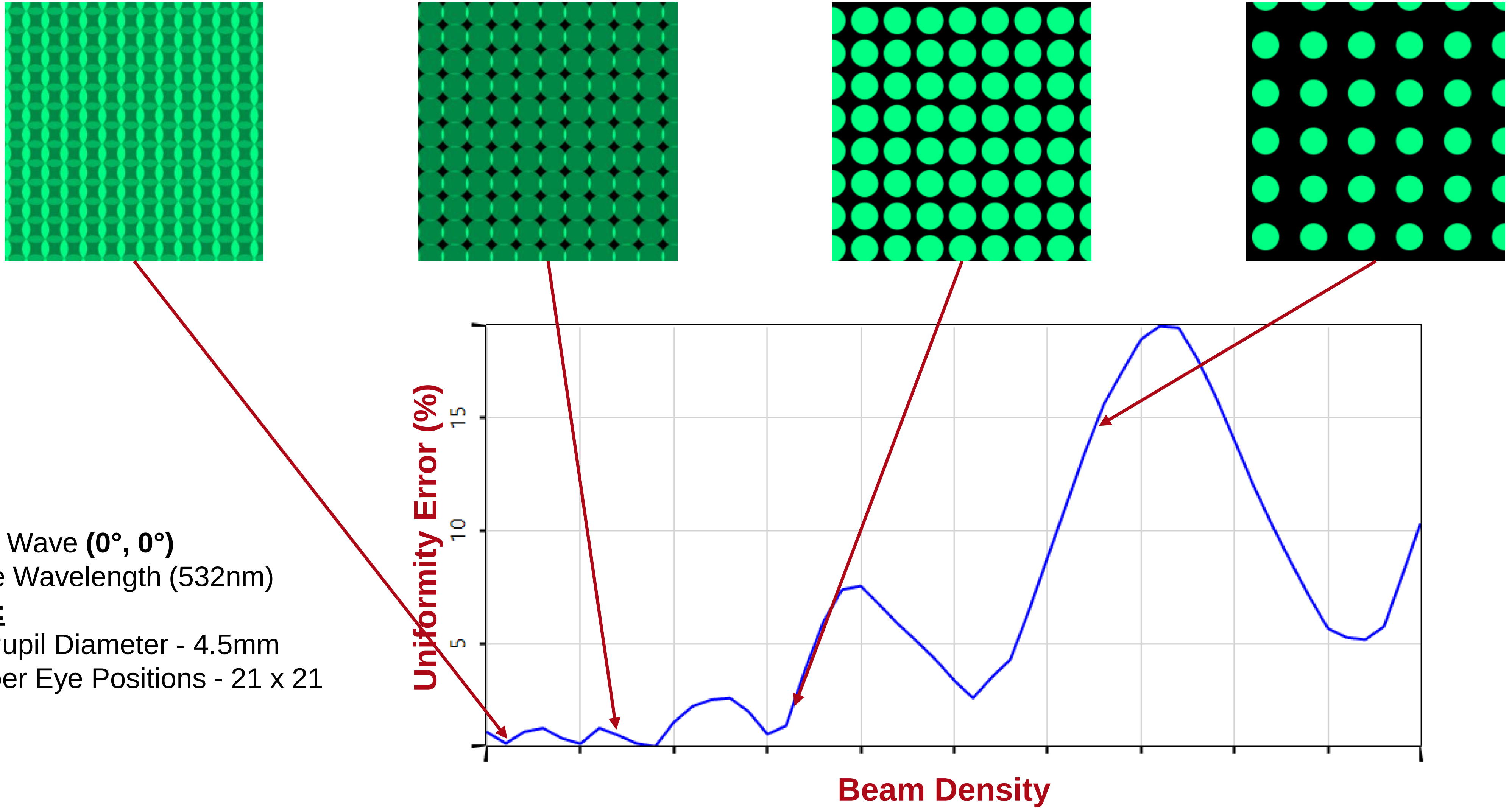
Source
- Plane Wave (0°, 0°)
- **Bandwidth – 10nm**

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Uniformity vs. Beam Density – Comparison Bandwidths



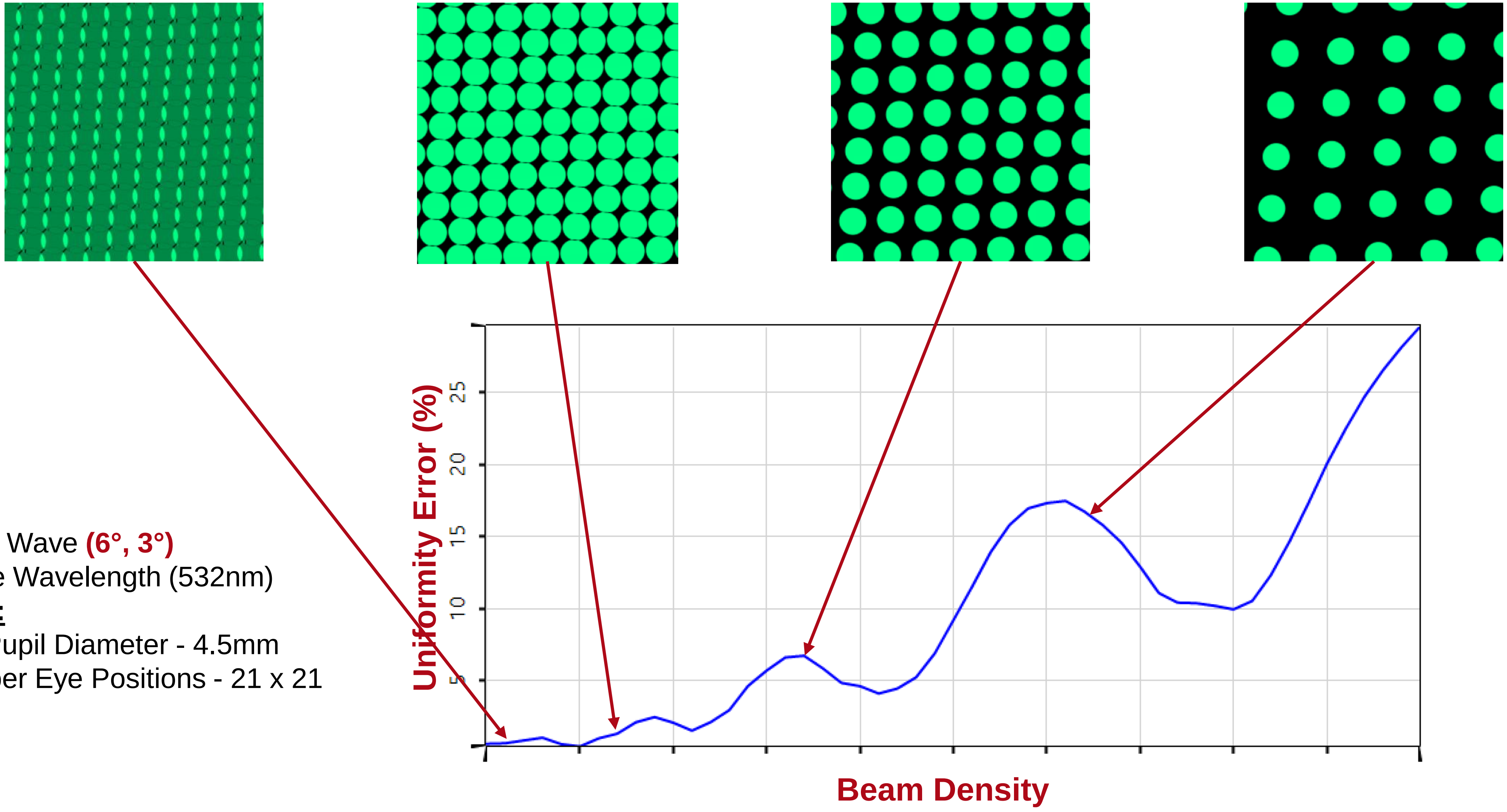
Eyebox Uniformity vs. Beam Density: FOV 1



Source
- Plane Wave **(0°, 0°)**
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

Eyebox Uniformity vs. Beam Density: FOV 2



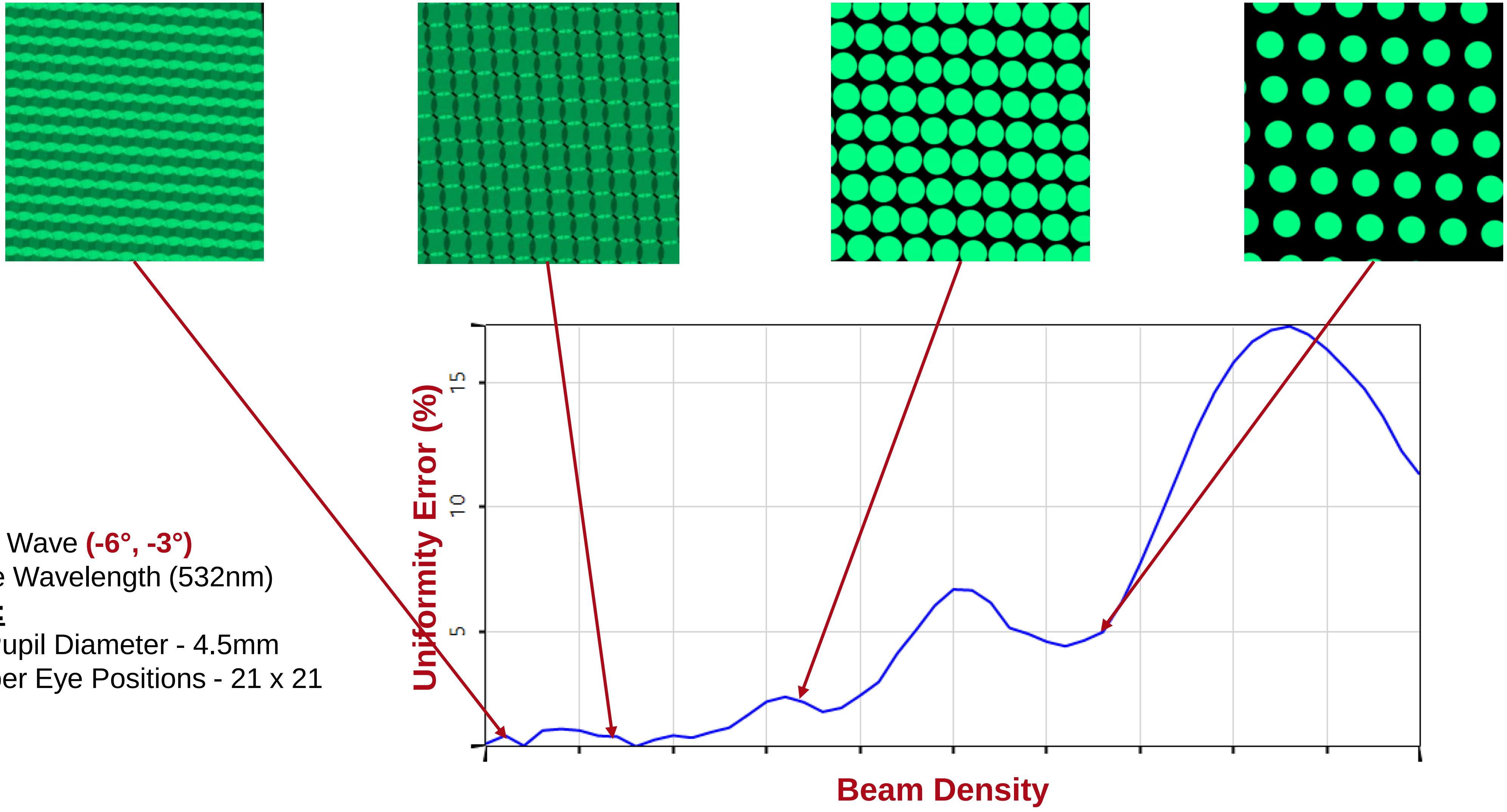
Source

- Plane Wave **(6°, 3°)**
- Single Wavelength (532nm)

Detector:

- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

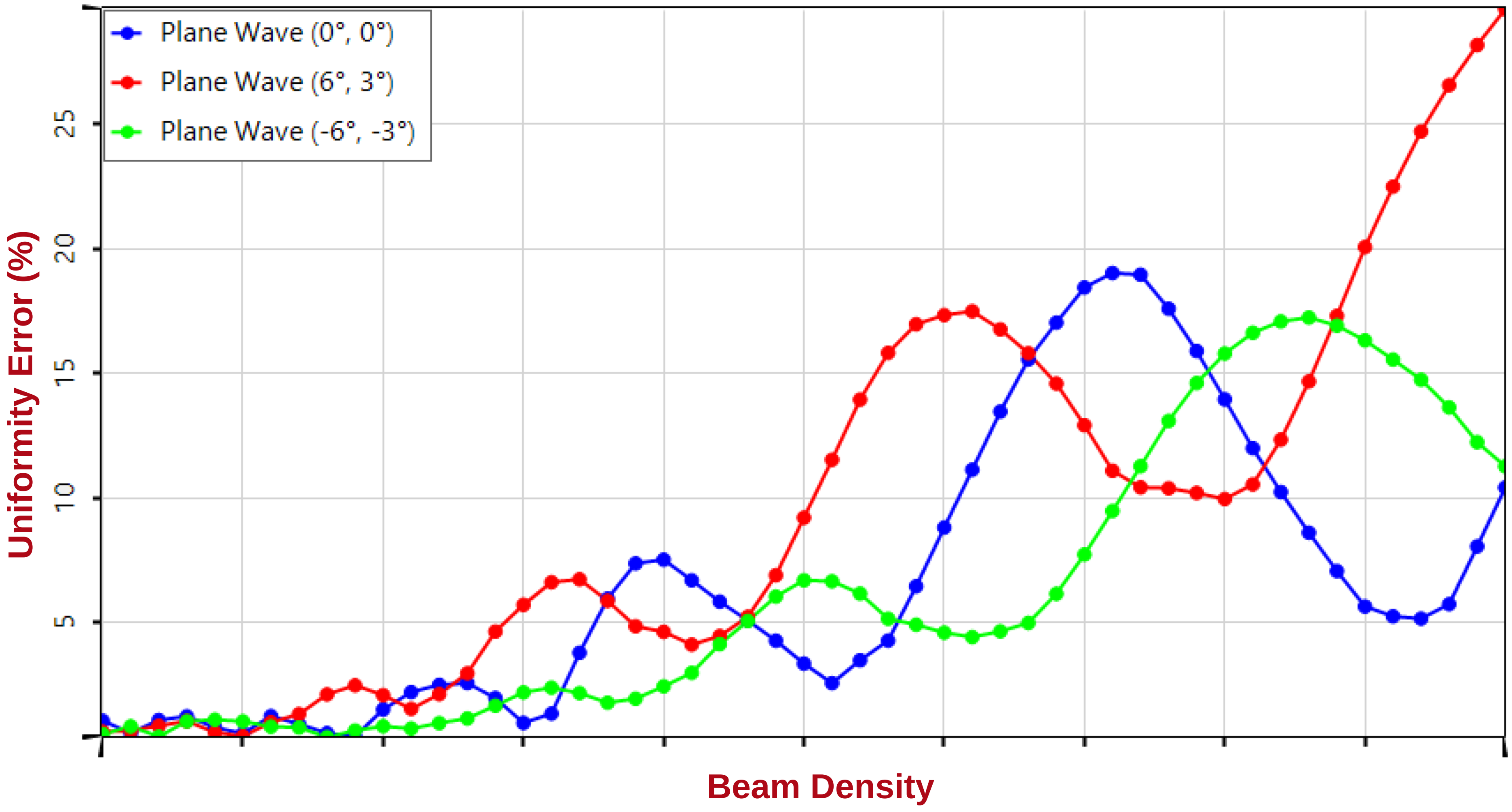
Eyebox Uniformity vs. Beam Density: FOV 3



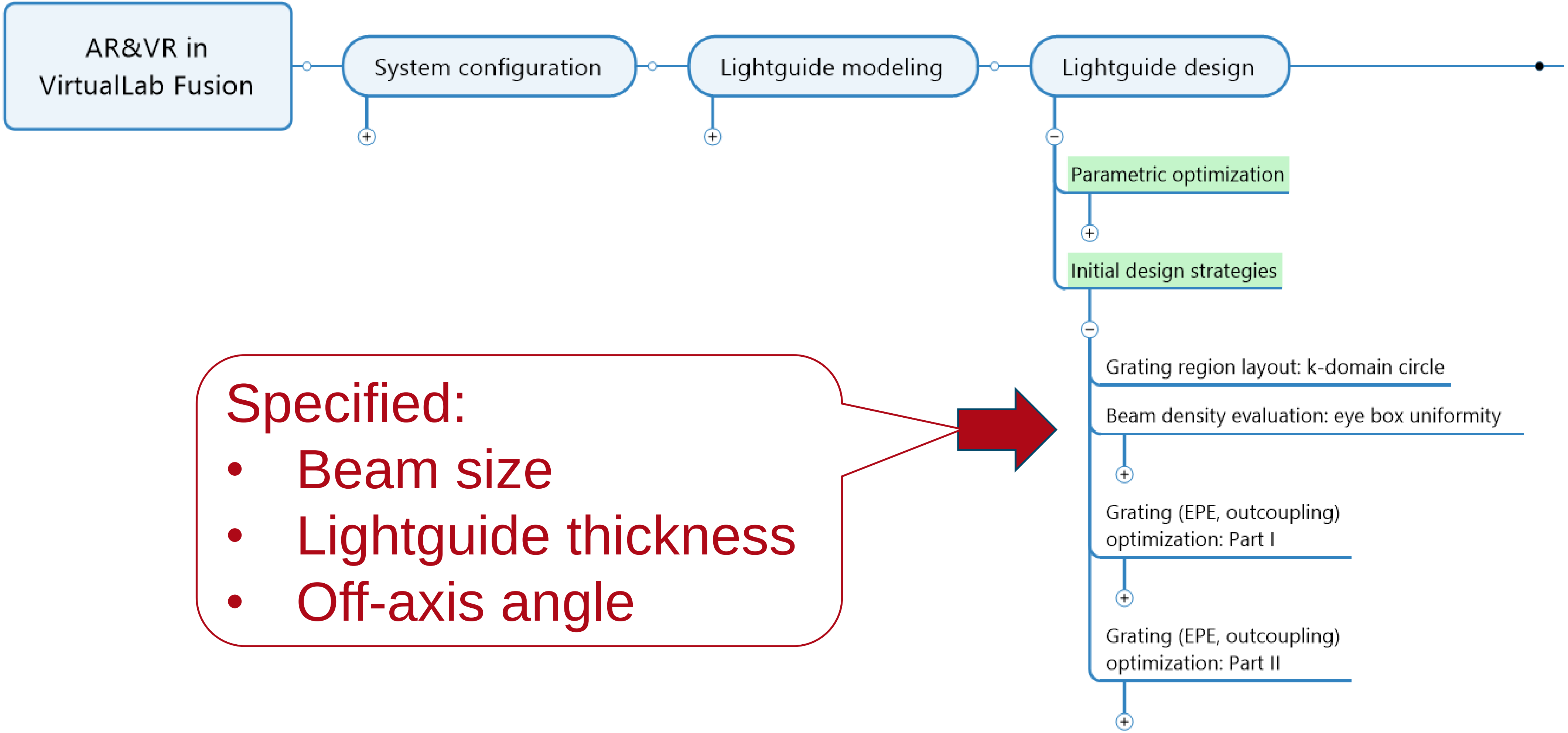
Source
- Plane Wave **(-6°, -3°)**
- Single Wavelength (532nm)

Detector:
- Eye Pupil Diameter - 4.5mm
- Number Eye Positions - 21 x 21

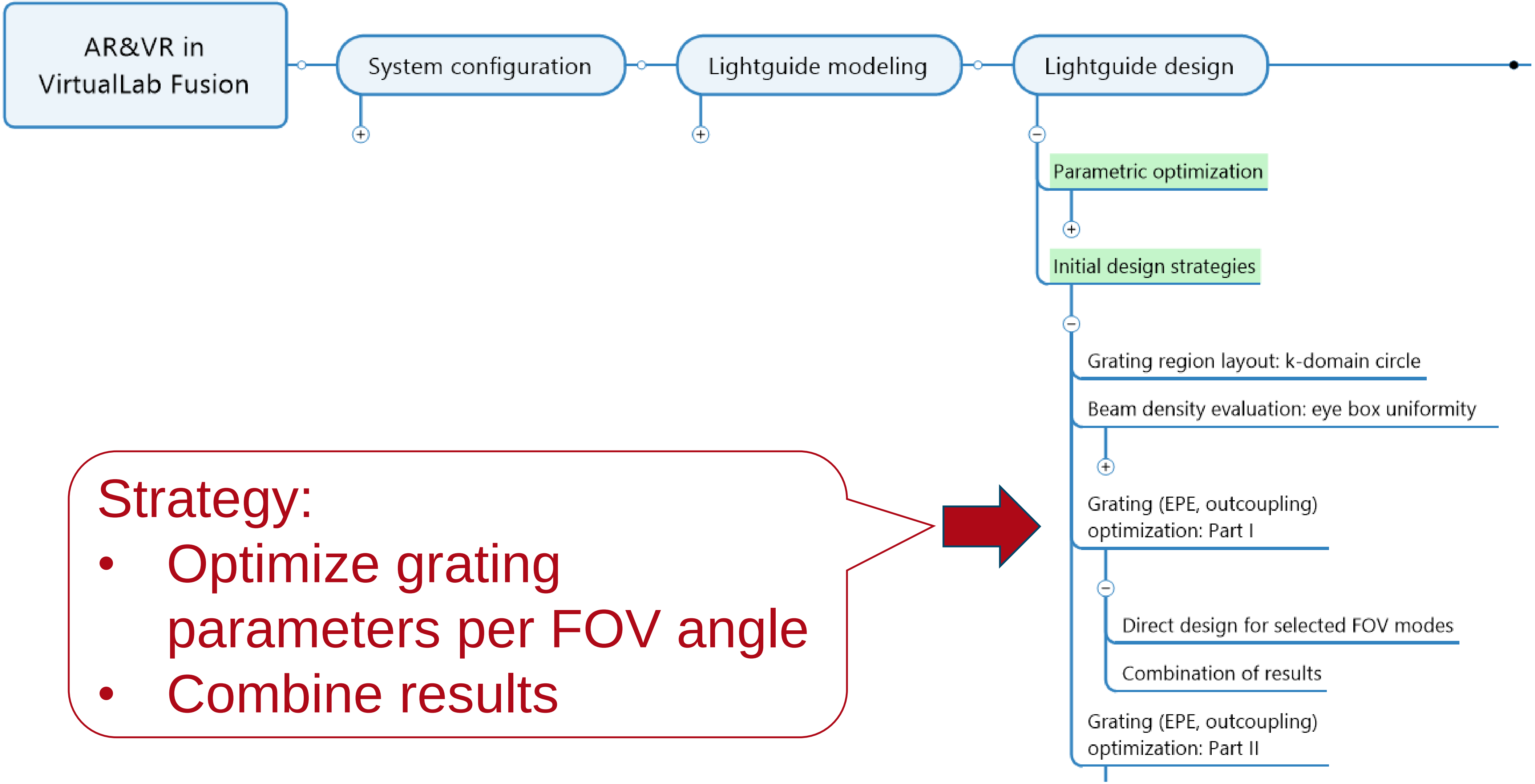
Uniformity vs. Beam Density: Comparison Different FOVs



Lightguide Modeling and Design: Grating Optimization



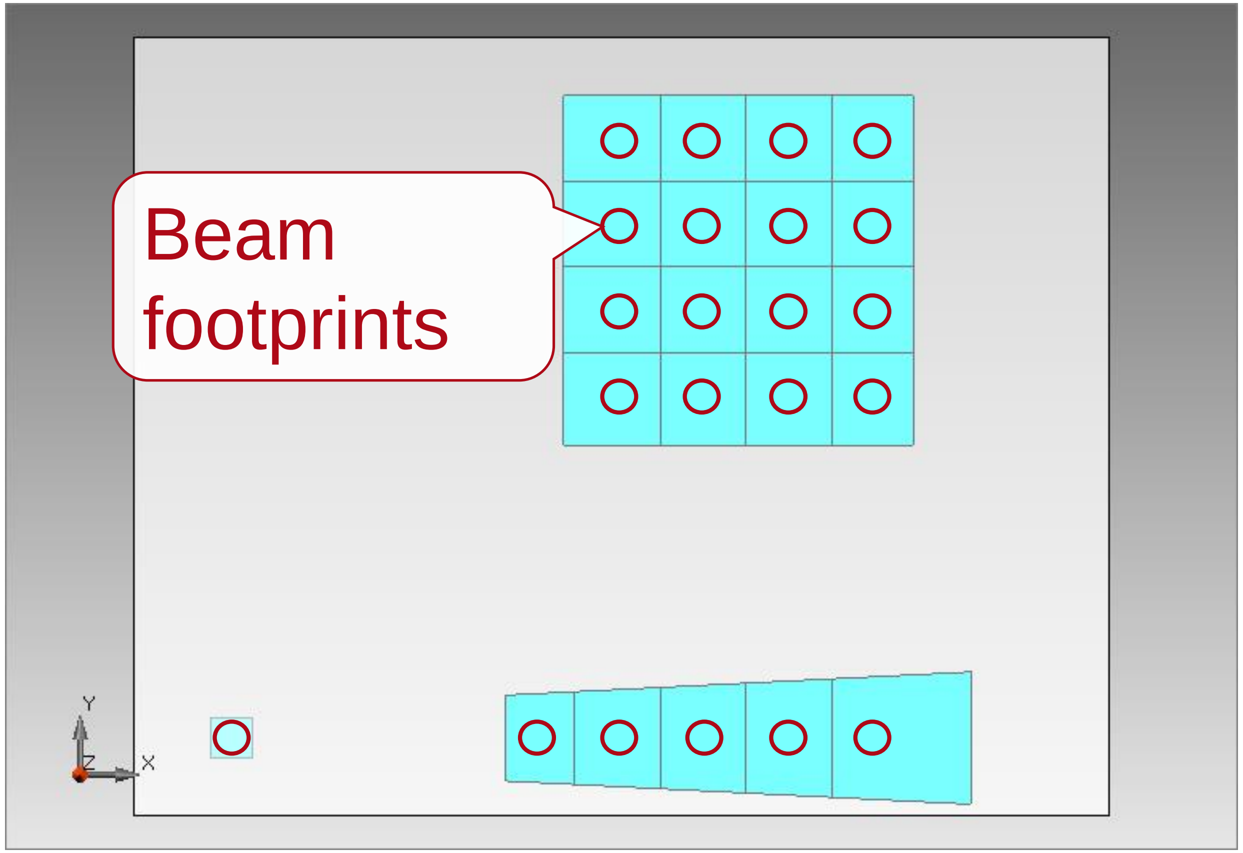
Lightguide Modeling and Design: Grating Optimization

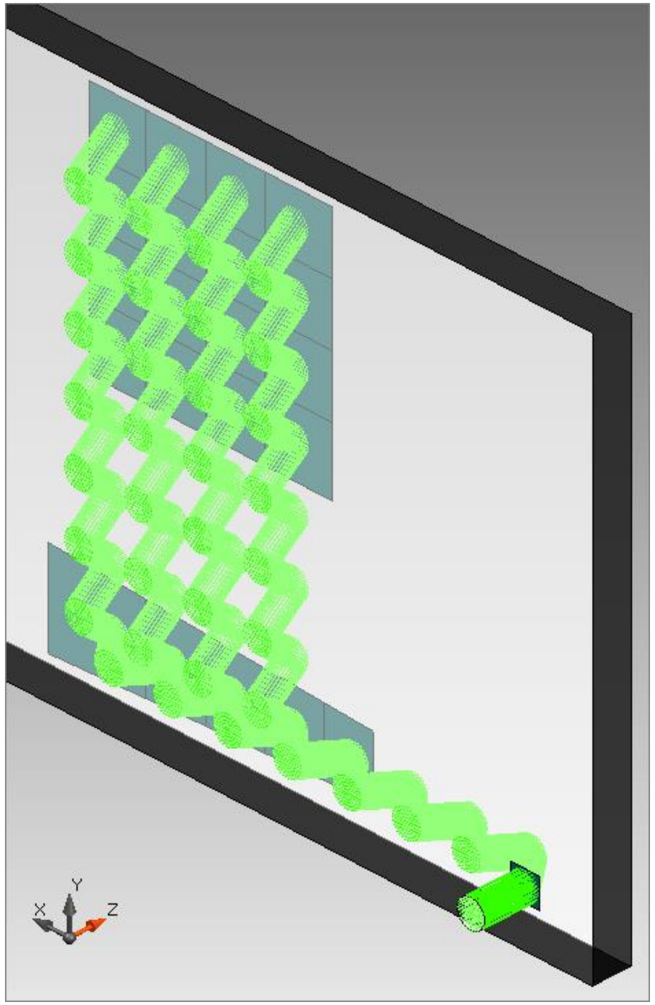


Strategy:

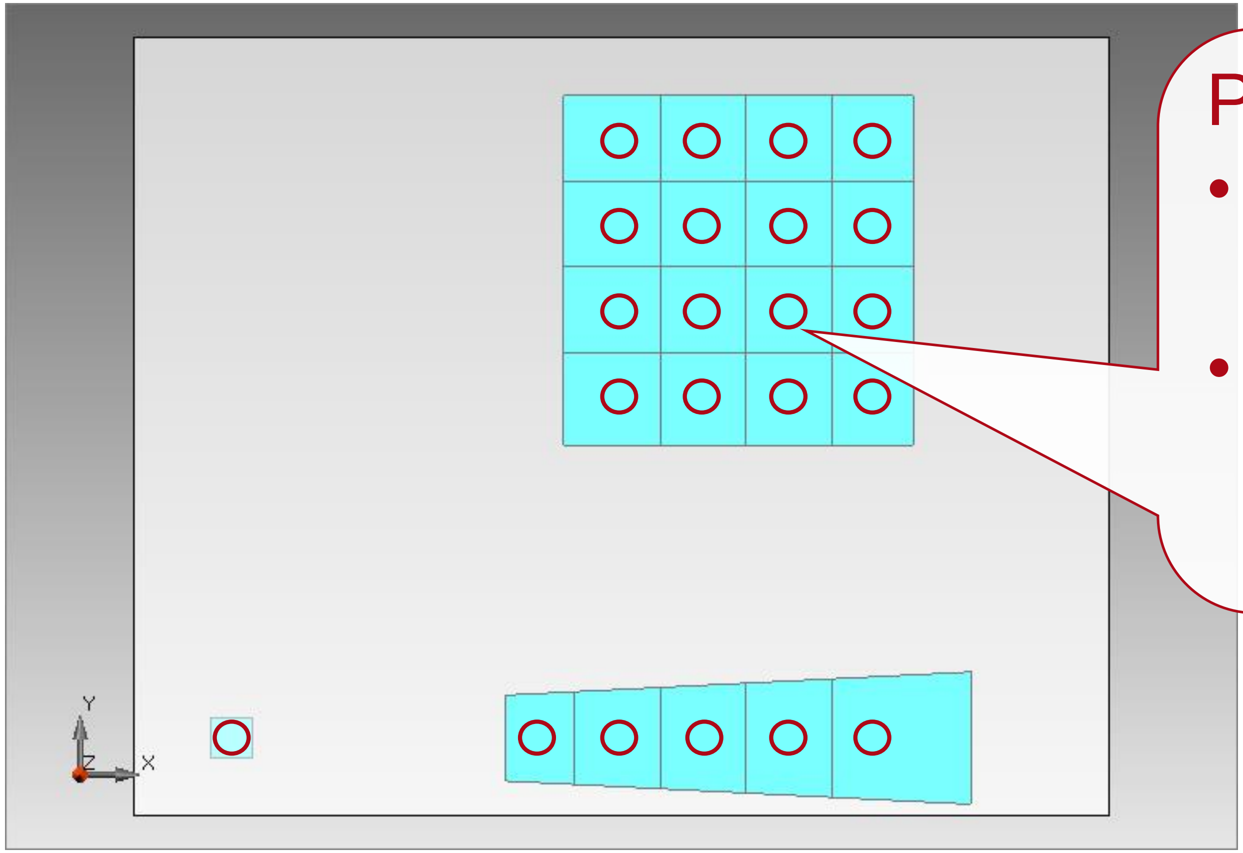
- Optimize grating parameters per FOV angle
- Combine results

Grating Design for FOV Angle (0°, 0°)





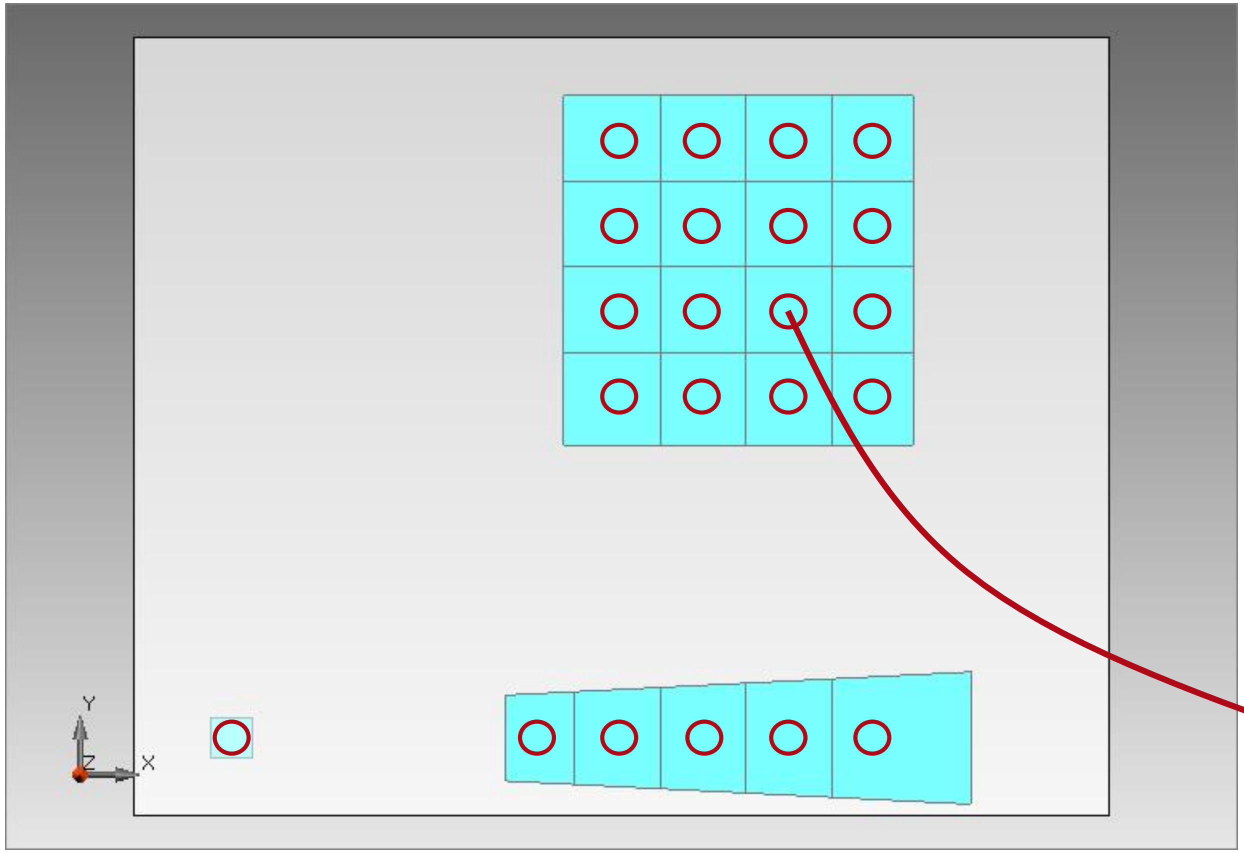
Grating Design per FOV Angle: Flux Control

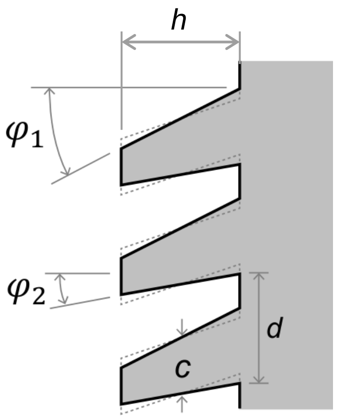


Per footprint of beam:

- Control percental flux into required directions
- Optimize local grating parameters to obtain required flux

Grating Design per FOV Angle: Grating Analysis and Selection





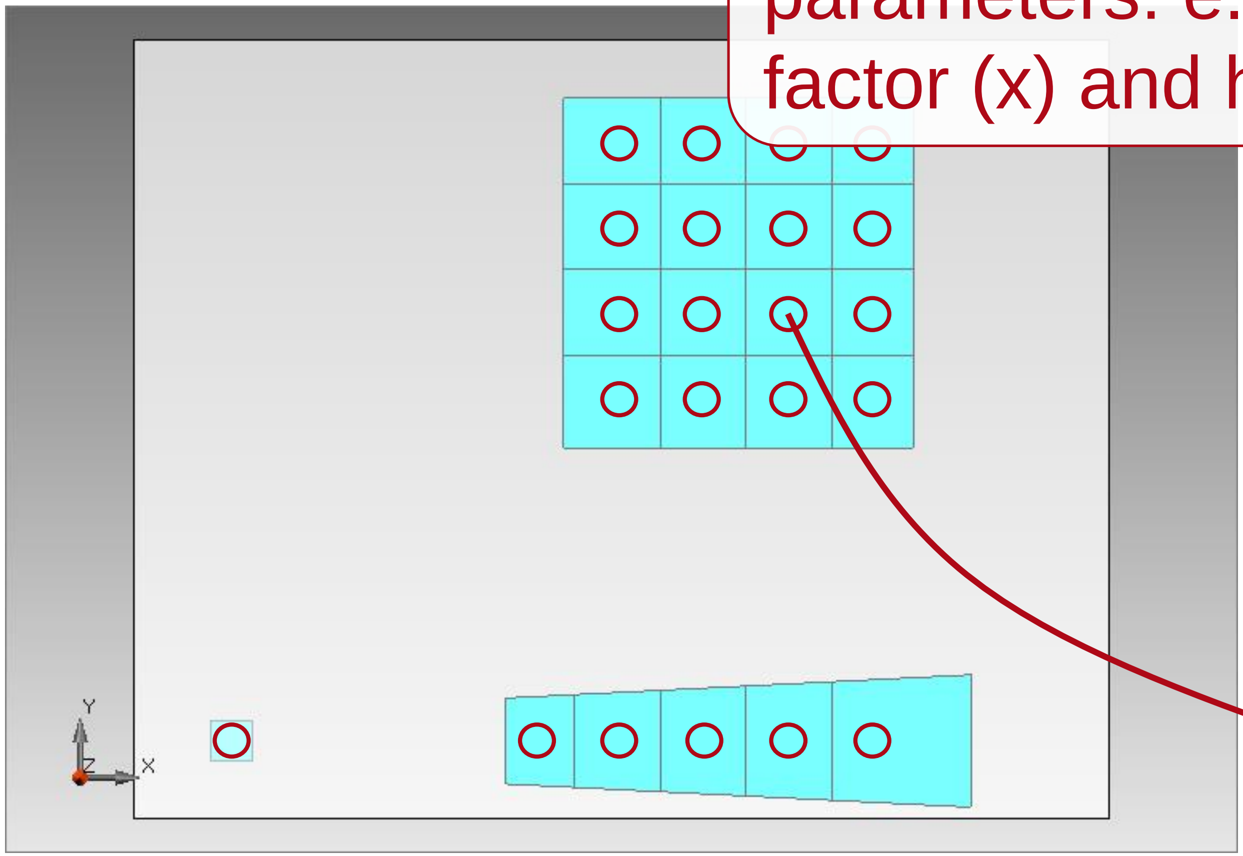
example slanted grating structure

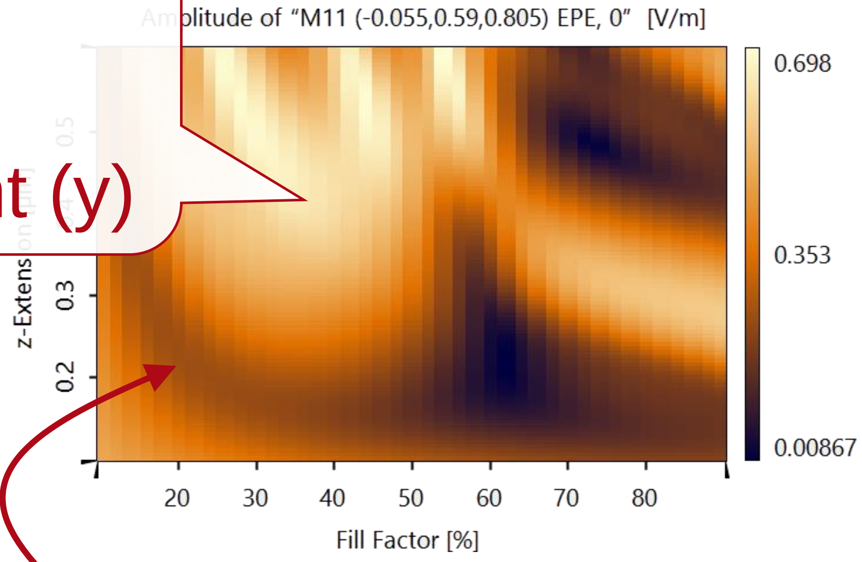
Calculation of Rayleigh matrix for given input beam parameters

$$\begin{pmatrix} E_{x,\mathrm{out}} \\ E_{y,\mathrm{out}} \end{pmatrix}_{k_{\mathrm{out},m}} = \begin{bmatrix} R_{xx} & R_{yx} \\ R_{xy} & R_{yy} \end{bmatrix} \cdot \begin{pmatrix} E_{x,\mathrm{arb,in}} \\ E_{y,\mathrm{arb,in}} \end{pmatrix}_{k_{\mathrm{in}}}$$

Grating Design per FOV Angle: Grating Analysis and Selection

Scan of grating parameters: e.g. fill factor (x) and height (y)



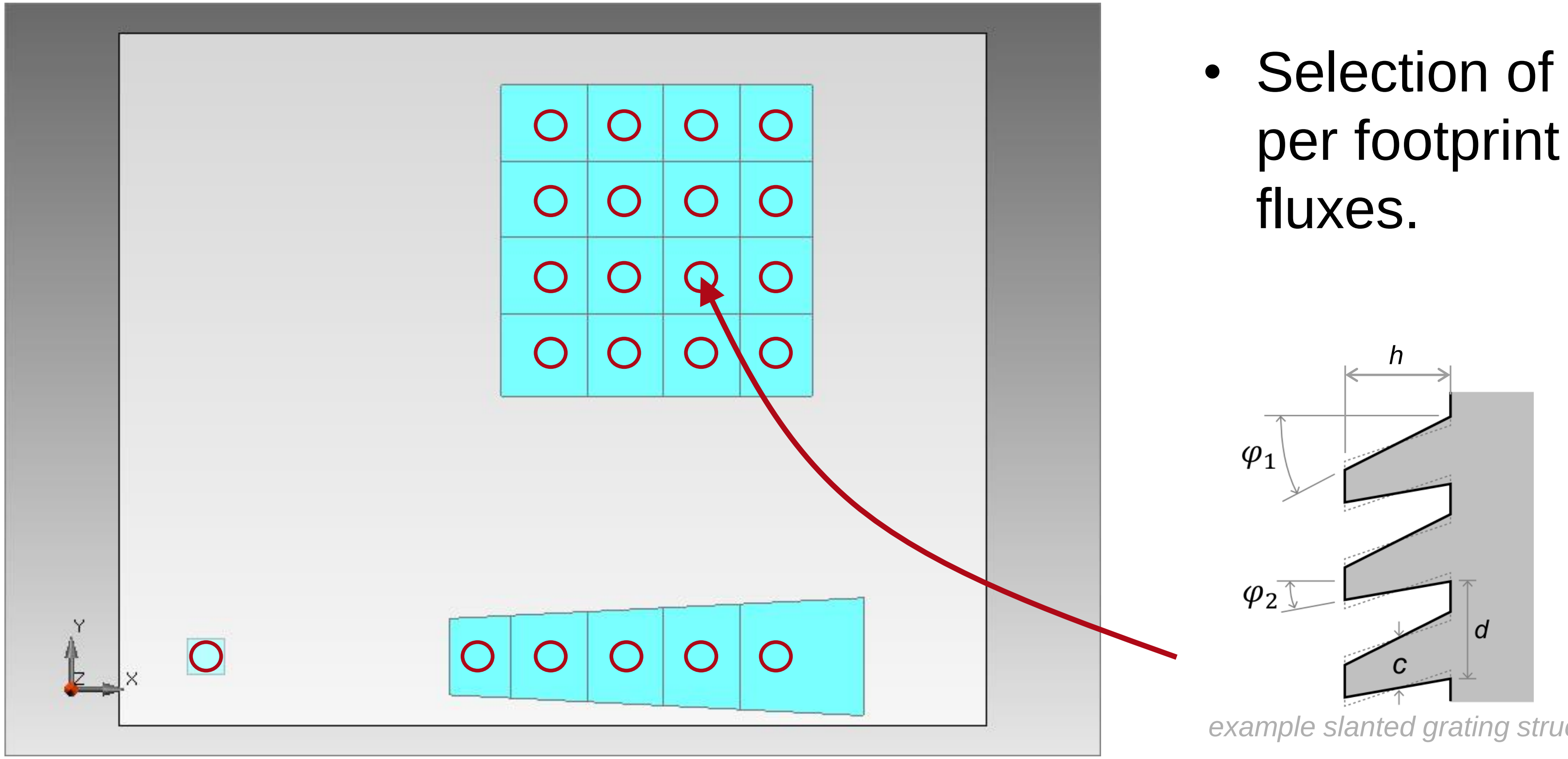


Calculation of Rayleigh matrix for given input beam parameters

$$\begin{pmatrix}E_{x,\mathrm{out}}\\ E_{y,\mathrm{out}}\end{pmatrix}_{k_{\mathrm{out},m}} = \begin{bmatrix}R_{xx} & R_{yx}\\ R_{xy} & R_{yy}\end{bmatrix}\cdot\begin{pmatrix}E_{x,\mathrm{arb,in}}\\ E_{y,\mathrm{arb,in}}\end{pmatrix}_{k_{\mathrm{in}}}$$

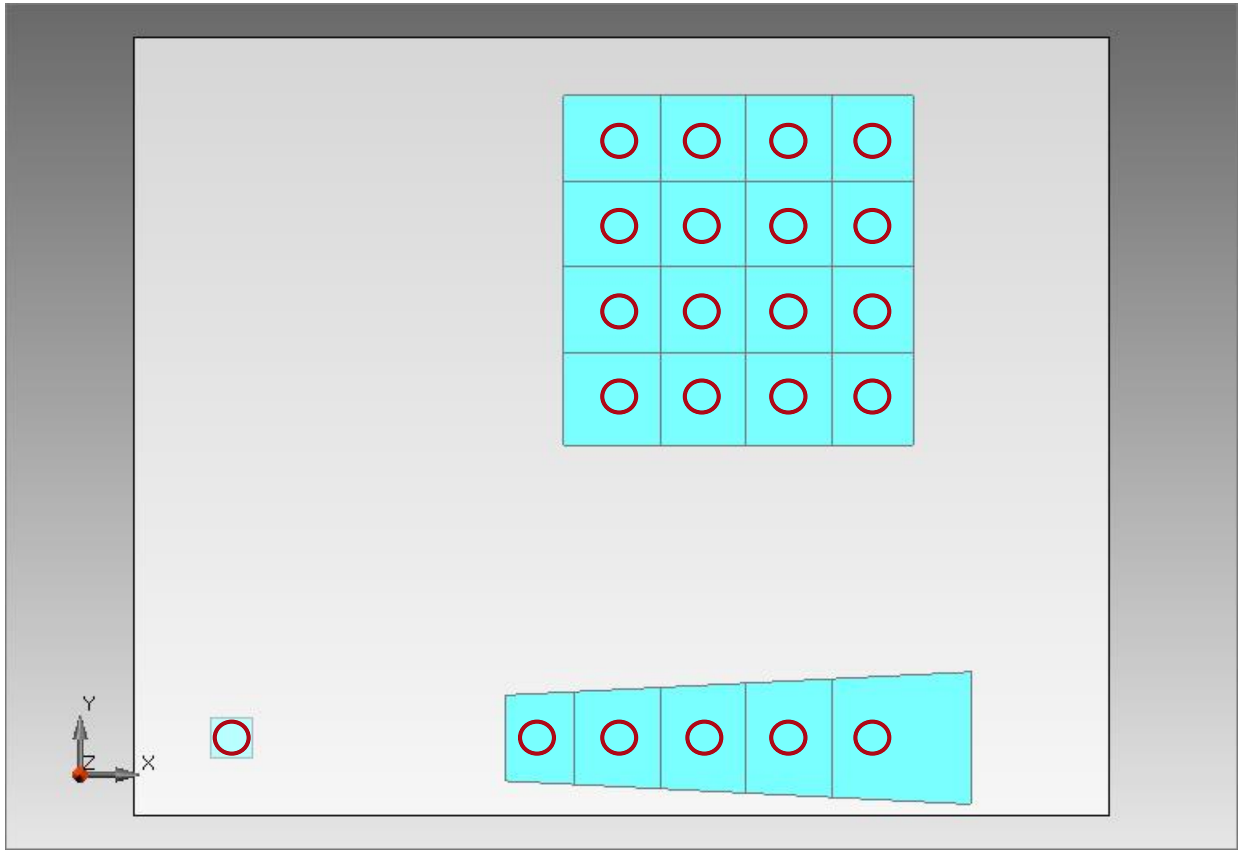
Grating Design per FOV Angle: Grating Analysis and Selection

- Selection of grating parameters per footprint to obtain required fluxes.



example slanted grating structure

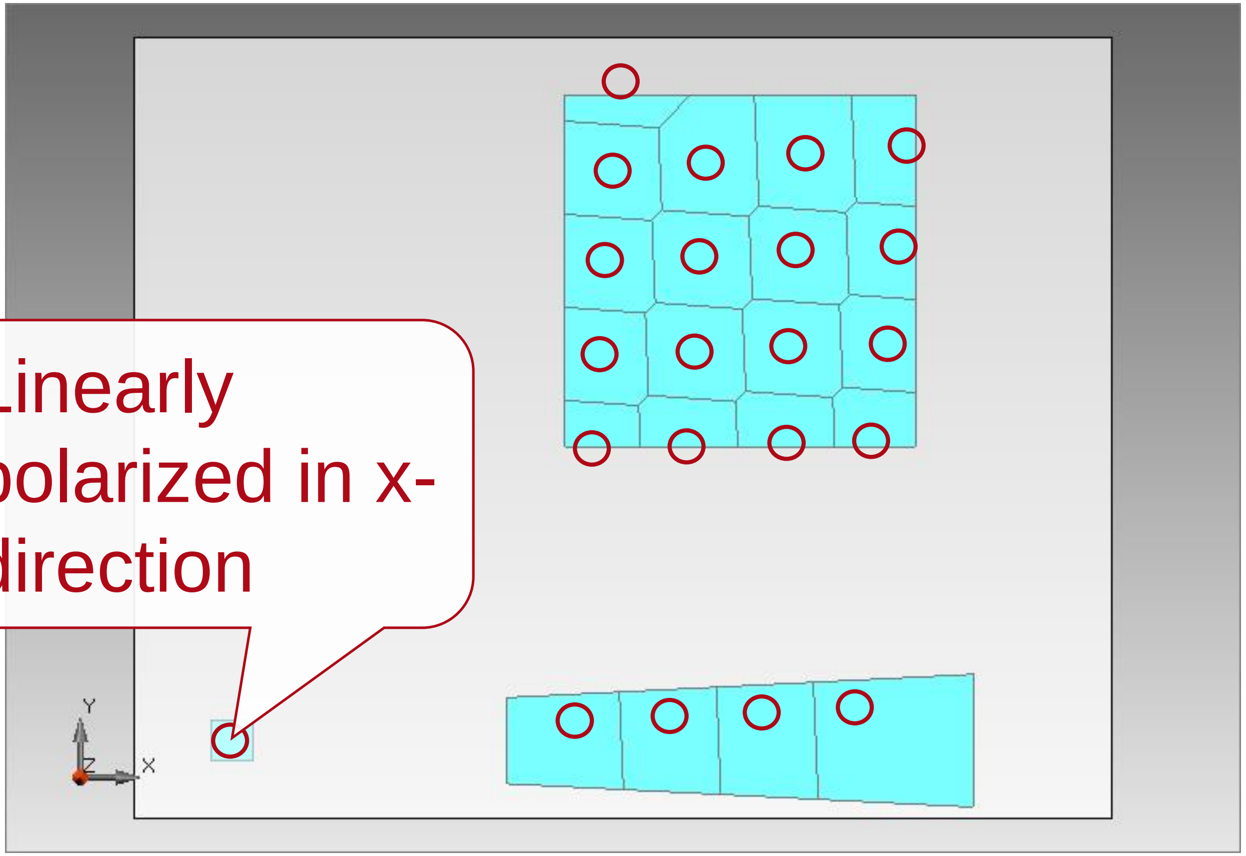
Grating Design per FOV Angle: Grating Analysis and Selection



$$\begin{pmatrix} E_{x,\mathrm{out}} \\ E_{y,\mathrm{out}} \end{pmatrix}_{k_{\mathrm{out},m}} = \begin{bmatrix} R_{xx} & R_{yx} \\ R_{xy} & R_{yy} \end{bmatrix} \cdot \begin{pmatrix} E_{x,\mathrm{arb,in}} \\ E_{y,\mathrm{arb,in}} \end{pmatrix}_{k_{\mathrm{in}}}$$

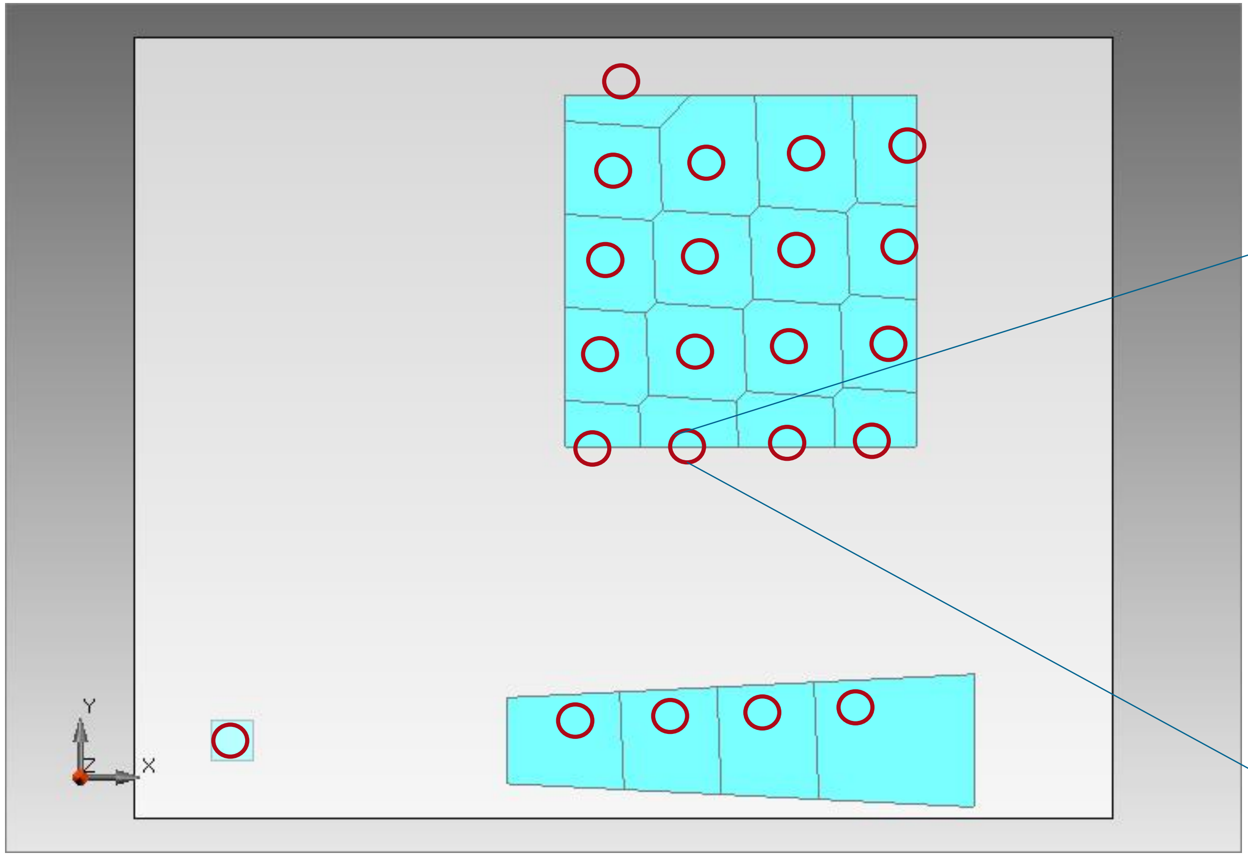
- Storage of Rayleigh matrices in lookup table.
- Can be applied to arbitrary polarization for optimizing grating parameters.

Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation

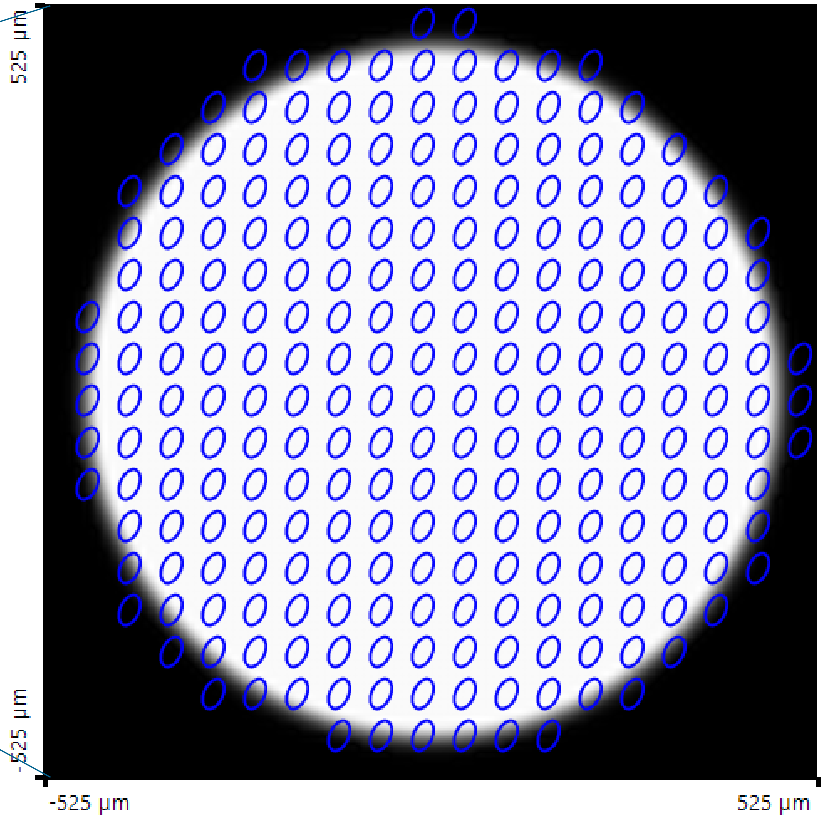


Linearly polarized in x-direction

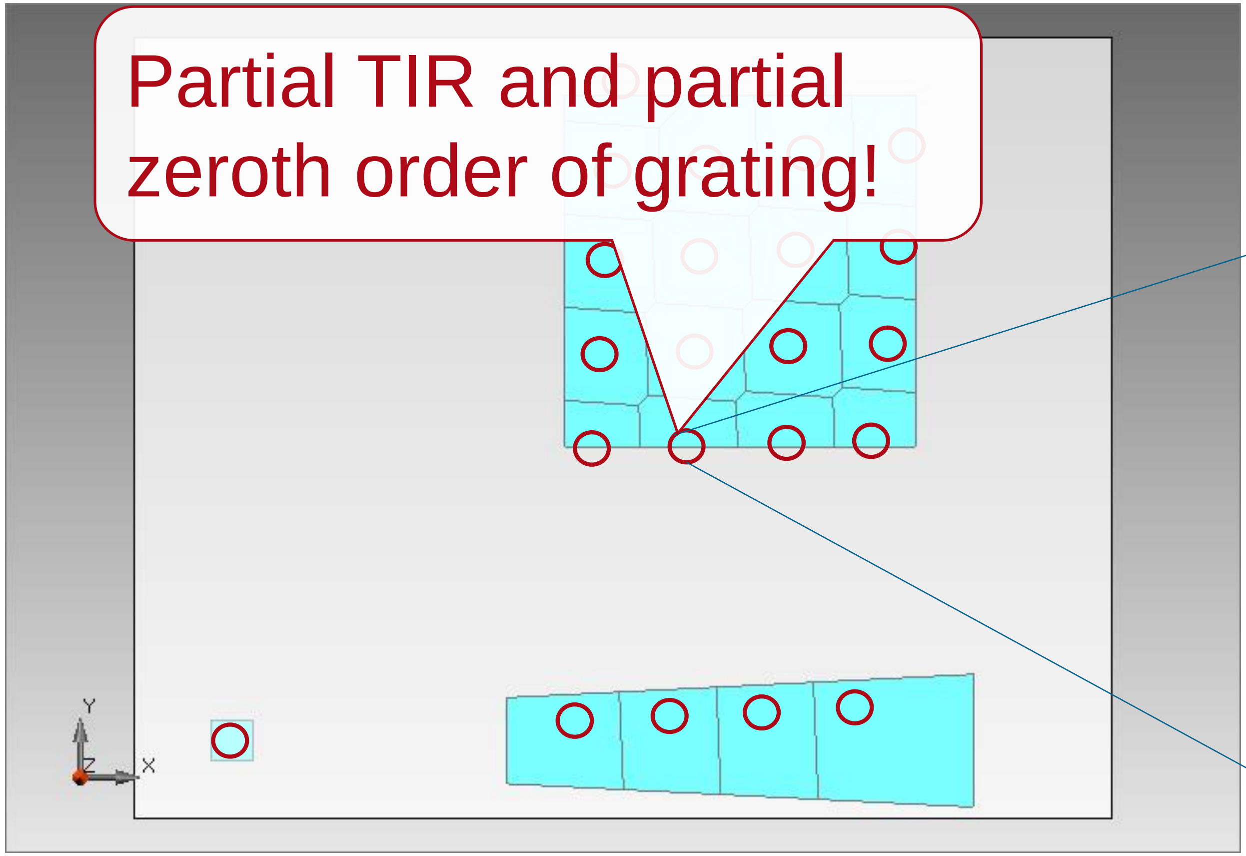
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



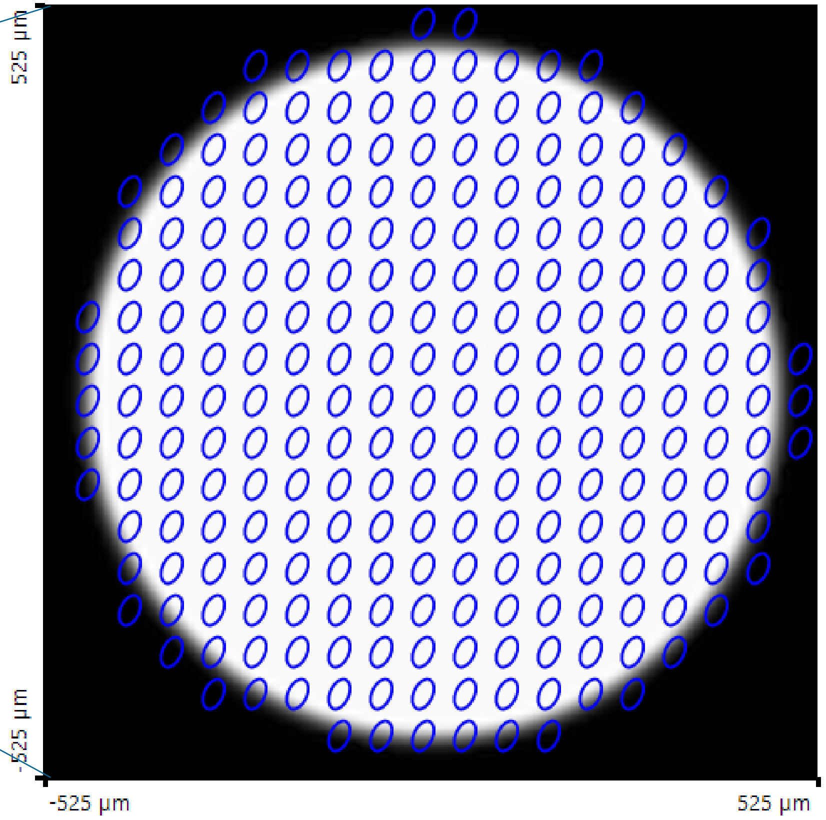
Incident light at grating interaction (uniform polarization)



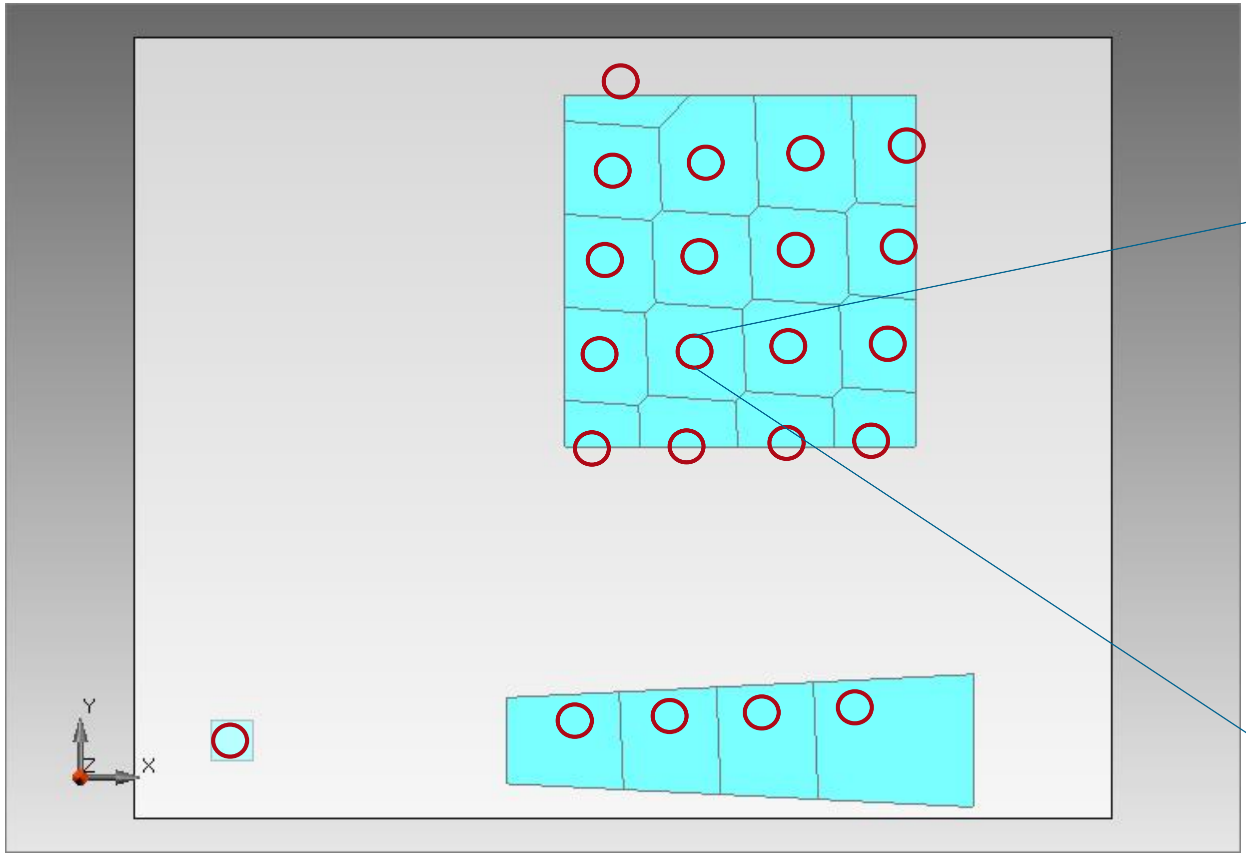
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



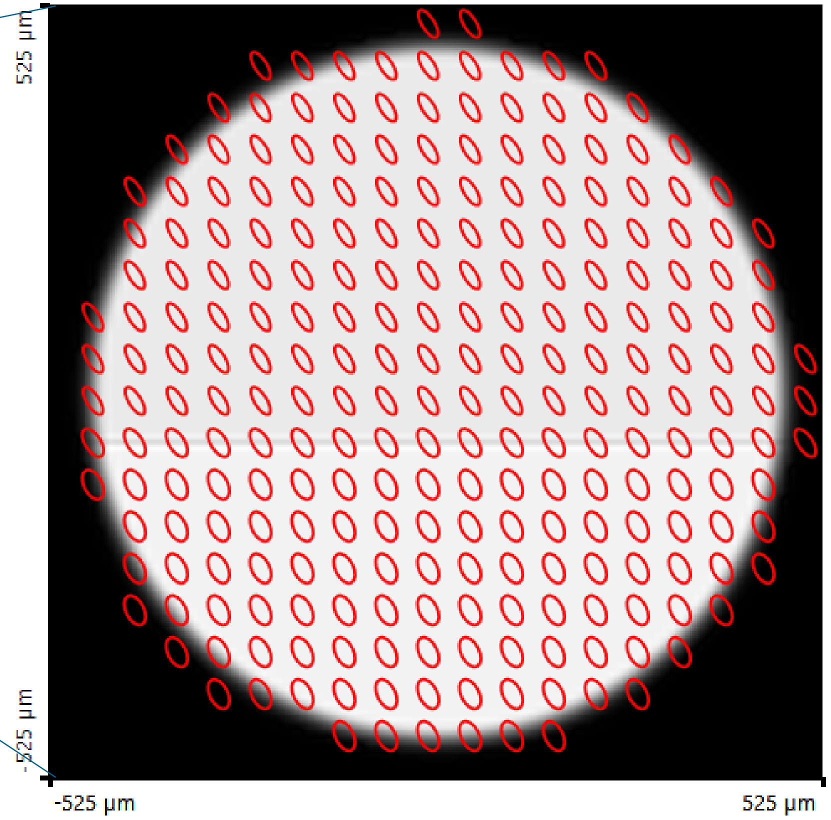
Incident light at grating interaction (uniform polarization)



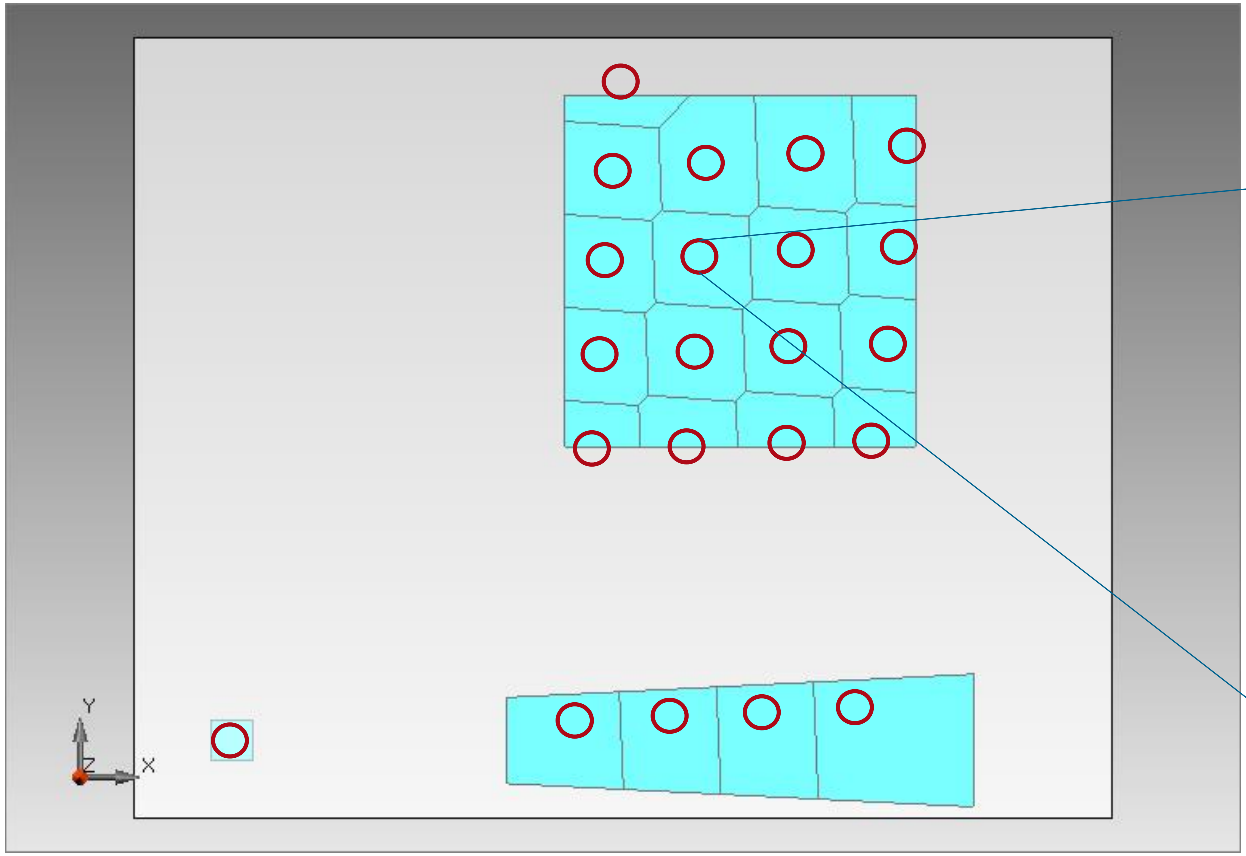
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



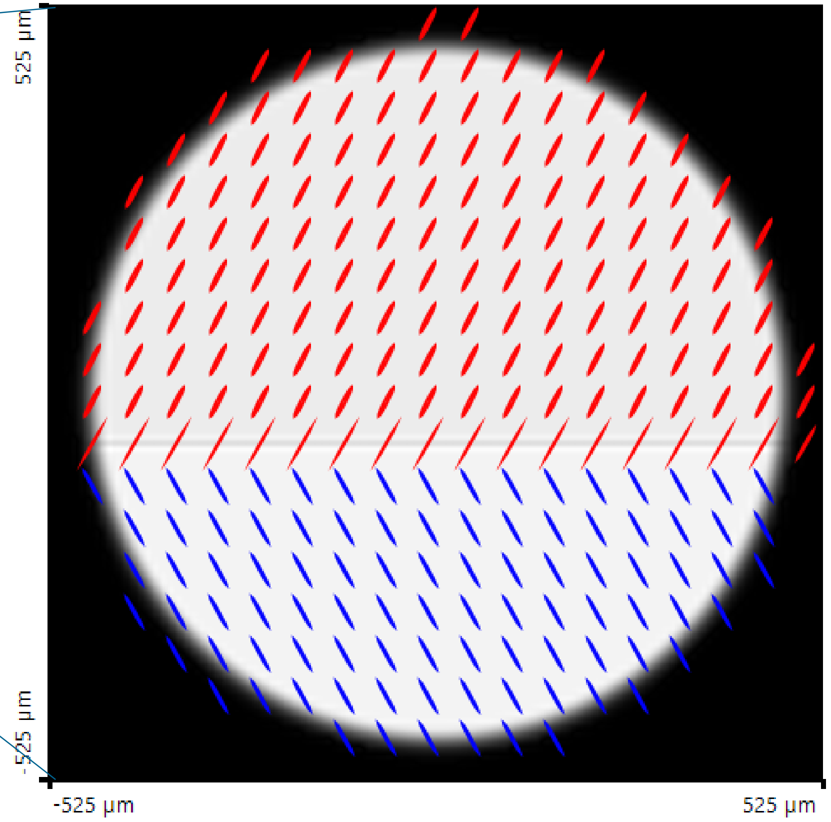
Incident light at grating interaction (non-uniform polarization)



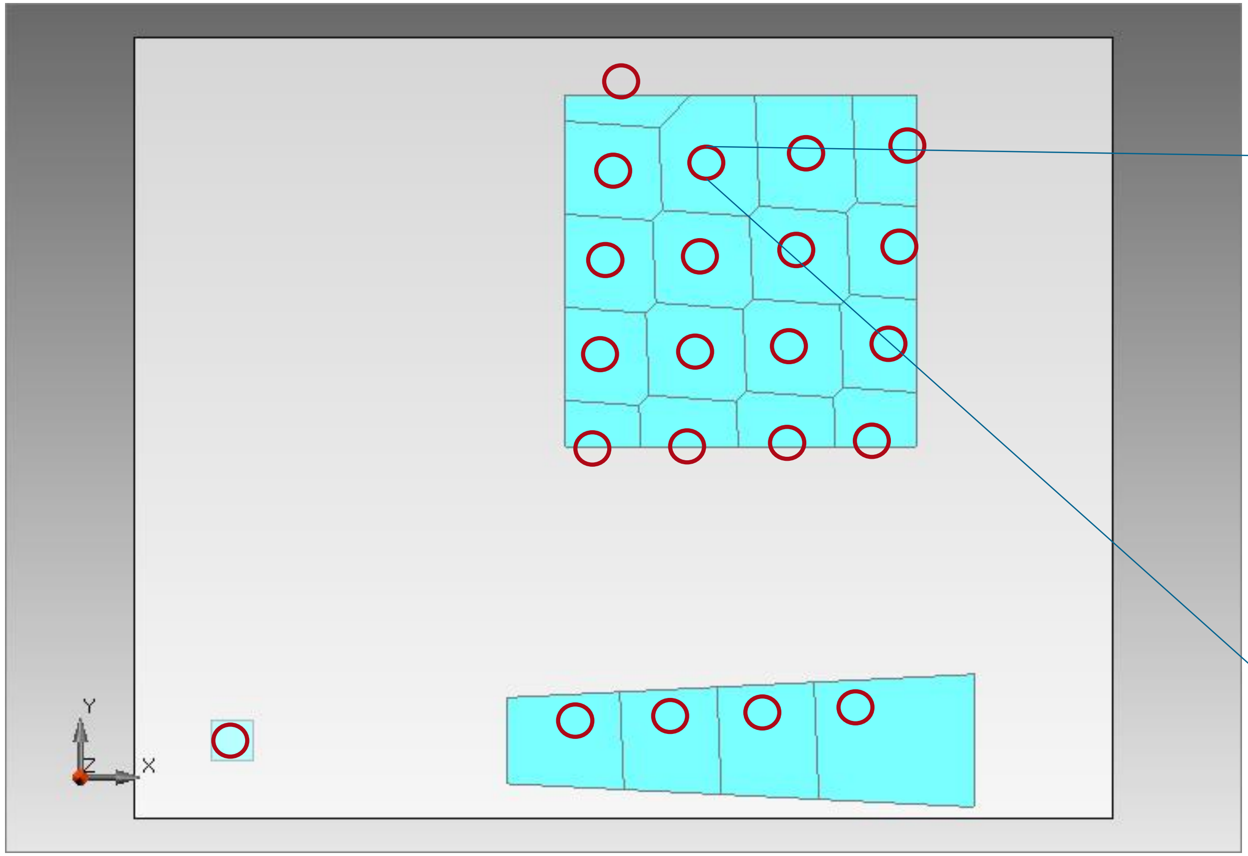
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



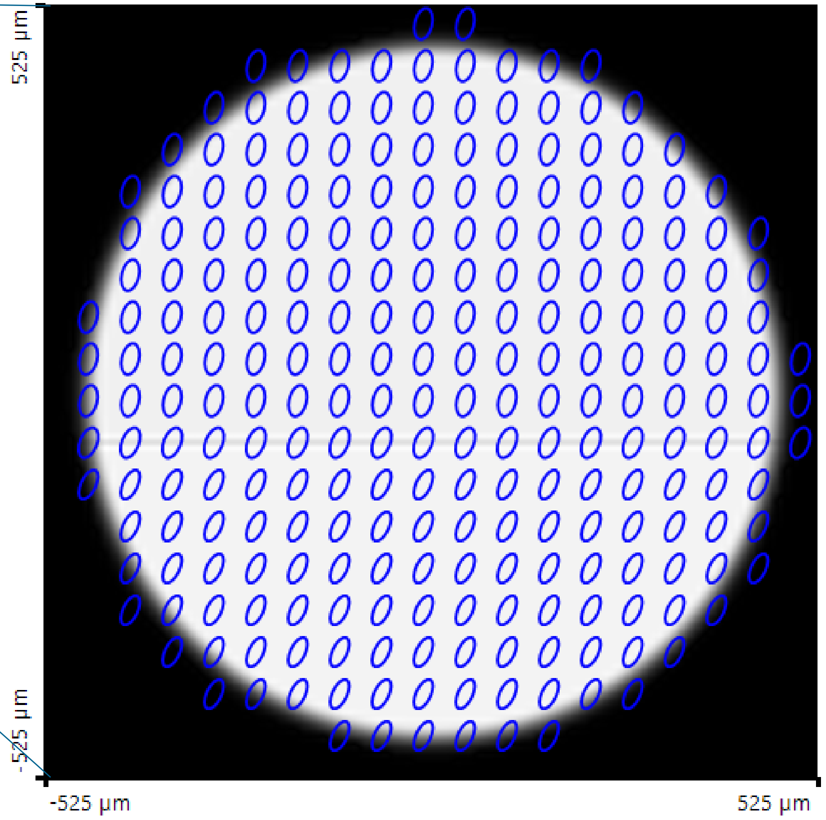
Incident light at grating interaction
(non-uniform polarization)



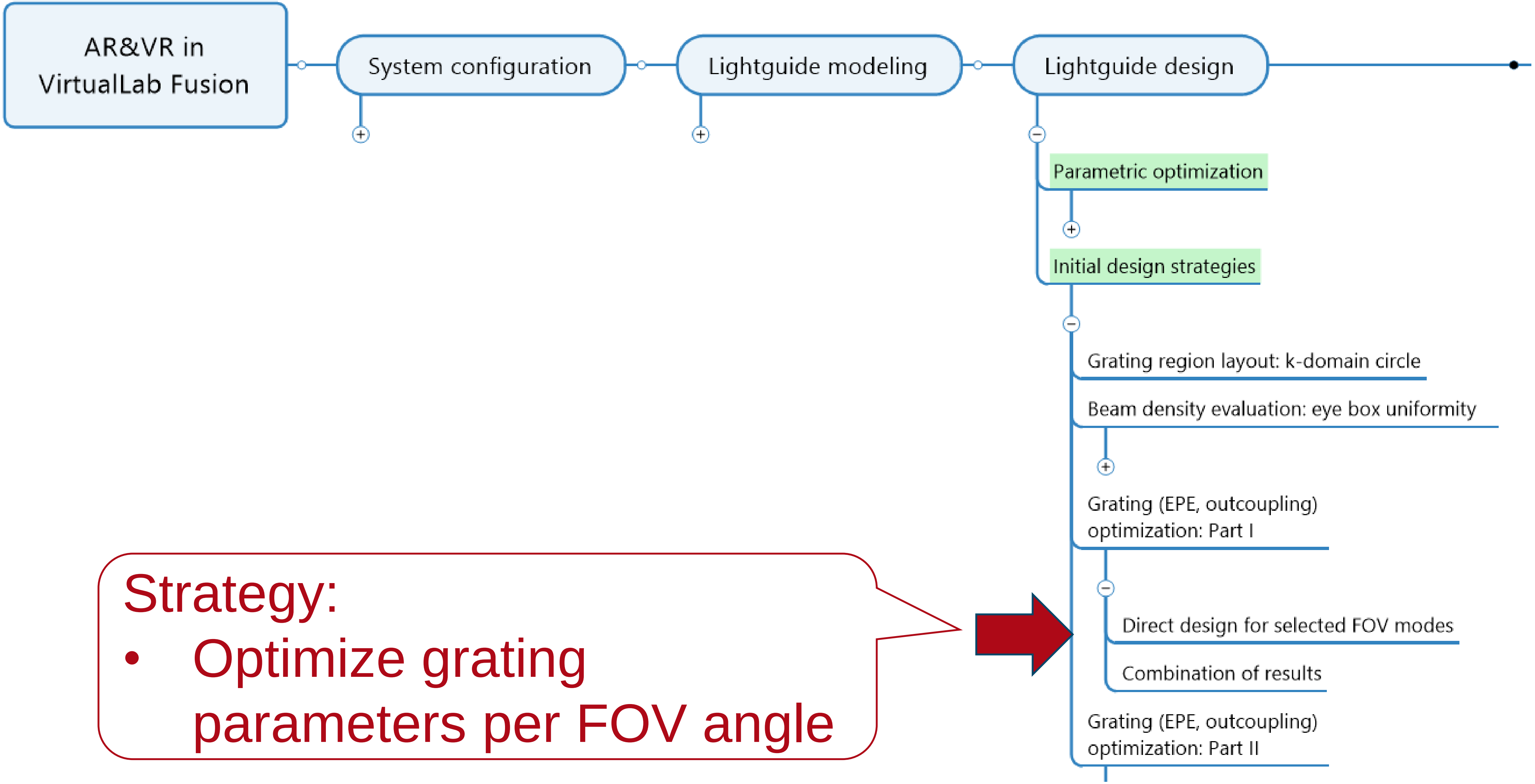
Grating Design for FOV Angle (5°, 3°) – Polarization Evaluation



Incident light at grating interaction
(non-uniform polarization)



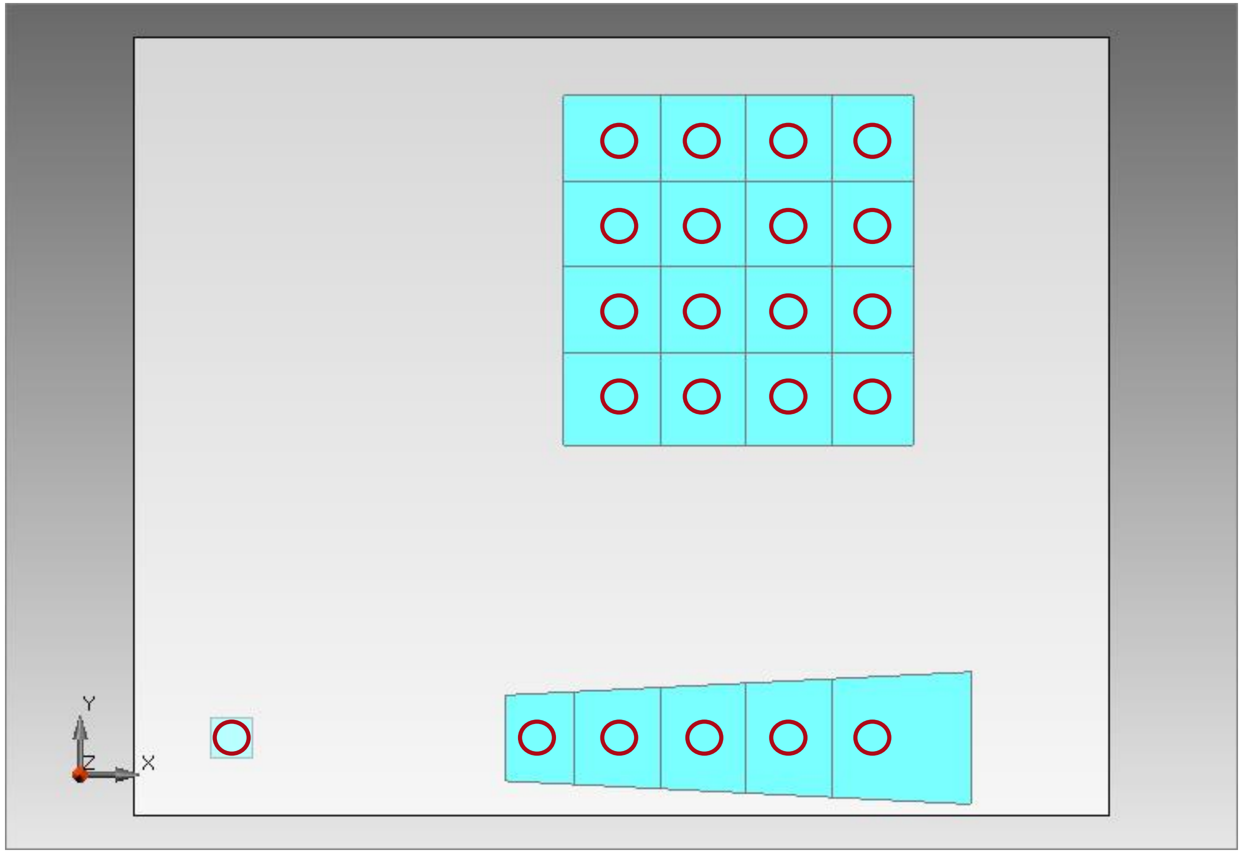
Lightguide Modeling and Design: Grating Optimization

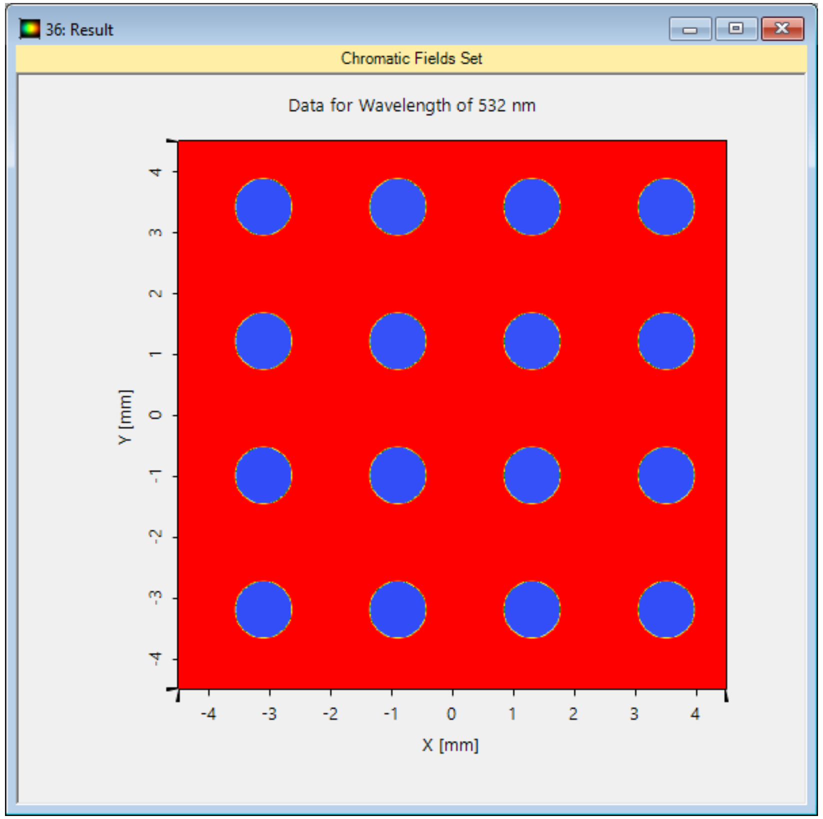


Strategy:

- Optimize grating parameters per FOV angle

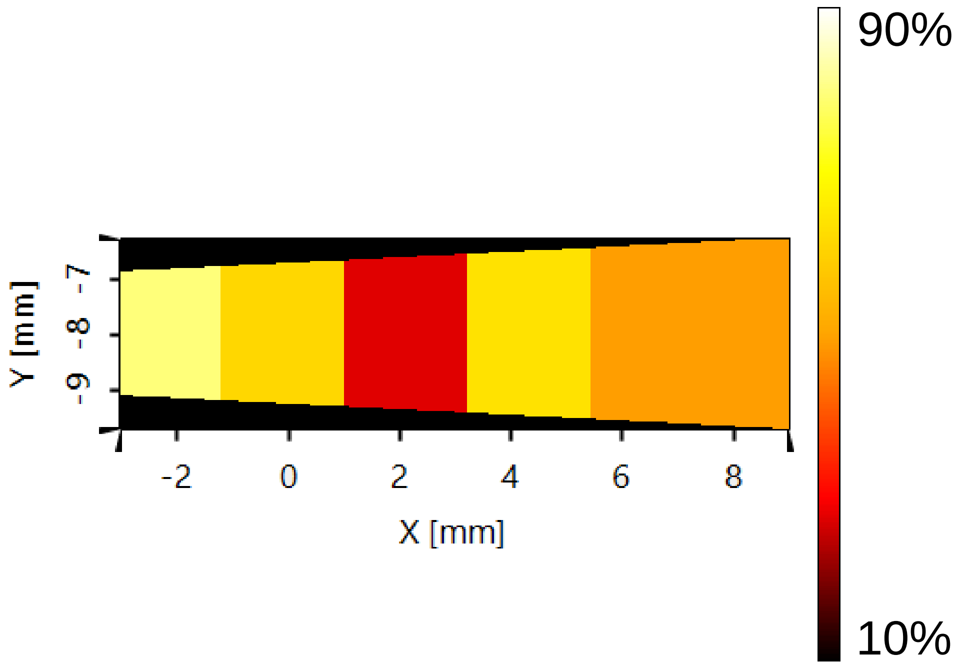
Grating Design for FOV Angle (0°, 0°)



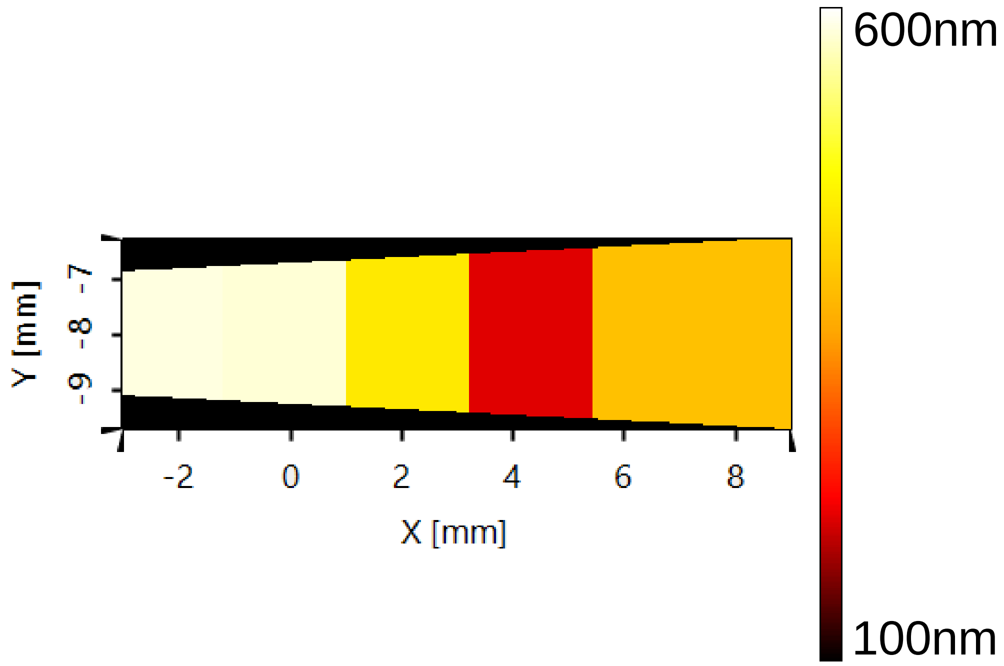


Merit Function	Value
FOV Angle	$\alpha = 0°\,;\,\beta = 0°$
Uniformity Error	0.34%

Optimized Grating Parameter EPE Grating

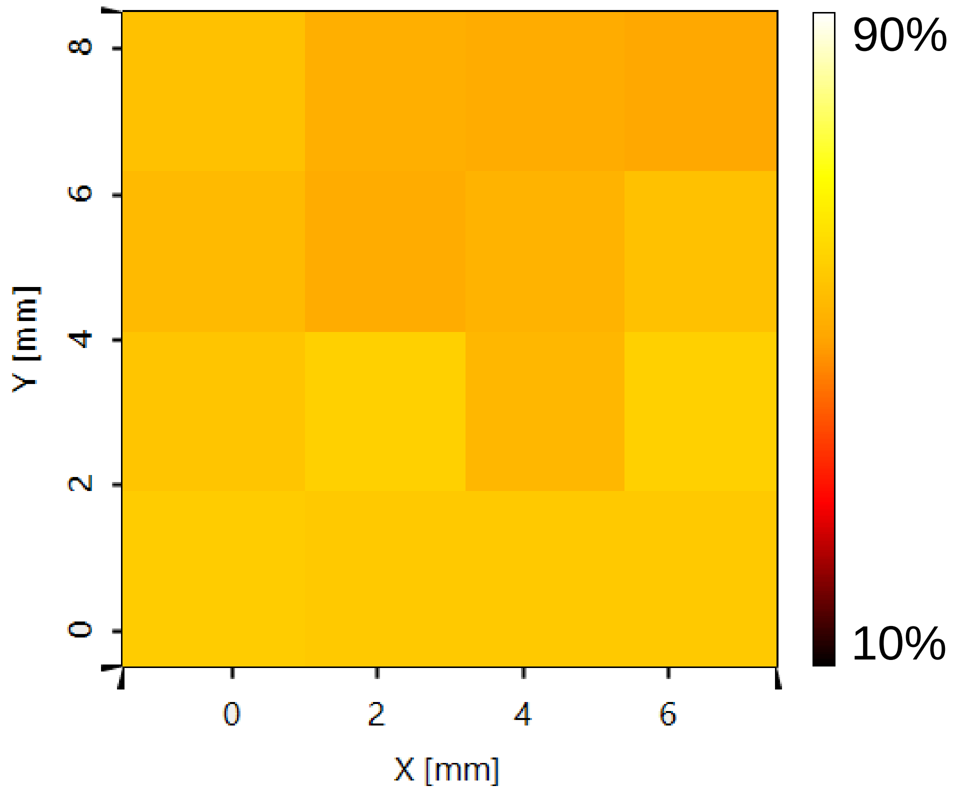


Optimized Fill Factors

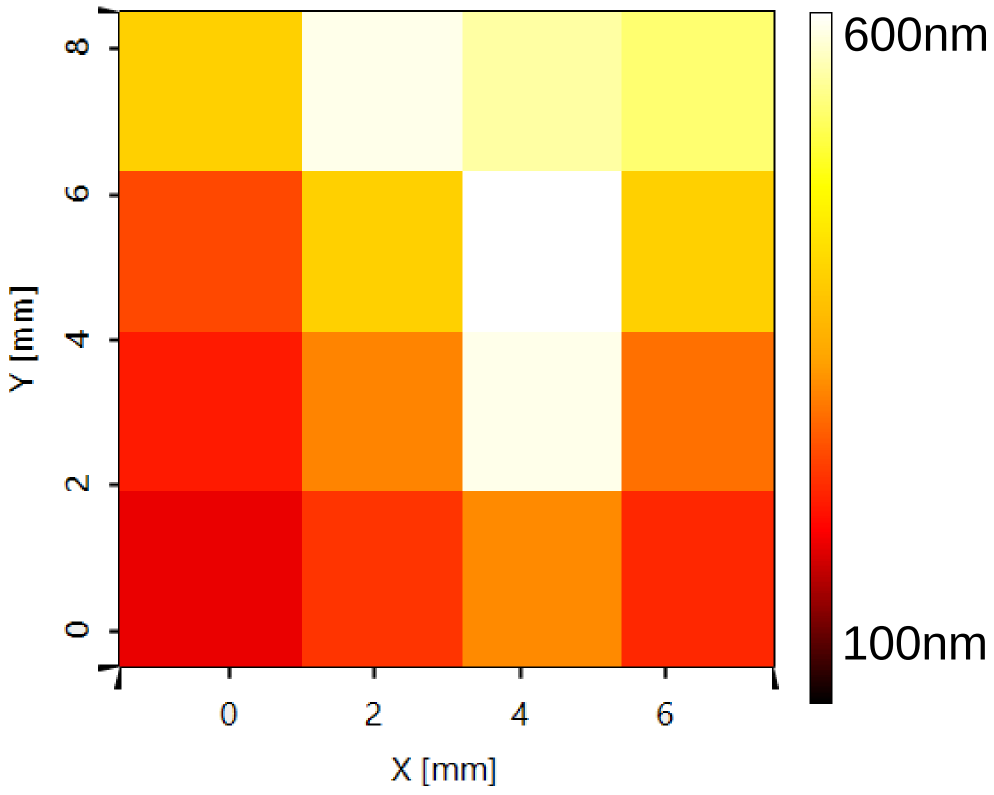


Optimized Modulation Depth

Optimized Grating Parameter Outcoupling Grating

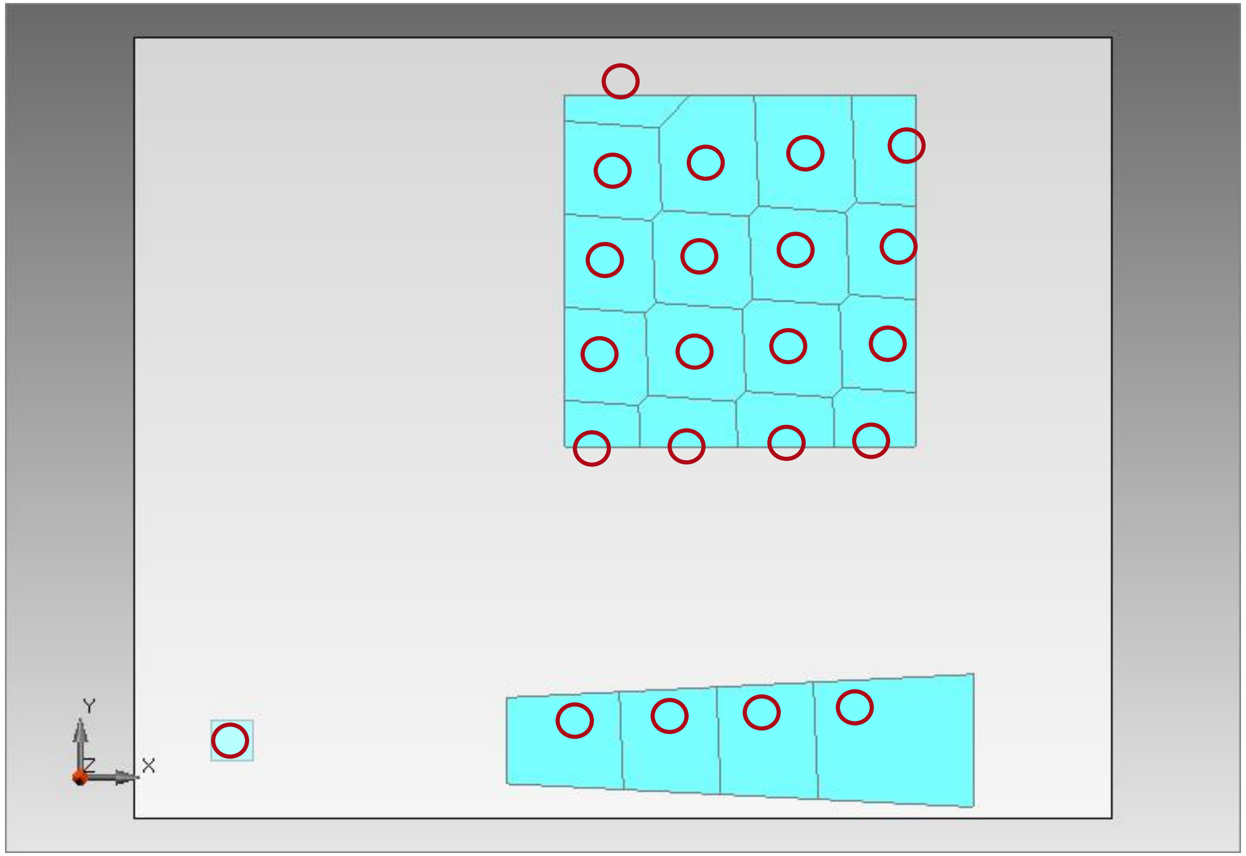


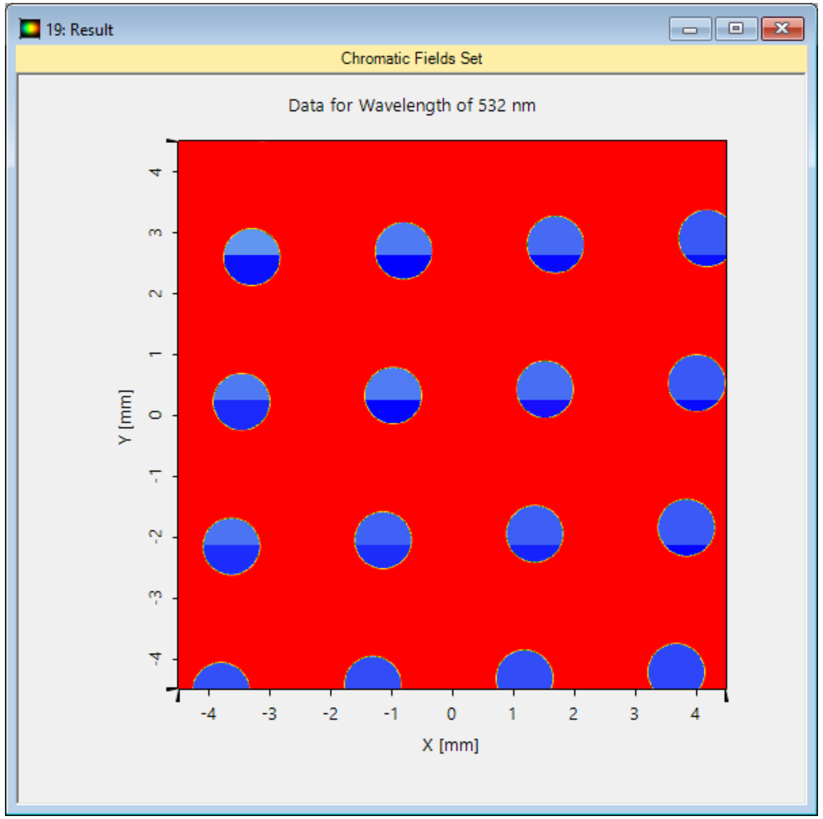
Optimized Fill Factors



Optimized Modulation Depth

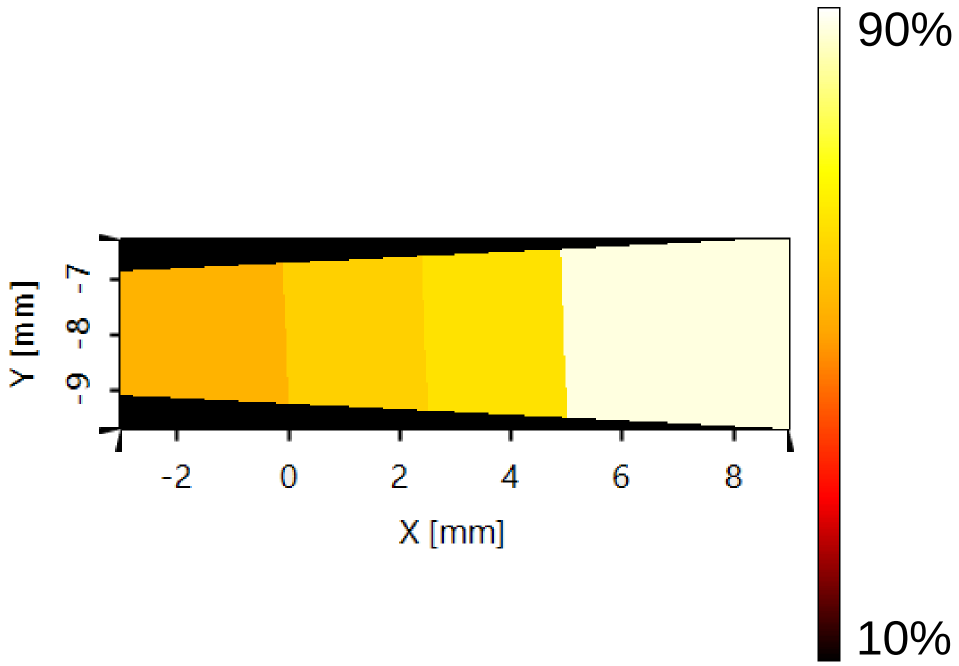
Grating Design for FOV Angle (5°, 3°)



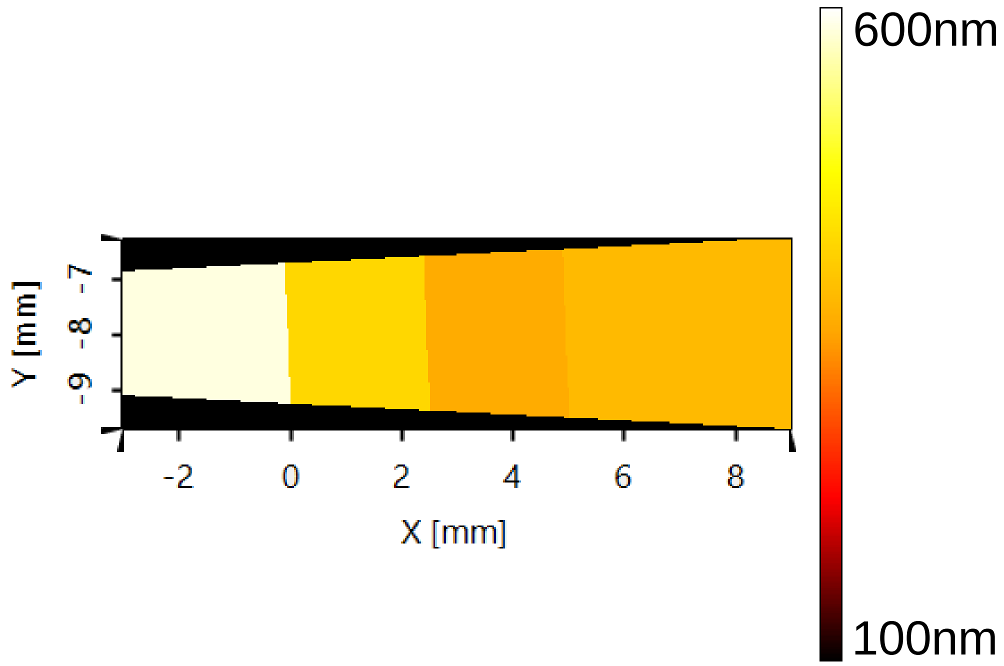


Merit Function	Value
FOV Angle	$\alpha = 5°; \beta = 3°$
Uniformity Error	**0.61%**

Optimized Grating Parameter EPE Grating

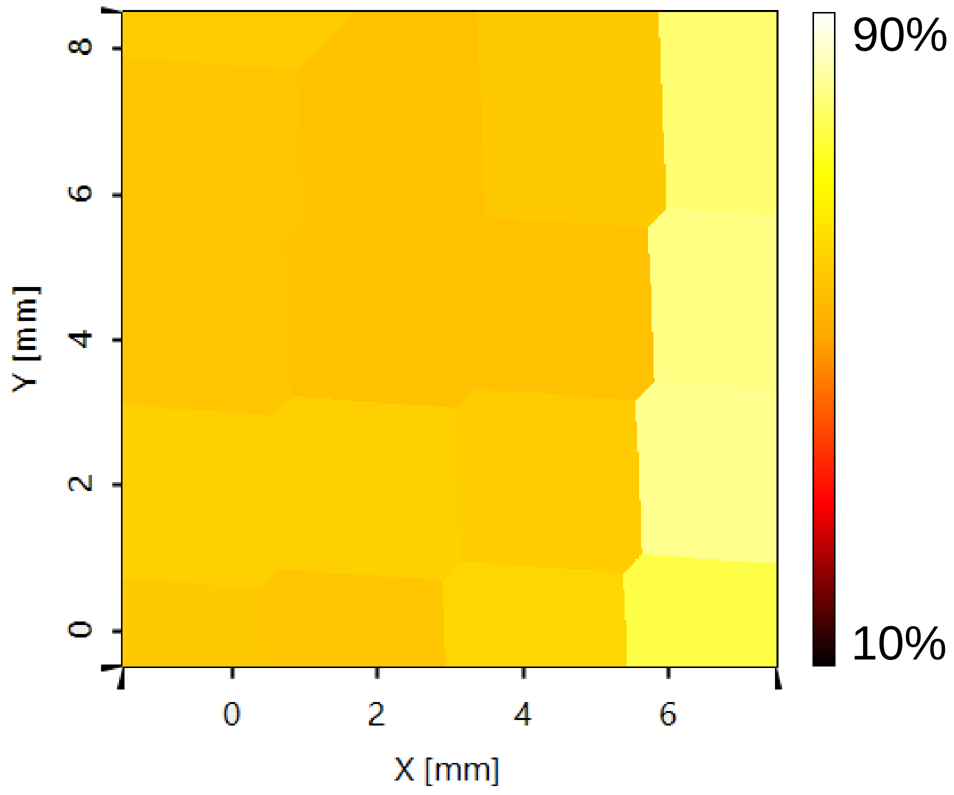


Optimized Fill Factors

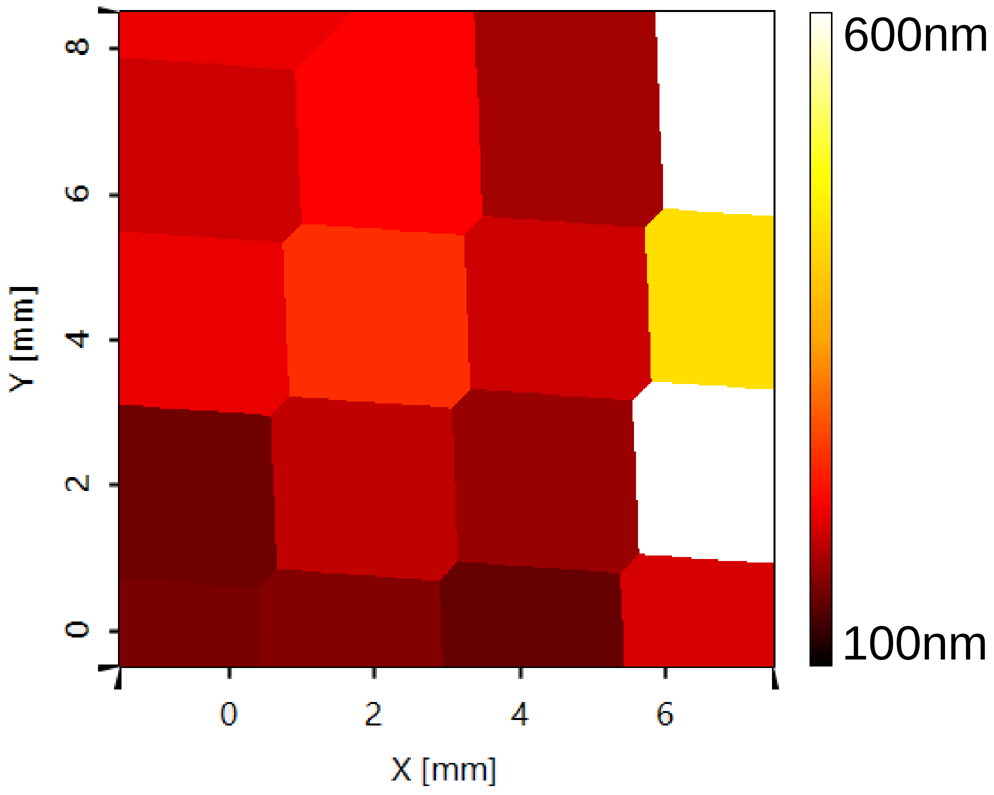


Optimized Modulation Depth

Optimized Grating Parameter Outcoupling Grating

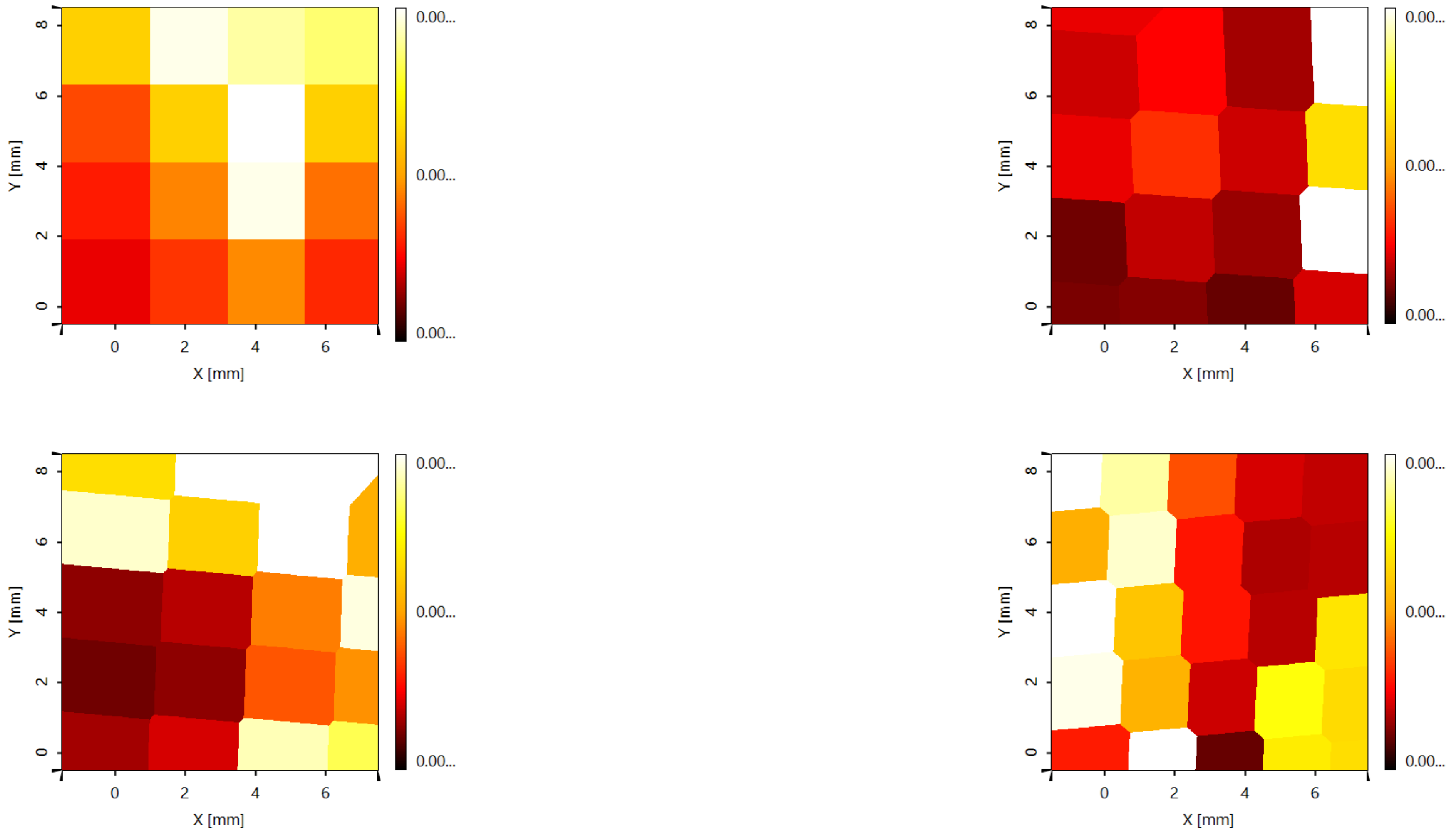


Optimized Fill Factors

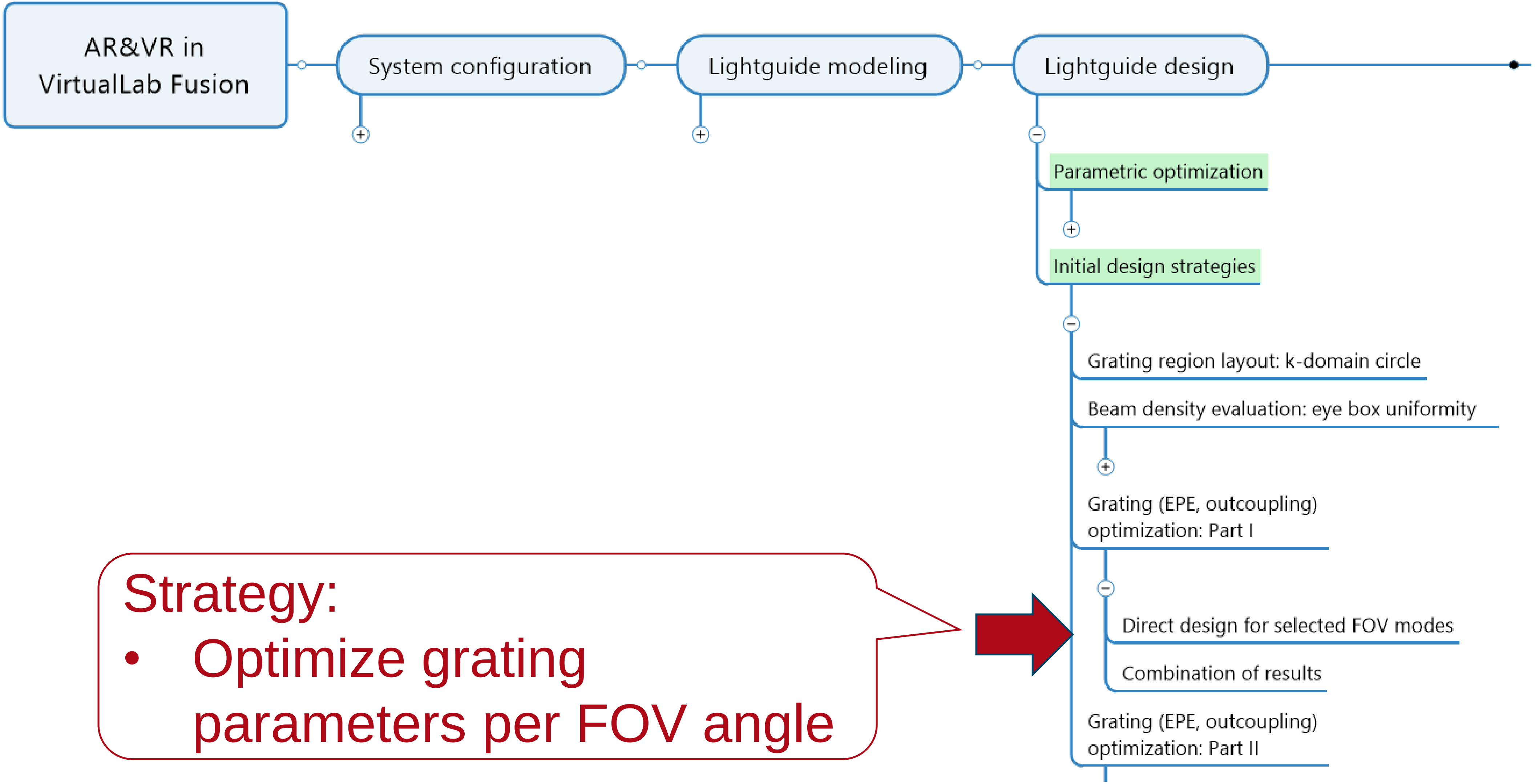


Optimized Modulation Depth

EPE Grating Design for Different FOV: Height



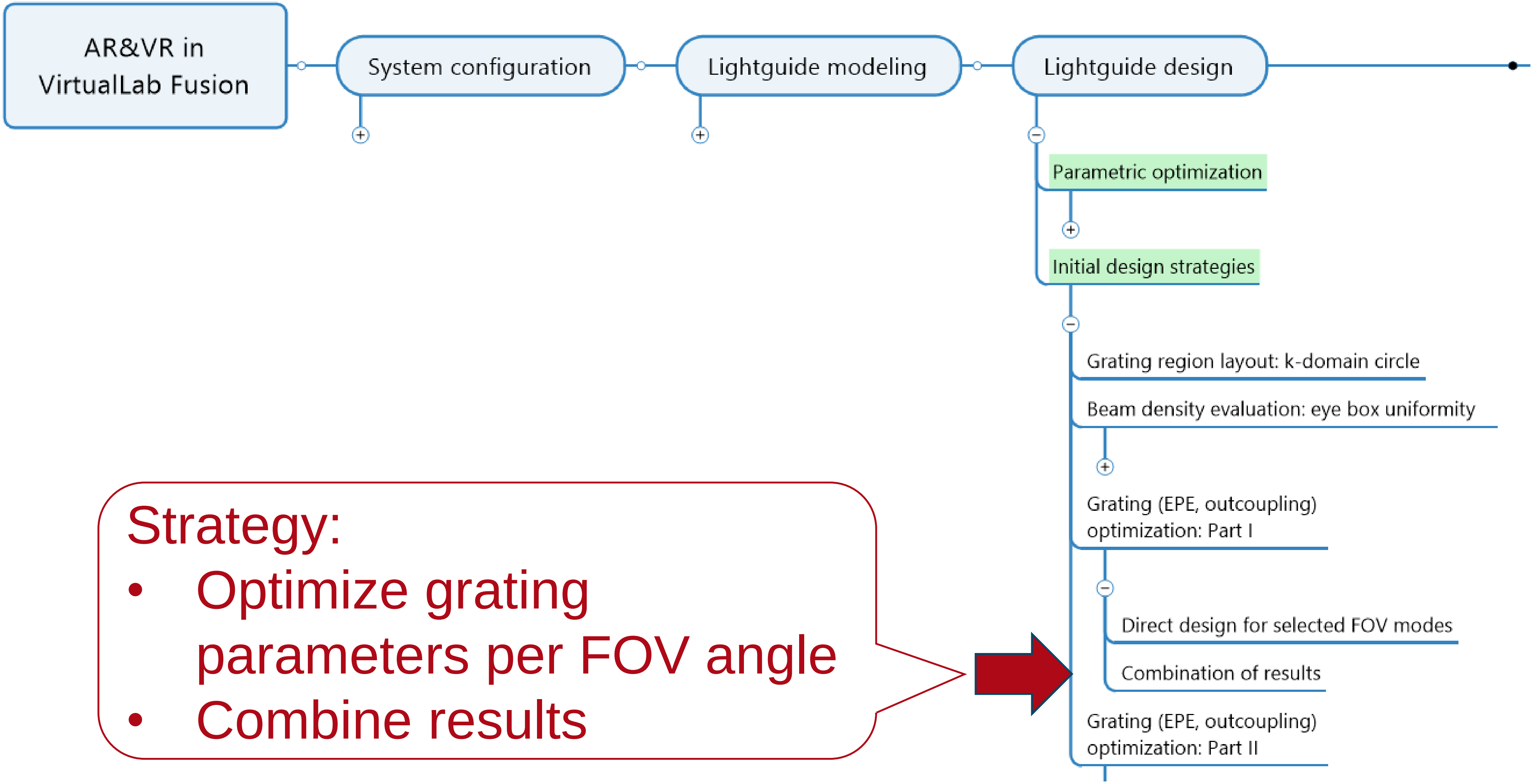
Lightguide Modeling and Design: Grating Optimization



Strategy:

- Optimize grating parameters per FOV angle

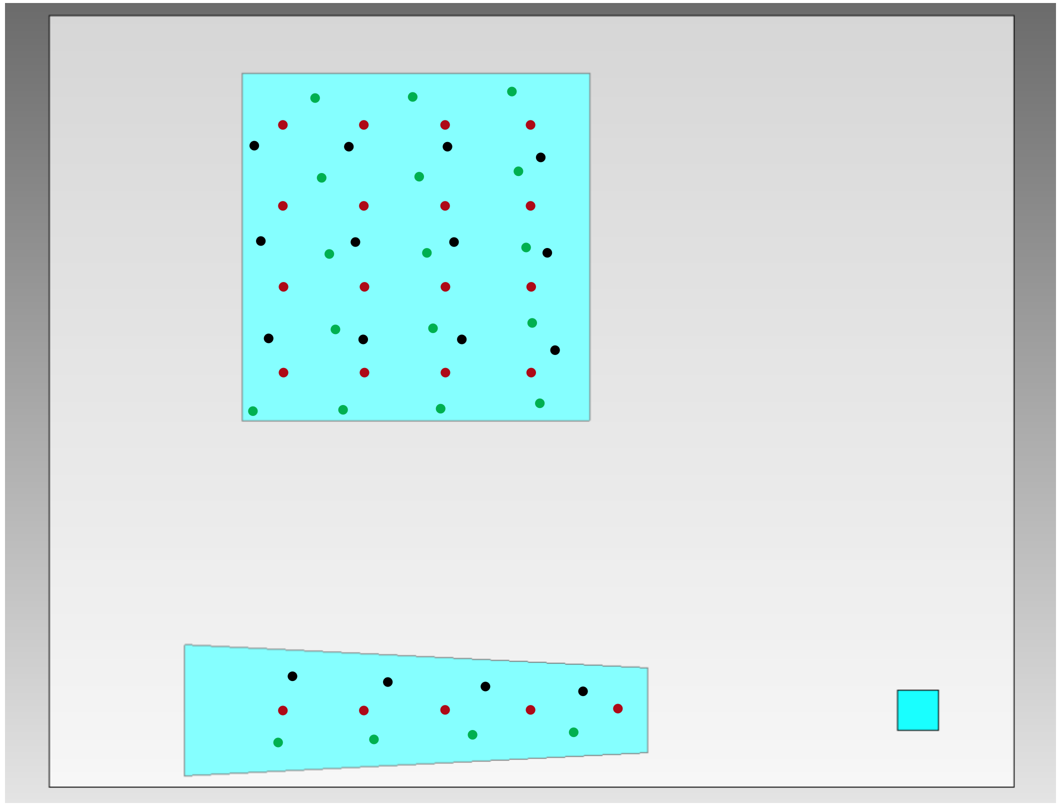
Lightguide Modeling and Design: Grating Optimization



Strategy:

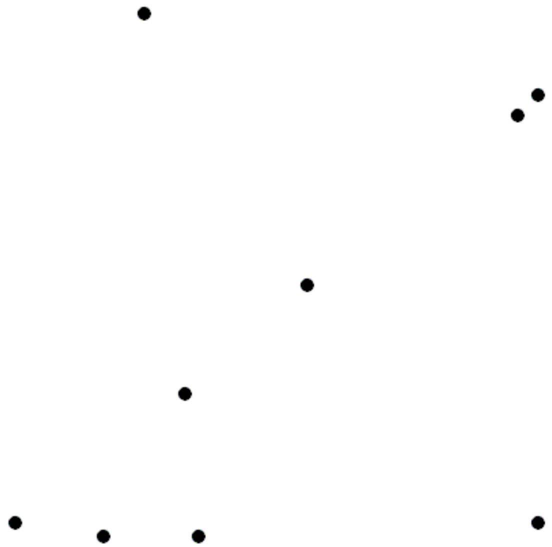
- Optimize grating parameters per FOV angle
- Combine results

Combination of Different FOV Designs



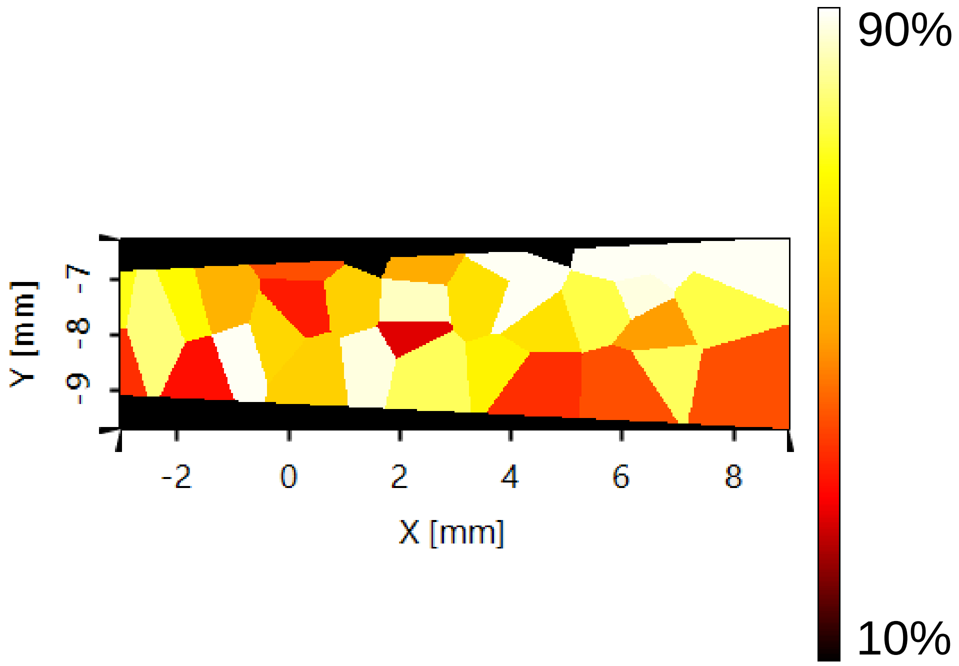
+

Voronoi Segmentation

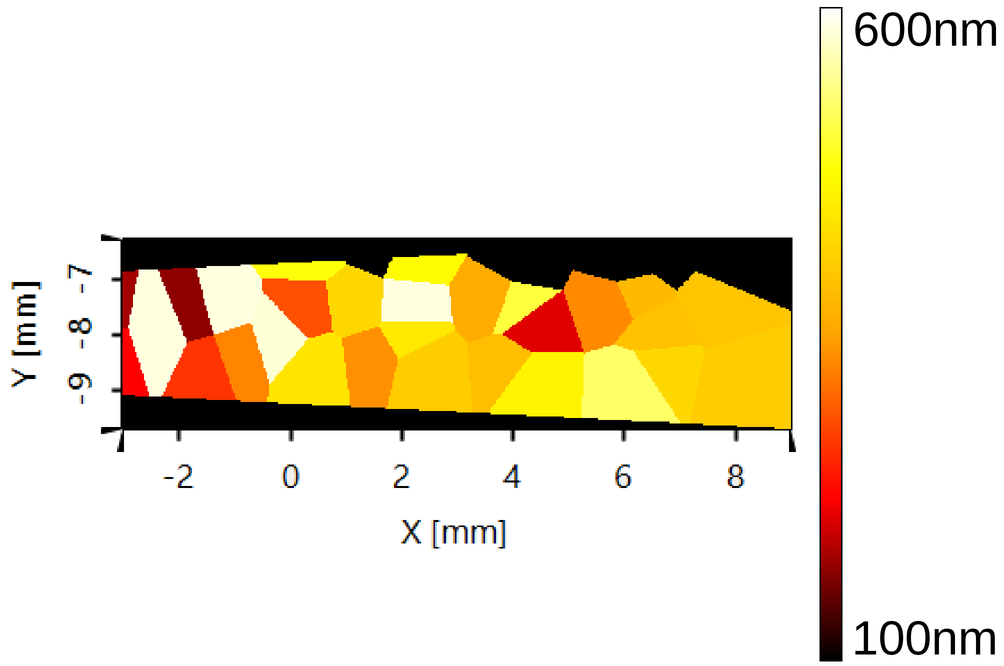


Source: www.wikipedia.com

Optimized Grating Parameter EPE Grating

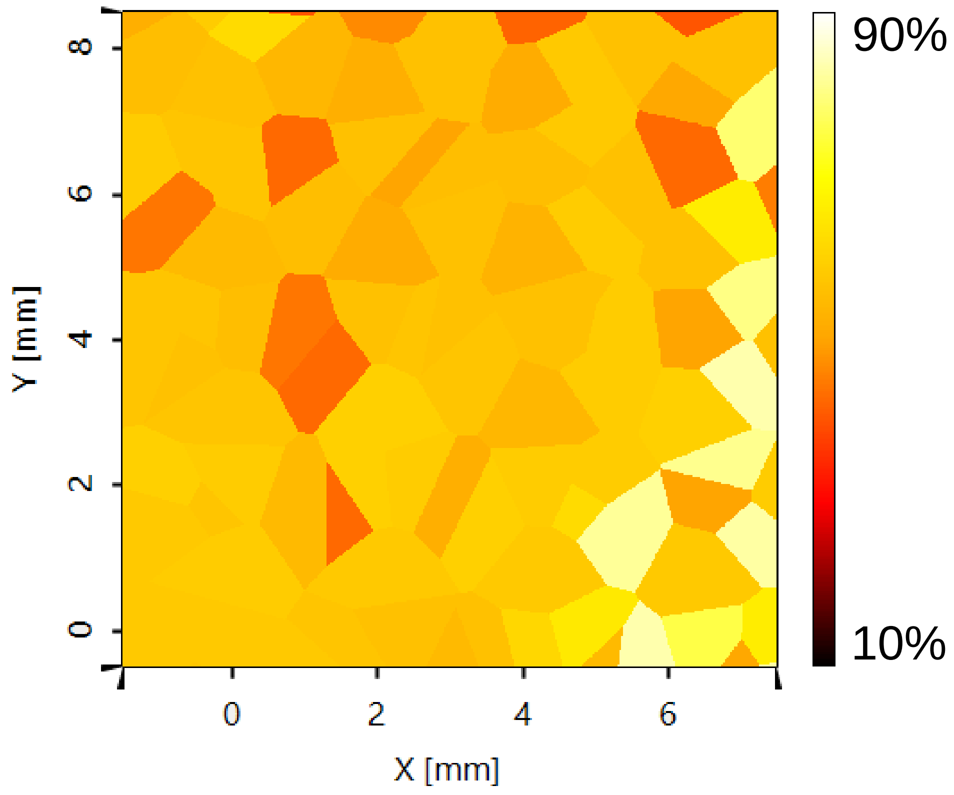


Optimized Fill Factors

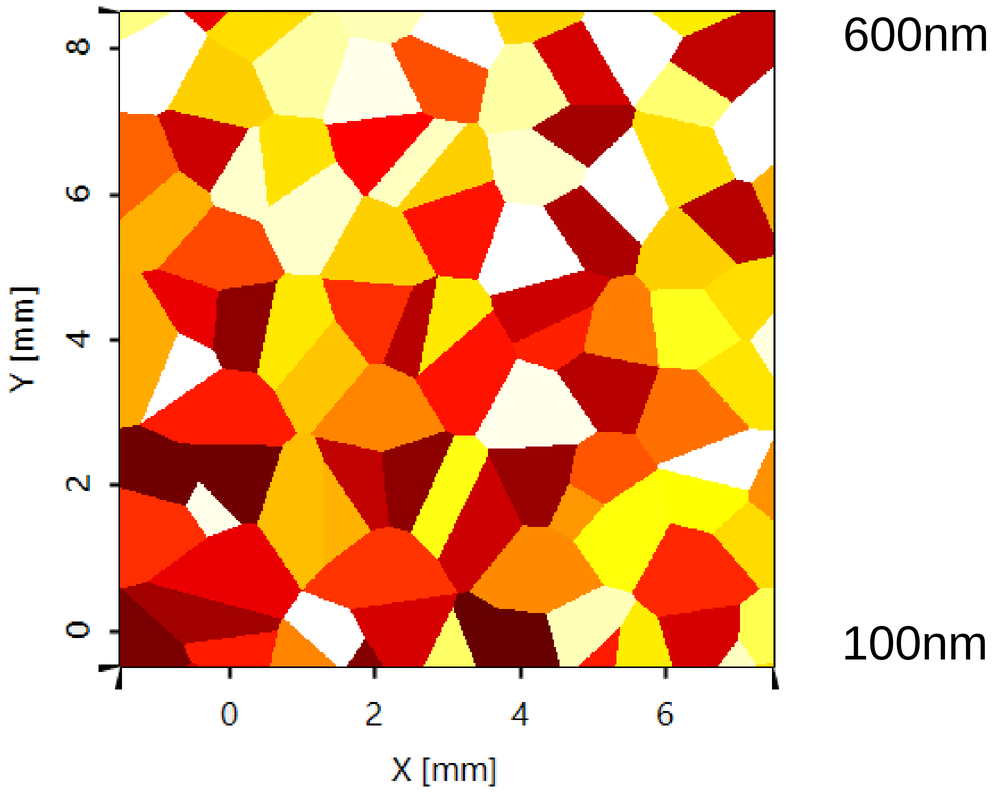


Optimized Modulation Depth

Optimized Grating Parameter Outcoupling Grating

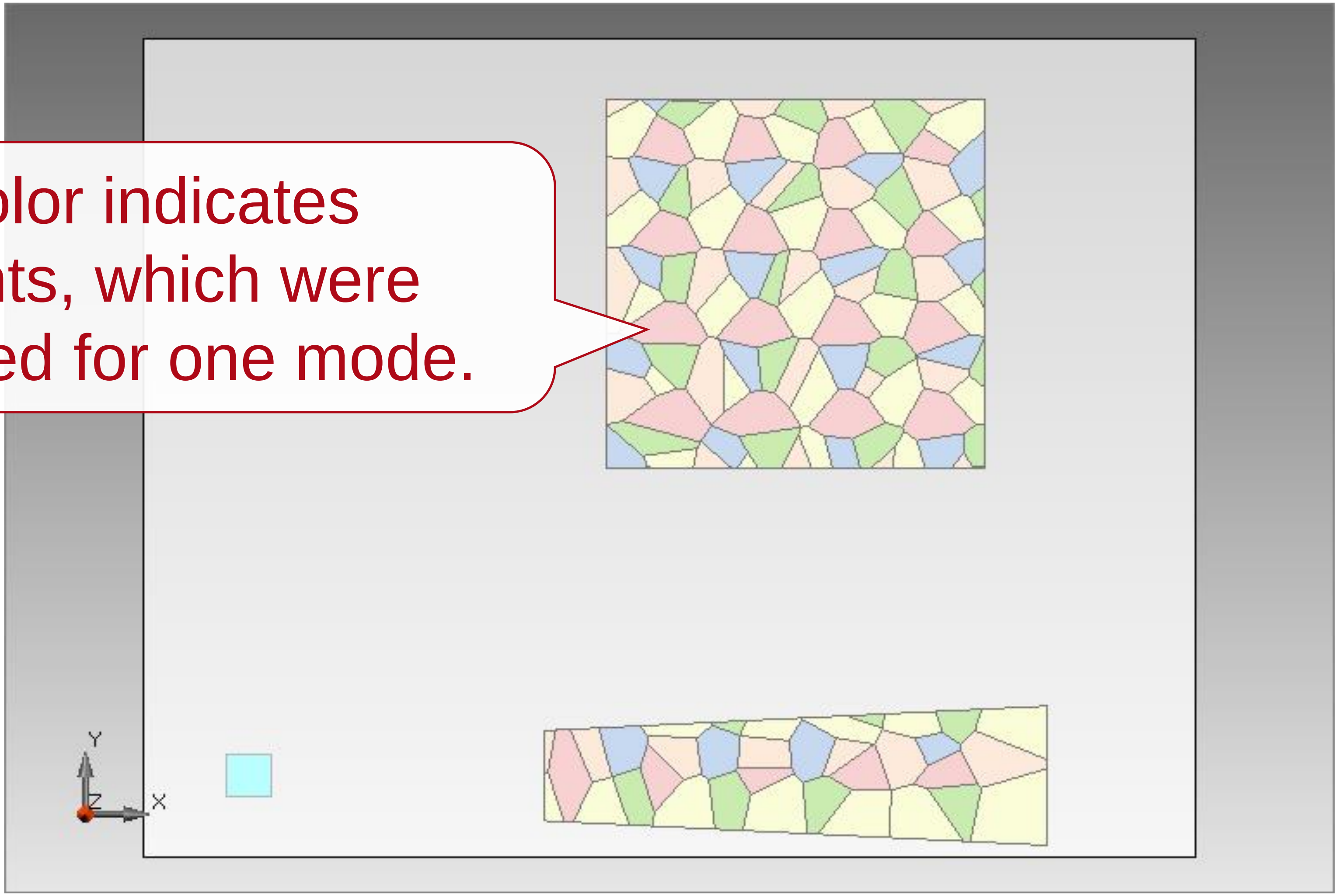


Optimized Fill Factors



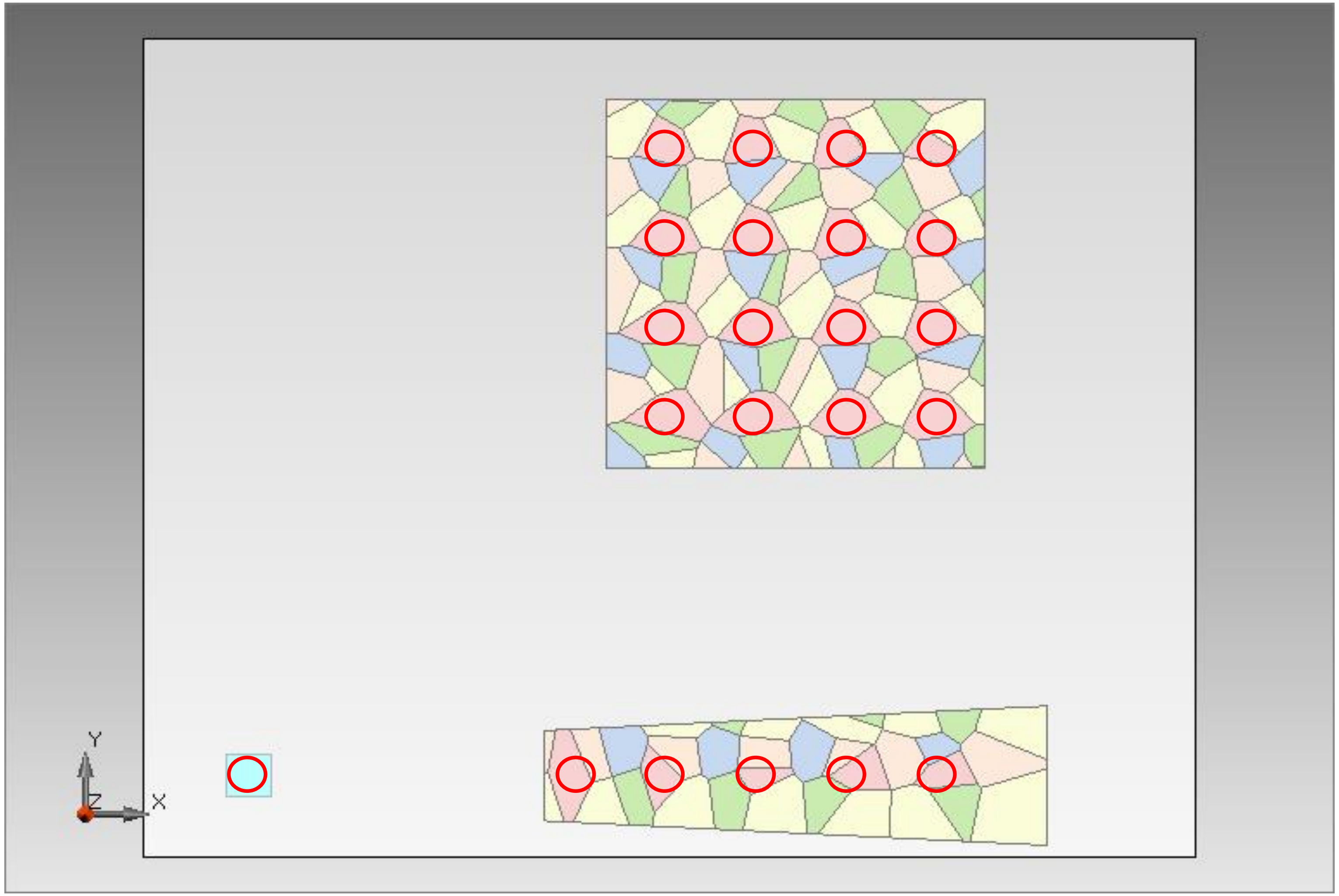
Optimized Modulation Depth

Result Combination of Modes (Segmentation)

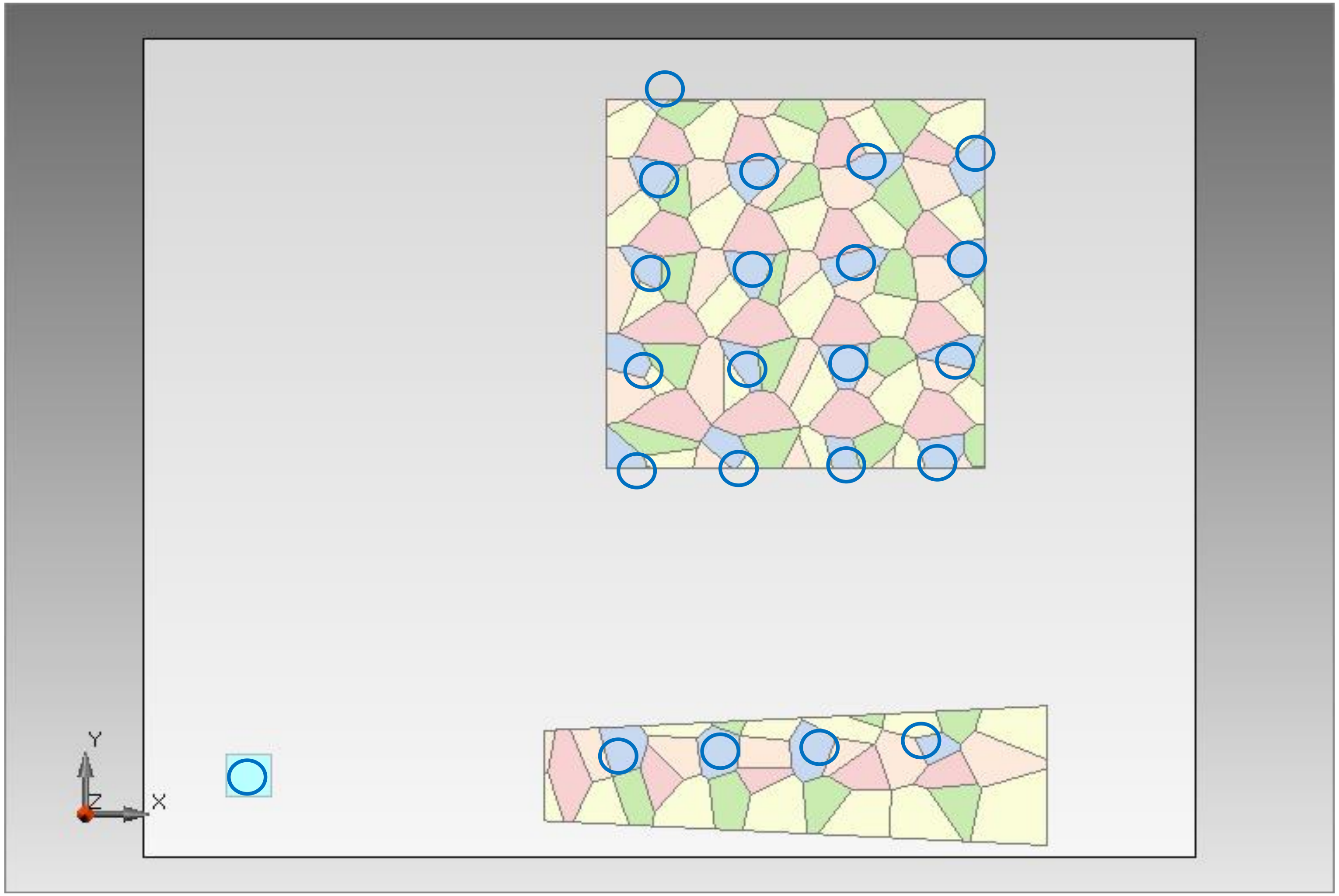


Each color indicates segments, which were optimized for one mode.

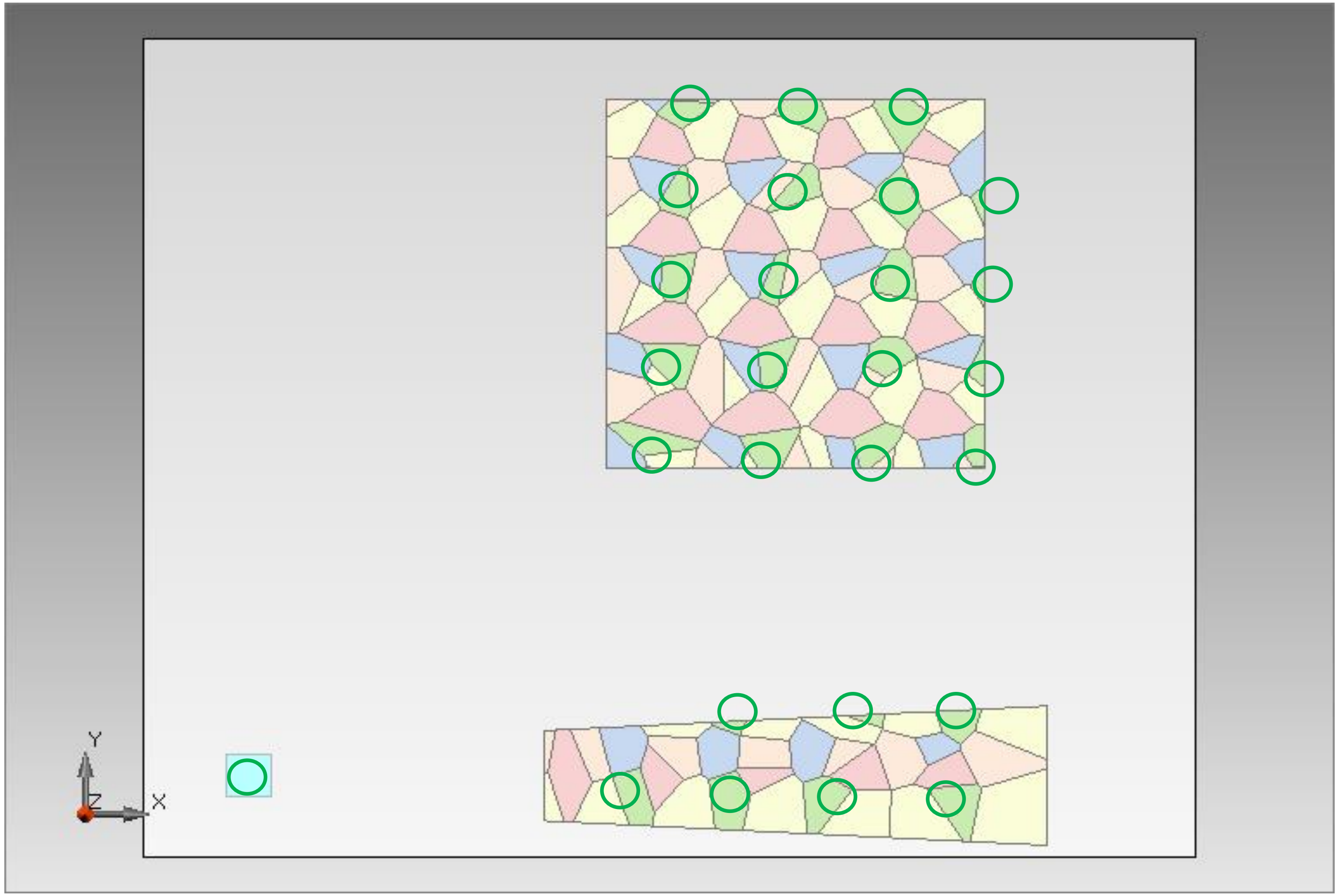
Result Combination of Modes (Segmentation)



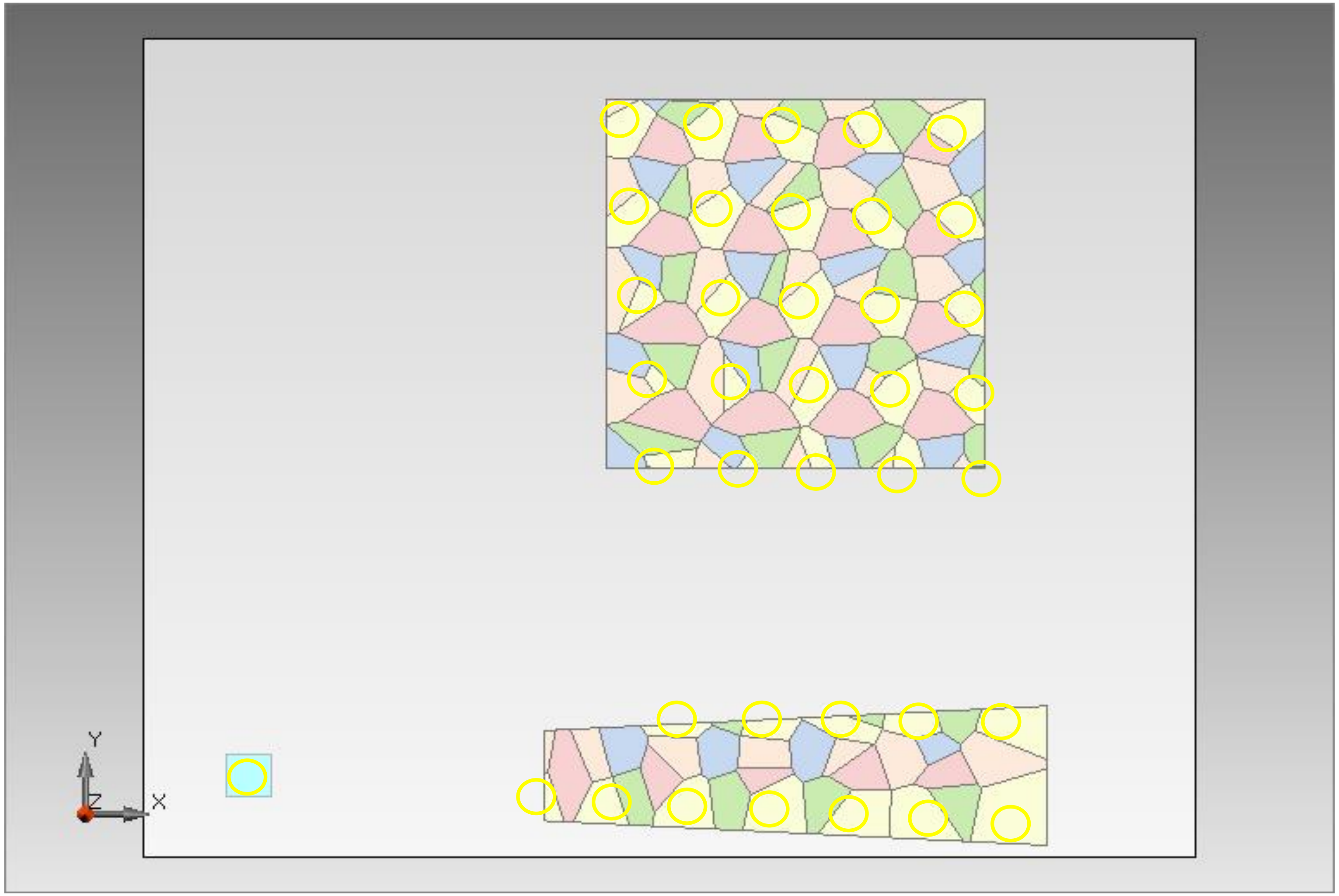
Result Combination of Modes (Segmentation)



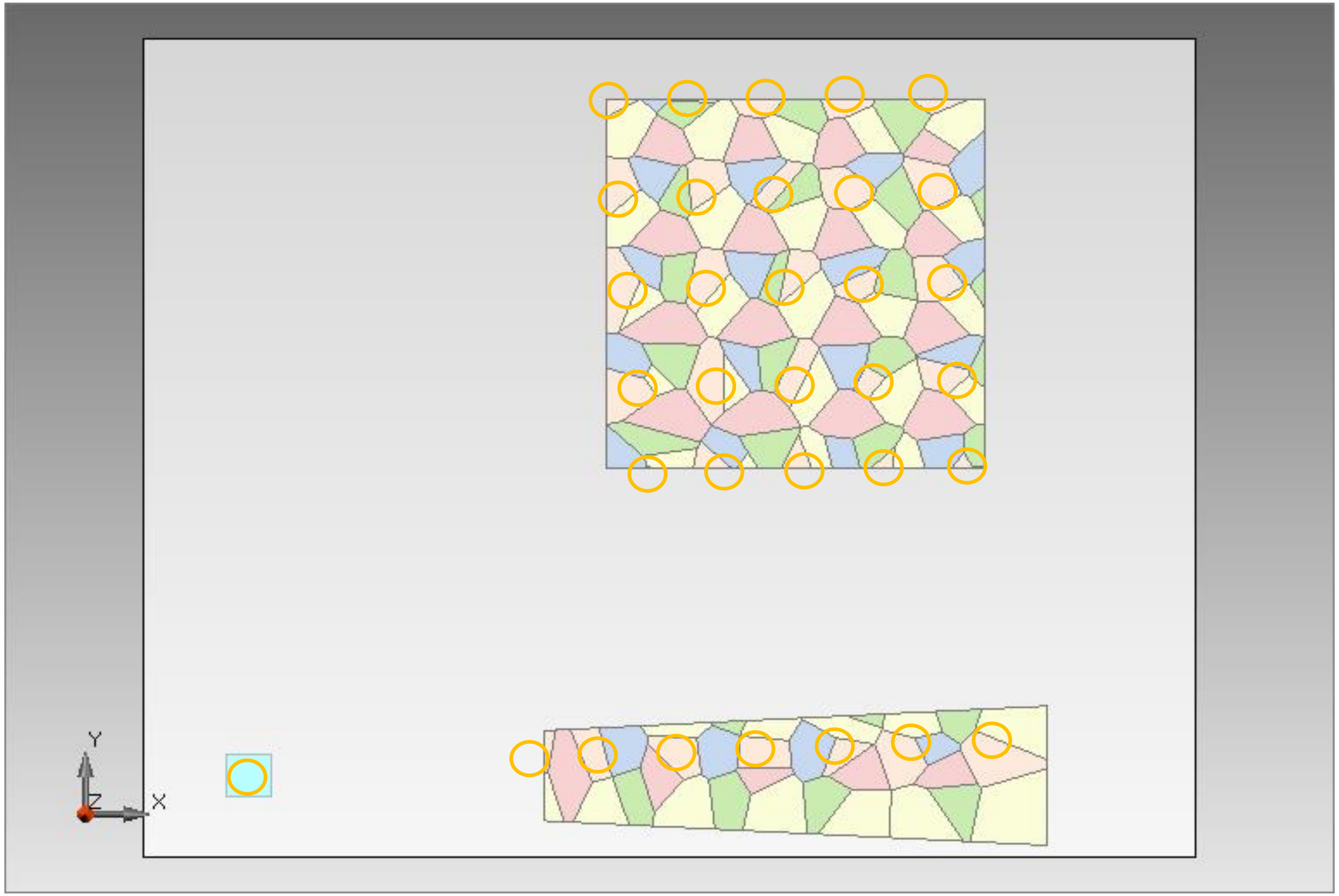
Result Combination of Modes (Segmentation)



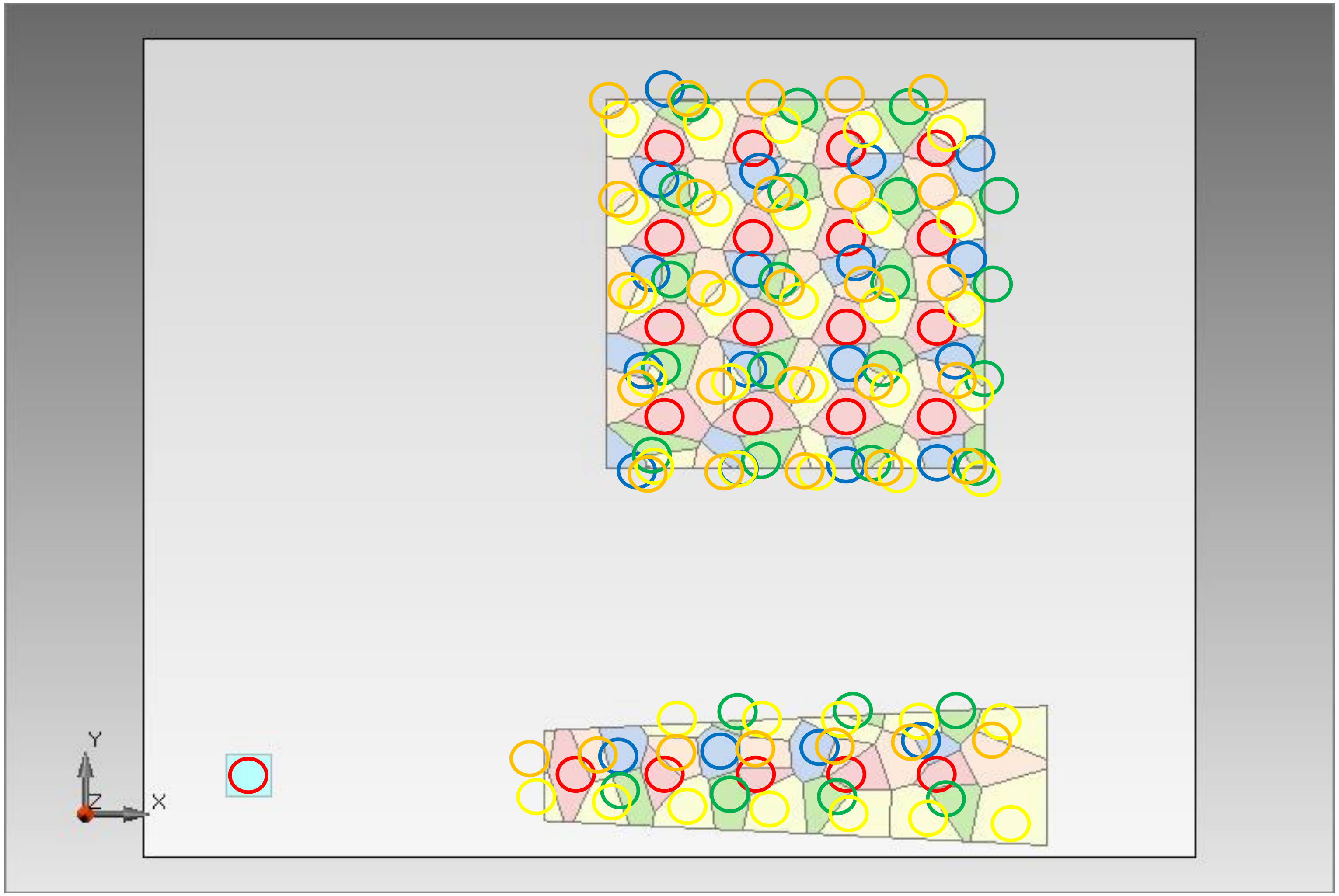
Result Combination of Modes (Segmentation)



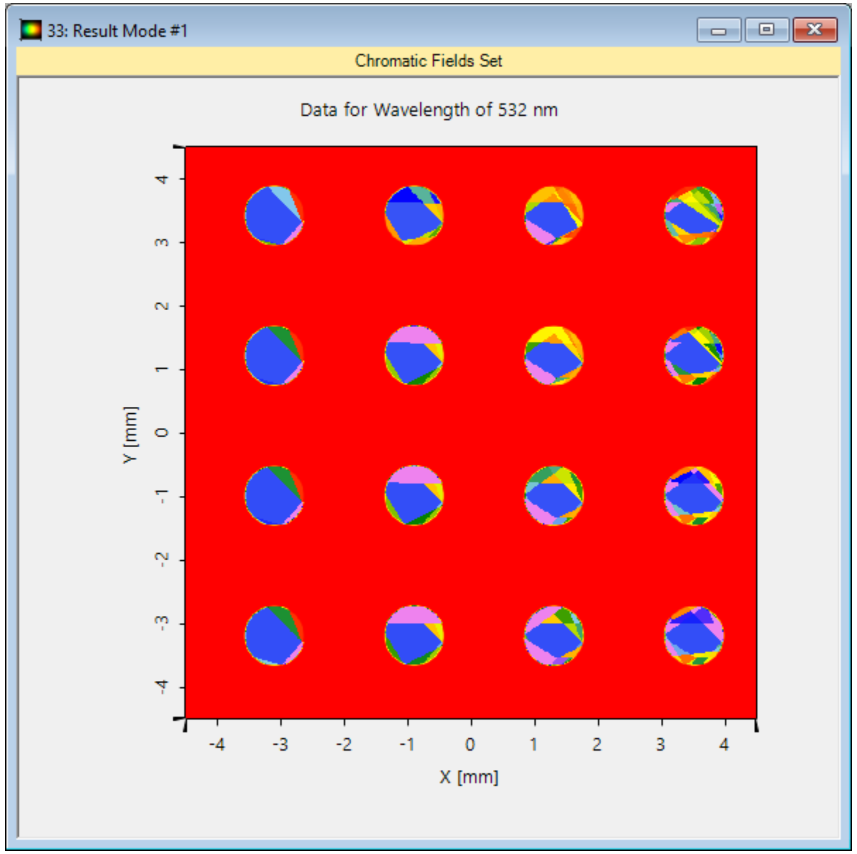
Result Combination of Modes (Segmentation)



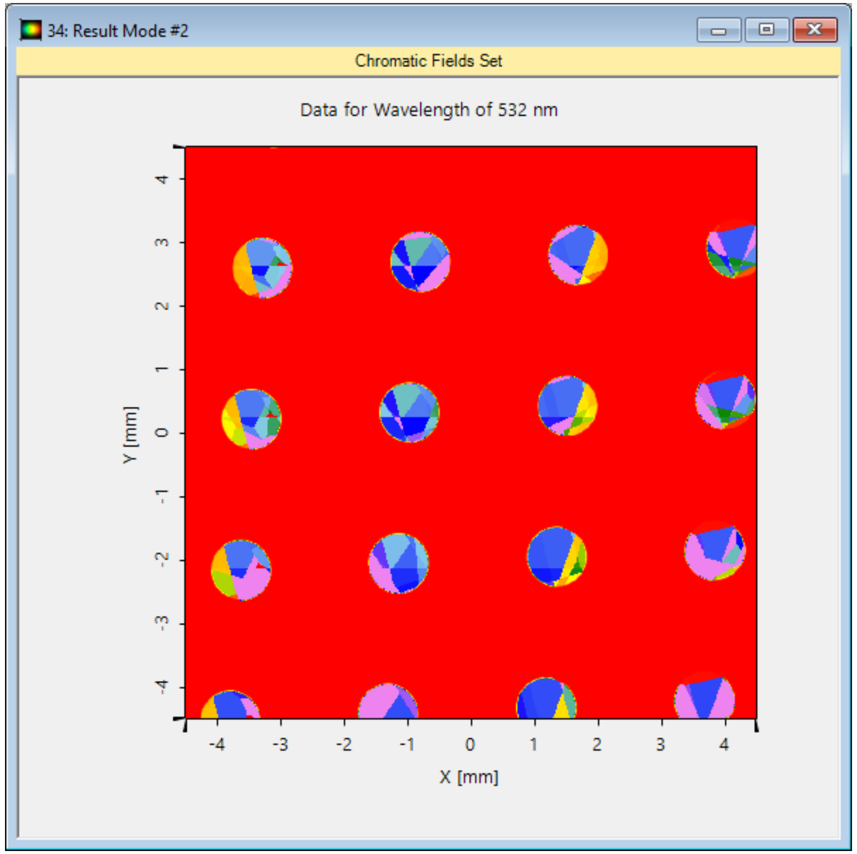
Result Combination of Modes (Segmentation)



Final Design Results Mode #1 + #2

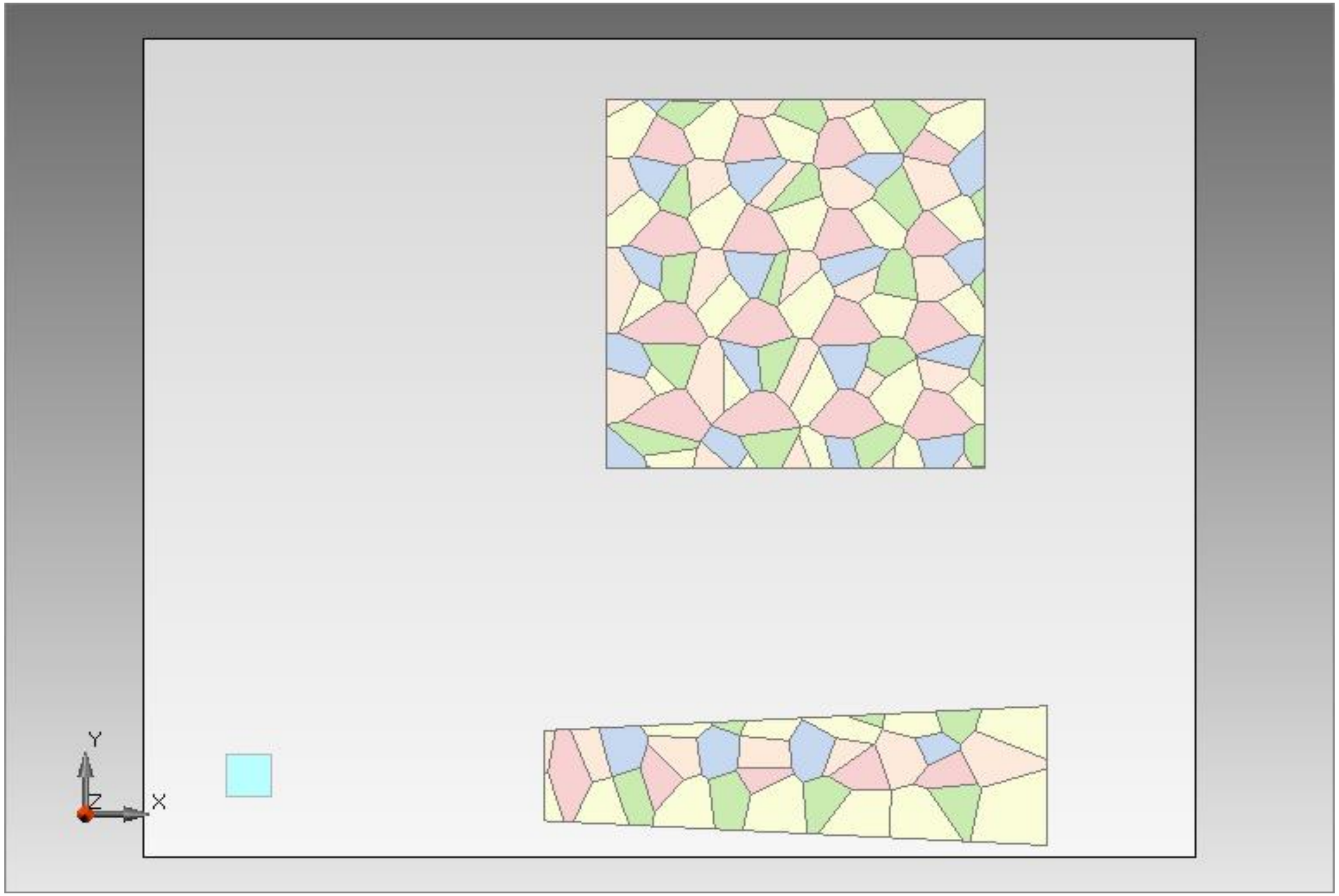


Mode	Merit Function	Value
#1	FOV Angle	$\alpha = 0°; \beta = 0°$
	Uniformity Error	**43.90%**



Mode	Merit Function	Value
#2	FOV Angle	$\alpha = 5°; \beta = 3°$
	Uniformity Error	**45.61%**

Result Combination of Modes (Segmentation)



Parametric Optimization and Initial Design

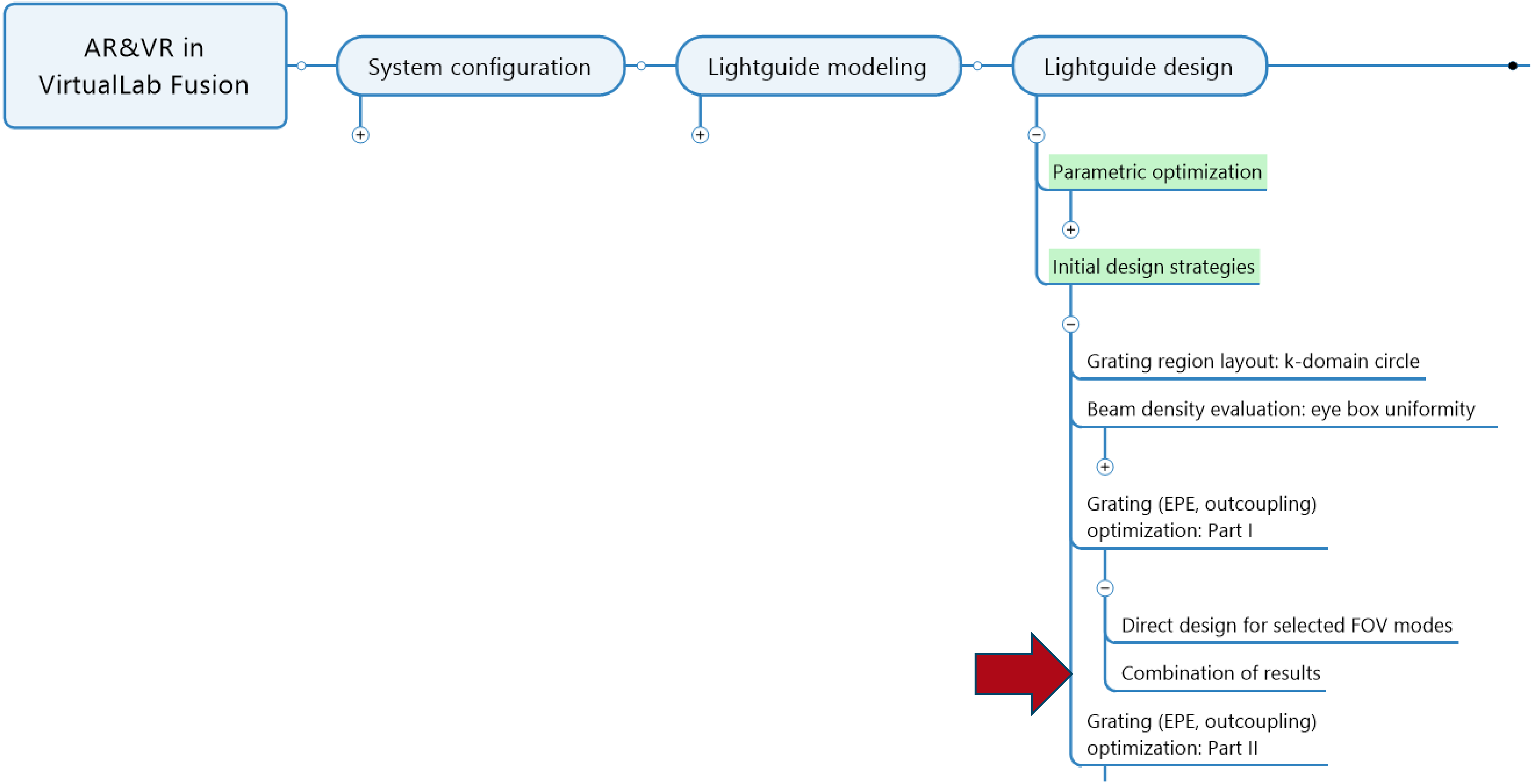
Initial design, e.g.

- Inverse approaches
- Functional design

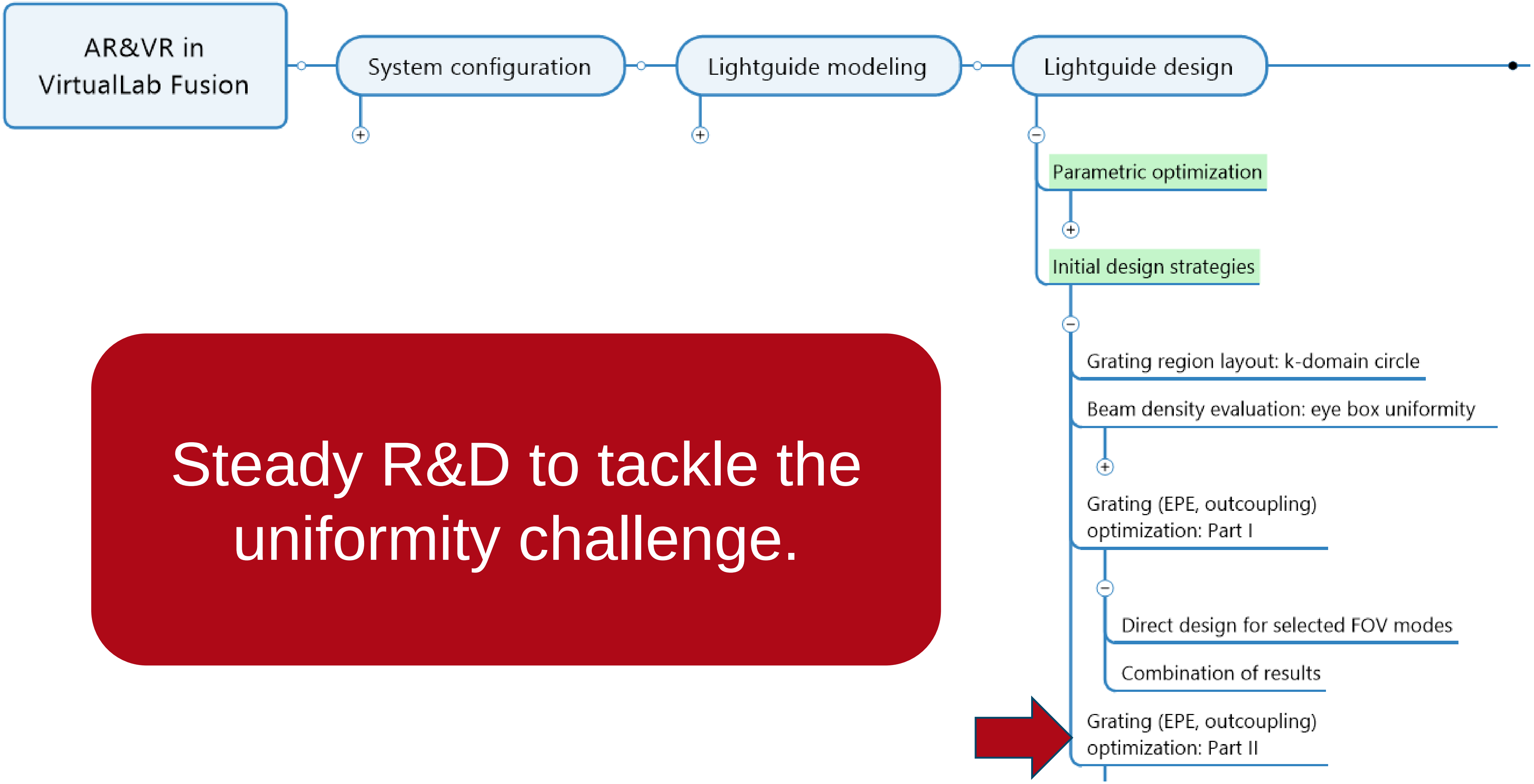
In suitable combination

Parametric optimization

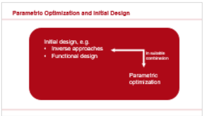
Lightguide Modeling and Design



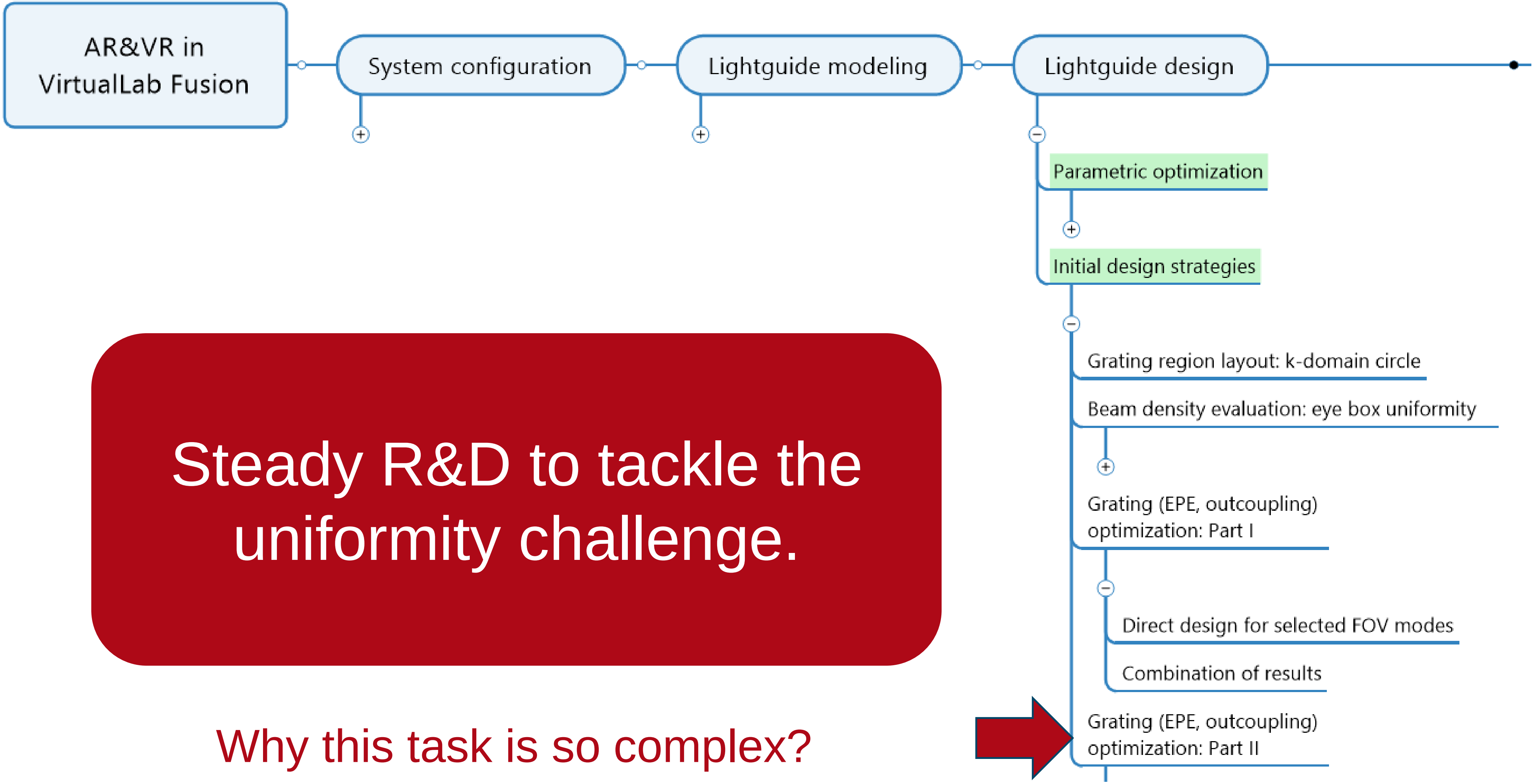
Lightguide Modeling and Design



Steady R&D to tackle the uniformity challenge.

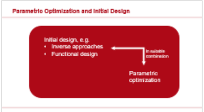


Lightguide Modeling and Design



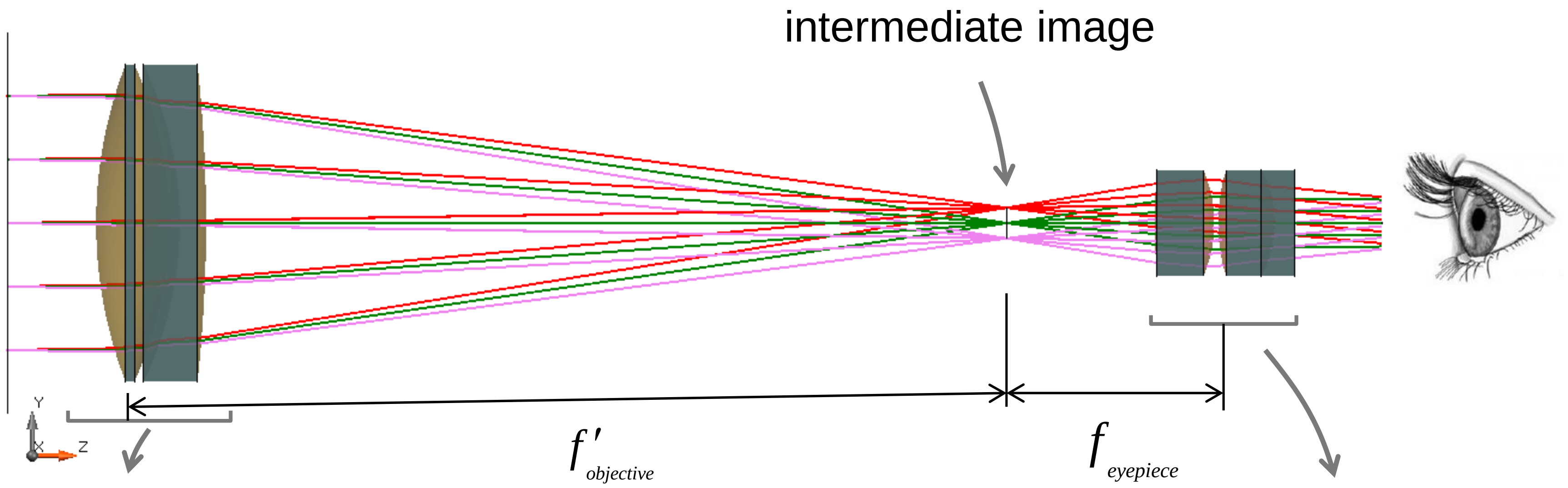
Steady R&D to tackle the uniformity challenge.

Why this task is so complex?



Telescope System

FOV modes behave somehow well-sorted



System parameters	
Magnification	5.5X
Field of view	4°

$$F/\# = f'/D'$$

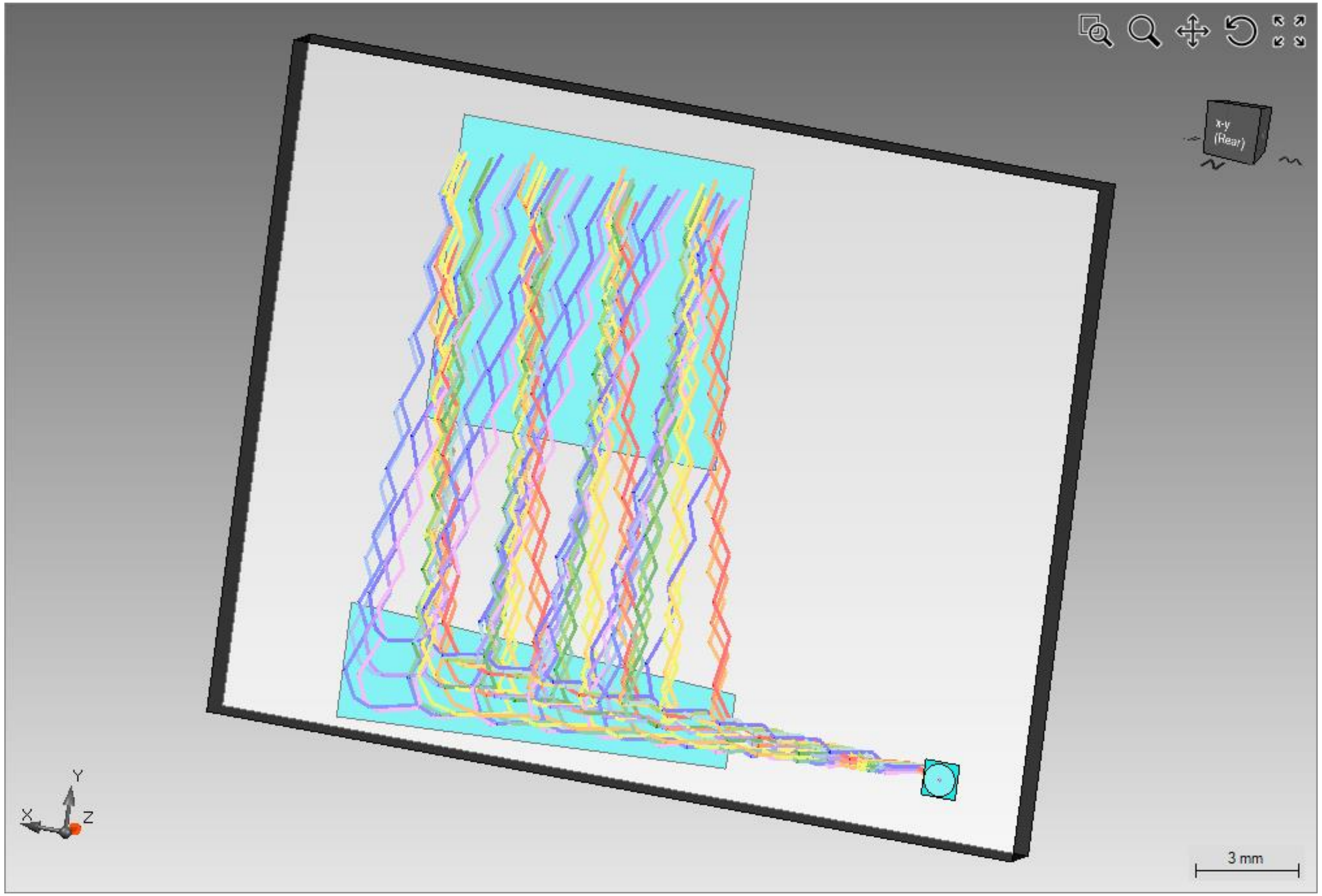
where, D ′is the diameter of the entrance pupil

Objective group	
Focal length $f'_{objective}$	100 mm
F/#	2.8
number of lenses	4

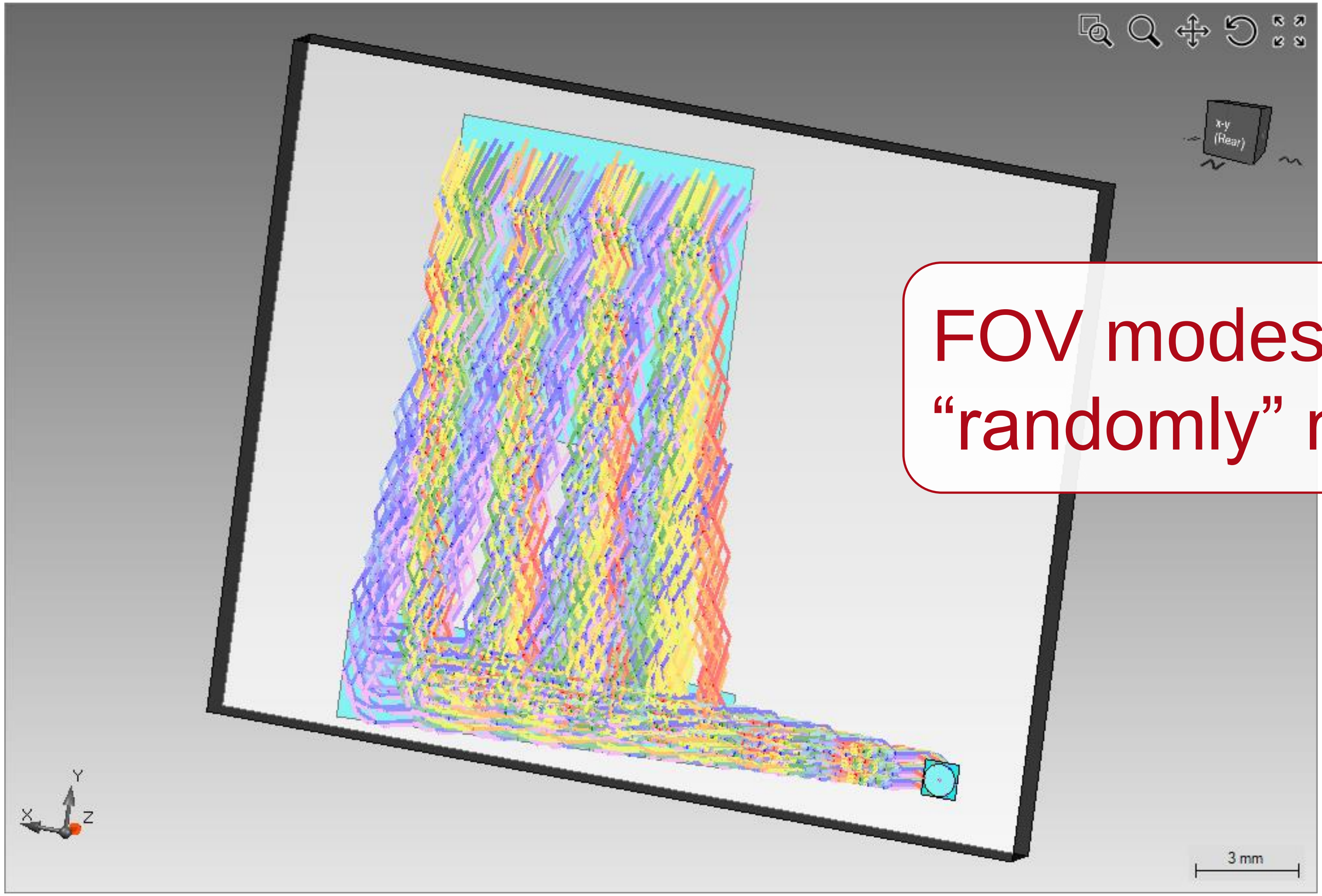
Eyepiece group	
Focal length $f_{eyepiece}$	18.3 mm
Exit Pupil Diameter	3.6 mm
number of lenses	5

Lens source: A_019 and C_001 in Zebase

Design for Multiple FOV Modes: Waveguide



Design for Multiple FOV Modes: Waveguide



FOV modes laterally "randomly" mixed up

Parametric Optimization and Initial Design

Initial design, e.g.

- Inverse approaches
- Functional design

In suitable combination

Parametric optimization

Thank You!