

Efficiency loss in ultrafast laser ablation due to spatial light modulator limitations in beam shaping

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June 2025



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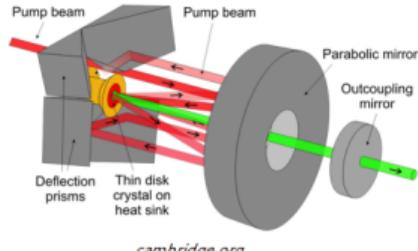
 **WIT** 
LiM
2025

Performances of ultrafast sources

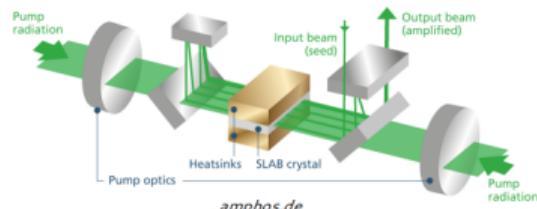
- Femtosecond lasers for processing : change of paradigm (*U. Brauch et al, App. Phys. B 128:58 - 2022*)
- Robust systems at 100 W and more (Direct diode pumping + Heat management)
- Pulse repetition rate increase → fast scanning solutions
- Pulse energy increase: need for beam duplication → spatial beam shaping

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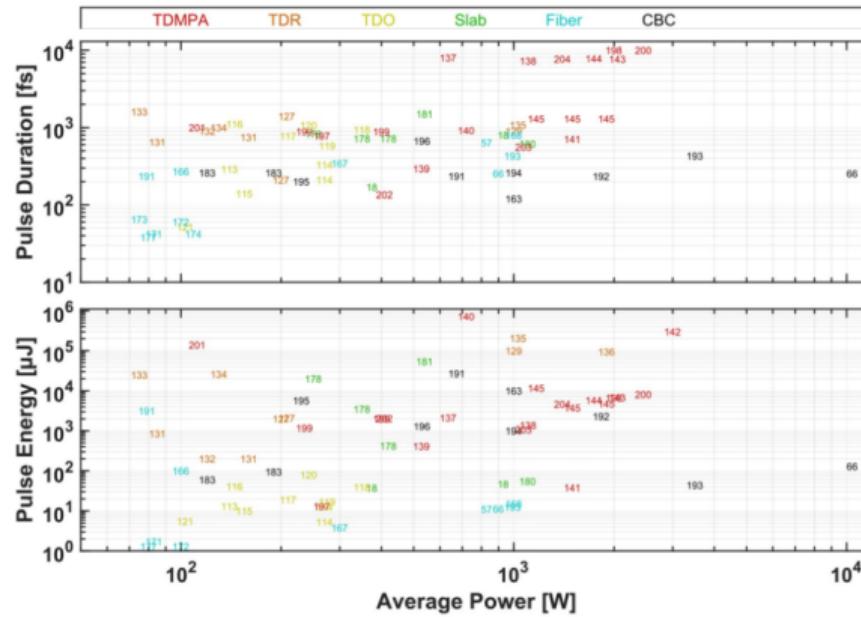
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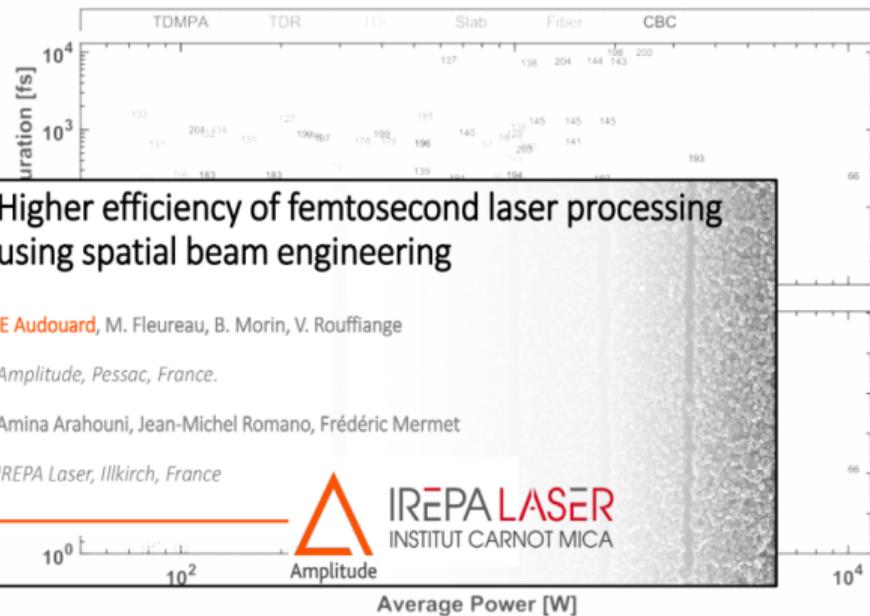
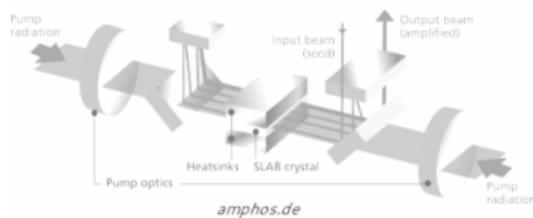
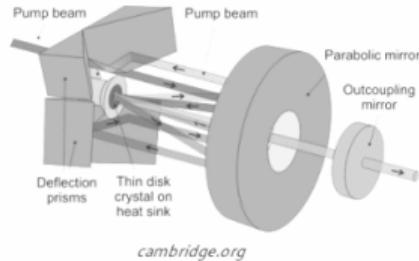


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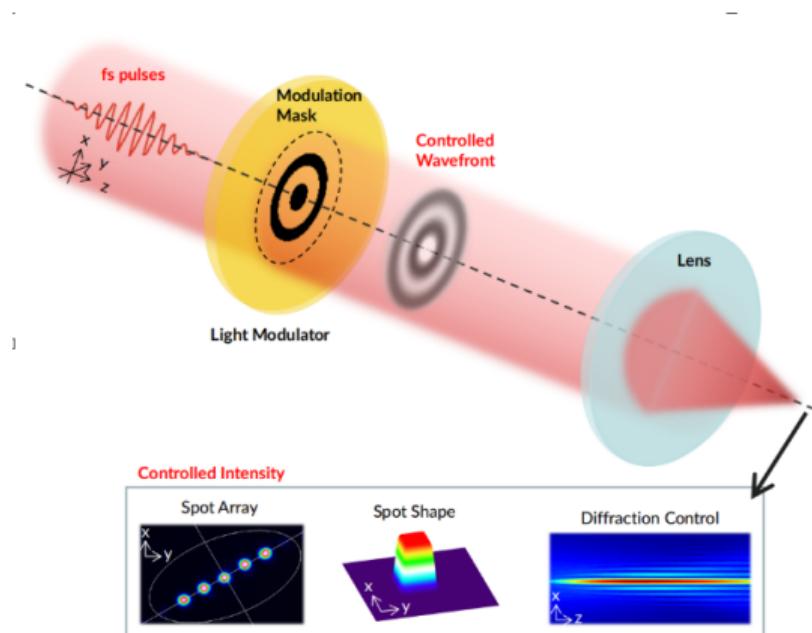


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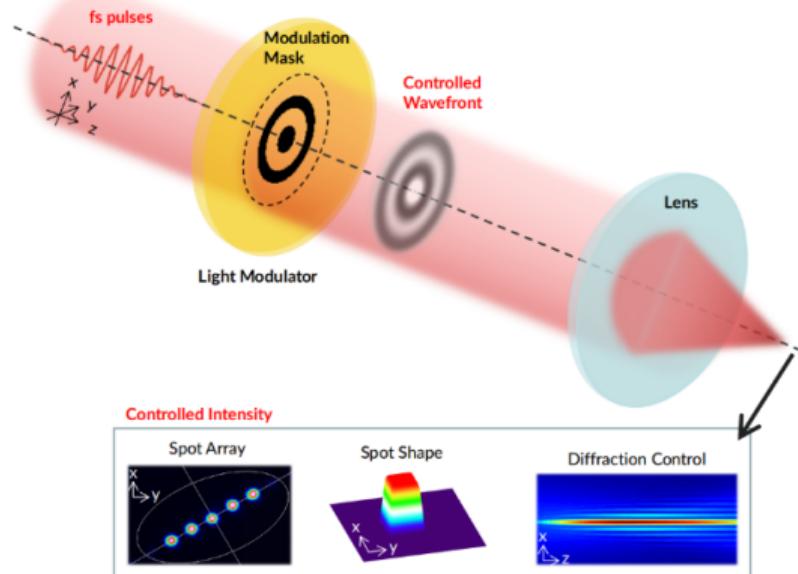
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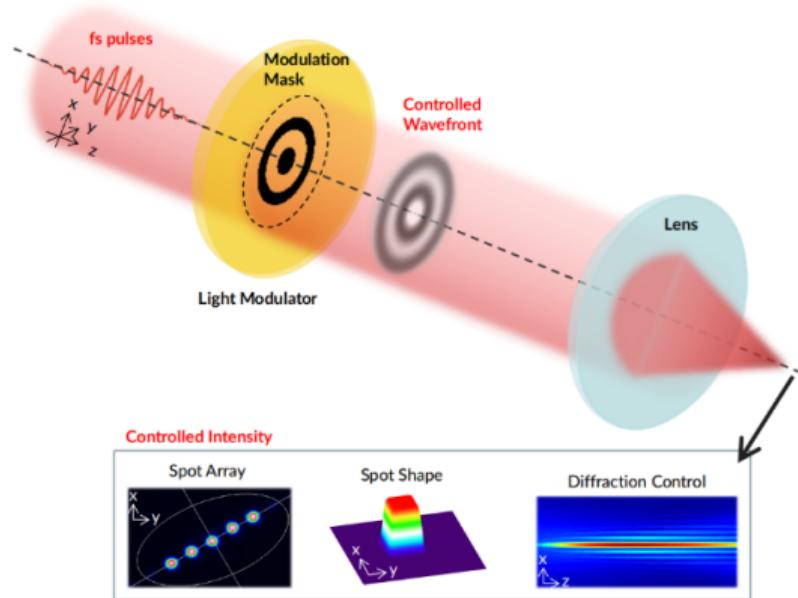
Dynamic spatial beam shaping for ultrafast laser processing: a review

Cyril Mauclair, Bahia Najih, Vincent Comte, et al.

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Increase of machining speed with parallel processing and/or more adapted beam shape to the desired application (structuring, cutting etc.)

How to modulate the laser wavefront $\phi(x, y)$?

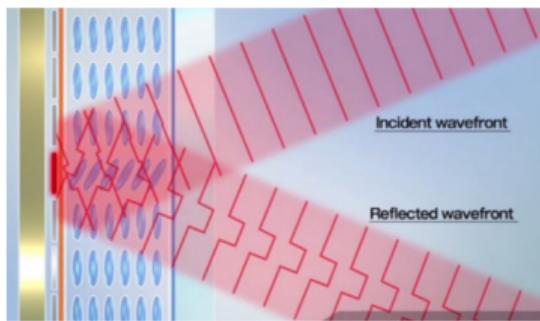
- Liquid Crystal (mesophase) in nematic phase (collective orientation)
- Birefringent properties with two optical indices n_e and n_o
- Orientation controllable by electric field \Rightarrow SLM: Spatial Light Modulator in reflection or in transmission with $E(x, y) \propto \phi(x, y)$

$$\Delta n = n_e(\theta_d) - n_o$$

Phasedelay:

$$\delta = \frac{2\pi}{\lambda_0} d |\Delta n|$$

d : LC thickness
 λ_0 : Wavelength

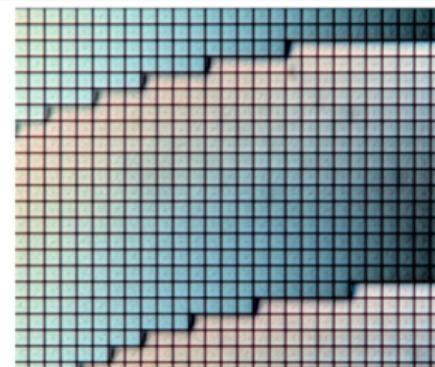
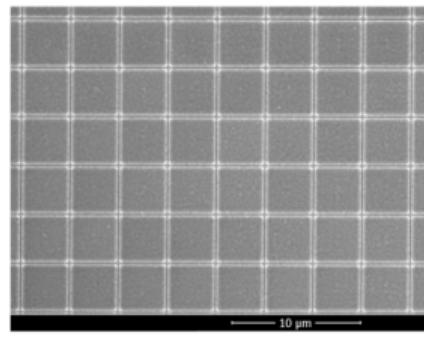
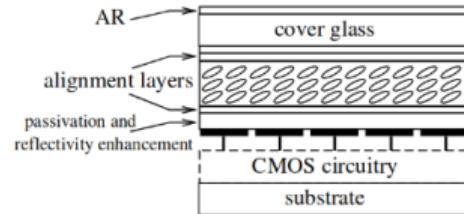


SLM's limitations

- SLM Resolution limit, Quantification of phase levels
- Fill factor < 100%, Cross talk between pixels

Consequences on Multispot arrays

- Non modulated portions of the beam end in the 0th order
- Appearance of unwanted orders (due to quantification of the phase)
- Loss of homogeneity between the spots

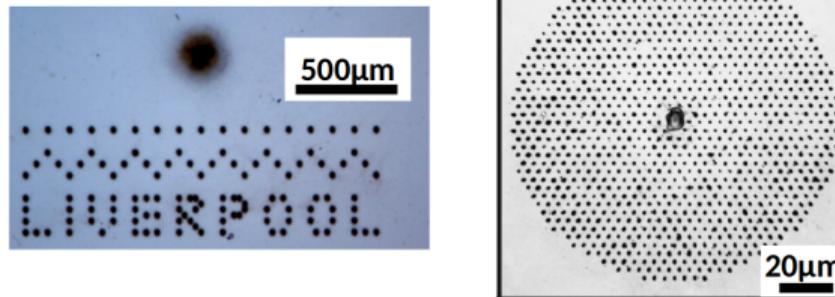


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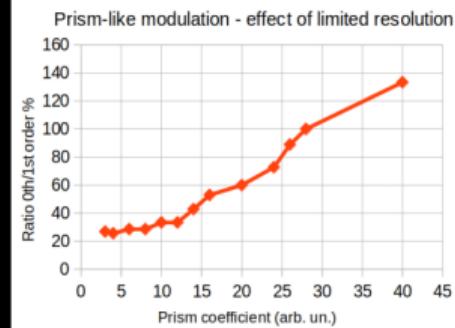
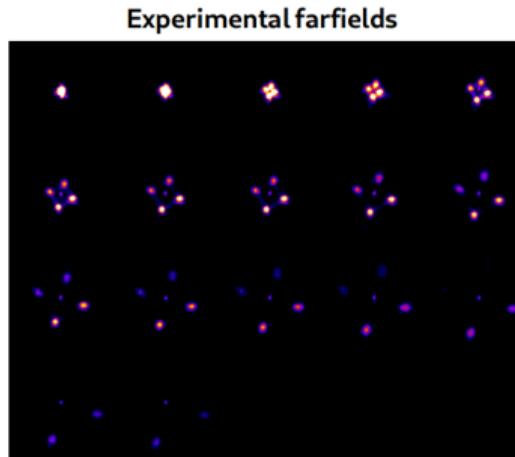
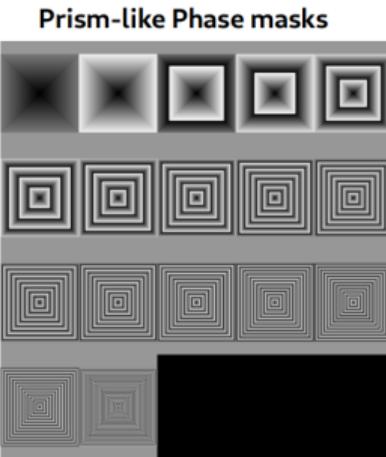
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Kuang et al. App. Surf. Sci. 255 (2008), Hasegawa et al. Opt. Express 24 (2016)

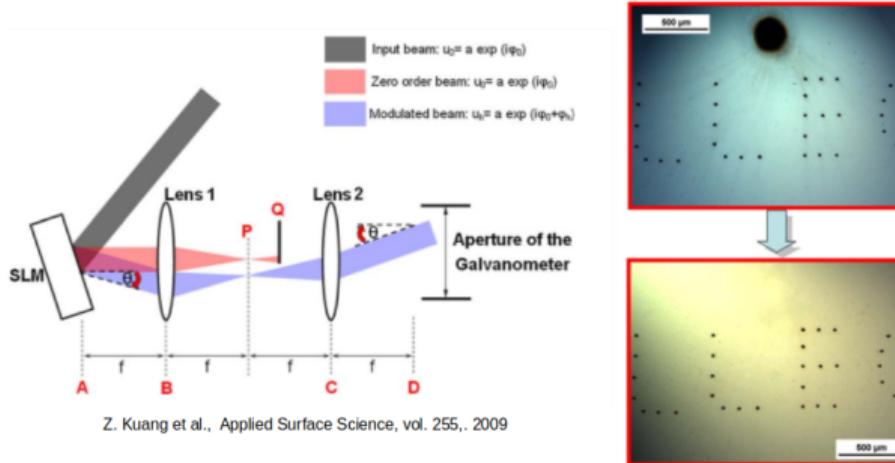
Effect of limited resolution on a prism-like phase modulations

- The SLM cannot perfectly reproduce phase jumps \Rightarrow phase ramps
- The energy losses in the 0th order increases with higher phase jumps frequency.
- Experimental solution : filtering out the 0th order adding a tilt or a defocus $\phi(x, y) \rightarrow$ Losses!



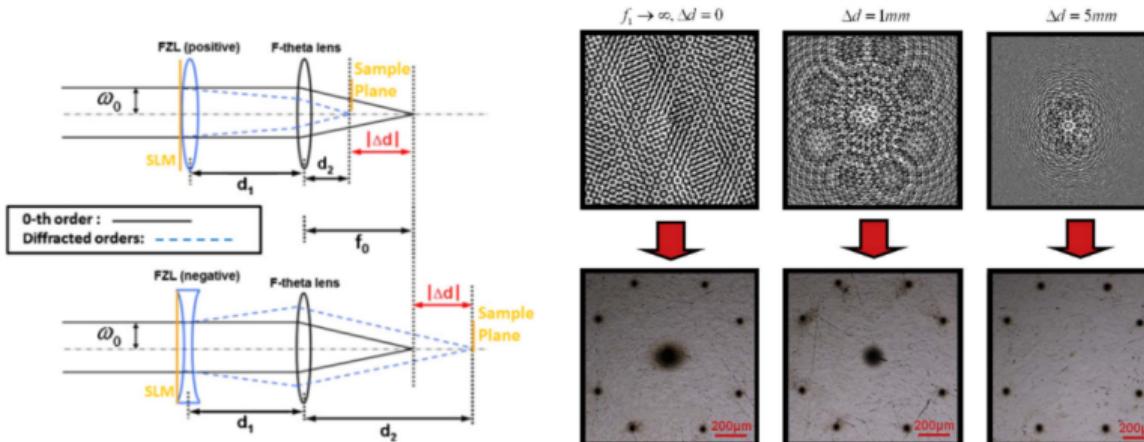
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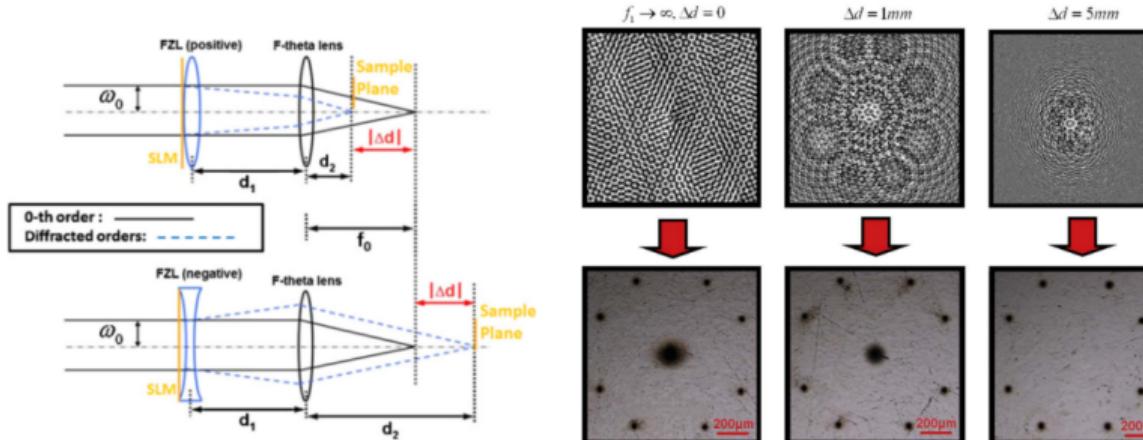
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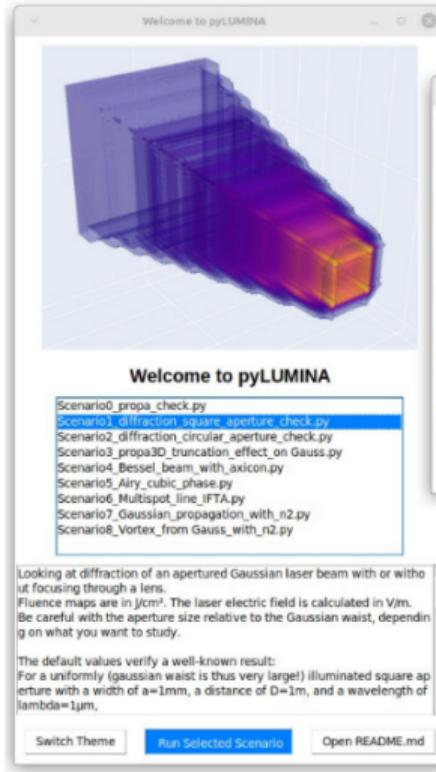
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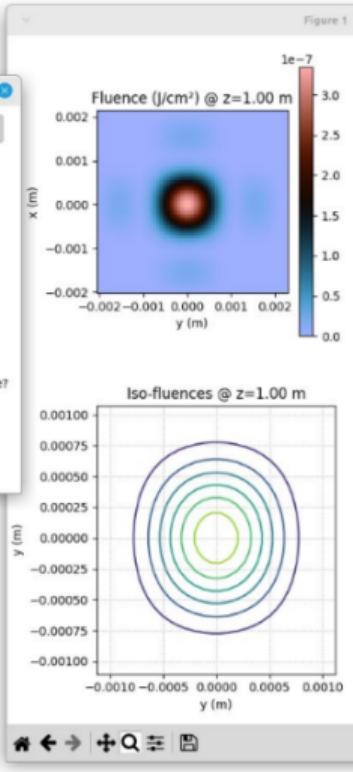
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In the following, we simulate the SLM resolution limit by adding a **Gaussian Blur** on the phase mask to estimate the **energy losses** in the stray 0th order.

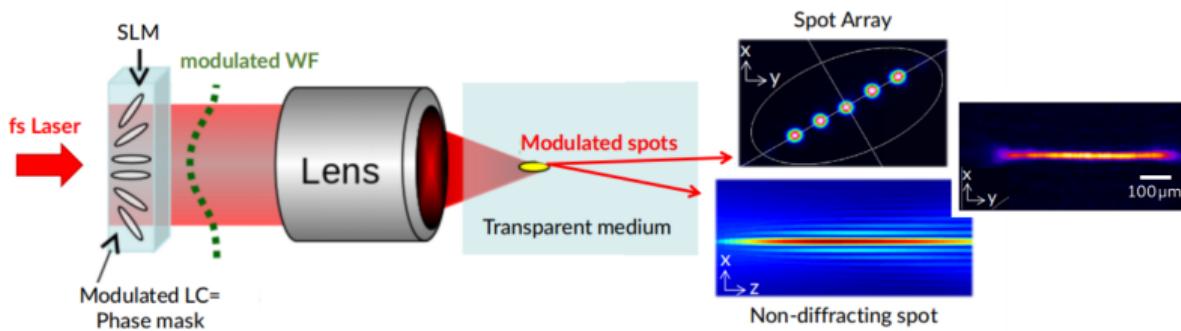


Laser Beam Propagation Simulator 3D

Number of pixels: 256
Beam waist (m): 1
Window size (m): 0.02
Propagation distance (m): 1.0
Wavelength (m): 1.03e-06
Pulse energy (J): 1e-06
Pulse FWHM (s): 1e-13
Number of planes: 10
Aperture width (m): 0.001
Focal Length (m): 1
 Apply Lens Phase?
Aperture Type: square Apply Aperture?
Colormap: berlin Wanna go 3D?
[Run Simulation](#)



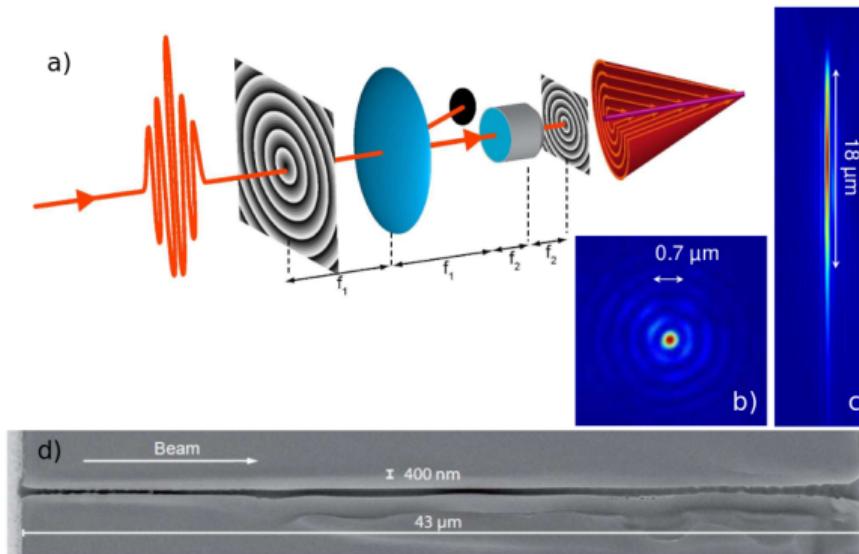
3 beam shapes : multislot, line and non-diffracting beams (Bessel)



Energy losses in the 0th order? key parameters?

Effect of limited resolution on axiconic modulation (Bessel Beam)

- Non-diffracting beams → transparent material processing *Courvoisier et al. Appl Phys Lett. 97 (2010)*
- SLM can dynamically reconfigure Bessel beam properties
- Effect of limited resolution ⇒ On-axis intensity modulation (Numerical results - pyLUMINA)

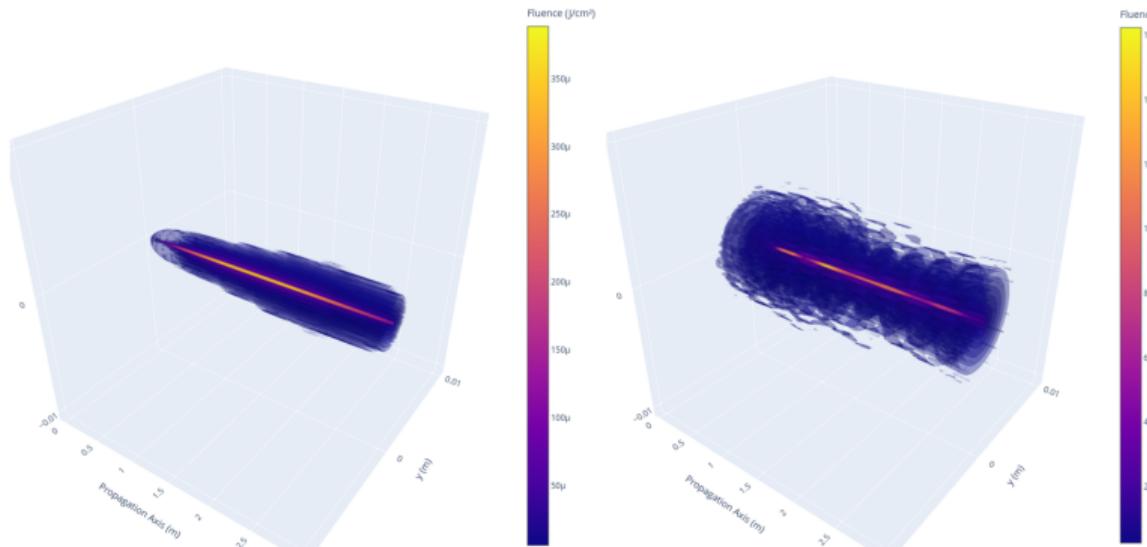


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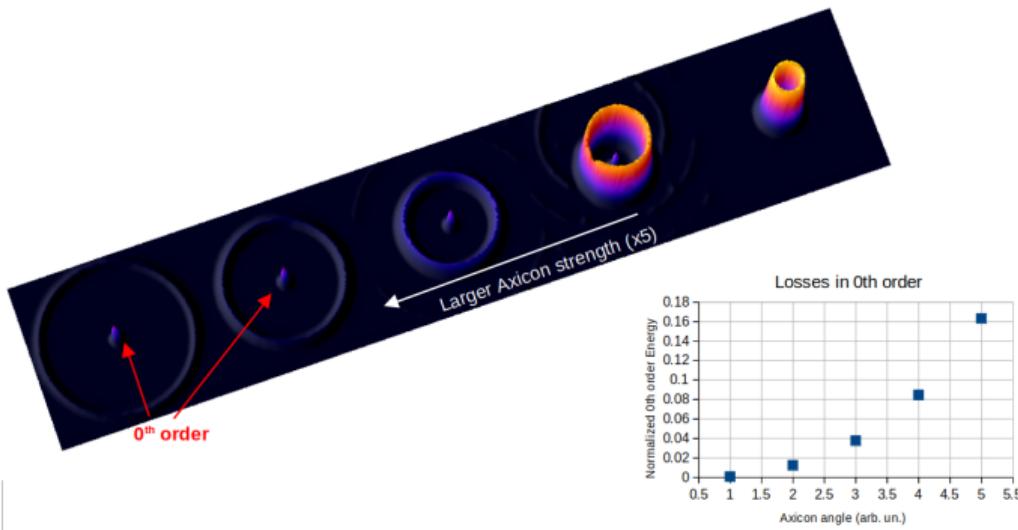
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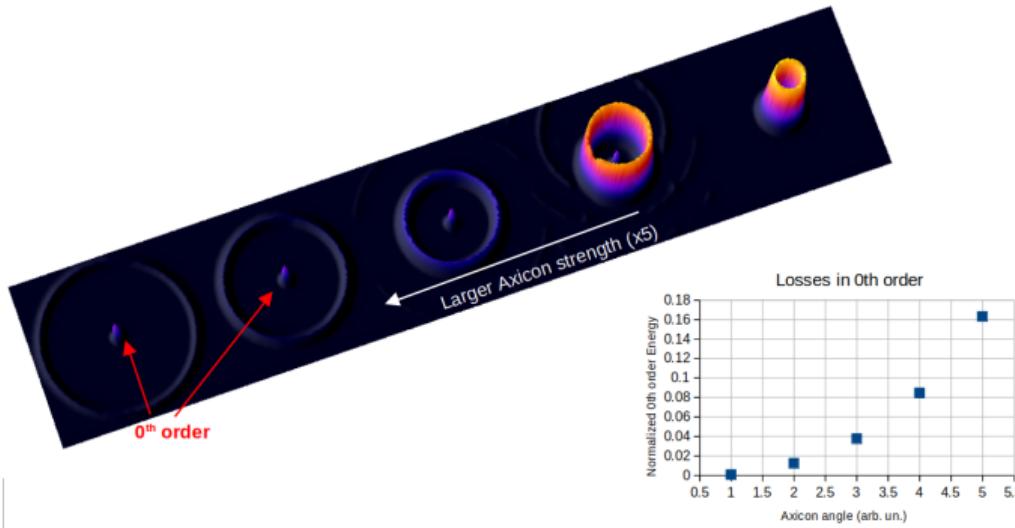
Energy in the 0th order?

- Simulation of the Bessel beam in the **Fourier plane**
→ annulus shape with the stray order on the optical axis.
- Numerically evaluating the energy wasted for various axicon angles → Up to 17% energy loss. To be compared to regular axicons (tip problem) or reflective axicons (Cailabs).



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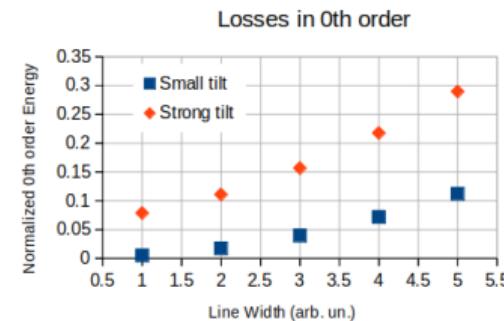
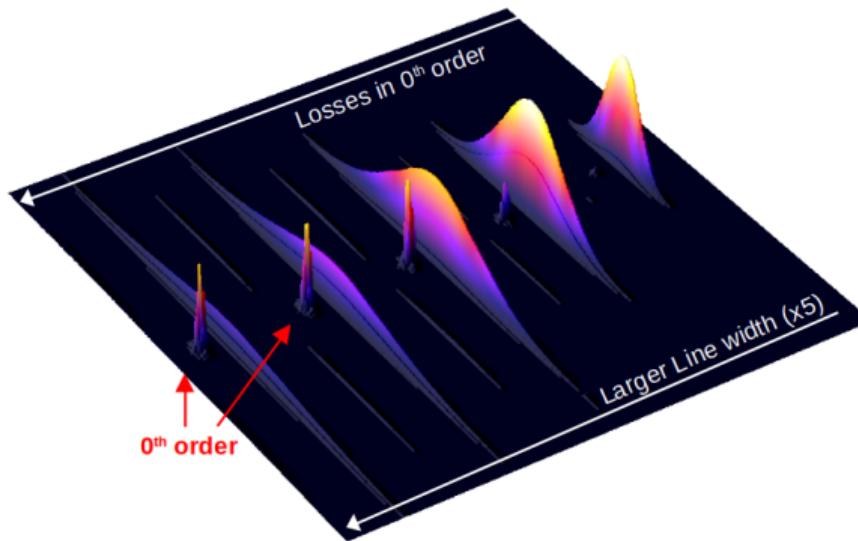


Effect of limited resolution on 2nd order phase mask

- 2nd order phase mask: \approx Cylindrical lens \rightarrow focal line.
- line-shaped beam: parabolic phase mask \Rightarrow Phase jumps on the SLM
- Phase jumps \Rightarrow Phase ramps yielding additional diffraction.

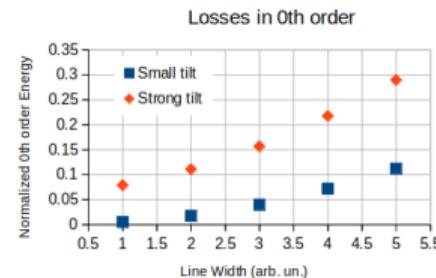
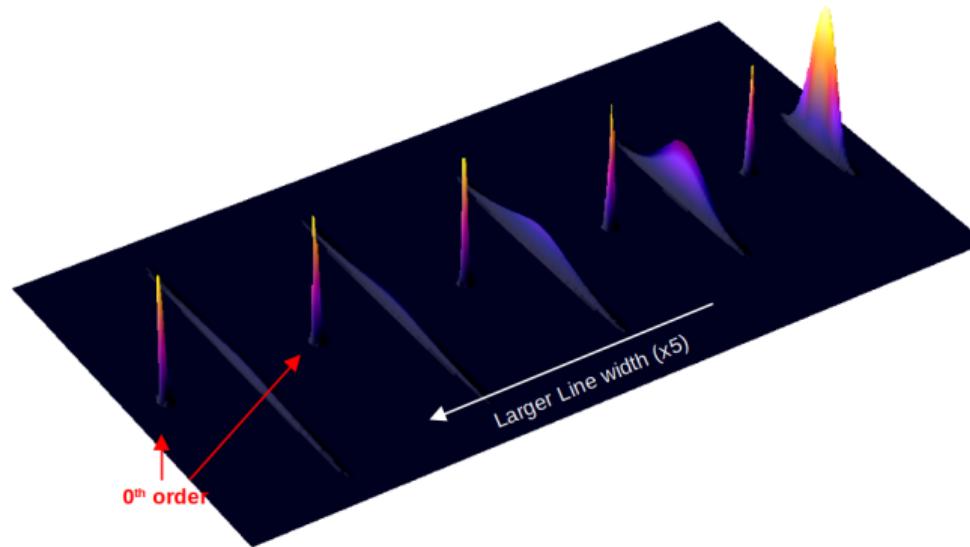
Energy in the 0th order?

- Simulation of the line beam in the **Fourier plane** with an added tilt
→ the line is displaced and the stray order remains on the optical axis.
- Numerically evaluating the energy wasted for various line width and tilt values → Up to 30% energy loss for the largest lines and tilts.



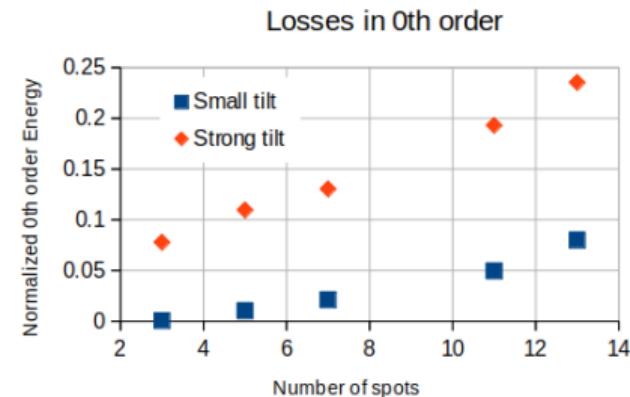
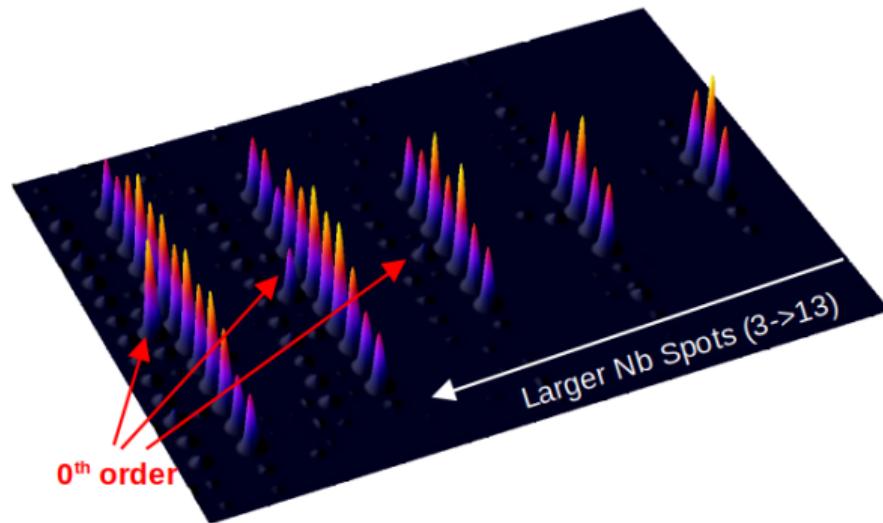
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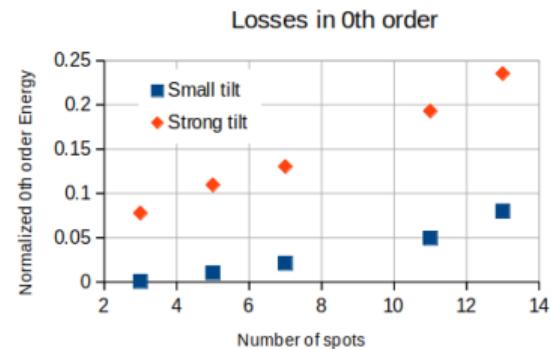
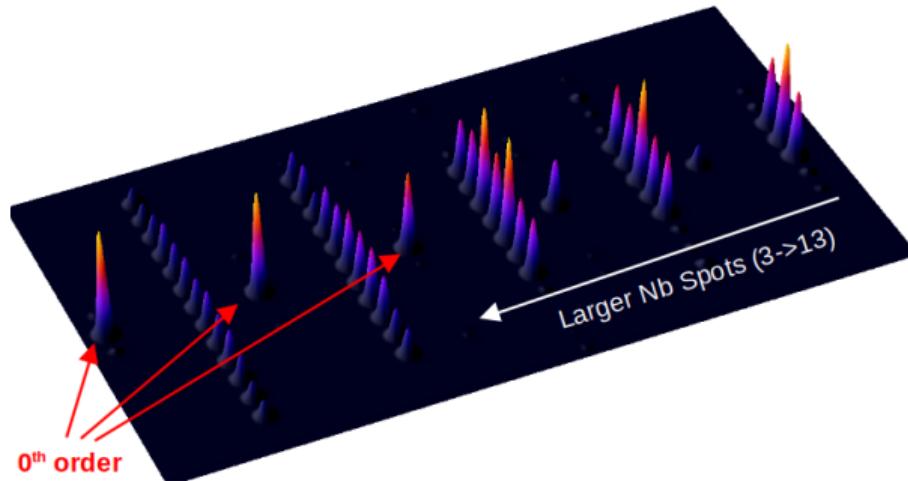
Energy in the 0th order?

- Simulation of a Multi spot beam in the **Fourier plane** with an added tilt
→ the spot array is displaced and the stray order remains on the optical axis.
- Numerically evaluating the energy wasted for various number of spots and tilt values. → Up to 27% energy loss for the largest number of spots and tilt.



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Summary/ Perspectives

Spatial beam shaping with SLMs

- Enables increase of the processing speed, with low energy losses
- Well-adapted for R & D: reconfigurability + progress of the technology (resolution, fill factor, stability, power handling)

Evaluating energy loss in the stray order

- Limits in resolution and quantization contribute to the 0th order and inhomogeneities
- resolution limitation simulated by a blur on the phase mask
- estimation of the losses for 3 beam shapes of interest
- the more 'complex', the more losses (amount of phase jumps)

Perspectives

- Feedback on the laser intensity can correct to some extent
- Feedback based on the process outcome more efficient (ask for an example).

