Synthesizing acoustic drill beams by the superposition of detuned vortices

Noé Jiménez, Enrique González-Mateo, Francisco Camarena and Kestutis Staliunas

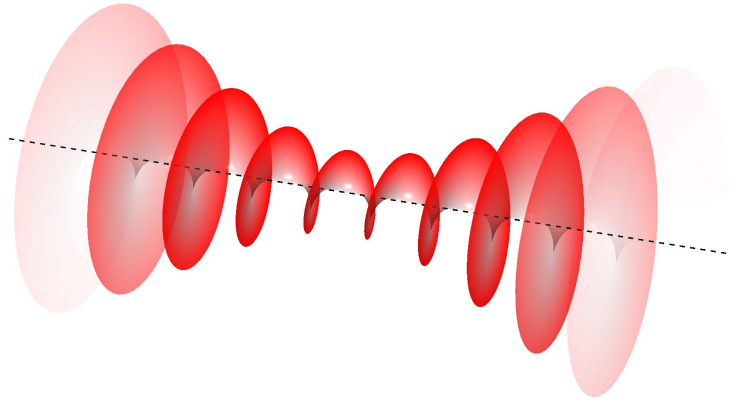
Instituto de Instrumentación para Imagen Molecular (I3M), Universitat Politècnica de València / CSIC, València, Spain
ICREA, Universitat Politècnica de Catalunya, Terrasa, Barcelona, Spain

182nd Meeting of the Acoustical Society of America, 23–27 May 2022, Denver, Colorado, USA

Introduction

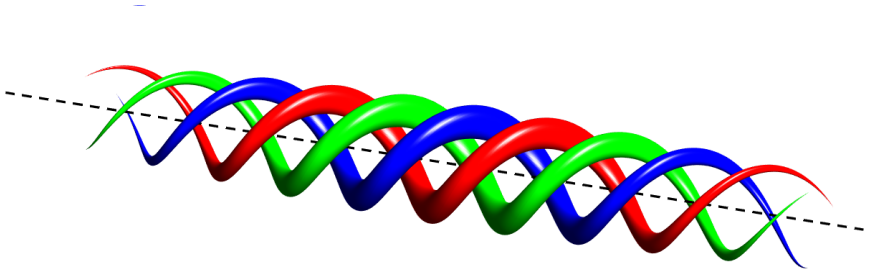
Phase and magnitude of a vortex beam

- Bessel beams present **helical phase** distribution
- However, its intensity distribution resembles a **hollow tube**



Goal

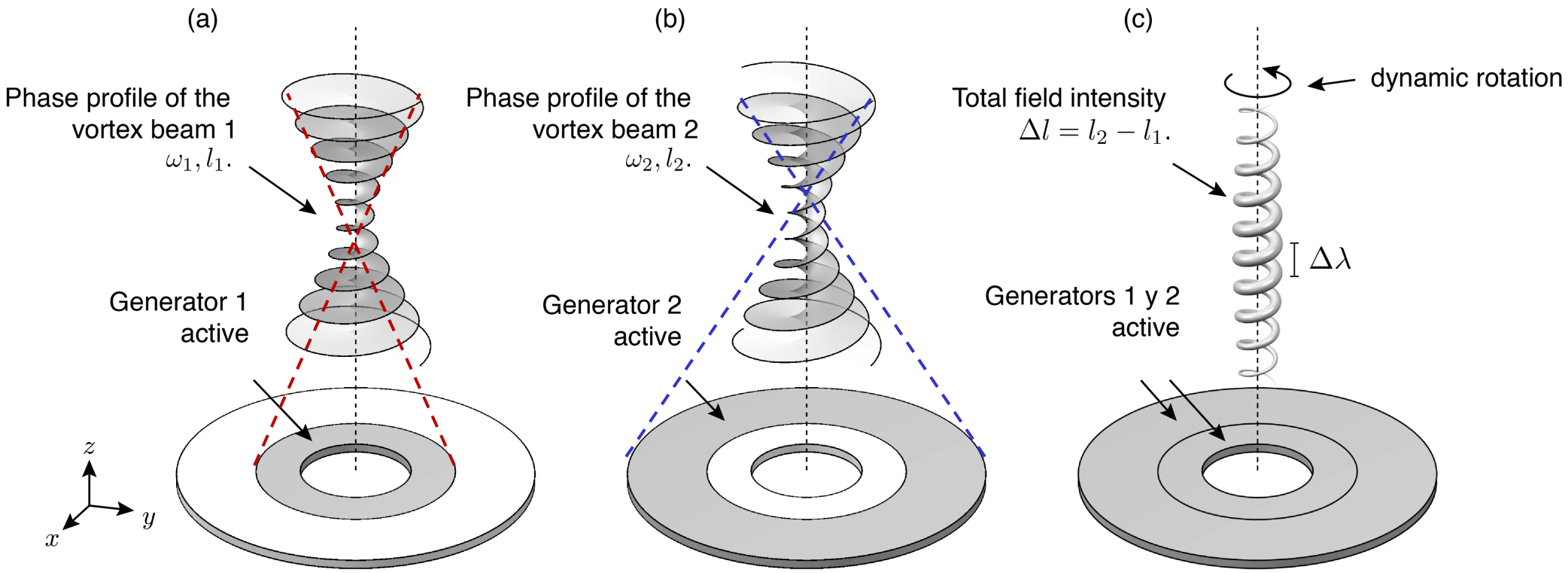
- Obtain a beam with **helical intensity** distribution
- Rotate the helical pattern in time
- “Drill beams”



Drill beams

Basic mechanism

- Spatio-temporal interference of detuned beams.
- Detuning in **axial wavenumber**, **topological charge**, and **frequency**.



Drill beams

Detuning in axial wavenumber

- Detune in k-space results in spatial beating

$$\Delta k_z = k_z^{[2]} - k_z^{[1]}$$

Detuning in frequency

- Detuning in frequency results in temporal beating

$$\Delta \omega = \omega_2 - \omega_1$$

Detuned topological charge

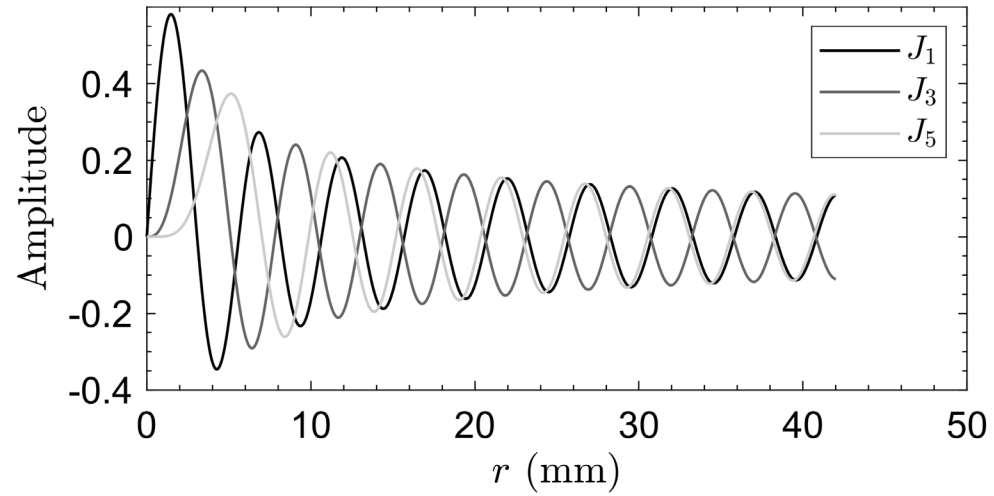
- Detuned topological charge result in angular beating

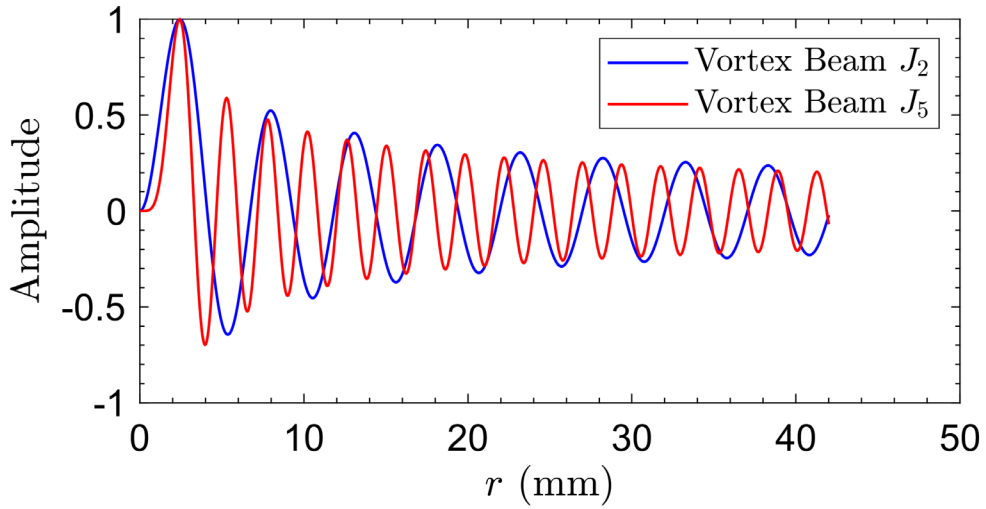
$$\Delta l = l_2 - l_1$$

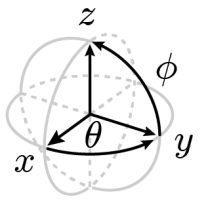
Drill beams emerge by the spatio-temporal interference of confocal beams of detuned axial wavenumber, frequency and topological charge

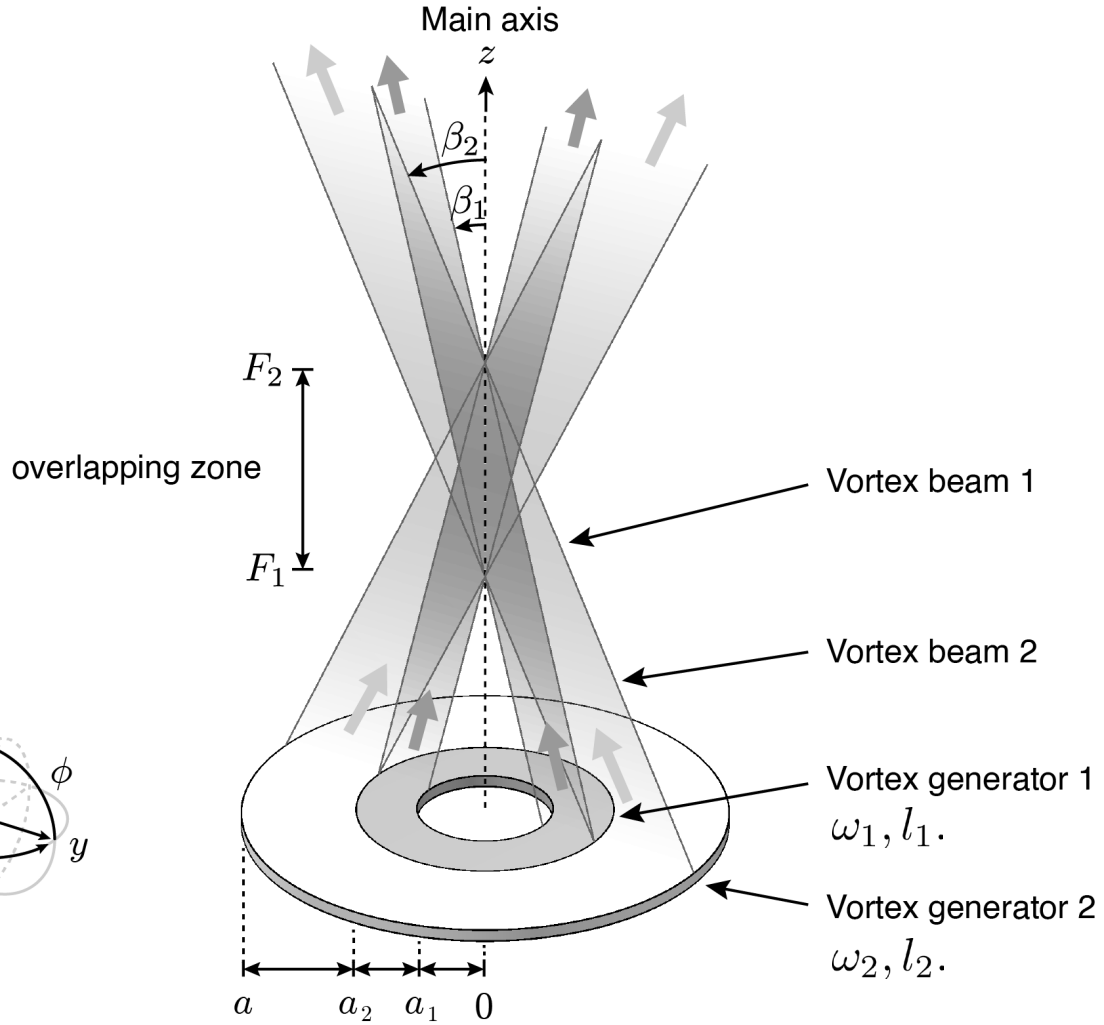
Finding the optimal overlap for Bessel beams

How to overlap Bessel beams with different topological charge?









Finding the optimal overlap for Bessel beams

Criteria (1): matching maxima of the Bessel function

- The **radial wavenumber** is

$$k_r^{[n]} = k_n \sin \beta_n,$$

where $k_{[n]} = \omega_n / c_0$ and $\omega_2 \approx \omega_1$.

- The **maxima** of the Bessel function is approximately at

$$r_w^{[n]} = \frac{|l_n| + 0.8086 \sqrt[3]{|l_n|}}{k_r^{[n]}}.$$

- Maximal overlap exist when $r_w^{[1]} = r_w^{[2]}$, then

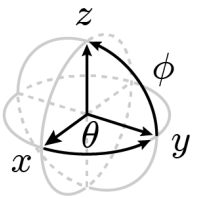
$$k_r^{[1]} = k_r^{[2]} \frac{|l_1| + 0.8086 \sqrt[3]{|l_1|}}{|l_2| + 0.8086 \sqrt[3]{|l_2|}}.$$

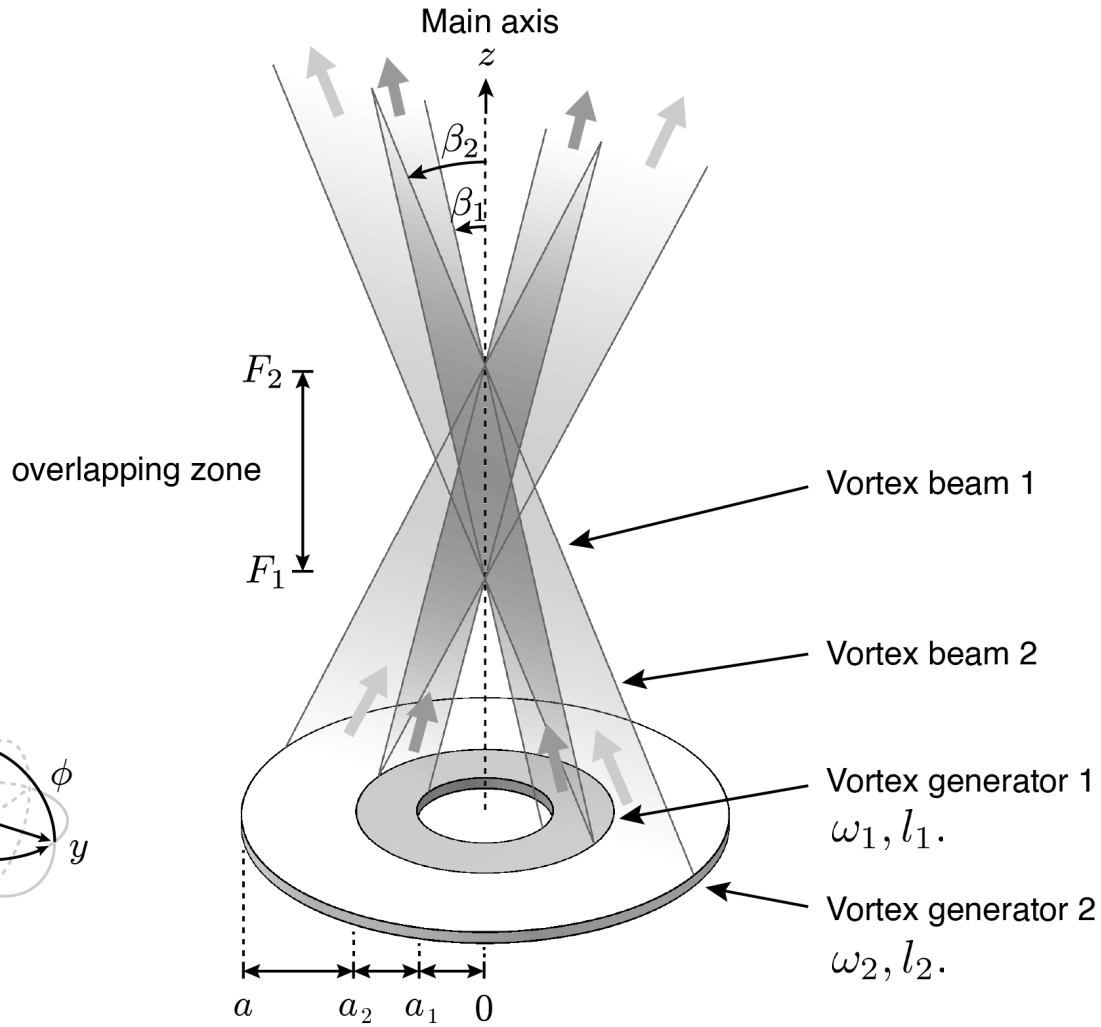
- The **angle** of the outer beam is given by

$$\beta_2 = \tan^{-1}(a/F_2).$$

- Then

$$\beta_1 = \sin^{-1}\left(k_r^{[1]}/k_1\right).$$





Finding the optimal overlap for Bessel beams

Criteria (2): axial overlapping zone

- The **first aperture** radius starts at

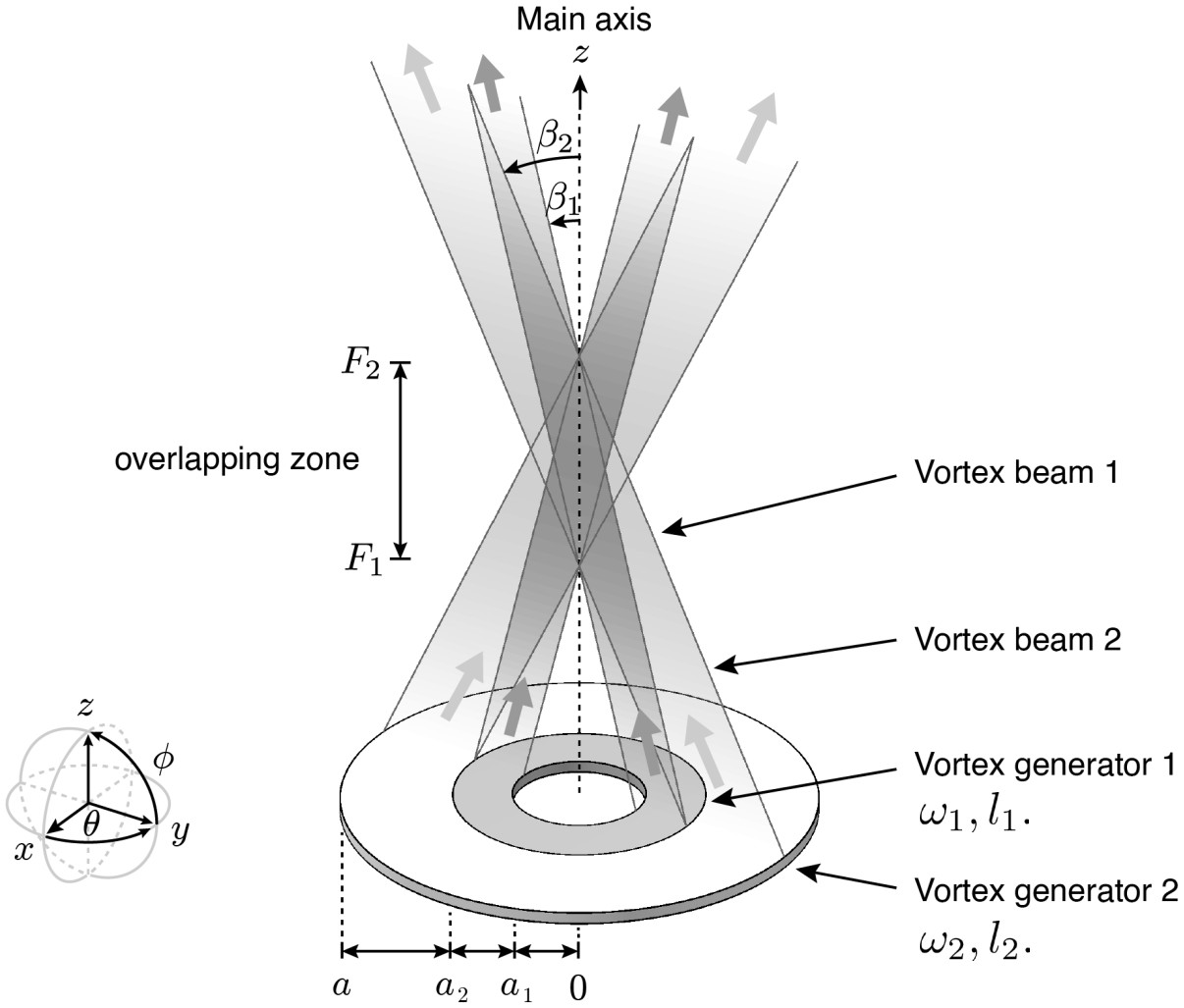
$$a_2 = F_2 \tan \beta_1.$$

- The overlapping axial zone starts at

$$F_1 = a_2 / \tan \beta_2.$$

- And the **inner aperture** radius

$$a_1 = F_1 \tan \beta_1.$$



Tuning drill beams

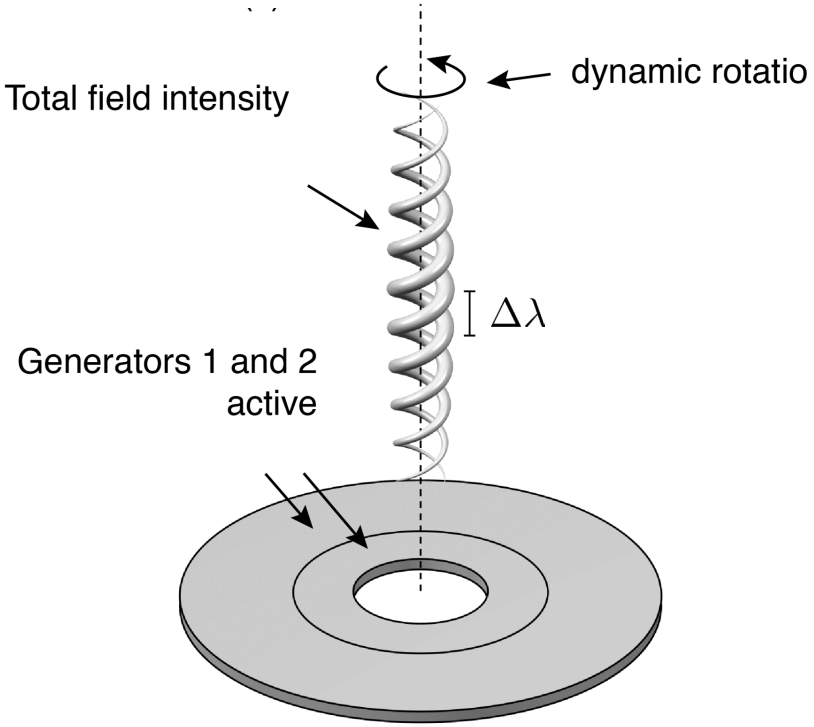
Parametric equation of a drill beam

- The trajectory of the helical beam is given by

$$x_m(\theta) = r_w \cos\left(\sigma\theta + \frac{m-1}{2\pi\Delta l} + \frac{\Delta\omega}{\Delta l}t\right),$$

$$y_m(\theta) = -r_w \sin\left(\sigma\theta + \frac{m-1}{2\pi\Delta l} + \frac{\Delta\omega}{\Delta l}t\right),$$

$$z_m(\theta) = \Delta\lambda\frac{\Delta l\theta}{2\pi},$$

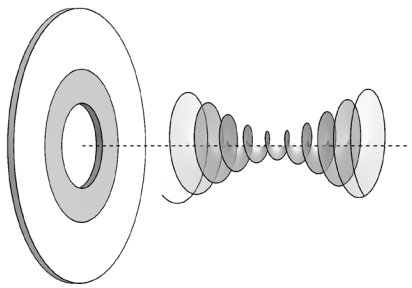


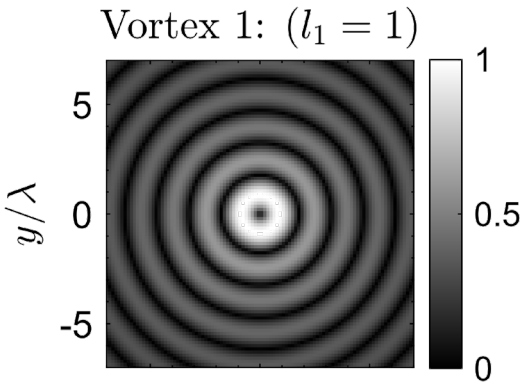
- where the detuning axial wavenumber fixes the winding period as

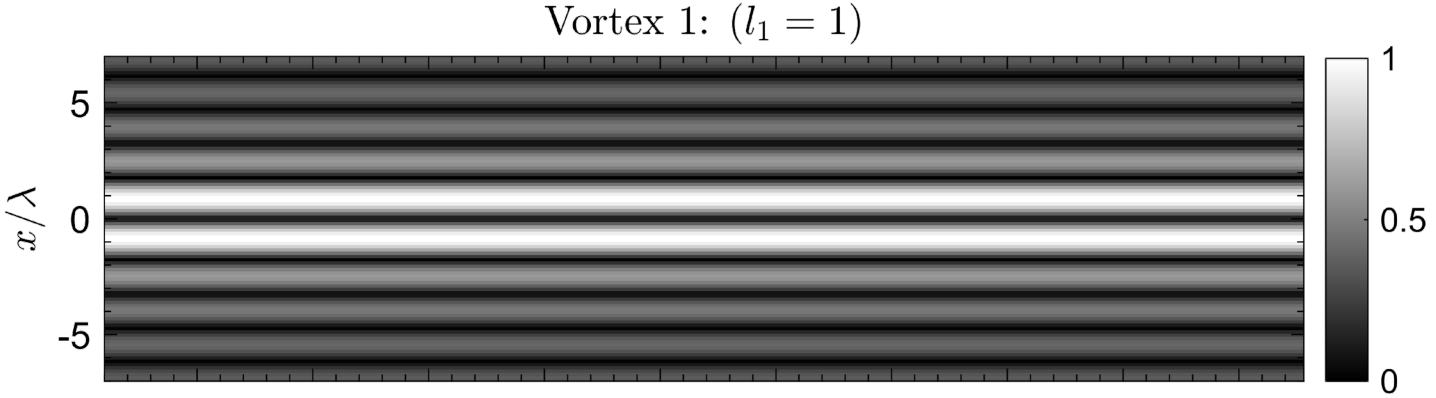
$$\Delta\lambda = \frac{2\pi}{\Delta k_z} = \frac{2\pi}{|k_z^{[2]} - k_z^{[1]}|},$$

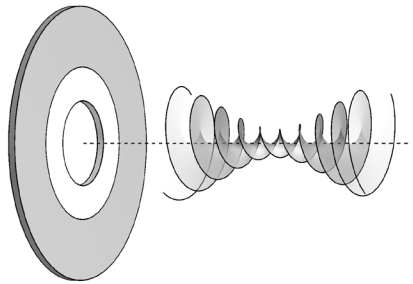
- Finally, the group speed of the helix along the axis can be estimated as

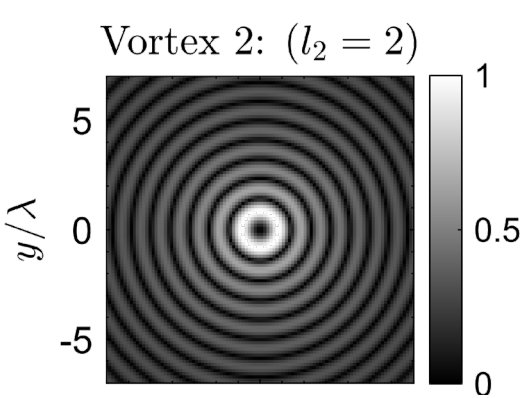
$$c_g = s_\theta\frac{\Delta\lambda\Delta\omega}{2\pi} = c_0\frac{\omega_1 - \omega_2}{\omega_1\cos\beta_1 - \omega_2\cos\beta_2}.$$

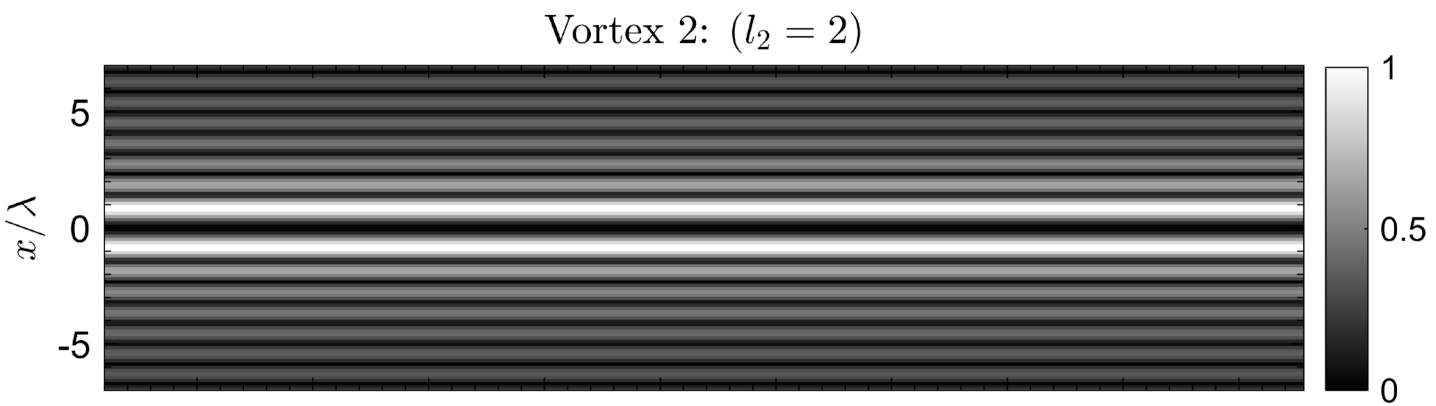


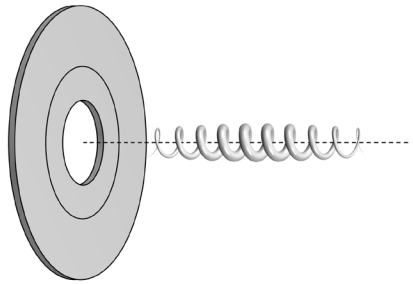

Vortex 1: $(l_1 = 1)$
y/λ
5
0
-5
1
0.5
0

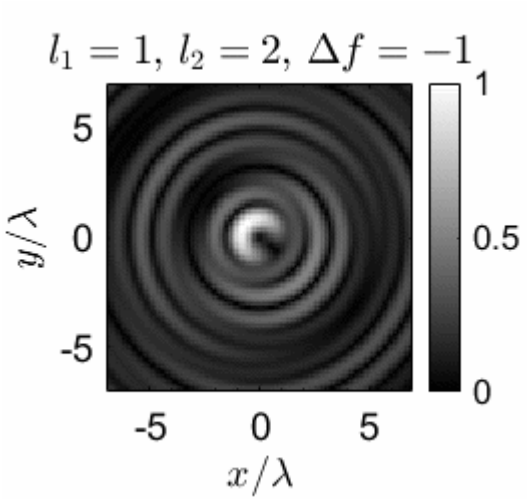

Vortex 1: $(l_1 = 1)$
x/λ
5
0
-5
1
0.5
0

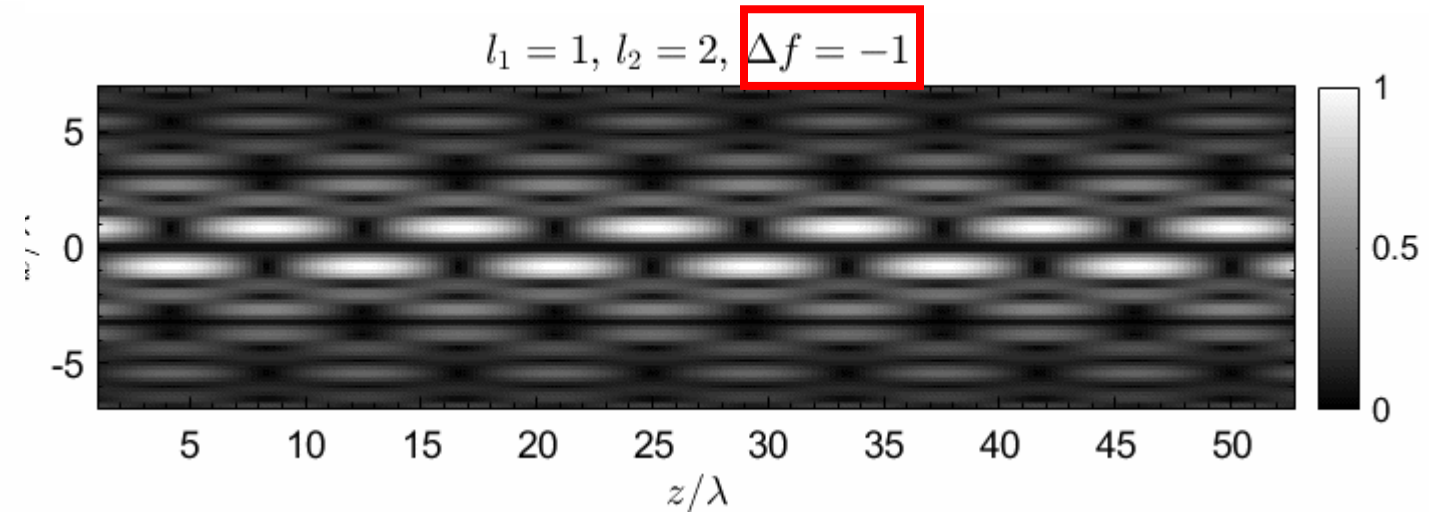



Vortex 2: $(l_2 = 2)$
y/λ
5
0
-5
1
0.5
0

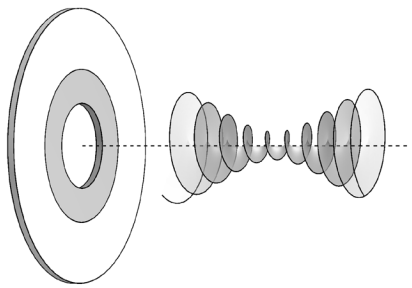

Vortex 2: $(l_2 = 2)$
x/λ
5
0
-5
1
0.5
0

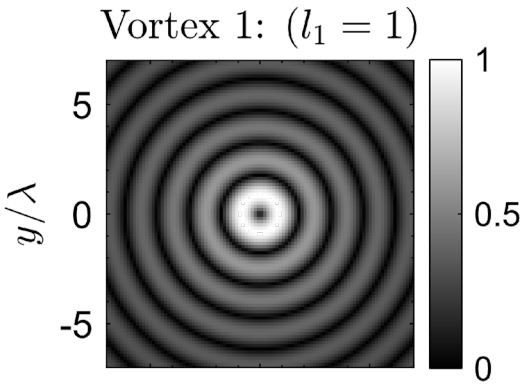


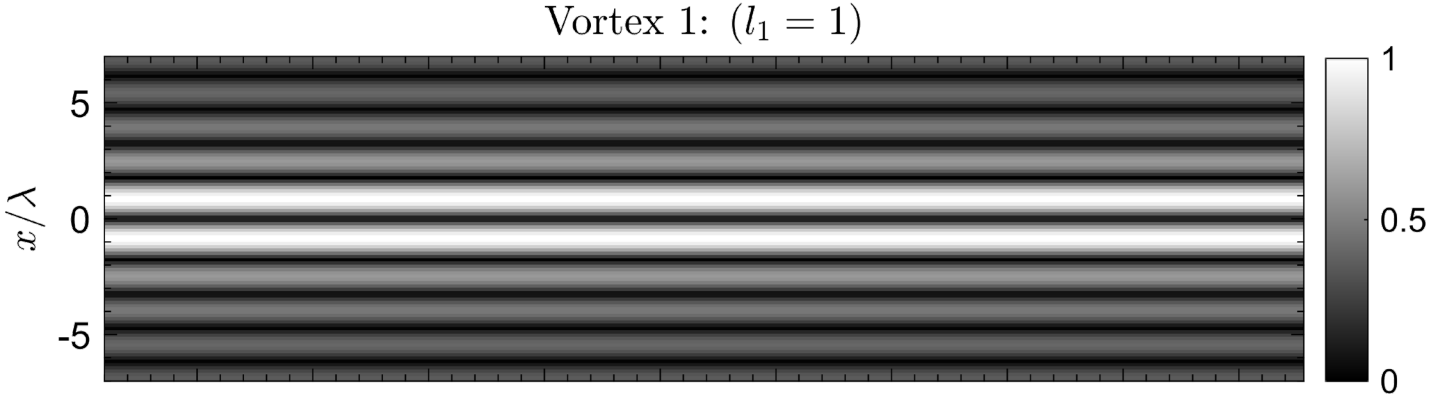

$l_1 = 1,\ l_2 = 2,\ \Delta f = -1$
y/λ
5
0
-5
1
0.5
0
-5
0
5
x/λ

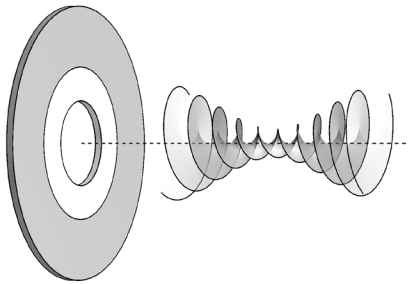

$l_1 = 1,\ l_2 = 2,\ \Delta f = -1$
5
0
-5
1
0.5
0
5
10
15
20
25
30
35
40
45
50
z/λ

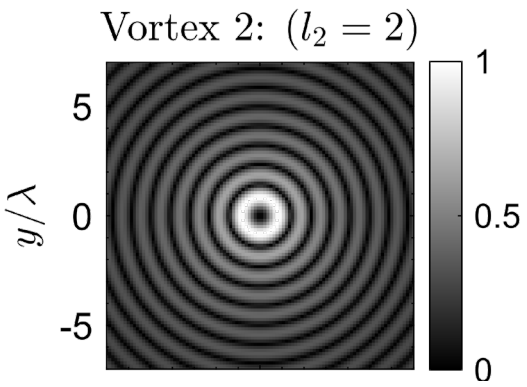
$$\Delta l = l_2 - l_1$$

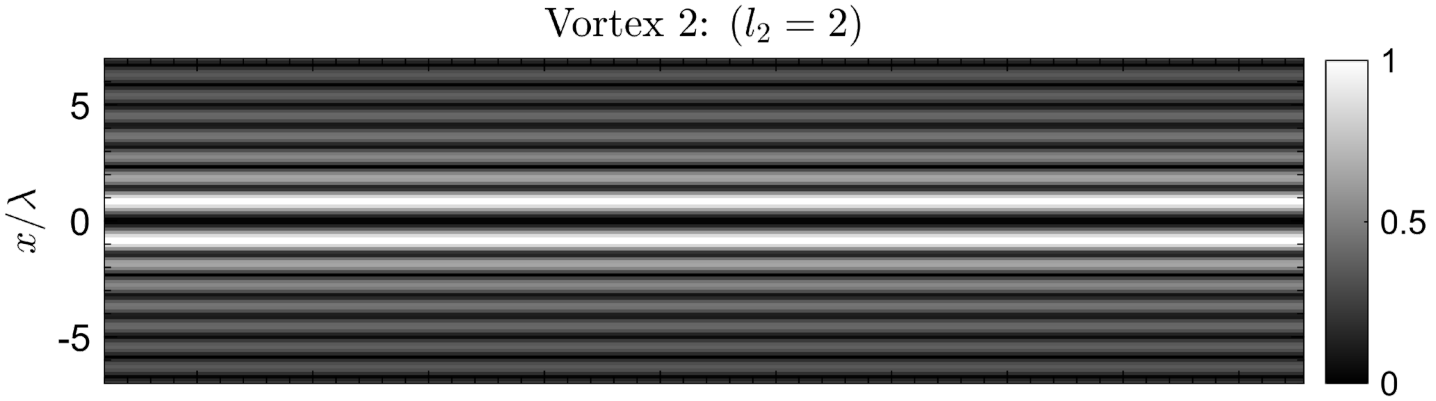


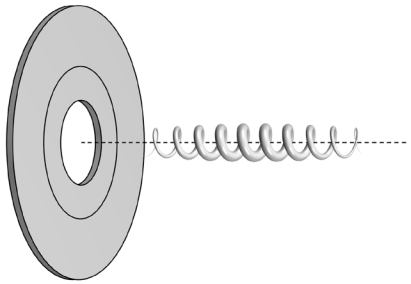

Vortex 1: $(l_1 = 1)$
y/λ
5
0
-5
1
0.5
0

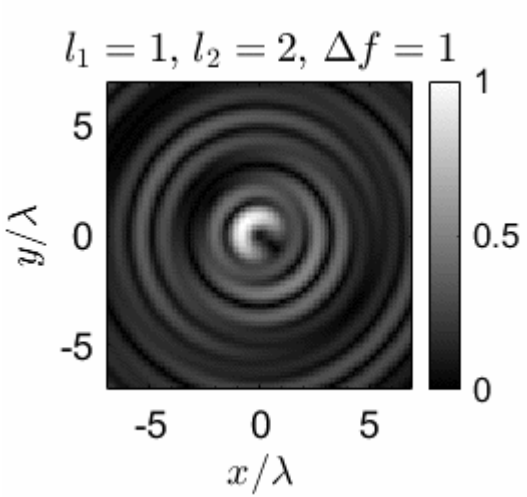

Vortex 1: $(l_1 = 1)$
x/λ
5
0
-5
1
0.5
0

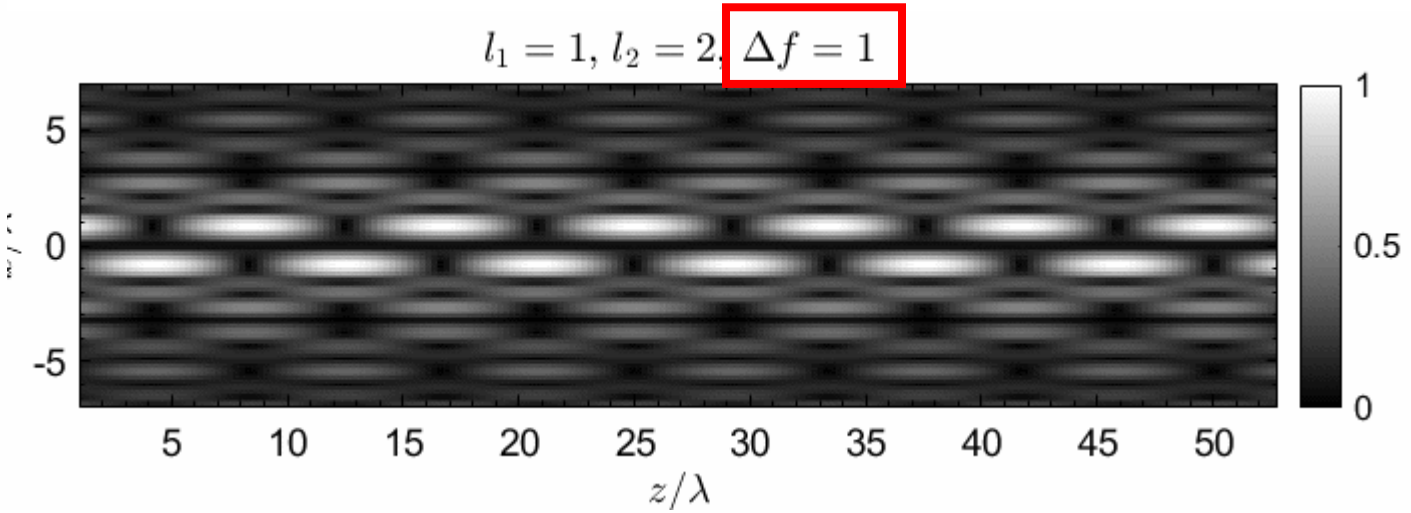



Vortex 2: $(l_2 = 2)$
y/λ
5
0
-5
1
0.5
0


Vortex 2: $(l_2 = 2)$
x/λ
5
0
-5
1
0.5
0




$l_1 = 1,\ l_2 = 2,\ \Delta f = 1$
y/λ
5
0
-5
1
0.5
0
-5
0
5
x/λ


$l_1 = 1,\ l_2 = 2,\ \Delta f = 1$
5
0
-5
1
0.5
0
5
10
15
20
25
30
35
40
45
50
z/λ

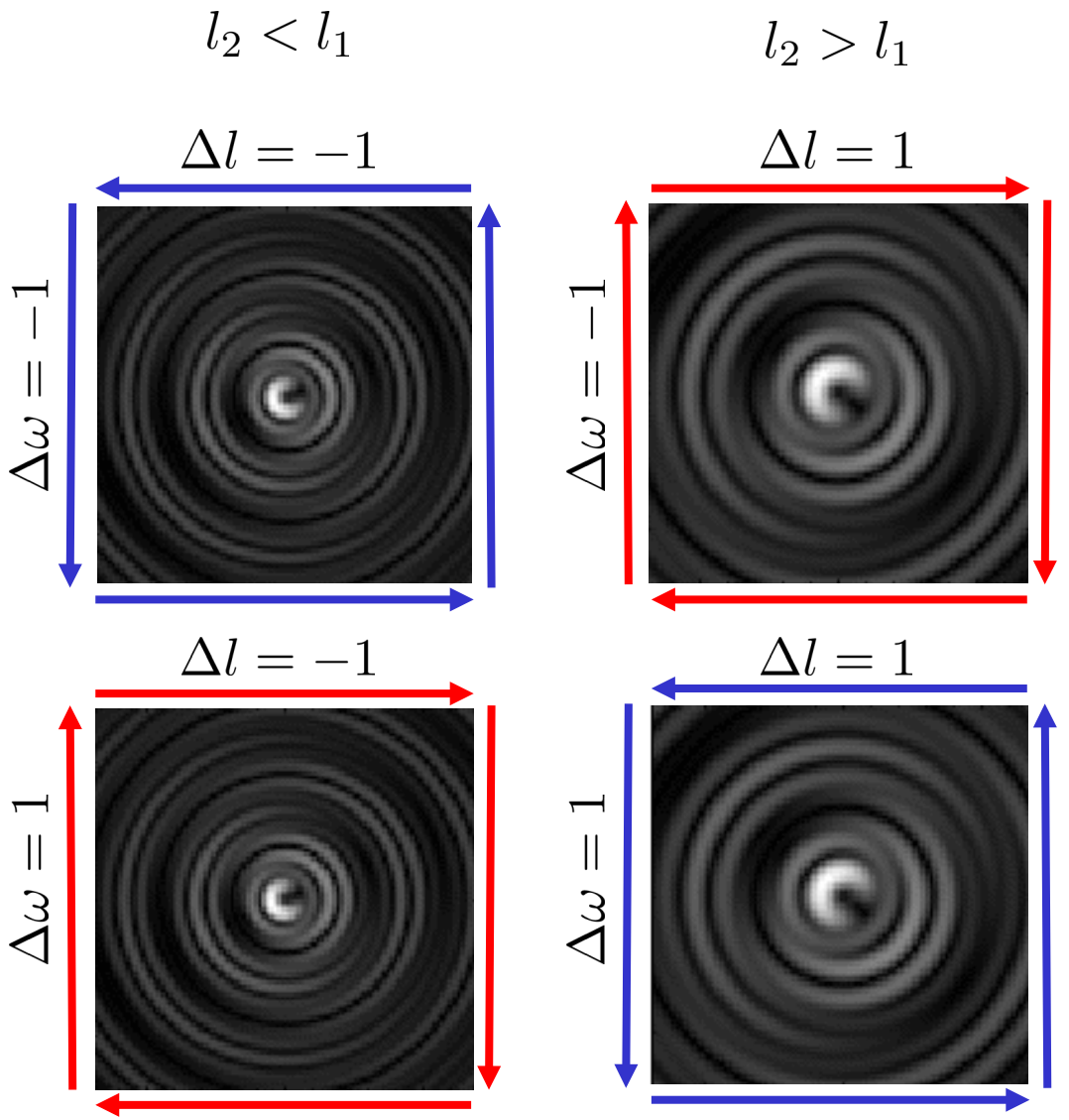
$$\Delta l = l_2 - l_1$$

Tuning drill beams

Rotation direction

- The direction is controlled by
  - The sign of the detuning frequency
  - The sign of the detuning topological charge

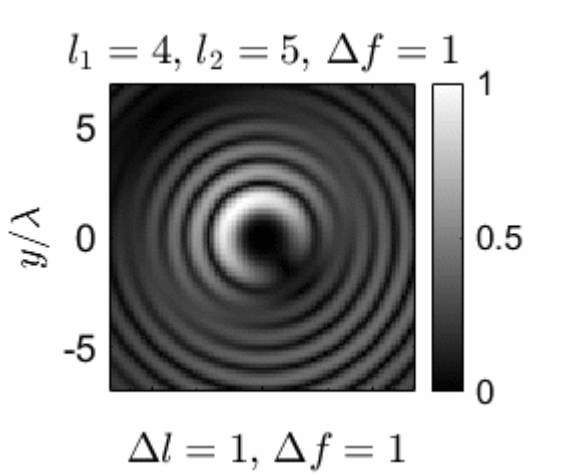
$$s_\theta = \mathrm{sign}(\Delta\omega)\mathrm{sign}(\Delta l)$$



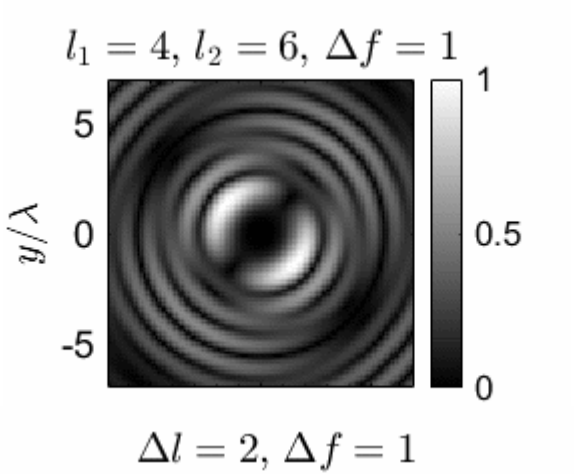
Tuning drill beams

Number of helices

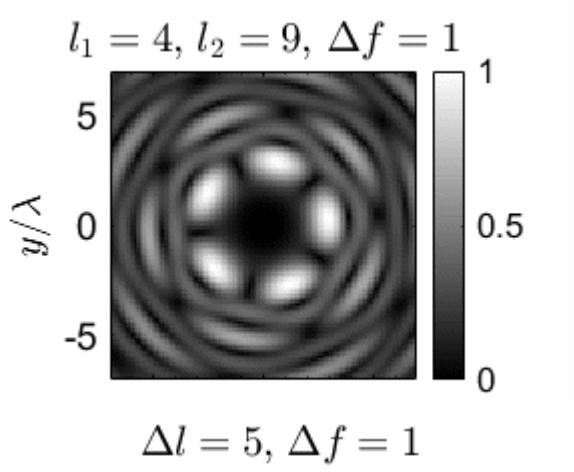
- Is fixed by the absolute value of the detuning topological charge: $N = |\Delta l|$



$\Delta l = 1,\ \Delta f = 1$



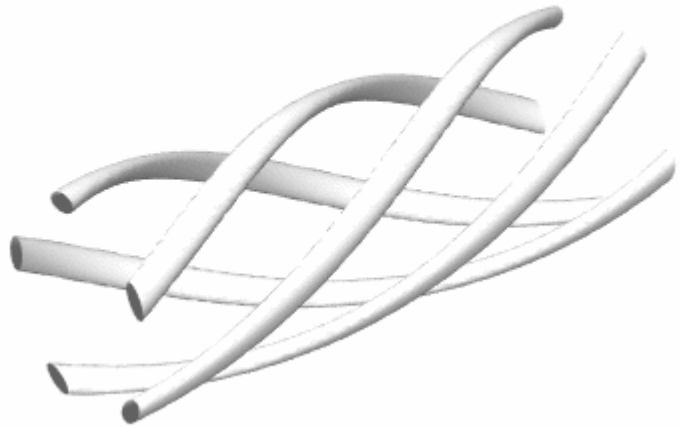
$\Delta l = 2,\ \Delta f = 1$



$\Delta l = 5,\ \Delta f = 1$







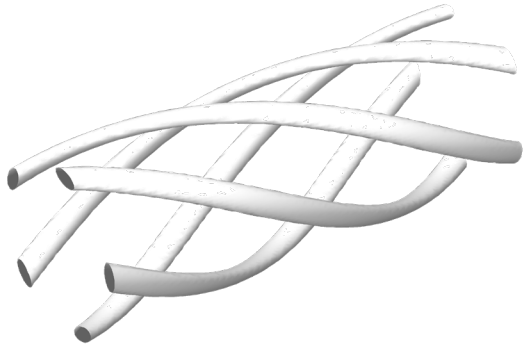
Tuning drill beams

Winding direction

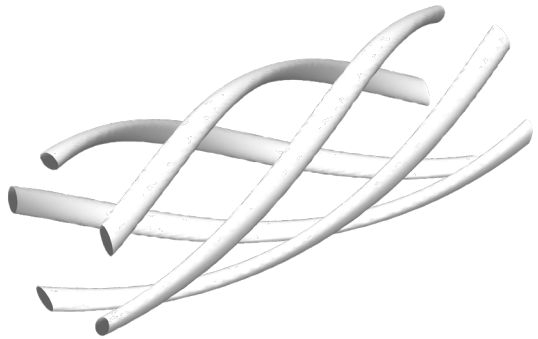
- Is controlled by the sign of the detuning topological charge:

$$s_{\text{winding}} = \text{sign}(\Delta l)$$

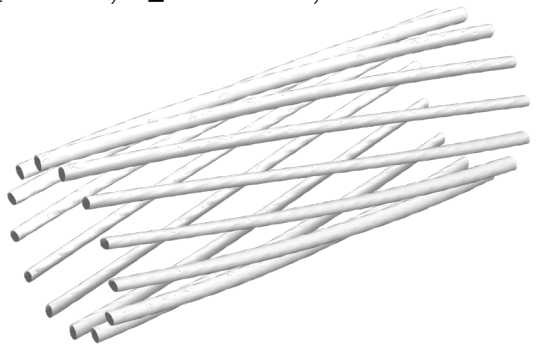
$l_1 = 9, l_2 = 4, \Delta l = -5$



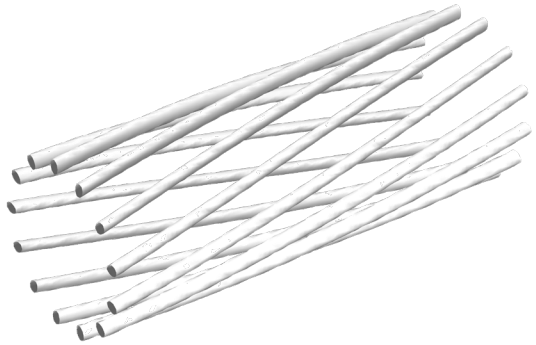
$l_1 = 4, l_2 = 9, \Delta l = 5$



$l_1 = 4, l_2 = -9, \Delta l = -13$



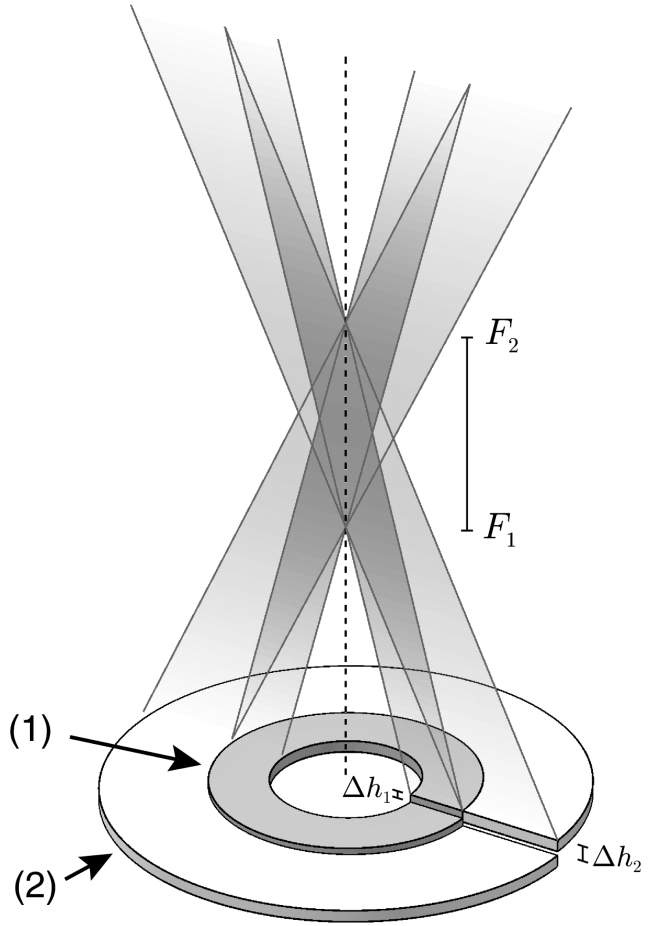
$l_1 = -4, l_2 = 9, \Delta l = 13$



Synthesis of confocal and detuned vortex beams

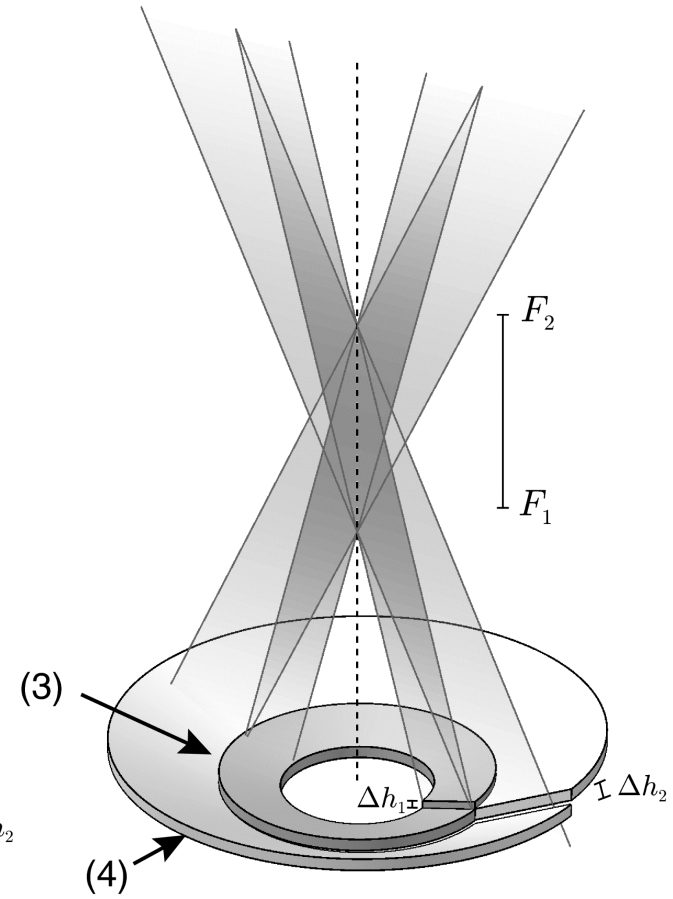
Helicoidal surfaces

Helicoidal surface



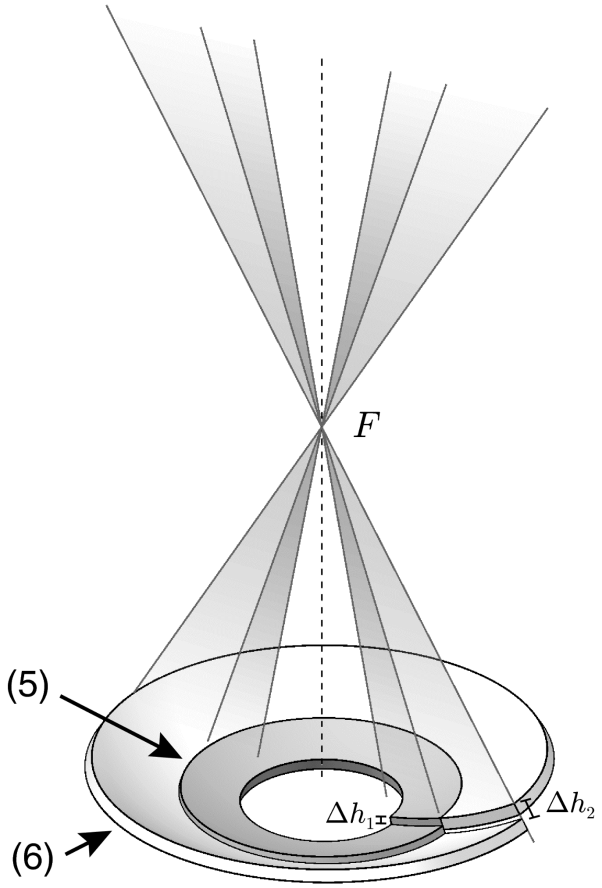
Hefner & Marston JASA 3313 (1999)

Helicoidal conical



Ealo, IEEE TUFFC (2011).

Helicoidal focused

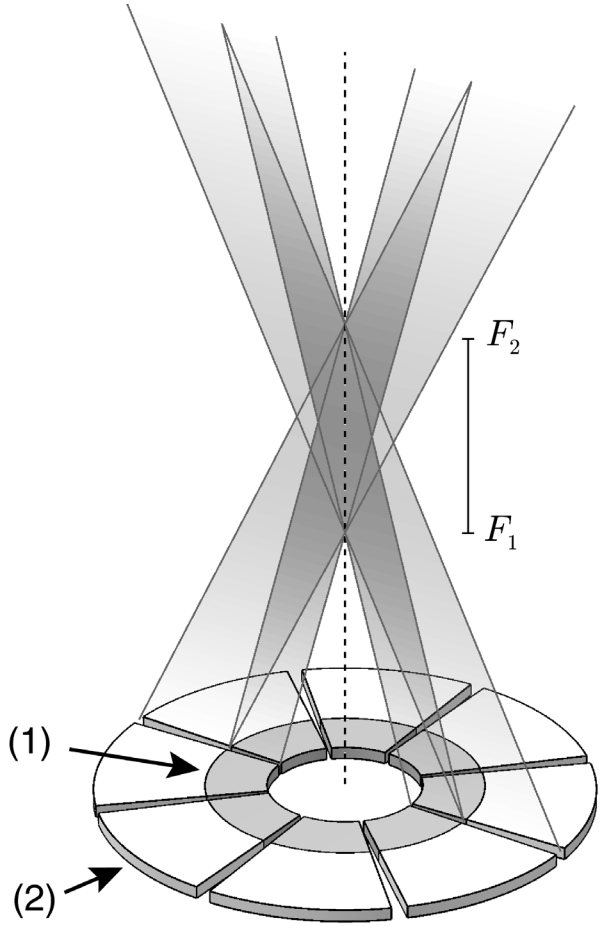


Jiménez, Phys Rev Applied (2021)

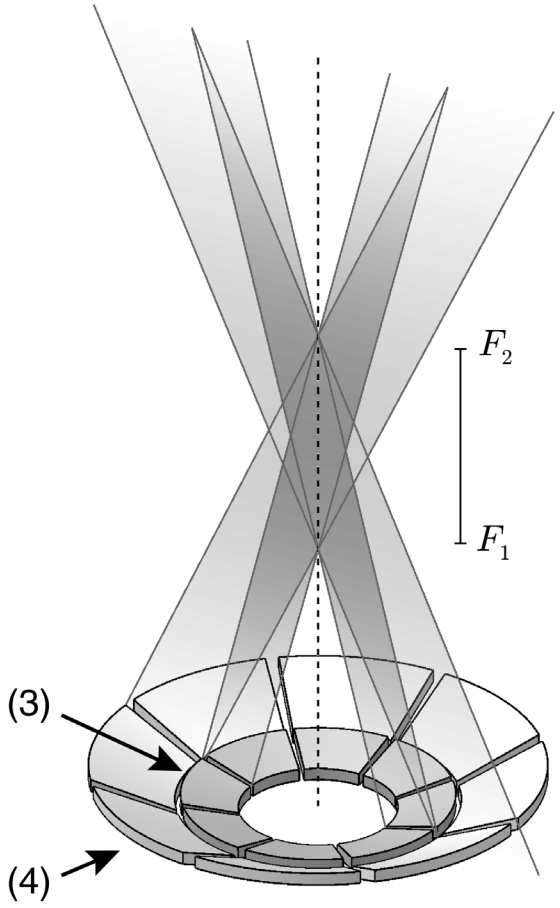
Synthesis of confocal and detuned vortex beams

Phased arrays

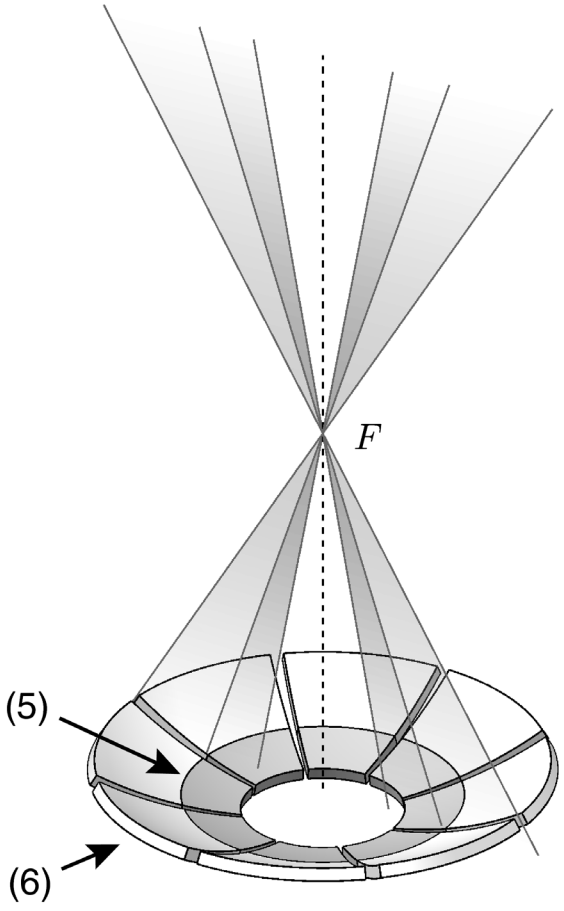
Flat array



Conical array



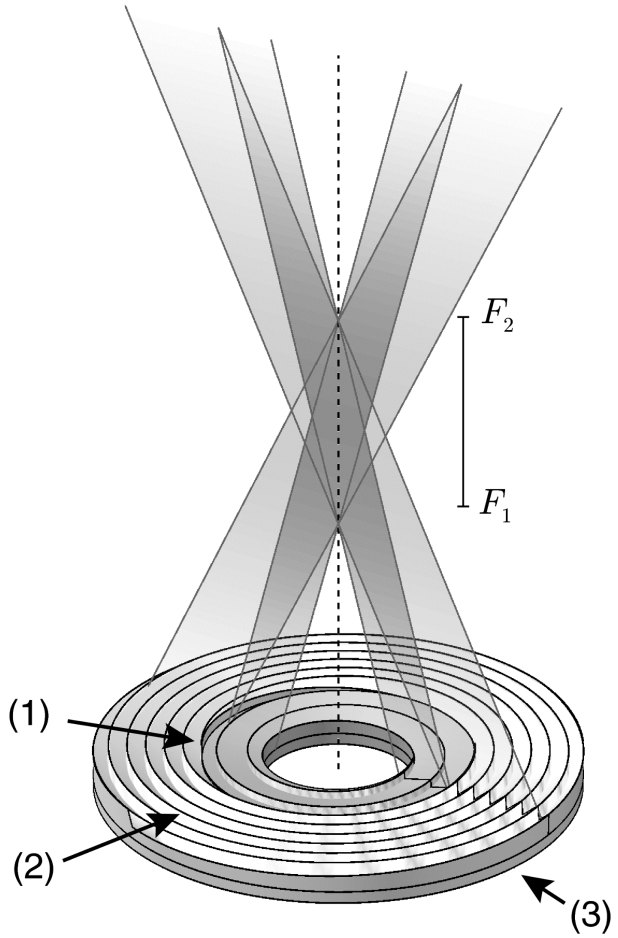
Focused array



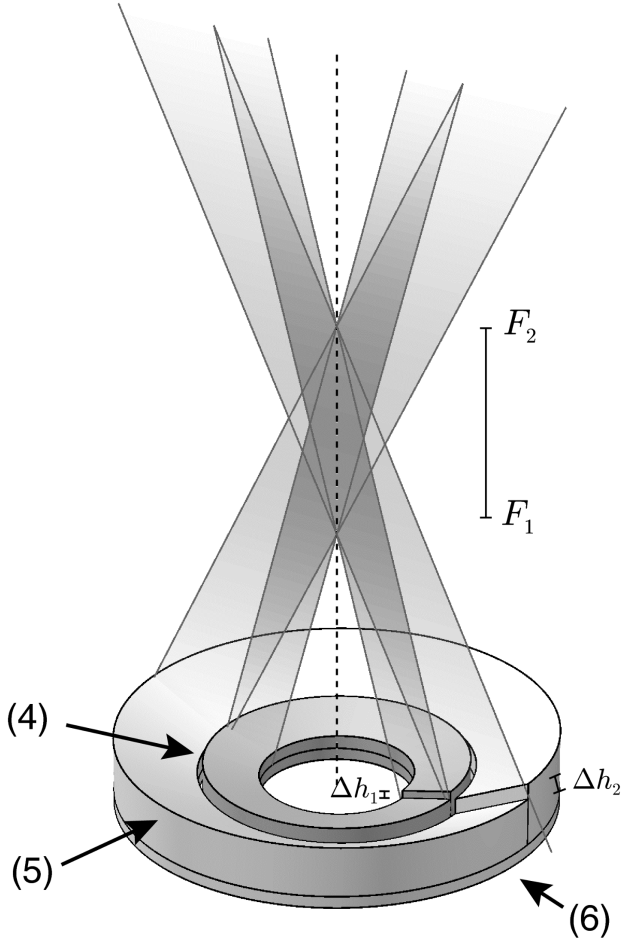
Synthesis of confocal and detuned vortex beams

Lenses and holograms

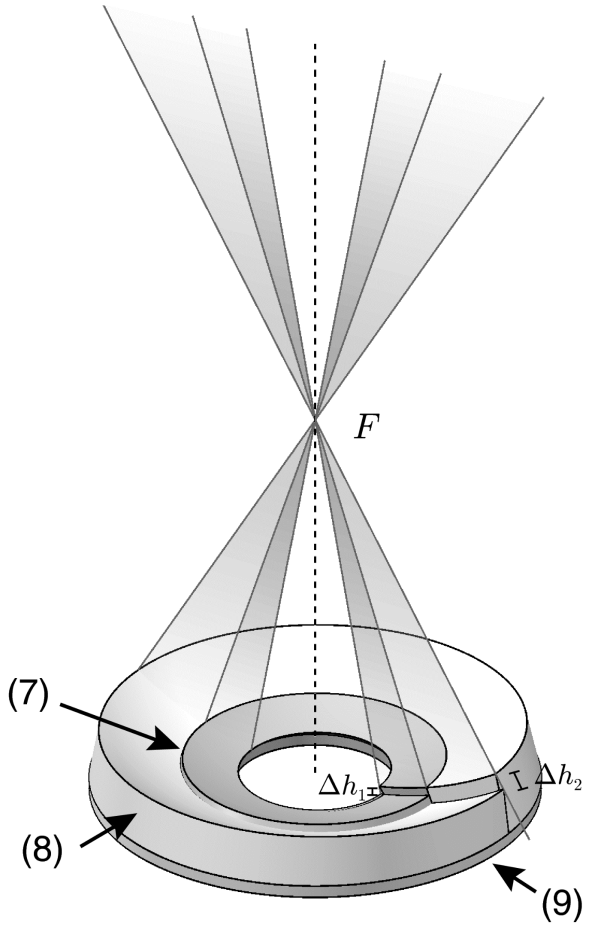
Hologram



Helicoidal conical

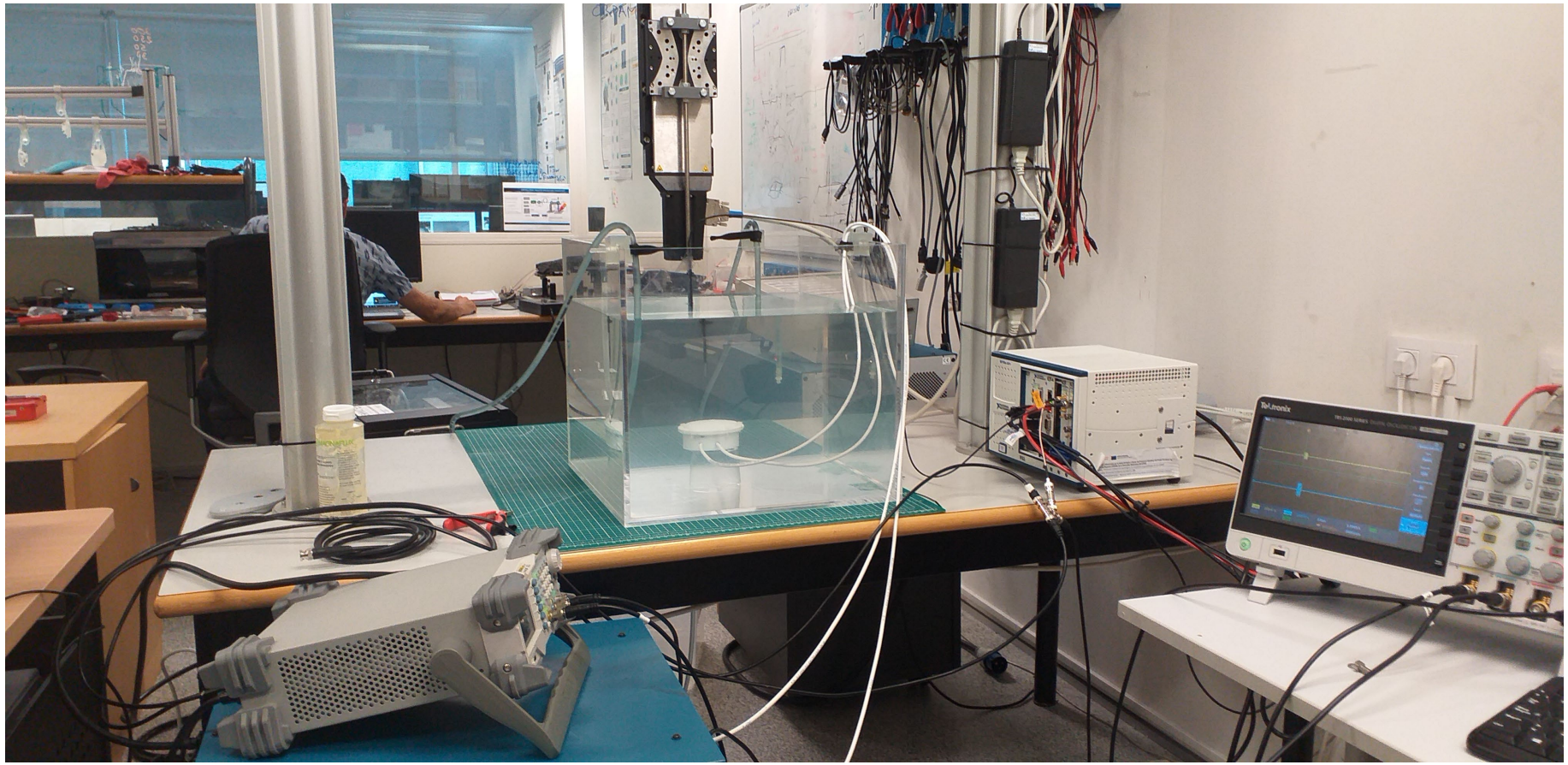


Helicoidal focused



Experimental setup

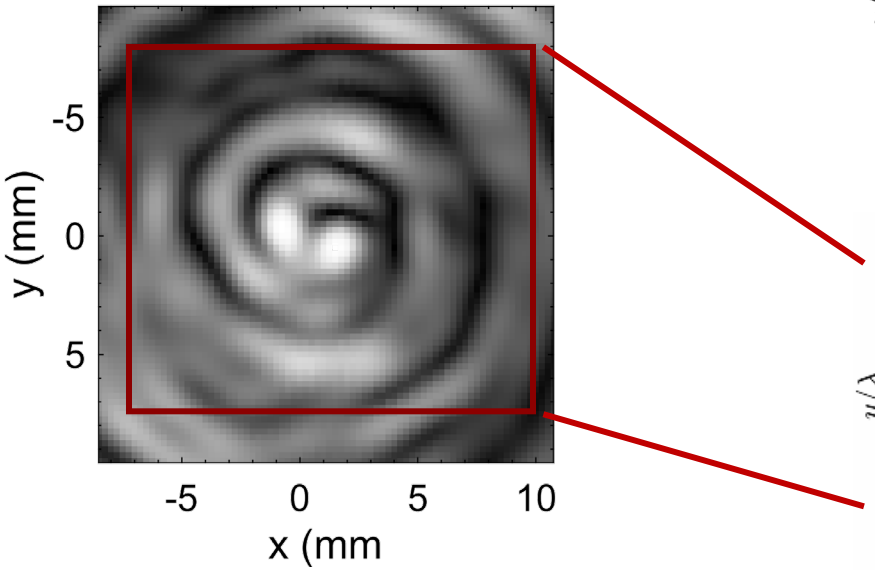
Lenses and holograms

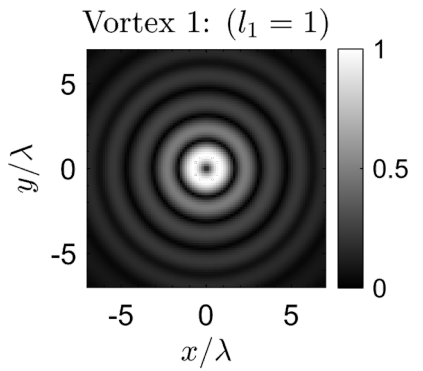


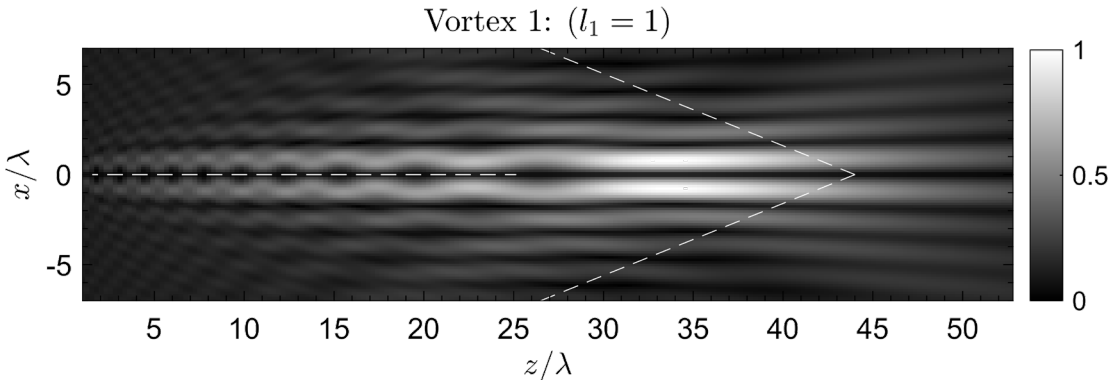
Results

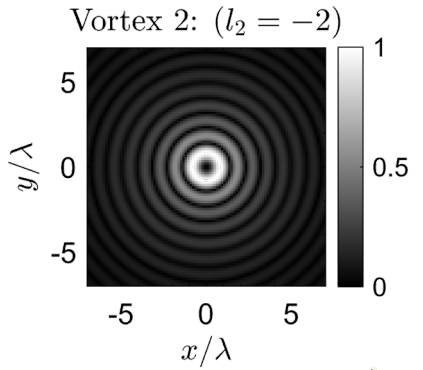
Realistic acoustic drill beam

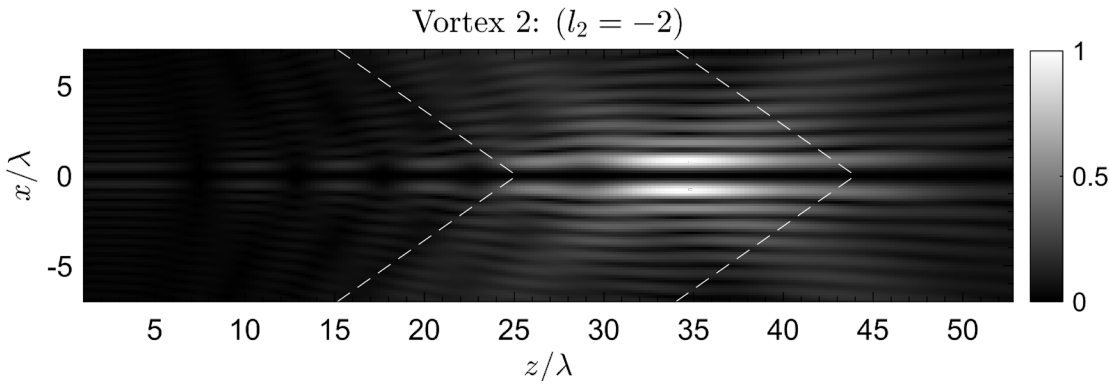
- Topological charge 1: $l_1 = 1$
- Topological charge 2: $l_2 = -2$
- Nominal frequency: $f_0 = 1$ MHz
- Detuning frequency: $f_d = 1$ Hz

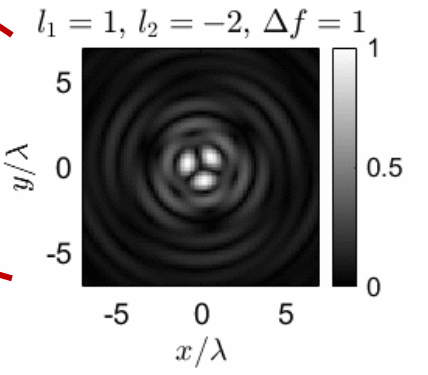


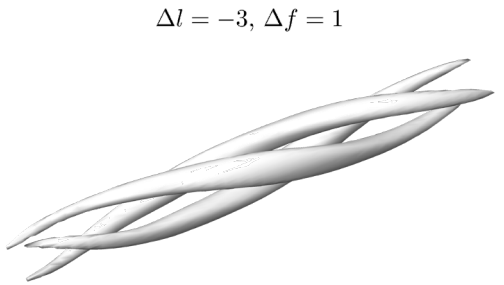








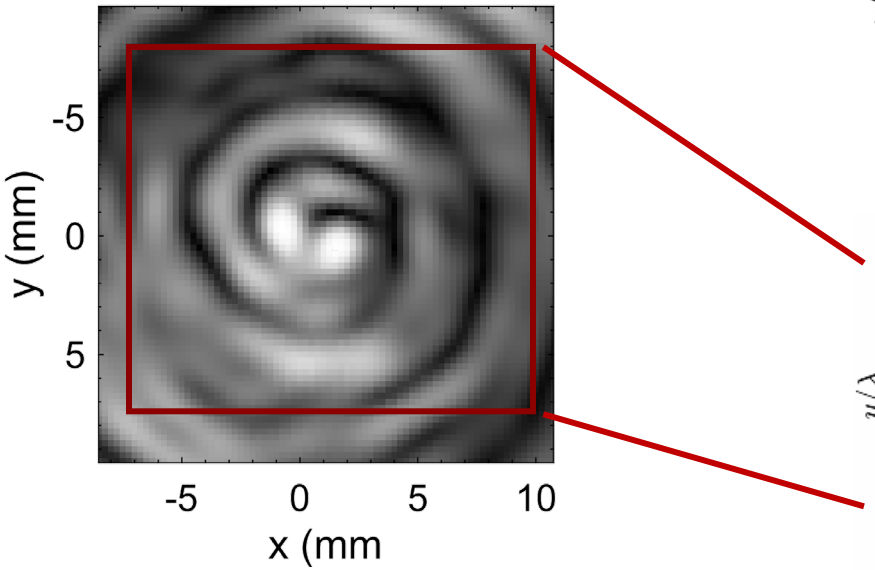


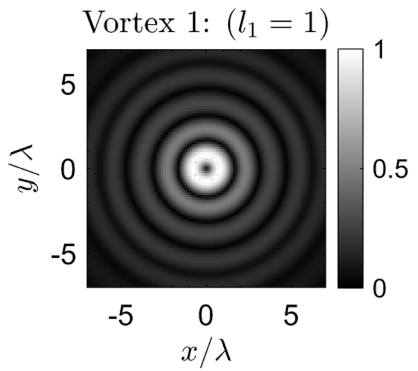


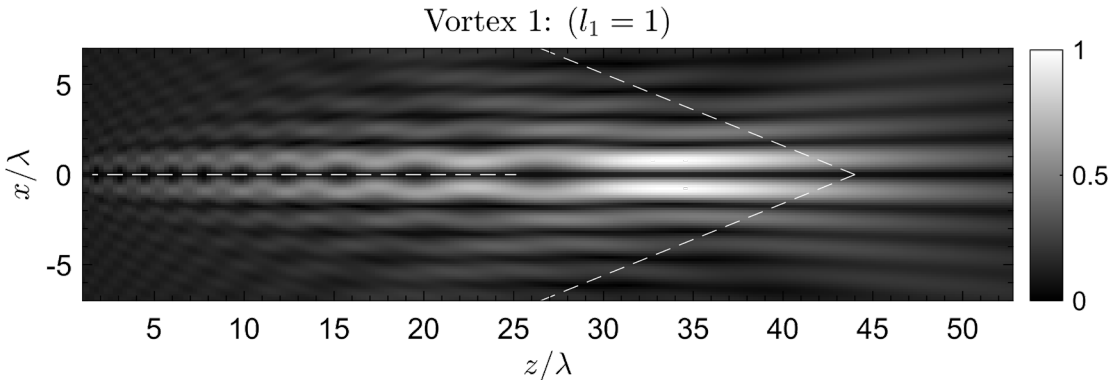
Results

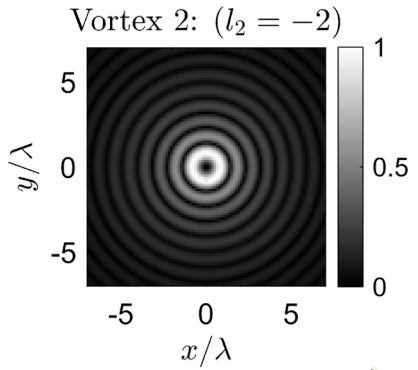
Realistic acoustic drill beam

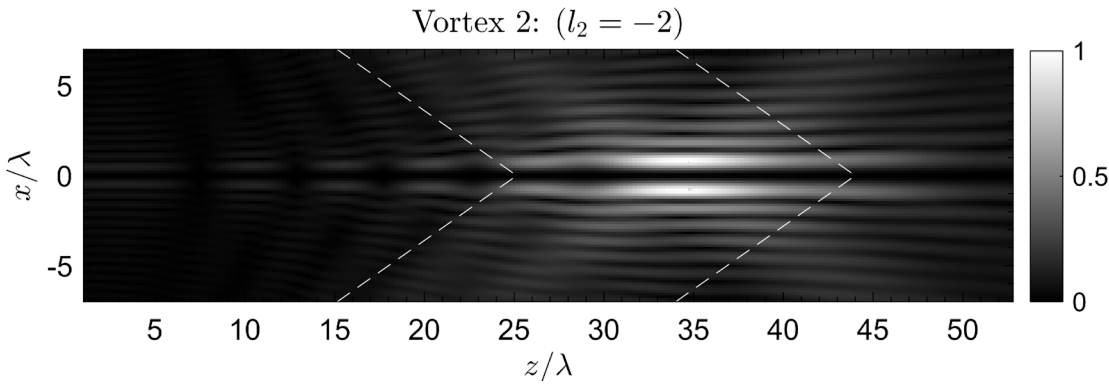
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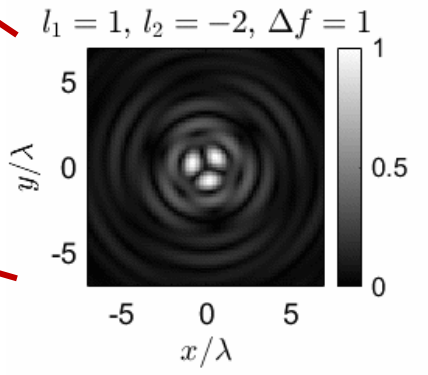


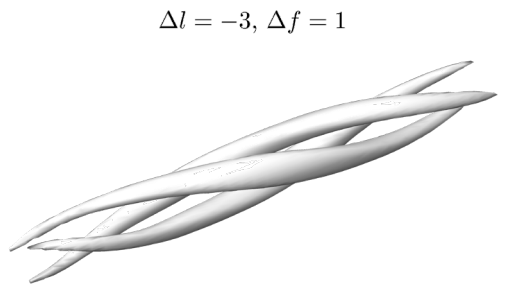








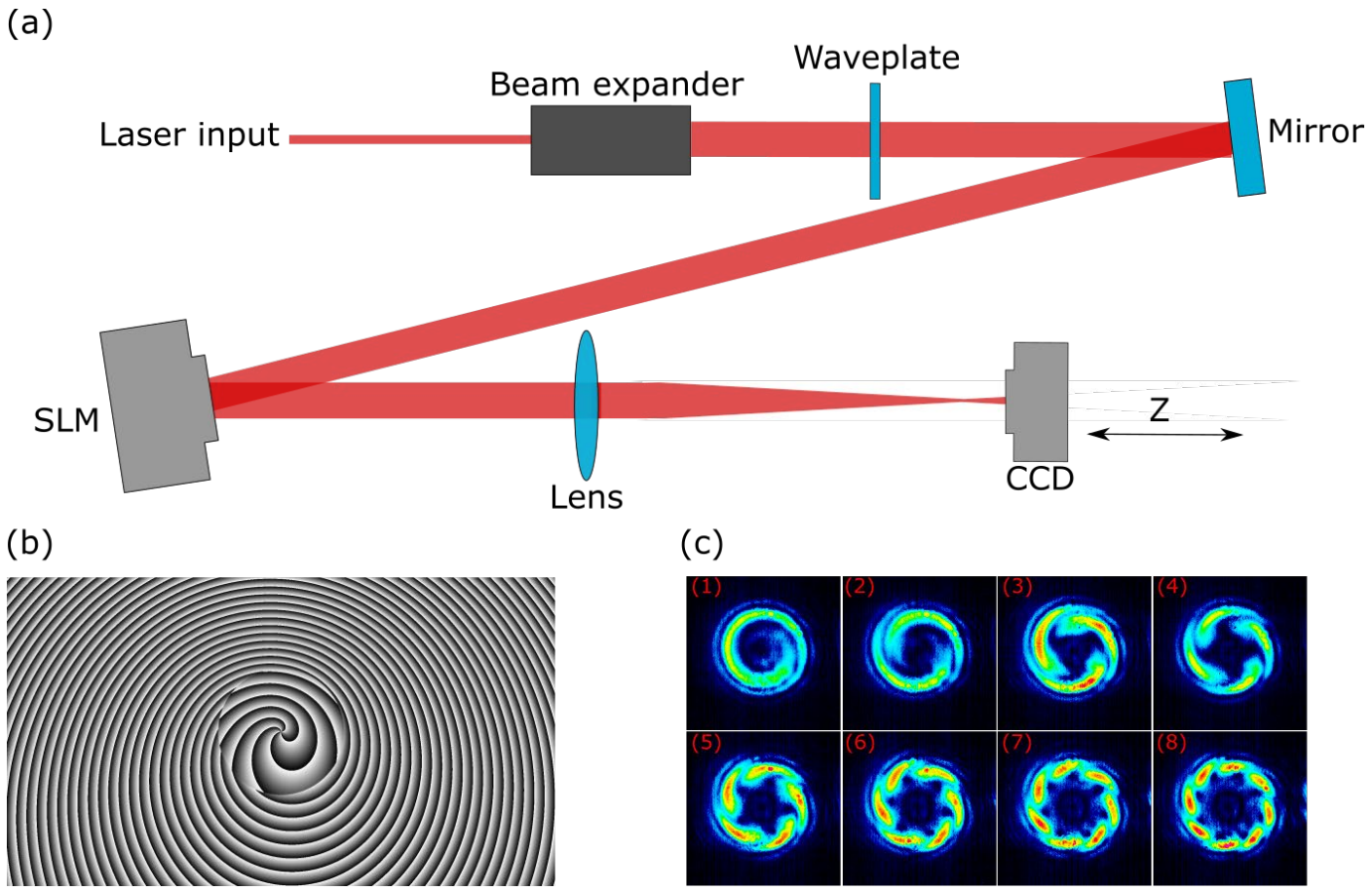




From acoustics to optics

Optical drills

- Experimental demonstration in optics
- Bessel beam generation: SLM
- Laser source: No coherence!
- Single beam: then use Doppler shift on a rotating hologram



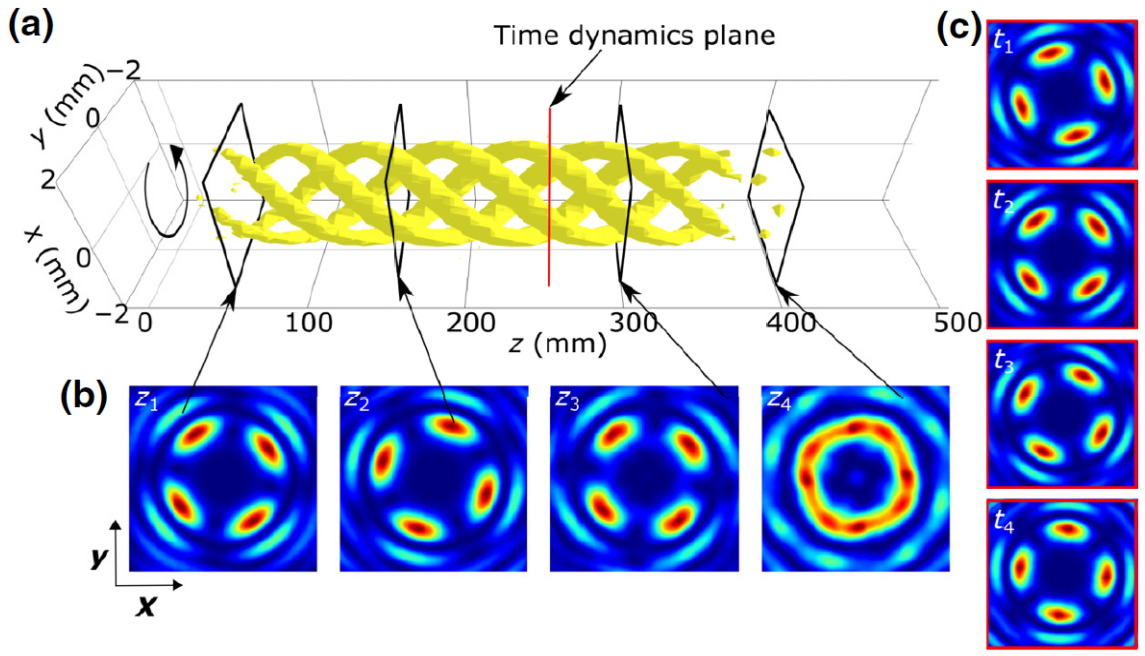
G Kontenis, D Gailevicius, N Jimenéz, K Staliunas
Optical drills by dynamic high-order Bessel beam mixing
Physical Review Applied, 17 (3), pp. 034059, (2022)

From acoustics to optics

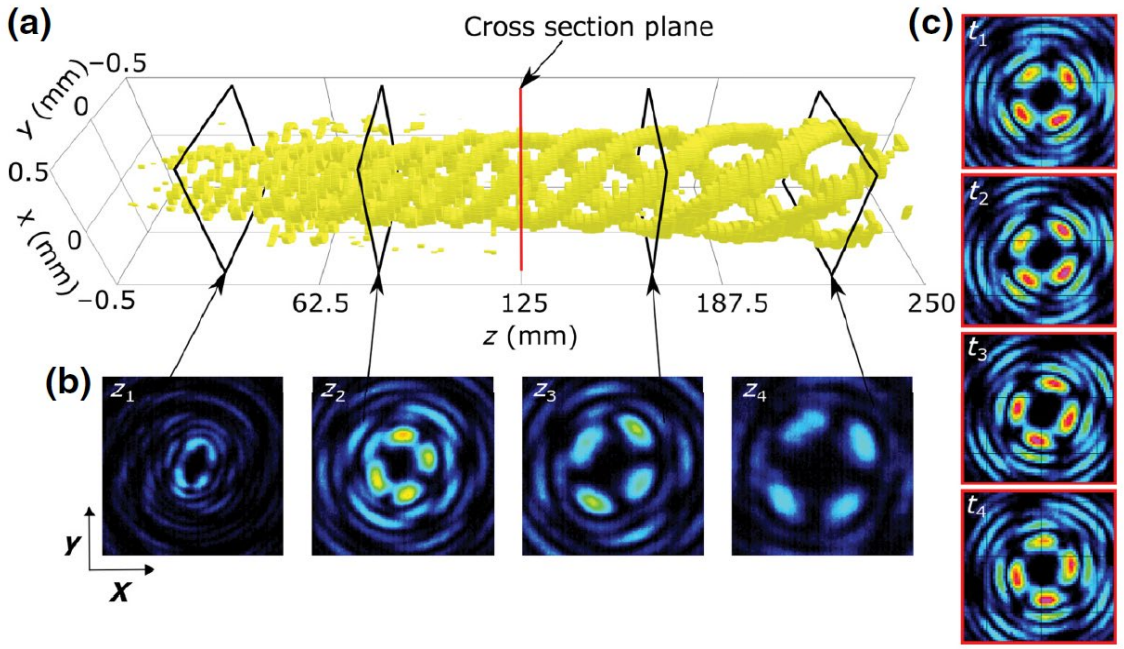
Optical drills

- Arbitrary drill beams can be generated

Simulation



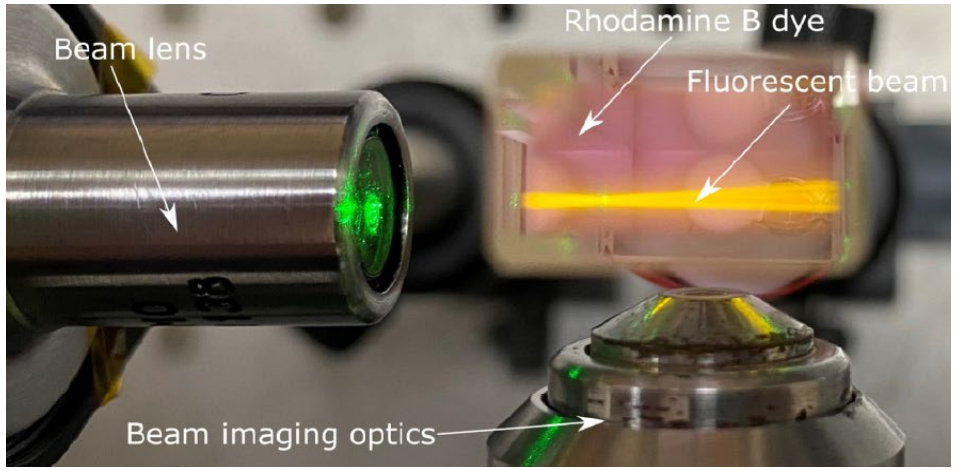
Experiment



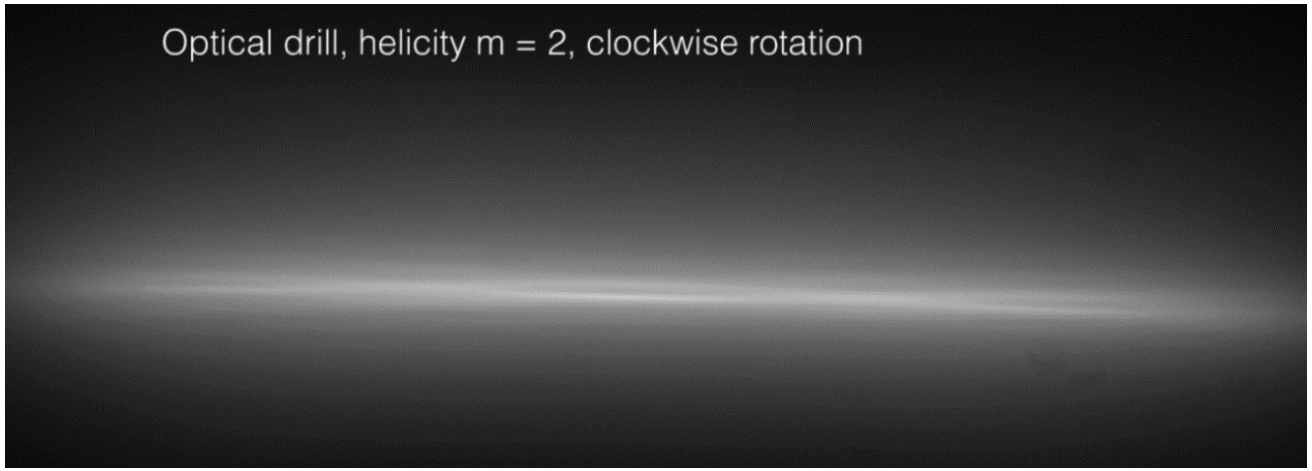
G Kontenis, D Gailevicius, N Jimenéz, K Staliunas. Physical Review Applied, 17 (3), pp. 034059, (2022)

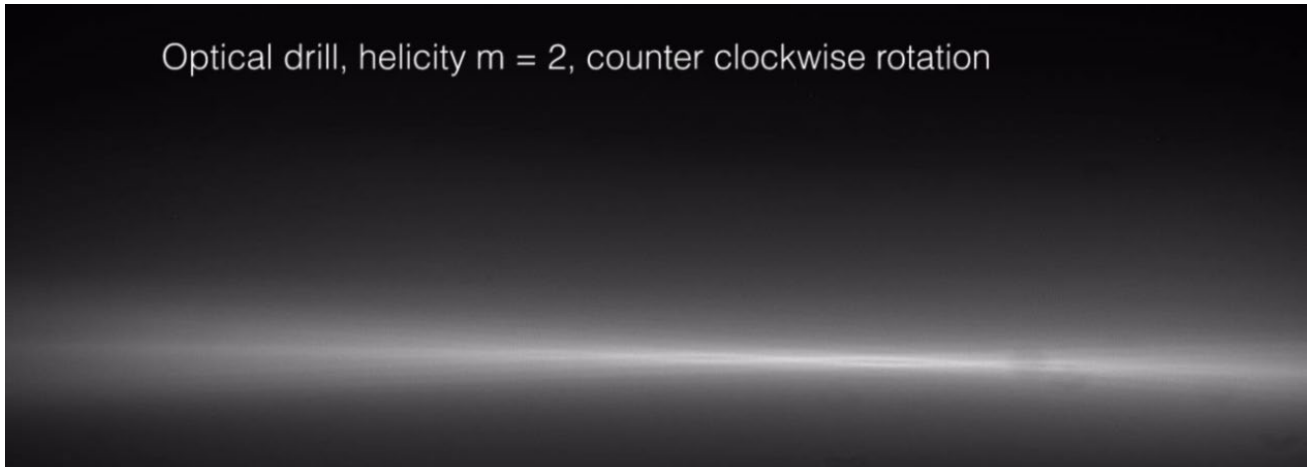
From acoustics to optics

Optical drills



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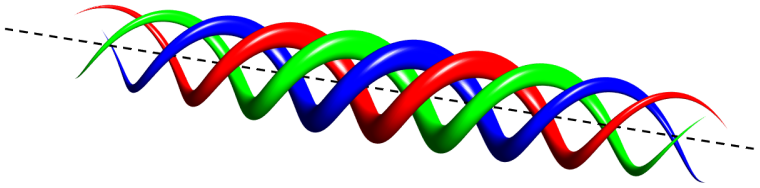




Conclusions

Acoustic drill beams

- Helical wave structure: **Intensity** (not phase) shows helical geometry
- They emerge as the spatio-temporal interference of **detuned** beams: topological charge, axial wavenumber and frequency.
- Parameters are fully tunable.
- They can be synthesized by cheap holograms and two-channel sources
- Demonstrated in optics



Ongoing work

- Can acoustic drill rotate objects in **arbitrary** directions?
- How they interact with particles?
- How they interact with absorbing media? Tuning shear waves?
- How is the angular momentum transferred into particles at boundaries?

Patent

- ES2811650. N. Jiménez, F. Camarena, K. Staliunas. Sistema y método de generación de haces acústicos confocales de vórtice con superposición espaciotemporal (06/08/2021)

Acknowledgements

Instituto de Instrumentación para Imagen Molecular

- Enrique González-Mateo, Francisco Camarena
  - Universitat Politècnica de València / CSIC, València, Spain
- Gabrielius Kontenis, Darius Gailevicius,
  - Laser Research Center, Vilnius University, Vilnius, Lithuania
- Kestutis Staliunas
  - ICREA, UPV, Tarrasa, Barcelona, Spain.

Funding

- Spanish Ministry of Science / AEI: Juan de la Cierva – Incorporación, IJC2018-037897-I, Plan Nacional Retos: PID2019-111436RB-C22.
- Agència Valenciana de la Innovació: INNVAL10/19/016, INNCON/2020/009.
- Generalitat Valenciana: ACIF/2017/045.
- European Union: IDIFEDER/2018/022



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24