Reflectores Helicoidales para la Focalización de Vórtices Acústicos de Alta Intensidad

Noé Jiménez, Enrique González-Mateo, Francisco Camarena

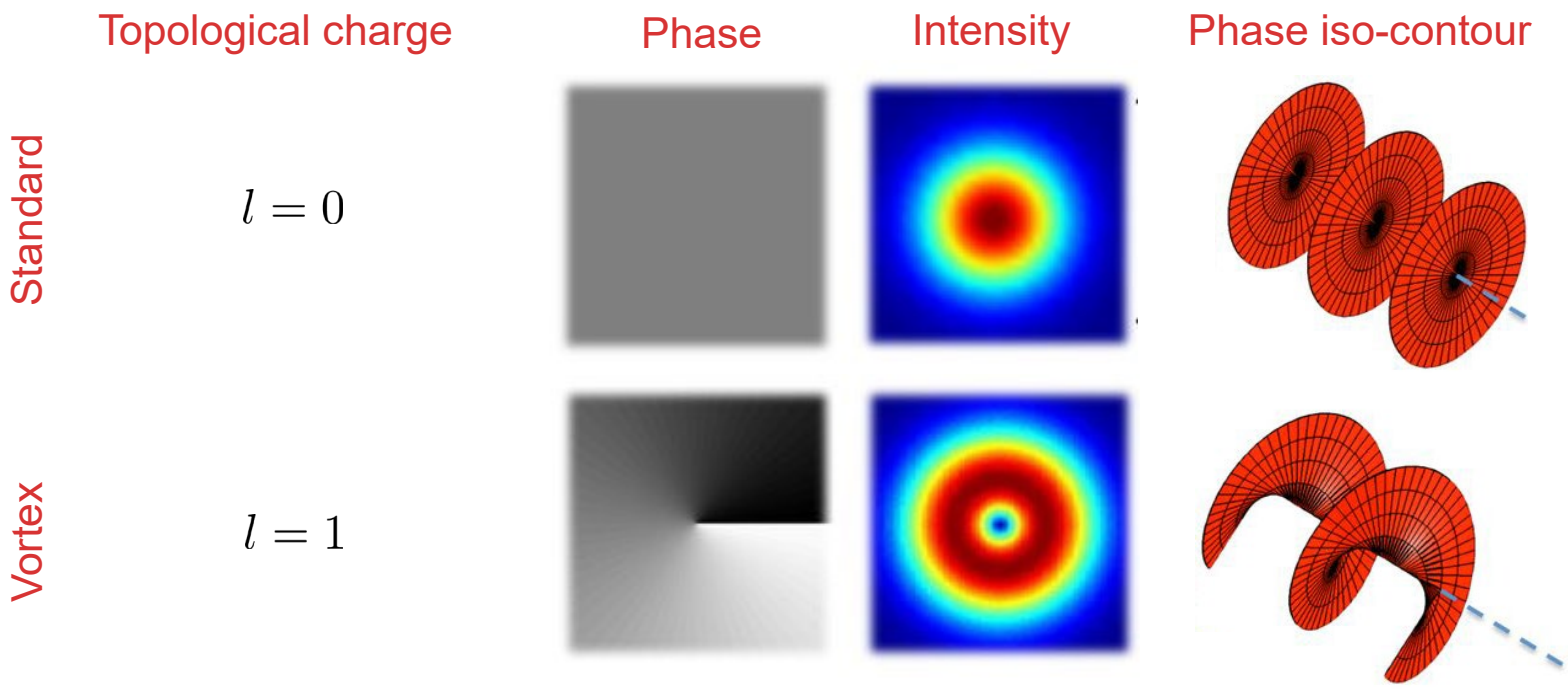
Instituto de Instrumentación para Imagen Molecular (I3M), Universitat Politècnica de València / CSIC, València, Spain

TECNIACÚSTICA 2023 - 54º Congreso Español de Acústica, October 18th – 20th, 2023

Introduction

Acoustic vortex beams

- Beams presenting a phase dislocation at the axis
- The phase of the field rotates l times with each turn
- Example, Gaussian beam in cylindrical coordinates:



Introduction

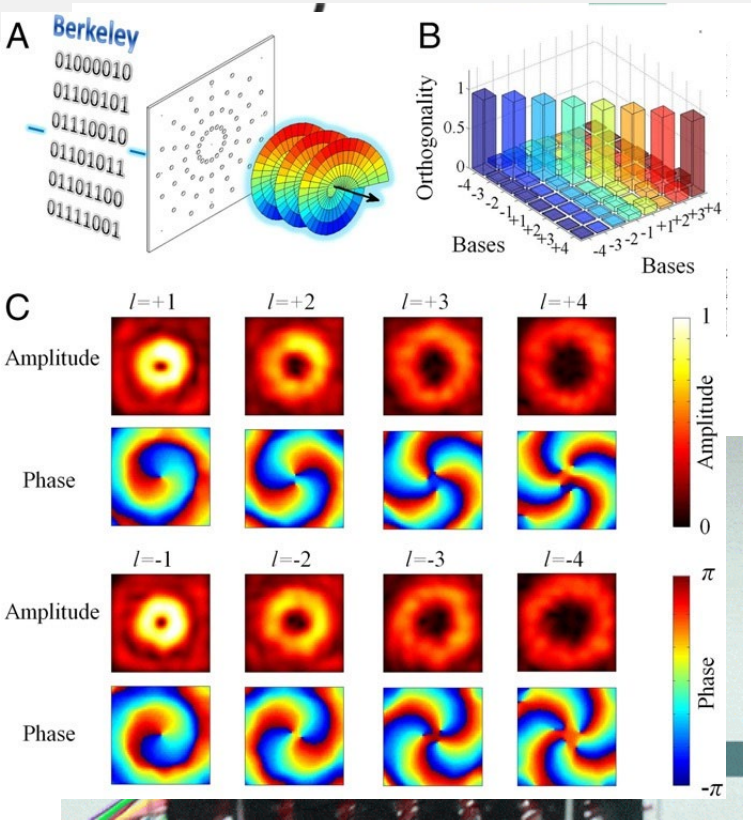
Applications

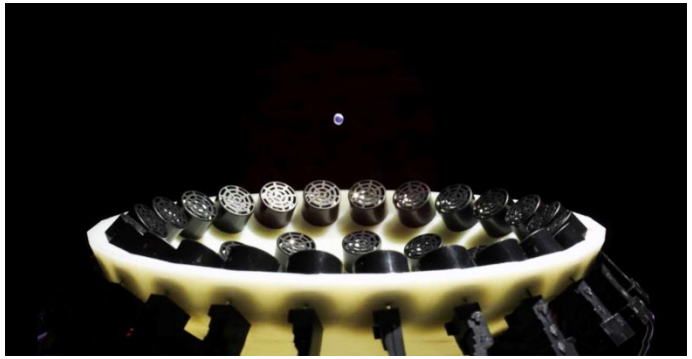
- **Acoustic communications**
  - Robust and fast information coding
  - Underwater communications / modems

[1] C. Shi, et. al. Proc. Nat. Ac. Sci., 114(28), 7250-7253 (2017)

- **Particle trapping and manipulation**
  - Trapping, manipulation, rotation
  - Levitation
  - Acoustic tweezers

[2] K. Volke-Sepúlveda, et al. PRL. 100, 024302 (2008)
[3] A. Marzo, et al. Nat. Commun. 6, 8661 (2015)
[4] D. Baresch, et al. PRL, 116(2), 024301 (2016)



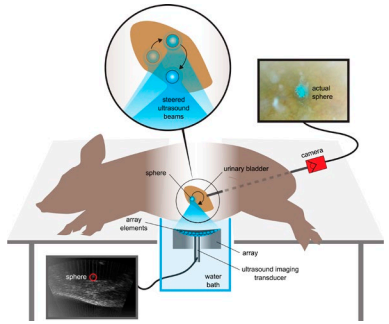


Introduction

Biomedical applications of acoustic vortices

- **Trapping solid particles at mesoscopic level**
  - Kidney stone manipulation, fragment propulsion/positioning

  [1] M. Ghanem, et al. PNAS, 117(29) 16848-16855 (2020)

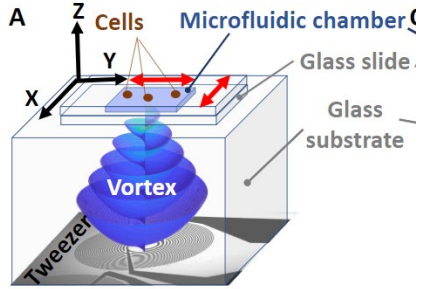




- **Trapping soft-tissue at cellular level**
  - Trapping and manipulation of individual cells
  - Clustering cells for 3D-printing organoids

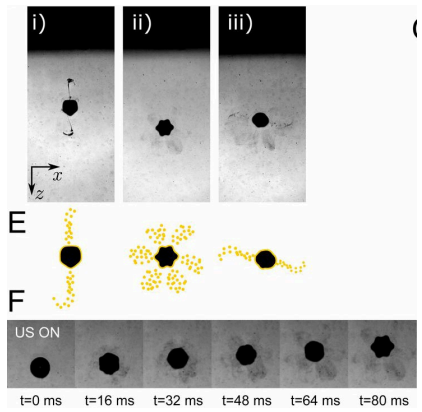
  [2] M. Baudoin, et al. Nature comm, 11(1), 1-10 (2020).

  [3] Z. Ma, et. Al. Advanced Materials 32 (4), 1904181 (2022)



- **Trapping gas particles**
  - Trapping individual bubbles for collapse/payload release
  - Trapping microbubble clusters for clot lysis

  [4] D Baresch, et al. PNAS 117 (27), 15490-15496 (2020)



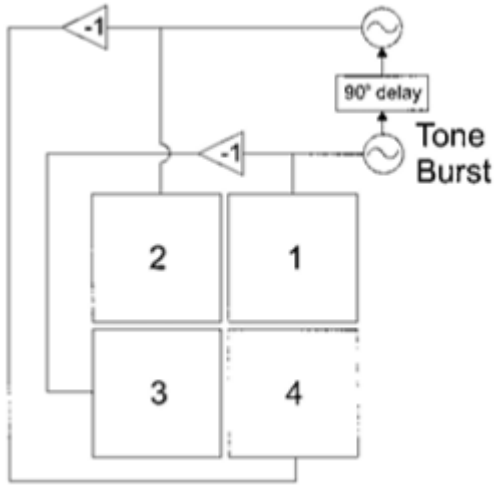
- **Elastography**
  - Induce torque to tissues to control shear wavefronts

  [5] N. Jiménez, et al. 2020 IEEE International Ultrasonics Symposium (IUS). IEEE, 2020.

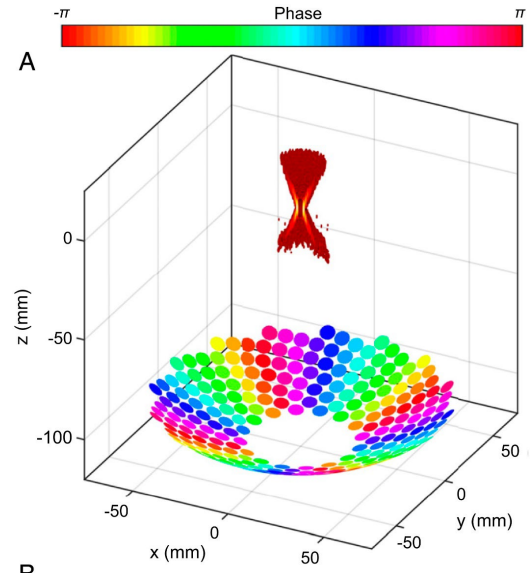
Vortex beam generation methods

How to generate acoustic vortices?

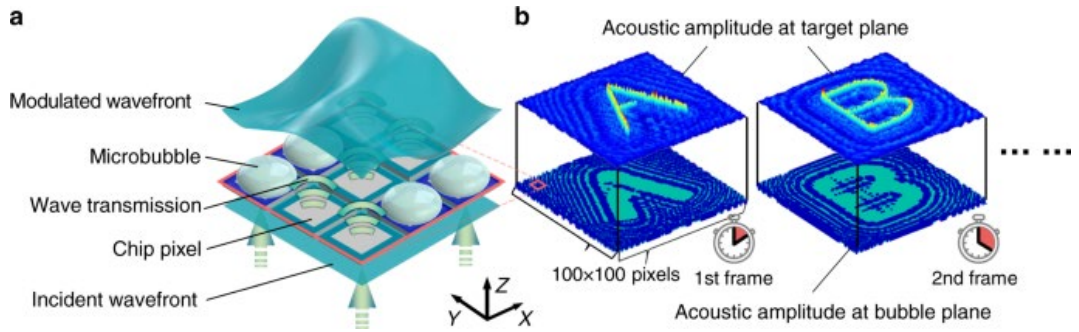
- **Active arrays**
  - Phase-array transducers



Hefner&Marston JASA 106 (6) (1999)



M. Ghanem, et al. PNAS (2020)

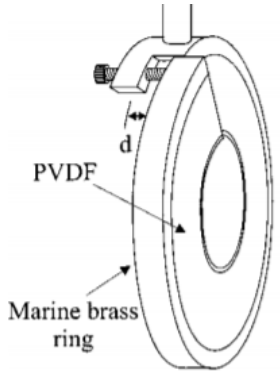


Ma, Nat Comms (2021)

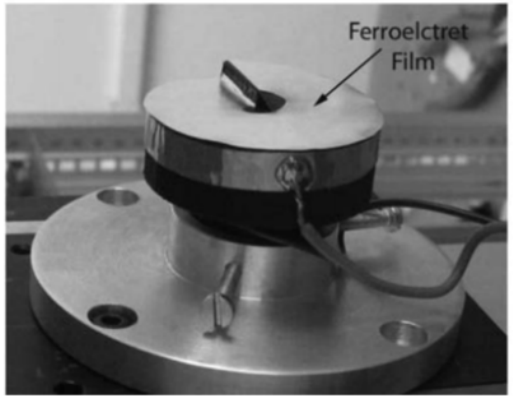
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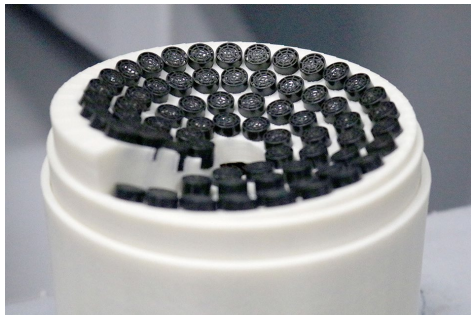
- **Active arrays**
  - Phase-array transducers
- **Helicoidal sources**
  - Helicoidal piezoelectric transducers
  - Photo-acoustic effect on helicoidal absorbers



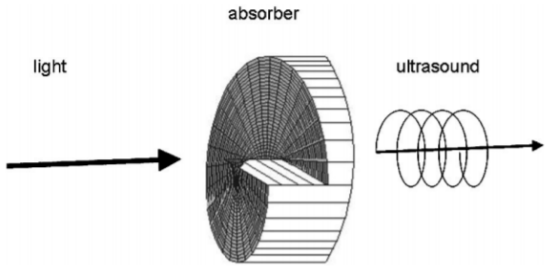
BT Hefner, PL Marston
J. Acoust. Soc. Am. *106*(6) 3313 (1999)



J. L Ealo, et al.
IEEE TUFFC, *58*(8), 1651-1657. (2011)



N Jiménez, at al.
Phys. Rev. Appl. 15(5) 054027 (2021)

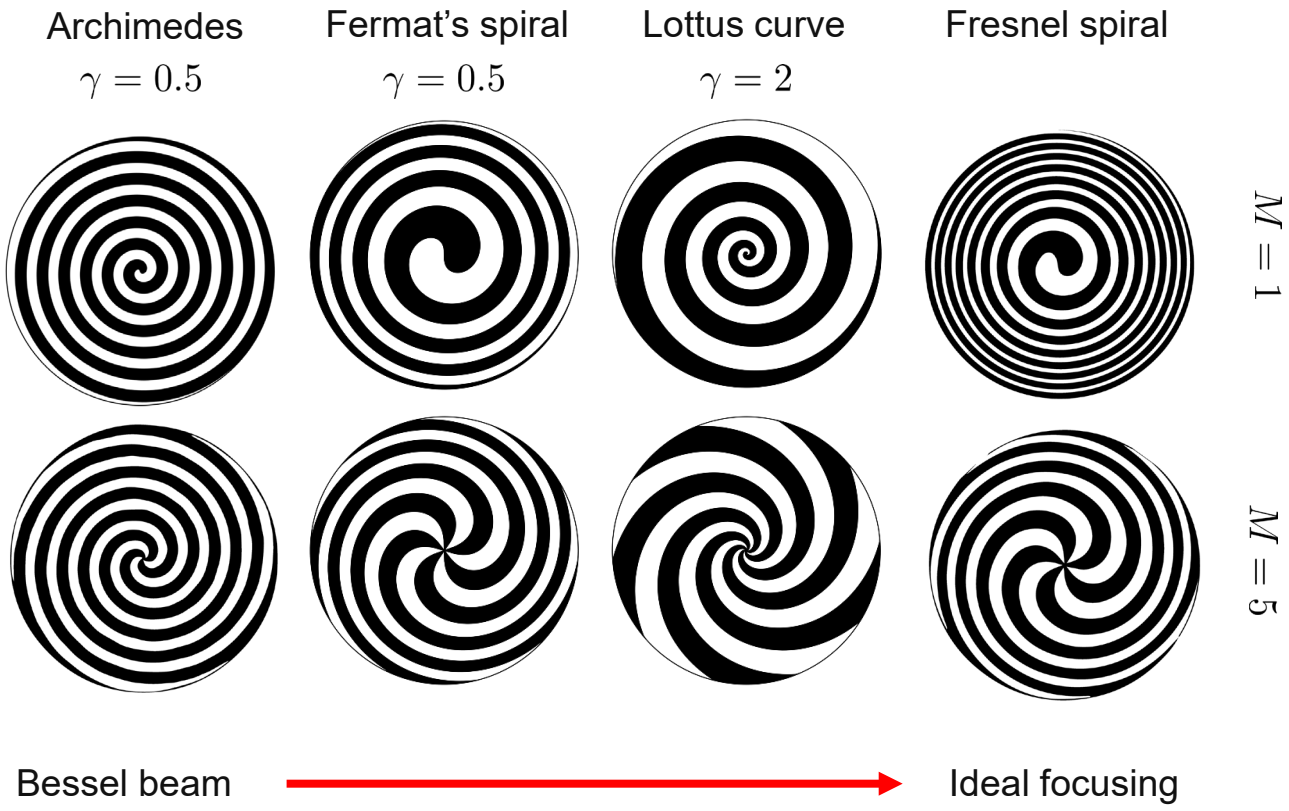


S. Gspan, et al.
J. Acoust. Soc. Am. 115, 1142 (2004)

Vortex beam generation methods

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- **Diffraction**
  - Spiral diffraction gratings
  - Archimedes spiral gratings
  - Fresnel spiral gratings
  - Pitchfork gratings

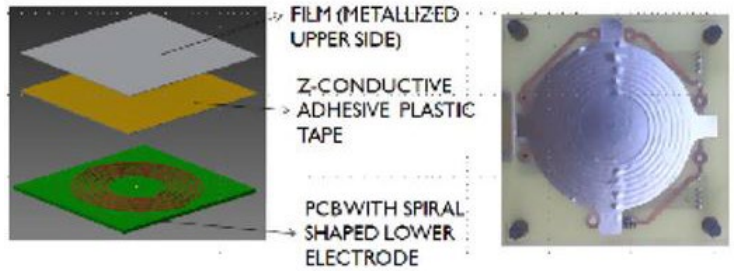


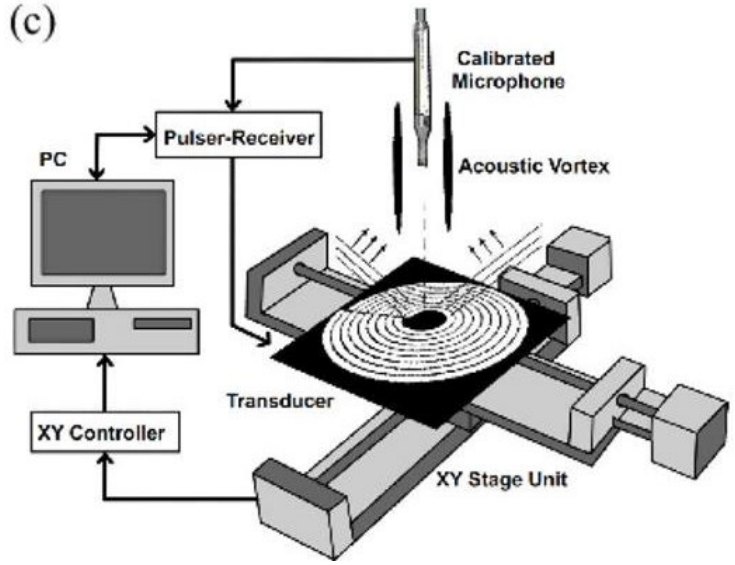
N Jiménez, et al. Phys Rev E 94 (5) 053004 (2016)
X Jiang, et al. APL 108.20:203501 (2016)
T Wang, et al. APL 109.12 :123506 (2016)
N Jiménez, et al. Appl Phys Lett 112 (20) 204101 (2018)

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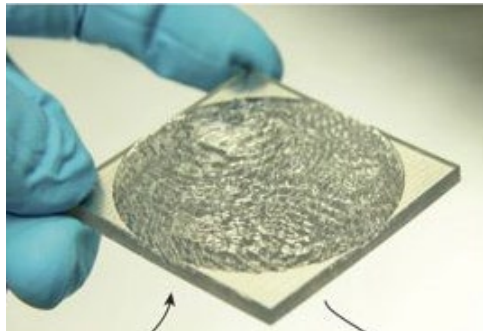


Ruben D. Muelas-Hurtado et al. Applied Physics Letters 112.8 (2018)

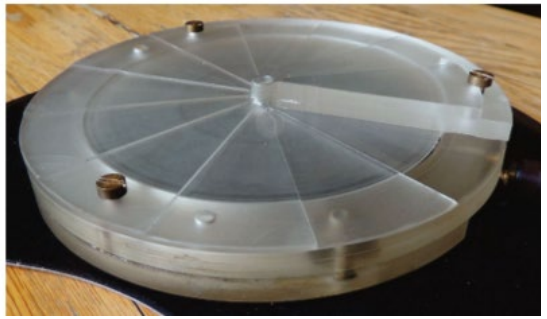
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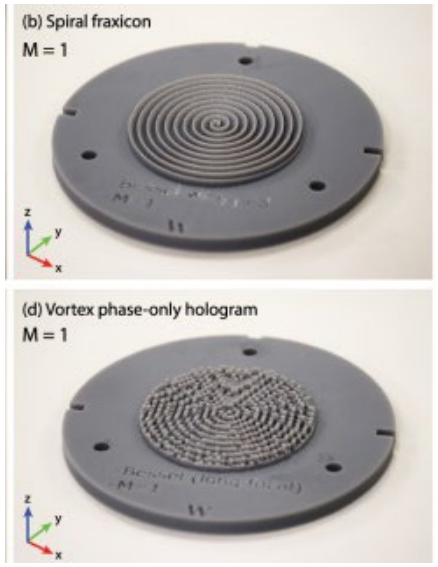
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- **Refraction**
  - Phase plates
  - Spiral axicons / fraxicons
  - Holograms



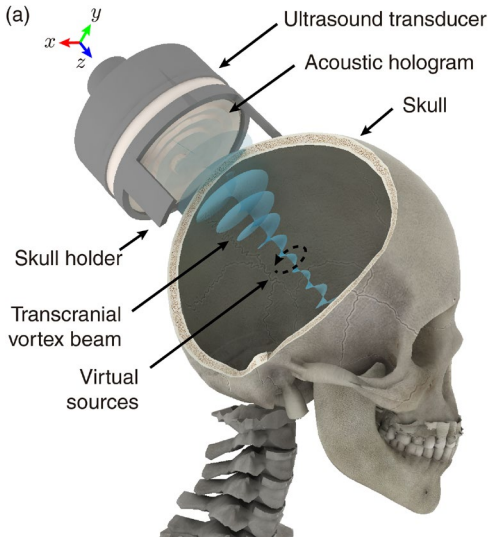
K Melde *et al*.
Nature 537.7621 518 (2016)



M. E. Terzi et al.
Moscow Univ Phys Bull, *72*(1),61. (2017)



S Jiménez-Gambín, et al.
Scientific reports, 9(1),20104.(2019)

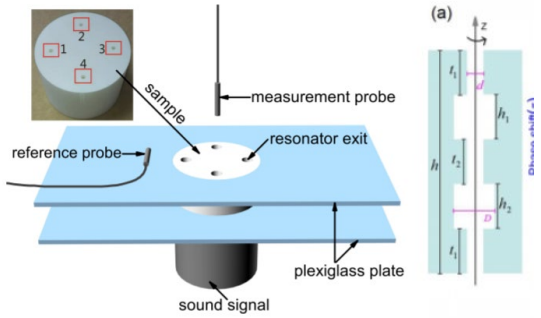


S. Jiménez-Gambín et al.,
Phys Rev App 12 014016 (2019)

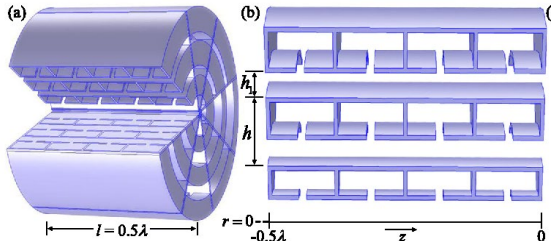
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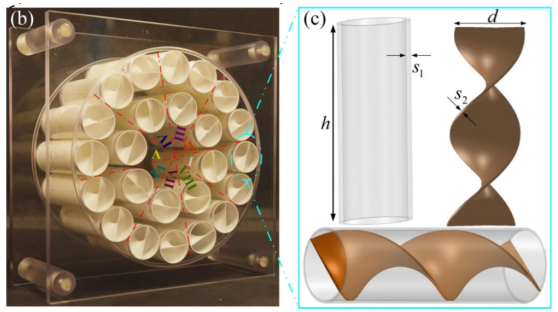
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  - Phase plates
  - Spiral axicons / fraxicons
  - Holograms
- **Resonance**
  - Metamaterials
  - Space coiled paths
  - Helicoidal / delay lines / labyrinthine structures
  - Leaky antennas



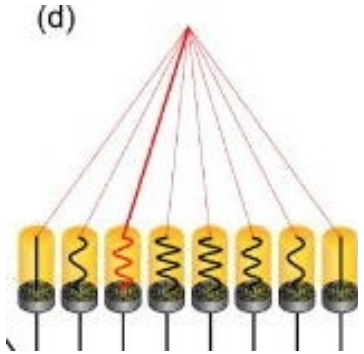
Liping Ye, et al.
AIP Adv. 6.8:085007 (2016)



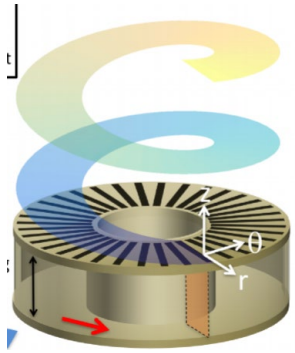
X Jiang at al.
PRL, 117(3), 034301. (2016)



H Esfahlani, et al.
PRB 95, 024312 (2017)



A Marzo et al.
APL 110 (1), 014102 (2017)



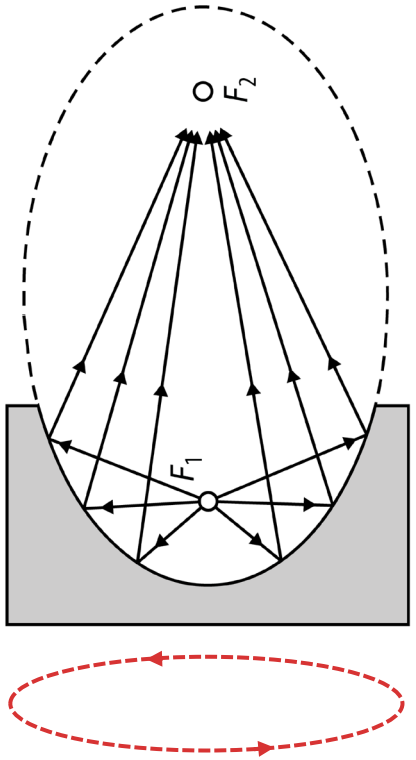
CJ Naify at al.
APL 108, 223503 (2016)

Reflectors

Focusing sound using reflection

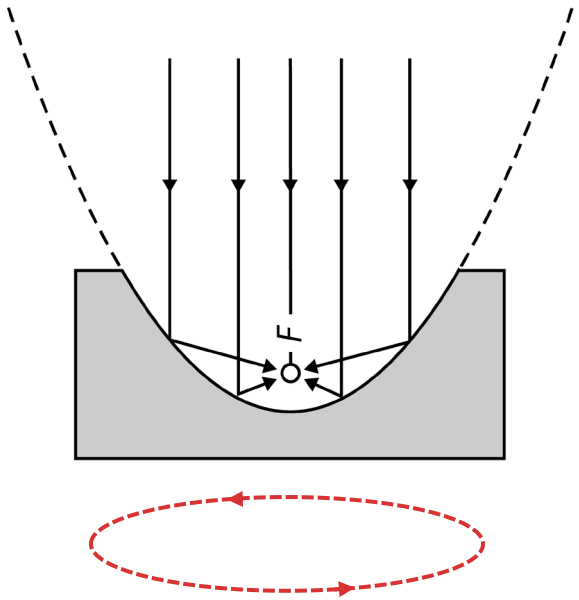
Point sources

- Elliptical reflector
- Electrohydraulic spark source



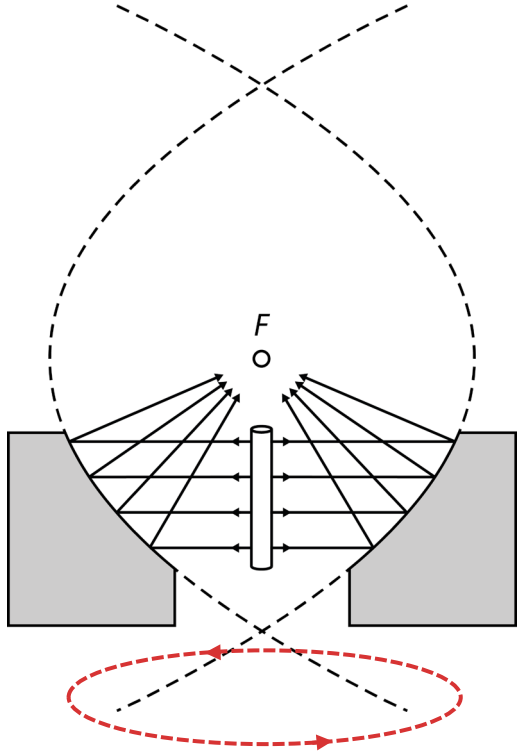
Plane waves

- Parabolic reflector



Cylindrical waves

- Paraboloidal reflector
- Electrodynamic impulse sources



Motivation and goals

Goal

- Design **reflectors** to focus intense acoustic vortices

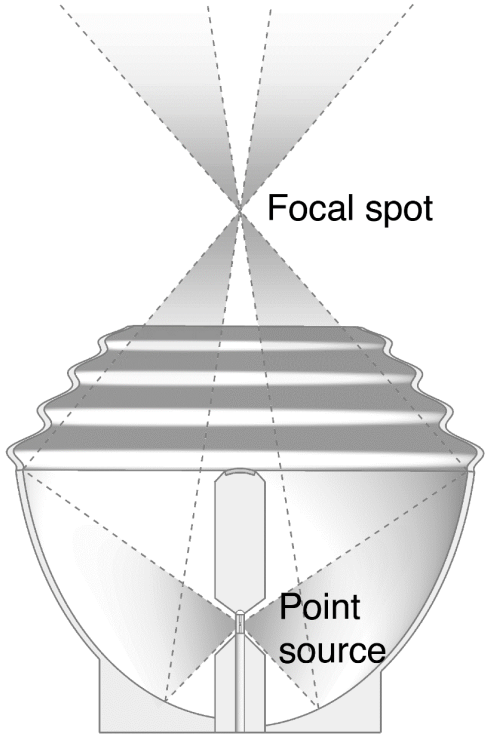
Focusing acoustic vortices by reflection

- Interest in therapeutical ultrasound
- New approaches in lithotripsy / histotripsy
- Single beam particle manipulation using pulsed signals

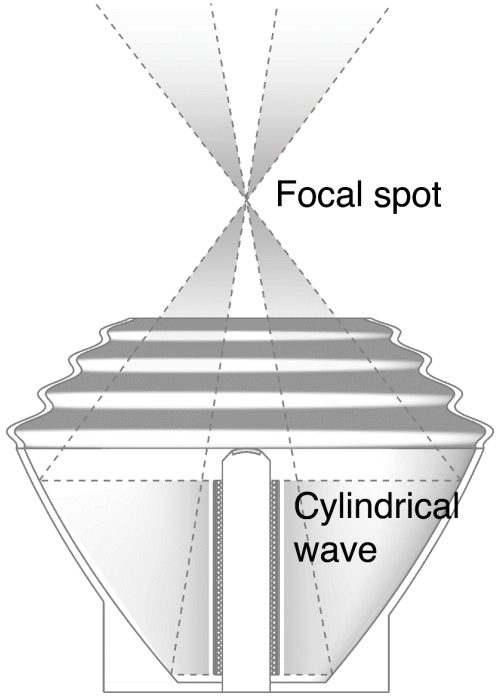
Helicoidal reflectors

1. Point source: **Helicoidal ellipsoid**
2. Cylindrical wave: **Helicoidal paraboloid**

Helicoidal ellipsoid
Point-source to focused vortex



Helicoidal paraboloid
Cylindrical wave to focused vortex



Methods

How to introduce a phase dislocation in the reflected field?

- Temporal **delay**

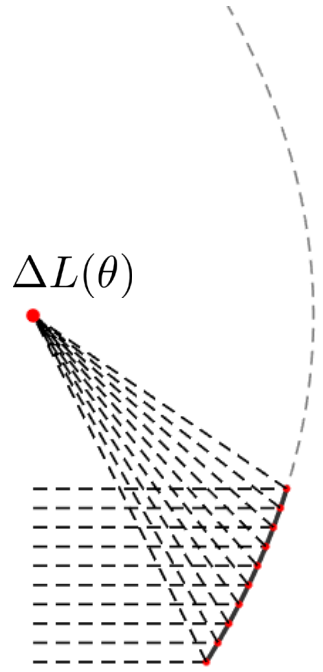
$$\Delta t(\theta) = \frac{l\theta}{\omega_0},$$

where ω_0 is the frequency, l is the topological charge and θ is the polar angle

- Path **difference**

$$\Delta L(\theta) = \Delta t(\theta) c_0 = \frac{l\lambda_0\theta}{2\pi},$$

where $\lambda_0 = 2\pi c_0/\omega_0$ is the wavelength at the design frequency and c_0 is the sound speed.



- The surface depends on the field radiated by the source.
- For axisymmetric sources, the reflector surface present chiral geometry.

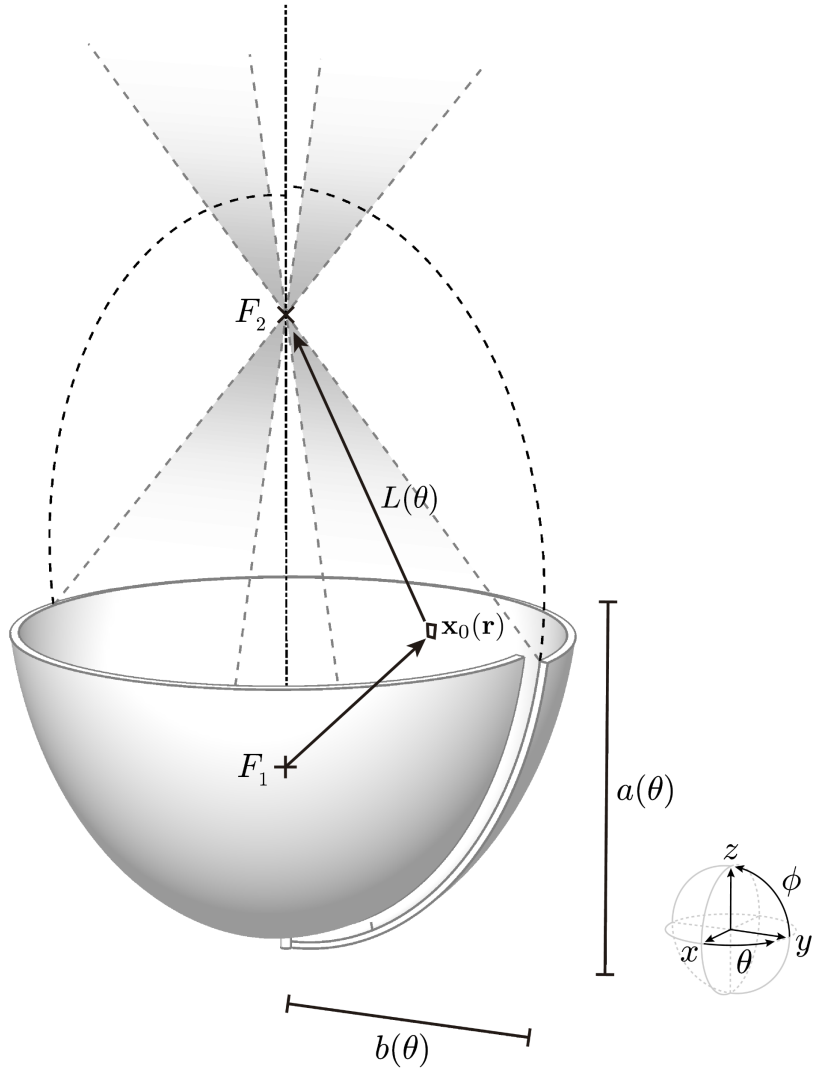
Helico-ellipsoidal reflector

Helicoidal ellipsoid

- Single point source: Electrohydraulic spark generator.
- Single focal spot: Helico-elliptical reflector.

Main design equations

- Define an elliptic curve with foci F_1 and F_2,
- All reflected waves should present a phase difference at the focus.
- There should be a **path difference** along the polar coordinate.
- Surface should be **helical**.



Helico-ellipsoidal reflector

Surface design

- Defining an **ellipsoid** with foci F_1 and F_2 ,
- The ellipsoid is given by

$$\frac{x^2}{b^2(\theta)} + \frac{y^2}{b^2(\theta)} + \frac{z^2}{a^2(\theta)} = 0,$$

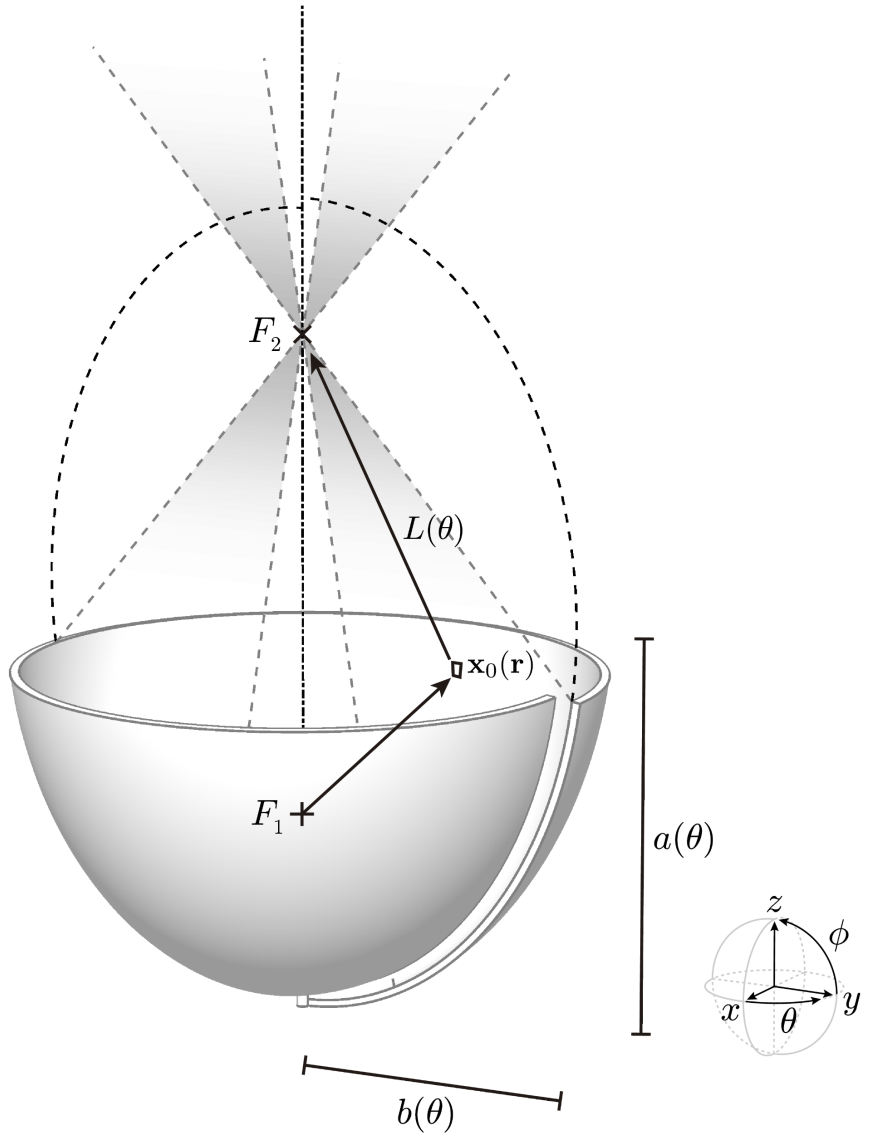
- The constant of the ellipse fulfils

$$a(\theta) = \frac{2a_0 - \frac{l\lambda_0\theta}{2\pi}}{2},$$

- where a_0 is the largest of the minor axis of the helico-ellipsoidal reflector for $\theta = 0$.

- The **semiaxis** of the reflector surface as a function of the azimuthal coordinate is

$$b(\theta) = \sqrt{a(\theta)^2 - F_2^2}.$$



Helicoidal paraboloid

Surface design

- The reflector is defined by a helico-parabolic surface, consisting of a **parabolic profile** of fixed focus.
- The paraboloid has its **vertex** at the point

$$\mathbf{r}(\theta, r, z) = (0, -1/4a(\theta), F)$$

- In cylindrical coordinates, this surface is defined as

$$r(\theta, z) = a(\theta)(z - F)^2 - \frac{1}{4a(\theta)}$$

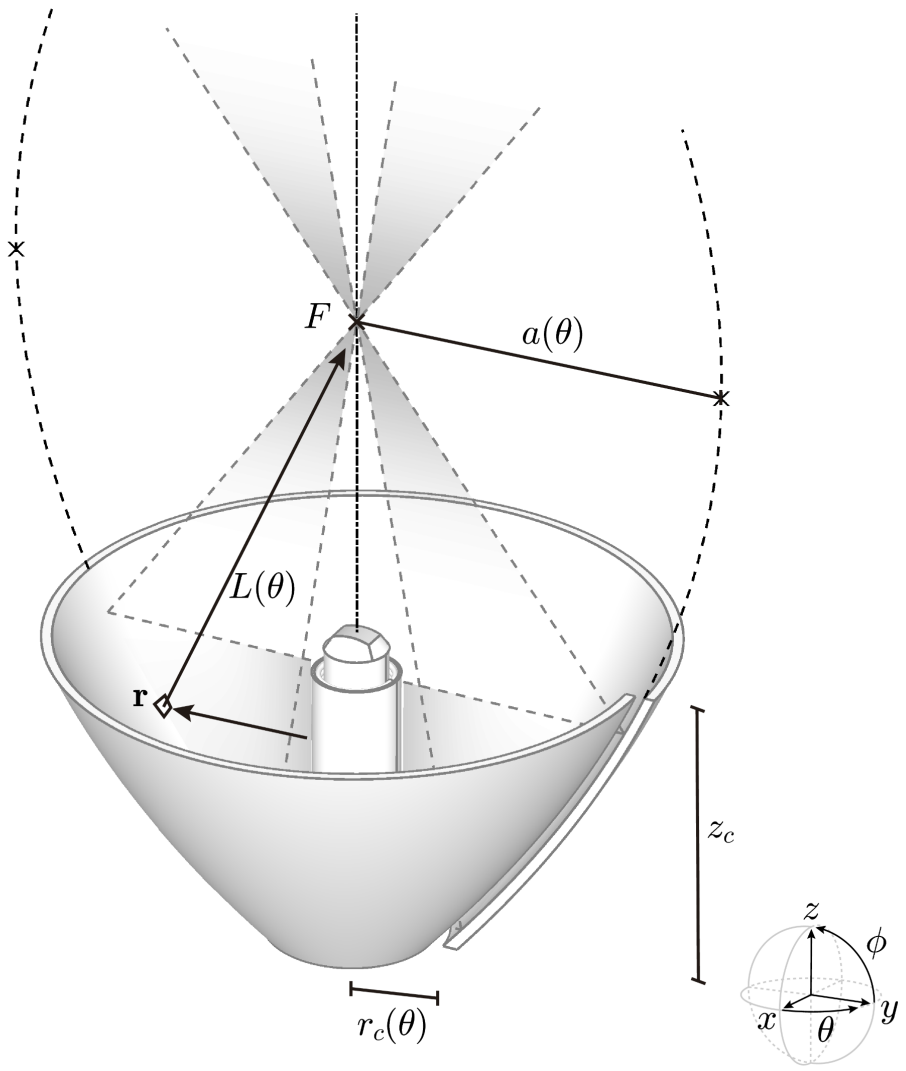
- Defining the minimum internal radius as

$$r_c(\theta) = R_m - m' \frac{M\lambda_0\theta}{2\pi},$$

- where the geometrical parameters a and m' are given by

$$a(\theta) = \frac{r_c(\theta) - \sqrt{F^2 - 2Fz_c + r_c(\theta)^2 + z_c^2}}{2\left(F^2 - 2Fz_c + z_c^2\right)}.$$

$$m' = \frac{1}{1 + \dfrac{R_m}{\sqrt{F^2 + R_m^2}}}.$$



Methods

Semi analytic method

- The total field is given by

$$p(\mathbf{r},\omega) = p_i(\mathbf{r},\omega) + p_s(\mathbf{r},\omega),$$

- Then we use the first Rayleigh-Sommerfeld integral for the source

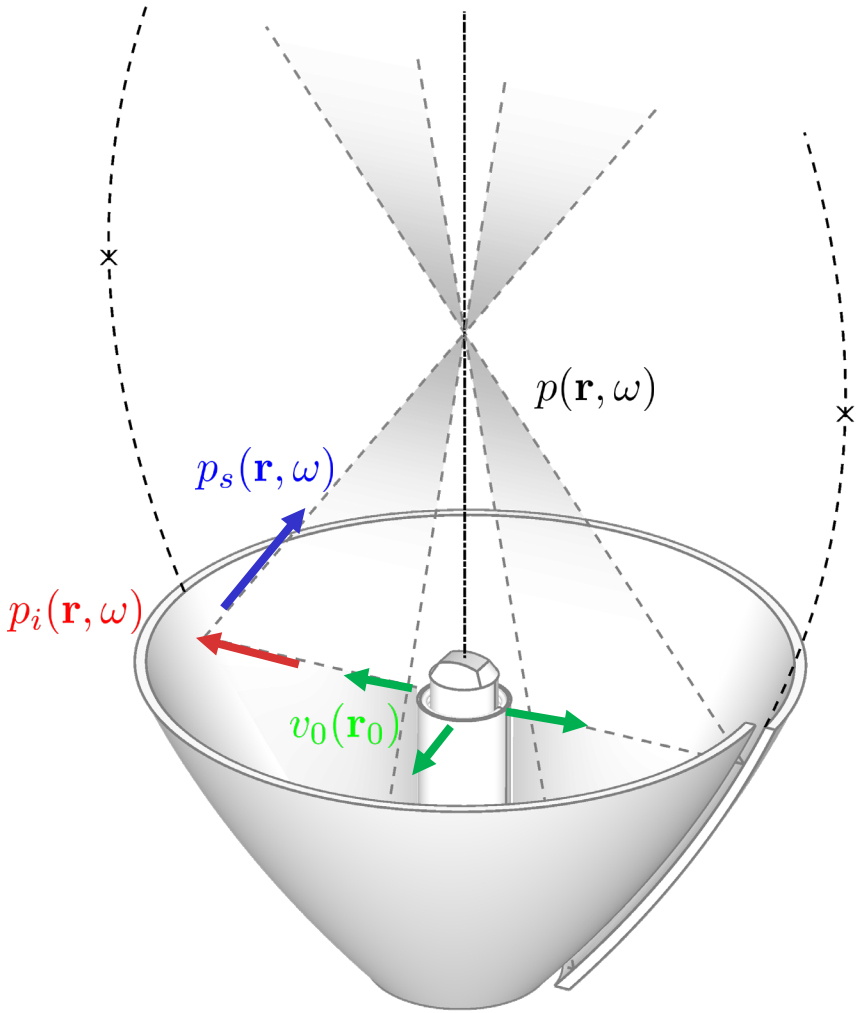
$$p_i(\mathbf{r},\omega) = \frac{i\omega\rho_0}{2\pi}\int_{S_0} \frac{v_0(\mathbf{r}_0)\exp\left(-ik_0\left|\mathbf{r}-\mathbf{r}_0\right|\right)}{\left|\mathbf{r}-\mathbf{r}_0\right|} dS_0,$$

which *approximates* the field radiated by a vibrating surface.

- And assuming a perfectly reflecting surface, we project the field

$$p_s(\mathbf{r},\omega) = \frac{1}{2\pi}\int_{S_r} \frac{p_i(\mathbf{r}_r,\omega)\frac{\partial}{\partial r}\exp\left(-ik_0\left|\mathbf{r}-\mathbf{r}_r\right|\right)}{\left|\mathbf{r}-\mathbf{r}_r\right|} dS_r,$$

which gives the field scattered by the surface.

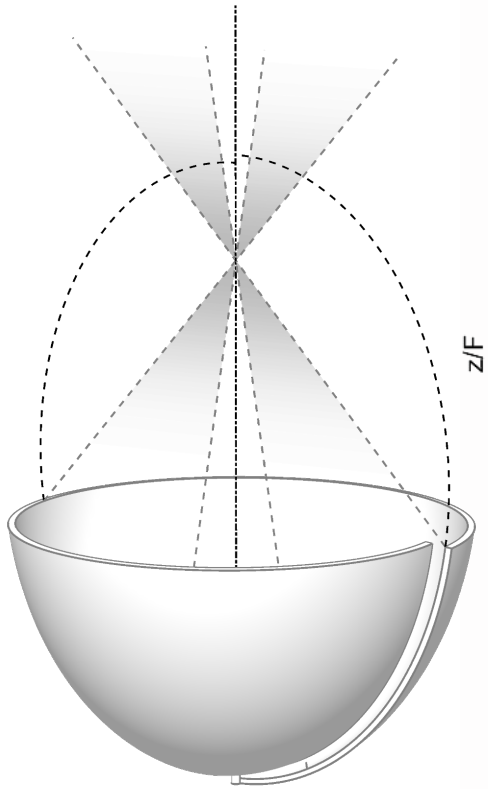


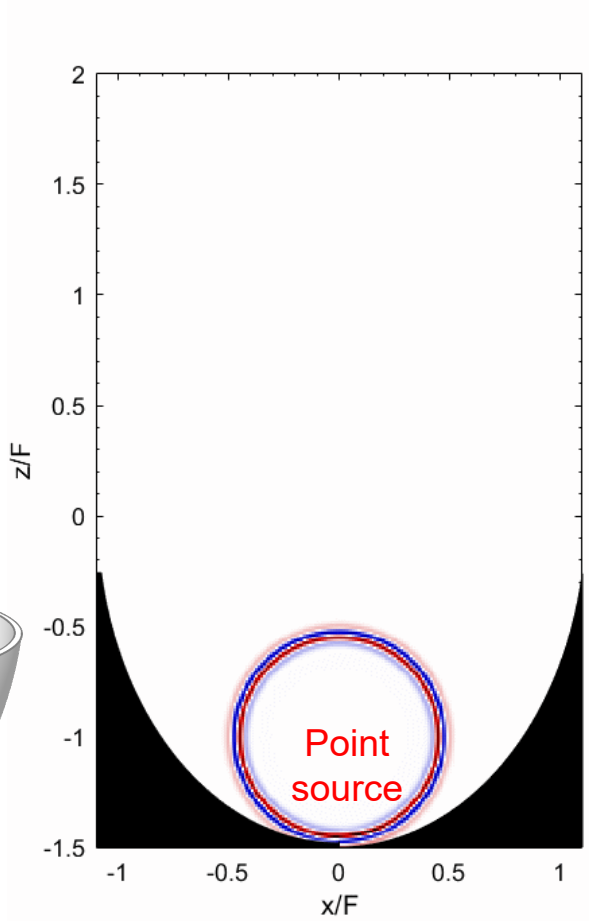
Results

Time domain field

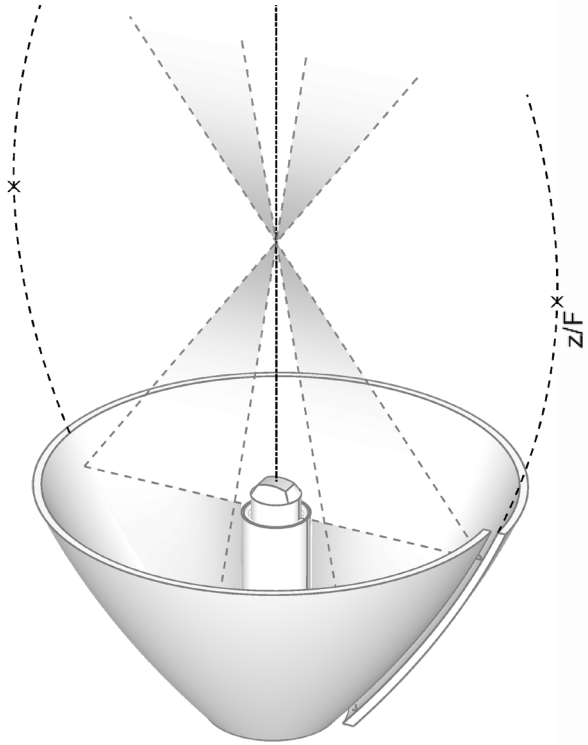
- Both reflectors concentrates the acoustic energy at the focus.
- A vortex is generated

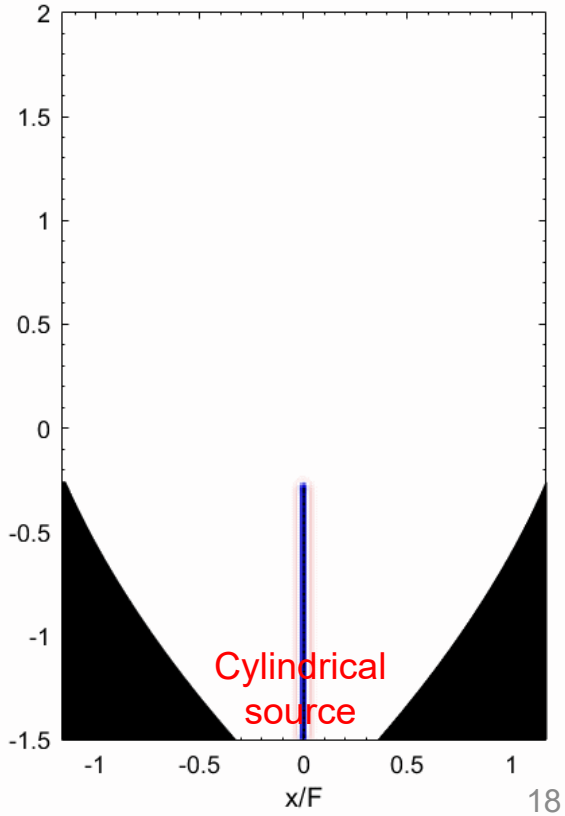
Helical ellipsoid





Helical paraboloid



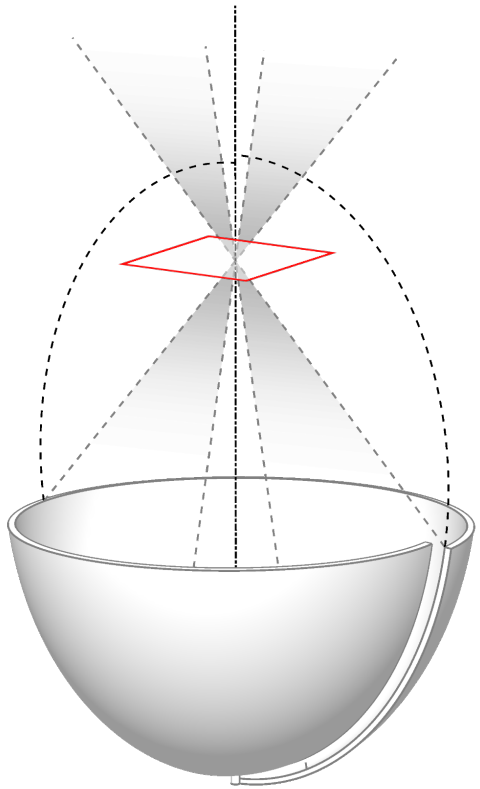


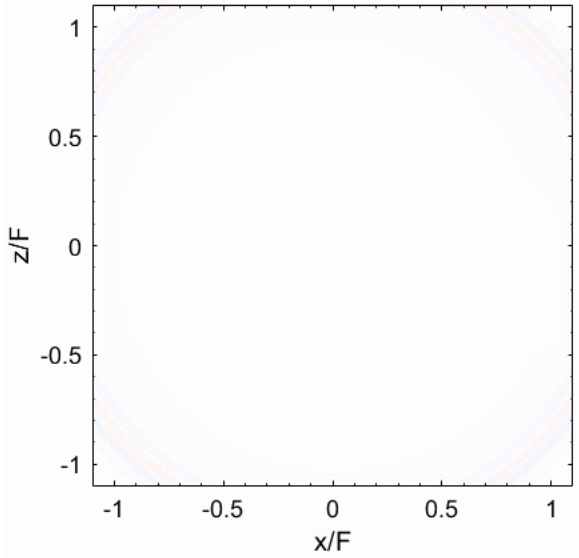
Results

Time domain field

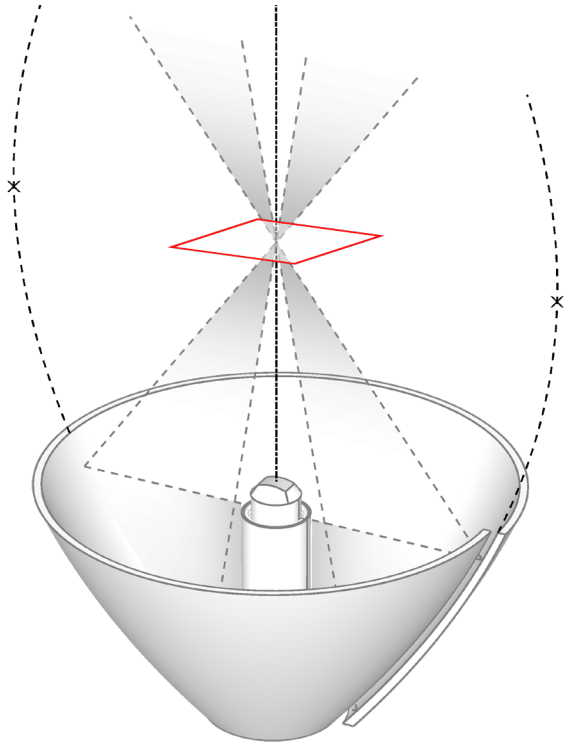
- Both reflectors concentrates the acoustic energy at the focus.
- A vortex is generated

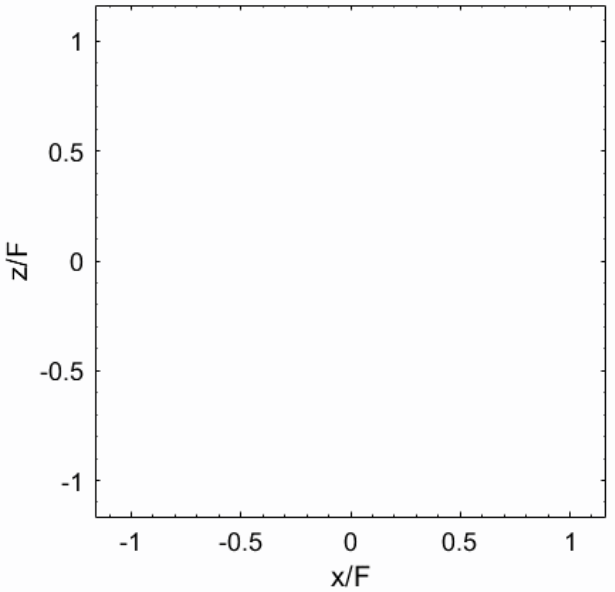
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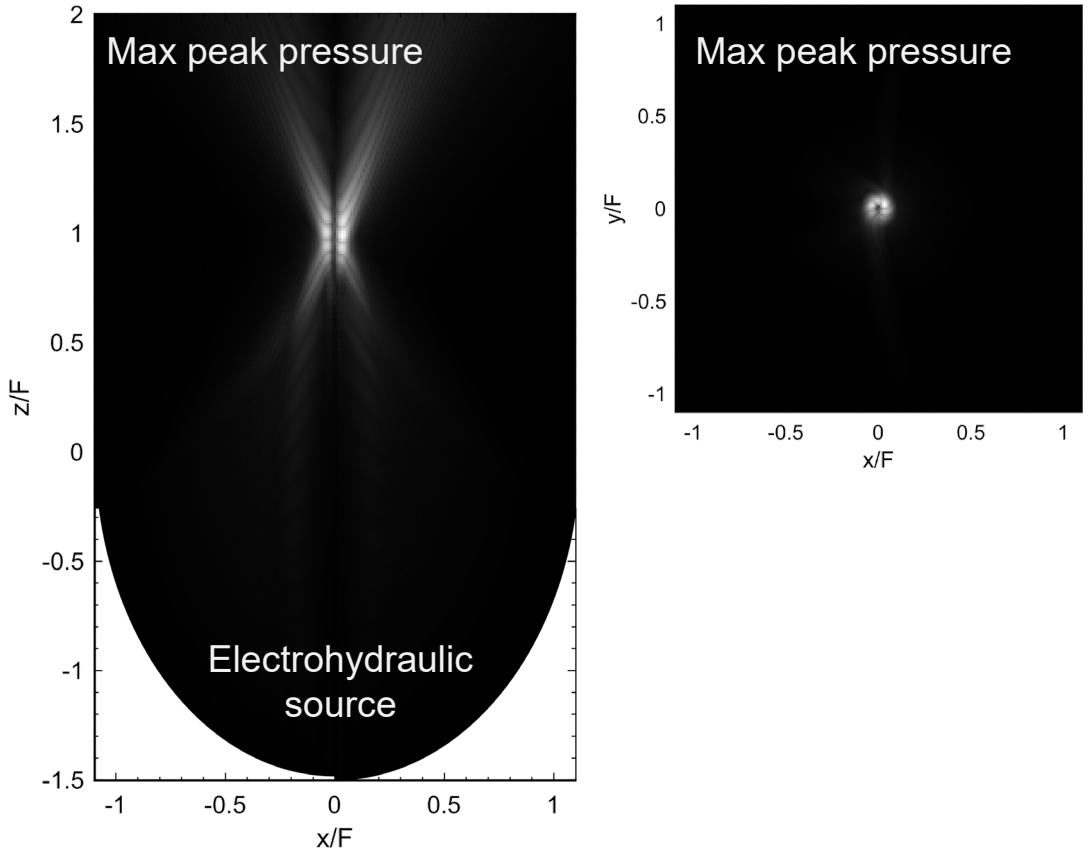


Results

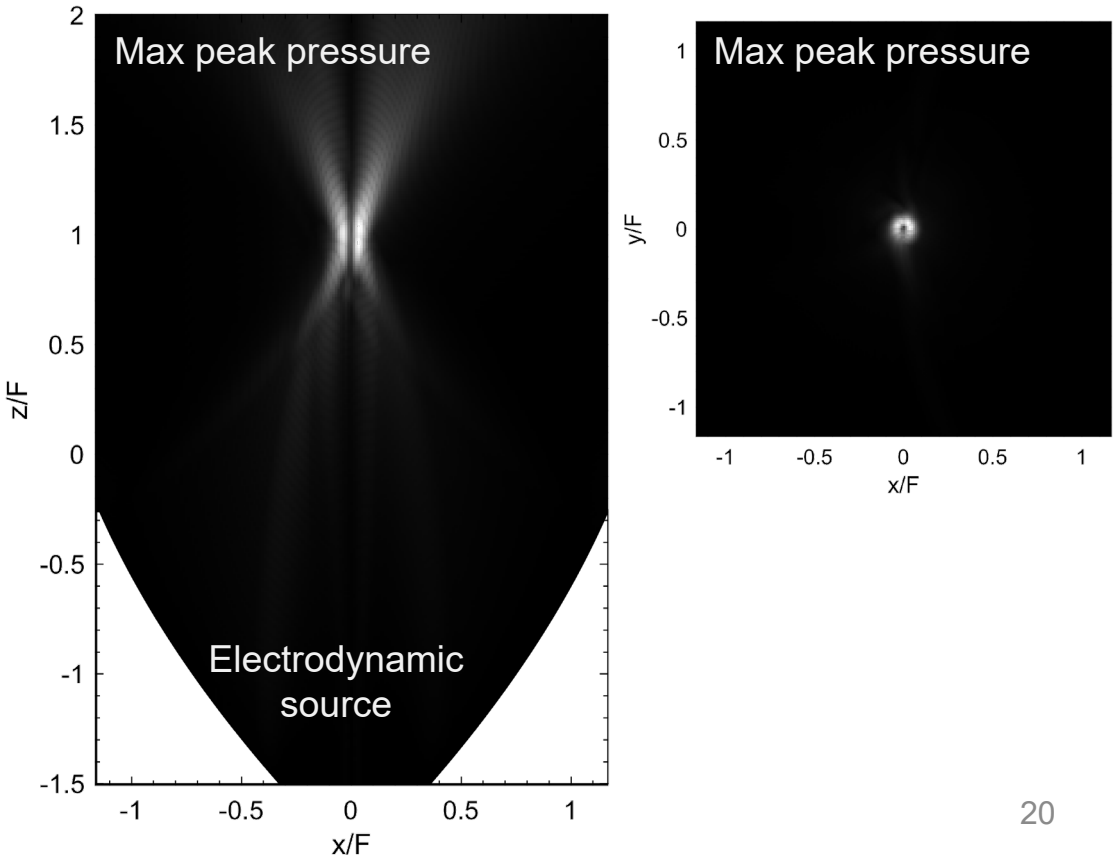
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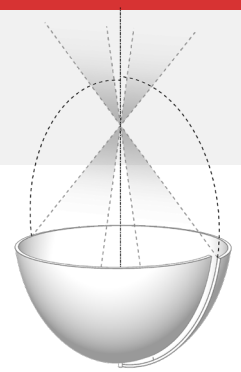
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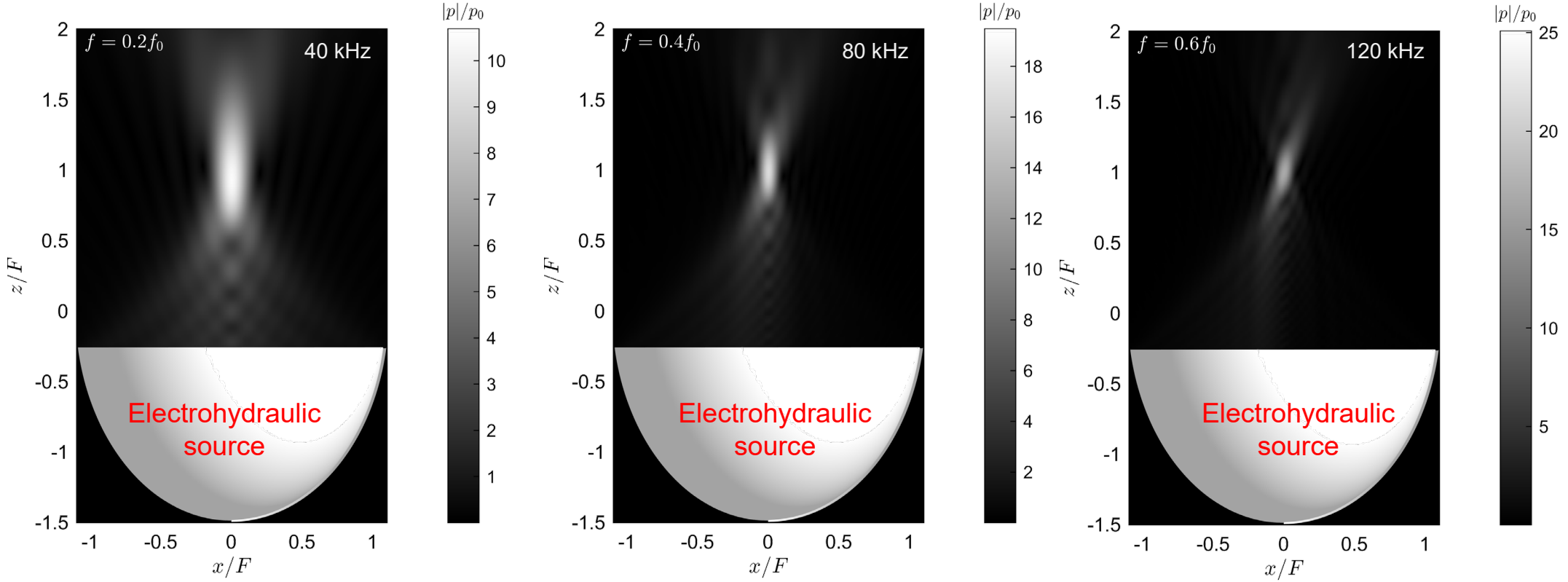


Results

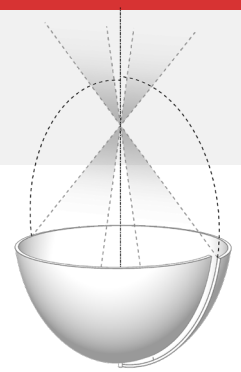


Helico-ellipsoidal reflector

- The helicoidal surface concentrates the acoustic field **at the focus**.
- Vortices of **integer topological** charge at integer multiples of the design frequency.
- Vortices of **arbitrary topological** charge are generated: fractional topological charge for impulsive signals.

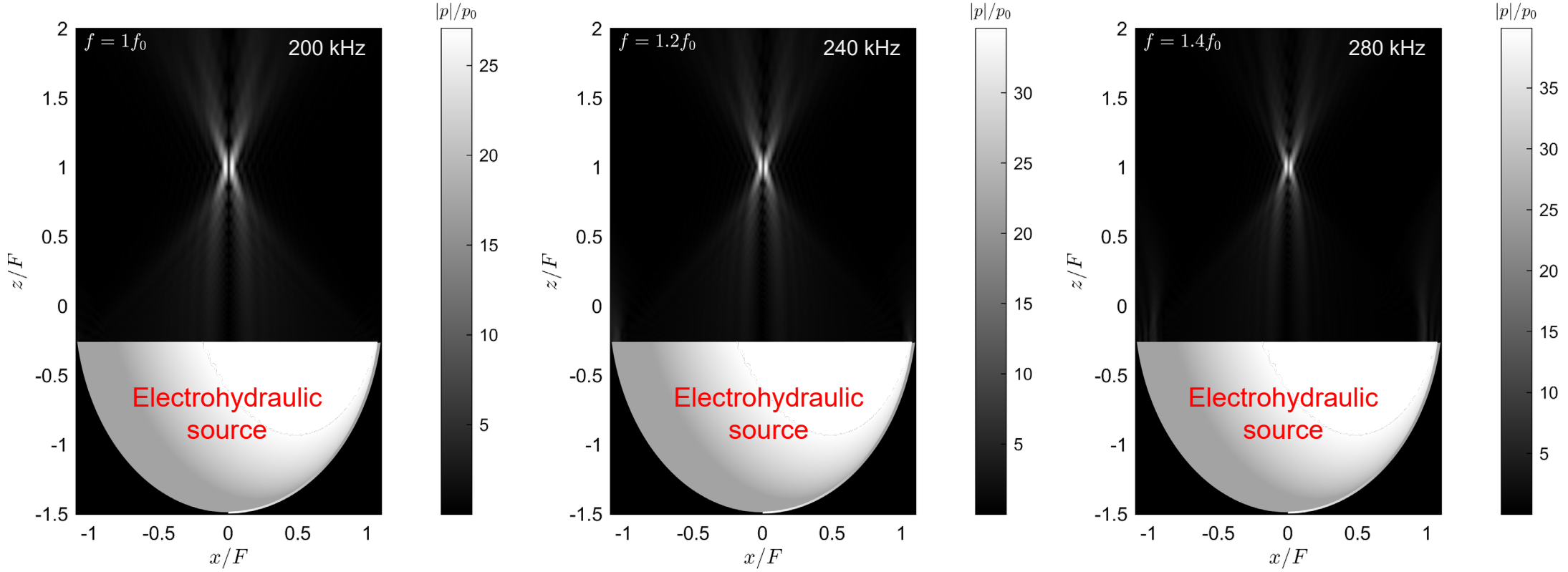


Results

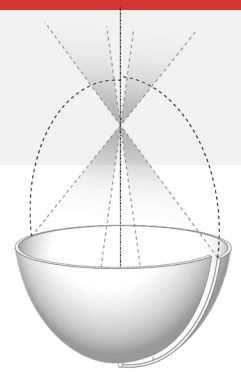


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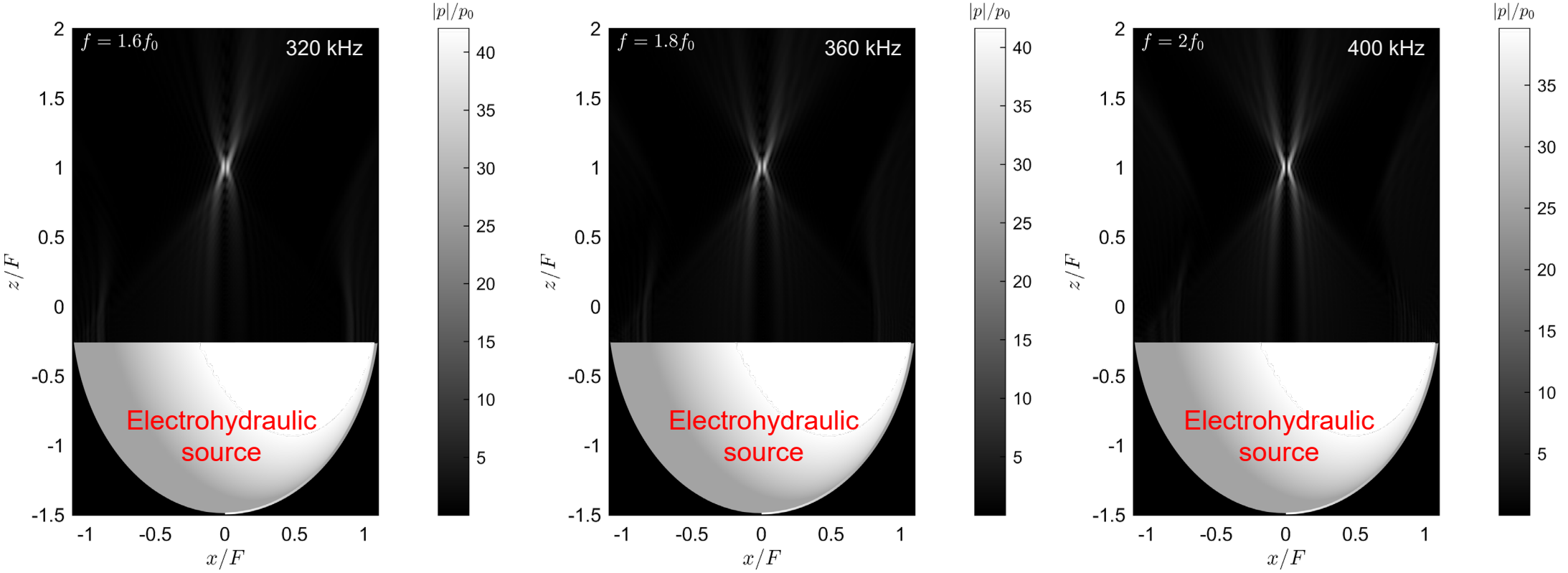


Results

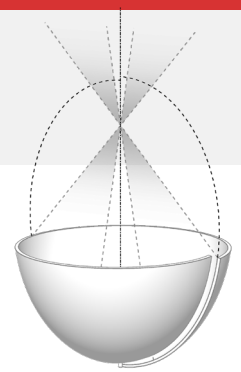


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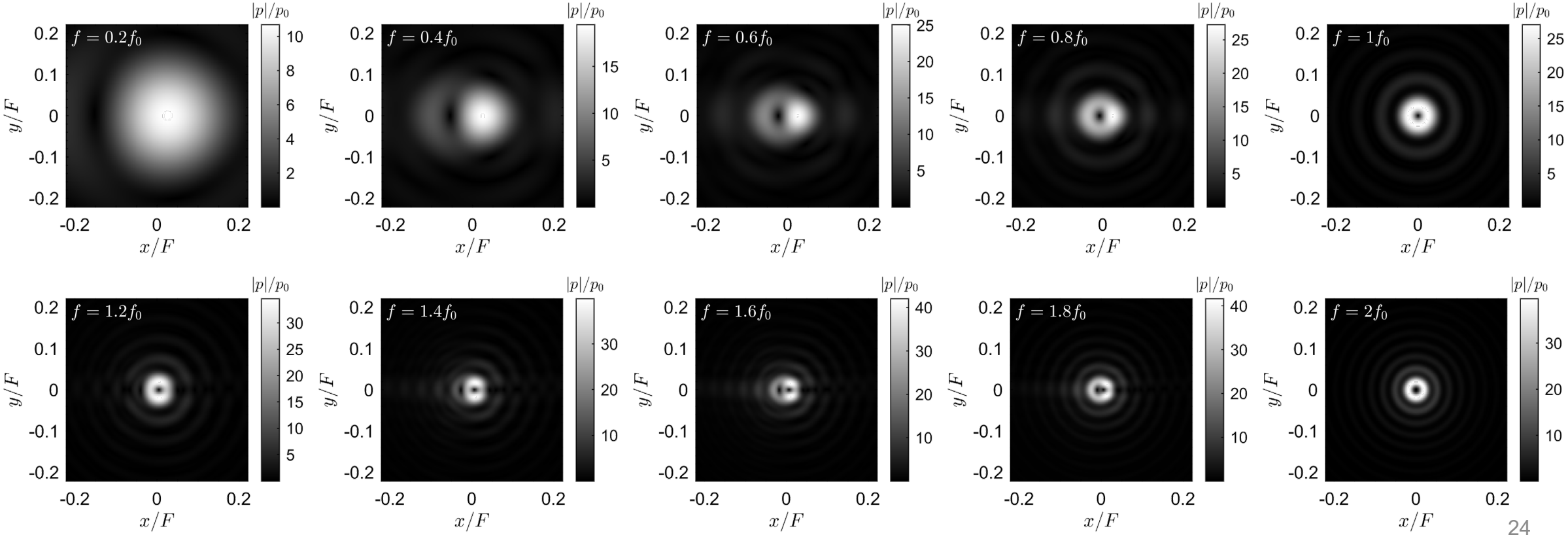


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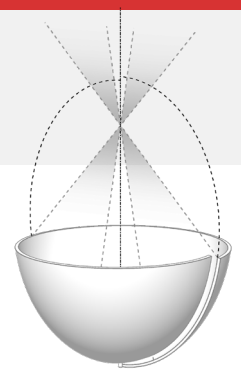


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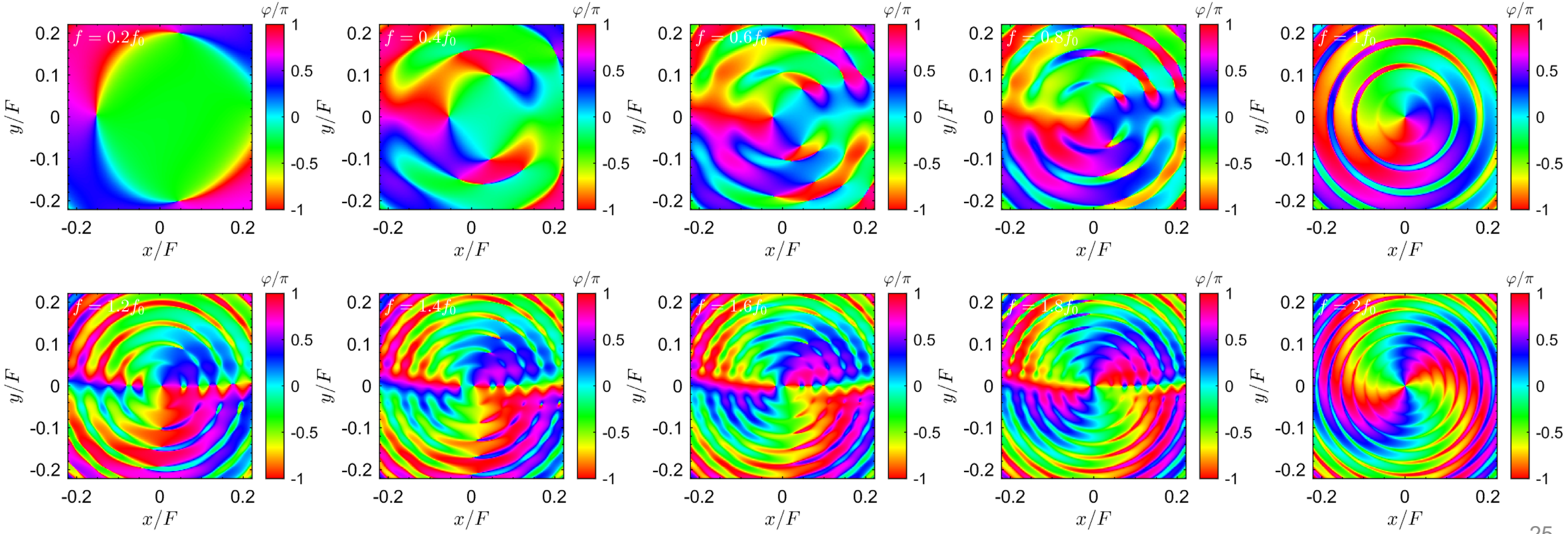


Results

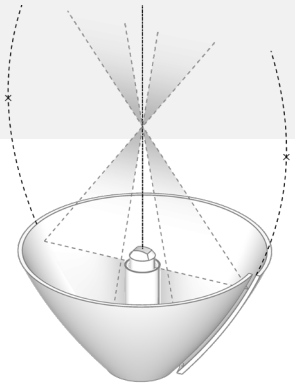


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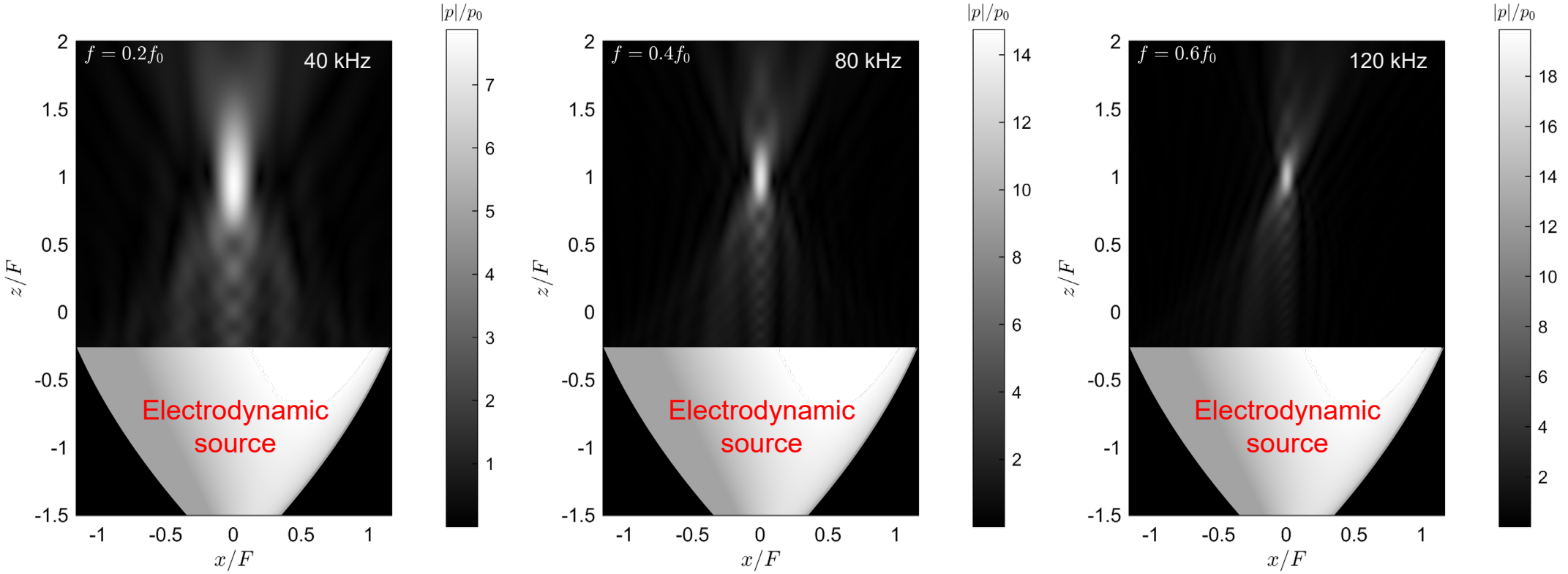


Results

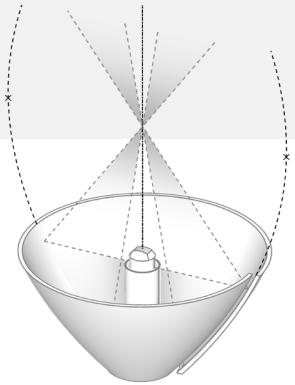


Helico-paraboloidal reflector

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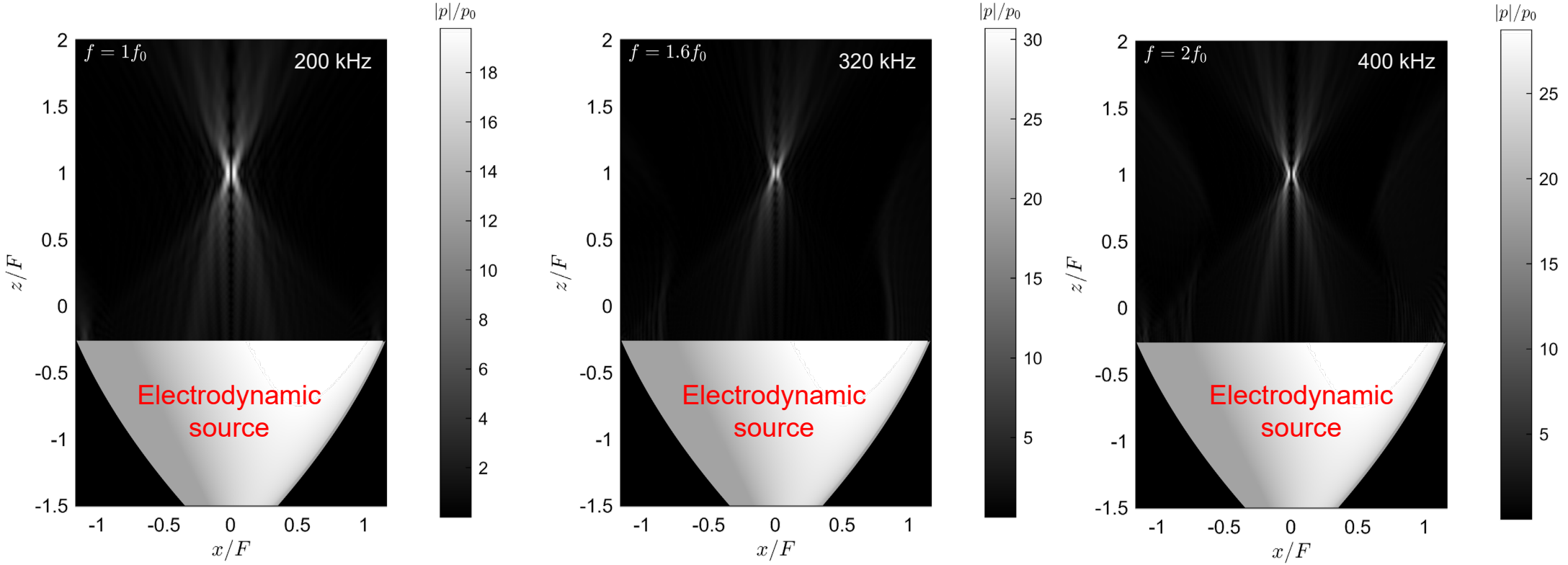


Results

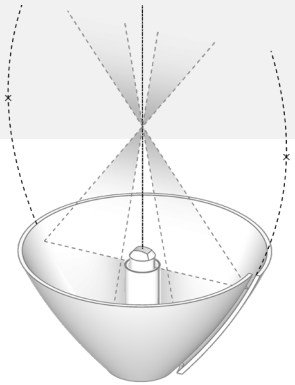


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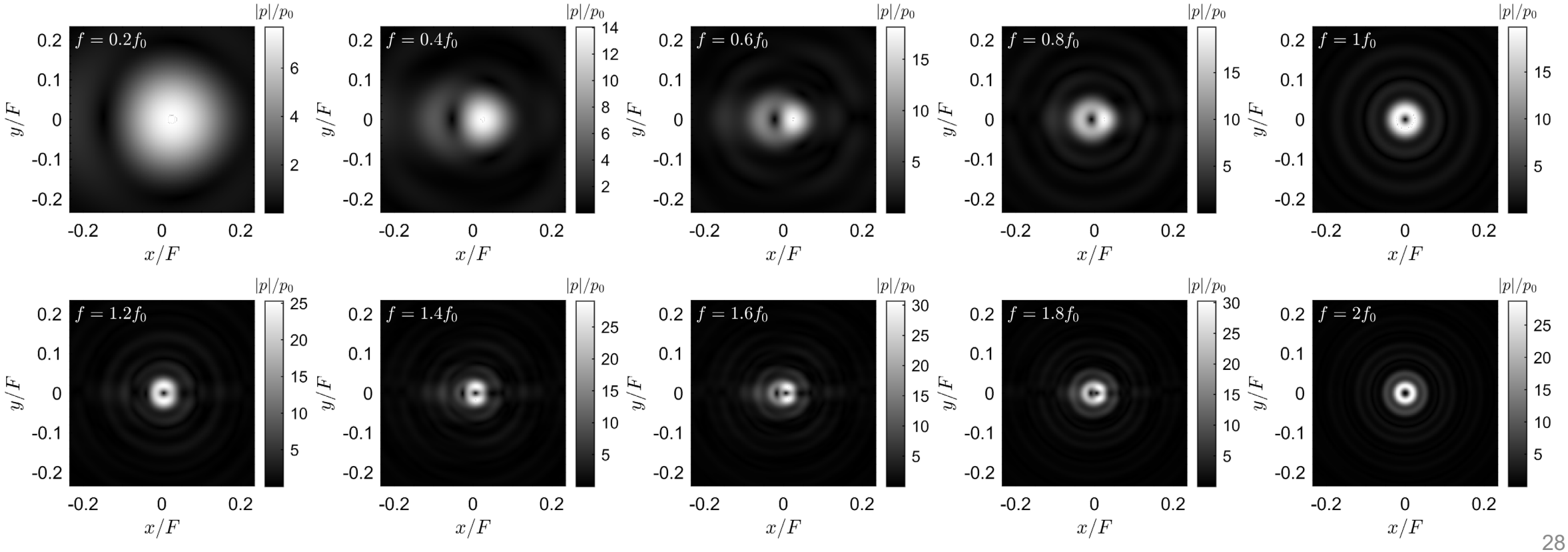


Results

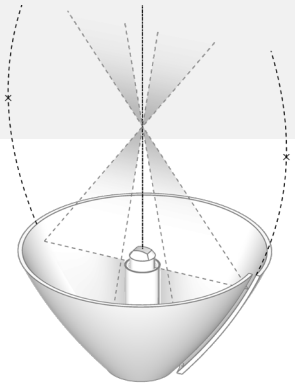


Helico-ellipsoidal reflector

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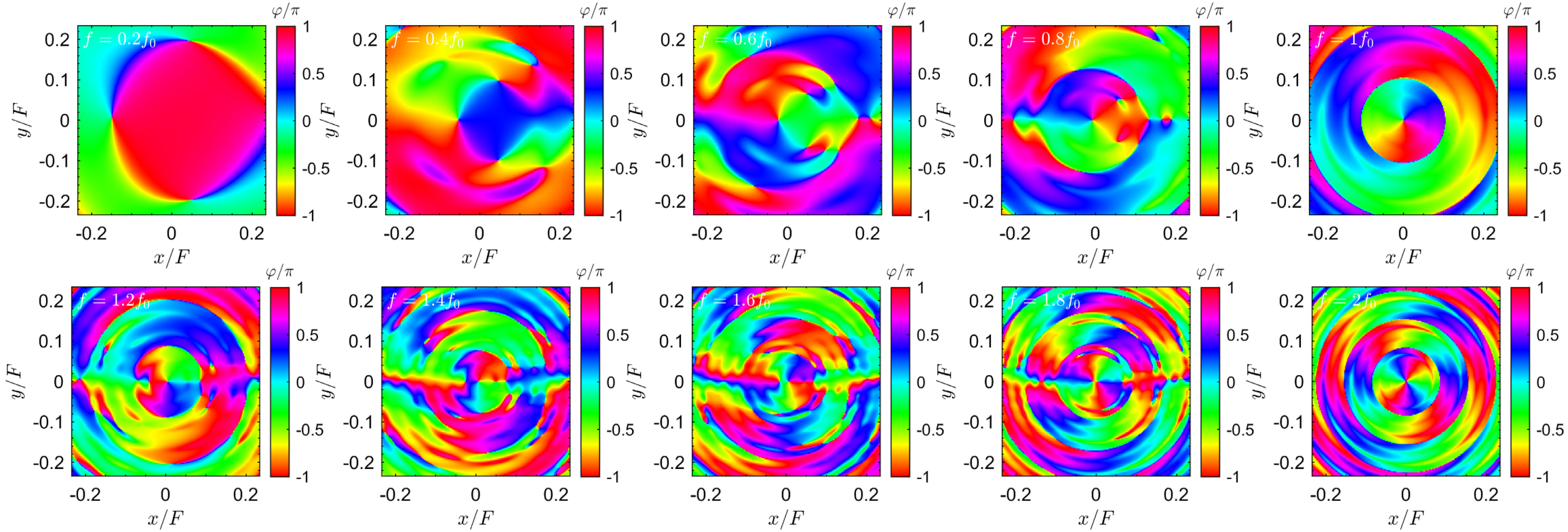


Results



Helico-ellipsoidal reflector

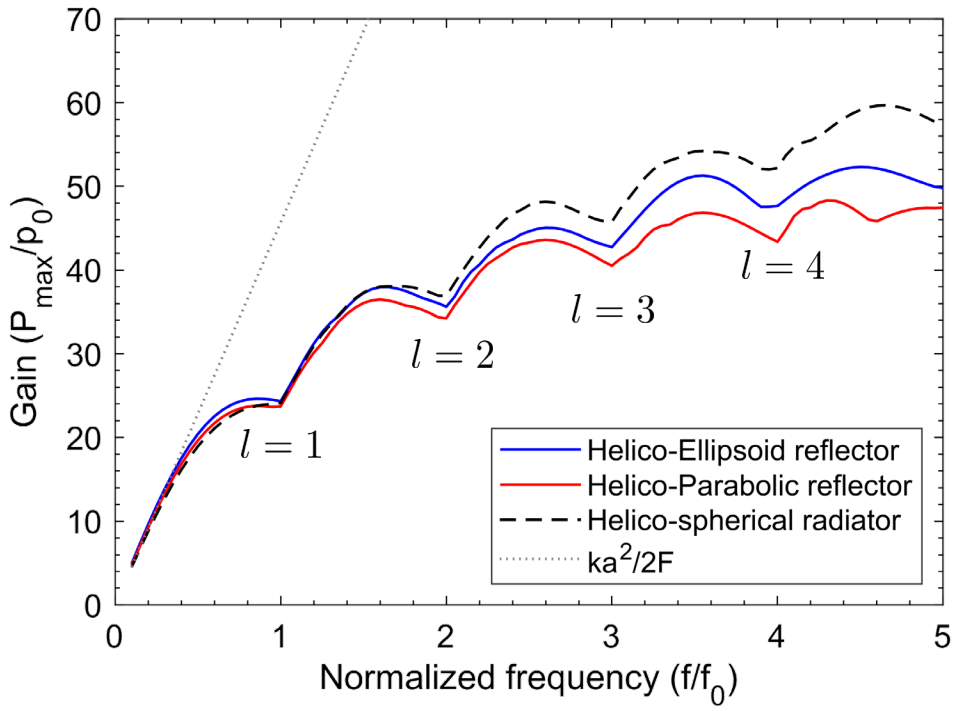
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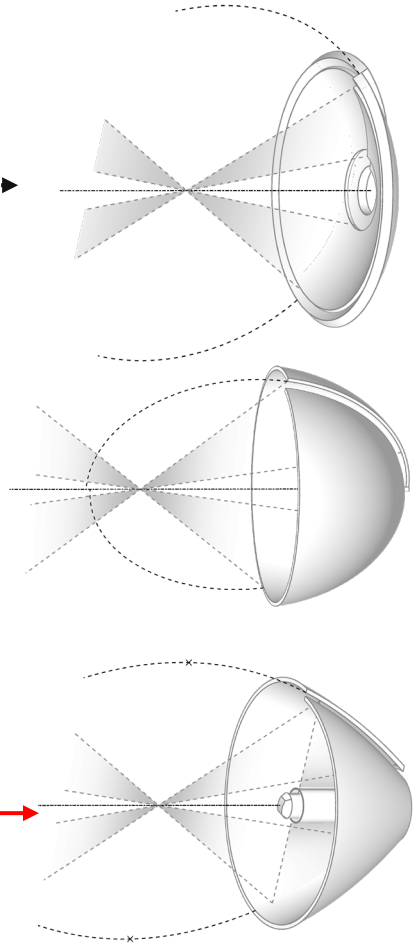


Results

Gain: *fixed design*

- Both reflectors behave similar as helical radiator
  - High-order topological charge: wide and sharp rings
  - High frequency: narrow rings
  - Fractional charge: unperfect destructive interference
- Vortex defocusing reduces the amplitude gain (not the intensity!)





Helico-spherical radiator
Helical piezoelectric surface

Helico-elliptic reflector
Electrohydraulic point source

Helico-parabolic reflector
Electrodynamic cylindrical source

Conclusions

Helicoidal reflectors

- Exact design equations can be found for
  - Monopole sources: helico-ellipsoidal reflector.
  - Cylindrical sources: helico-paraboloidal reflector.
- Focusing and vortex parameters are fully tunable.
- Vortices with **integer** topological charge emerge at integers of the **design** frequency
- Vortices of **fractional** topological charge are observed at other frequencies.

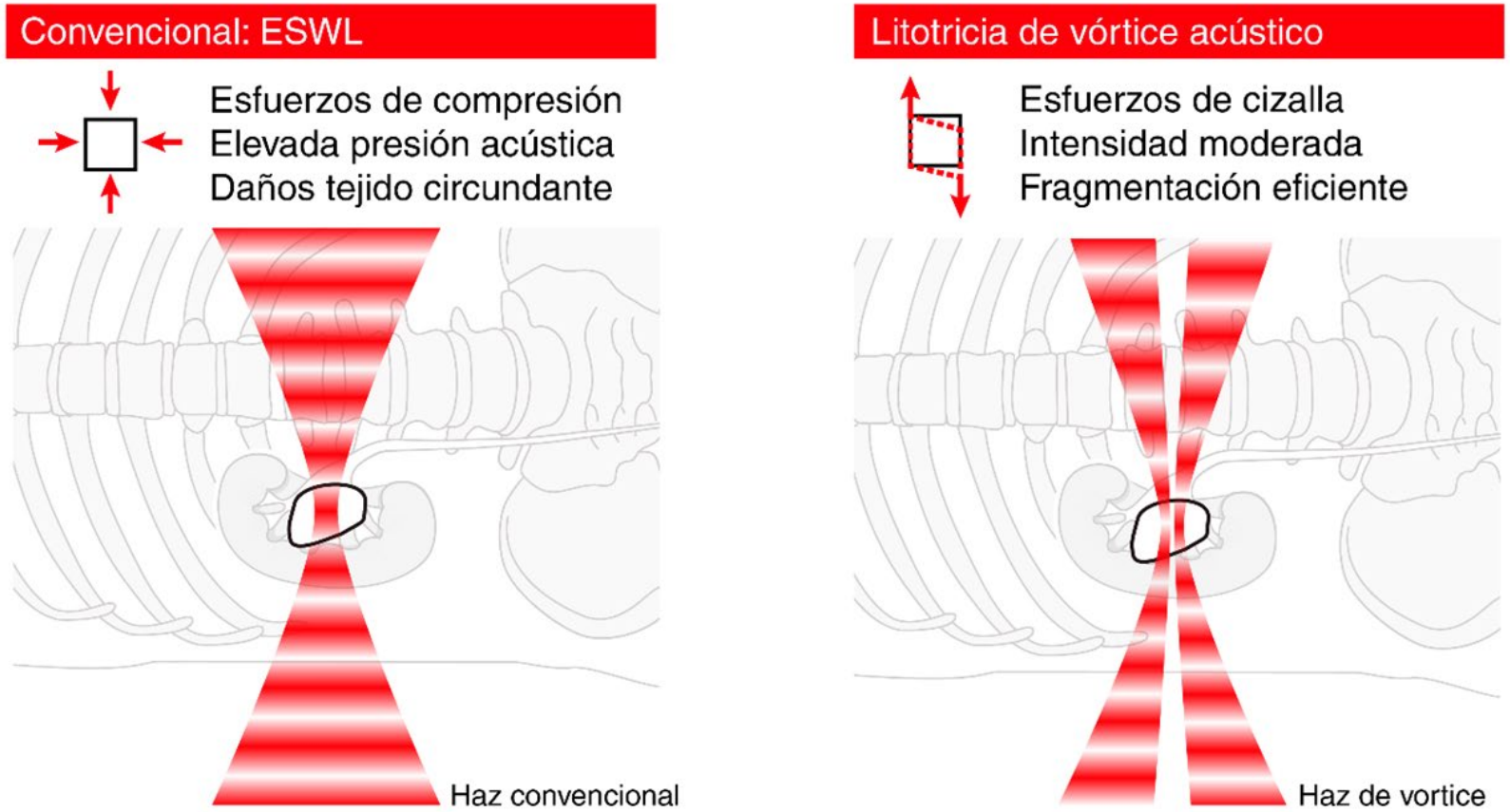
Why reflectors?

- Vortices can be generated by lenses, but they introduce attenuation.
- These reflectors can be used for high-amplitude vortex generation: vortex = defocusing!
- Lithotripsy, histotripsy, and/or particle and tissue manipulation applications.
- Ongoing experimental validation: **efficient kidney stone comminution?**

Patent

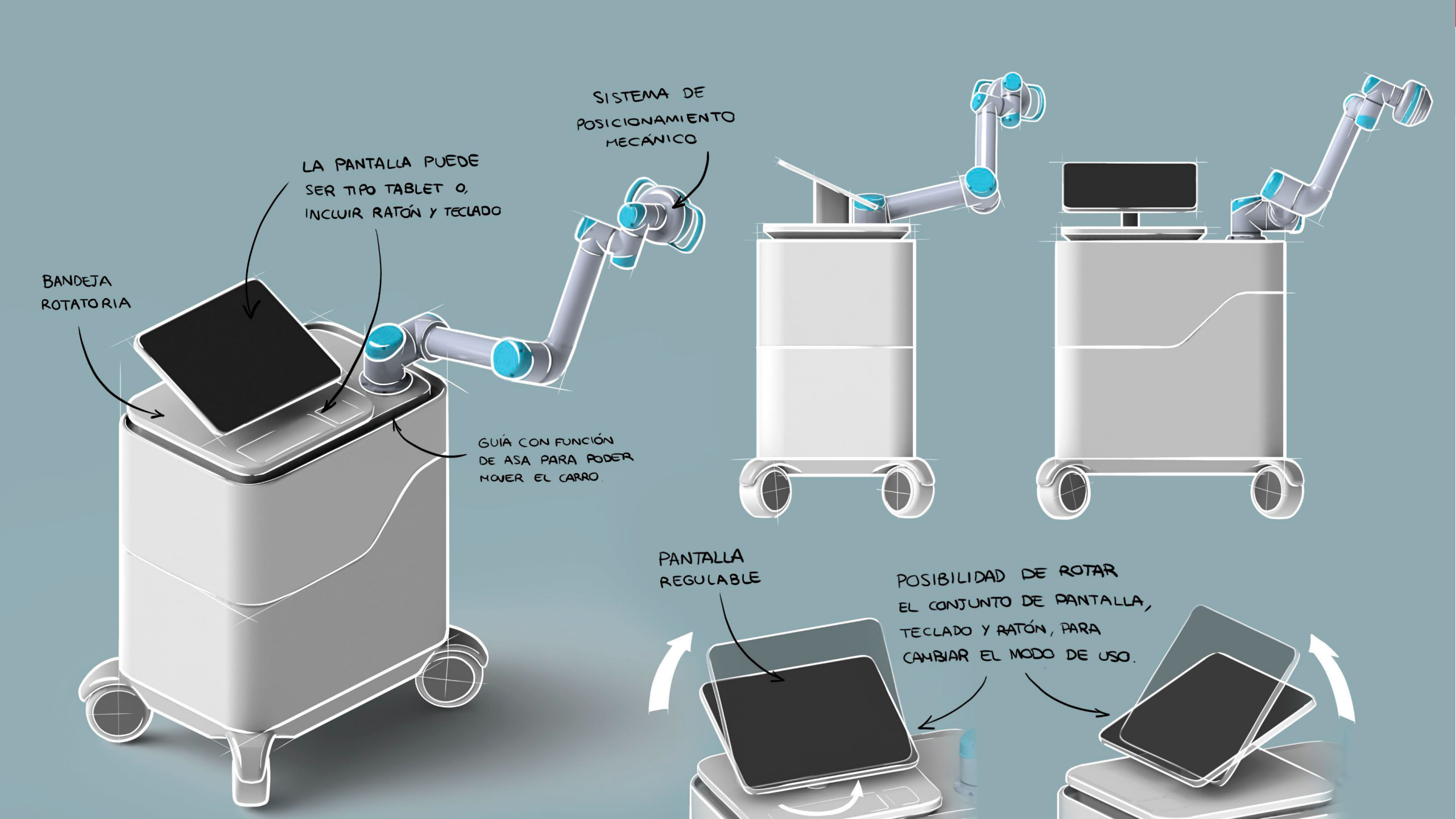
- N. Jiménez, F. Camarena, JM Benlloch. “System for the controlled fragmentation of solids by means of vortex sound beams” (06/08/2021) EP4183355A1, ES JP CN CA EP AU KR WO

Ongoing research



Patent

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SISTEMA DE POSICIONAMIENTO MECÁNICO
LA PANTALLA PUEDE SER TIPO TABLET O, INCLUIR RATÓN Y TECLADO
BANDEJA ROTATORIA
GUÍA CON FUNCIÓN DE ASA PARA PODER MOVER EL CARRO
PANTALLA REGULABLE
POSIBILIDAD DE ROTAR EL CONJUNTO DE PANTALLA, TECLADO Y RATÓN, PARA CAMBIAR EL MODO DE USO.

Acknowledgements

Hospital La Fe (Valencia)

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  - UCIE (INNCON/2020/009)
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  - Infraestructuras (IDIFEDER/2018/022)



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