# Optical trapping in counter-propagating Bessel beams


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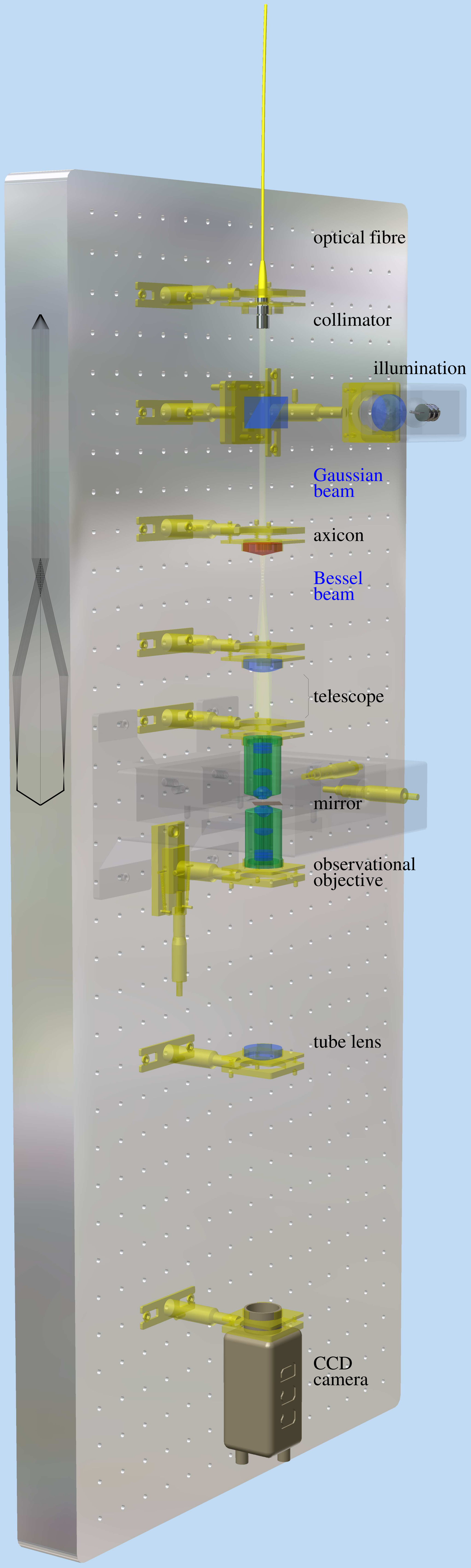


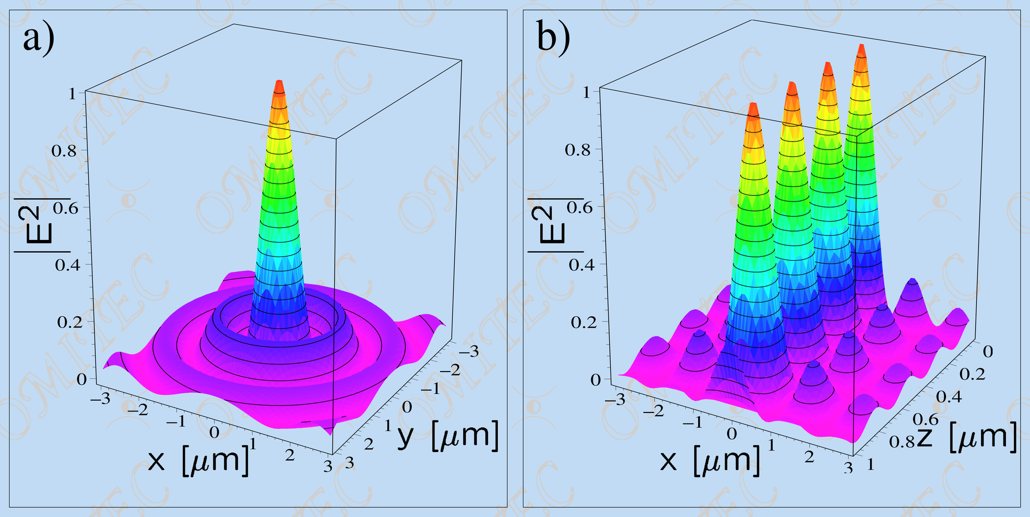

## Introduction

The diffractionless propagation of electromagnetic waves plays an important role in many branches of the optics especially because its width does not spread during propagation and can even posses orbital angular momentum (optical vortex). These beams can be generated with the use of an axicon, an annular aperture placed at the focal plane of a lens, or a hologram and their radial intensity profile is described by Bessel or Mathieu functions. Another useful property of the non-diffracting beam is its ability to reconstruct itself after passing through a disturbing obstacle. Both mentioned features can be directly used for 2D manipulation of objects in distinct sample cells displaced even several millimeters

## The intensity profile of the standing Bessel beam

$$\mathbf{E}^{(i)SW}(\mathbf{r}) = E_0\{[I_0^{SW} + \cos(2\varphi_r)I_2^{SW}]\cos(k_z z)\mathbf{e}_x + \sin(2\varphi_r)I_2^{SW}\cos(k_z z)\mathbf{e}_y + [2\cos\varphi_r I_1^{SW}]\sin(k_z z)\mathbf{e}_z\}$$

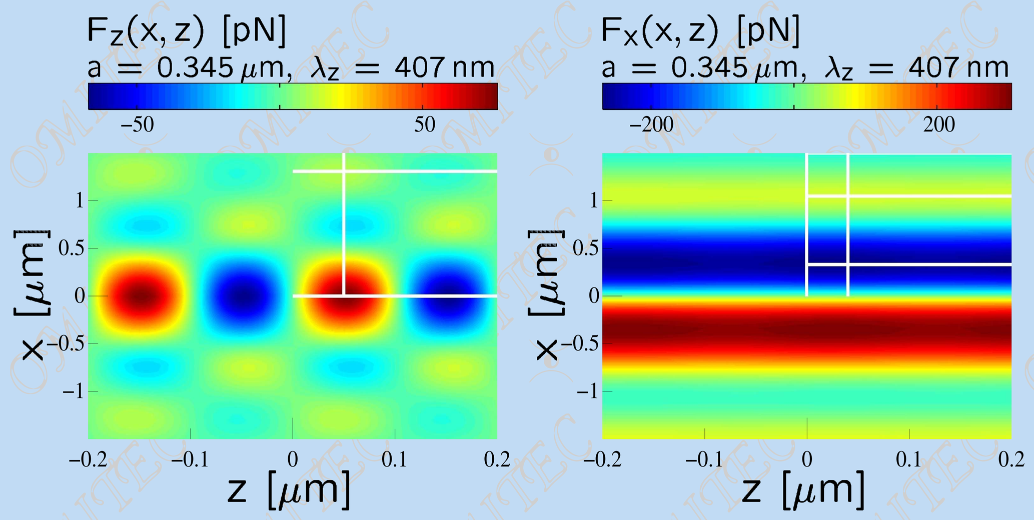
$$\mathbf{B}^{(i)SW}(\mathbf{r}) = \frac{ik}{\omega}E_0\{\sin(2\varphi_r)I_2^{SW}\sin(k_z z)\mathbf{e}_x + [I_0^{SW} - \cos(2\varphi_r)I_2^{SW}]\sin(k_z z)\mathbf{e}_y - [2i\sin\varphi_r I_1^{SW}]\cos(k_z z)\mathbf{e}_z\}$$



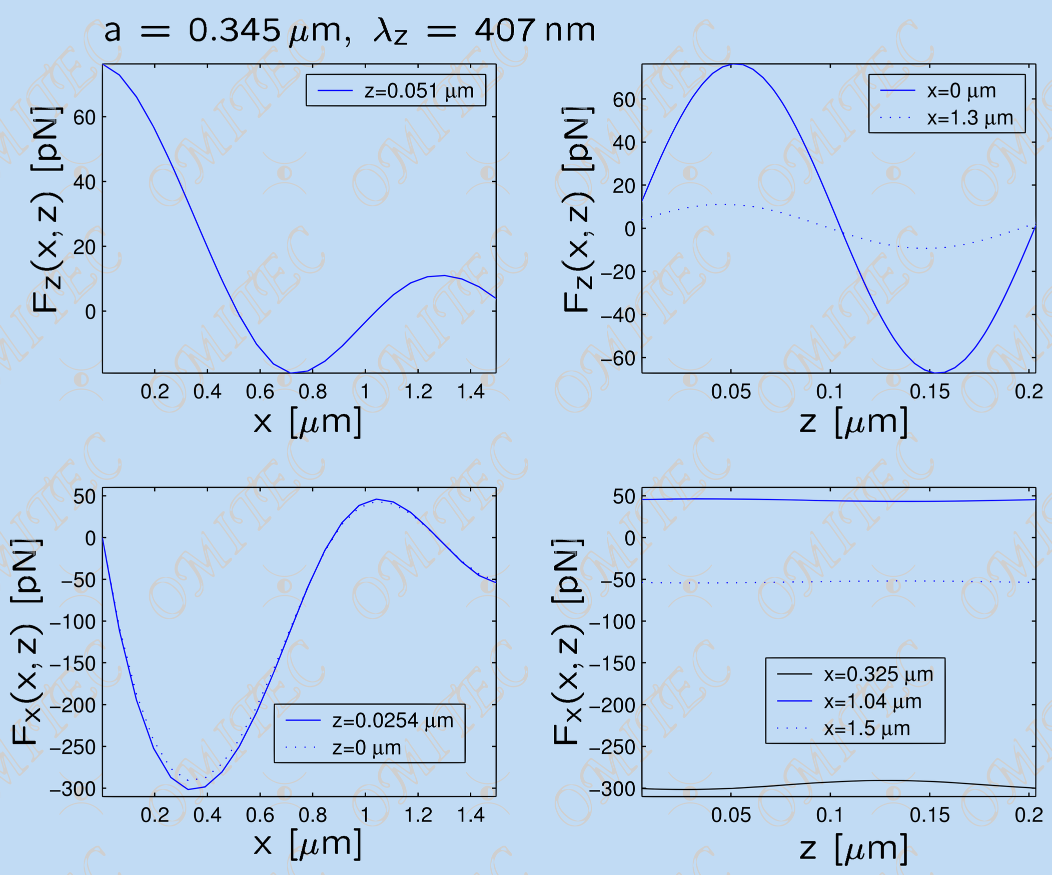

$$I_0^{SW} = A_0(1+\cos\Theta_0)J_0(k_x\rho)$$
$$I_1^{SW} = A_0\sin\Theta_0 J_1(k_x\rho)$$
$$I_2^{SW} = A_0(1-\cos\Theta_0)J_2(k_x\rho)$$

Figures shows an example of the field distribution in standing Bessel beam for the same parameters ($\lambda = 532\,nm, \Theta_0 = 11^o$) as we used in experiments. The radius of the Bessel beam core is less than one micrometer and the field pattern does not change along $z$ axis.

## Calculation of optical forces



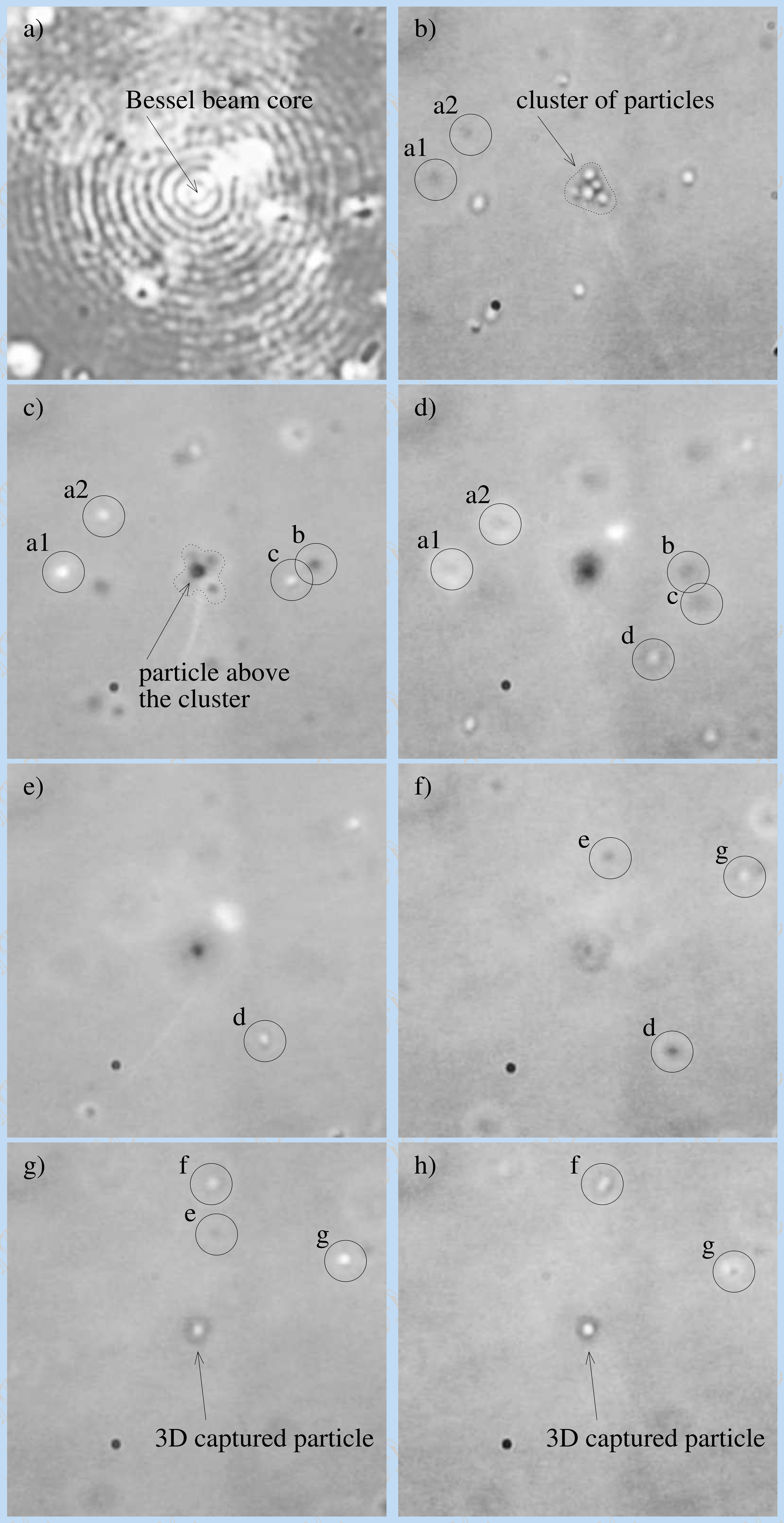

Optical forces acting on micro-particles placed in standing Bessel beam were counted by use of the Barton's method. It has been shown that the equilibrium position of these spheres centre is in the intensity maximum along $x$ axis but in intensity minimum (standing wave node) along $z$ axis.




## Experimental results

Maximal power of 1W from the laser (Coherent Verdi V6) was delivered by a fibre. The output beam from the fibre was collimated, its polarisation was adjusted, and then it was transformed into the Bessel beam by an axicon. Afterwards its width was decreased about 6× by a telescope assembled from a lens and a microscope objective. The final diameter of the core of the Bessel beam was about $2\,\mu m$. The particles were injected into a trapping cell that consisted of a cover glass and a dielectric mirror. The constant separation of both surfaces was set by spacers (polystyrene particles of diameter $14\,\mu m$). The particles were imaged on CCD camera placed behind the mirror by a microscope objective and tube lens. Laser light impinging on the CCD was further attenuated by a filter. The particles were visualised using microscope illumination unit coupled with laser beam on polarising beam splitter.

Each of the studied polystyrene particles of radii 150, 345 and 535 nm was successfully 3D confined laterally in the core of the Bessel beam and axially in the standing wave. Confinement of the particles with radius of 345 nm is demonstrated in following set of images.




The first a) image shows the Bessel beam with the core of diameter equal to about $2\,\mu m$. The $b$) picture images 2D-trapped cluster of particles at the level of the mirror. On the c) image there is another particle captured in the Bessel beam core in the second layer of the cluster's structure. Subsequent images are obtained in gradually higher planes of the sample space. Each of them shows corresponding free space particles, marked with letters $a$-$g$. After passing an empty space in the Bessel beam core the 3D-trapped particle in the Bessel beam standing wave is displayed in pictures $g$), $h$).

## Conclusions

We presented a theoretical description of the Bessel beam coming through the axicon and the standing Bessel beam created by retroreflection of such beam from a dielectric mirror. We also reported experimental 3D confinement of polystyrene spheres of diameters equal to 0.30 $\mu m$, 0.69 $\mu m$, and 1.07 $\mu m$ in the standing Bessel beam.

## Acknowledgements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