Particle Self-Organizing in Non-Diffracting Laser Beams

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Introduction

The self-organizing by light is based on the confinement of several particles in optical fields coming from the momentum transfer from the light scattered by the particles to the objects. If position of one object strongly influences the position of the others via the scattered light, this kind of inter-particle interaction is called optical binding.We focus on non-diffracting beams because they keep their lateral profile unchanged while they propagate. Therefore they are very uniform in the direction of propagation (up to hundreds of micrometres) and provide very good conditions for experimental observations of optical binding. At the same time these beams self-reconstruct behind an obstacle or particle and so the light distribution in the beam incoming to the other particle has almost its original form. Therefore the particle interactions based on scattered light are less influenced by the light redistribution in the incident beam due to the passage through other particles.

Results

Bessel beams provide very good conditions for both theoretical, numerical and experimental study of binding. From the comparison of theoretical analysis with numerical model based on CDM we can explain behaviour of particles optically bound in contra—propagating non–interfering Bessel beams. We discovered two main phenomenons connected with binding in Bessel beams named as waves and wavelets of forces. Origin of both is the interference of incident fields with scattered field which in the case of the Bessel beams propagate with different phase velocity. Using our numerical model we found locations of optically bound beads in Bessel beams.

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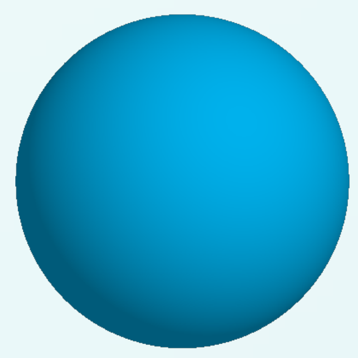
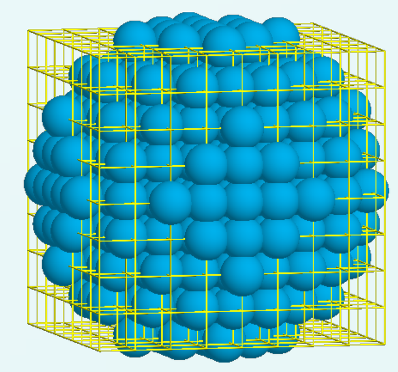
Coupled Dipole Method



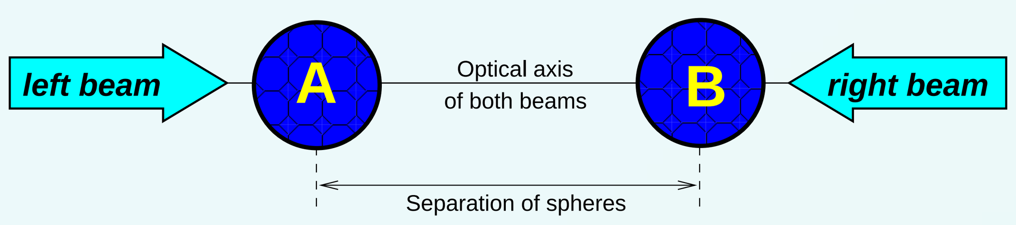
For sizes of particles comparable with wavelength scattering on such objects is computationally difficult.



The CDM divides the object into sufficiently small parts which can treated as dipoles.

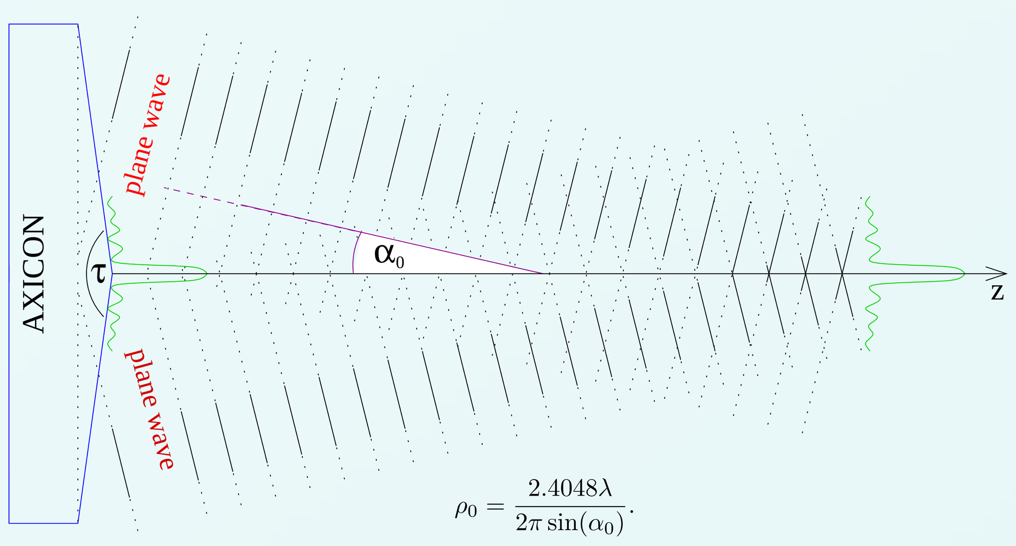
We used for computation of scattering on many objects coupled dipole method (CDM) to numerically study this phenomenon for two and more objects arbitrarily placed. The CDM is for such application very useful tool because the object is assembled from many induced dipoles and so we are not restricted to any preferred geometry and number of objects and their positions. The interaction between each pair of the objects' dipoles is considered and so the inter-particle interactions are wholly embedded in the model. Two and more objects arbitrarily placed in the space can be easily treated.The CDM computes distribution of dipole polarisations in the objects and the total field composed from incident and scattered. From this quantities the forces acting on all dipoles and objects are computed. We calculate how these forces depend on the positions of objects and on other parameters.

The setup for binding



In this setup two counter-propagating Bessel beams do not interfere. On their common optical axis are located two polystyrene beads of size comparable with wavelength. We vary their separation and calculate the total forces acting on them by method based on CDM. We get the distribution of dipole polarisations inside the beads and forces acting on individual dipoles.

Description of Bessel beams

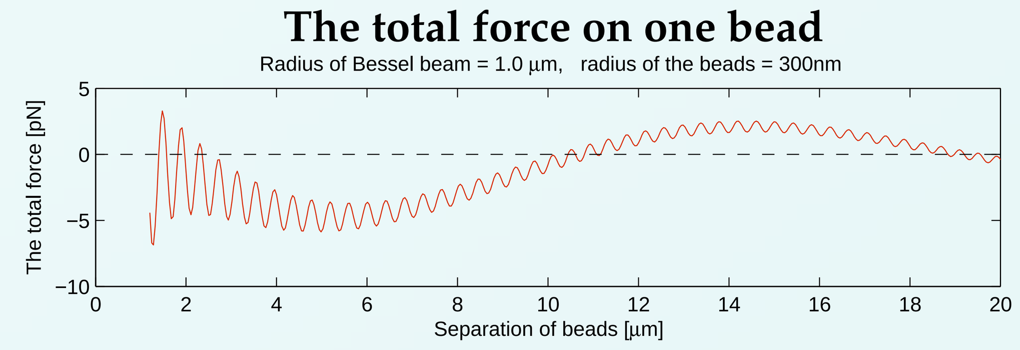


$$\rho_0 = \frac{2.4048\lambda}{2\pi \sin(\alpha_0)}.$$

The easiest way how to obtain Bessel beam is to illuminate axicon by Gaussian beam. The plane waves behind the axicon propagate with the same angle α_0 to the optical axis. This angle determines the size of the core of the Bessel beam as is shown in the above formula. The smaller the core the bigger tilt of plane waves coming from axicon. The propagation of Bessel beams in axial direction is given by wave vector k_z:

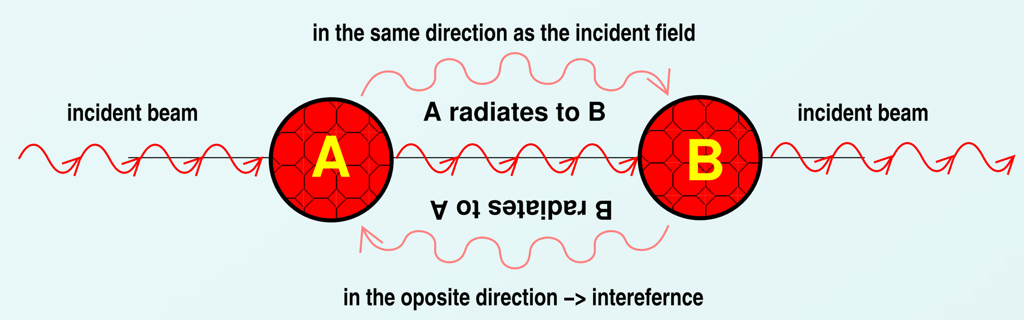
$$k_z = \sqrt{k^2 - \frac{2.4048^2}{\rho_0^2}}.$$

The total force on one bead



The shape of total force acting on one bead shows wavy character. There are apparent little wavelets and also one wave with size of the region. The incident Bessel beams have wavelength 800 nm in water and their core radius is 1 μm. The force was computed by CDM.

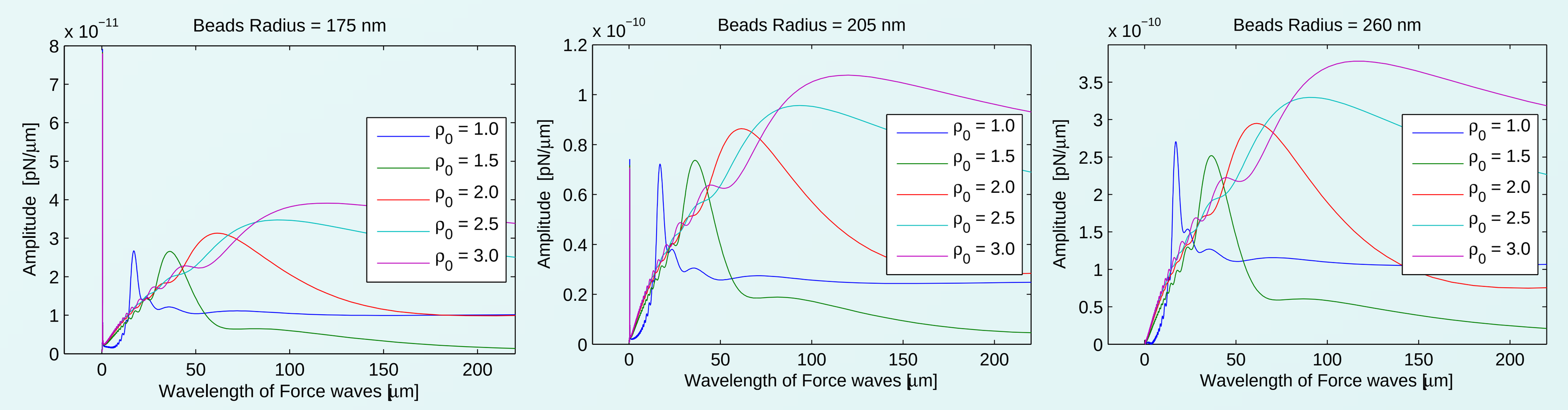
Explanation of wavelets and waves



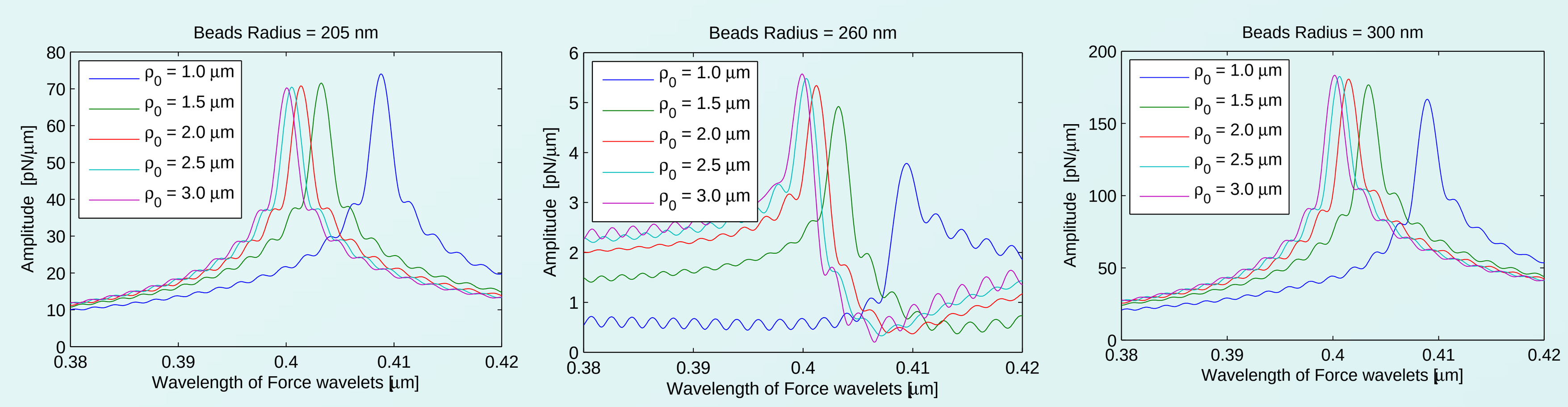
For simplicity we show only one incident beam propagating from the left to the right. Both beads are sources of scattered field but their effect on the other bead depends on the direction of propagation. The radiated field from bead A propagates in the same directions as the incident field. But the radiated field from B to A propagates in the opposite and therefore interferes with incident field. As the scattered field propagates with k the incident and scattered field interfere and give rise to waves and wavelets of resulting forces acting on beads. According to the theoretical model the wavelength of force wavelets is given by sum $k + k_z$ and the wavelength of force waves by difference $k - k_z$. The wavelengths are therefore:

$$\lambda_{\text{wavelets}} = \frac{\lambda\lambda_z}{\lambda_z + \lambda}, \qquad \lambda_{\text{waves}} = \frac{\lambda\lambda_z}{\lambda_z - \lambda}, \qquad \lambda_z = \lambda\left[1 - \left(\frac{2.4048\lambda}{2\pi\rho_0}\right)^2\right]^{-1/2}.$$

Amplitudes of spatial spectra components of total force



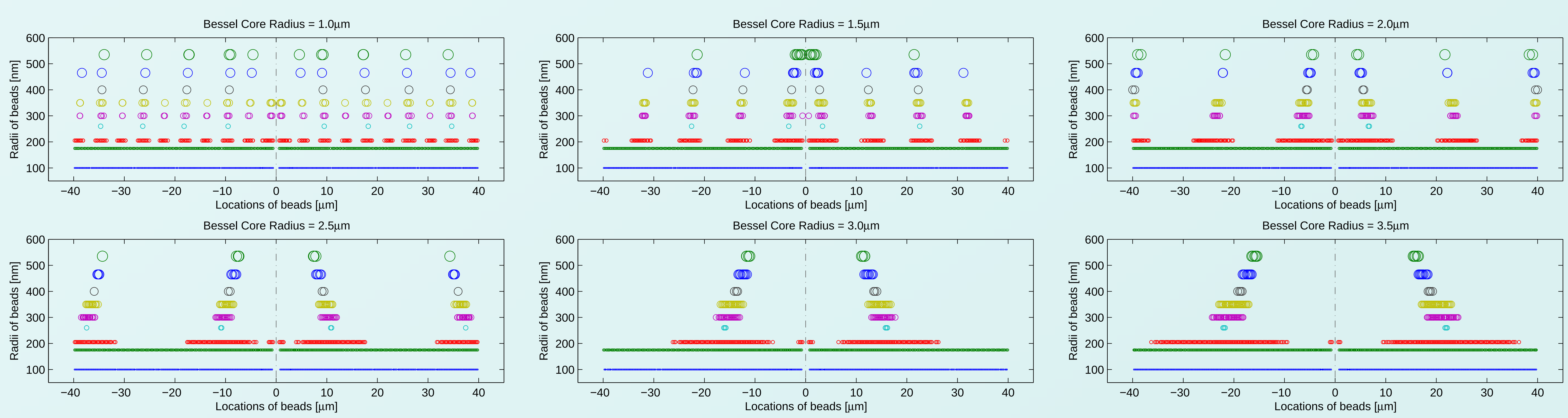
From the CDM-computed dependence of forces on beads' separation we made FFT to get to know the periodicity of forces. The maximal amplitudes correspond to the dominant spectral components of the force. At the above plots is demonstrated the dependence of long-wave spectral components on the core size for several sizes of the beads. The positions of maximal amplitudes correspond with the shown expression for the wavelength of the force waves. The beads size determines if the long-wave spectral components are dominant over the short-wave (wavelets). The wavelets prevail for smaller beads sizes.



Detailed view in the short-wave region shows shift of the maximal amplitudes in accordance to the expression for the wavelength of the wavelets. The beads size modifies the shape of the spectra. The distortion from symmetry in case of radius 260 nm corresponds to the disappearance of wavelets.

The maps of locations of optically bound beads

- regions of stable positions are computed by our model based on CDM
- size of the core greatly changes the locations of the beads through wavelength of the force waves
- range of locations is given by force wavelets
- size of the beads determines the dominance of the wavelets or the waves
- very short range of locations for the beads with radii of 260 nm
- beads with radius < 200 nm have very long range of locations given by dominant wavelets



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