Optofluidic Force Induction Scheme for the Characterization of Nanoparticle Ensembles

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Abstract

Momentum transfer from light to matter provides the basic principle of optical tweezers, which have been awarded the Nobel Prize in Physics 2018.[1] Most studies have hitherto employed this principle for trapping and manipulation of single nanoparticles. However, in a microfluidic channel one can also monitor the effect of optical forces exerted on ensembles of dielectric nanoparticles, to acquire knowledge about various nanoparticle parameters, such as size, shape or material distributions.

In this paper we present an optofluidic force induction scheme (OF2i) for real-time, on-line optical characterization of large ensembles of nanoparticles.[2] Our experimental setup builds on precisely controlled fluidics as well as optical elements, in combination with a focused laser beam with orbital angular momentum (OAM). By monitoring the single-particle light scattering and nanoparticle trajectories, we obtain detailed number-based information about the properties of the individually tracked particles.

We analyse the trajectories using a simulation approach based on Maxwell's equations and Mie's theory, in combination with realistic laser fields and fluidic forces.[3] We discuss the basic physical principles underlying the OF2i scheme and demonstrate its applicability using standardized Latex particles with a pre-determined size distribution. Our results prove that OF2i provides a flexible work bench for numerous pharmaceutical and technological applications, as well as medical diagnostics.

Introduction

Here we employ optofluidic forces on ensembles of nanoparticles using a laser tuned at 532 nm with precise micro-fluidic pumps. Both, optical and fluidic components generate forces acting on dielectric nanoparticles as shown in figure (A). Under certain conditions, particles are constrained to a 2D-optical trap and travel along characteristic trajectories.

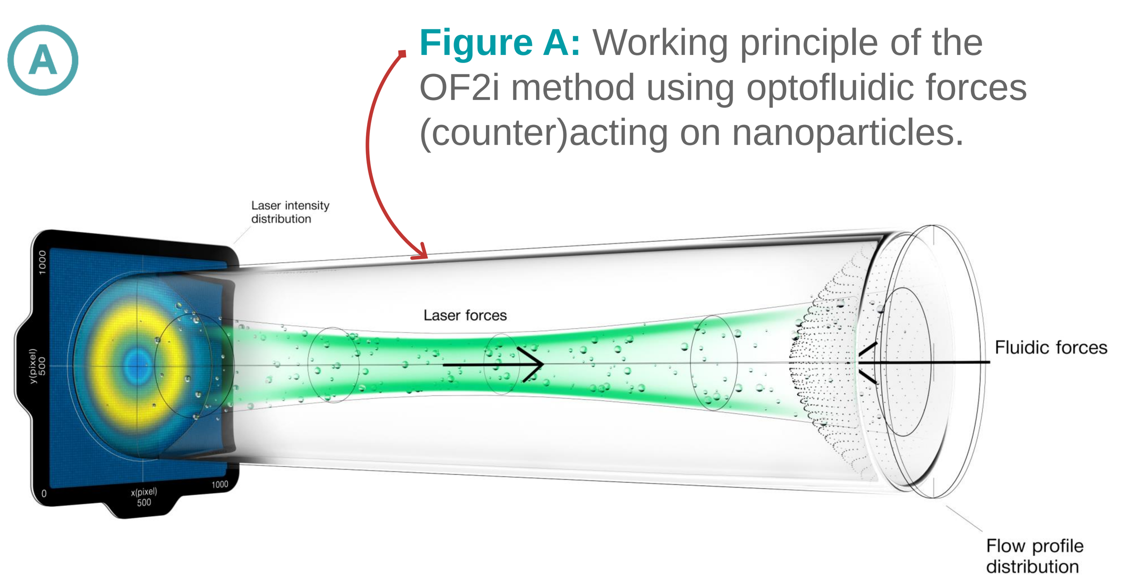


Figure A: Working principle of the OF2i method using optofluidic forces (counter)acting on nanoparticles.

Particle trajectories are processed in real-time by recording single particle light scattering via an ultramicroscope setup and a CCD camera.

Laser Beam Properties

- A higher-order Laguerre-Gaussian (LG) mode enables parallel processing in direction of flow
- by additionally carrying *Orbital Angular Momentum* acting in transverse direction.

Flow Profile

- A laminar and parabolic flow profile is established using microfluidic pumps with pumping rates in the order of µL/min.
- Trapped particles are travelling at the flow profiles maximum velocity in the focal region.

Methods

In order to calculate optical forces, we start by expanding the LG-beam in the basis of the vector wave functions $\mathbf{M}_{jm}^{(\alpha)}$ and $\mathbf{M}_{jm}^{(\alpha)}$. Within Mie's theory electric and magnetic fields for both incoming and scattered fields $\alpha = \{inc, sca\}$, are given by

$$\mathbf{E}_\alpha = \sum_{jm} \left[\alpha_{jm}^{(\alpha)} \mathbf{M}_{jm}^{(\alpha)}(\rho_i, \hat{\mathbf{r}}) + \beta_{jm}^{(\alpha)} \mathbf{N}_{jm}^{(\alpha)}(\rho_i, \hat{\mathbf{r}}) \right]$$

$$\mathbf{H}_\alpha = \frac{n_i}{\mu_i} \sum_{jm} \left[\alpha_{jm}^{(\alpha)} \mathbf{N}_{jm}^{(\alpha)}(\rho_i, \hat{\mathbf{r}}) - \beta_{jm}^{(\alpha)} \mathbf{M}_{jm}^{(\alpha)}(\rho_i, \hat{\mathbf{r}}) \right]$$

, respectively, together with amplitudes $\alpha_{jm}^{(\alpha)}$ and $\beta_{jm}^{(\alpha)}$.

Optical Forces

The time-averaged optical forces are computed using

$$\langle \mathbf{F} \rangle^{opt} = \int_{\partial V} \left\langle \overleftrightarrow{\mathbf{T}}(\mathbf{r}, t) \right\rangle \cdot \mathbf{n}(\mathbf{r}) \, d\mathbf{a},$$

where

$$\overleftrightarrow{\mathbf{T}} = \left[\epsilon_0 \epsilon \mathbf{E}\mathbf{E} - \mu_0 \mu \mathbf{H}\mathbf{H} - \frac{1}{2} \left(\epsilon_0 \epsilon E^2 + \mu_0 \mu H^2 \right) \overleftrightarrow{\mathbf{I}} \right]$$

is the Maxwell's Stress Tensor (MST). The integration is performed using a Gauss-Legendre quadrature for spherical particles with ϵ and μ being material constants. A general scheme is depicted in figure (B) (1).

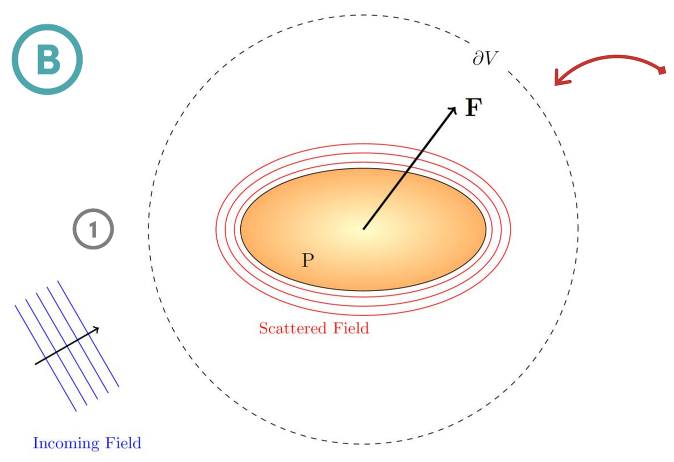
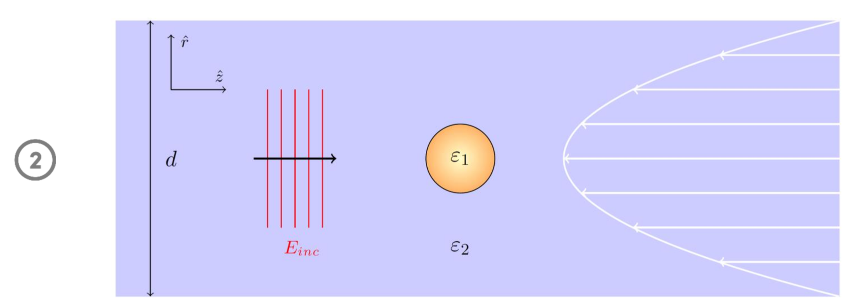


Figure B: (1) General calculation of optical forces using the MST.

(2) Acting forces on a dielectric particle in a cylindrical capillary of diameter d.



Simulation

We now combine optical forces and fluidic forces as depicted in figure (B) (2) which are given by Stokes's equation and solve the particle's equation of motion

$$\dot{r} = \frac{F^{opt} + F_z^{drag}}{\Gamma_T}, \quad \Gamma_T \ \ldots \ \text{Drag Tensor},$$

using the Runge-Kutta method.

Simulation Steps

1. Calculate optical forces at many (x,y,z) positions within the capillary for various particle sizes and materials
2. Calculate fluidic drag force for each particle size assuming spherical particles and (counter wise) flows of various speeds.
3. Generation of Lookup tables for faster computation.
4. Solving the equation of motion for each particle within the capillary.

Results

The simulated trajectories and velocities for standardized Latex particles are depicted in figure (C).

1. Particles start on a regular grid in the far-field region of the laser beam.
2. Trapped particles are directed into the focal region where they reach the maximum velocity.
3. Non-trapped particles move with the fluids velocity.
4. Experimental velocity histogram overlayed with theoretical single particle velocities.

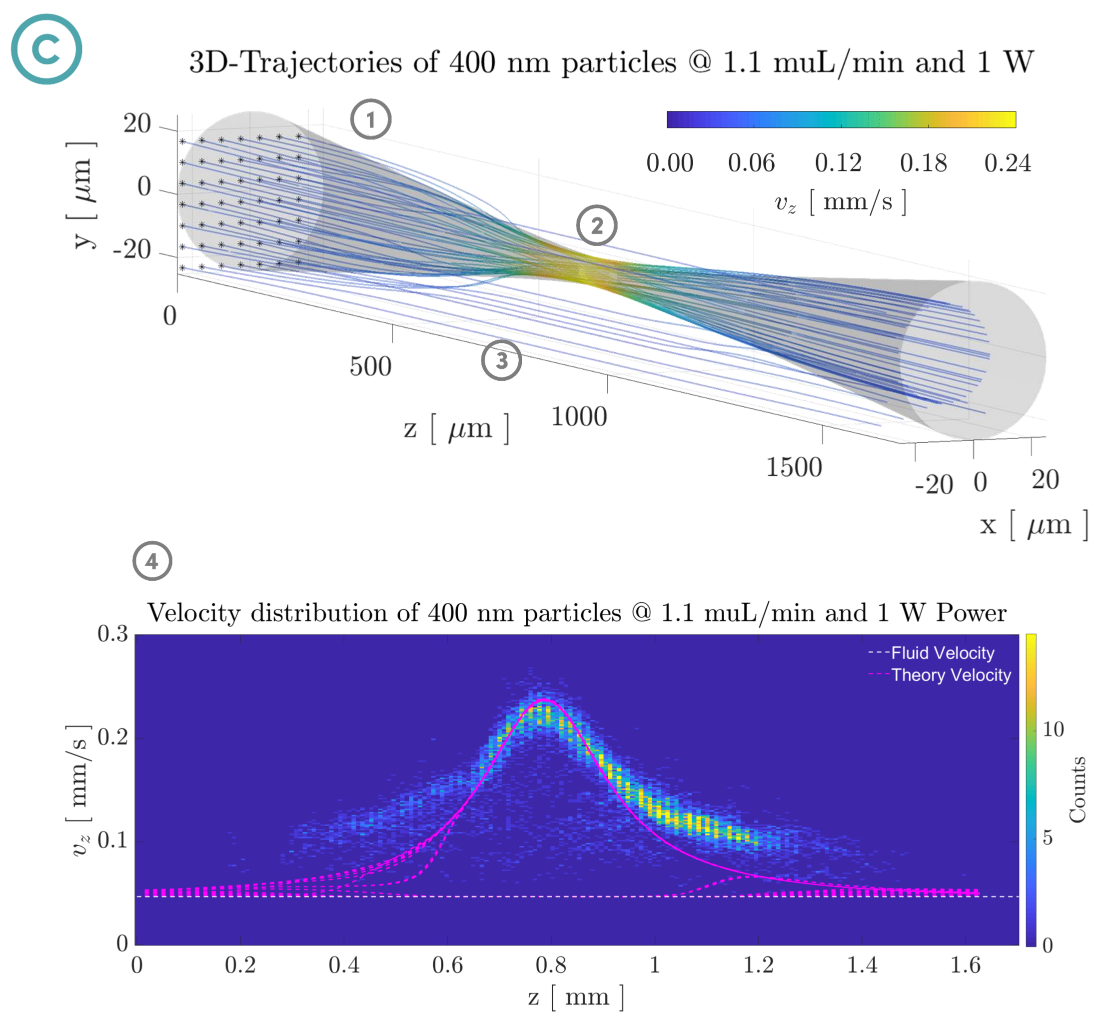


Figure C: (1) - (3) Simulated trajectories of standardized Latex-particles with diameters of 400 nm where optical and fluidic forces act in the same direction. (4) Theoretical calculations and experimental data (histogram) of single particle trajectories.

Discussion

The OF2i scheme is presented with its underlying physical principles together with a theoretical description based on Mie's theory and higher order Laguerre-Gaussian modes.
Our results show very good agreement between experimental and theoretical data on the example of 400 nm standardized Latex particles. Furthermore, we prove the working principle of OF2i and demonstrate its applicability to various nanoparticles.

Acknowledgments

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