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. 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.

Here, we present an optofluidic force induction scheme (OF2i) for real-time, on-line optical characterization of nanoparticles. Our experimental setup builds on precisely controlled fluidics as well as optical elements, in combination with a focused laser beam with orbital angular momentum. By monitoring the single particle light scattering and trajectories in presence of optical and fluidic forces, we obtain detailed information about the properties of the individually tracked particles.

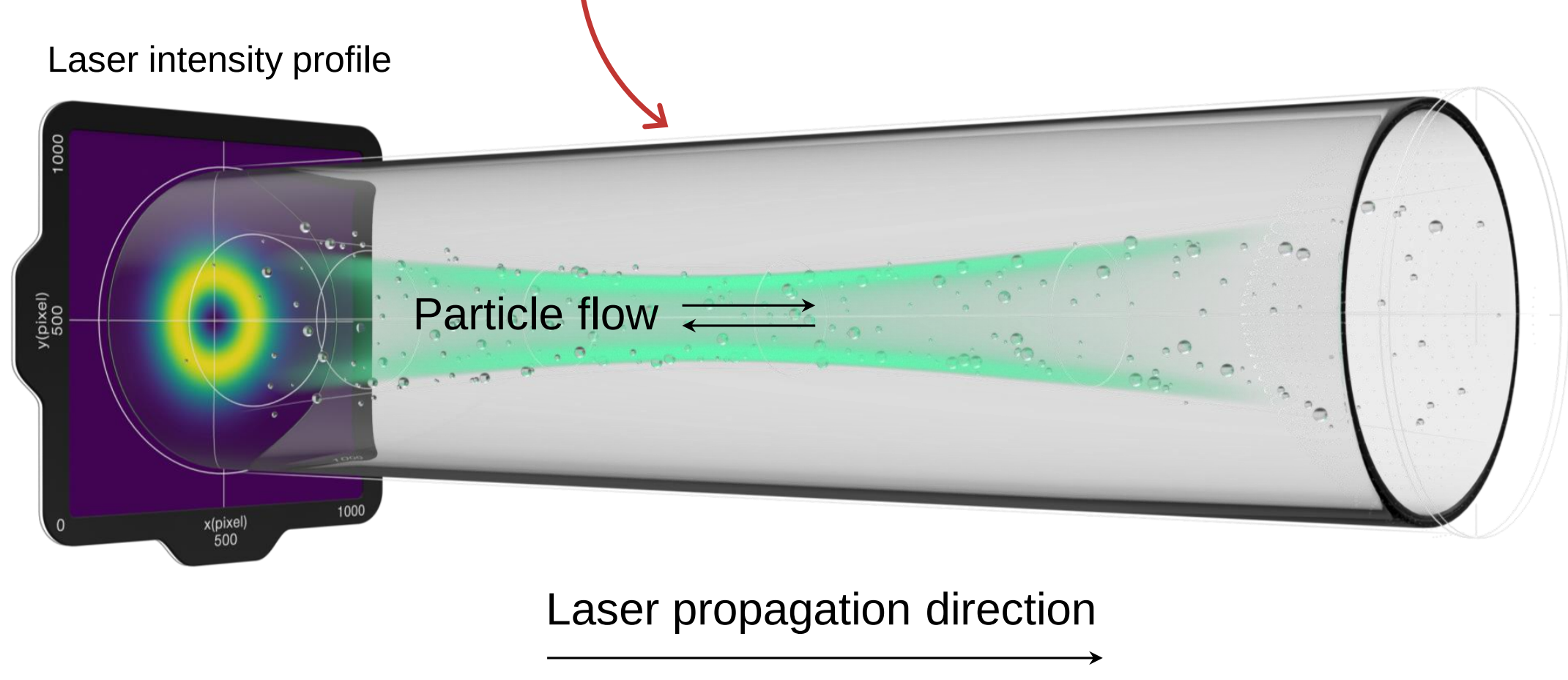
We analyse the trajectories using a detailed simulation approach based on Maxwell's equations and Mie's theory, in combination with laser fields and fluidic forces. We discuss the basic physical principles underlying the OF2i scheme and demonstrate its applicability. Our results prove that OF2i provides a flexible work bench for numerous applications.

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 Ⓐ and Ⓑ.

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

Ⓐ



Under certain conditions, particles are constrained to a 2D-optical trap and travel along characteristic trajectories, see figure Ⓑ.

Ⓑ

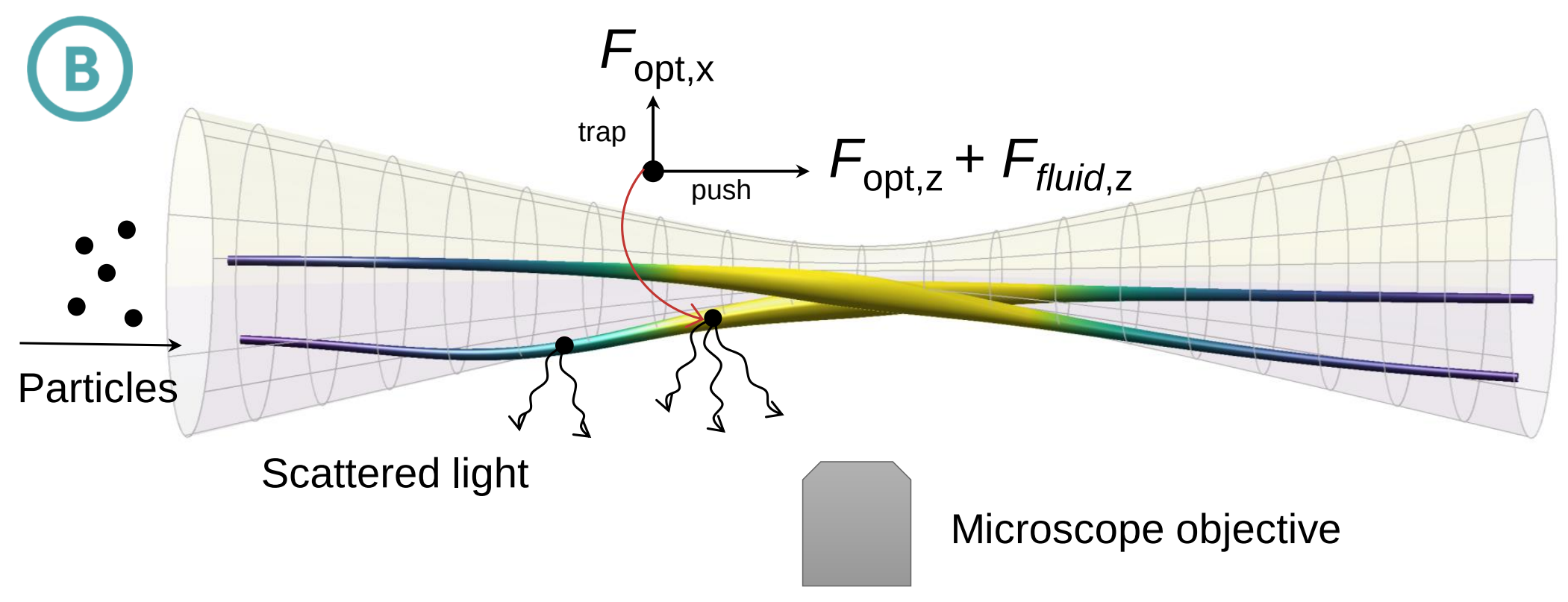


Figure B: Simulated trajectories of two nanoparticles due to optical and fluidic forces. The scattered light is recorded using a CMOS camera.

Single-particle trajectories shown in Ⓒ are processed in real-time by recording single particle light scattering via an ultramicroscope setup and a CMOS camera.

Ⓒ

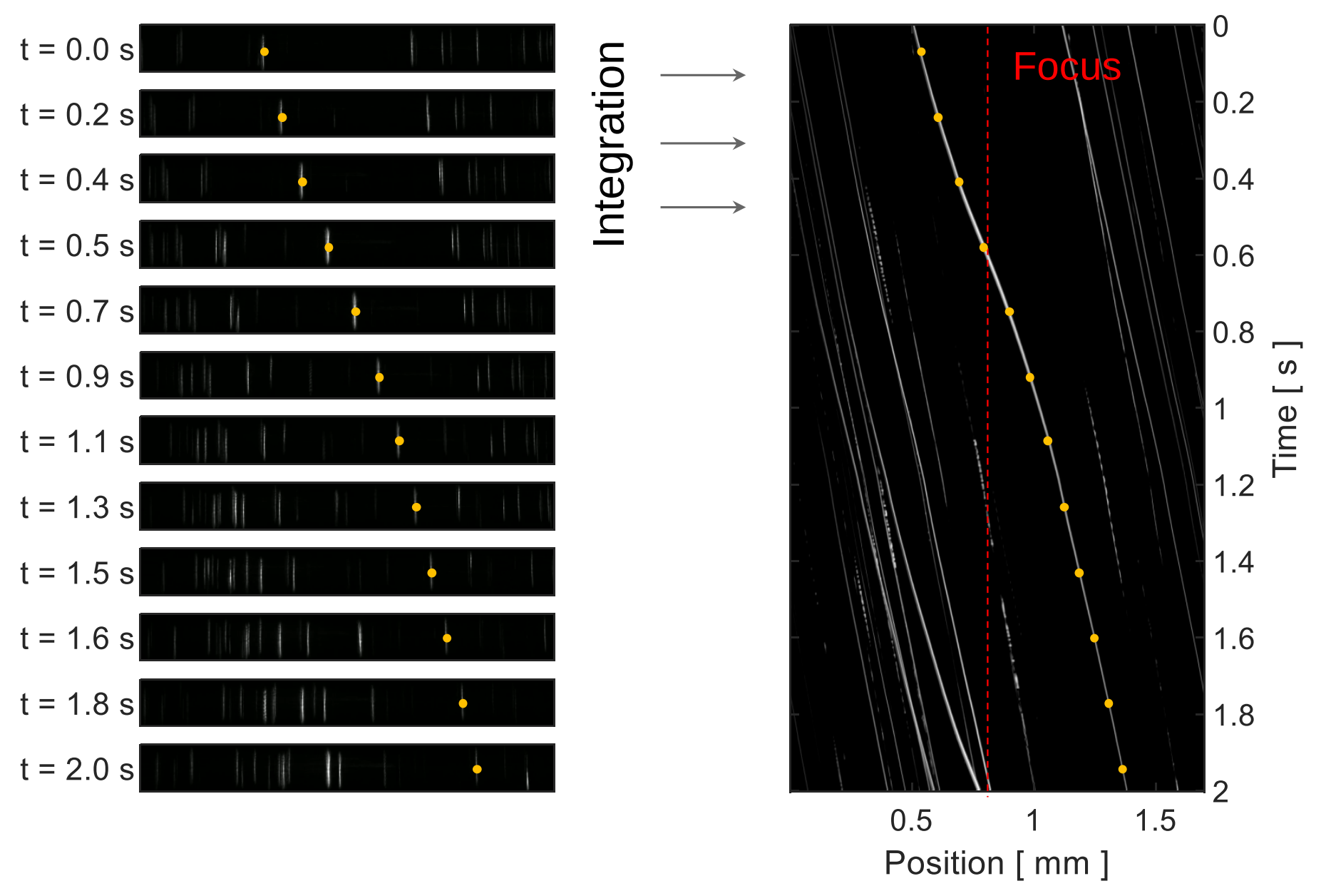


Figure C: Selected frames of raw data (left). Integration over transversal direction results in a waterfall diagram (right).

Methods

In order to simulate particle motion within our capillary, we perform a multipole expansion of the incoming fields $\mathbf{E}_{inc}, \mathbf{H}_{inc}$ and solve for the scattered fields $\mathbf{E}_{sca}, \mathbf{H}_{sca}$ employing Mie's theory for Laguerre-Gaussian beams.

The time-averaged optical forces are computed by

$$\langle \mathbf{F}_{\text{opt}}(\mathbf{r}) \rangle = \int_{\partial V} \left\langle \overset{\leftrightarrow}{\mathbf{T}}(\mathbf{r}, t) \right\rangle \cdot \mathbf{n}(\mathbf{r}) \; da,$$

where

$$\overset{\leftrightarrow}{\mathbf{T}} = \left[\varepsilon_0 \varepsilon \mathbf{E}\mathbf{E} - \mu_0 \mu \mathbf{H}\mathbf{H} - \frac{1}{2} \left(\varepsilon_0 \varepsilon E^2 + \mu_0 \mu H^2 \right) \overset{\leftrightarrow}{\mathbf{I}} \right]$$

is Maxwell's Stress Tensor. The integration is performed using the total fields $\mathbf{E}, \mathbf{H}$ and a Gauss-Legendre quadrature for spherical particles with ε and μ being material constants.

Simulations

We now combine Newton's equation of motion with Stokes' drag and obtain for the particle's velocity

$$\boldsymbol{v}(\boldsymbol{r}) = \boldsymbol{v}_{\text{fluid}} + \frac{\boldsymbol{F}_{\text{opt}}(\boldsymbol{r})}{6\pi\eta R},$$

at any position within the capillary. Integrating particle velocity, we obtain the corresponding trajectory using a Runge-Kutta scheme. Figure Ⓓ shows selected trajectories for 200 nm, 400 nm, 600 nm and 900 nm using above's model.

Ⓓ

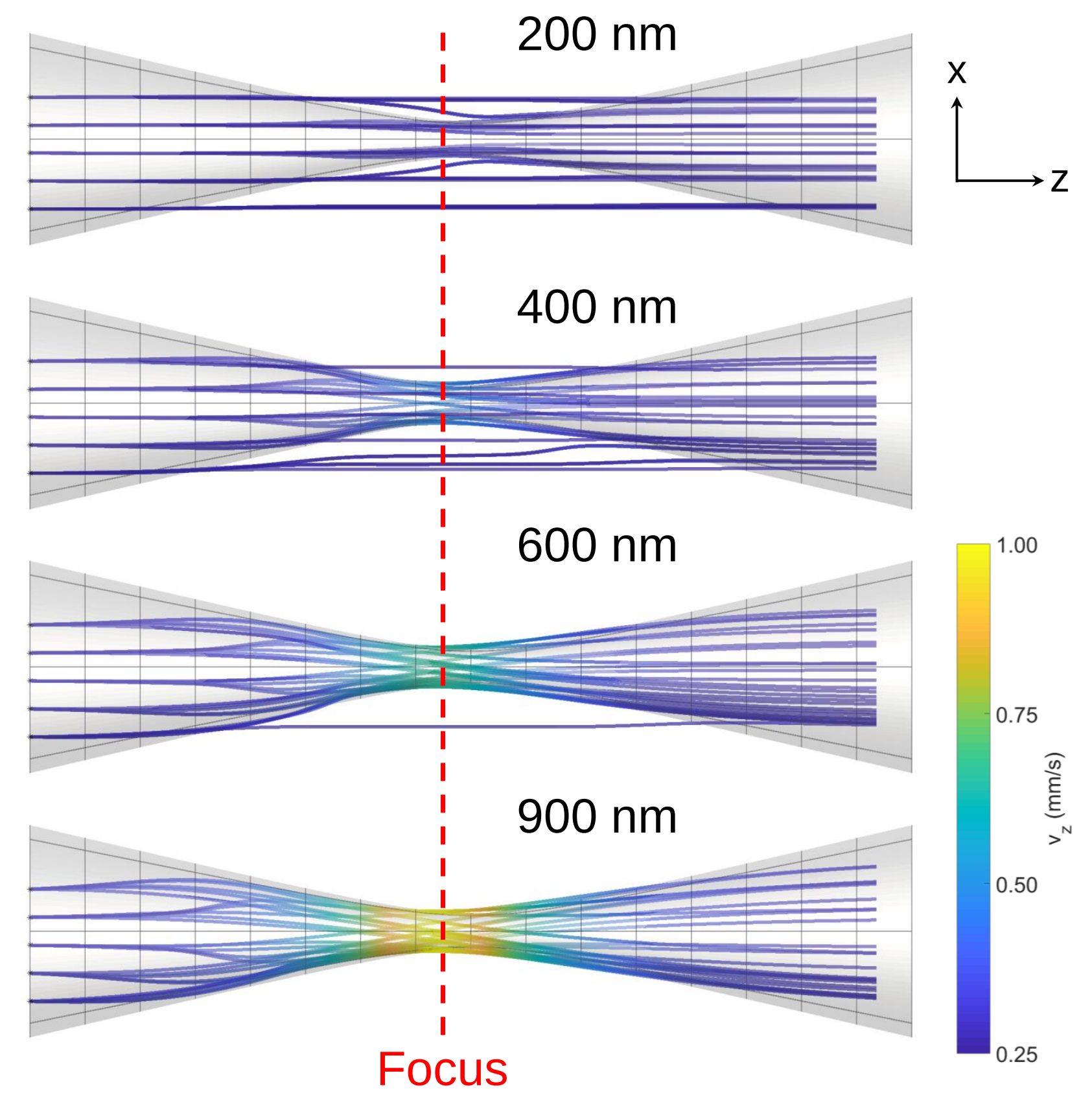


Figure D: Selected trajectories for different nanoparticle sizes. Bigger particles become more easily trapped in transverse direction. Approaching the focal region, the particles velocity increases. The velocity differs in the focal region depending on particle size.

Results

The experimental data for 400 nm Standard-Latex particles is compared to simulated velocities and depicted in figure Ⓔ ①. The resulting size distributions are shown in figure Ⓔ ② for mono- and polydisperse samples. We compare our results to those of Nanoparticle Tracking Analysis (NTA).

Ⓔ ①

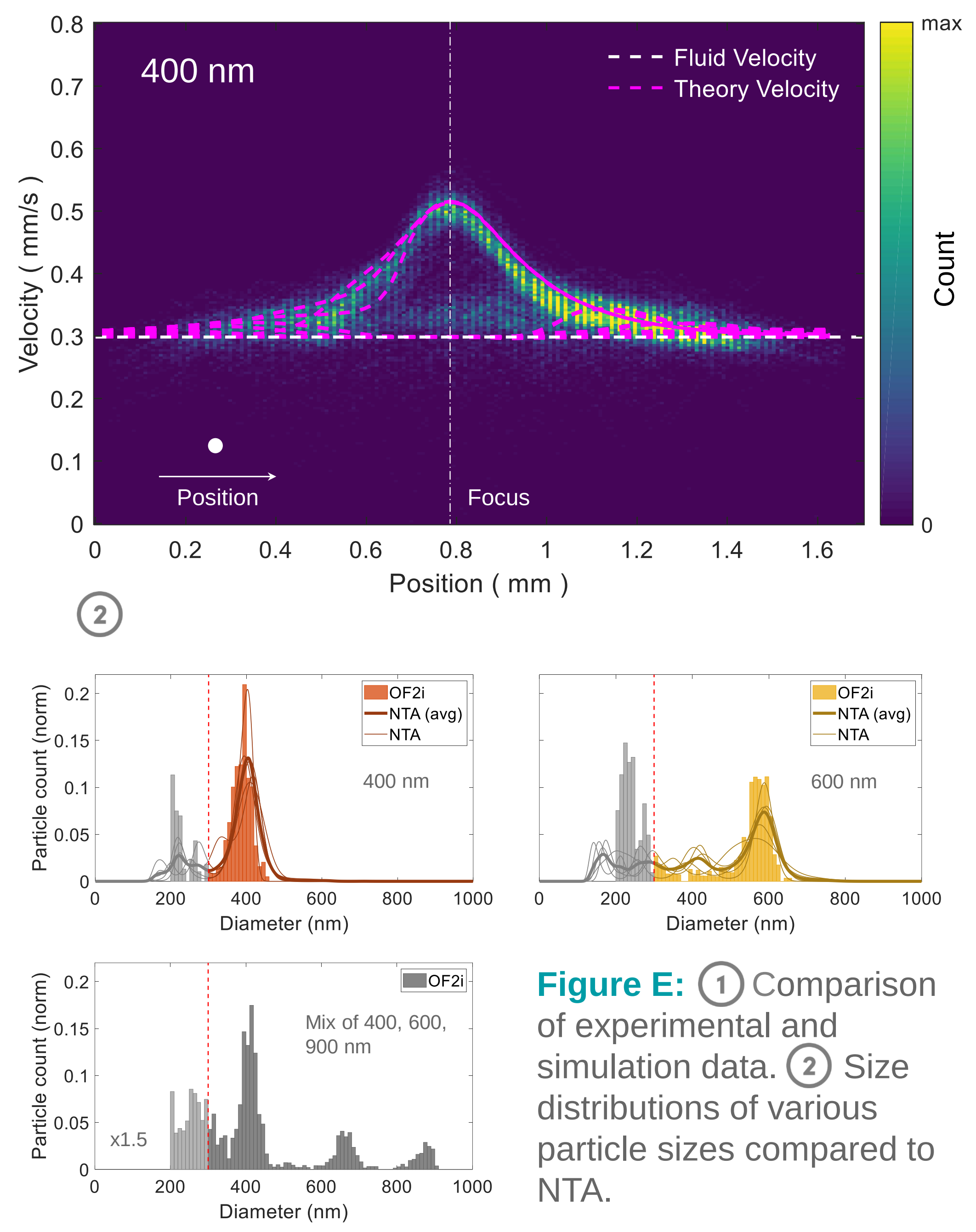


Figure E: ① Comparison of experimental and simulation data. ② Size distributions of various particle sizes compared to NTA.

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 various standardized Latex particles. Furthermore, we prove the working principle of OF2i and demonstrate its applicability to various nanoparticles.

Acknowledgments

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References

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