Trapping particles by optical tweezers

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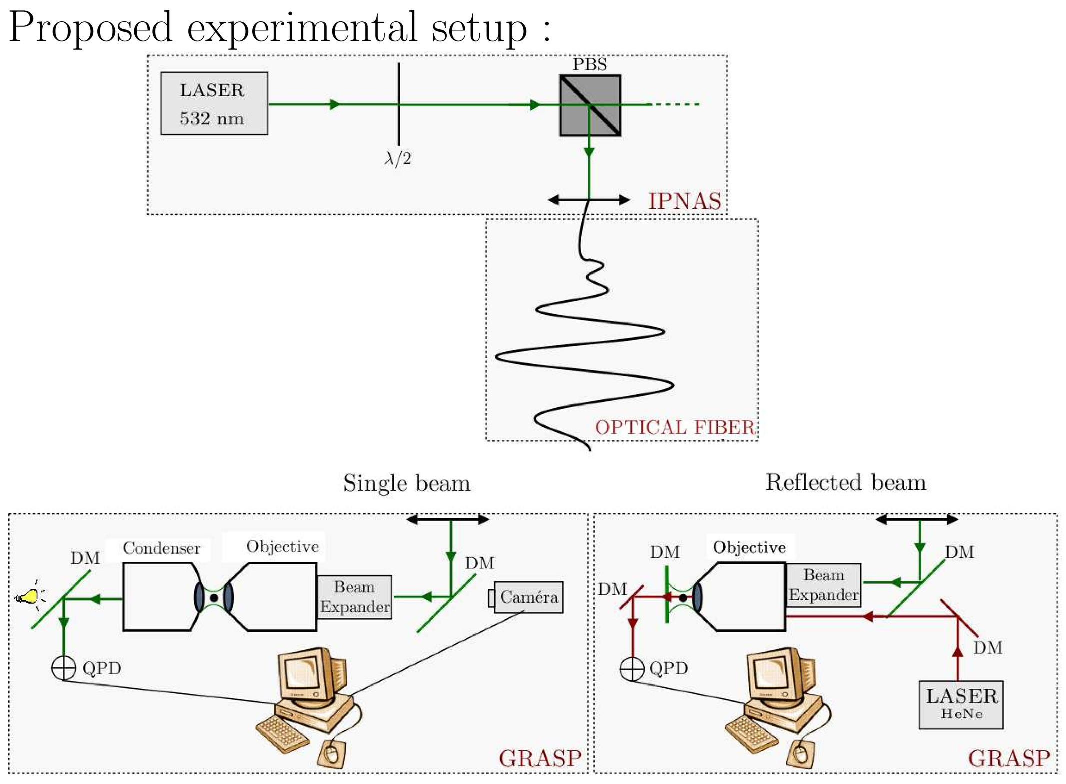
Introduction

The story of optical tweezers started in 1970 in the Bell laboratories with Arthur Ashkin. A highly focused laser beam was used to spatially trap dielectric particles [1].

- Many developments since then. Optical tweezers have been used to trap bacteria (*Escherischia Coli*) and to study the RNA synthesis.
- Nowadays, the scientific community focus their research on
  - laser beams [2],
  - possibilities of conveyor belts [3],
  - non-spherical particles [4].
- Industries have a lot of problems to store cohesive powders because of, for instance, the triboelectric effect. More generally, the force between two powder grains is not well understood.
- **Goal of the study** : To characterize forces between cohesive powders thanks to an optical tweezer setup. This particular technique is very interesting since it could enable us to control each grain of powder individually.
- Depending on the size a of the trapped particles with respect to the wavelength λ of the laser beam, different theories must be used to modelize the trapping force :
  - the Rayleigh regime for small particles ($a/\lambda < 1/20$),
  - the Mie regime for big particles (until $a/\lambda \sim 5000$),
  - the geometrical optic regime for huge particles (not studied here).

Experimental setup

Proposed experimental setup :



- **Laser :** High power (~ 1W), high pointing stability (~ ±50μrad), low power fluctuation (1-2%),
- **Inversed Microscope :** High NA objective, dichroïc mirror to reflect laser beam,
- **Beam Expander :** so as to light the whole surface of the high NA lens.,
- **Trapped particle position detection :** Different possibilities, each with pros and cons :
  - high-speed camera,
  - Quadrant Photo-Diode (QPD).

Trapping forces

The trapping forces in an optical tweezer setup have been modelized in two scattering regimes (Rayleigh and Mie). In both regimes, we used the cartesian coordinates with z the beam propagation axis and x the laser polarization axis. Gaussian laser beams with waist w_0 have been considered.

Rayleigh regime

The Rayleigh regime is very instructive because the theory is solved analytically and we can estimate all the effects of the different parameters. The forces acting on the trapped particles are :

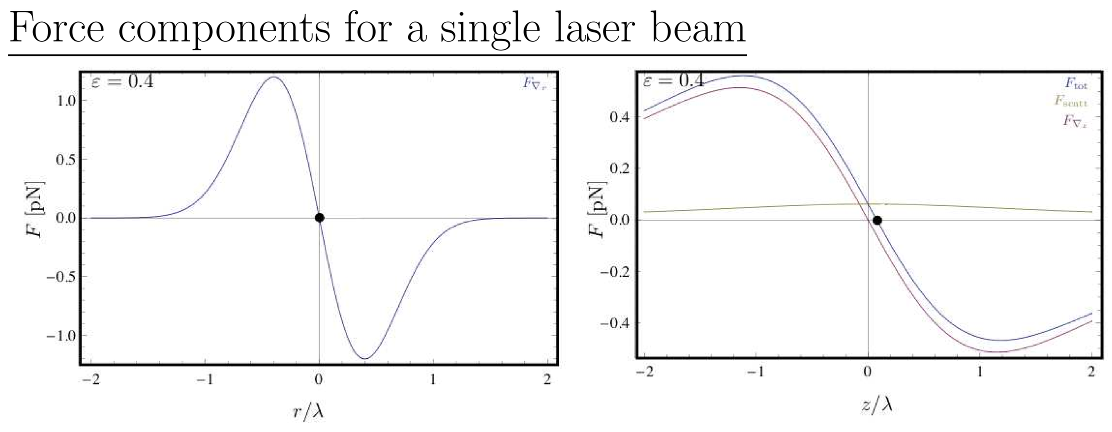
$$\mathbf{F}_{\text{scatt}} = \frac{8\pi}{3c} n_2 (ka)^4 a^2 \left(\frac{m^2-1}{m^2+2}\right)^2 I(r,z) \quad \text{(destabilizing)},$$
$$\mathbf{F}_{\nabla} = \frac{1}{2}\alpha \nabla \langle |E|^2 \rangle_T \quad \text{(stabilizing)},$$

with :

c : speed of light,
k : wavenumber,
a : size of the trapped particle,
n_2 : refractive index in the surrounding medium,
$m = n_1/n_2$ and n_1 refractive index of the particle,
$I(r,z)$: Intensity of the laser beam at (r,z),
α : polarisability of the material.

This system is very odd because the particle creates its own potential by polarisation.

Force components for a single laser beam



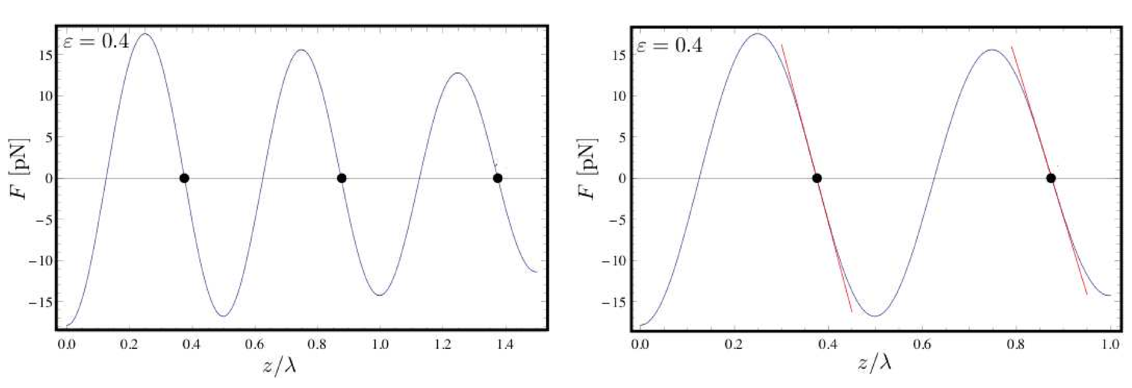
No need to differentiate the x and y direction, no role of polarisation. Moreover we define $\varepsilon = \lambda/\pi w_0$.

z : Competition between the gradient force and the scattering force. To make the trap efficient, the parameters need to follow theses rules :
- I ↗,
- a ↘,
- w_0 ↘.

r : No competition at all, the gradient force is alone and confining the particle.

Force components for two counter-propagating laser beams

Interference created by the reflection of the laser beam on a mirror.



z : The trap efficiency is much greater... Almost 400 times better ! Possibility of an array of traps.

Conclusion : Trapping particles in Rayleigh regime is simple because the scattering force is very weak ($\mathbf{F}_{\text{scatt}} \sim a^6$ and $\mathbf{F}_{\nabla} \sim a^3$). This regime is very useful to understand the physics underlying the phenomenon. The standing wave case is an efficient way to increase the trapping efficiency.

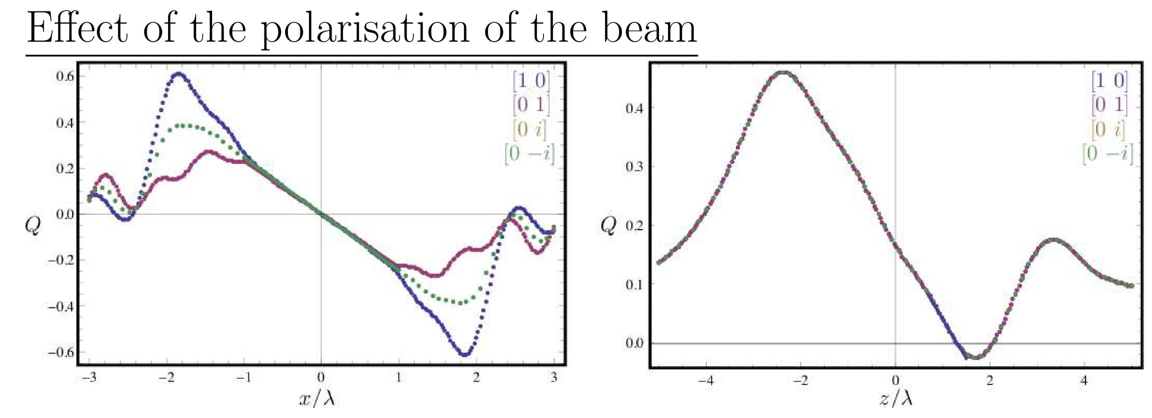
Mie regime

The Mie regime is very complex and needs numerical simulations, but packages already exist [5]. The effect of the polarisation, the waist size and the size of the particles have been studied. We define Q such as :

$$Q = \frac{n_2 P}{c}$$

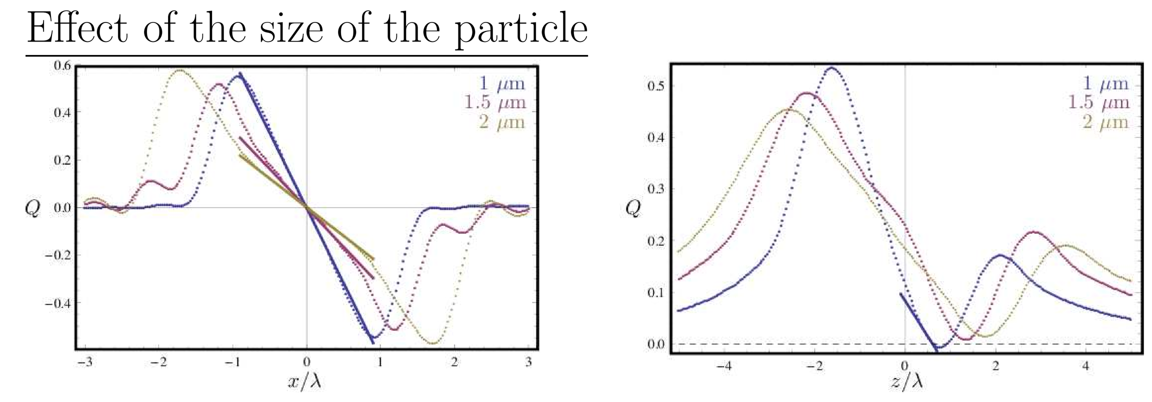
where P is the power of the laser beam.

Effect of the polarisation of the beam



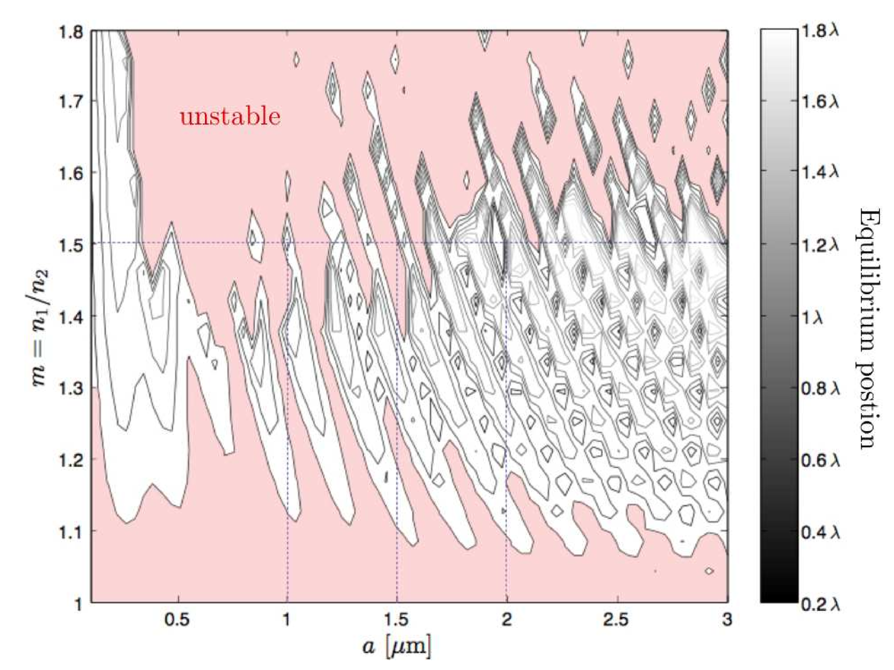
x : Small differences : ${}^{\text{lin}}\kappa_x \approx 770$ pN/μm and ${}^{\text{circ}}\kappa_x = 820$ pN/μm.
z : No difference at all : $\kappa_z = 446$ pN/μm.

Effect of the size of the particle



x : If a ↗, the corresponding spring constant decreases.
z : If a ↗, the stability of the trap decreases.

Stability diagram



- Very complex diagram,
- if $m < 1.1$ or $m > 1.8$ generally unstable (different from Rayleigh : $m < 1$),
- stability depends strongly on a, probably maximization of reflexion-refraction inside the particle,
- for $a < 0.5\mu$m we seem to encounter a decomplexification of the diagram, we recover the Rayleigh regime.

Conclusion : Trapping particles in Mie regime is more complex because the scattering force can be dominant compared to the gradient force. The stability diagram is required to predict whether a given particle can be trapped or not.

Conclusions

– We have proposed an experimental setup that is able to confirm our theoretical approach,
– We have calculated all orders of magnitude relative to the scattering of particles in the Rayleigh regime and the Mie regime,
– We have shown that it might be possible to experimentally trap cohesive powder grains by use of a tightly focused laser beam,
– The next step is to study the reflection in the case of a Mie scatterer based on [6]. It could greatly enhance the trapping efficiency thanks to a standing wave (the scattering force is nearly suppressed).

References

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