UNIVERSITÉ LAVAL

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COPL
Centre d'optique, photonique et laser

Dynamic deformation of a soft particle in dual-trap optical tweezers

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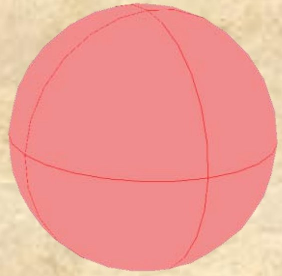
國立陽明大學

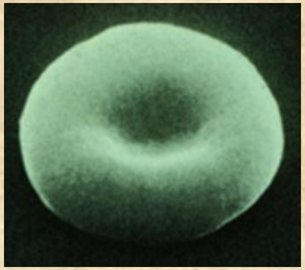
Cell elasticity measurement

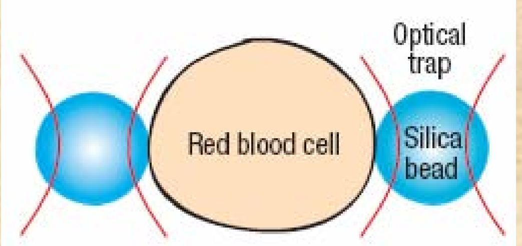
- Suspended cells:

(Micro-Rheology)

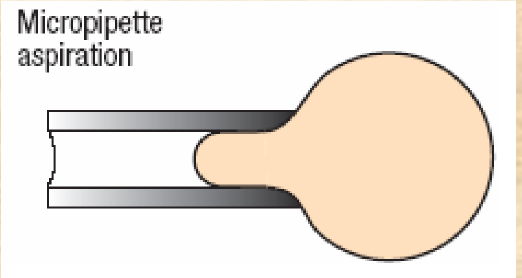
  - Spherical RBC (swollen)
  - Biconcave RBC





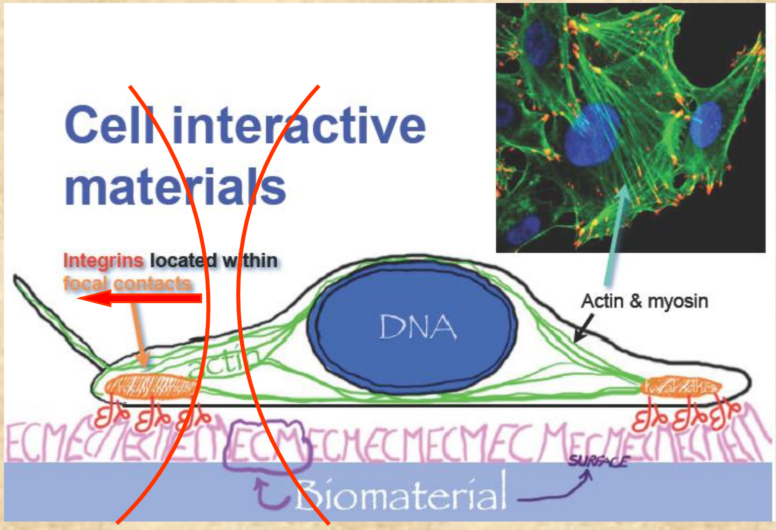


Suresh, 2003



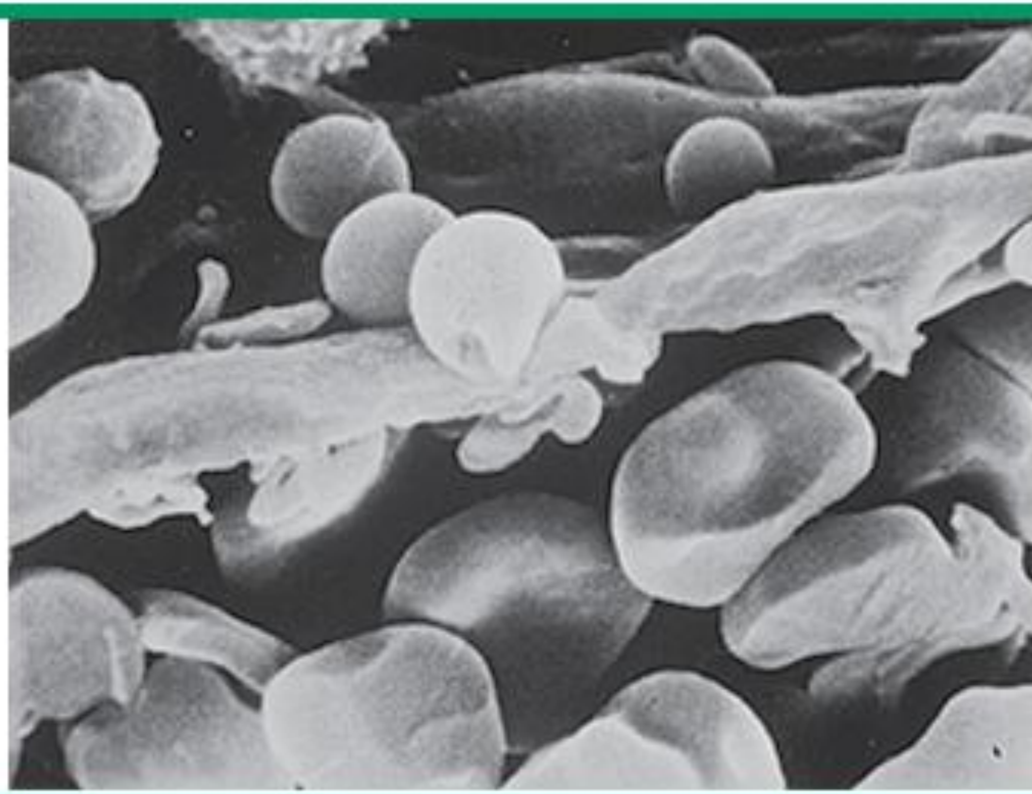
- Adhered cells

(Tensegrity)



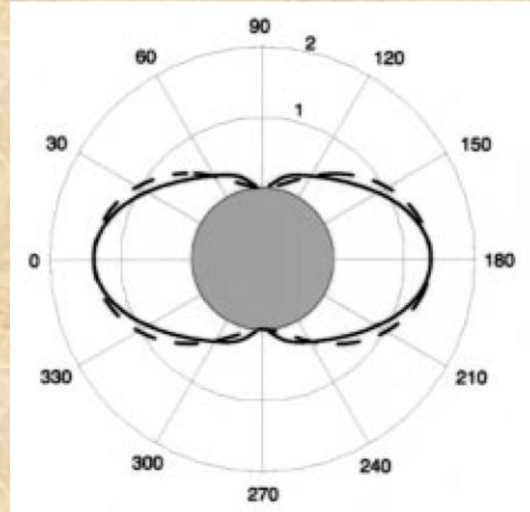
Free RBC squeezed through hole

Red blood cells in the spleen

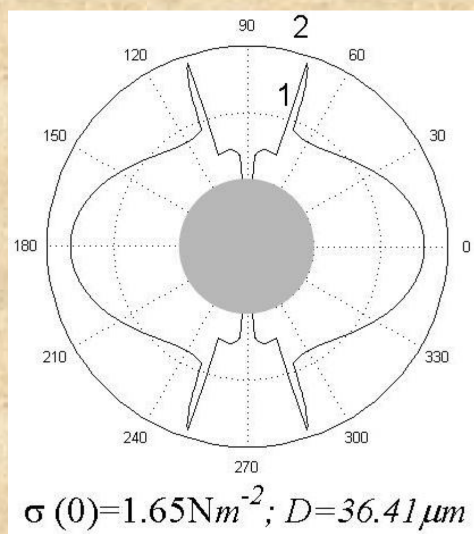


Scanning electron microphotograph of normal murine red blood cell passing from a splenic cord (below) through the sinusoidal barrier and into the splenic sinusoid (above). Note the deformation necessary to squeeze through the slit in the sinusoidal wall and how a surface area depleted spherocyte would be incapable of transversing the barrier. *Courtesy of Mohandas Narla, ScD.*

Optical fiber dual counter-propagating beam stretcher



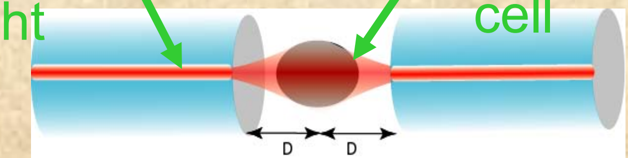
Guck, Biophys. J. 2001

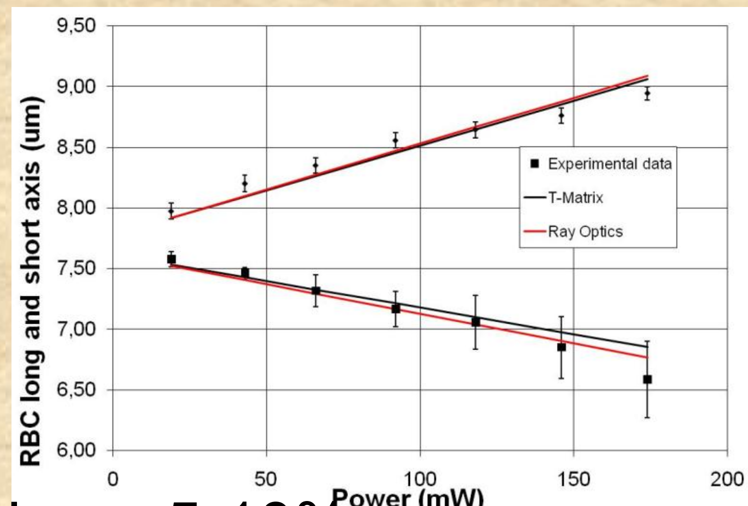


Bareil, et al Opt. Express **14,** 12503 (2006).

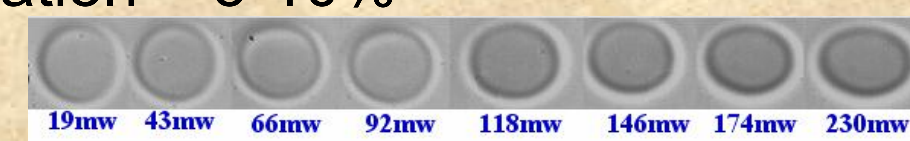
Laser Light

Trapped stretched cell

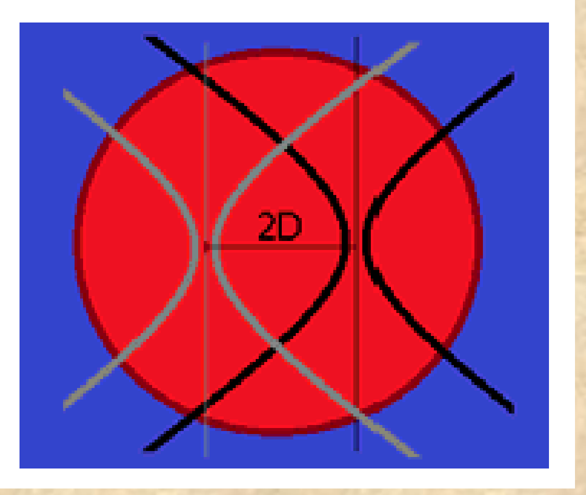




Deformation < 5-10%

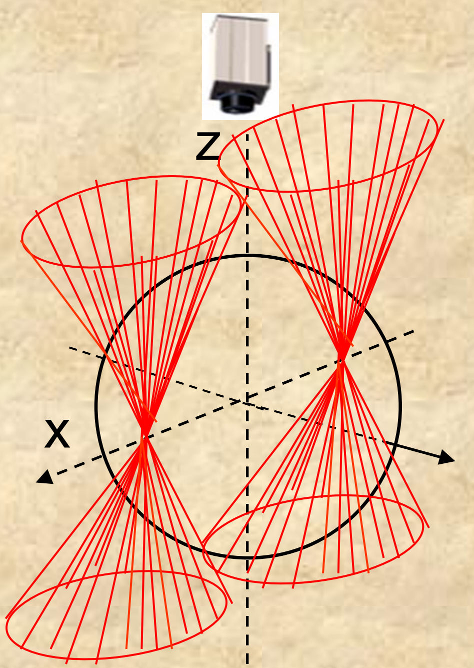


Outline

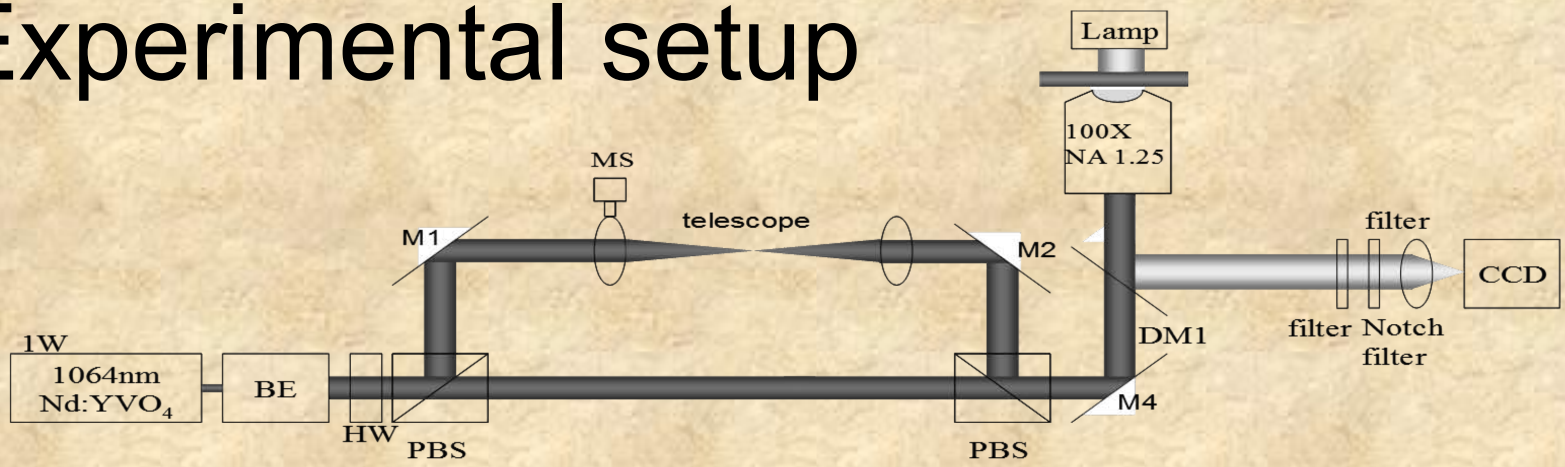


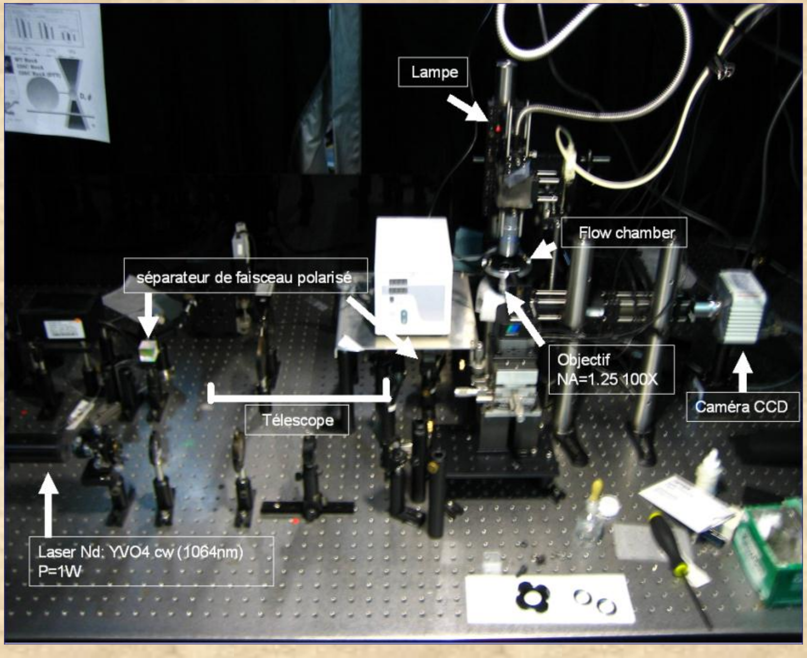
- Dual-trap tweezers experiments
- 3D stress distributions
  - Geometric Optics, Matlab
  - Generalized Mie Scattering theory
  - Comsol RF module, FDTD,
- 3D static deformation, Deformation 5-10%
  - analytical solution,
  - Comsol structural mechanics
- 3D Dynamic deformation
  - Comsol Multiphysics
- Fitting

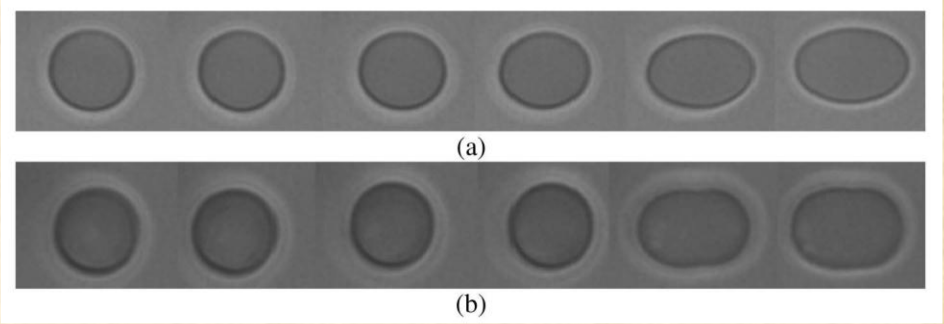
Deformation 20 %



Experimental setup



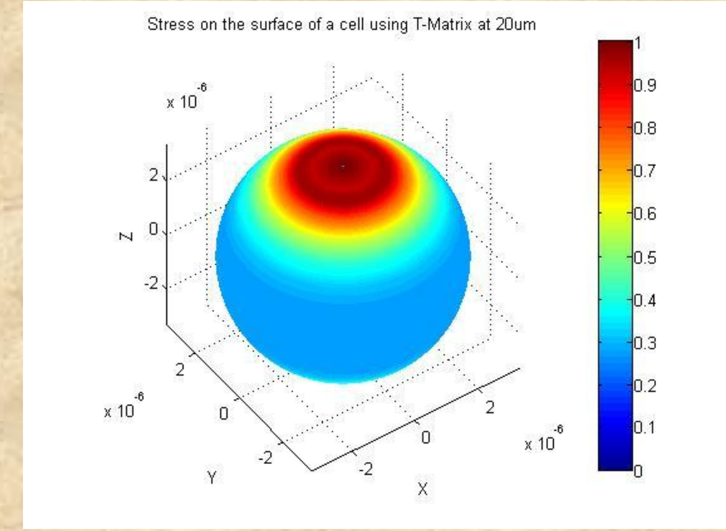




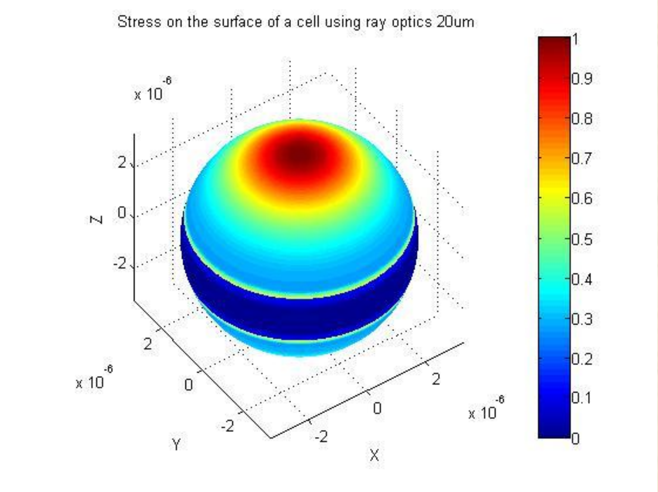
- Two laser beams with a controlled separation between their optical axes
- (a) Normal RBC; (b) RBC immersed in solution de 1mM de N-ethylmaleimide (NEM) solution for 30 minutes

3D stress distribution

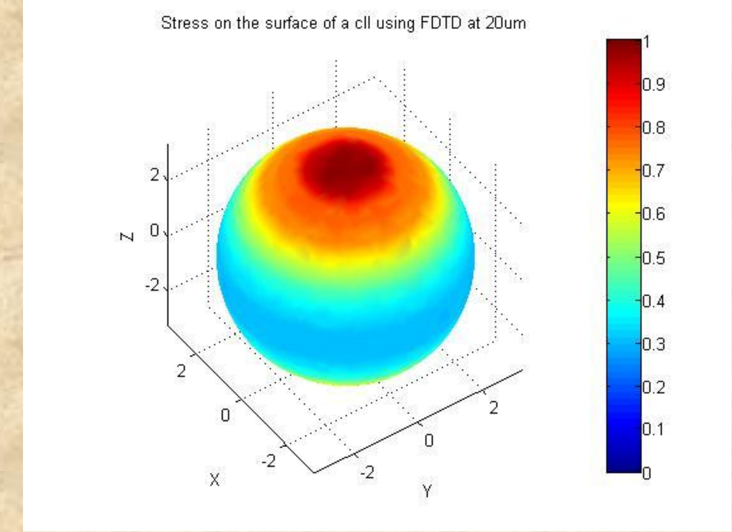
Single beam centered



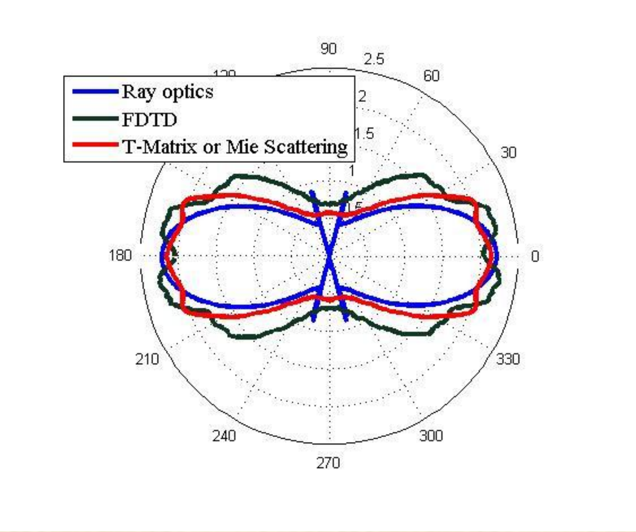
T-Matrix, Point Matching Method



Ray Tracing



FDTD



NA=0.16
Dual Beams
D=20um

3D stress, Dual-beam tweezers

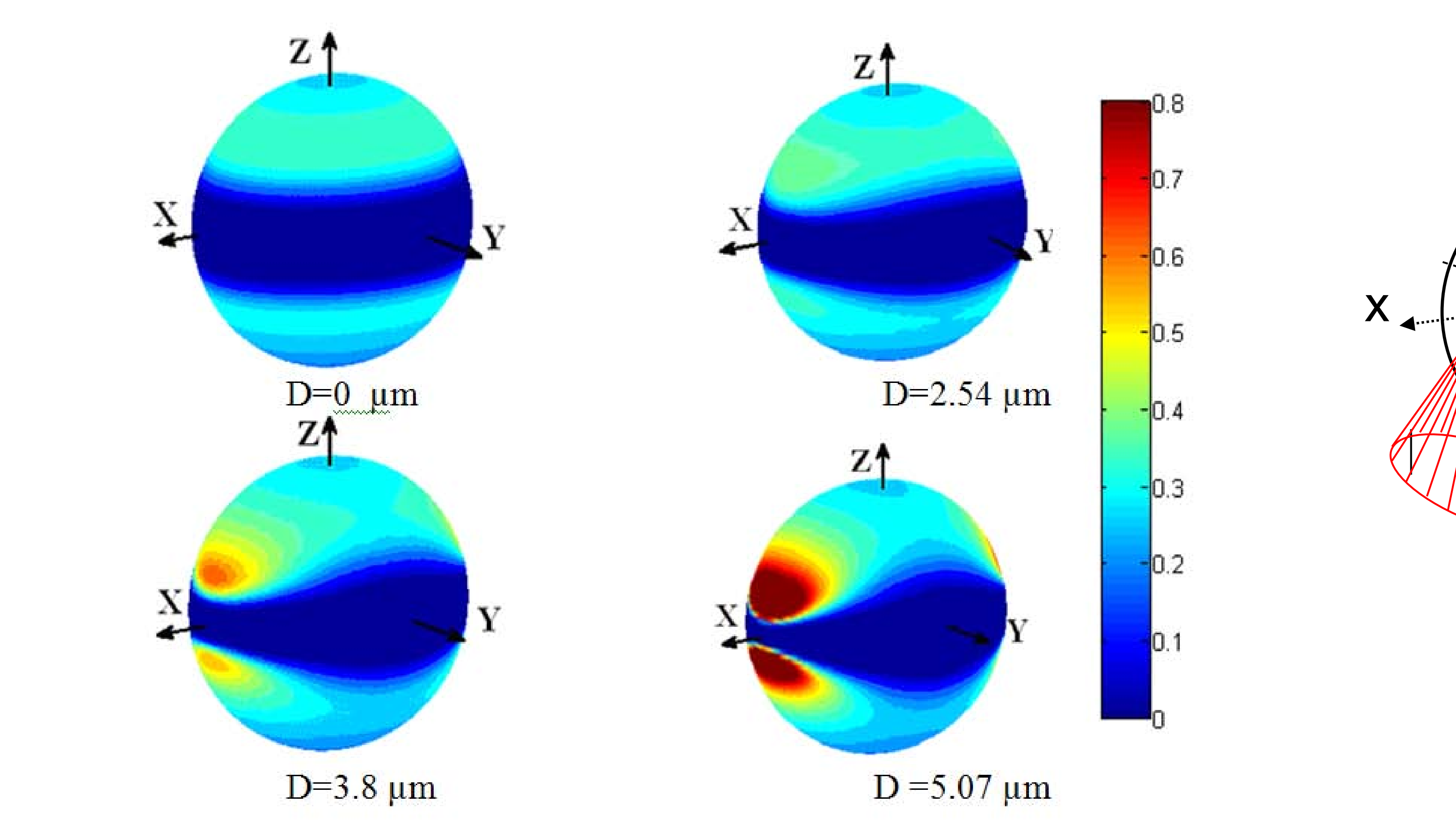
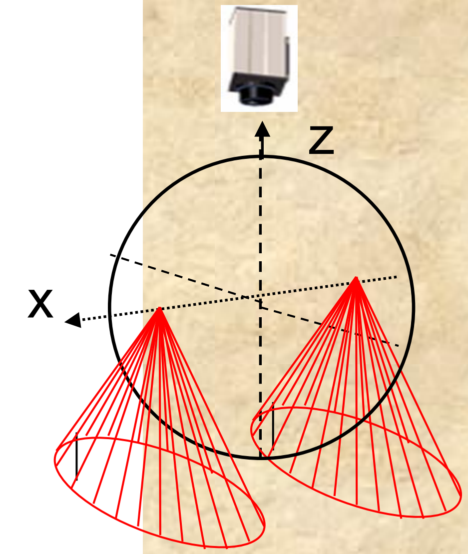
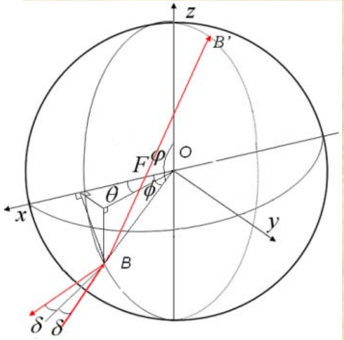


Fig. 4. 3D distribution of radiation stress on a spherical surface, as a function of the separation *D* between two trapping beams in the dual-beam optical tweezers. The maximum stress is 0,8 N/m²





Geometrical approach

Multi-Physics Solutions

- 3D field distribution
  - Geometric optics ray tracing
  - FDTD
  - Generalized Mie-scattering
  - T-Matrix
  - Comsol RF module

  - Approximate
  - Modeling high NA Gaussian beam
  - More accurate
  - Modeling high NA beam

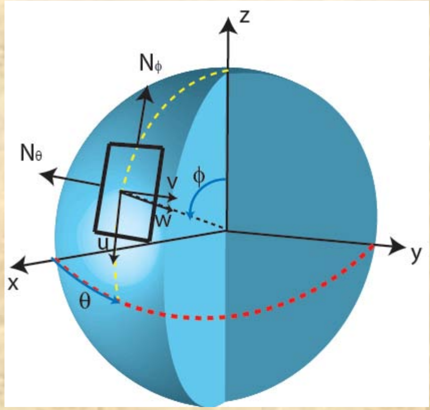
Static deformation of membrane

- Compute to membrane internal stress for a spherical RBC

$$\frac{\partial N_\theta}{\partial \theta} + \sin(\varphi)\frac{\partial N}{\partial \varphi} + 2N\cos(\varphi) + R\sin(\varphi)\sigma_\theta = 0$$

$$\frac{\partial N}{\partial \theta} + \sin(\varphi)\frac{\partial N_\varphi}{\partial \varphi} + (N_\varphi - N_\theta)\cos(\varphi) + R\sin(\varphi)\sigma_\varphi = 0$$

$$N_\theta + N_\varphi + R\sigma_R = 0$$



- Compute the strain from the stress by Hook's law

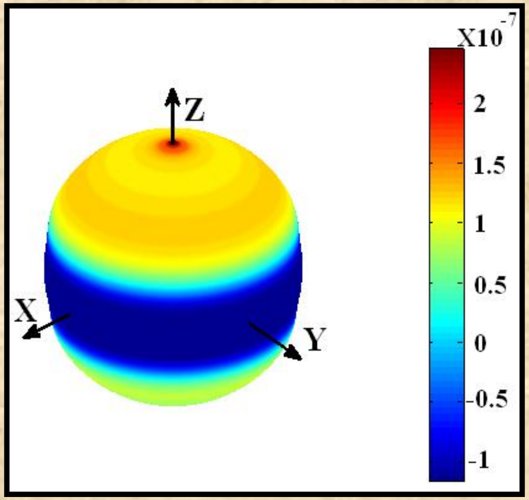
$$N_\varphi = \frac{Eh}{1-\upsilon^2}(\varepsilon_\varphi + \upsilon\varepsilon_\theta) \qquad N_\theta = \frac{Eh}{1-\upsilon^2}(\varepsilon_\theta + \upsilon\varepsilon_\varphi) \qquad N = \frac{Ehw}{2(1+\upsilon)}$$

- Compute the displacements of the membrane from the strains

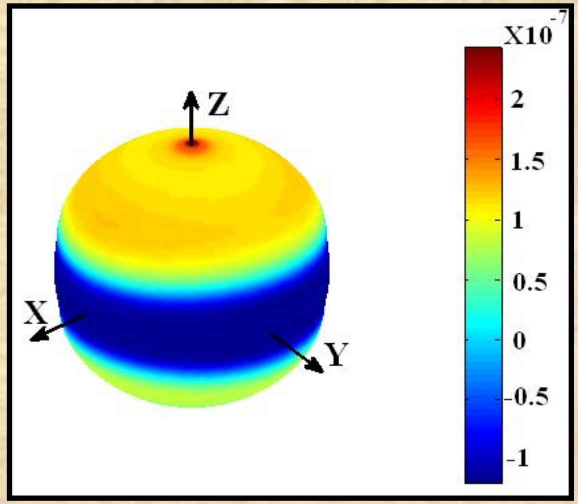
$$\varepsilon_\theta = \frac{1}{R\sin(\varphi)}\frac{\partial u}{\partial \theta} + \frac{1}{R}(v\cot(\varphi) - w) \qquad \varepsilon_\varphi = \frac{1}{R}(\frac{\partial v}{\partial \varphi} - w)$$

$$w = \frac{1}{R\sin(\varphi)}\frac{\partial v}{\partial \theta} + \frac{1}{R}\frac{\partial u}{\partial \varphi} - \frac{u\cot(\varphi)}{R}$$

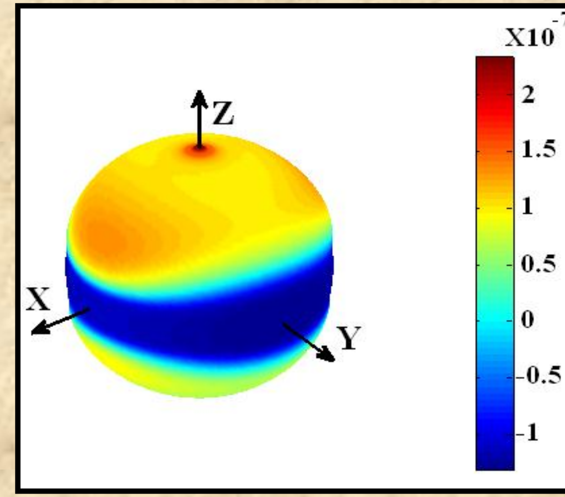
Static deformation analytical solution



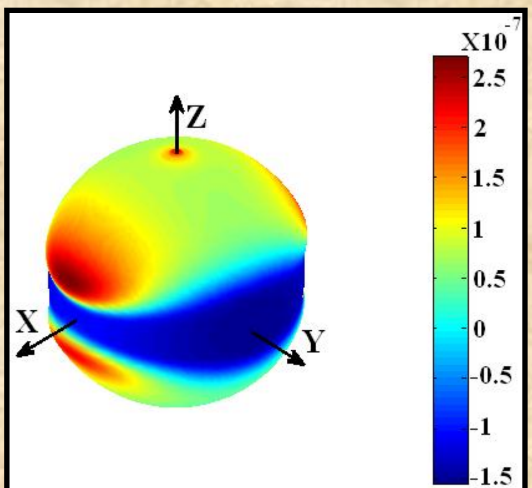
D=0,00μm



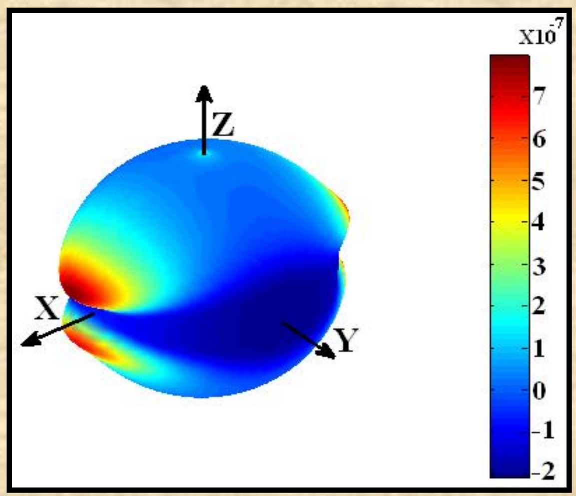
D=0,63μm



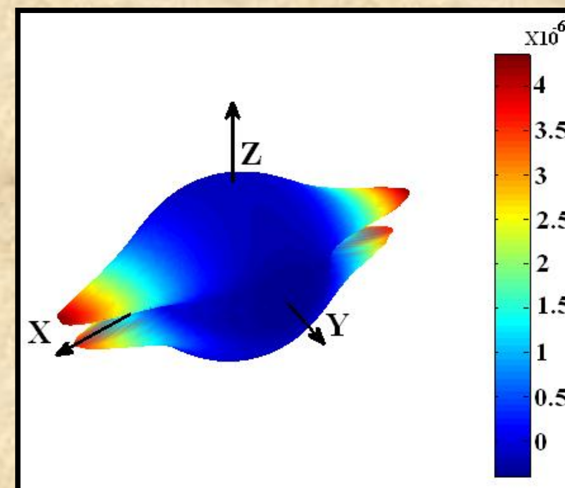
D=1,27μm



D=1,90μm



D=2,54μm



D=3,17μm

Multi-Physics Solutions

- Static deformation of cell
  - Analytical solution
    - Only for Spherical cells
    - Validation of numerical calculation
  - Comsol Structural Mechanics module
    - Deformed non-spherical cells

Stress redistribution as RBC is gradually deformed

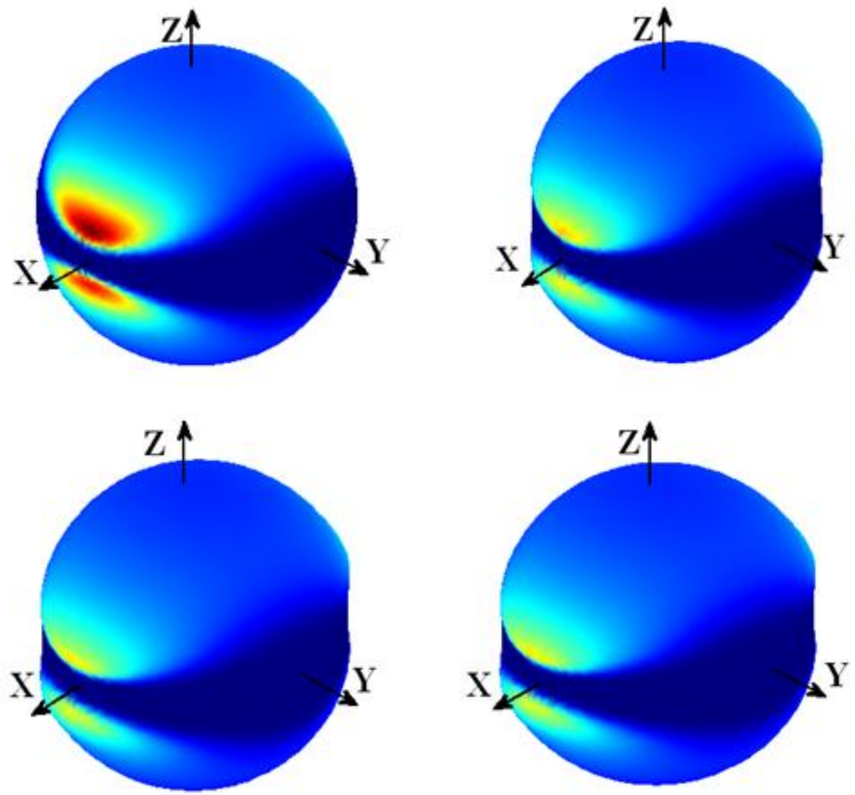


Fig. 5 Computed redistribution of radiation stress as the cell is deformed gradually in the iterations of the linear solver

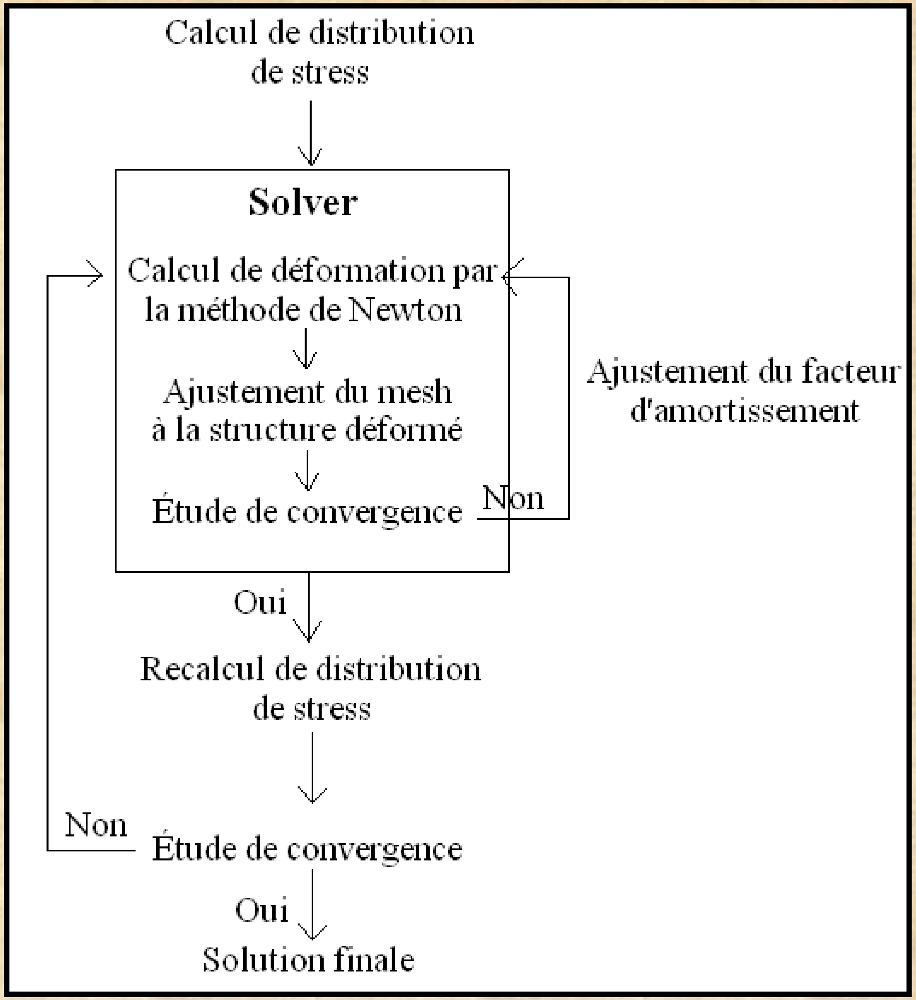
Comsol™ Structured Mechanics + Embadded Geometrical optics Matlab code

Computing stress and deformation for any shape of the cell membrane

- FE Comsol Multiphysics™
  - RF module;
  - Structural Mechanics module
- Embedded Matlab codes of geometrical optics
- Deformable mesh
- Linear Solver of a huge system of linear equations by iterations
- Minimize the errors

$$f'(U_0)\,E = -f(U_1)$$

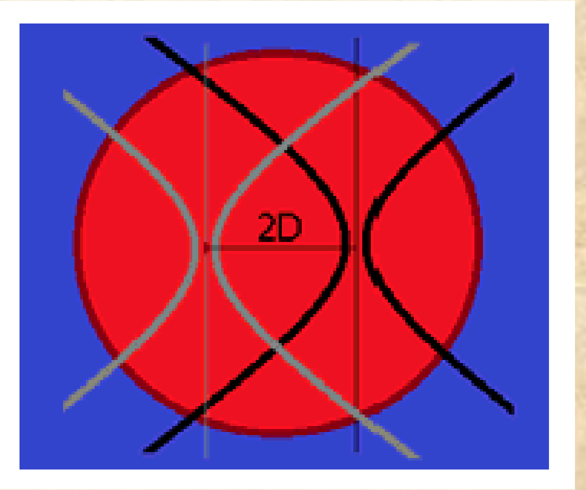
$$C = \left(\frac{1}{N} \sum_{i=1}^{N} \left(|E_i| / W_i \right)^2 \right)^{1/2}$$



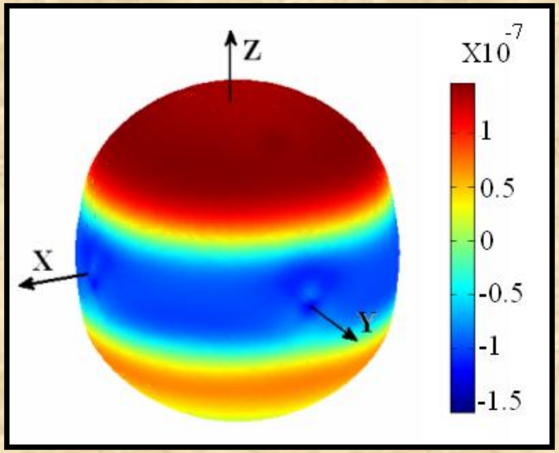
N = numbre of degree of feedom
W = mean deformations

Comsol Multiphysics™

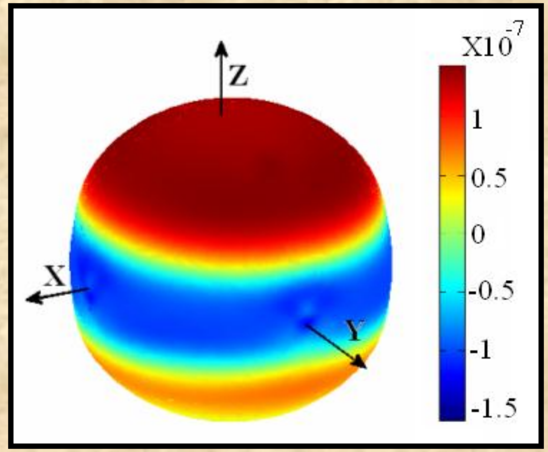
- 3D Dynamic deformation:
- Iterating
  - Stress redistribution on defomred cell
  - Deformation of the deformed cell
- Computing
  - RF module;
  - Structural Mechanics module
  - Embedded Matlab code of ray tracing



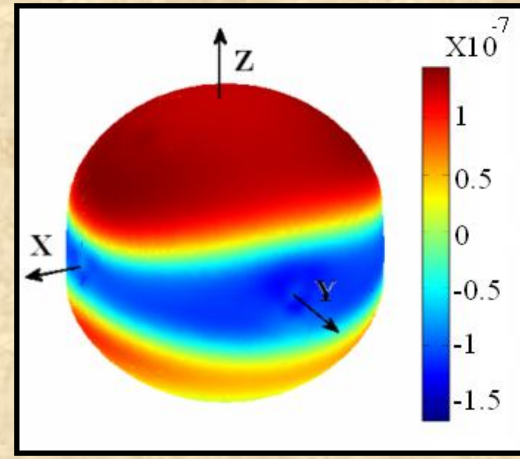
3D deformation of spherical RBC as the stress re-distribution on the deformed cell is considered



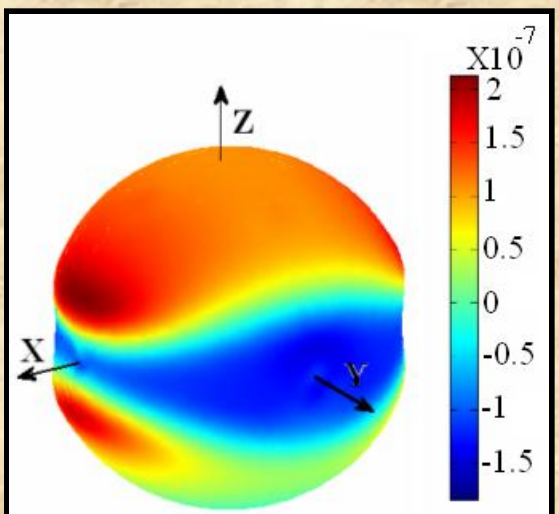
D=0,00μm



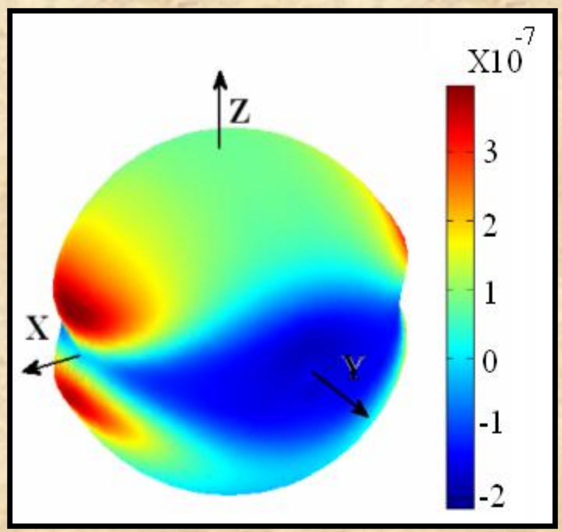
D=0,63μm



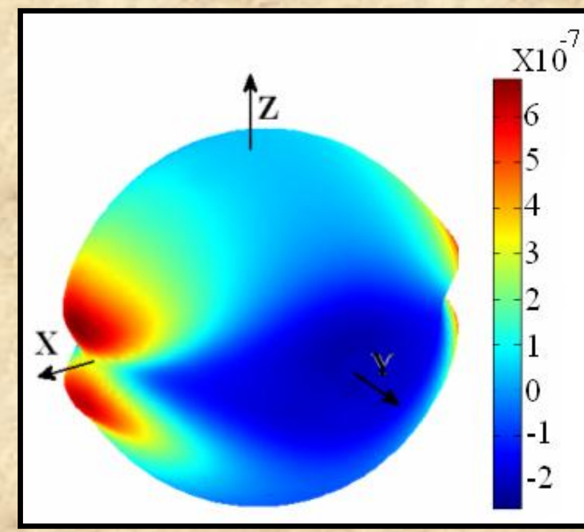
D=1,27μm



D=1,90μm

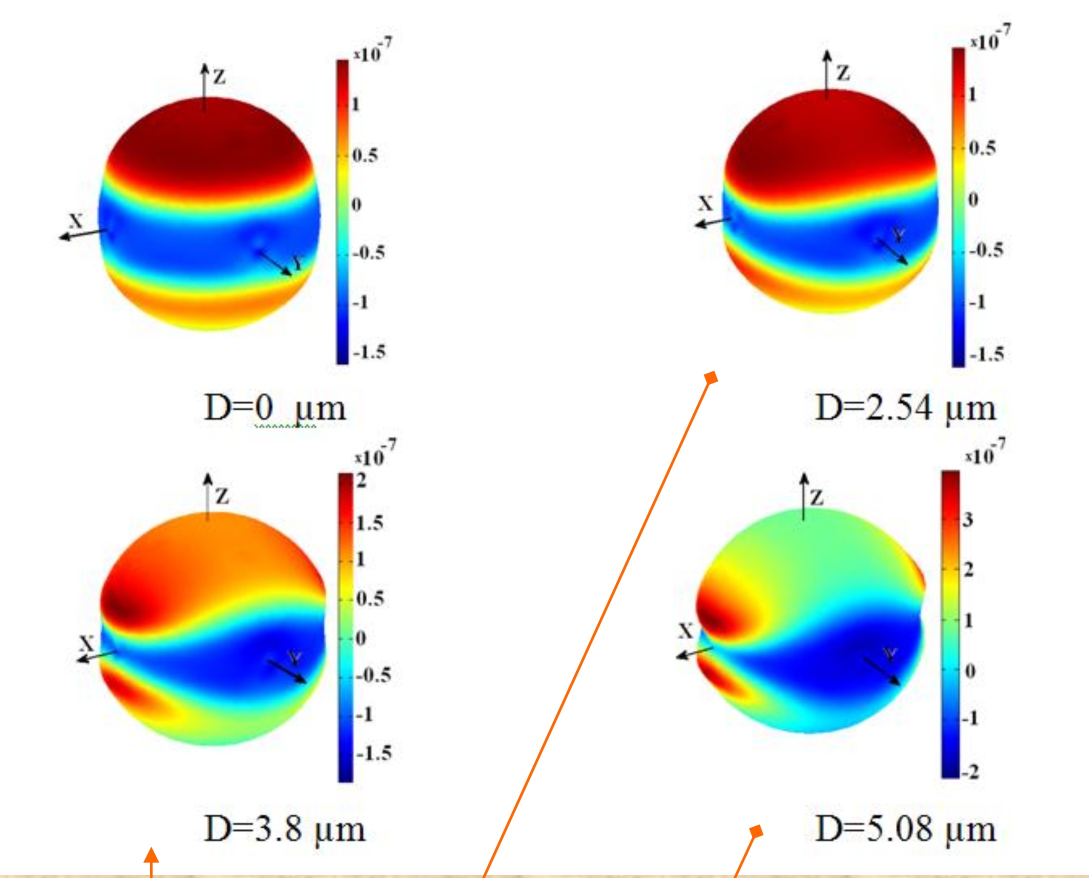


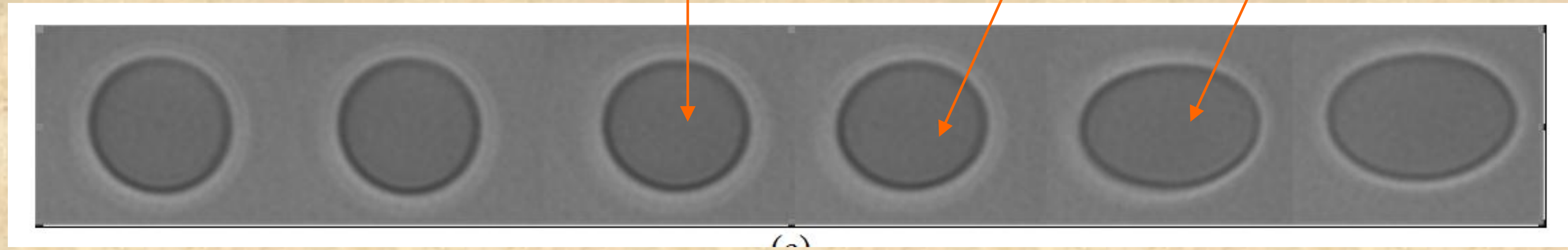
D=2,54μm



D=3,17μm

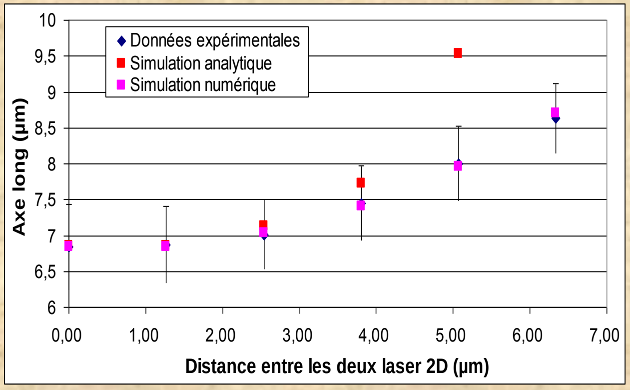
Equilibrium deformation



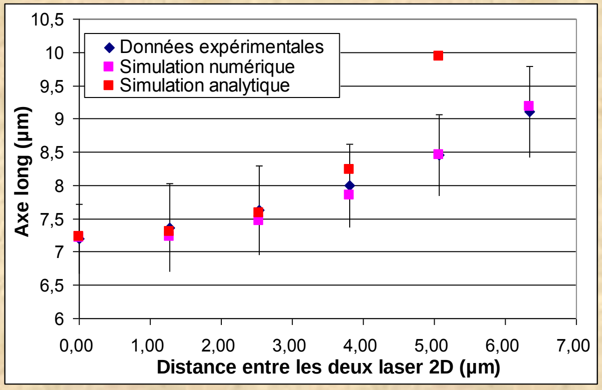


Rancourt, Opt. Exp. 10462-72 (2010)

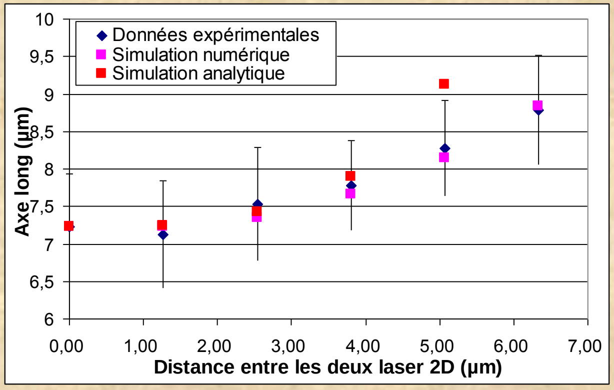
Theory fits to experimental data



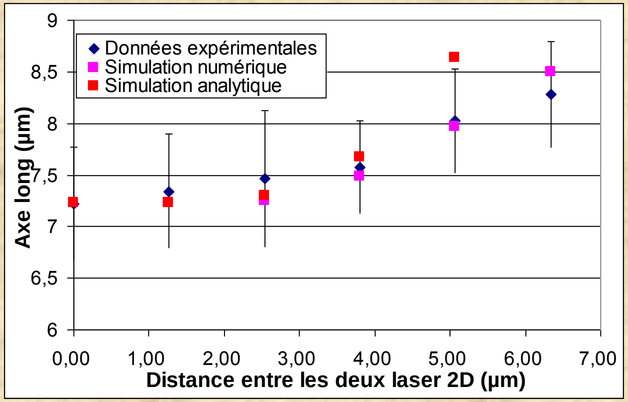
T= 24°C (sans NEM)



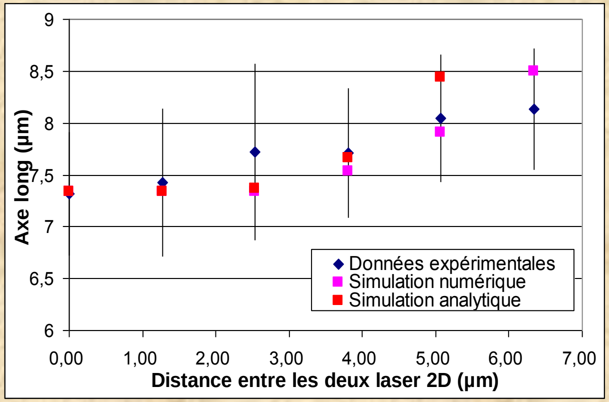
T= 37°C (sans NEM)



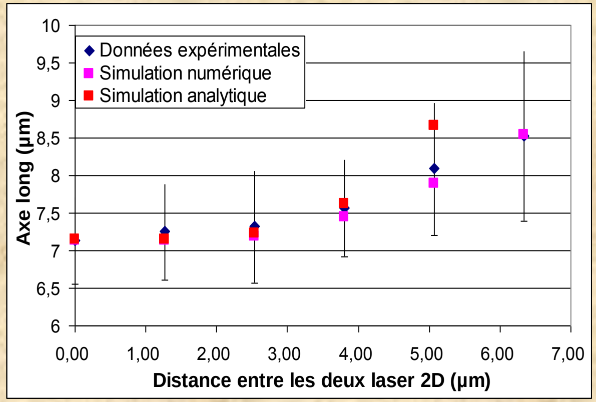
T= 42°C (sans NEM)



T= 24°C (avec NEM)



T= 37°C (avec NEM)



T= 42°C (avec NEM)

Conclusion

1) Computed 3D radiation stress distribution by GO, FDTD and T-matrix on a sphere in dual-trip tweezers
2) Compute static 3D deformation of the spherical membrane with asymmetrical external load
3) Computed the stress redistribution and membrane re-deformation with finite element method
4) Theory is fit to experimental results for membrane's deformation > 20 %
5) Differentiate normal and NEM treated RBCs, by their elasticity

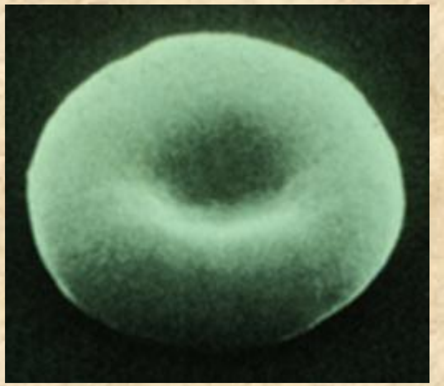
$$Gh = (5,07 \pm 1,11)\mu N / m$$

(Normal RBC)

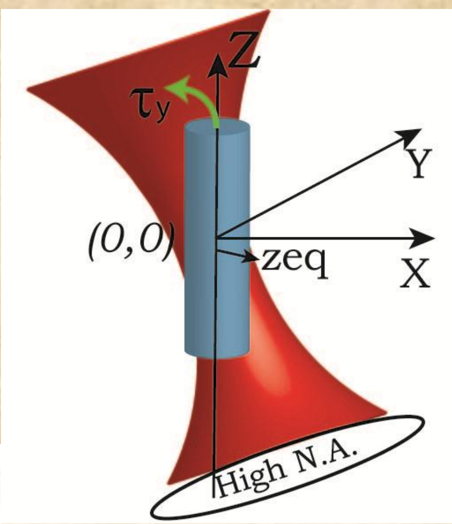
$$Gh = (8,59 \pm 1,14)\mu N / m$$

(NEM treated)

Future Work



- Biconcave shape of RBC
  - Comsol CAD module
- High NA Gaussian beam as background field
- Trapped particle floats
- Nanoparticle Scattering
  - RF module solver of EM field



- Other deformable particles
- Other type of tweezers
- Cell mechanics