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STRETCHING PROCESS OF PLASMID DNA MOLECULE IN OPTICAL TWEEZERS USING CW GAUSSIAN LASER BEAM

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ABSTRACT

The trapping dynamics of plasmid DNA molecule linking to polystyrene microsphere (trapped bead) in optical tweezers are investigated in the CW regime using the finite difference Langevin equation (FDLE). The obtained results show that, due to the extension of DNA moleucle, the stretching process characterizing by its pulling time, and stretched length depend on the peak intensity of laser beam and its initial position. The conditions to stretch plasmid DNA molecule in stretching state are discussed and the threshold value of energy of lase beam is found out and compared to that of λ-phage DNA moeucle.

Indexing terms/Keywords

Laser trapping, Optical devices, Medical and Biotechnology.

Academic Discipline And Sub-Disciplines

Physics and Medical and Biotecnology

SUBJECT CLASSIFICATION

Dynamics of molecule

TYPE (METHOD/APPROACH)

Theory, Simulation, Computation physics

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1. INTRODUCTION

There are many works interesting on using optical tweezers to trap the biological molecules, especially the DNA proteins

[1-8]. In almost of previous works, the optical tweezers is using to measure the extension force of all phage of DNA [1-14], [17-20], only. Lately, the equation of extension force of DNA molecule is modified [21] and the dynamics of polystyrene microsphere linking to λ-phage DNA molecule in optical tweezers are simulated [22]. In the last work, we have investigated the influence of all parameters as the peak intensity, duration and beam waist of the laser Gaussian beam well as the initial position of trapped beat on the pulling and stability times. The obtained results also show that, due to the contour length is too long more than the waist of trapping laser beam, so before doing a trapping process, the trapped bead must be pulled by certain ways into irradiated region, and in opposite, the λ-phage DNA molecule can't be in full stretching state, never. There are questions that what is the DNA molecule could be stretched by optical tweezers, and what are the conditions to stretch it at the contour length? To answer above questions, in this paper using FDLE the dynamics of the polystyrene microsphere linking to plasmid DNA molecule in CW regime are simulated. Then the conditions to stretch plasmid DNA molecule are discussed.

2. FINITE DIFFERENT LAGEVIN EQUATION

2.1.The model of optical tweezers for DNA molecule

Consider plasmid DNA molecule is embedded in a suitable fluid, i.e., the refractive indexes ratio m>1 [23, 24]. One end of plasmid DNA molecule is linked to a glass cover slip through a surface-anchored RNA (ribonucleic acid) polymerase, the opposite end is attached to polystyrene microsphere, which is captured or held under tension with optical tweezers, and its position is monitored by a CW laser Gaussian beam.

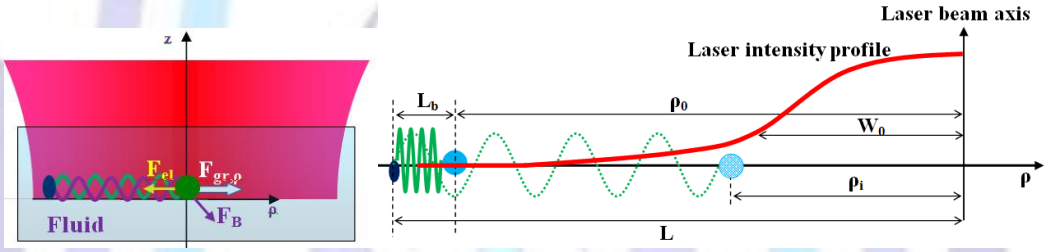

Fig 1: a) Cartoon of an proposed experimental geometry and

b) The beginning set-up of trapped bead in tweezers

The proposed experimental geometry of plasmid DNA molecule with optical tweezers is shown in Fig. 1a [11, 13]. The aim of proposed optical tweezers is to keep the DNA molecules in stretching state. The polystyrene microsphere plays the role linking plasmid DNA molecules to center of optical tweezers and glass cover slip. As shown in Figure 1a, the polystyrene microsphere is under acting of three forces: the elastic force of DNA molecules, Brownian force of fluid and optical force.

2.2. Finite different Lagevin equation

The general Langevin equation (GLE) describing the dynamic of bead linking to DNA molecules in optical tweezers [25].

$$m\ddot{r}(t) = -\gamma\dot{r}(t) + F_{gr,r}(r(t)) - F_{el}(r(t)) + \sqrt{2k_BT\gamma}W_r(t) \quad (1)$$

where m is the bead mass, $\gamma = 6\pi\eta a$ is the friction coefficient, η is the viscosity of fluid, a is the radius of bead, $W_r(t)$ is the white noise at position $r(t)$, $F_{gr,r}(r(t))$ is the transverse gradient optical force, which depends on the intensity distribution of laser beam, radius of trapped bead, and polarizability of the bead in the fluid [21, 26, 32], $F_{el}(r(t))$ is the elastic force, which depends on the extension of DNA molecule $r_i - r_0$ (see Fig.1b), $k_B = 1,38 \times 10^{-23} J/K$ is the Boltzmann's constant, and T is absolute temperature (K) [21]. The term in the left of Eq.1 is inertial. In the right of Eq.1, the first term is friction, second is restoring, third is stretching and the last is white noise. We consider a polystyrene microsphere with radius $a \approx 0.05\mu m$ [15, 27], average density of 1.35g/cm^3 [24, 28], and its mass of $m \approx 1.5 \times 10^{-18} kg$. It is embedded in water with viscosity $\eta = 0.001 Ns/m$ at temperature T of 300K [15] so the friction coefficient is $\gamma = 6\pi\eta a \approx 94.3 \times 10^{-10} kg/s$. Thus, the momentum relaxation time $t = m/\gamma \approx 0.17 \times 10^{-8} s$ is much smaller than the time scales of typical experiments [29], consequently, it is often possible to drop the inertial term (i.e. set $m = 0$).

Finite difference simulation of GLE are straight-forward: the continuous-time solution $r(t)$ of an GLE is approximated by

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a discrete-time sequence r_i, which is the solution of corresponding finite difference equation (FDE) evaluated at regular time steps $t_i = i\Delta t$. If Δt is sufficiently small, $r_i \approx r(t_i)$, a FDE is obtained from the GLE as follows [21, 22, 25, 26,]:

$$r_i = r_{i-1} + \frac{-F_{gr,r}(r_{i-1}) + F_{el}(r_{i-1})}{g}\Delta t + \sqrt{2k_B T / g}\left(\sqrt{W_1 W_2} - \sqrt{W_3 W_4}\right)\Delta t \quad , \qquad (2)$$

which is called as a finite different Langevin equation (FDLE), where $W_i, i = 1,2,3,4$ are random values of white noise at t_i [15, 33]. The solution is obtained by solving the resulting FDLE recursively for r_i, using the values r_{i-1} and r_{i-2} from previous iterations.

3. STRETCHING PROCESS OF PLASMID DNA MOLECULE

As an example for simulation, we consider a single plasmid DNA molecule with ionic condition of 10mM Na^+ having a stable length of $L_b = 47nm$ and contour length of $L = 1.33mm$ [18] is attached to a polystyrene microsphere with refractive index of $n_b = 1.57$,[25, 30] which is embedded water with refractive index of $n_f = 1.326$ [27, 31]. The optical tweezers is using a CW laser Gaussian beam with wavelength of $l = 1.06mm$, which can be focused by lens so that its waist is constant and peak intensity can be changed. The trapped bead is placed at the beginning position, $r_0(mm)$ with a distance of $L_{set} \approx L - L_b$ (μm) on the left from the center of tweezers. That means $r_0 = -L_{set} \approx L_b - L(mm)$ as shown in Fig. 1b.

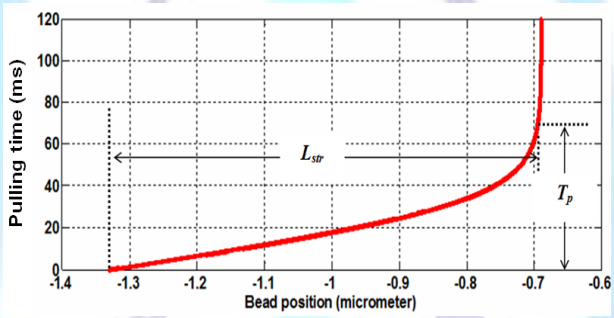

Fig 2: Stretching process of DNA molecule at initial position of $r_0 \approx 1.33mm$ for the case of $I_0 = 1' 10^2 W / cm^2$, $W_0 = 1mm$.

The dynamic, i.e., the position-time characteristic of polystyrene bead in optical tweezers describing the called "stretching" process of plasmid DNA molecule is simulated by Eq.(2) with time step of 1μs (Δt=1x10^{-9}s) for the case of CW laser Gaussian beam with peak intensity of $I_0 = 1' 10^2 W / cm^2$ and beam waist of $W_0 = 1mm$, and the bead's initial position $r_0 \approx 1.33mm$, is simulated and illustrated in Fig. 2.

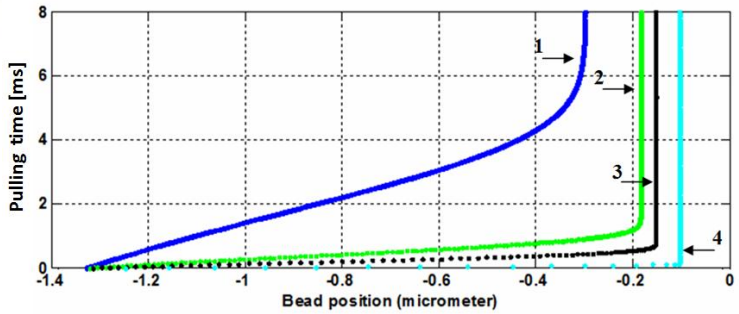

Fig 3: Stretching processes of plasmid DNA molecule at initial position of $r_0 \approx 1.33mm$ and $W_0 = 1mm$. for different peak intensities $I_0 = 5' 10^2 W / cm^2$ (1), $I_0 = 1' 10^3 W / cm^2$ (2), $I_0 = 5' 10^3 W / cm^2$ (3) and $I_0 = 1' 10^4 W / cm^2$ (4)

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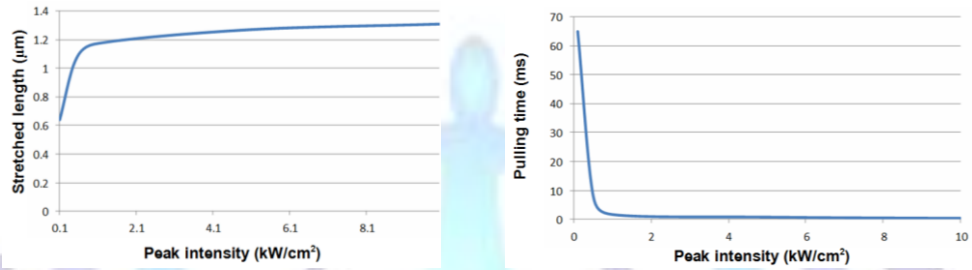
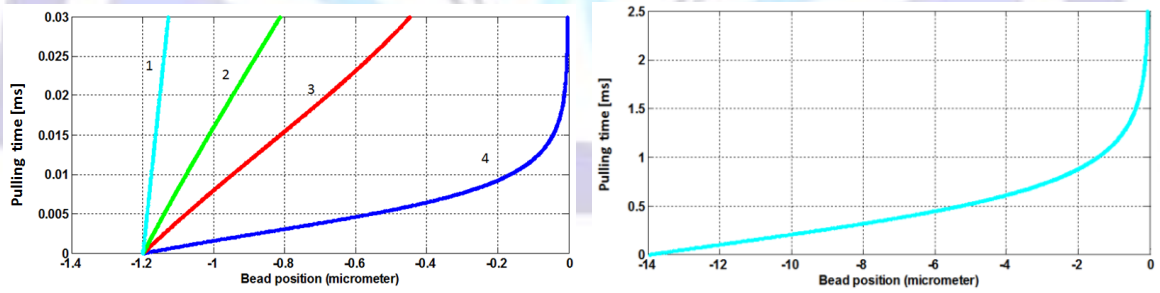
As is shown in Fig.2, after a pulling time about $T_p \approx 65ms$ the trapped bead is kept stability in the called "stable" position of $r_{st} = -0.69mm$, and the maximum stretched length $L_{st} = r_{st} - r_0 = 0.64mm$. That means, at stable position the elastic force is balance with optical one and the maximum stretched length, will be constant ($L_{st} = 0.64mm = const$) after the pulling time, $T_p \approx 65ms$. To enhance the maximum stretched length, i.e., to pull the trapped bead more near to tweezers center, the peak intensity must be increased. That can be seen in Fig.3, which describes the stretching processes of plasmid DNA molecule with different peak intensities. The results show that with increasing of peak intensity, the maximum stretched length of plasmid DNA molecule increases, meanwhile the pulling time reduces with increasing of peak intensity. It is more clearly in Fig.4, which illustrates the dependence of the maximum stretched length and pulling time on peak intensity. There are two asymptotes for pulling time $\lim_{I_0 \to \infty} T_p = 0$, and maximum stretched length $\lim_{I_0 \to \infty} L_{str} = L$.



a **b**

Fig 4: Stretched length (a) and pulling time (b) vs. peak intensity when $r_0 = 1.33mm = L$.

Since the peak intensity of conditional laser beam has a certain limited value, i.e., $I_0 << \infty$, the trapped never reaches the center of tweezers (it means $r_{st} < 0$ always), and the plasmid DNA molecule is never be in stretching state (it means $L_{st} < L$ always) when initial position is of $r_0 = 1.33mm$. From Fig.4, we also see that, it is most sensible to choice the maximum stretched length of $L_{str} = 1.2mm \approx 90\%L$, for which the plasmid DNA molecule could be seen to be in stretching state with reduced pulling time by increasing the peak intensity. Thus, now we find the peak intensity for that the trapped bead is stable in center of tweezers. For this purpose the stretched processes of plasmid DNA molecule at initial position of $r_0 = 1.2mm$ for different peak intensities are simulated and illustrated in Fig.5a.



a **b**

Fig 5: a) Stretching processes of plasmid DNA molecule at initial position of $r_0 = 1.2mm$ (90% of contour length) using laser beam with beam waist $W_0 = 1mm$ and different peak intensities $I_0 = 1' 10^4 W/cm^2$ (1), $I_0 = 5' 10^4 W/cm^2$ (2), $I_0 = 1' 10^5 W/cm^2$ (3) and $I_0 = 5' 10^5 W/cm^2$ (4);

b) Stretching process of λ-phage DNA molecule at initial position of $r_0 = 14mm$ (90% of contour length) using laser beam with $W_0 = 14mm$ and peak intensities $I_0 = 1' 10^6 W/cm^2$.

From Fig.5a, we can see that in this case, to stretch a plasmid DNA molecule to state of stretched length of $L_{str} = 1.2mm$,

it is convenient to enhance the peak intensity of laser beam with $W_0 = 1mm$ to $I_0 = 1 \times 10^6 W / cm^2$, which is the obtainable value from a popular laser used for optical tweezers. Moreover, with this peak intensity the pulling time reduces to $T_p = 0.03ms$. That means, to pull trapped bead into center tweezers and to stretch a plasmid DNA molecule in stretching state it must use a maximum laser energy of $E = I_0 \times p \times r_0^2 \times T_p \approx 66 \times 10^{-8} J$, only, which is more smaller than that for a λ-phage DNA molecule, $\approx 1 \times 10^{-2} J$ (see Fig.5b).

4. Conclusion

The stretched processes of the plasmid DNA molecule with ionic condition of 10mM Na^+ linking to a polystyrene microsphere placed at different initial positions in optical tweezers using CW laser Gaussian beam with given beam waist in scale of contour length and controllable peak intensity are investigated. The dependence of the pulling time, stable position of trapped bead and the maximum stretched length of DNA molecule on the peak intensity of laser beam is simulated, and the condition for that the trapped beat stable in center of tweezers is discussed. The results show that the pulling time and peak intensity (or maximum energy) of laser beam to trap a plasmid DNA molecule are reduced in comparison to that to trap a λ-phage one.

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