Supplementary Information for

Electrophoretic propulsion of matchstick-shaped magnetodielectric particles in the presence of external magnetic fields in a nematic liquid crystal

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Table S1

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1. Brownian motion of dipoles and quadrupoles in ZLI-2293 NLC

Isolated elastic dipoles and quadrupoles in a planar cell are video recorded and the particle trajectories are obtained using a suitable particle tracking software. The mean square displacement (MSD) is calculated from the *x*- and *y*-position coordinates which vary linearly with time delay τ (Fig. S1). The translational diffusion equation is given by, $\langle(\Delta r_i)^2\rangle = 2D_i\tau$ where D_i is the diffusion coefficient, $i = \parallel$ or $\perp$ to the director, r_i can be x or y. The difference in values of $\langle(\Delta x)^2\rangle$ and $\langle(\Delta y)^2\rangle$ is due to the anisotropy in motion of the particle (Fig. S1). Then the diffusion coefficients, $D_\parallel$ and $D_\perp$ are obtained from the slopes of linear fits of $\langle(\Delta x)^2\rangle$ and $\langle(\Delta y)^2\rangle$ as a function of τ and the corresponding drag coefficients, $\zeta_\parallel$ and $\zeta_\perp$ (Table S1). are obtained using the relation $\zeta_i = \frac{k_BT}{D_i}$ where T is the room temperature at which experiment is carried out.

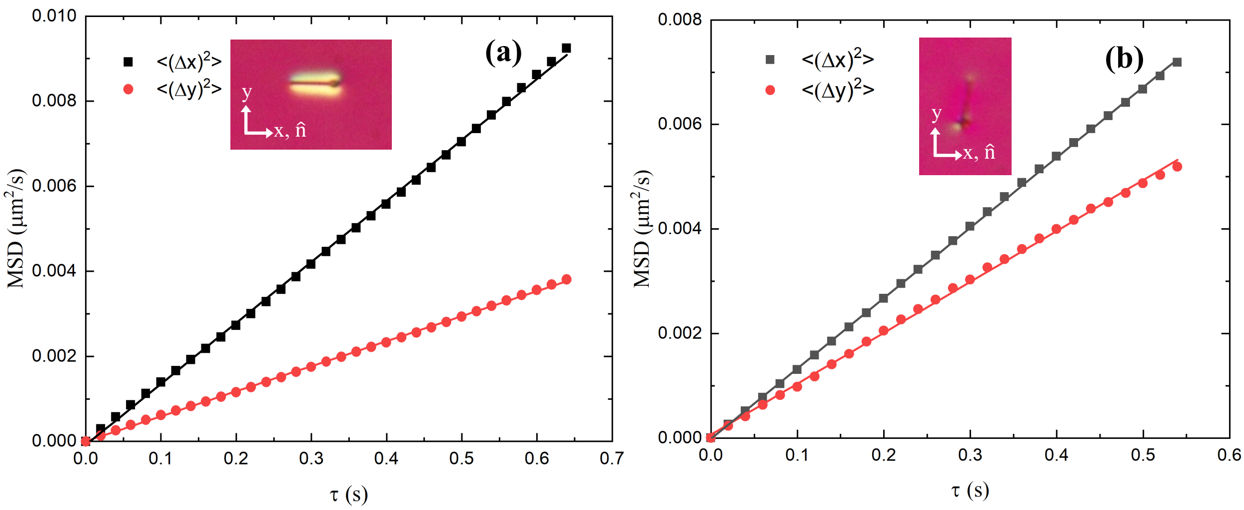

Figure S1: The position coordinates *x* and *y* of an elastic dipole and quadrupole. Mean square displacements along x- and y-axes in a planar cell as a function of τ for a (a) dipole and (b) quadrupole. POM images of both dipole and quadrupole are shown with director n̂ along the *x*-axis. Diffusion coefficients and drag coefficients are given in Table S1.

	$D_\parallel (10^{-2}\mu m^2/s)$	$D_\perp (10^{-2}\mu m^2/s)$	$\zeta_\parallel (10^{-6}kg/s)$	$\zeta_\perp (10^{-6}kg/s)$
Dipole	0.67 ± 0.1	0.49 ± 0.1	0.61 ± 0.1	0.84 ± 0.1
Quadrupole	0.71 ± 0.1	0.29 ± 0.1	0.58 ± 0.1	1.39 ± 0.1

Table S1: Diffusion coefficients ($D_\parallel$ and $D_\perp$) and drag coefficients ($\zeta_\parallel$ and $\zeta_\perp$) for dipoles and quadrupoles along parallel and perpendicular to the director.

2. Interaction energy of dipole and quadrupole pairs in ZLI-2293 NLC.

The particles experience long-range elastic interactions. Here elastic force (F_{el}) is balanced by the viscous drag force, $F_{drag} = -\zeta \frac{dR(t)}{dt}$ in a nematic medium where ζ is the drag coefficient, *R(t)* is the interparticle separation and the equation of motion is given by, $F_{el} + F_{drag} = 0$. Elastic forces are given by $F_{el}^{dipole} = -\frac{k}{R^4}$ and $F_{el}^{quadrupole} = -\frac{k}{R^6}$ for dipoles and quadrupoles respectively. From these relations, we will get the interparticle separation, $R(t) = \left(R_0{}^5 - 5\alpha t\right)^{\frac{1}{5}}$ and $R(t) = \left(R_0{}^7 - 7\alpha t\right)^{\frac{1}{7}}$ for dipoles and quadrupoles, respectively, where $\alpha = \frac{\mathrm{k}}{\zeta}$. The elastic interaction potential energy is given by, $W = \int F_{drag} \, . \, dR$. The interactions of two colinear particles are attractive with minimum $W \approx$ -3400 k_BT *and* $\approx$ -120 k_BT for dipoles and quadrupoles, respectively (See Fig. S2).

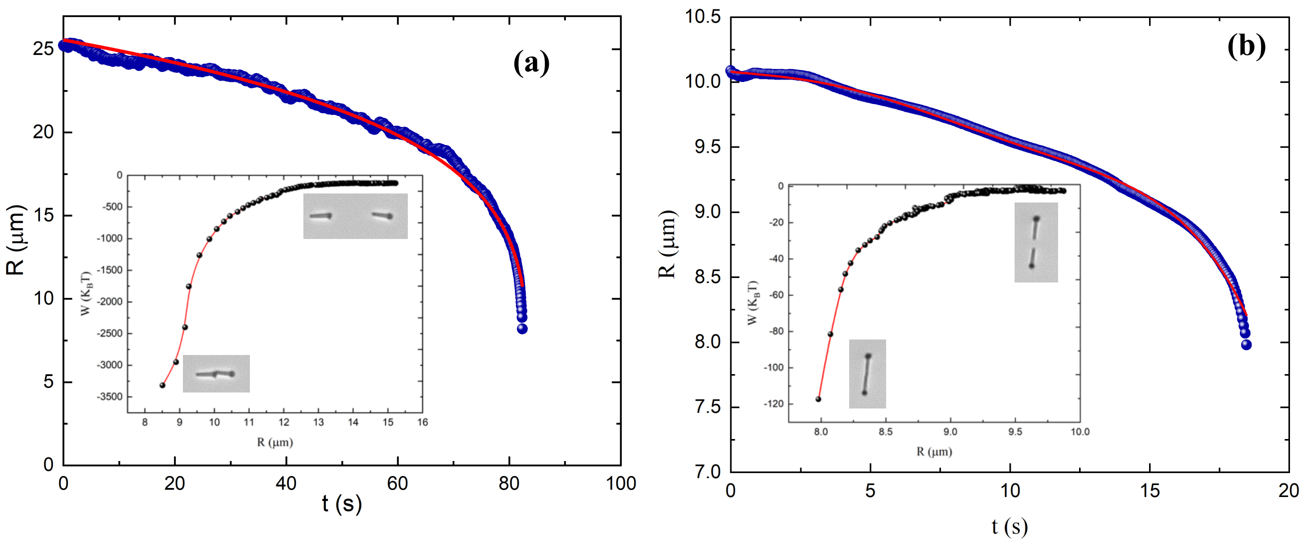

Figure S2: Variation of interparticle separation *(R)* with time *(t)* for (a) dipoles and (b) quadrupoles. The red curves show the nonlinear least square fit with the equations $R(t) = \left(R_0{}^5 - 5\alpha t\right)^{\frac{1}{5}}$ and $R(t) = \left(R_0{}^7 - 7\alpha t\right)^{\frac{1}{7}}$ for dipoles and quadrupoles, respectively. R_0 is the separation at time *t = 0* and α is obtained as (2.61±0.01) $\times 10^4$ $\mu m^5/s$ and (3.47±0.13) $\times 10^4$ $\mu m^7/s$ for dipoles and quadrupoles, respectively. The inset shows the interaction potential energy (*W*) in units of k_BT as a function of separation (*R*).

3. Dipolar assembly of match-stick shaped particles in NLC

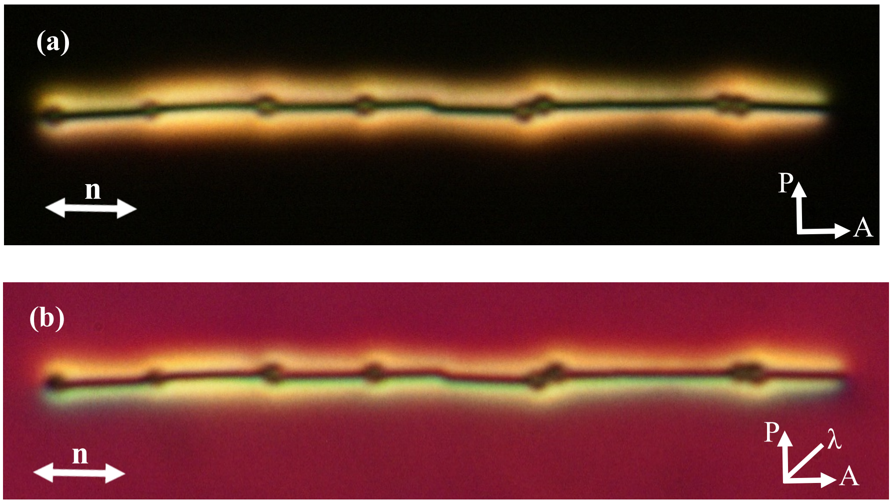

Figure S3: (a) POM and (b) full wave plate images of dipolar chains of matchstick-shaped particles. Double headed arrow shows the alignment direction of the director **n**.

4. Motion of matchstick particles under in-plane transverse DC electric and magnetic fields in ZLI – 2293 NLC.

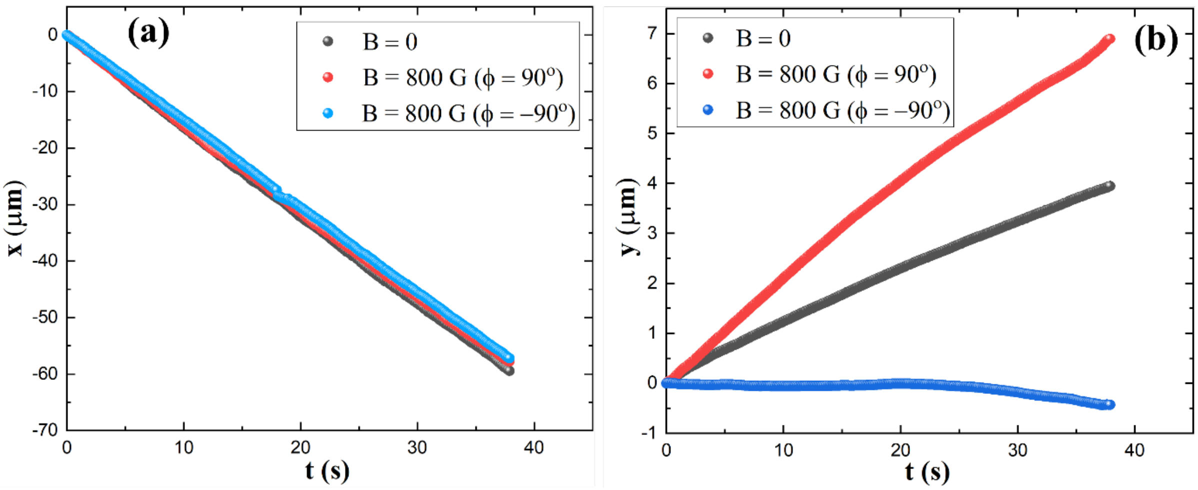

Figure S4: Variation in relative (a) x- and (b) y- coordinates with time for different values of **B** for the particles under in-plane DC electric field ($7.5 \times 10^3 V/m$).

5. Motion of matchstick particles under in-plane transverse DC electric and magnetic fields in ZLI – 2293 NLC when the polarity of E is reversed.

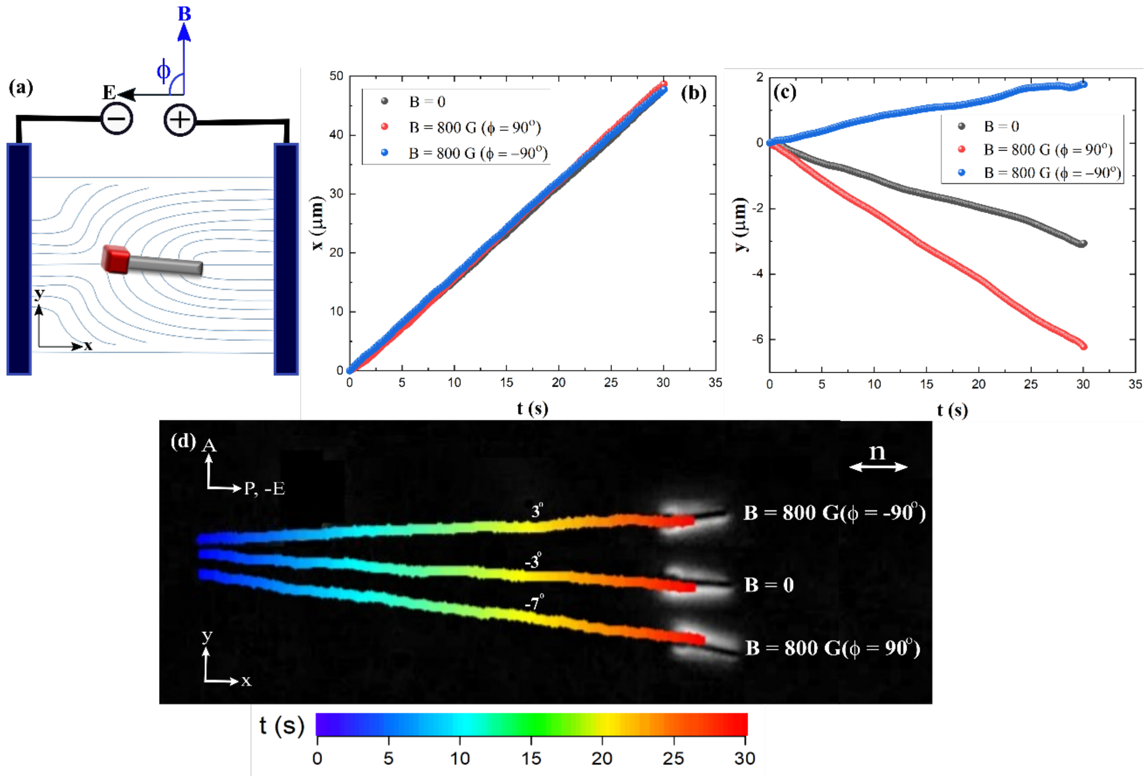

Figure S5: (a) Schematic of a planar cell with electric field **E** (7.5 mV/μm) between in-plane electrodes and magnetic field **B** (800G) applied perpendicular to **E**. The director distortion and initial orientation of the matchstick is as shown. (b,c) Variation of *x*- and *y*- coordinates of the particle with time for different values of **B**. (d) Color coded trajectories depicting the motion of the particle when $B = 0$, and $B = 800G$ ($\phi = \pm 90^0$); $t_{min} = 0$s and $t_{max} = 30$s (see Movie S2). The angle subtended by **B** with the director is denoted by ϕ. The trajectory angles with respect to the director are mentioned in each case. Double-headed arrow denotes the director. The specified angles are accurate within $\pm 1.5^0$.

6. Variation of particle velocity with electric field and frequency in NLC (XV7039-200).

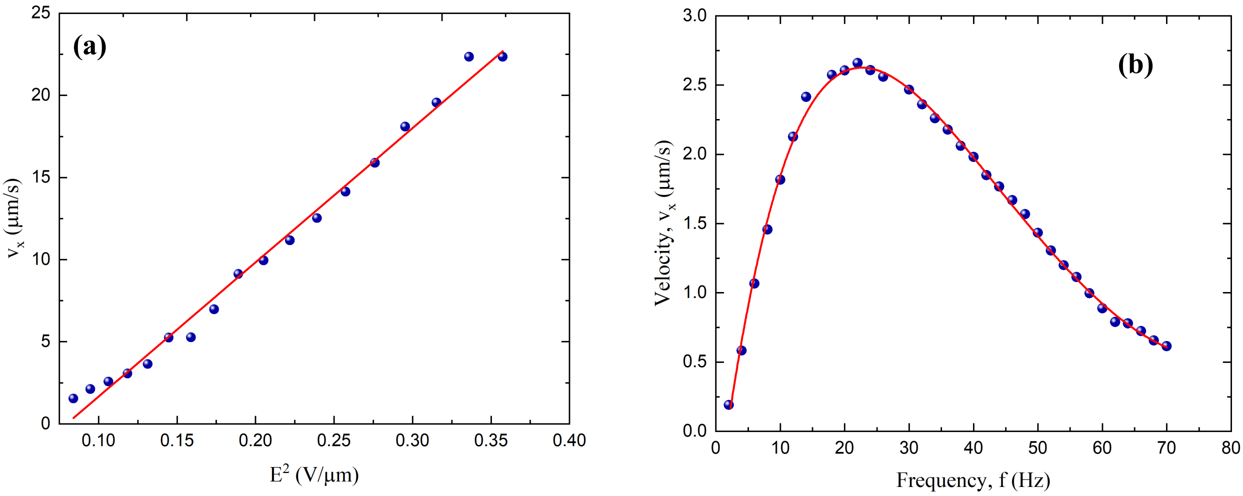

Figure S6: (a) Electric field dependent velocity (v_x) at a fixed frequency 30 Hz for E above a threshold. Red line shows the linear least square fit to $v_x = \beta E^2$ with slope β = (81.7$\pm$ 1.9) $\mu m^3 s^{-1} V^{-2}$. (b) Variation of particle velocity with frequency at a fixed electric field (0.38 V/μm). The red curve is a guide to the eye.

7. Motion of matchstick particles under out of plane transverse AC electric and magnetic fields in XV7039-200 NLC.

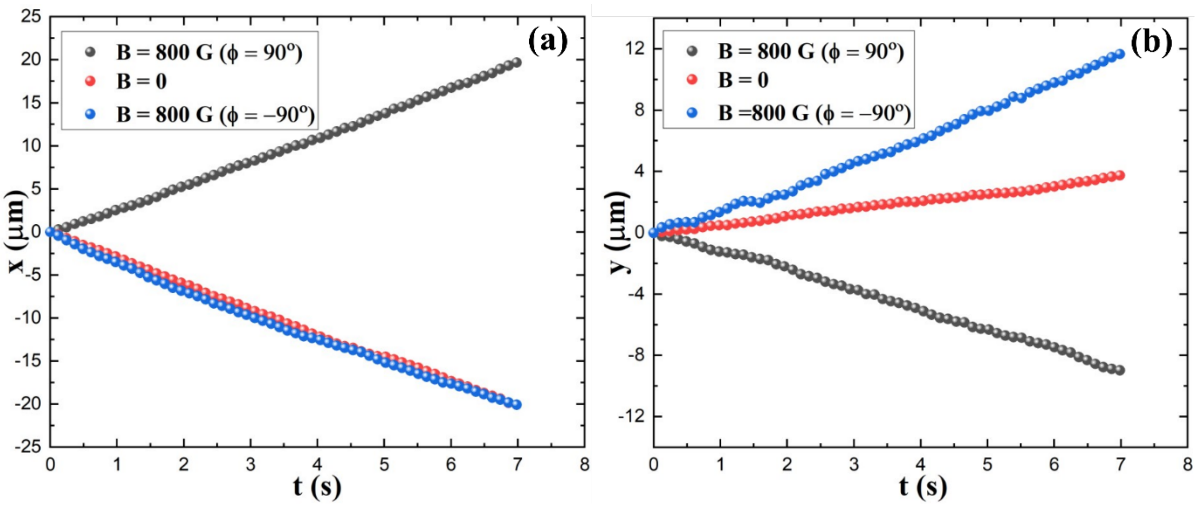

Figure S7: Variation in relative (a) x- and (b) y- coordinates with time for different values of **B** for the particles under out of plane AC electric field **E**(0.38 V/μm, 30 Hz).

8. Movies

Movie S1: Movie of a matchstick particle in ZLI-2293 with dipolar distortion moving under in-plane transverse DC electric and magnetic fields as shown in Fig.5a. The particle always moves towards the positive electrode. The value of the DC electric field, **E** (= 7.5 mV/µm, and the magnetic field, **B** = 800 G. The angle subtended by **B** with the director is denoted by ϕ. (a) When ϕ = 90^0, the trajectory makes an angle ≈ 7^0 with the director; the *x*- component of velocity v_x = -1.5 µm/s, and the *y*- component of velocity v_y = 0.2 µm/s. (b) When B = 0, the trajectory makes an angle ≈ 4^0 with the director; v_x = -1.5 µm/s, and v_y = 0.1 µm/s. (c) When ϕ = -90^0, the trajectory makes an angle ≈ -1^0 with the director; v_x = -1.5 µm/s and v_y = -0.01 µm/s. The specified angles are accurate within ± 1.5^0.

Movie S2: Movie of a matchstick particle in ZLI-2293 with dipolar distortion near the head of the matchstick moving under in-plane transverse DC electric and magnetic fields as shown in Fig. S4(a). The particle always moves towards the positive electrode. The value of the DC electric field, **E** = 7.5 mV/µm, and the magnetic field, **B** = 800 G. The angle subtended by **B** with the director is denoted by ϕ. (a) When ϕ = -90^0 , the trajectory makes an angle ≈ 3^0 with the director; the *x*- component of velocity v_x = 1.6 µm/s, and the *y*- component of velocity v_y = 0.1 µm/s. (b) When B = 0, the trajectory makes an angle ≈ -3^0 with the director; v_x = 1.6 µm/s, and v_y = -0.1 µm/s. (c) When ϕ = 90^0, the trajectory makes an angle ≈ -7^0 with the director; v_x = 1.6 µm/s and v_y = -0.2 µm/s. The specified angles are accurate within ± 1.5^0.

Movie S3: Microscopic video recording of a matchstick particle in XV7039-200 with dipolar distortion near the head of the matchstick moving under out-of-plane AC electric field, **E** (0.38 V/µm, 30 Hz) and an in-plane orthogonal magnetic field, **B** = 800 G. The angle subtended by **B** with the director is denoted by ϕ. Due to the AC electric field $E\hat{\mathbf{z}}$, the particle tilts in the z-direction and moves in the *xy*- plane. (a) When ϕ = 90^0, the particle trajectory makes an angle ≈ -25^0 with the director. The *x*- component of velocity v_x = 2.8 µm/s, and *y*- component of velocity v_y = -1.3 µm/s. (b) When B = 0, the trajectory makes an angle ≈ 10^0 with the director; v_x = -2.8 µm/s, and v_y = 0.5 µm/s. (c) When ϕ = -90^0, the trajectory makes an angle ≈ 37^0 with the director; v_x = -2.9 µm/s, and v_y = 1.7 µm/s. The specified angles are accurate within ± 1.5^0.