Frequency-Controlled Manipulation of Particles in a Liquid Column Based on AC Dielectrophoresis

Ingo Kuehne[1*], Nadine Philippin[1,2] and Alexander Frey[3]
[1] Heilbronn University of Applied Sciences, Kuenzelsau, BW, Germany
[2] Technical University of Munich, Chair of Physics of Electrotechnology, Munich, BY, Germany
[3] Augsburg Technical University of Applied Sciences, Augsburg, BY, Germany
[*]ingo.kuehne@hs-heilbronn.de

In this paper, the topic of frequency-controlled manipulation of sinking particles in a stationary liquid column based on AC dielectrophoresis is studied in depth. For this purpose, the fundamentals of dielectrophoresis are presented at the beginning, in particular taking into account the radius-dependent electrical conductivity of dielectric particles. Subsequently, the modeling of the stationary liquid column is discussed in detail. The simulation results illustrate the vertical separation due to gravity and show the transient frequency- and amplitude-controlled horizontal deflection of the particles as a function of size. Thus, a flexible method for dielectric particle manipulation according to their size was verified by simulations.

***Keywords*—electrokinetics, dielectrophoresis, field-assisted particle manipulation, microfluidics**

I. Introduction

Researchers are making great efforts regarding the manipulation of particles at the micro- and nano-scale. The ability to control and direct particles with precision holds immense promise for a wide range of applications, from advanced drug delivery systems in medicine to cutting-edge porous materials in nanotechnology [1, 2]. Among the multitude of techniques developed for this purpose, one of the most intriguing and versatile methods is elektrokinetics, a branch of science that employs electric fields to manipulate particles [3, 4]. Thereby, the electrokinetic effects are manifold, such as electrophoresis, electroosmosis and diffusiophoresis. In this paper, dielectrophoresis is examined in more detail. Elektrokinetics is not only a powerful tool for scientists and engineers but also a fascinating intersection of physics, chemistry and engineering.

II. Theoretical Preliminary

A. Dielectrophoresis

Dielectrophoresis (DEP) is the phenomenon where dielectric particles experience a force when subjected to a non-uniform electric field [5, 6]. This force is dependent on the dielectric properties of the solid particle and the surrounding liquid medium. The fundamental principle of DEP is based on the application of an electric field force on charged particles due to their polarization. Particles with different dielectric properties will experience different forces, leading to their separation or manipulation within the electric field. The dielectrophoretic force F_{DEP} acting on a particle can be calculated as followed with r as particle radius, ϵ_0 as vacuum permittivity, ϵ_m as relative permittivity of the medium, $\Re\{K(\omega)\}$ as real part of the Clausius-Mossotti factor and E_{rms} as applied electrical field strength.

$$F_{DEP} = 2\,\pi \cdot r^3 \cdot \epsilon_0 \cdot \epsilon_m \cdot \Re\{K(\omega)\} \cdot \nabla|E_{rms}|^2 \tag{1}$$

There are two main types of DEP. On the one hand positive dielectrophoresis (pDEP) occurs when particles with higher permittivity than the surrounding medium are attracted to regions of higher electric field strength. On the other hand negative dielectrophoresis (nDEP) occurs when particles with lower permittivity than the surrounding medium are repelled from regions of higher electric field strength. This behavior is represented by the real part of the Clausius-Mossotti factor $\Re\{K(\omega)\}$ [7]:

$$\Re\{K(\omega)\} = \frac{\omega^2 \cdot \epsilon_0^2 \cdot (\epsilon_p - \epsilon_m) \cdot (\epsilon_p + 2\epsilon_m) + (\sigma_p - \sigma_m) \cdot (\sigma_p + 2\sigma_m)}{\omega^2 \cdot \epsilon_0^2 \cdot (\epsilon_p + 2\epsilon_m)^2 + (\sigma_p + 2\sigma_m)^2} \tag{2}$$

with ω as angular frequency of the applied electrical field, ϵ_p as relative permittivity of the particle, σ_p as effective electrical conductivity of the particle and σ_m as electrical conductivity of the medium. Fig. 1 shows an exemplary course of the frequency-dependent Clausius-Mossotti factor of a polystyrene particle in pure water.

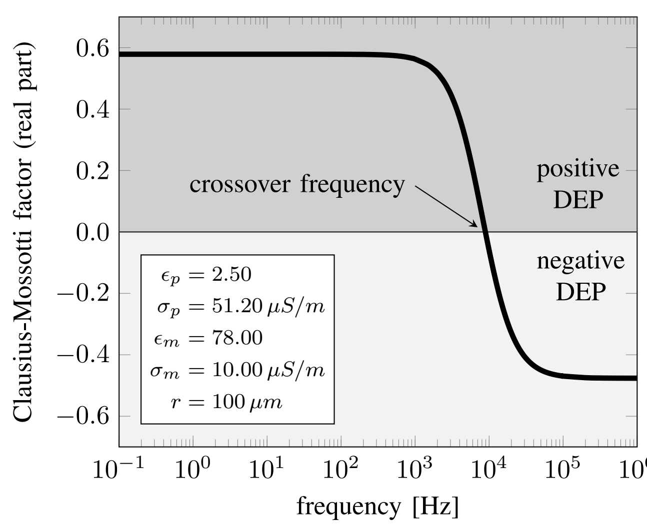


Fig. 1: Frequency-dependent real part of the Clausius-Mossotti factor illustrating the shift from positive to negative DEP.

B. Effective Particle Conductivity

The electrical conductivity of dielectric particles, such as polystyrene particles, is closely related to their size or radius [8]. This correlation arises from the fundamental principles of electrical conduction and the behavior of dielectric materials in electric fields. O'Konski [9] has shown in his work that the effective particle conducivity σ_p of homogeneous spheres depends – in addition to the bulk conductivity – in particular on the surface conductance:

$$\sigma_p = \sigma_b + \frac{2\,\kappa_s}{r} \tag{3}$$

with σ_b as bulk electrical conductivity of the particle and κ_s as surface conductance of the particle. For most particles in the (sub)micrometer range, the bulk electrical conductivity is in fact irrelevant. Fig. 2 illustrates the radius-dependent effective particle conductivity of typical polystyrene spheres.

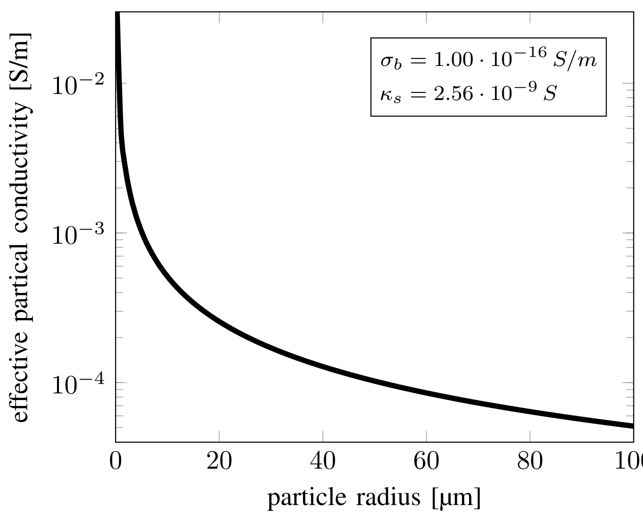


Fig. 2: Radius-dependent effective particle conductivity.

As a consequence, the Clausius-Mossotti factor also varies depending on the radius of the particle. In particular, the crossover angular frequency ω_C separating pDEP from nDEP shifts accordingly (see Fig. 3):

$$\omega_C = \sqrt{\frac{(\sigma_p - \sigma_m)\cdot(\sigma_p + 2\,\sigma_m)}{\epsilon_0^2\cdot(\epsilon_p - \epsilon_m)\cdot(\epsilon_p + 2\,\epsilon_m)}} \tag{4}$$

The consideration of surface conductance is essentially valid for particles in the micrometer range. Smaller particles require more detailed model descriptions taking into account the Stern layer conductance as well as the diffusive layer conductance [10].

III. COMSOL Modeling

With the help of COMSOL, a geometric 2D model of a stationary separation column filled with a liquid was built up. In the upper section (surface of the liquid) is the inlet, where a certain amount of particles of different sizes are centrally and simultaneously fed to the separation column. The separation column itself consists of two sections. The upper section is used for vertical separation of particles of different sizes due to gravity. The lower section contains two electrodes and is used for horizontal deflection of the particles based on dielectrophoresis. At the bottom of the separation column are compartments designed to hold a respective size range of particles. The compartments could alternatively be designed as individual outlets. Fig. 4 illustrates the design of the separation column.

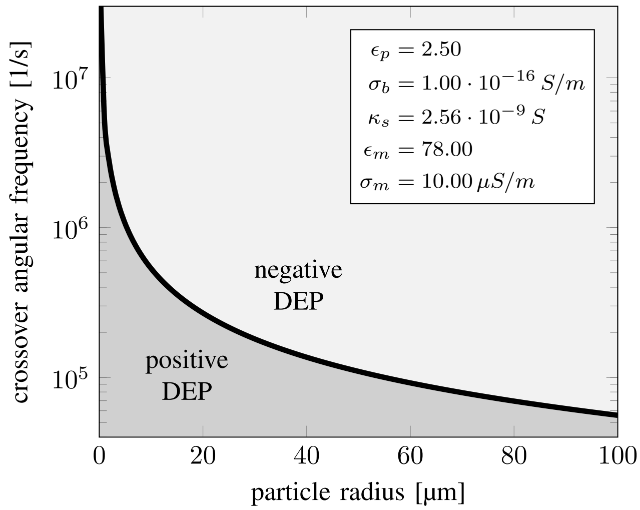


Fig. 3: Radius-dependent crossover angular frequency.

The goal of the separation column is the defined size-dependent separation or rather sorting of the particles. For this purpose, the simulation requires the physical COMSOL interfaces: *Electric Currents*, *Laminar Flow* and *Particle Tracing for Fluid Flow*. In a first study, the electric field distribution is investigated by means of a *Frequency Domain* analysis. The obtained results are the basis for a subsequent *Time Domain* study for calculating the particle trajectories, which is controlled by a frequency- and amplitude-variable AC signal applied to the electrodes.

All simulation results are based on the material properties of spherical polystyrene particles sinking in pure water listed in the previous figures.

IV. Simulation Results

A. Vertical Separation

In the upper section, the particles are essentially subject to the balance of forces from gravitational force F_G, buoyancy F_A, and Stokes friction F_R in the fluid:

$$F_G = F_A + F_R \tag{5}$$

The force balance can easily be resolved analytically according to the sink velocity:

$$v = \frac{2\,g\cdot(\varrho_p - \varrho_m)}{9\,\eta_m}\cdot r^2 \tag{6}$$

with g as acceleration of gravity, ϱ_p as particle density, ϱ_m as medium density and η_m as medium dynamic viscosity.

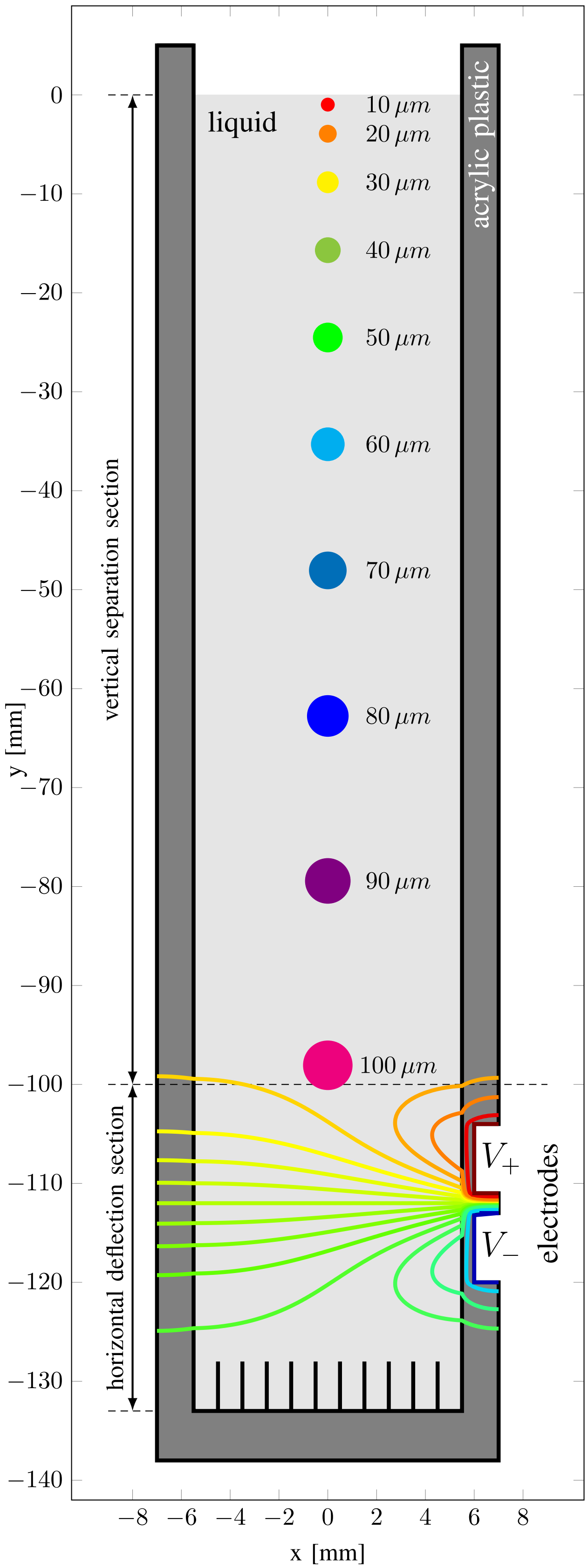


Fig. 4: Stationary liquid column with radius-dependent vertically separated particles (size scaled up for visibility) during a sink time of $t = 90s$.

The simulation results visualized in Fig. 4 and Fig. 5 confirm the quadratic relationship between sink velocity and particle radius.

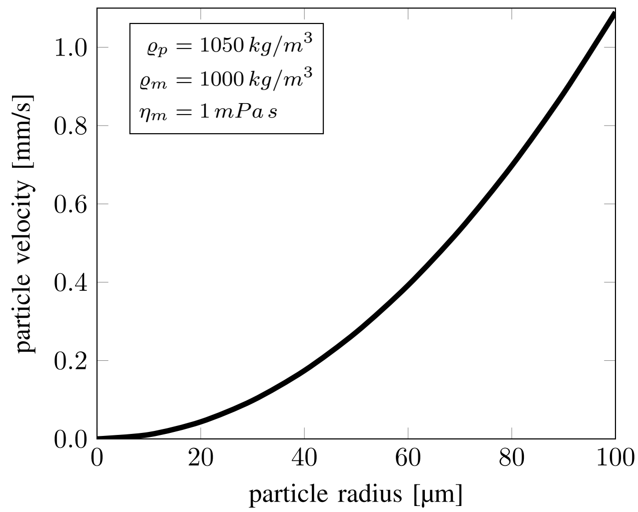


Fig. 5: Radius-dependent particle velocity.

B. AC Field Coupling

Dielectrophoresis requires a sufficient coupling of the applied AC field into the liquid. Since the electrodes are not located directly in the liquid, but are isolated from each other by a dielectric material, the coupling is capacitive. It is of decisive importance that sufficient coupling only occurs above the so-called cutoff frequency, which is strongly dependent on the electrical conductivity of the medium. Fig. 6 illustrates this phenomenon.

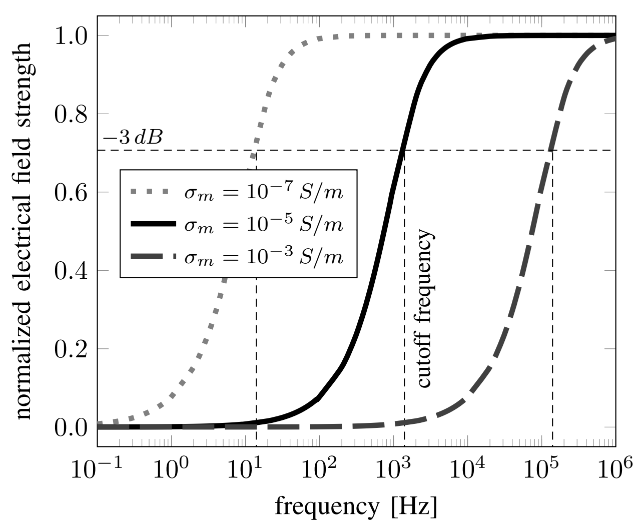


Fig. 6: Frequency-dependent electrical field strength within liquid phase for different electrical conductivities.

The lower the electrical conductivity of a liquid, the lower the cutoff frequency. Accordingly, liquids of high electrical conductivity require high operating frequencies, which in practice can be challenging for an experimental setup [11, 12].

C. Horizontal Deflection

The particles separated in time in the upper section can now be deflected horizontally in the lower section, where the electrodes are located, due to the acting dielectrophoresis. This requires a reasonable control of the transient AC signal $U_{AC}(t)$ with respect to time varying voltage amplitude $\hat{U}(t)$ and frequency $f(t)$:

$$U_{AC}(t) = \hat{U}(t) \cdot \sin(2\,\pi \cdot f(t) \cdot t) \tag{7}$$

Fig. 7 shows the simulated particle trajectories as a function of their radii. The larger the particles here, the stronger they are deflected to the left by means of nDEP. The smaller the particles, the stronger the effect of pDEP which forces a stronger deflection to the right.

The transient AC signal could also be interpreted differently and force an alternative sort order than presented here.

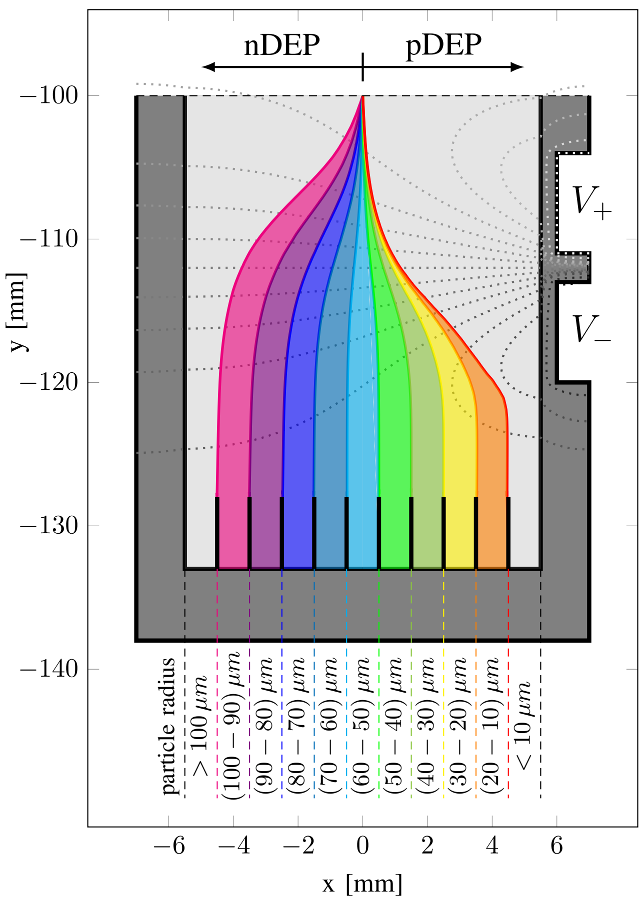


Fig. 7: Stationary liquid column showing radius-dependent deflection corridors of particles (controlled by appropriate AC-signal).

Frequency Control

The simplest way of control is to vary in time the frequency of the AC signal linearly piecewise at a constant voltage amplitude, so that the desired deflection is obtained depending on the particle size. Here, the Clausius-Mossotti factor is explicitly exploited in the region of the slope transition from nDEP to pDEP. Fig. 8 illustrates the relationship between the frequency of the AC signal and the resulting deflection.

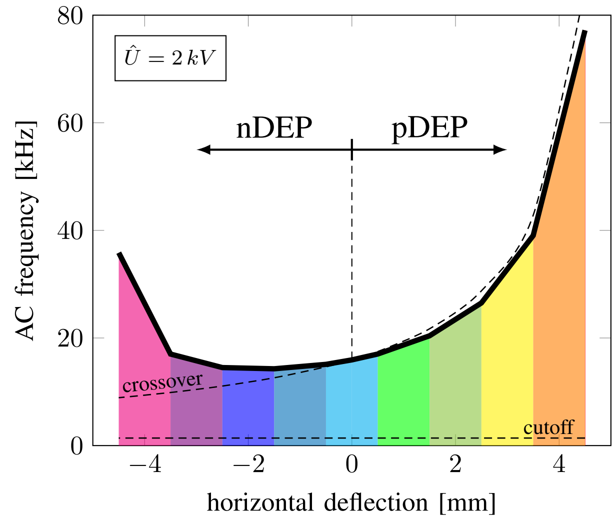


Fig. 8: Frequency-controlled horizontal deflection.

The corresponding transient behavior of the AC signal is shown in Fig. 9. Necessary conditions for a successful separation of a particle size mixture are a sufficiently high voltage amplitude for all particle sizes and the condition that the crossover frequency must be significantly higher than the cutoff frequency. The latter guarantees that the electric field couples strongly enough into the liquid and so the dielectrophoresis can be effective. The continuous variation of the Clausius-Mossotti factor between pDEP and nDEP (cf. Fig. 1) allows a precise control of the dielectrophoretic force and thus a defined horizontal deflection.

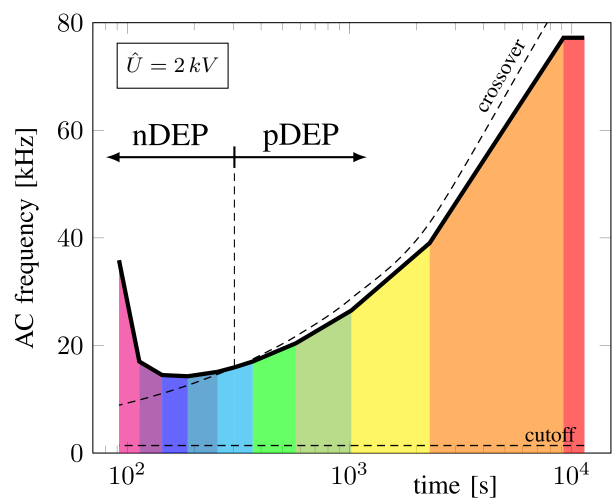
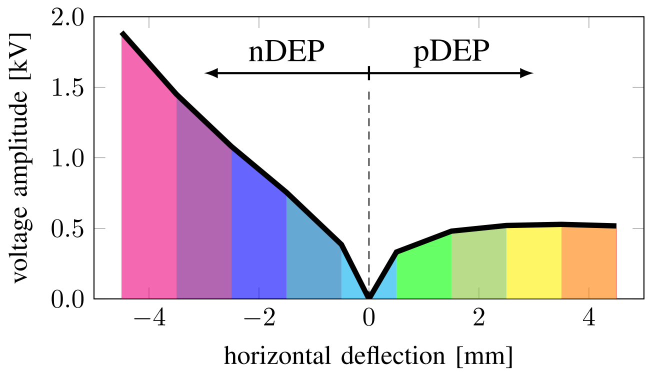


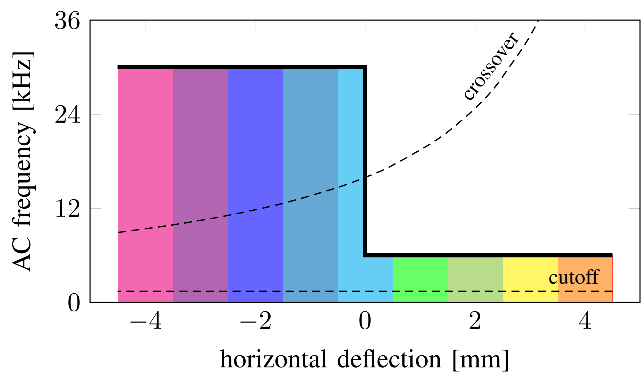
Fig. 9: Time-controlled AC frequency.

Combined Amplitude and Frequency Control

Alternatively, a somewhat more variable control consists of simultaneously varying both the voltage amplitude and the frequency of the AC signal over time. In this case, the frequency can be selected outside the slope region of the Clausius-Mossotti factor, i.e. either far below or far above the crossover frequency. It is assumed that, in this way an electrical control can be realized more robustly in an experiment and thus more reproducible horizontal deflections can be achieved. Fig. 10 presents the relationship between the voltage amplitude and the frequency of the AC signal and the resulting deflection. The transient behavior of the AC signal with respect to voltage amplitude and frequency can be seen in Fig. 11.



(a) Amplitude-controlled horizontal deflection.



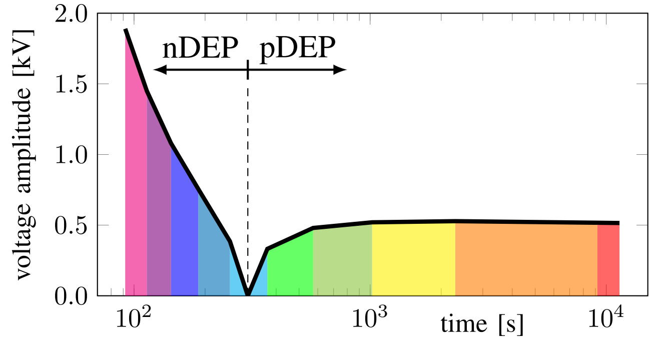
(b) Frequency-controlled horizontal deflection.

Fig. 10: Combined amplitude- and frequency-controlled horizontal deflection.

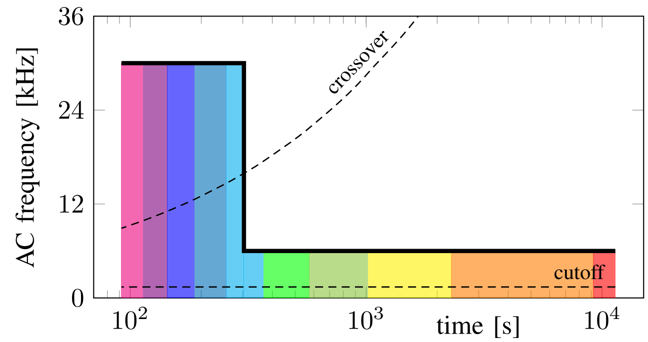
It can be seen that, for simplicity, the frequency response was only changed abruptly between nDEP and pDEP. Here, the fine control is primarily done with the help of the voltage amplitude.

V. Conclusions and Outlook

The present work has demonstrated the fundamentals of dielectrophoretic particle manipulation in a stationary liquid column. Simulation results show that in the vertical separation section, particles are successfully separated due to their different sizes. This allows the particles to be deflected horizontally in the electric field in the lower region, staggered in time according to size, by the action of the dielectrophoretic force. A defined time-dependent control of the AC signal offers the



(a) Time-controlled voltage amplitude.



(b) Time-controlled AC frequency.

Fig. 11: Time-controlled AC signal.

possibility of largely elective particle deflection or sorting. Both a purely frequency-controlled and a combined amplitude- and frequency-controlled AC signal could be successfully simulated.

Further investigations will include, on the one hand, the integration of particle focusing electrodes between the vertical separation section and the horizontal deflection section to ensure that the particles are centered in the stationary liquid column. In addition, optimized deflection electrodes are being investigated to guarantee improved and robust operation in practice. On the other hand, an experimental setup will be realized to validate the simulation results.

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