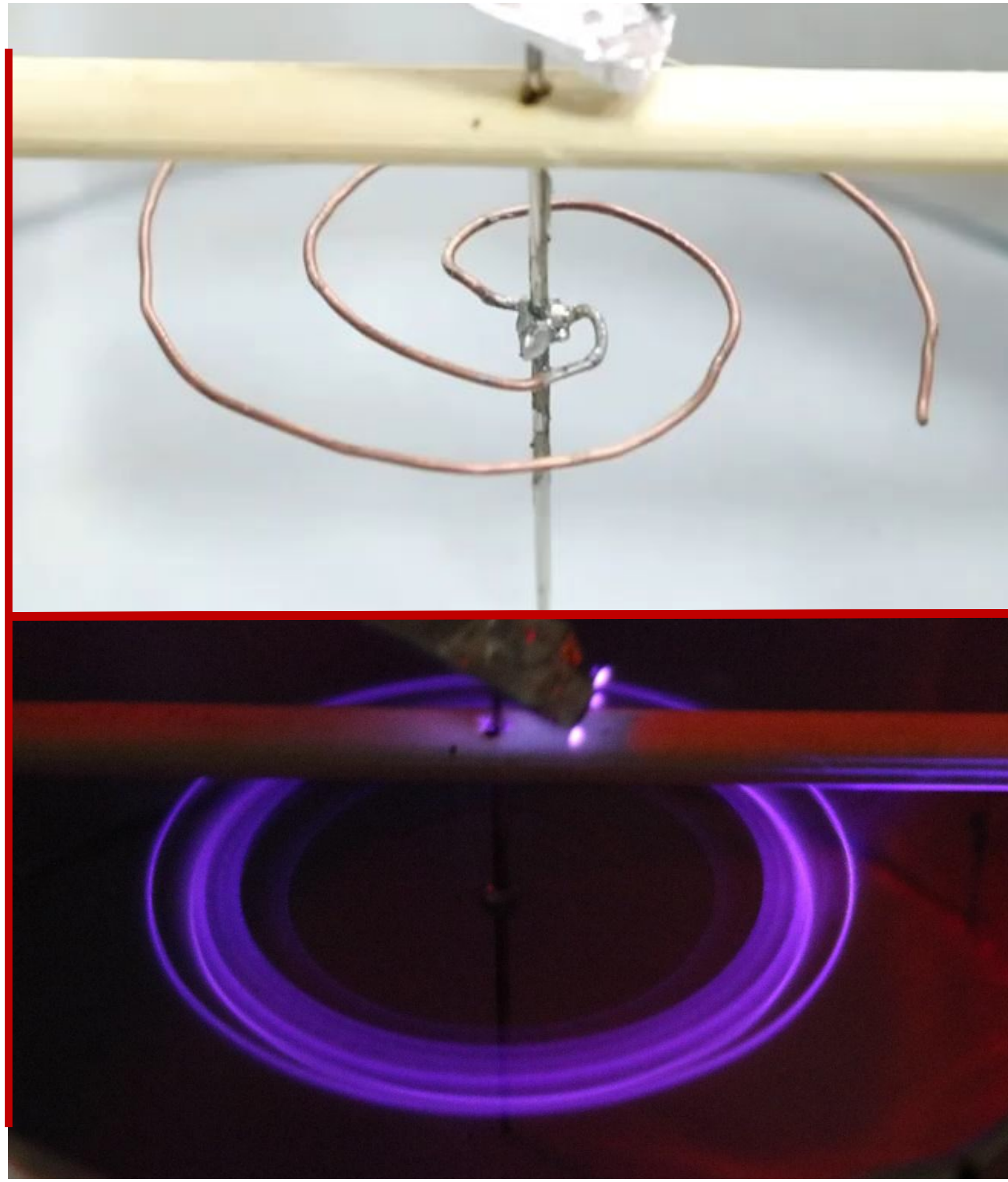
Problem № 1
«Invent Yourself»

Build a simple motor whose propulsion is based on corona discharge. Investigate how the rotor's motion depends on relevant parameters and optimize your design for maximum speed at a fixed input voltage.



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Outline

Qualitative description of the operating principle of the electrostatic motor

Development and construction of the device

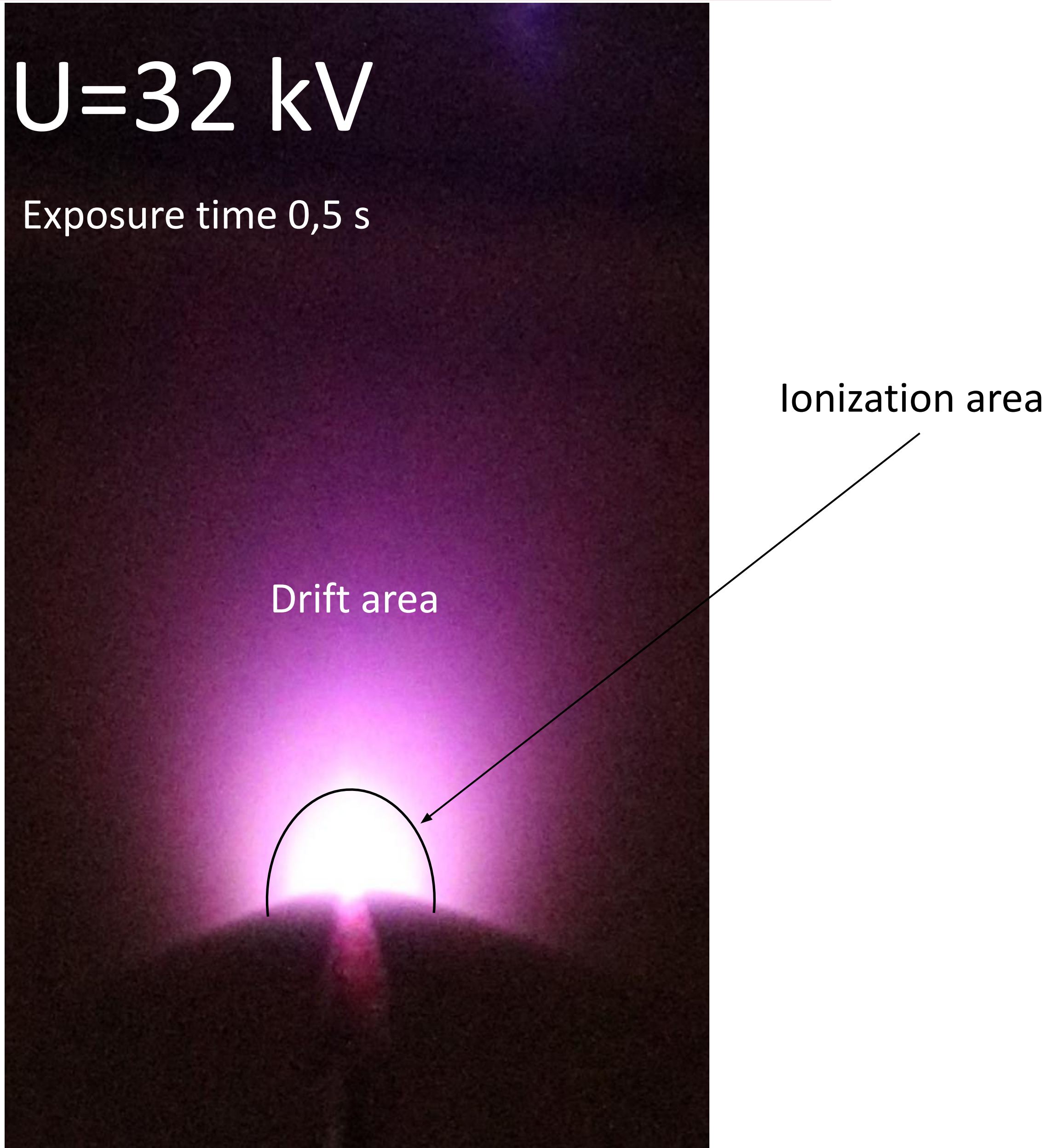
Physical and mathematical models of the rotor movement

Optimization of the device

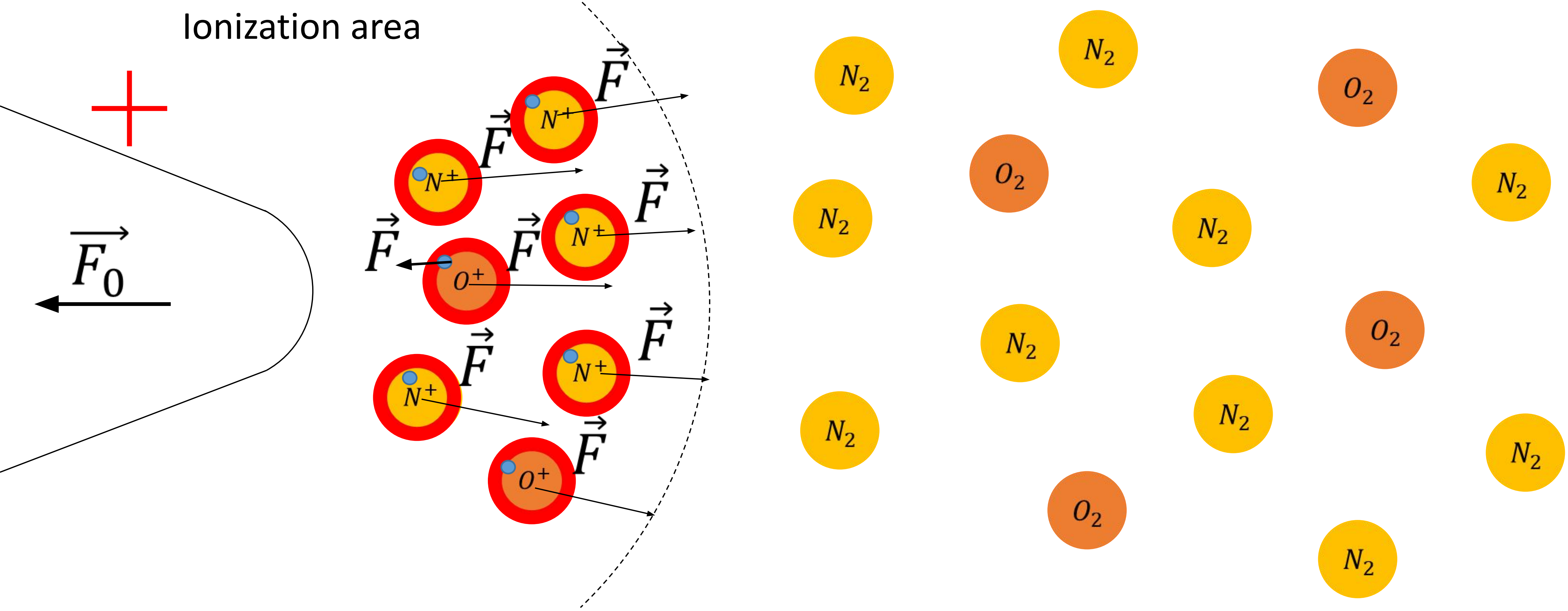
Conclusion remarks

Basic concepts

A **corona discharge** is an electrical discharge brought on by the ionization of a fluid such as air surrounding a conductor that is electrically charged. A corona discharge may occur in **highly inhomogeneous** electric fields near the electrodes with a high curvature of the tip.



Qualitative explanation

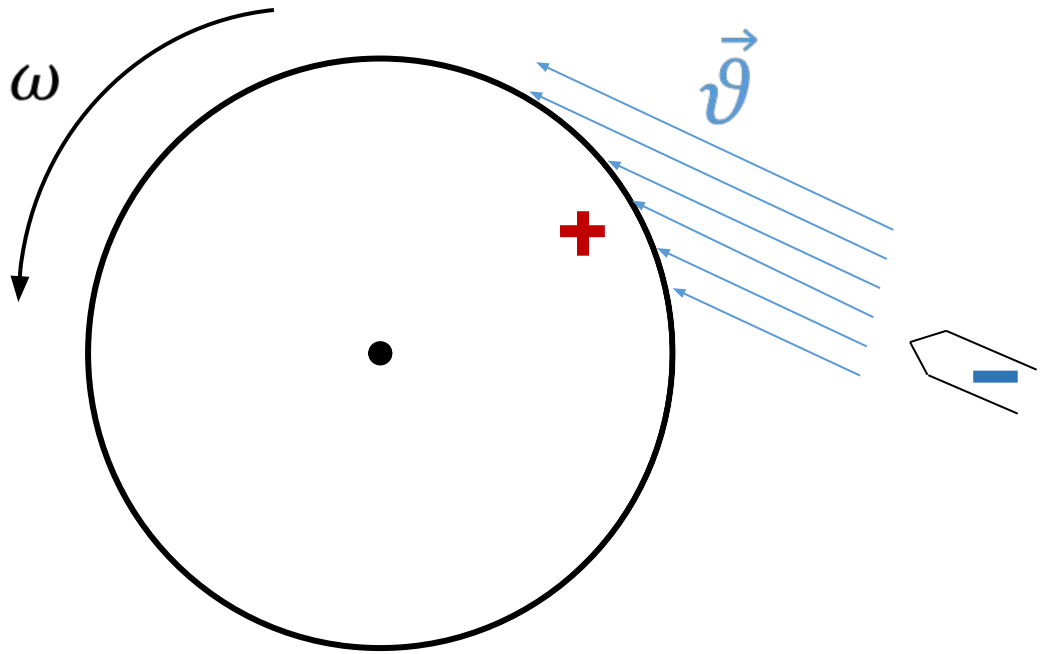


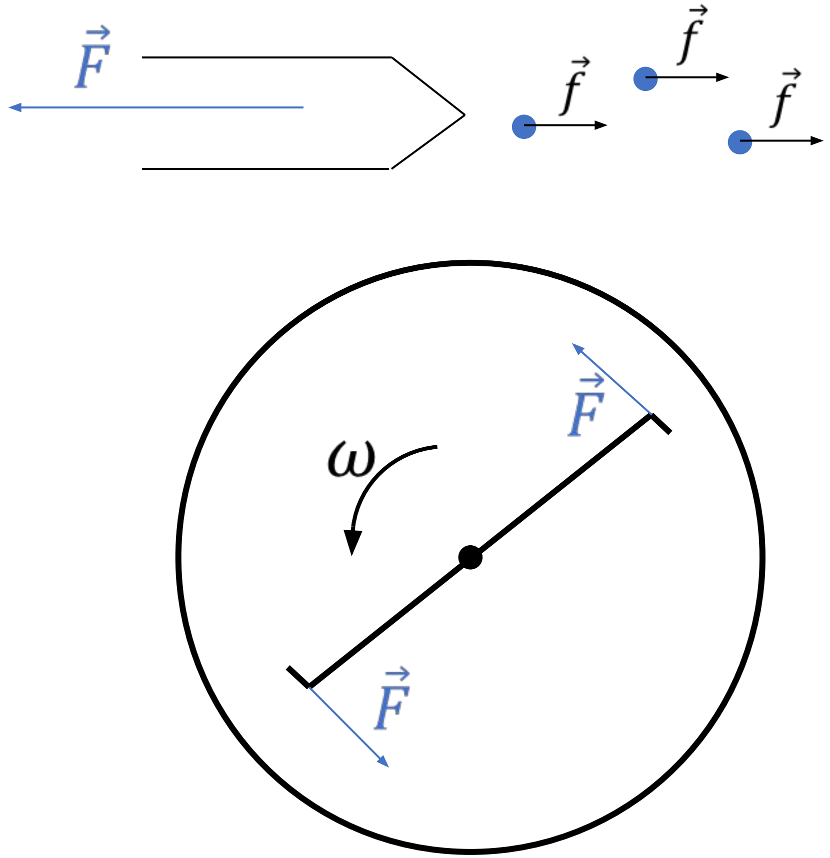
Qualitative explanation

Possible design

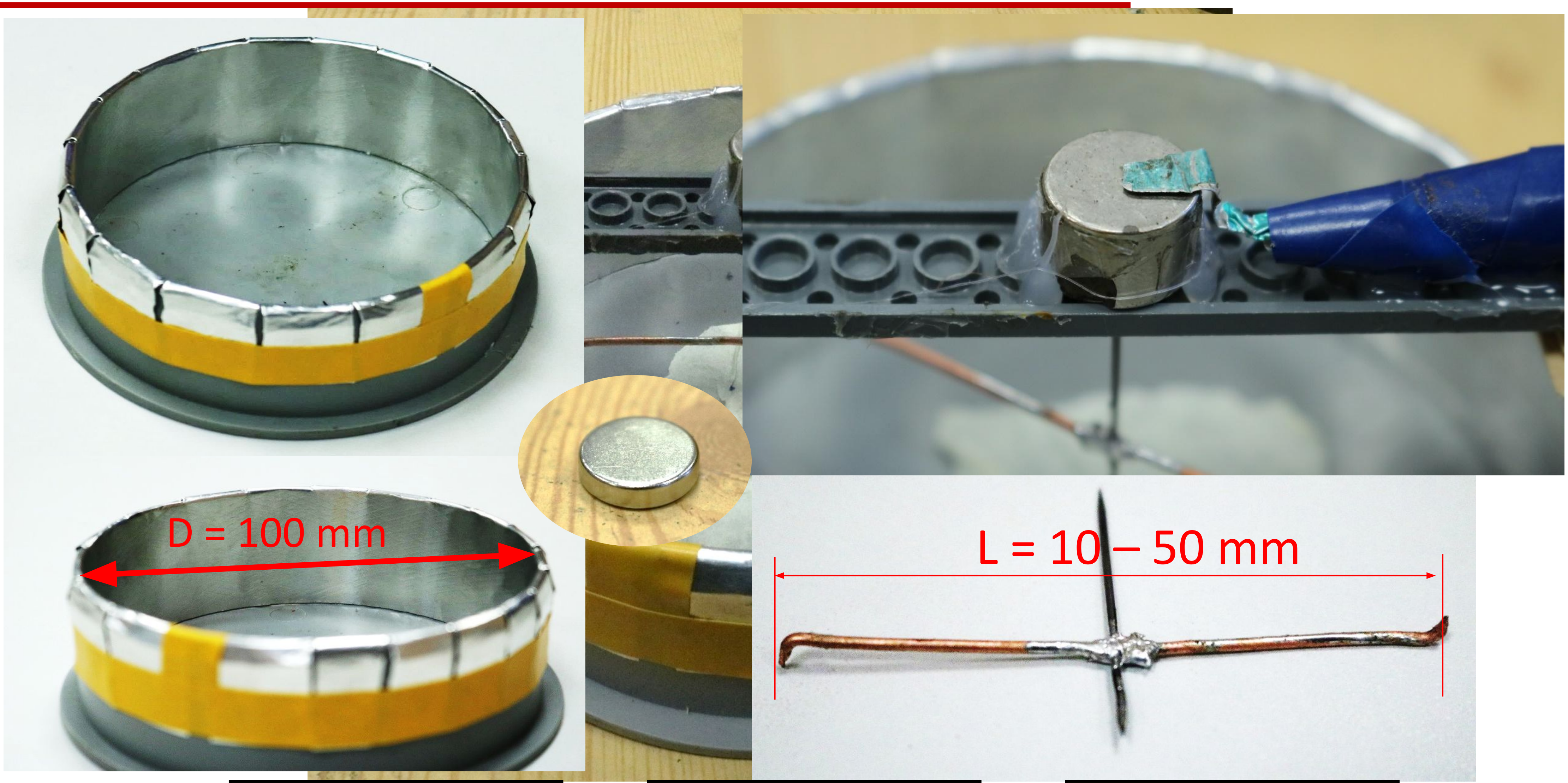
Experimental setup

Possible design





Experimental setup

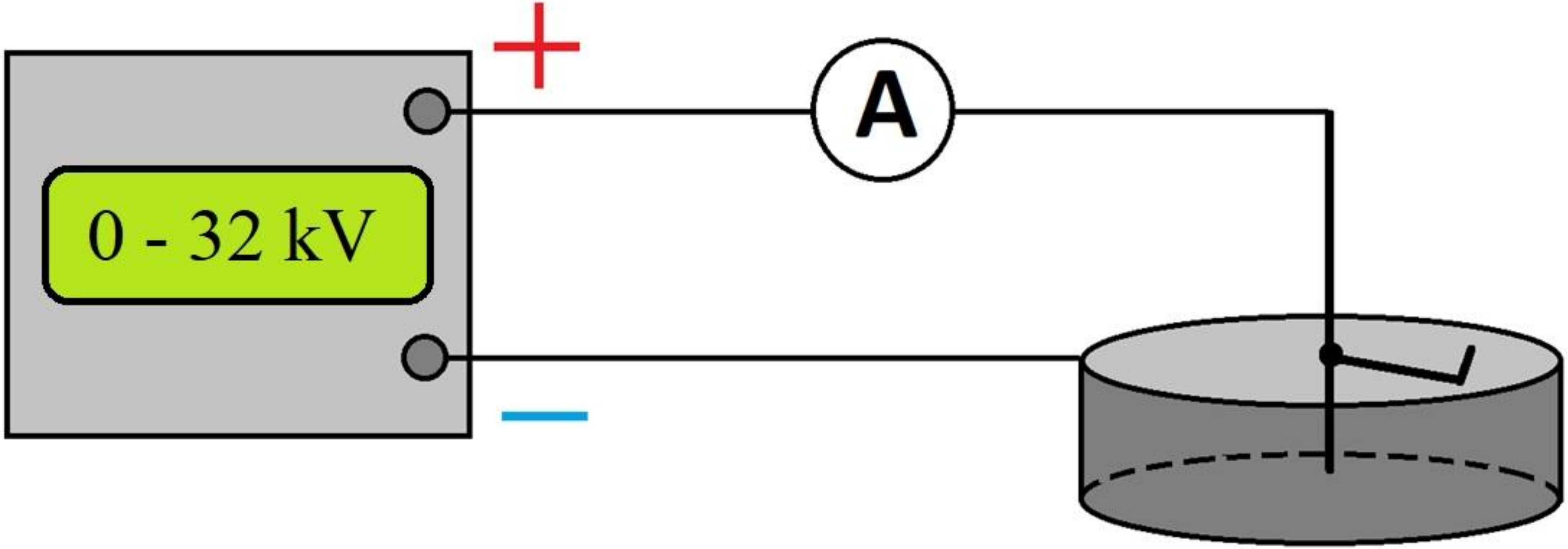


Qualitative explanation

Possible design

Experimental setup

Experimental setup

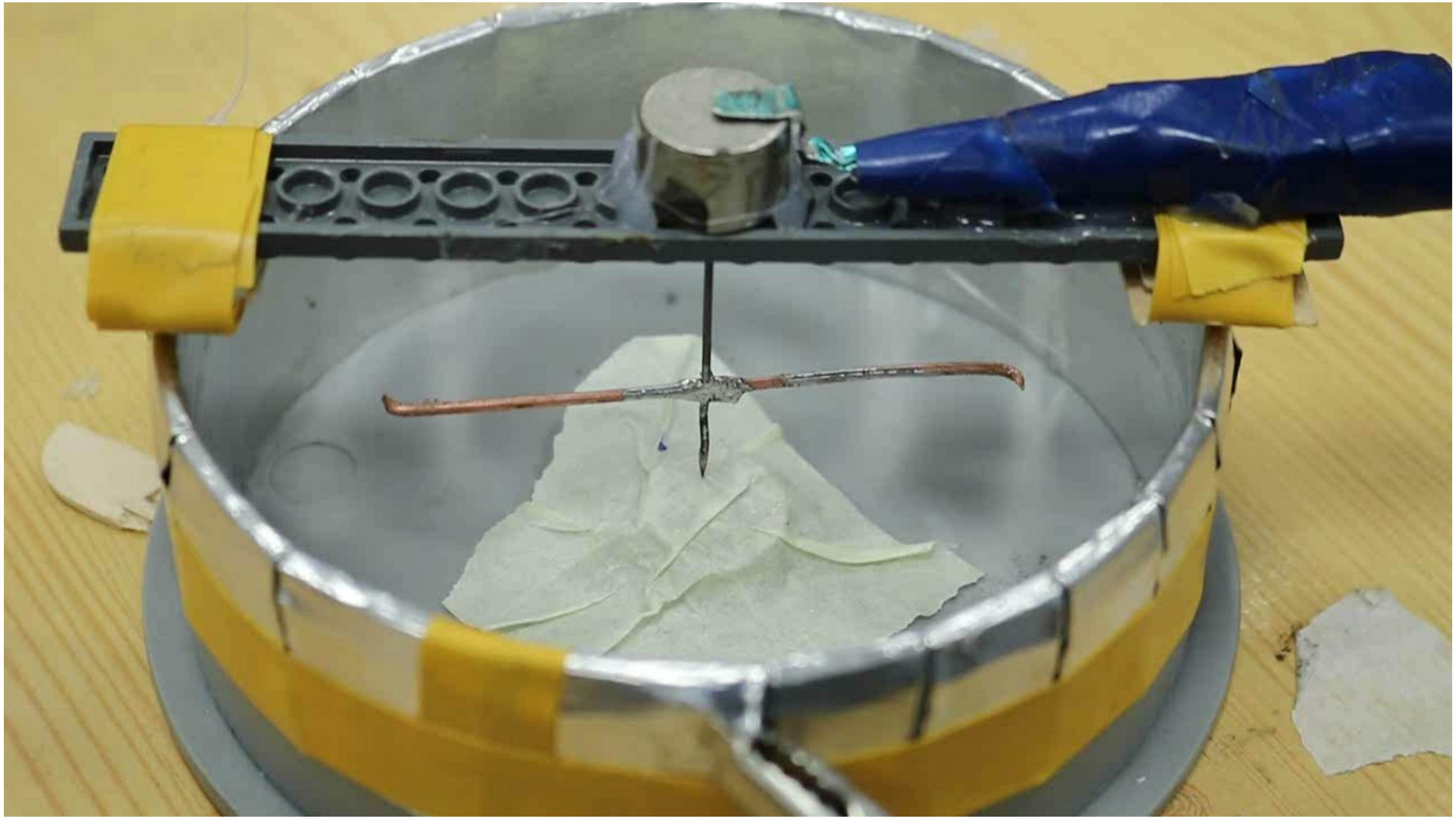


Qualitative explanation

Possible design

Experimental setup

Experimental setup

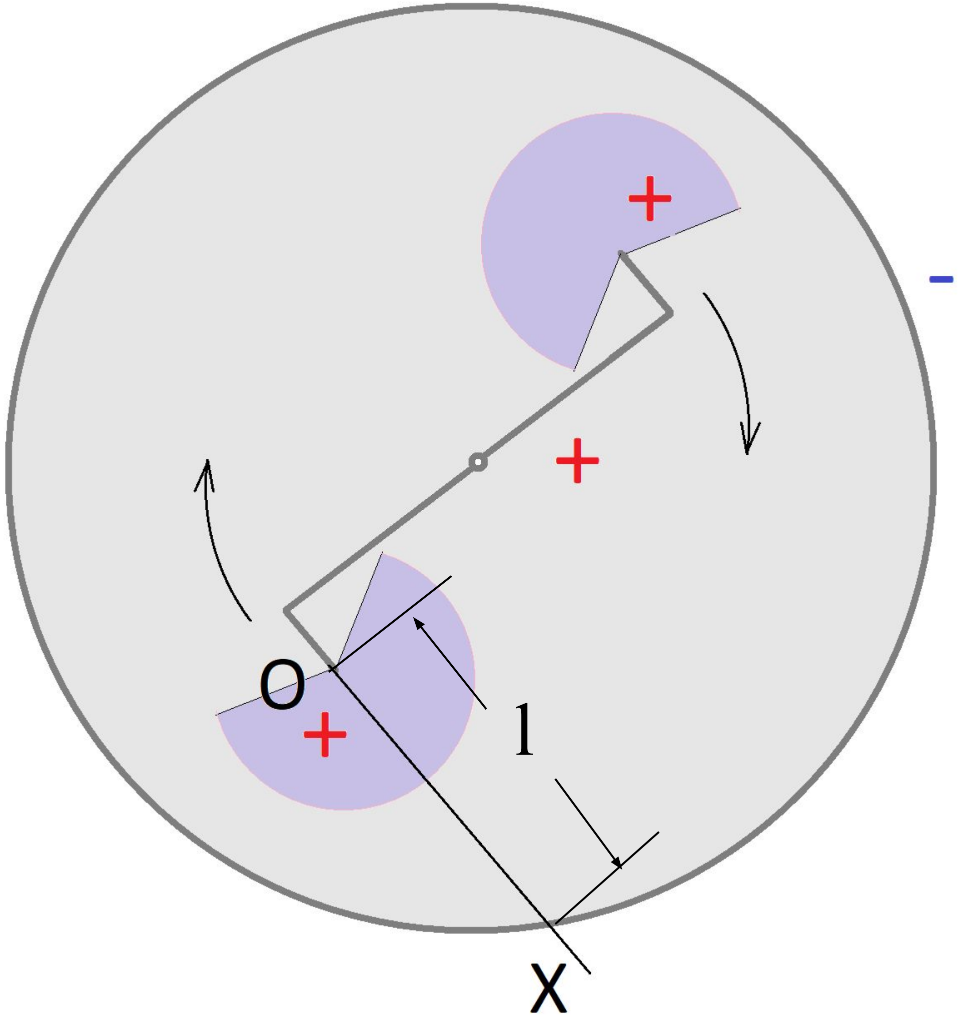


Qualitative explanation

Possible design

Experimental setup

Driving force



$$\vec{F} = \sum \vec{E} q$$

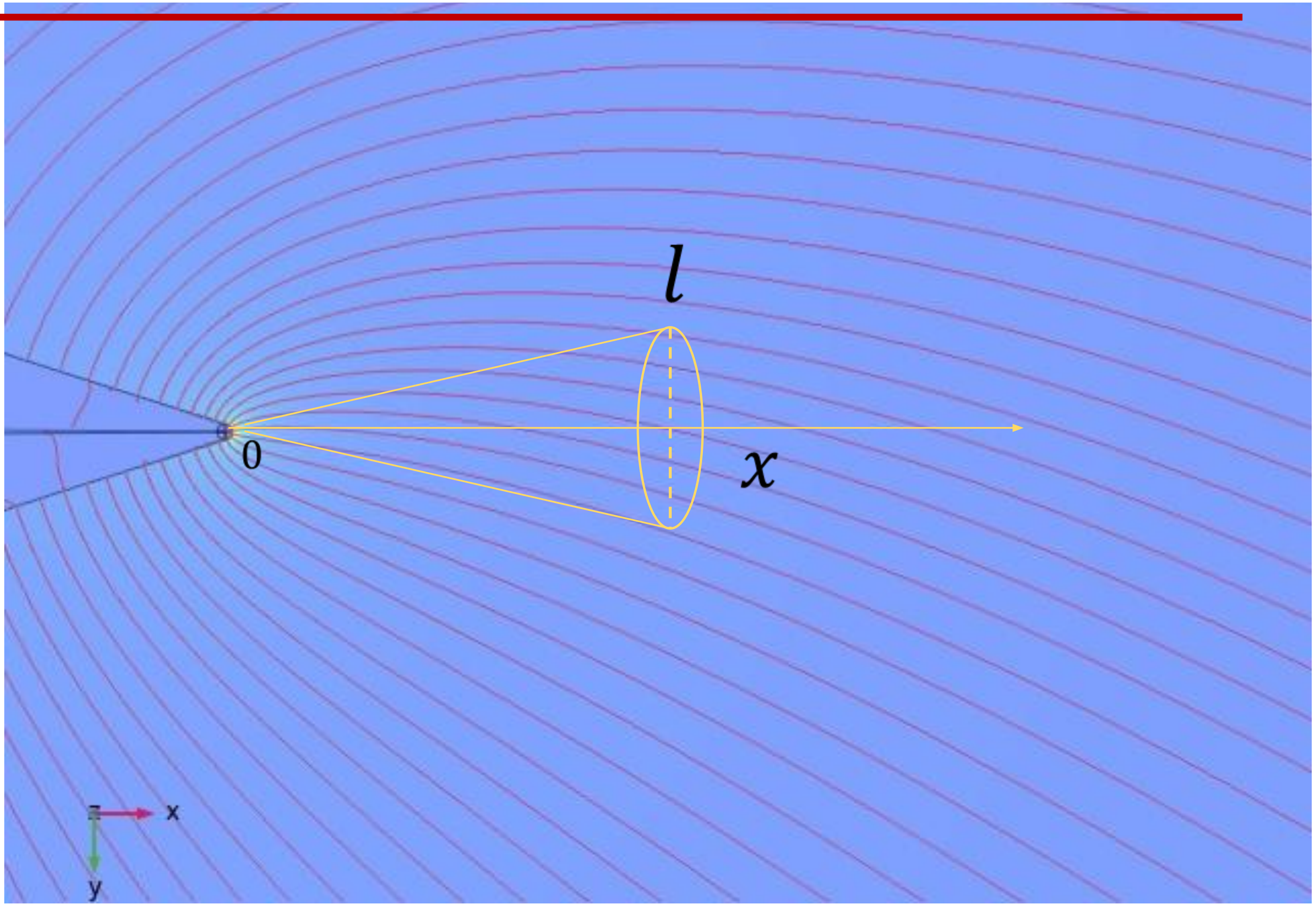
$$F_x = \sum E_x q$$

$$F_x = \int_r^l E_x(x) \rho(x) dV$$

r – curvature of the tip
l – distance from the tip to the outer electrode

Experimental setup | Theory | Optimization

Driving force: calculation of the electric field

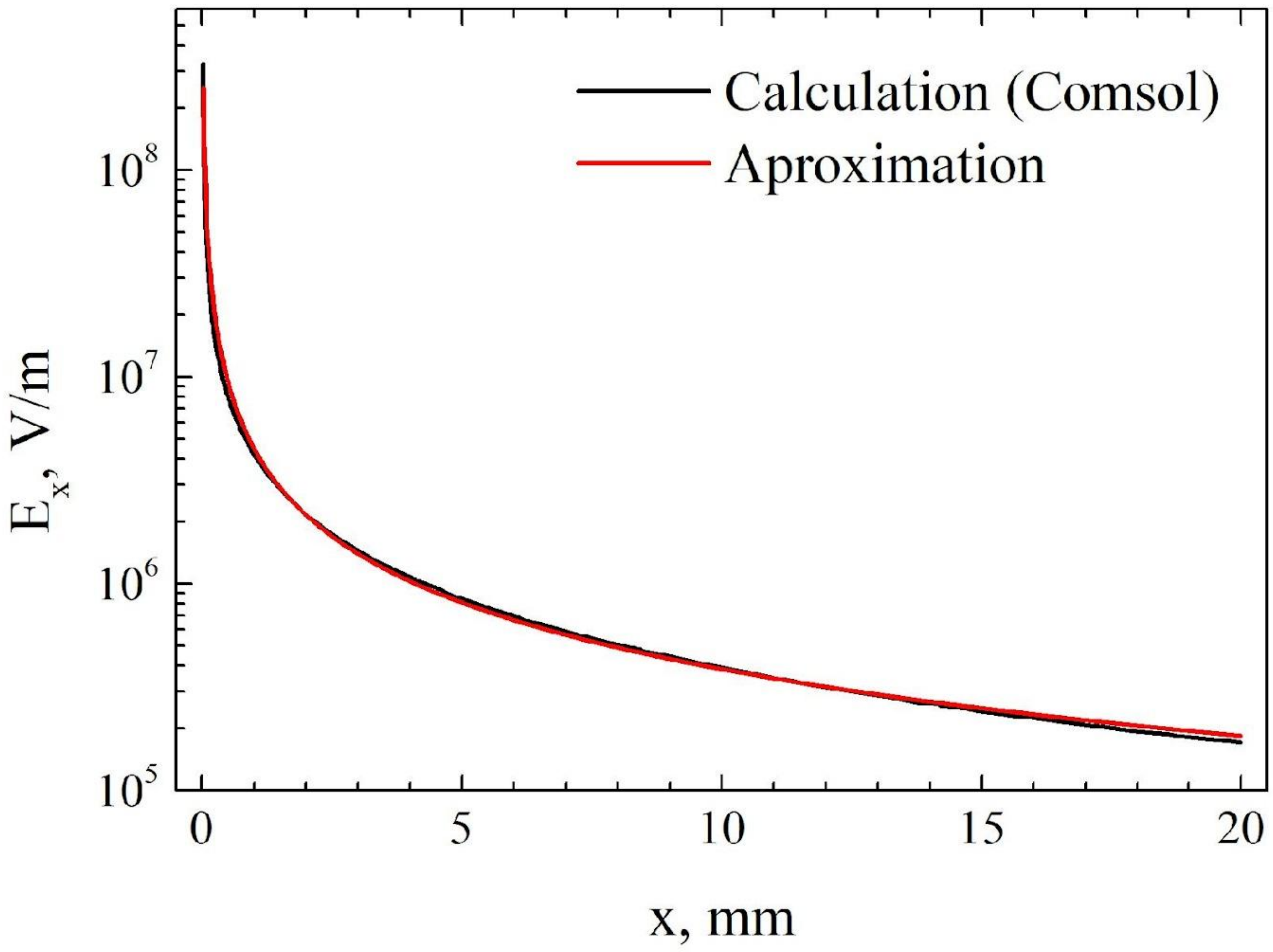


COMSOL calculation

Parameters:
r = 0.0002 m
T = 296 K
$P = 10^5$ Pa
φ = 32 kV

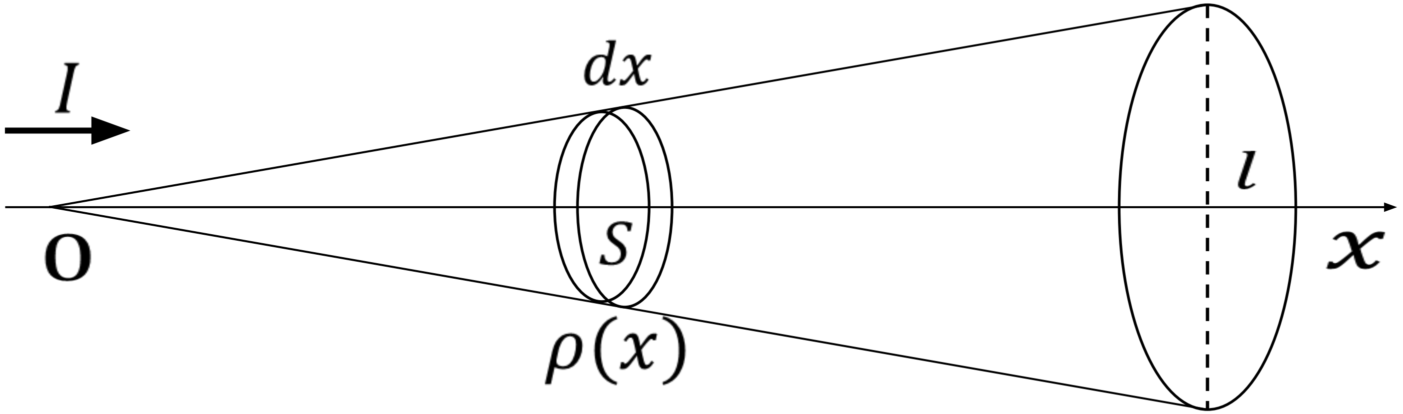
Experimental setup | Theory | Optimization

Driving force: calculation of the electric field



Optimization

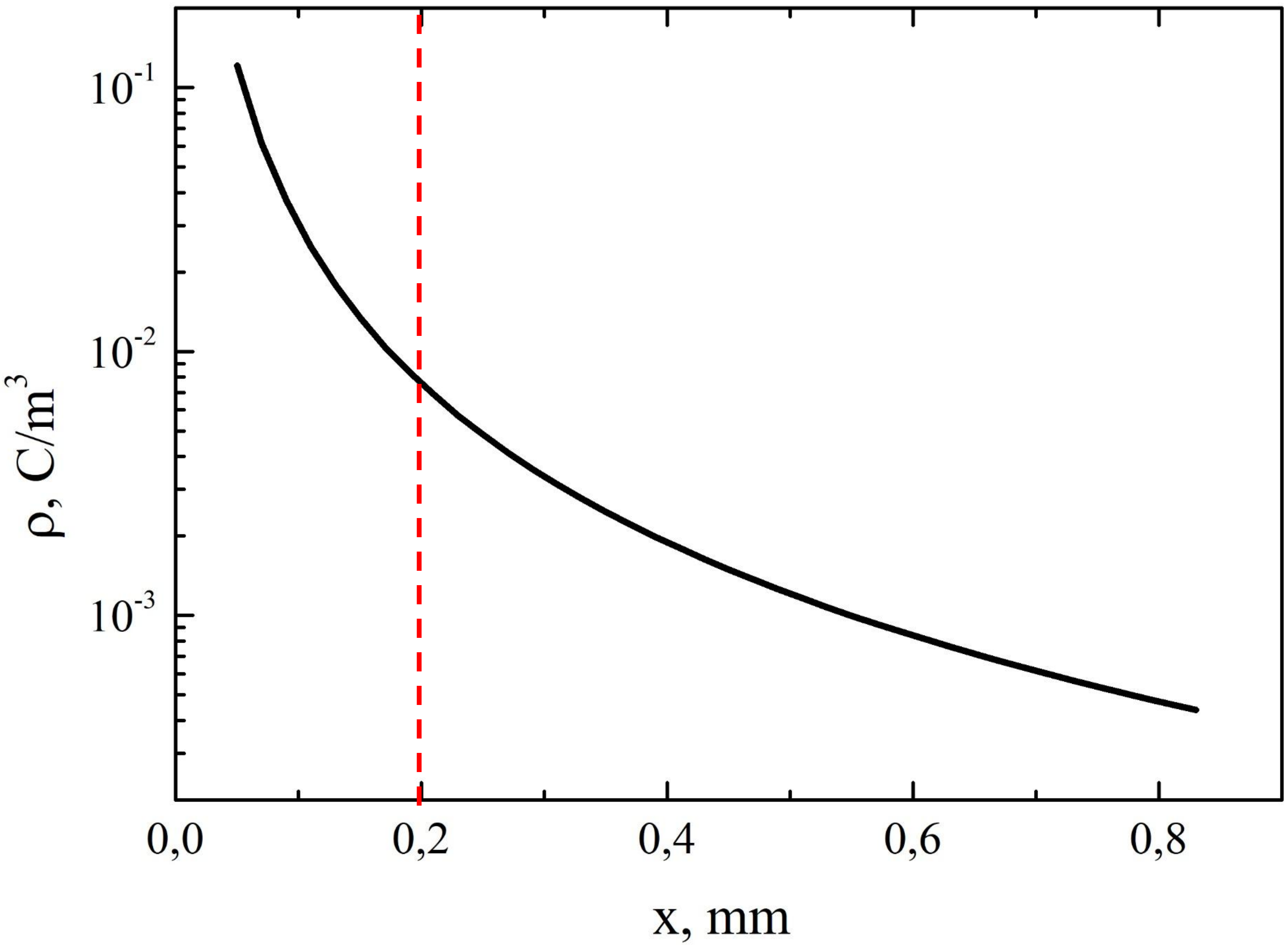
Driving force: calculation of the volume charge density



$$\rho(x) = \frac{dq}{dV(x)} = \frac{I_0 dt}{x^2 \Omega dx} = \frac{I_0}{x^2 \Omega (\frac{dx}{dt})}$$

Charge density

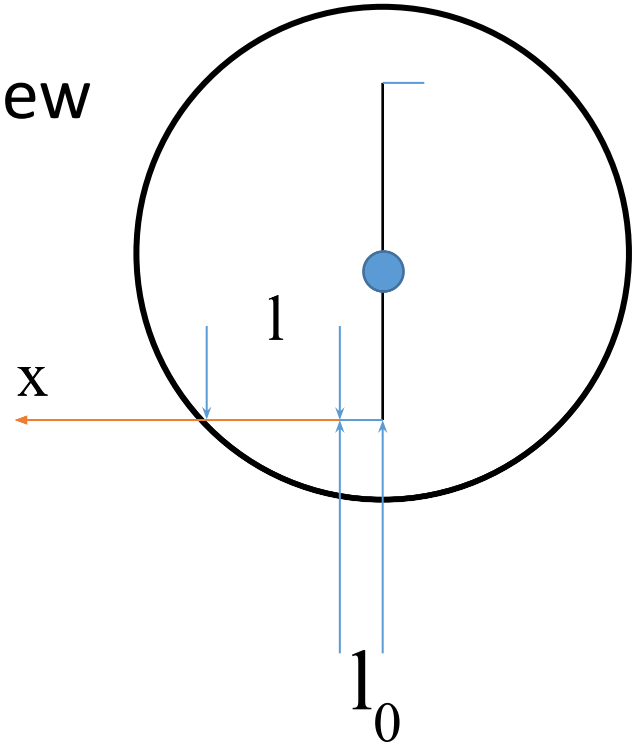
$$\rho(x) = \frac{I_0}{x^2\Omega}\sqrt{\frac{2m}{\gamma e}}$$



Experimental setup | Theory | Optimization

Driving force

Top view



$$F_x = \int_r^l E_x(x)\rho(x)x^2\Omega dx$$

$$\rho(x) = \frac{I_0}{x^2\Omega}\sqrt{\frac{2m}{\gamma e}}$$

$$E_x(x) = \frac{\gamma(U)}{x}$$

$$F = \frac{I}{N}\sqrt{\frac{2\gamma m}{e}} ln\frac{l}{r}$$

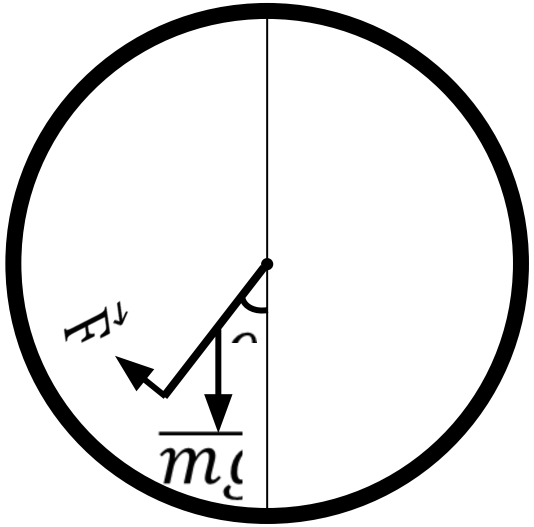
l – distance from the tip to the outer electrode

r – curvature of the tip

$I = NI_0$, where N – number of tips

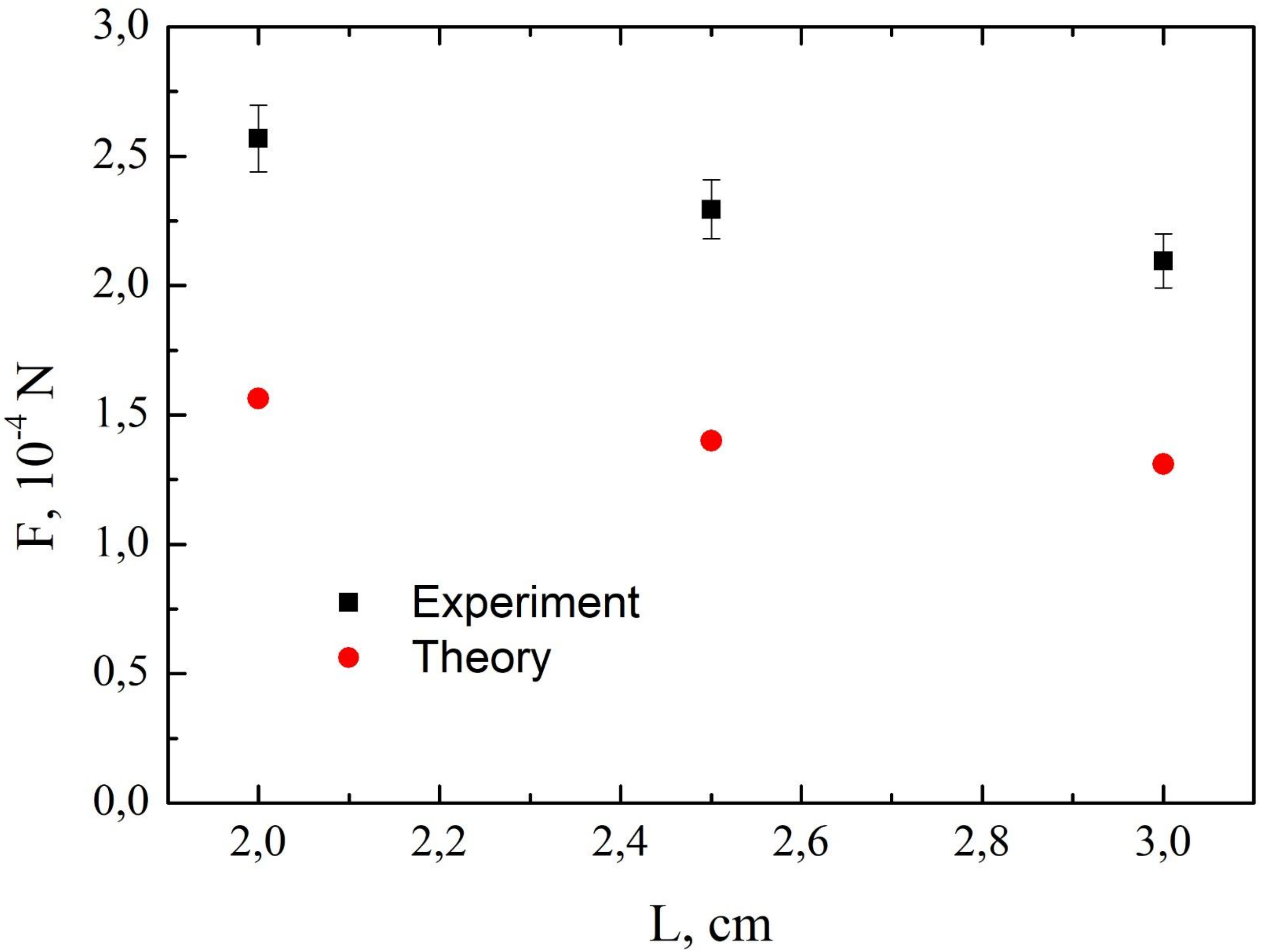
Experimental setup | Theory | Optimization

Measurement of the driving force

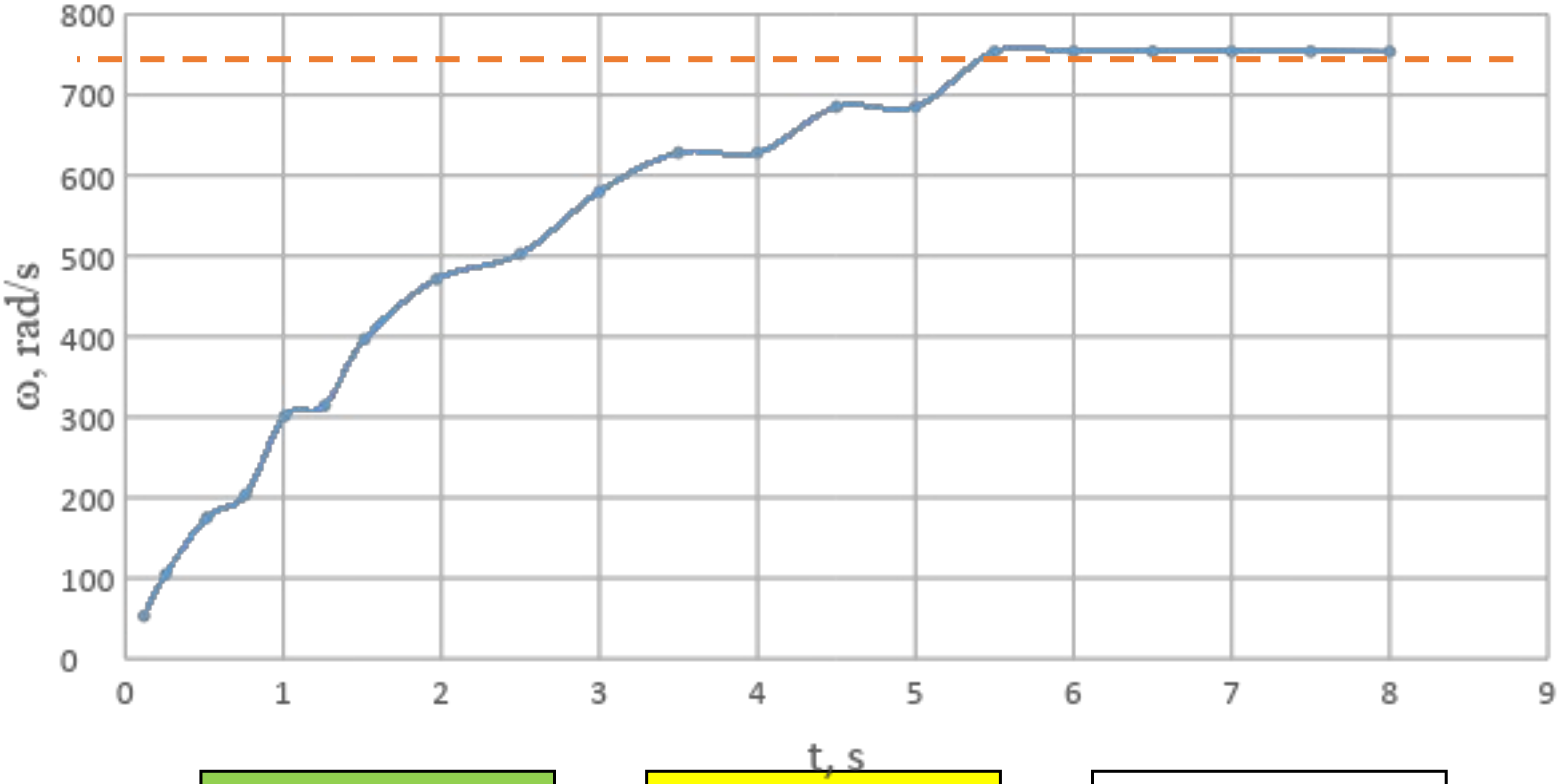


$$F_{exp} = \frac{mg\sin\alpha}{2}$$

$$F_{teor} = I\sqrt{\frac{2\gamma m}{e}ln\frac{l}{r}}$$



Angular velocity

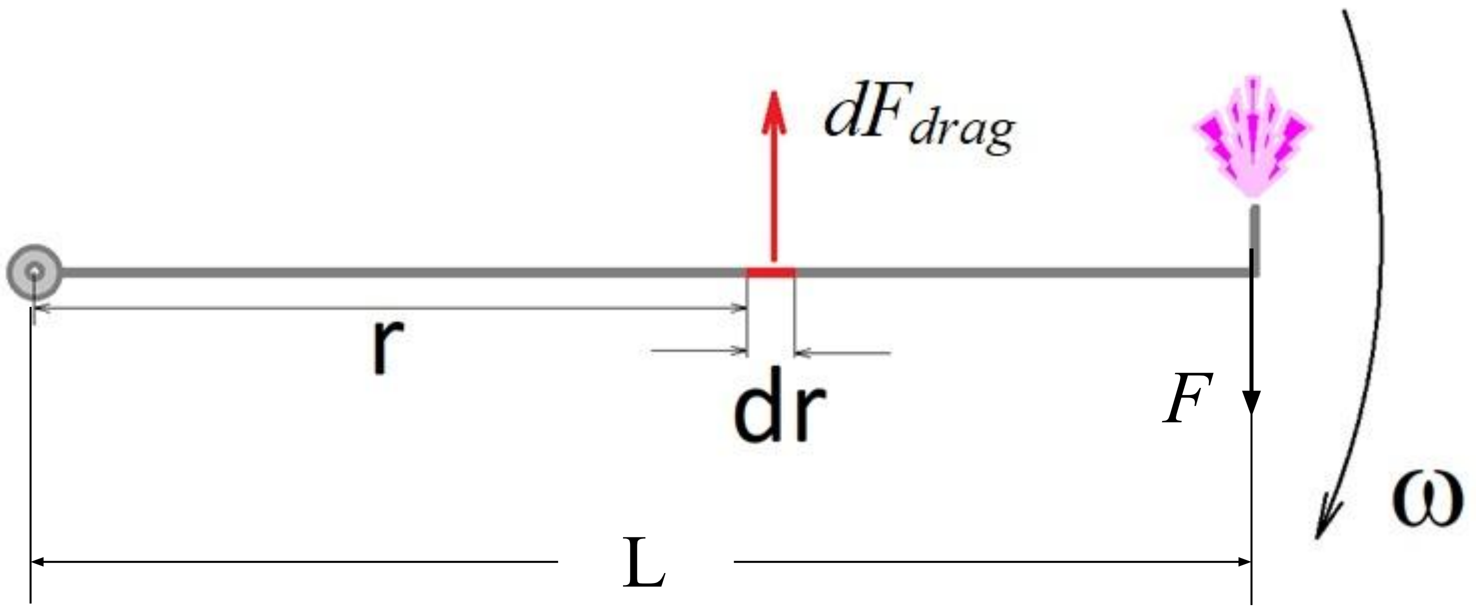


Experimental setup

Theory

Optimization

Drag force torque



$$dF_{drag} = -C_x \frac{\rho V^2}{2} dS$$

$$V(r) = \omega r$$

$$C_x = 0.8 \quad \text{(for cylinder)}$$

$$dM_{drag} = r \cdot dF_{drag}$$

d_0 – diameter of the arm cross section

$$M_{drag} = \int_0^L C_x \frac{\rho \omega^2 r^3}{2} d_0 dr = FL \quad \Rightarrow \quad F = \frac{1}{8R} C_x \cdot \frac{PM}{T} \cdot d_0 \omega^2 L^3$$

Angular velocity

$$F = \frac{I}{N}\sqrt{\frac{2\gamma m}{e}}\ln\frac{l}{r}$$

$$l = \sqrt{R_0^2 - L^2} - l_0$$

$$F = \frac{1}{8R} C_x \cdot \frac{PM}{T} \cdot d_0 \omega^2 L^3$$

$$\omega = \sqrt{\frac{6IRT}{N C_x P M d_0 L^3}\sqrt{\frac{2\gamma m}{e}}\ln\frac{l}{r}}$$

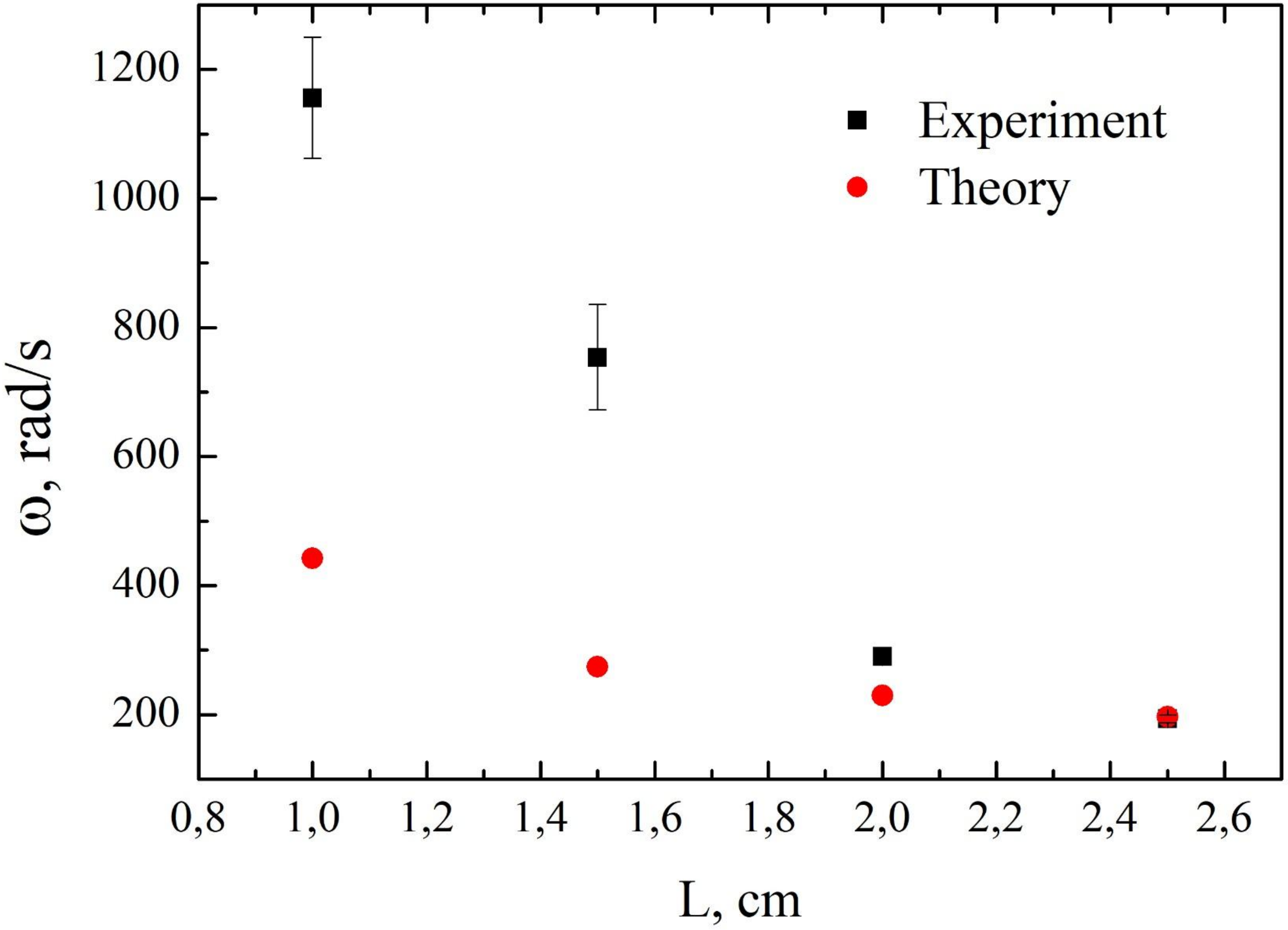
R – gas constant (8.314 J/mol·K)
T – air temperature (296 K)
C_x – drag coefficient (0.8 for the cylinder)
P – ambient pressure (1 atm)
M – air molar mass (29 g/mol)
d_0 – rotor crossection diameter
L – arm length
I – current
r – curvature of the tip
R_0 – radius of the outer electrode
l_0 – length of the tip
N – number of tips

Variable parameters

d_0 | **L** | **C_x** | **R_0** | **l_0**

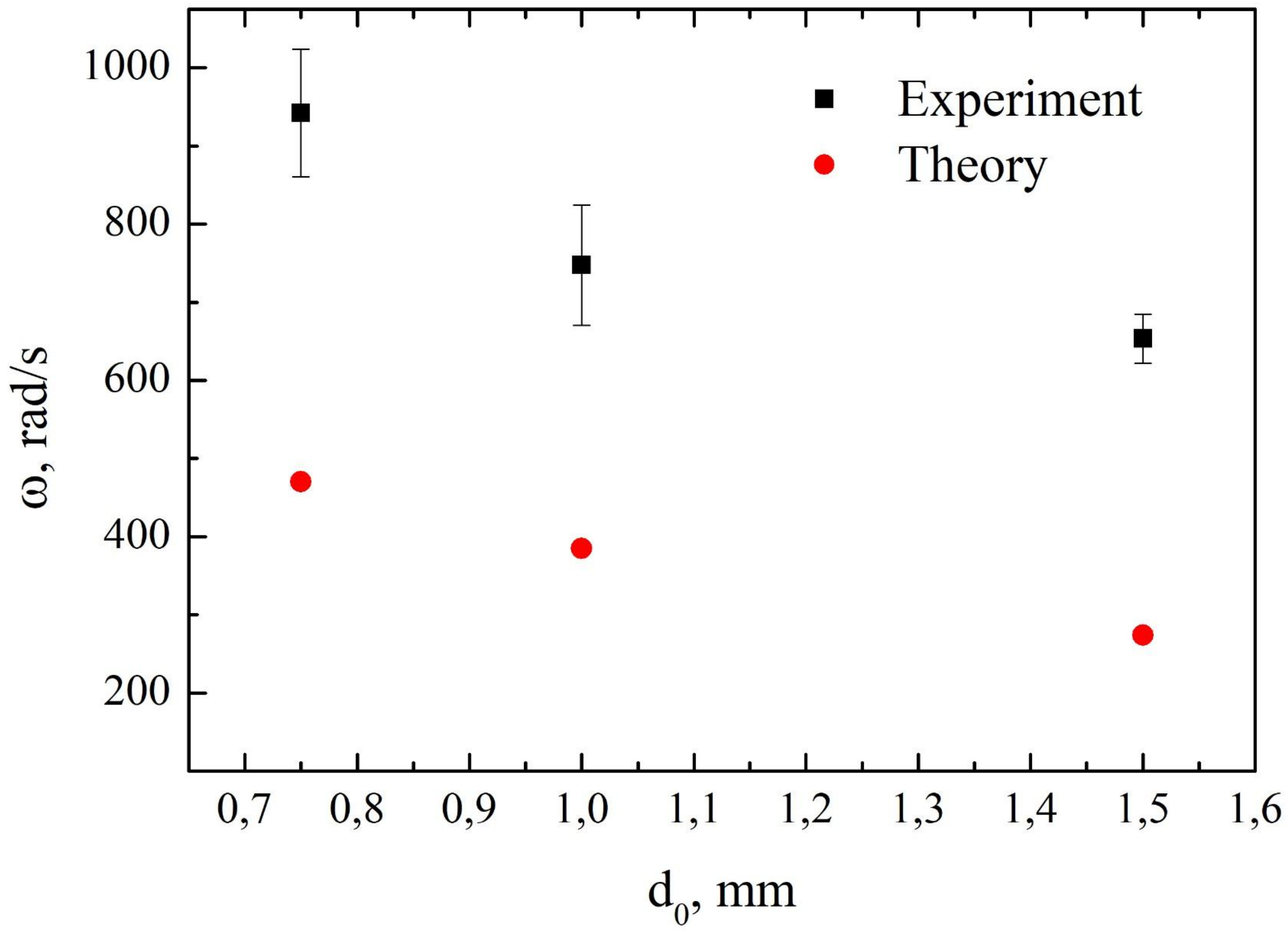
Experimental setup | Theory | Optimization

Relevant parameters: arm length



$r = 0.03$ mm
$l_0 = 5$ mm
$d_0 = 0,75$ mm
$N = 2$

Relevant parameters: arm diameter

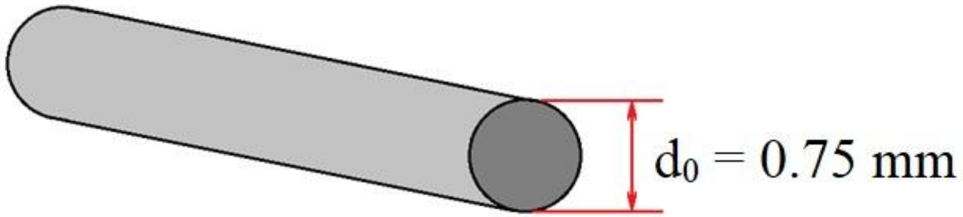


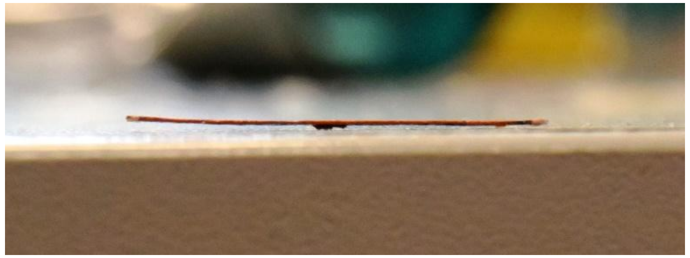
$r = 0.03$ mm
$l_0 = 5$ mm
$L = 1$ cm
$N = 2$

Experimental setup | Theory | Optimization

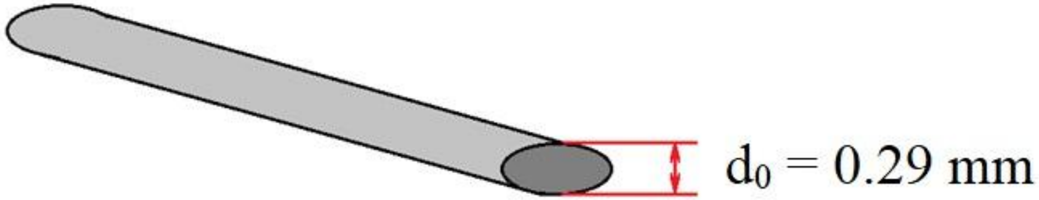
Relevant parameters: drag coefficient

$$C_x = 0.8$$





$$C_x = 0.08$$



$L = 1$ cm

$d_0 = 0.29$ mm

$$\omega_{max} = 1510\, rad/s$$

Experimental setup | Theory | Optimization

Conclusion

- The operation principle of the corona discharge electrostatic motor is explained.
- The device was constructed
- A theoretical model, which determines the driving force, torque, angular velocity of the rotor was developed;
- The relevant parameters, which determine the angular velocity of the rotor, were revealed at a fixed applied voltage. There are: the arm length, the number of arms, the cross section of the wire.
- The angular velocity was maximized at a constant applied voltage. The maximal value was 1510 rad/s.

Thank you for your attention!

Driving force: calculation of the volume charge density

$$x(t) = x_0 + v_0 t + \frac{at^2}{2} \qquad x_0 = 0;\ v_0 \ll v(t);\ E(x) = \frac{\gamma}{x}$$

$$x(t) = \frac{at^2}{2} = \frac{Ft^2}{2m} = \frac{\gamma \bar{e} t^2}{2mx} \quad \Rightarrow \quad t(x) = x\sqrt{\frac{2m}{\gamma \bar{e}}} \qquad \frac{dx}{dt} = \sqrt{\frac{\gamma \bar{e}}{2m}}$$

$$\rho(x) = \frac{I}{x^2 \Omega}\sqrt{\frac{2m}{\gamma e}}$$

I – current ($2 \cdot 10^{-4}$ A)
x – distance to the tip
Ω – solid angle (~2.5 π)
$\gamma = 2500$ V·m – parameter of the approximation
$e = 1.6 \cdot 10^{-19}$ C
$m = 2.41 \cdot 10^{-26}$ kg – average mass of the air ions

Efficiency

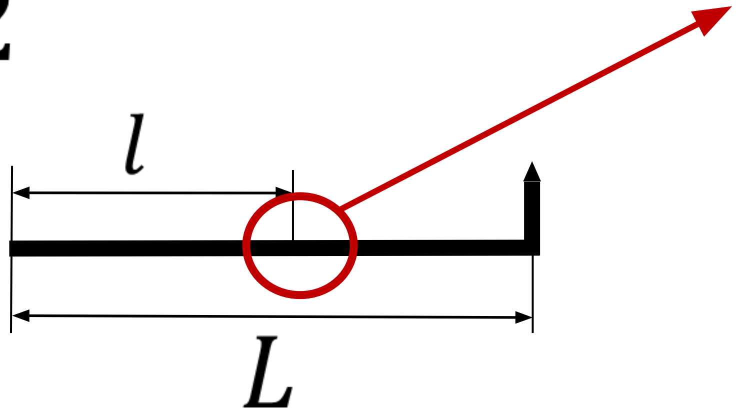
$$\eta = \frac{A_{\Pi}}{A} = \frac{FS}{UIt} = \frac{F\omega R}{UI} \sim 1\%$$

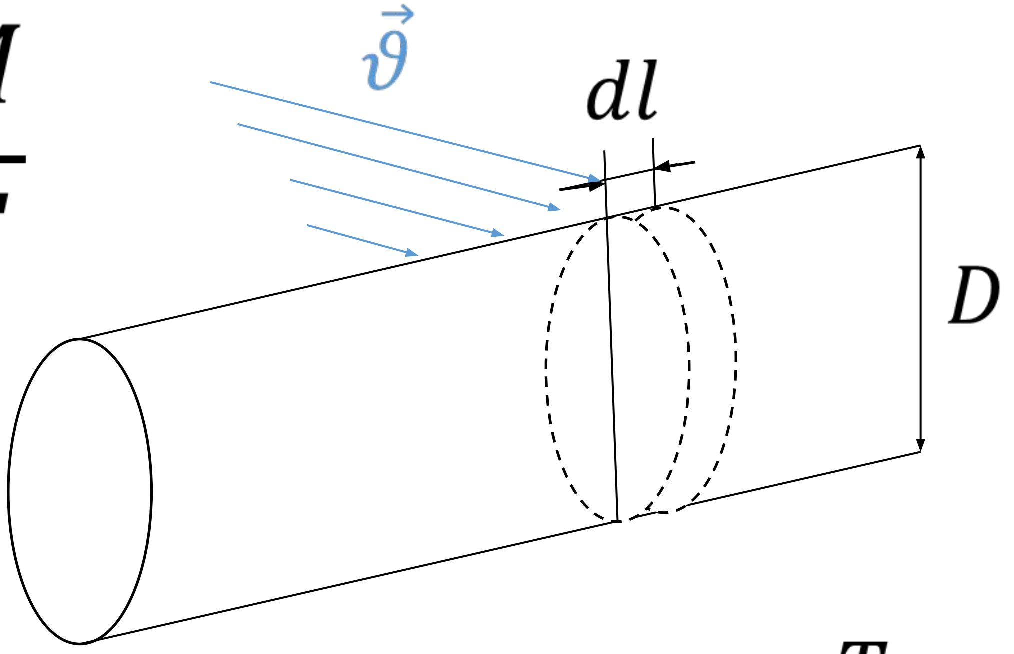
Experimental setup | Theory | Optimization

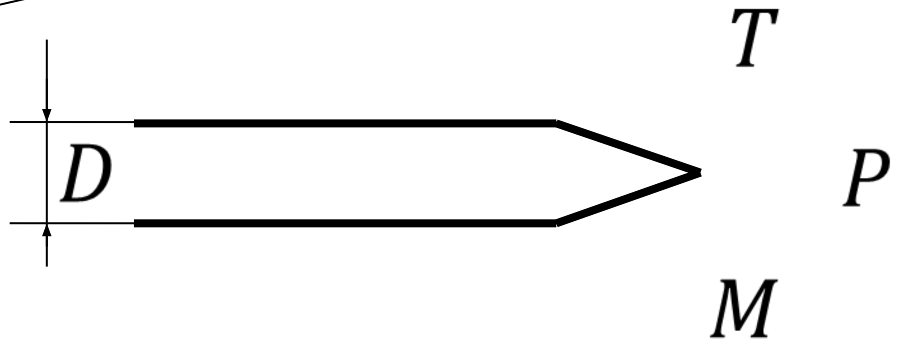
Drag force

$$\delta F = C \cdot \frac{\rho v^2}{2} dS \qquad \rho = \frac{PM}{RT}$$

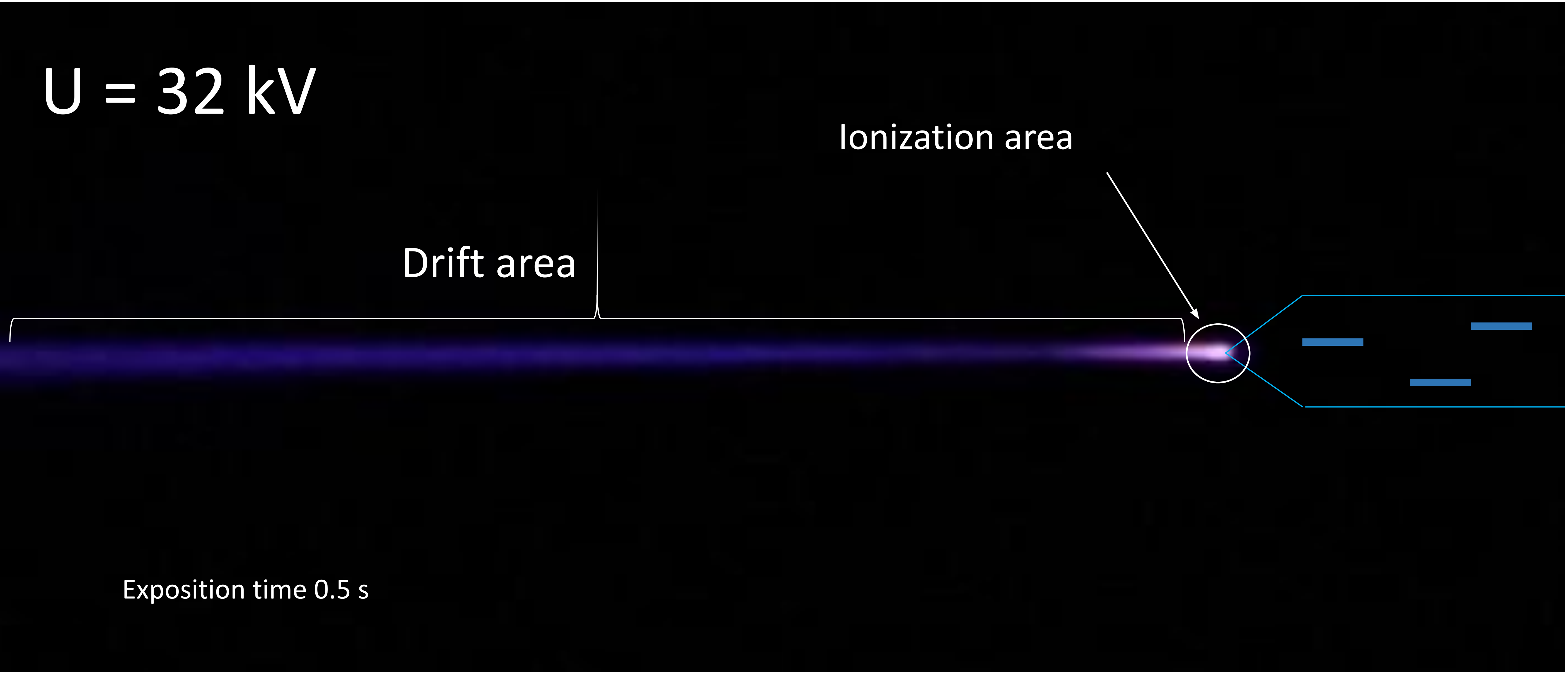
$$\delta M = C \cdot \frac{\rho v^2}{2} l dS$$





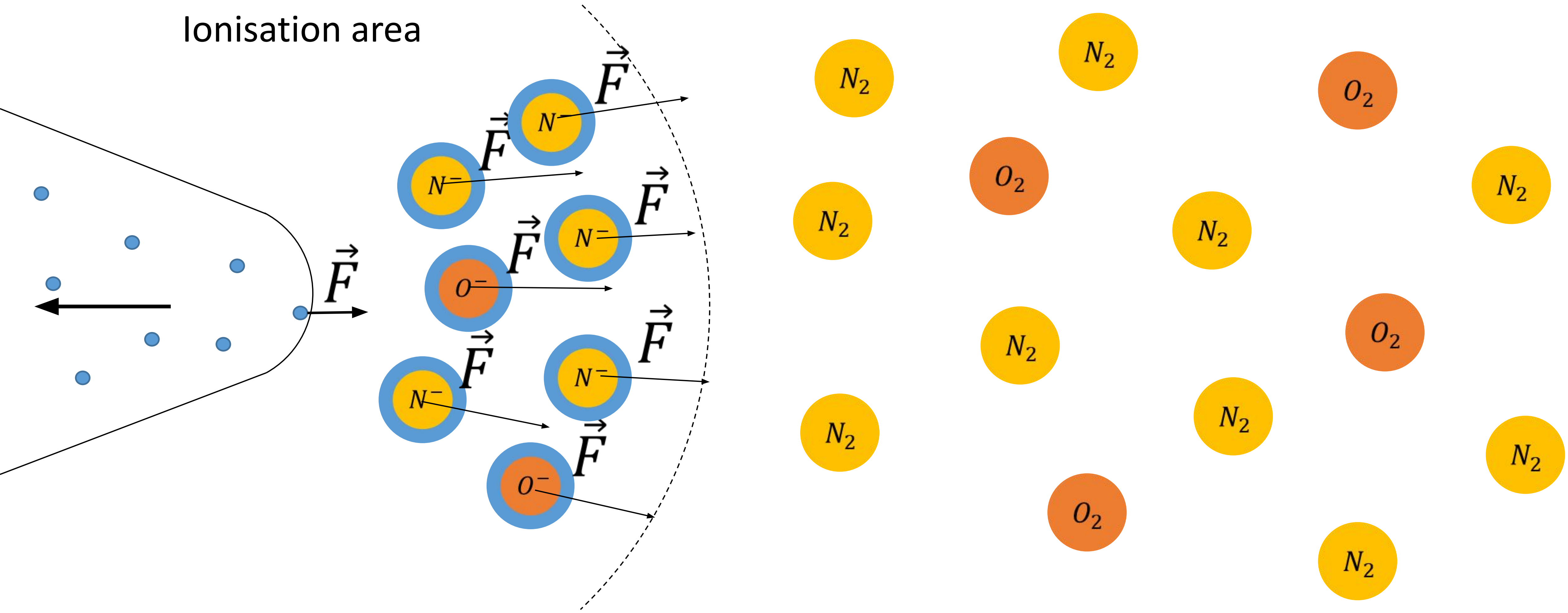


Negative corona discharge



Qualitative explanation

Ionisation area



Positive corona discharge