Problem № 1
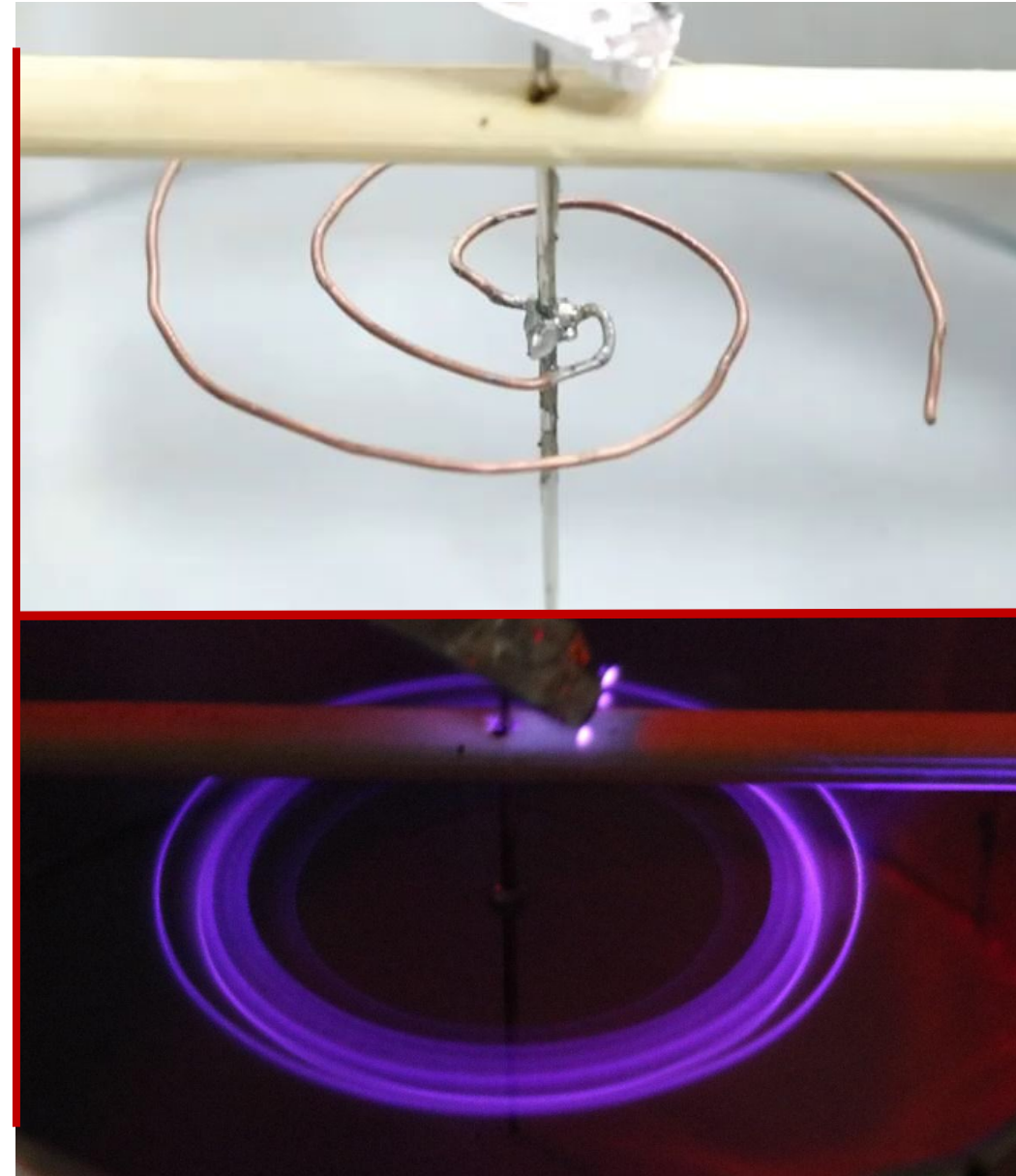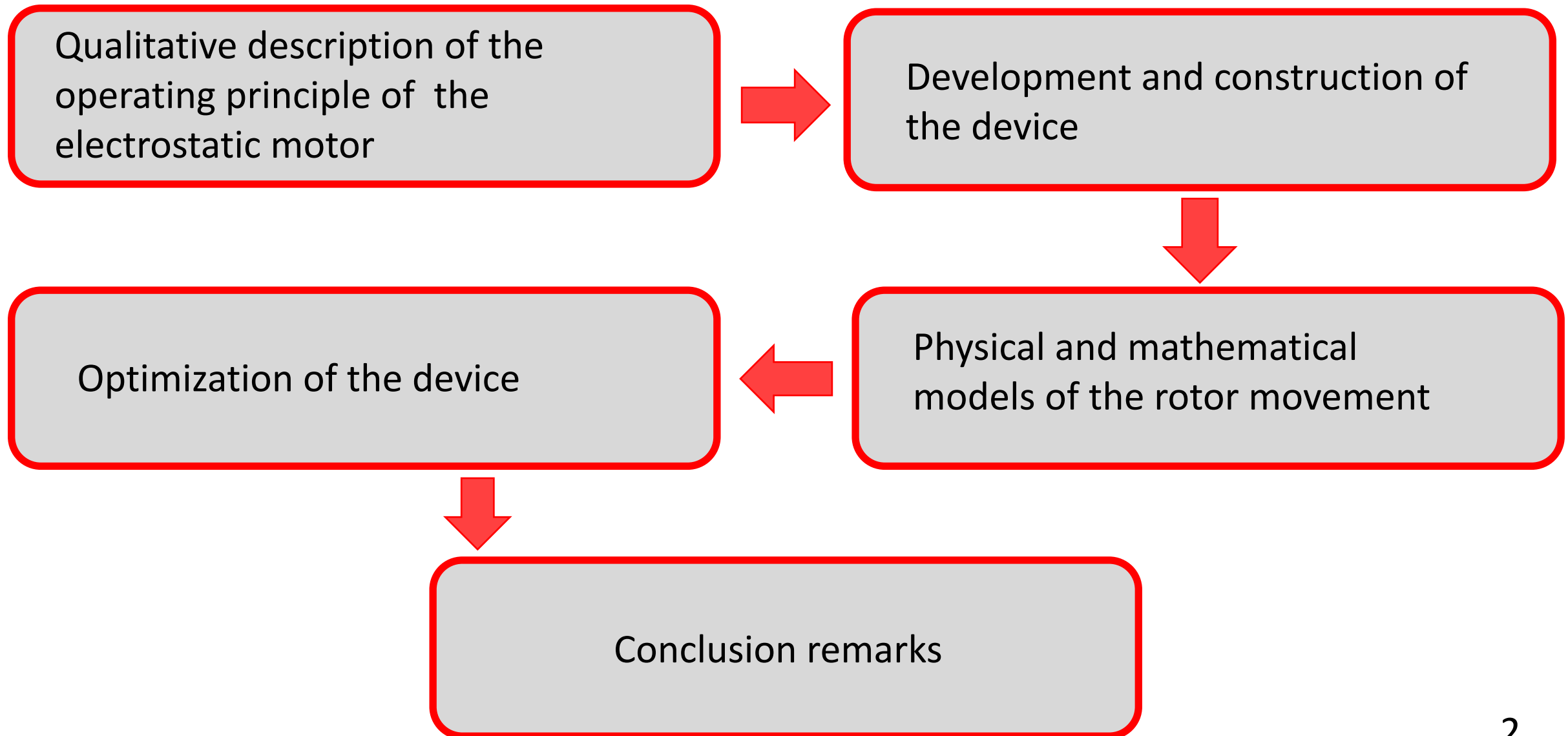# «Invent Yourself»

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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Team Russia, IYPT-2019

Outline

Qualitative description of the operating principle of the electrostatic motor

→

Development and construction of the device

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Physical and mathematical models of the rotor movement

←

Optimization of the device
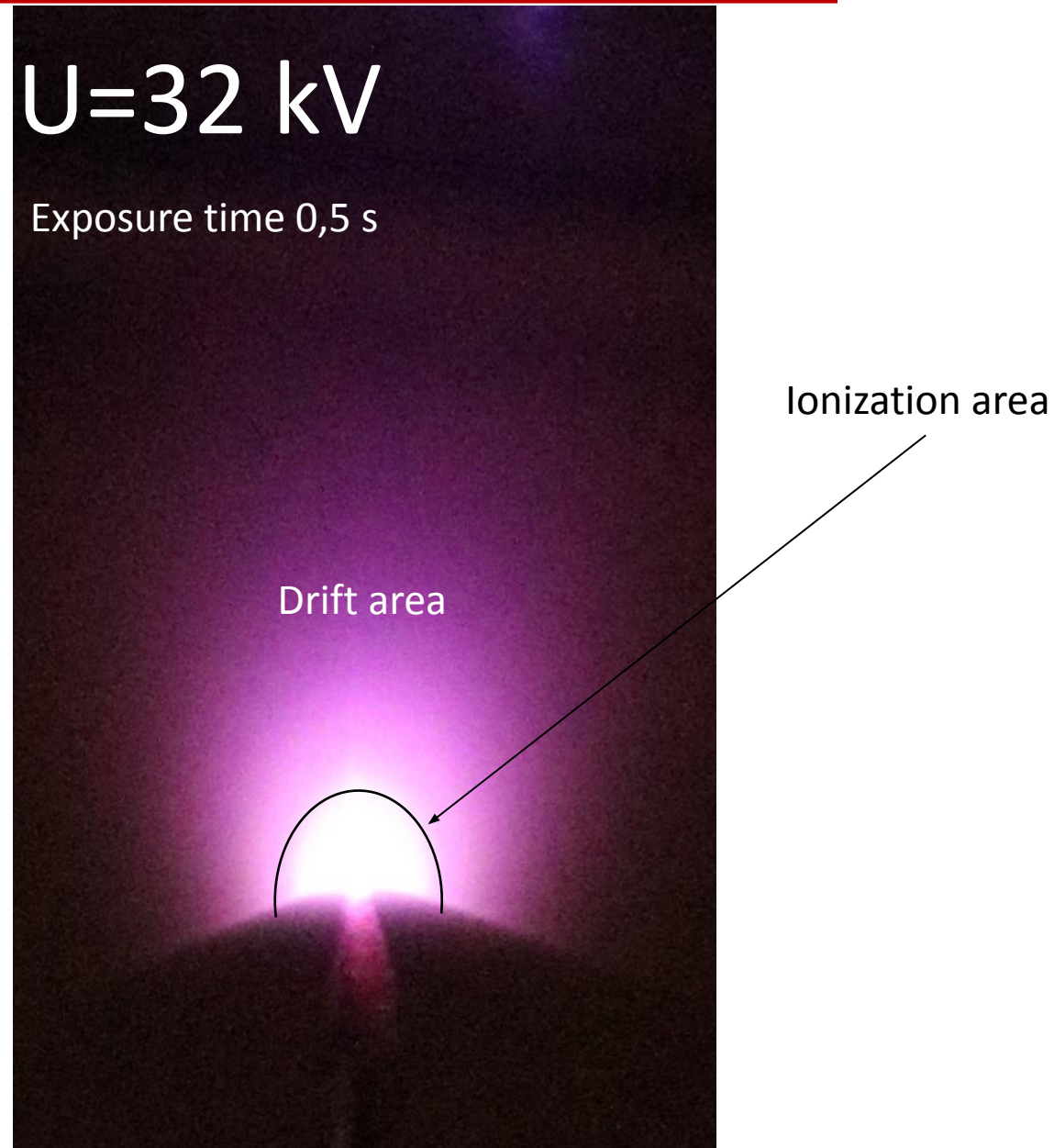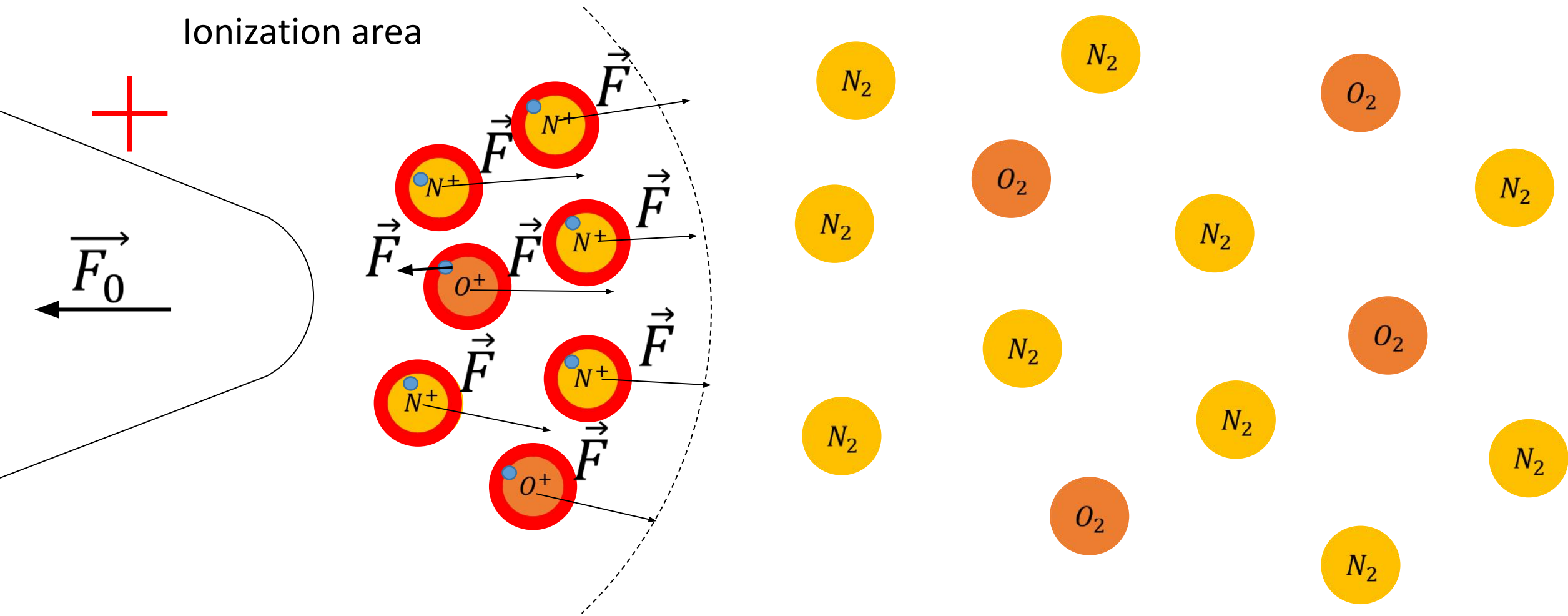
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Conclusion remarks

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.
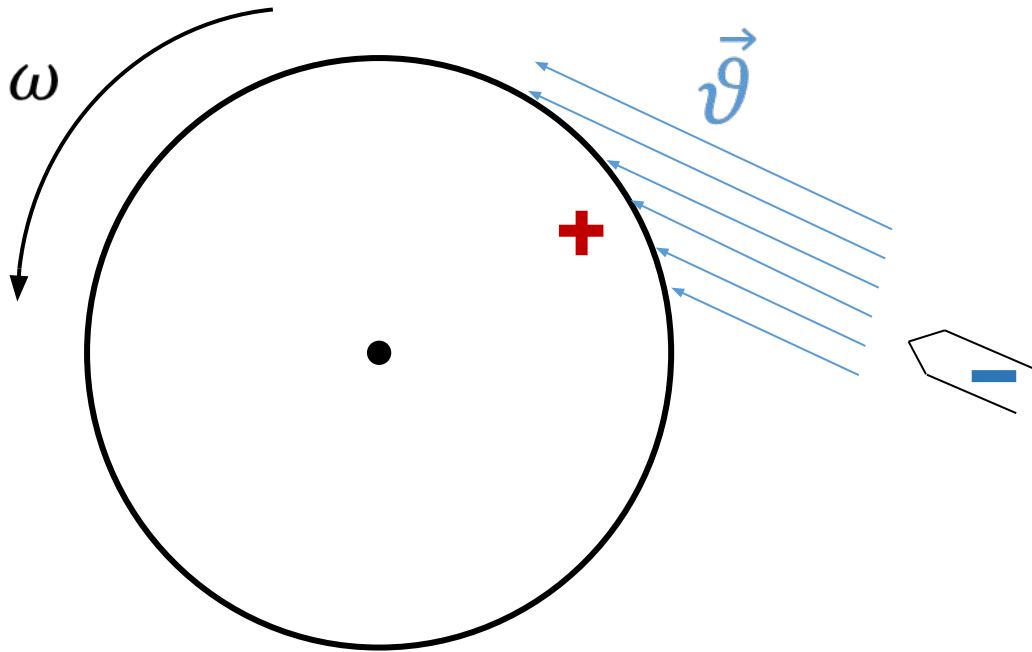
U=32 kV

Exposure time 0,5 s

Ionization area

Drift area

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Qualitative explanation

Ionization area

$\vec{F}$ N^+

$\vec{F}$ N^+

$\vec{F}$ N^+

$\vec{F}$ O^+

$\vec{F}$

$\vec{F}$ N^+

$\vec{F}$ N^+

$\vec{F}$ O^+

$\overrightarrow{F_0}$

N_2 N_2 O_2 N_2 N_2 N_2 O_2 O_2 N_2 N_2 N_2 N_2 O_2 N_2

Qualitative explanation	Possible design	Experimental setup

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Possible design

Qualitative explanation

Possible design

Experimental setup

Experimental setup

D = 100 mm

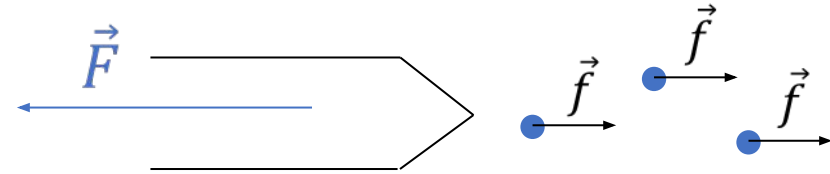L = 10 – 50 mm

Qualitative explanation
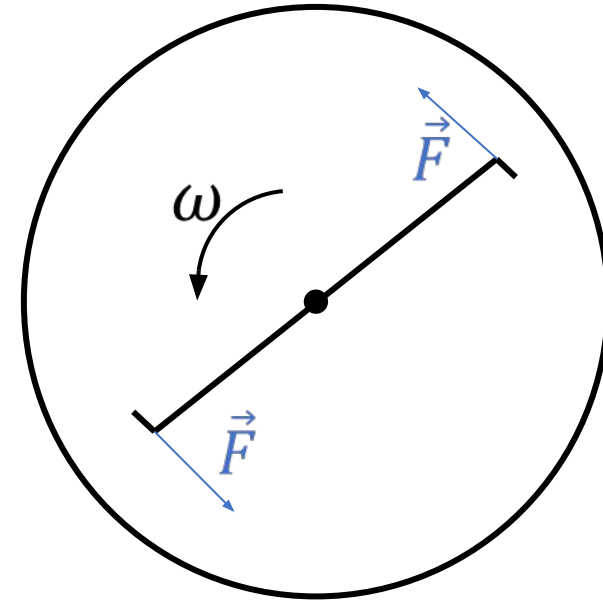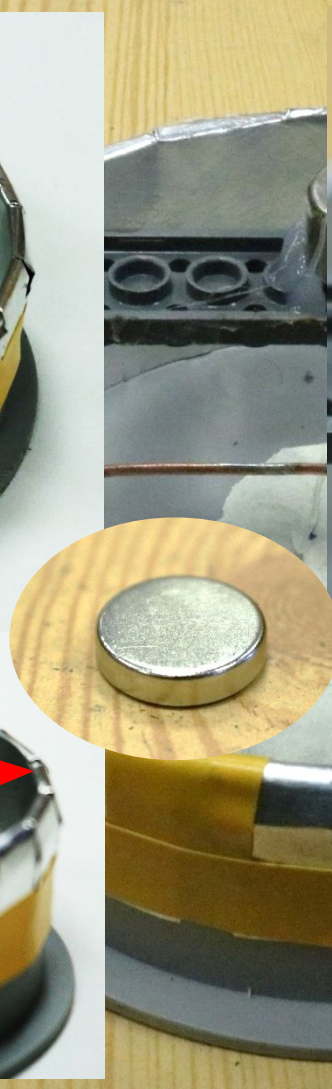
Possible design
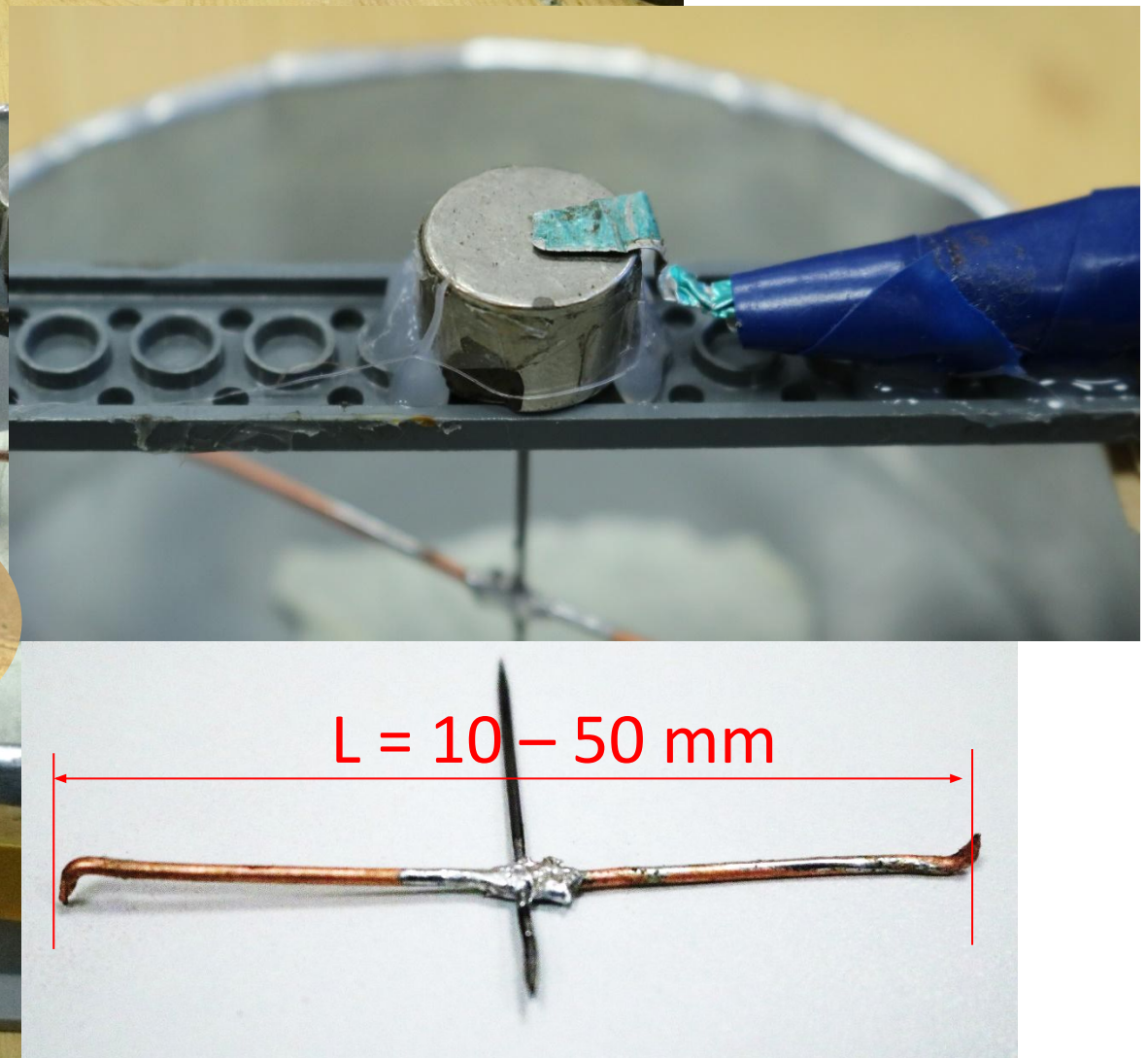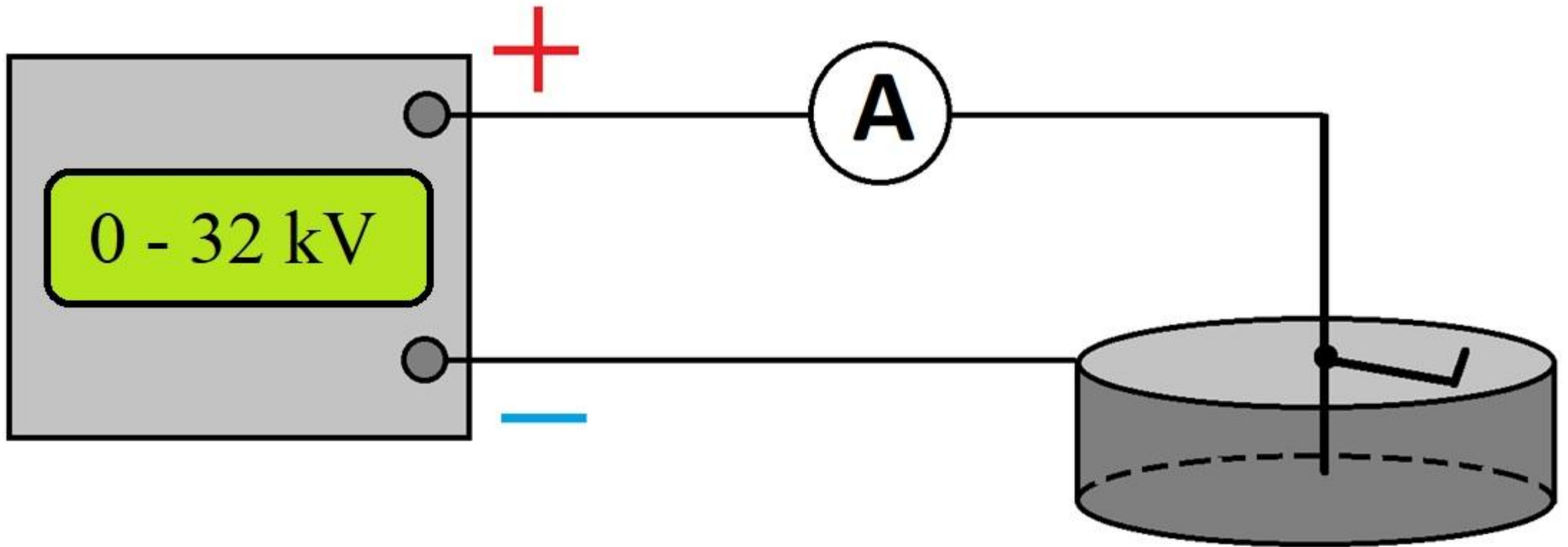
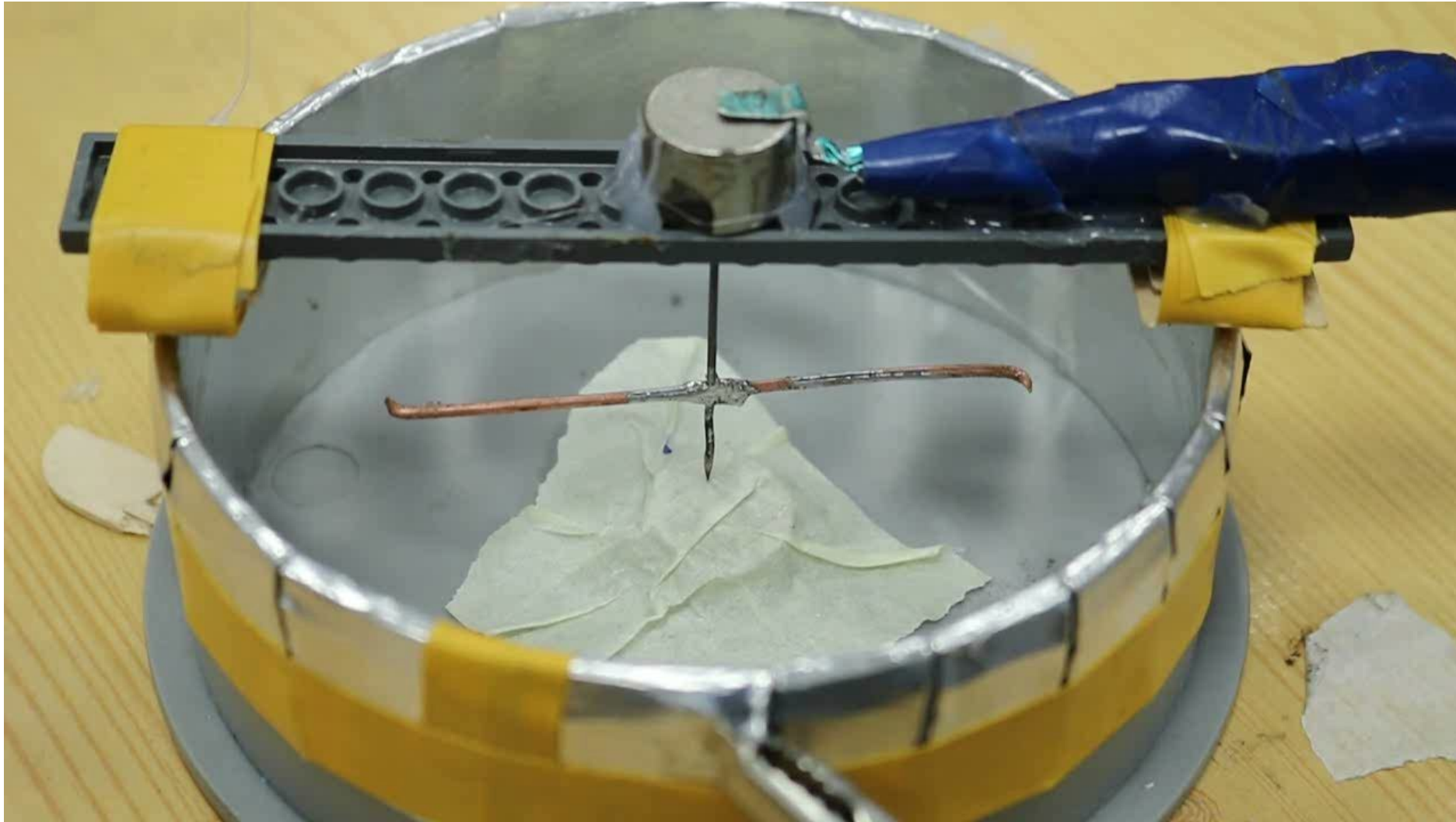Experimental setup

Experimental setup

Qualitative explanation

Possible design

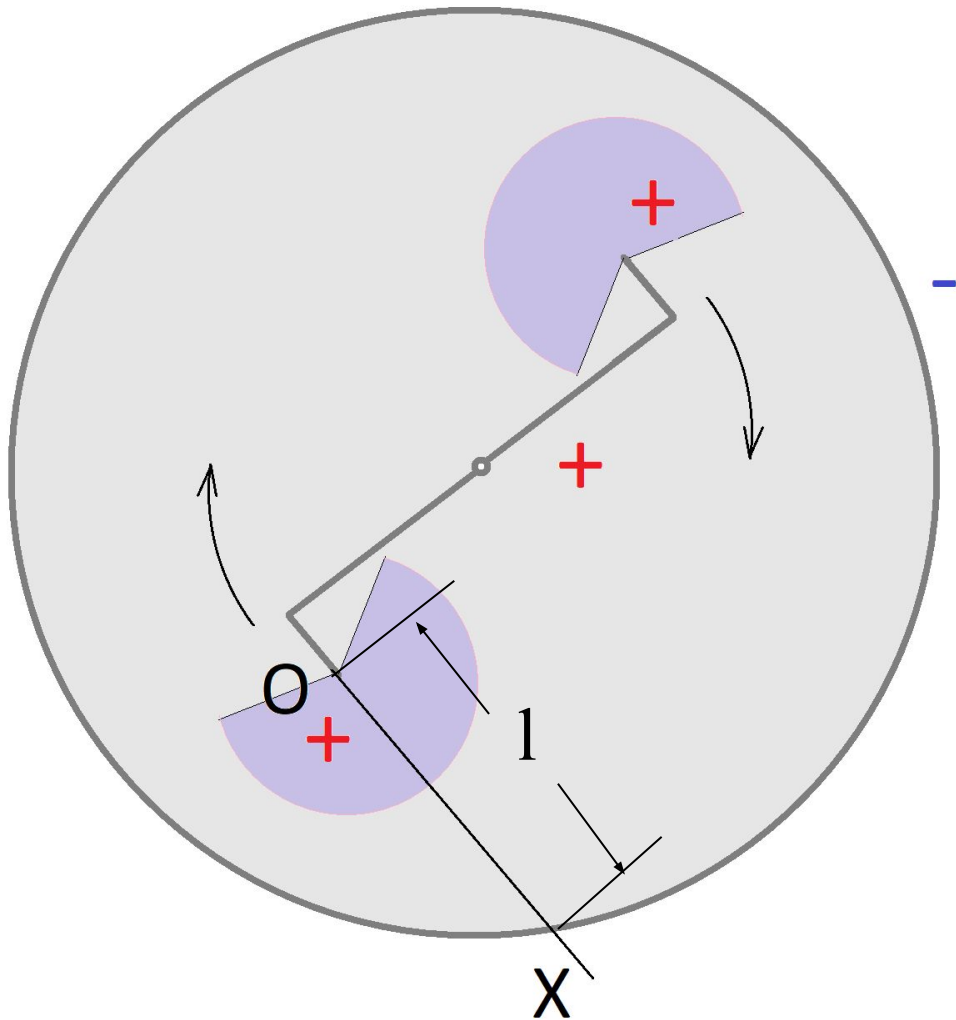Experimental setup

Experimental setup

Qualitative explanation

Possible design

Experimental setup

Driving force

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

$$F_x = \sum E_x q$$

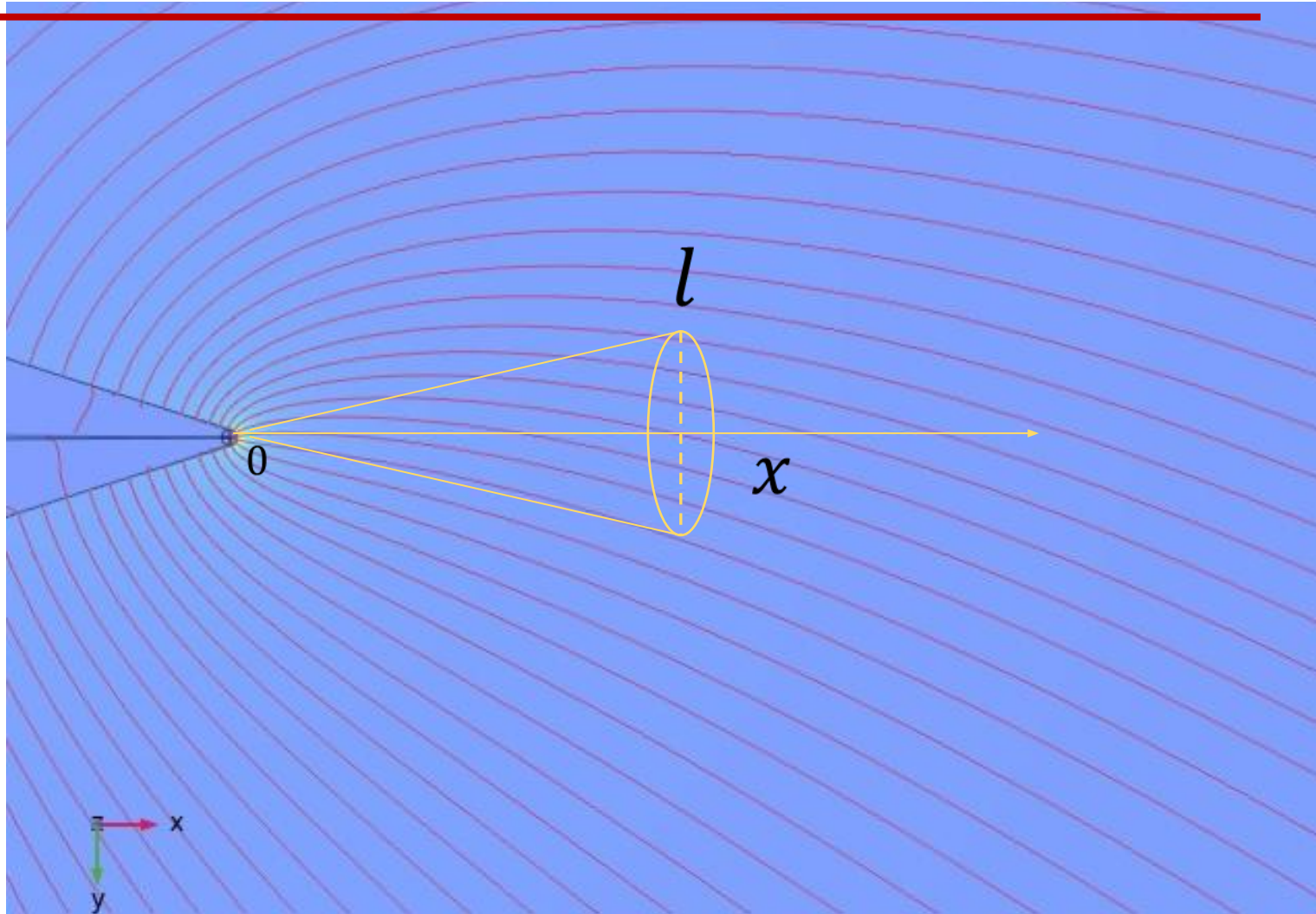$$F_x = \int_r^l E_x(x)\rho(x)dV$$

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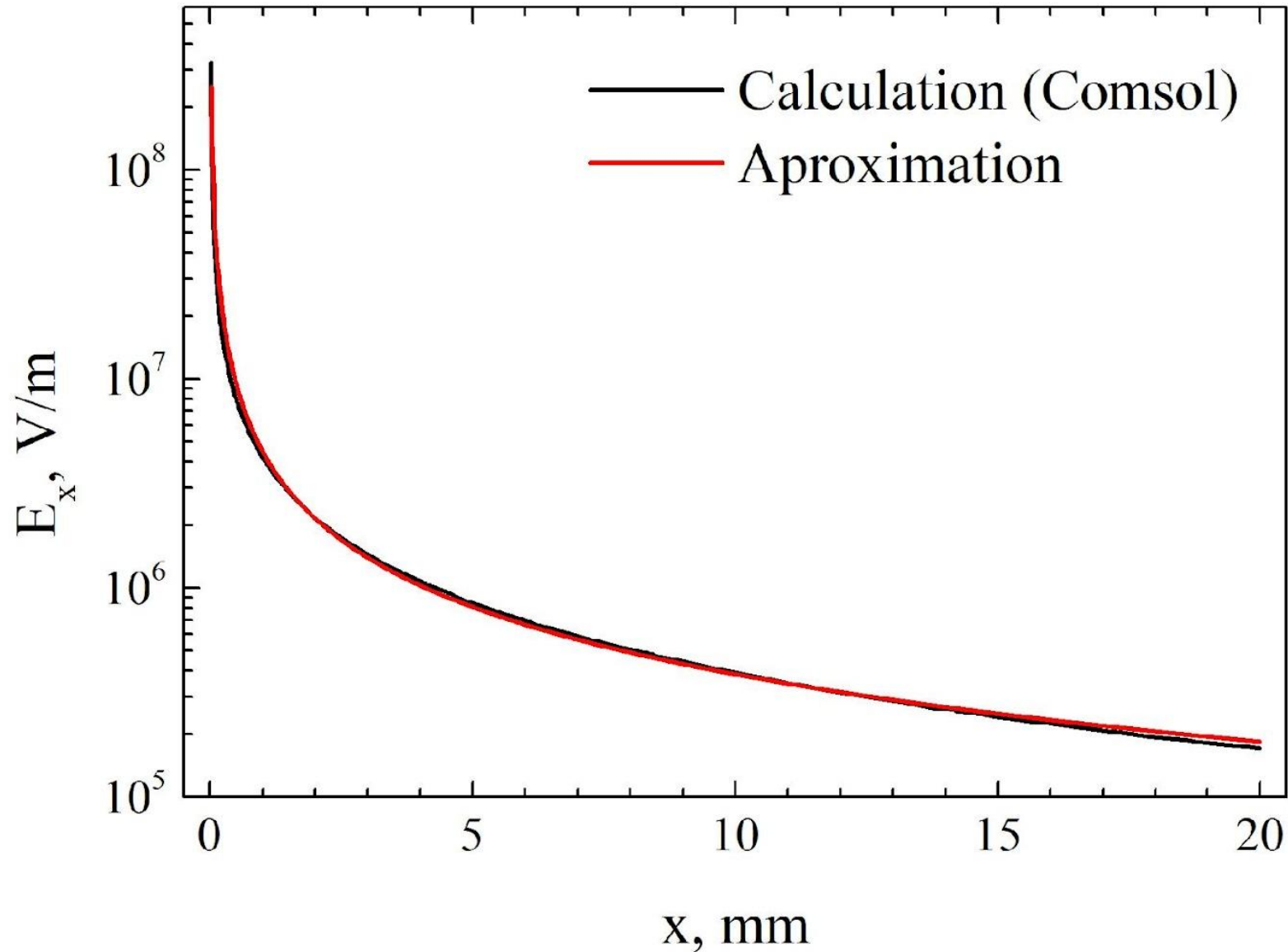$r = 0.0002$ m
$T = 296$ K
$P = 10^5$ Pa
$\varphi = 32$ kV

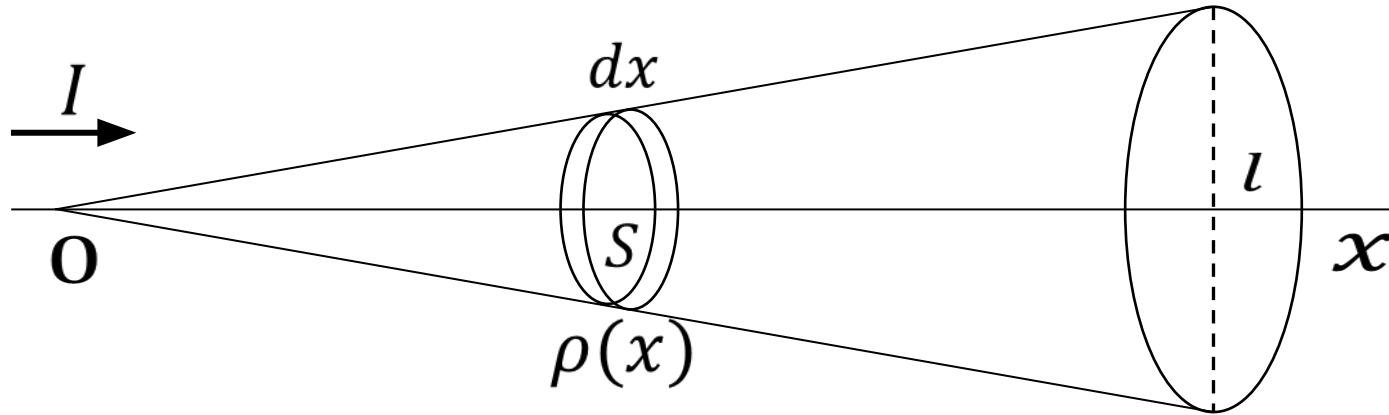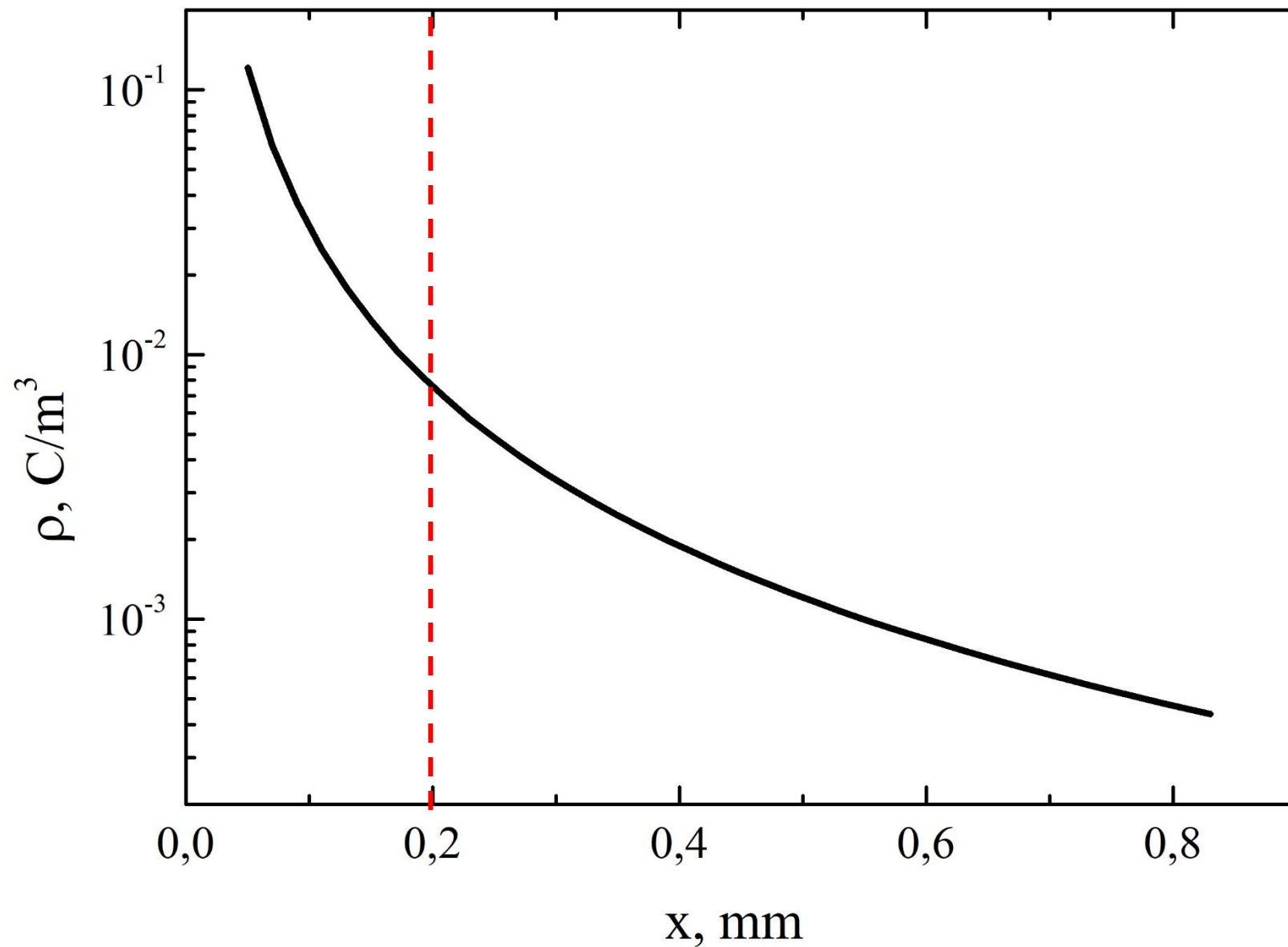| Experimental setup | Theory | Optimization |

Driving force: calculation of the electric field

Driving force: calculation of the volume charge density

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

Experimental setup   Theory   Optimization

Charge density

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

Experimental setup

Theory

Optimization

Driving force

Top view

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

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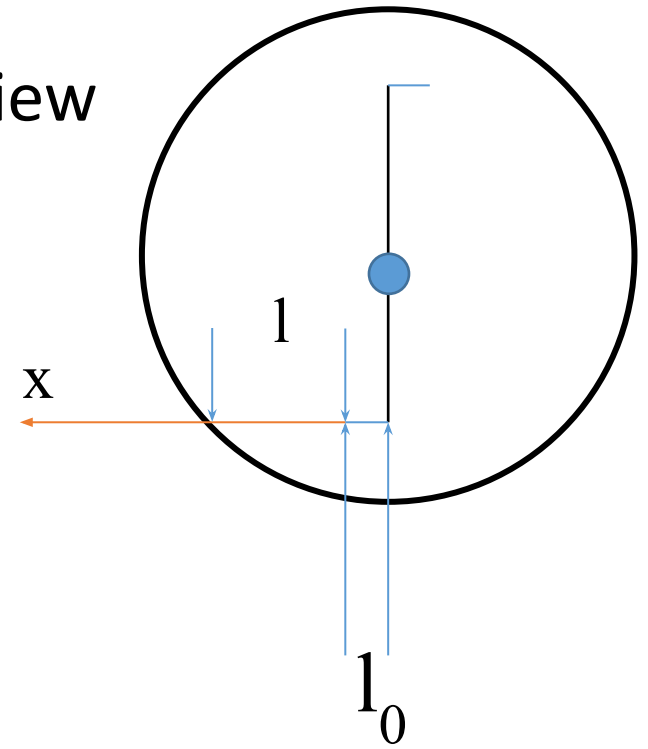
$$E_x(x) = \frac{\gamma(U)}{x}$$

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

l – distance from the tip to the outer electrode
r – curvature of the tip
$I = NI_0$, where N – number of tips

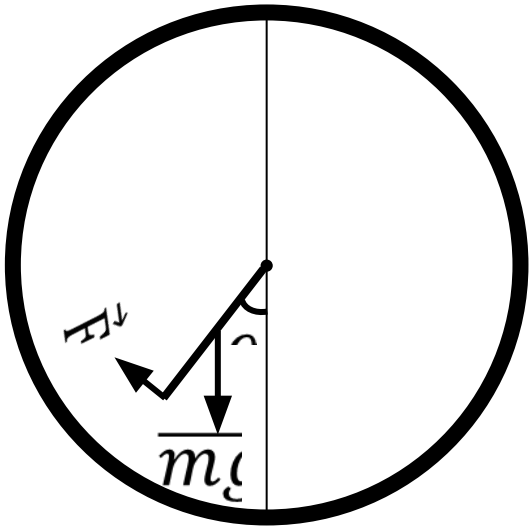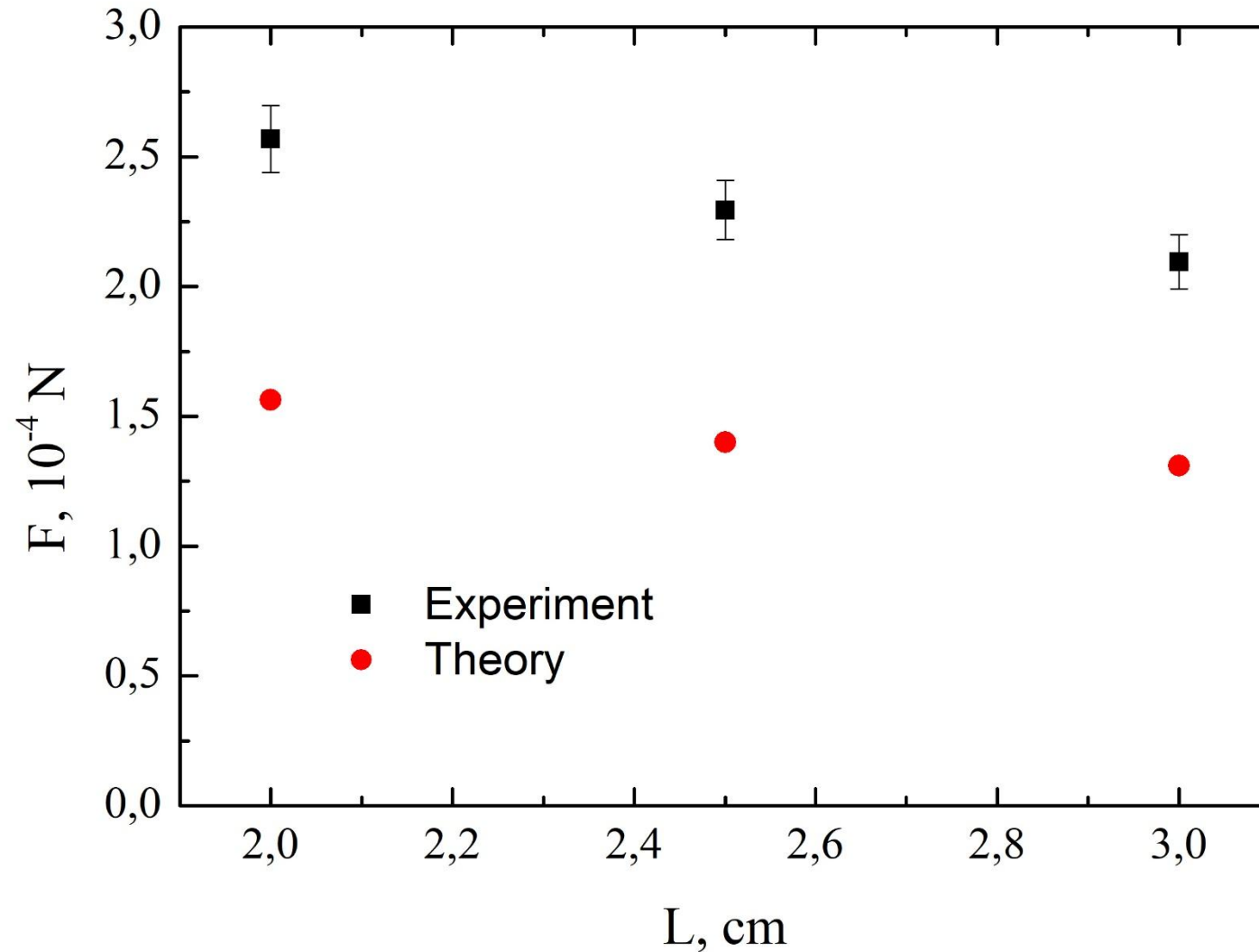| Experimental setup | Theory | Optimization |

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Measurement of the driving force

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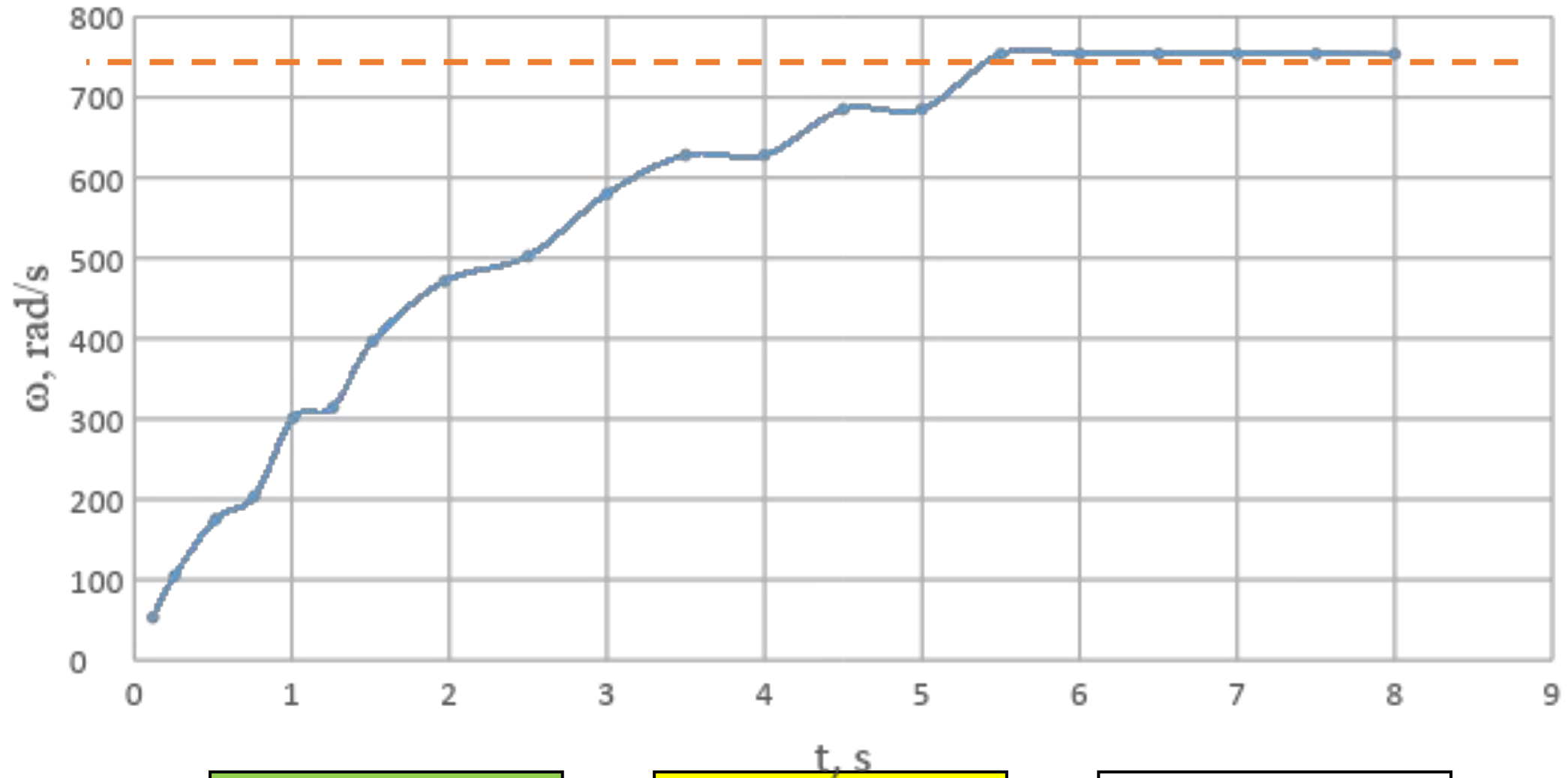
$$F_{teor} = I \sqrt{\frac{2\gamma m}{e} \ln \frac{l}{r}}$$

Experiment

Theory

Experimental setup   Theory   Optimization

Angular velocity

Experimental setup | Theory | Optimization

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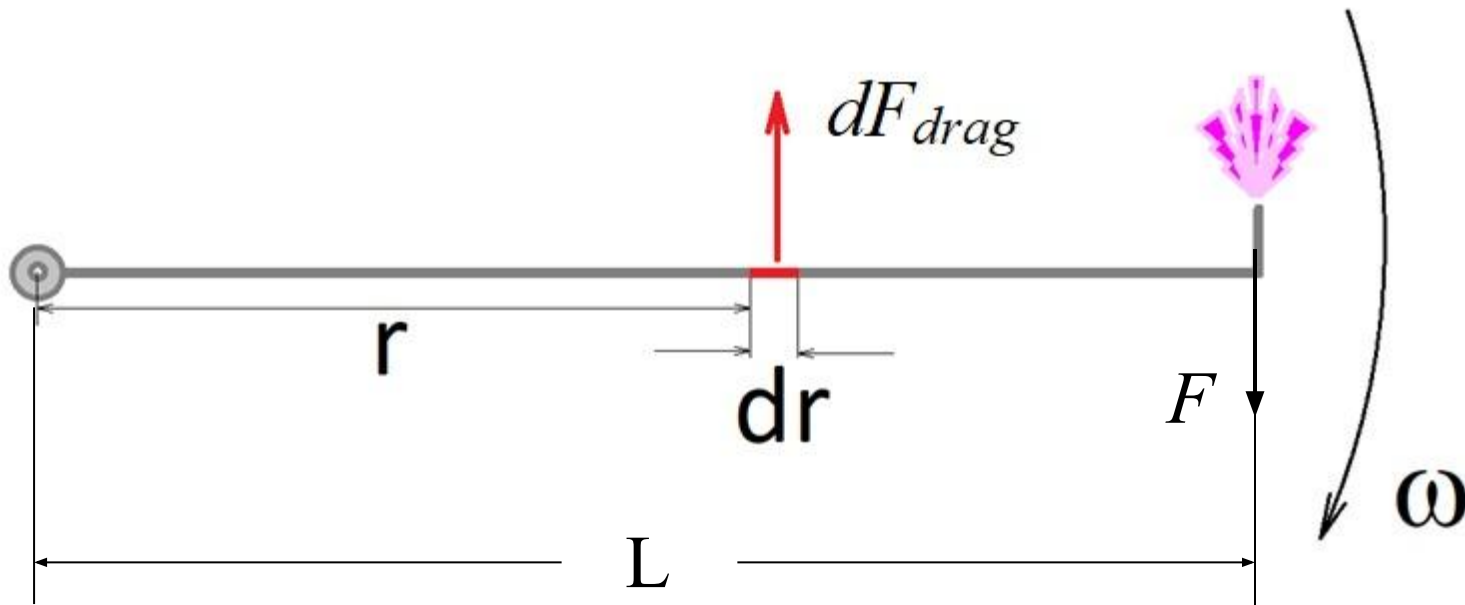
$$dF_{drag} = -C_x \frac{\rho V^2}{2} dS$$

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

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

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

d_0 – diameter of the arm cross section

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

Experimental setup	Theory	Optimization

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

$$F = \frac{1}{8R} R_0^2 C_x \cdot \frac{PM}{T} \cdot d_0 \omega^2 L^3$$

$$\omega = \sqrt{\frac{6IRT}{NC_x PMd_0 L^3}} \frac{I}{N}\sqrt{\frac{2\gamma m}{e} ln \frac{l}{r}}$$

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
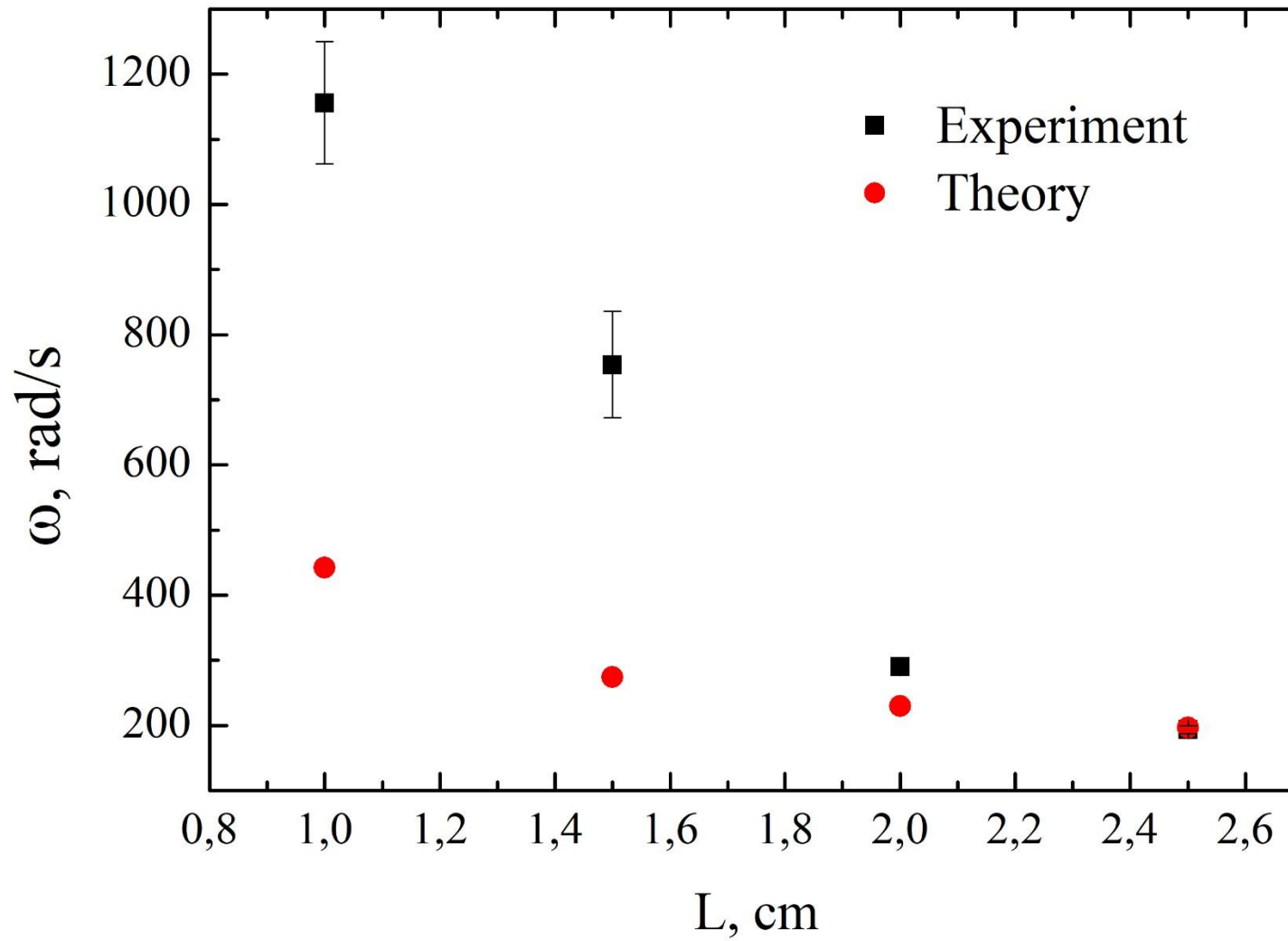
| d_0 | L | C_x | R_0 | l_0 |

| Experimental setup | Theory | Optimization |

Relevant parameters: arm length

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

Experimental setup	Theory	Optimization

Relevant parameters: arm diameter
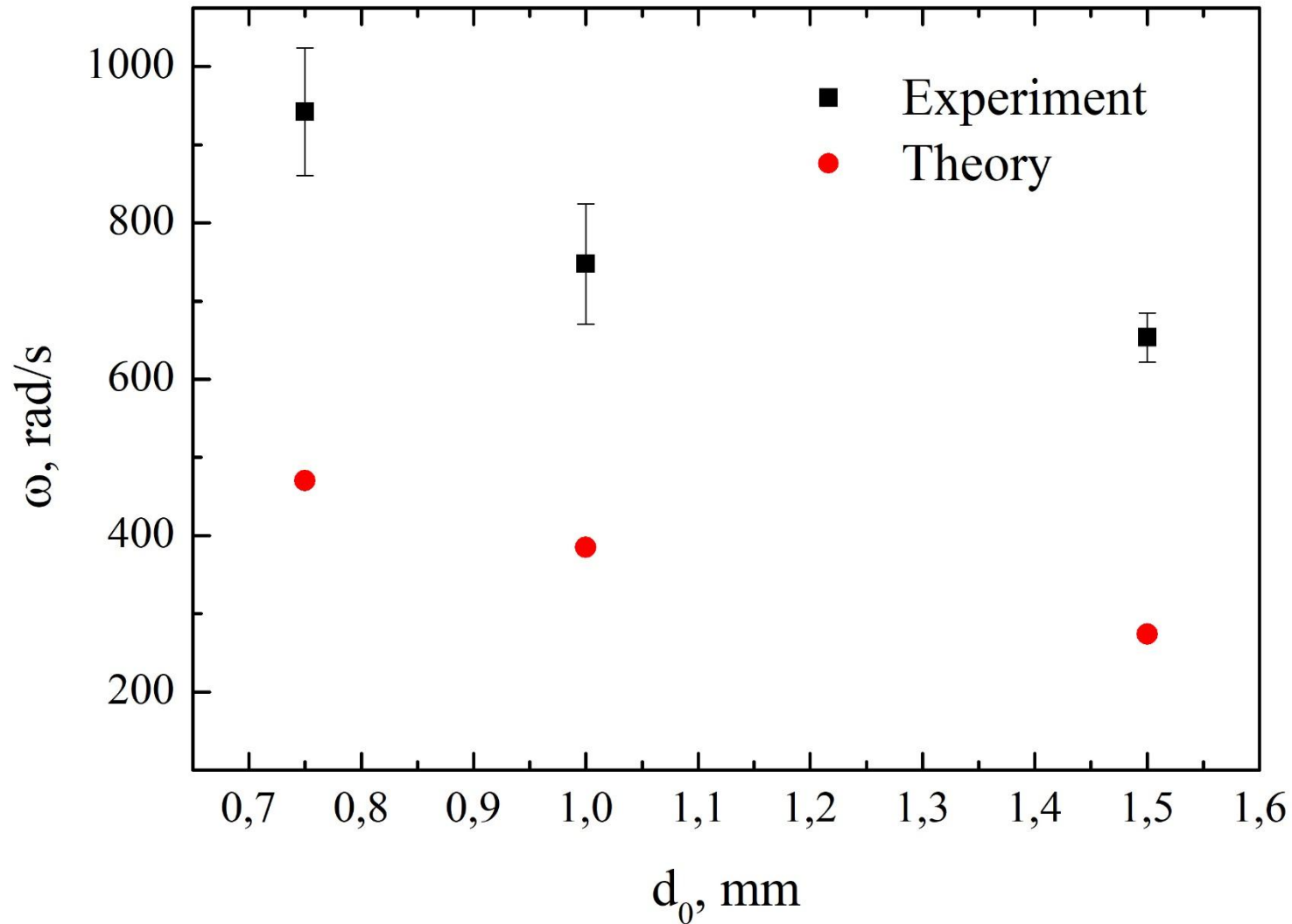
$r = 0.03$ mm
$l_0 = 5$ mm
$L = 1$ cm
$N = 2$

| Experimental setup | Theory | Optimization |

Relevant parameters: drag coefficient

$C_x = 0.8$

$d_0 = 0.75$ mm
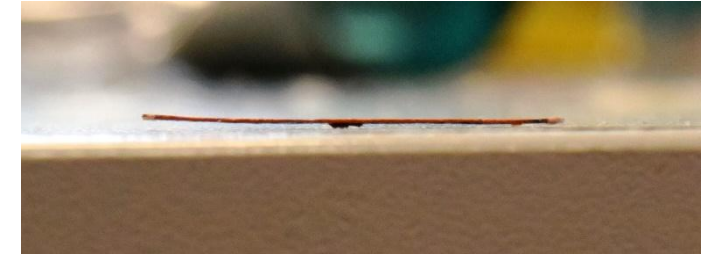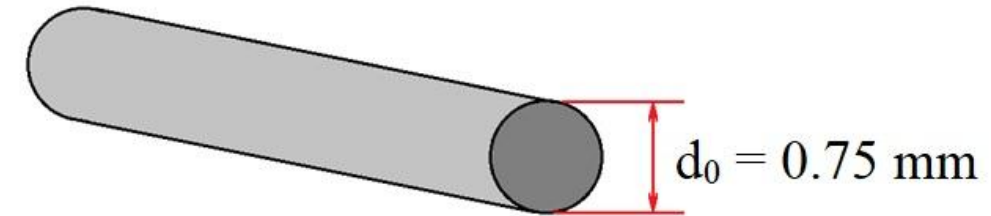
$C_x = 0.08$
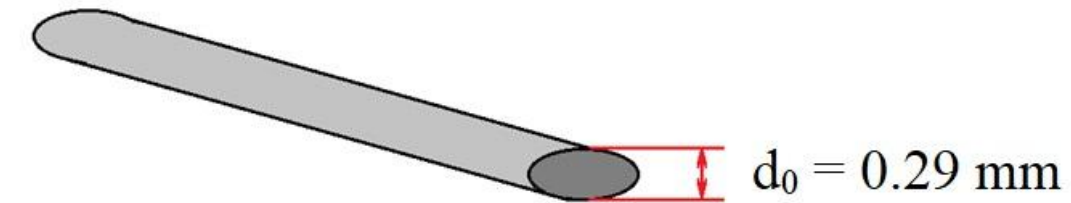
$d_0 = 0.29$ mm

$L = 1$ 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

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

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

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

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

Experimental setup   Theory   Optimization

Efficiency

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

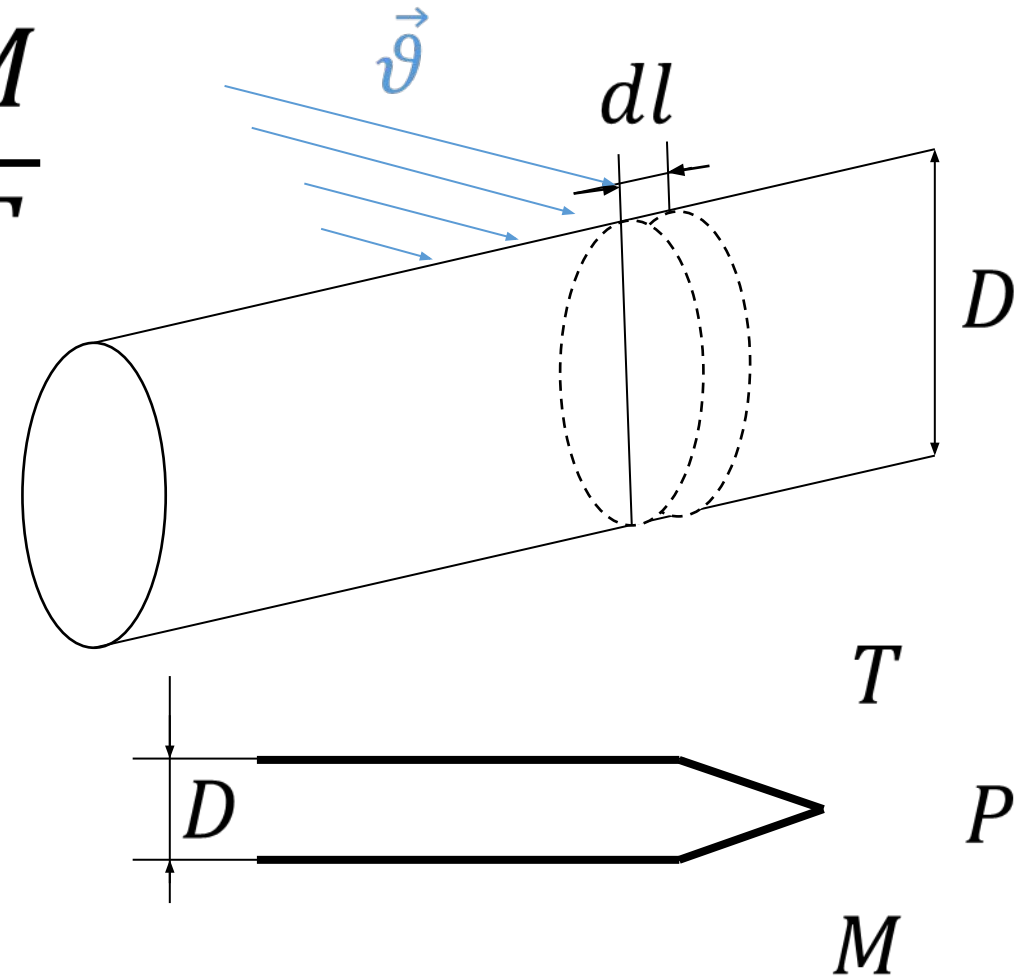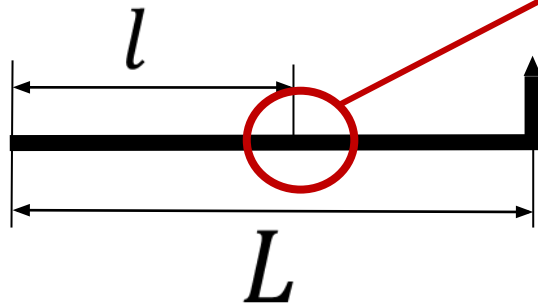| Experimental setup | Theory | Optimization |

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

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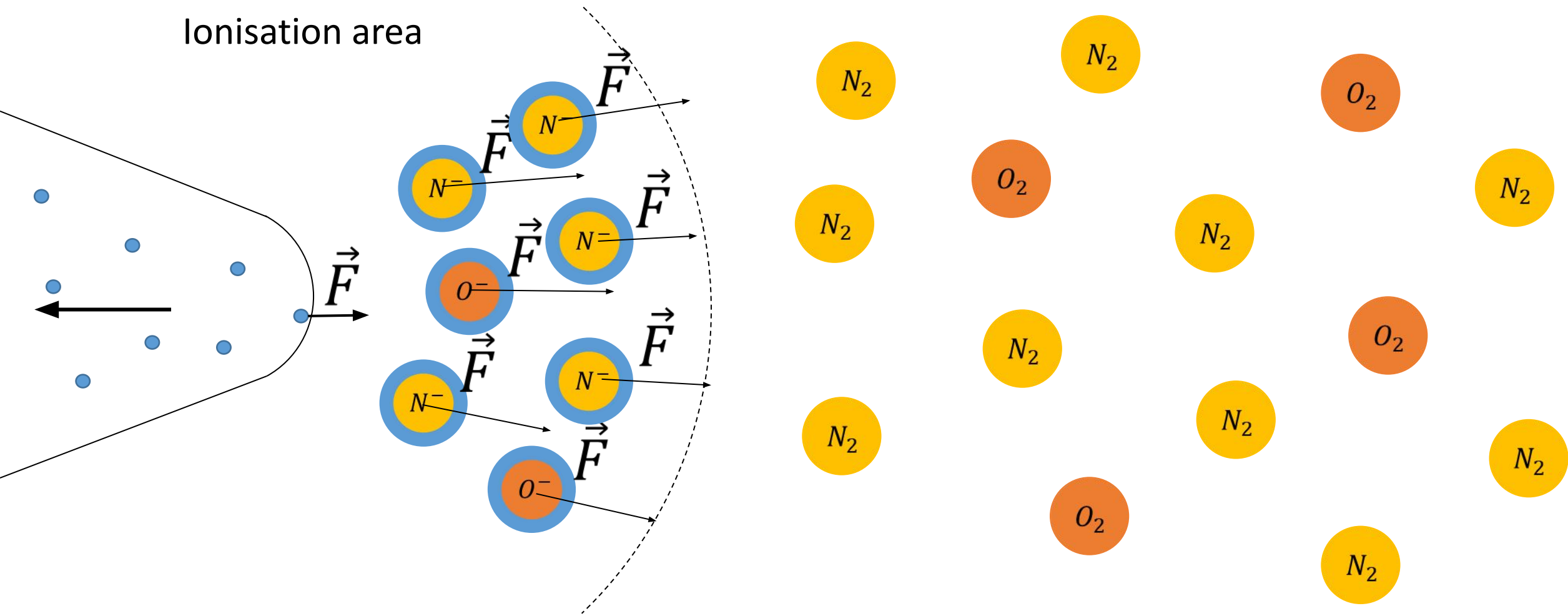
$$\delta M = C \cdot \frac{\rho v^2}{2} l dS$$

Negative corona discharge

U = 32 kV

Ionization area

Drift area

Exposition time 0.5 s

Qualitative explanation

Ionisation area

Positive corona discharge

U = 32 kV

Ionization area

Drift area

Exposition time 0.5 s