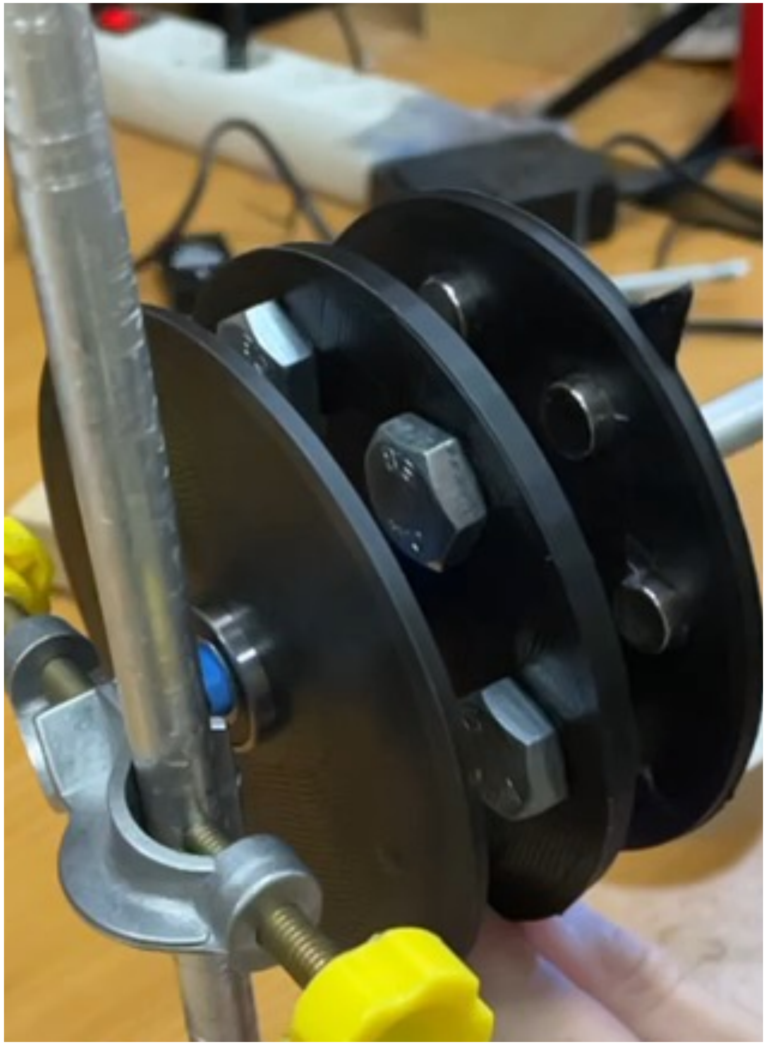
Magnetic gears

INTERNATIONAL PHYSICISTS' TOURNAMENT

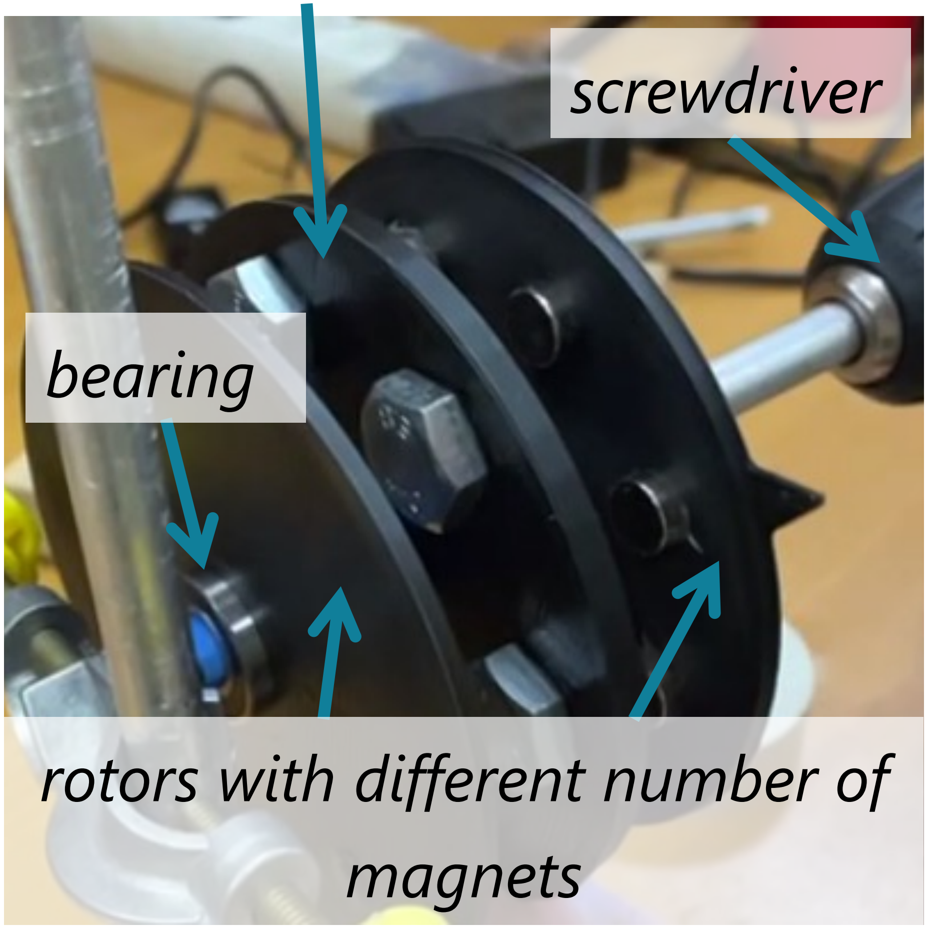
Reporter: *Sophia Kaniukova*

The coupling of mechanical gears is usually done through their teeth, but an equivalent mechanism can be made using magnets, so that the gears do not touch each other. Explain ***how the device works*** *and* ***explore its limitations****. How does it depend on* ***the arrangement of the magnets?***

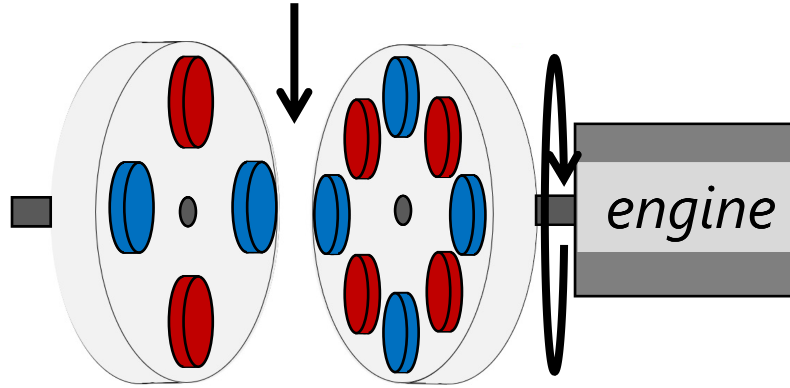


Setup

removable stator



removable stator

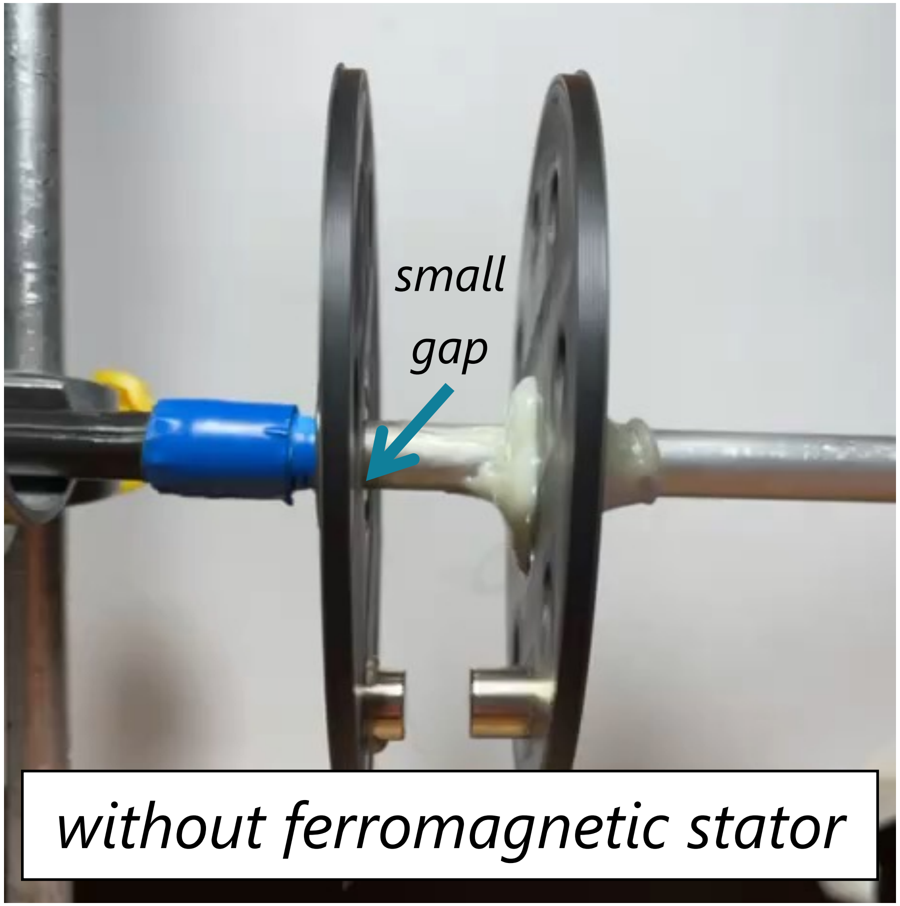


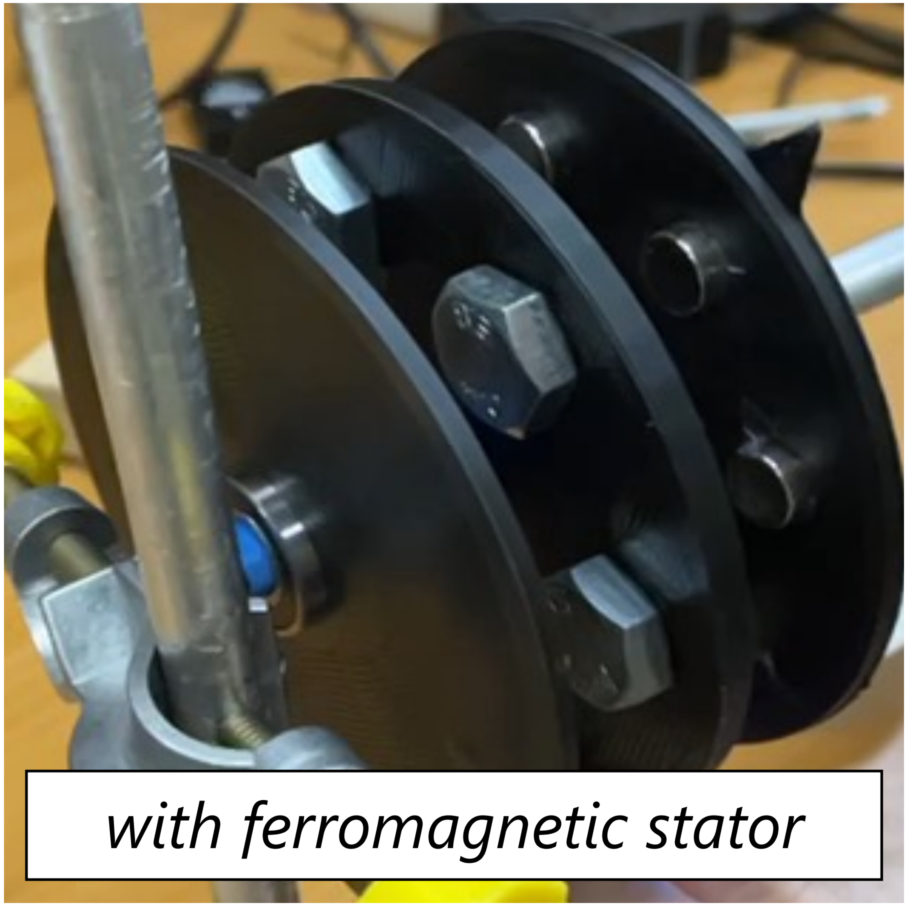
constant velocity control

Types of construction

$$\omega_1 = \omega_2$$
same direction

$$\omega_1 = k\omega_2$$
different direction





Overview

1 **Magnets interaction**

Forces between magnets. Magnetic field. Launch criterion. System of magnets.

2 **Case without stator**

Potential pit and state equilibrium. Field model. Gear ratio.

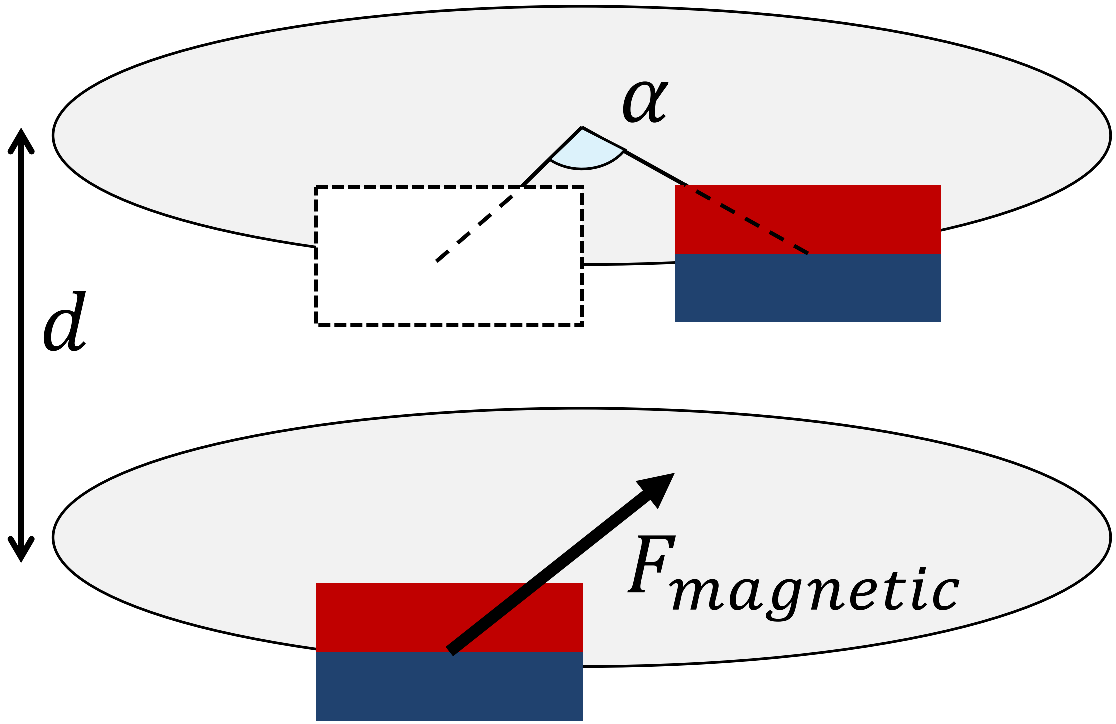
3 **Case with stator**

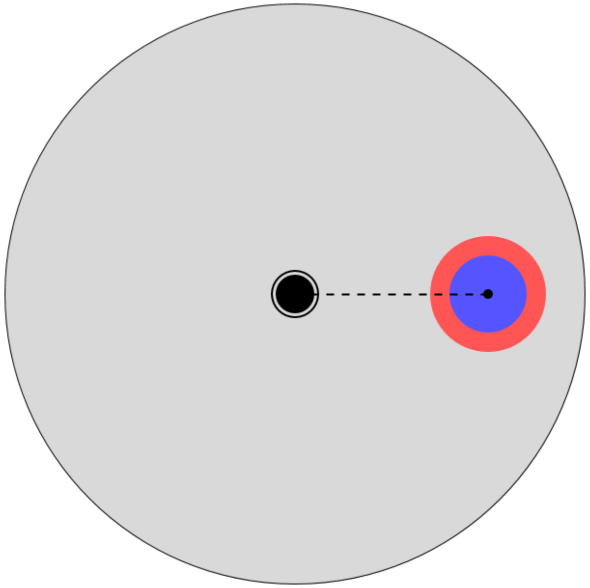
Velocity changes explanation. Different direction explanation

4 **Experimental verification**

Gear ratio(velocities). Limitations.

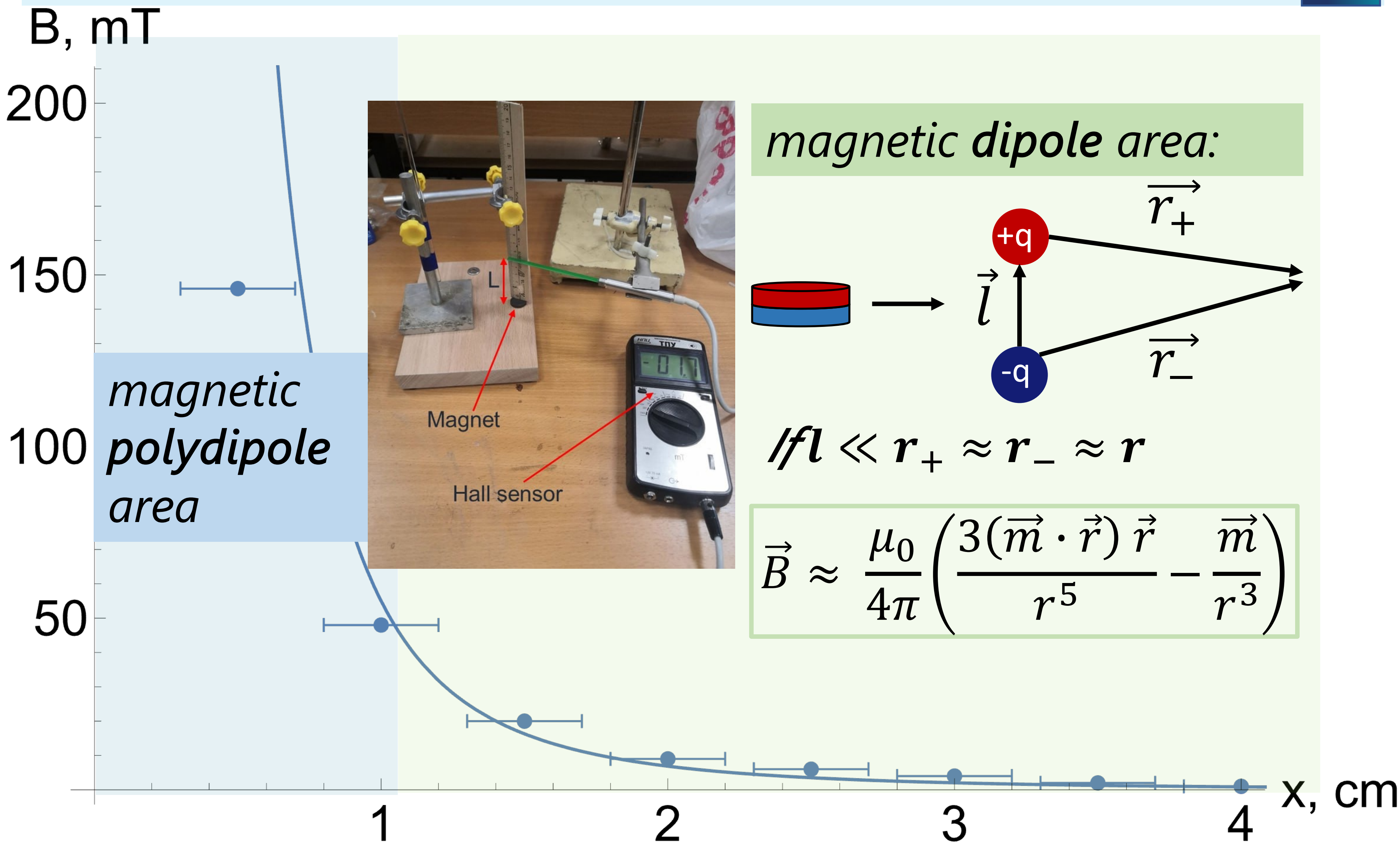
Forces between magnets





*Magnetic torque occurs when one **magnet is shifted***

Field model



magnetic ***polydipole*** *area*

magnetic ***dipole*** *area:*

$$l \ll r_+ \approx r_- \approx r$$

$$\vec{B} \approx \frac{\mu_0}{4\pi}\left(\frac{3(\vec{m}\cdot\vec{r})\,\vec{r}}{r^5} - \frac{\vec{m}}{r^3}\right)$$

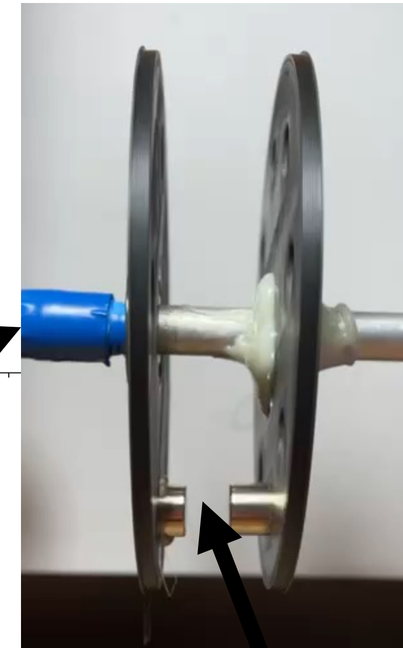
Interaction without stator

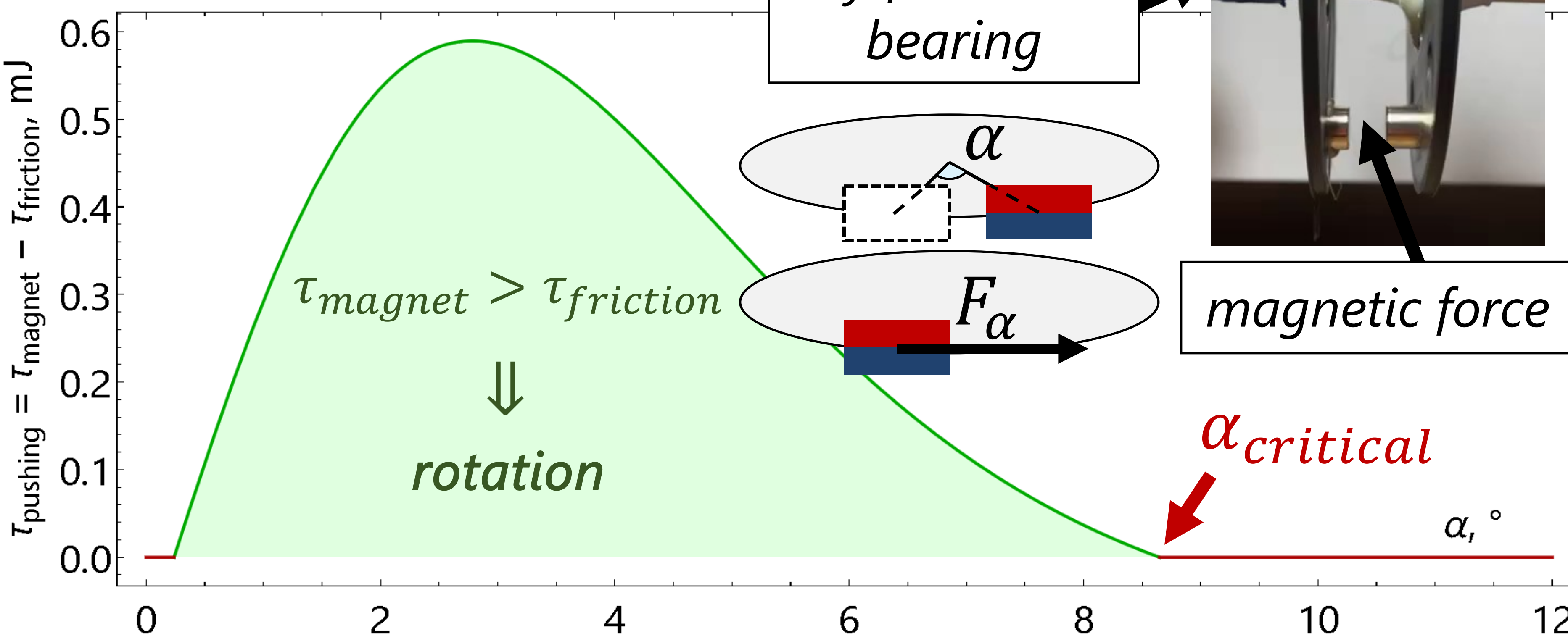
Launch criterion

Magnets rotate, ***when*** $\tau_{magnet} > \tau_{friction}$

$$\vec{\boldsymbol{B}} \Rightarrow \vec{\boldsymbol{F}} = \nabla(\vec{m} \cdot \vec{B}) \Rightarrow \boldsymbol{\tau_{magnet}} = R \cdot F_\alpha$$

according to ***dipole model***





Magnets interaction

Different types of motion

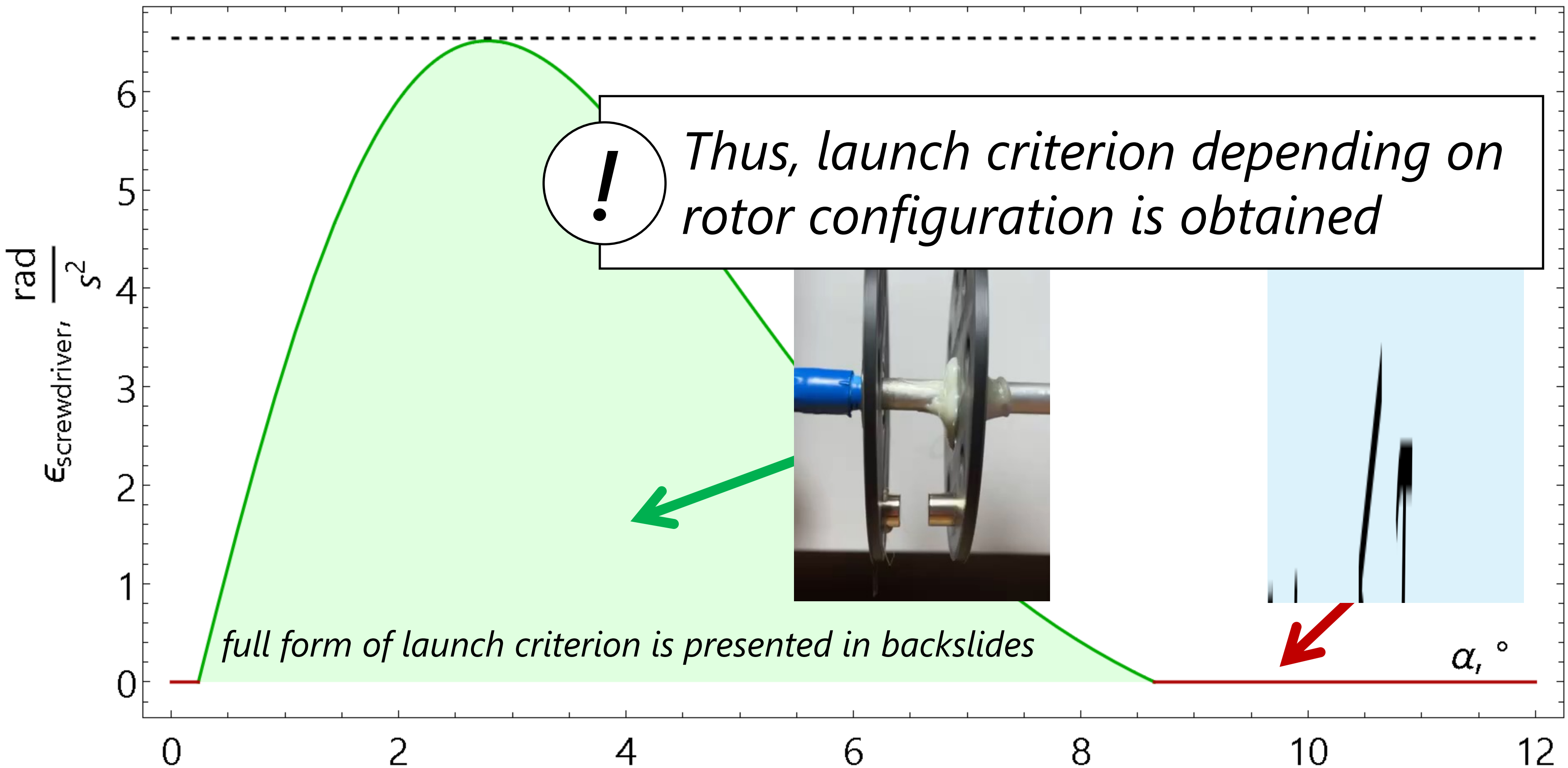
$$J\epsilon_{relative} = \tau_{pushing}$$

Magnets interaction

Launch criterion

*Magnets rotate, **when***

$$J\epsilon_{screwdriver} < \tau_{magnet} - \tau_{friction}$$



Thus, launch criterion depending on rotor configuration is obtained

full form of launch criterion is presented in backslides

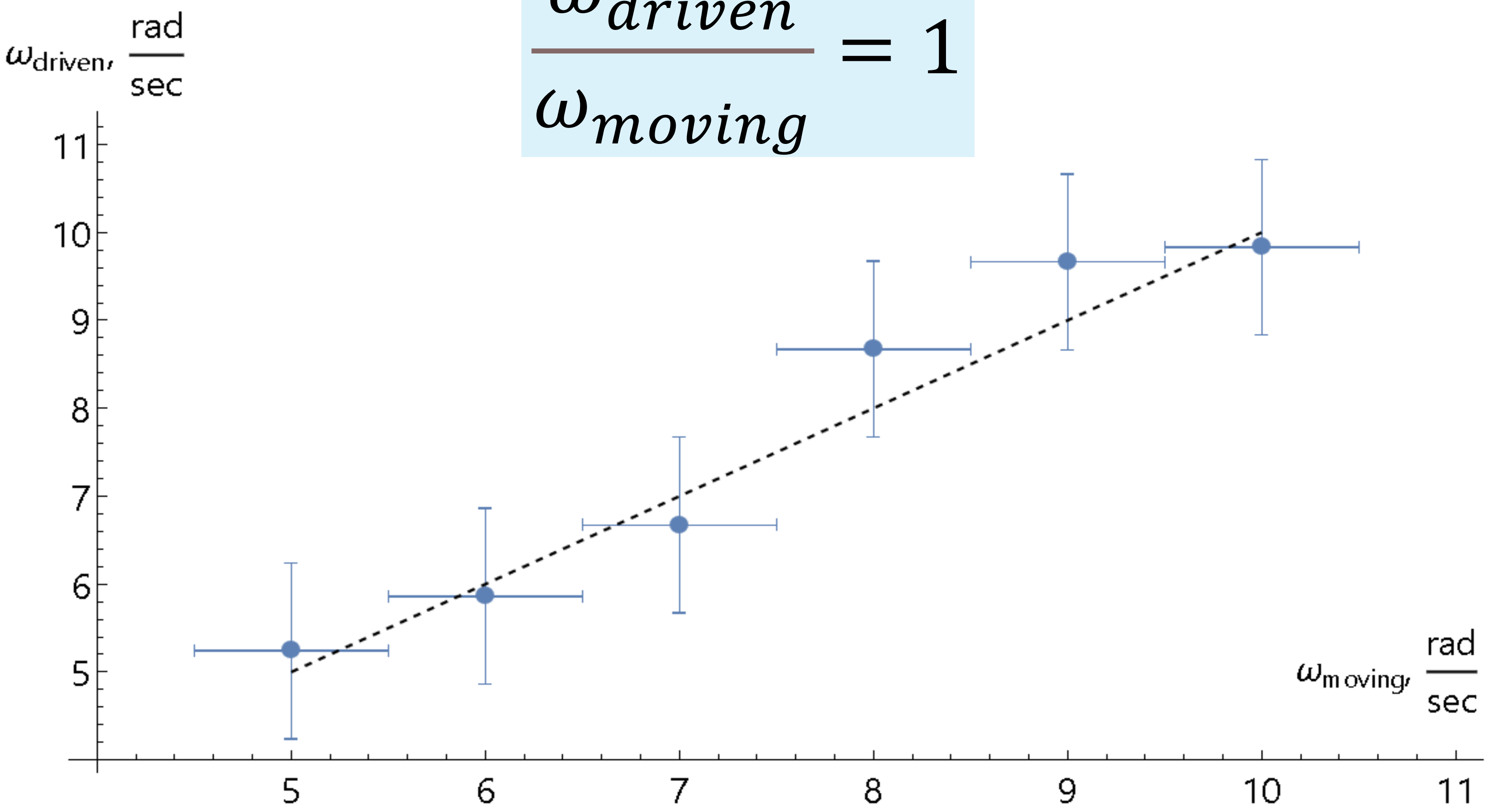
Magnets interaction

Gear ratio

1

In the reference frame of the driven rotor, the field between magnets is static ⇒ no reason for relative motion

$$\frac{\omega_{driven}}{\omega_{moving}} = 1$$



Case without stator

Overview

Magnets interaction

Forces between magnets. Magnetic field. Launch criterion. System of magnets.

Case without stator

Potential pit and state equilibrium. Field model. Gear ratio.

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Case with stator

Velocity changes explanation. Different direction explanation

4

Experimental verification

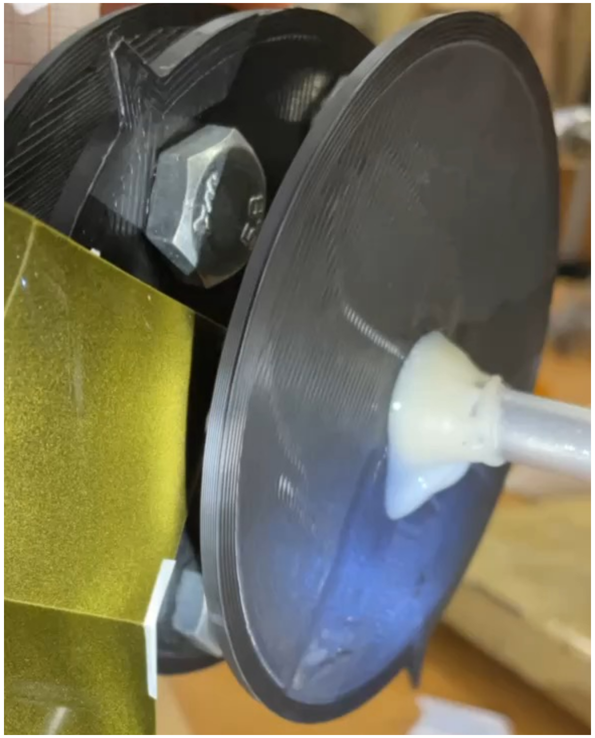
Gear ratio(velocities). Limitations.

Ferromagnetic stator influence

paper brightness shows field value

without screw

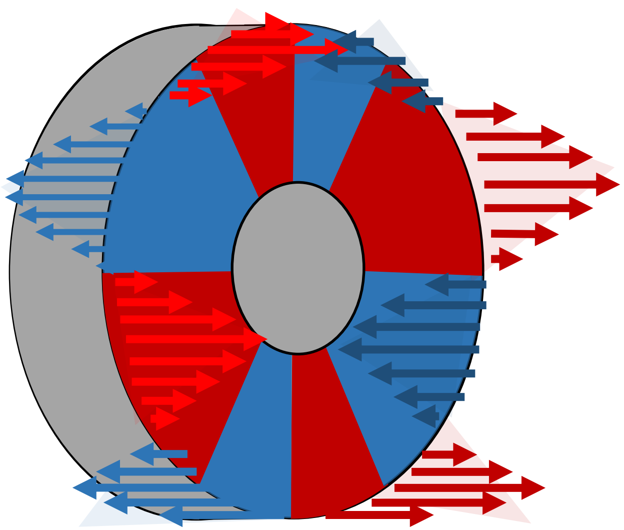
with screw



ferromagnet** is drawn into **strong magnetic field

Field analogy

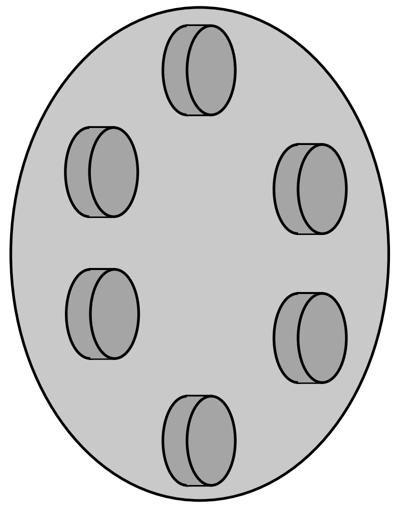
M magnets



field spatial frequency

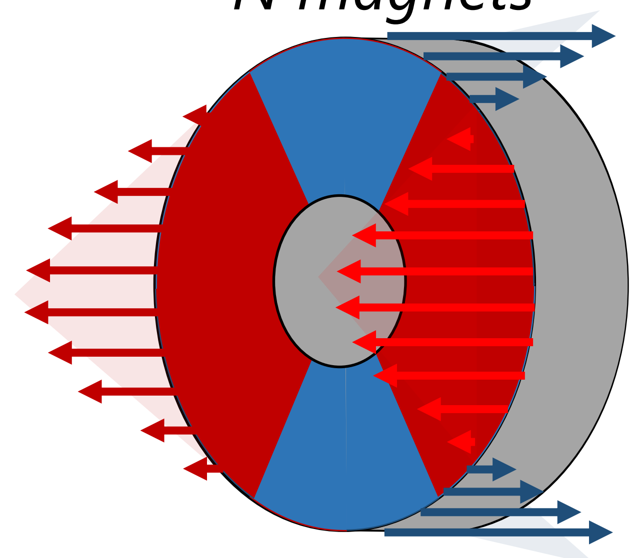
$$f_s = \frac{M}{2}$$

absolute value



$$\boldsymbol{f_s = \frac{M+N}{2}}$$

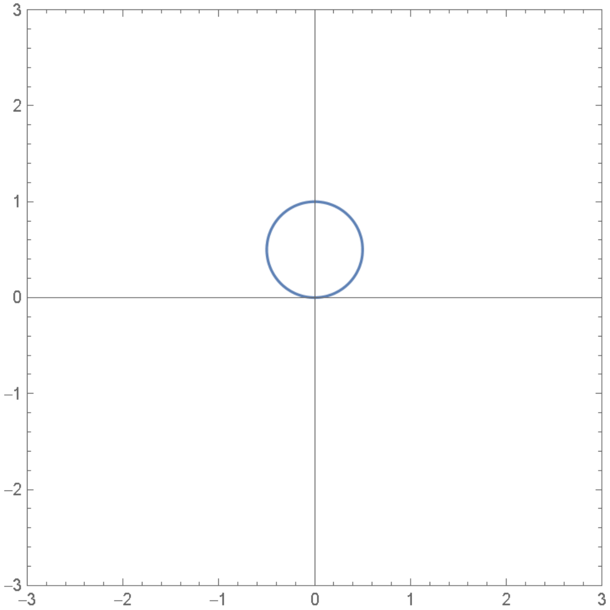
N magnets



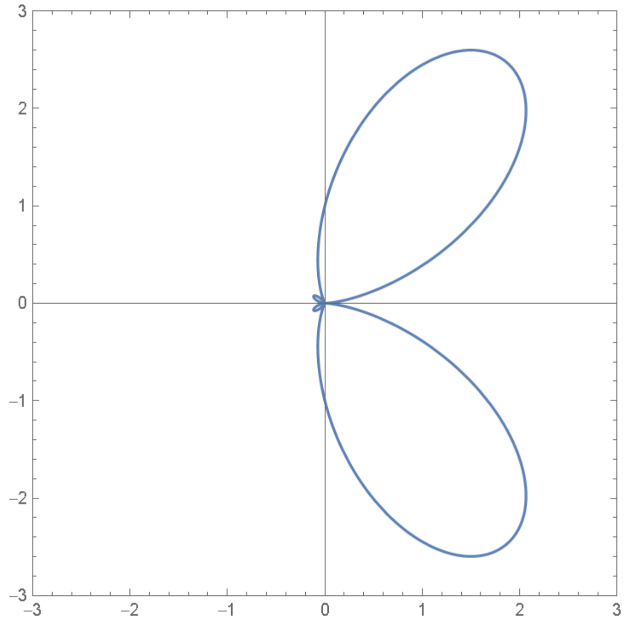
field spatial frequency

$$f_s = \frac{N}{2}$$

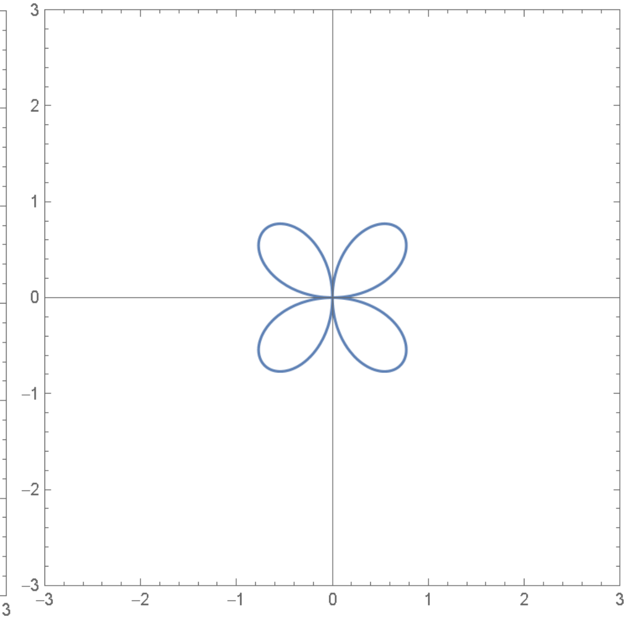
Field analogy



driven with screwdriver



absolute value of the field on the stator

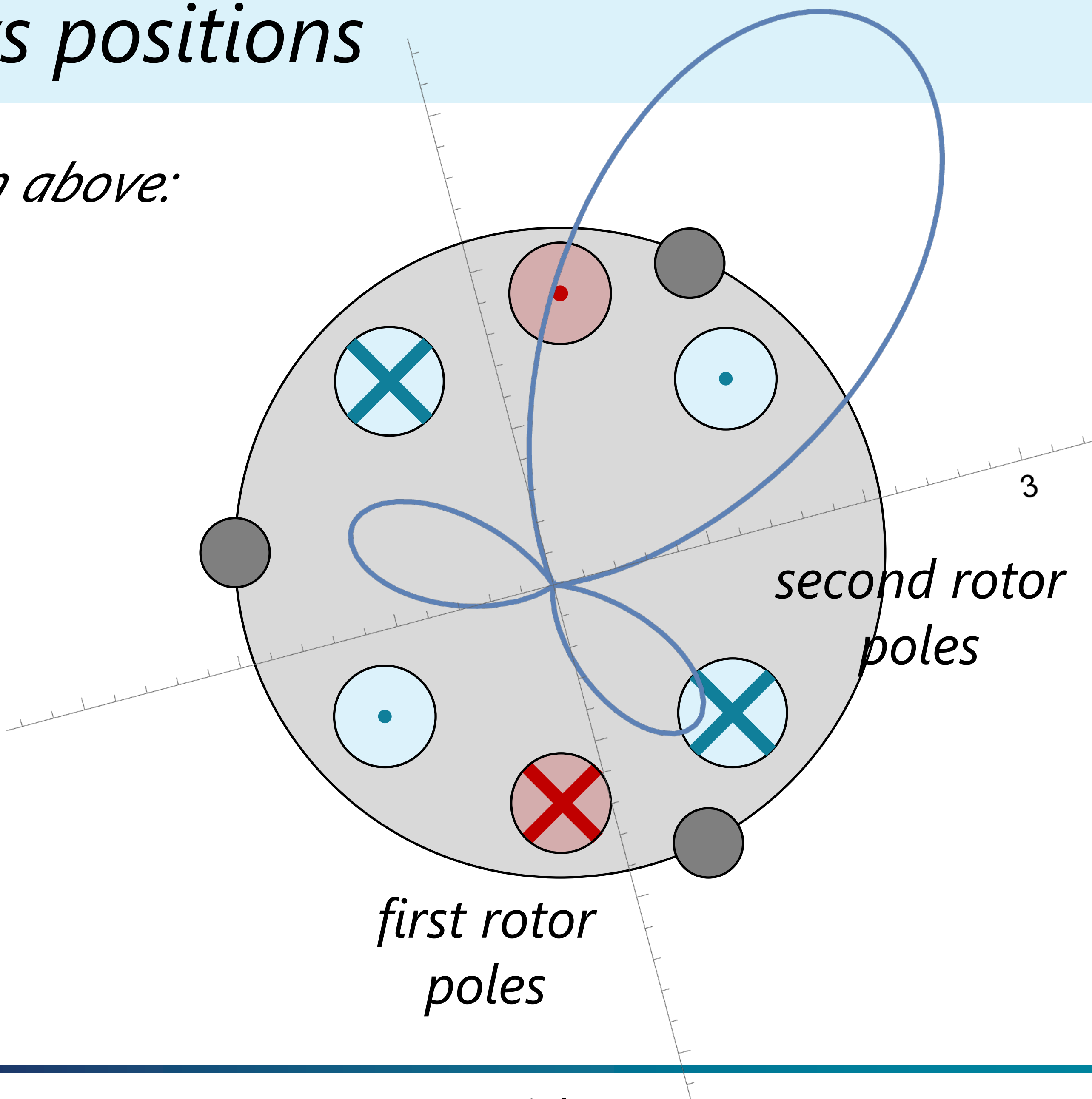


Driven rotor (frame reference)

Case with stator

Screws positions

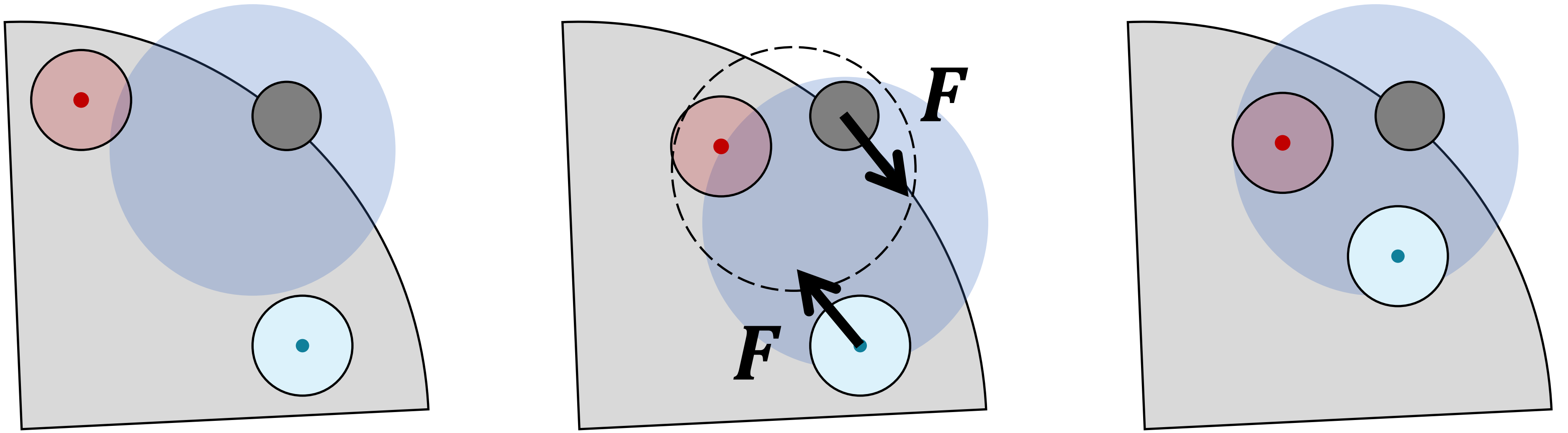
view from above:



Case with stator

Different directions explanation

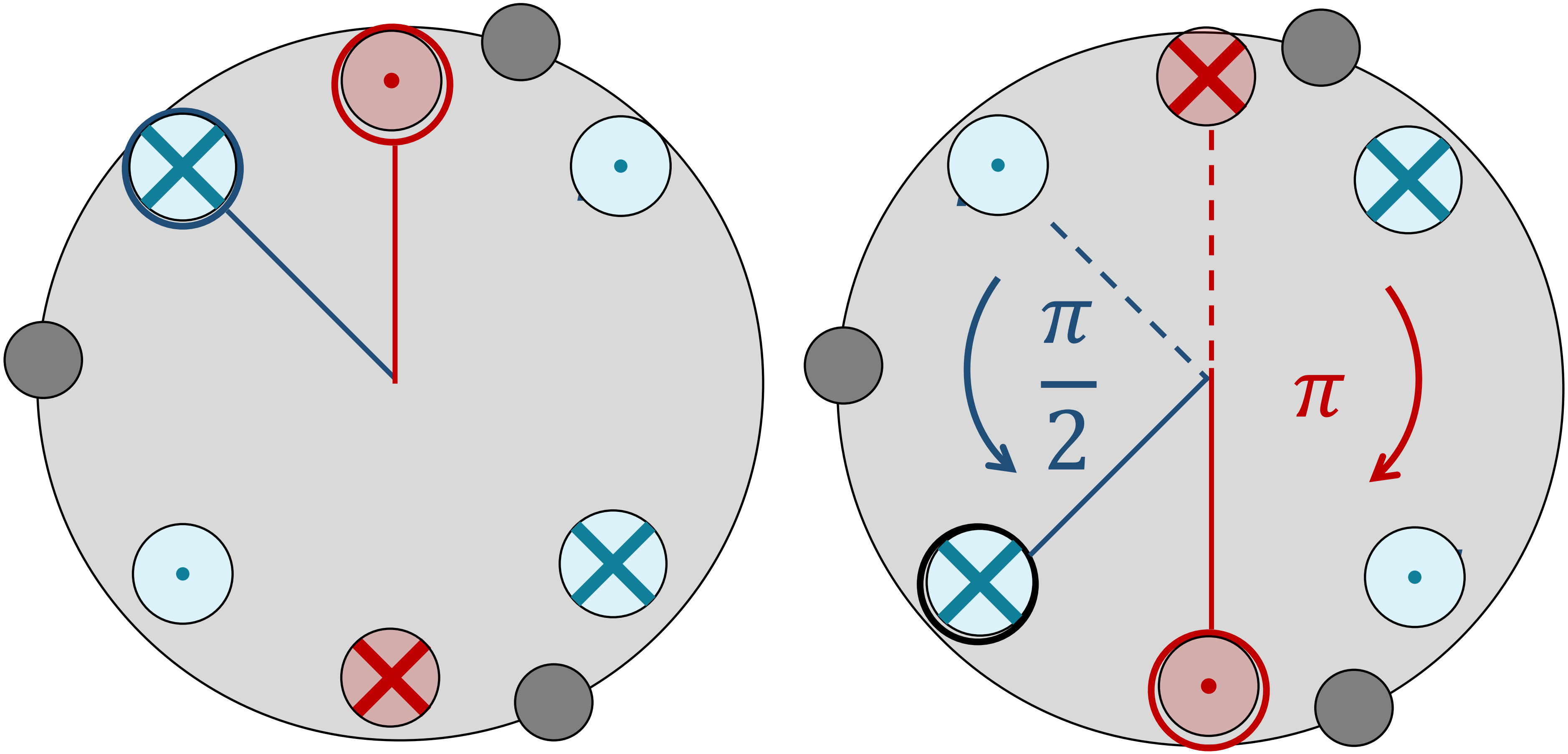
let's move one rotor and look at the forces that will begin to act on the second rotor



opposite directed force** acting on the driven rotor occurs due to the **3d Newton law

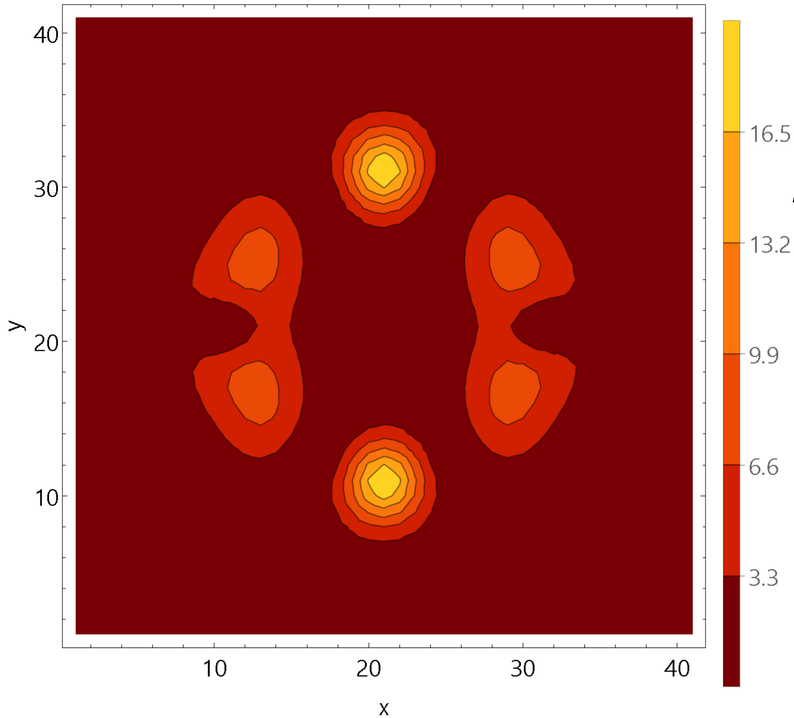
Case with stator

Velocity changes explanation

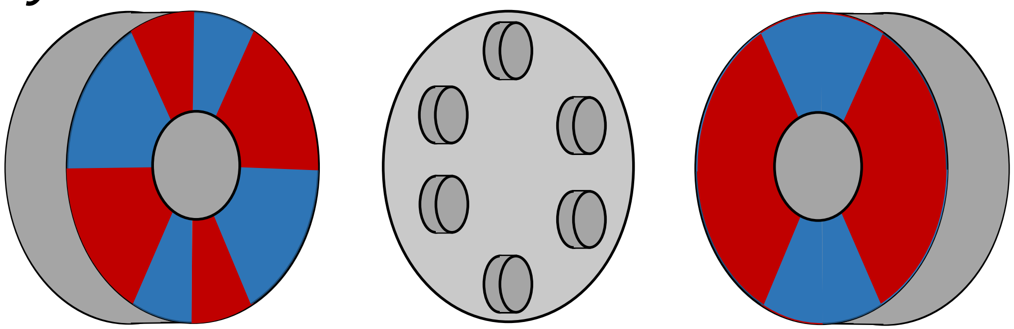


Case with stator

Energy calculation



In most cases, stator is fixed, one rotor and second rotor can be rotated. In second rotor frame reference field distribution can be described in simplest way:



fixed *can be rotated* *rotate by screwdriver*

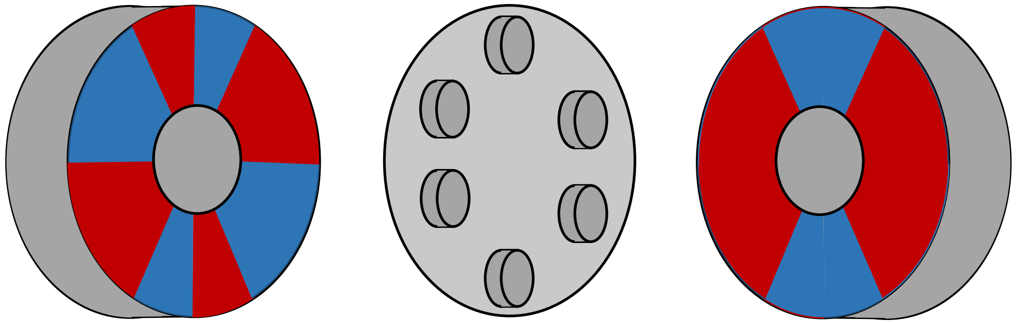
Calculations for 4 and 8 magnets are presented

*There are 6 clearly defined energy maximums ⇒ **6 screws** are drawn in this **6 maximums***

Interaction with stator

Second rotor frame reference

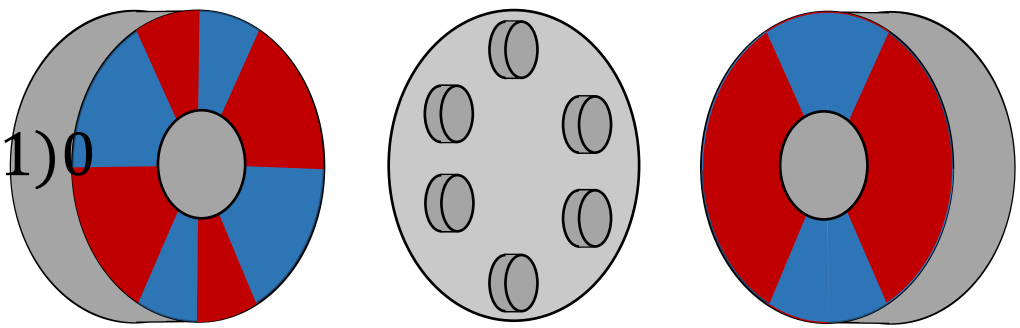
$\omega_{r1} = k\Omega$



$\omega_{r2} = \Omega$

$\omega_s = 0$

$\omega_{r1} = (k-1)0$



$\omega_{r2} = 0$

static rotor gear ratio

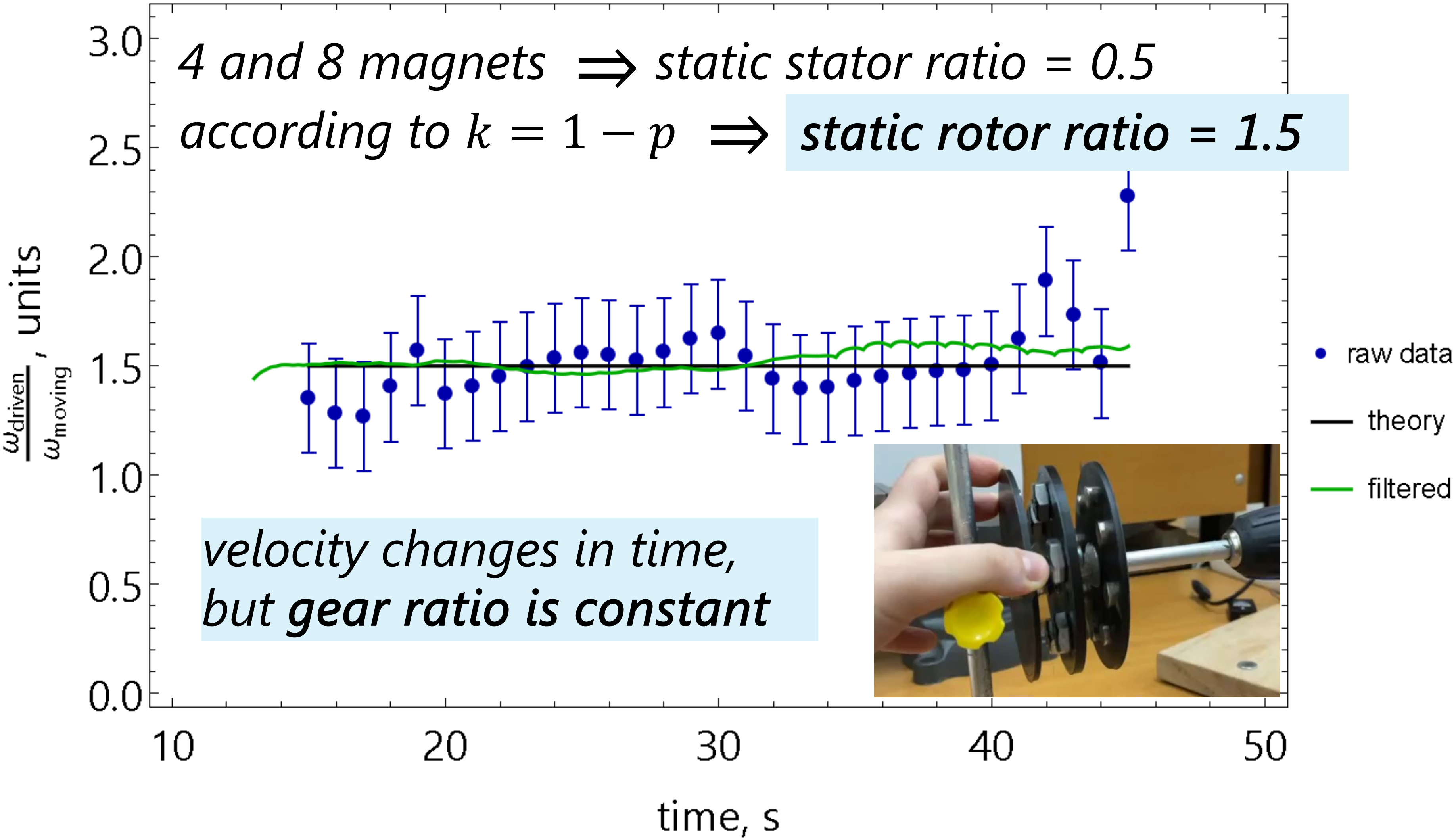
$\omega_s = -\Omega$

$p = 1 - k \quad \Rightarrow \quad \boldsymbol{k = 1 - p}$

static stator gear ratio

Interaction with stator

Gear ratio verification



Overview

V

Magnets interaction

Forces between magnets. Magnetic field. Launch criterion. System of magnets.

V

Case without stator

Potential pit and state equilibrium. Field model. Gear ratio.

V

Case with stator

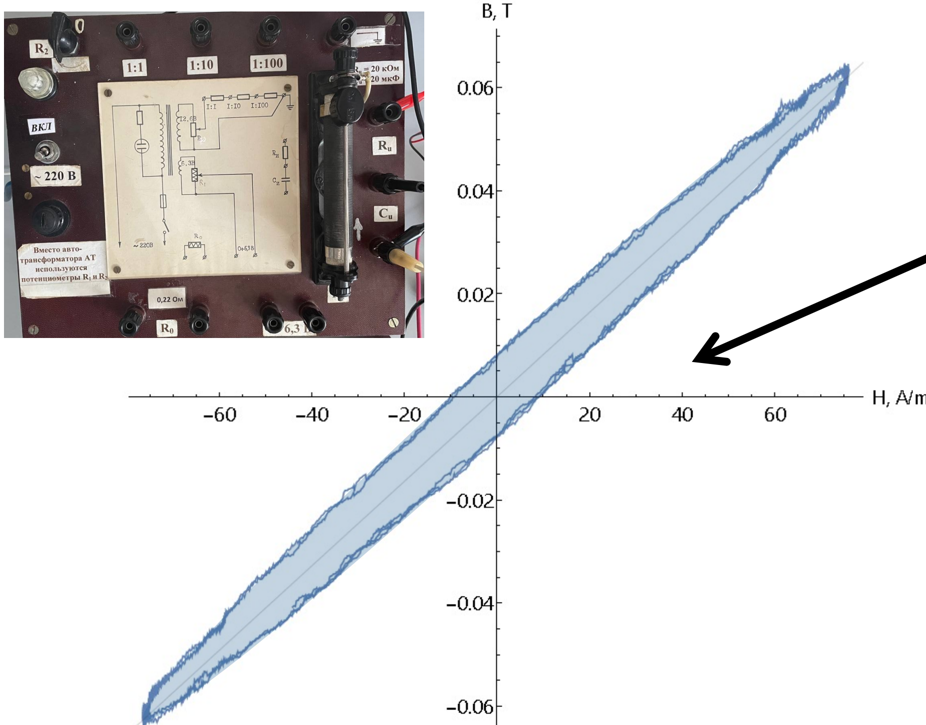
Velocity changes explanation. Different direction explanation

4

Limitations

Gear ratio(velocities). Limitations.

Hysteresis



energy loss due to ***magnetization reversal*** *of screws*

total screws volume

$$\Delta E = V \int B \, \mathrm{d}H$$

hysteresis loop area

for our screws losses power :

$$N_+ = 10^{-6} \, {}^{\omega}\!/_{2\pi}$$

screwdriver power :

$$N_{loss} = 10^{-5} \, {}^{\omega}\!/_{2\pi}$$

$\Rightarrow$

efficiency for steel screws :

$$\eta = \frac{N_+}{N_+ + N_{losses}} = 0.1$$

Limitations

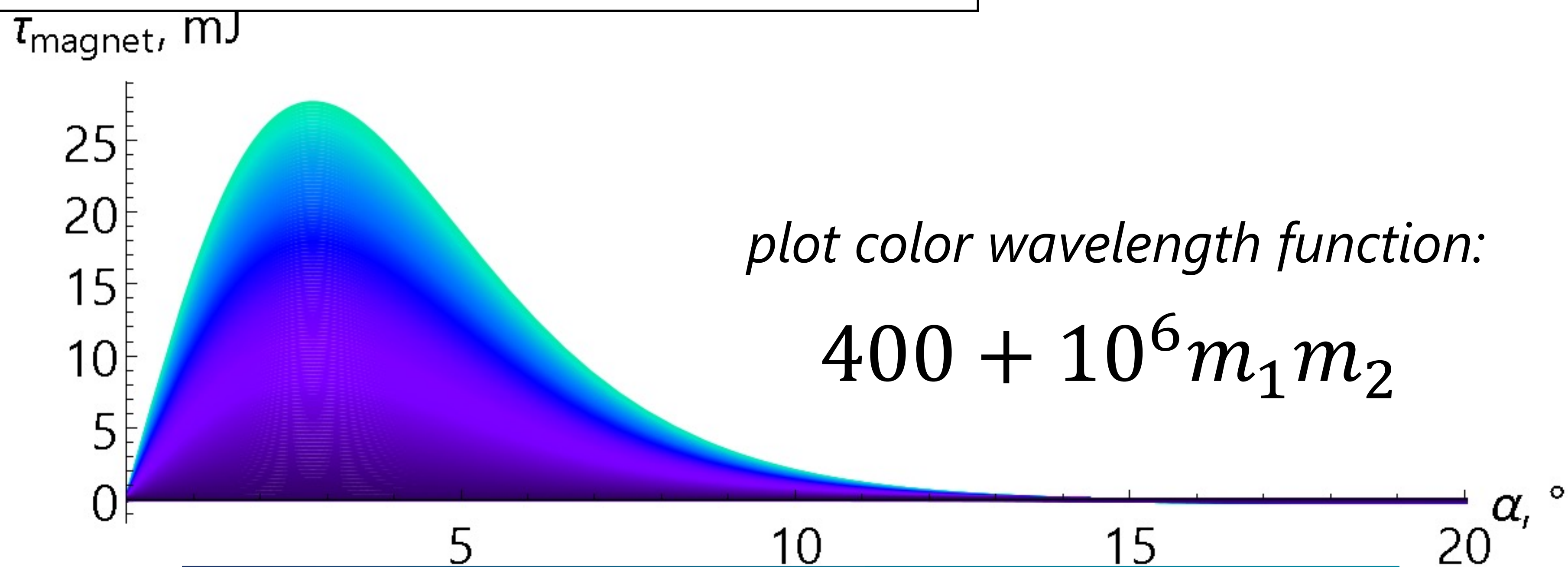
Magnetic force

Launch criterion can be modified as :

$$\vec{\boldsymbol{B}} \Rightarrow \vec{\boldsymbol{F}} = \nabla(\vec{m} \cdot \vec{B}) \Rightarrow \boldsymbol{\tau_{magnet}} = Q \cdot R \cdot F_\alpha$$

amount of magnets interaction

! *Critical value for dipole moments product was found*

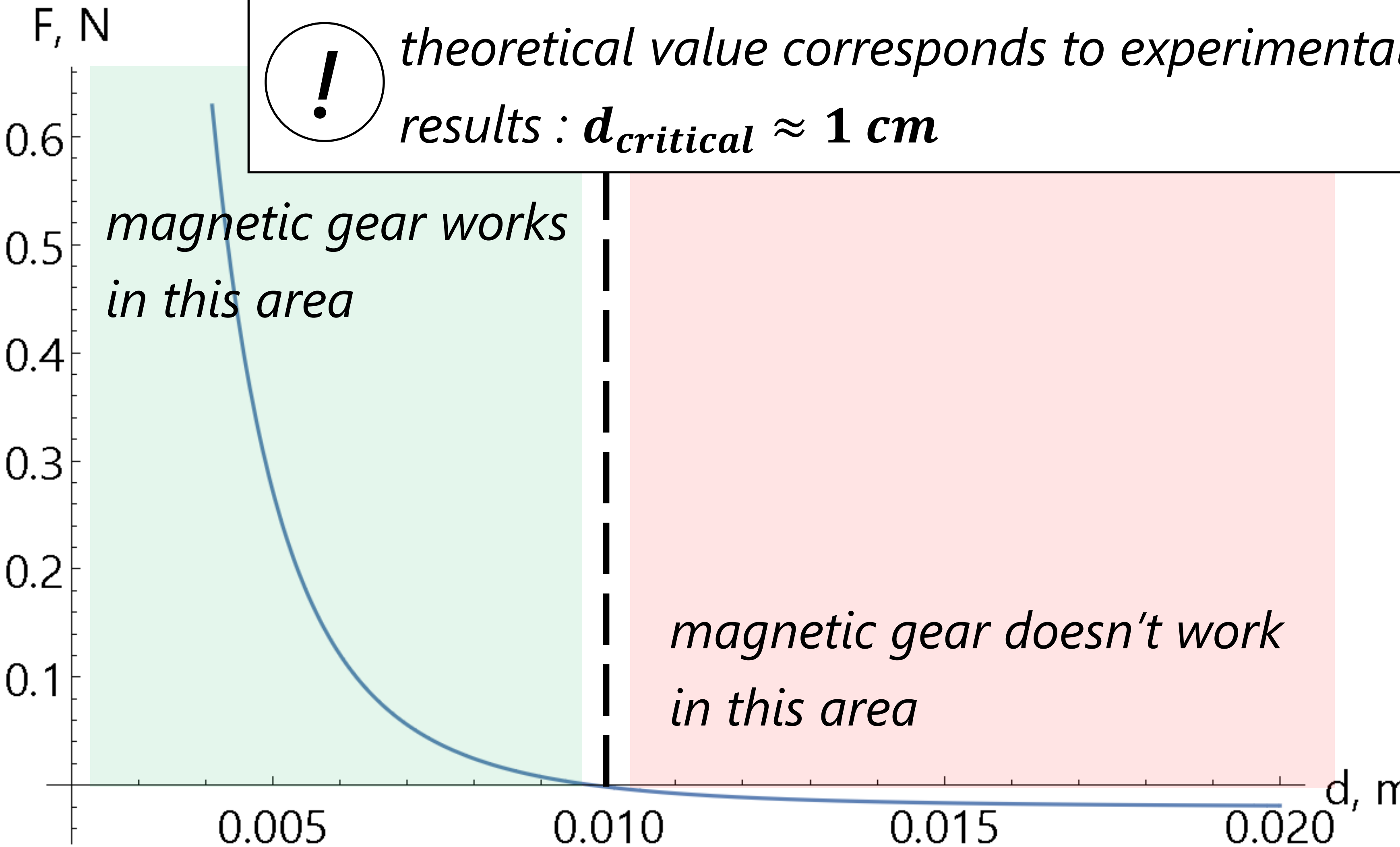


plot color wavelength function:

$$400 + 10^6 m_1 m_2$$

Limitations

Magnets arrangement

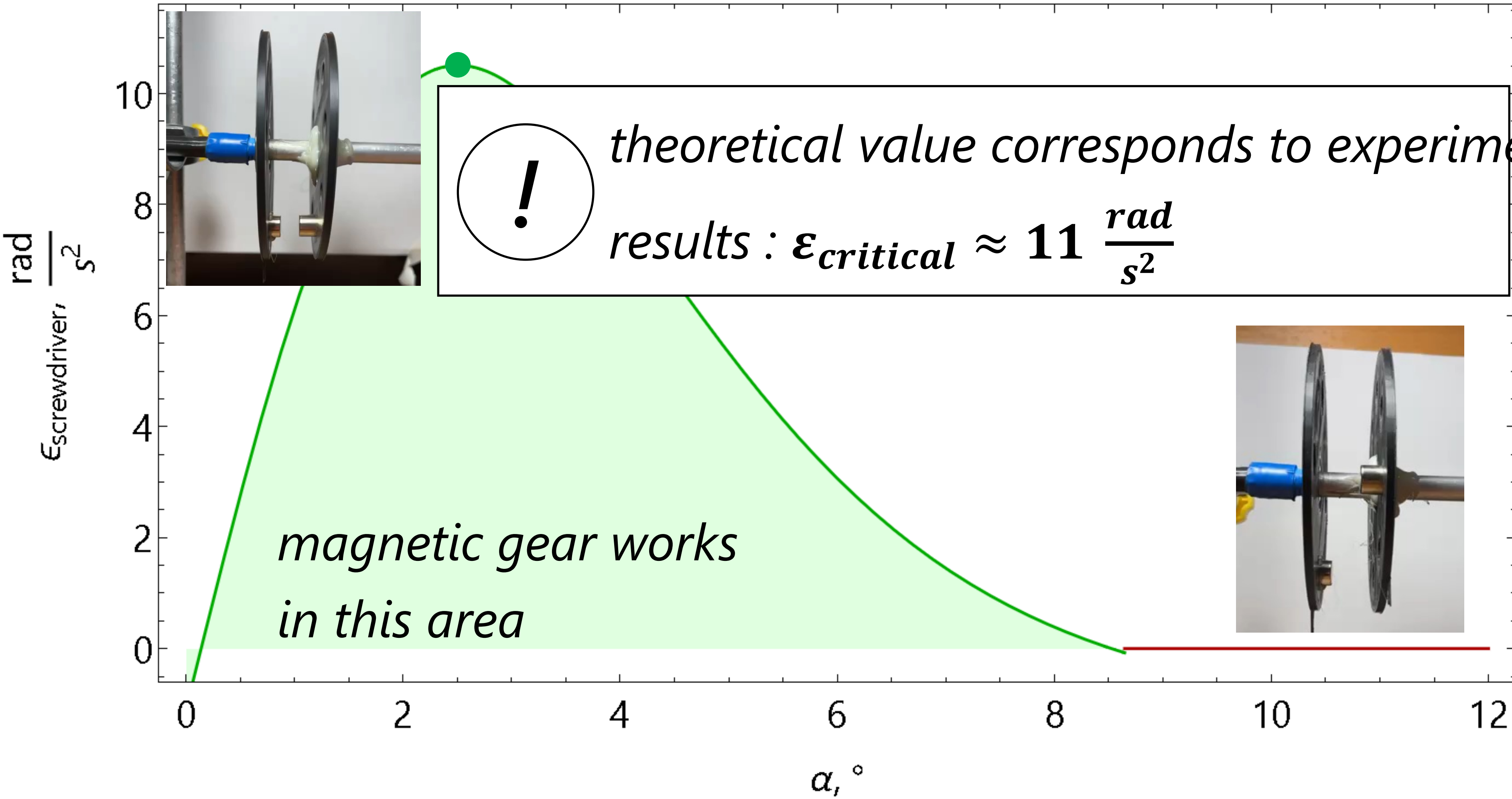


!

theoretical value corresponds to experimental results : $\mathbf{d_{critical} \approx 1\ cm}$

Limitations

Screwdriver acceleration



Limitations

Final limitations

! *Dipole moment* $\boldsymbol{m_{critical}} \approx \mathbf{0.001}\ \boldsymbol{\frac{J}{Tl}}$

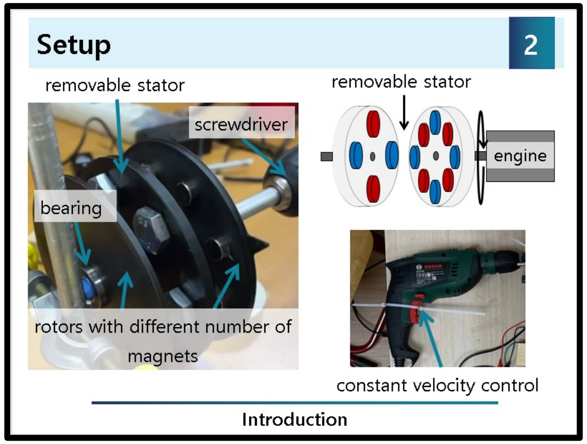
! *Distance between rotors* $\boldsymbol{d_{critical}} \approx \mathbf{1\ cm}$

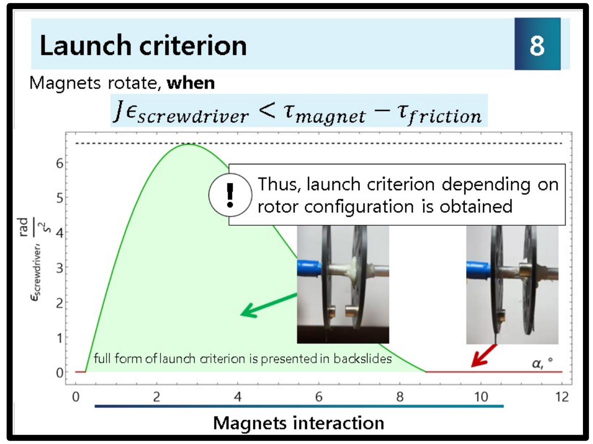
! *Screwdriver acceleration* $\boldsymbol{\varepsilon_{critical}} \approx \mathbf{11}\ \boldsymbol{\frac{rad}{s^2}}$

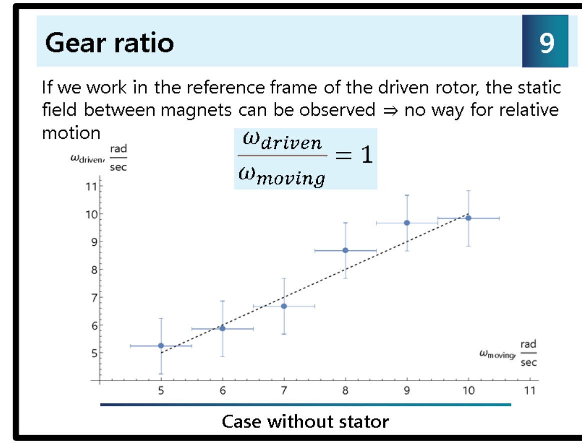
+

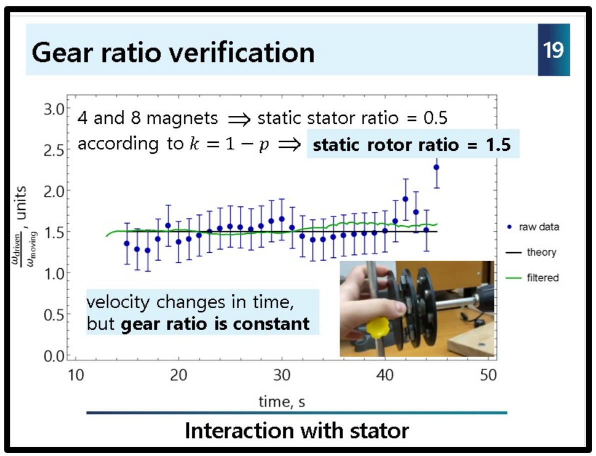
inertia moment, air resistance, magnets size

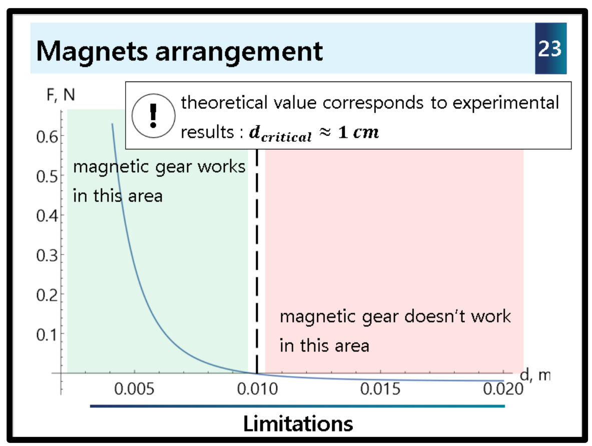
Conclusions

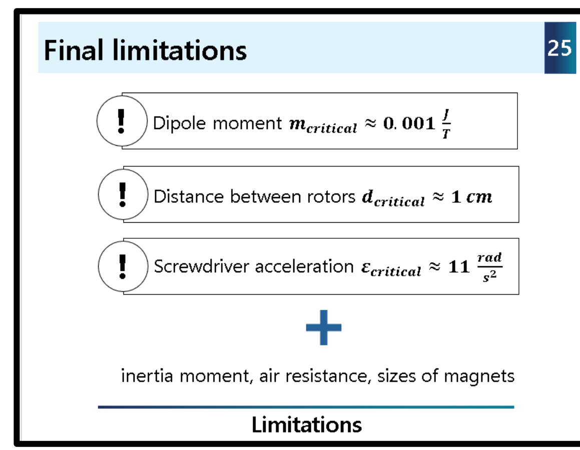












Problem No. 10

Magnetic gears

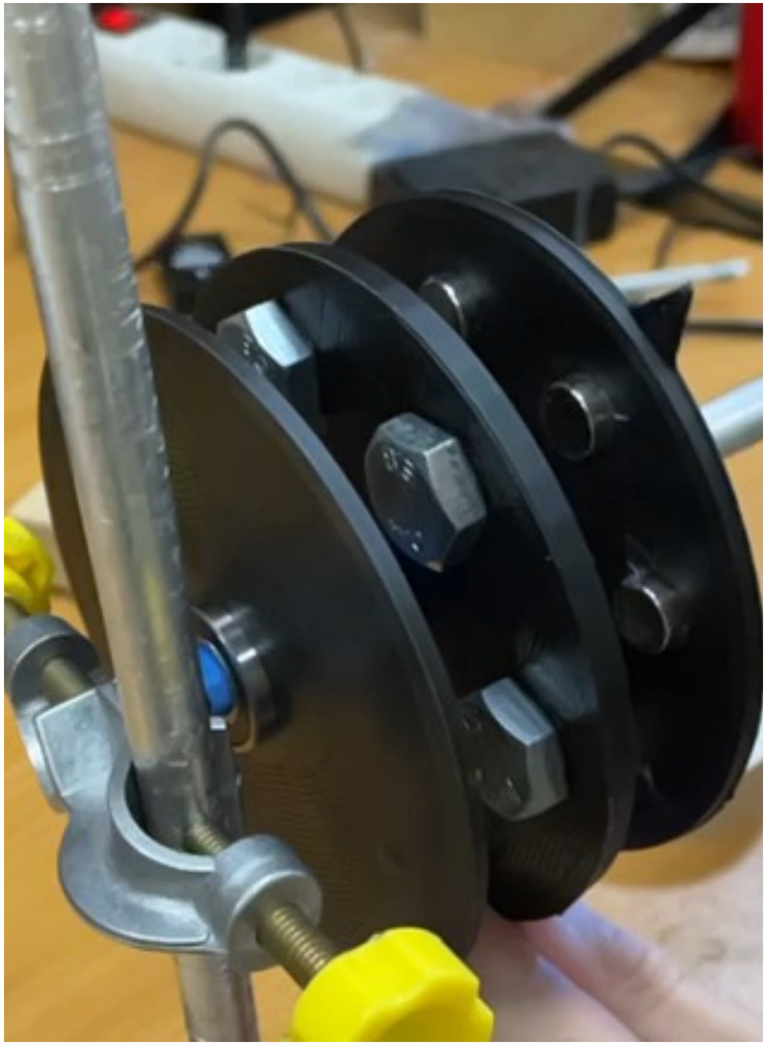
Thank you!

Questions?

Also was investigated:

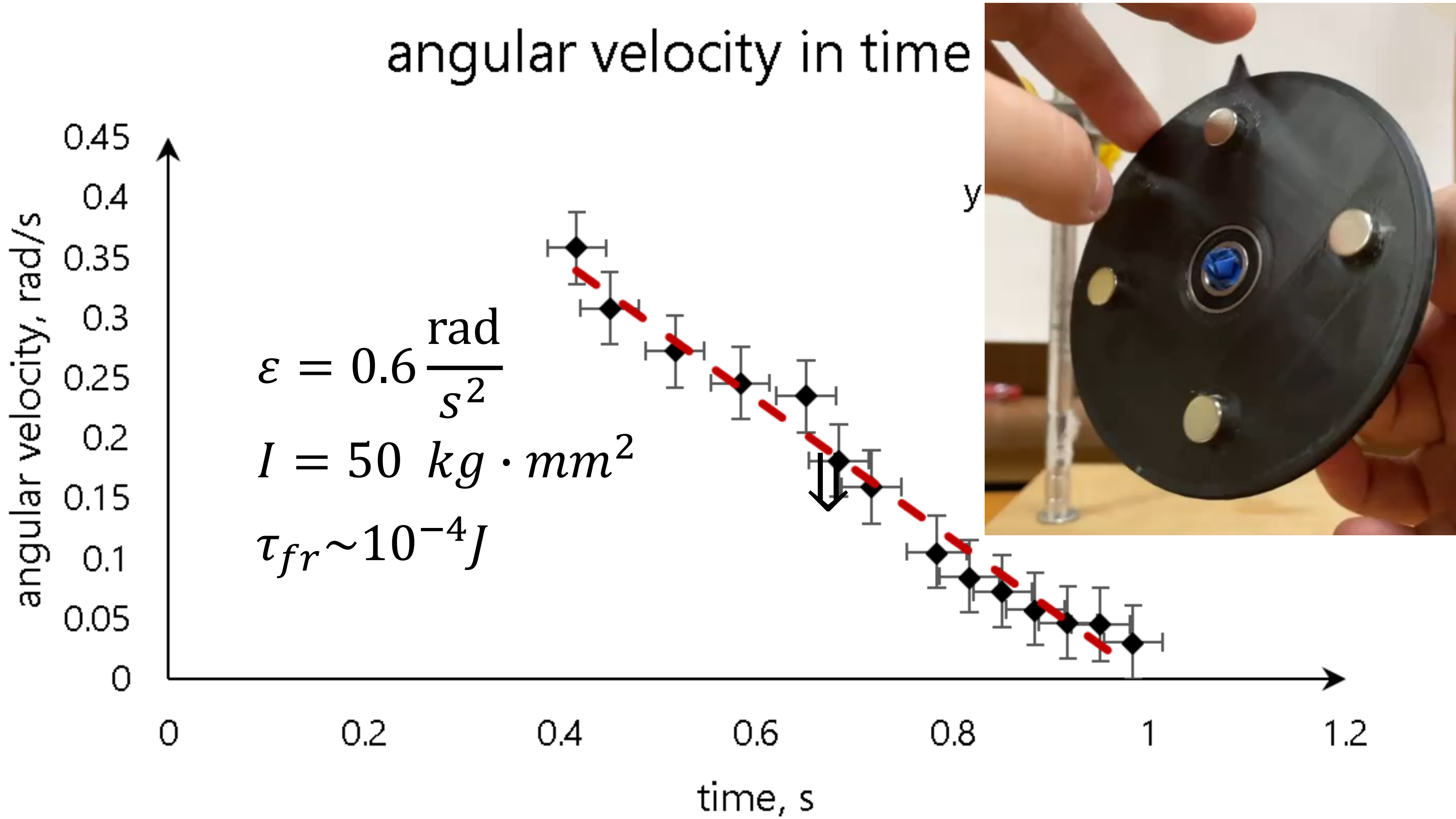
- *Dynamics of magnet depending on parameters*
- *Magnets size*
- *Comsol modelling + torque*
- *Experimental torque measurements*

Reporter: *Sophia Kaniukova*



Backslides

Forces between 2 magnets



$$\varepsilon = 0.6\,\frac{\text{rad}}{s^2}$$

$$I = 50\ \ kg \cdot mm^2$$

$$\tau_{fr} \sim 10^{-4} J$$

General criterion

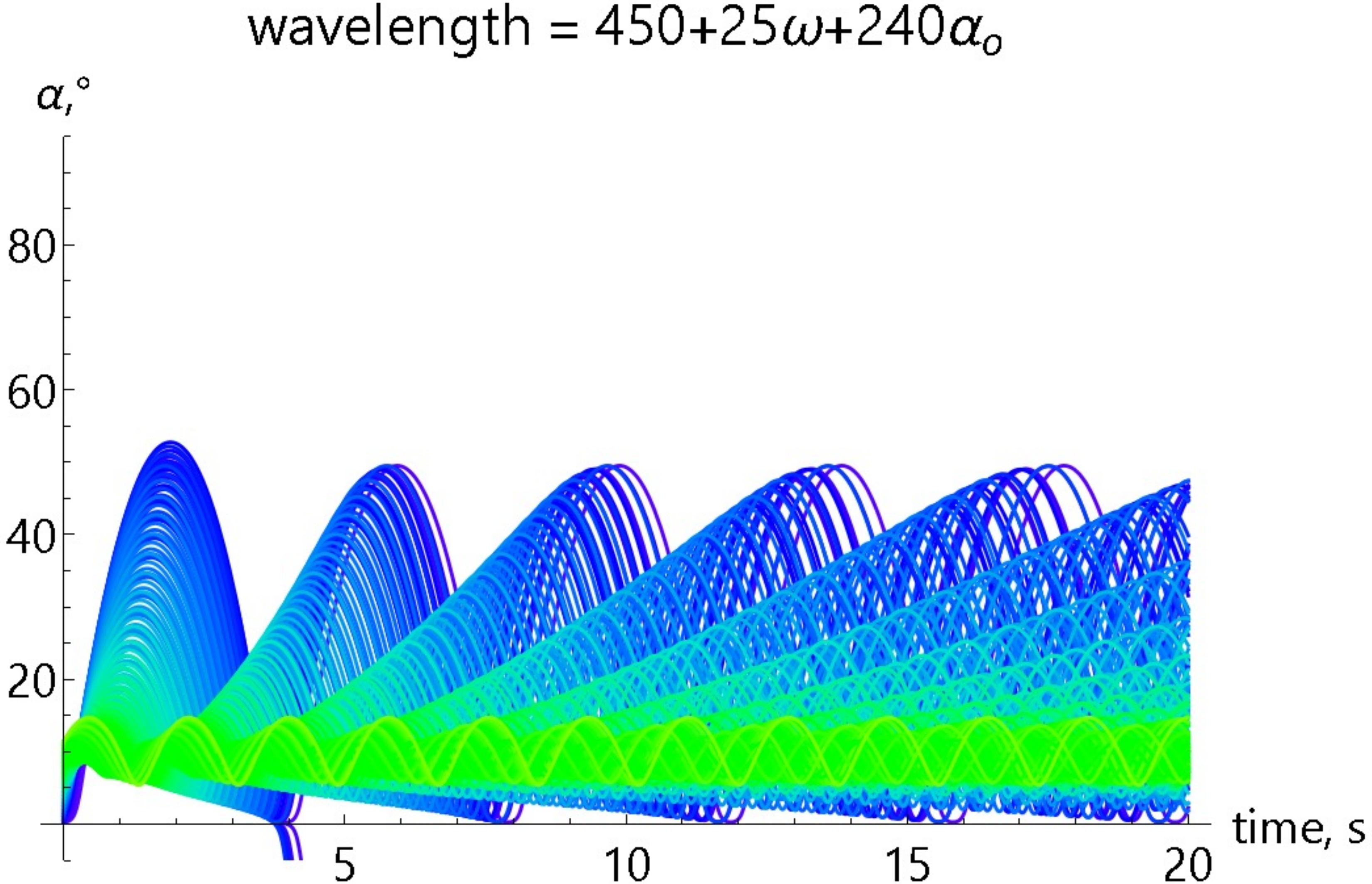
$$F_\alpha = \frac{-5m_1m_2\,\mathrm{d}^2 y\sin\alpha}{(2R^2(1-\cos\alpha)+d^2)^{3.5}} - \frac{3m_1m_2 y\sin\alpha}{(2R^2(1-\cos\alpha)+d^2)^{2.5}}$$

$$\tau_\alpha = \left(\frac{-5m_1m_2\,\mathrm{d}^2}{2R^2(1-\cos\alpha)+d^2} - 3m_1m_2\right)\frac{y\,R\sin\alpha}{(2R^2(1-\cos\alpha)+d^2)^{2.5}}$$

$$\Downarrow$$

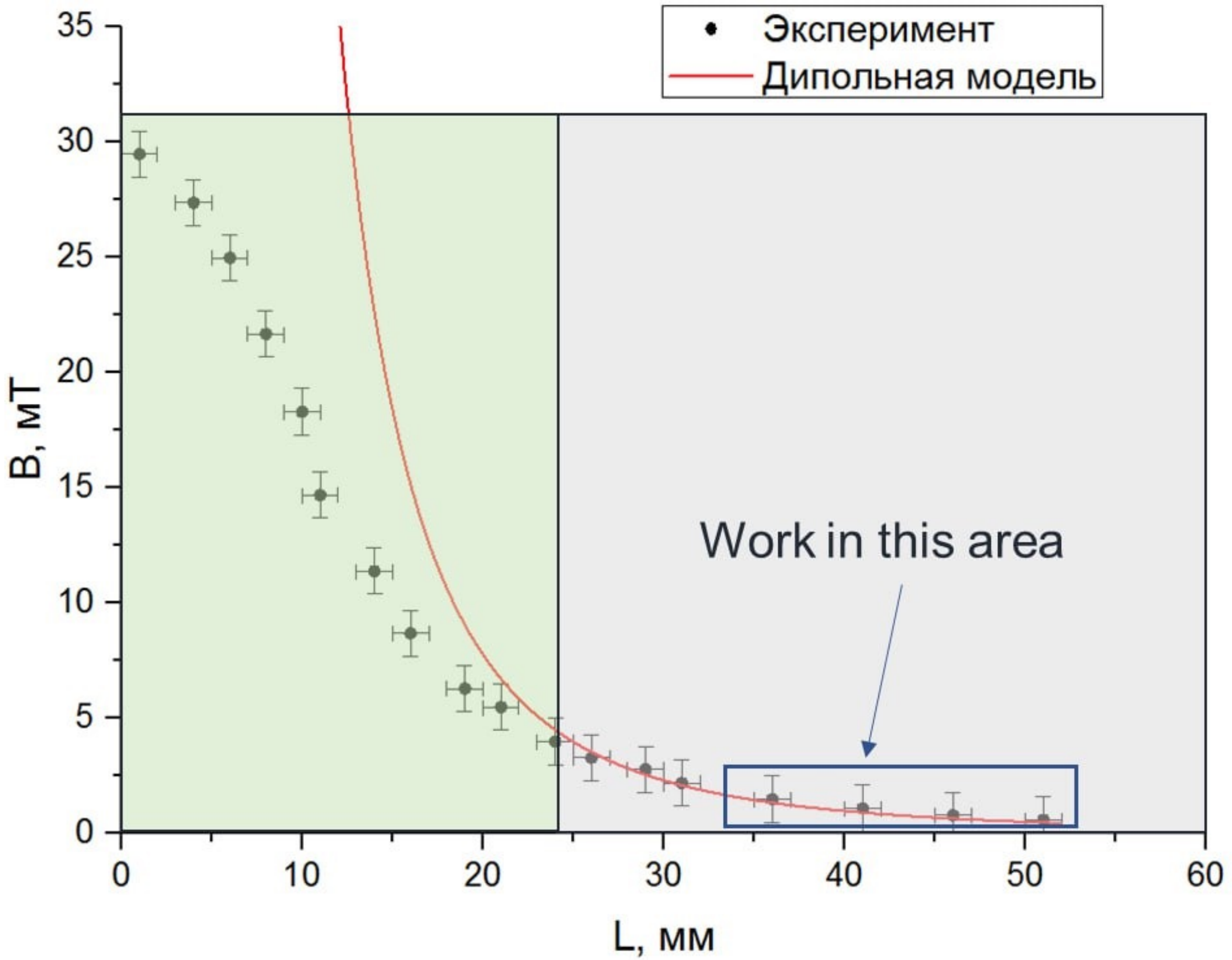
$$J\ddot{\alpha} = \left(\frac{-5m_1m_2\,d^2}{2R^2(1-cos\ \alpha)+d^2} - 3m_1m_2\right)\frac{y\ R\ sin\ \alpha}{(2R^2(1-cos\ \alpha)+d^2)^{2.5}} - \tau_{fr}$$

Magnets dynamics



Backslides

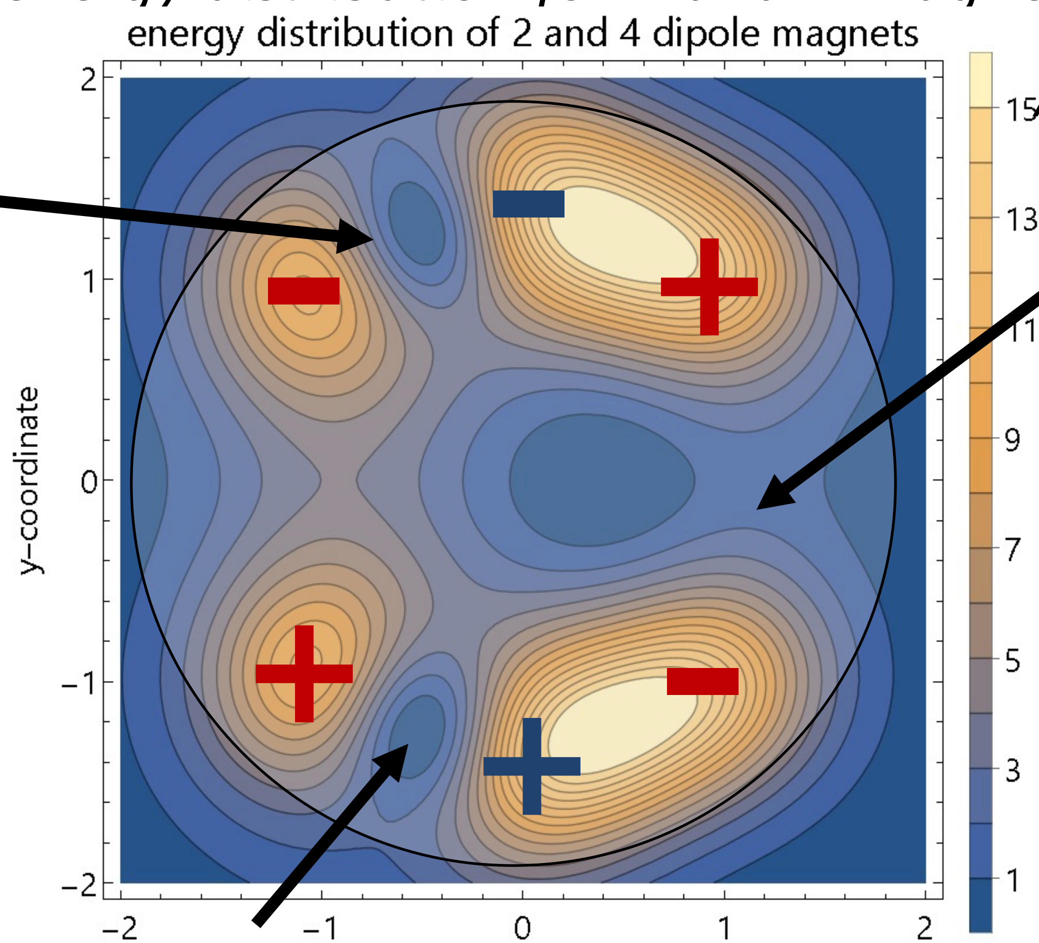
Fields distribution



System of magnets

Calculation of energy distribution for 4 and 2 magnets

pit because of $\boldsymbol{B_\varphi = 0}$



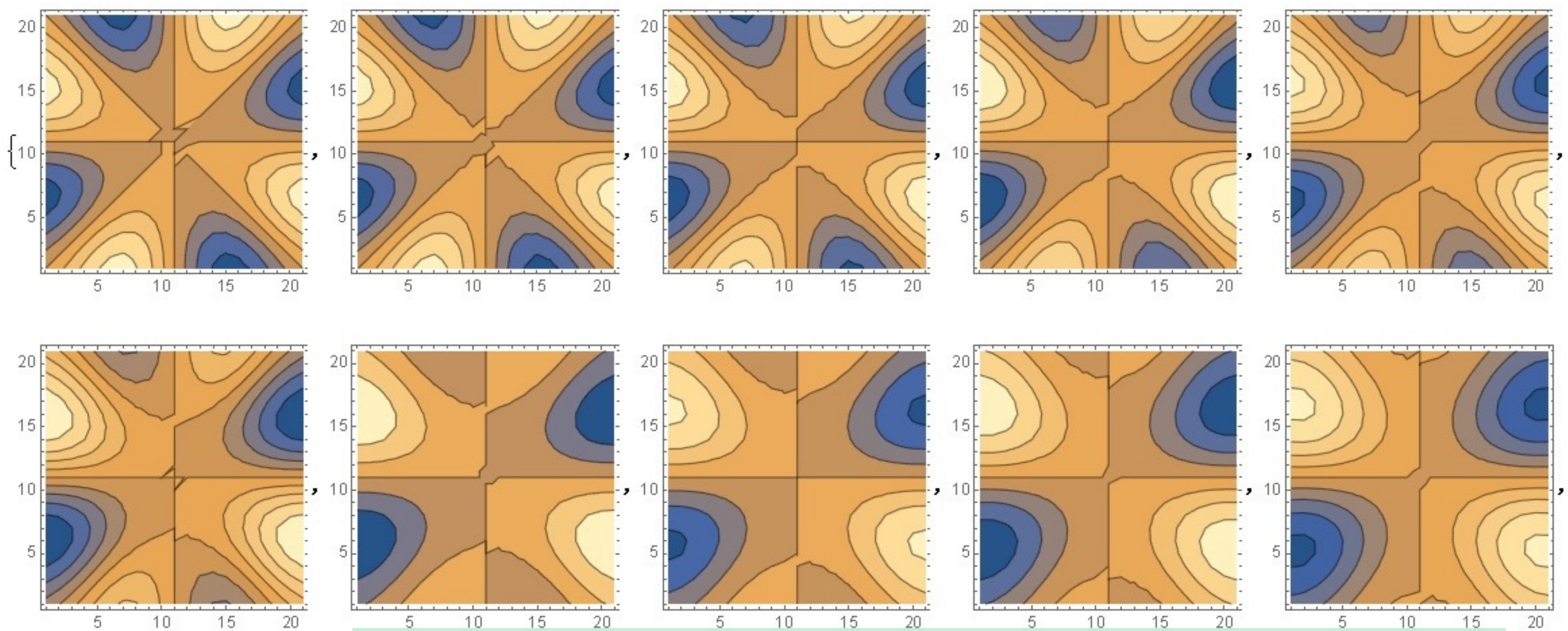
pit because of distance between + and -

pit because of $\boldsymbol{B_\varphi = 0}$

Case without stator

Magnet size limitations

$\frac{d_1}{d_2} = 0$ $\frac{d_1}{d_2} = 0.1$ $\frac{d_1}{d_2} = 0.2$ $\frac{d_1}{d_2} = 0.3$ $\frac{d_1}{d_2} = 0.4$



$\frac{d_1}{d_2} = 0.5$ $\frac{d_1}{d_2} = 0.6$ $\frac{d_1}{d_2} = 0.7$ $\frac{d_1}{d_2} = 0.8$ $\frac{d_1}{d_2} = 0.9$

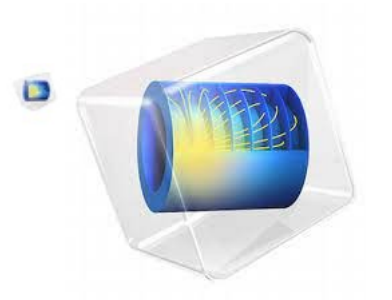
Interaction with stator

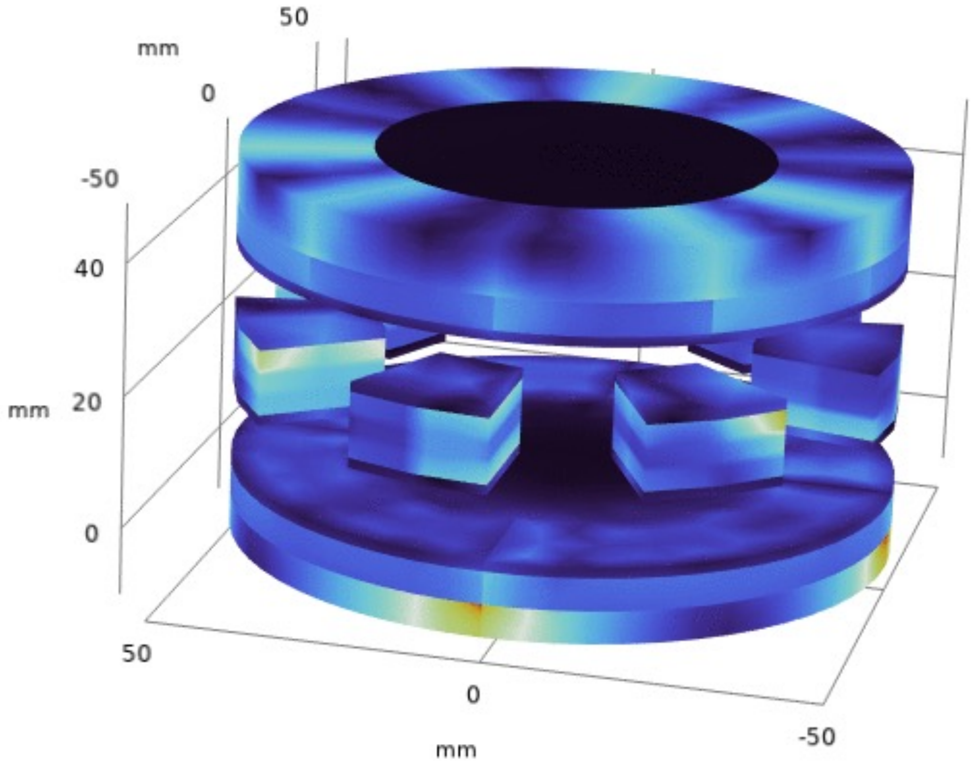
Way to calculate

dipole approximation gives wrong angular velocity ratio

$\Downarrow$

Use Comsol Multiphysics





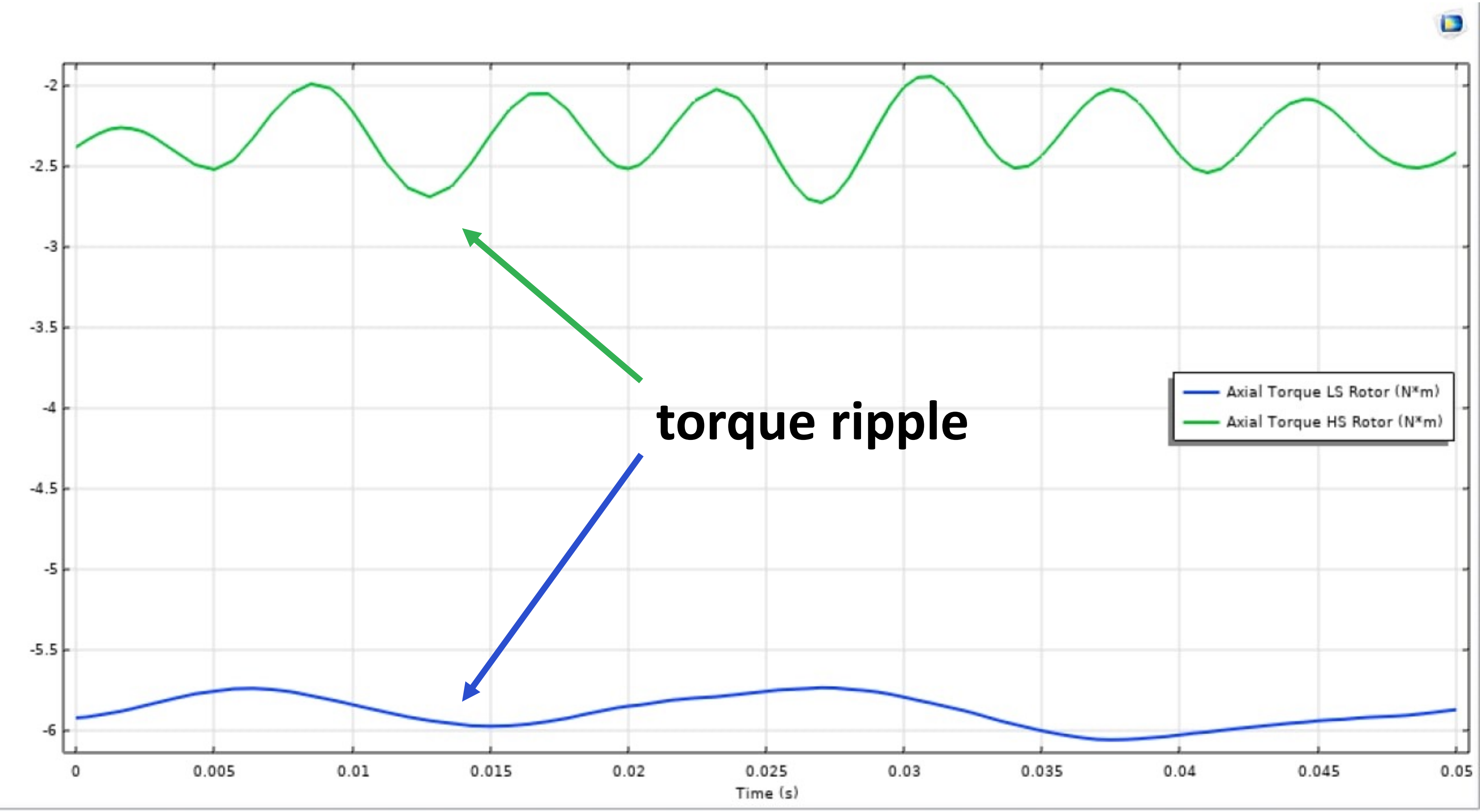
parameters of modeling

non-linear BH Curve material model
in the soft iron region

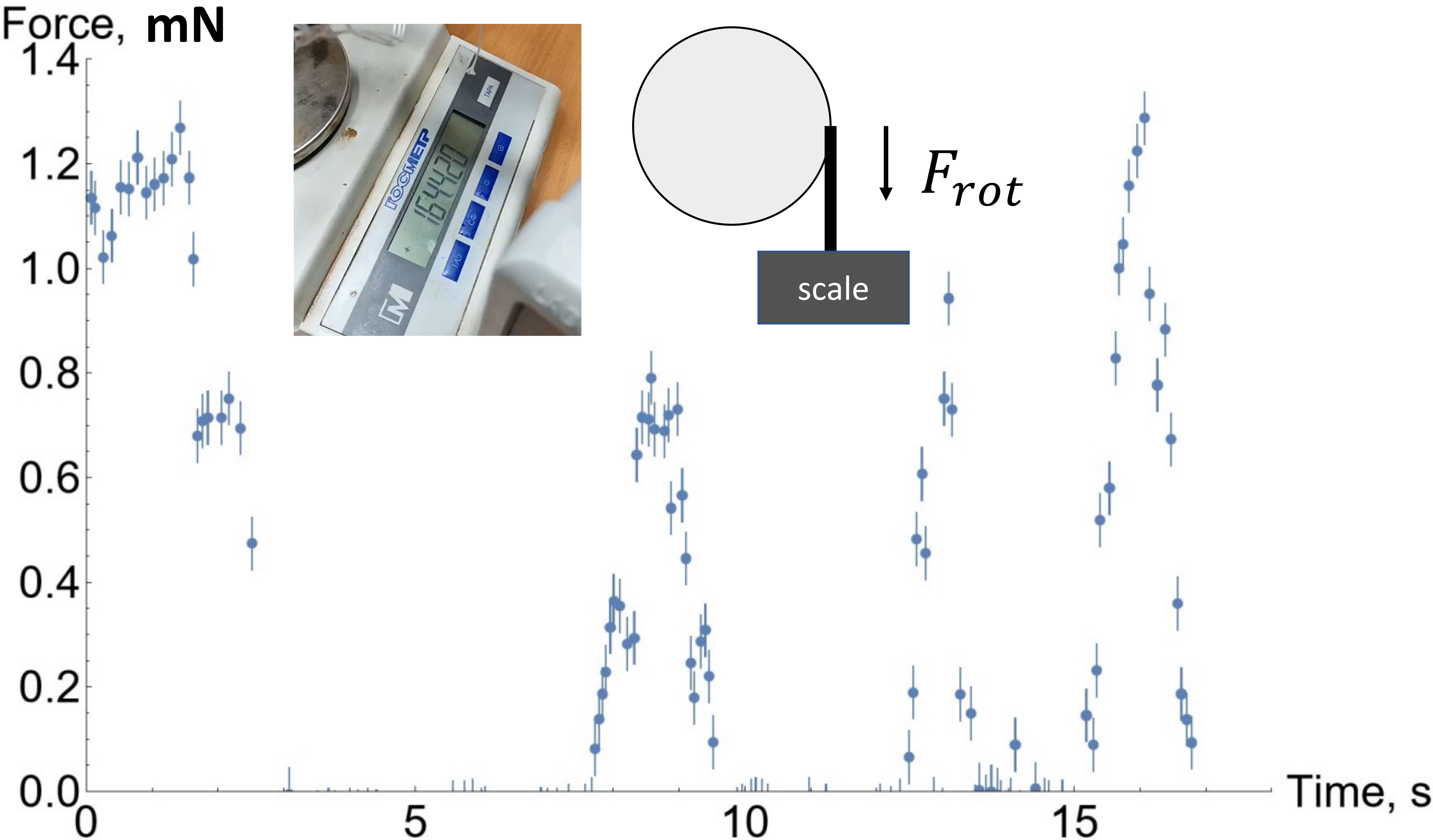
the fixed steel pole pieces is a linear
material with relative permeability 4000

axial torque of both rotors is calculated
based on the Maxwell stress tensors

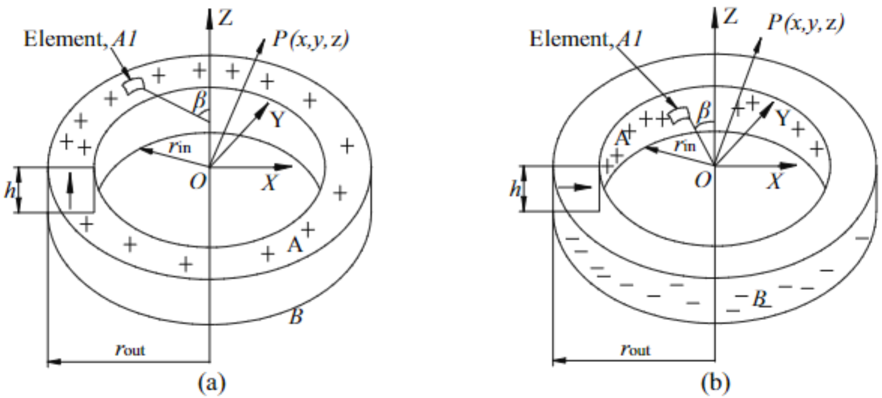
Rotational torque

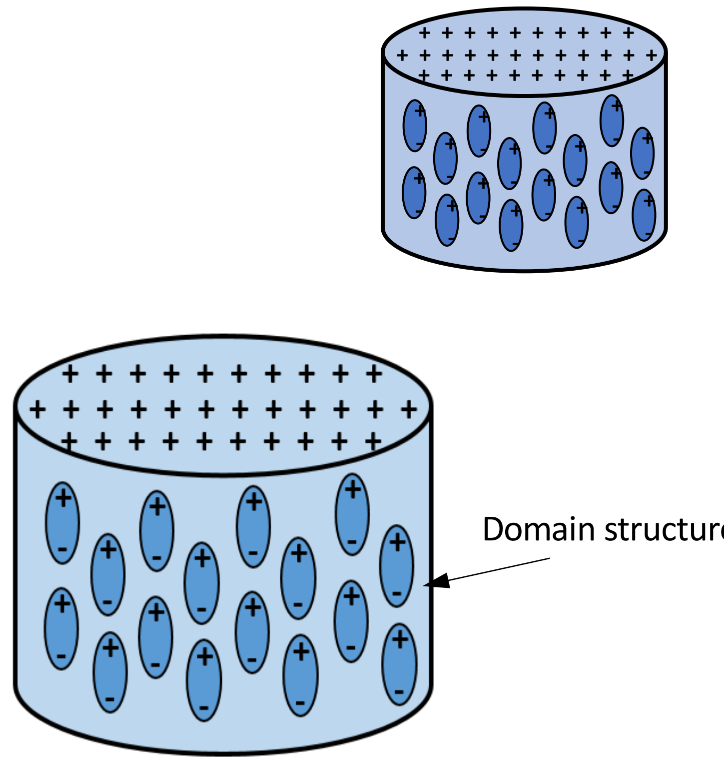


Rotational force ripples



Literature overview





Depend om material

Field created by
a small piece of magnet

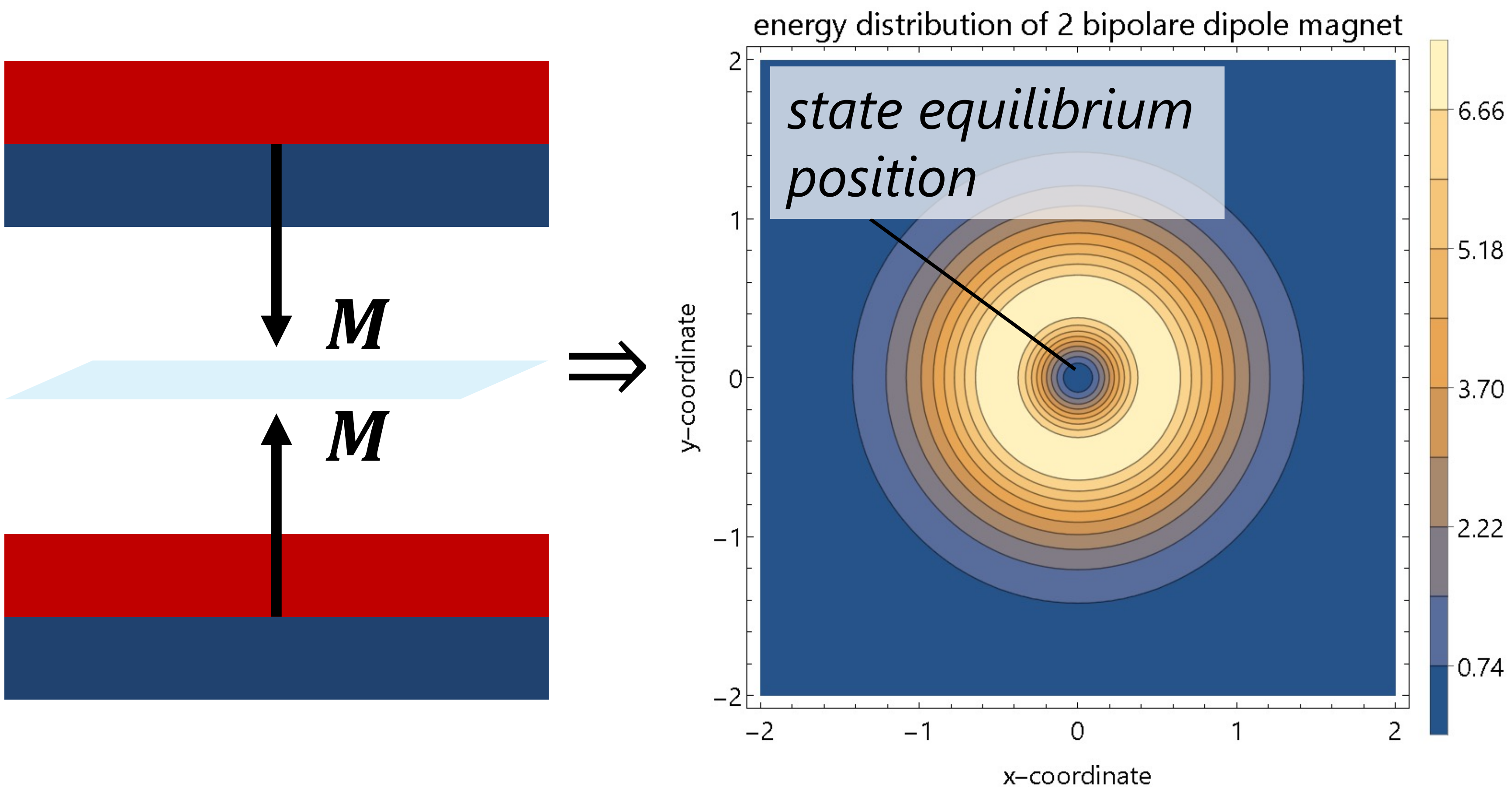
$$\vec{H}_{A1} = \frac{\boxed{(+J)}\,S_{A1}}{4\pi\mu_0 r_{A1P}^3}\vec{r}_{A1P}$$

$$\vec{H}_{B1} = \frac{\boxed{(-J)}\,S_{B1}}{4\pi\mu_0 r_{B1P}^3}\vec{r}_{B1P}$$

"Analysis of the magnetic field created by permanent magnet rings in permanentmagnet bearings"
Siddappa Iranna Bekinal, Tumkur Ramakrishna rao Anil, 2014

Potential pit and state equilibrium

Using the principle of the field superposition, one can calculate general field ⇒ ***energy distribution***



Case without stator

System of magnets

Modified start criterion:

total magnetic force between each 2 magnets (amount of pairs)

$$\tau_{magnet}^{total} \approx N\tau_{magnet}$$

Case without stator