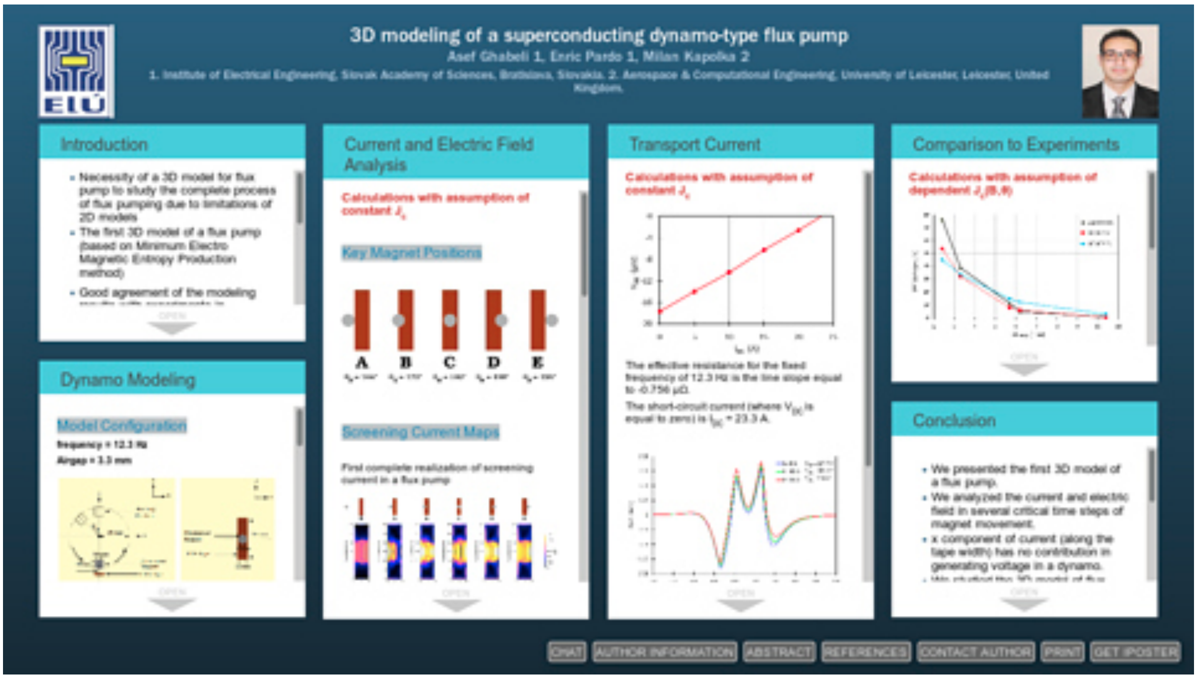
# 3D modeling of a superconducting dynamo-type flux pump

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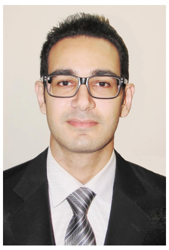


PRESENTED AT:

# INTRODUCTION

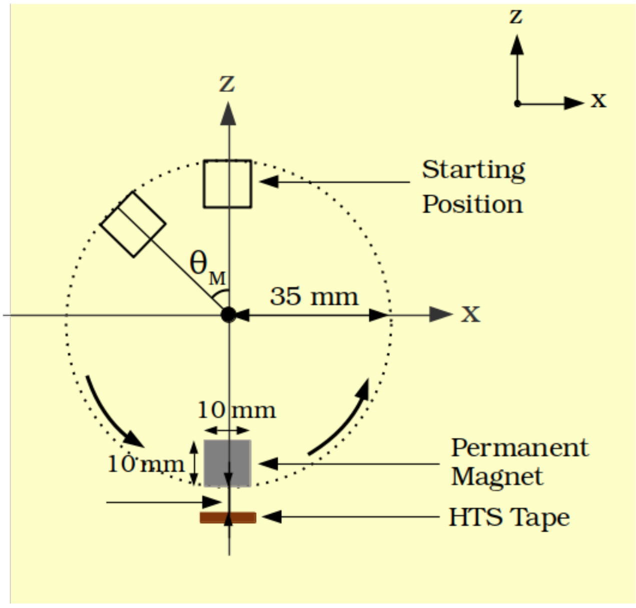
- Necessity of a 3D model for flux pump to study the complete process of flux pumping due to limitations of 2D models
- The first 3D model of a flux pump (based on Minimum Electro Magnetic Entropy Production method)
- Good agreement of the modeling results with experiments in open-circuit mode
- Analyzing the screening current and electric field of flux pump in several critical time steps in open-circuit mode
- Studying the case with DC transport current

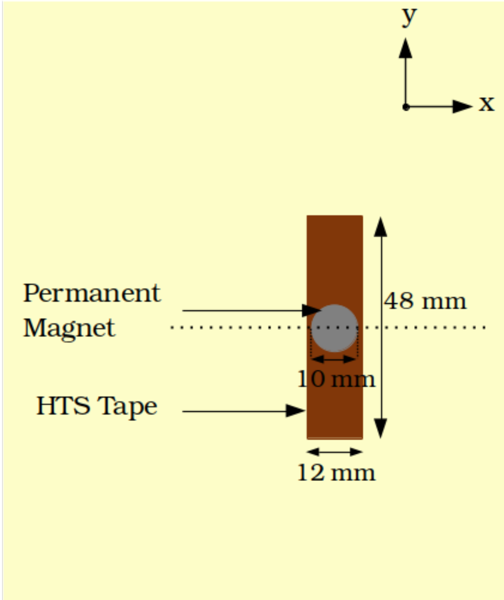
# DYNAMO MODELING

## Model Configuration

**frequency = 12.3 Hz**

**Airgap = 3.3 mm**




## MEMEP 3D

$$\nabla \times \mathbf{T} = \mathbf{J}$$

effective magnetization

$$\mathbf{E}(\mathbf{J}) = -\dot{\mathbf{A}} - \nabla\varphi$$

vector potential; $\nabla\varphi$ → electrostatic potential

$$\nabla \cdot \mathbf{J} = \mathbf{0}$$

change between two times steps ($\Delta \mathbf{A}_J$); vector potential due to applied field ($\Delta \mathbf{A}_a$)

$$L = \int_V dv[\frac{1}{2}\frac{\Delta \mathbf{A}_J}{\Delta t} \cdot (\nabla \times \Delta \mathbf{T}) + \frac{\Delta \mathbf{A}_a}{\Delta t} \cdot (\nabla \times \Delta \mathbf{T}) + U(J)]$$

$$U(\mathbf{J}) = \int_0^J \mathbf{E}(\mathbf{J}').d\mathbf{J}'$$

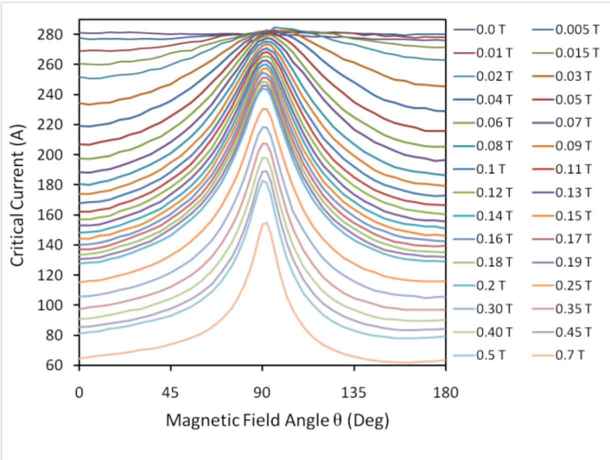
## Tape Modeling

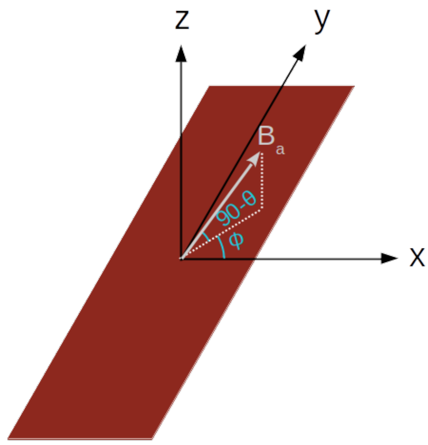
Superpower SF12050CF wire

12 mm width, 1 μm thickness

$$\mathbf{E}(\mathbf{J}) = E_c \left(\frac{|\mathbf{J}|}{J_c}\right)^n \frac{\mathbf{J}}{|\mathbf{J}|}$$

$I_c(B,\theta)$ experimental data at 77 K derived from [1]




Angle Φ was negelected in the model for $J_c(B,\theta)$ calculations ($\Phi = 0$)

Output Voltage Calculation

$$V = -\frac{1}{wl}\left(\int_{-\frac{w}{2}}^{+\frac{w}{2}} dx \int_{-\frac{l}{2}}^{+\frac{l}{2}} dy \left[\frac{\partial \varphi}{\partial y}\right]\right) . \, l$$

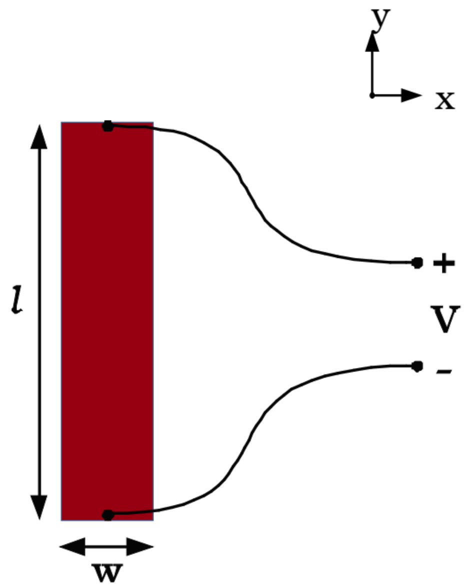
$$V = \, l . \, [\frac{\partial A_{y,av}}{\partial t} + E_{y,av}]$$

$$V_{DC} = \, l . \, E_{y,av}$$

because $A_y$ is periodic in a cycle

$$\Delta V(t) = V_{77\,K}(t) - V_{300\,K}(t)$$

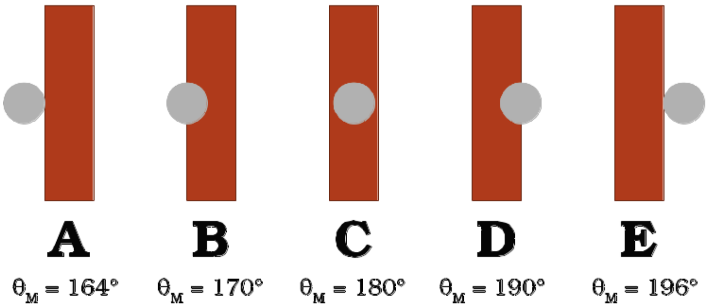
$$\Delta V_{oc} \approx [\partial_t A_{av,J} + E_{av}(J)] . \, l$$ [2]



# CURRENT AND ELECTRIC FIELD ANALYSIS

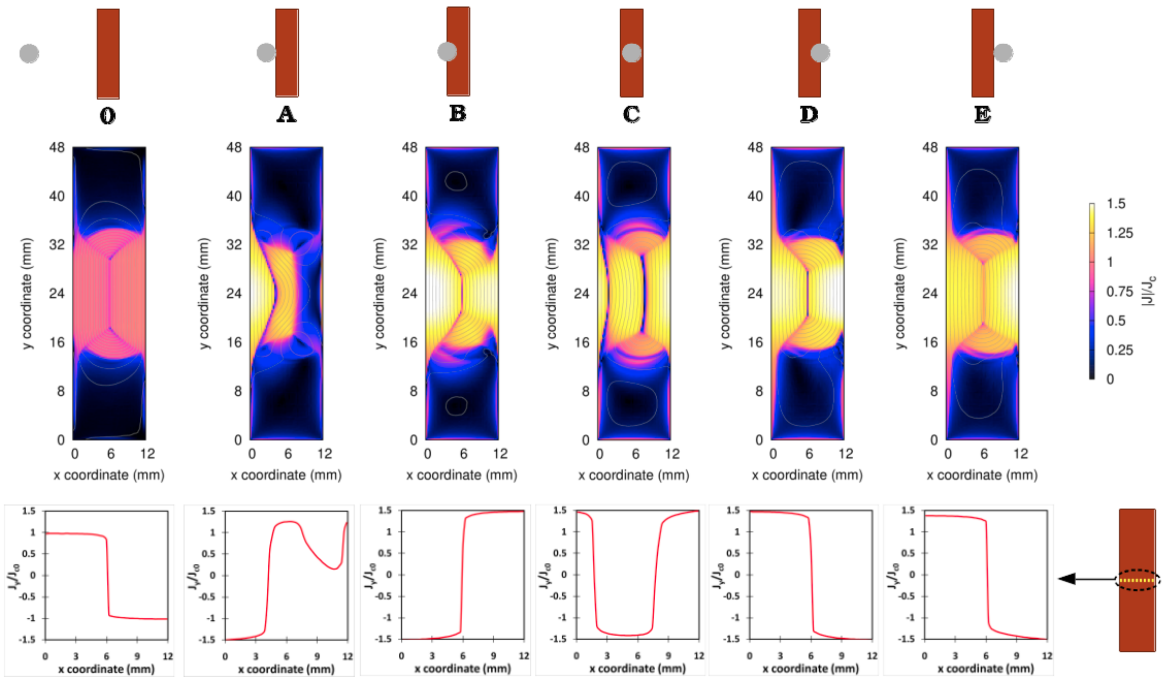
**Calculations with assumption of constant $J_c$**

## Key Magnet Positions




## Screening Current Maps

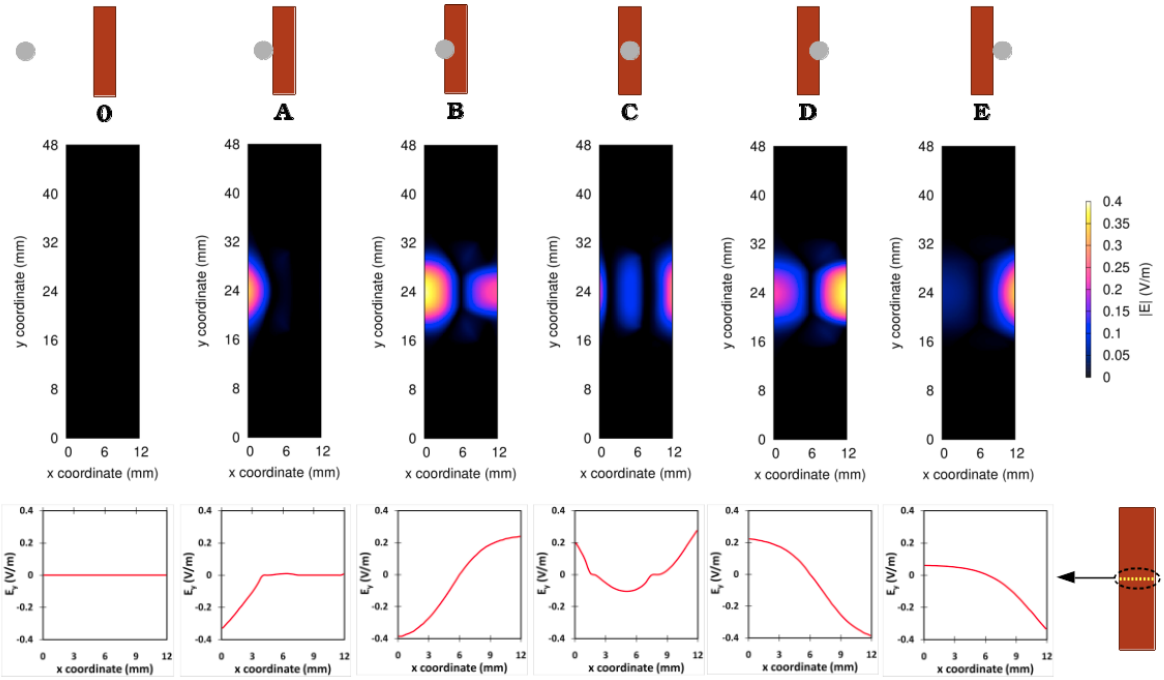
First complete realization of screening current in a flux pump




Screening currents only appears in the center of the tape.

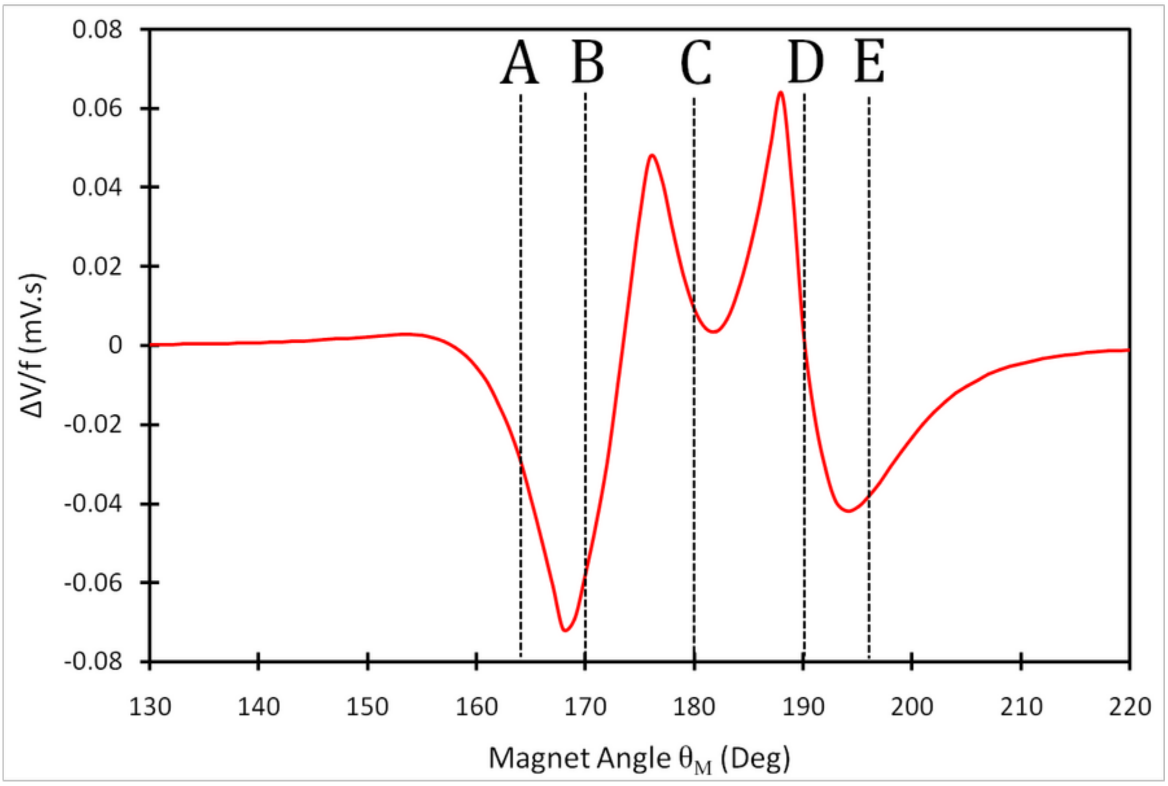
Small values of screening currents can be observed at the ends of the tape and also on the tape edges along the length.

## Electric Field Maps



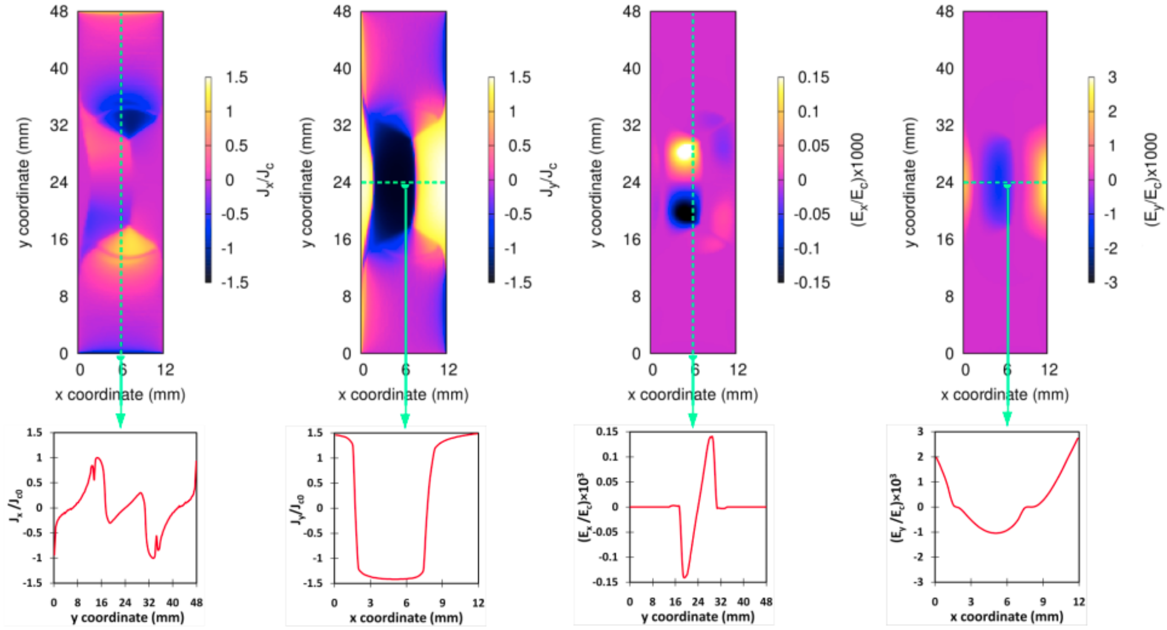

Voltage generation occurs only in the area of the tape where magnet traverses.

## ΔV versus Magnet Angle $\theta_M$




Similar qualitative behavior in 3D as 2D and measurements.

## Components of Current and Electric Field

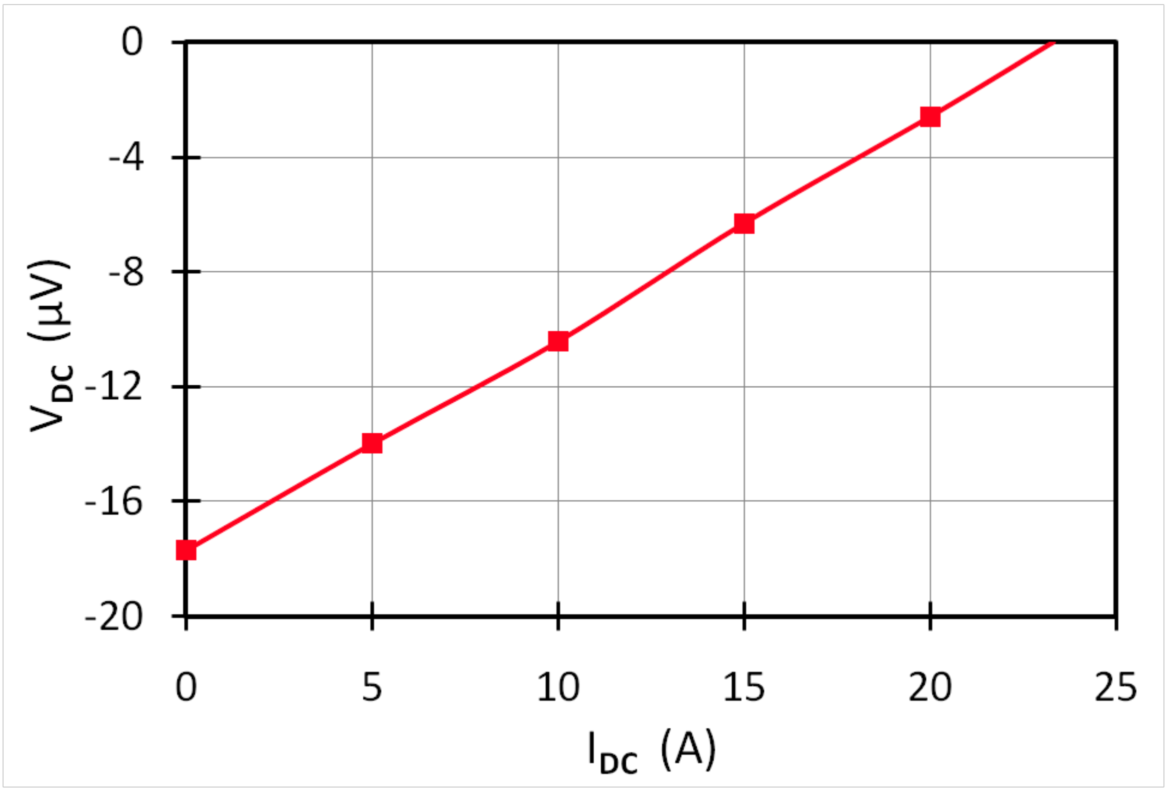



$J_x$ and $E_x$ are symmetrical along the tape length.

$E_x$ is more than one order of magnitude smaller than $E_y$.

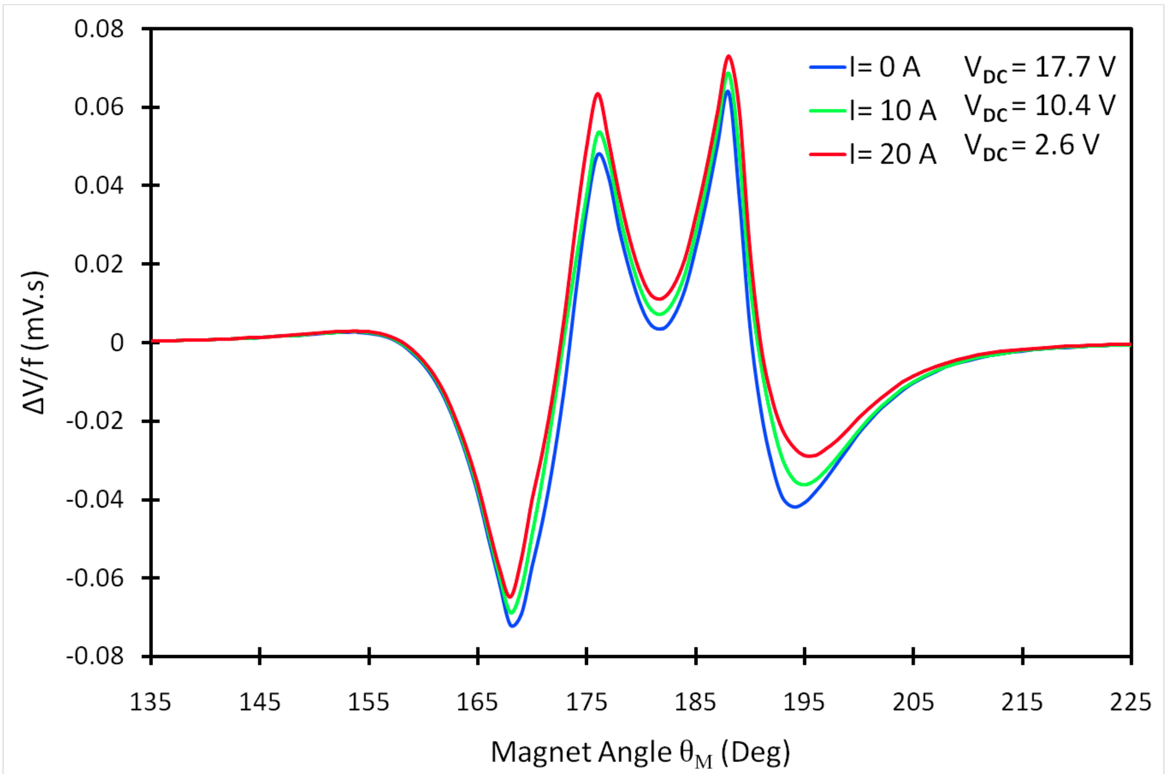
# TRANSPORT CURRENT

**Calculations with assumption of constant $J_c$**




The effective resistance for the fixed frequency of 12.3 Hz is the line slope equal to -0.756 μΩ.

The short-circuit current (where $V_{DC}$ is equal to zero) is $I_{DC}$ = 23.3 A.

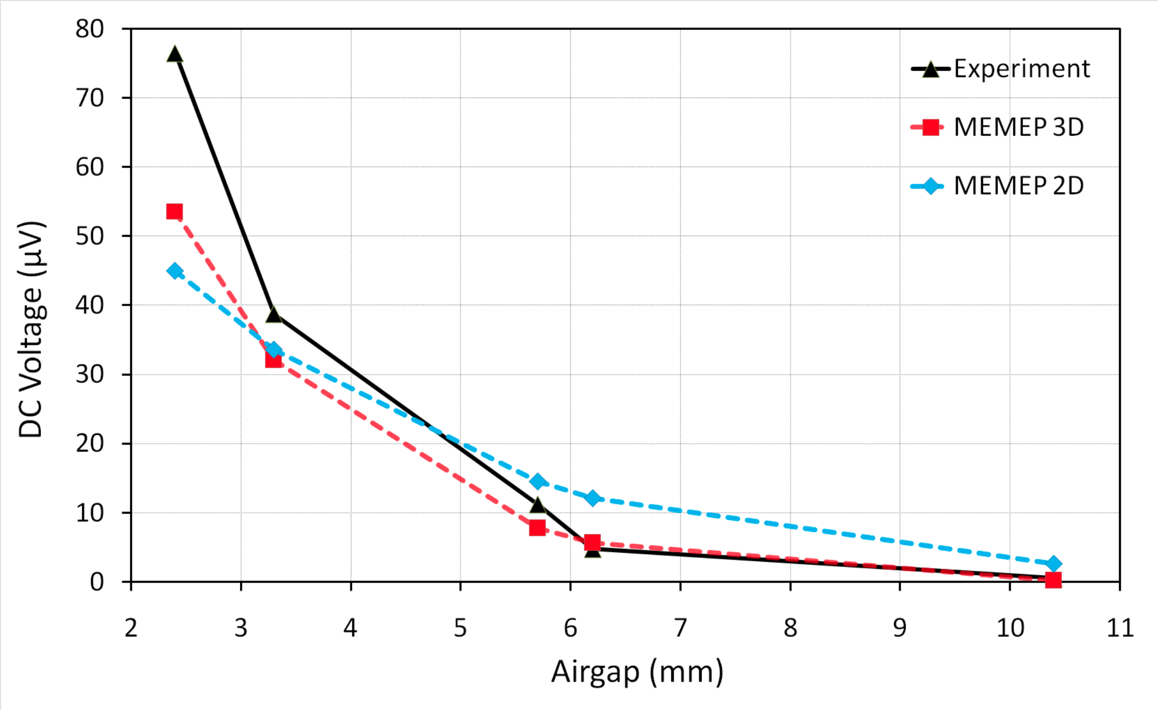



ΔV keeps the same qualitative shape with change of $I_{DC}$.

Vertical shift of the curve with the change of $I_{DC}$ is the reason for changing $V_{DC}$ (the area under the curve).

# COMPARISON TO EXPERIMENTS

**Calculations with assumption of dependent $J_c(B,\theta)$**




MEMEP 2D results derived from [2]

Experimental results derived from [3]

3D results are in close agreement with measurements and yet better agreement than 2D.

Modeling the exact shape of the cylindrical magnet is the reason for better agreement in 3D.

# CONCLUSION

- We presented the first 3D model of a flux pump.
- We analyzed the current and electric field in several critical time steps of magnet movement.
- x component of current (along the tape width) has no contribution in generating voltage in a dynamo.
- We studied the 3D model of flux pump with imposed DC transport current.
- Our 3D model has very good agreement with measurements in different airgaps.

# AUTHOR INFORMATION

I have obtained M.Sc. degree in Electrical Power Engineering from Shahed University in Tehran, Iran at 2014 and B.Sc. degree from University of Mazandaran in Electrical Engineering at 2010. My main fields of interest are applied superconductivity, electrical machines especially transformers. I have also worked on application and modeling of superconducting power transformers and superconducting fault current limiters and also finite element analysis of electrical machines. Currently, I am researcher and third-year PhD student at Institute of Electrical Engineering Slovak Academy of Sciences. I am working on modeling and analysis of superconducting flux pumps. If you have any question or suggestion about my work and poster please do not hesitate to contact me via email:

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# ABSTRACT

High $T_c$ superconducting (HTS) flux pumps are promising devices in order to inject large DC currents into the winding of superconducting machines or magnets in a contactless way. The superconducting dynamo, as a type of flux pump with simple structure and easy maintenance has become very popular during the recent years. Using the dynamos, employing troublesome brushes in HTS machines or bulky currents leads with high thermal losses will be no more required. The working mechanism of HTS dynamo in open-circuit mode and with transport current is complicated and not fully investigated yet, despite several explanations and models that have been proposed. In this work, we present the first 3D model of an HTS flux pump with good agreement with experiments. With taking advantage of this efficient 3D model, it is possible to pinpoint the process of generating voltage across the superconducting tape surface. This can be realized with analyzing the screening current and electric field distribution on the tape surface in several crucial time steps of traversing the magnet over the tape. This is important since the overcritical screening current has been shown to be the reason for flux pumping. We also analyzed the impact on the voltage generation of both in-tape components of the electric field and screening current, which in the former cases have not been studied before. In addition, we studied the performance of the dynamo in presence of fixed transport currents.

# REFERENCES

[1] Mataira, R., Ainslie, M., Badcock, R. & Bumby, C. Origin of the dc output voltage from a high-tc superconducting dynamo. Appl. Phys. Lett. 114, 162601 (2019)

[2] Ghabeli, A. & Pardo, E. Modeling of airgap influence on DC voltage generation in a dynamo-type flux pump. Supercond. Sci. Technol. 33, 035008 (2020).

[3] Bumby, C., Jiang, Z., Storey, J., Pantoja, A. & Badcock, R. Anomalous open-circuit voltage from a high-tc superconducting dynamo. Appl. Phys. Lett. 108, 122601 (2016).