3D Modeling of Screening Currents and Voltage in a Superconducting Flux Pump with Transport Current

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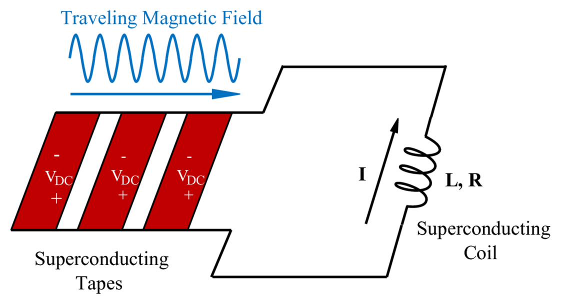
HTS Flux Pump

Traveling wave HTS flux pump

Traversing varying magnetic field relative to the HTS tapes causes DC voltage

Very common due to simplicity and ease of maintenance



Dynamo-type flux pump

A type of traveling wave HTS flux pump

The varying magnetic field is originated from rotating permanent magnets

Application in superconducting electrical machines and magnets

Injection of DC current into the rotor without using brushes

Improving the efficiency of cryogenic system by avoiding current leads

Calculation method

MEMEP 3D (Minimum Electromagnetic Entropy Production)

$$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$$

From current density — From magnet — Change between 2 time steps

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

Dissipation factor

$$\nabla \times \mathbf{T} = \mathbf{J}$$ T is effective magnetization

Dissipation factor

$$U(\mathbf{J}) = \int_0^{\mathbf{J}} \mathbf{E}(\mathbf{J}')\cdot d\mathbf{J}' \xrightarrow{\text{In our model}} \mathbf{E}(\mathbf{J}) = E_c\left(\frac{|\mathbf{J}|}{J_c}\right)^n \frac{\mathbf{J}}{|\mathbf{J}|}$$ Isotropic E-J power law

For solving the problem, the functional *L* is minimized

T only exists inside HTS tape ⟶ limited mesh numbers ⟶ fast method

General definitions

$$V_{DC} = \frac{1}{T}\int_t^{t+T} V(t')\,dt'$$ DC output voltage

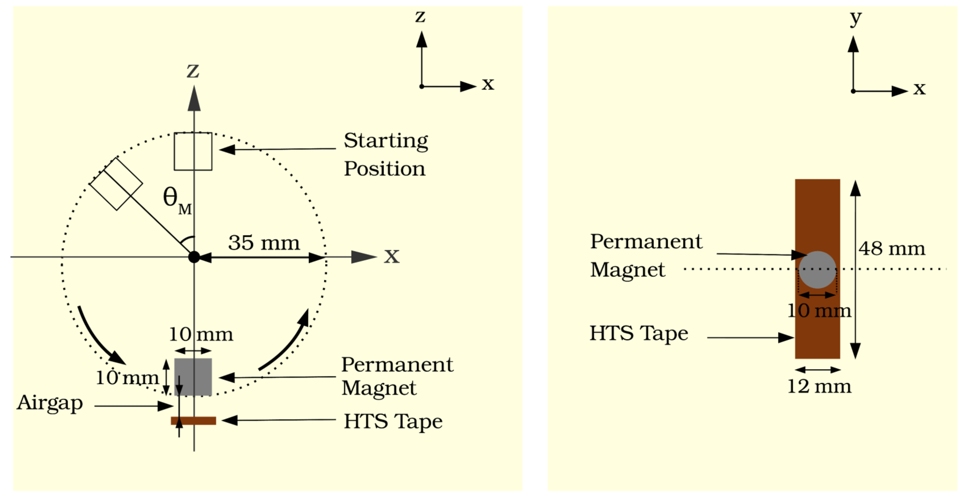
$$\Delta V = V_{77\mathrm{K}} - V_{300\mathrm{K}}$$ Voltage created by the non-linear resistivity of HTS tape

Total output voltage

Average electric field in the volume

$$V(t) = l\cdot[E_{av}(J) + \partial_t A_{M,av} + \partial_t A_{J,av}]$$

3D model configuration



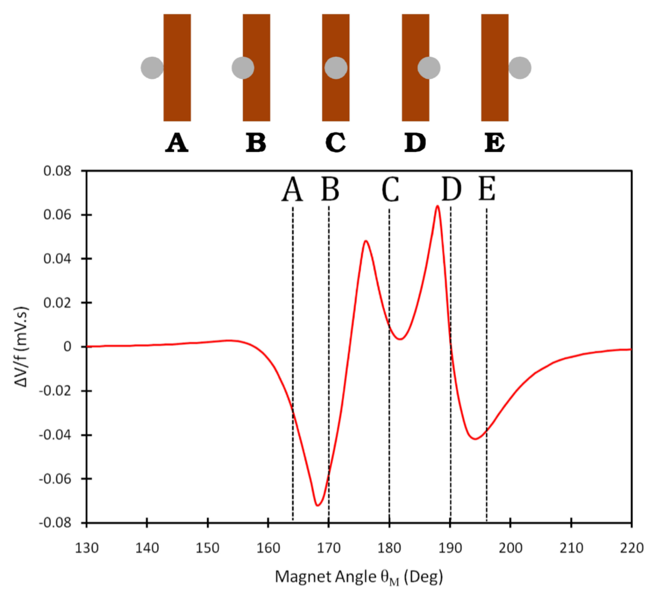
Magnet diameter = 10 mm
Magnet height = 10 mm
Remanent flux density (B_r) = 1.3 T

Tape width = 12 mm
Tape length = 48 mm
Tape thickness = 1 µm

Critical current I_c = 281 A
n-value = 20

R_{rotor} = 35 mm
Airgap = 3.3 mm
Rotation frequency (f) = 12.3 Hz

Calculated ΔV

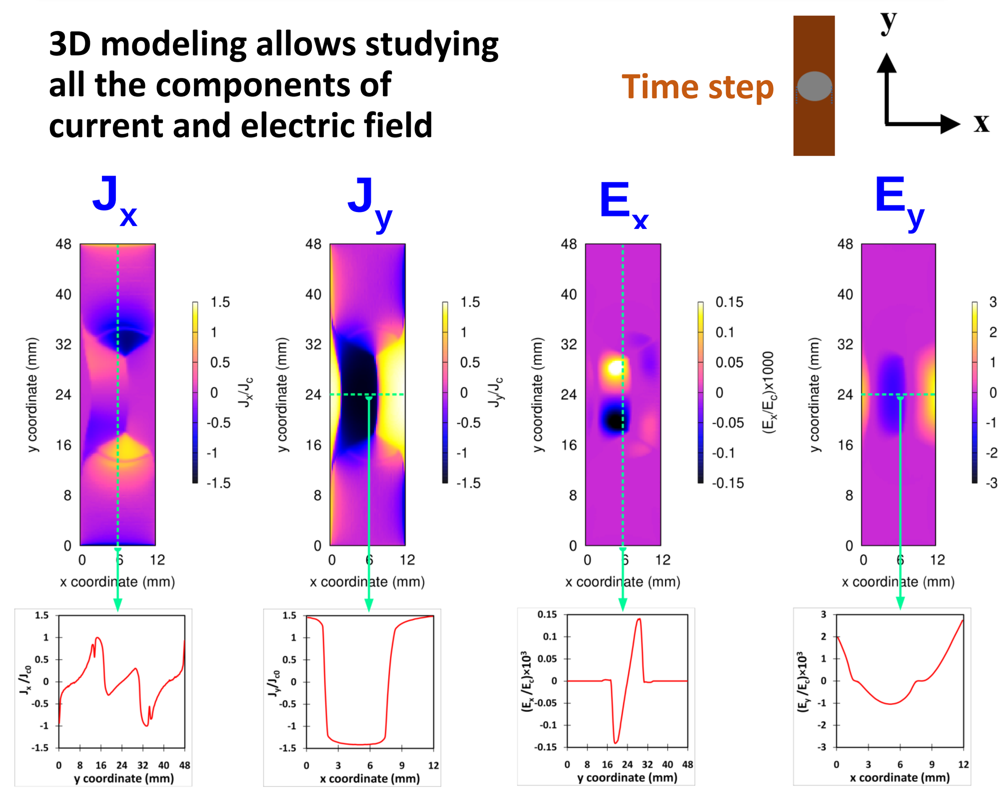


ΔV can be obtained directly from measurement

The calculated ΔV agrees with measurements

Components of current and electric field

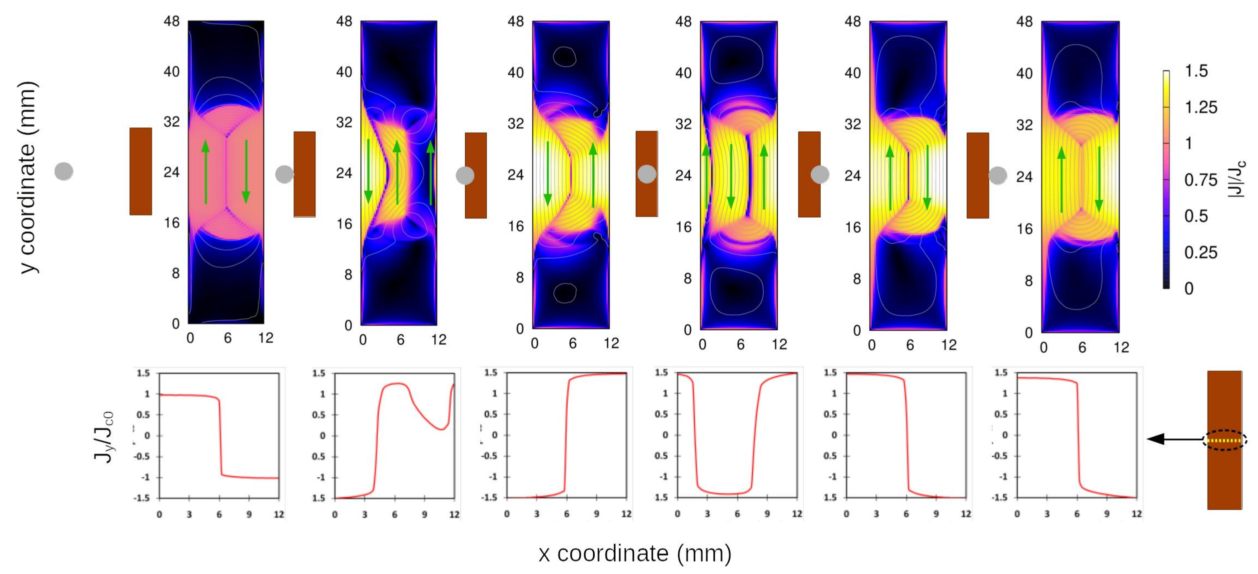
3D modeling allows studying all the components of current and electric field



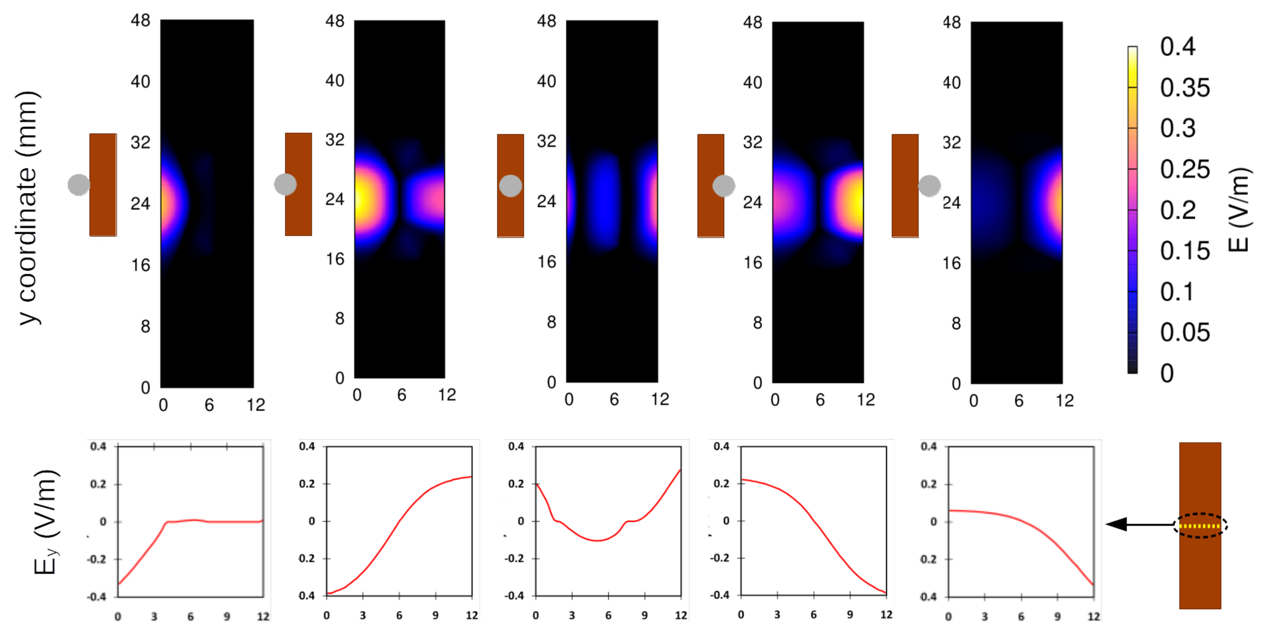
J_x and thus E_x and are symmetrical along the tape length

E_y is more than one order of magnitude larger than E_x

Screening current and electric field map

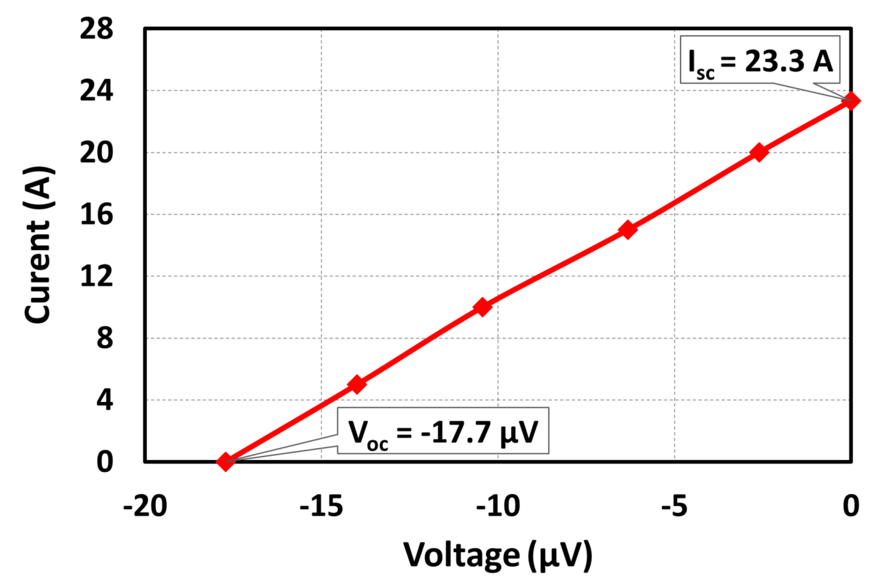


Overcritical screening currents are responsible for generating voltage in flux pump

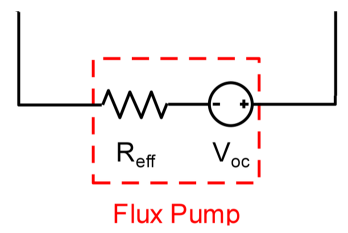


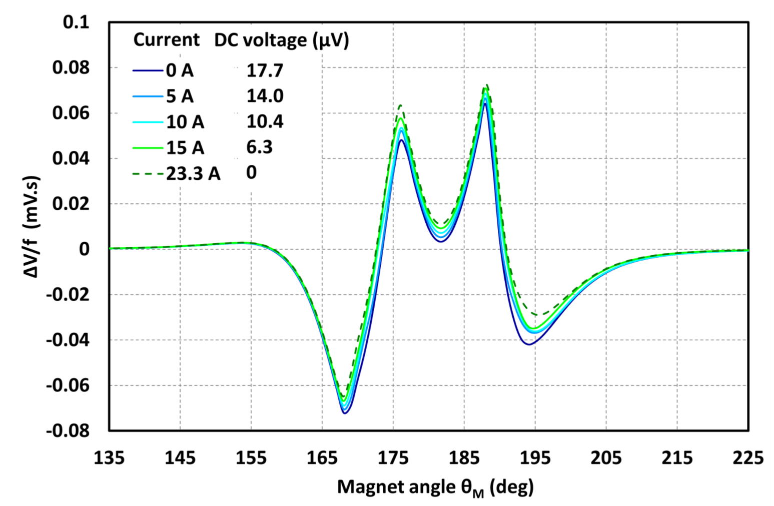
Voltage is generated mostly in the areas under the magnet cross section

Transport current



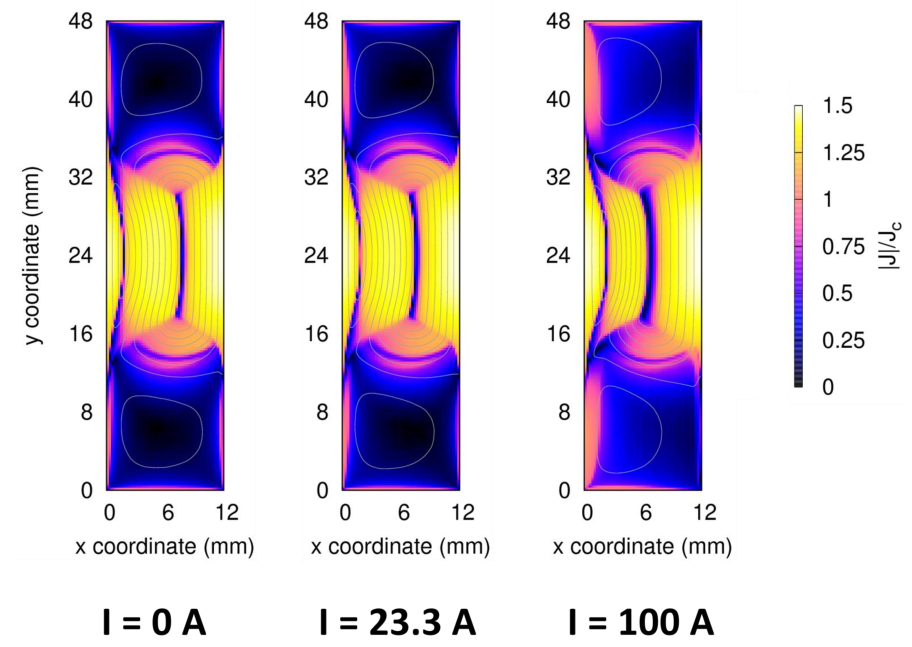
A flux pump can be modeled as a DC voltage source (V_{oc}) in series with an effective resistance R_{eff} (slope of I-V curve)





ΔV curve shifts slightly upwards as the transport current increases

The shifts in the ΔV curve changes the DC value which is proportional to the area under the curve



I = 0 A   I = 23.3 A   I = 100 A

Change of current distribution is negligible between 0 A and 23.3 A

By increasing the current to 100 A the change is more obvious, although the flux pump does not charge anymore

Summary

- Introduction of the first 3D model of an HTS flux pump
- MEMEP 3D method is efficient and fast for modeling a flux pump in 3D
- Exploring screening current and electric field in several key positions
- Calculating the component of screening current and electric field along the tape width is only possible via 3D modeling
- Modeling the flux pump with transport current enables the calculation of internal resistance of the flux pump
- Studying the screening current distribution in the tape surface with transport current

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