HTS 2020 Modelling

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Modeling HTS dynamo-type flux pumps: open-circuit mode and charge of an HTS coil

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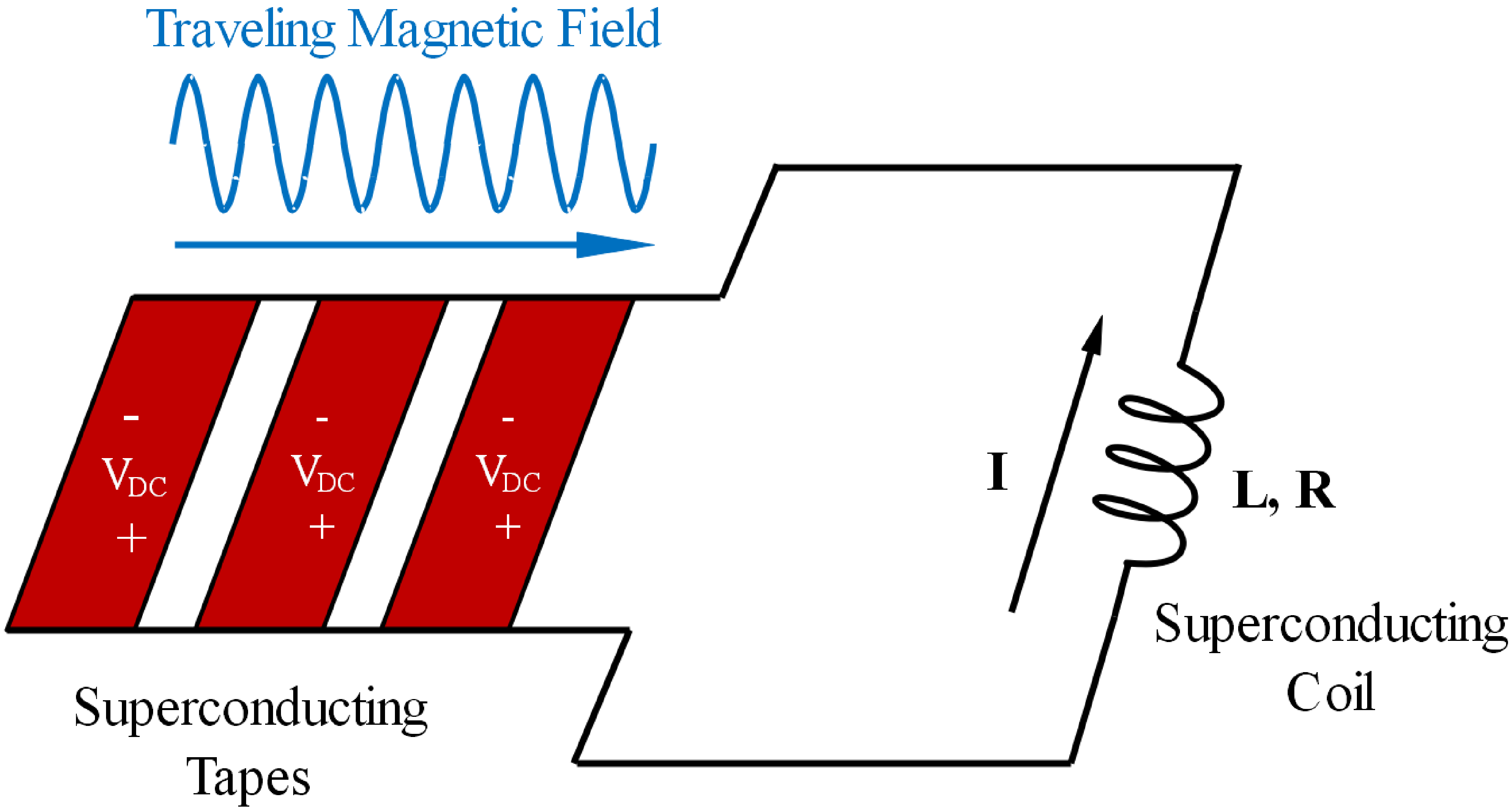
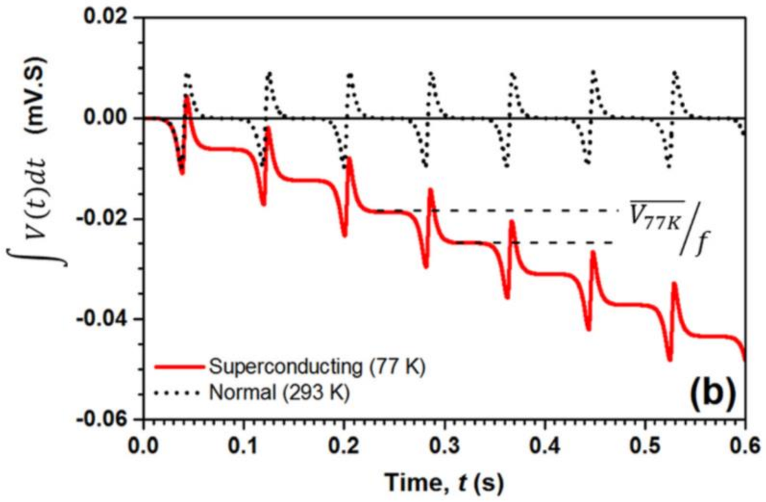
Principle of an HTS Flux Pump



What is a dynamo-type flux pump?

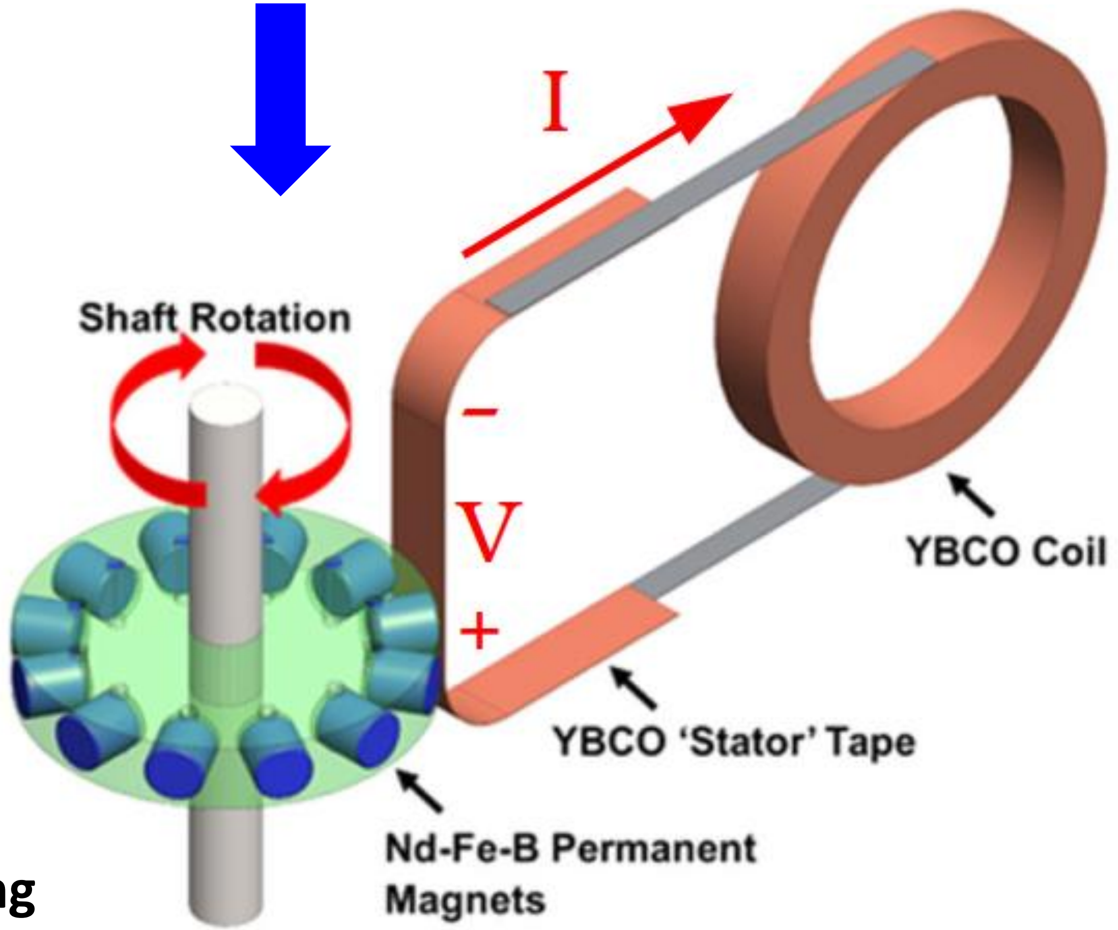
DC voltage is created by non-linear resistivity in HTS Tape

Accumulation of DC voltage energizes the coil in many cycles



Bumby, et al., Appl. Phys. Lett., 2016

HTS dynamo-type flux pump



Source of varying magnetic field

Application of flux pump

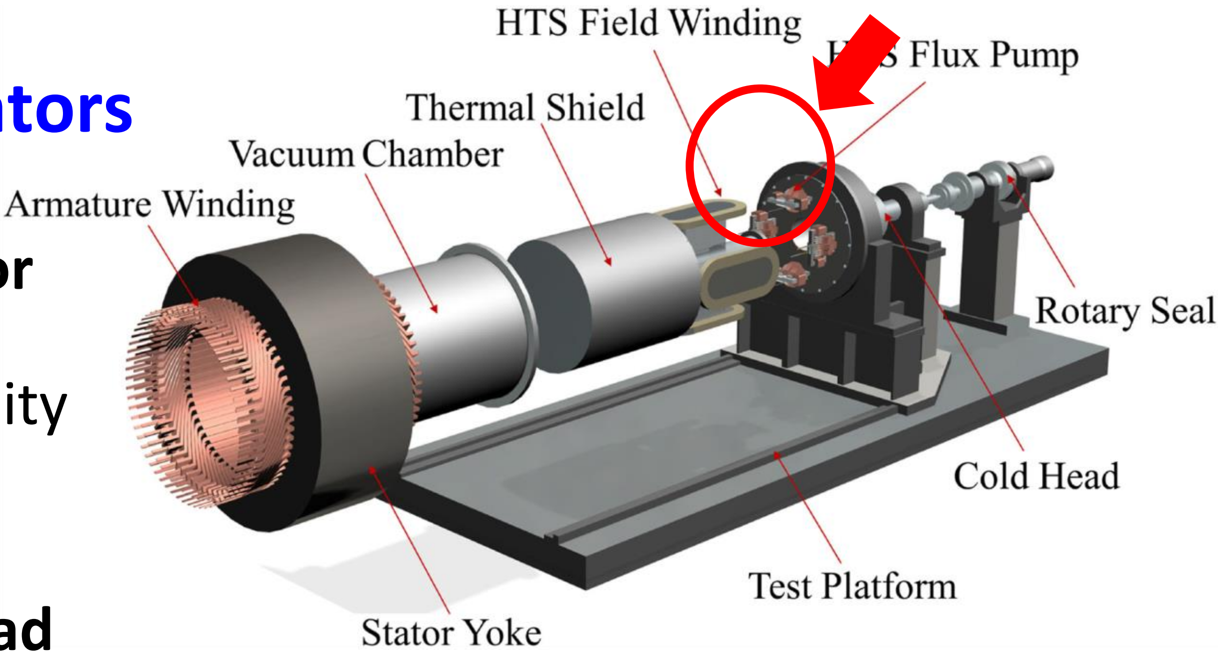
Superconducting Motors and Generators

Brushless injection of DC current into rotor

🙂 Reduces maintenance and improve reliability

Avoiding current leads and its thermal load

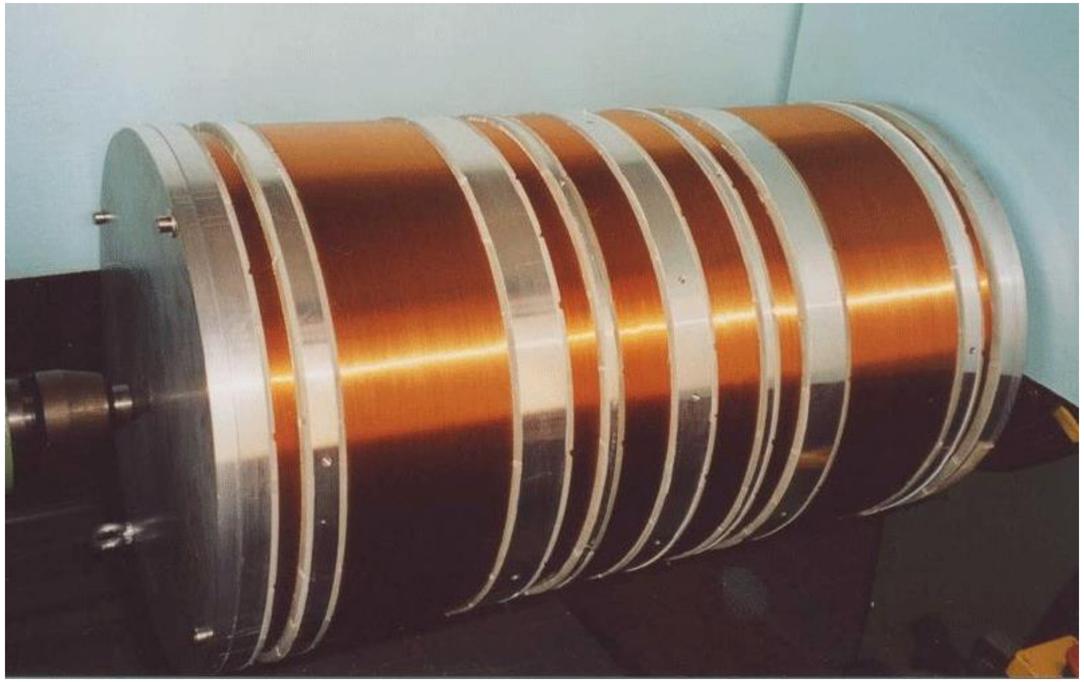
🙂 Improve efficiency of cryogenic system



Gao et al. 2019 IEEE TAS

Application of flux pump

Superconducting Magnets



Injection of DC current without using power supply

🙂 Maintaining persistent current mode

Avoiding current leads and its thermal load

🙂 Improve efficiency of cryogenic system

General definition

Vector potential

$$\mathbf{E}(\mathbf{J}) = -\frac{\partial \mathbf{A}}{\partial t} - \nabla \varphi$$

Scalar potential

$\nabla \cdot \mathbf{J} = 0$ Current conservation equation **Always Satisfied!**

$\nabla \cdot \mathbf{A} = 0$ Coulomb's gauge

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

Isotropic E-J power law

MEMEP 2D method

$$F = \int_{\Omega} \mathrm{d}^3\mathbf{r}\left[\frac{1}{2}\frac{\Delta\mathbf{A}_J}{\Delta t}\cdot\Delta\mathbf{J} + \frac{\Delta\mathbf{A}_M}{\Delta t}\cdot\Delta\mathbf{J} + U(\mathbf{J}_0 + \Delta\mathbf{J})\right]$$

Superconducting or normal conducting region in 3D

Due to current density

Due to magnet

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

Change between two time steps

Dissipation factor

Isotropic E-J power law

$$\mathbf{E}(\mathbf{J}) = E_c\left(\frac{|\mathbf{J}|}{J_c}\right)^n\frac{\mathbf{J}}{|\mathbf{J}|} \xleftarrow{\textbf{In our model}} U(\mathbf{J}) = \int_0^{\mathbf{J}}\mathbf{E}(\mathbf{J}')\cdot d\mathbf{J}'$$

MEMEP 2D method

$$F = \int_{\Omega} \mathrm{d}^3\mathbf{r}\left[\frac{1}{2}\frac{\Delta\mathbf{A}_J}{\Delta t}\cdot\Delta\mathbf{J} + \frac{\Delta\mathbf{A}_M}{\Delta t}\cdot\Delta\mathbf{J} + U(\mathbf{J}_0+\Delta\mathbf{J})\right]$$

Superconducting tape, coil and series resistance

Assumption of superconducting tape, coil, series resistance far away from each other:

$$F = F_S + F_L + F_R$$

Assumption of infinitely long tape and magnetic field: Coil inductance

Resistance

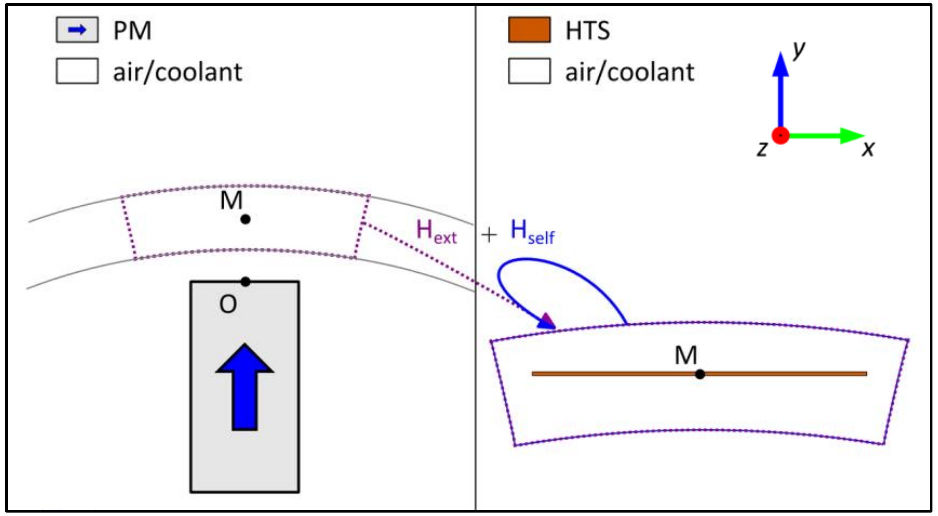
$$F = l\int_{S_S} d^2\mathbf{r}_2 \underbrace{\left[\frac{1}{2}\Delta J\frac{\Delta A_J}{\Delta t} + \Delta J\frac{\Delta A_M}{\Delta t} + U(J)\right]}_{\text{Superconducting tape}} + \underbrace{\frac{1}{2}L\frac{(\Delta I)^2}{\Delta t}}_{\text{Ideal coil}} + \underbrace{\frac{1}{2}RI^2}_{\text{Series resistance}}$$

Segregated *H*-formulation method

H-formulation: Independent variables are the components of the magnetic field strength *H*

Magnetostatic magnet model +
Time-dependent *H*-formulation HTS tape model

Unidirectional coupling between magnet and HTS models using electromagnetic boundary conditions and a rotation operator



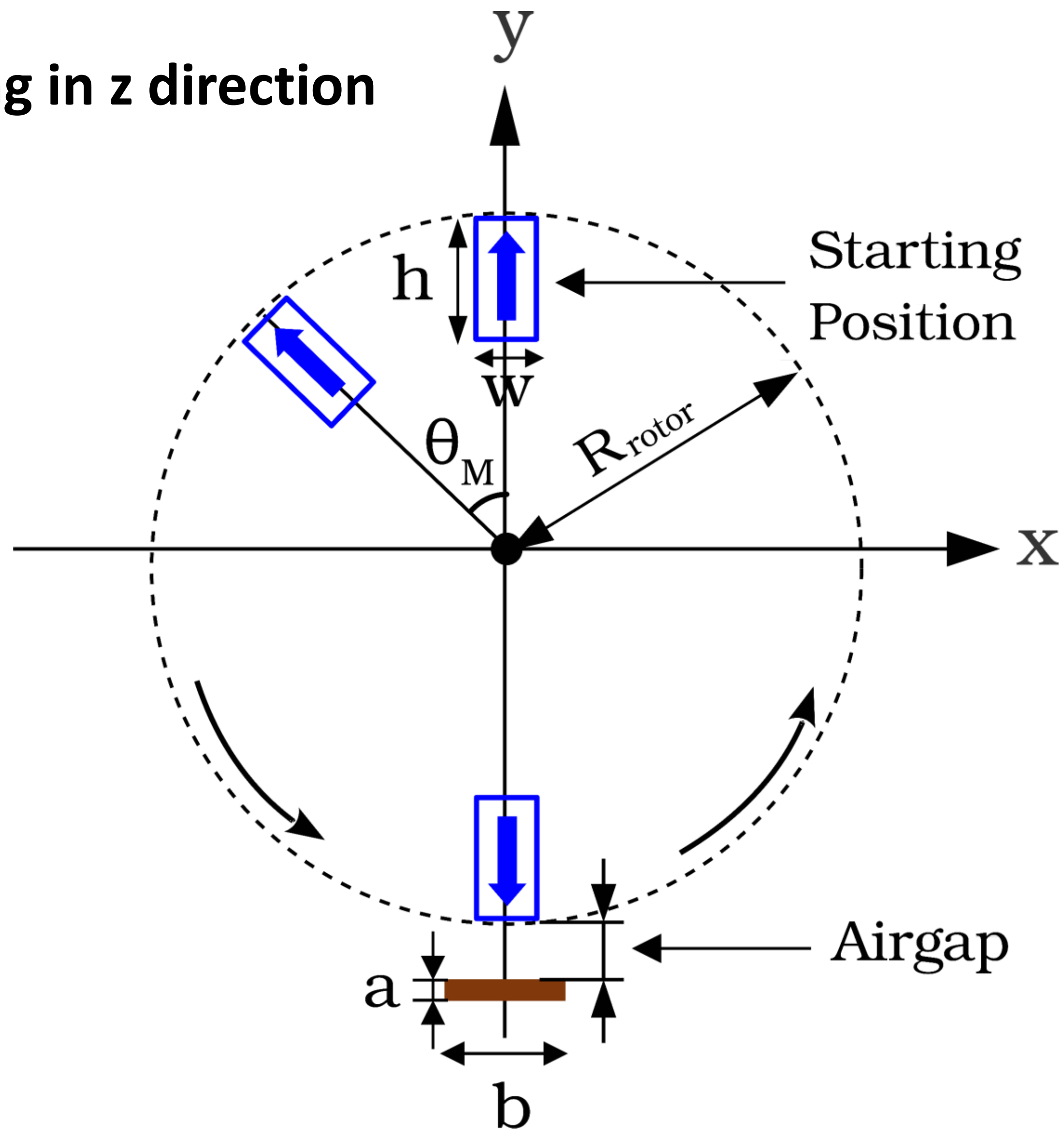
Magnetostatic magnet model

Time-dependent *H*-formulation HTS wire model

Configuration of 2D model: Coil charging case

Tape and magnet are defined infinitely long in z direction

J_c assumed constant for simplicity



Magnet width (w) = 6 mm
Magnet height (h) = 12 mm
Effective depth (l) = 12.7 m
Remanent flux density (B_r) = 1.25 T

Tape width (b) = 12 mm
Tape thickness (a) = 1 µm
Critical current I_c = 283 A
n-value = 20

R_{rotor} = 35 mm

Configuration of 2D model: Coil charging case

Assumptions

Ideal HTS coil

Lumped parameter elements

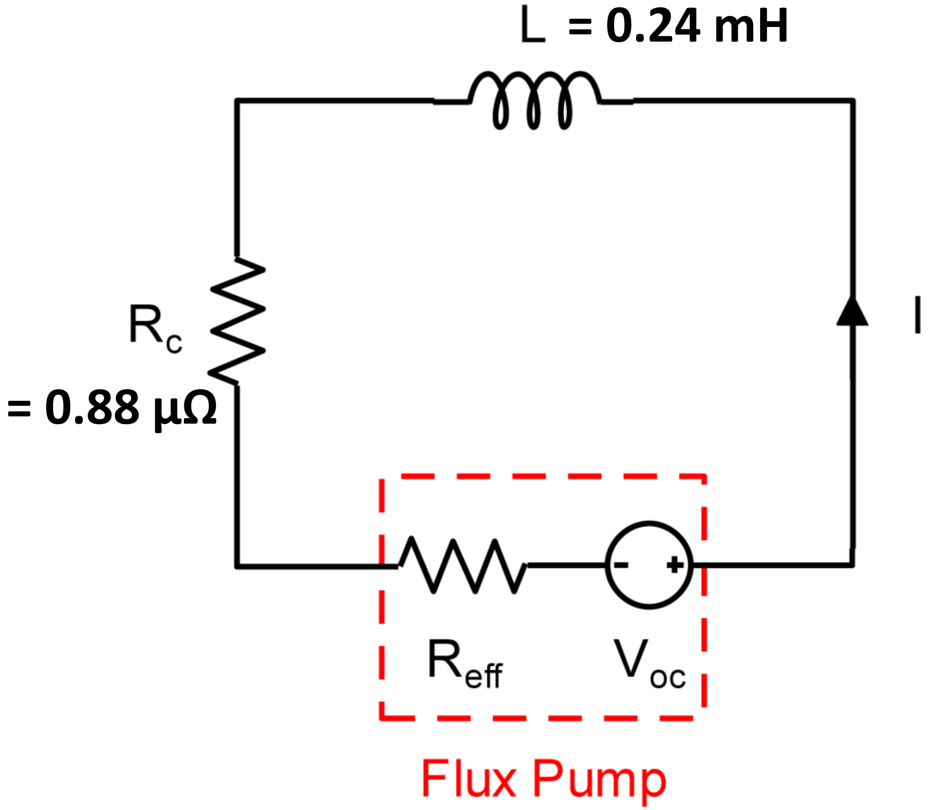
Flux pump can be modeled as a DC voltage source in series with an effective resistance

The coil can be treated as an independent LR circuit charged by the voltage source

$$i(t) = I_{sat}\left[1 - e^{-t/\tau}\right]$$

$$I_{sat} = V_{oc}/(R_c + R_{\text{eff}})$$

$$\tau = L/(R_c + R_{\text{eff}})$$



Calculation methods: Coil charging case

Two different numerical methods + Analytical method

to cross-check the validity of the results

1. MEMEP 2D method

2. Segregated H-formulation Finite Element Method

3. Analytical Method

$$i(t) = I_{sat}\left[1 - e^{-t/\tau}\right]$$

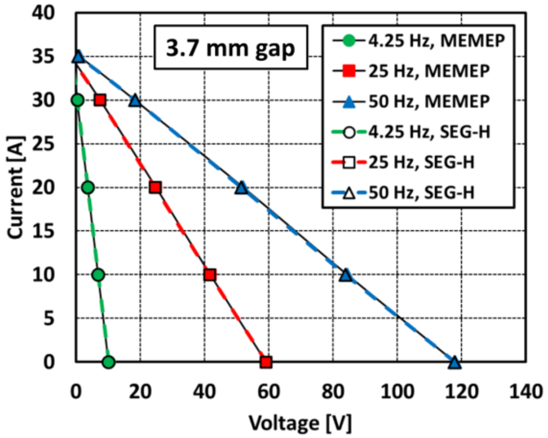
I-V curve of the flux pump

Slope of I-V curve shows effective resistance R_{eff}

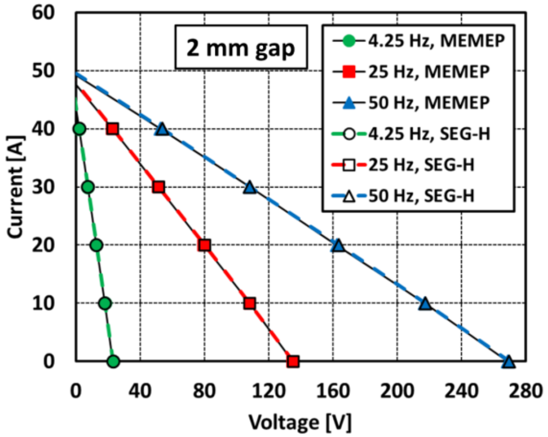
R_{eff} is constant for each frequency in superconducting regime

R_{eff} increases directly proportional to frequency

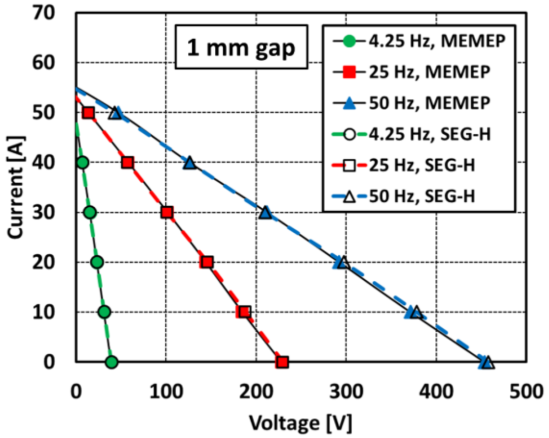
Excellent agreement between methods!



3.7 mm



2 mm



1 mm

Instantaneous voltage components

Airgp 3.7 mm

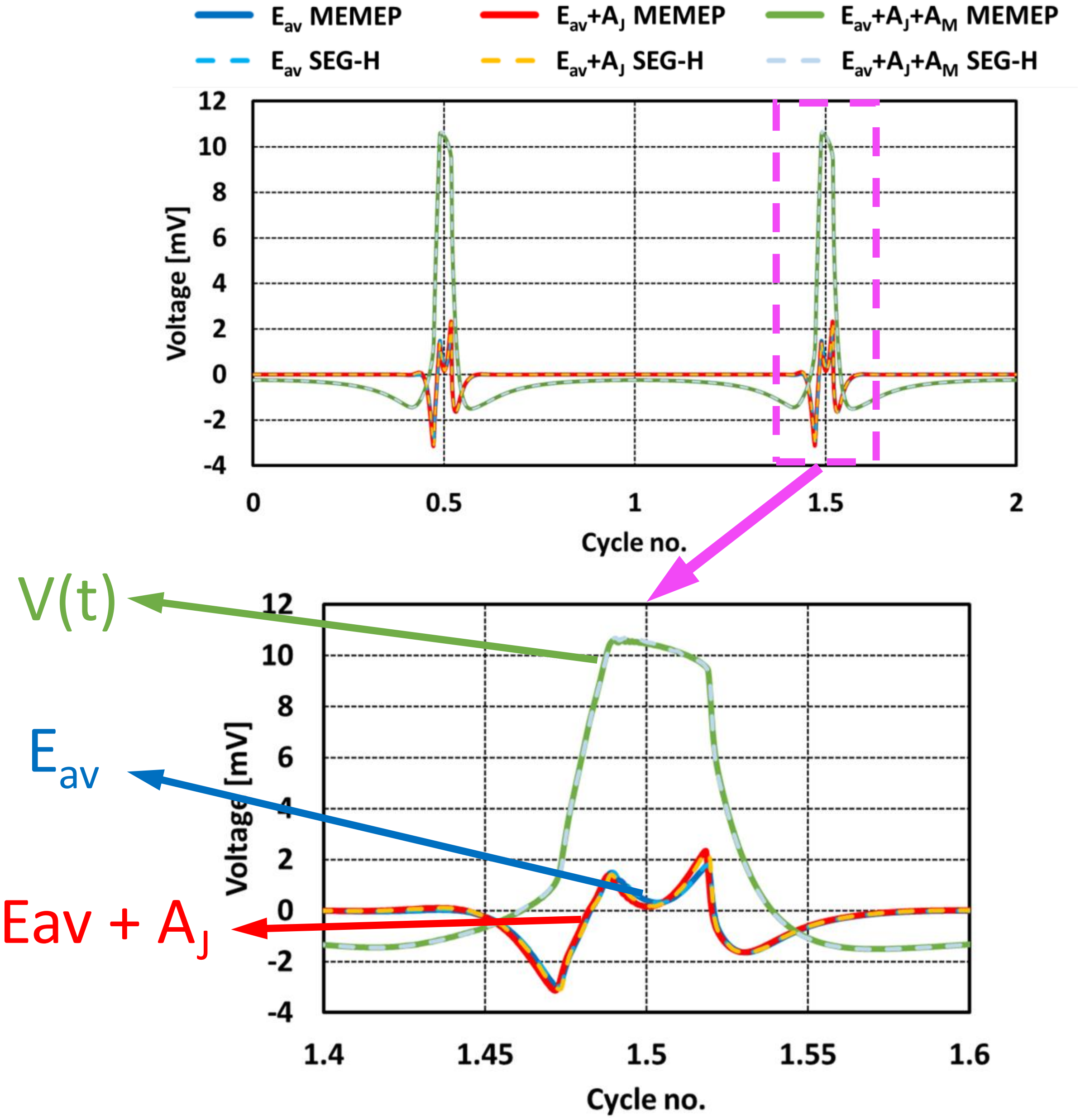
f = 25 Hz

$$E_{av}(t) = \frac{1}{S}\int_{S_S} d^2\mathbf{r}_2\,\rho[J(\mathbf{r}_2)]J(\mathbf{r}_2)$$

$$l\cdot[E_{av}(J)\;+\partial_t A_{J,av}]$$

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

Very good agreement between methods!



V(t)

E_{av}

Eav + A_J

Dynamic charging of the coil

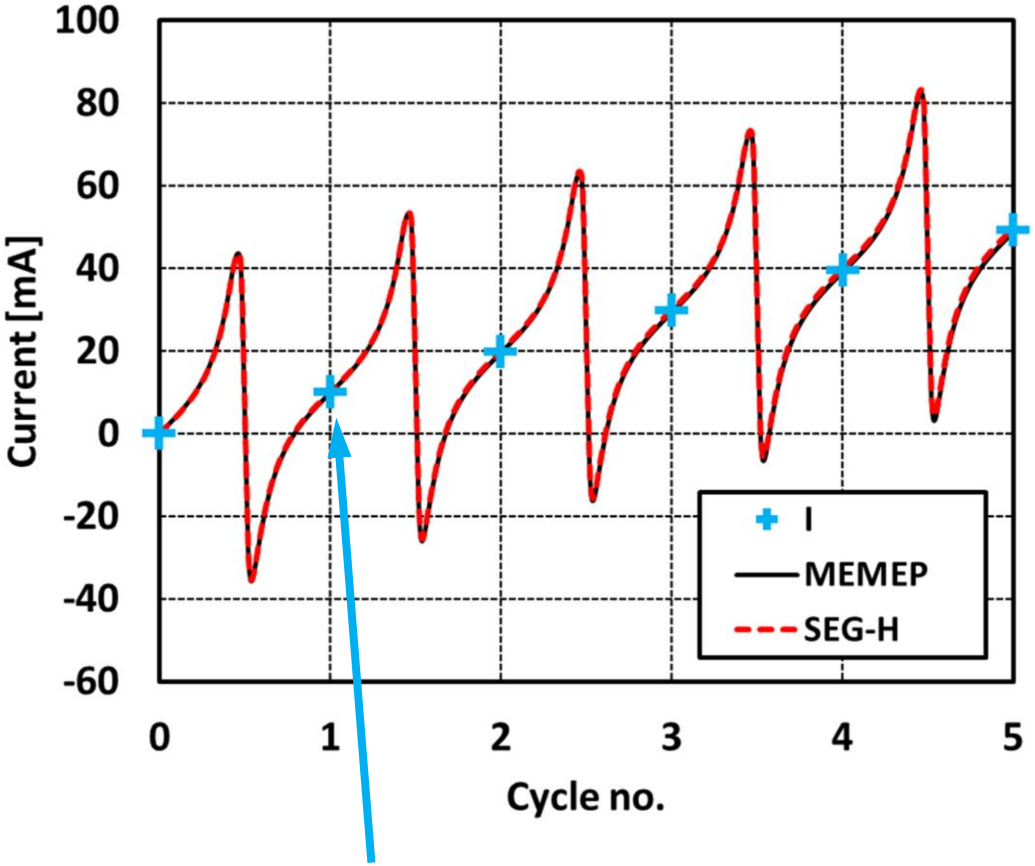
Airgap 3.7 mm

f = 25 Hz

Ripples resemble the ripples of the cumulative total output voltage V_{cumul}

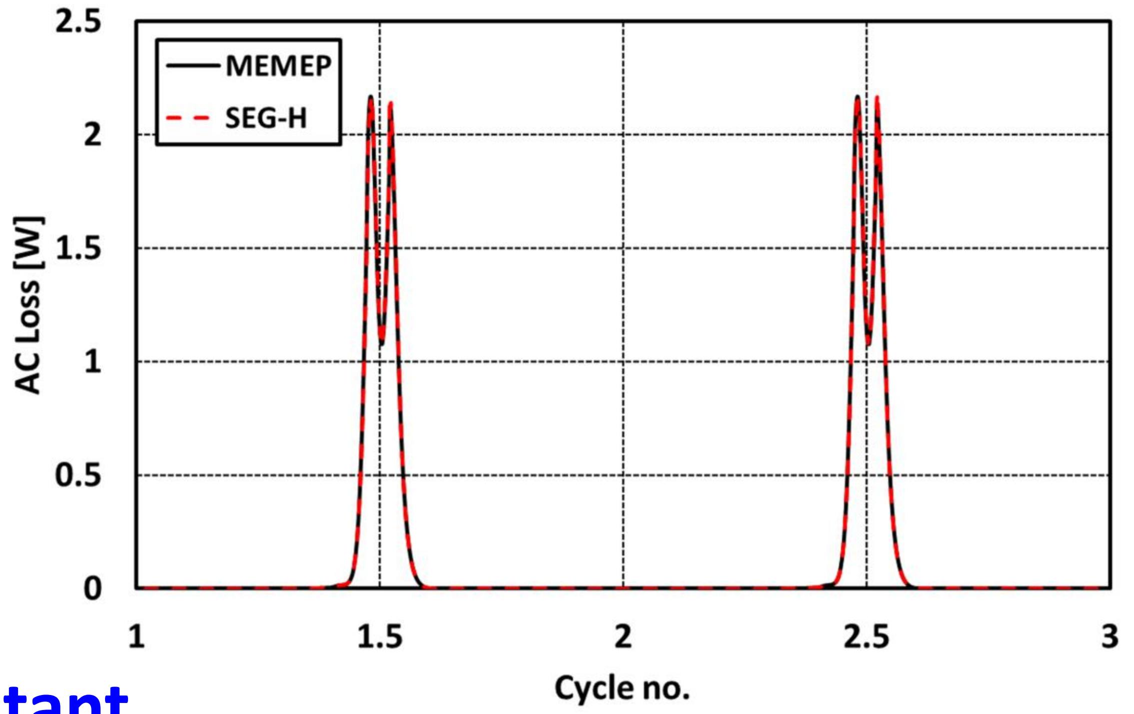
$$V_{cumul}(t) = \int_0^t V(t')\,dt'$$

Excellent agreement between methods!



Extracted data points at the end of each cycle

Ripple AC loss



Average AC loss cycle no. 1-5 ≈ 135.6 mW

Average AC loss cycle no. 5001 ≈ 135.8 mW

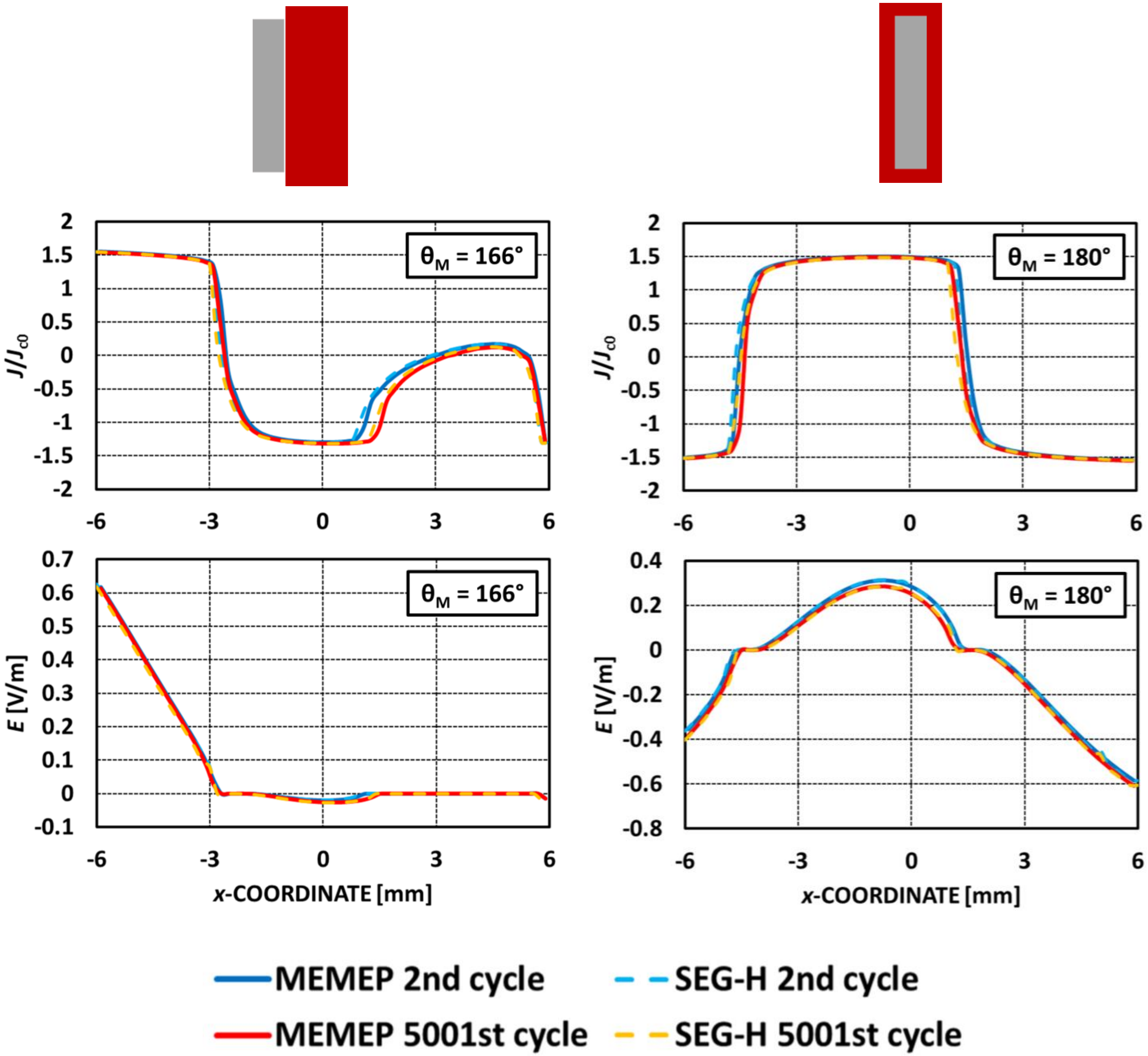
Calculated ripple AC loss is almost constant for a given frequency

Agrees with measurements presented in
Hamilton et al. IEEE Trans. Appl. Supercond. 2020

Ripple AC loss

Current density and electric field distributions are mostly similar

AC loss remains largely the same!

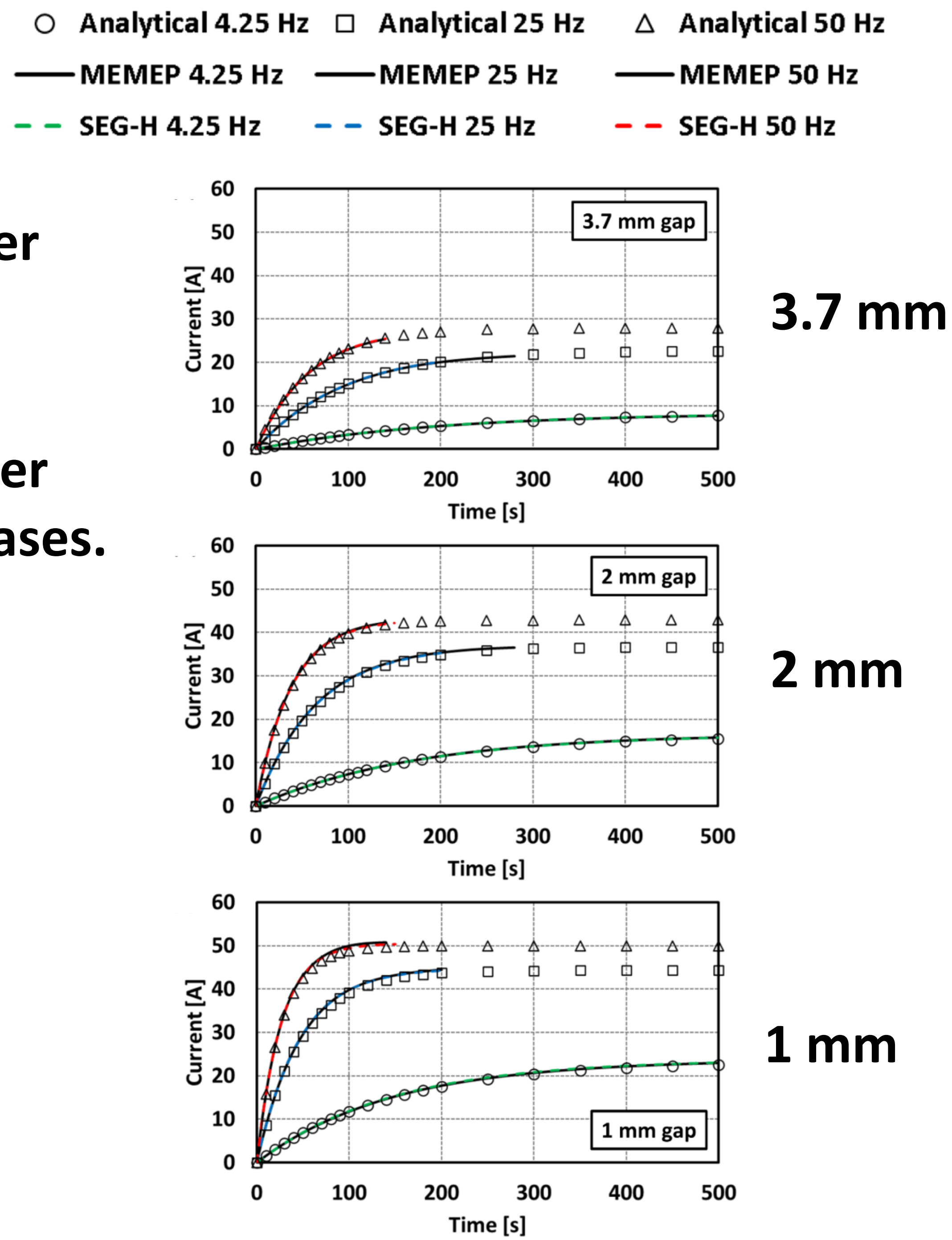


Coil charging behavior

For a given frequency, coil current saturates faster and at a higher value as the airgap decreases.

For a given airgap, the coil current saturates faster with a higher value of I_{sat} as the frequency increases.

Very good agreement between numerical and analytical methods!



Summary

- **Two novel numerical methods for modeling the charging process of a coil by an HTS dynamo were presented**
- **Nine different cases including various airgaps and frequencies over thousands of cycles were compared**
- **Current charging curve contains ripples within each cycle, which cannot be captured via the analytical method**
- **Current ripples cause ripple AC loss in the HTS dynamo**
- **The ripple AC loss is almost constant during the whole charging process**
- **The two numerical methods and the analytical method showed excellent quantitative and qualitative agreement**
- **The numerical modeling frameworks presented here have the potential to be coupled with other multiphysics analyses as well as with a model of an HTS coil**

For more details regarding this work:

Ghabeli et al 2021 *Supercond. Sci. Technol.* https://doi.org/10.1088/1361-6668/ac0ccb

Ghabeli, Asef, et al. "Modeling the charging process of a coil by an HTS dynamo-type flux pump." arXiv preprint arXiv:2105.00510 (2021).