2-LP-SMA-S07:
Modelling an HTS dynamo using a segregated finite-element model

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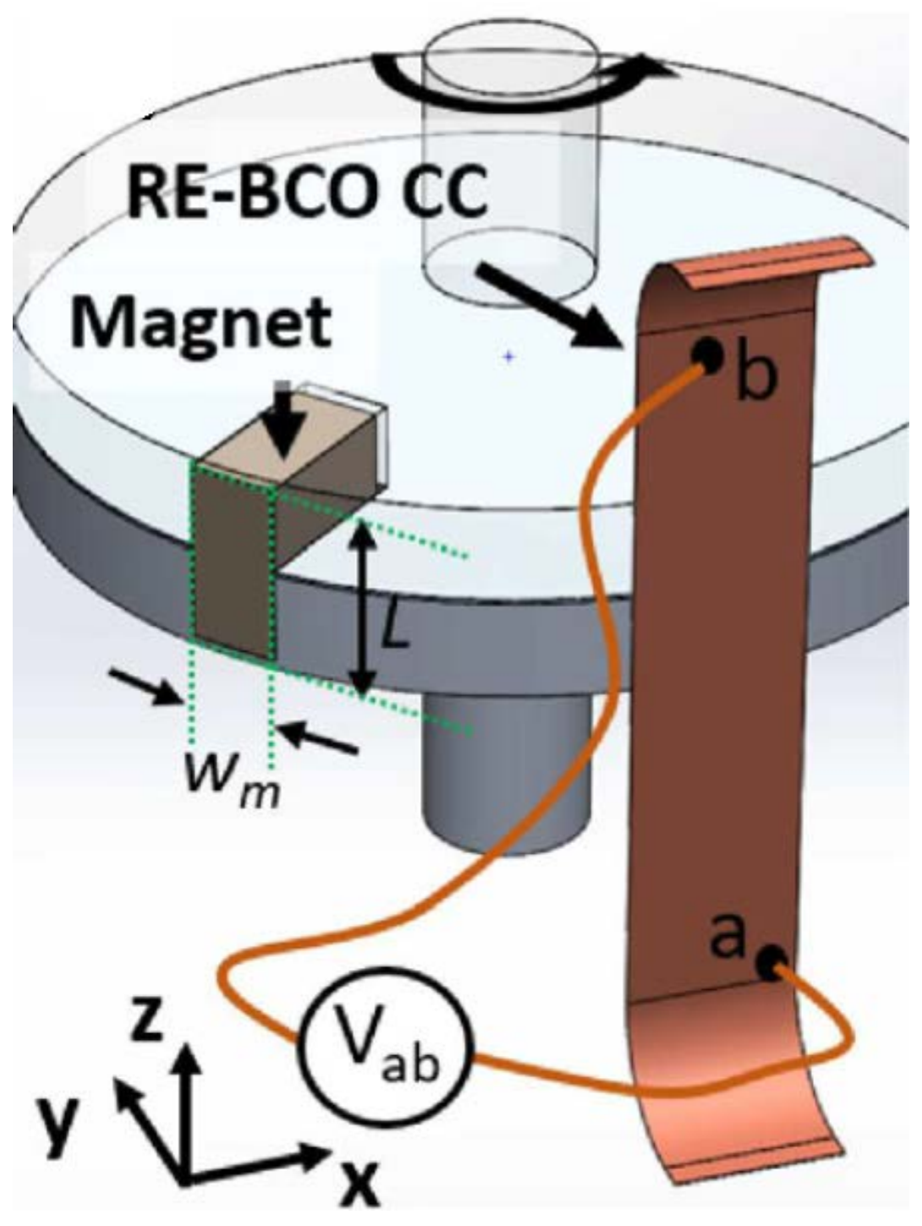
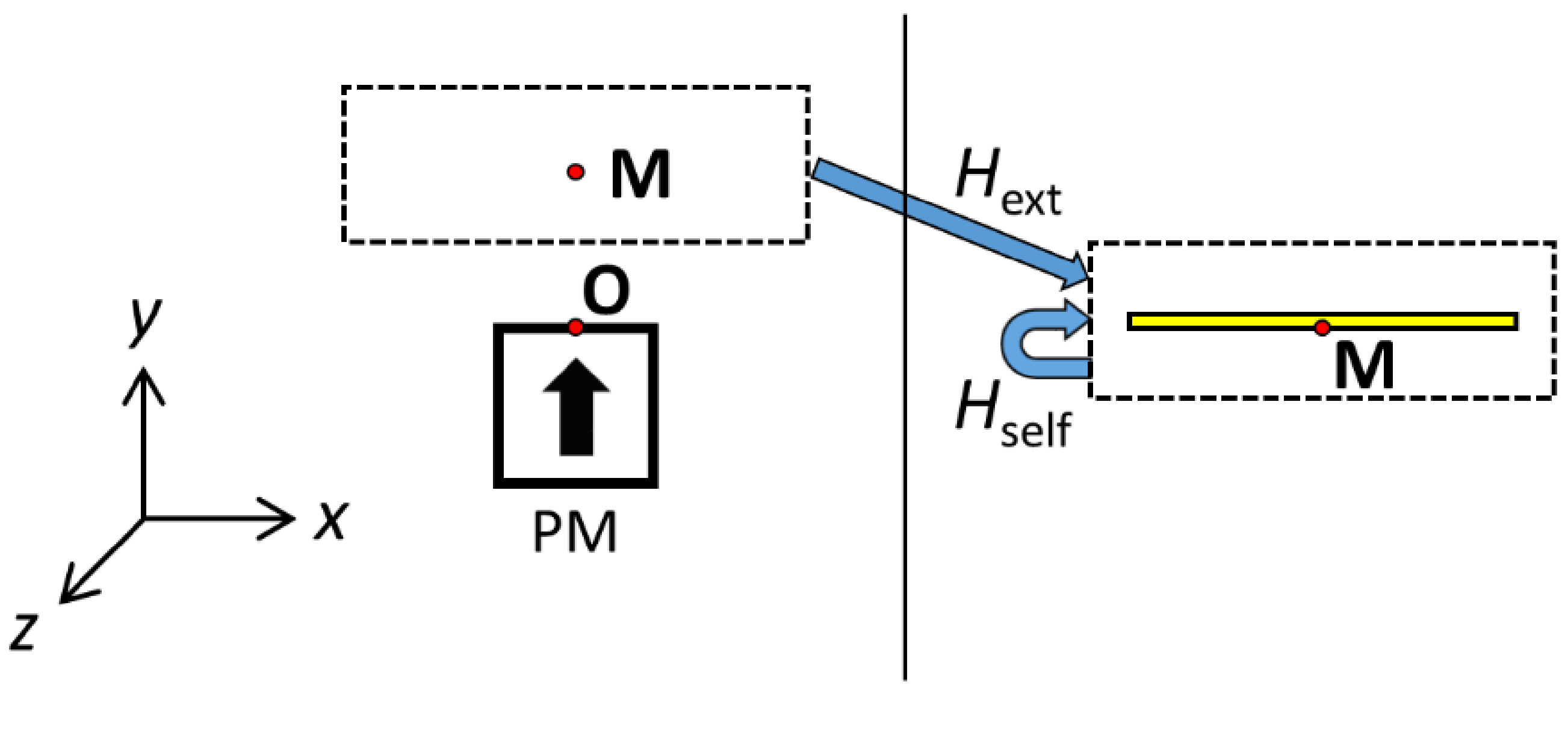
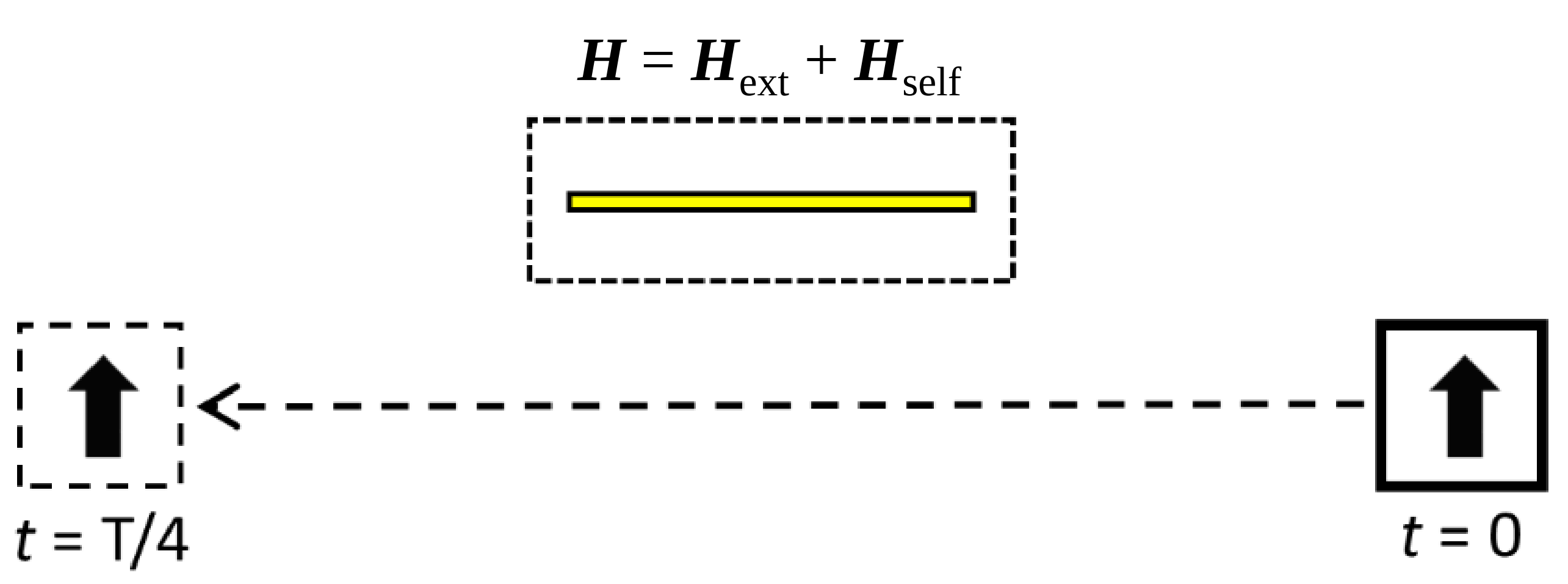
Modelling Framework



Experimental HTS dynamo schematic



Segregated finite-element model geometry: permanent magnet model, time-independent (left), HTS wire, time-dependent (right)



Permanent magnet movement past the HTS wire is simulated using time-dependent boundary conditions &a translation operator for the magnet’s static magnetic field

Electromagnetic model:

2D (infinitely long) ***H***-formulation
COMSOL Multiphysics 5.3a

$$\nabla \times \boldsymbol{E} + \left(\frac{d\boldsymbol{B}}{dt}\right) = \nabla \times \boldsymbol{E} + \frac{d(\mu_0 \mu_r \boldsymbol{H})}{dt} = 0$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}$$

$$\boldsymbol{E} = \frac{E_0}{J_c(B,\theta)} \left| \frac{J}{J_c(B,\theta)} \right|^{n-1} \boldsymbol{J}$$

$E_0 = 10^{-4}$ V/m

Current constraint (open-circuit):

$$I_{sc} = \int_{\Omega_{sc}} \boldsymbol{J} \cdot d\boldsymbol{s} = 0$$

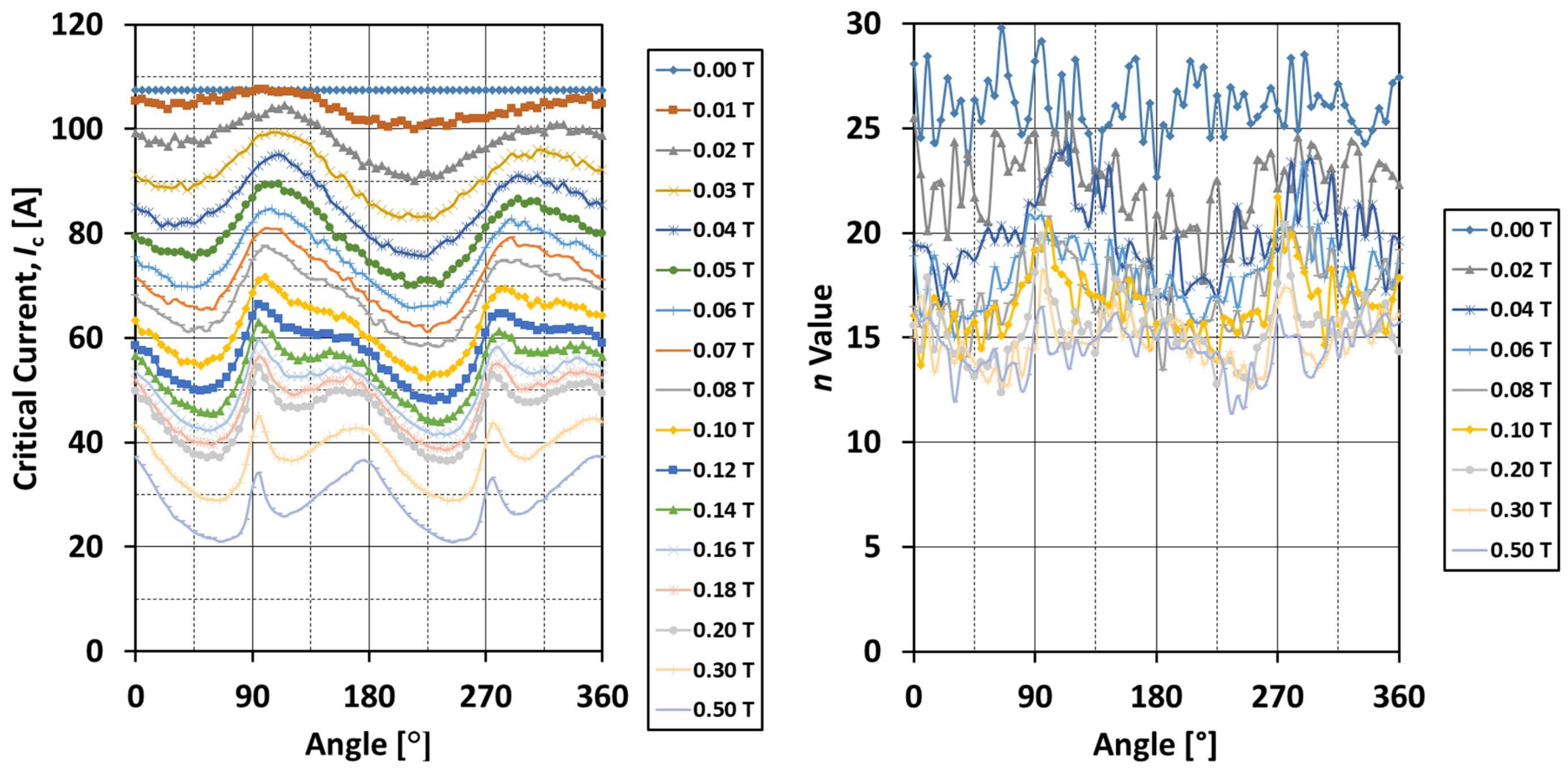
Permanent magnet properties:

$B_r = 0.5$ T
Width (w_m) = length (L) = depth = 10 mm
Gap between wire & PM: 3 mm
Voltage scaled by active magnet length, L

$$V(t) = E_{ave}(t) \cdot L = \frac{\int_{\Omega_{sc}} \boldsymbol{E} \cdot d\boldsymbol{s}}{S} L$$

Assumed wire properties:

SCS4050-AP, width 4 mm, extrapolated to 12 mm for the model
$I_c \approx 320$ A (self-field)
1 μm HTS layer, artificially expanded to 5 μm to improve computational speed
50 μm substrate (Hastelloy), 266 nΩ·m
25 μm top/bottom copper stabiliser, 3 nΩ·m



Measured $J_c(B,\vartheta)$ characteristics (left) & $n(B,\vartheta)$ (right) for the SuperPower SCS4050-AP HTS wire

Electromagnetic boundary conditions:

On outer boundary: $\boldsymbol{H} = \boldsymbol{H}_{ext} + \boldsymbol{H}_{self}$
where $\boldsymbol{H}_{ext}(x,y,t) = T_t \boldsymbol{H}_{PM}(x,y) = \boldsymbol{H}_{PM}(x+x_M(t), y+y_M(t))$

(x_M, y_M) is the time-dependent position of the HTS assembly relative to O

$\boldsymbol{H}_{self}$ is obtained by the 2D integration of the Biot-Savart law:

$$H_{self,x}(x,y,t) = \frac{1}{2\pi} \iint_{\Omega_{sc}} \frac{-J_z(x',y',t) \cdot (y-y')}{(x-x')^2 + (y-y')^2} dx'dy'$$

$$H_{self,y}(x,y,t) = \frac{1}{2\pi} \iint_{\Omega_{sc}} \frac{J_z(x',y',t) \cdot (x-x')}{(x-x')^2 + (y-y')^2} dx'dy'$$

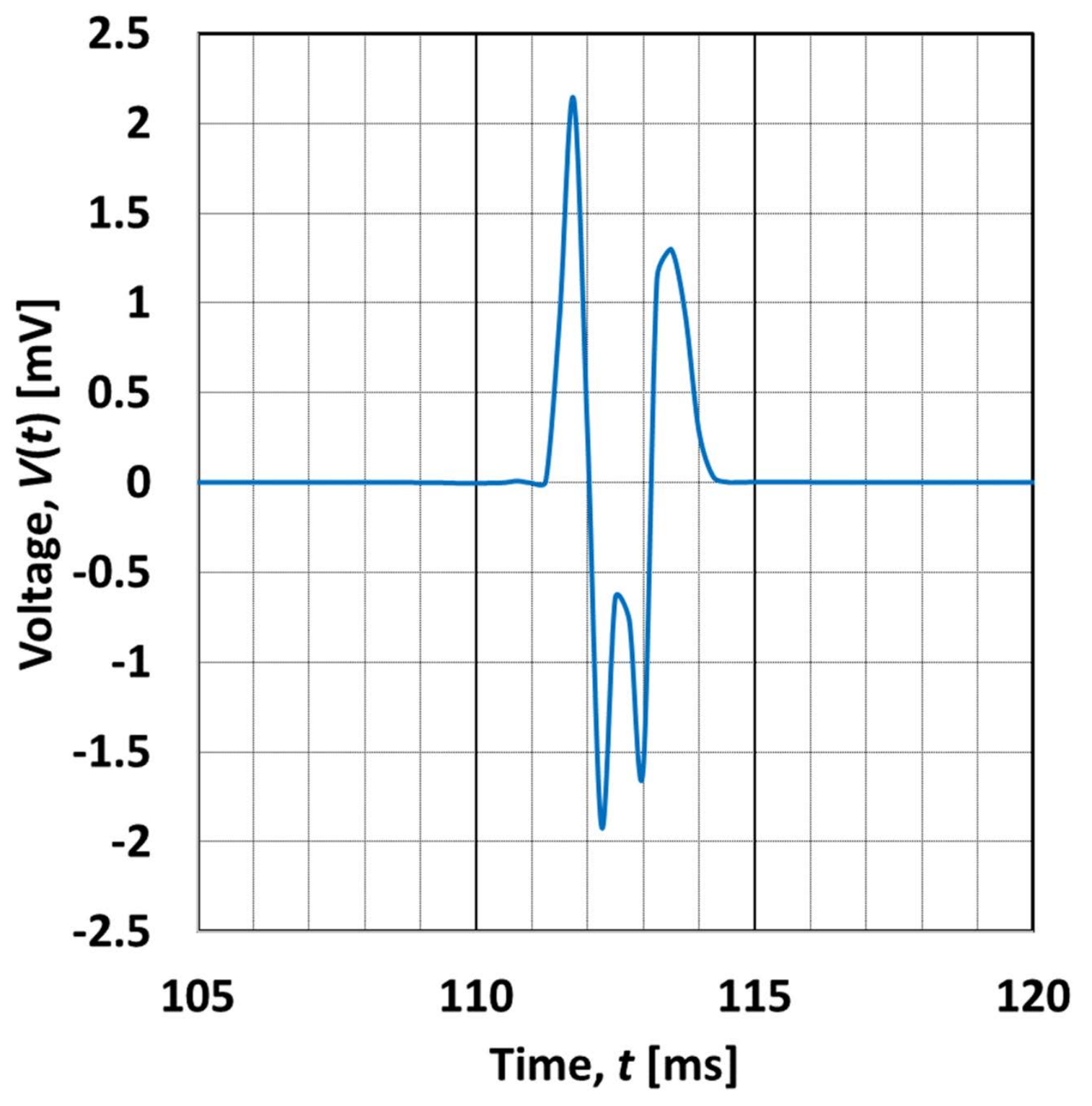
Thermal model (when included):

$$\rho \cdot C \frac{dT}{dt} = \nabla \cdot (\kappa \nabla T) + Q$$

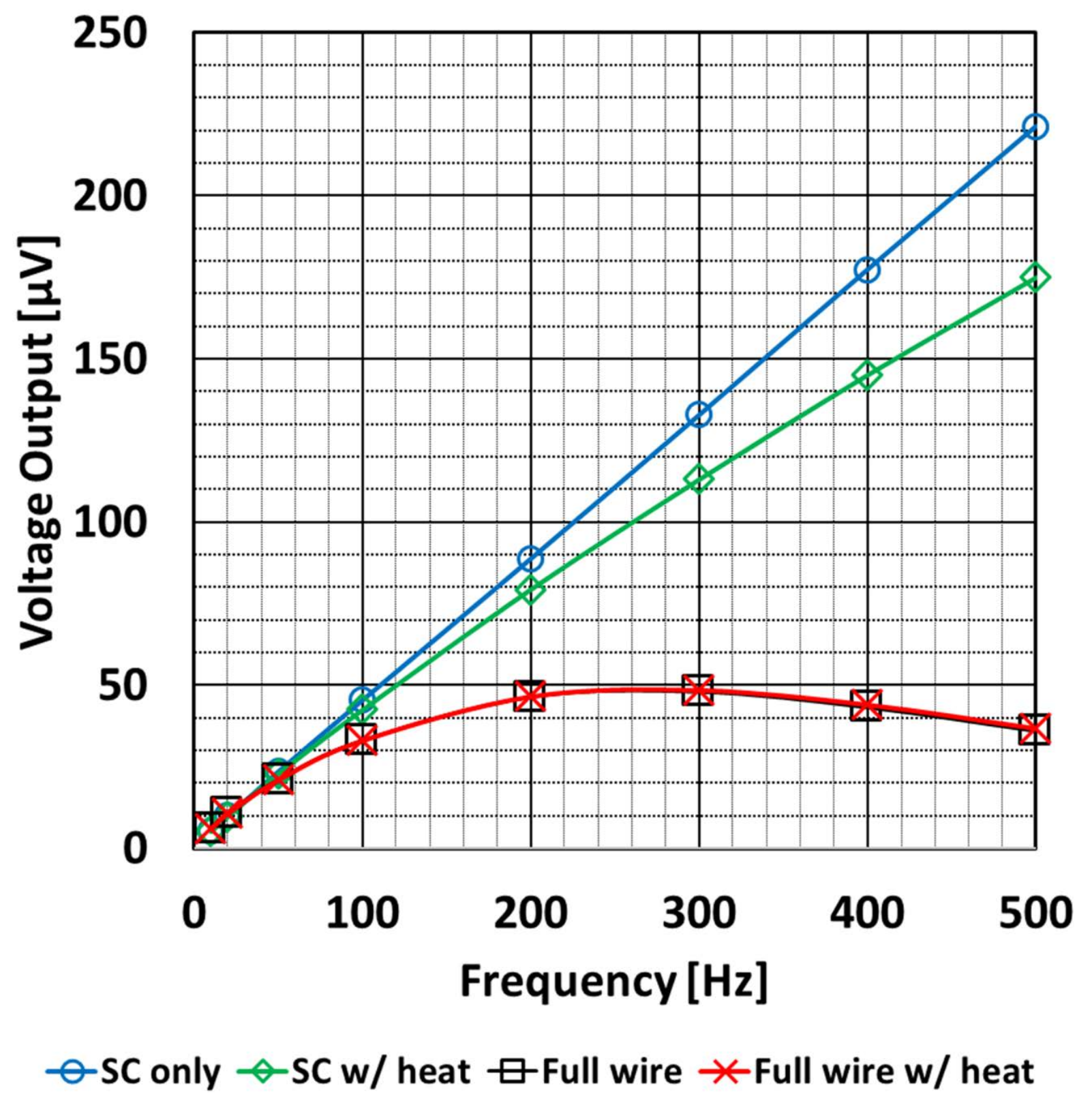
Heat source, $Q = \boldsymbol{E} \cdot \boldsymbol{J}$

Assumed thermal properties for YBCO, copper & Hastelloy substrate from reference data published in Zhang *et al.* J. Appl. Phys. **112**, 043912 (2012)

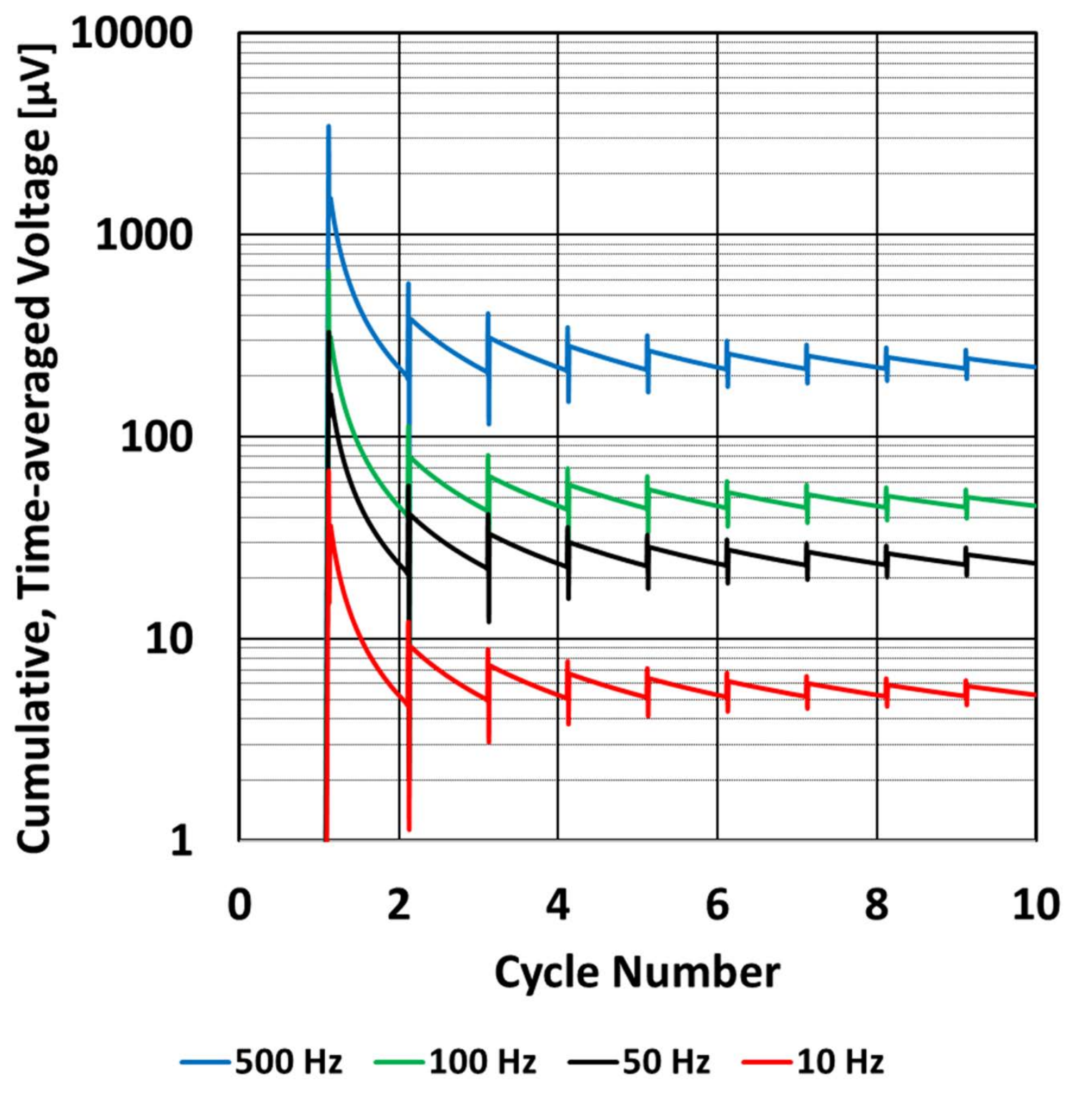
Modelling Results



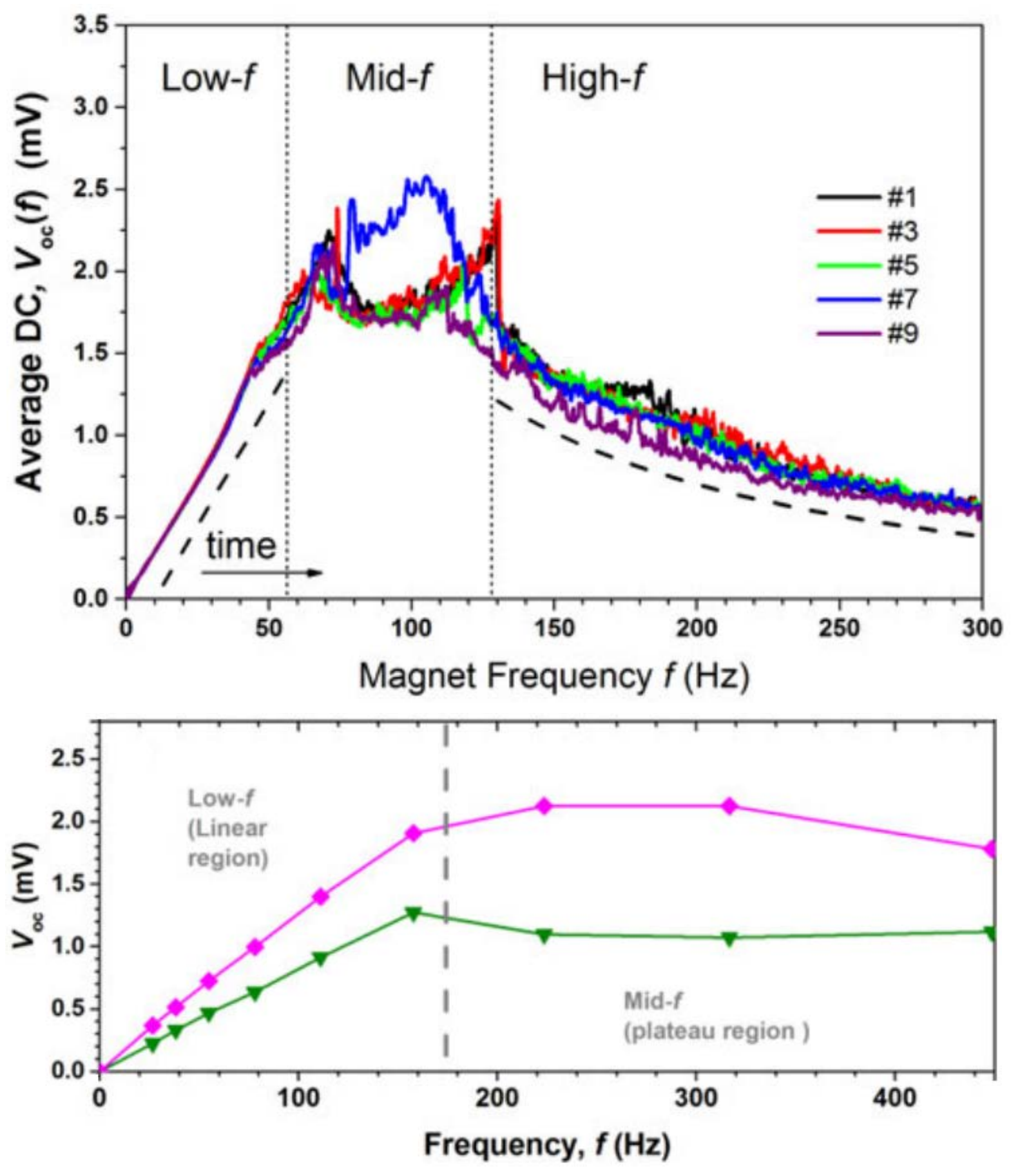
Calculated open-circuit waveform for a magnet frequency, f = 10 Hz (HTS layer only)



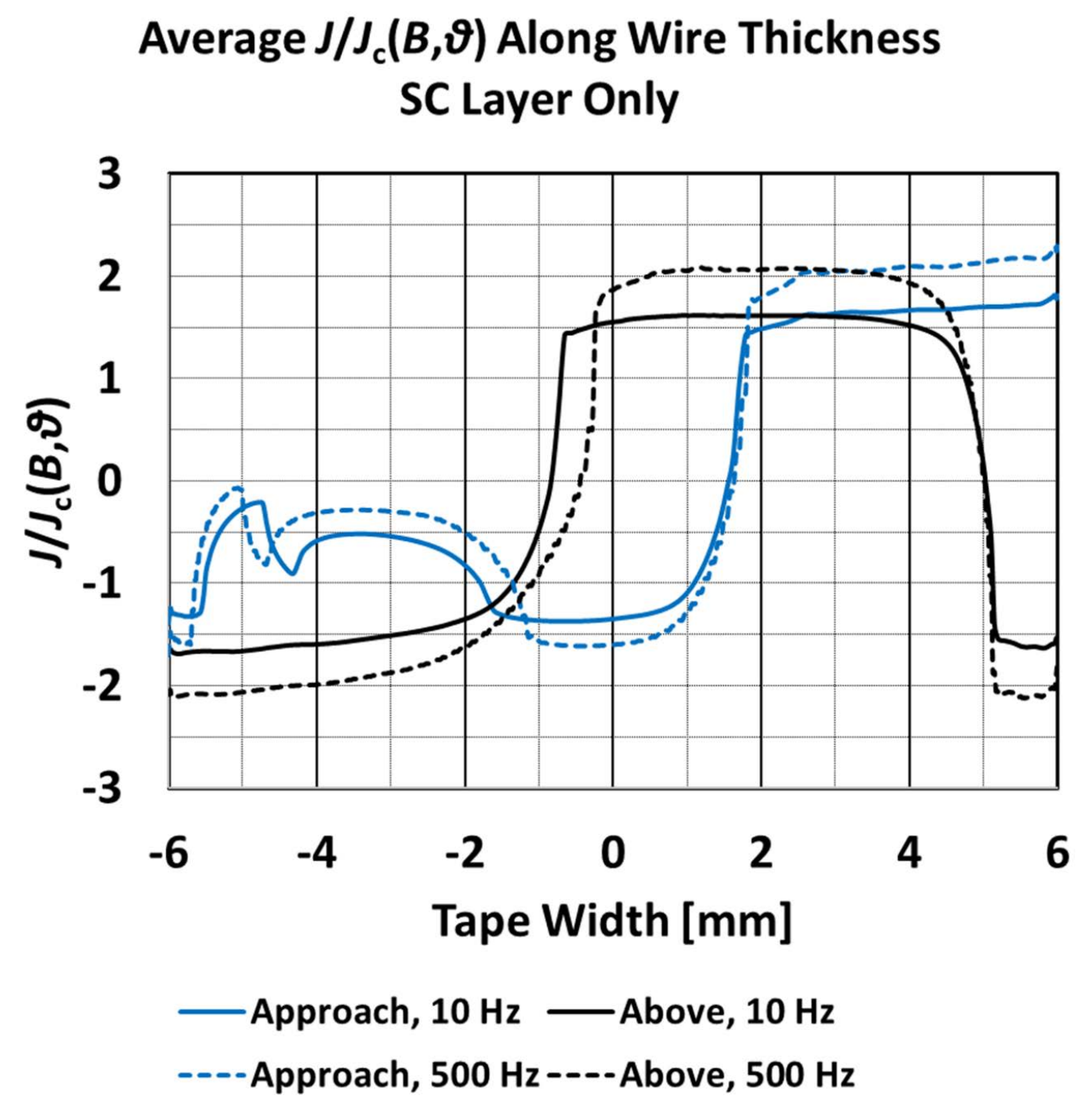
Time-averaged DC voltage (2nd-10th cycles) for magnet frequencies, f = 10 – 500 Hz



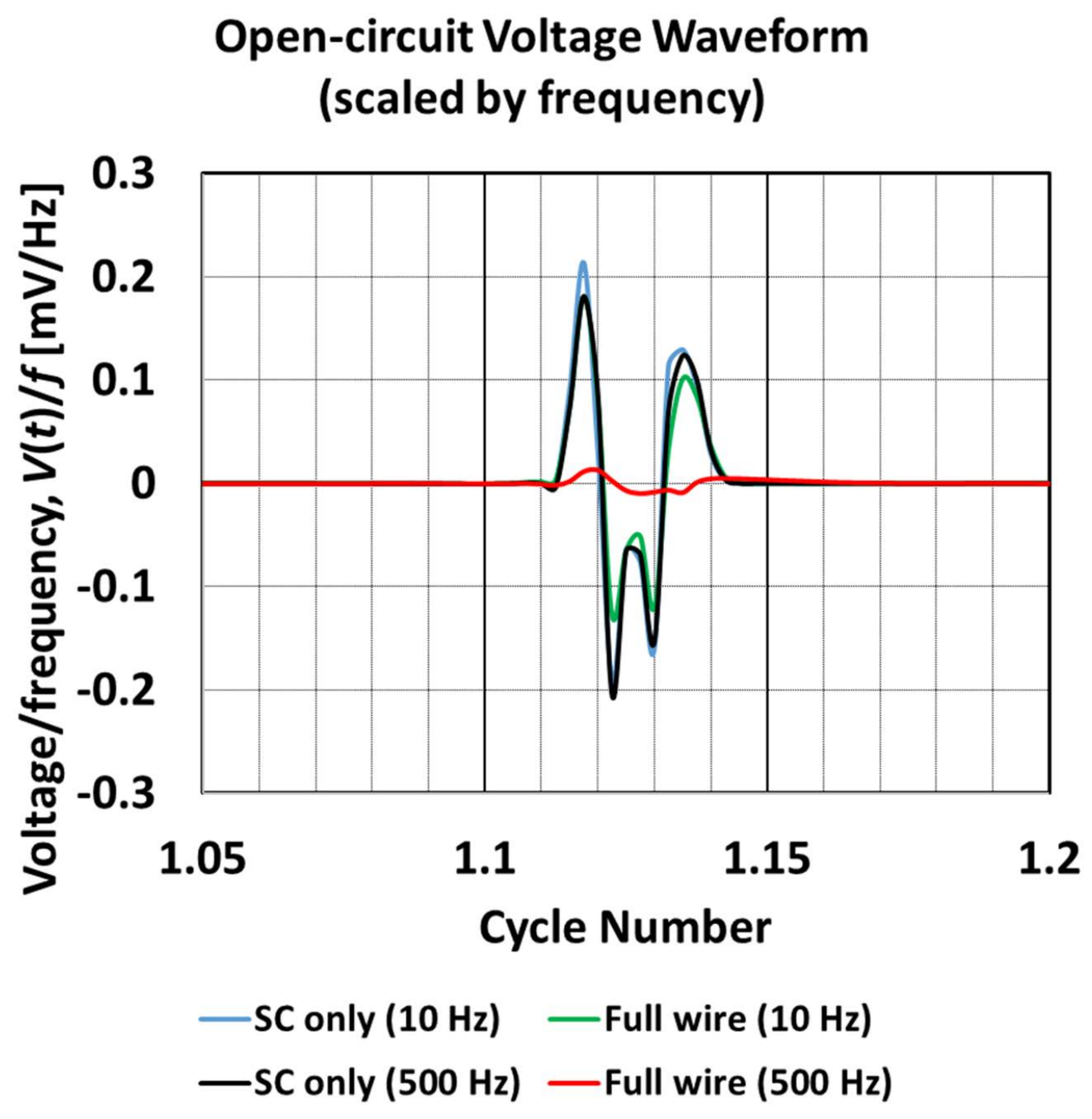
Cumulative, time-averaged DC voltage for magnet frequencies, f = 10, 50, 100 & 500 Hz (HTS layer only)



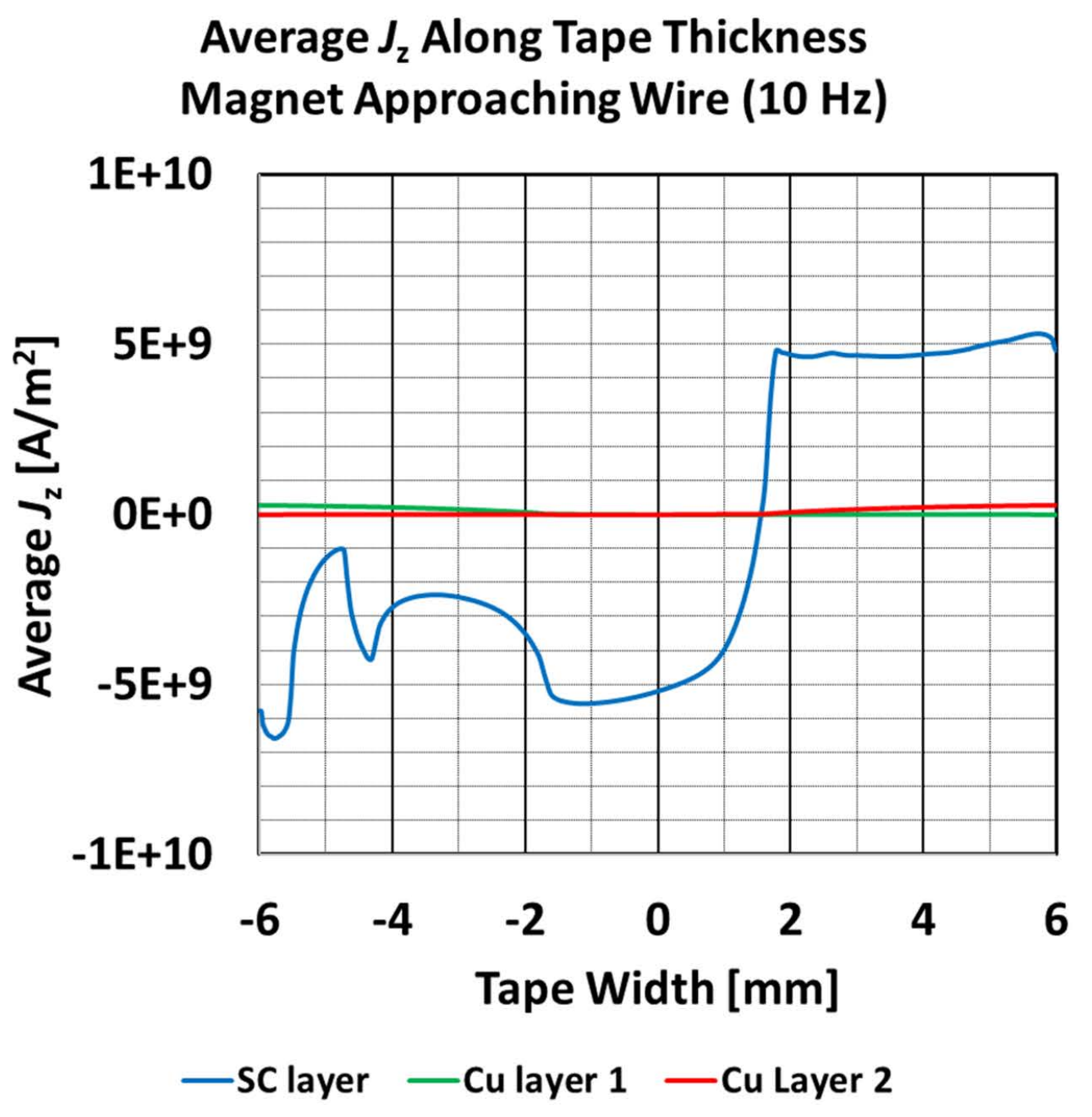
Experimental results from Pantoja *et al*. IEEE TAS 28 5202205 (top) Pantoja *et al*. IEEE TAS 26 4805208 (bottom)



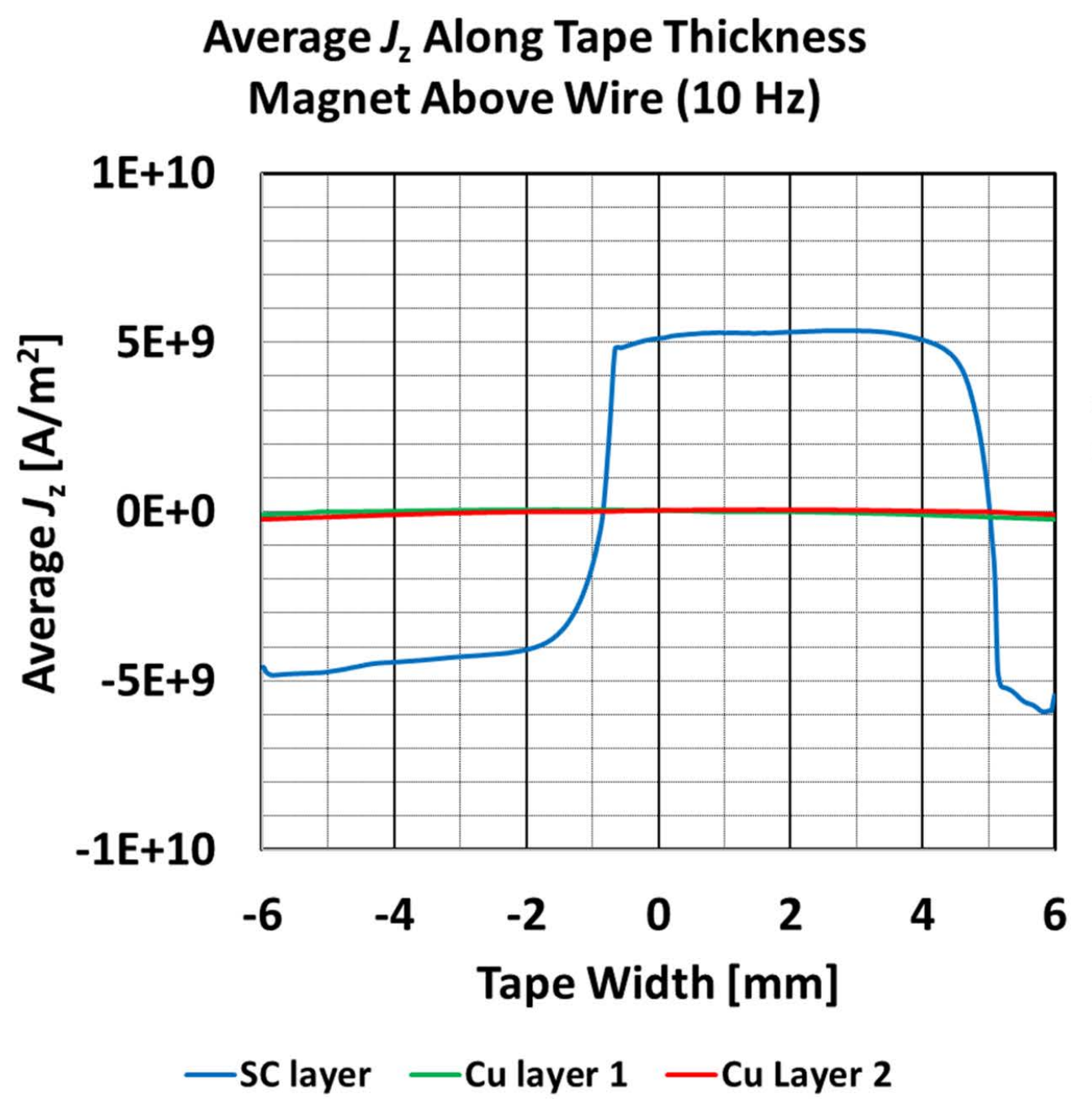
Average $J/J_c(B,\vartheta)$ Along Wire Thickness SC Layer Only



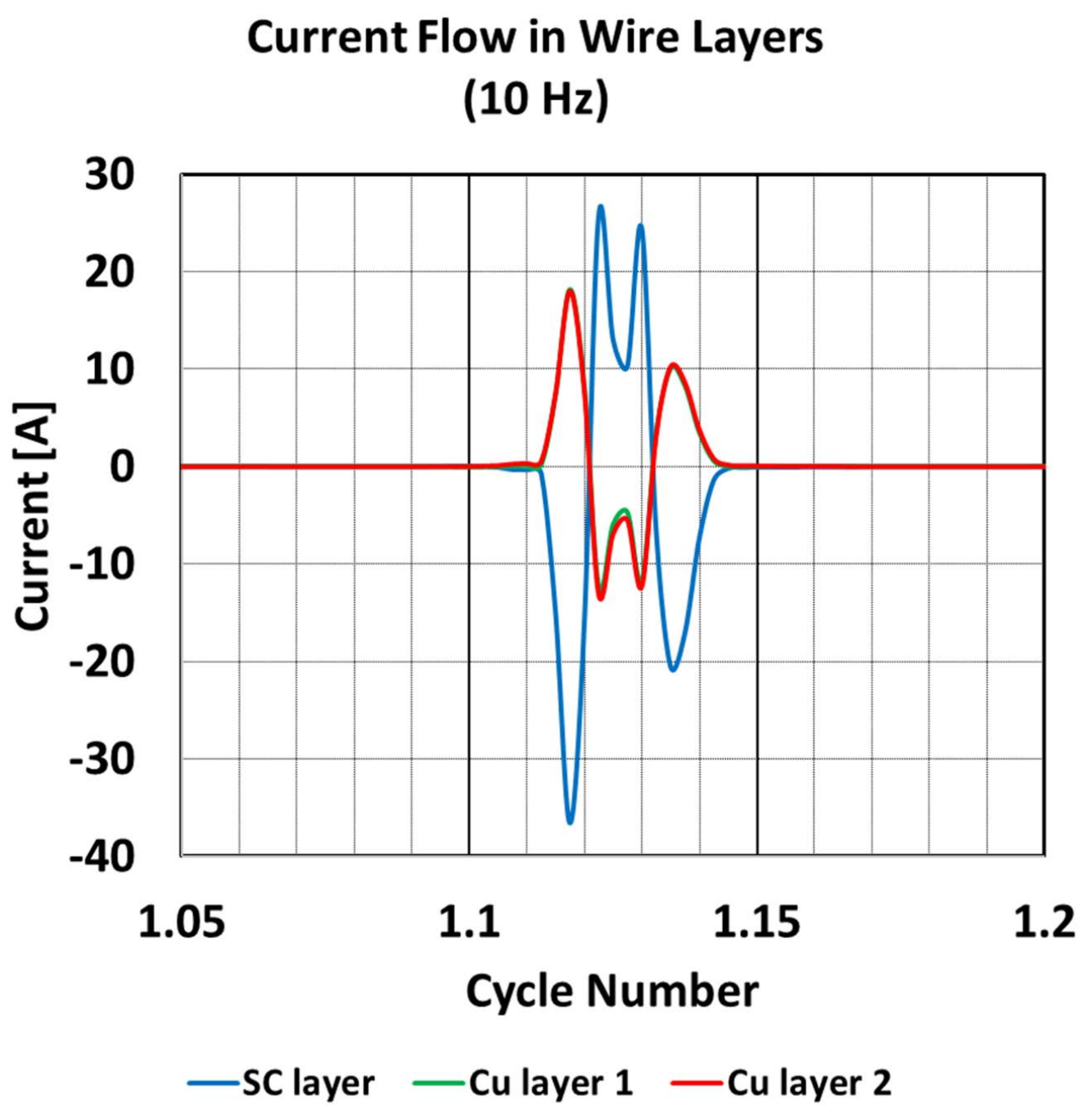
Open-circuit Voltage Waveform (scaled by frequency)



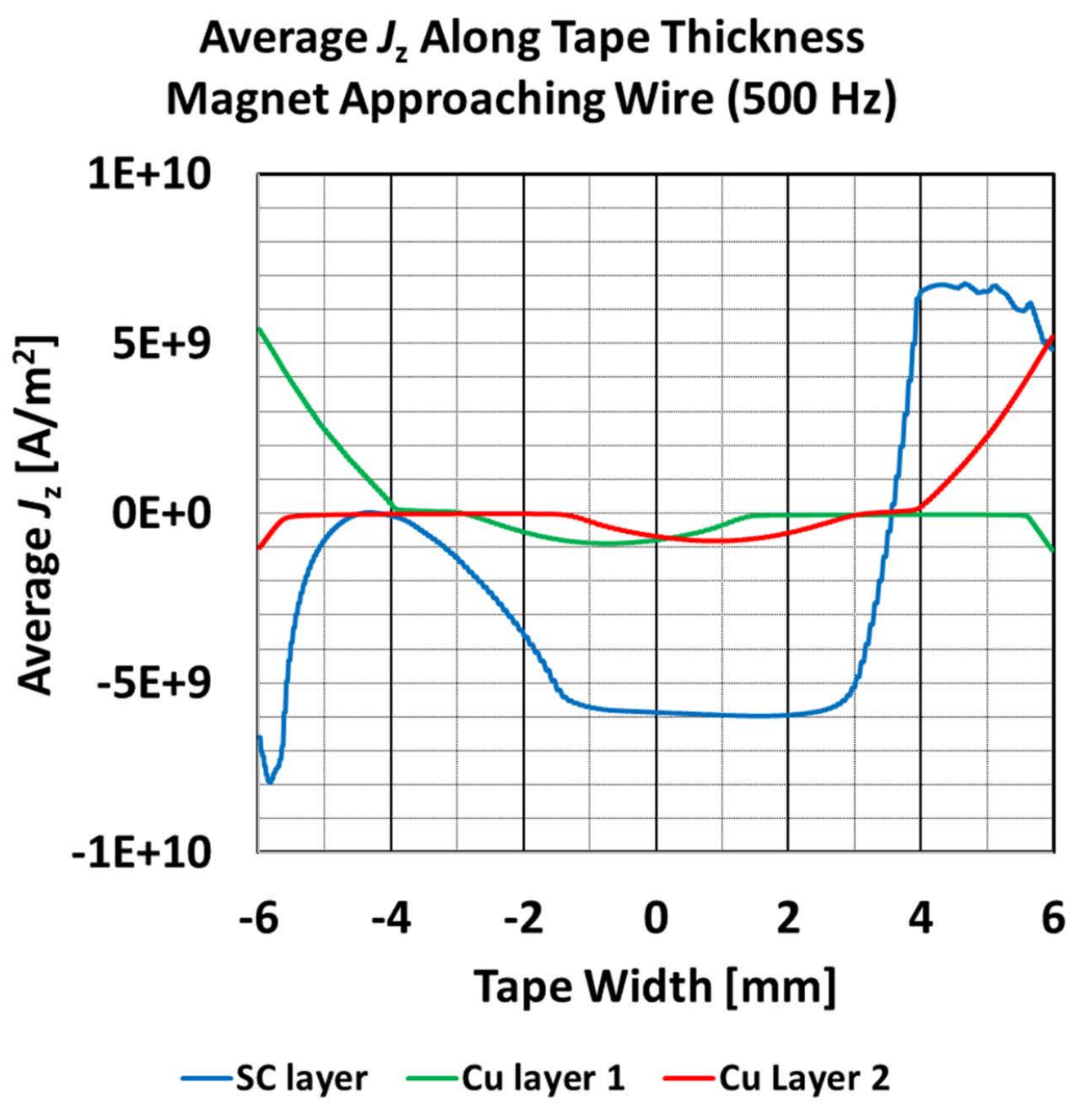
Average J_z Along Tape Thickness Magnet Approaching Wire (10 Hz)



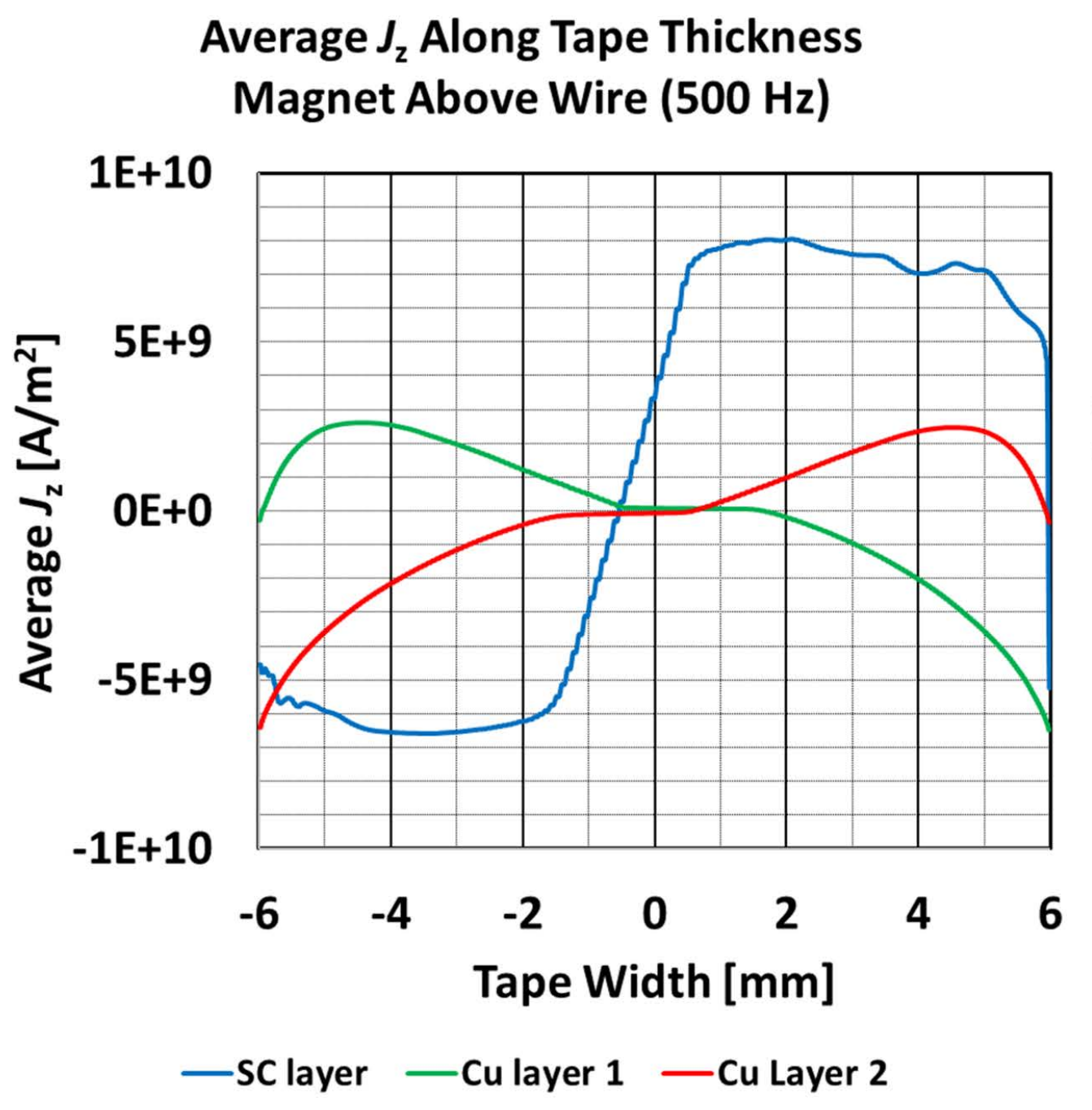
Average J_z Along Tape Thickness Magnet Above Wire (10 Hz)



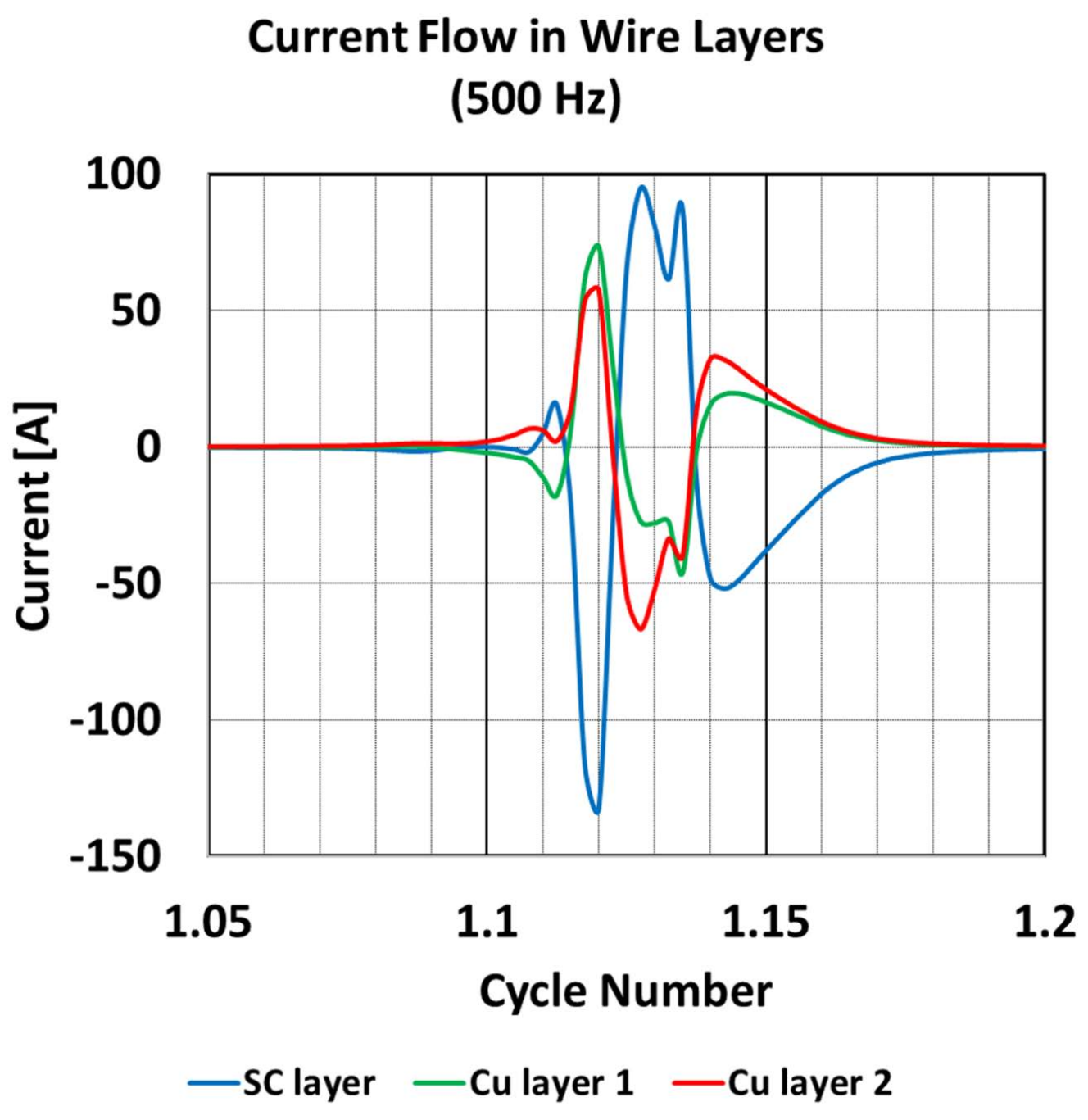
Current Flow in Wire Layers (10 Hz)



Average J_z Along Tape Thickness Magnet Approaching Wire (500 Hz)



Average J_z Along Tape Thickness Magnet Above Wire (500 Hz)



Current Flow in Wire Layers (500 Hz)

For the HTS wire only, the output increases linearly. The inclusion of generated heat reduces the output, this effect increasing with frequency.
Including the whole wire architecture produces results observed in experiments: a linear output for low-f, a plateau & then reducing output for high-f.
For high-f, current sharing between the layers in the HTS wire architecture become important; in particular, current flow into the Cu stabiliser due to excessive overcritical currents developing in the HTS layer.
The numerical models give an important insight into what is occurring inside the HTS wire in the HTS dynamo.