

Modelling the behavior of HTS coils under overcurrent conditions

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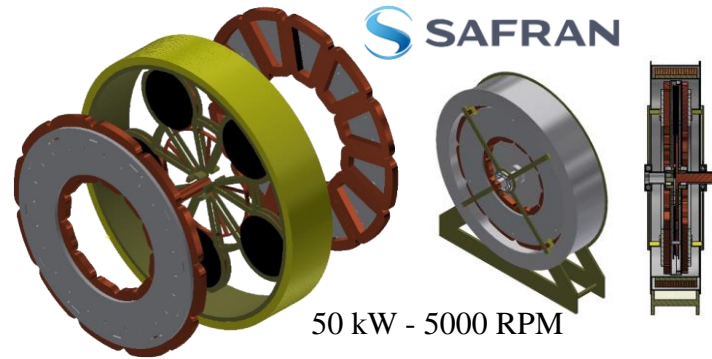
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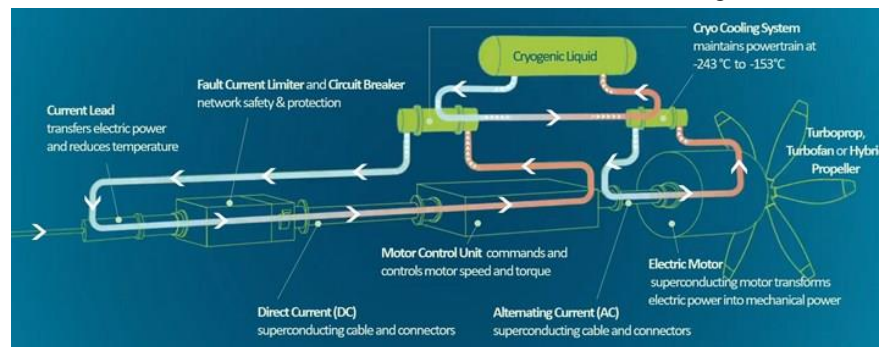
Background

Axial flux machine with DC HTS Coil

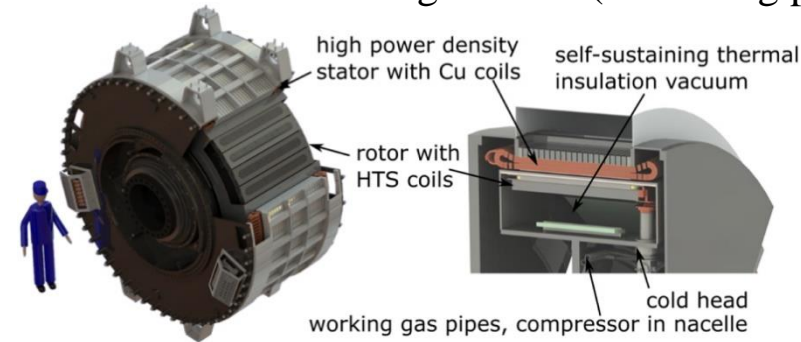


Airbus ASCEND program to explore liquid hydrogen and superconductivity for zero-emission aircraft

Ludovic Ybanez *et al*, 2022 IOP Conf. Ser.: Mater. Sci. Eng. 1241 012034



Design and in-field testing of the world's first REBCO rotor for a 3.6 MW wind generator (EcoSwing project)



Anne Bergen *et al*, 2019 Supercond. Sci. Technol. 32 125006

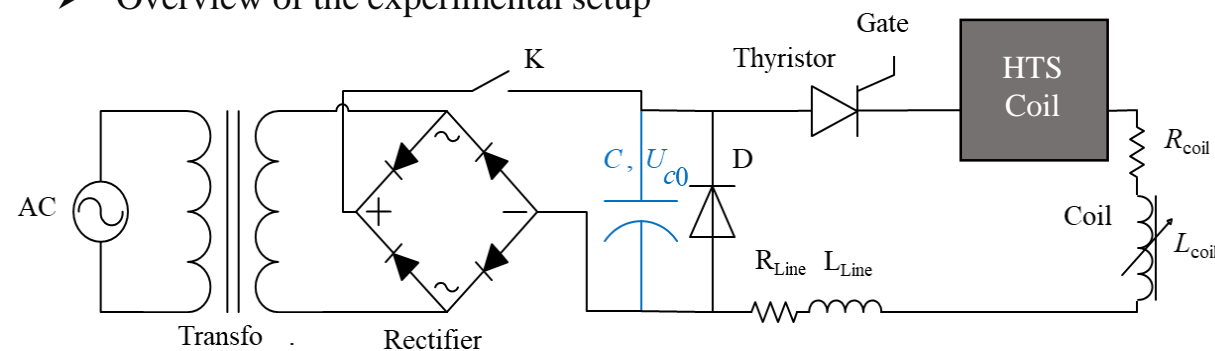
Most of HTS applications are intended to be connected to the electrical grid! **What about modelling?**

In this work, a coupling between an electrical system and an HTS coil in overcurrent conditions will be detailed.

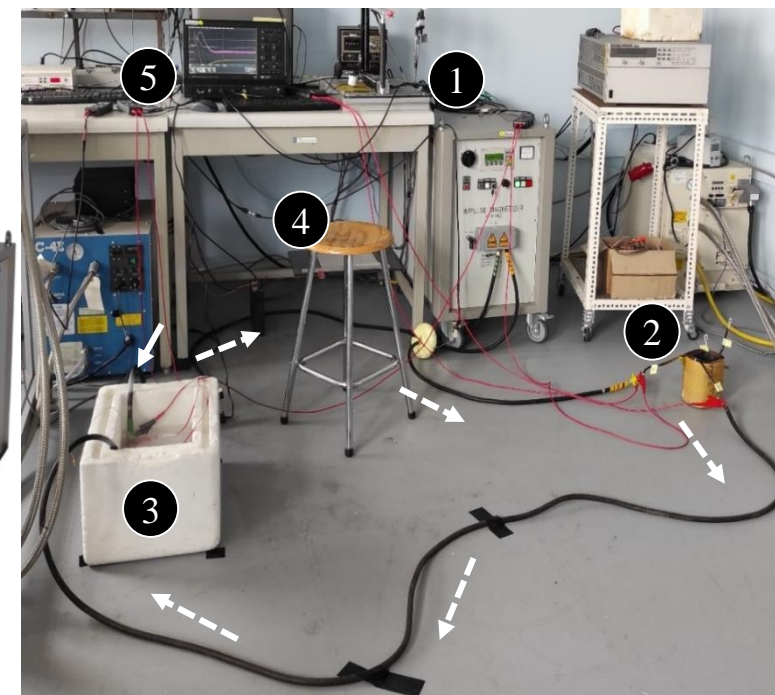
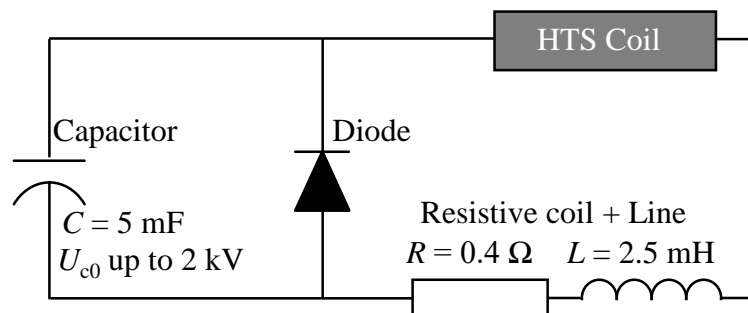
Experience to be modeled

- ❑ First validation of the model, including over regimes and heating effects, by discharging a capacitor bank into a superconducting coil.

- Overview of the experimental setup



- Simplified diagram of the experimental electrical circuit



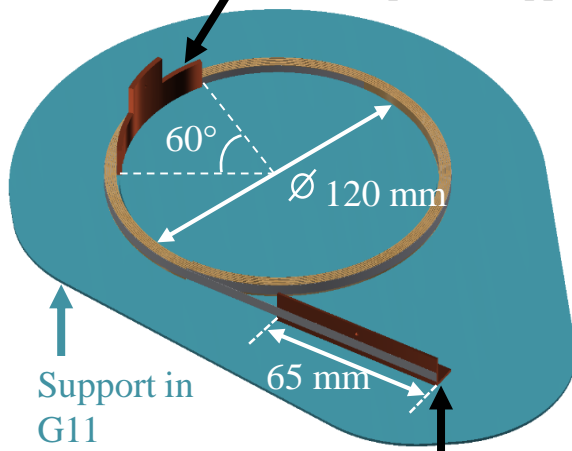
- | | |
|-------------------------|--|
| 1 Capacitor bank | 4 Current clamp |
| 2 Resistive coil | 5 Oscilloscope with differential probe |
| 3 REBCO Coil + Cryostat | |

REBCO tape and coil: DC characterisation @ 77 K

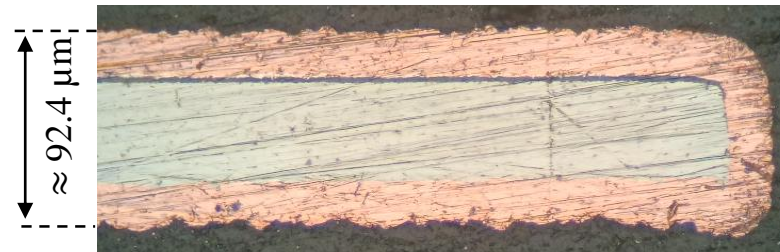
➤ DC measurement @ 77 K to determine the model parameters



Connection to the power supply



Connection to the power supply



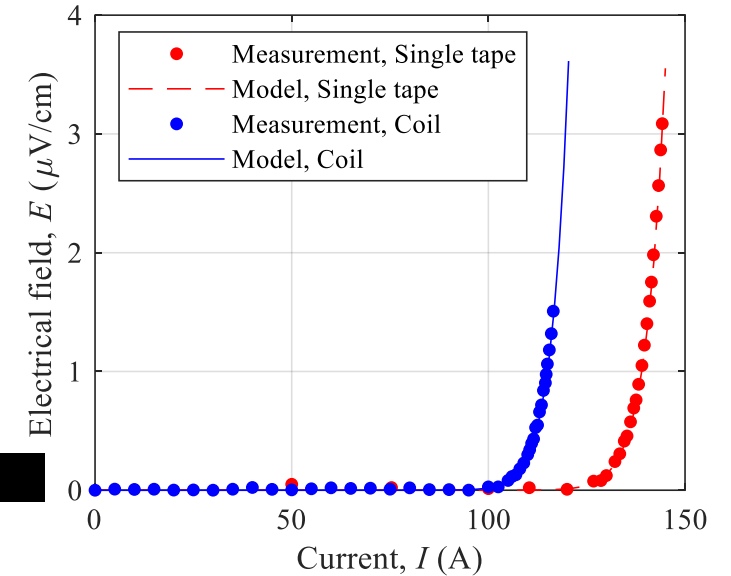
Top copper (CuT) $\approx 21.9 \mu\text{m}$
 Bottom copper (CuT) $\approx 17.7 \mu\text{m}$
 Substrate (Sub) $\approx 49.3 \mu\text{m}$
 YBaCuO $\approx 3.5 \mu\text{m}$

Short sample

I_c at 77.3 K, in self-field 138.5 A
 Index of transition n 22

HTS Coil

Length between voltage taps, l 2.26 m
 I_c at 77.3 K 114.5 A
 Index of transition n 21.5
 Numbers of turns N 6
 Inner/Outer diameter 120/124.5 mm



Power law: $E = E_c \left(\frac{I}{I_c}\right)^n$
 $E_c = 1 \mu\text{V/cm}$

REBCO tape and coil: equivalent resistivity @ $T > T_c$

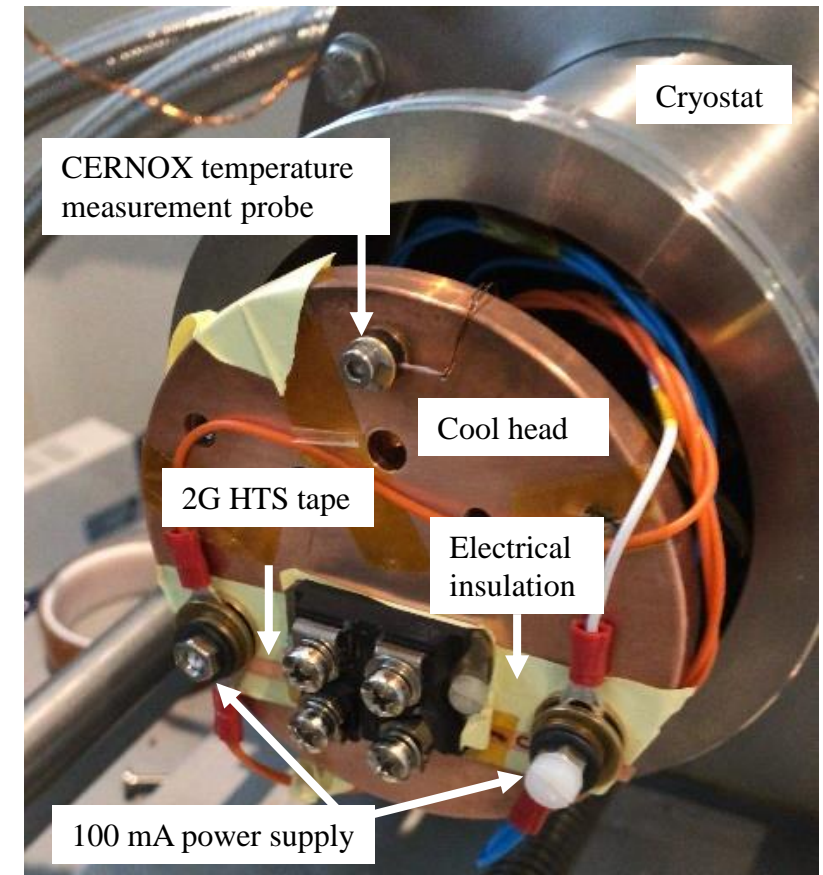
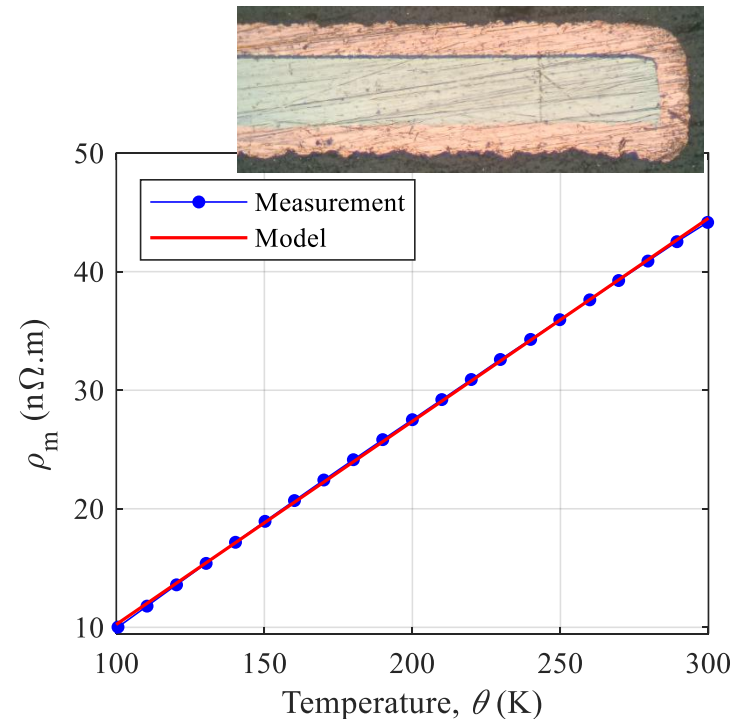
- ✓ Direct measurement of the HTS tape temperature is complicated (in LN2 bath)
- ✓ Indirect measurement above T_c
- ✓ Tape's $R(T)$ characteristics is measured with a cryocooler
- ✓ Temperature determined by measuring voltage above T_c

The corresponding linear fit yields the following expression,

$$\rho_m = 10^{-9} \times (0.1713 \cdot \theta [\text{K}] - 6.8849)$$

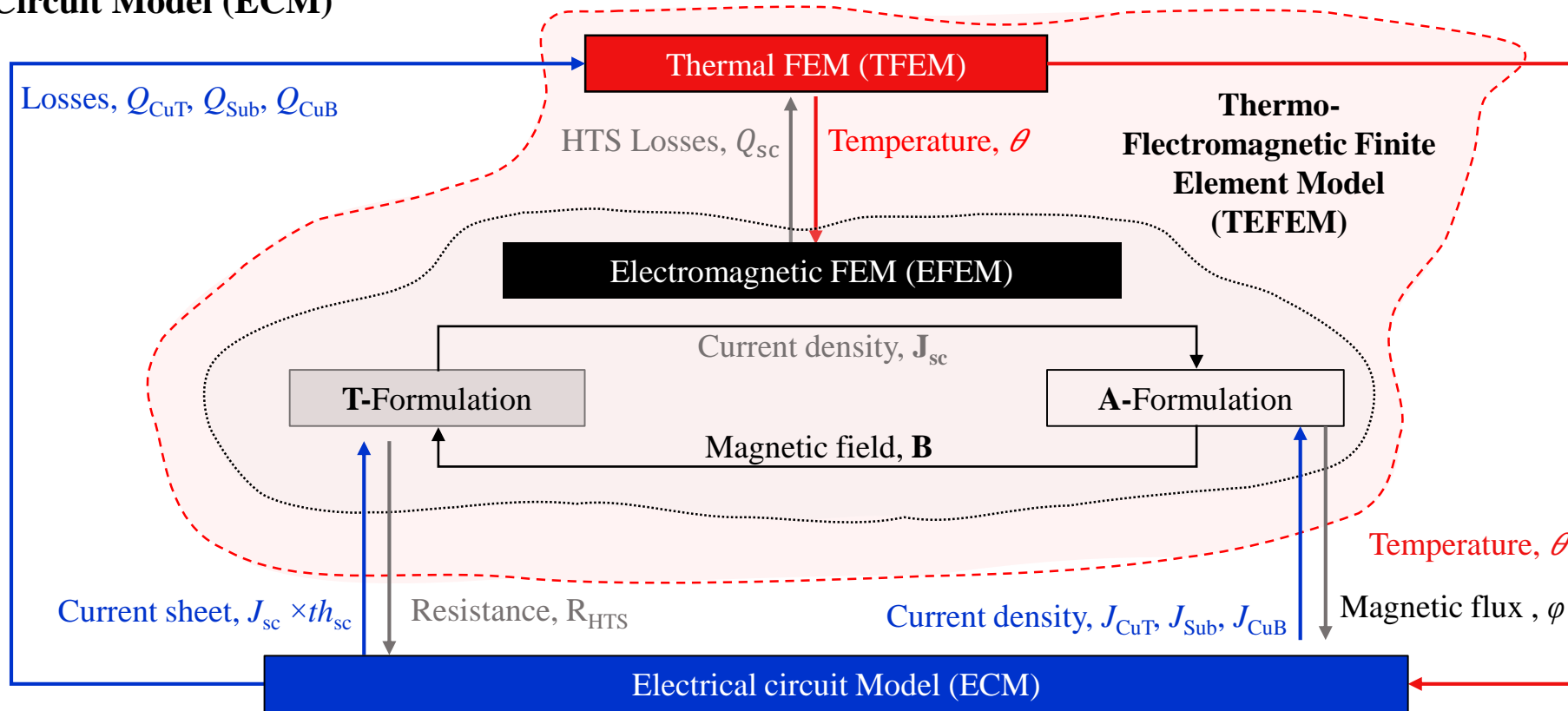
Model :

$$\frac{S_m}{\rho_m^*} = \frac{S_{\text{CuT}}}{\rho_{\text{CuT}}} + \frac{S_{\text{CuB}}}{\rho_{\text{CuB}}} + \frac{S_{\text{Sub}}}{\rho_{\text{Sub}}}$$



Overview of the TEFEM - ECM

□ Modelling and coupling between the Thermo-Electromagnetic Finite Element Models (TEFEM) and the Electrical Circuit Model (ECM)

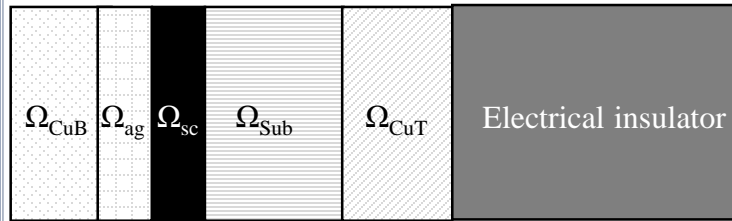


Paper submitted to Elsevier Cryogenics: Coupled thermo-electromagnetic finite element model with a reduced electrical circuit for the simulation of HTS inductive coils under overcurrent conditions.

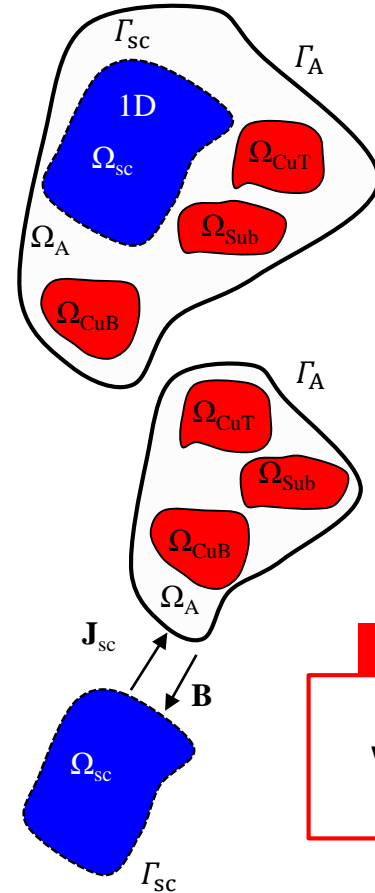
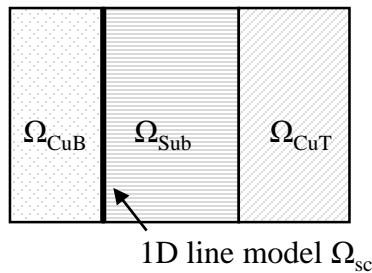
Electromagnetic Finite Element Model (EFEM)

Geometric approximation

One turn of the coil with its insulation and the HTS tape



Geometric model used in the TFEM and the EFEM



T-Formulation

$$\nabla \times (\rho \nabla \times \mathbf{T}) = -\frac{d\mathbf{B}}{dt}$$

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

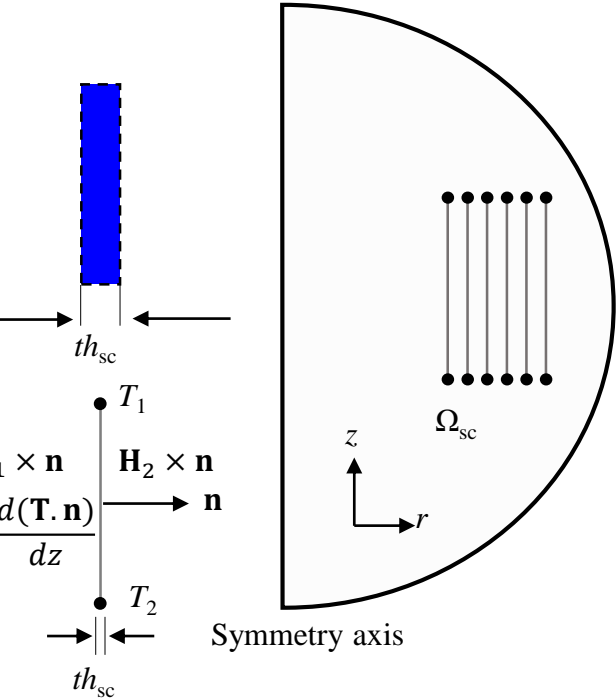
A-Formulation

$$\mathbf{n} \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{J}_{sc} th_{sc}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{J}_{sc} = \frac{d(\mathbf{T} \cdot \mathbf{n})}{dz}$$

$$\nabla \times \left(\frac{1}{\mu_0} \nabla \times \mathbf{A} \right) = \mathbf{J} \begin{cases} \mathbf{J}_{CuT}, \Omega_{CuT} \\ \mathbf{J}_{Sub}, \Omega_{Sub} \\ \mathbf{J}_{CuB}, \Omega_{CuB} \end{cases}$$

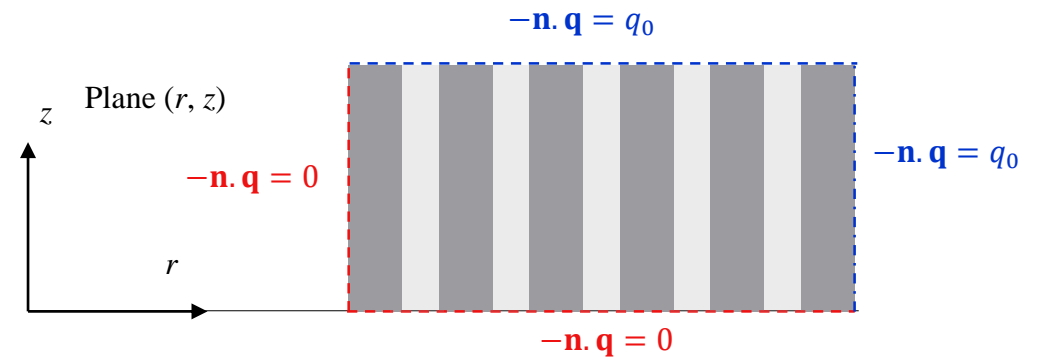
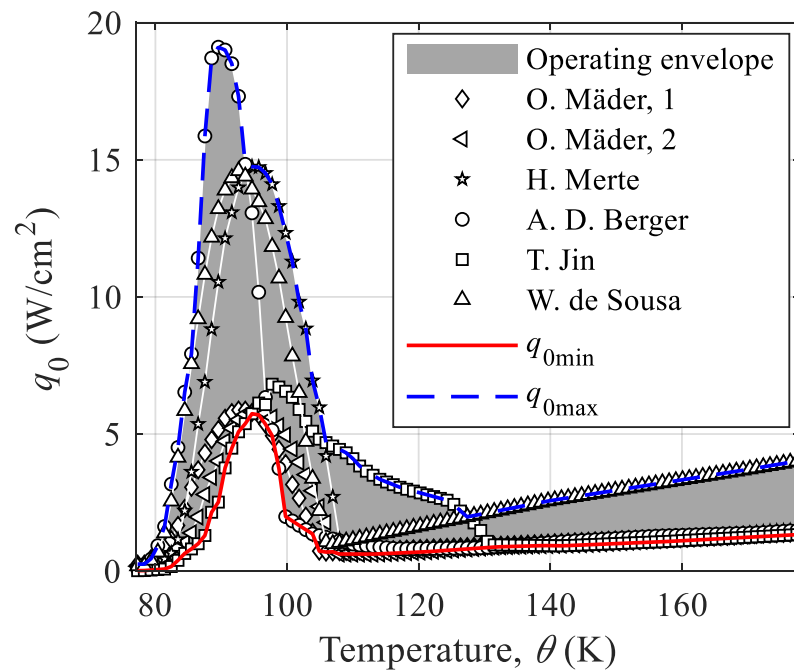


• Dirichlet Boundary Condition

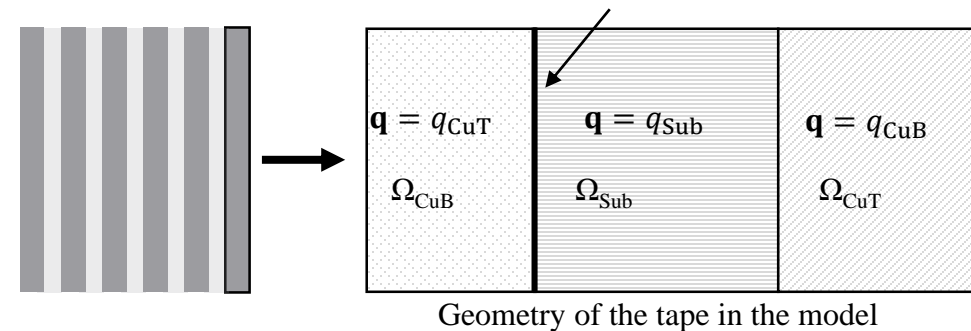
Thermal Finite Element Model (TFEM)

The governing heat balance equation is:

$$\gamma C_p \frac{d\theta}{dt} + \nabla \cdot (-k \nabla \theta) = q$$



Boundary condition Ω_{sc} , $-n \cdot \mathbf{q} = q_{sc} \times th_{sc}$

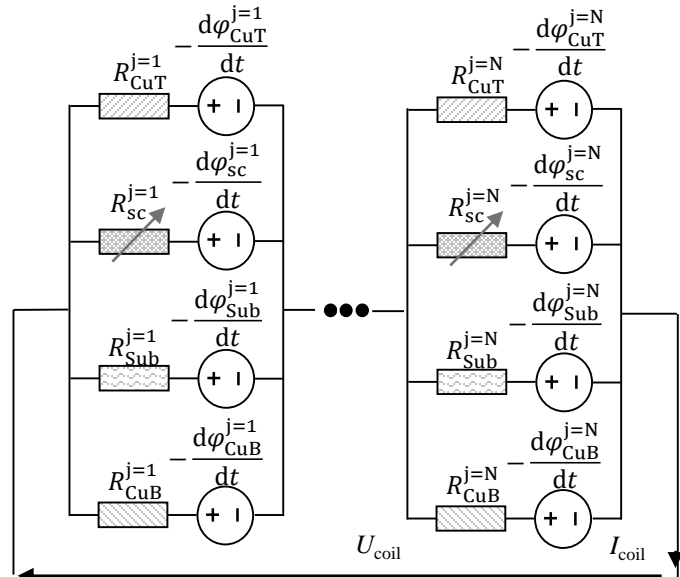


Reduction of the Electrical Circuit Model (ECM)

Layer-Based Model (LBM)

$$R_{j,sc} = \frac{2\pi r_{sc,j} \int_{l_j} \rho_{sc}(J_j, B_j, \theta_j) dy}{\int_{l_j} dy} \quad R_{j,m} = \frac{2\pi \langle r_j \rangle \rho_j(T_j)^*}{wth_i}$$

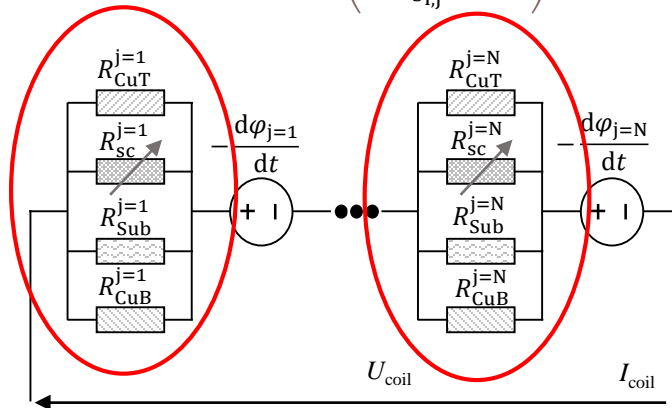
$$U_{j,sc} = -\frac{d}{dt} \left(\frac{\int_w \mathbf{A}_j \cdot d\mathbf{y}_j}{\int_w d\mathbf{y}_j} \right) \quad U_{j,m} = -\frac{d}{dt} \left(\frac{\iint_{S_{i,j}} \mathbf{A}_{i,j} \cdot d\mathbf{S}_{i,j}}{\iint_{S_{i,j}} d\mathbf{S}_{i,j}} \right)$$



Turn-Based Model (TBM)

$$R_{j,sc} = \frac{2\pi r_{sc,j} \int_{l_j} \rho_{sc}(J_j, B_j, \theta_j) dy}{\int_{l_j} dy} \quad R_{j,m} = \frac{2\pi \langle r_j \rangle \rho_j(T_j)^*}{wth_i}$$

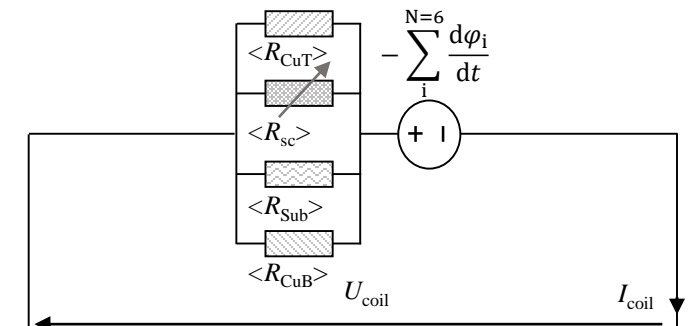
$$U_{j,m} = -\frac{d}{dt} \left(\frac{\iint_{S_{i,j}} \mathbf{A}_{i,j} \cdot d\mathbf{S}_{i,j}}{\iint_{S_{i,j}} d\mathbf{S}_{i,j}} \right)$$



Coil-Based Model (CBM)

$$R_{j,sc} = \sum_{j=1}^N \frac{2\pi r_{sc,j} \int_{l_j} \rho_{sc}(J_j, B_j, \theta_j) dy}{\int_{l_j} dy} \quad R_{j,m} = \sum_{j=1}^N \frac{2\pi \langle r_j \rangle \rho_j(T_j)^*}{wth_i}$$

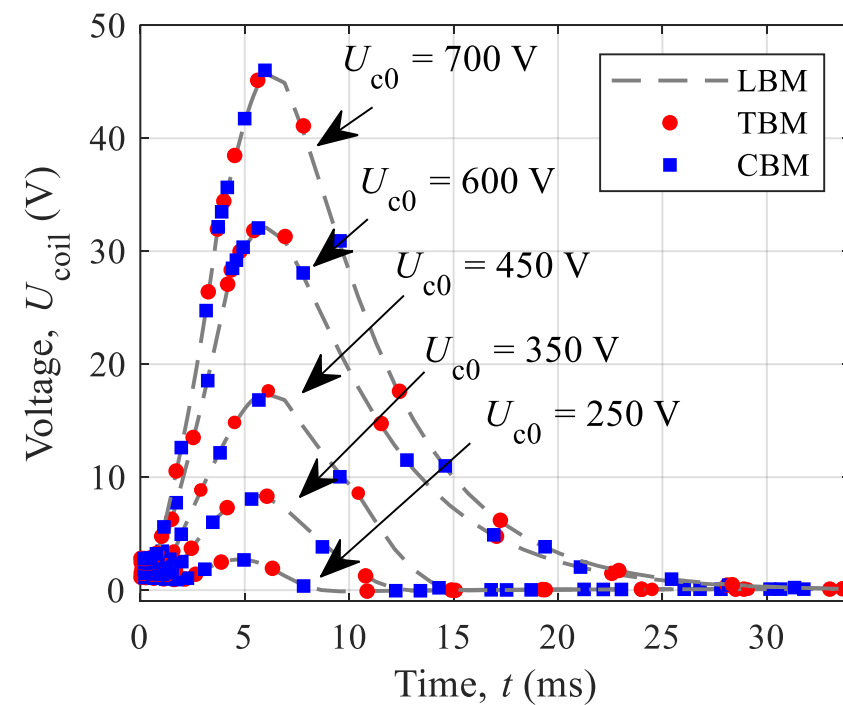
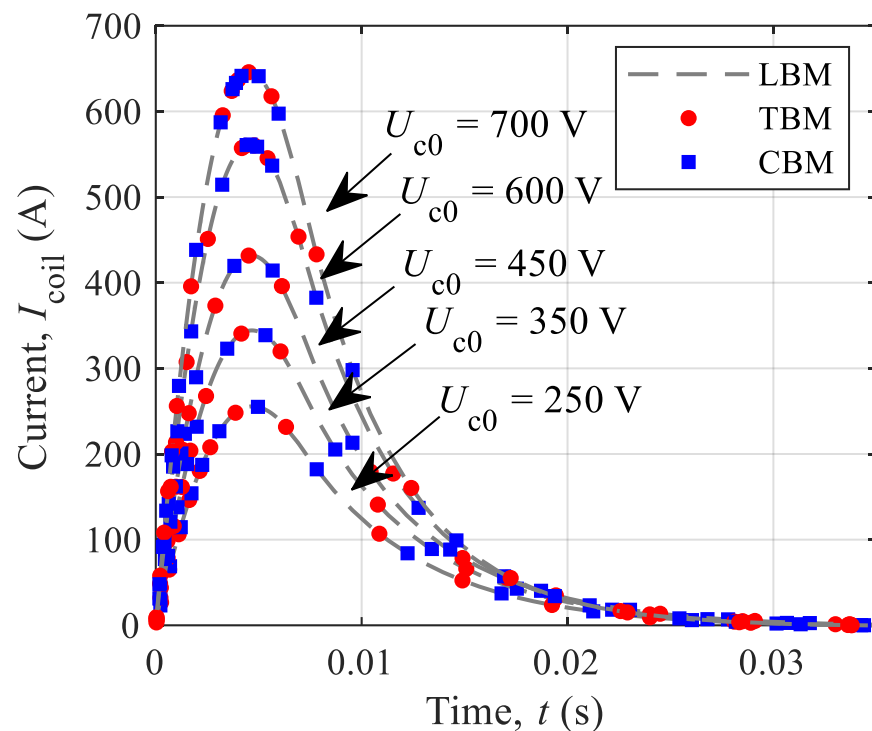
$$U_{j,m} = \sum_{j=1}^N \frac{d}{dt} \left(\frac{\iint_{S_j} \mathbf{A}_j \cdot d\mathbf{S}_j}{\iint_{S_j} d\mathbf{S}_j} \right)$$



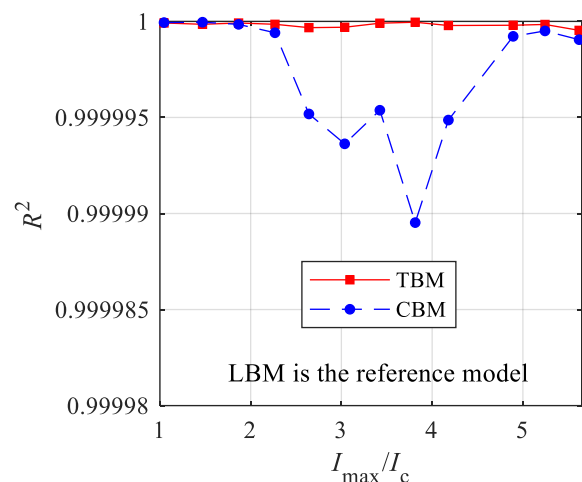
Reduction of the Electrical Circuit Model (ECM)

□ Values of I_{\max}/I_c according to the peak capacitor voltage U_{c0}

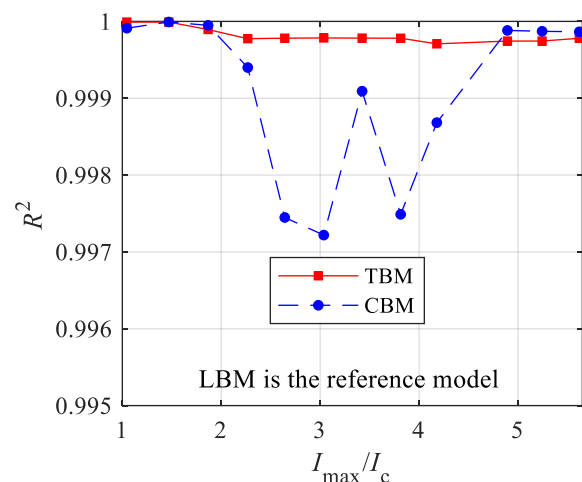
U_{c0}	250 V	350 V	450 V	600 V	700 V
I_{\max}/I_c	1.87	2.64	3.42	4.89	5.62



Reduction of the Electrical Circuit Model (ECM)



Coefficient of determination (R^2) of the current as a function of I_{\max}/I_c .



Coefficient of determination (R^2) of the coil voltage as a function of I_{\max}/I_c .

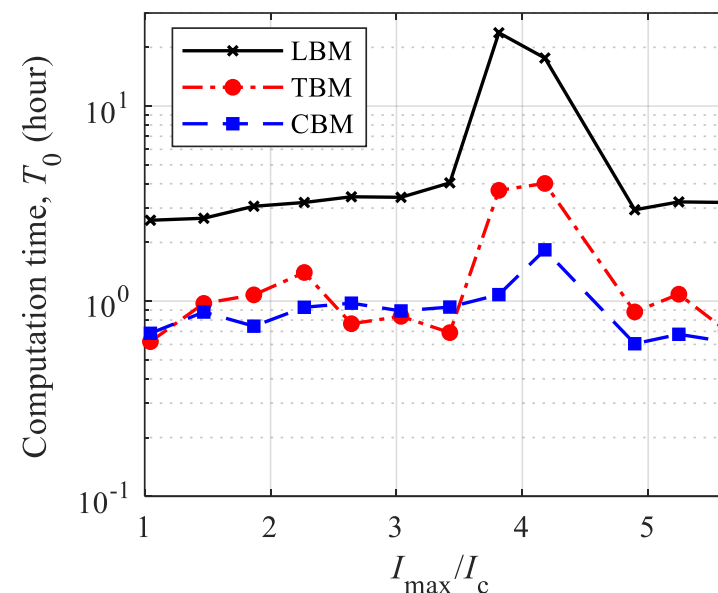
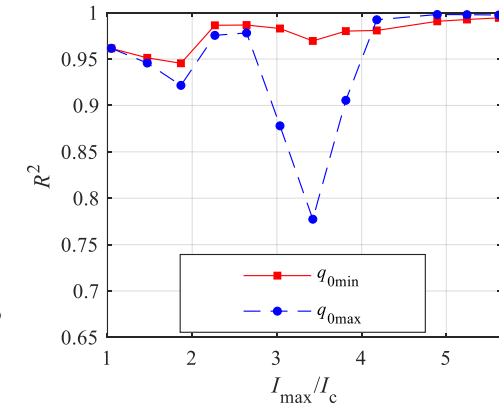
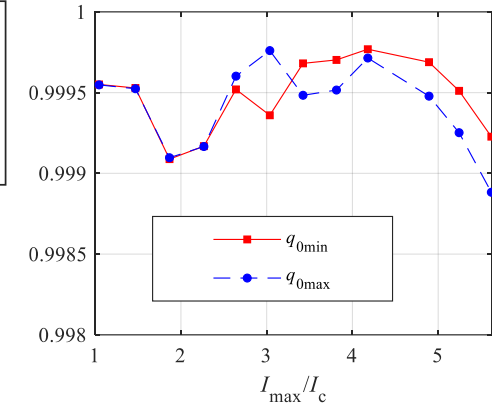
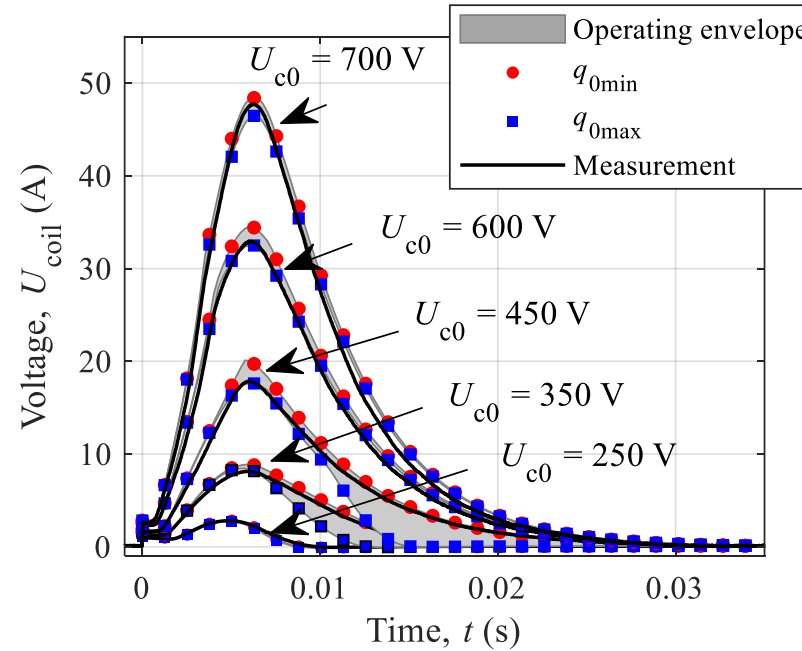
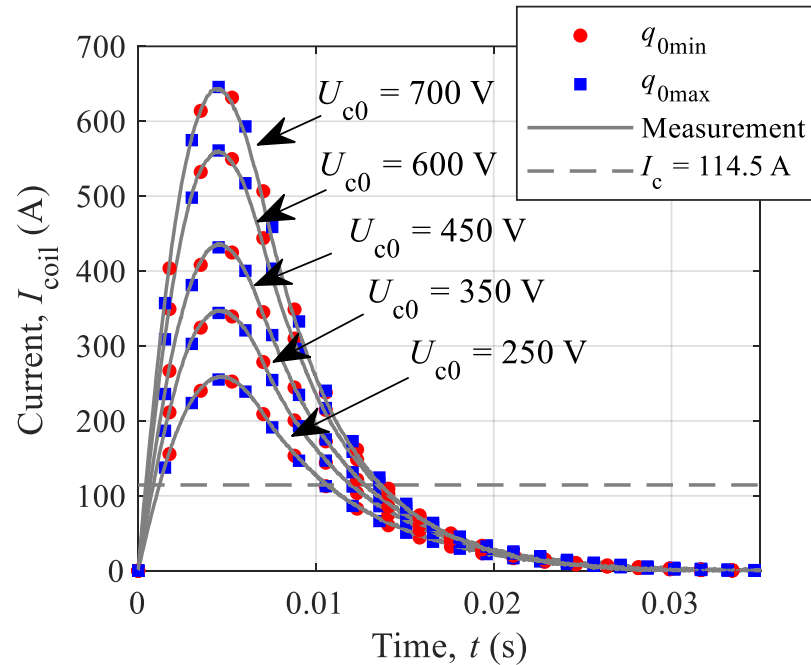


Table. Comparison of TEFEM - ECM coupling for three configurations: LBM, TBM, and CBM

Model	DOF	$\langle R^2 \rangle$ of current	$\langle R^2 \rangle$ of voltage	Average Computation time $\langle T_q \rangle$
LBM	71,243	Reference Model	Reference Model	6.097 h
TBM	57,536	0.9999998	0.9997832	1.396 h
CBM	57,516	0.9999971	0.9990667	0.904 h

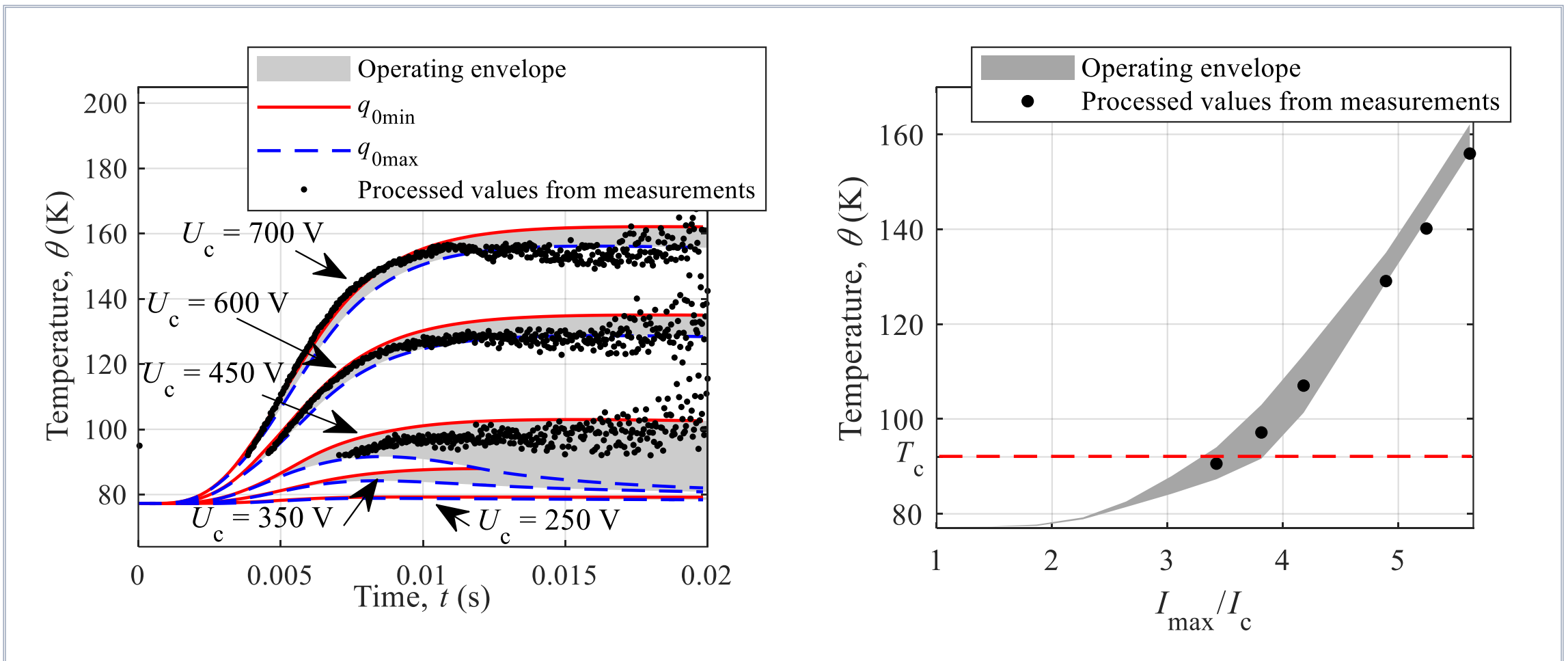
$\langle R^2 \rangle$ and $\langle T_q \rangle$ are calculated from the average value of all pulses performed between $I_{\max}/I_c = 1$ and $I_{\max}/I_c = 5.6$.

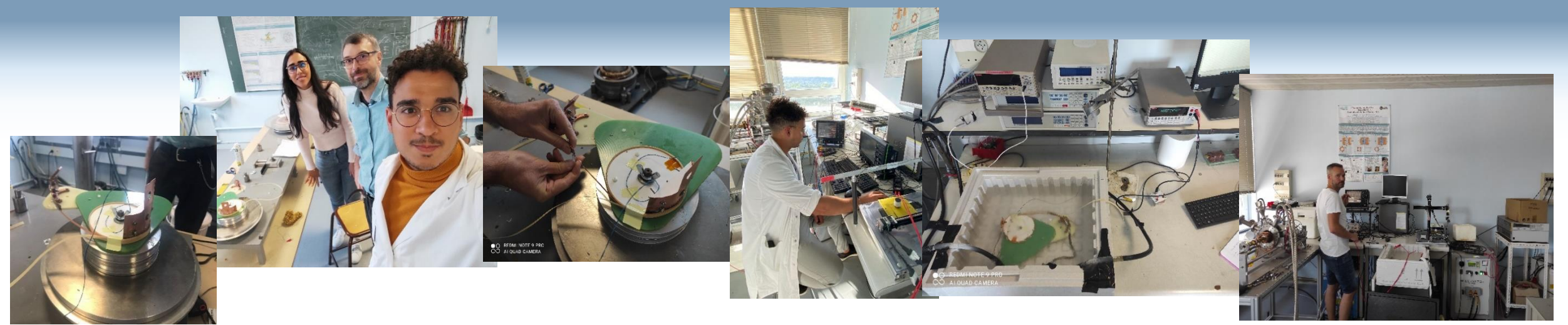
CBM comparison with experimental data



- ❑ CBM with minimal cooling q_{0min} (red circles) is closer to the experimental results,
- ❑ The heat exchange coefficient has a stronger impact during the recovery phase.

Temperature estimation from model vs. experiment





Thank you for your attention

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