Influence of HTS Wire and Coil Configuration on Quench Propagation

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Chats
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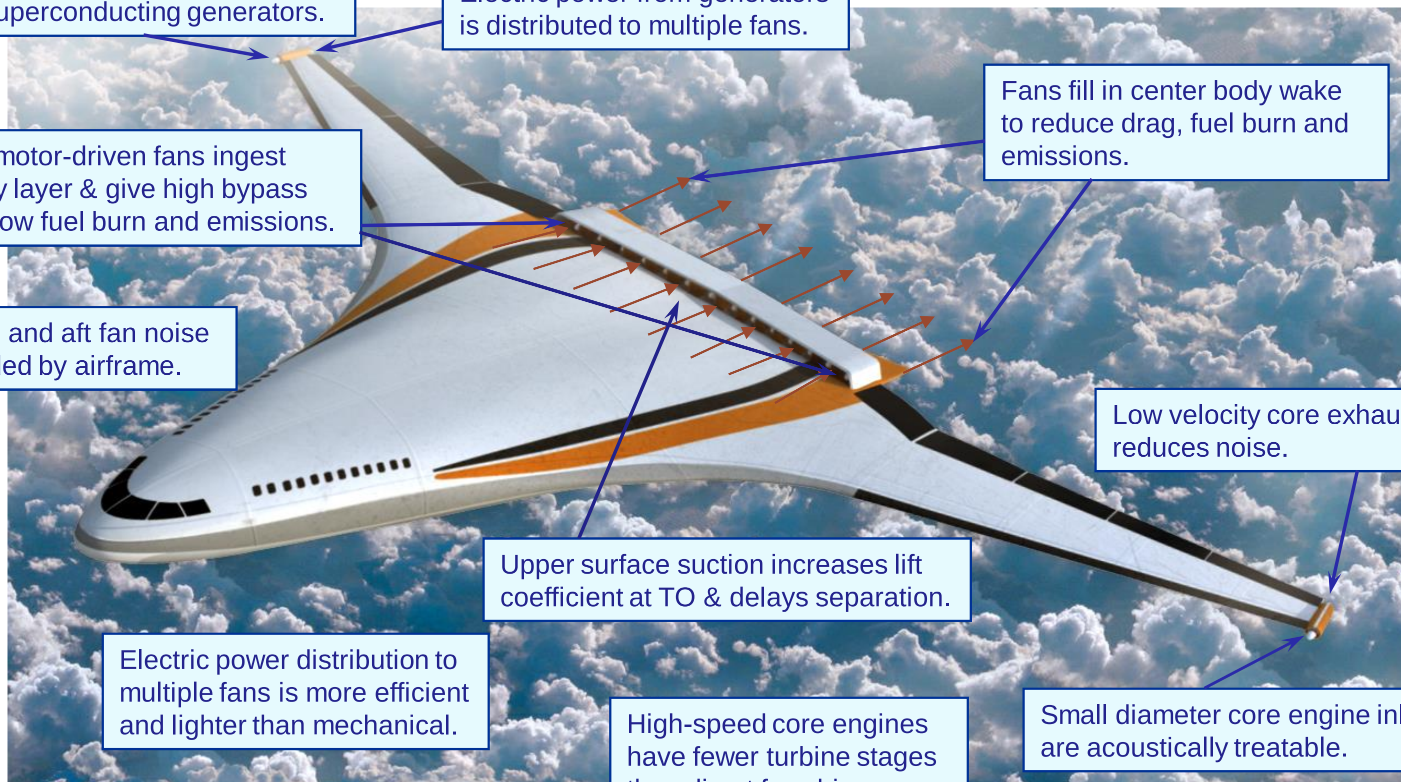
NASA's Distributed Propulsion Aircraft

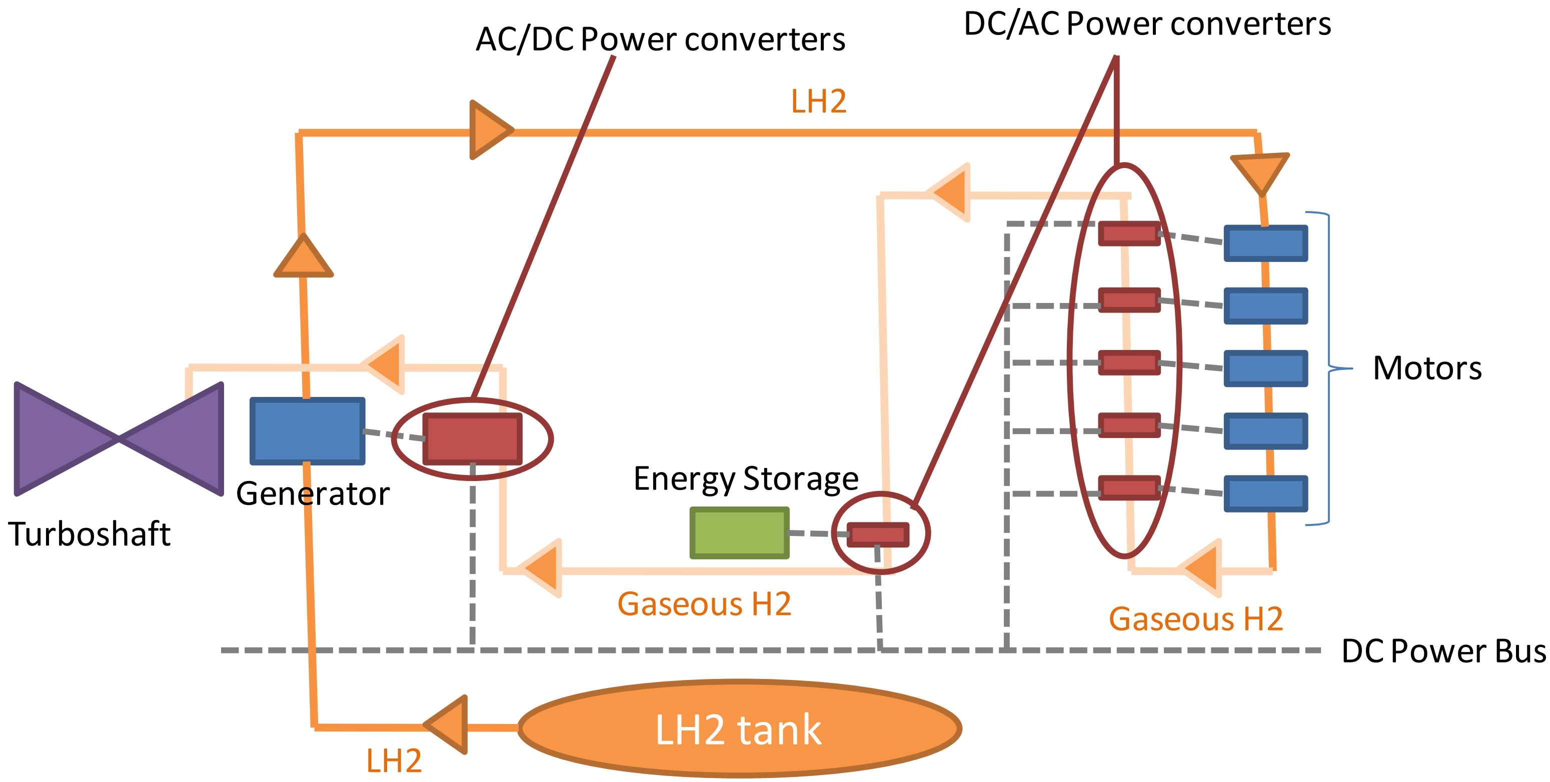
BENEFITS



THE TURBOELECTRIC APPROACH CONTRIBUTES TO EVERY CORNER OF THE SFW TRADE SPACE

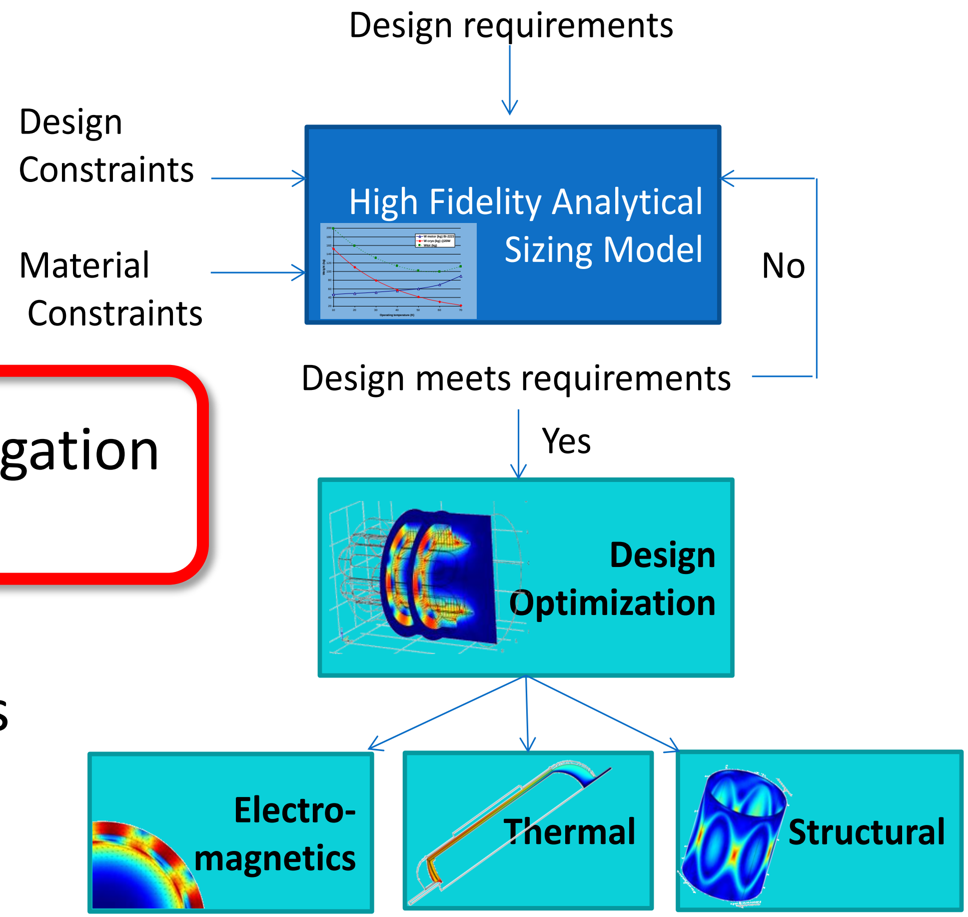
Distributed Propulsion – LH2 Cooling Network

- LH2 can be used to cool-down superconducting components and power converters
- Network dynamic simulation is used to determine the requirements of energy storage devices and reconfiguration



Project Objectives

- Develop a **high fidelity** sizing tool for **fully superconducting rotating machines**.
  - Accurate 3D geometry represented
    - Electromagnetics, mechanical and thermal
  - Portable code in Python and C



- Develop model for quench propagation
  - Address detection and protection

- Develop **new model** for AC losses for superconducting stators
  - Based on FEA simulations

- Validate AC losses model **experimentally**

Sizing Model "Amber" Version 0.9

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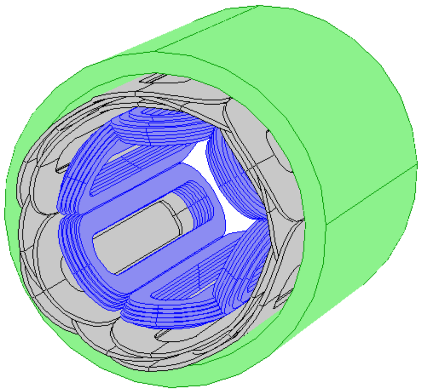
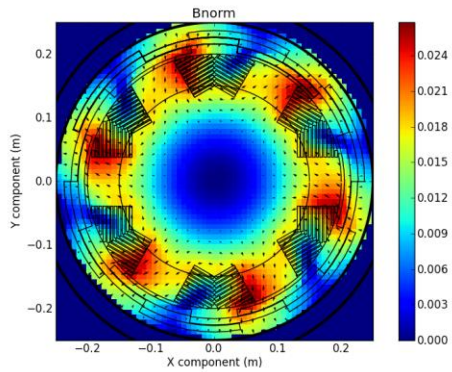
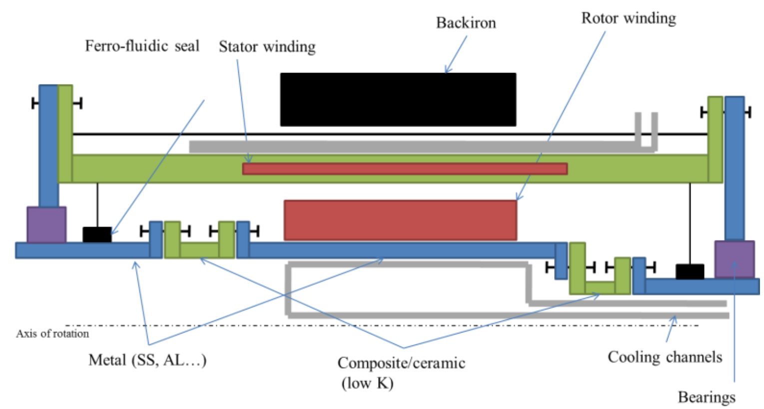
- Zeroth order analytical sizing model (2D) used for preliminary optimization



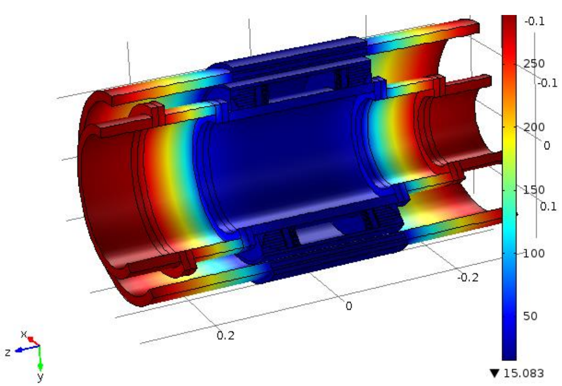


Electromagnetic model

- Geometry accurately represented
- No mesh in air
- Based on integral methods (GFUN – Biot Savart)



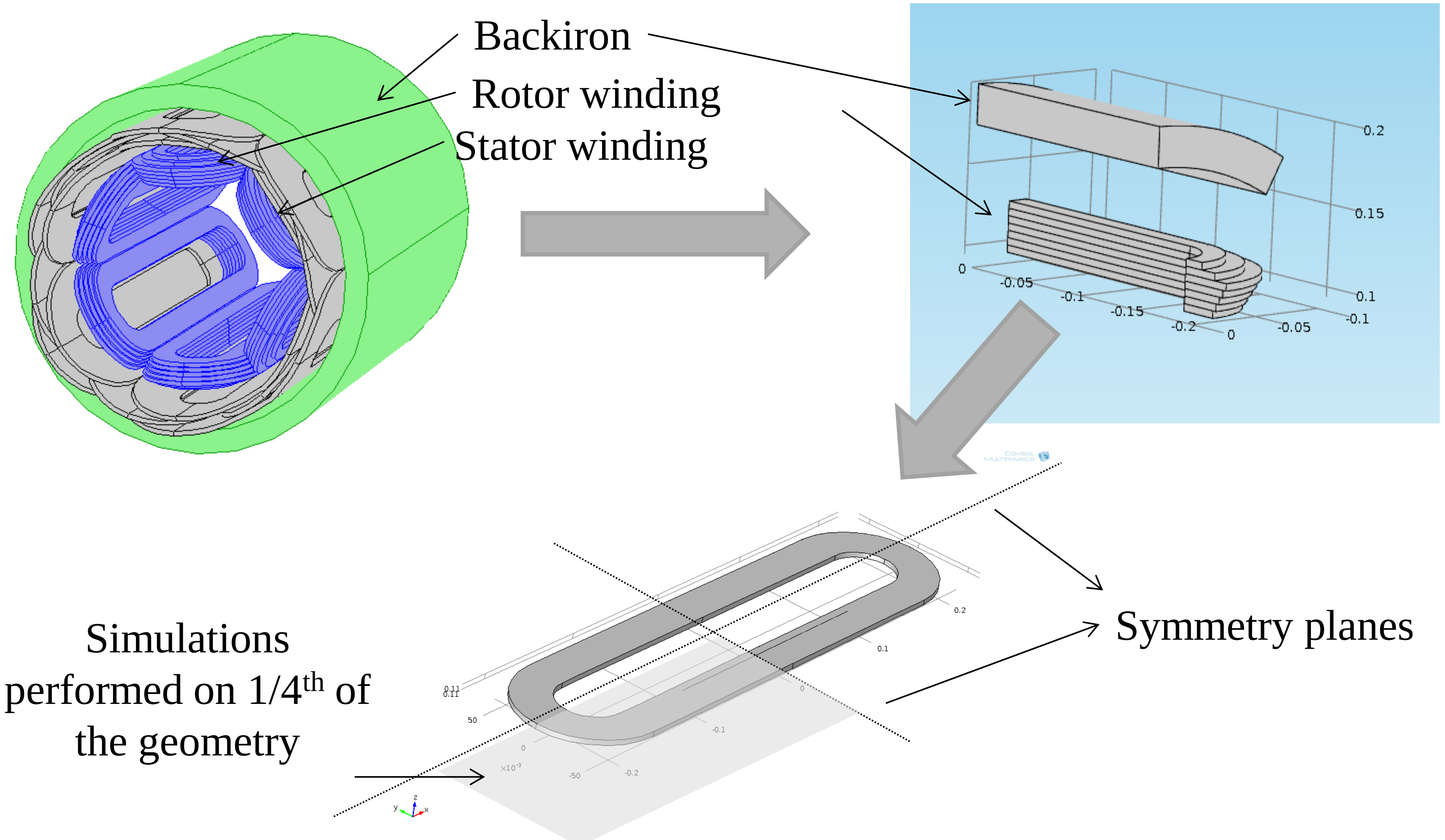
- Mechanical model
  - Geometry accurately represented
  - Steel and composite materials
  - Thermal and force induced stress



- Thermal model
  - Total cryogenic heat load and temperature distribution estimated using finite differences
  - Cryogenic system based on LH2 or Ghe and Reversed Turbo-Brayton cryocoolers

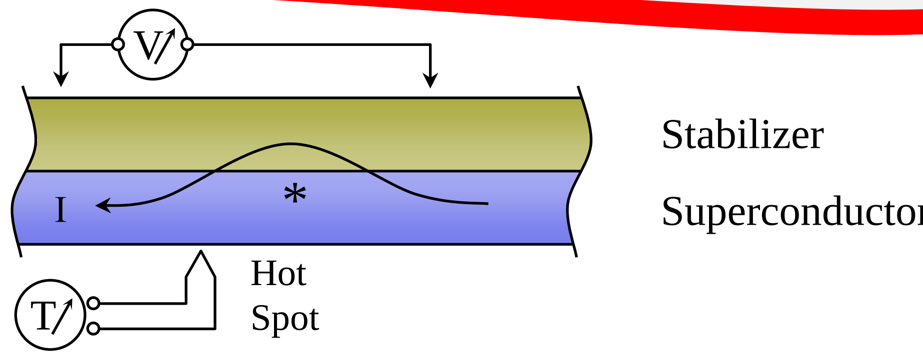
Winding Geometry

- First step focuses on quench in the rotor winding
- Objective is to evaluate the impact of quench protection on the machine design



Quench in Superconductors

A quench is an electro-thermal instability



Localized energy input (disturbance), e.g., low Jc area, heat input, etc.

+ΔQ

Hot-spot localized temperature rise

+ ΔT

Quench positive feedback loop

+ΔQ

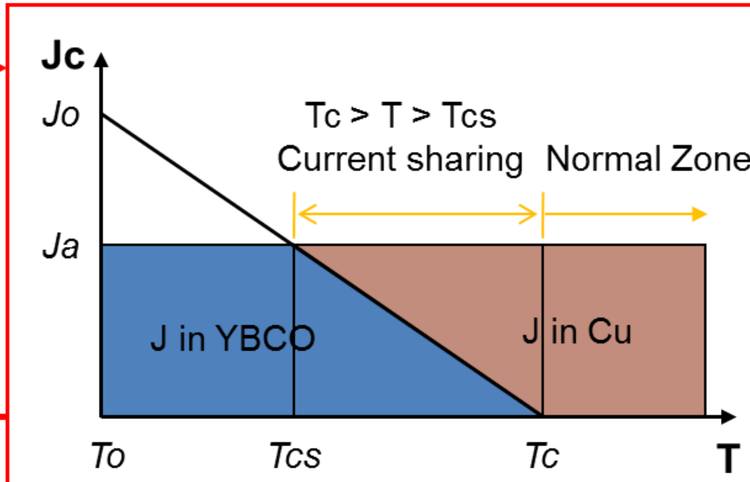
+ Δ Jcu

Q = Joule Heating - Cooling

- Δ Q

- Δ Q => - Δ T => - ΔJcu

Recovery loop



Minimum Quench Energy (MQE)

Normal Zone Propagation Velocity (NZPV)

Quench model

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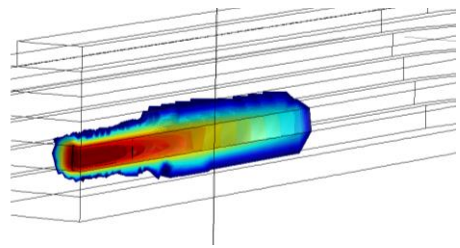
Conductor topology/materials →

Winding geometry →

Model



→ NZPV

→ MQE

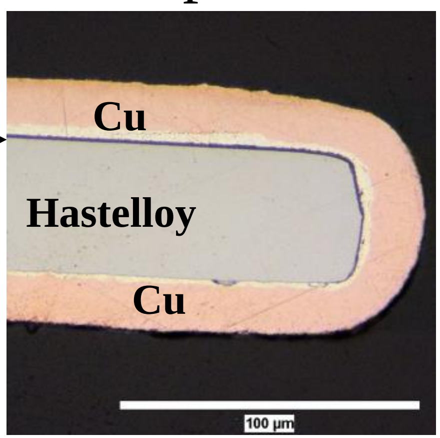
→ Peak temperature versus $\tau_{discharge}$

↑

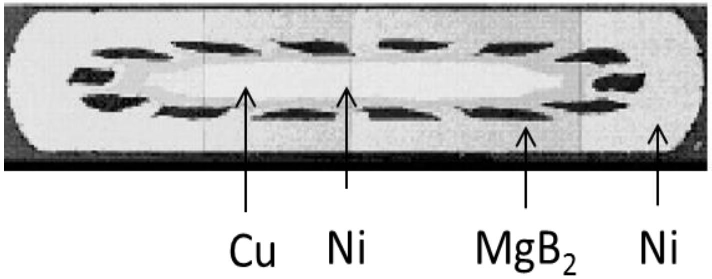
Detection parameters (Voltage)

Protection parameters ($\tau_{discharge}$)

YBCO Tapes



MgB2 conductors

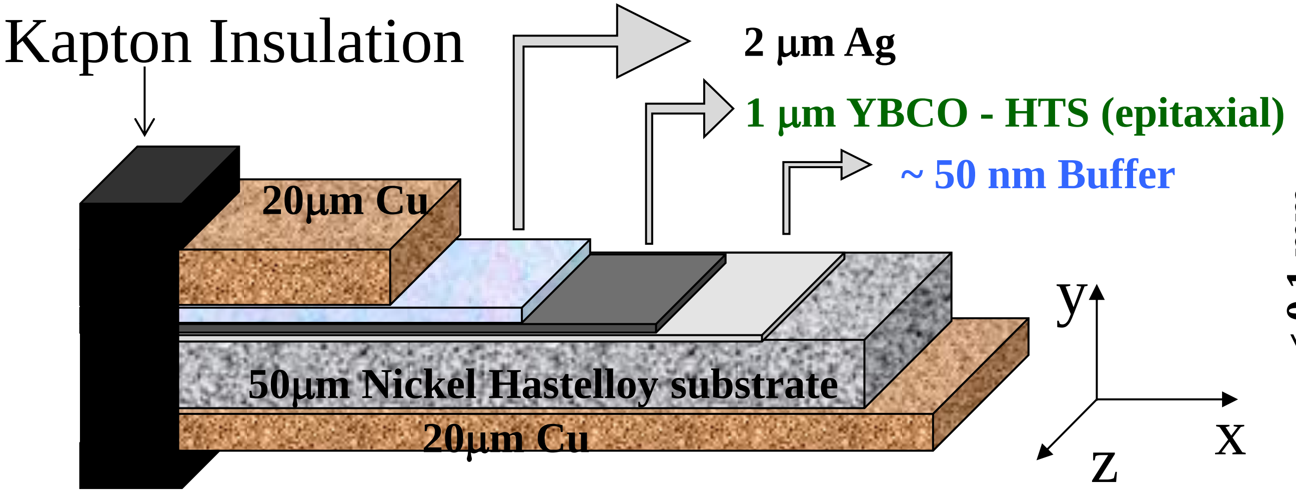


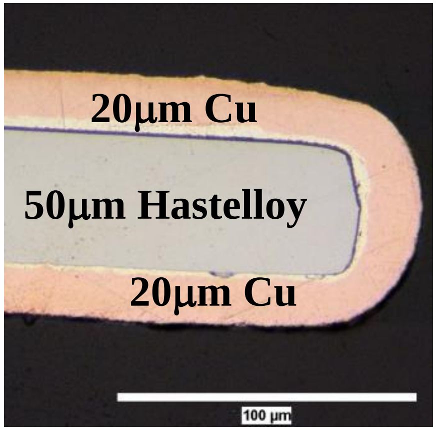
NZPV: Normal zone propagation velocity

MQE: Minimum quench energy

$\tau_{discharge}$: time constant of the discharge

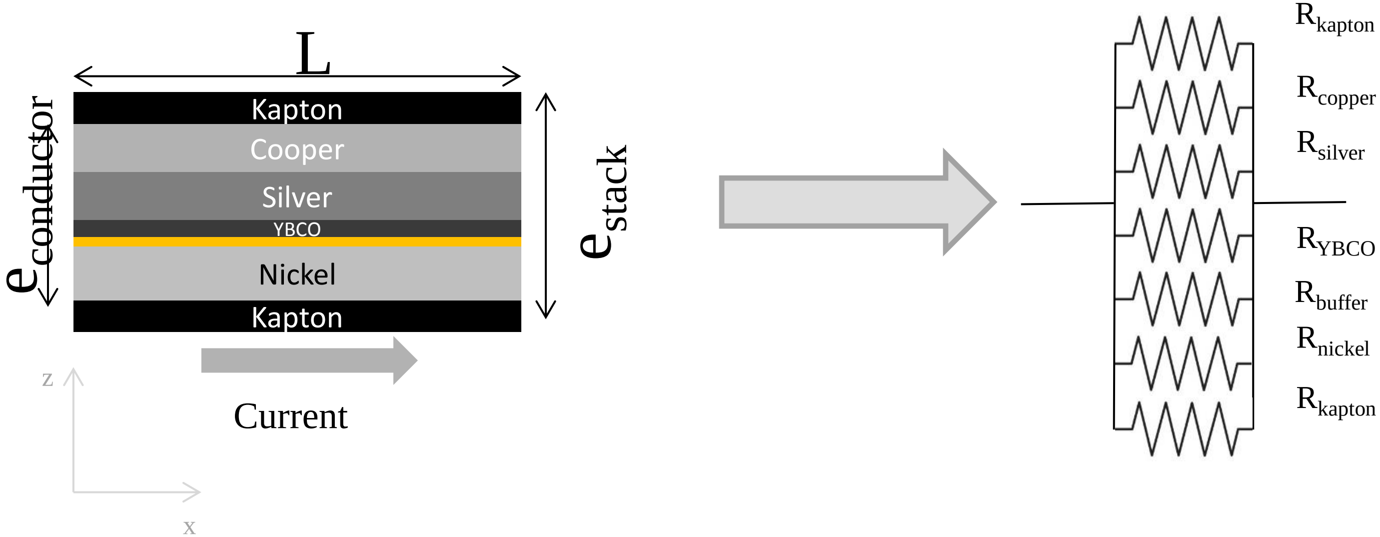
YBCO Tape Configuration



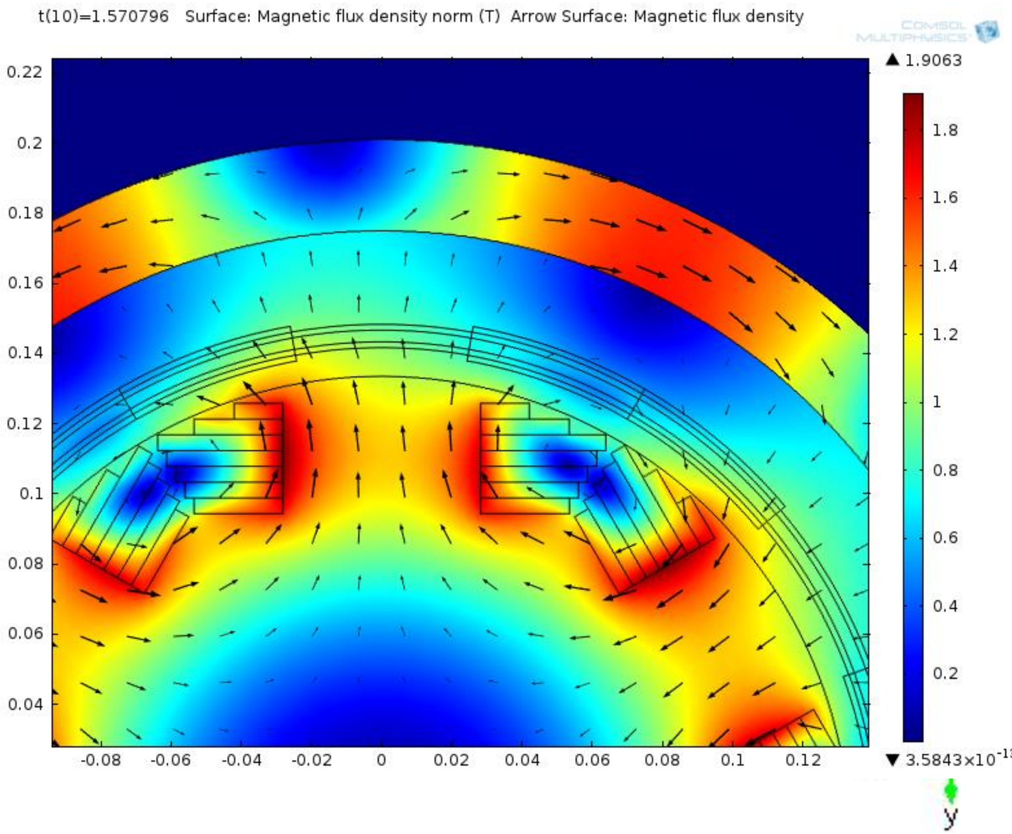


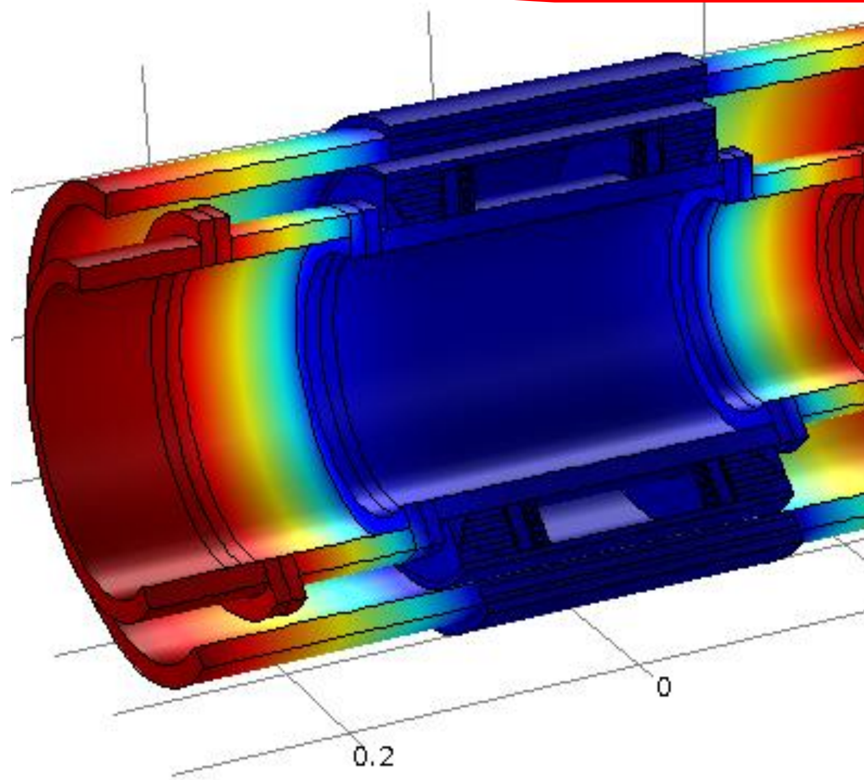
Electrical Properties

- Anisotropic model
- Infinite transversal equivalent resistivity (insulator)
  - Resistivity on x-axis
  - Infinite resistivity on y-axis and z axis (Use of Katpon)



Flux and Temperature Distribution in Superconducting Machine





- Need to consider field distribution and temperature gradient in winding for YBCO equivalent resistivity

YBCO Layer Critical Current

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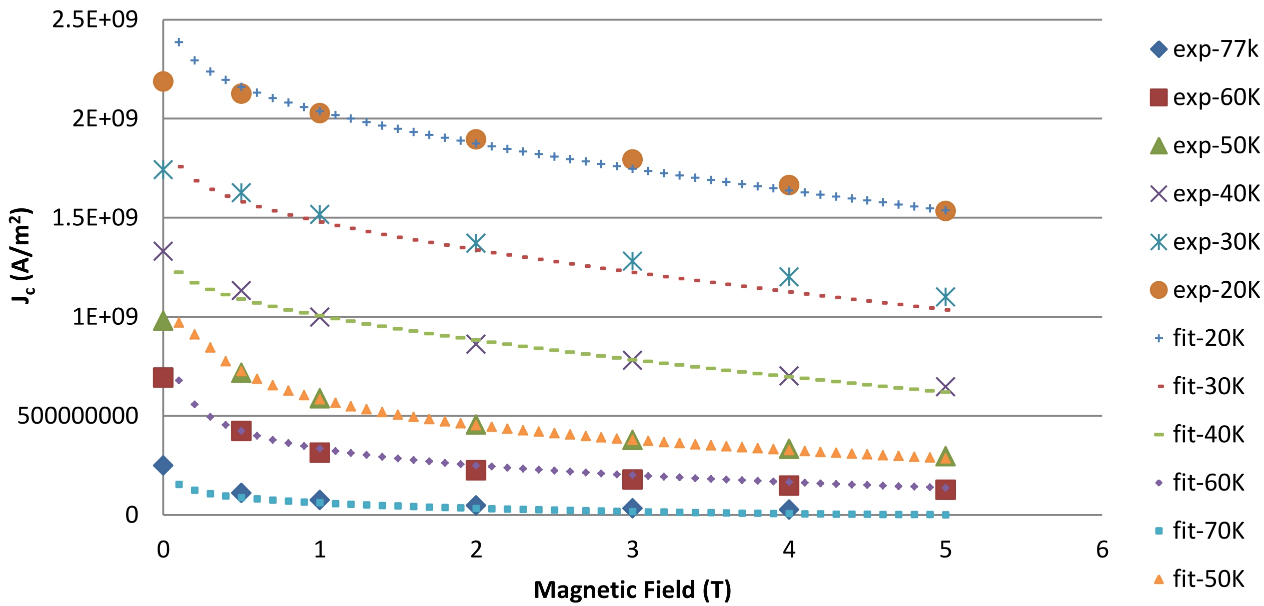
	YBCO T<50K	YBCO T≥50K
Tc(K)	92	92
p	0.95	0.73
q	2.568	1.69
m	1.98	1.98
λ	1.98	1.54
B_{irr0} (T)	88	91
C_0	3.5e7	1e7
E_c (V/m)	10^{-6}	10^{-6}
n	30	30

YBCO Jc(B,T) Scaling Law

$$J_c(B,T) = \frac{C_0}{B} \cdot B_{irr}(T)^m \cdot \left(\frac{B}{B_{irr}(T)}\right)^p \cdot \left(1 - \frac{B}{B_{irr}(T)}\right)^q \text{ A/m}^2$$

with $$B_{irr}(T) = B_{irr0} \cdot \left(1 - \frac{T}{T_c}\right)^\lambda \quad T$$

and $$\rho_{sc} = \frac{E_c}{Jc(B,T)} \cdot \frac{J}{J_c(B,T)}^{n-1} \quad \Omega.m$$

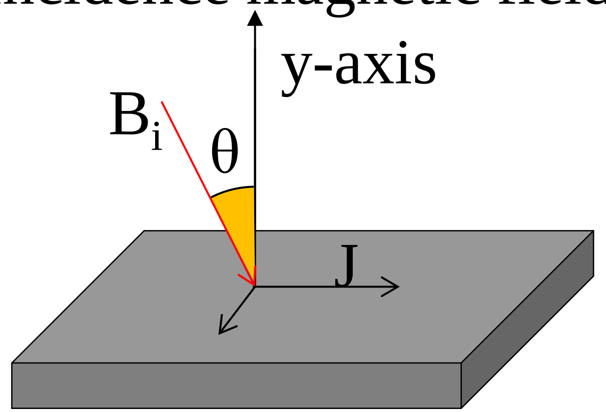


Jc data from SuperPower – 2G HTS Tape w/ Advanced Pinning

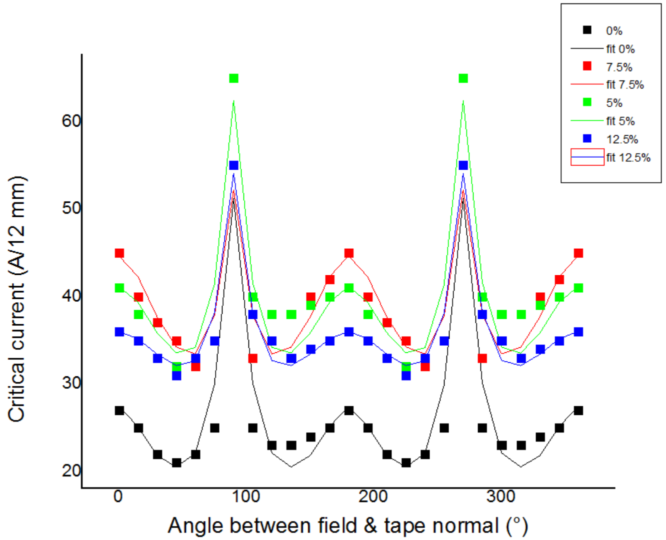
YBCO Jc Dependence on Field Direction

Anisotropic critical current, magnetic field dependency

Incidence magnetic field



Percentage of improved pinning by Zr in YBCO tape



$$J_c(\theta) = J_c(90°).(A.(\cos(\theta)^2 + \gamma^{-2}.\sin(\theta)^2)^{-\frac{1}{2}} + B.(\cos(\theta)^2 + \beta^{-2}.\sin(\theta)^2)^{-\frac{1}{2}})$$

J_c: Critical current density (A/m^2)
B_i: Incidence magnetic field (T)

Fit values for 0% Zr doping	
A=5.97	γ=7
B=21.39	β=0.438

Electrical Equivalent Properties

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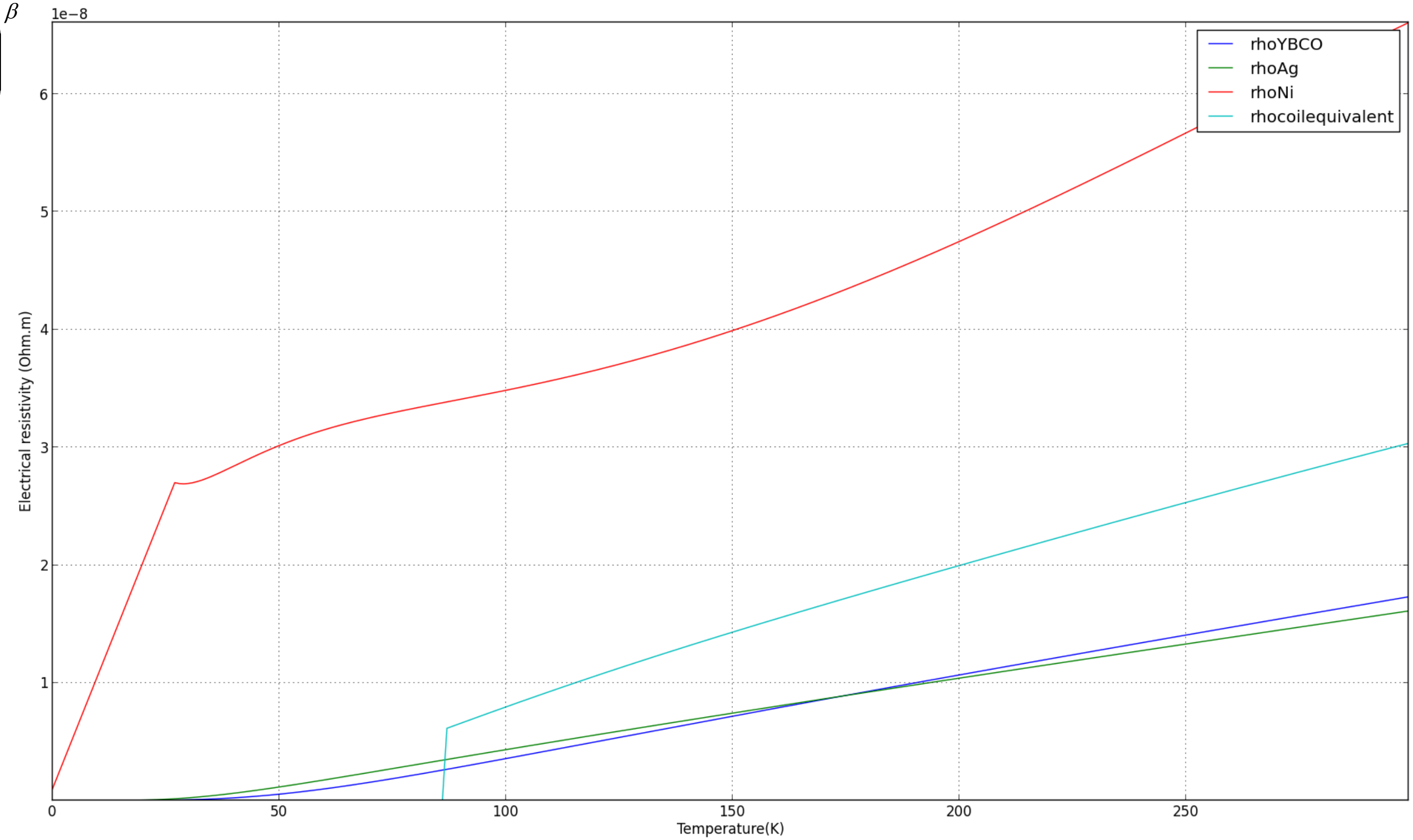
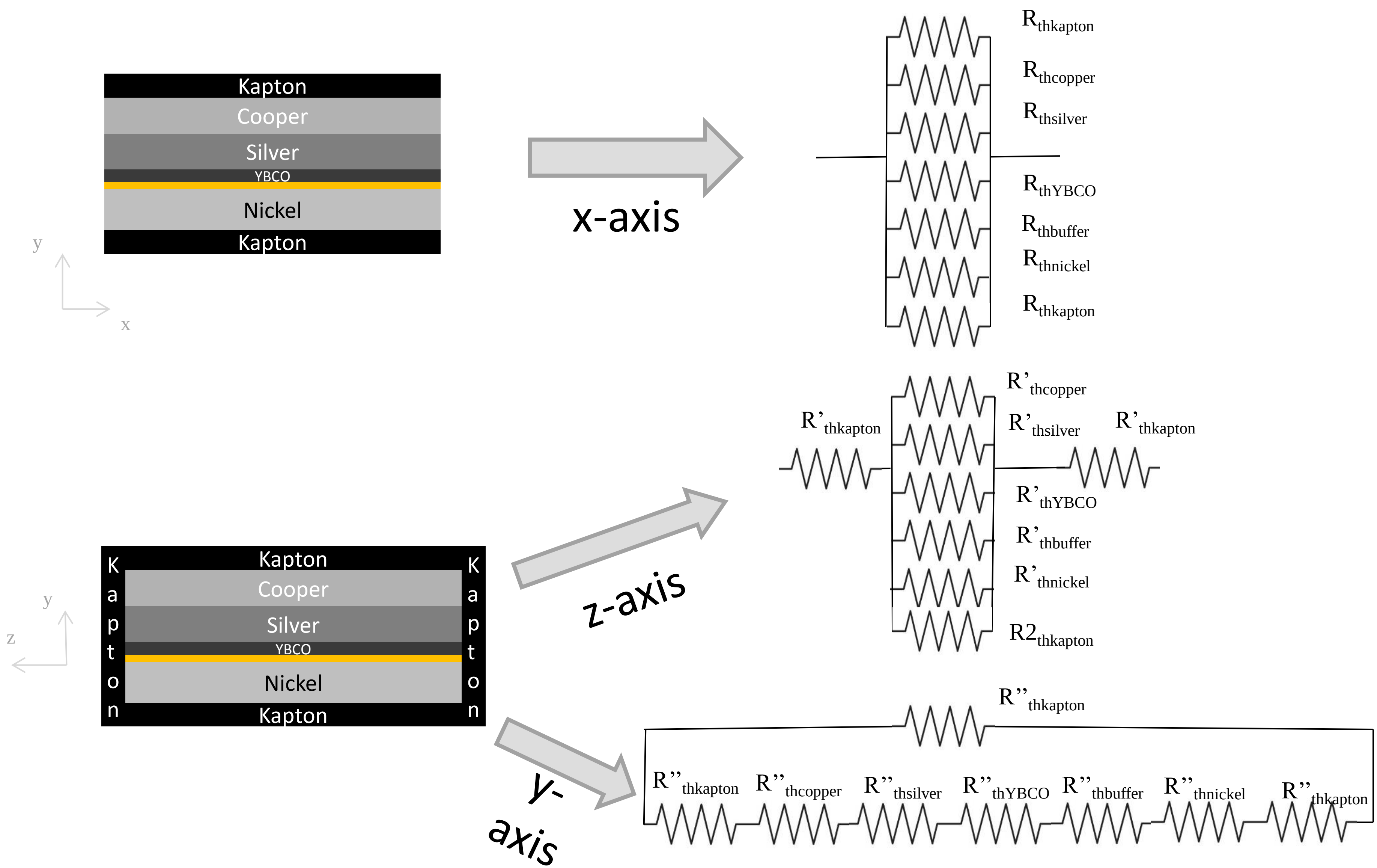
- Example of electrical resistivity of material and coil for J/Jc = 0.6, no field

$$\sigma_{YBCO} = \frac{E_c}{J_{c0}(\theta,T)\frac{B_0}{|B|+B_0}}\left(\frac{J}{J_{c0}(\theta,T)\frac{B_0}{|B|+B_0}}\right)^{1/n(T,B)}$$

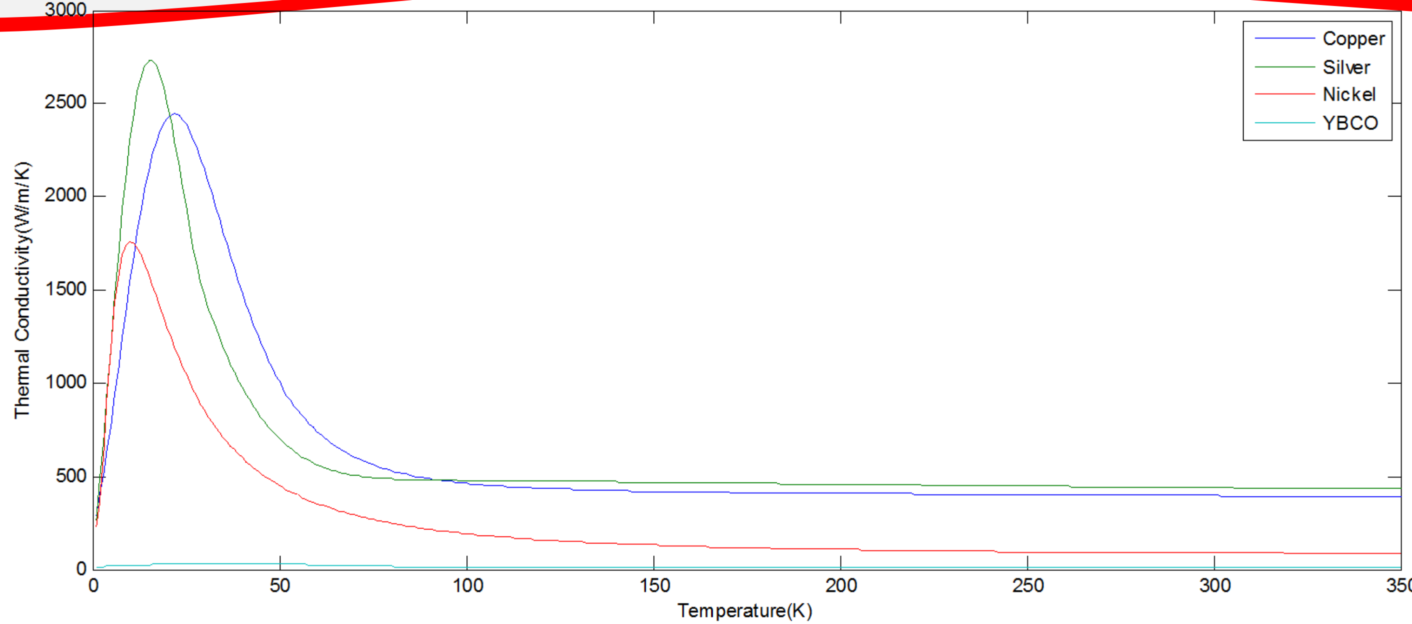
$$J_{c0}(T) = \alpha\left(1-\frac{T}{T_{c0}}\right)^{\beta}$$

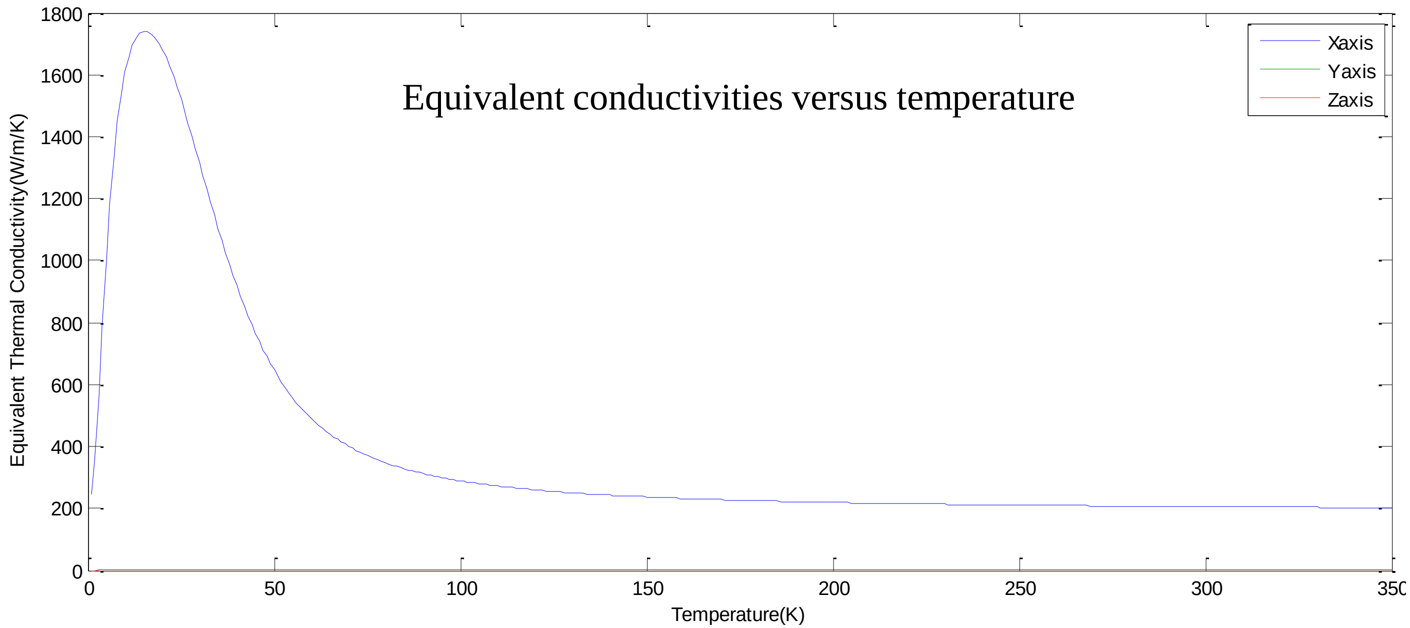


Equivalent Thermal Properties



Thermal conductivities





Equivalent Heat Capacity

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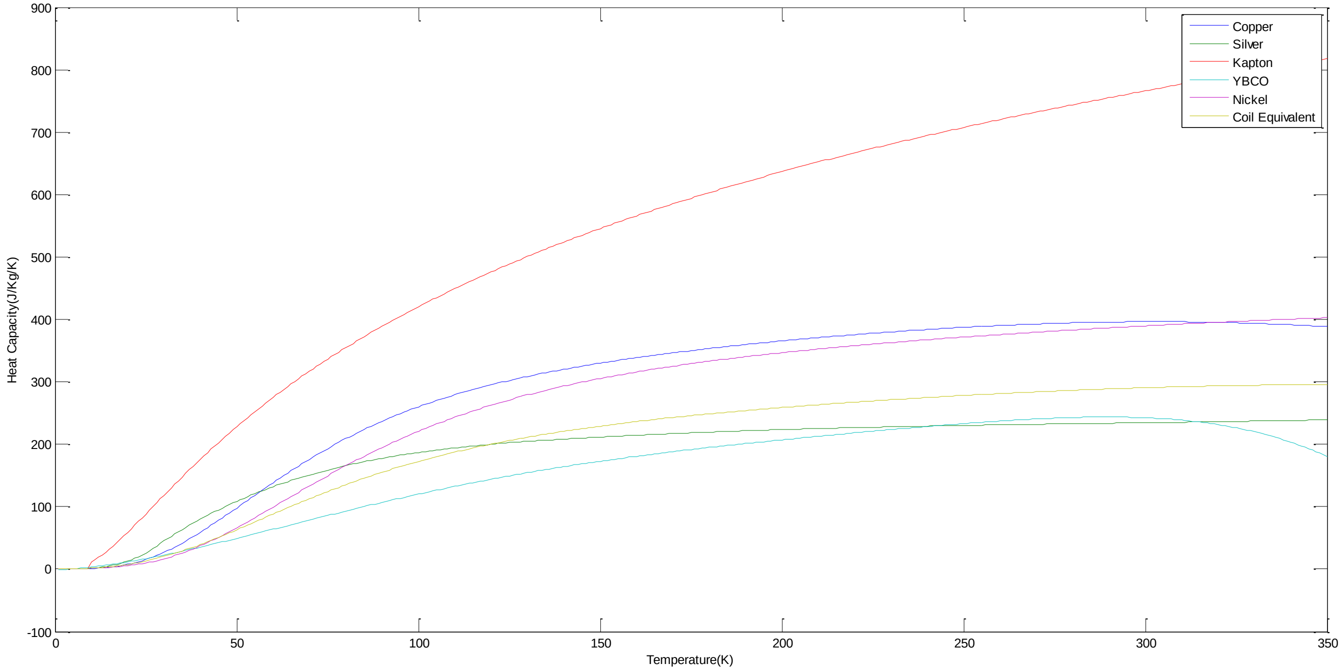
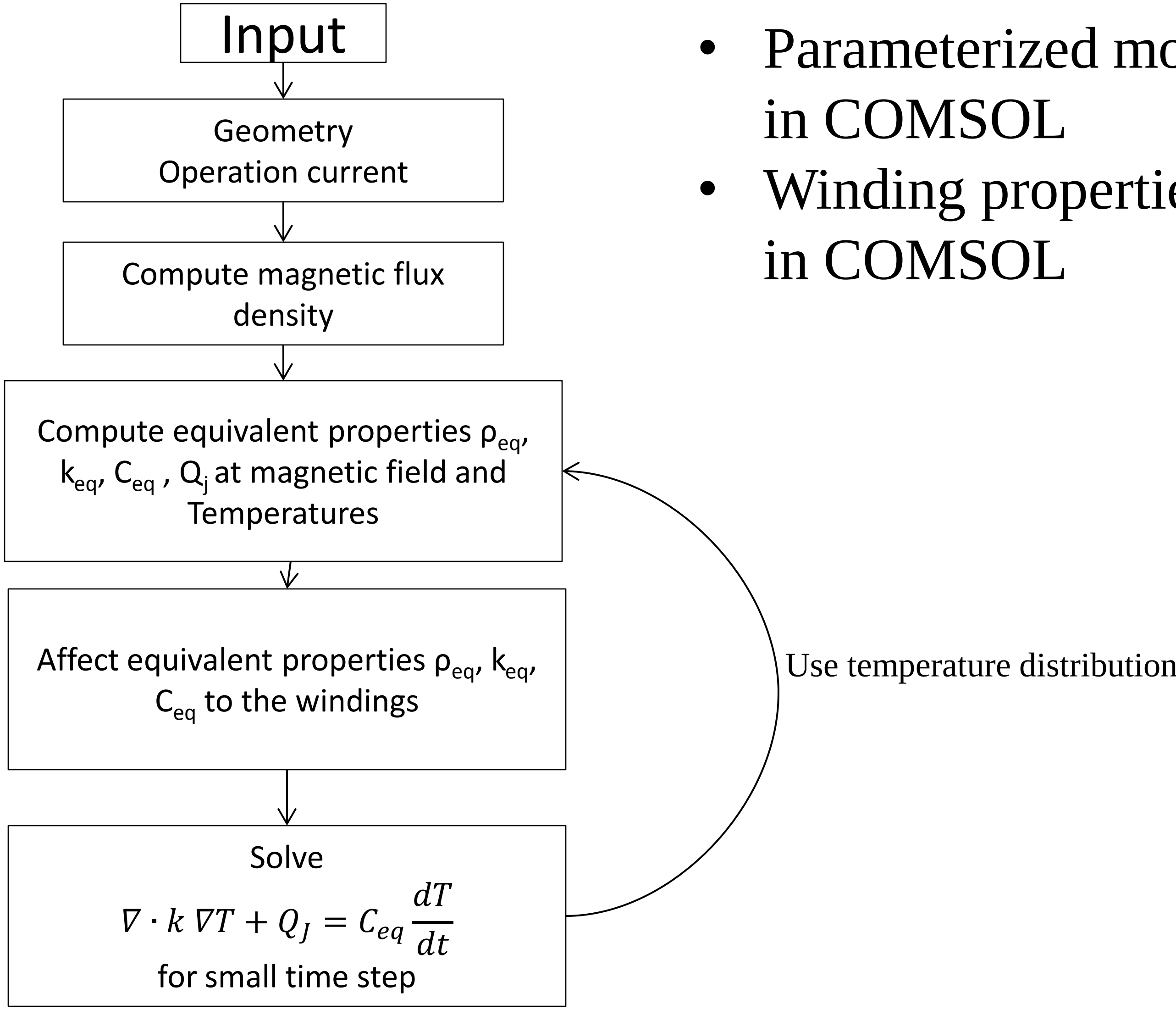
- Heat capacity:

$$C_{eq} = \frac{\sum m.C}{\sum m}$$

C_{eq}: equivalent heat capacity (J/Kg/K)
C: heat capacity of layers (K/Kg/K)
m: mass of layers (Kg)

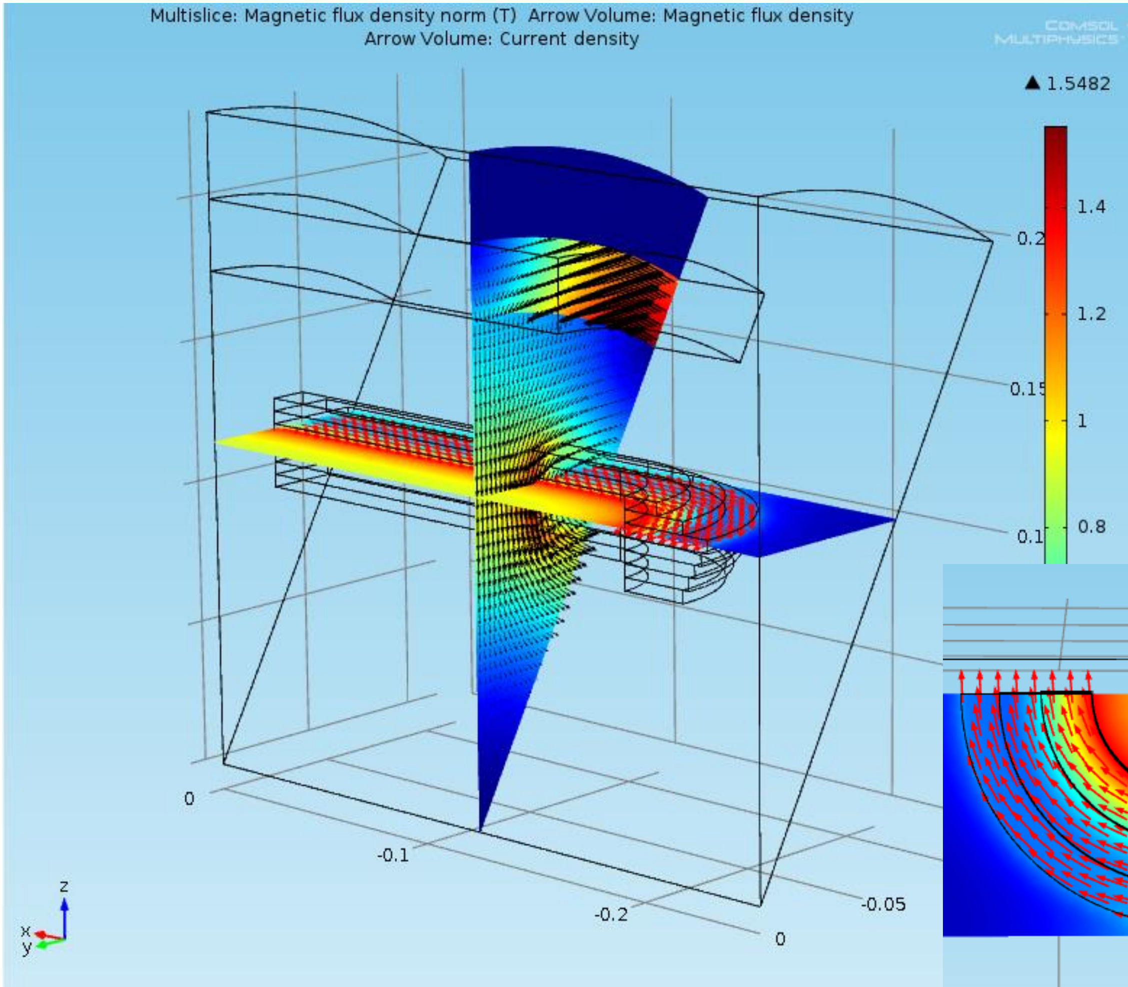


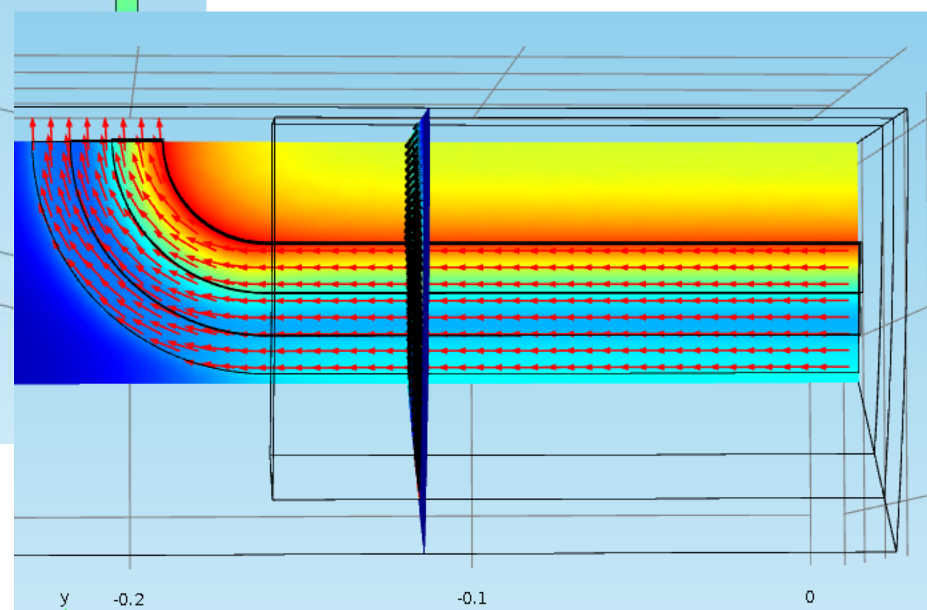
COMSOL Computational Model



- Parameterized model implemented in COMSOL
- Winding properties are calculated in COMSOL

Magnetic Flux Density Distribution



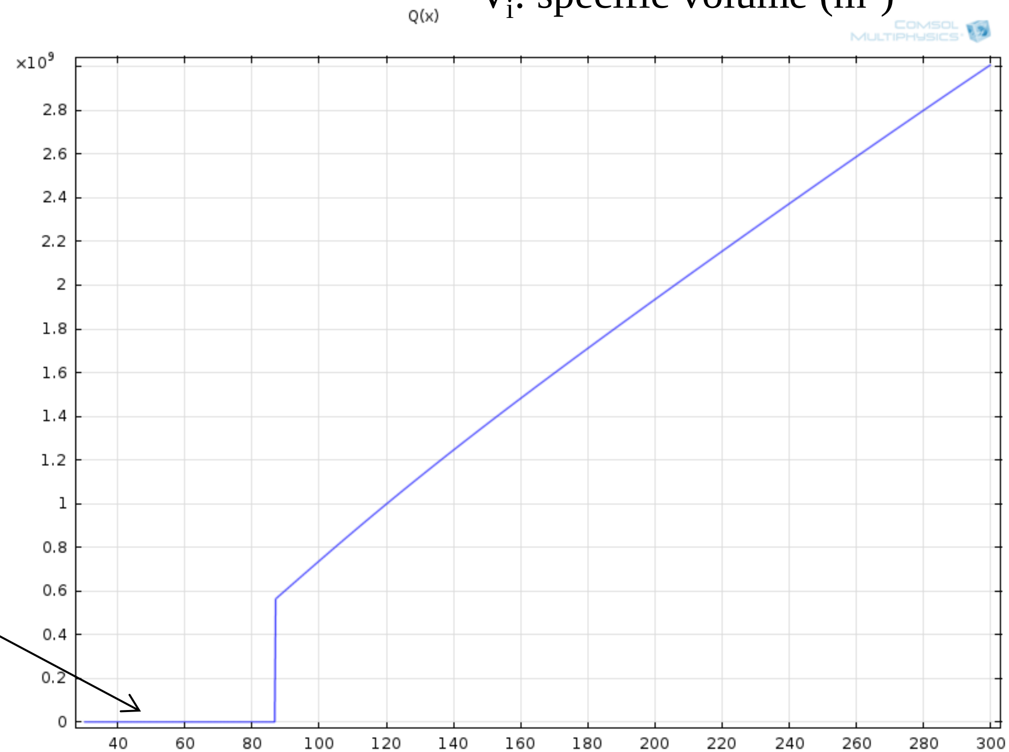


Coil heat source

$$Q_J = \frac{1}{V_i} \iiint_{V_i} E(t).J(t)dv = \frac{J_{operating}^{\;2}}{\sigma_{coil}(T,B)}$$

With:
- $J_{operating}$: operating current density (A/m^2)
- σ_{coil}: equivalent conductivity of the coil (S/m)
- P_j: Joule losses in the coil (W/m^3)
- V_i: specific volume (m^3)

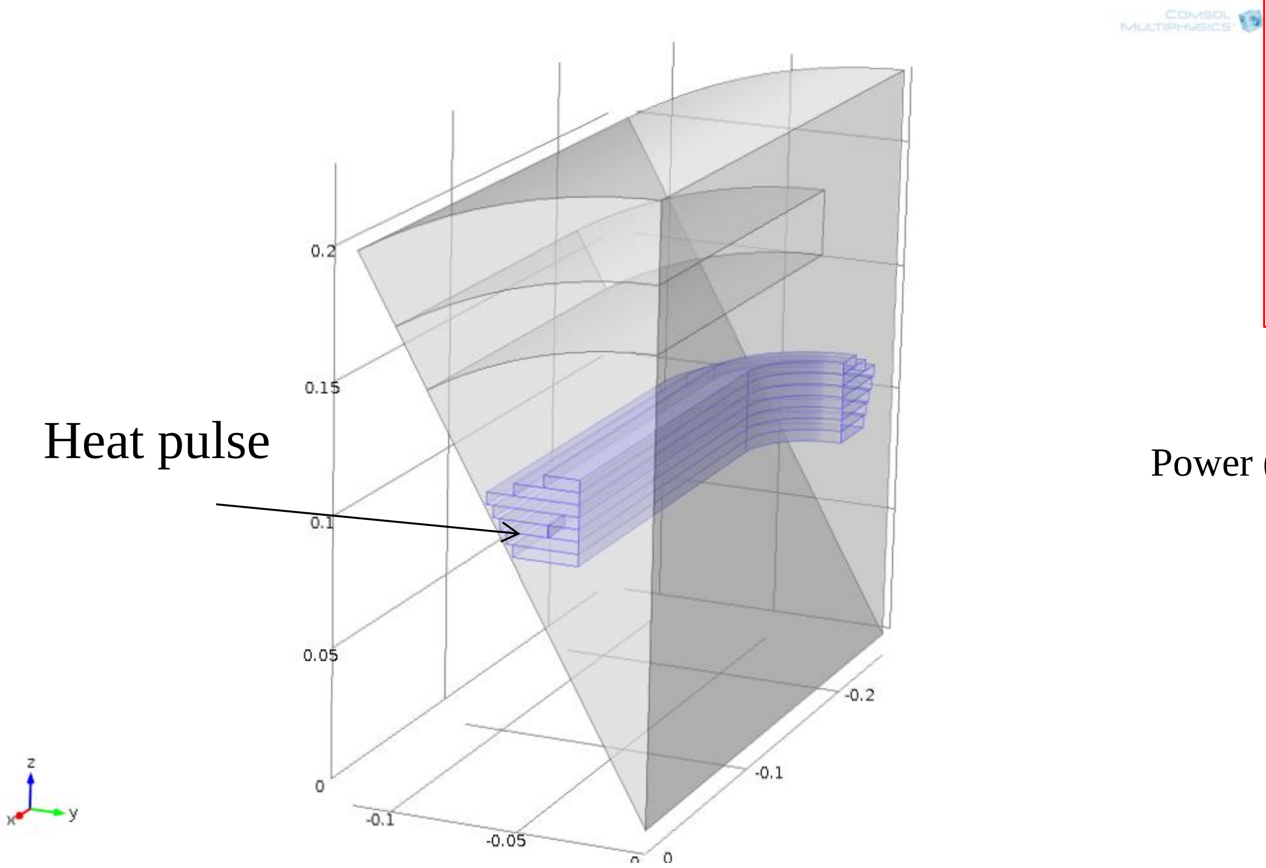
Superconducting state



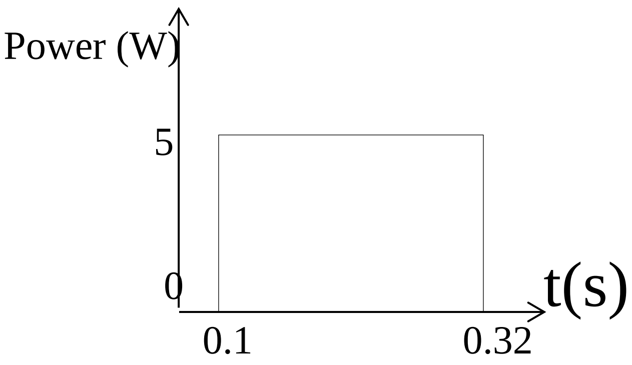
Joule losses versus temperature at constant magnetic field (1T)

Thermal model

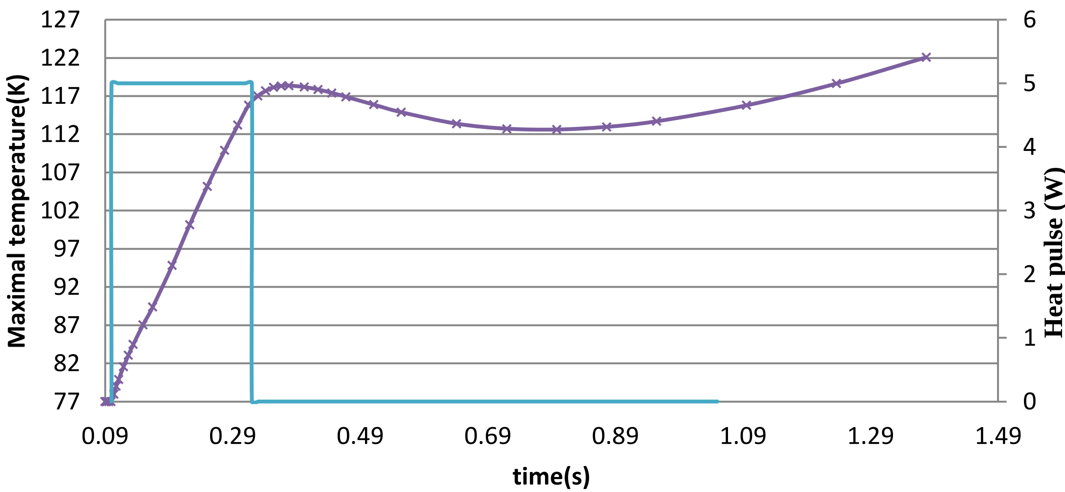
- Cooling from inner pole surface (heat exchange coefficient)
- Joule losses in the winding as Heat source

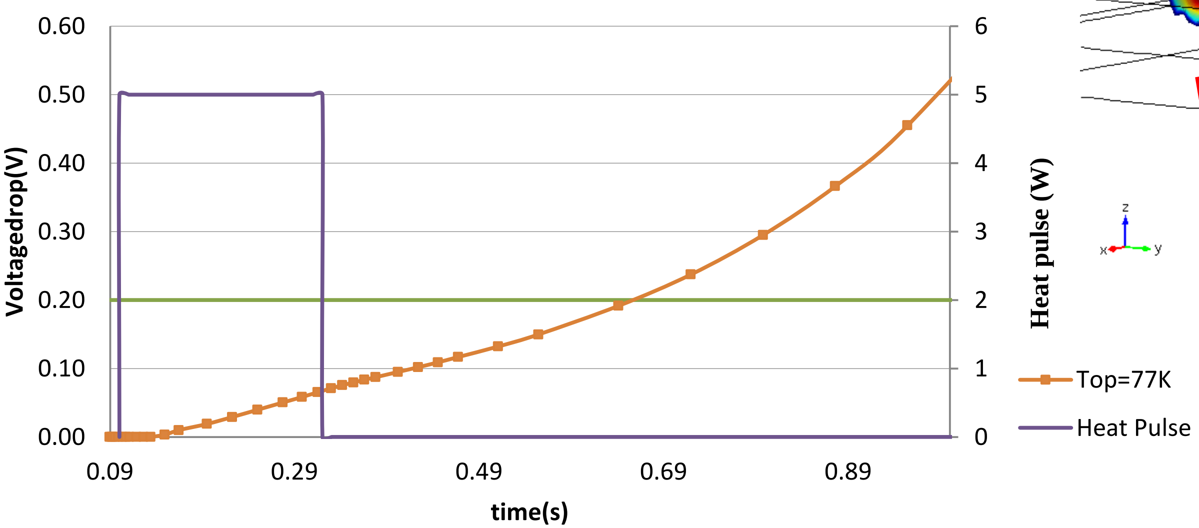


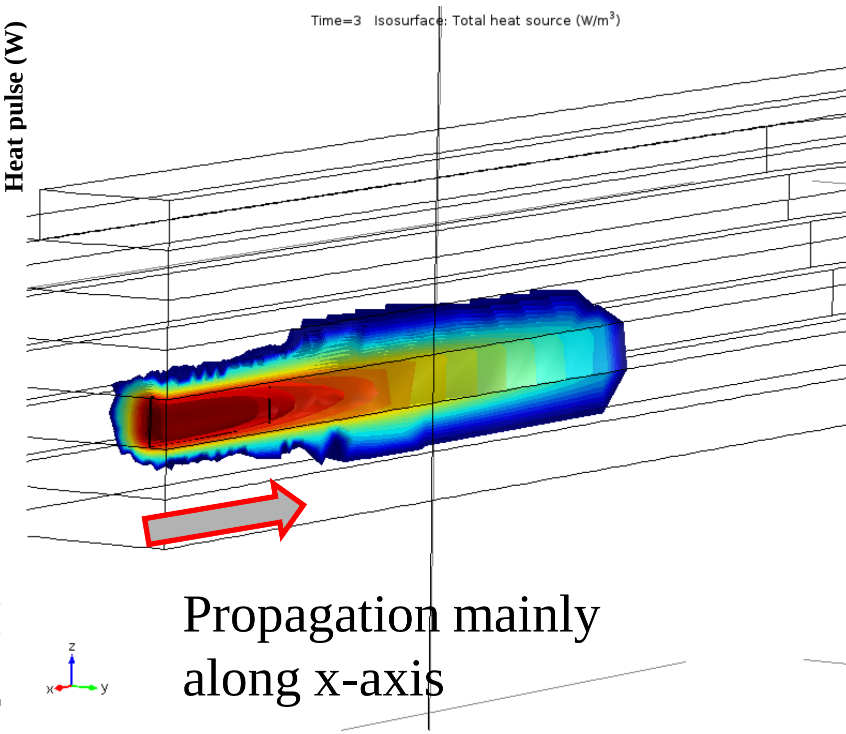
Heat source:
- Rectangle pulse
- Start time: 0.1s
- Duration 220 ms
- Value ≈ 5 W at 77K



Example of Quench Simulation at 77 K







Propagation mainly along x-axis

Normal Zone Propagation Velocity

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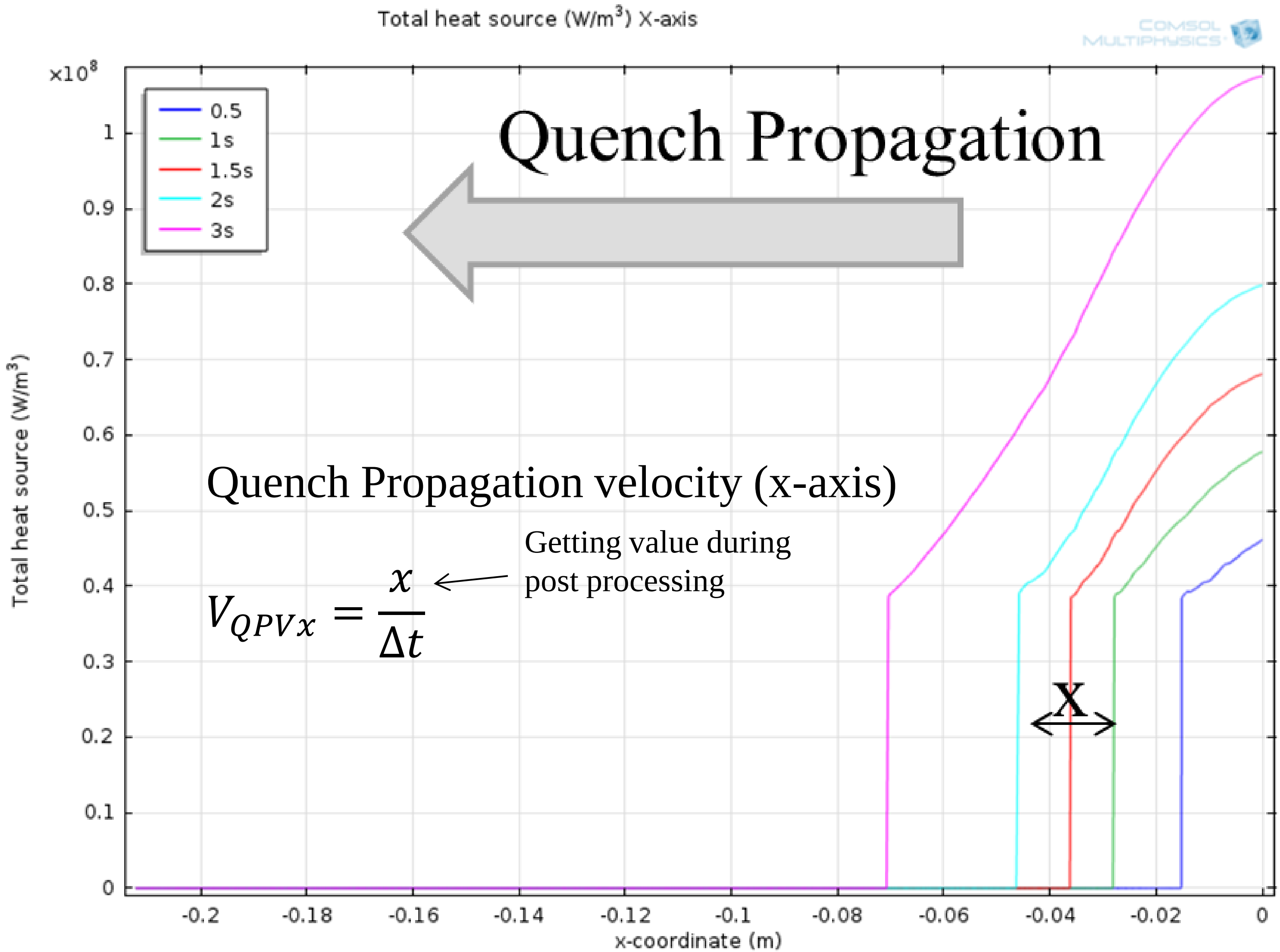


$$V_{QPVx} = \frac{x}{\Delta t}$$

Quench detection

Voltage probe
if V< $V_{threshold}$
then 0
else
then 1

→

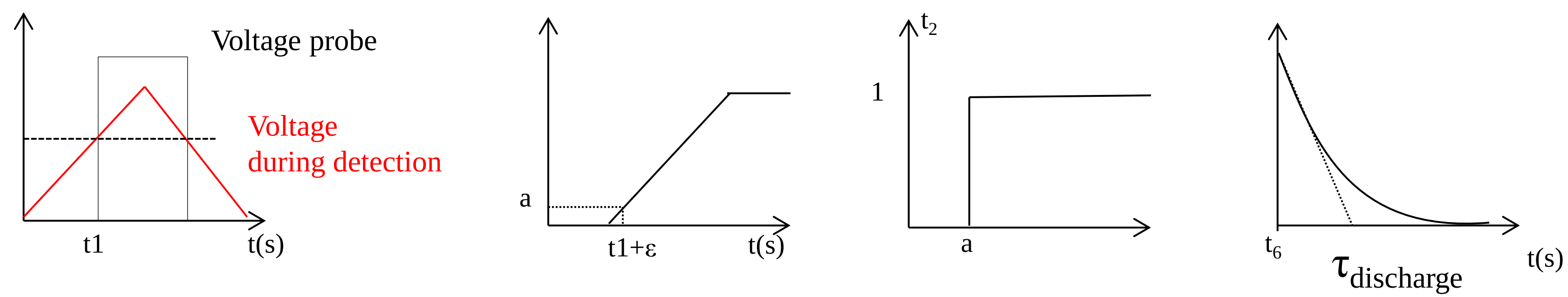
Integration of the voltage probe

→

Step to trigger coil discharge

→

Total heat source time exponential decrease:
$$\exp\left(-\frac{(t-t_6)}{\tau_{discharge}}\right)$$



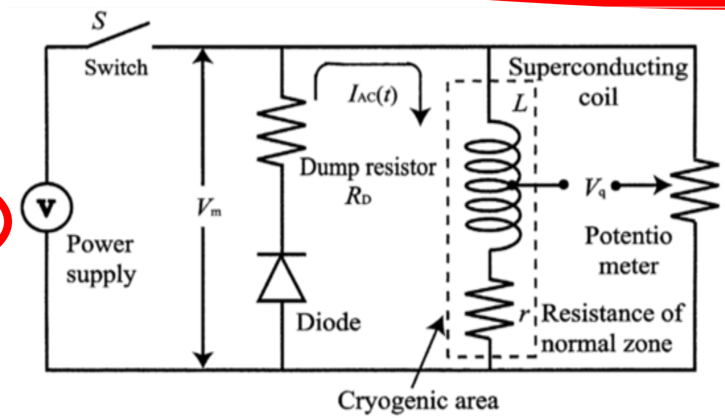
With $\tau_{discharge} = \frac{L}{R}$ the discharge time constant

L the inductance of the winding, R: the dump resistance

And $t_6 = \int (t_2 < 1)dt$

Example of Quench Simulations

- Voltage detection
  - Threshold: **400 mV**
  - Current discharge time constant: **0.5 s**



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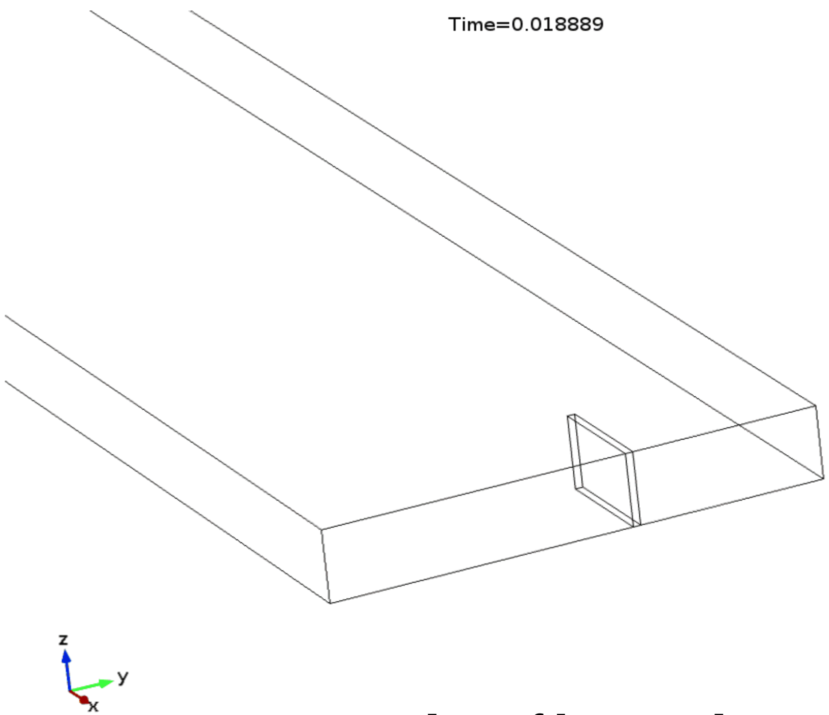
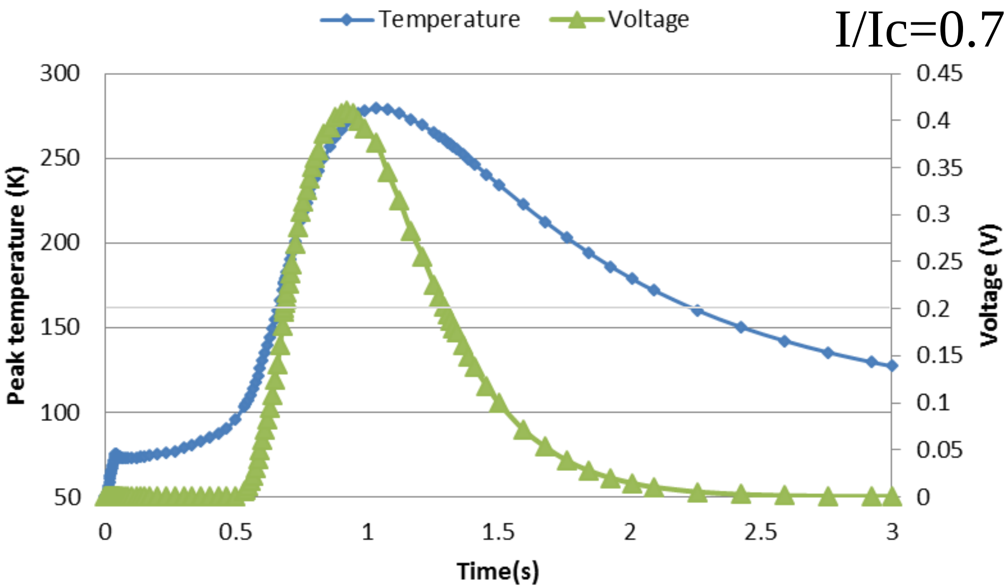


Top: 50 K
I/Ic=0.7



Pulse of heat induces quench in winding

Minimum Quench Energy

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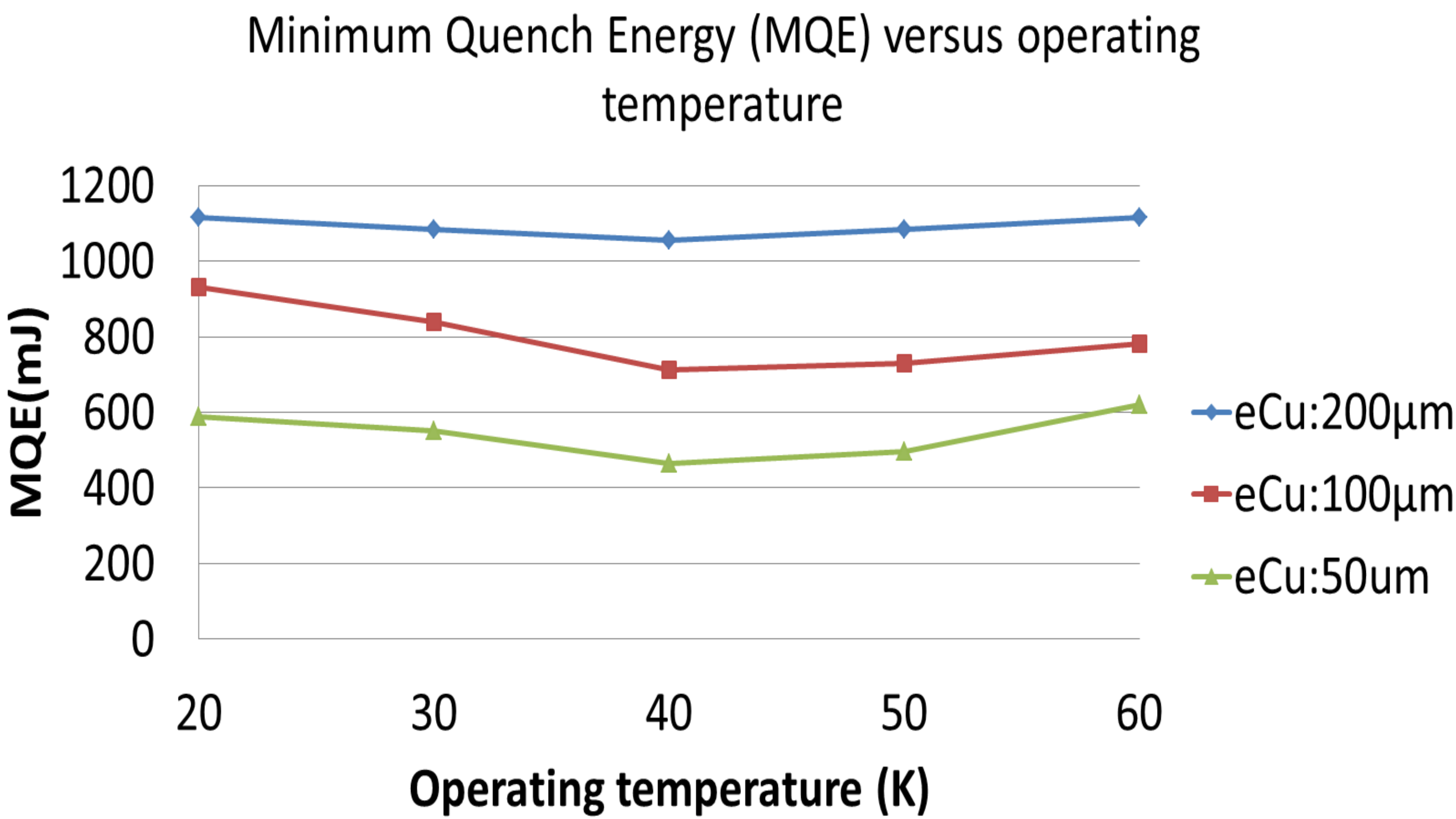

Temperature Profiles for Different Discharge τ

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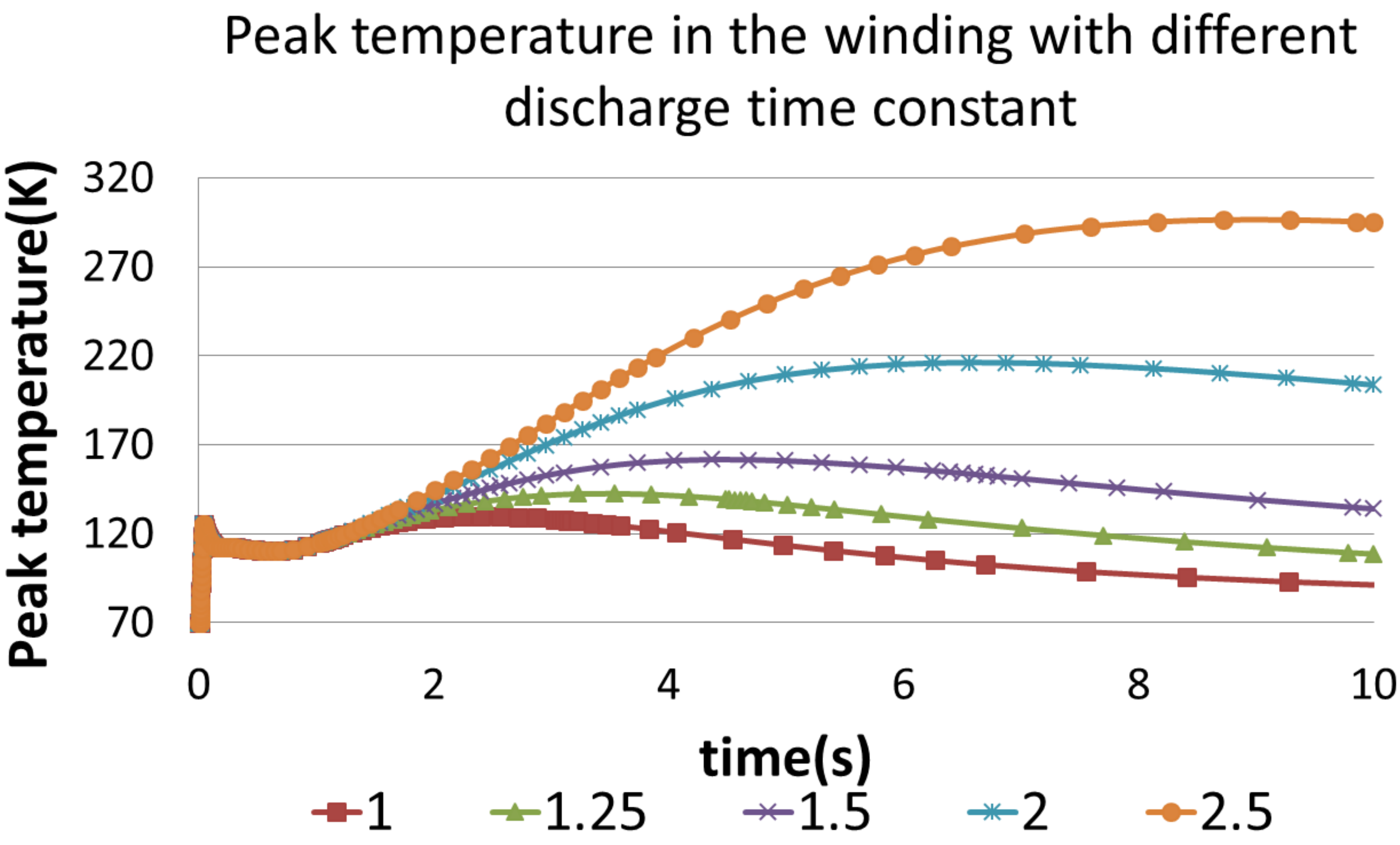
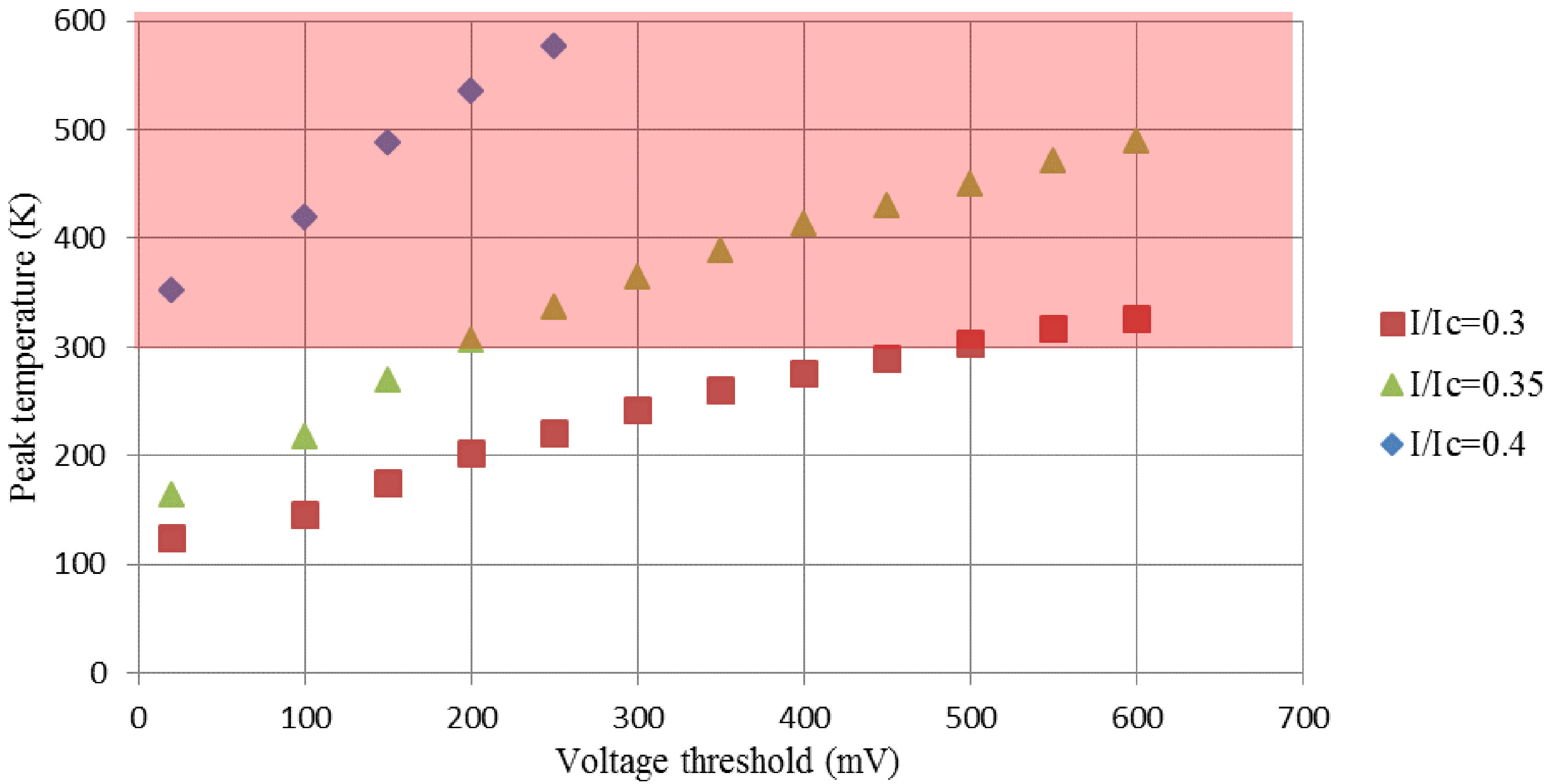
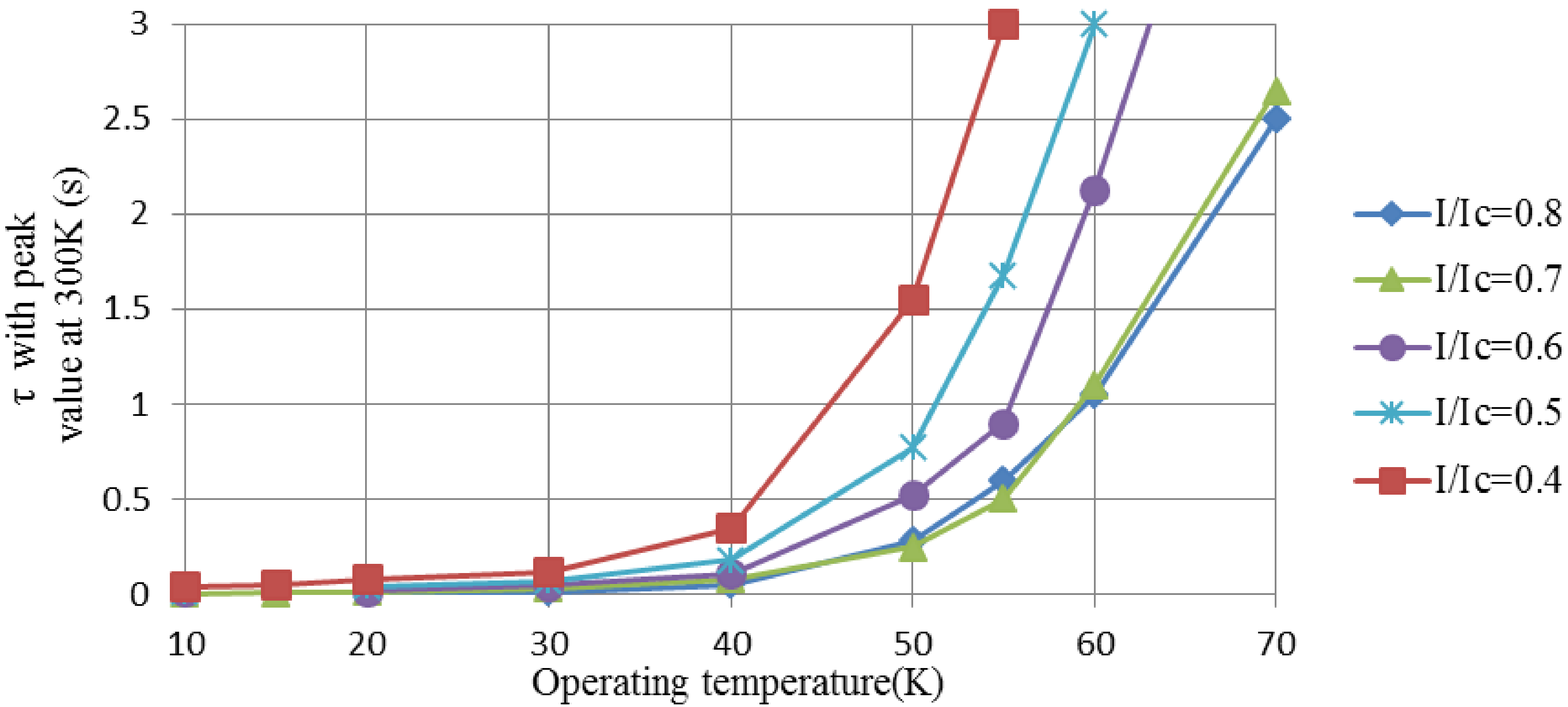


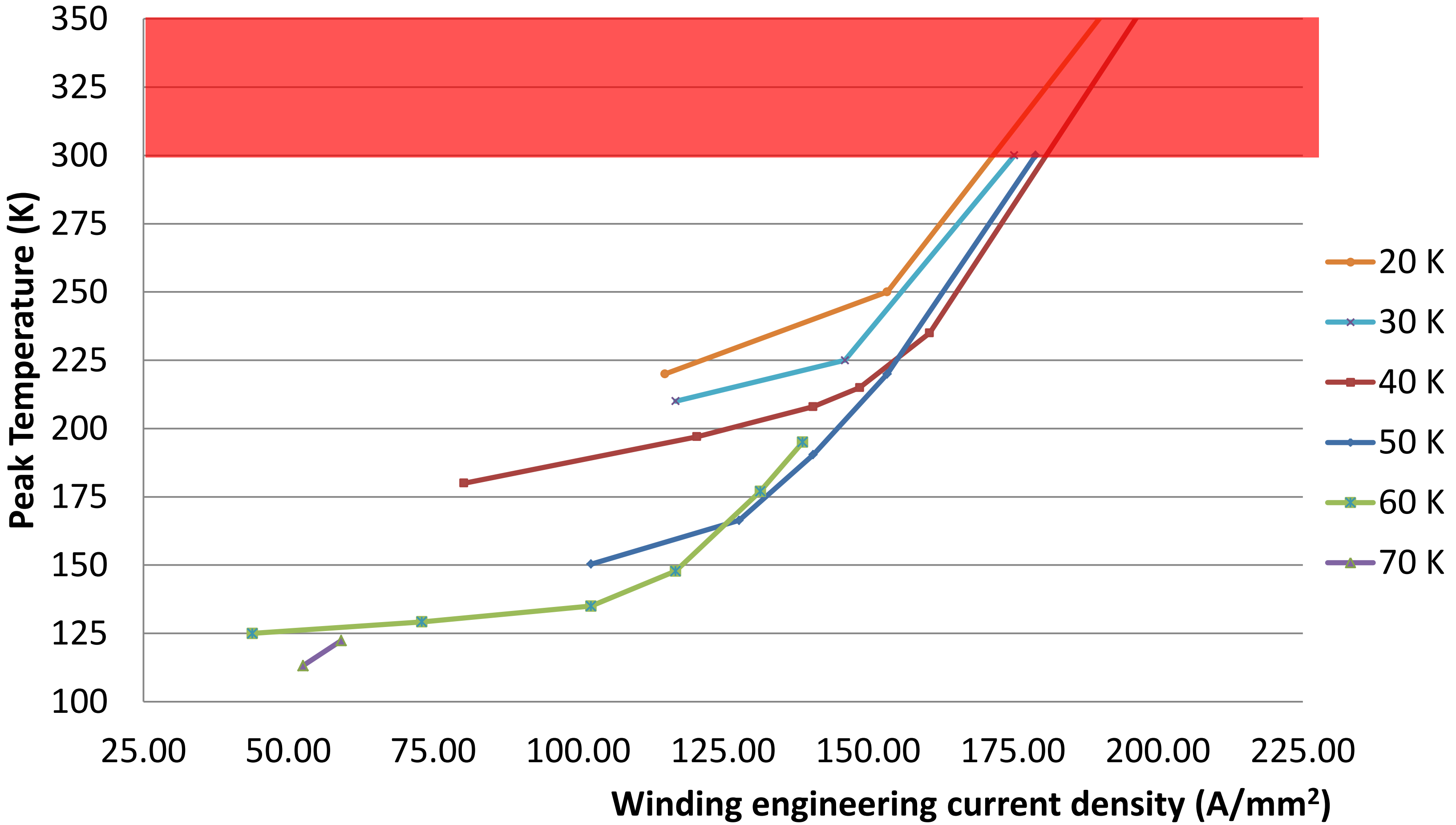
Impact of Detection Threshold on Peak Temp.



Impact of I/Ic on the Discharge Time Constant



Peak Temperature vs. Je



Influence of Copper Content on Coil Performance

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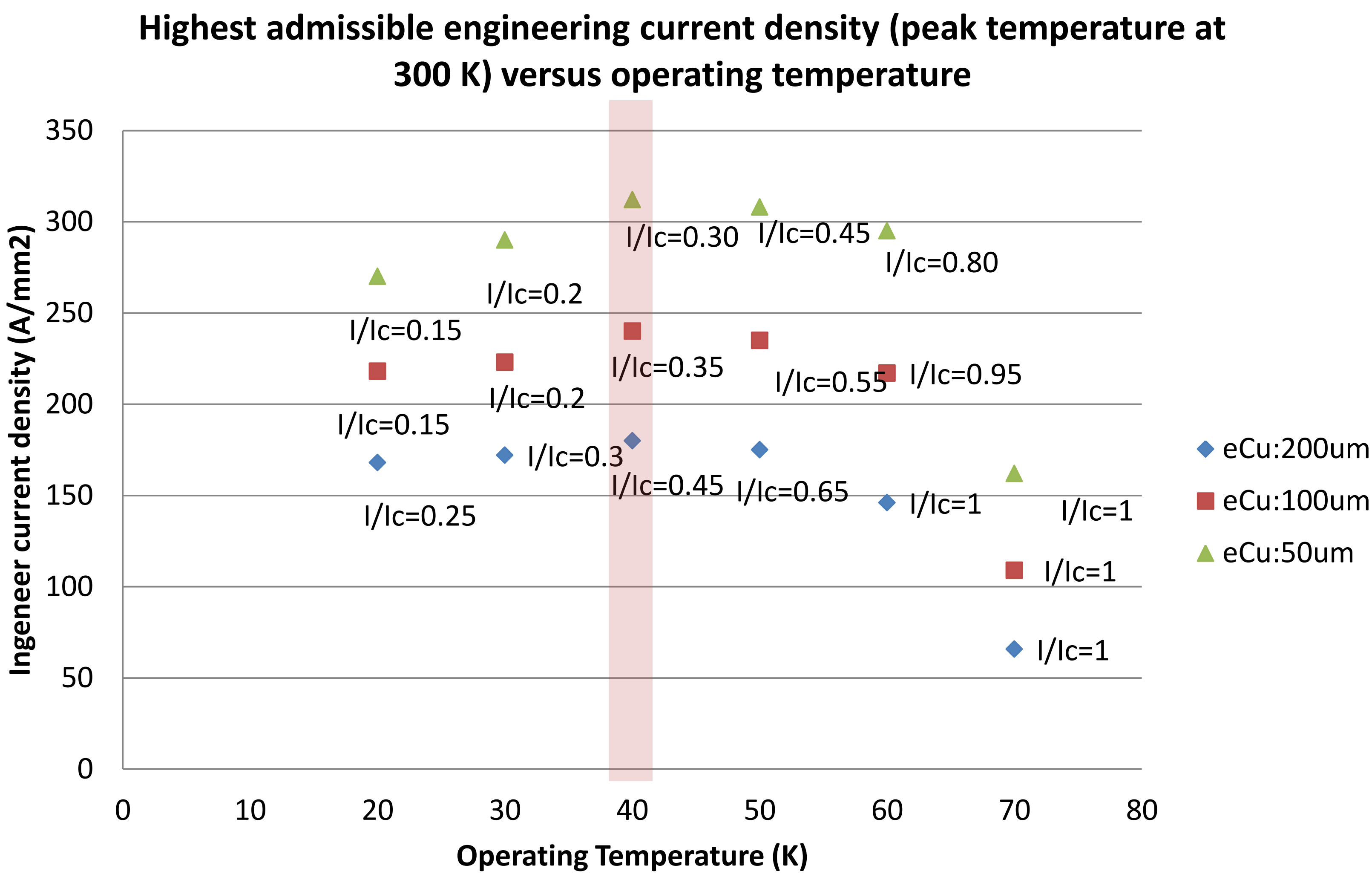

Influence of Copper Content on Coil Performance (40K)

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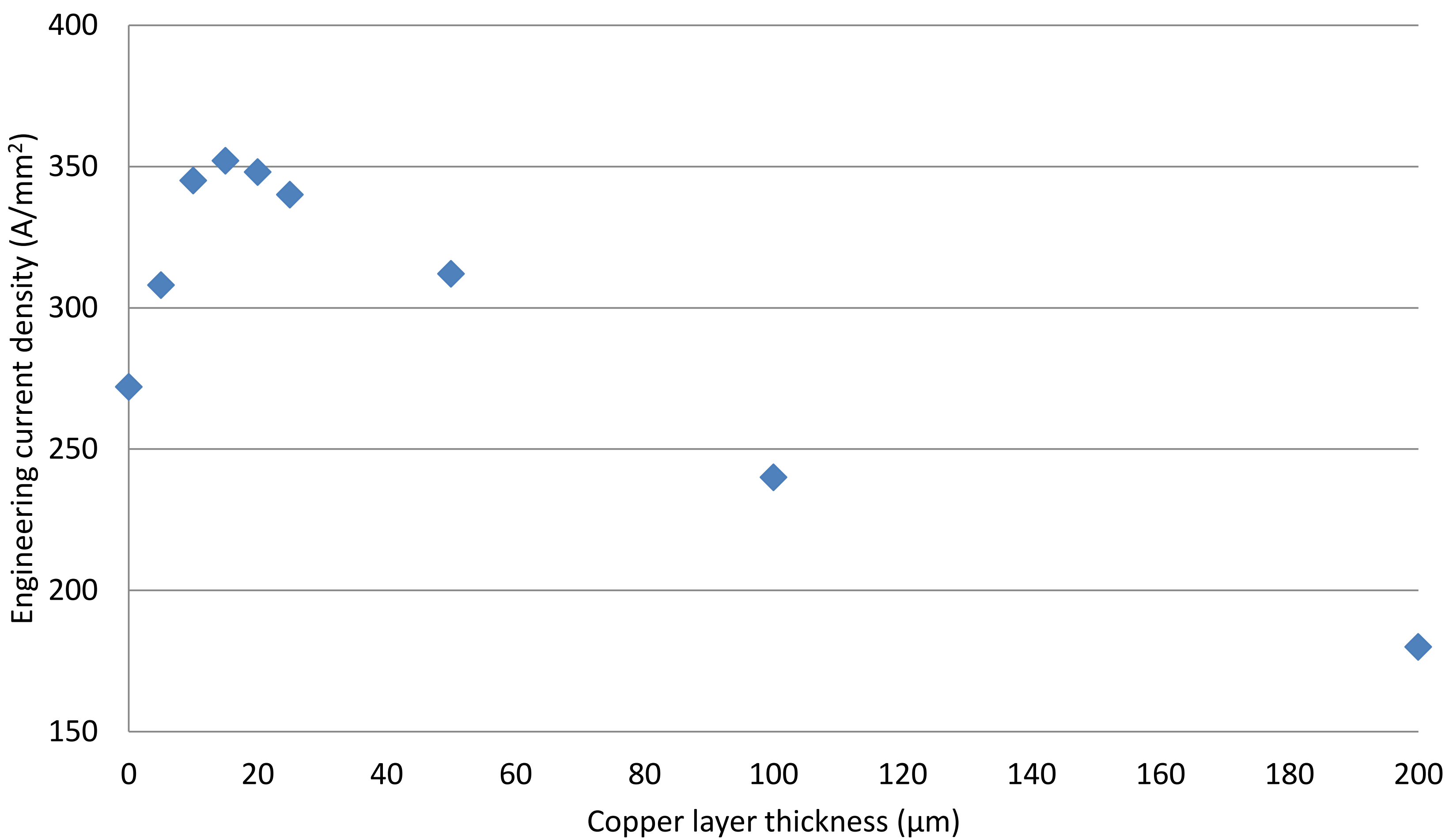

15 µm copper layer thickness leads to the highest engineering. current density in the winding

Summary and Perspectives

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- Parameterized model developed for YBCO
  - Quench behavior can be estimated from
    - Materials composing winding
    - Jc(B,T) characteristic of the superconductor
    - Voltage detection threshold
    - Discharge time constant
- Python code is being generated based on simulation results and will be implemented in Amber
  - Quench protection will be used as additional constrains for the machine design

- More data needs to be generated to extract response surface
- Need coupling with external electric circuit model
  - magnetic coupling, quench back

- Development of an in house flexible tool independent from FEA commercial packages is being considered