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ELÚ
SAV

Modeling of Electro-Thermal Quench of a REBCO Superconducting Coil for Aircraft Propulsion Motors

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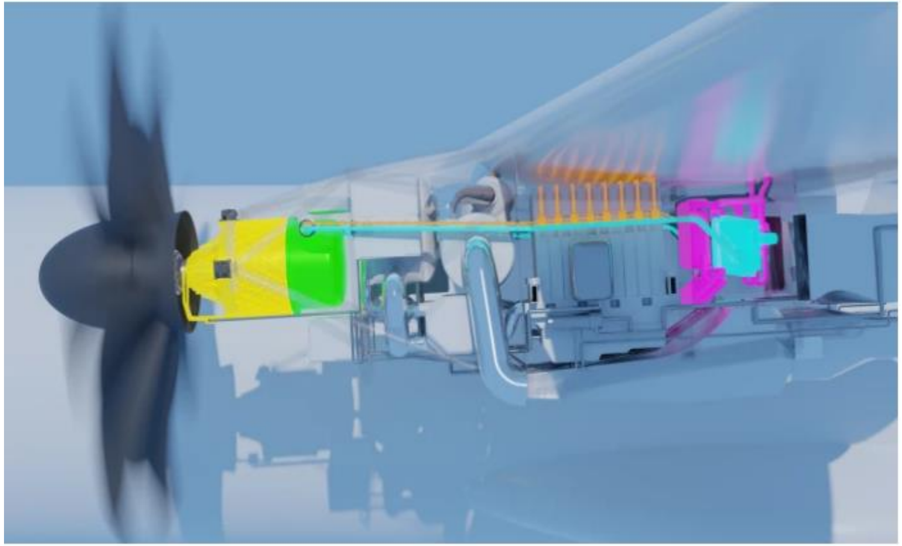
HTS Motors for Aviation in Hydrogen Electric Aircrafts

- High power-over-weight ratio
- Improved Efficiency
- Compact Size
- Higher Torque
- LH_2 is used as fuel and coolant



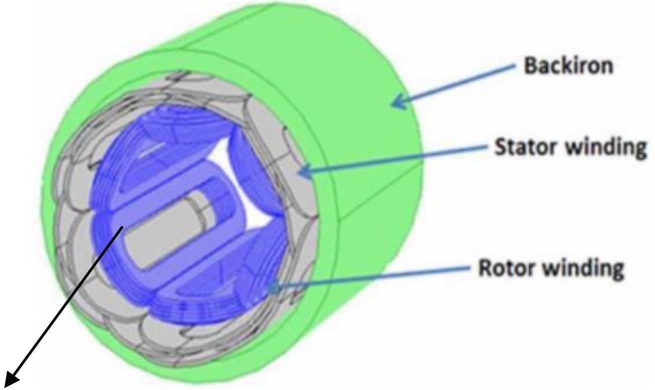
CRYOPROP Project

- Superconductor motors:

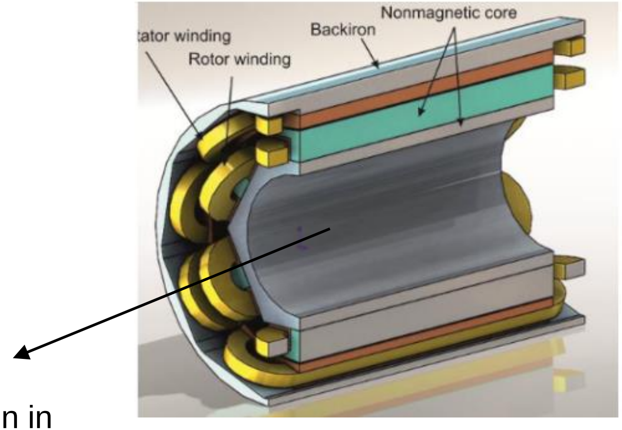
  racetrack coils

- Reduced Iron:

  compared to conventional motors



Racetrack coil



Reduced iron in superconducting motor

K. Kovalev et. al. 2019, J. IEEE

- Modeling methods
- Studied configuration
- Varying short-circuit voltages
- Conclusion

- **Modeling methods**
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Modeling Methods

Minimum Electro-Magnetic Entropy Production (MEMEP)

- Electro-Magnetic behavior

$$\mathbf{E}(\mathbf{J}) = -\frac{\overset{\overset{\text{Vector potential}}{\uparrow}}{\partial \mathbf{A}}}{\partial t} - \nabla\varphi \longrightarrow \text{Scalar potential}$$

$$\nabla.\mathbf{A} = 0, \text{also}$$
$$\mathbf{A} \dashrightarrow 0 \text{ at } \mathbf{r} \dashrightarrow \infty$$

Coulomb's gauge

Electro-Magnetic Behavior

Solving the equation is same as minimizing the functional

Vector potential due
to current density

Vector potential due
to applied field

J at previous
time step

$$L[\Delta\mathbf{J}] = \int_V dV \left[\frac{1}{2}\Delta\vec{\mathbf{J}}.\frac{\Delta\mathbf{A}_J}{\Delta t} + \Delta\mathbf{J}.\frac{\Delta\mathbf{A}_a}{\Delta t} + U(\mathbf{J}) + \nabla\varphi.(\mathbf{J}_0 + \Delta\mathbf{J})\right]$$

E. Pardo, M. Kapolka, J. Comp. Phys. 2017

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E(J) Power Law

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

$$U(\mathbf{J}) = \int_0^{\mathbf{J}} \mathbf{E}(\mathbf{J}').d\mathbf{J}'$$

E. Pardo, M. Kapolka, J. Comp. Phys. 2017

Benefits of MEMEP

- Self-programmed software in C++
- Considers screening currents
- Easily take voltage input
- Highly efficient and robust
- Order of magnitude faster compared to commercial software

Thermal Response

Temperature dependent thermal parameters

$$C_{pv}\frac{\partial T}{\partial t} = \boldsymbol{\nabla}.\left(k(T).\boldsymbol{\nabla}T\right) + p(\mathbf{J})$$

Thermal Diffusion Equation

Time Evolution using Finite Difference

$$\mathrm{p} = \mathbf{J}.\mathbf{E}(\mathbf{J},\mathrm{T})$$

Power loss per unit volume

$$T(t) = T(t-\Delta t) + \frac{\Delta t}{C_{pv}(T)}\boldsymbol{\nabla}.\left(k(T).\boldsymbol{\nabla}T\right) + \frac{\Delta t p(\mathbf{J})}{C_{pv}(T)}$$

Heat capacity per unit volume

Thermal conductivity

A Hussain, A Dadhich, E Pardo, submitted to Supercond. Sci. Technol.

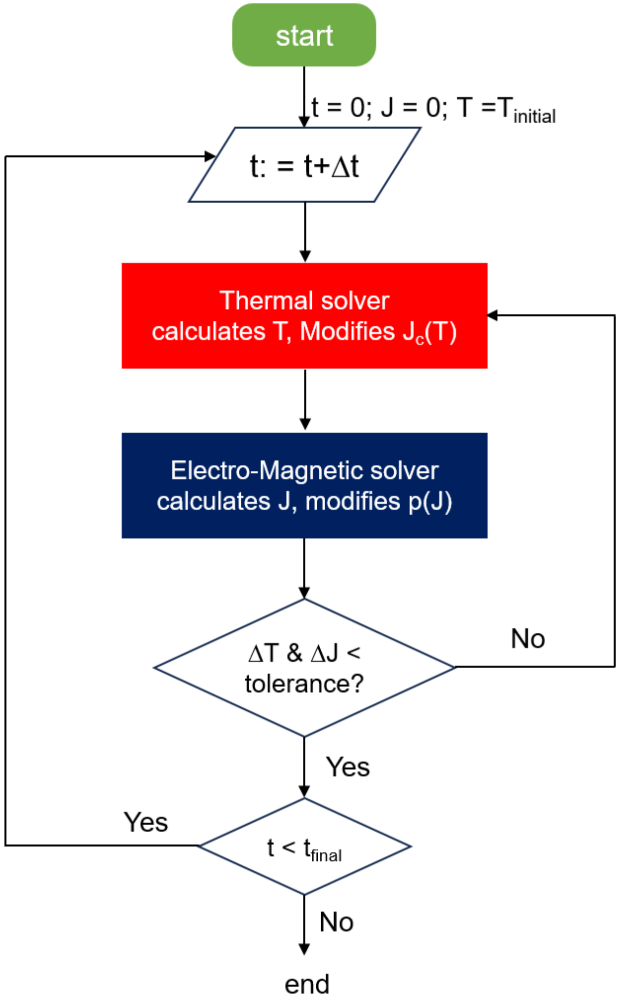
Finite Difference Approximation

- Explicit discretization

- Stability condition

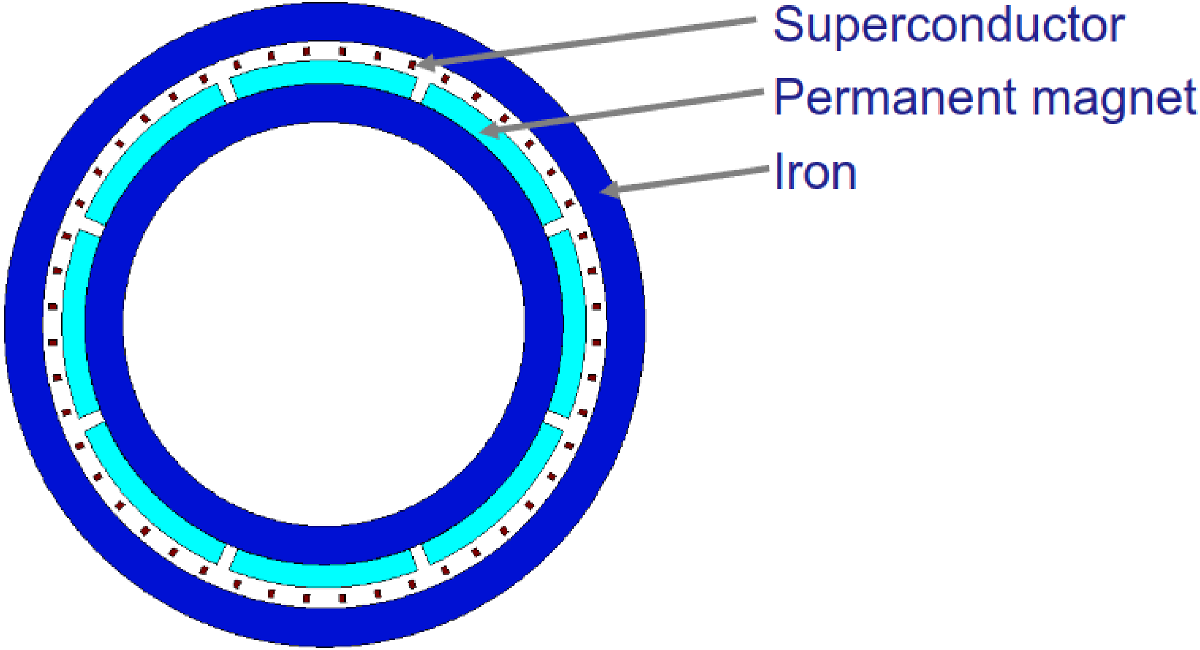
$$\Delta t \;\leq\; \frac{1}{2} \cdot \frac{C_{pv}(T) \cdot \min(\Delta x^2, \Delta y^2)}{k(T)}$$

Coupling Electro-Magnetic and Electro-Thermal Models



- Modeling methods
- **Studied configuration**
- Varying short-circuit voltages
- Conclusion

Tentative design of motor for aviation

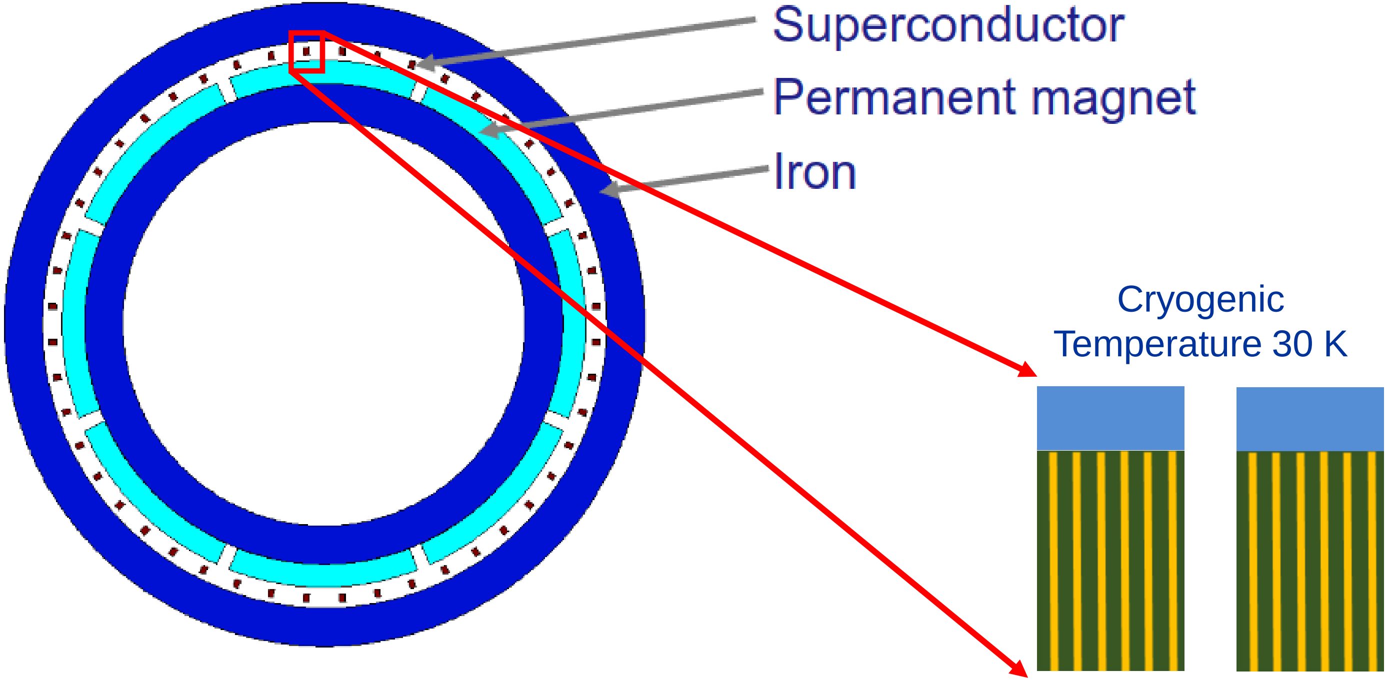


Superconductor

Permanent magnet

Iron

Tentative design of motor for aviation



Cryogenic
Temperature 30 K

Liquid hydrogen coolant

Studied Configuration

Racetrack coil in superconducting motors

No. of turns: 30

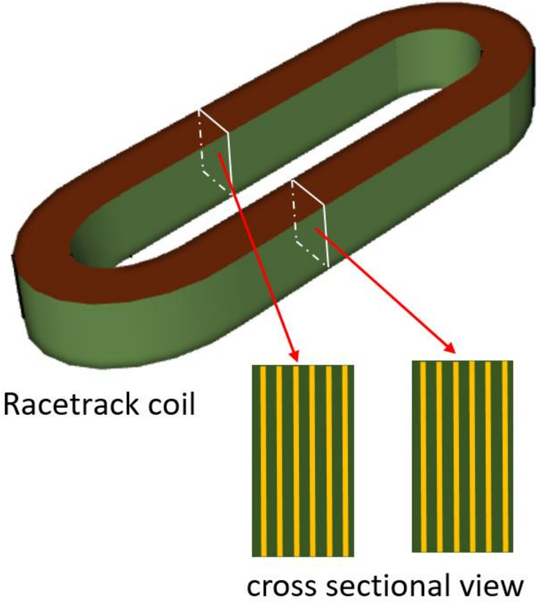
Length: 20 cm

Width: 4 mm

Airgap: 50 mm

I_c: 470 A

T_c: 92 K



Dimensions of superconducting tape

Silver: 2 µm

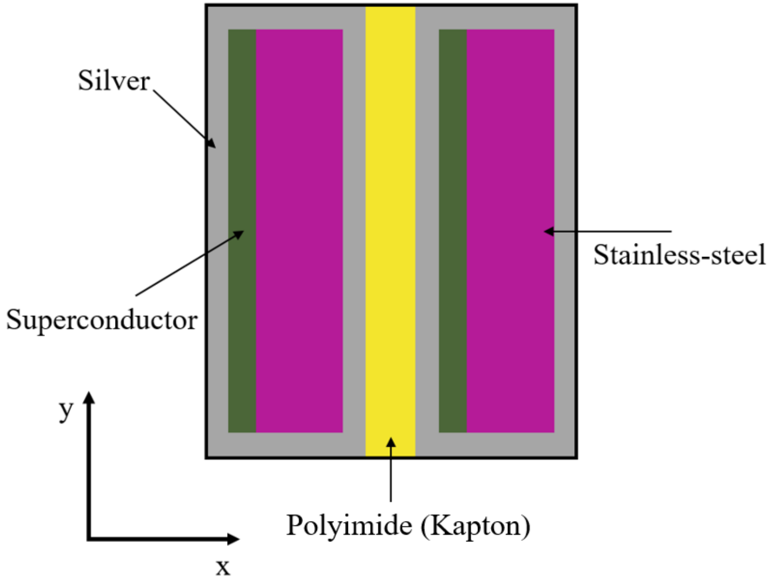
REBCO superconductor: 2 µm

Polyamide: 20 µm

Stainless steel: 100 µm

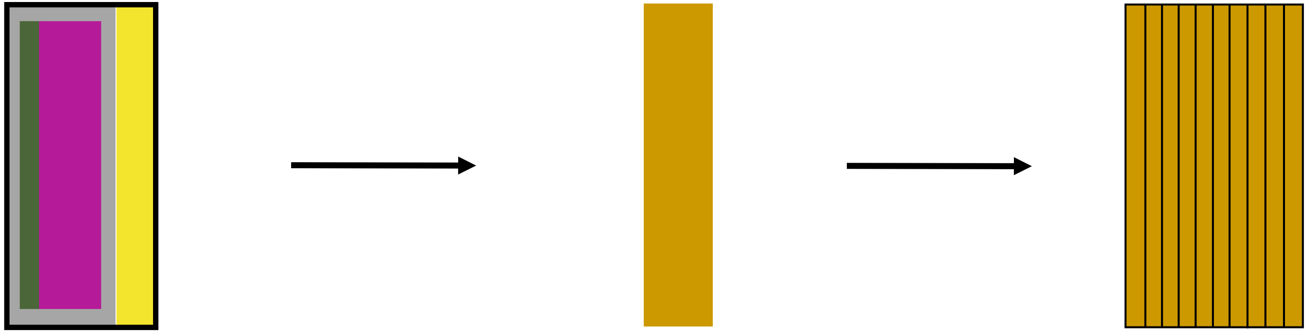
k(T) for each material

C_v(T) for each material



Material properties from NIST database:
https://trc.nist.gov/cryogenics/materials/materialproperties.htm

Homogenization Approximation

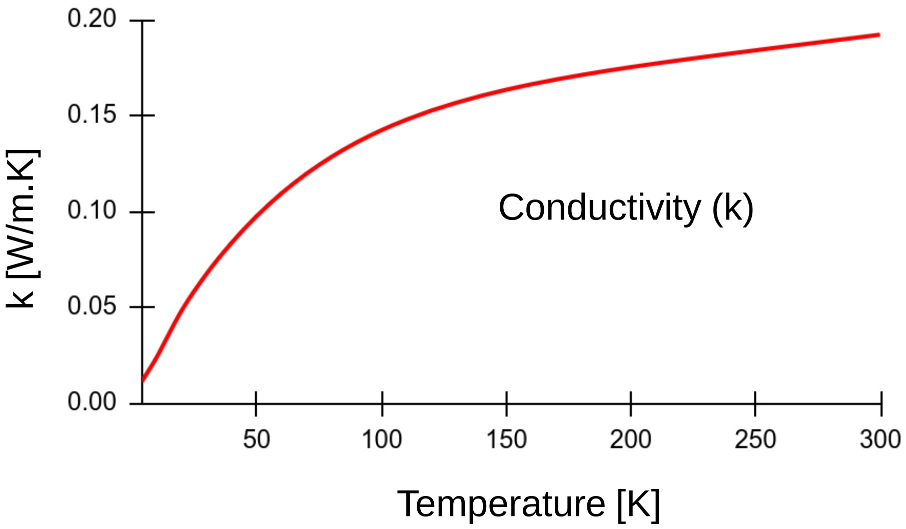


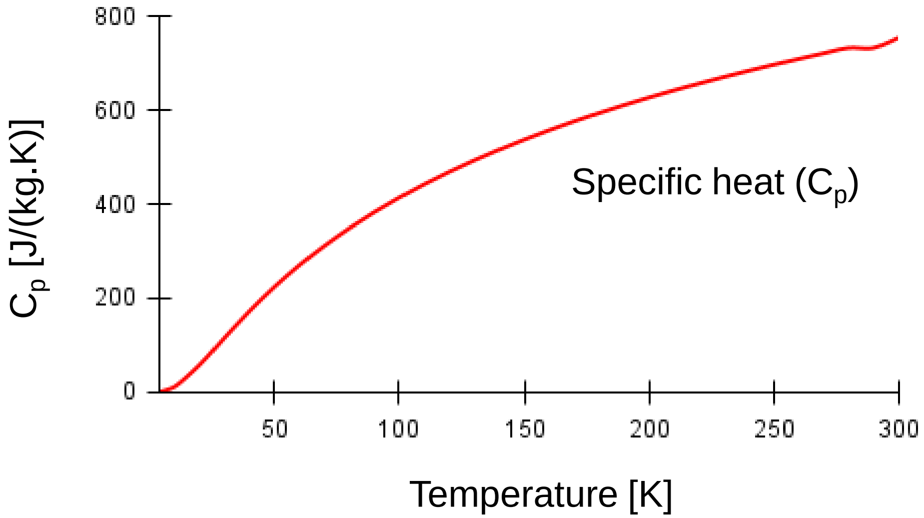
Single Tape

Homogenized
tape

Homogenized
coil

Temperature dependent thermal parameters for polyimide (Kapton)





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- Modeling methods
- Studied configuration
- **Varying voltage cases**
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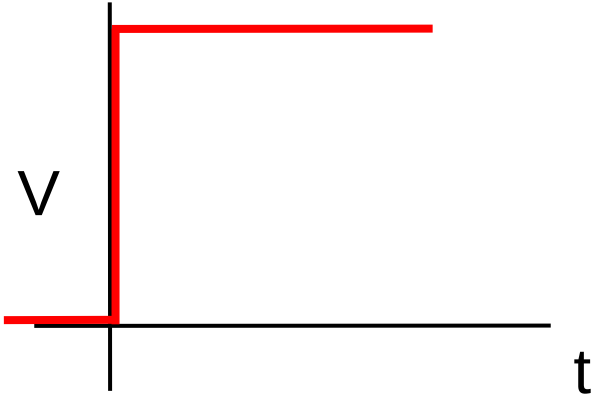
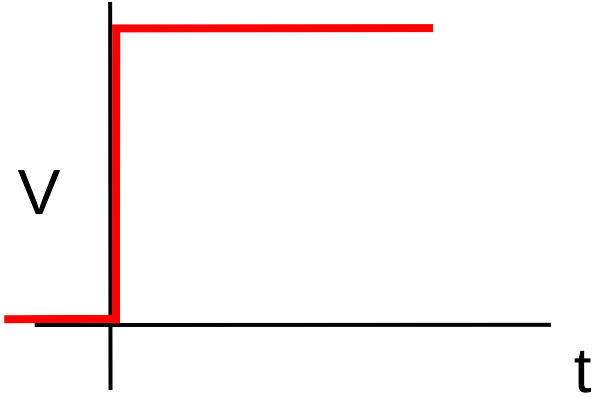
Short-Circuit DC Voltage

- Insulation damage
- Over voltage or lightning strike
- Fault in power source



Short-Circuit DC Voltage



1 V

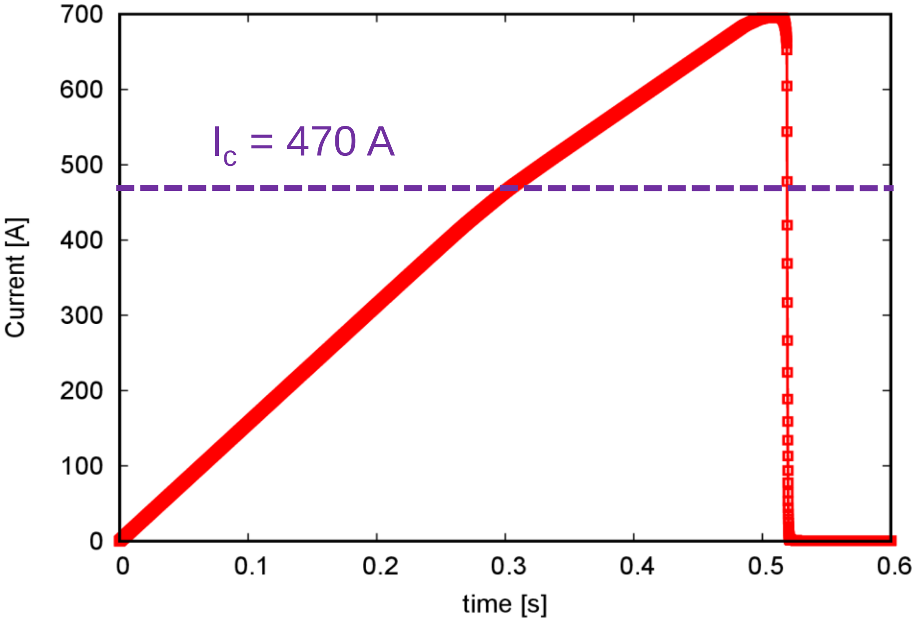
10 V

100 V

1000 V

Short-Circuit DC Voltage

1 V DC

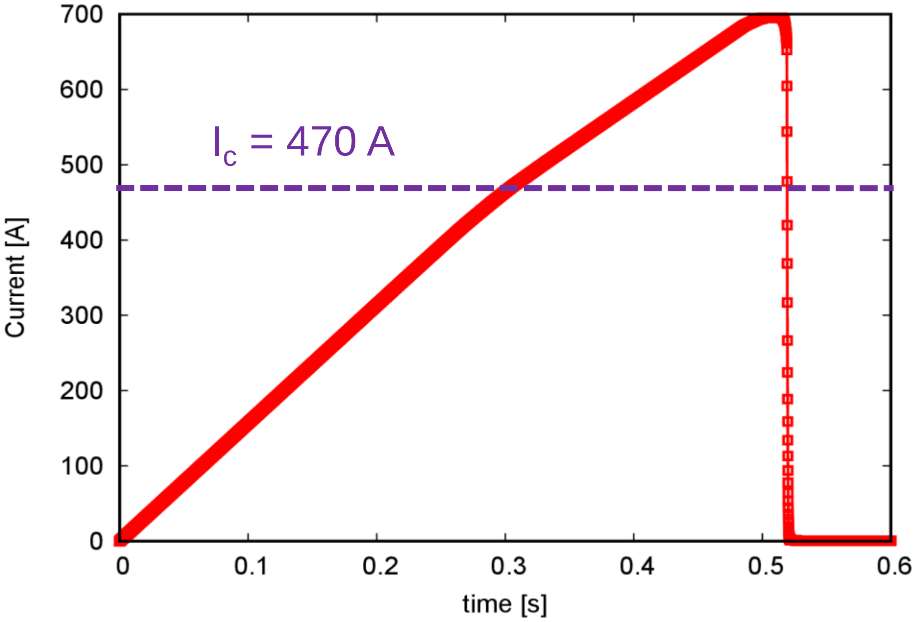


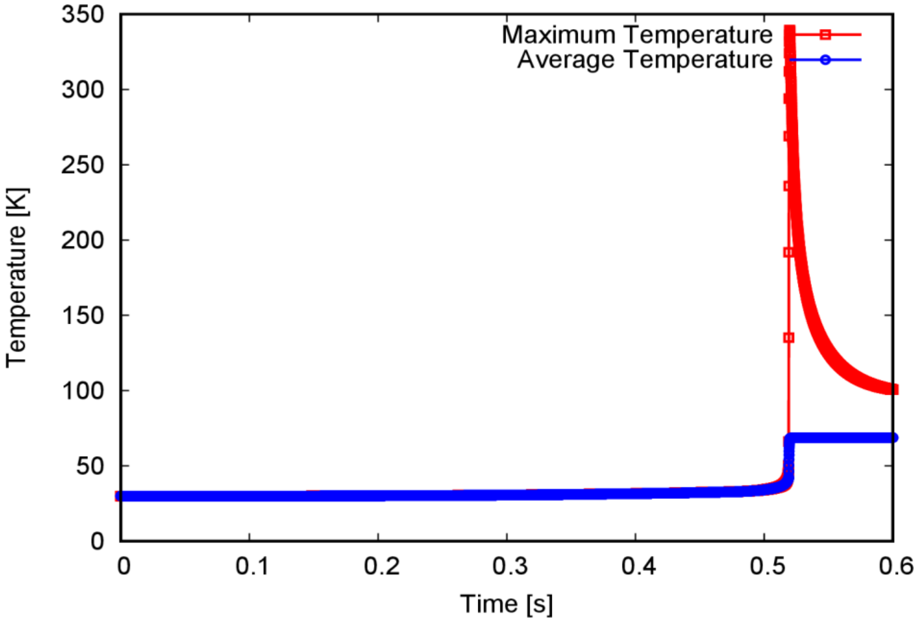
Estimated I_c from the load-line technique

Data for SuperOx REBCO tape from VUW database.

Short-Circuit DC Voltage

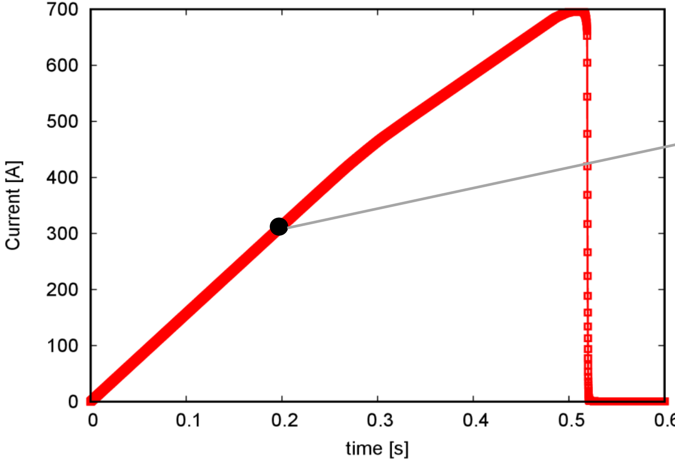
1 V DC

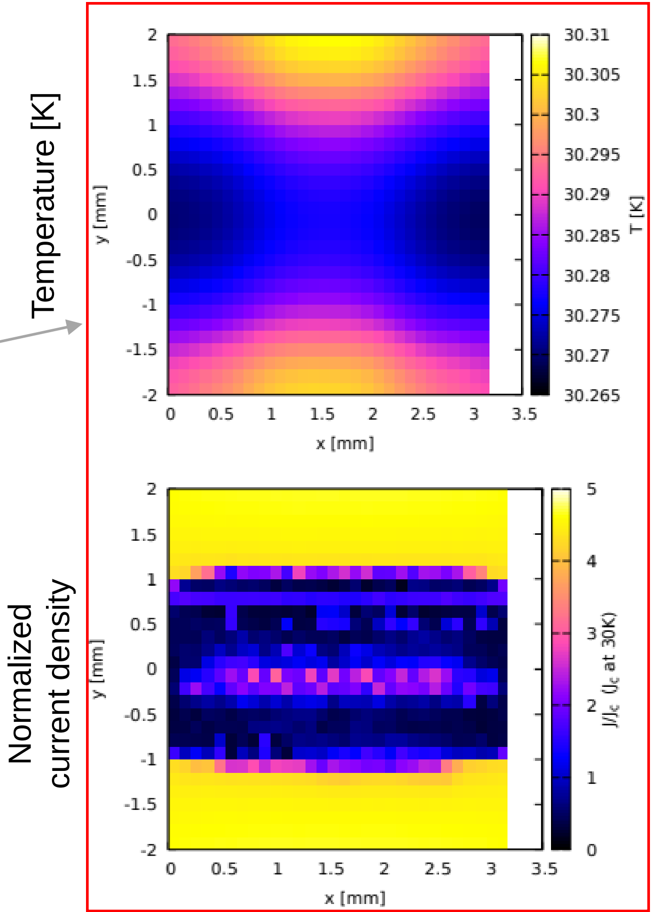




Short-Circuit DC Voltage

1 V DC

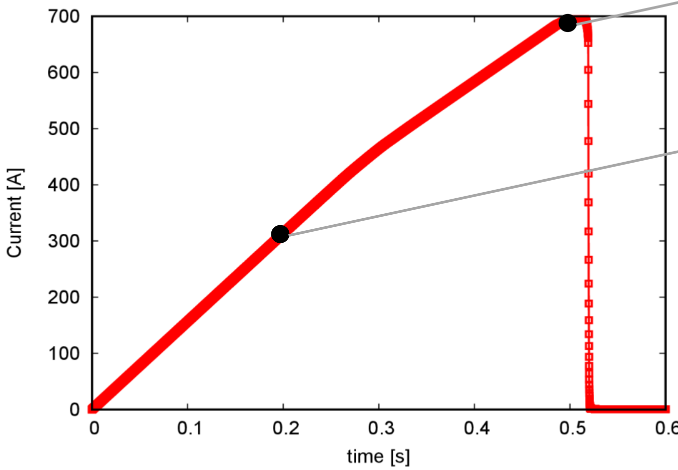


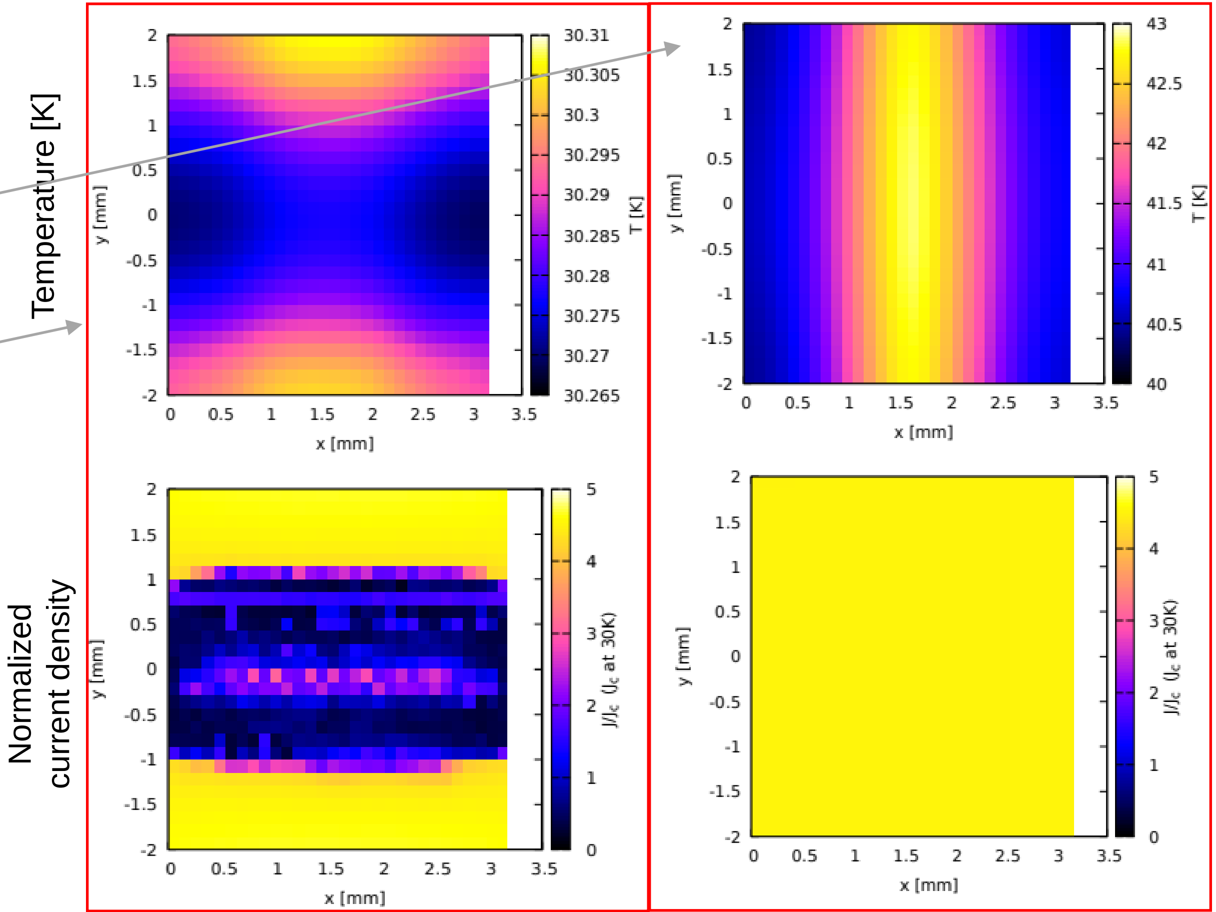


- Small Temperature rise

Short-Circuit DC Voltage

1 V DC

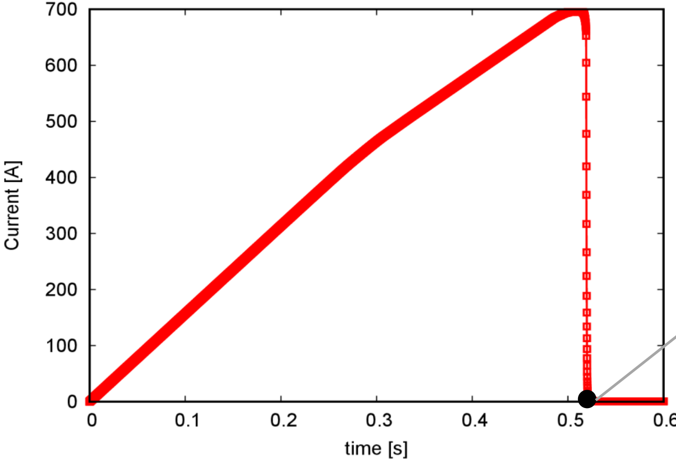


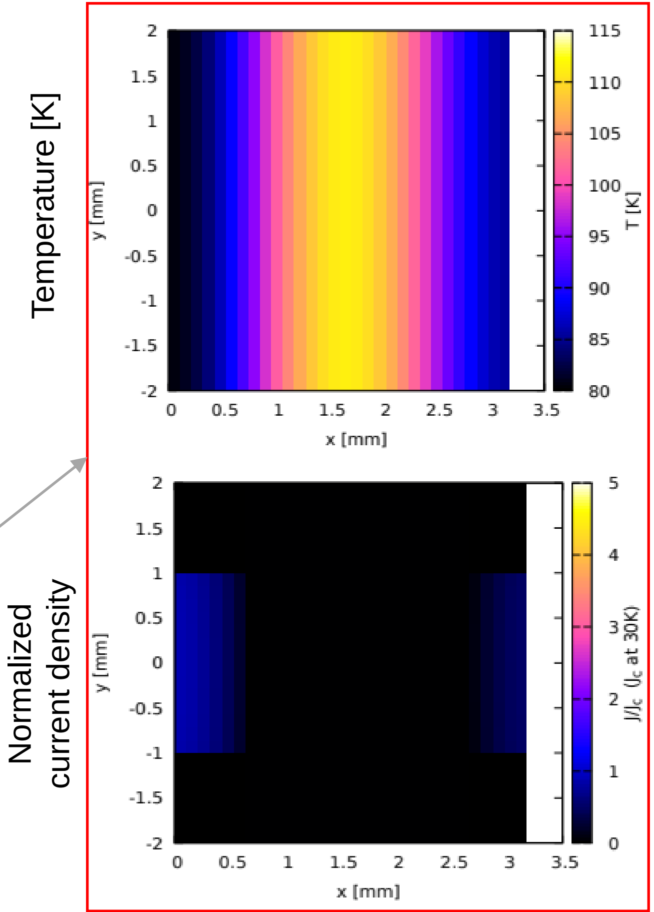


- Significant Temperature rise
- Uniform current density

Short-Circuit DC Voltage

1 V DC

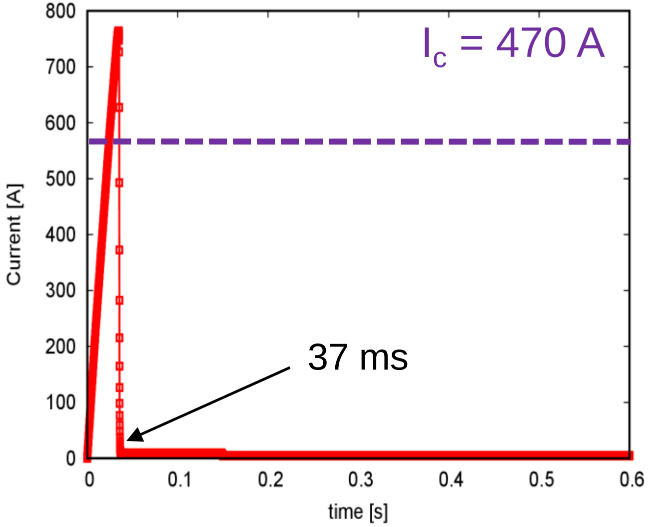




- $T > T_c$ in the middle turns
- Current density reduces

Short-Circuit DC Voltage

10 V DC

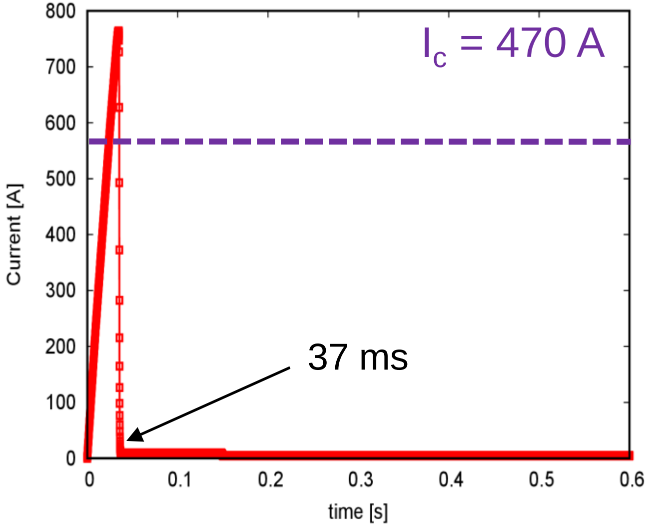


I_c = 470 A

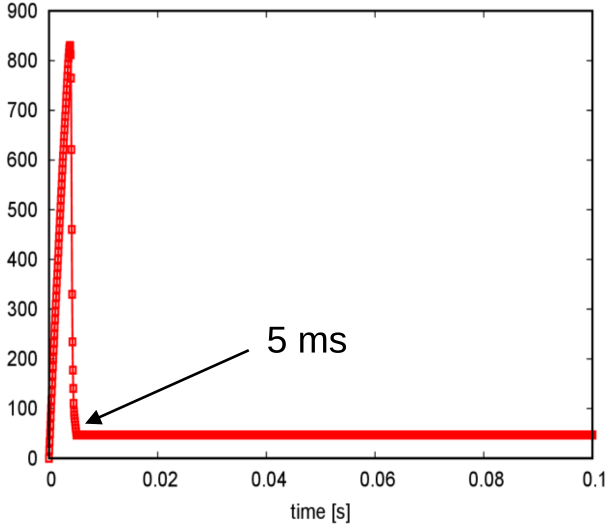
37 ms

Short-Circuit DC Voltage

10 V DC

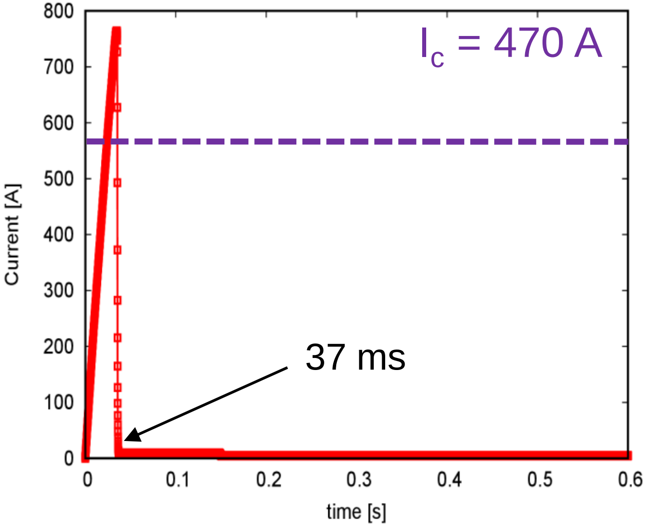


100 V DC

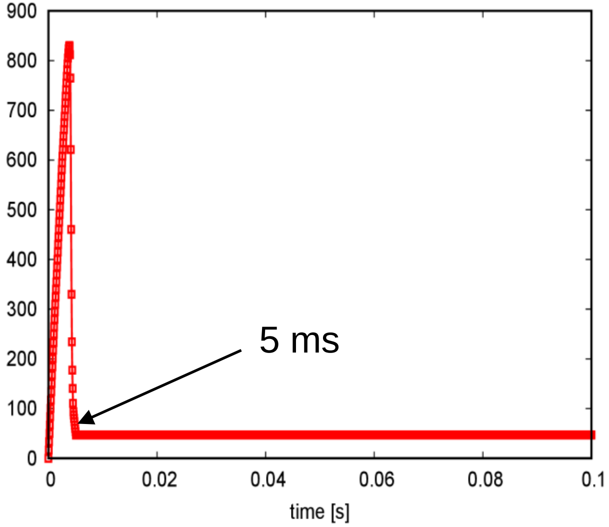


Short-Circuit DC Voltage

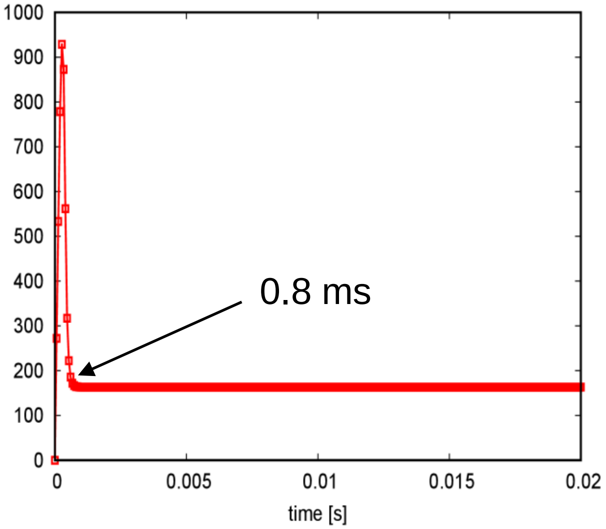
10 V DC



100 V DC



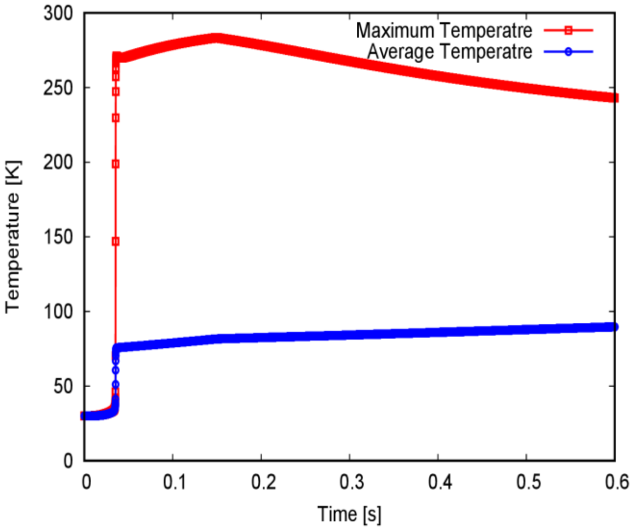
1000 V DC



Quench occurs earlier for higher amplitude of short-circuit DC voltage

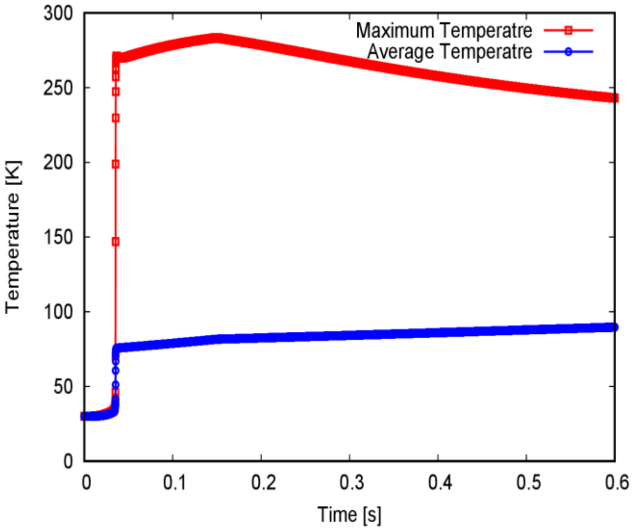
Short-Circuit DC Voltage

10 V DC

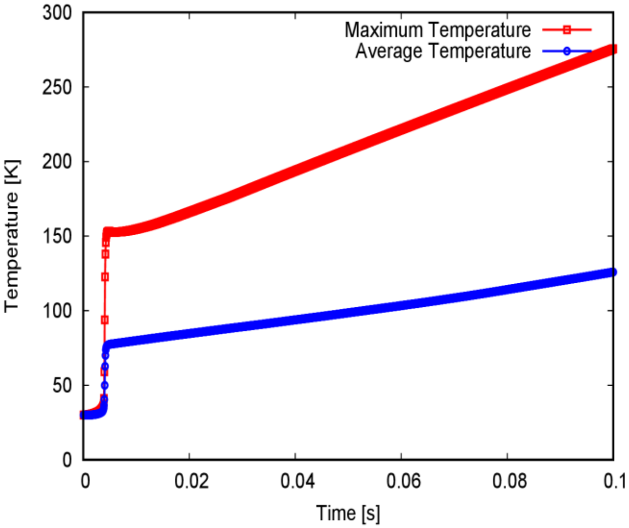


Short-Circuit DC Voltage

10 V DC

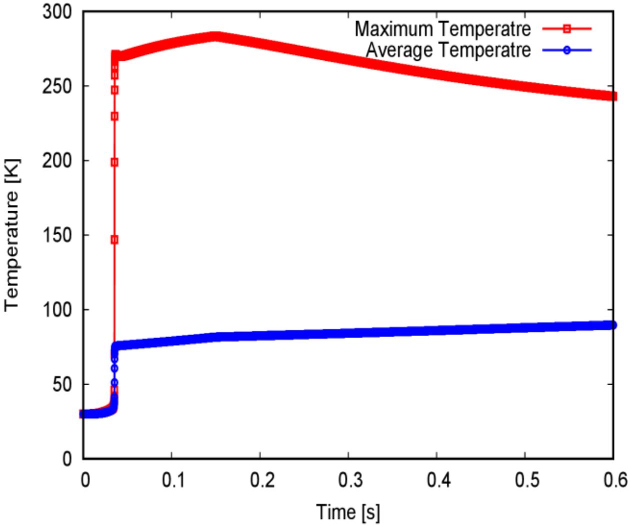


100 V DC

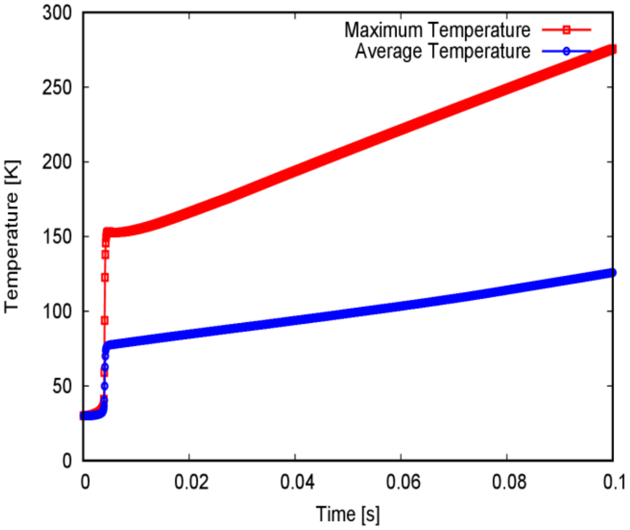


Short-Circuit DC Voltage

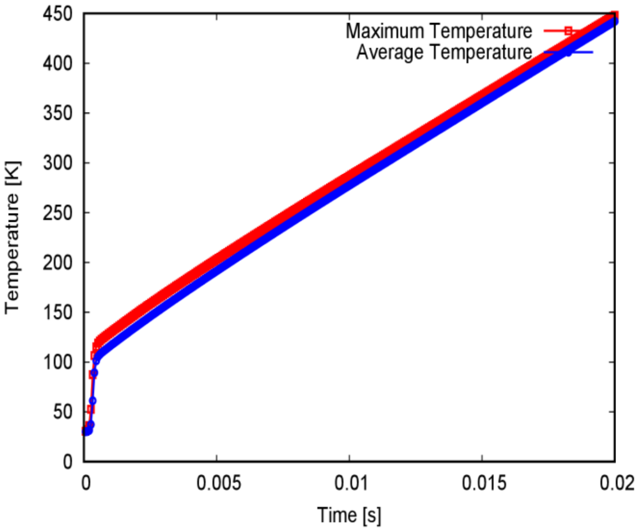
10 V DC



100 V DC



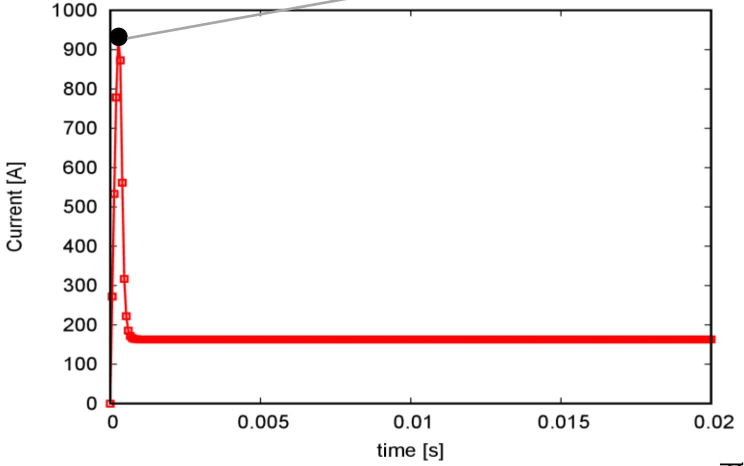
1000 V DC

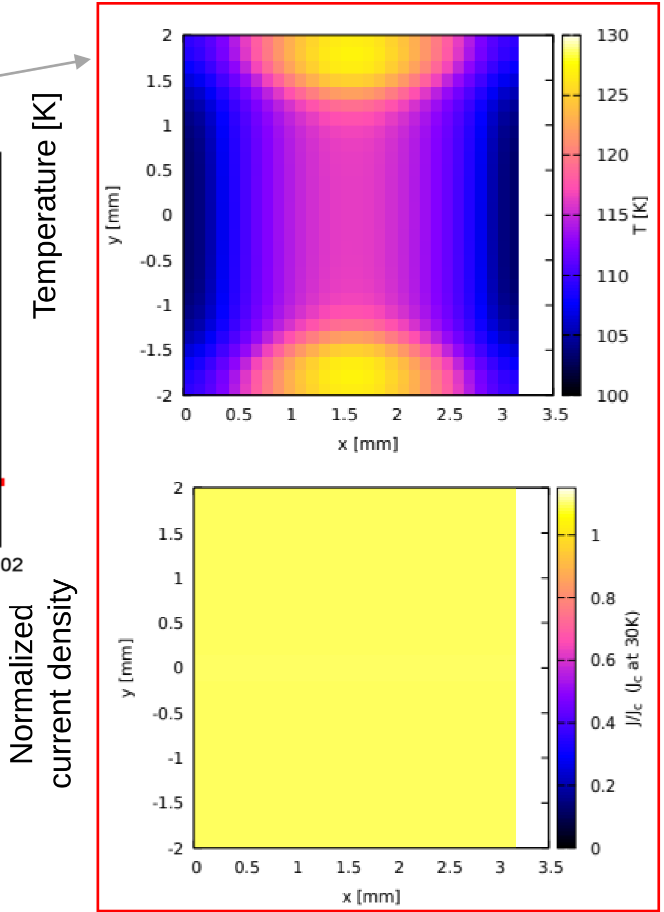


Sharp temperature rise occur for higher amplitude of short-circuit DC voltage

Short-Circuit DC Voltage

1000 V DC

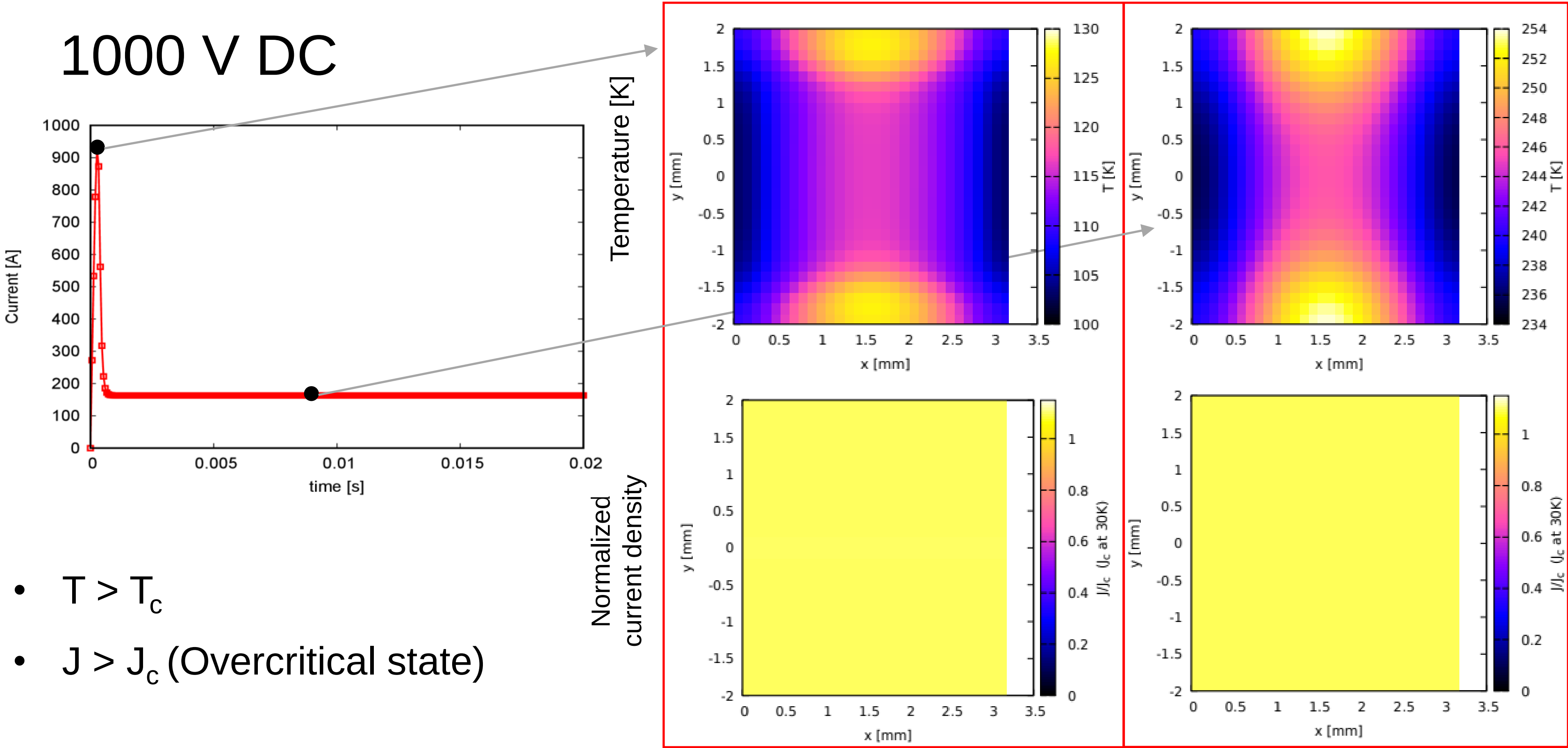




- Significant Temperature rise

Short-Circuit DC Voltage

1000 V DC



- $T > T_c$
- $J > J_c$ (Overcritical state)

- Modeling methods
- Studied configuration
- Varying voltage cases
- **Conclusion**

Conclusion

- Multiphysics electromagnetic and thermal modeling of racetrack coil in motor for aviation

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- Electrothermal modeling with temperature dependent thermal variables

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- Electrothermal modeling with temperature dependent thermal variables
- For both 1 V DC and 10 V DC, at 30 K, temperature does not exceed the maximum limit to damage the superconductor

Conclusion

- Multiphysics electromagnetic and thermal modeling of racetrack coil in motor for aviation
- Electrothermal modeling with temperature dependent thermal variables
- For both 1 V DC and 10 V DC, at 30 K, temperature does not exceed the maximum limit to damage the superconductor
- For both 100 and 1000 V DC, maximum temperature could damage the superconductor

Thank you for your attention!