

Modeling of HTS coils with complex geometries by using the homogenization of the T-A formulation in 3D

Carlos Roberto Vargas-Llanos¹, Felix Huber², Nicolò Riva³, Min Zhang², Francesco Grilli¹

¹ *Institute for Technical Physics, Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany.*

² *Applied Superconductivity Laboratory, Department of Electronics and Electrical Engineering, University of Strathclyde, Glasgow, G1 1XQ, United Kingdom.*

³ *MIT Plasma Science and Fusion Center, Cambridge, US.*

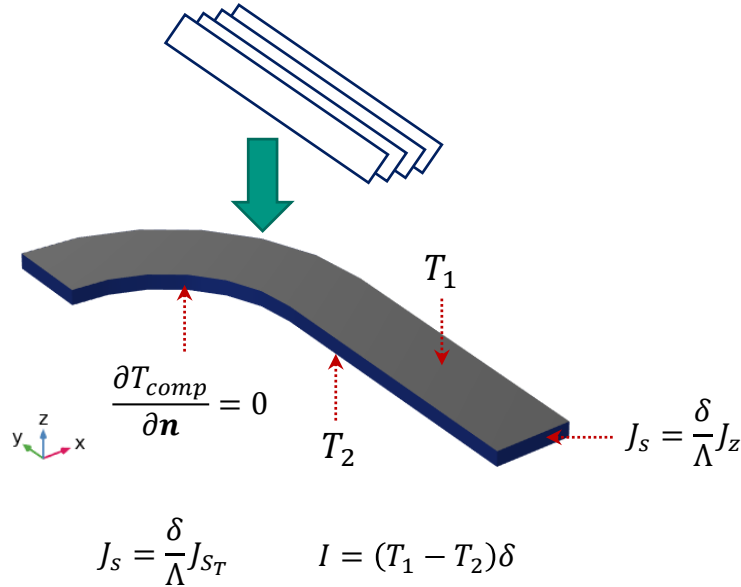
Modeling of HTS coils with complex geometries by using the homogenization of the T-A formulation in 3D

- Homogenization of the T-A formulation in 3D
(Complex geometries and curvilinear coordinate system)
- Critical current of the tape used in the simulations
- Case studies:
 - Validation – Racetrack coil
 - Saddle coil
(magnet sector and electrical machines)
 - Transport current
 - Transport current and magnetic field
 - Twisted coil
(Fusion applications)

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Homogenization of the T-A formulation in 3D



Ampere's law

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A} \right) = \mathbf{J}$$

(Comsol's magnetic field module)

Faraday's law

$$\begin{bmatrix} \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} \\ \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \end{bmatrix} \vec{n} + \begin{bmatrix} \frac{\partial B_x}{\partial t} \\ \frac{\partial B_y}{\partial t} \\ \frac{\partial B_z}{\partial t} \end{bmatrix} \vec{n} = 0$$

Current vector potential

$$\begin{bmatrix} J_x \\ J_y \\ J_z \end{bmatrix} = \begin{bmatrix} \frac{\partial(T \cdot \mathbf{n}_z)}{\partial y} - \frac{\partial(T \cdot \mathbf{n}_y)}{\partial z} \\ \frac{\partial(T \cdot \mathbf{n}_x)}{\partial z} - \frac{\partial(T \cdot \mathbf{n}_z)}{\partial x} \\ \frac{\partial(T \cdot \mathbf{n}_y)}{\partial x} - \frac{\partial(T \cdot \mathbf{n}_x)}{\partial y} \end{bmatrix}$$

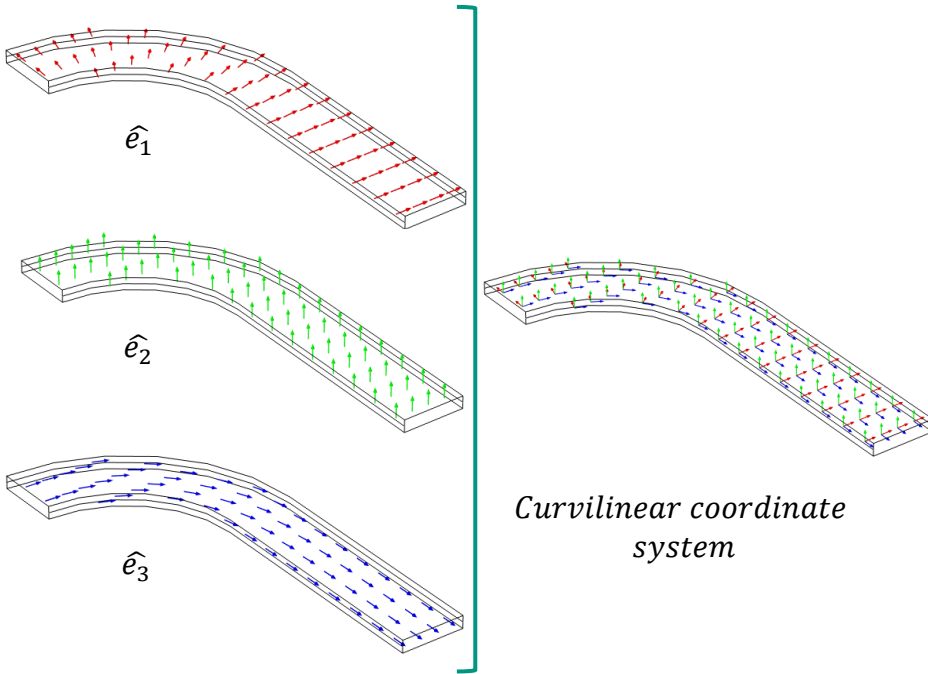
$$\rho_{HTS} = \frac{E_c}{J_c(\mathbf{B})} \left| \frac{\mathbf{J}}{J_c(\mathbf{B})} \right|^{n-1}$$

δ : Thickness of the superconducting layer

Λ : Thickness of the unit cell

*C. R. Vargas-Llanos and F. Grilli, "3D homogenized T-A formulation for modelling HTS coils", 2021, arXiv:2103.06590.

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Current vector potential

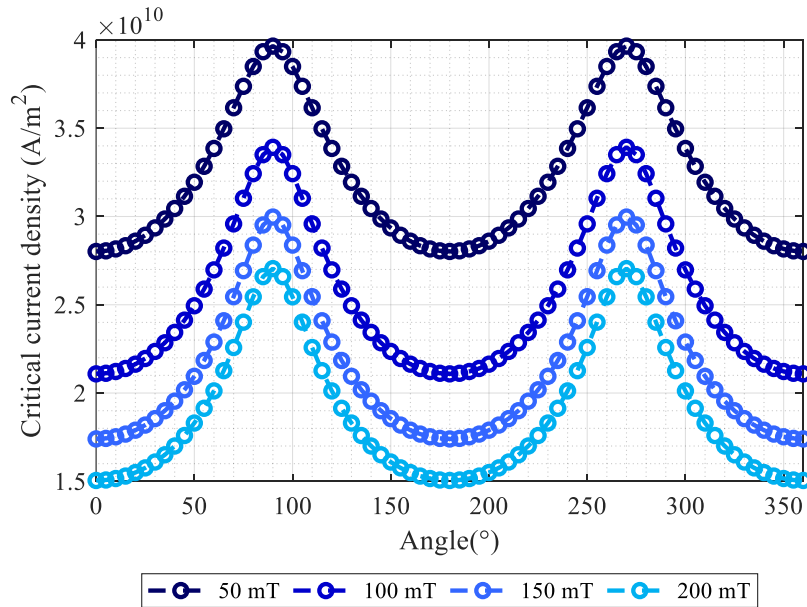
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Critical current / 4 mm REBCO tape



$$J_c(B_{\parallel}, B_{\perp}) = \frac{J_{c0}}{\left[1 + \frac{\sqrt{(B_{\parallel}k)^2 + B_{\perp}^2}}{B_c} \right]^b}$$

I_{c-77K}	160 A
J_{c0}	49 GAm ⁻²
k	0.275
B_c	32.5 mT
b	0.6

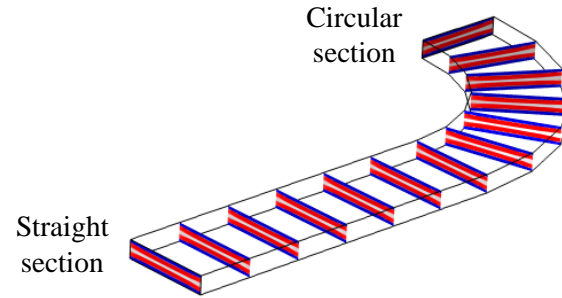
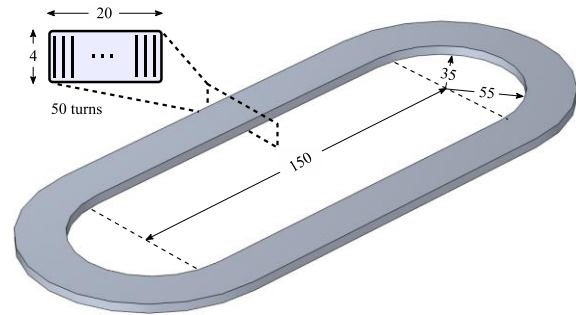
*V. M. R. Zermeño and F. Grilli, '3D modeling and simulation of 2G HTS stacks and coils', *Supercond. Sci. Technol.*, vol. 27, no. 4, p. 044025, Mar. 2014, doi: [10.1088/0953-2048/27/4/044025](https://doi.org/10.1088/0953-2048/27/4/044025).

**A. Kario *et al.*, 'Investigation of a Rutherford cable using coated conductor Roebel cables as strands', *Supercond. Sci. Technol.*, vol. 26, no. 8, p. 085019, Aug. 2013, doi: [10.1088/0953-2048/26/8/085019](https://doi.org/10.1088/0953-2048/26/8/085019).

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Validation - Racetrack coil



Time = 0.01 s / $f = 50$ Hz

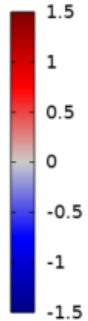
Circular section

Straight section

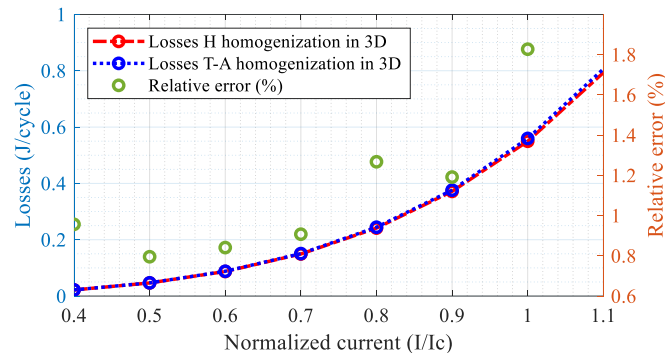
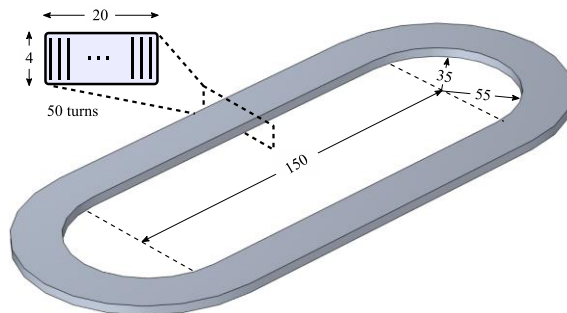
Homogenization of the H formulation



Homogenization of the T-A formulation



Validation - Racetrack coil



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Circular section

Straight section

Homogenization of the H formulation



Homogenization of the T-A formulation

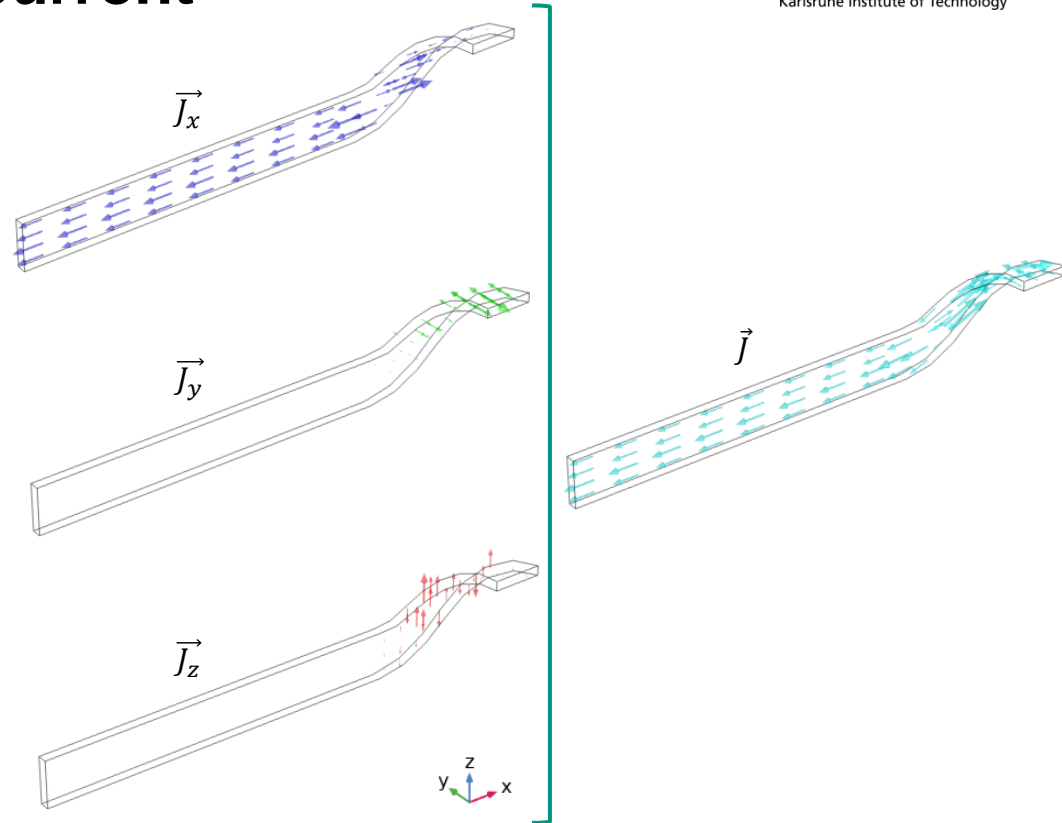
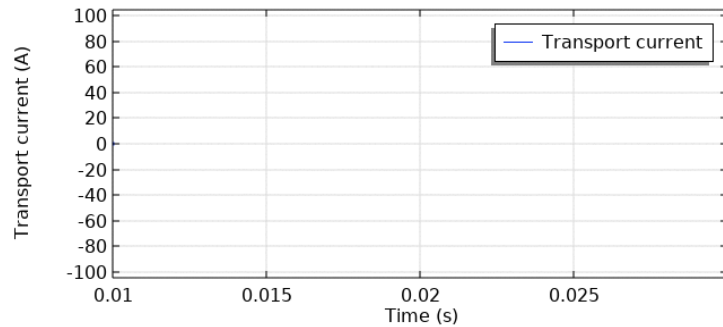
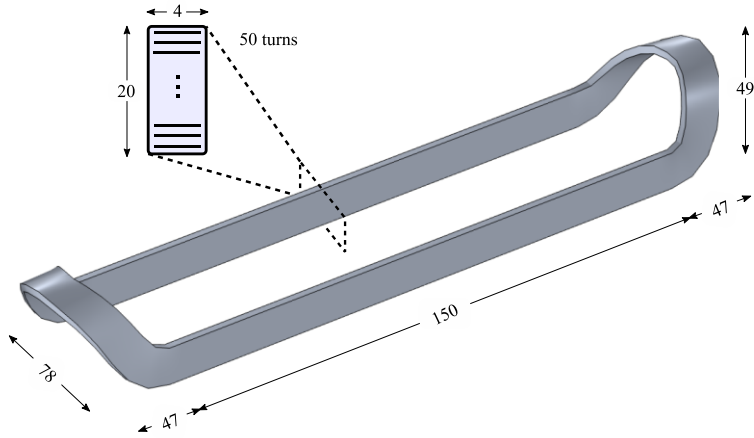


V. M. R. Zermeño and F. Grilli, '3D modeling and simulation of 2G HTS stacks and coils', *Supercond. Sci. Technol.*, vol. 27, no. 4, p. 044025, Mar. 2014, doi: [10.1088/0953-2048/27/4/044025](https://doi.org/10.1088/0953-2048/27/4/044025).

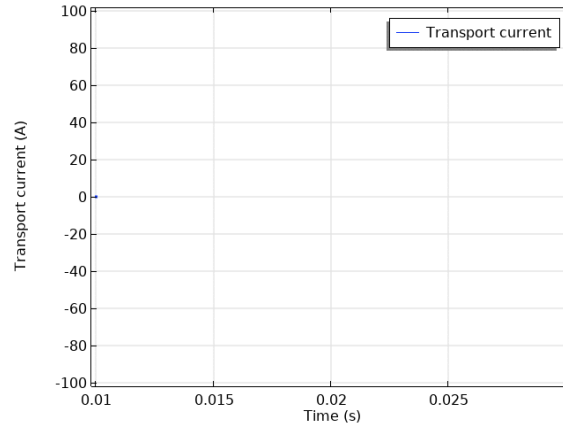
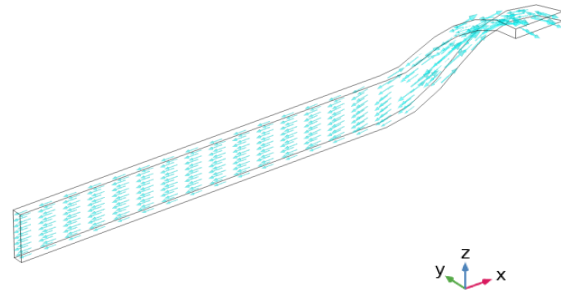
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Saddle coil – Transport current



Saddle coil – Transport current

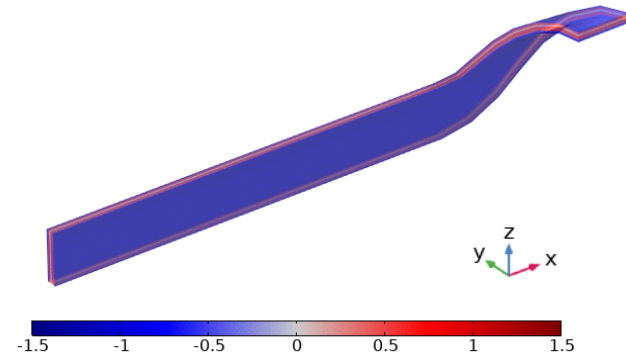


$$\frac{\sqrt{J_x^2 + J_y^2 + J_z^2}}{Jc(B_{\parallel}, B_{\perp})}$$

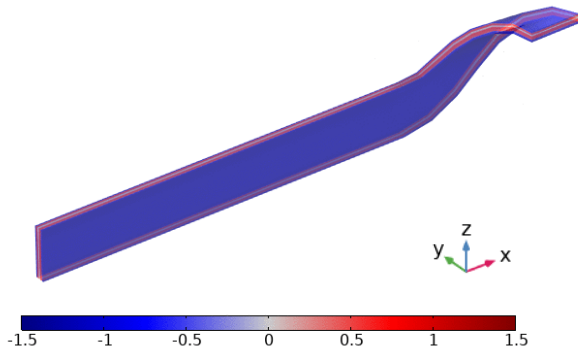
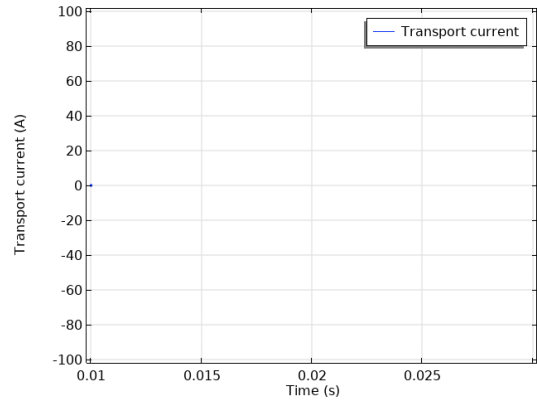
The transition between positive and negative direction is not visual.

$$\frac{\vec{J} \cdot \hat{e}_z}{Jc(B_{\parallel}, B_{\perp})}$$

The transition between positive and negative direction is visual.



Saddle coil – Transport current



3D Model

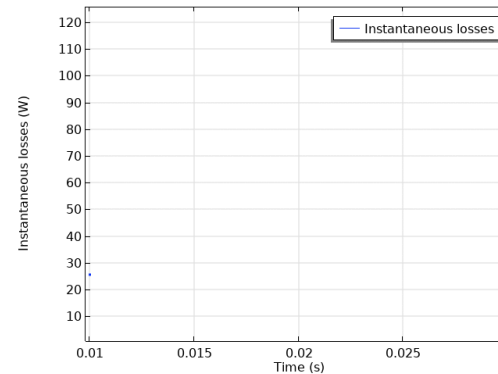
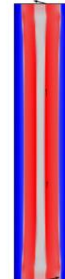
Curved section



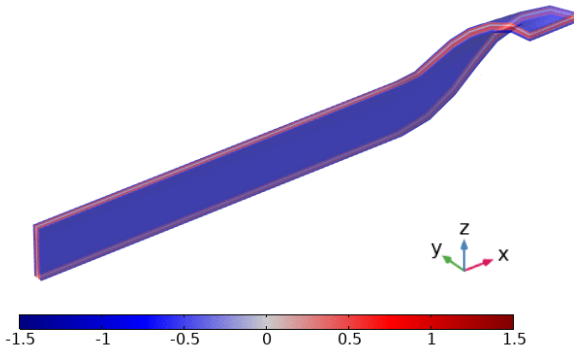
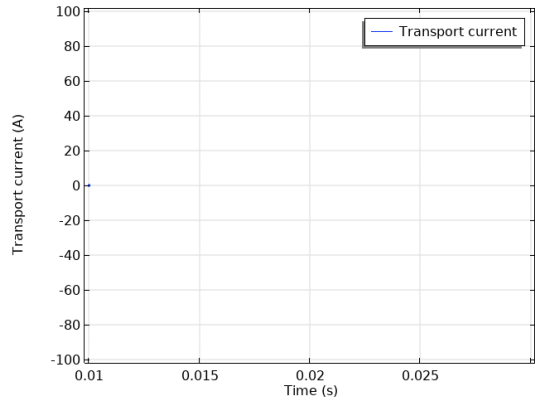
Straight section



2D Model



Saddle coil – Transport current



3D Model

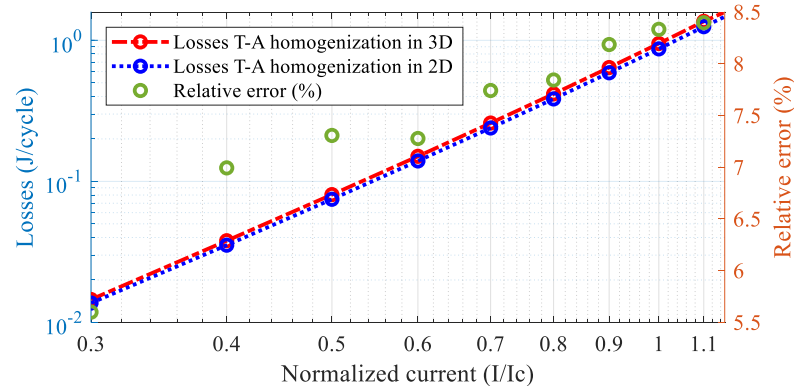
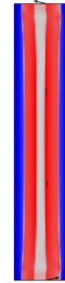
Curved section



Straight section



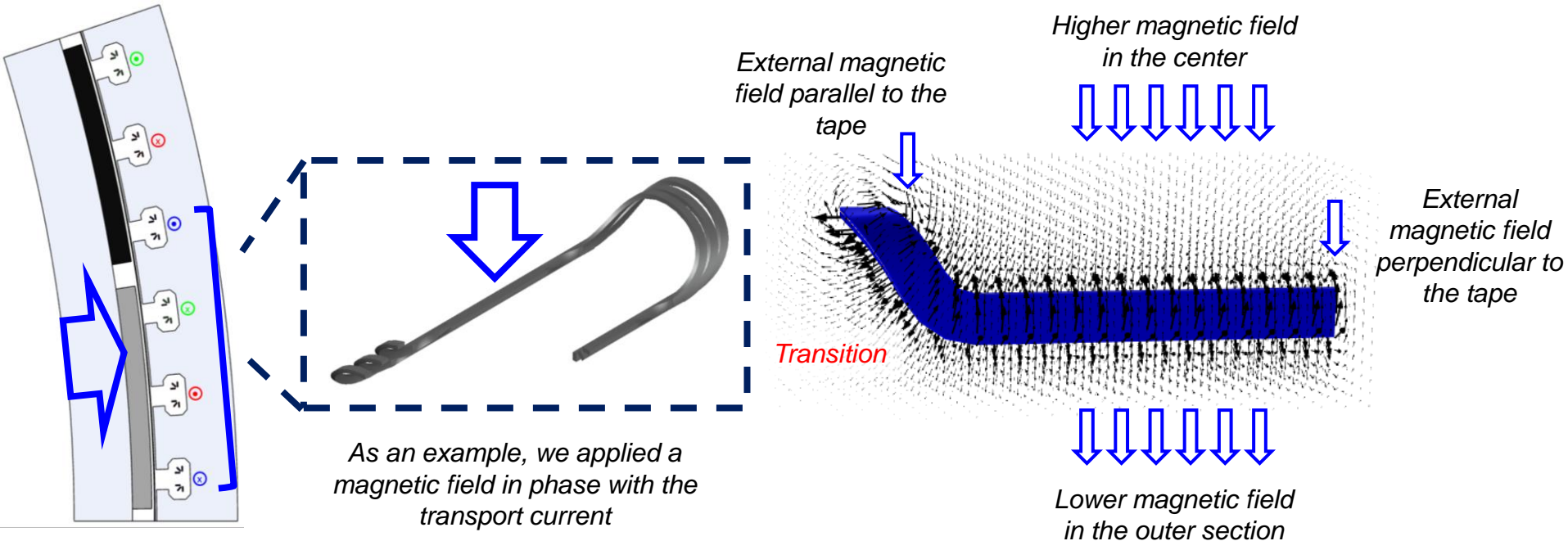
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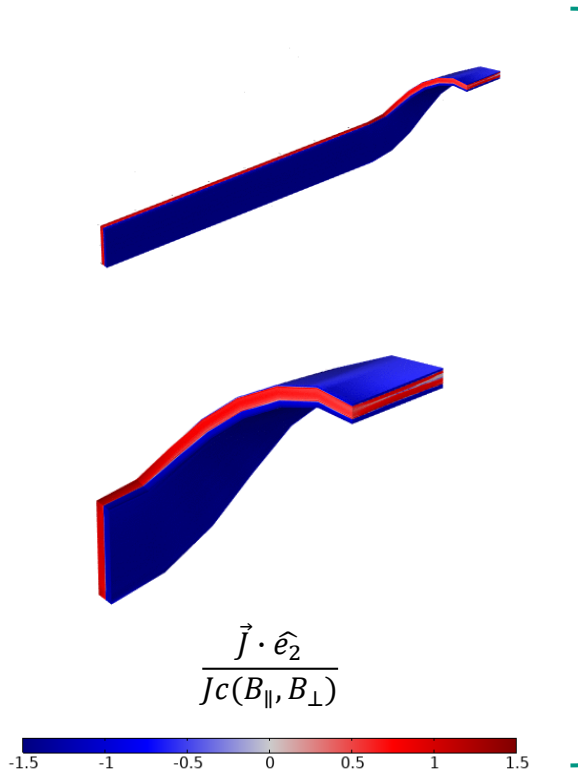
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Saddle coil – Transport current and external magnetic field



C. R. Vargas-Llanos, S. Lengsfeld, M. Noe, T. Arndt and F. Grilli, "Influence of coil position on AC losses of stator superconducting windings of a synchronous machine for a 10 MW wind turbine", *IEEE transactions on applied superconductivity*, vol. 31, no. 7, p. 5206509, Oct. 2021, doi: [10.1109/TASC.2021.3104983](https://doi.org/10.1109/TASC.2021.3104983).

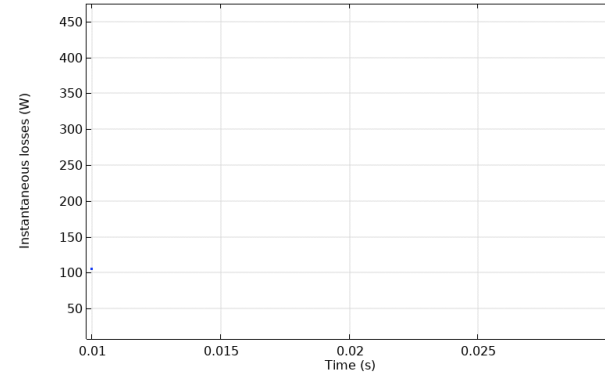
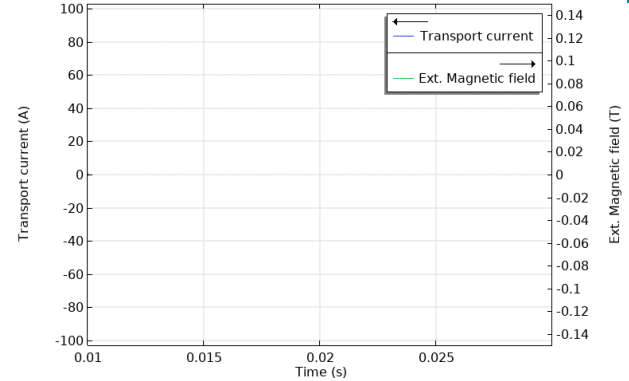
Saddle coil – Transport current and external magnetic field



Curved section



Straight section

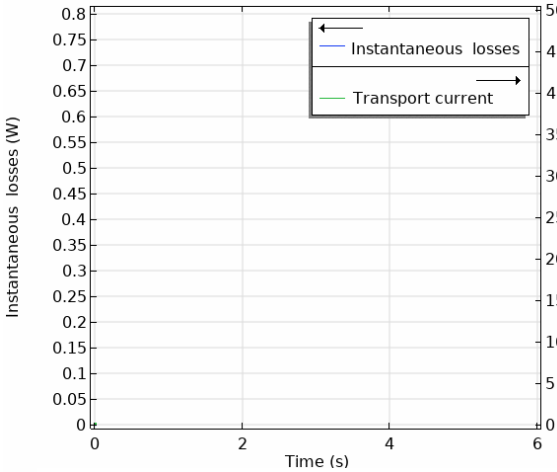


Losses
3.622 J/cycle

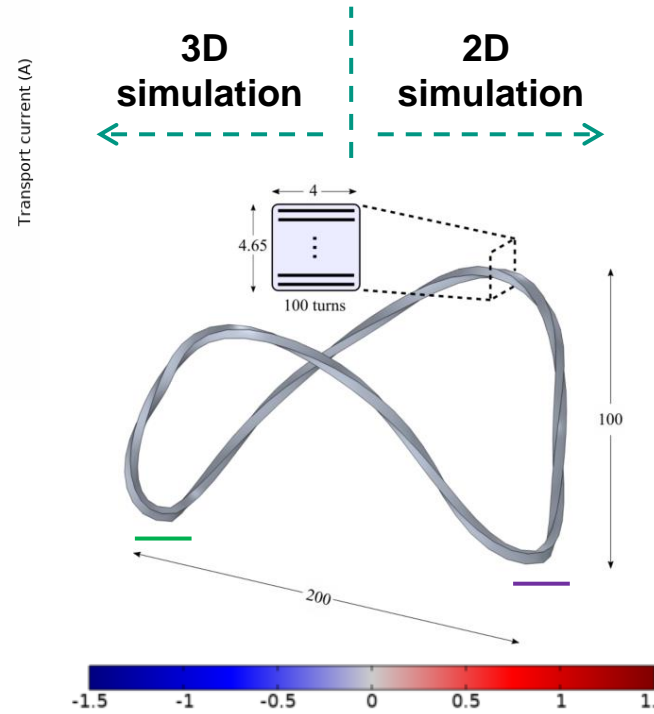
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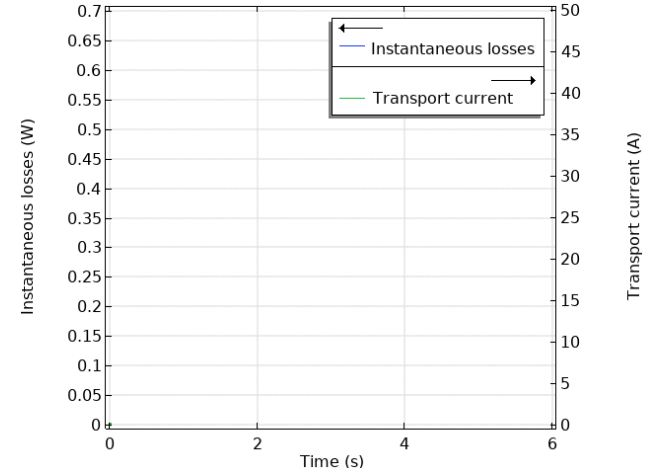
Twisted coil – Load cycle



Current penetration



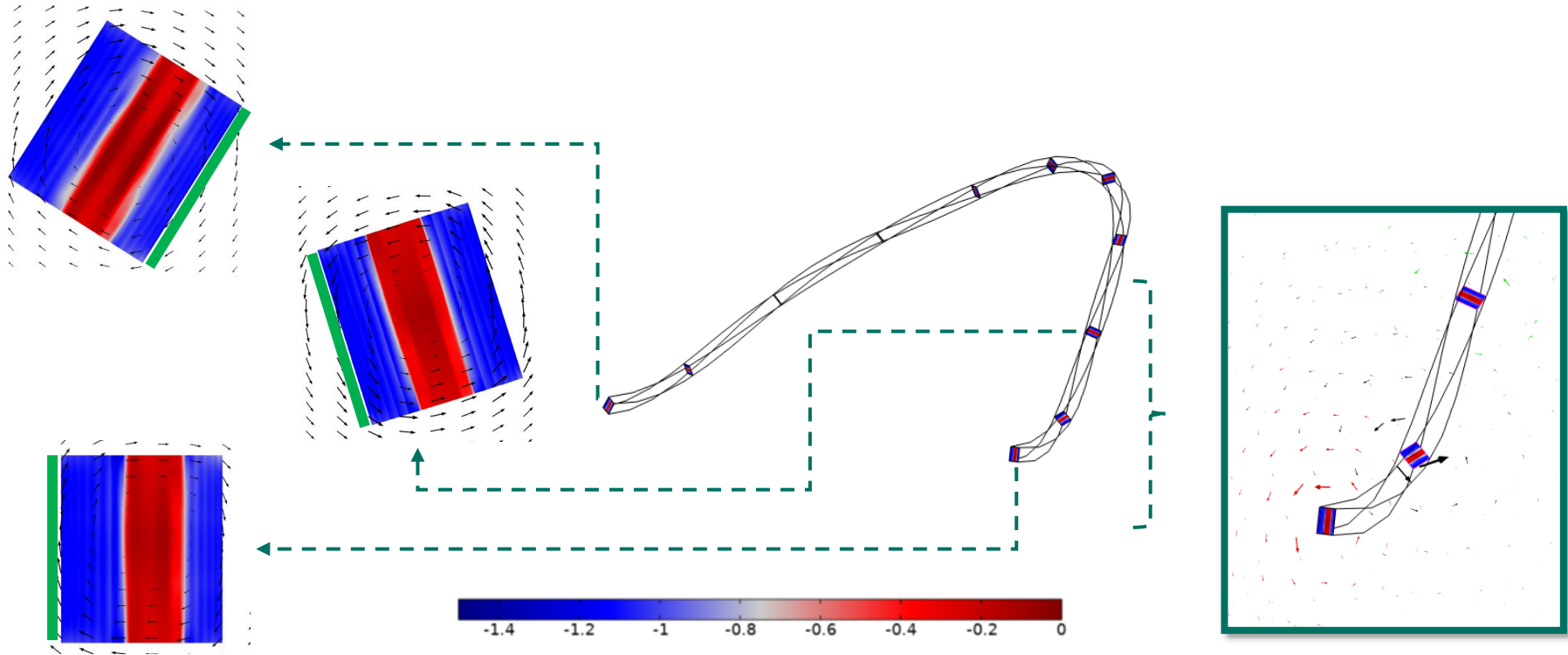
3D simulation 2D simulation



Current penetration



Twisted coil – Current penetration – $t = 2.5$ s



Conclusion

- The modeling approach was validated for a racetrack coil geometry.
- The 2D modeling approach was in good agreement with the 3D simulations, for transport current in a saddle coil.
- The transport current and magnetic field operating conditions can not be fully predicted with a 2D model.
- The twisted coil ramp-up/down process was studied, and compared with a 2D modeling approach.

Thanks!