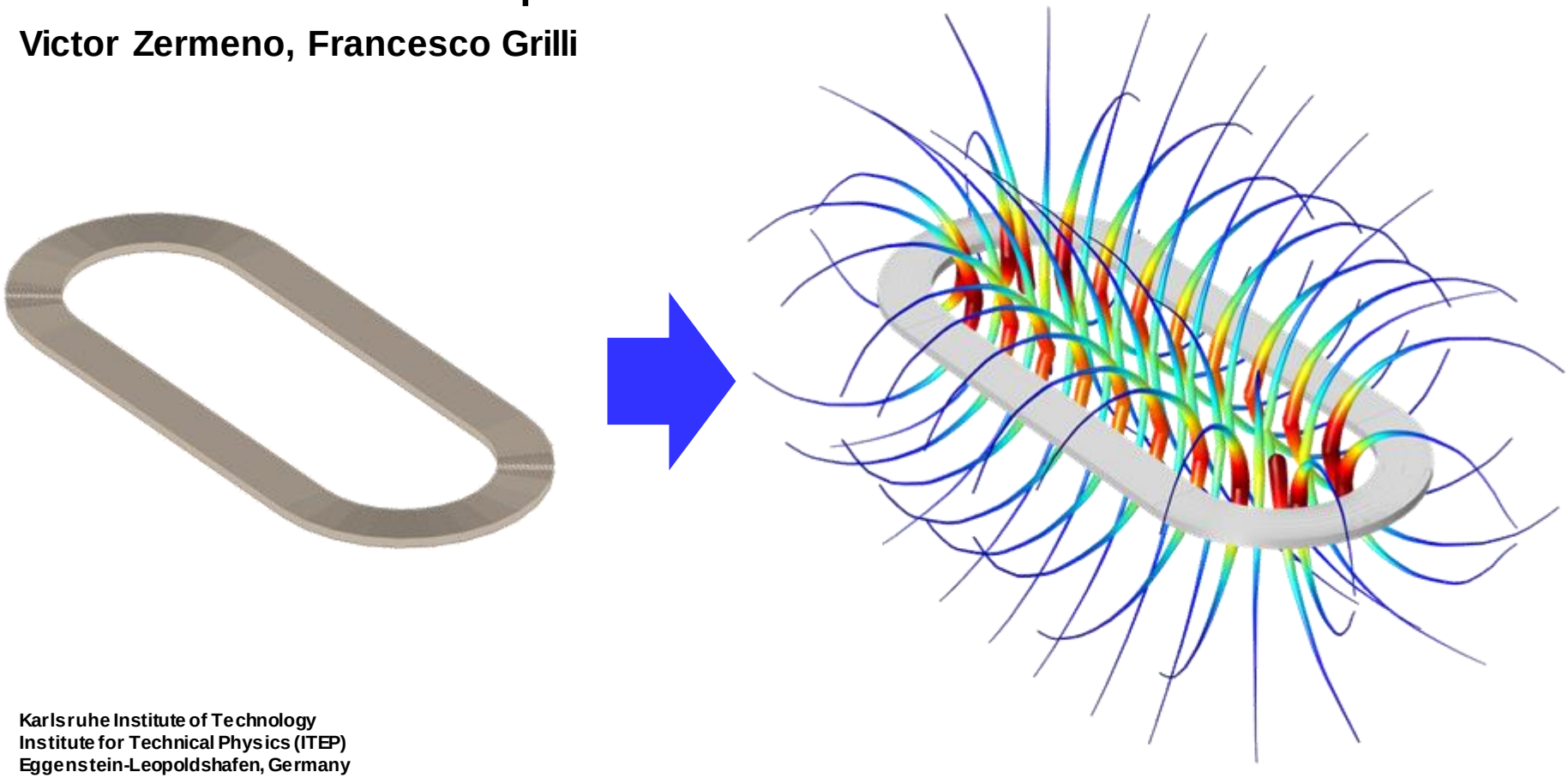
Karlsruhe Institute of Technology

3-D Homogenization: A new technique for fast calculation of AC losses in non-circular HTS pancake coils

Victor Zermeno, Francesco Grilli



Karlsruhe Institute of Technology
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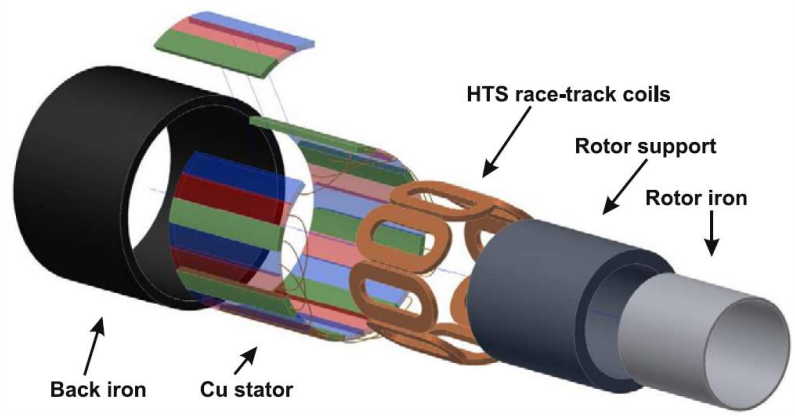
Eggenstein-Leopoldshafen, Germany

Non circular coils

- Important in many applications:

Non circular coils

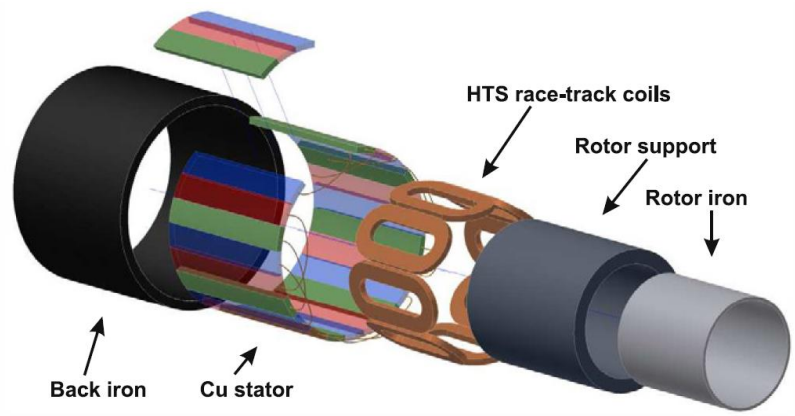
- Important in many applications:
  - Generators and motors



A B Abrahamsen *et al.* Supercond. Sci. Technol. 23 (2010) 034019

Non circular coils

- Important in many applications:
  - Generators and motors
  - Magnetic confinement of plasma



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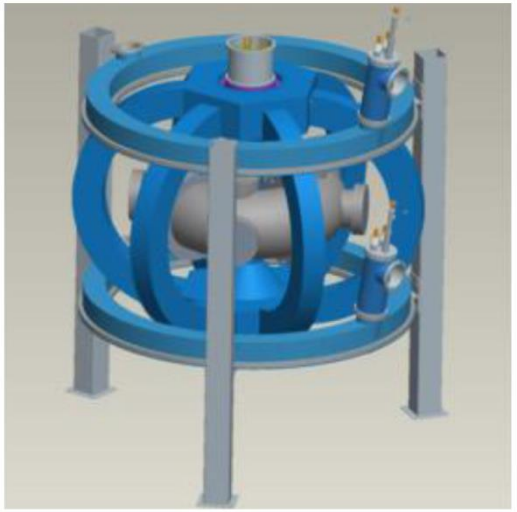

M. Gryaznevich, et al. Fusion Engineering and Design (2013)

Non circular coils

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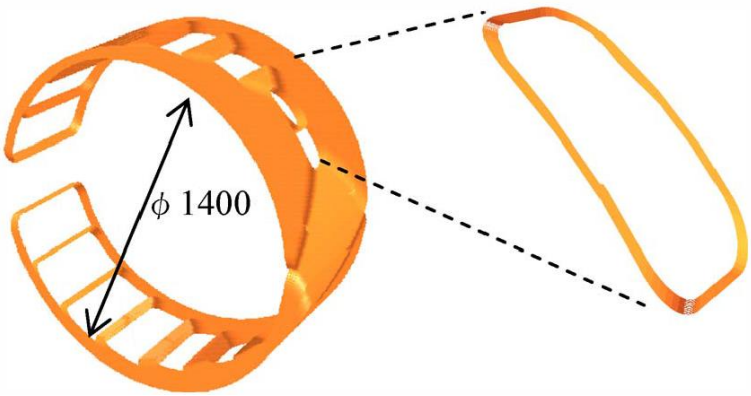
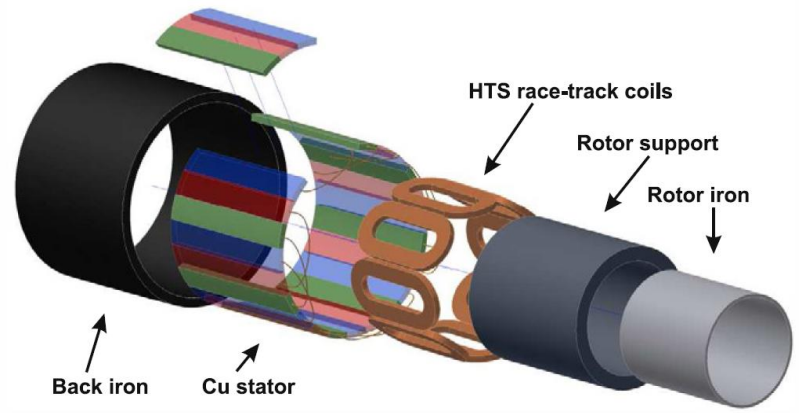
  - Generators and motors
  - Magnetic confinement of plasma
  - Accelerator magnets



Koyanagi et al IEEE Trans App Supercond 23-3 (2013)



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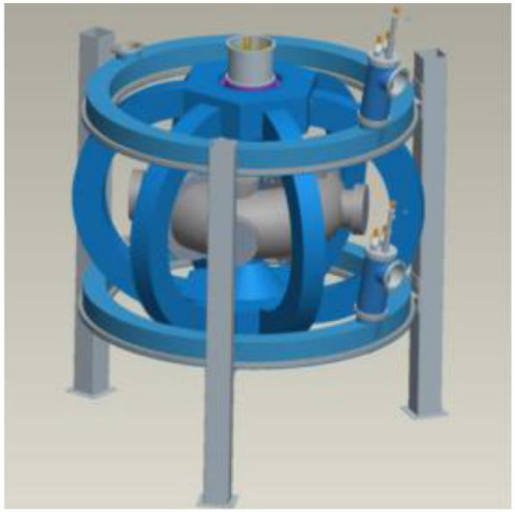
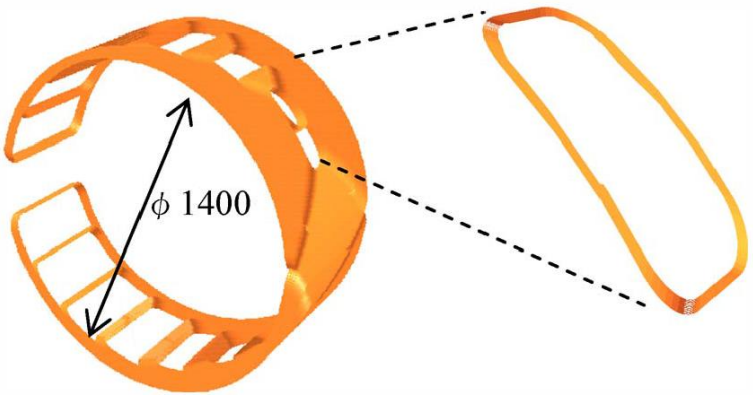


M. Gryaznevich, et al. Fusion Engineering and Design (2013)

Non circular coils

- Important in many applications:
  - Generators and motors
  - Magnetic confinement of plasma
  - Accelerator magnets
  - Magnetic resonance
  - Characterization of materials



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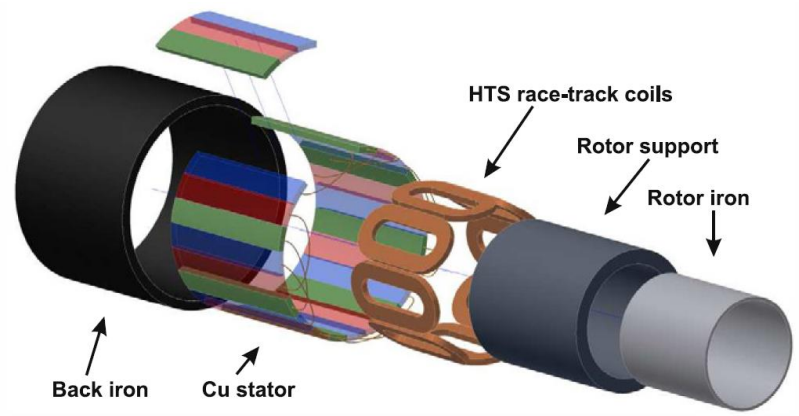

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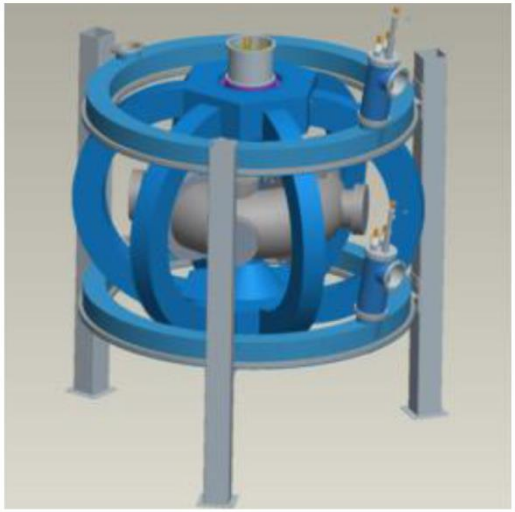


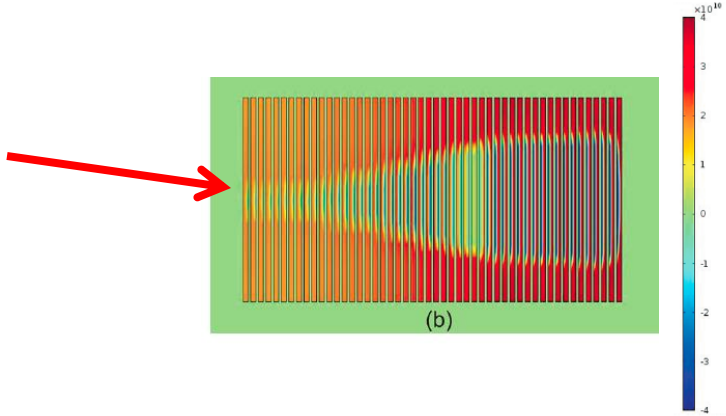
M. Gryaznevich, et al. Fusion Engineering and Design (2013)

Non circular coils

- Design challenges

Non circular coils

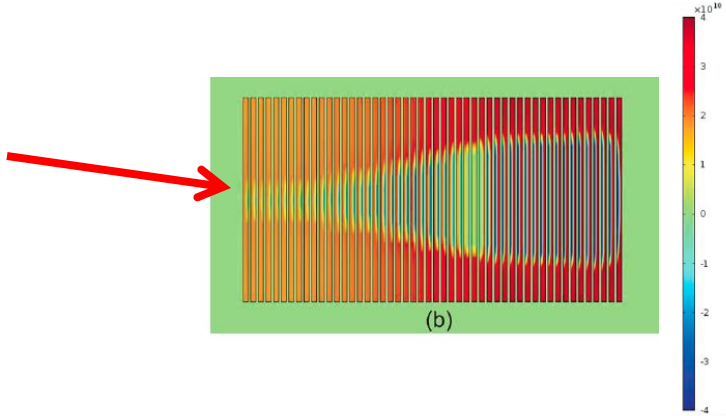
- Design challenges
  - Critical current



Zhang et al. J. Appl. Phys. 111, 083902 (2012)

Non circular coils

- Design challenges
  - Critical current
  - Transient or AC losses
    - Inherent: AC or transient currents
    - External: Ripple fields



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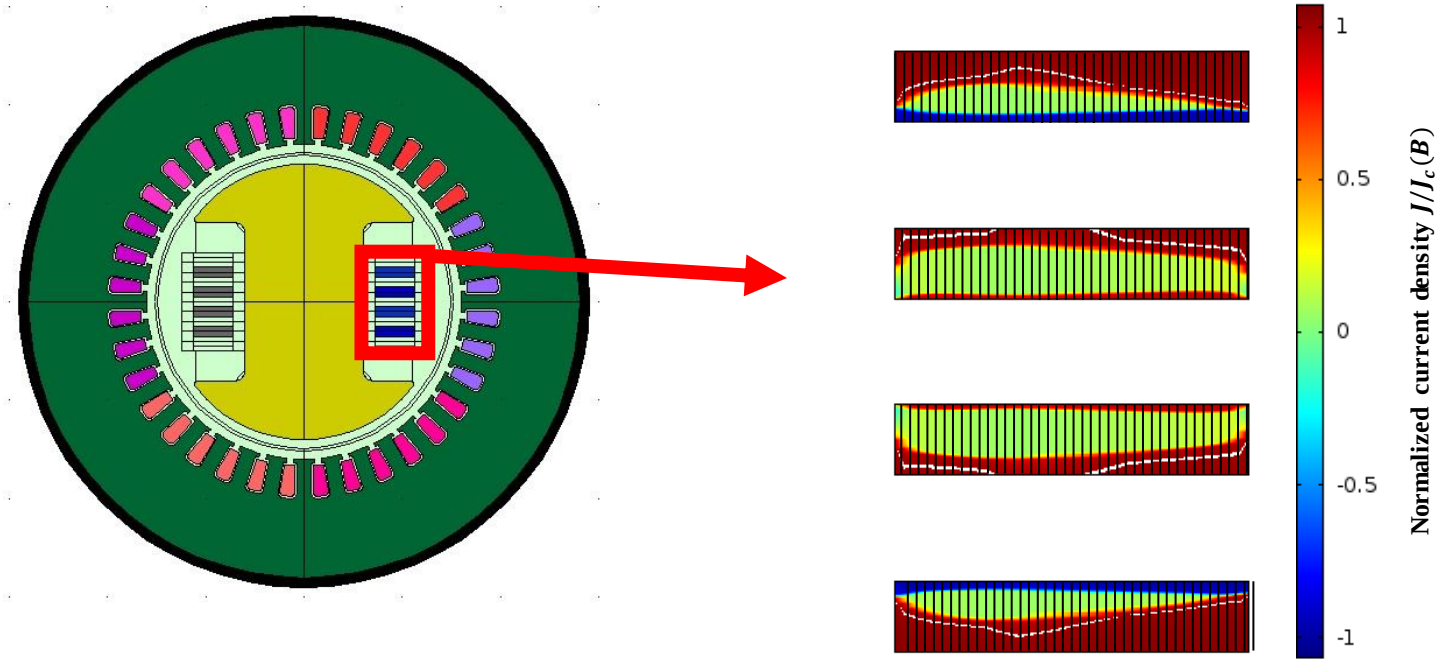
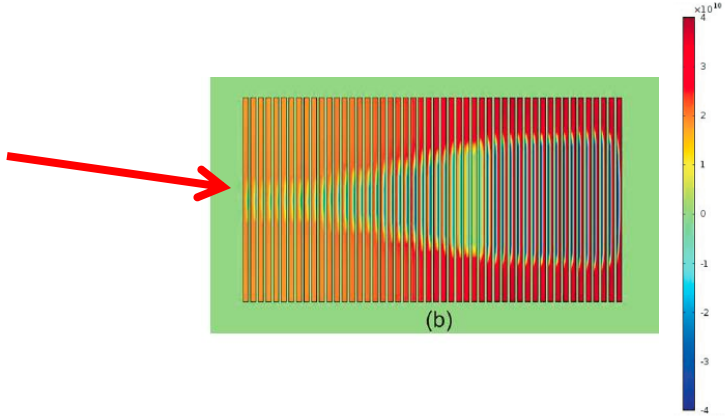


Non circular coils

- Design challenges
  - Critical current
  - Transient or AC losses
    - Inherent: AC or transient currents
    - External: Ripple fields
  - Maximum load rate



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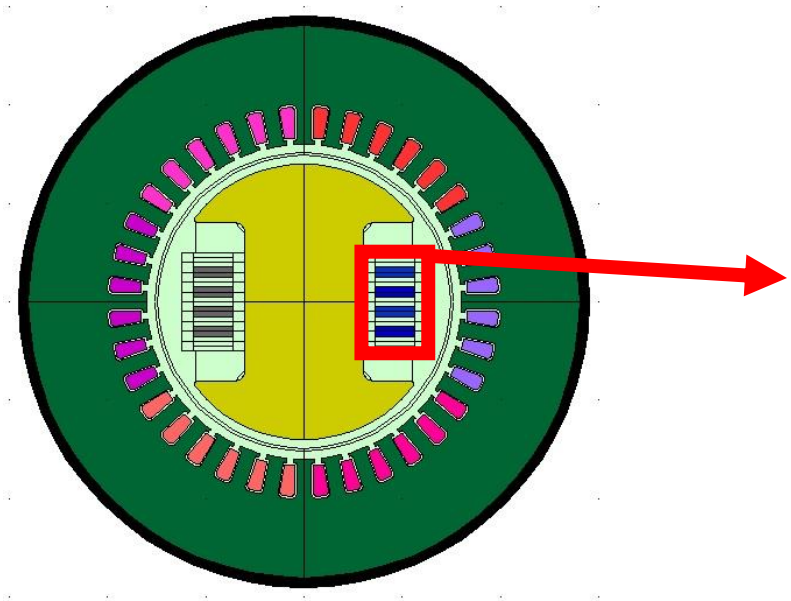
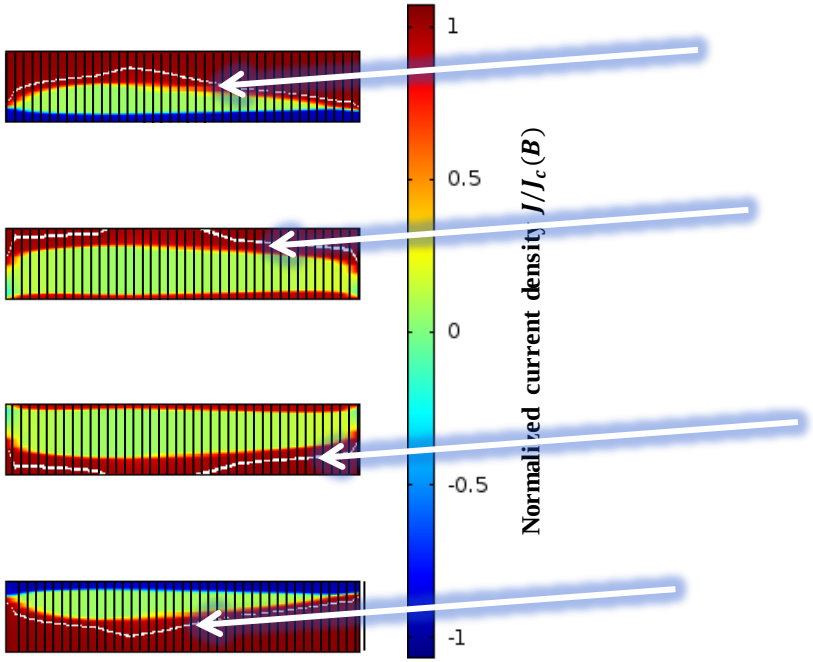
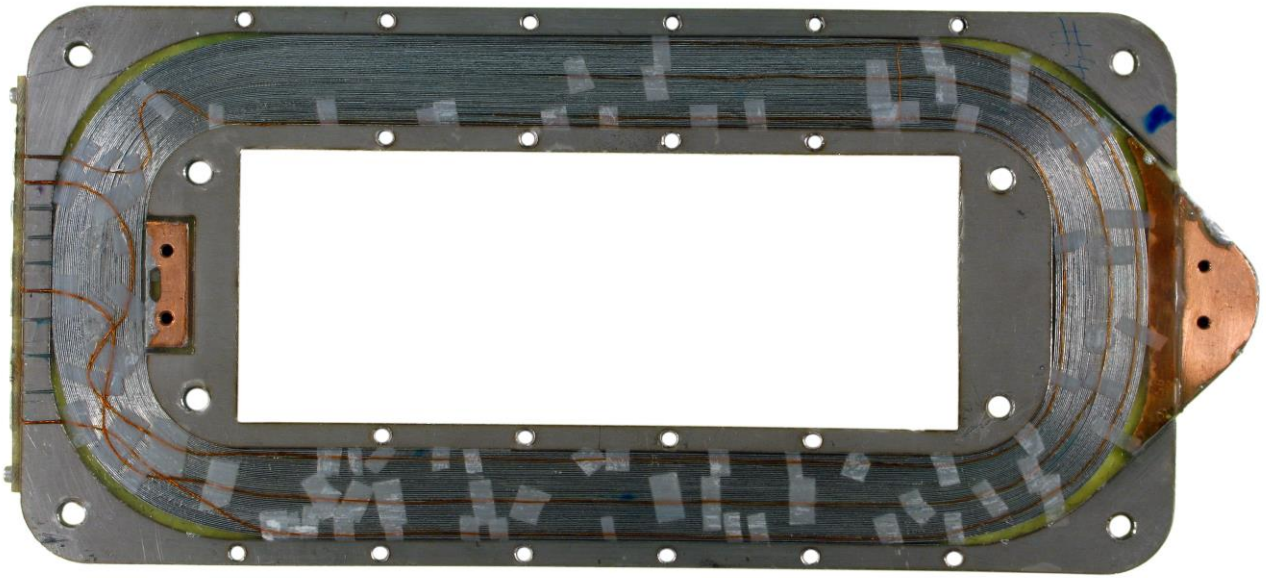




2G CC Non circular coils

- Modeling Challenges
  - Lack of symmetries prevents realistic 2D modeling
  - Detailed 3D model taking into account every turn is computationally too expensive.



A B Abrahamsen *et al.* Physica C, Vol 471, 21–22, 1464–9 (2011)

Mathematical modeling using H formulation

$$\nabla \times \rho \nabla \times \boldsymbol{H} = -\mu \frac{\partial \boldsymbol{H}}{\partial t} \quad in\ \Omega$$

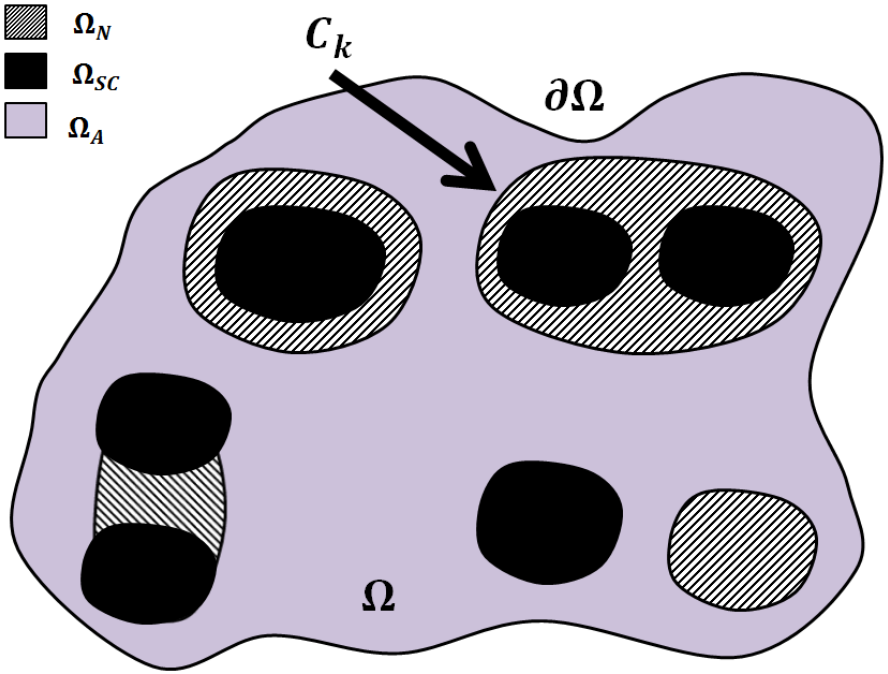
$$\boldsymbol{H} = \boldsymbol{H}_{self} + \boldsymbol{H}_{ext} \quad on\ \partial\Omega$$

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

$$\boldsymbol{H}\Big|_{\boldsymbol{t=0}} = \mathbf{0}$$

$$I_k(t) = \int_{C_k} J(x,y,t)\, dxdy$$

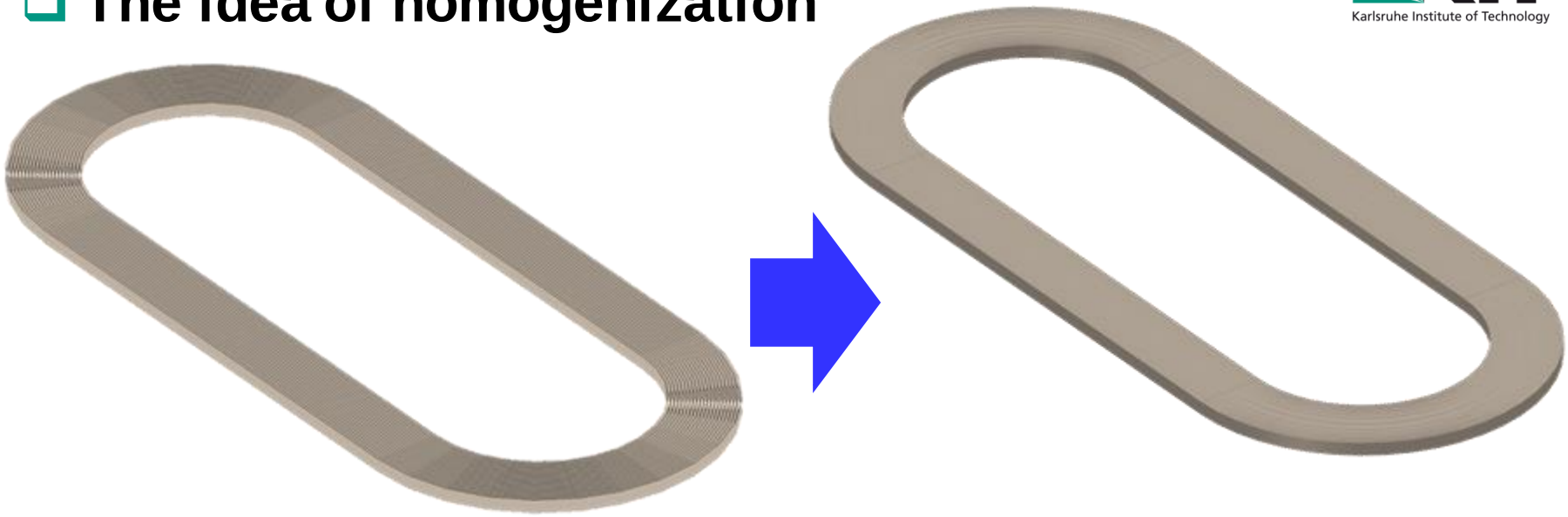
$$I_k(t)\ \forall k \in \{1,2,\dots,n_c\}$$



R. Brambilla, et al., Supercond. Sci. and Tech. vol. 20, p. 16, 2007.

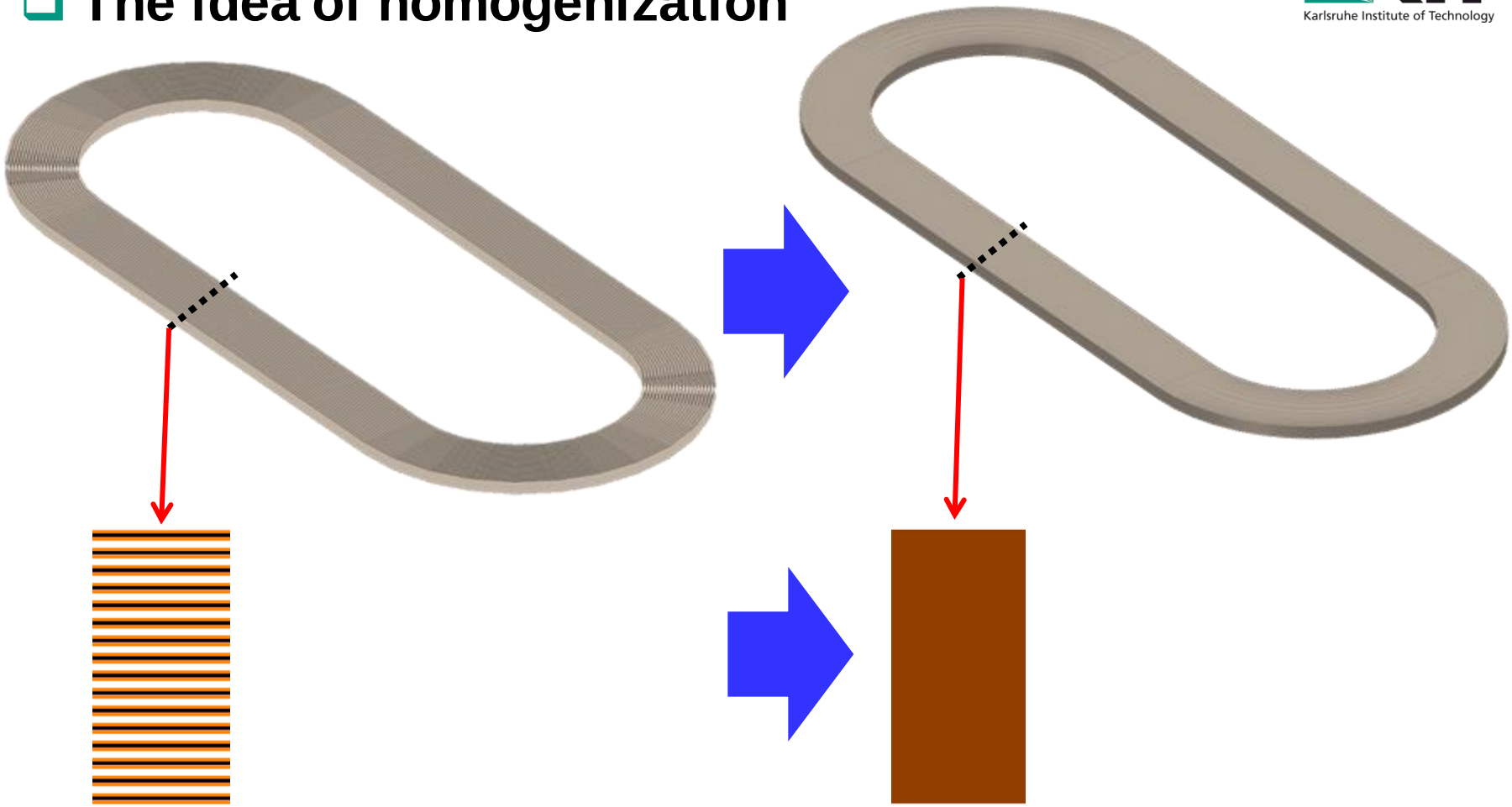
Z. Hong, et al. Supercond. Sci. Technol., vol. 20, pp. 331-337, 2007.

The idea of homogenization



- Internal geometric features are washed out
- Electromagnetic properties preserved

The idea of homogenization



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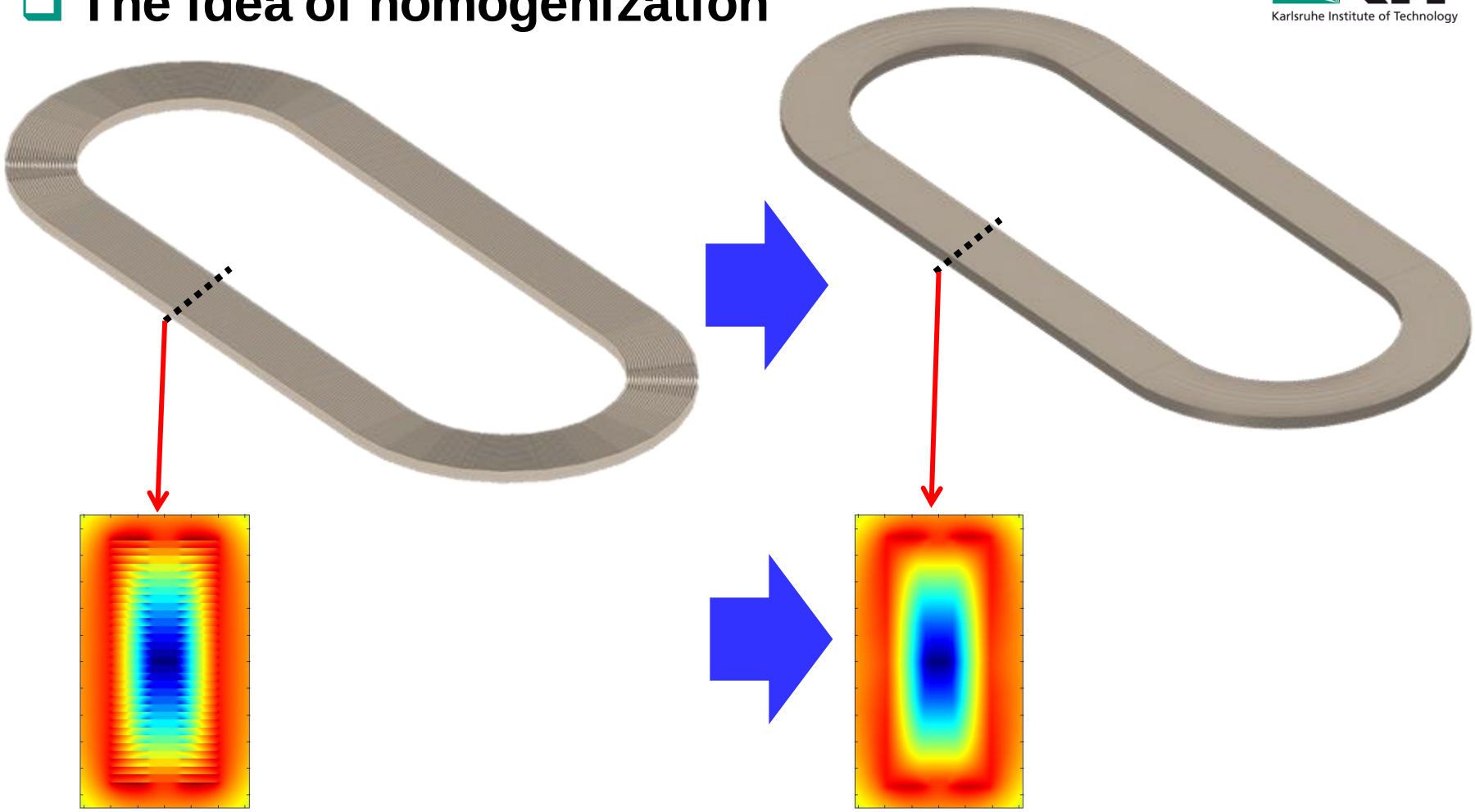

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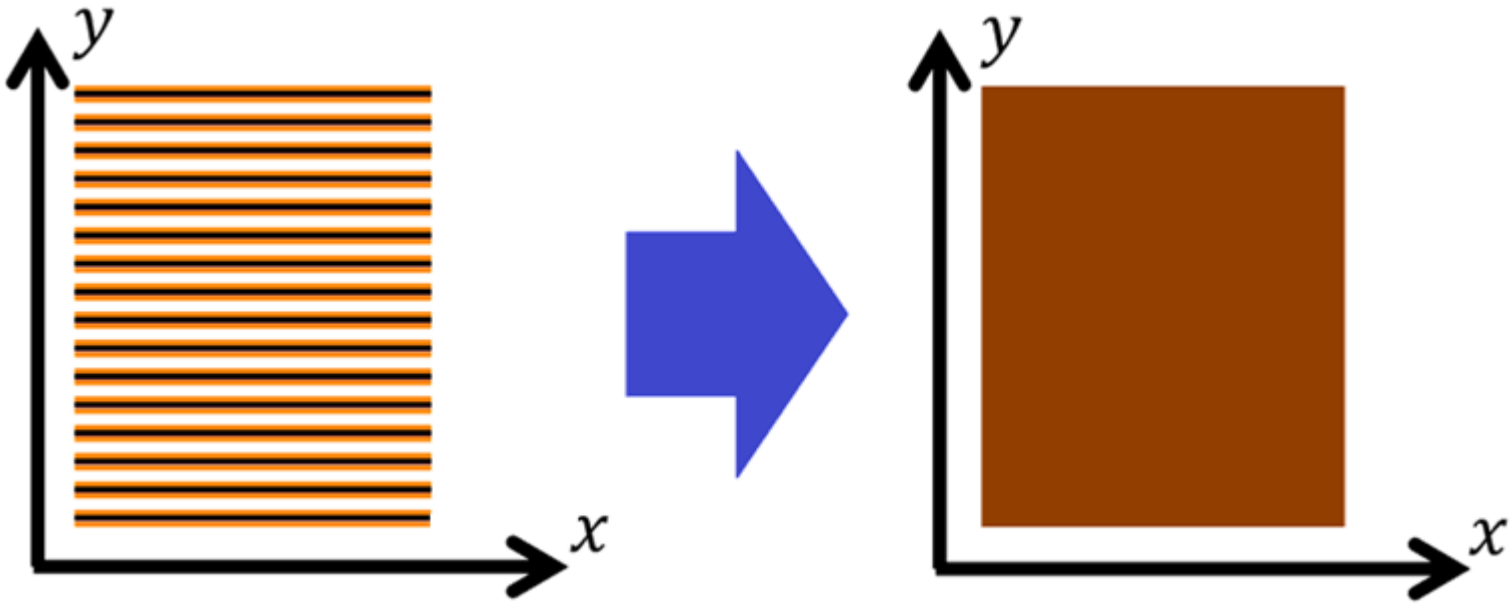
The idea of homogenization in 2D



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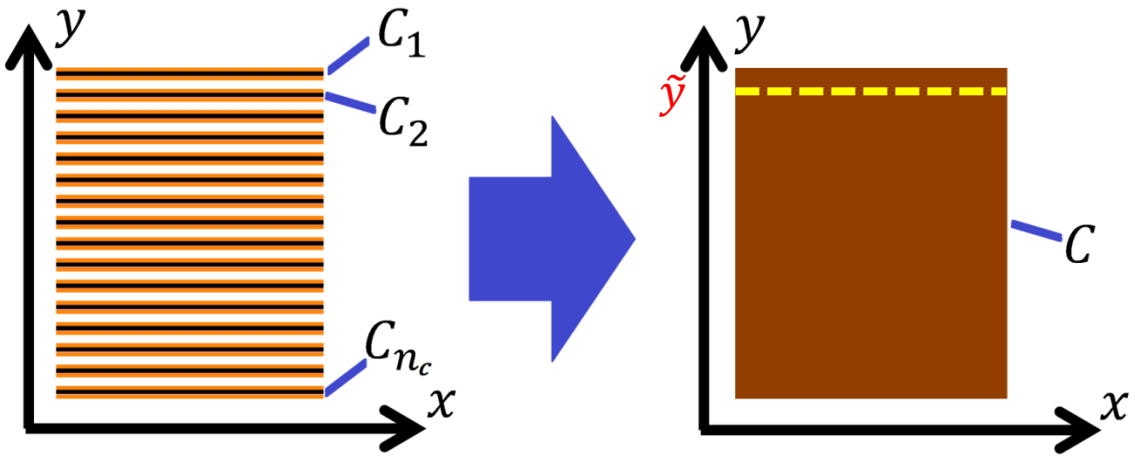
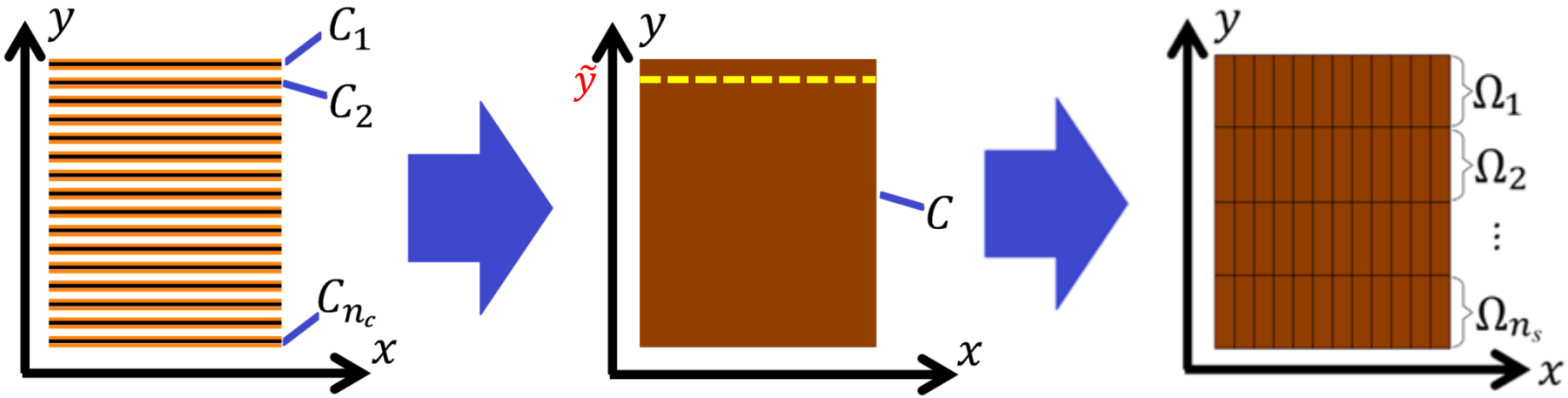
2D Homogenization



$$I_k(t) = \int_{C_k} J(x, y, t)\,dx\,dy \qquad \forall k \in \{1,2, \dots, n_c\}$$

$$K(\tilde{y}, t) = \int_{C} J(x, \tilde{y}, t)\,dx$$

❑ 2D Homogenization



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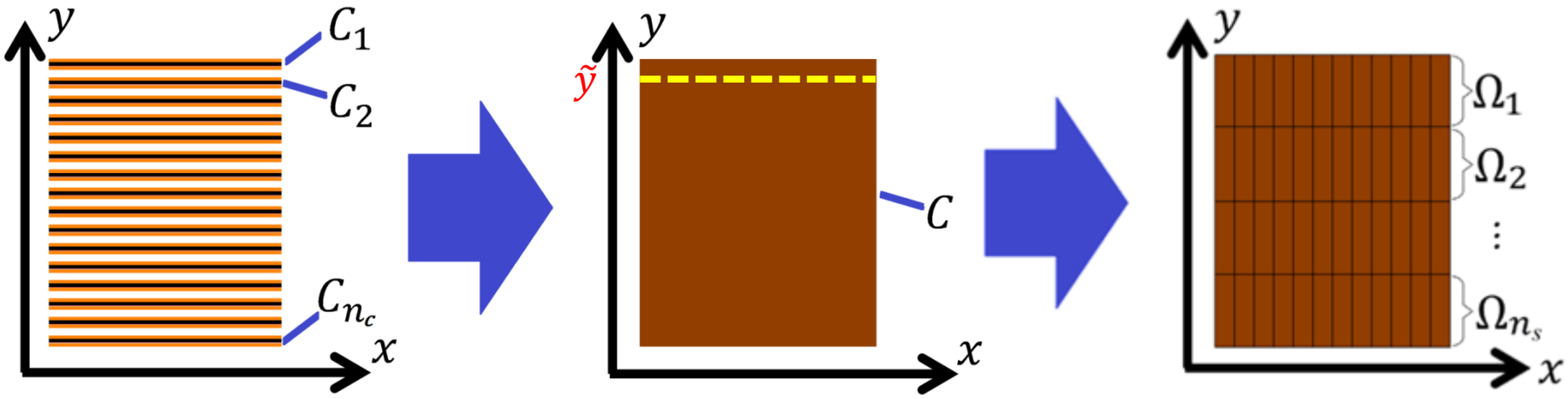
$$I_i(t) = \int_{\Omega_i} J(x,y,t)\,dxdy$$

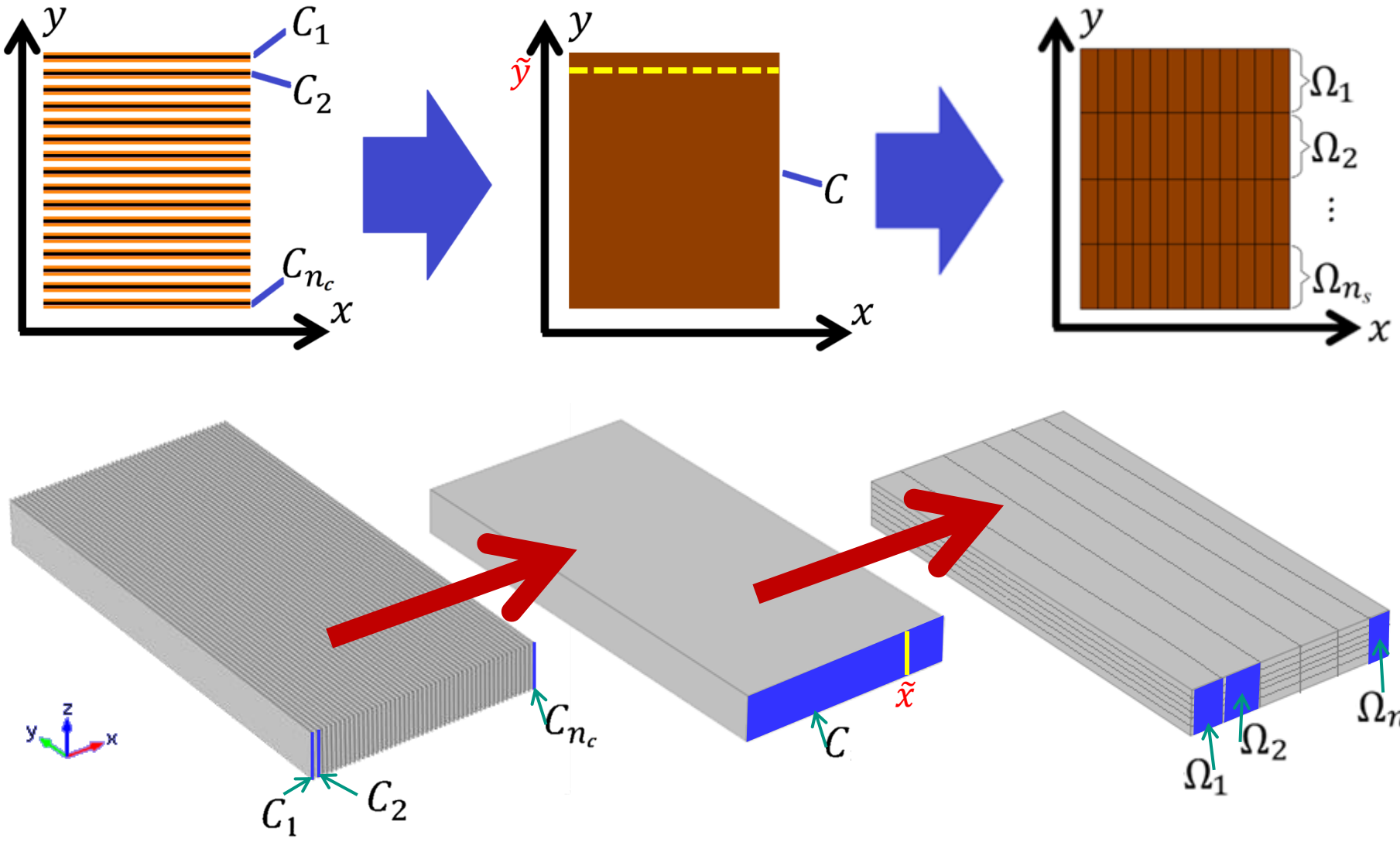
$$\forall i \in \{1,2,\dots,n_s\}$$

$$n_C > n_s$$

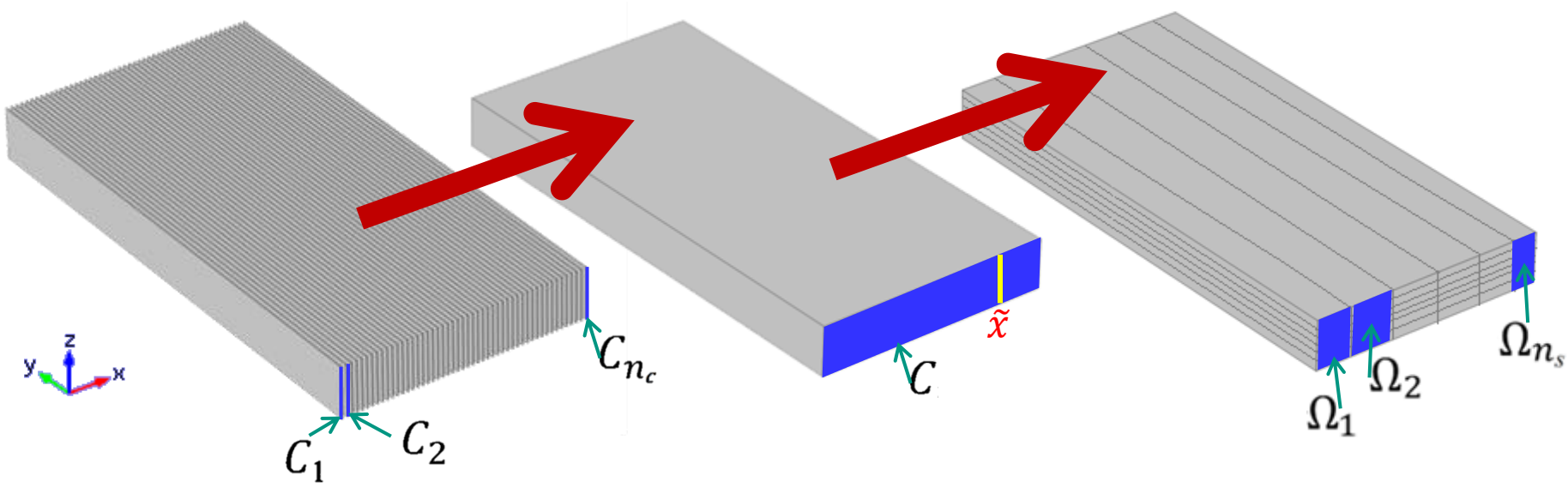
From 2D to 3D



From 2D to 3D



3D Homogenization



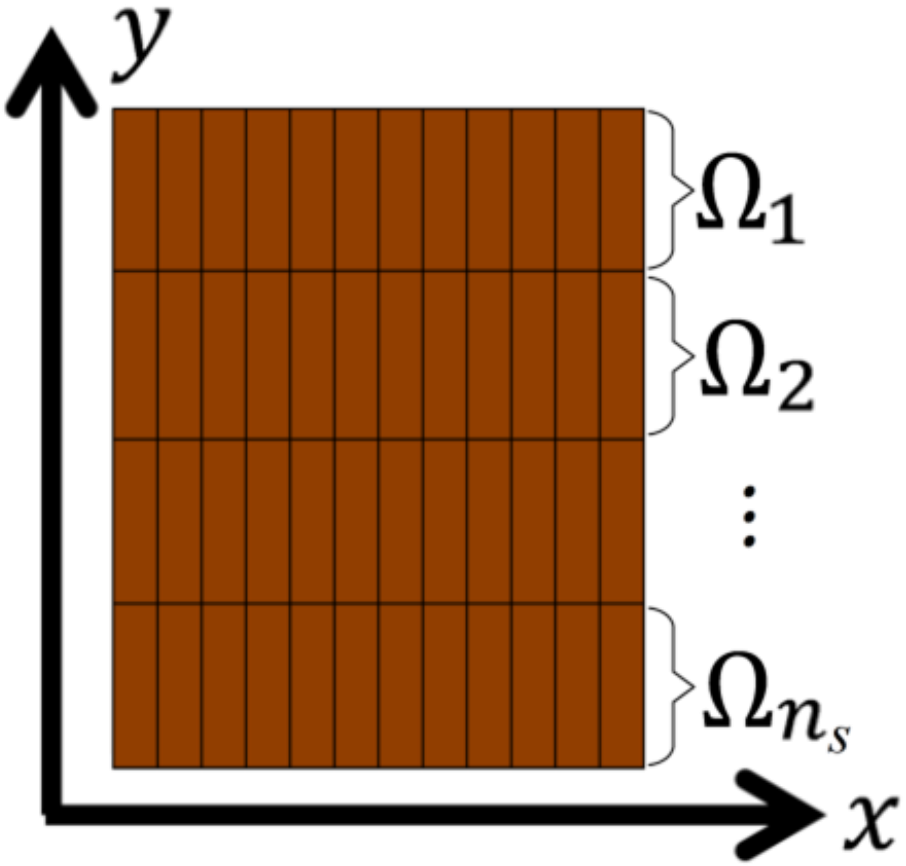
$$I_k(t) = \int_{C_k} J(x,z,t)\,dxdz \qquad \forall k \in \{1,2,\dots,n_c\}$$

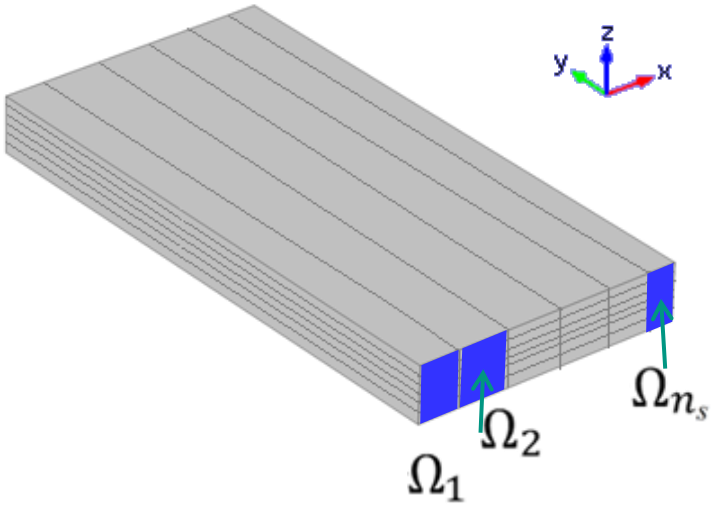
$$K(\tilde{x},t) = \int_{C} J(\tilde{x},z,t)\,dz$$

$$I_i(t) = \int_{\Omega_i} J(x,z,t)\,dxdz \qquad \forall i \in \{1,2,\dots,n_s\}$$

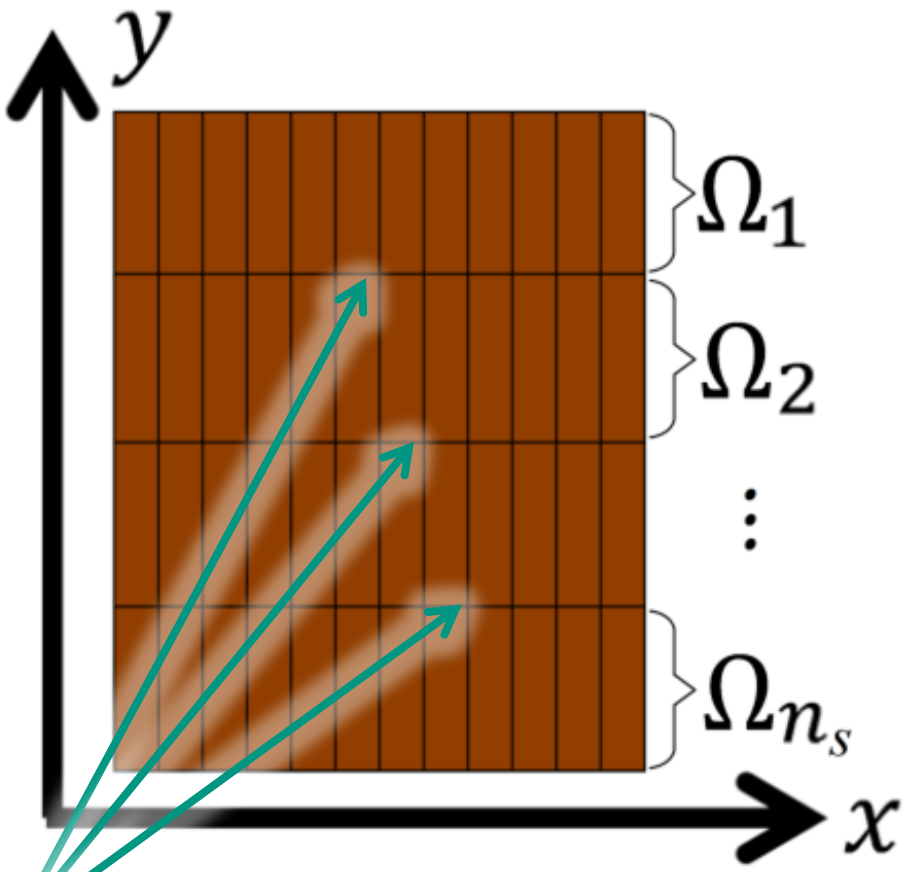
$$n_C > n_s$$

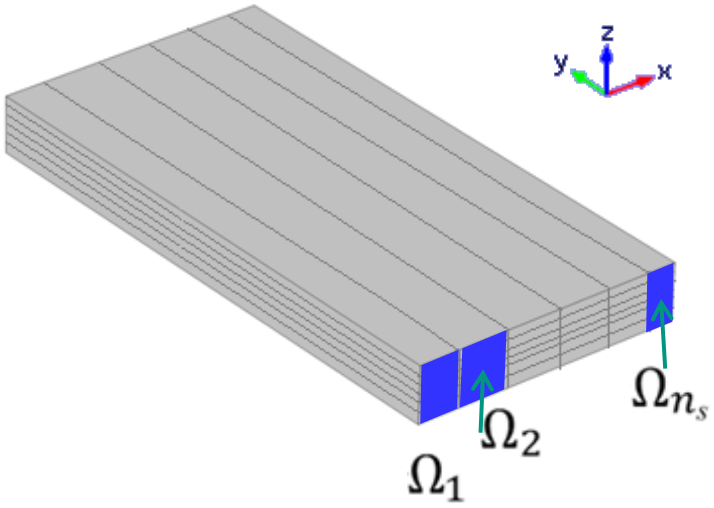
Perpendicular Conductivity





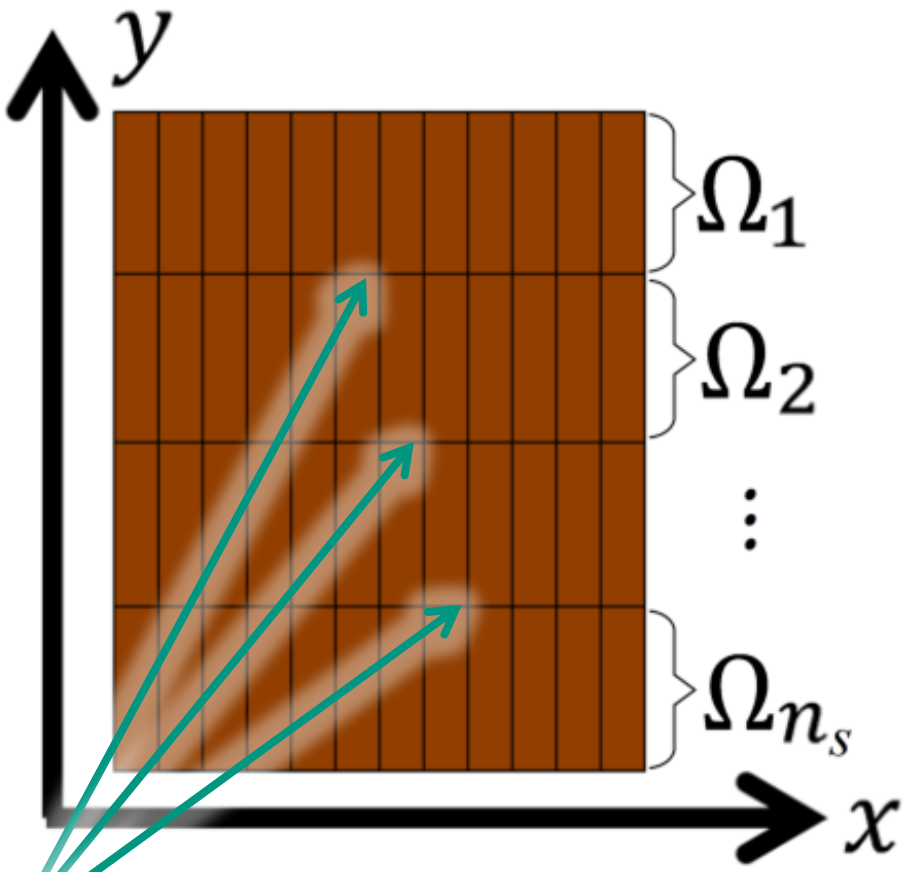
Perpendicular Conductivity



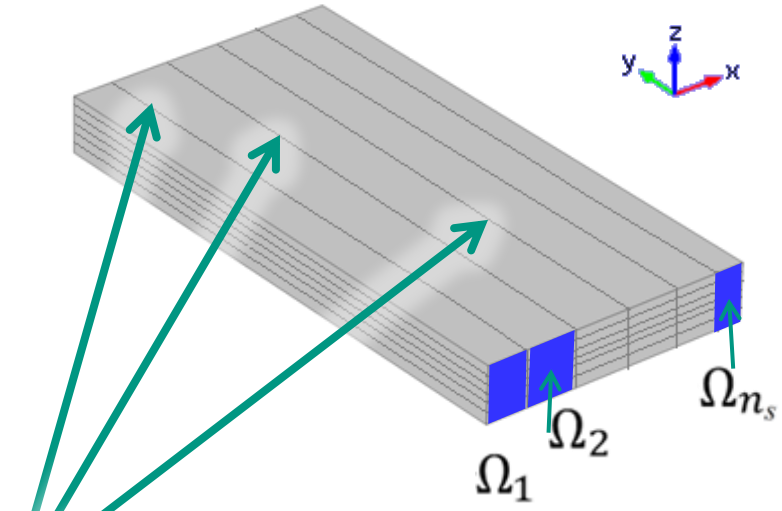


- Zero conductivity interphase condition between domains given by construction (y direction).

Perpendicular Conductivity

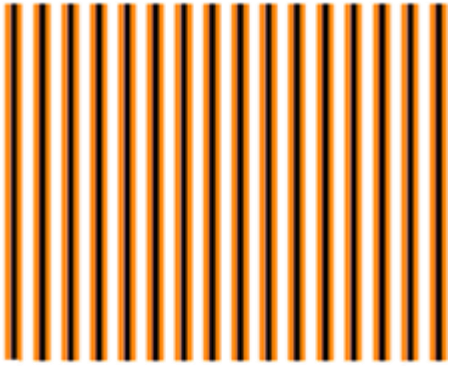


- Zero conductivity interphase condition between domains given by construction (y direction).

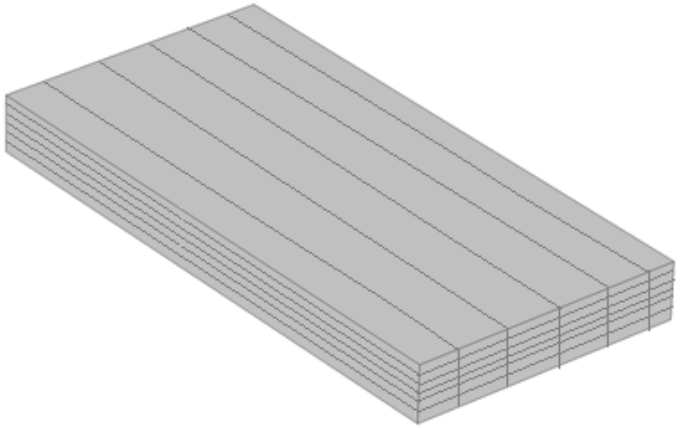


- Zero conductivity interphase condition between domains (x direction) needs to be enforced externally.
- Thin air domains used instead

❑ Validation



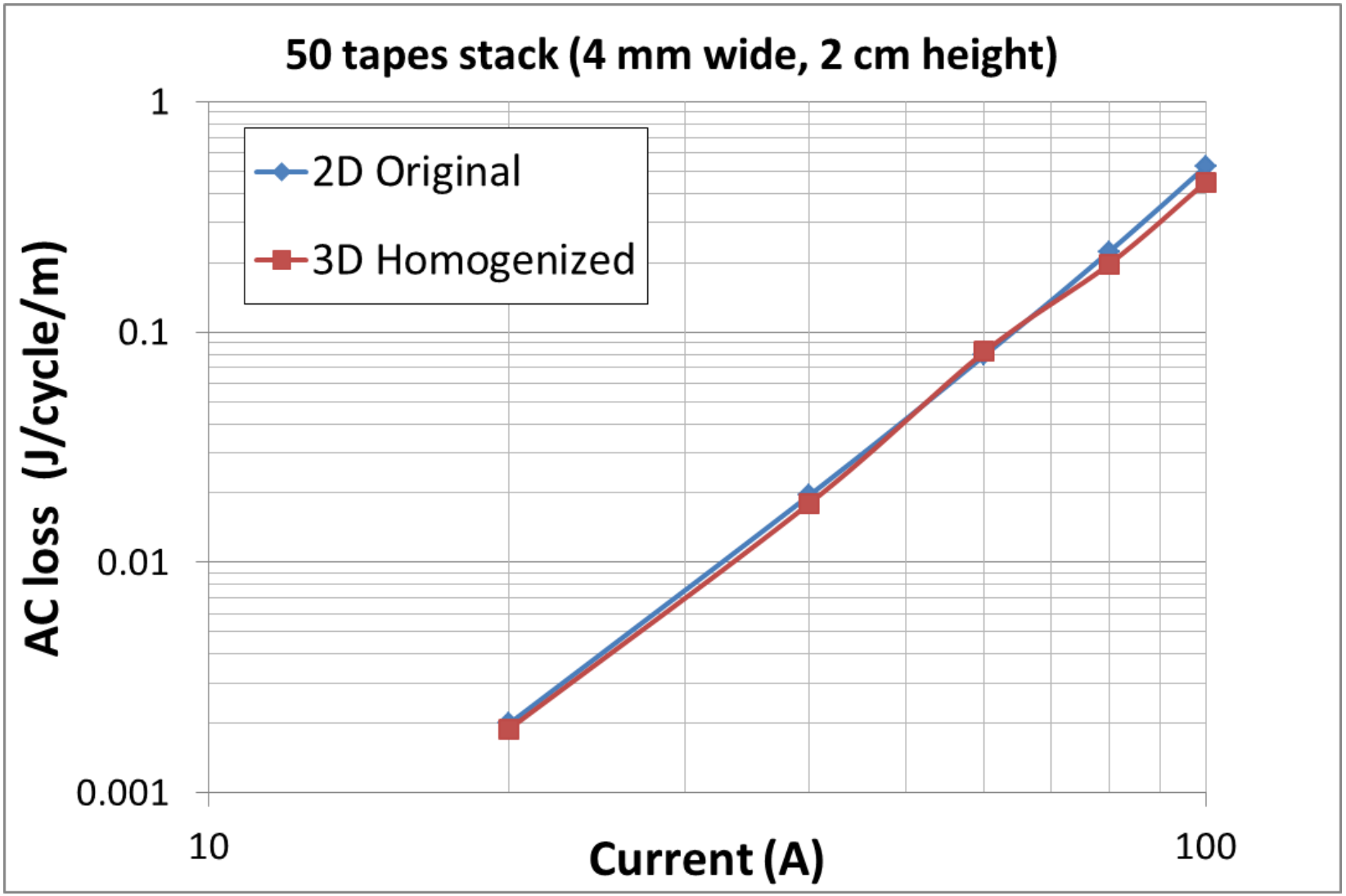
Vs.



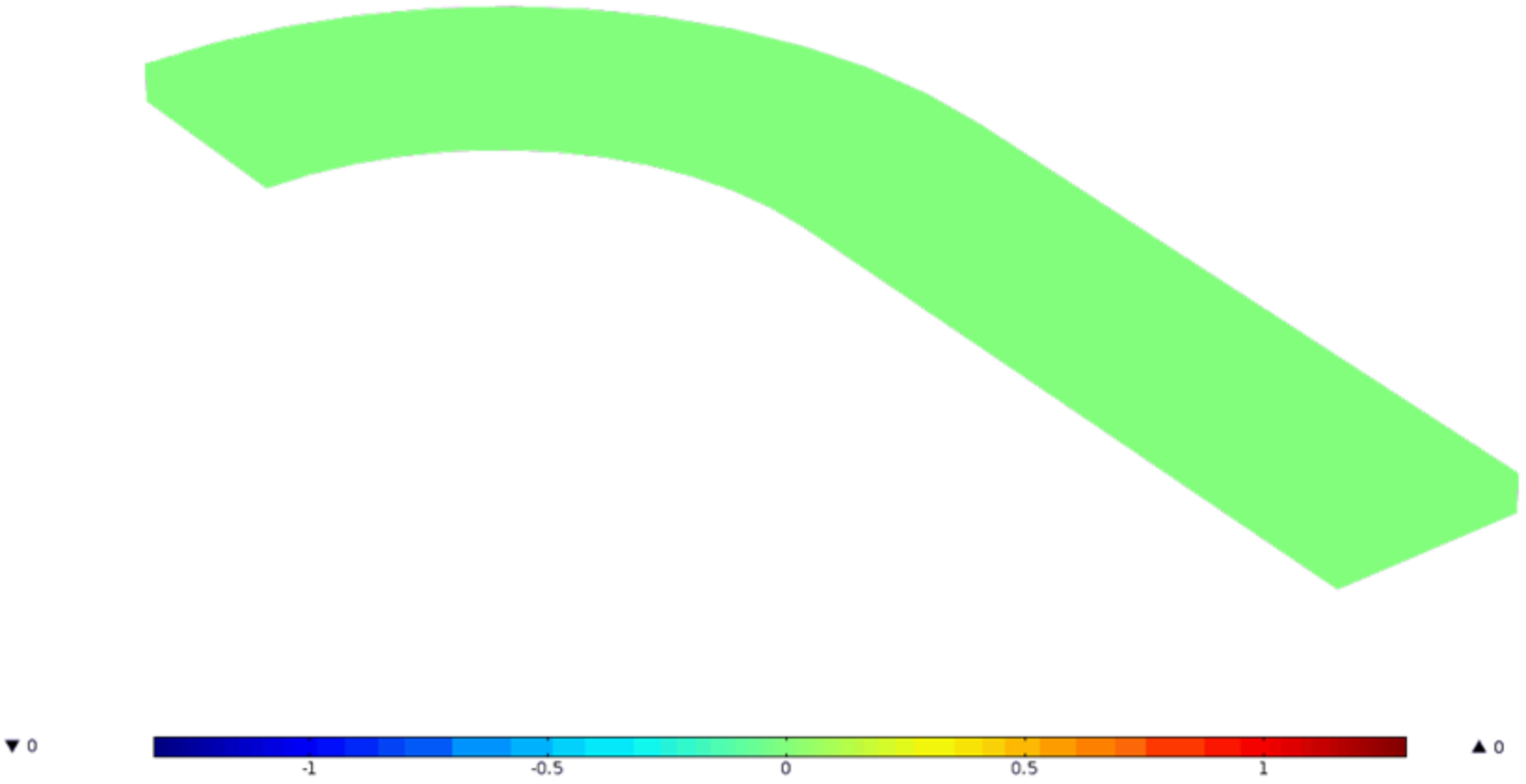
2D Original stack

3D Homogenized stack

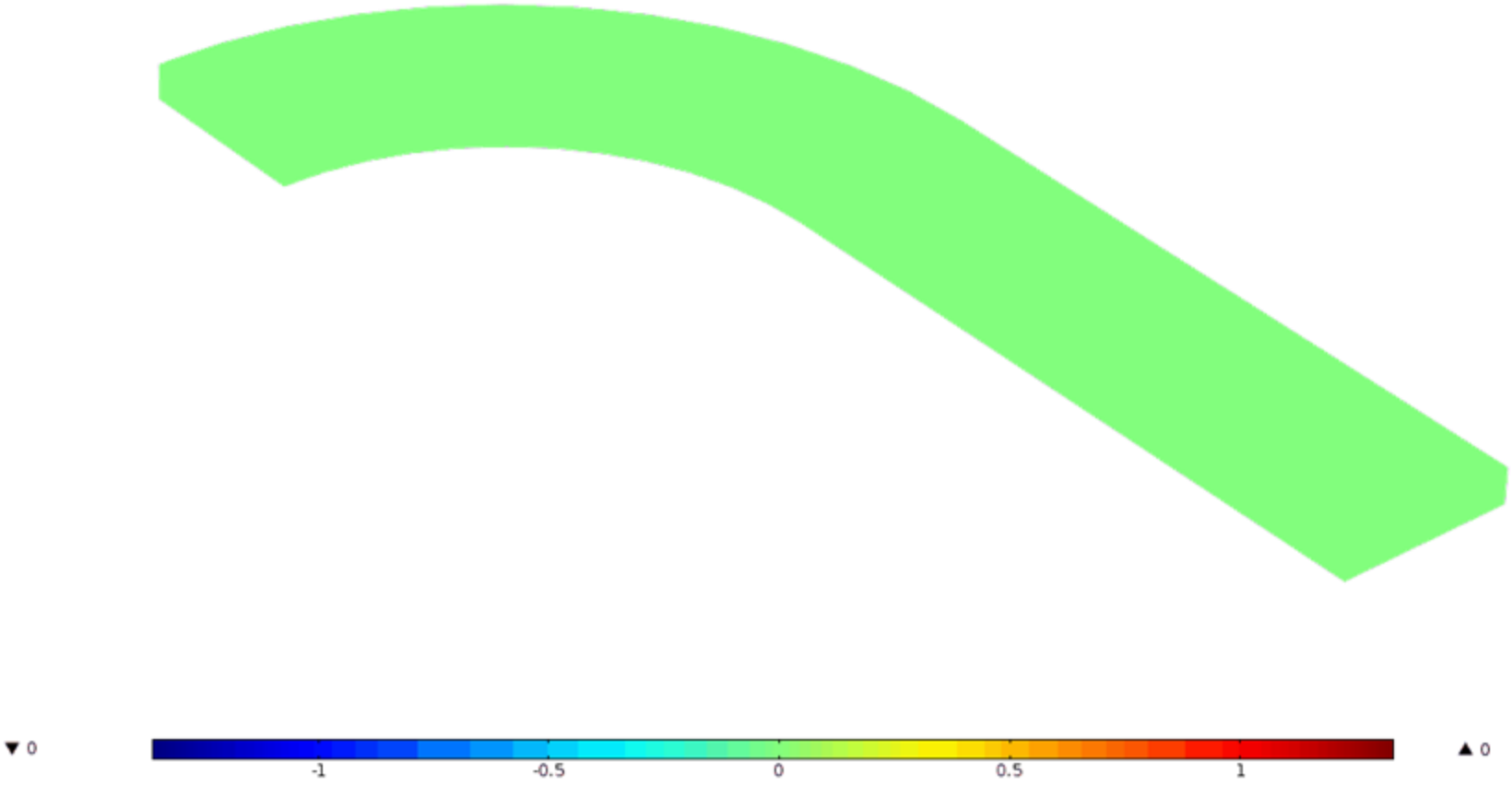
Validation in a straight stack



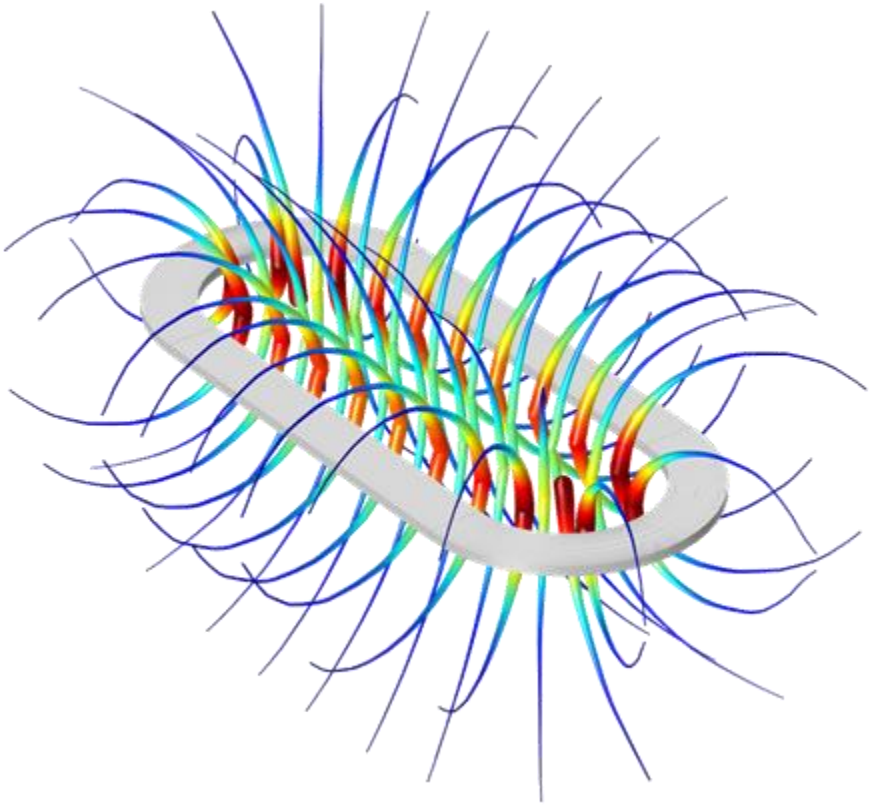
Transport Current in a Racetrack coil ~75% Ic



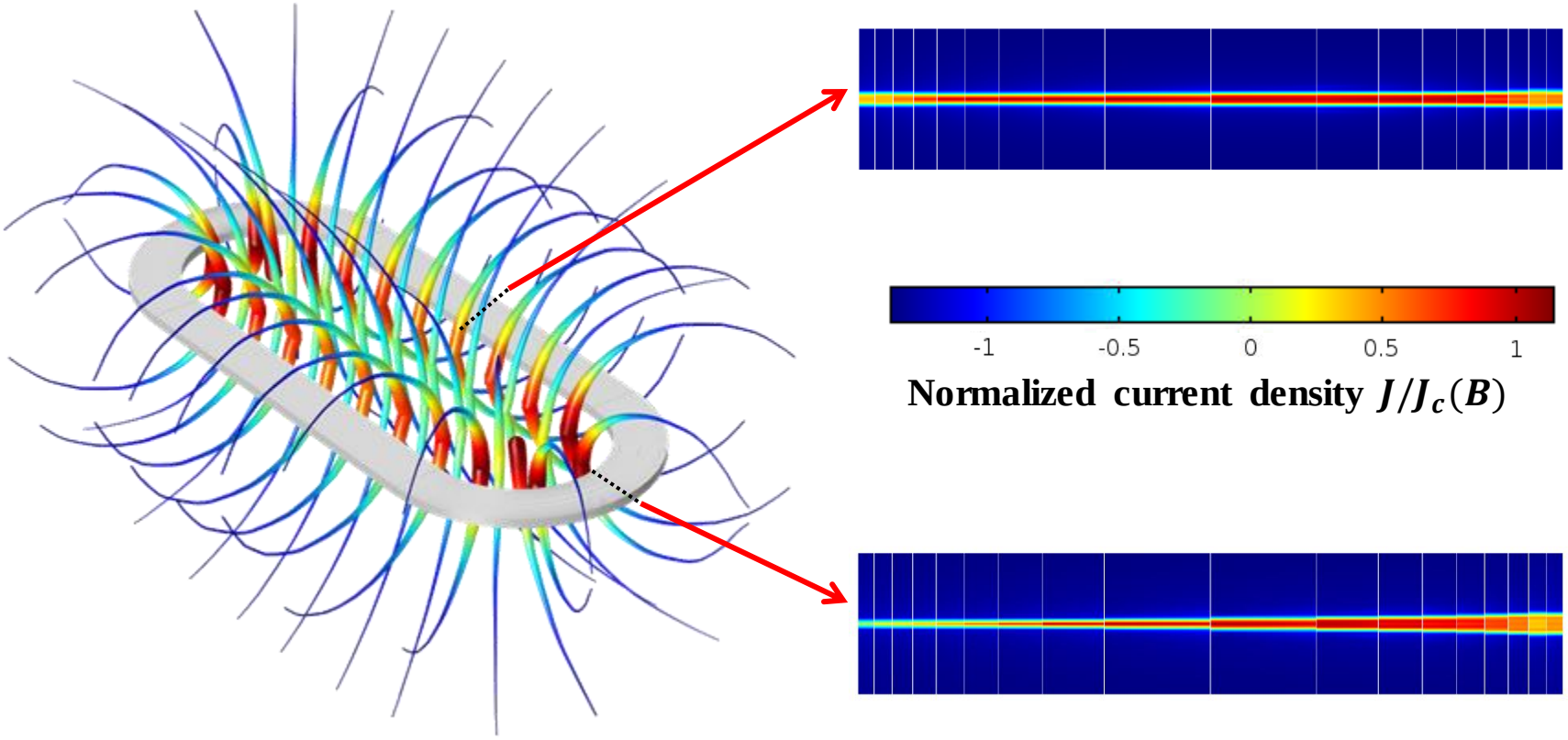
Transport Current in a Racetrack coil ~90% Ic



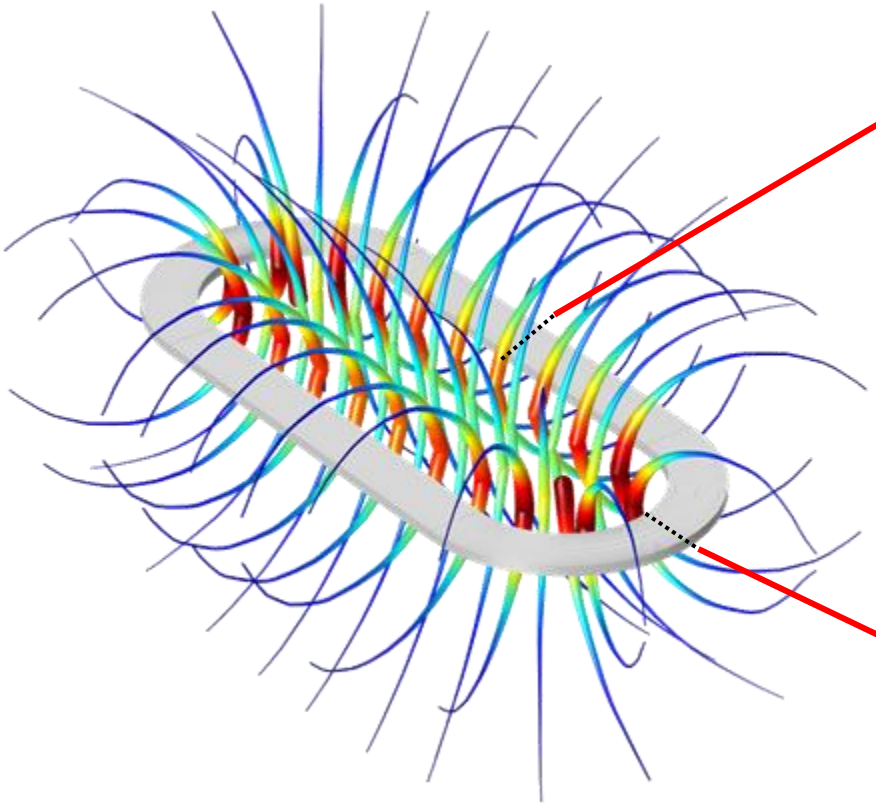
Magnetic Field Profile

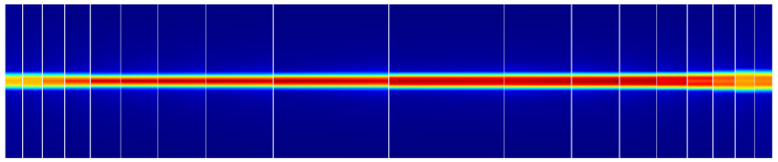


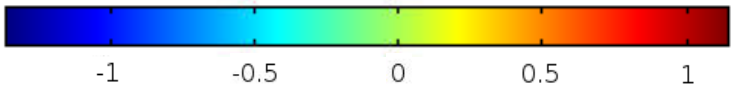
❑ Current distribution



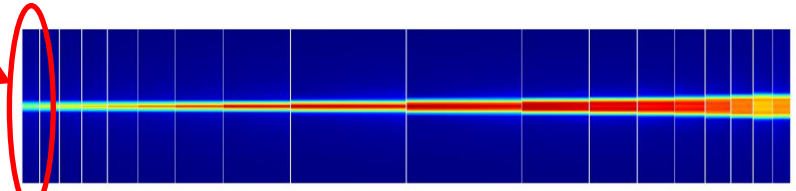
Ic determination





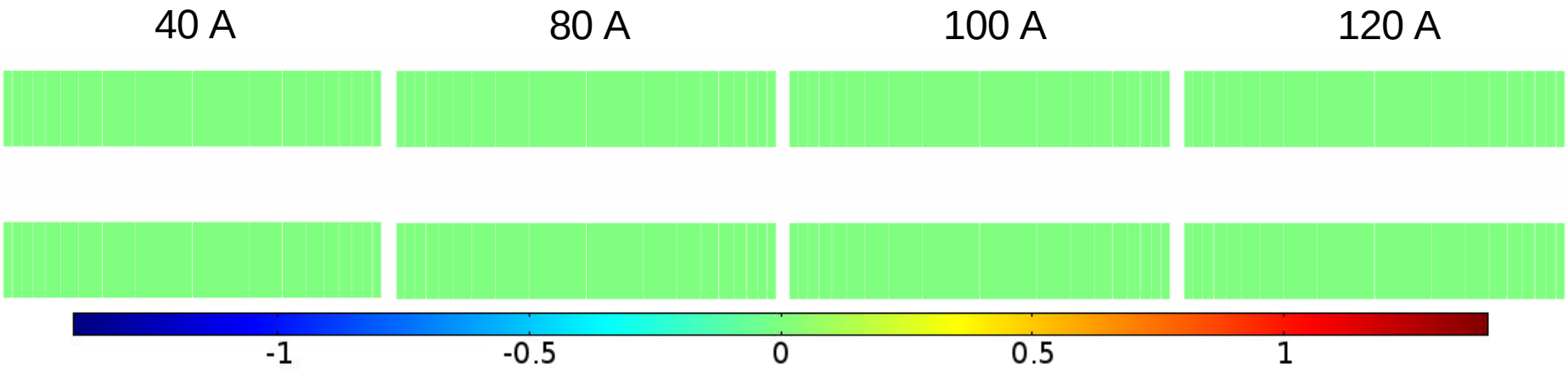


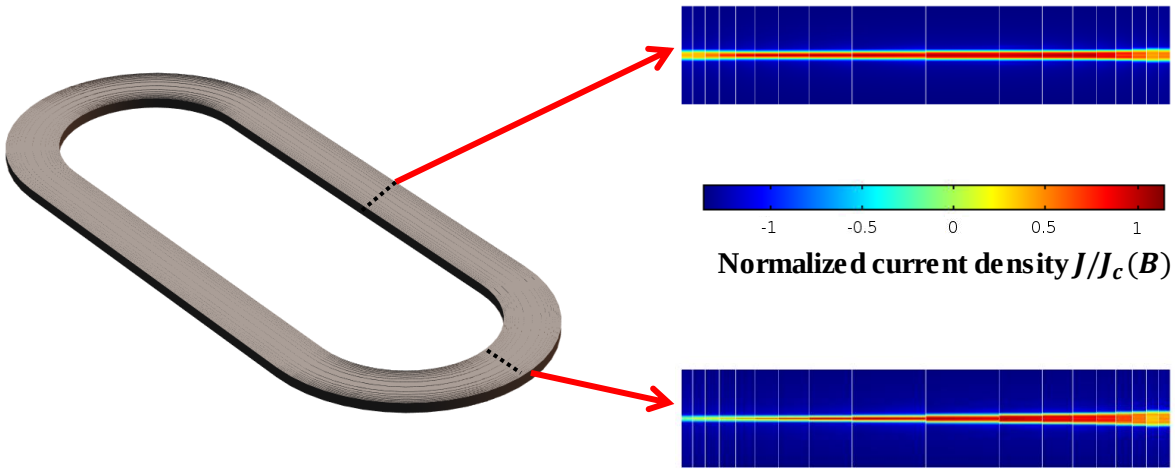
Normalized current density $J/J_c(B)$



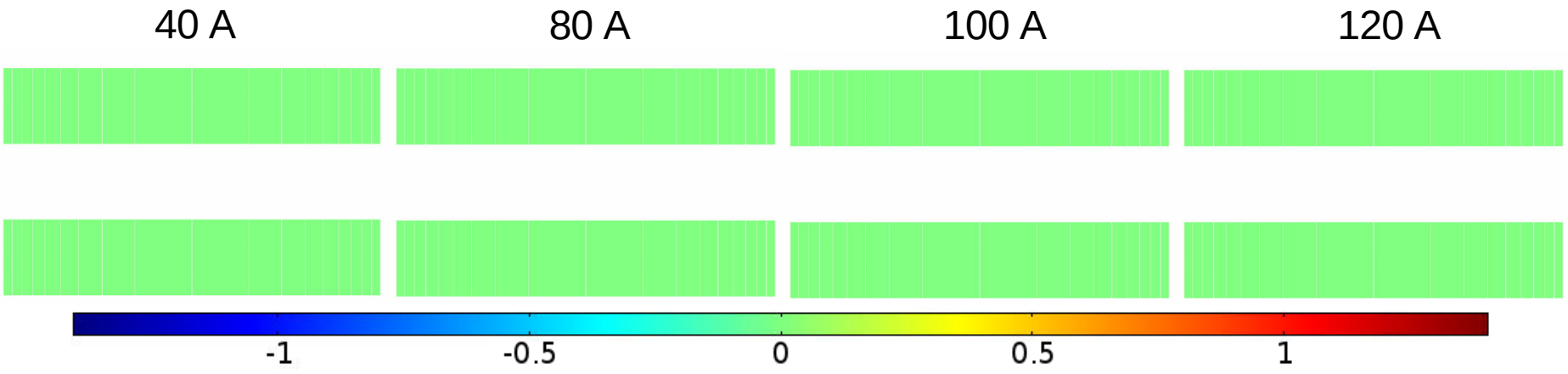
Ic limited by the inner turn
in the round section

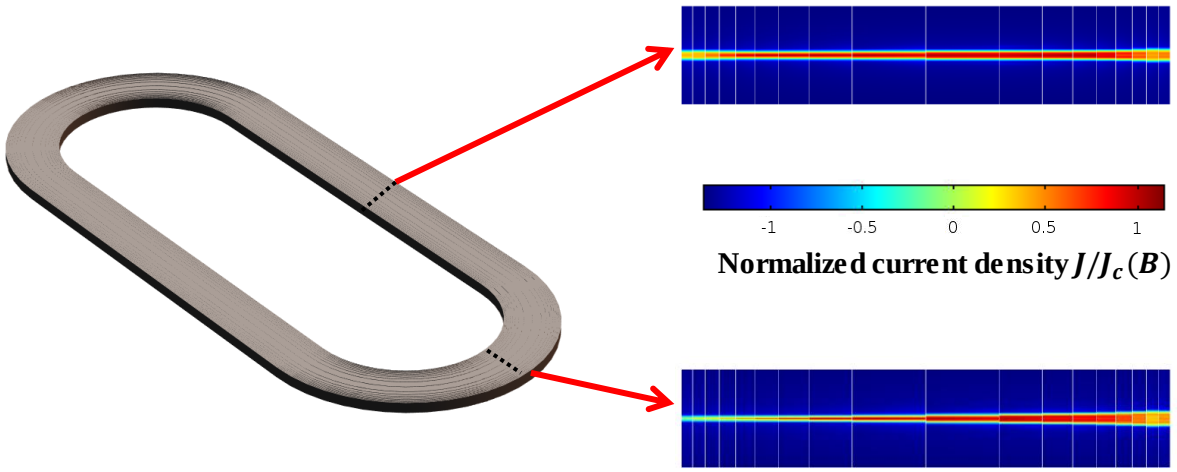
Transport Current in a Racetrack coil



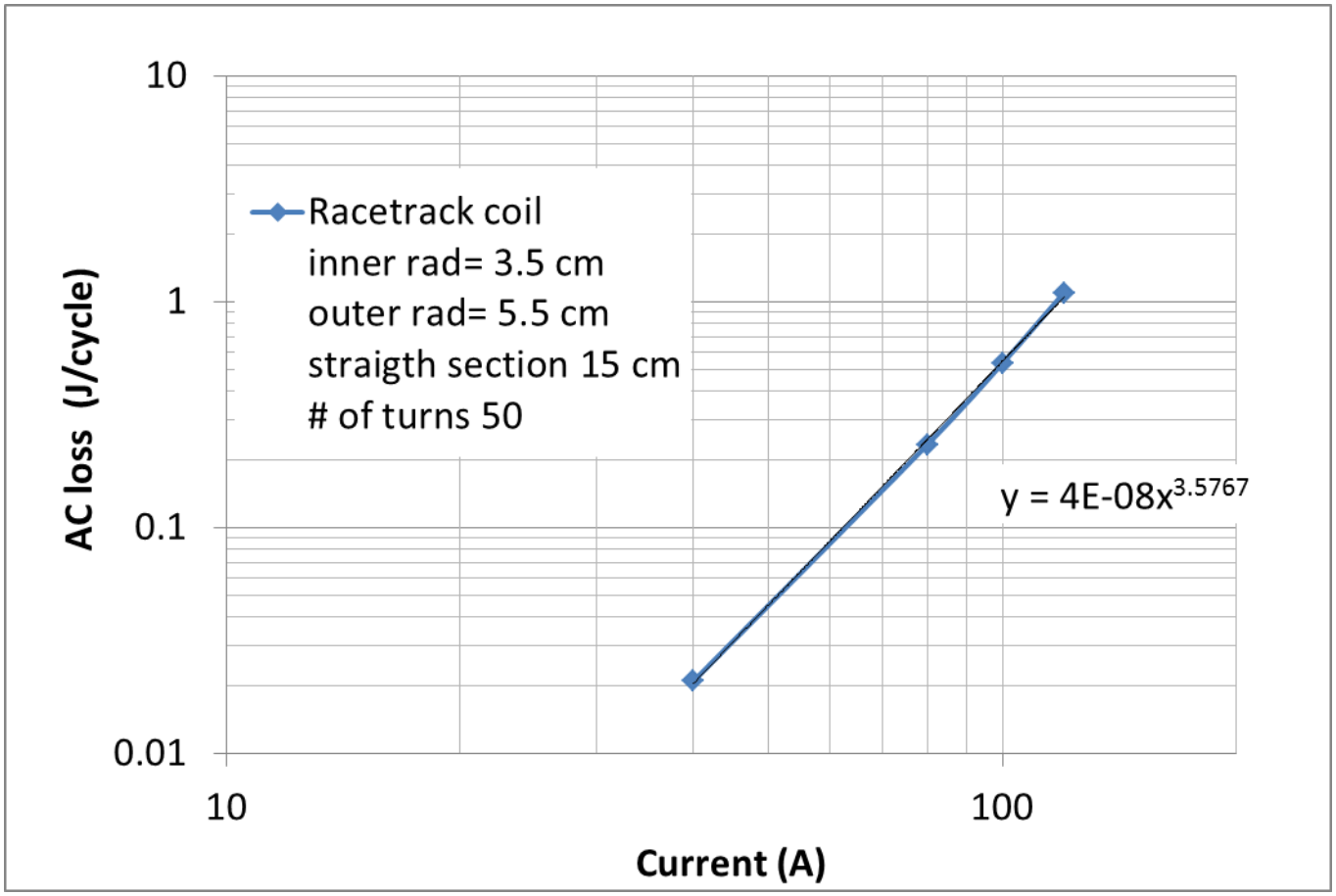


Transport Current in a Racetrack coil





AC losses


10
1
0.1
0.01
AC loss (J/cycle)
Racetrack coil
inner rad= 3.5 cm
outer rad= 5.5 cm
straigth section 15 cm
# of turns 50
y = 4E-08x^3.5767
10
100
Current (A)

Conclusions

- A 3D homogenization technique was developed to model stacks and coils of 2G HTS coated conductors.
  - The technique complements previous work in 2D.
  - Although no zero conductivity perpendicular to the tapes' surface was implemented, use of thin air domains proved to be a good solution.
- For validation purposes, 3D homogenization was used to model and simulate current transport in stacks.
- The method was latter used to simulate the current profiles inside racetrack coils and to estimate their AC losses.

Furture work

- Implement 3D homogenization in other stack-like structures and non-planar coils i.e. saddle shaped coils.

Thank you