# Numerical modelling of a compact trapped field magnet using HTSc tapes as energizing coil during PFM


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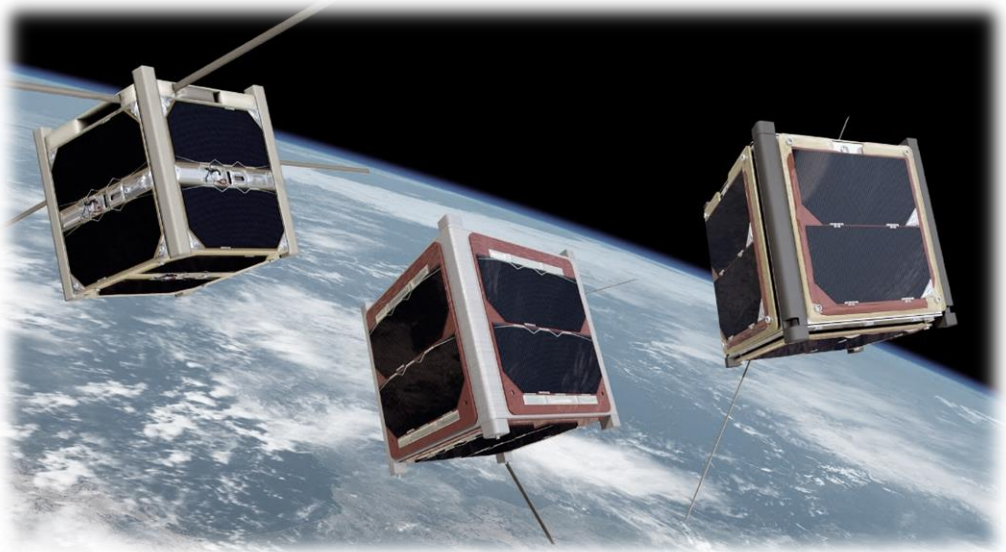
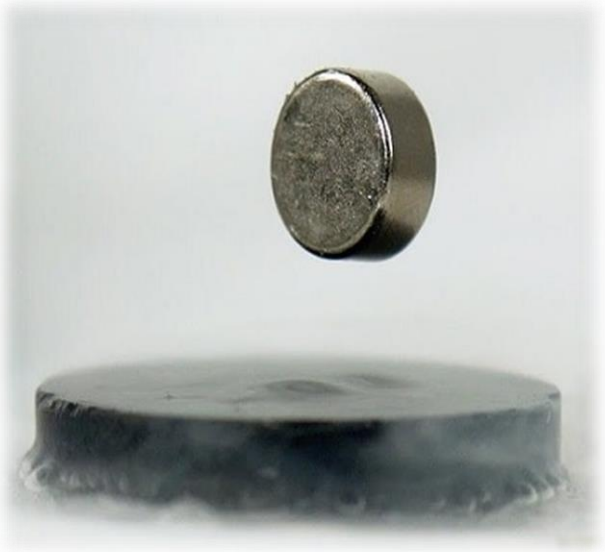
# Flux-Pinned Interfaces for Spacecraft





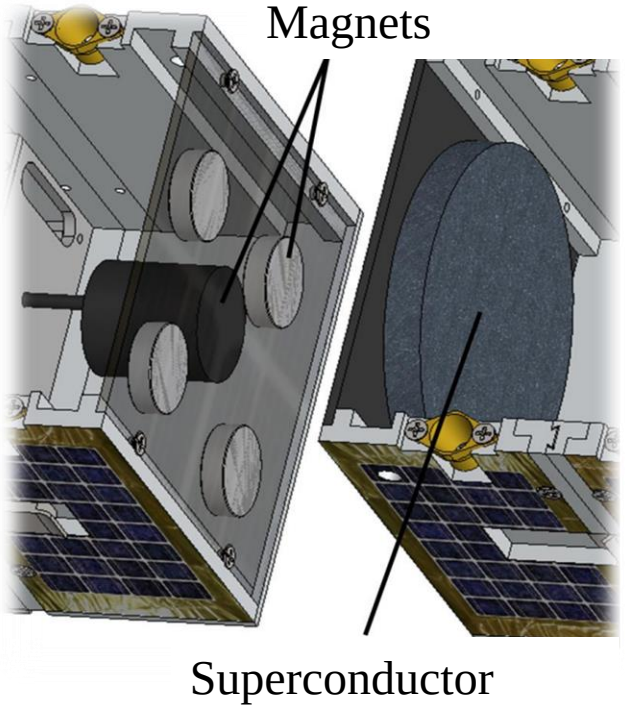
M. R. Koblischka *et al*., "Flux Pinning Docking Interfaces in Satellites Using Superconducting Foams as Trapped Field Magnets," in *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 4, pp. 1-5, June 2022, Art no. 4900105, doi: 10.1109/TASC.2022.3147734.

- Typical small satellites are usually less than 50 kg.

# Current work and context

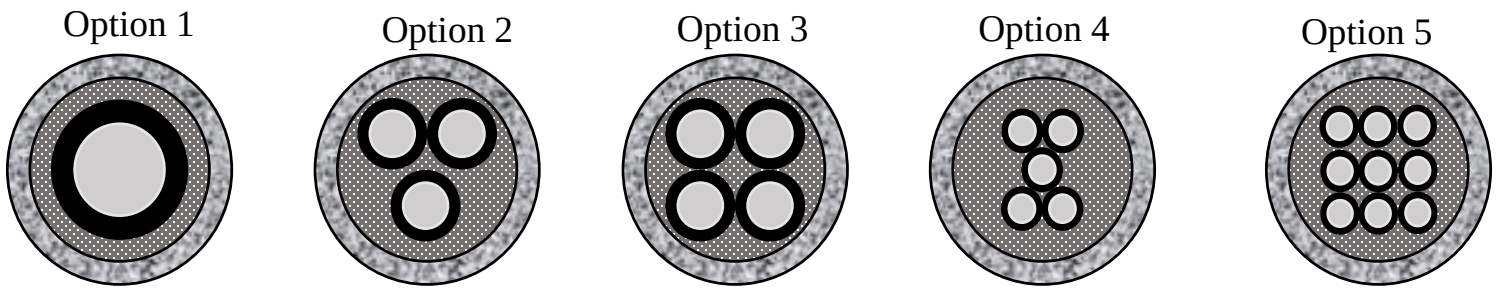
FC

Jones, Laura. "The Dynamics and Control of Flux-Pinned Space Systems: Theory and Experiment." (2012).




What about the use of PFM?

- **Magnetized** and **unmagnetized** superconducting bulks to **hang** or **unhang** satellites
- **Flexibility** of magnetization through an electromagnet
- HTS coil (HTSc) **less** losses by providing a copper coil.

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# Description of the system to be studied

The system contains:

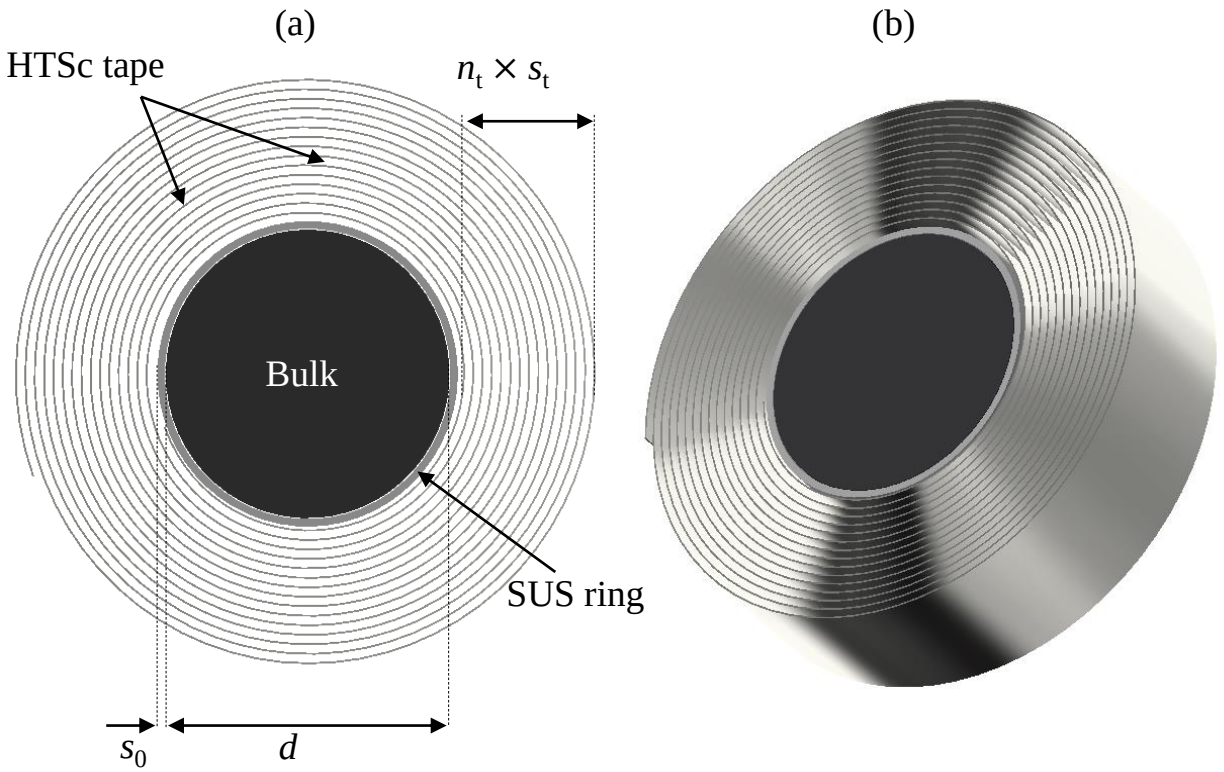
- ❑ A (RE)BaCuO superconducting coil
- ❑ A (RE)BaCuO bulk

Optimization is about:

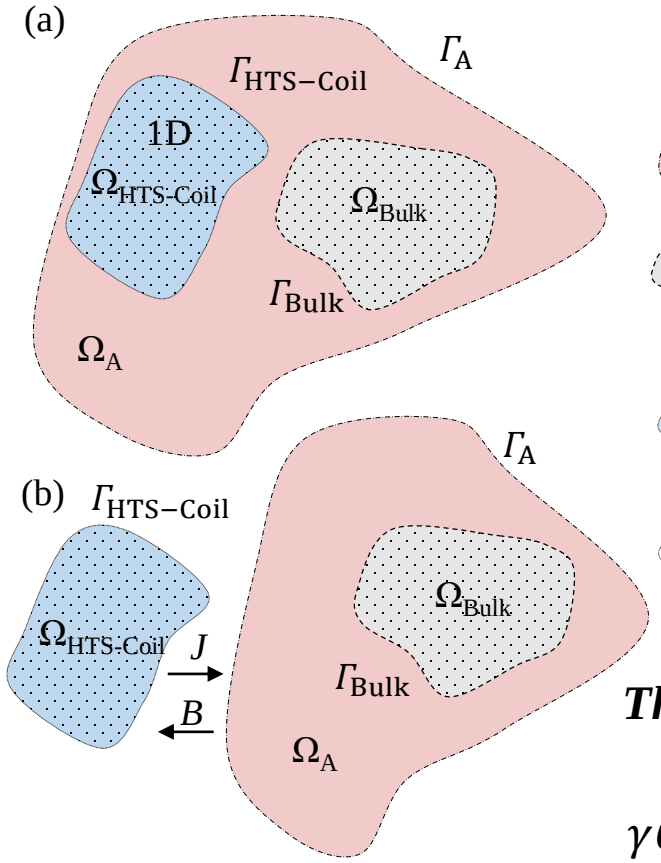
- ❑ Minimize **weight**
- ❑ Minimize **losses**
- ❑ Maximize the trapped magnetic field/flux

Electromagnetic formulation?

**T-A-H Formulation**



# T-A-H Formulation




## Governing equation and coupling

**A** Formulation

**H** Formulation

**T** Formulation

*Th* Heat transfer in solids

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad \nabla \times (\mu_0{}^{-1} \nabla \times \mathbf{A}) = 0$$

$$\mathbf{J} = \nabla \times \mathbf{H} \qquad \mu_0 d_t \mathbf{H} + \nabla \times (\rho_{\text{HTSc}} \nabla \times \mathbf{T}) = 0$$

$$\mathbf{J} = \nabla \times \mathbf{T} \qquad \mu_0 d_t \mathbf{H} + \nabla \times (\rho_{\text{Bulk}} \nabla \times \mathbf{H}) = 0$$

**HTSc model**

$$\rho_{\text{HTSc}} = \frac{E_c}{J_{c,\text{HTSc}}} \left( \frac{J_{\text{HTSc}}}{J_{c,\text{HTSc}}(B, Th)} \right)^{n_{\text{HTSc}}(B,Th)}$$

**Bulk model**

$$\rho_{\text{bulk}} = \frac{E_c}{J_{c,\text{bulk}}} \left( \frac{J_{\text{bulk}}}{J_{c,\text{bulk}}(B, T)} \right)^{n_{\text{bulk}}(B,Th)}$$

***Th* Heat transfer in solids**

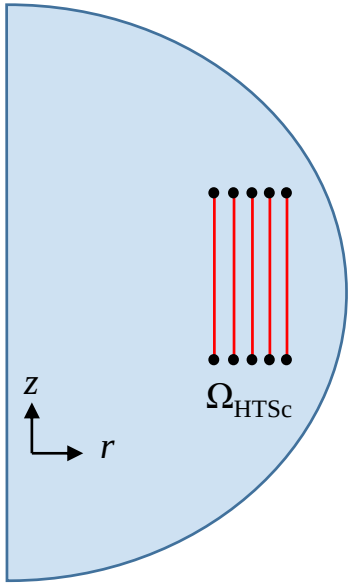
$$\gamma C_p \frac{dTh}{dt} + \nabla \cdot (-k \nabla Th) = \begin{cases} Q_{\text{HTS}} & T \in \Omega_{\text{HTS}} \\ Q_{\text{Coil}} & T \in \Omega_{\text{Coil}} \\ 0 & T \in \Omega_{\text{N2}} \end{cases}$$

# Modelling T-A-H

I. T-A-H MultiScale

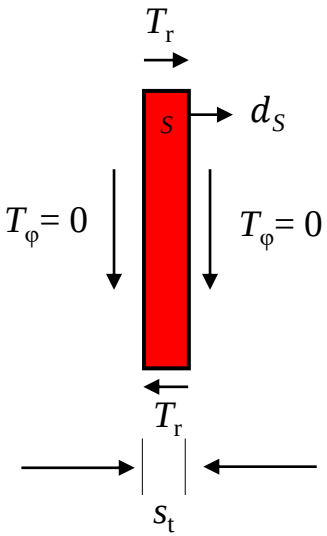
II. T-A-H Homogenized

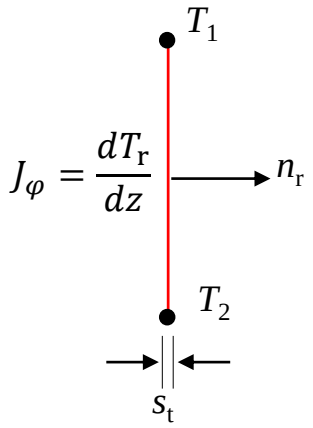
# T-A-H MultiScale



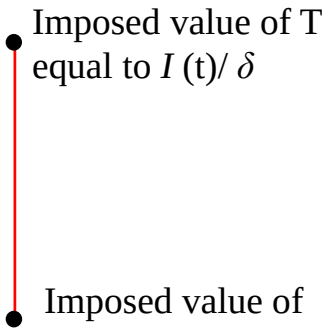

Symmetry axis

## T-A-H MultiScale




Implementation in COMSOL

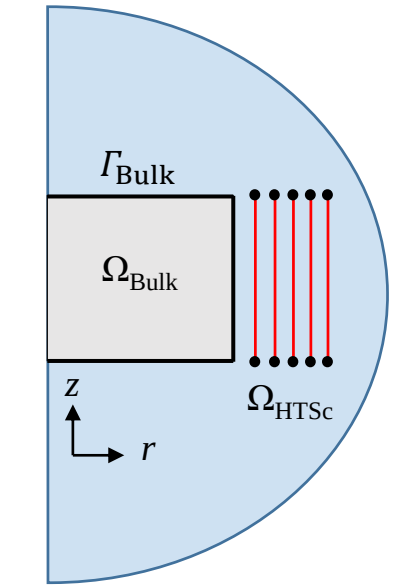



- Dirichlet Boundary Condition

How to enforce the current?

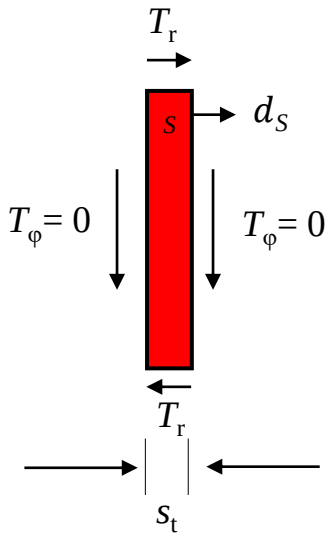
$$I = (T_1 - T_2) / \delta$$

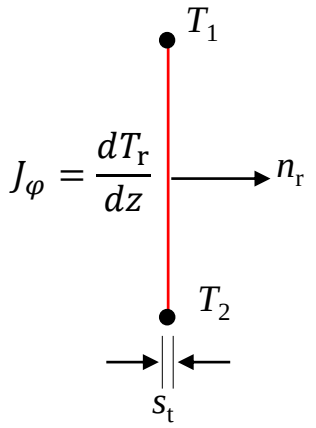
# T-A-H MultiScale




Symmetry axis

## T-A-H MultiScale



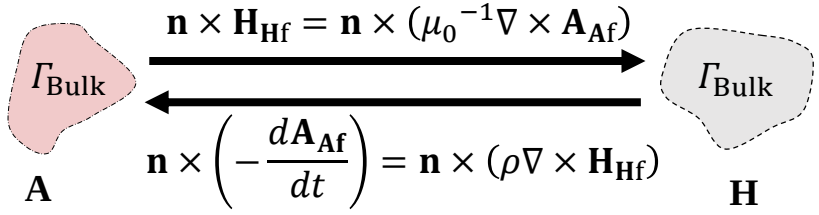

Implementation in COMSOL

- Imposed value of T equal to $I$ (t)/ $\delta$
- Imposed value of T equal to zero

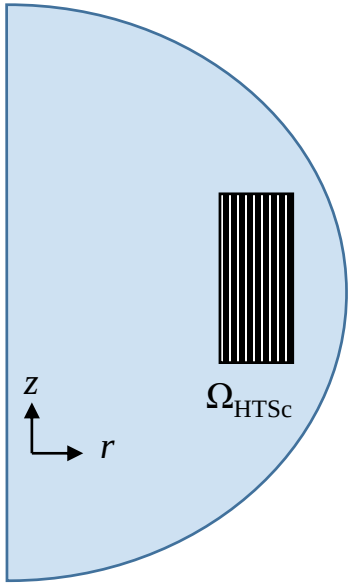
- Dirichlet Boundary Condition

How to enforce the current?

$$I = (T_1 - T_2) / \delta$$



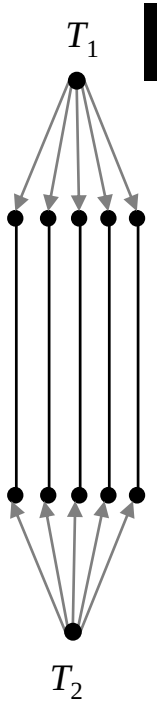
# T-A-H Homogenized



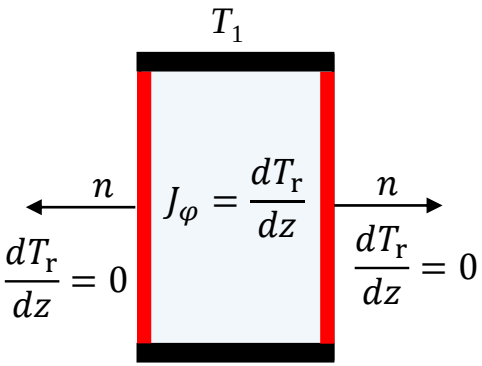

Symmetry axis

How to enforce the current?

$$I = (T_1 - T_2) / \delta$$



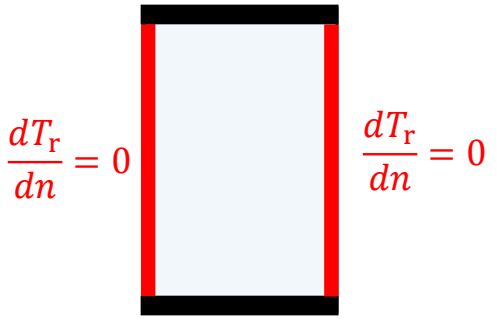

## T-A-H Homogenization




$$J_s = -J_\varphi \frac{s_t}{\gamma_t}$$

Implementation in COMSOL

Imposed value of T equal to $I$ (t)/ $\delta$

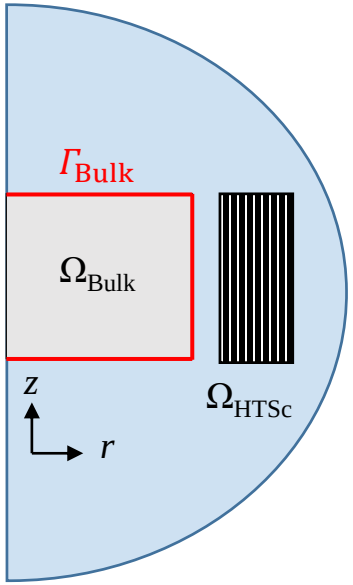



Imposed value of T equal to zero

Dirichlet Boundary Condition

Neumann Boundary Condition

# T-A-H Homogenized

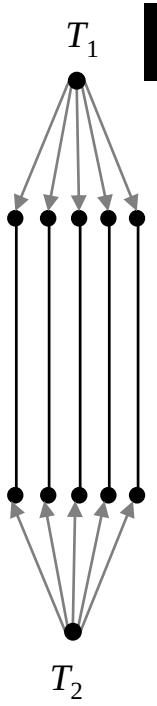


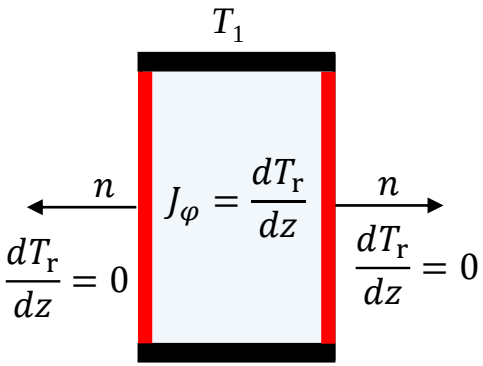

Symmetry axis

How to enforce the current?

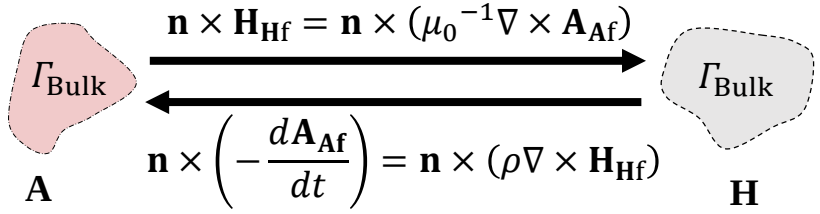
$$I = (T_1 - T_2) / \delta$$

## T-A-H Homogenization



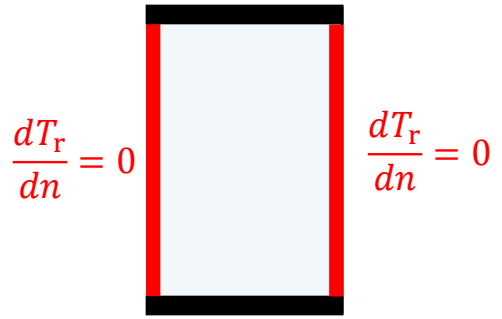




$$J_s = -J_\varphi \frac{s_t}{\gamma_t}$$




Implementation in COMSOL

Imposed value of T equal to $I$ (t)/ $\delta$




Imposed value of T equal to zero

Dirichlet Boundary Condition

Neumann Boundary Condition

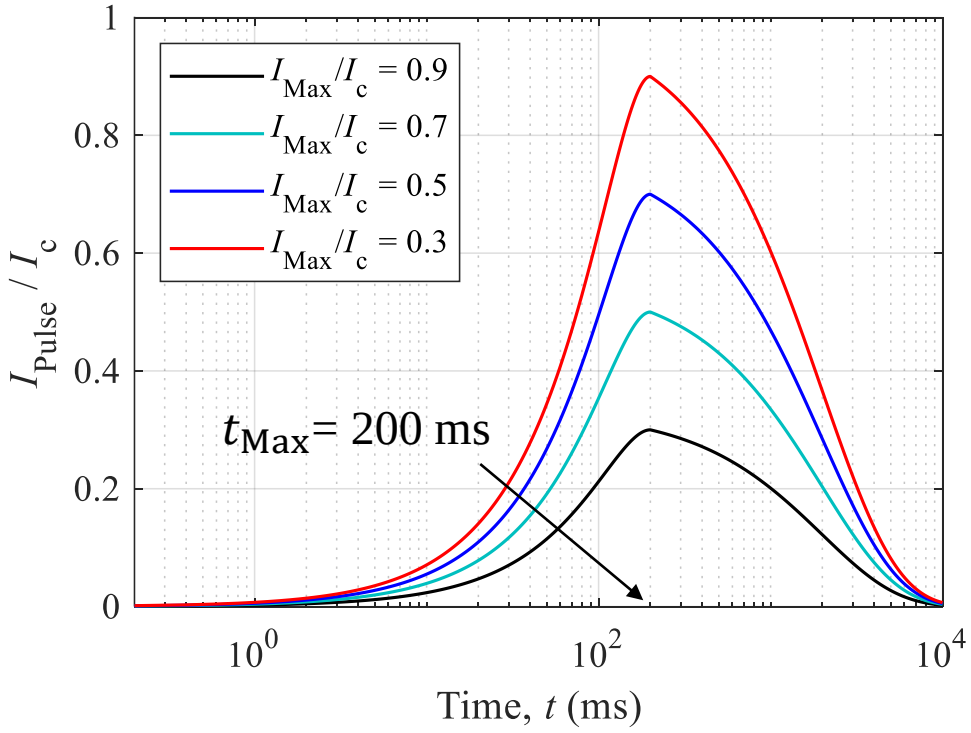
# The equations of the pulsed current

$$I_{\text{Pulse}}(t) = \begin{cases} I_{\text{Max}} \sin\left(\frac{\pi}{2}\frac{t}{t_{\text{Max}}}\right), t \le t_{\text{Max}} \\ I_{\text{Max}} e^{-\frac{(t-t_{\text{Max}})}{\tau}}, t > t_{\text{Max}} \end{cases}$$

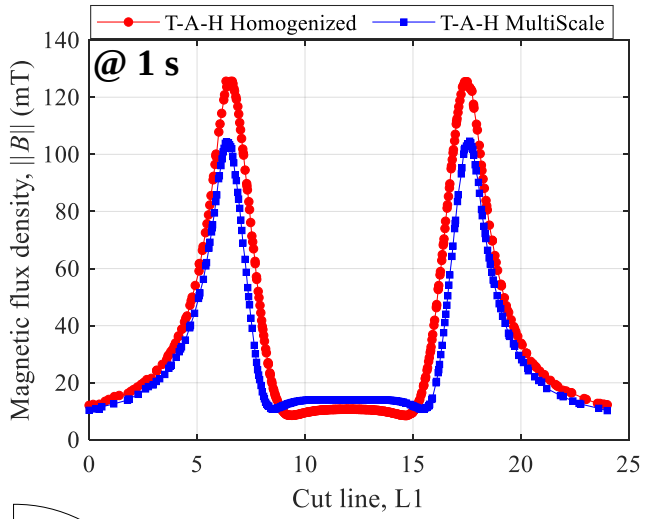
- Tape parameter:
  $n_{\text{HTSc}}$= 25
  $J_{\text{HTSc}}$= 879 A
  Tape width : 12 mm

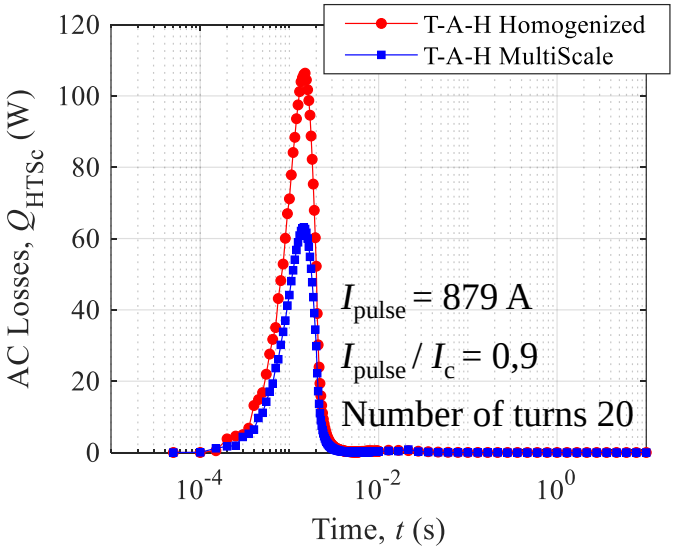
- Tape parameter:
  $n_{\text{Bulk}}$= 8
  $J_{\text{Bulk}}$= 500 A/mm$^2$
  Bulk radius = 10 mm
  Height of the bulk = 12 mm

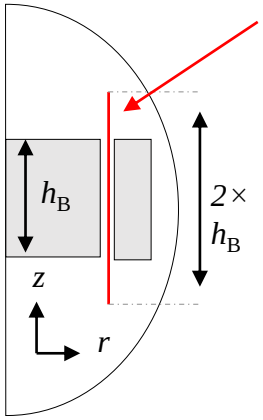
- Cooling with liquid nitrogen 77 K



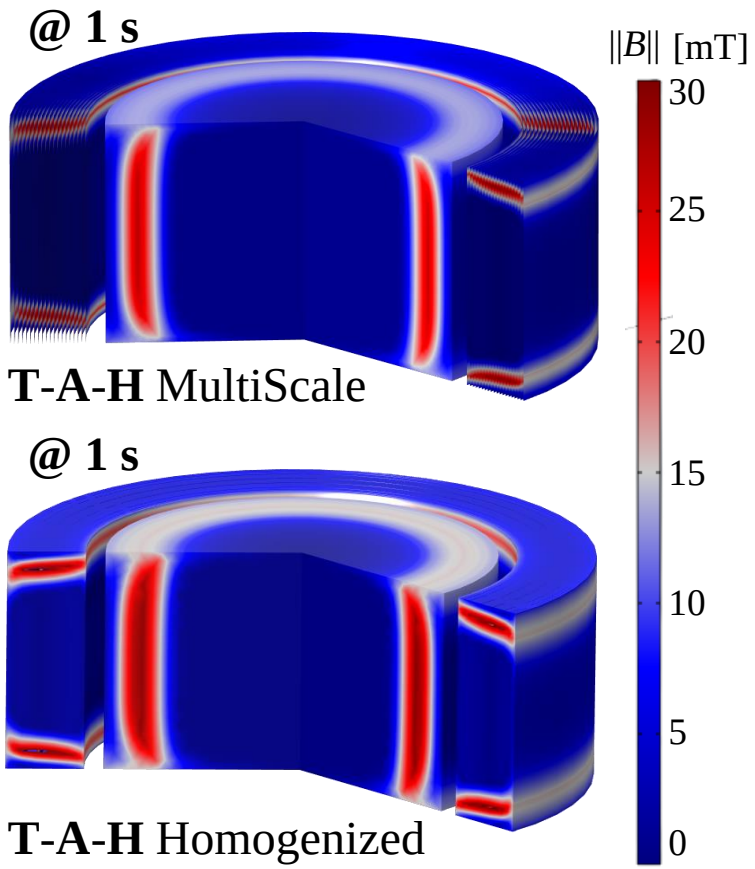
# Comparison of two formulations



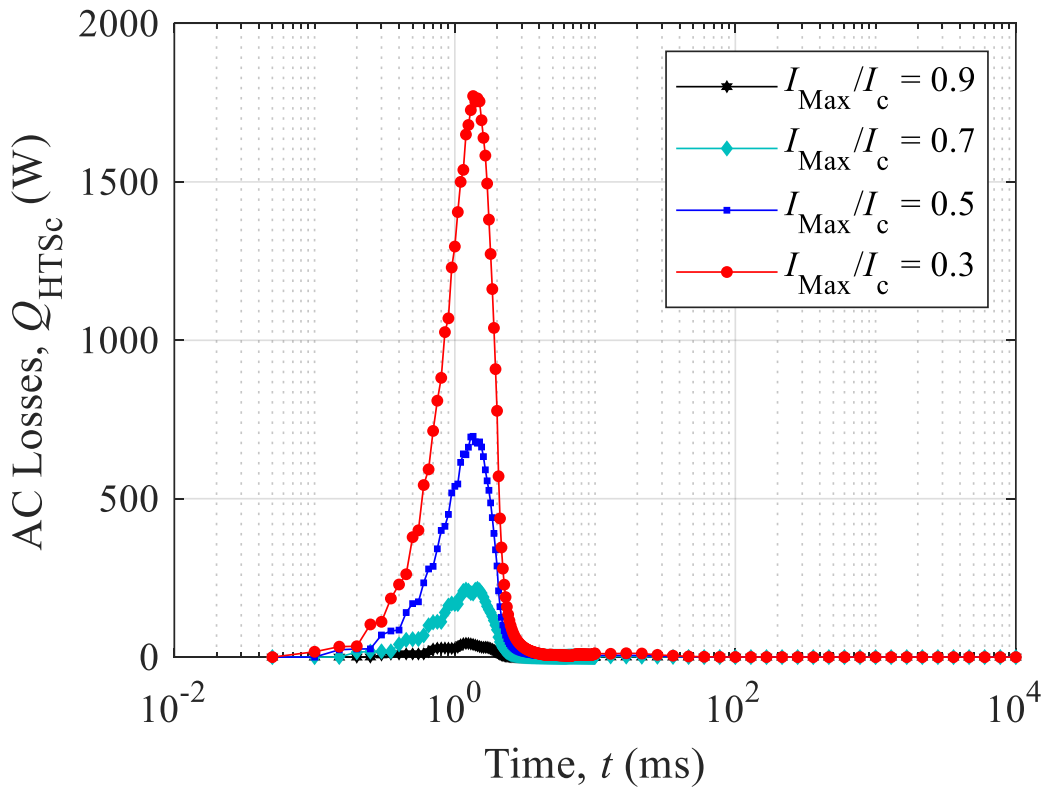




| | Time |
|---|---|
| **T-A-H** MultiScale | 15 min, 35 s |
| **T-A-H** Homogenized | 4 min, 5 s |



# Electical Losses

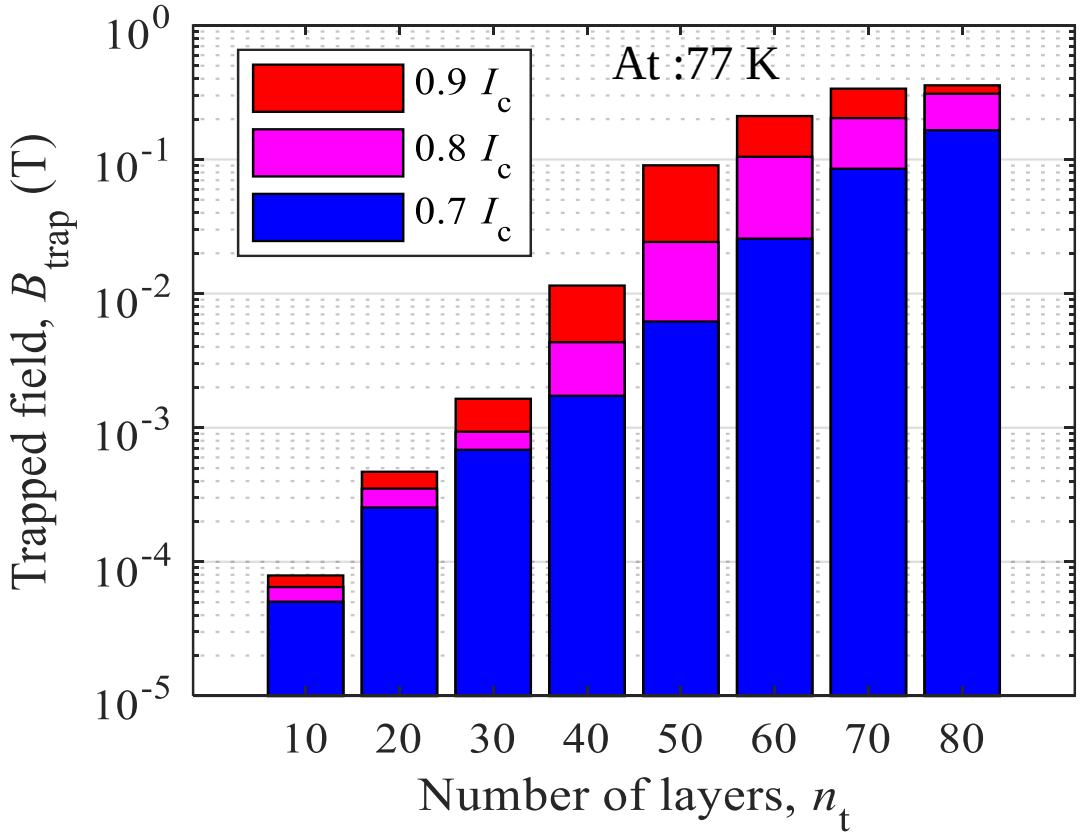
- The losses of a resistive coil for the same number of turns and the same current are about 10 MW peak.
- The losses are **negligible** compared to a resistive coil.



# Trapped field

**Trapped field :≈ 0,34 T with 80 layers**

How to increase the trapped field

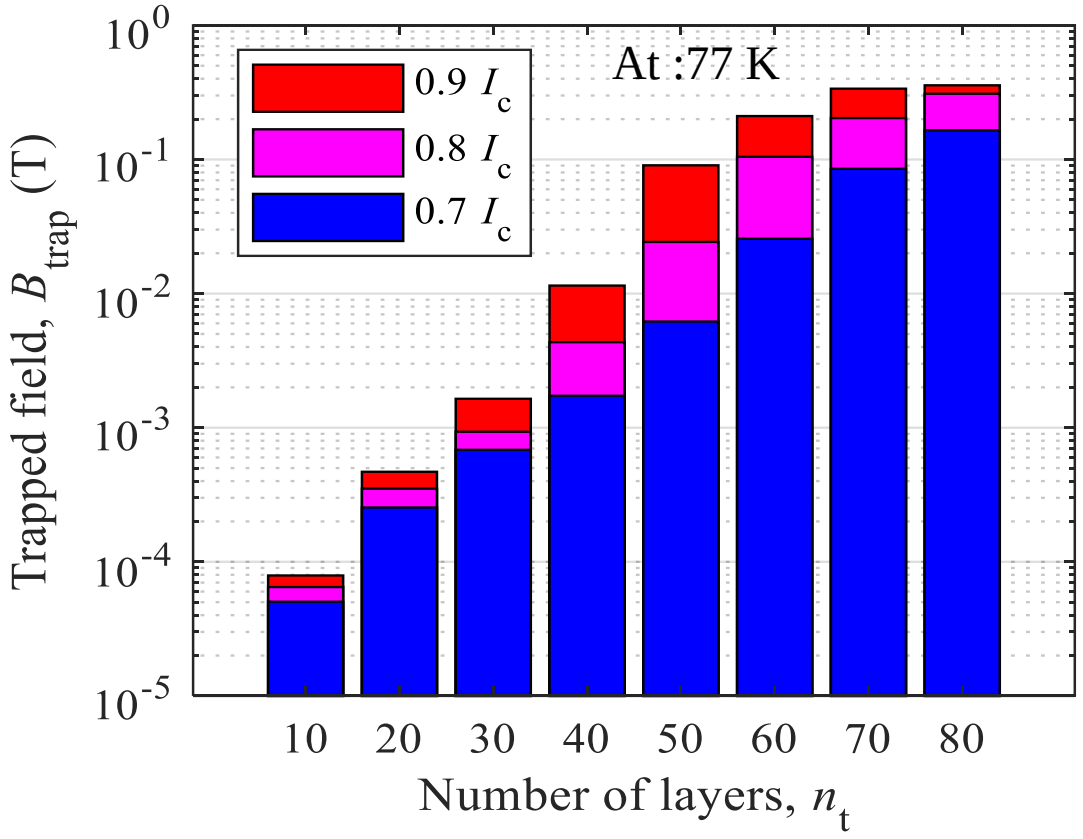


# Trapped field

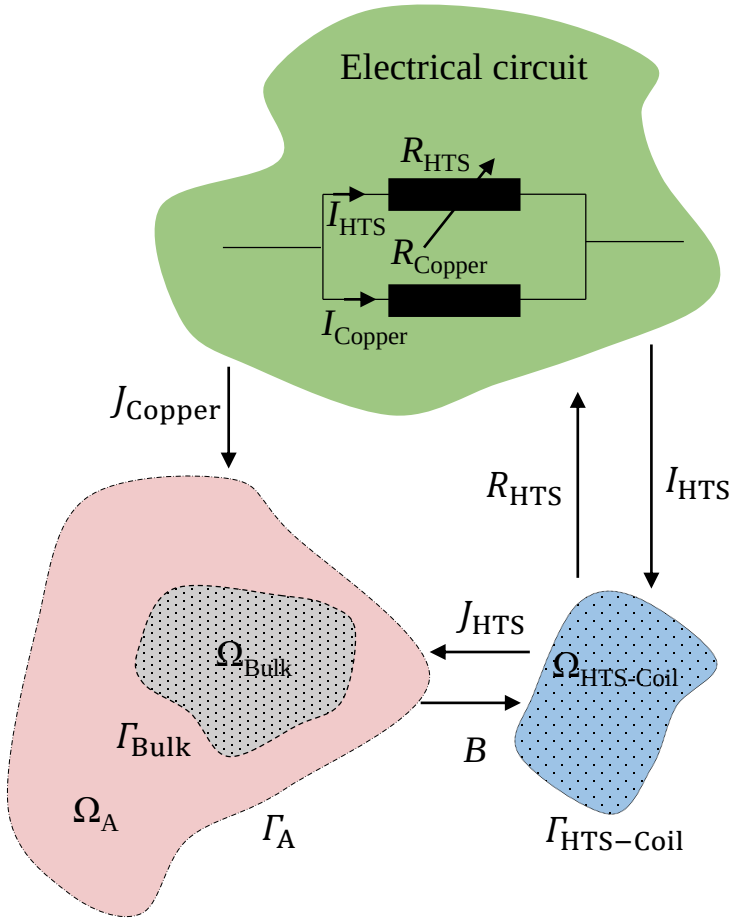
**Trapped field :≈ 0.34 T with 80 layers**

How to increase the trapped field

Over current!
$I_{Pulse} > I_c$



# Over current modelling based on the T-A-H formulation




Electrical circuit  **A** Formulation  **H** Formulation

**T** Formulation  *Th* Heat transfer in solids

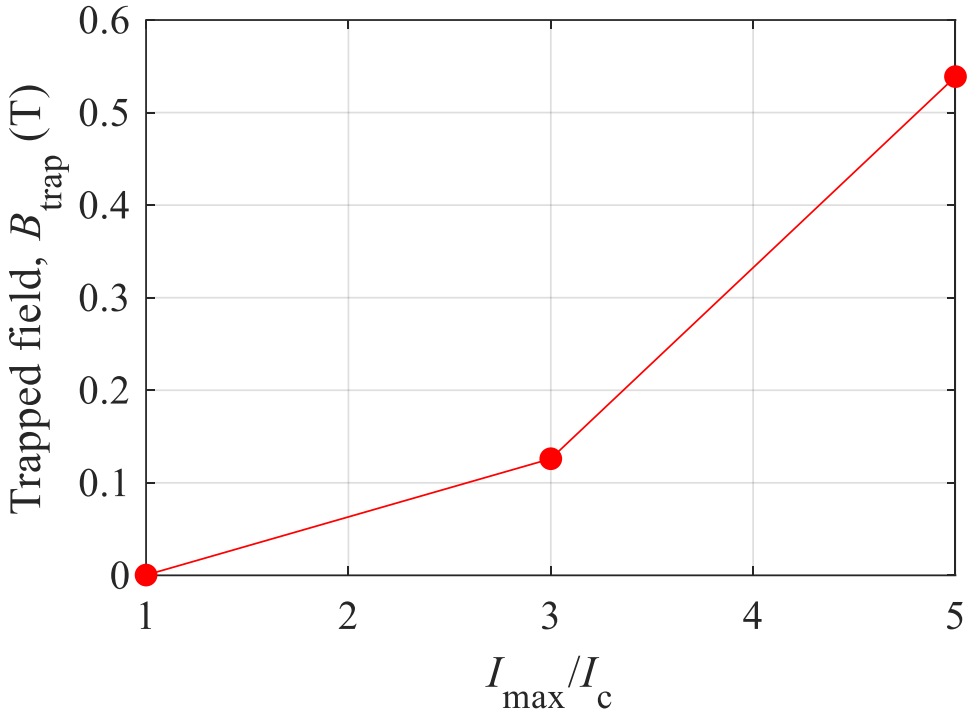
**Electrical circuit**

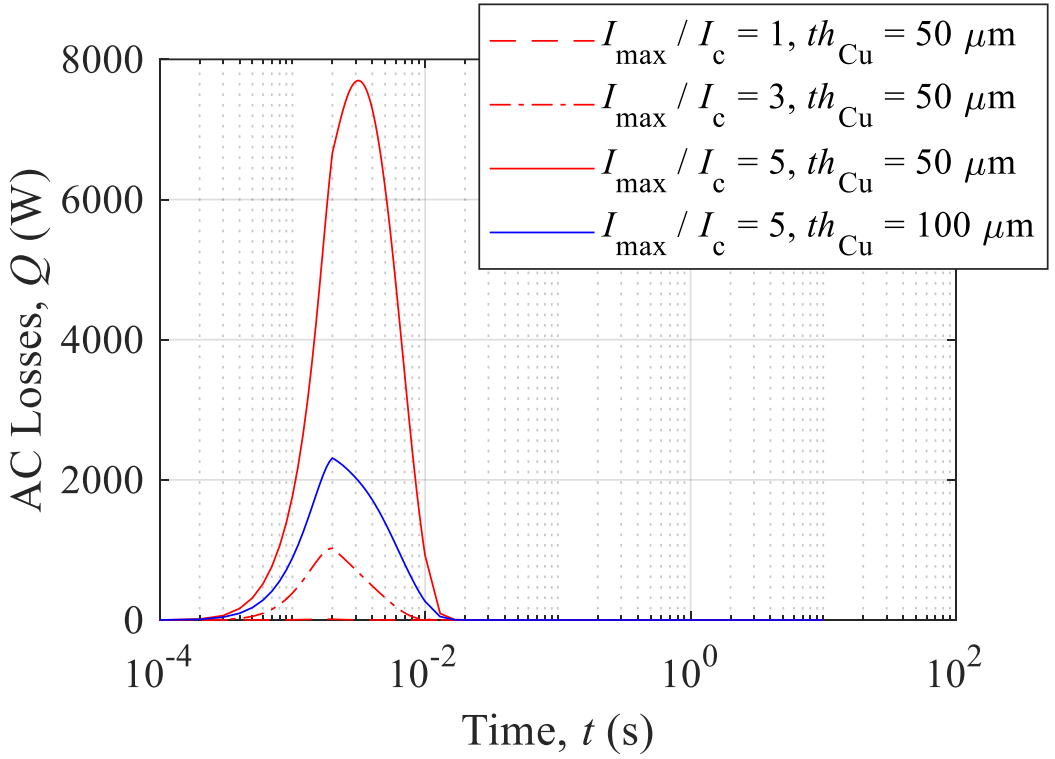
$$I_{Pulse}(t) = I_{HTS}(t) + I_{Copper}(t)$$

***Th* Heat transfer in solids**

$$\gamma C_p \frac{dT}{dt} + \nabla \cdot (-k\nabla T) = \begin{cases} Q_{HTS} + \boldsymbol{Q_{Copper}} & T \in \Omega_{HTS} \\ Q_{Coil} & T \in \Omega_{Coil} \\ 0 & T \in \Omega_{N2} \end{cases}$$

# Conclusion




- A **compromise to be found** between the losses, the copper section and the trapped field

# Thank you for your attention

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