NORMAL-CONDUCTING MAGNET ANALYSIS

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CHALLENGE OVERVIEW

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NORMAL-CONDUCTING MAGNETS

Challenges

1. **Pulsed** operation.
2. **Non-linearities** and multiple **loss** types.
3. **Heat** generation and **cooling**.
4. Linked to **power supply**.
5. Magnet as **3D** element.

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Our software Pyrit

✓ Transient FEM solver.

✓ Appropriate material models.

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Power supply = ideal current supply.

2D simulations.

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Upcoming extensions:

Thermal loss model.

Circuit coupling.

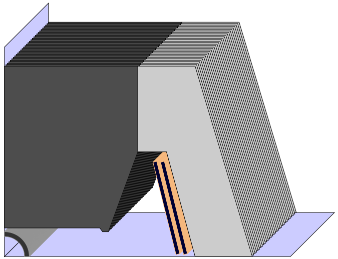
Quasi-3D simulations.

NON-LINEARITIES AND LOSS TYPES

IRON CORE

NON-LINEARITIES AND MULTIPLE LOSS TYPES

- Focus on single centered slice (2D).
  - B optimal = no longitudinal component.
  - No currents in plane.
- Laminated **iron core** $\Rightarrow$ conductivity $\sigma_{Fe,z} = 0$.
- Eddy current loss $\dot{w} = \sigma_{Fe,z}\mathbf{E}^2 = 0$?



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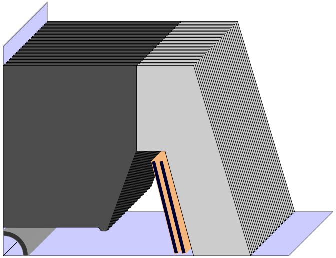

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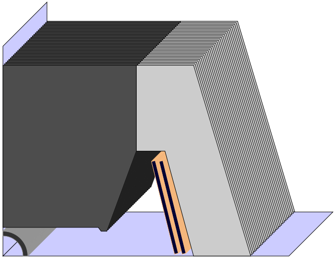


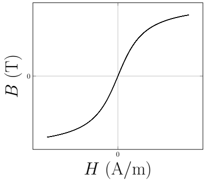
Homogenization

IRON CORE HOMOGENIZATION

NON-LINEARITIES AND MULTIPLE LOSS TYPES

Material model

$$\mathbf{H} = \mathbf{H}_{\text{rev}}(\mathbf{B}) + \mathbf{H}_{\text{eddy}}(\dot{\mathbf{B}}) + \mathbf{H}_{\text{hyst}}(\dot{\mathbf{B}}).$$



Reversible

$$\mathbf{H}_{\text{rev}}(\mathbf{B}) = \nu(\mathbf{B})\mathbf{B}.$$

$$w_{\text{mag}} = \int_0^{\mathbf{B}} \nu(\mathbf{B})\mathbf{B} \cdot \mathrm{d}\mathbf{B}.$$

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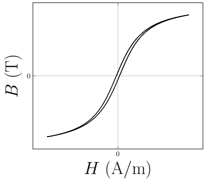

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Eddy current

$$\mathbf{H}_{\text{eddy}}(\dot{\mathbf{B}}) = p_3\dot{\mathbf{B}}.$$

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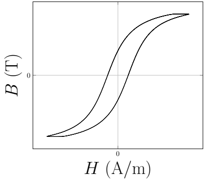

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Hysteresis

$$\mathbf{H}_{\text{hyst}}(\dot{\mathbf{B}}) = \frac{p_4}{|\dot{\mathbf{B}}|}\dot{\mathbf{B}}.$$

$$\dot{w}_{\text{hyst}} = p_4|\dot{\mathbf{B}}| \propto f.$$

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NON-LINEARITIES AND MULTIPLE LOSS TYPES

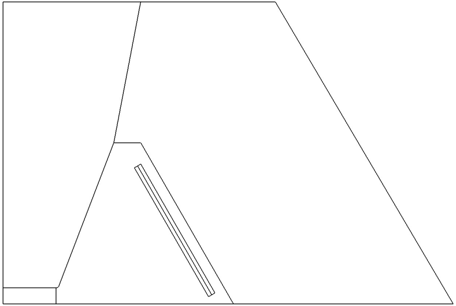
Electric field strength $$\mathbf{E} = \underbrace{-\nabla\varphi_s}_{\text{source}} + \underbrace{-\dot{\mathbf{A}}}_{\text{induced}}$$

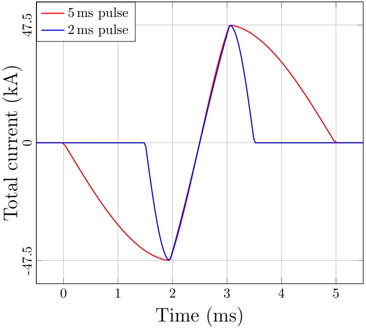
Loss density $$\dot{w}_{Cu} = \sigma_{Cu}\mathbf{E}^2 = \underbrace{\sigma_{Cu}\left(\nabla\varphi_s\right)^2}_{\text{resistive } \propto Gu^2} + \underbrace{2\sigma_{Cu}\nabla\varphi_s\cdot\dot{\mathbf{A}} + \sigma_{Cu}\dot{\mathbf{A}}^2}_{\text{induced loss}}$$

- Resistive loss homogeneously distributed.
- Induced loss highly localized.

MAP HOURGLASS DIPOLE

DIFFERENT PULSE DURATIONS





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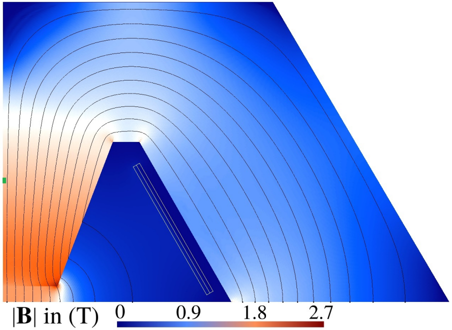

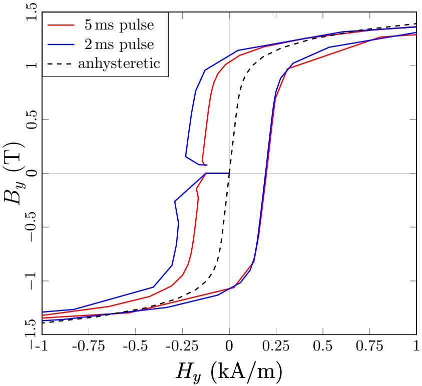

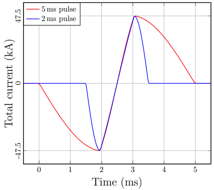

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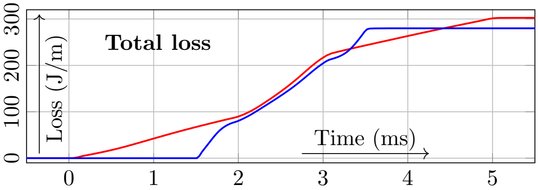

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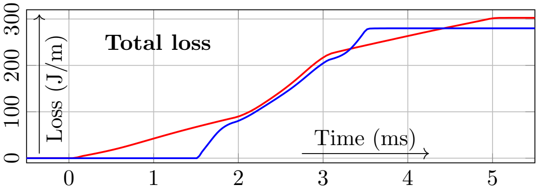

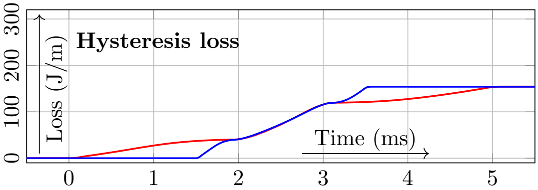

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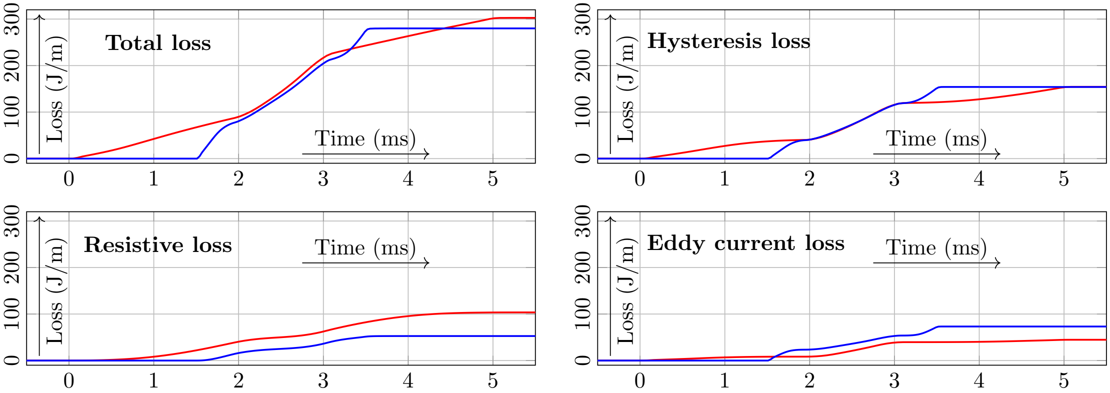


HEAT GENERATION AND COOLING

MAP HOURGLASS DIPOLE

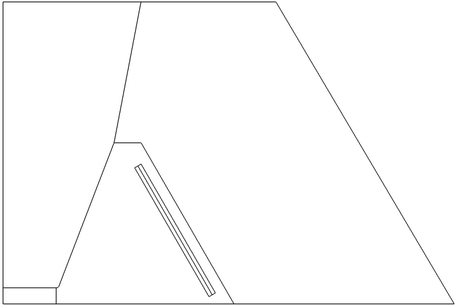
STEADY STATE TEMPERATURE

Simplification, worst case:

1. Long conductors.
2. Only heat radiation.

$$0 = P_{\text{loss}} - \sigma_B \epsilon A (T^4 - T_{\text{air}}^4)$$

3. Air temperature constant.



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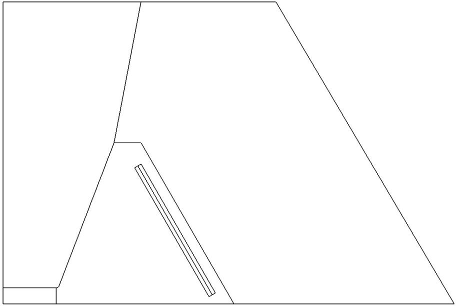
$$\epsilon = 0.2,\ T_{air} = 300\,\text{K},\ P_{\text{loss}} = \frac{1}{4}\frac{100\,\text{J}}{200\,\text{ms}},$$
$$A = 2 \cdot (140\,\text{mm} + 7\,\text{mm}) \cdot 1\,\text{m}$$
$$\Rightarrow \quad \underline{T = 462\,\text{K}}$$



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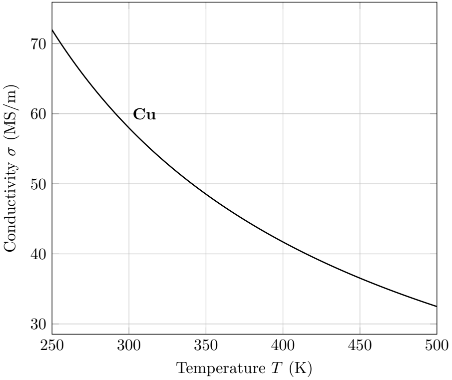
STEADY STATE TEMPERATURE

High temperature working point of $\underline{T = 462\,\text{K}}$.

$\Rightarrow$ Low conductivity.

$\Rightarrow$ High loss.



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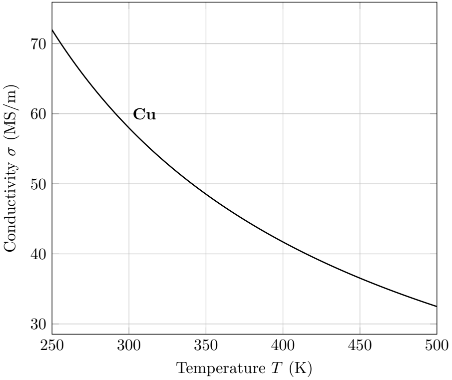
Cooling required.



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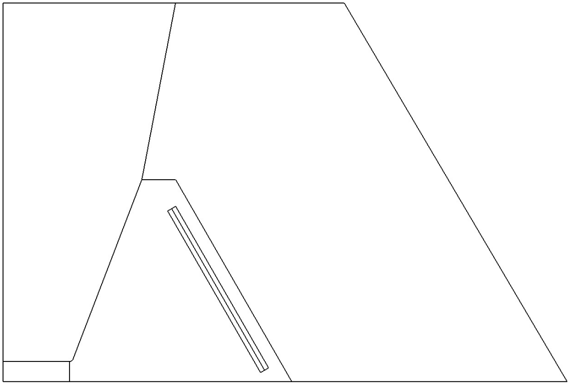
TEMPERATURE RISE PER CYCLE

Average temperature rise (conductors).

$$\delta T_{\text{avg}} \approx \frac{W_{loss}}{k\gamma V} = \underline{7.5\,\text{mK}}$$



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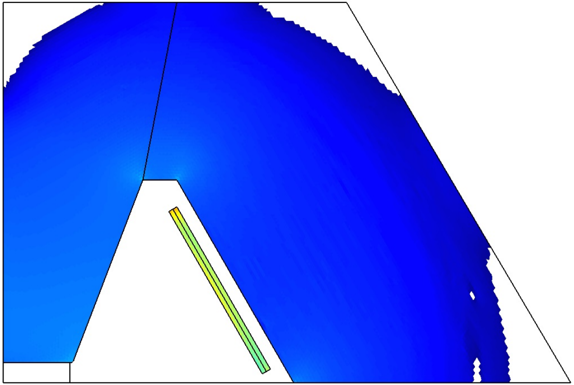
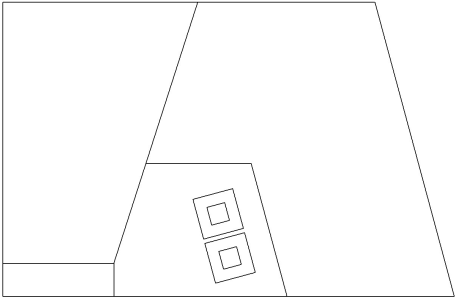
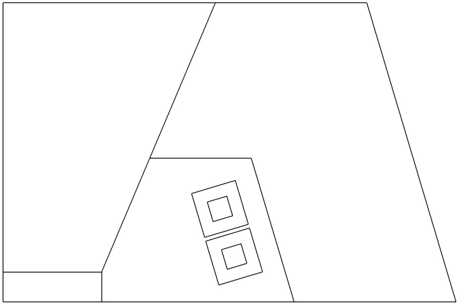
Simulation: $\delta T_{\text{max}} \approx \underline{40\,\text{mK}}$



HOLLOW CONDUCTOR MODELS



Low energy



Low loss

Not in scale! All models feature same air gap.

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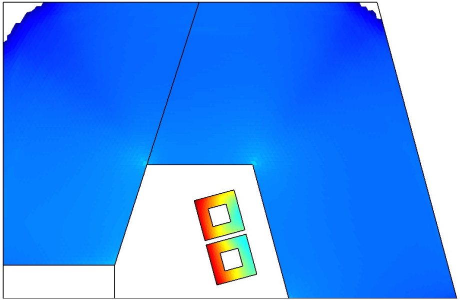
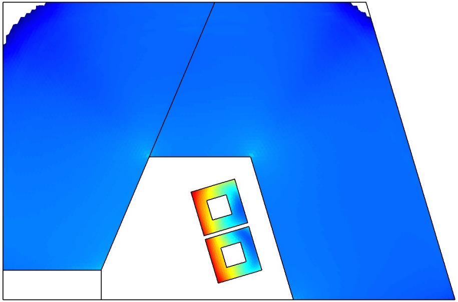


Low energy, $\delta T_{max} \approx$ 400 mK



Low loss, $\delta T_{max} \approx$ 270 mK

Temperature rise per cycle (mK)

0.05 0.5 5 50 500

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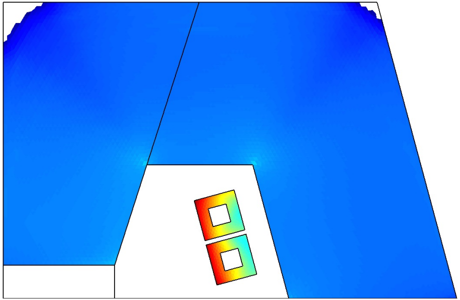

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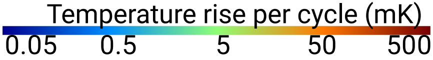


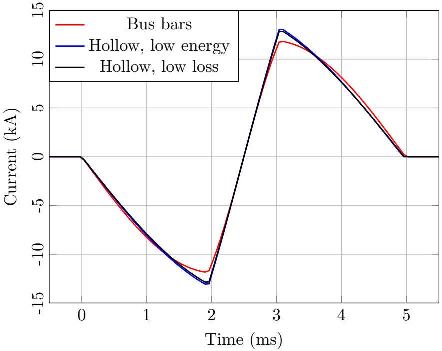
- Copper resistivity changes by $\approx 0.4\,\%/\mathrm{K}$.

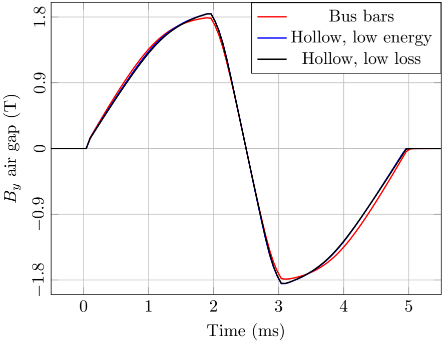
$\Rightarrow$ Resistivity change during one cycle below 0.2 %.

$\Rightarrow$ Material properties during one cycle almost unchanged.

$\Rightarrow$ No thermal updates required for simulation of a single pulse.

MAGNET COMPARISON





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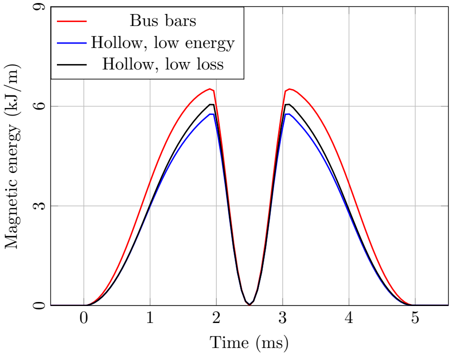

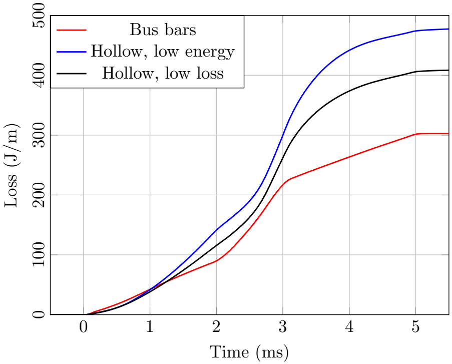

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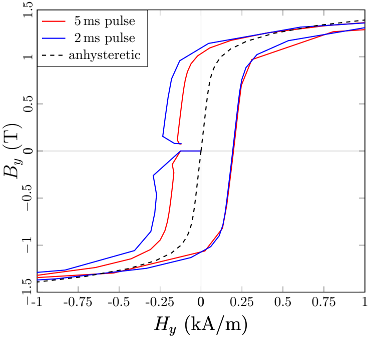

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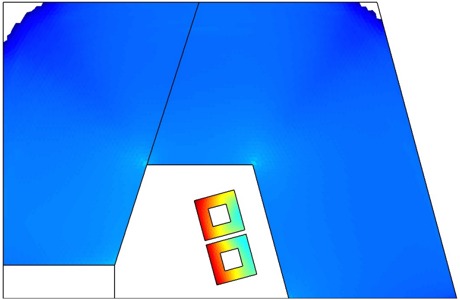

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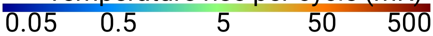

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Magnet surrogate representation with non-linear matrices **R** and **L**.

$$\mathbf{u} = \mathbf{R}\mathbf{I} + \mathbf{L}\frac{\mathrm{d}\mathbf{I}}{\mathrm{d}t}$$

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3D FEM or Quasi-3D approach:

$$\mathbf{A}_{3D}(x,y,z) = \underbrace{\sum_{k=1}^{N_l} \mathbf{A}_k^l(x,y) b_k^l(z)}_{\mathbf{A}^l \propto \mathbf{e}_z} + \underbrace{\sum_{n=1}^{N_t} \mathbf{A}_n^t(x,y) b_n^t(z)}_{\mathbf{A}^t \propto \mathbf{e}_x, \mathbf{e}_y}$$

ACKNOWLEDGEMENT

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