TRANSIENT ANALYSIS OF FAST RAMPING NORMAL-CONDUCTING MUON-COLLIDER MAGNETS

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COLLIDING MUONS?

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Future at CERN: Muon Collider?

	electron e^-	muon μ^-	proton p^+
Elementary, clean collision	✓	✓	x
Energy at $\gamma = 1$	0.5 MeV	105 MeV	938 MeV
Synchrotron radiation negligible	x	✓	✓
Simple generation	✓	x	✓
Lifetime at $\gamma = 1$	∞	2.2 µs	∞
New collision experiments	2045 FCC(ee)	2045 MuCol	2070 FCC(hh)

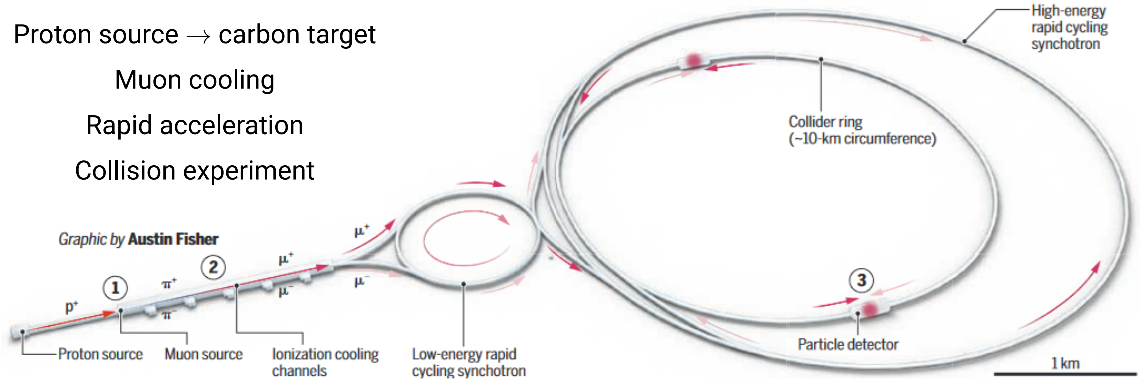
COLLIDING MUONS?

Proton source → carbon target

Muon cooling

Rapid acceleration

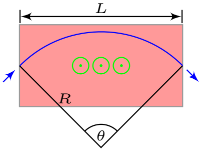
Collision experiment



https://www.science.org/content/article/muon-collider-could-revolutionize-particle-physics-if-it-can-be-built

COLLIDING MUONS?

RAPID CYCLING SYNCHROTRONS - BENDING

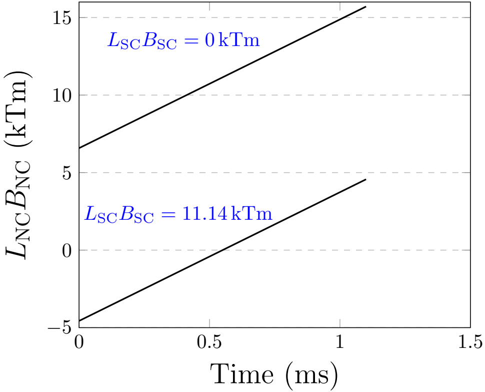


SC NC hybrid RCS:

$$2\pi = n_{\mathrm{NC}}\theta_{\mathrm{NC}} + n_{\mathrm{SC}}\theta_{\mathrm{SC}}$$

$$L_{\mathrm{NC}}B_{\mathrm{NC}} = \frac{2\pi p}{e} - L_{\mathrm{SC}}B_{\mathrm{SC}}$$

Optimal factorization: L_{NC} and B_{NC}?



NC MAGNETS - COST FUNCTION

Optimal factorization: L_{NC} and B_{NC}?

Cost function: $$\underbrace{Q}_{\text{Cost}} = \left(\underbrace{Q_{\mathrm{kWh}}}_{\text{Energy cost}} \cdot \underbrace{T_{\mathrm{op}}}_{\text{Time}} \cdot {\color{red}P'_{\mathrm{Loss}}} + \underbrace{Q'_{\mathrm{mat}}}_{\text{Material cost}} \right) \cdot {\color{blue}L_{\mathrm{NC}}}$$

- Different peak currents:

→ Material cost constant

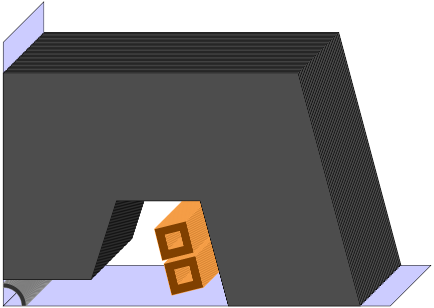
→ Tradeoff: ${\color{red}P'_{\mathrm{Loss}}}$ and ${\color{blue}L_{\mathrm{NC}}}$

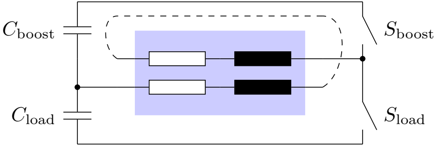
- Operation time: $T_{\mathrm{op}} = 20\mathrm{y} \cdot 6000\mathrm{h/y}$
- Energy cost: $Q_{\mathrm{kWh}} = 0.09€/\mathrm{kWh}$
- Copper: $Q_{\mathrm{Cu}} = 100€/\mathrm{kg}$
- Iron: $Q_{\mathrm{Fe}} = 25€/\mathrm{kg}$

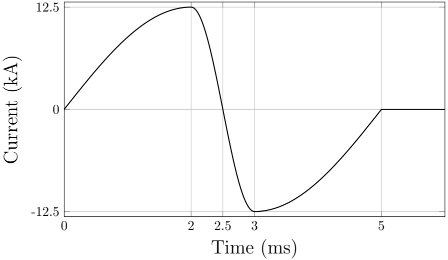
NC MAGNET ANALYSIS

MAGNET POWERING

- Air gap: 30 mm × 100 mm
- Switched resonance circuit







EQUATIONS

Ampère's law:

$$\nabla \times \mathbf{H} + \sigma \dot{\mathbf{A}} = \sum_n u_n G_n \mathbf{X}_n$$

Voltage-current relation:

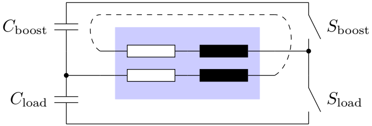
$$u_n = R_n I_n + \dot{\phi}_n$$

Flux:

$$\phi_n = \int_{\mathbb{R}^3} \mathbf{A} \cdot \mathbf{X}_n \mathrm{d}^3 x$$

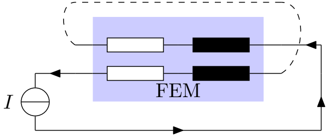
Cascadic approach:

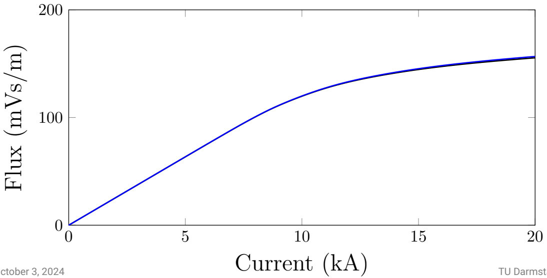
1. Static FEM magnet analysis
   → nonlinear RL surrogate, adequate capacitances
2. Transient circuit analysis with RL surrogate
   → current excitation
3. Transient FEM magnet analysis for given current
   → loss, field, ...

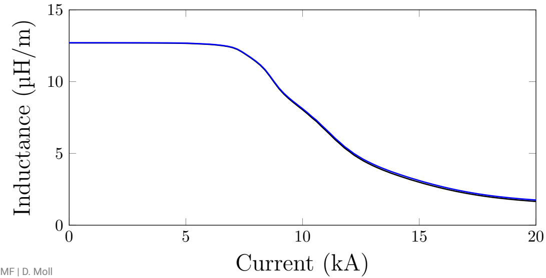


RL SURROGATE

- Assumption: Anhysteretic magnetic model
- Resistances $R'_n = \int_{\mathbb{R}^2} \mathbf{X}_n \cdot \sigma^{-1}\mathbf{X}_n \mathrm{d}^2x = 39\,\mu\Omega/\mathrm{m}$
- Inductance $L'_n = \frac{\mathrm{d}}{\mathrm{d}I}\phi'_n$



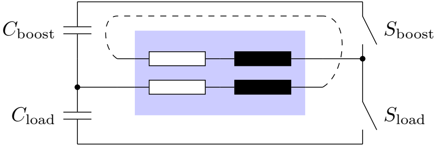


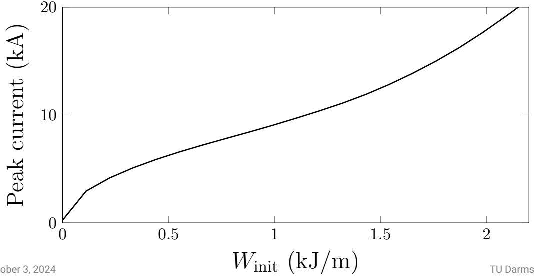


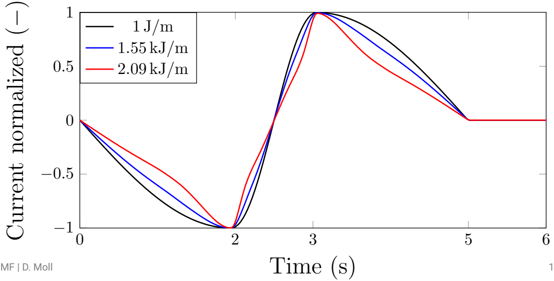
TRANSIENT CIRCUIT ANALYSIS

- Different initial energies at C_{load}

→ Different current shapes



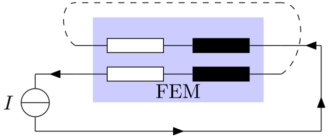




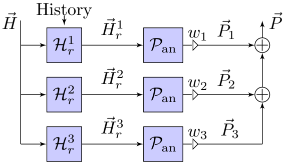
TRANSIENT MAGNET ANALYSIS

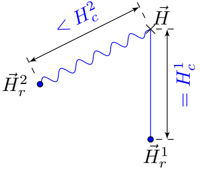
FERROMAGNETIC MODEL

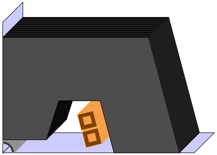
$$\mathbf{H} = \underbrace{(\mu_0 + \mathcal{P})^{-1}\mathbf{B}}_{\text{Hysteresis model}} + \underbrace{\frac{\sigma d^2}{12}\dot{\mathbf{B}}}_{\text{Eddy current effect}}$$



Magnetic polarization operator $\mathcal{P}$ of EB hysteresis model.

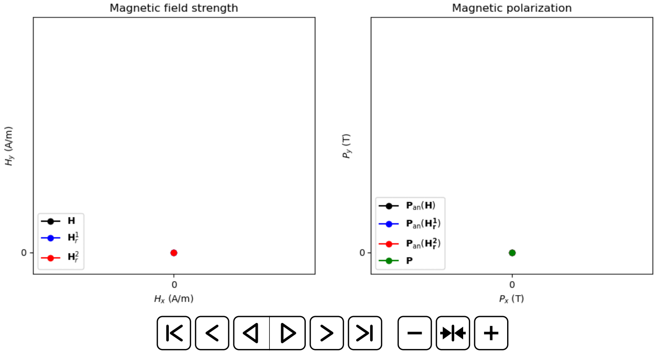




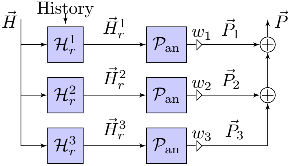


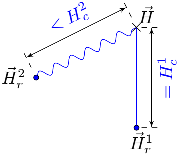
TRANSIENT MAGNET ANALYSIS

FERROMAGNETIC MODEL



$$\mathbf{B} = \mu_0 \mathbf{H} + \mathbf{P}$$





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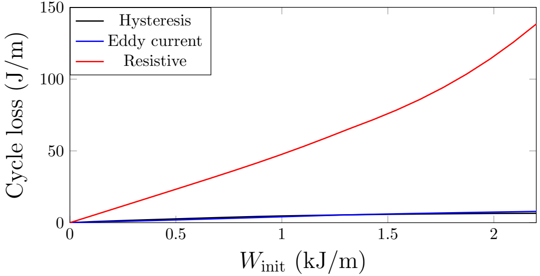
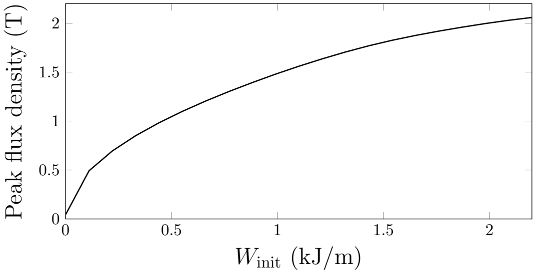
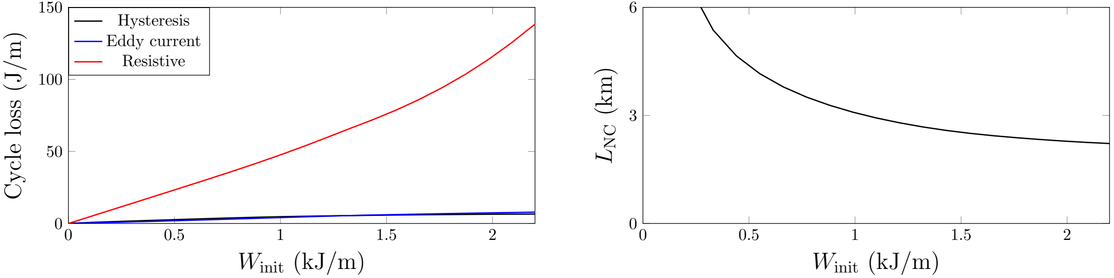




Cost function: $Q = (T_{\mathrm{op}} \cdot Q_{\mathrm{kWh}} \cdot P'_{\mathrm{Loss}} + Q'_{\mathrm{mat}}) \cdot L_{\mathrm{NC}}$

$$L_{\mathrm{NC}} = \frac{4567\,\mathrm{Tm}}{\max_t B_{\mathrm{NC}}}$$

TRANSIENT MAGNET ANALYSIS



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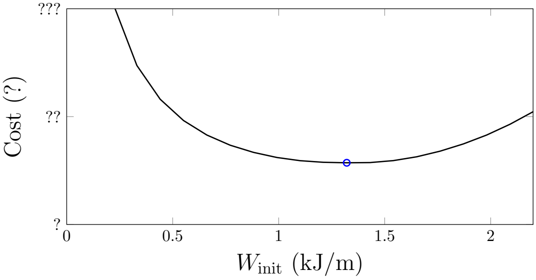
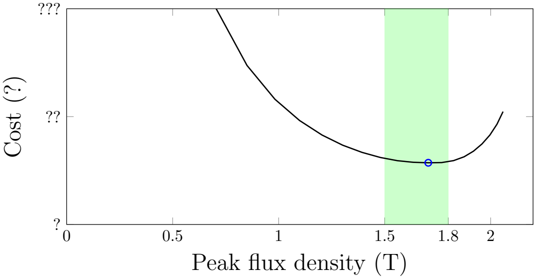
COST ANALYSIS

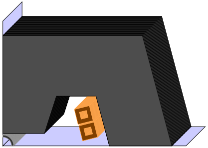


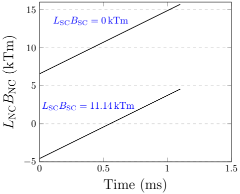


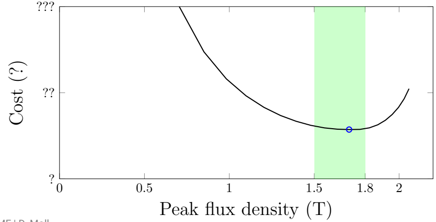
- Costs are not yet to be published.

CONCLUSIONS

- Material reduction profitable
  - Below 1% savings: 100€/m · 3 km = 300k€
- Lowering of resistive loss recommendable
  - Different coil layout → lower skin- and proximity-effect
  - Narrower air gap 30 mm → 24 mm: Loss reduction to 64%.
- Additional tradeoff: number of SC-magnets ↔ high NC flux densities?







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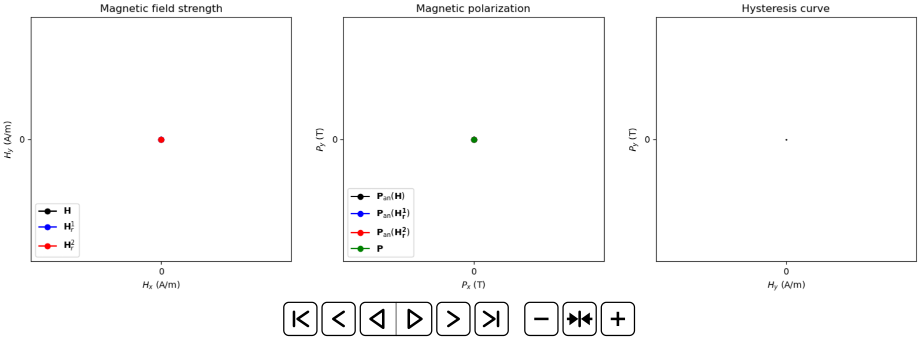
TRANSIENT MAGNET ANALYSIS

FERROMAGNETIC MODEL



TRANSIENT MAGNET ANALYSIS

FERROMAGNETIC MODEL

$$\mathbf{H} = (\mu_0 + \mathcal{P})^{-1}\mathbf{B} + \frac{\sigma d^2}{12}\dot{\mathbf{B}} = \mathbf{H}_{\mathrm{avg}} + \mathbf{H}_{\mathrm{eddy}}$$

$$\dot{w}_{\mathrm{stored}} = \mu_0 \mathbf{H}_{\mathrm{avg}} \cdot \dot{\mathbf{H}}_{\mathrm{avg}} + \sum_m \mathbf{H}_r^m \dot{\mathbf{P}}_m$$

$$\dot{w}_{\mathrm{hyst}} = \sum_m (\mathbf{H}_{\mathrm{avg}} - \mathbf{H}_r^m)\dot{\mathbf{P}}_m \geq 0$$

$$\dot{w}_{\mathrm{eddy}} = \frac{\sigma d^2}{12}|\dot{\mathbf{B}}|^2 \geq 0$$

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