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Dynamic Analysis of Normal-Conducting Magnets

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IMCC and MuCol Annual Meeting
May 2025

Funded by the European Union under Grant Agreement n.101094300

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Outline

- Time-domain analysis of normal-conducting magnets
  - Field quality evaluation
  - Excitations with higher duty cycles
- Frequency-Domain Analysis & Equivalent Circuit Modeling
  - Frequency- Domain Loss Evaluation Method
  - Equivalent Circuit & Nonlinear Dynamic Modeling
  - Cross-Validation :Simplified Time-Harmonic & High-Fidelity Transient FEA Model

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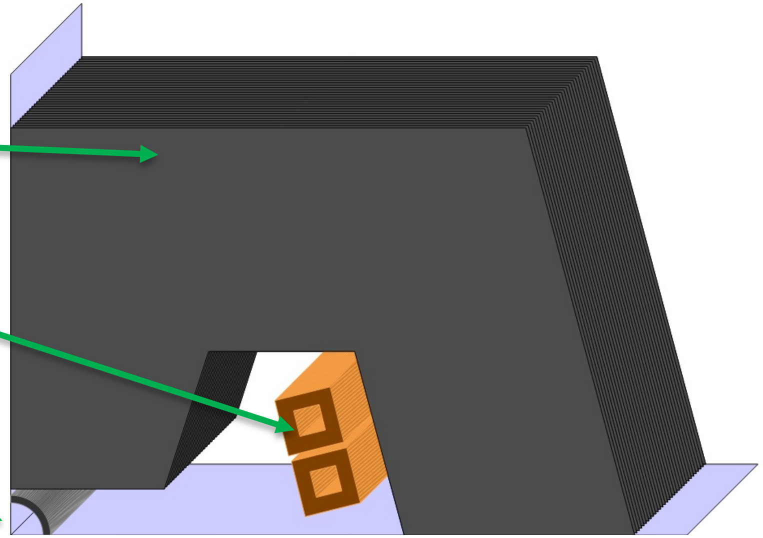
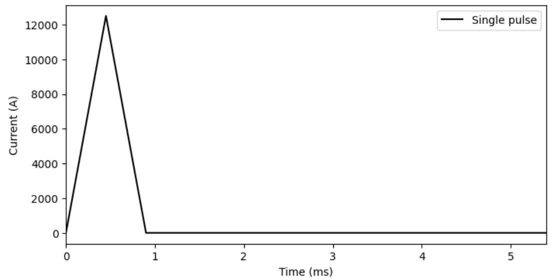
Fast ramping magnets

- **Main components:**
  - **Laminated iron core**: nonlinear, hysteretic
  - **Conductors**: skin- & proximity effects
    - Cooling system?
  - **Beam pipe:** induced currents



- **Different operation modes:**
  - RCS 2,3,4: zero mean operation
  - RCS 1 with DC offset
  - Duty cycle ~ 1%



	RCS1	RCS2	RCS3	RCS4
Inj Energy [GeV]	63	314	750	1500
Acc. length [km]	5.99	5.99	10.7	35.0
Res. mags length [km]	3.65	2.54	4.37	20.38
Binj in gap [T]	0.36	−1.8	−1.8	−1.8
Bextr in gap [T]	1.8	1.8	1.8	1.8
B ramp time Tramp [ms]	0.35	1.10	2.37	6.37
Dipoles Pmax [GW]	111	54	43	74
Dipoles Vmax [MV]	2.4	1.1	0.9	1.5

IMCC Interim report, 2024

Numerical modeling - Maxwell

- Maxwell's equations:
  - Magnetic Gauss: $\nabla \cdot \mathbf{B} = 0 \quad \Rightarrow \quad \mathbf{B} = \nabla \times \mathbf{A}$
  - Faraday-Lenz: $\nabla \times \mathbf{E} = -\dot{\mathbf{B}} \quad \Rightarrow \quad \mathbf{E} = -\dot{\mathbf{A}} - \nabla \boldsymbol{\varphi}$
  - Ampère: $\nabla \times \mathbf{H} = \mathbf{J}$

Distribution functions

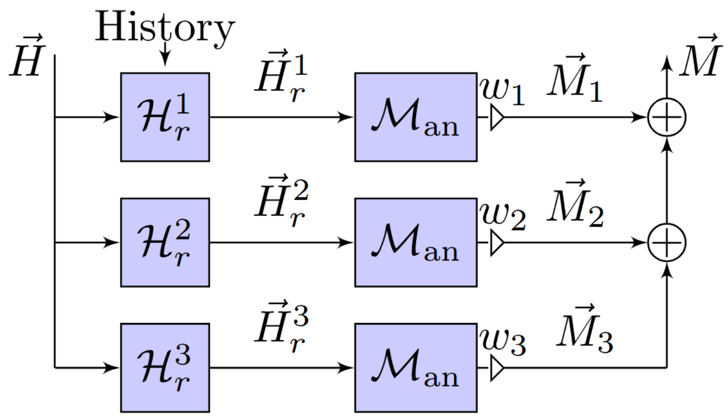
- Ohm's law: $\mathbf{J} = \sigma \mathbf{E} = -\sigma \dot{\mathbf{A}} - \sigma \nabla \boldsymbol{\varphi} = -\sigma \dot{\mathbf{A}} + \sum_m u_m \sigma \mathbf{x}_m$

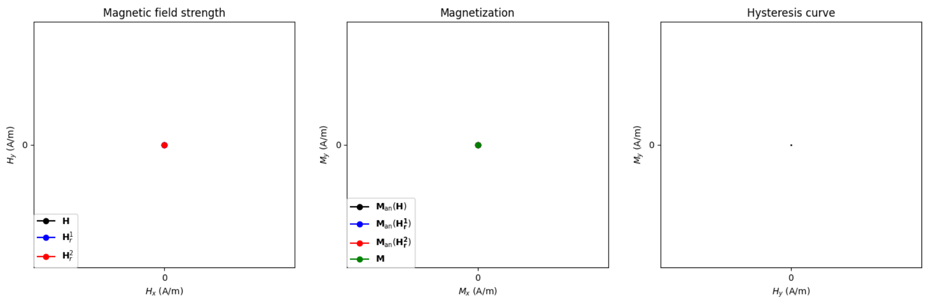
Voltages of every conductor

- Ampère's law: $\nabla \times \mathbf{H} + \sigma \dot{\mathbf{A}} = \sum_m u_m \sigma \mathbf{x}_m$
  - Constitutive relationship $\mathbf{A} \to \mathbf{H}$ (or $\mathbf{B} \to \mathbf{H}$) needed
    - Linear: $\mathbf{H} = \mu_0^{-1}(1+\chi)^{-1}(\mathbf{B} - \mathbf{B_r})$
    - Nonlinear, anhysteretic, isotropic: $|\mathbf{H}| = \mathrm{LUT}(|\mathbf{B}|)$
    - Hysteretic models: Energy-based, Preisach, …

Hysteretic magnetic material model

- Magnetization $\mathbf{M}$: $\mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M}$
- $\mathbf{M} = \sum_k w_k \, \mathrm{M}_{\mathrm{an}} \mathrm{H}_{\mathrm{rev}}^{k} \, \mathbf{H}$, requires:
  1. Weights $\sum_k w_k = 1$
  2. Anhysteretic magnetization operator M_{an}
  3. Distinct history operators $\mathrm{H}_{\mathrm{rev}}^{k}$





- $\mathbf{H} \rightarrow \mathbf{B}$ straightforward, inversion $\mathbf{B} \rightarrow \mathbf{H}$ cumbersome
  - Fixed-point iteration needed

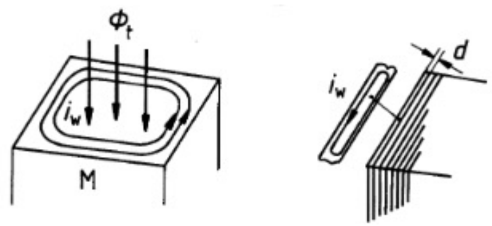
A. Bergqvist, "Magnetic vector hysteresis model with dry friction-like pinning", Physica B, 233:342–347, 1997

F. Henrotte et al., "An energy-based vector hysteresis model for ferro-magnetic materials", COMPEL, 25:71–80, 2006.

Ferromagnetic material model – Eddy currents

- Dipole magnet length: 5 m ≫ gap height: 30mm ⇒ **2D analysis**
- Laminates feature eddy currents in x-y plane
  - Not explicitly included in 2D simulations

  ⇒ Homogenization approach: $\mathbf{H} = \mathbf{H}_{\mathrm{static}} + \frac{\sigma d^2}{12}\,\dot{\mathbf{B}}$

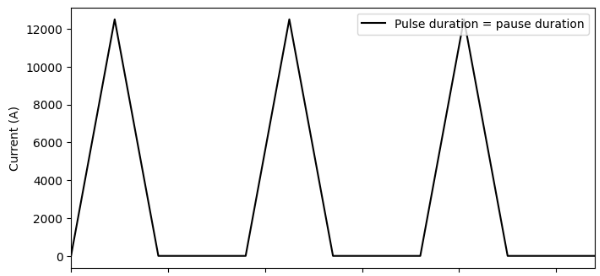


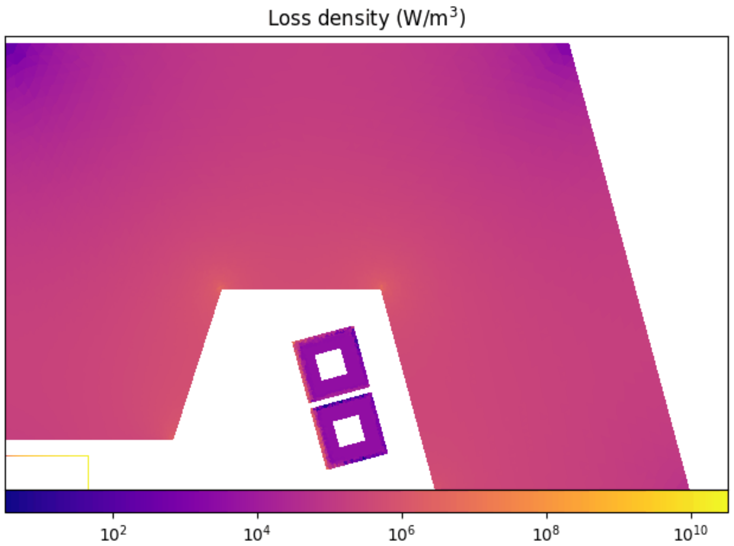
- Loss calculation:
  - Resistive: $p_{\mathrm{ohm}} = |\mathbf{J}|^2/\sigma$
  - Eddy currents: $p_{\mathrm{eddy}} = \frac{\sigma d^2}{12}\,|\dot{\mathbf{B}}|^2$
  - Hysteresis: $p_{\mathrm{hyst}} = \sum_k (\mathbf{H}_{\mathrm{static}} - \mathbf{H}_{\mathrm{rev}}^{\mathrm{k}}) \cdot \mu_0 \dot{\mathbf{M}}_{\mathrm{k}}$

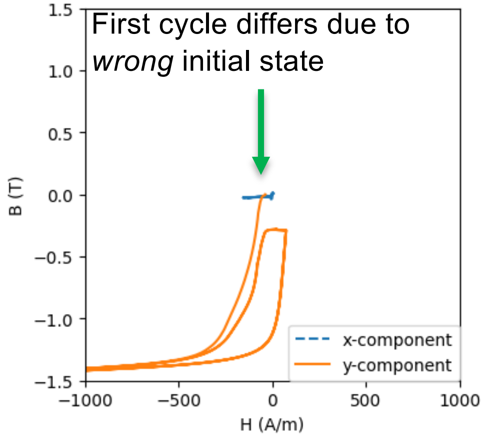
P. Dular et al., “A 3-D magnetic vector potential formulation taking eddy-currents in lamination stacks into account”, IEEE Trans. Magn., vol. 39, no. 3, pp. 1424–1427, 2003

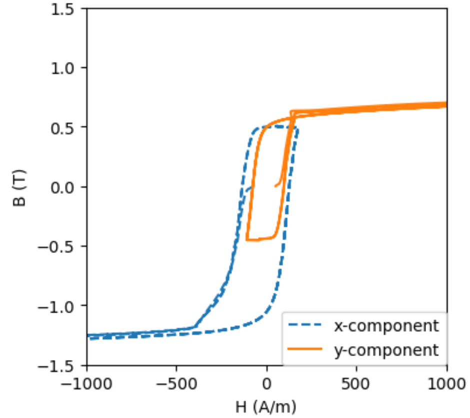
Insights of FEM analysis

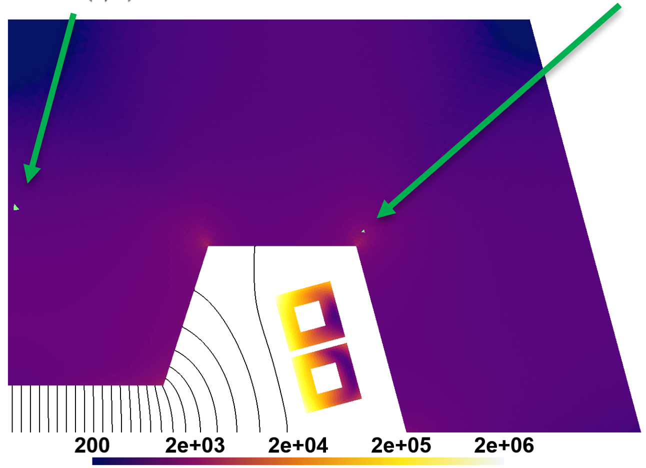
Peak excitation current: 50kAt (12.5kA per bar)









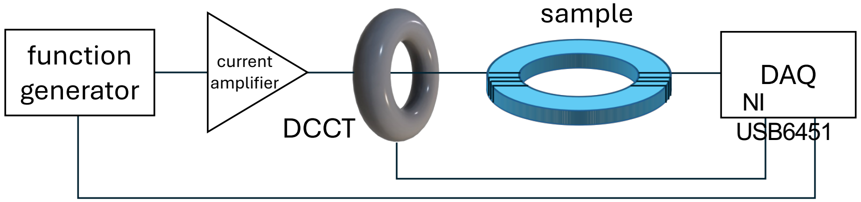


Loss density of single pulse (J/m³)

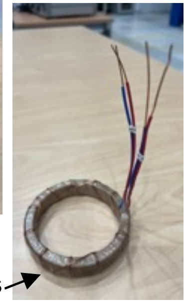
Material Properties for Accelerator Magnets

Courtesy Nicholas Sammut, Marco Buzio

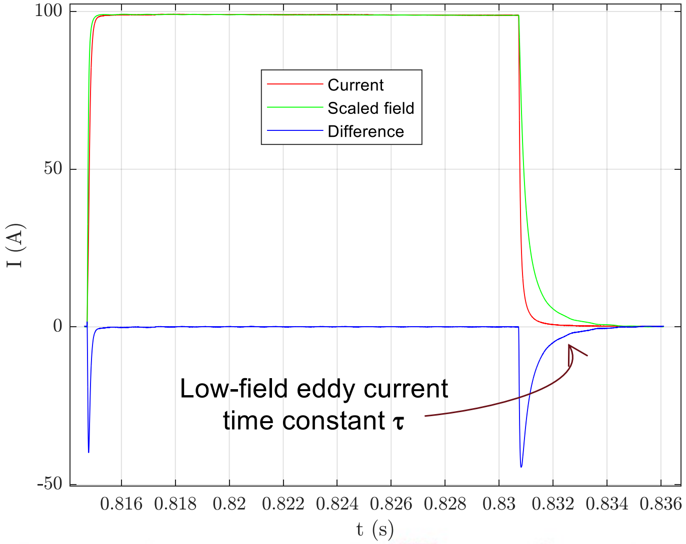
Two laminated FeCo permeameter ring samples with/without interleaved Kapton rings

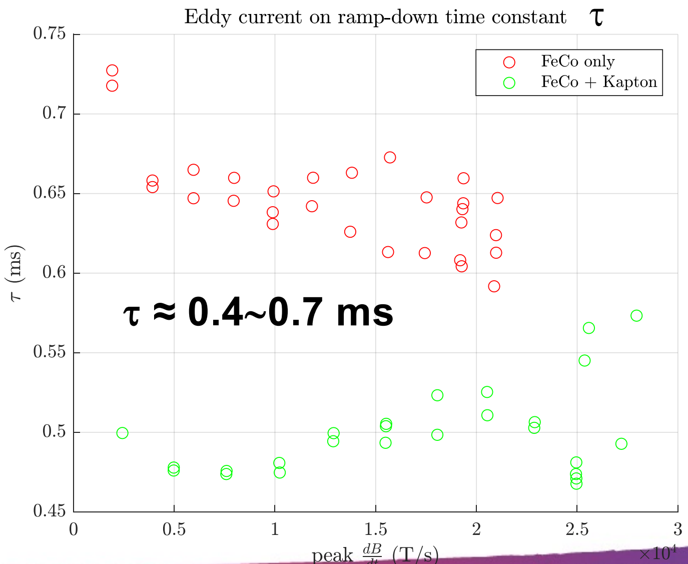


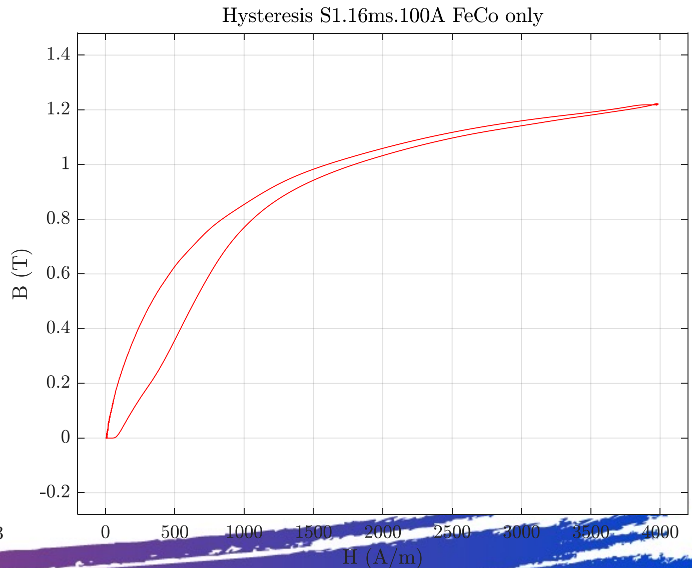
DCCT Zero-Flux MACC



First results: 54 different current pulses up to 1.2 T, 28 kT/s
Example: 100 A, 16 ms current pulse, FeCo rings only







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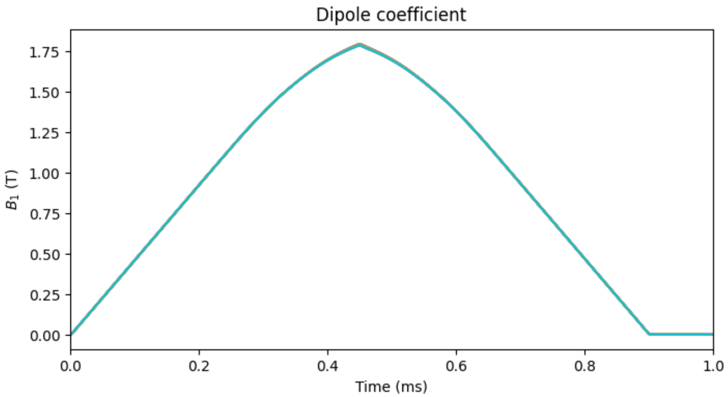
Field quality analysis

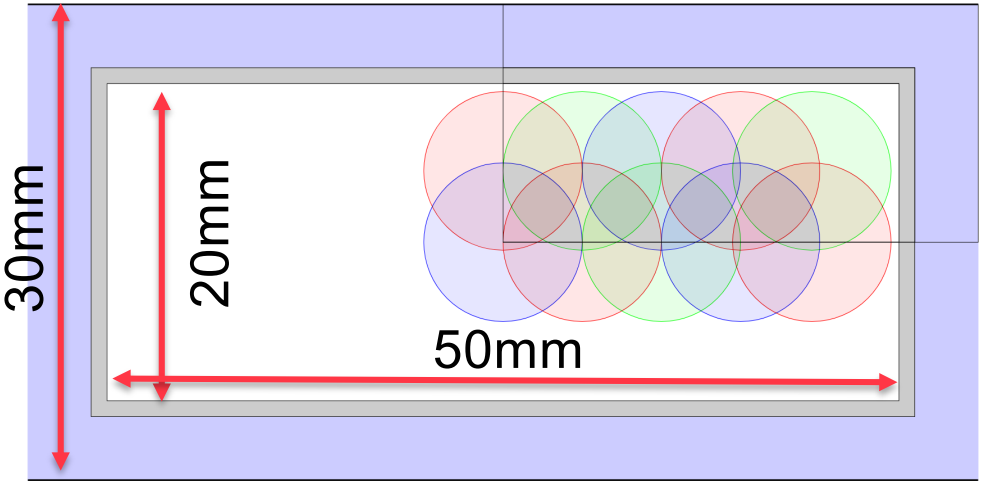
- Field quality evaluated on several 5 mm reference circles. (All in vacuum chamber)
- Multipole coefficients $C_n = A_n + jB_n$ [T] as function of time and position

$$A_n(r_0) = \frac{1}{\pi}\int_0^{2\pi} B_r(r_0,\varphi)\cos n\varphi \, d\varphi, \qquad n = 1,2,3,\ldots,$$

$$B_n(r_0) = \frac{1}{\pi}\int_0^{2\pi} B_r(r_0,\varphi)\sin n\varphi \, d\varphi, \qquad n = 1,2,3,\ldots.$$

$$A_n(r) = \left(\frac{r}{r_0}\right)^{n-1} A_n(r_0), \qquad B_n(r) = \left(\frac{r}{r_0}\right)^{n-1} B_n(r_0).$$

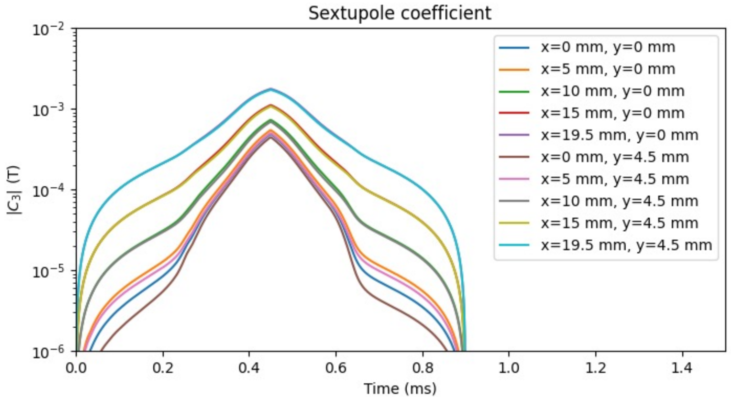


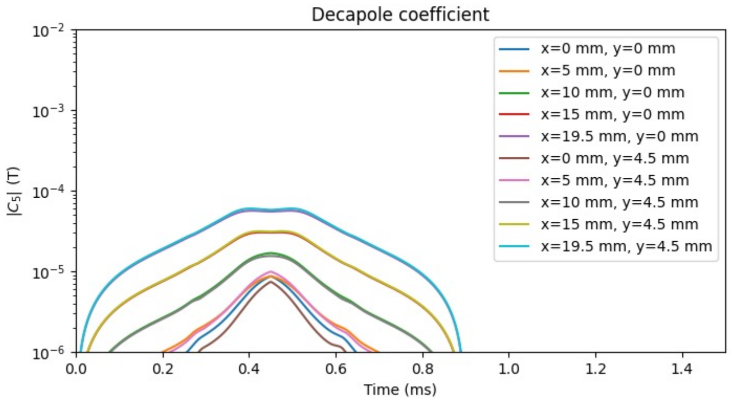


Air gap and beam pipe with 10μm Titanium coating

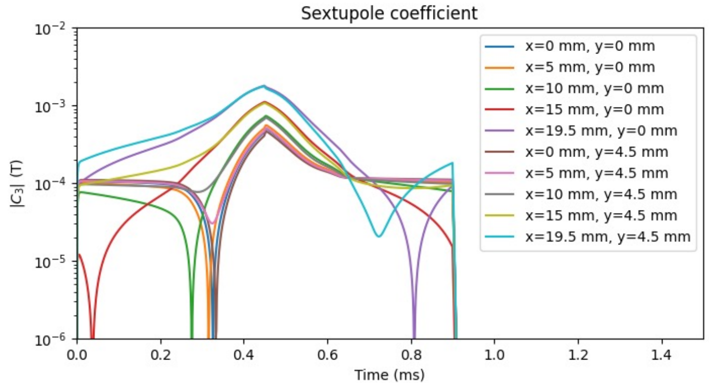
Beam pipe affecting field quality

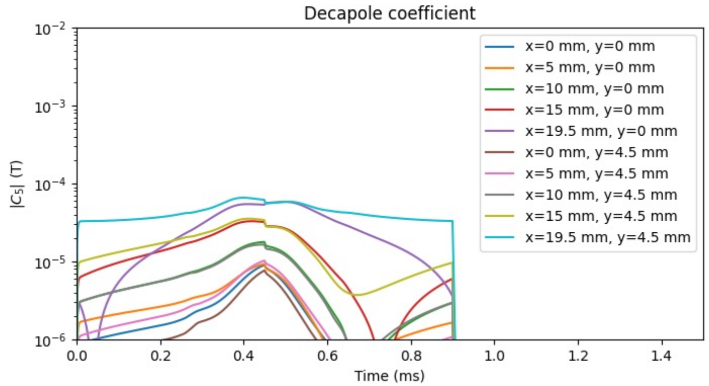
Without beam pipe:

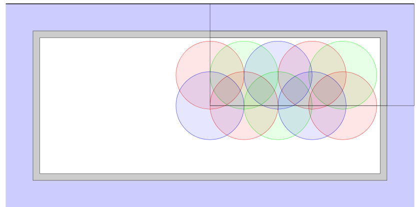




With beam pipe:



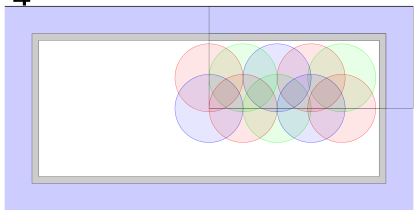




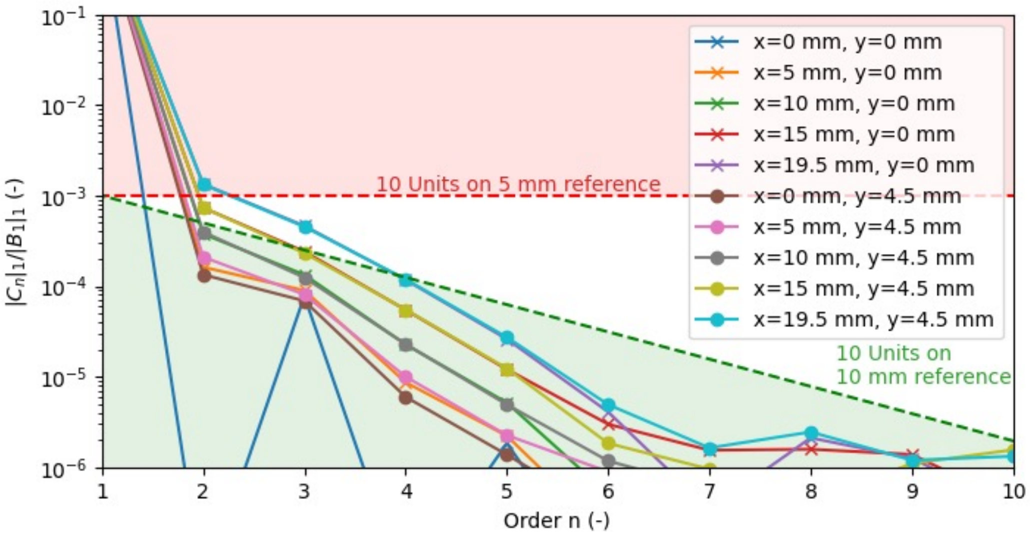
Unwanted multipole coefficients are larger on average. Similar peak values.

Relative multipole coefficients

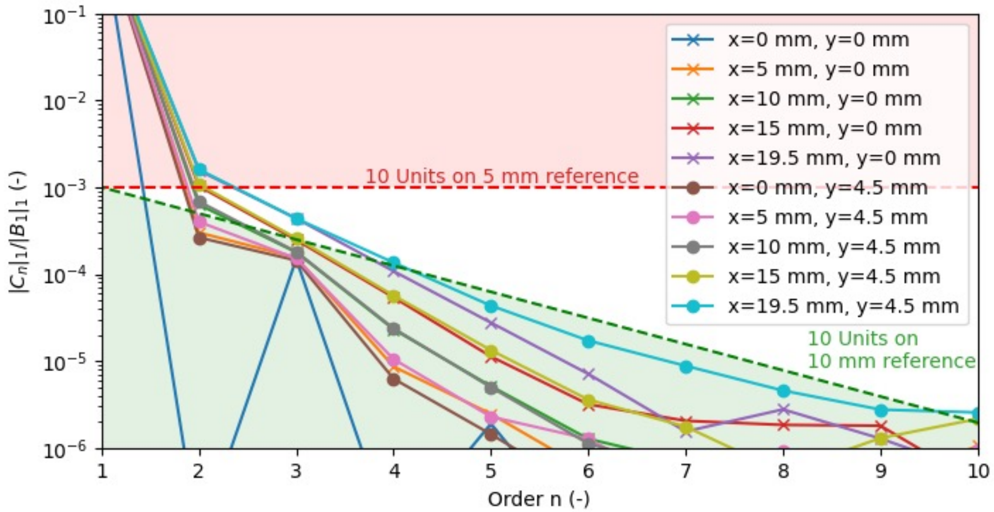
- Relative multipole coefficients: $\frac{||C_n||_1}{||B_1||_1} = \frac{\int |C_n| \mathrm{d}t}{\int |B_1| \mathrm{d}t} = R_n(r = 5\mathrm{mm})$
- Requirement: **10 Units on 10 mm reference circle** $\Leftrightarrow R_n(r = 10\mathrm{mm}) < 10^{-4}$
  - $R_n(r = 5\mathrm{mm}) = \left(\frac{5\mathrm{mm}}{10\mathrm{mm}}\right)^{n-1} R_n(10\mathrm{mm}) < \left(\frac{1}{2}\right)^{n-1} 10^{-4}$ **Green region**
- Strong quadrupole and sextupole coefficients: Shim design recommended / ongoing



Without beam pipe:



With beam pipe:



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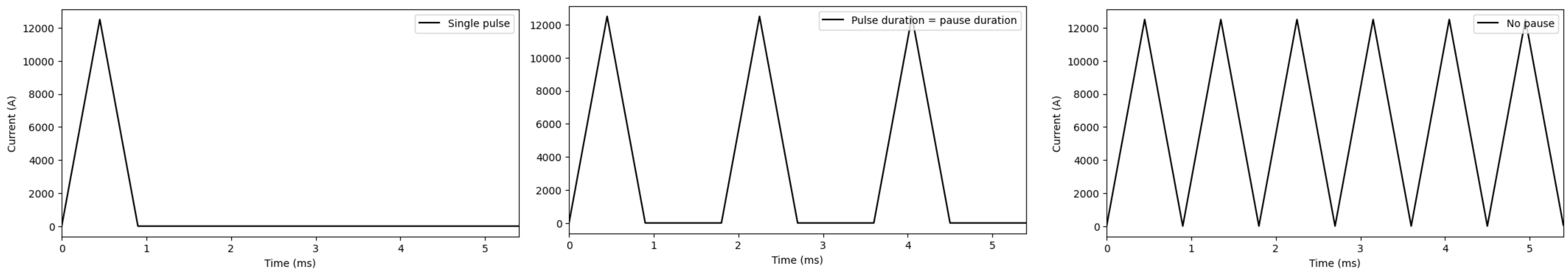
Excitations with higher duty cycles

Time domain analysis:
+ Captures all details
- Too slow for optimization routines

Frequency domain analysis:
+ Fast heuristic
- Assumes finite number of significant frequencies
    - Requires larger duty cycles



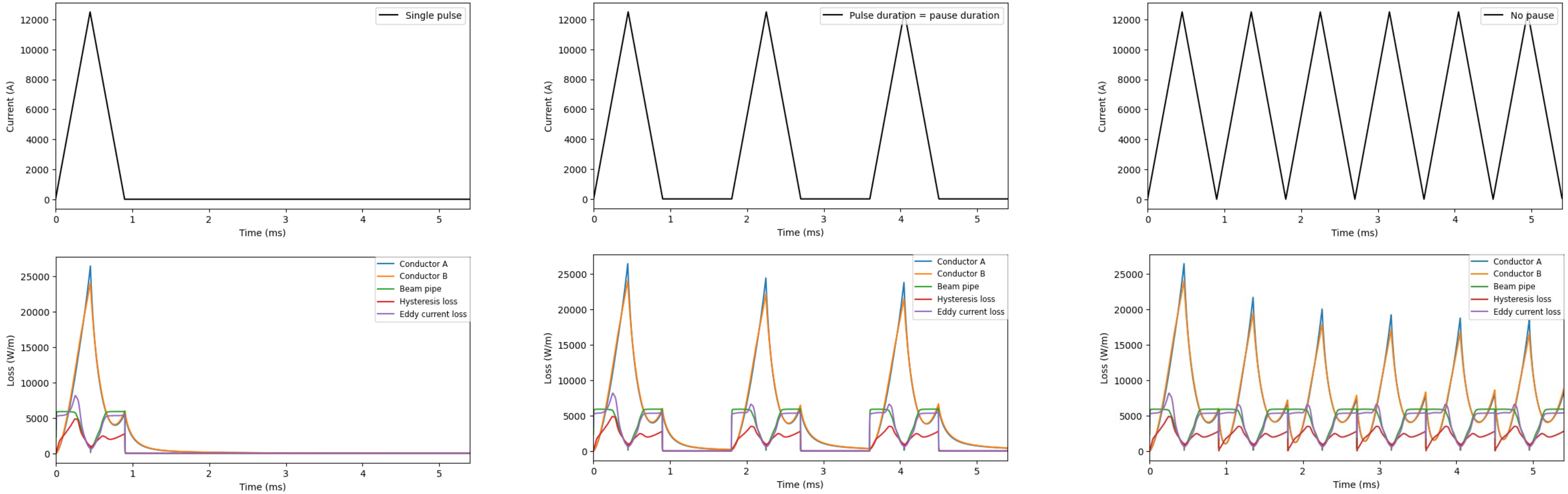
Duty cycle: 0.9ms/200ms <0.5%

Duty cycle: 0.9ms/1.8ms =50%

Duty cycle: 100%

How much does magnet behavior differ for these excitations?

Losses per period



- Copper loss: 75.93 J/m
- Titanium loss: 16.46 J/m
- Iron loss: 25.11 J/m
  - Hysteresis: 8.76 J/m

- Copper loss: 69.21 J/m
- Titanium loss: 16.43 J/m
- Iron loss: 22.89 J/m
  - Hysteresis: 7.48 J/m

- Copper loss: 48.24 J/m
- Titanium loss: 16.31 J/m
- Iron loss: 22.69 J/m
  - Hysteresis: 7.41 J/m

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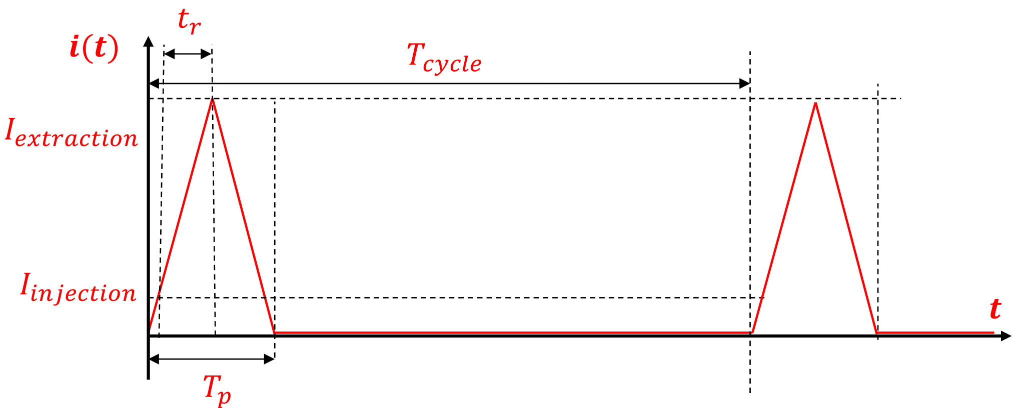
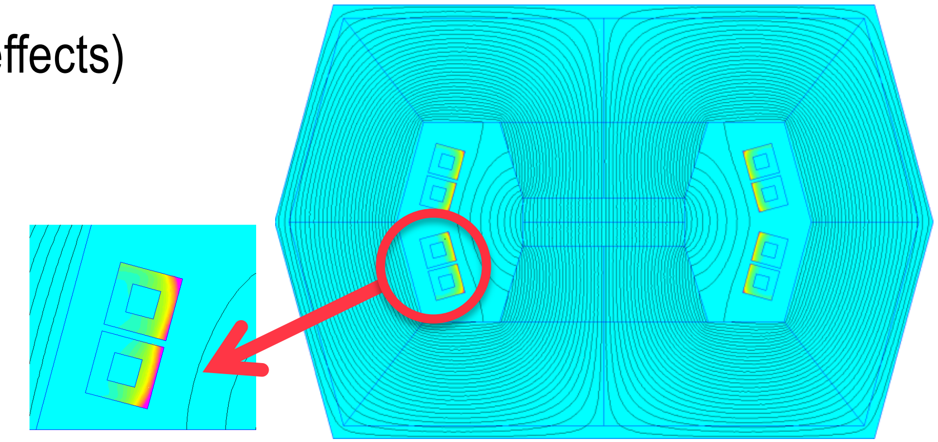
Problem Statement

- Pulsed operation of Normal Conducting magnets leads to additional losses such as :
  - Magnetic losses in the ferromagnetic yokes
  - Joule losses in windings (skin & proximity effects)



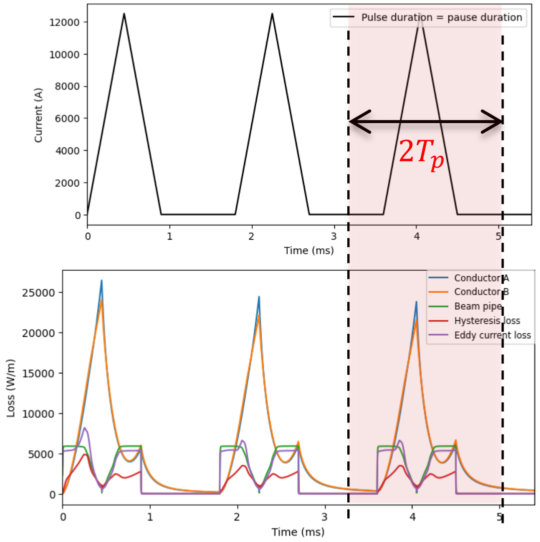


- Accurate **loss evaluation** is critical for:
  - Global efficiency & Magnet Thermal design
- A **dynamic magnet model** or equivalent circuit is essential for:
  - Power converter sizing
  - Current pulse control strategy development

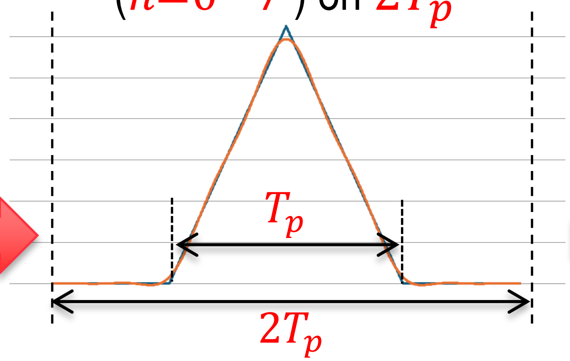
Frequency- Domain Loss Evaluation Method

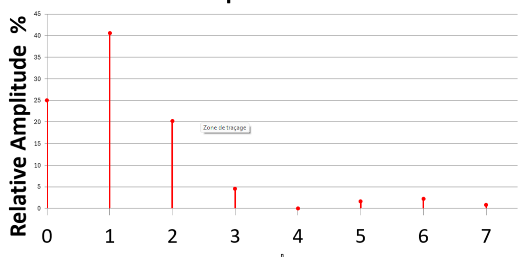
- Objective: Balance accuracy& computational speed for loss estimation in **pulsed steady-state regimes** with **Time-harmonic FEA** for efficient iterative optimal design

Steady-state obtained on on $2T_p$ with **Transient FEA**



Real & Reconstructed Signal (n=0 - 7) on $2T_p$





Fourier decomposition of periodic current pulse on 2 T_p

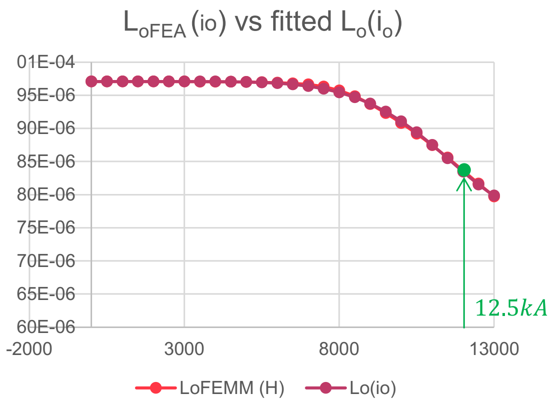
Time-harmonic FEA for each harmonic n=0 - 7

Sum harmonic contributions to compute steady-state losses P_p on 2 T_p

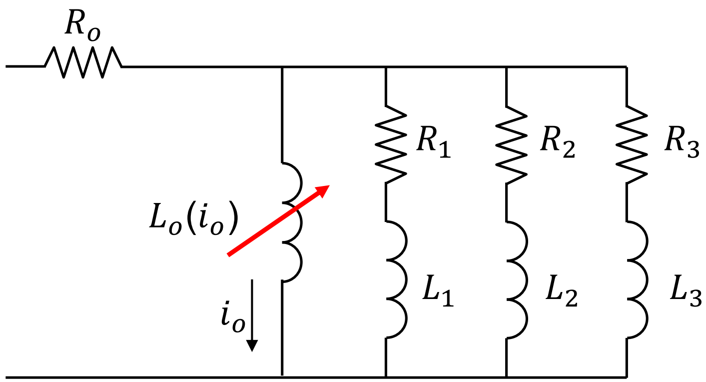
Sum Compute average steady-state losses on T_{cycle}: $P_{cycle} = P_p \frac{2.T_p}{T_{cycle}}$

Equivalent Circuit & Nonlinear Dynamic Modeling

- Time-Harmonic FEA results allow identification of an equivalent circuit with the same frequency response, usable in time-domain simulation
  - 3 R-L cells fitted by least-squares to match impedance frequency response obtained by **Time-harmonic FEA** & to model induced eddy current in bars
- Nonlinear extension of the dynamic model:
  - $L(I)$ obtained via saturated magnetostatic FEA using magnetic material B(H)
  - Analytical fit $\longrightarrow$ nonlinear inductance $L_o(i_o)$ inserted into equivalent circuit
- **Nonlinear hybrid equivalent circuit**:



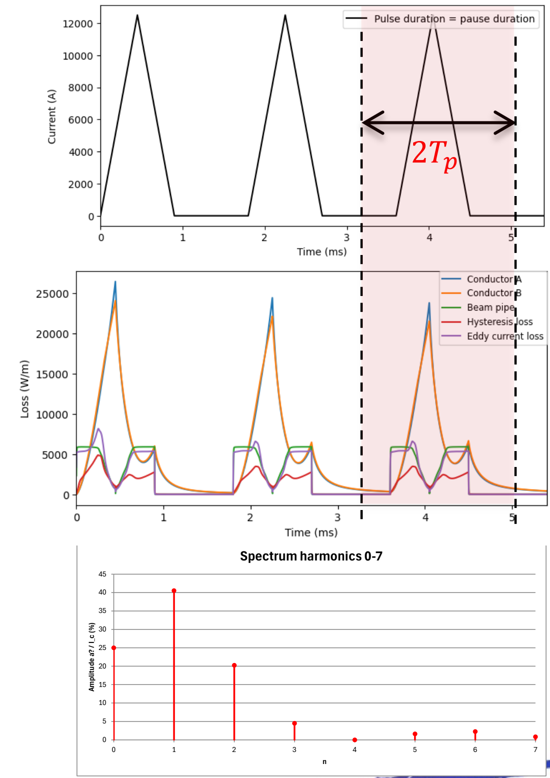
$$\boxed{L_o(i_o) = \frac{L_{iom}}{1 + \left[\frac{i}{I_s}\right]^n + \beta\left[\frac{i}{I_s}\right]^m}}$$



Cross-Validation Between Simplified Time-Harmonic and High-Fidelity Transient FEA Model

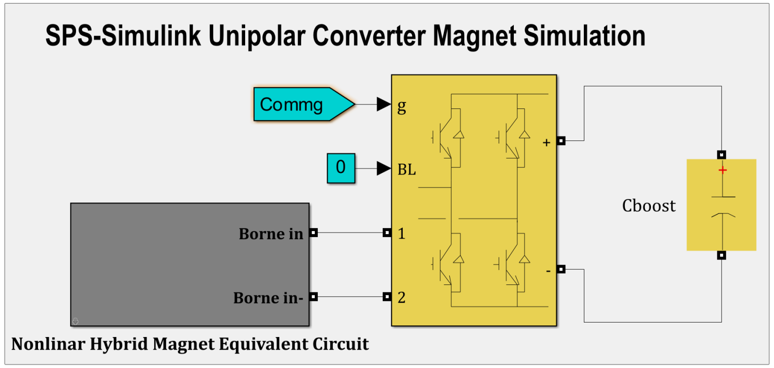
- Benchmark: Transient FEA with magnetic saturation & dynamic hysteresis
- Simplified Time-Harmonic FEA (linear, frequency-domain) faster to compute steady-state Joule & magnetic losses
- Loss evaluation with both methods
  - for steady-state operation on $2T_p$
  - Valid despite simplified assumptions (*steady-state, linear*)

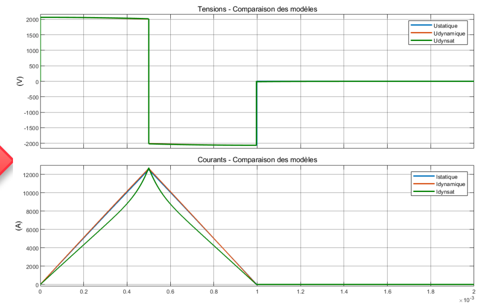
Magnet Length 1 m	Transient FEA with a	Simplified	
Magnet Loss (W)	**high-fidelity model**	**Time-harmonic FEA**	**% err**
Copper loss	346.05	339.11	-2.0%
Ti Chamber loss	82.17	113.34	37.9%
Total Copper loss	**428.22**	**452.45**	**5.7%**
Iron Loss	114.45	142.49	24.5%
Total loss	**542.67**	**594.94**	**9.6%**



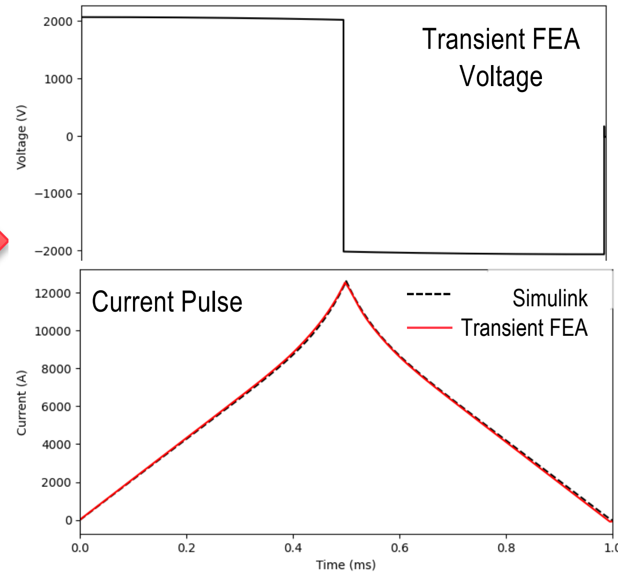
Cross-Validation Between Simplified Time-Harmonic and High-Fidelity Transient FEA Model

- Dynamic Validation of the Equivalent Circuit Using Transient FEA
- Validation scenario:
  - Nonlinear hybrid equivalent circuit model driven by pulsed power converter in Simulink
  - Simulated input magnet voltage applied to **Voltage supplied full Transient FEA model**





SPS-Simulink



- Agreement on Current waveform reproduction

Conclusion & Perspectives

- High-Fidelity Transient FEA Magnet Model with saturation for:
  - accurate dynamic loss estimation under pulsed regime
  - spatial field quality analysis
- Simplified Time Harmonic FEA Methodology :
  - for loss computation under steady-state pulsed regime
  - for identification of nonlinear hybrid equivalent circuit model usable in circuit simulations & Magnet-converter-control co-design
  - suitable for implementation in iterative design optimization with computational efficiency
- Cross-validation with acceptable accuracy

- **High-fidelity &simplified FEA models are complementary tools used at different levels of modeling complexity within an integrated CAD & simulation environment.**

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