TECHNISCHE UNIVERSITÄT DARMSTADT

Institute for Accelerator Science and Electromagnetic Fields (TEMF)
Electromagnetic Field Theory
Computational Electromagnetics

TASK 3 OF MMWG

Dynamic analysis of fast-ramping normal conducting magnets

© Axel Becker

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AGENDA

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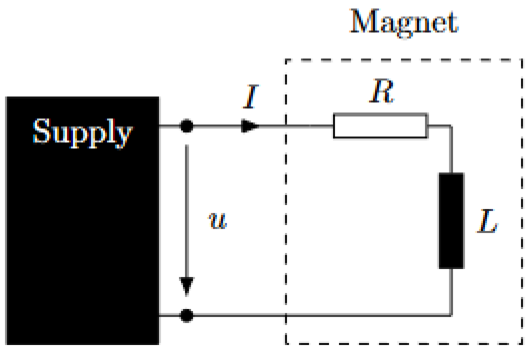
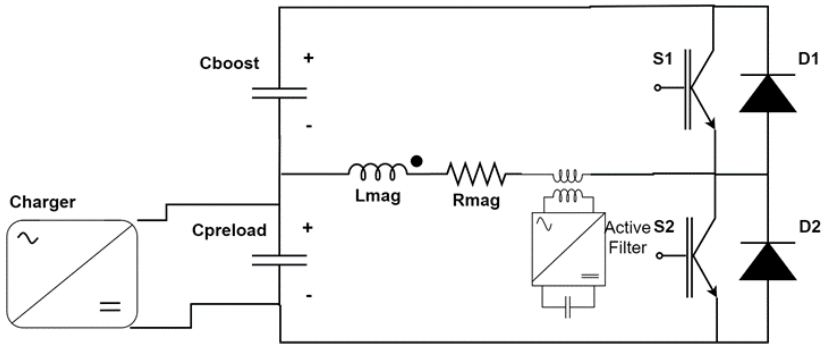
SYSTEM DESCRIPTION

- **Supply circuit**: non-linear
- **Magnet**: normal conducting, non-linear, hysteretic
- **Separate design challenges**
  - Supply circuit → CERN
  - Magnet → Bologna (Static) + Darmstadt (Dynamic)
- **Simplifications**
  - Every magnet as one-port powered by its own supply
  - …





Switched Resonance Cell

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CONSTRAINTS

- IMCC Parameters pg 13, 17, 18

	RCS1	RCS2	RCS3	RCS4
Inj Energy [GeV]	63	314	750	1500
Acc. length [km]	5.99	5.99	10.7	35.0
Res. mags Lm [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
Trepetition [ms]	200	200	200	200
Dipoles Gap w [mm]	100	100	100	100
Dipoles Gap h [mm]	30	30	30	30
Dipoles Egap@Bext [MJ]	14.1	9.8	16.9	78.8
Dipoles Etot@Bext [MJ]	21.2	14.7	25.3	118.2
Dipoles Pmax [GW]	111	54	43	74

			RCS1	RCS2	RCS3	RCS4
Total length	l_{mag}	km	3.65	2.54	4.37	20.38
Max flux density	B_{max}	T	1.8	1.8	1.8	1.8
Air gap width	w_g	mm	100	100	100	100
Air gap height	h_g	mm	30	30	30	30
Magnets peak energy	E_{mag}	MJ	21.2	14.7	25.3	118.2
B ramping time	T_{ramp}	ms	0.35	1.1	2.37	6.37
Repetition times	T_{rep}	ms	200	200	200	200
Magnets inductance	L_{mag}	uH/m	6.3	6.3	6.3	6.3
Magnets Resistance	R_{mag}	uΩ/m	69.3	69.3	69.3	69.3
Power converter peak power	P_{pk}	GW	121	54	43	74
Power converter peak current	I_{peak}	kA	43	43	43	43
Power converter total output voltage	V_{outpk}	MV	2.8	1.27	1.03	1.88

Complex	Magnet	Aperture [mm]	Length [m]	Field [T]	Ramp-rate [T/s]	Temperature [K]
Target, decay and capture	Solenoid	1200	19	20	SS	20
6D cooling	Solenoid	90–1500	0.08–0.5	4–15	SS	4.2–20
Final cooling	Solenoid	50	0.5	> 40	SS	4.2
Rapid cycling synchrotrons	NC Dipole	30×100	5	± 1.8	4200	300
	SC Dipole	30×100	1.5	10	SS	4.2–20
Collider ring	Dipole	160–100	4–6	11–16	SS	4.2–20

Parameter	Symbol	Unit	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	-	-	No	Yes	Yes	Yes
Repetition rate	f_{rep}	Hz	5	5	5	5
Circumference	C	m	5990	5990	10700	35000
Injection energy	E_{inj}	GeV	63	314	750	1500
Ejection energy	E_{ej}	GeV	314	750	1500	5000
Energy ratio	E_{ej}/E_{inj}	-	4.98	2.39	2.00	3.33
Assumed survival rate	N_{ej}/N_{inj}	-	0.9	0.9	0.9	0.9
Acceleration time	τ_{acc}	ms	0.343	1.097	2.37	6.37
Revolution period	T_{rev}	µs	20	20	36	117
Number of turns	n_{turn}	-	17	55	66	55
Required energy gain per turn	ΔE	GeV	14.8	7.9	11.4	63.6
Average accel. gradient	G_{avg}	MV/m	2.44	1.33	1.06	1.83
Number of bunches/species	-	-	1	1	1	1
Bunch population at injection	N_{inj}	1×10^{12}	2.7	2.4	2.2	2.0
Bunch population at ejection	N_{ej}	1×10^{12}	2.4	2.2	2.0	1.8
Vertical norm. emittance	$\epsilon_{v,n}$	mm	25	25	25	25
Horiz. norm. emittance	$\epsilon_{h,n}$	mm	25	25	25	25
Long. norm. emittance $\sigma_E \times \sigma_t$	$\epsilon_{z,n}$	eVs	0.025	0.025	0.025	0.025
Tot. straight section length	L_{str}	m	2335	2336	3976	10367
Total NC dipole length	L_{NC}	m	3655	2539	4366	20376
Total SC dipole length	L_{SC}	m	0	1115	2358	4257
Max. NC dipole field	B_{NC}	T	1.80	1.80	1.80	1.80
Max. SC dipole field	B_{SC}	T	-	10	10	16
Ramp rate	$\dot{B}$	T/s	4200	3282	1519	565
Main RF frequency	f_{RF}	MHz	1300	1300	1300	1300
Max RF voltage	V_{RF}	GV	20.9	11.2	16.1	90

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CODE AT TU DARMSTADT

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- **Pyrit:** In house 2D FEM solver written in Python
- Three available simulation types

	Static	Time Harmonic	Transient
Source type	Constant	Sinusoidal	Any / Circuit Coupling
Material law	$H = \nu(B)B$	$H = \nu(\omega)B$ Complex quantities	$H = \nu(B)B + \frac{\sigma d^2}{12}\dot{B}, J = J_s - \sigma\dot{A}$
Resolves saturation / nonlinear reluctivity	✓	X	✓
Skin effect (solid conductor model)	X	✓	✓
Eddy currents	X	✓	✓
Accurate hysteresis model	X	X	(✓)
Total iron losses, as postprocess quantity (Steinmetz)	(✓)	✓	✓
Computational cost compared to static	1 (Newton iteration)	<1 (Direct solving of lin. sys.)	Number of timesteps (Newton at every timestep)

Work in progress

- Reliable hysteresis description
- Temperature development and cooling
- Forces and stress
- End effects

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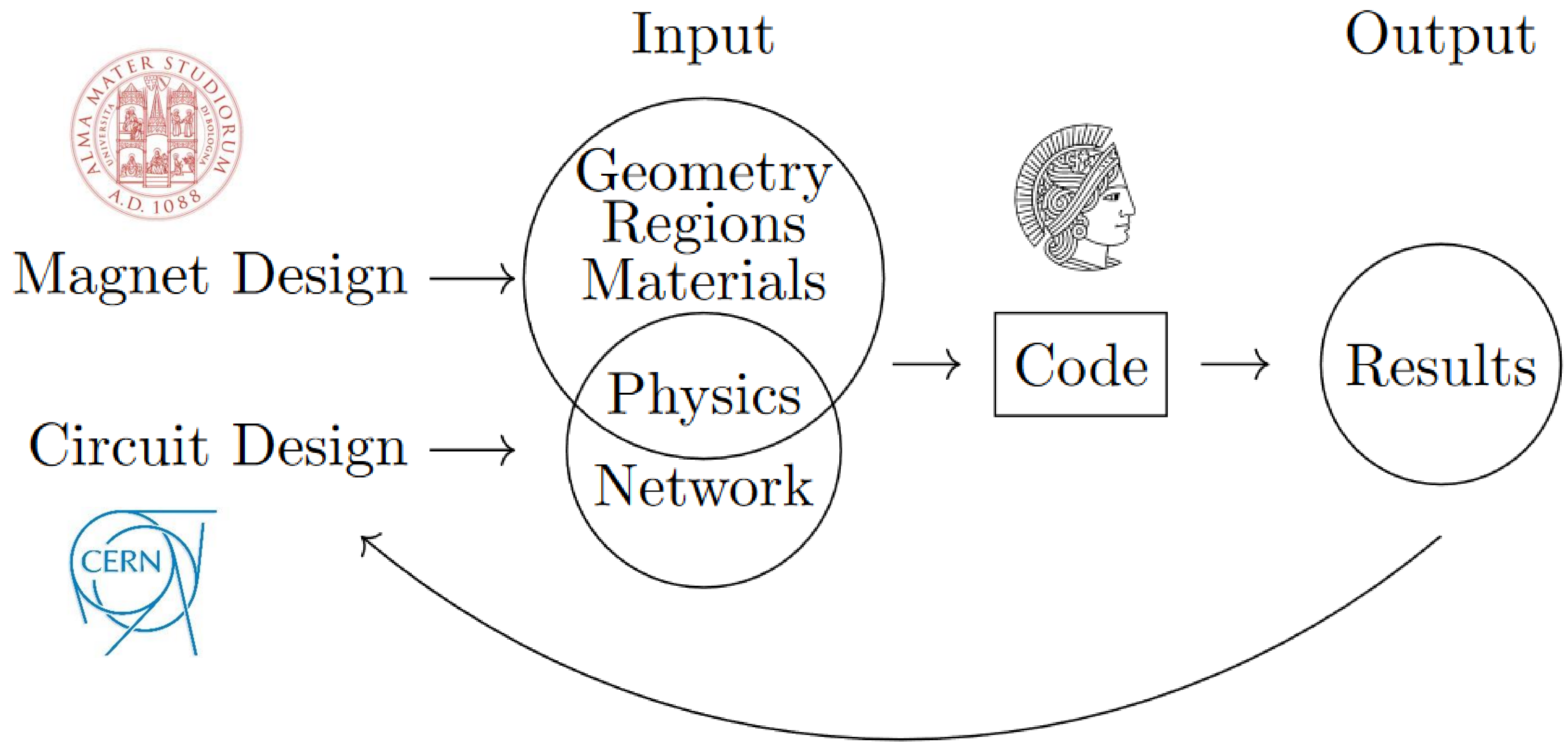
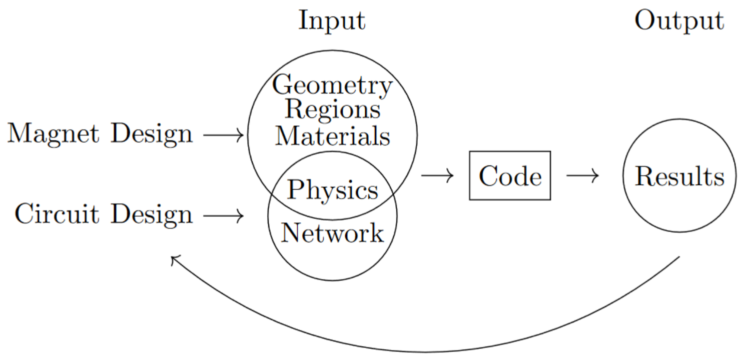
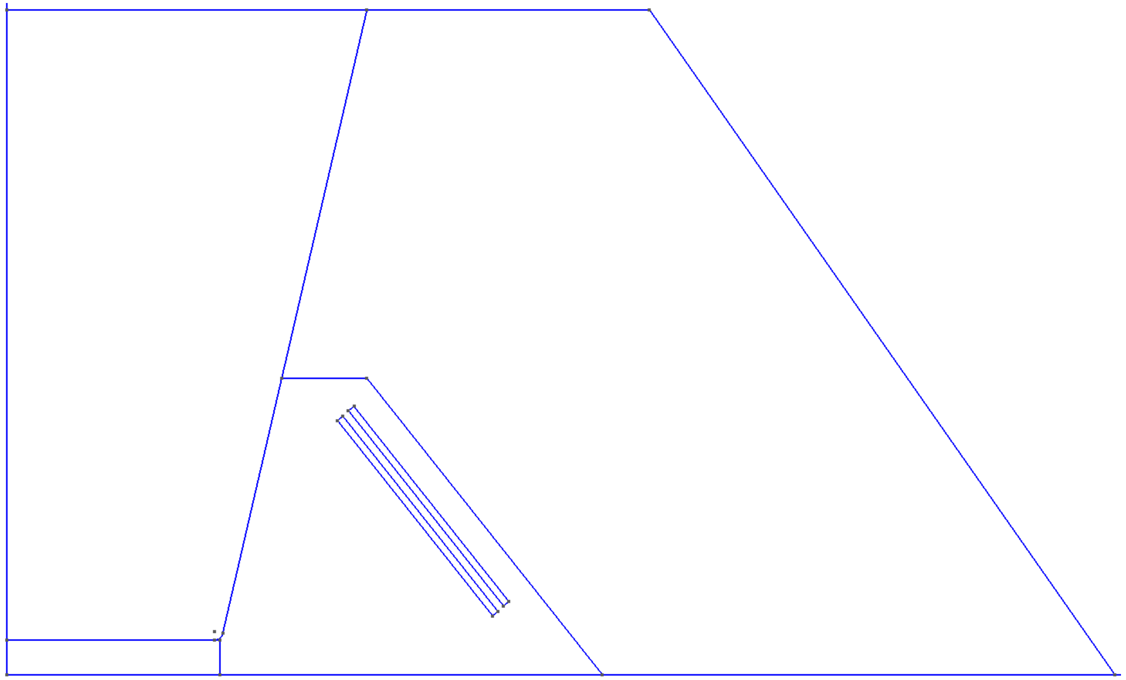
GENERAL WORKFLOW



GENERAL WORKFLOW – GEOMETRY AND REGIONS

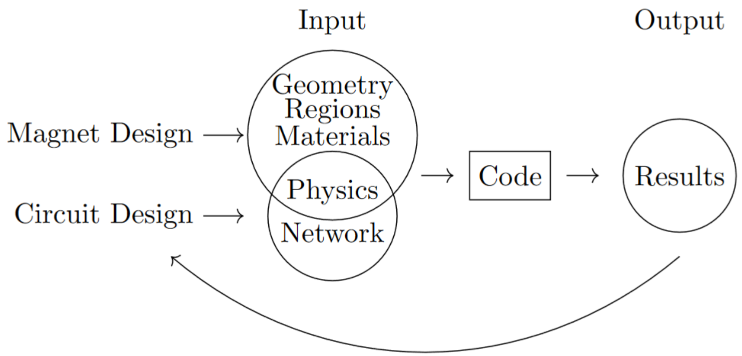


- **Geometry** is defined by
  - Points
  - Lines
  - Faces (intermediate step: loops)
- **Physical Regions** are defined as
  - Boundaries (1D) via lines
  - Regions (2D) via faces

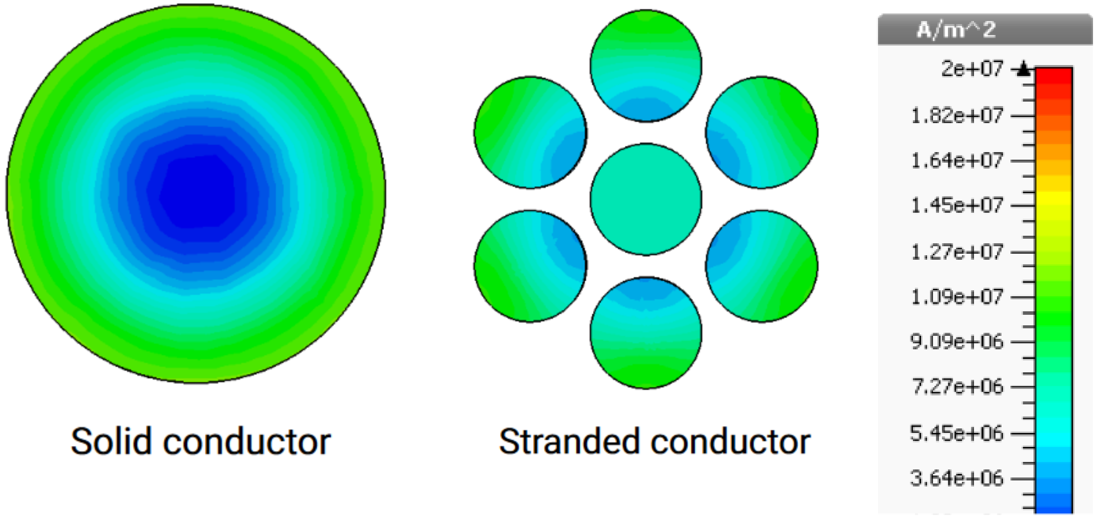


USMAP Hourglass

GENERAL WORKFLOW – PHYSICS



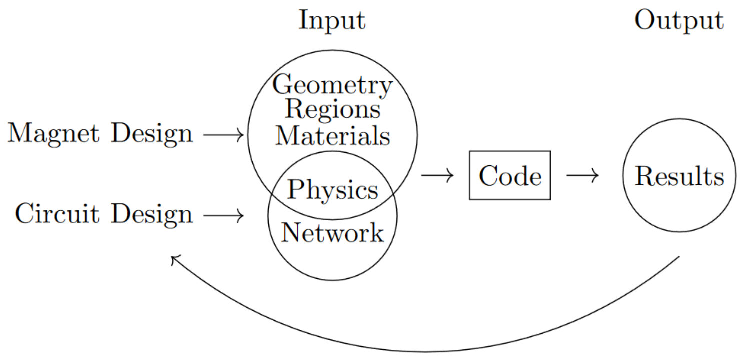
- **Physics** is defined by
  - Boundary conditions for every boundary
  - Materials for every region
  - Sources: current or voltage
  - Type of conductors: solid or stranded
  - Length of the magnet
  - …



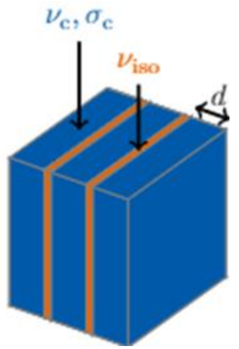
Solid conductor

Stranded conductor

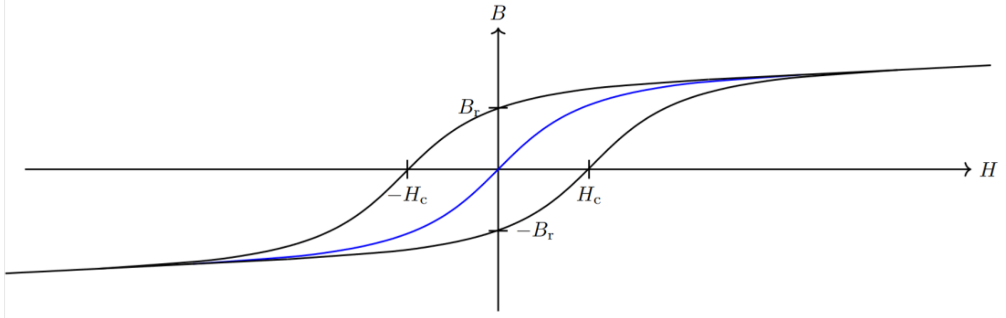
GENERAL WORKFLOW – MATERIALS



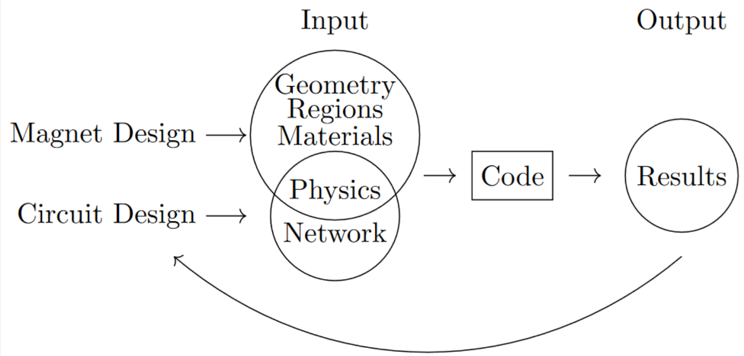
- **Materials** are defined by
  - **Lamination thickness** d in m (if laminated)
  - **Conductivity** σ as a constant in S/m
  - **Density** $\gamma = m/V$ as a constant in kg/m³
  - **Steinmetz parameters** $k, a1, a2$ in W/kg, 1, 1 to fit $\frac{P}{m} = k \frac{\hat{B}}{1\text{T}}^{a1} \frac{f}{1\text{Hz}}^{a2}$
  - **Reluctivity**/anhysteretic **BH** relationship
    - BH table or models with few parameters (linear, arctan, …)



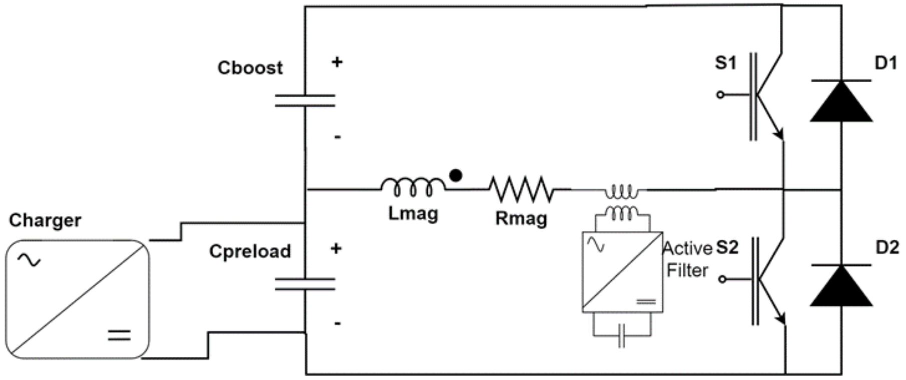
- **Issues**
  - Steinmetz parameters not an intrinsic material property
    - Time consuming to retrieve from data sheets
  - Anhysteretic BH relationship not physical
  - Temperature dependency



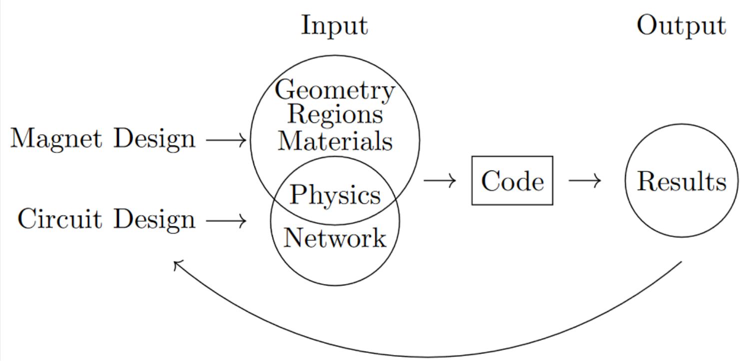
GENERAL WORKFLOW – NETWORK



- Network/Circuit is defined by
  - (Oriented) edges with circuitelements
- Code solves system of equations $M\dot{y} + Ky = s$
  - Mass M is singular (and possibly non-linear)
  - Stiffness K is non-linear
- System size ≈ amount of magnet's DoFs
  - Linear inductance: 2 DoFs
  - FEM magnet: minimum 5k DoFs



GENERAL WORKFLOW – RESULTS



- Electrical network will automatically store trivial quantities
  - Current, voltage, power, energy for every element
- Magnet as element of interest
  - Magnetic flux density in predefined positions
  - Averaged current densities
  - Losses (power and energy)
  - Stored magnetic energy
  - Steinmetz hysteresis approximation
  - Selected visualizations

Work in progress
- Multipole coefficients

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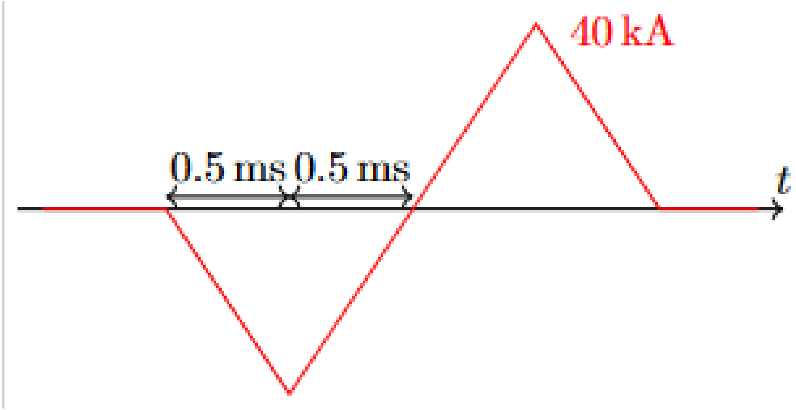
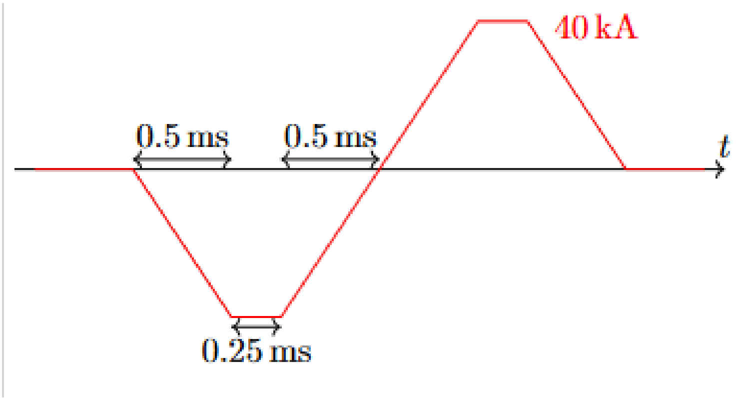
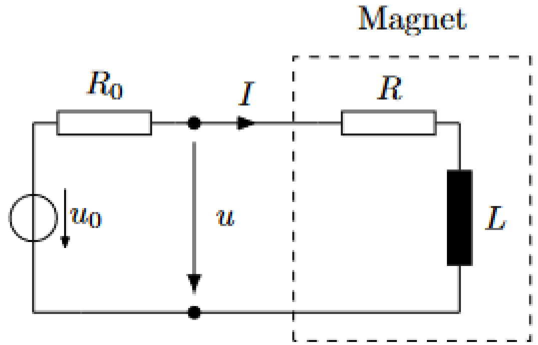
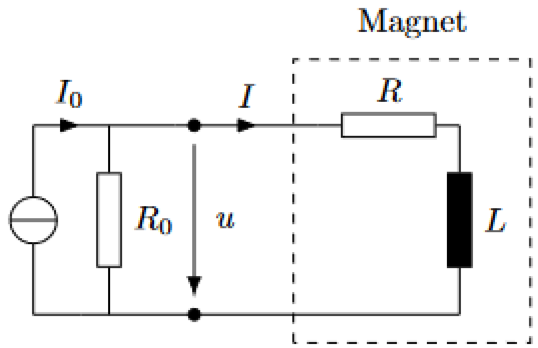
TRANSIENT ANALYSIS

- Ideal current source
  - Trapezoidal shaped current with peak of 40kA (Hourglass)









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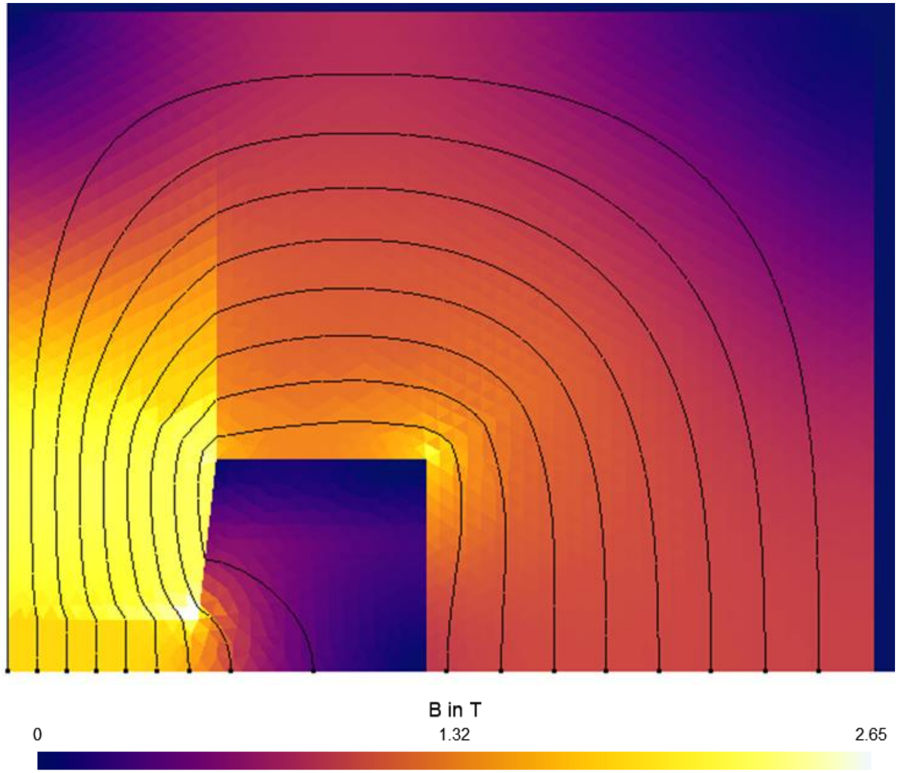
H-TYPE DIPOLE - TRANSIENT

H-Type Dipole	2ms Trapezoidal without flat top	2.5ms Trapezoidal with flat top (2x 0.25ms)
Bgap [T]	1.8	1.8
Gap size [mmxmm]	110 x 30	110 x 30
Mmf [kAt]	43	43
Iron losses (yoke) [J/cycle-m]	15.6 *	15.6 *
Iron losses (pole) [J/cycle-m]	26.9 *	26.9 *
Coil Losses [J/cycle-m]	135	210
Total losses [J/cycle-m]	178	253
Stored energy (total / gap) [J/m]	5550 / -	5550 / -

*Iron losses based on 0.178mm pole and 0.1mm yoke.
Same parameters as in USMAP study.



One conductor per quarter: $54.5 \cdot 20\ mm^2$

CONDUCTORS AND SKIN DEPTH

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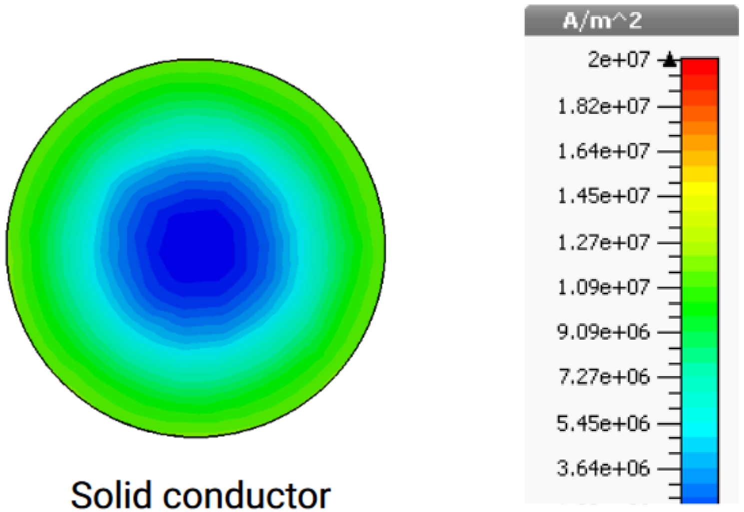
- Copper: $\mu = 4\pi \cdot\ 10^{-7}\ \mathrm{Vs/Am}, \sigma = 6 \cdot 10^{7}\mathrm{A/Vm}$
- Frequency $f \leq 1\mathrm{kHz}$
- Skin depth $\delta = \sqrt{\frac{1}{\pi\mu f\sigma}} = \frac{1}{2\pi}\sqrt{\frac{1}{6f/\mathrm{Hz}}}\mathrm{m} \geq 2\mathrm{mm}$
- USMAP Hourglass Dipole: bus bars of $2.4\mathrm{mm}$ width



Solid conductor

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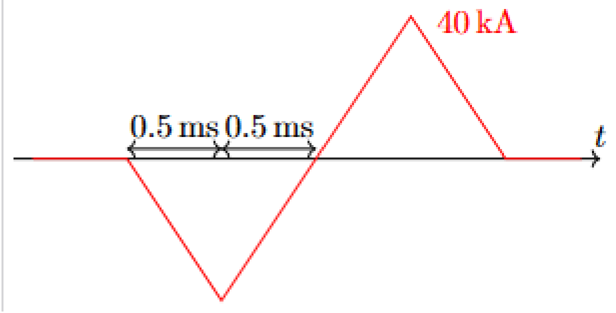
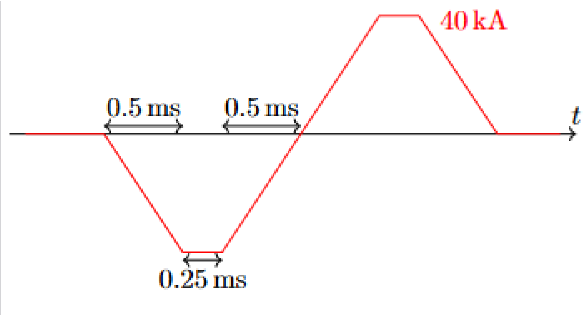
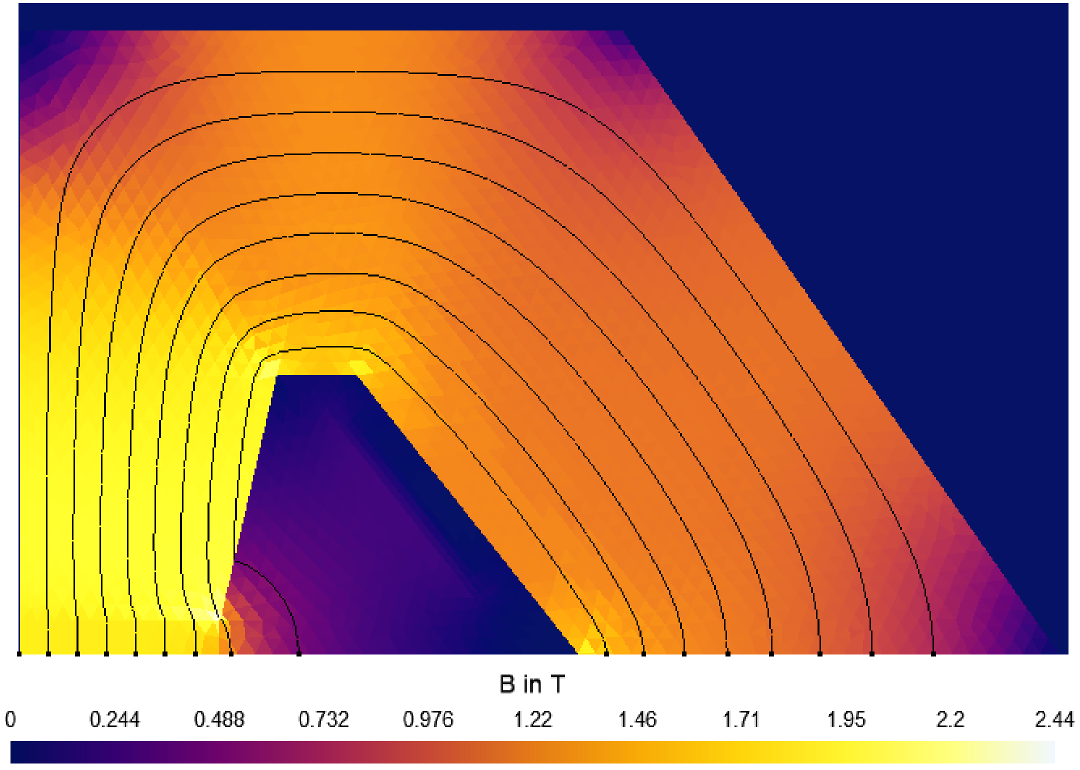
USMAP DIPOLE - TRANSIENT

MAP Dipole (Hourglass)	2ms Trapezoidal without flat top	2.5ms Trapezoidal with flat top (2x 0.25ms)
Bgap [T]	1.8	1.8
Gap size [mmxmm]	154 x 25	154 x 25
Mmf [kAt]	40	40
Iron losses (yoke) [J/cycle-m]	31.2	31.2
Iron losses (pole) [J/cycle-m]	57.8	57.8
Coil Losses [J/cycle-m]	55 + 12 = 67	84 + 24 = 108
Total losses [J/cycle-m]	156	197
Stored energy (total / gap) [J/m]	6500 / 4770	6500 / 4780







Two conductors per quarter, each: 2.4 · 90 mm²

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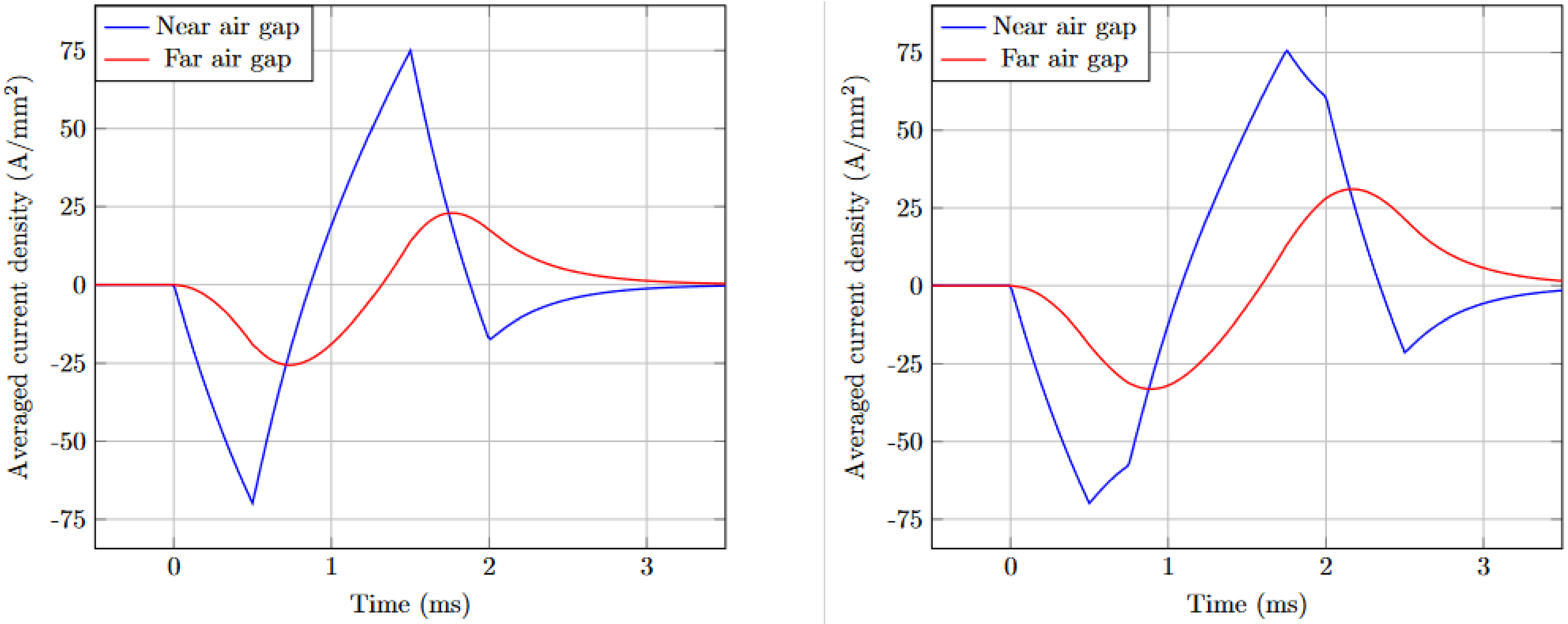
USMAP DIPOLE - TRANSIENT

- Current densities: without and with flat top



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OVERVIEW

Done

- Specialized on RCS2 (±1.8 in 1.1ms) Dipoles
- Tools to couple circuit and field model (2D)
  - Magnet as one-port element
- Results for two magnet models: H-Type and Hourglass
- Eddy current losses via core homogenization
- Entire core loss via Steinmetz formula

To Do

- Other Dipoles, Quadrupoles
- Simulation with more elaborate circuit
  - Magnet as four-port element
- Accurate hysteresis and core loss description
  - Lamination problem
- Temperature development, cooling
- Beam pipe
- Forces, stress, coil displacement
- End effects

ADDITIONAL SLIDES

WORK IN PROGRESS - LAMINATES & HYSTERESIS

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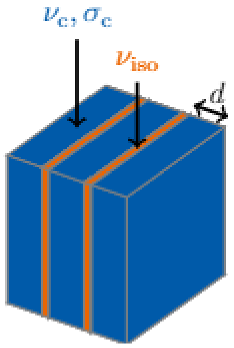
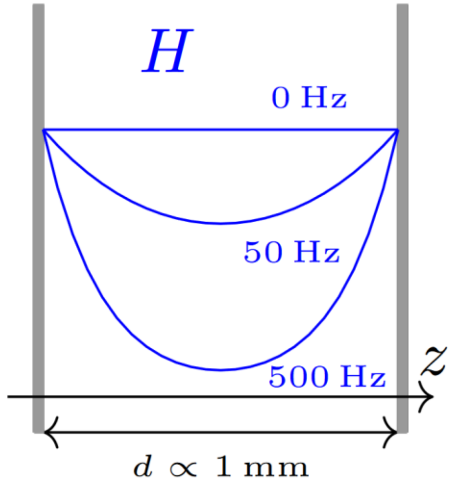
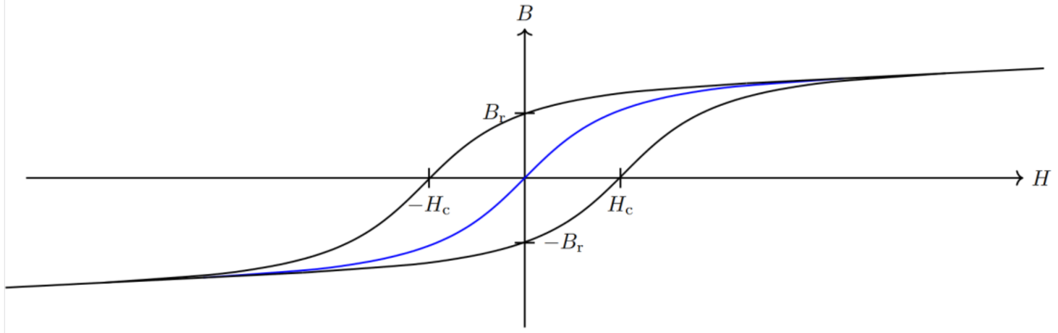
- **1D lamination problem**
  - $\dot{B} = \frac{1}{\sigma}\partial_z^2 H$, assuming $B_z \approx 0, H_z \approx 0$ and $B, H\ as\ fct(t, z)$
  - $B = \mu_0 H + M$
  - Magnetization M dependent on history!
    - Difficult to retrieve of data sheets
- **2D FEM and 1D lamination as iteratively solved subproblems**
  - Results of 1D problem homogenized and expressed using a model $H = \text{fct}(B, \dot{B})$







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MAP DIPOLE - STATIC

MAP Dipole (Hourglass)	MAP	CERN (Maxwell2D)	TUDa 1.5T	TUDa 1.8T
External Dimensions [mm x mm]	800 X 480	800 X 480	Circle of radius 500	Circle of radius 500
Bgap [T]	1.5	1.5	1.5	1.8
Gap size [mmxmm]	156 x 25	156 x 25	154 x 25	154 x 25
Mmf [kAt]	31.2	31.2	30.8	40.7
Iron losses (yoke) [J/cycle-m] (*)	1.1E6/(2200x15)=33 **27**	59085x2x0.001=59 (pole and Joke have the same material M235-35A)	21.8 * (3 without hysteresis)	32 * (5 without hysteresis)
Iron losses (pole) [J/cycle-m] (*)	2.1E6/(2200x15)=63 **55**	61167x2x0.001=61	40.2 * (17 without hysteresis)	58 * (24 without hysteresis)
Coil losses [J/cycle-m] (*)	0.55E6/(2200x15)=16	4*(3174+5106)x0.001=33	17.8 for a 1ms cycle	31 for a 1ms cycle
Total losses [J/cycle-m] (*)	112 **98**	153	80	121
Stored energy (total / gap) [J/m]	4200 / 3490	4900 / 3490	4551 / 3426	6644 / 4849

Stranded conductor model

* density of material defined as 7500kg/m³

USMAP study might have used 10000kg/m³

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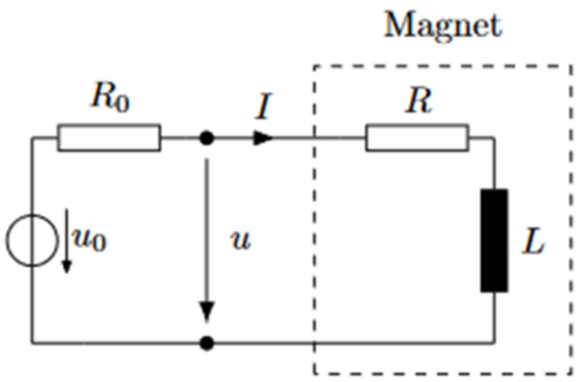
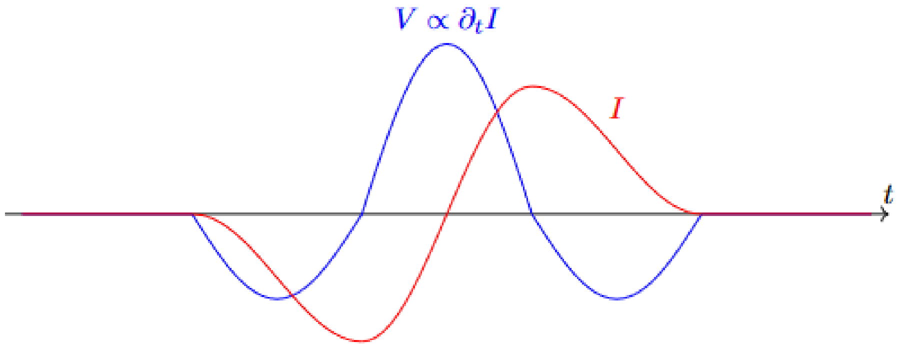
MAP DIPOLE - TRANSIENT

MAP Dipole (Hourglass)	TUDa 1.5T	TUDa 1.8T
External Dimensions [mm x mm]	Circle of radius 500	Circle of radius 500
Bgap [T]	1.5	1.8
Gap size [mmxmm]	154 x 25	154 x 25
Mmf [kAt]	30.9	40.7
Iron losses (yoke) [J/cycle-m] (*)	21.8 *	31.9 *
Iron losses (pole) [J/cycle-m] (*)	40.8 *	58.5 *
Coil losses [J/cycle-m] (*)	42.8	67.5
Total losses [J/cycle-m] (*)	105.4	158
Stored energy (total / gap) [J/m]	4522 / 3418	6591 / 4836
	model_001, nw_004_1500mT	model_001, nw_004_1800mT





Stranded conductor model

* density of material defined as 7500kg/m³

MAP DIPOLE – TRANSIENT (1.8T)

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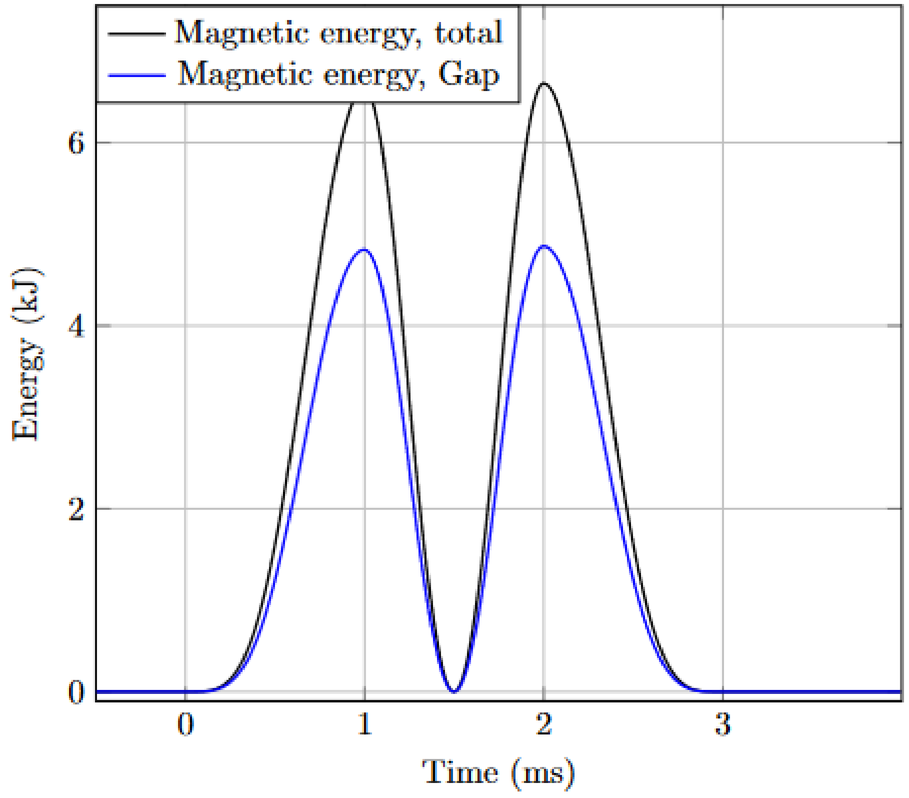
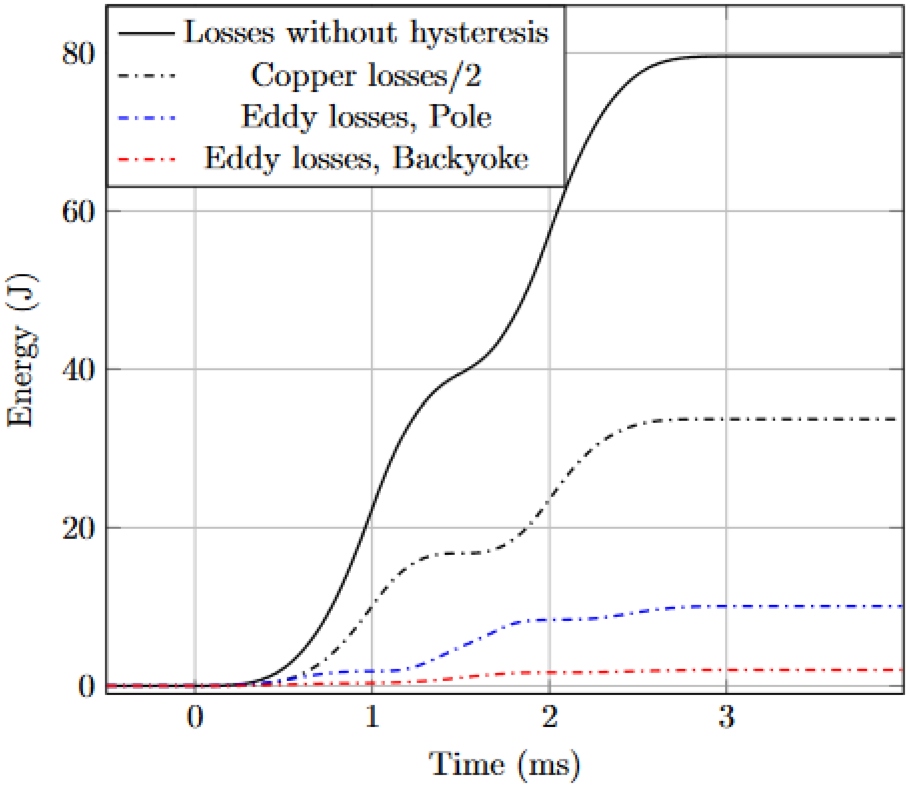
Electromagnetic Field Theory
Computational Electromagnetics





Eddy current losses below 20J/cycle/m.

Steinmetz estimates iron losses with 90J/cycle/m.

Hysteresis as predominant loss factor. Accurate description required.

Stranded conductor model

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NETWORK

- Kirchhoff current law for all nodes besides one
- Kirchhoff voltage law for all independent loops
- Every circuitelement features certain equations
  - Magnet stranded: $u = RI + \dot{\Phi}$ and $\Phi = \int_\Omega B \, dA$ as magnetic flux in [Vs]
  - Magnet solid: $I = Gu - \dot{\Phi}_\sigma$ and $\Phi_\sigma = \int_\Omega l_z \sigma B dA$ in [As]