ALMA MATER STUDIORUM
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Technology options for the accelerator magnets

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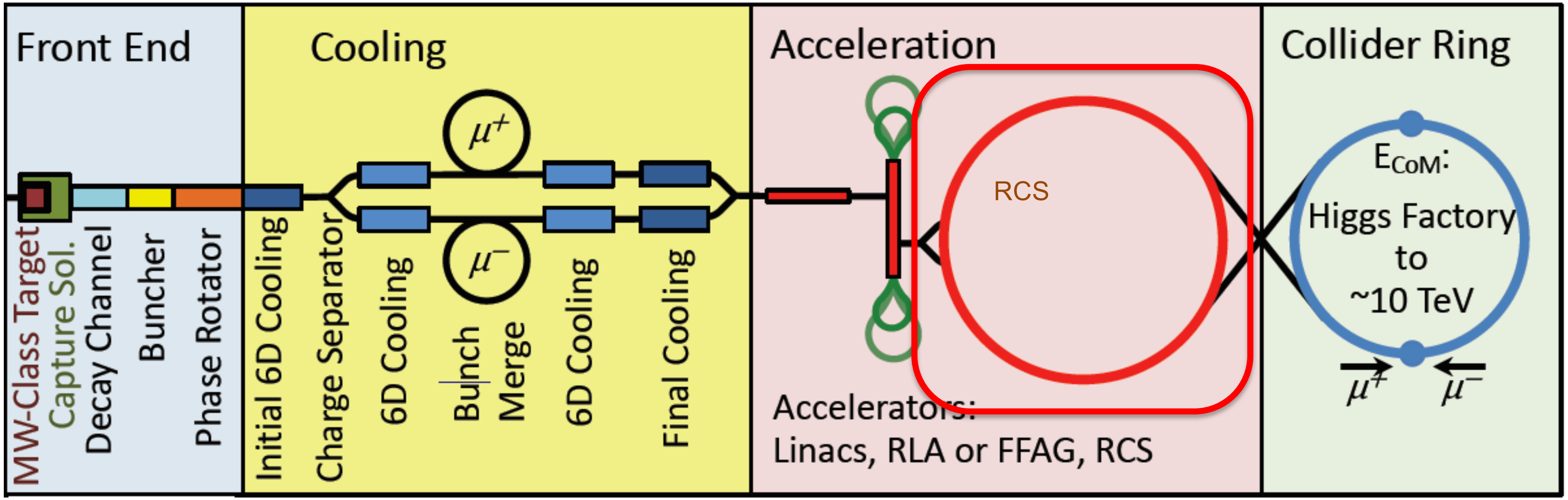
Outline

- Resistive dipole magnets specifications and identification of the performance drivers
- Design methodology for the resistive magnets
- Comparison of three magnet configurations
    - Windowframe magnet with 1, 2, 3 coils
    - ‘Hourglass’ magnet from the US study
    - H-type magnet
- Superconducting dipole magnets
- Summary and future activities

Muon Collider accelerator magnets

Field: ±1.8 T (NC), < 10 T (SC)
Rate: 400 Hz (NC), SS (SC)
Bore: 100 mm(H) x 30 mm(V)
Length: 3 m … 5 m (x 1500)
Radiation heat: ≈ 3 W/m
Radiation dose: TBD



Resistive dipole magnets in the Muon Collider

Complex	Sector	Baseline	Magnet Type	Magnet technology	Field (T)	Gradient (T/m)	Aperture (mm)	Gap (mm)	Width (mm)	Length (m)	Number (-)	Ramp time (s)	Field rate (T/s) / (T/m/s)	Homogeneity (units)	Persistance (units/s)	Beam power deposition (kW/m)	Comments
Target and Capture	Target	baseline	solenoid	LTS	15		2400			2	1	21600	0.0007	100		1	baseline 15 T, 2.4 m bore design, assumes 6 hours ramp-up time and 5 kW deposited total power
		baseline	solenoid	NC	5		150			0.5	1	1	5.0000	100		100	baseline 5 T resistive insert
		option	solenoid	HTS	20		600			1.5	1	21600	0.0009	100	0.1	5	option based on a HTS cable, reduced bore and shielding, operating at 10…20 K
	Capture and decay channel		solenoid	TBD													
Cooling	Ionization Cooling	baseline	solenoid	TBD	2.2		600			2	66	21600	0.0001	100	0.1		cell A1
		baseline	solenoid	TBD	3.4		500			1.32	130	21600	0.0002	100	0.1		cell A2
		baseline	solenoid	TBD	4.8		380			1	107	21600	0.0002	100	0.1		cell A3
		baseline	solenoid	TBD	6		264			0.8	88	21600	0.0003	100	0.1		cell A4
		baseline	solenoid	TBD	2.2		560			2.75	20	21600	0.0001	100	0.1		call B1
		baseline	solenoid	TBD	3.4		480			2	32	21600	0.0002	100	0.1		call B2
		baseline	solenoid	TBD	4.8		360			1.5	54	21600	0.0002	100	0.1		call B3
		baseline	solenoid	TBD	6		280			1.27	50	21600	0.0003	100	0.1		call B4
		baseline	solenoid	TBD	9.8		180			0.806	91	21600	0.0005	100	0.1		call B5
		baseline	solenoid	TBD	10.5		144			0.806	77	21600	0.0005	100	0.1		call B6
		baseline	solenoid	TBD	12.5		98			0.806	50	21600	0.0006	100	0.1		call B7
		baseline	solenoid	TBD	13.6		90			0.806	61	21600	0.0006	100	0.1		call B8
	Final Cooling	baseline	solenoid	HTS	30		50			0.5	17	21600	0.0014			0	baseline design from US-MAP
		minimal option	solenoid	HTS	40		60			0.5	17	21600	0.0019	100	0.1	0	HTS NI option, including aperture margin
		target option	solenoid	HTS	60		60			0.5	17	21600	0.0028	100	0.1	0	HTS NI option, including aperture margin
Accelerator	RCS1		dipole	NC	1.8			30	100	8.08	432	7.35E-04	2448.980	10			
	RCS2		dipole	LTS	10		100			2.4	288	1000	0.010	10			
			dipole	NC	1.8			30	100	6.06	432	1.80E-03	1000.000	10			
	RCS3		dipole	LTS	10		100			2.6	288	1000	0.010	10			
			dipole	NC	1.8			30	100	5.05	432	1.80E-03	1000.000	10			
	RCS4		dipole	LTS	10		100			2.6	288	1000	0.010	10			
			dipole	NC	1.8			30	100	5.05	432	8.46E-03	212.716	10			
Collider	Arc		dipole	HTS	10	300	150					1000	0.010	10		0.5	
	IR		quadrupole	HTS		466.32	171.4			2	4	1000	0.000	10			IQF1
			quadrupole	HTS		376.93	212.2			2	4	1000	0.000	10			IQF1a
			quadrupole	HTS		300.71	266			2	4	1000	0.000	10			IQF1b
			quadrupole	HTS		191.41	417			13.6	4	1000	0.000	10			IQD1
			quadrupole	HTS		214.03	411.2			5	4	1000	0.000	10			IQF2

Resistive dipole magnets main specifications

- The **resistive dipole magnets** to be designed for the Muon Collider accelerator are characterized by the following main specifications:

  1) Magnetic field in the aperture about **1.8 T**

  2) Ramps from $-B_{max}$ to $+B_{max}$ in **1 ms.** The objective for the value of B_{max} is 2.0 T

  3) Limit the **magnetic stored energy** (crucial design specification to limit the supplied power). This is the **first priority** of the magnet design.

  4) Limit the **total losses (iron + copper).** This is the **second priority** of the magnet design.

  5) Magnetic field homogeneity within $10 \times$ **10^{-4}** in the good field region (**30 mm * 100 mm)** This is the **third priority** of the magnet design.

Design methodology for the resistive magnets

The design methodology adopted is based on the following **guidelines**.

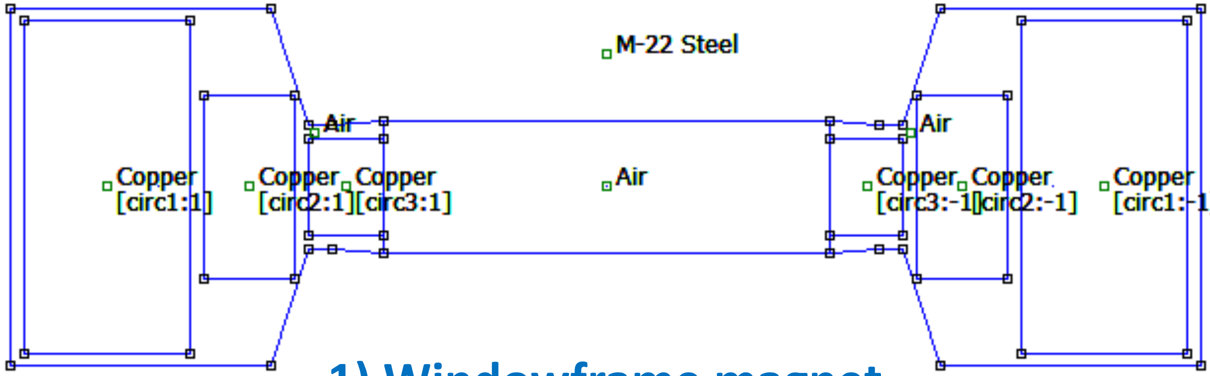
- The **first priority** for the design of the resistive magnets is the **minimization of the total energy stored in the magnet**
- The very fast ramps (1 ms) specified require a huge amount of power (**order of GWs**) from the power supply, which can only be reduced by minimizing the stored energy: $P = \Delta E / \Delta t$
- The **second priority** is minimizing the **losses in the magnet** during the fast ramps, as they affect the overall operation costs and sustainability of the machine
- The losses occur both in the **ferromagnetic core,** in the **copper coils** and in the **mechanical structure**. All these loss sources must be minimized.
- The loss minimization in the ferromagnetic materials can be achieved by **reducing the thickness of lamination and the electrical conductivity**, as far as the eddy current losses are concerned.

Design methodology for resistive magnets

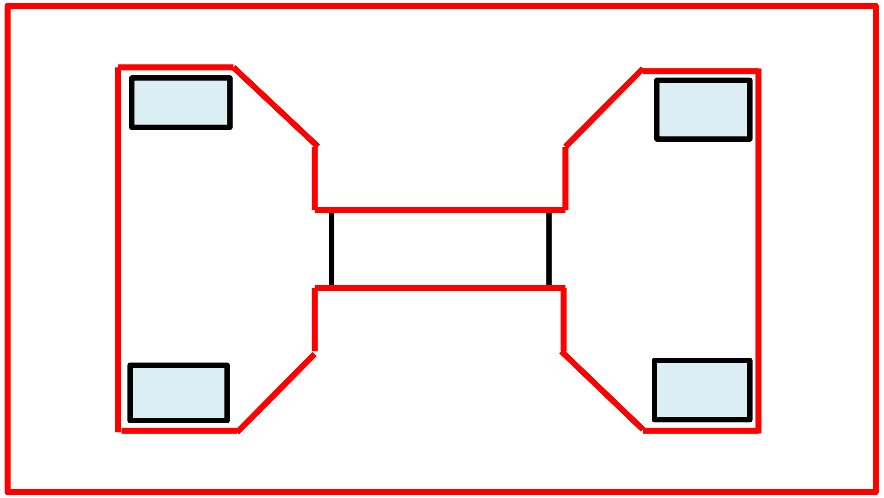
- The reduction of hysteresis losses in the ferromagnetic materials can be achieved by selecting **soft materials**, with **small hysteresis cycle area** and **high saturation magnetic field**.
- The reduction of losses in the copper can be obtained by proper **segmentation of the conductor**, also accounting for the local direction of the magnetic field
- The third design target is the **magnetic field quality in the gap**. Its optimization can be performed by properly modifying the geometric configuration of the magnet
- The field shaping in resistive magnets, differently from superconducting ones, is not performed by modifying the coils geometry, but by properly **shaping the ferromagnetic core**
- Indications on the required magnetic field quality, either in terms of field homogeneity in the good field region or tolerable **field harmonics** are an essential prerequisite for this optimization

Possible configurations for the resistive magnets

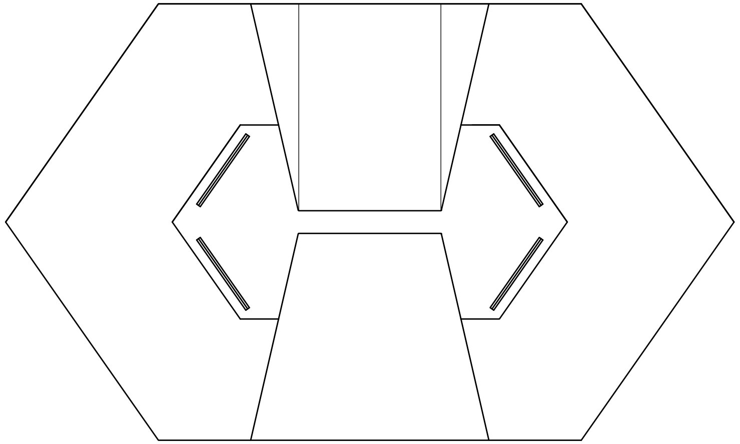
- In this study 3 main configurations are analyzed: **Windowframe magnet, H-type magnet, Hourglass magnet** (from the US MAP study)



1) Windowframe magnet



2) H magnet



3) 'Hourglass' magnet

J. Scott Berg and Holger Witte, "Pulsed synchrotrons for very rapid acceleration", AIP Conference Proceedings 1777, 100002 (2016); https://doi.org/10.1063/1.496568.

Minimization of the stored magnetic energy

- The design of the resistive magnet is obtained by solving the following **constrained optimization problem**:

$$\min F(\boldsymbol{x})$$
$$\boldsymbol{x}_{min} \leq \boldsymbol{x} \leq \boldsymbol{x}_{max}$$
$$\boldsymbol{G}(\boldsymbol{x}) \leq 0$$

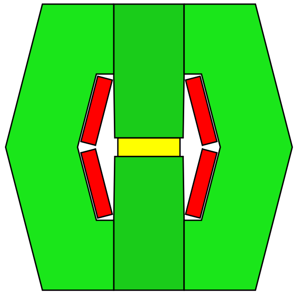
$\boldsymbol{x}$ = vectors of geometrical variables which define the **magnet geometry**

$F(\boldsymbol{x})$ = function to be minimized: **total magnetic energy of the magnet in DC, active or reactive power in AC simulations.**

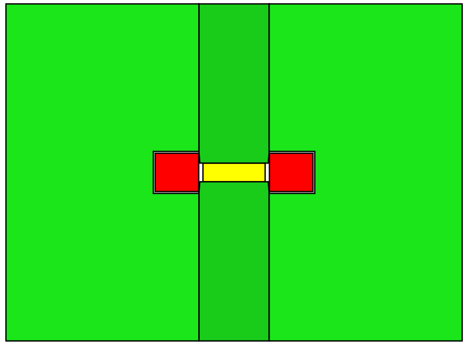
$\boldsymbol{x}_{min}, \boldsymbol{x}_{max}$ = lower and upper bounds of each variable.

G$(\boldsymbol{x})$ = nonlinear constraint. The *y*-component of the magnetic flux density field in the centre of the free gap ($B_{0,y}$) should be **greater than the reference value**: $B_{ref} - B_{0,y}(x) \leq 0$ (B_{ref}=1.8 T)

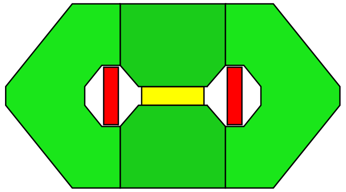
Comparison of the optimized geometries



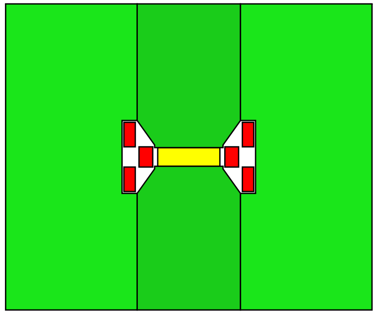
HG (J=10 A/mm^2): Emag = 5.71 [kJ/m]



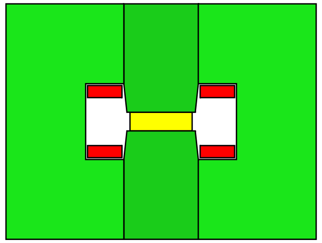
WF1: (J=10 A/mm^2 Emag = 5.37 [kJ/m]



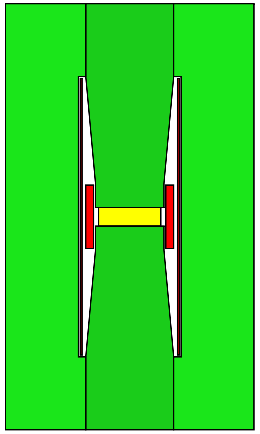
WF1M: (J=20 A/mm^2 Emag = 6.05 [kJ/m]



WF3: (J=20 A/mm^2 Emag = 5.36 [kJ/m]



HM: (J=20 A/mm^2 Emag = 5.74 [kJ/m]



WF2: (J=20 A/mm^2 Emag = 5.44 [kJ/m]

- The cross sections look quite *elongated*: no material quantity in the cost function
- Energy in the gap at 1.8 T: **3.9 kJ/m (lower bound)**, about 65 – 73 % of the total energy
- All optimal configurations fall between **5.3 and 6.0 kJ/m**

Further optimization studies

- Further studies should be performed by optimizing the following quantities:

  a) **Losses in the iron** (by changing the ferromagnetic material from a library)

  b) **Losses in the copper conductors** (by modifying the number of turns, with a careful check on the maximum allowed voltage)

  c) **Volume of the ferromagnetic core** (affecting the weight and capital costs of the magnets)

  d) **Current density** in the copper conductors

  e) **Magnetic field harmonics** in the air gap, by properly shaping the magnetic poles geometry

  f) **Cooling system** (water cooling along the magnet length, cooling from the magnet ends, etc..)

  g) Evaluate the **impact of cooling the copper conductors** on transport current losses

Development of a simplified model of the magnet

- To perform a global optimization of both the **magnet and the power supply system,** a simplified model of the magnet would be very useful

- The model should be able to determine:

  1) The **ϕ vs *I* characteristics of the magnet**

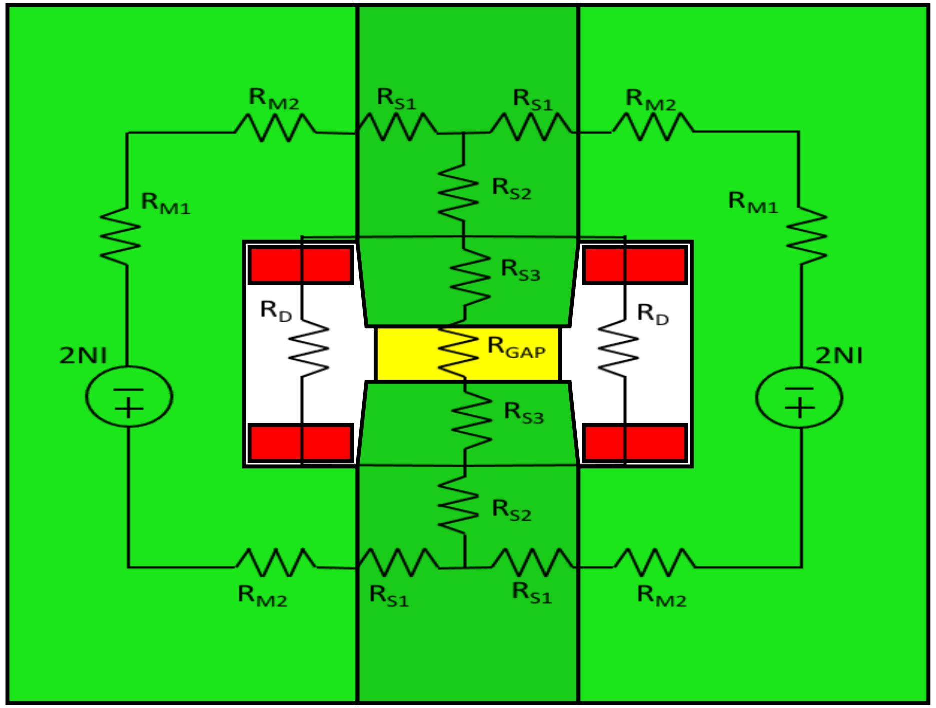
  2) Magnetic energy stored in the magnet

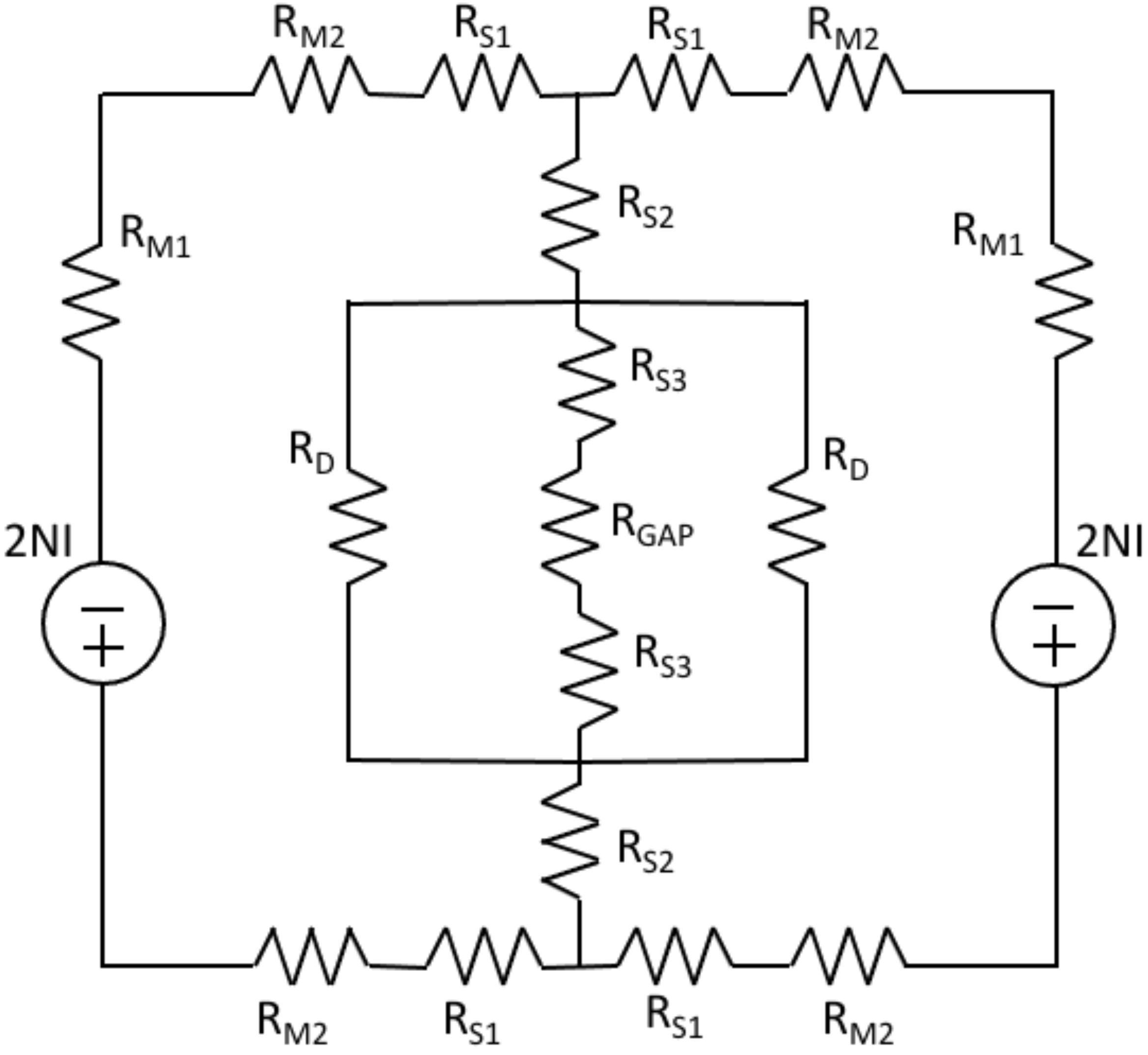
  3) **Losses in the iron** and copper (possibly through analytical formulae)

  4) Average magnetic field in the midplane of the good field region vs winding current

Magnetic circuit model of the H-type Magnet

- An **equivalent lumped elements circuit model** of the H-type magnet is under development
- The **non-linear reluctances** depend on the value of the magnetic flux density: $R(B) = l / \mu(B) S$



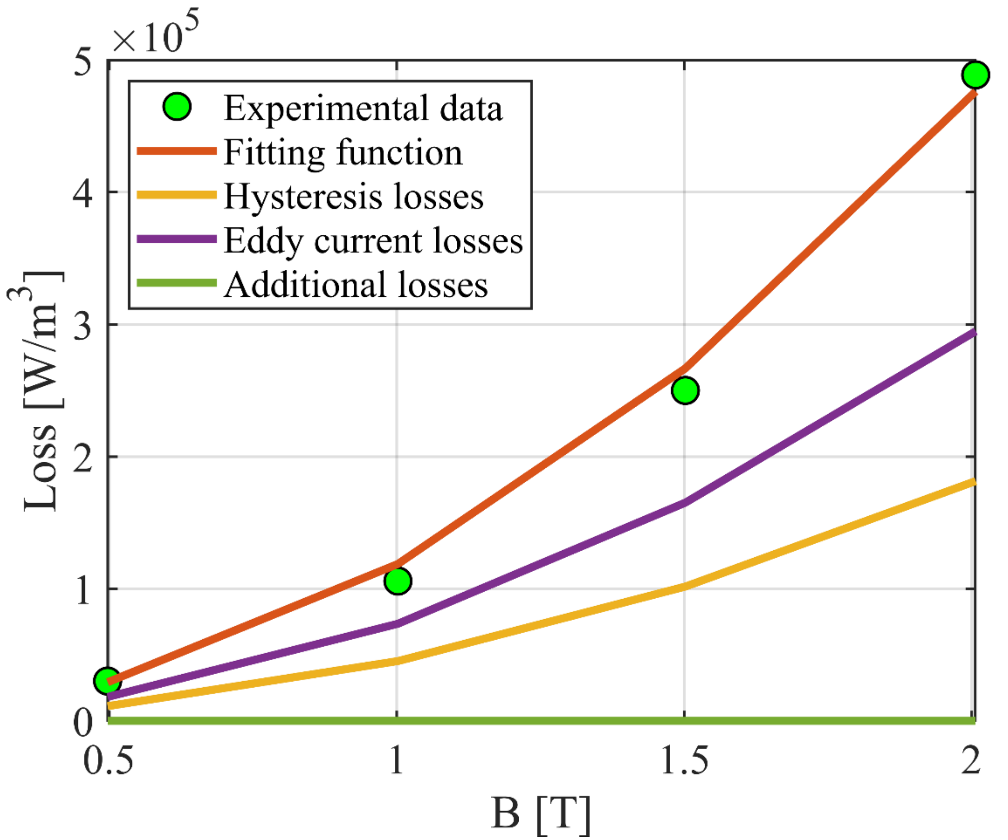


Analytical computation of the iron losses

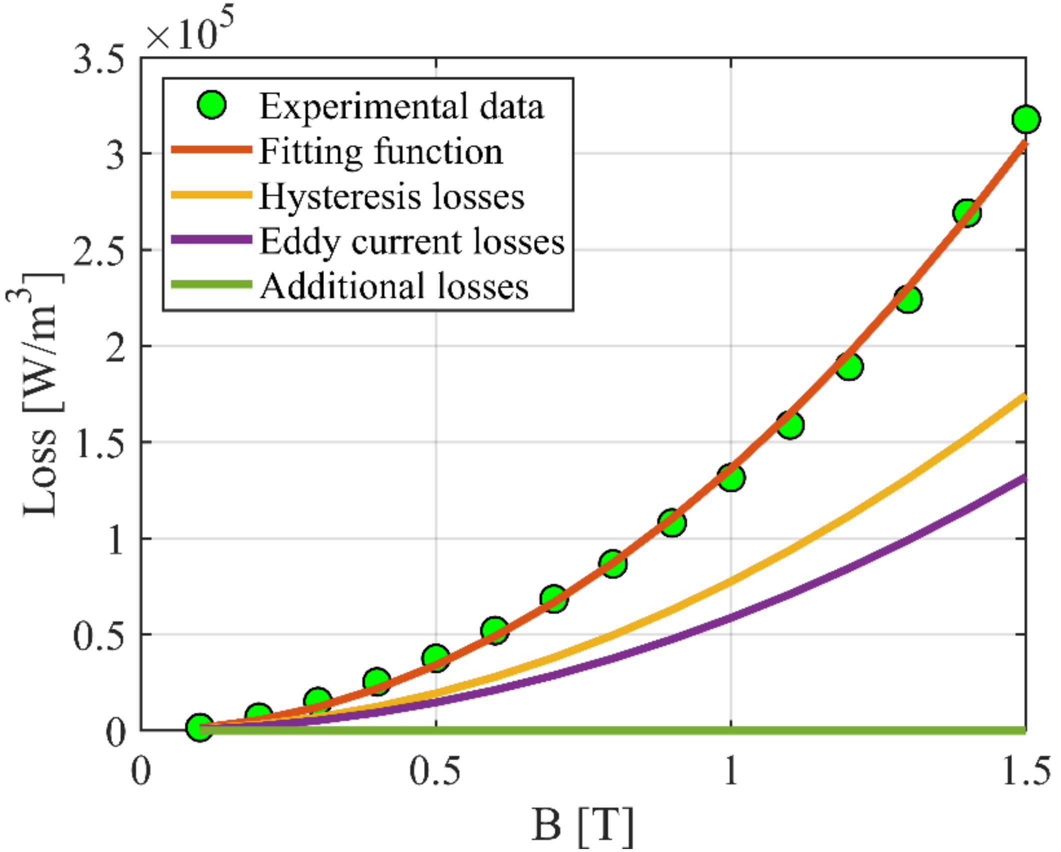
- Available experimental data on losses in the two selected commercial materials were **fitted by an analytical formula,** thus retrieving the values of the parameters k_{hyst}, k_{eddy}, and k_{addit}.

$$P_{Fe} = \left(K_{hyst} \cdot f \cdot B^2 + K_{eddy} \cdot f^2 \cdot B^2 + K_{addit} \cdot f^{1.5} \cdot B^{1.5}\right)$$

Vacoflux48 f = 400 Hz

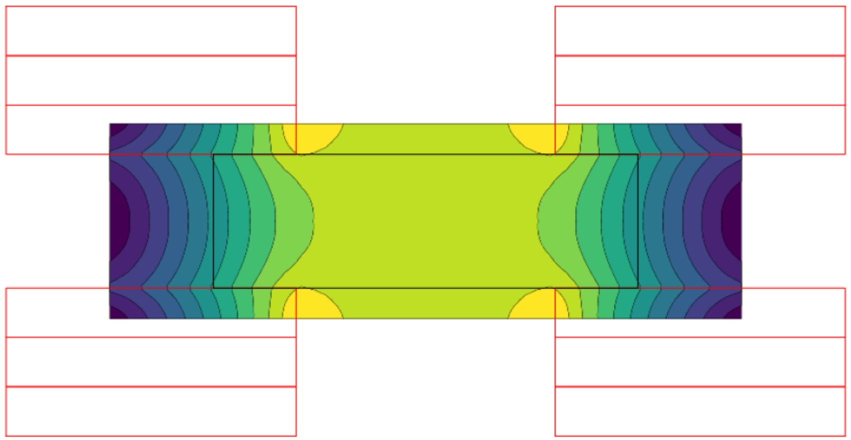


M235-35A at f = 400 Hz

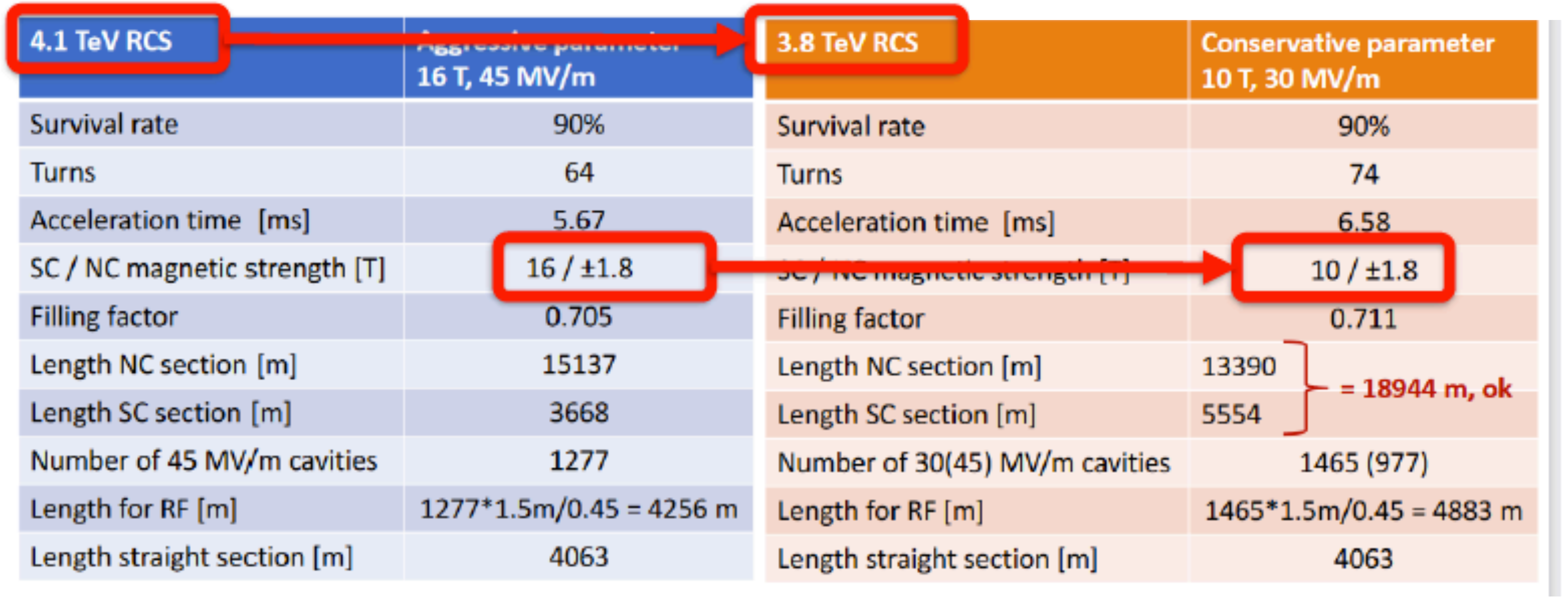


Superconducting 10 T magnets for the accelerator

- The design of the 10 T SC magnet for the accelerator is at an early stage; a possible configuration has been proposed, based on a **flat racetrack coil**



SC 10 T flat racetrack coil



4.1 TeV RCS	Aggressive parameter 16 T, 45 MV/m
Survival rate	90%
Turns	64
Acceleration time [ms]	5.67
SC / NC magnetic strength [T]	16 / ±1.8
Filling factor	0.705
Length NC section [m]	15137
Length SC section [m]	3668
Number of 45 MV/m cavities	1277
Length for RF [m]	1277*1.5m/0.45 = 4256 m
Length straight section [m]	4063

3.8 TeV RCS	Conservative parameter 10 T, 30 MV/m
Survival rate	90%
Turns	74
Acceleration time [ms]	6.58
SC / NC magnetic strength [T]	10 / ±1.8
Filling factor	0.711
Length NC section [m]	13390
Length SC section [m]	5554
Number of 30(45) MV/m cavities	1465 (977)
Length for RF [m]	1465*1.5m/0.45 = 4883 m
Length straight section [m]	4063

= 18944 m, ok

Summary

- The main performance drivers of the resistive magnets have been identified as the **total magnetic energy**, **total losses** and **magnetic field quality**
- An optimization study in DC conditions performed on **three resistive magnet configurations** provided useful information on the most suited configuration
- The **H-type magnet** leads to a low value of both the stored magnetic energy and the losses and was selected for the following analyses
- A simplified model of the magnet, to be coupled with the power supply system model, is under development (**non-linear magnetic circuit model** and **analytical formula for the losses in ferromagnetic materials** identified)

Future activities

Design activities

- Validation of the 2D FEM model of the magnet, by studying the actual **electrodynamic transient with non-linear materials** (the AC model implies linearizing the ferromagnetic materials)
- Studies for the optimization of the **ferromagnetic materials** (to be selected from available libraries), **iron losses**, **copper losses** (with segmentation of the conductor), **cooling technology**
- Development of a **thermal model of the magnet** including heat exchange with a coolant
- Further development of the simplified model of the magnet, including **analytical formulae for the losses in the copper conductor**

Experimental activities

- Proposal: Realization of a small resistive magnet prototype to validate the power supply system design, the magnetic field quality, the *B-H* curve of the ferromagnetic materials and the computation models of losses in the iron core and copper conductors

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Thank you for your kind attention !

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Magnetic field homogeneity calculation

- In order to compare the different configurations, the **homogeneity** of the magnetic field in the free gap is evaluated by means of the following parameter δ_B:

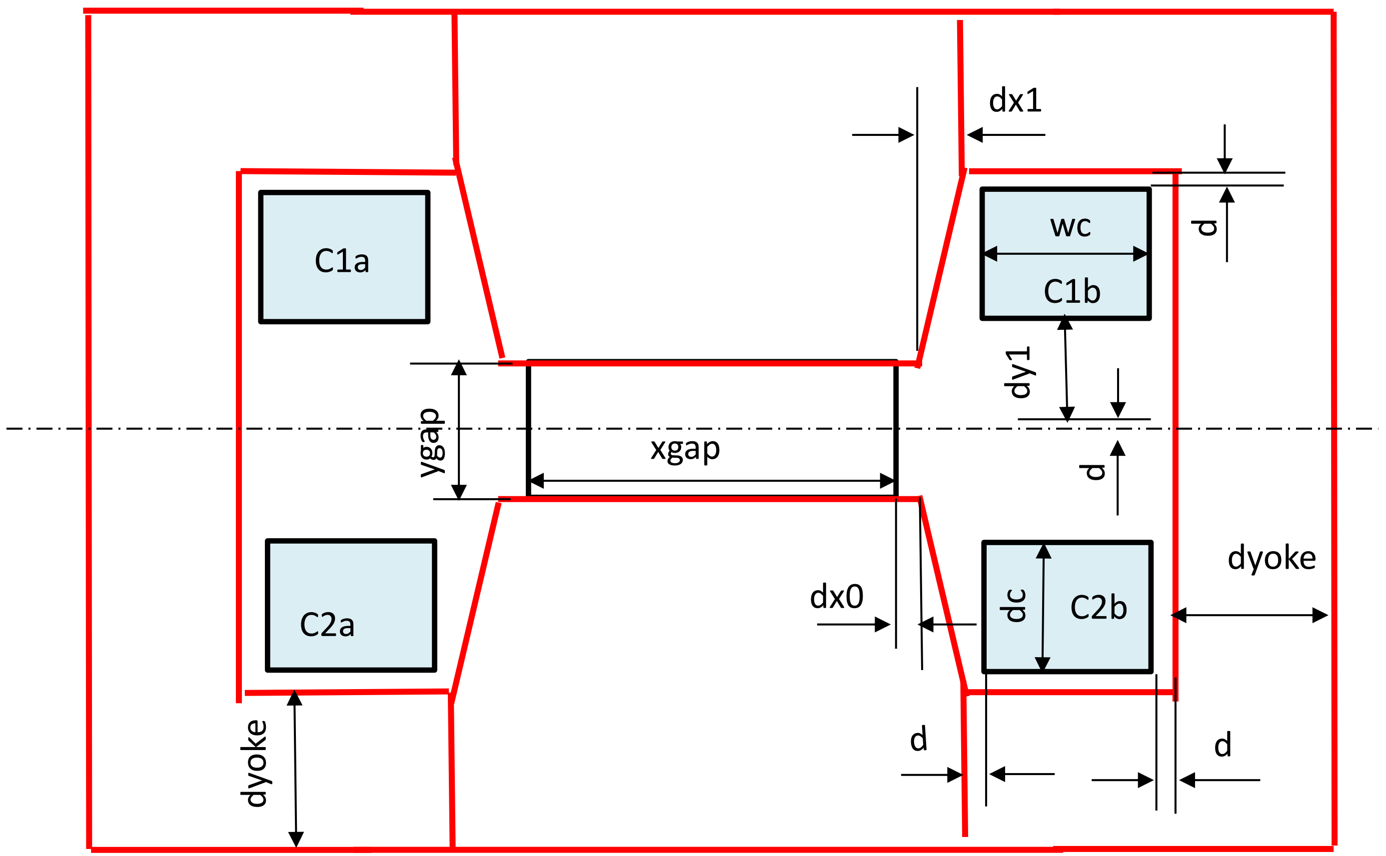
$$\delta_B = \frac{\sqrt{\frac{1}{A_{gap}} \iint_{A_{gap}} \left[\left(B_x - B_{xref} \right)^2 + \left(B_y - B_{yref} \right)^2 \right] dx\, dy}}{B_{ref}}$$

where:

- A_{gap} is the cross section of the free gap (100 mm × 30 mm)
- B_{yref} is the reference value of the magnetic flux density field (1.8 T)

The objective is that Bx should be **as small as possible**: B_{xref} = 0 T

H-type magnet: geometry



- Several magnet configurations have been analyzed with the same strategy, minimizing the stored magnetic energy

GEOMETRICAL DATA:

- xgap = 100 [mm]
- ygap = 30 [mm]
- dx0 = 5 [mm]
- d = 3 [mm]

MATERIAL DATA:

- Supermendur in poles
- M-22 steel in yoke

UNIFORM CURRENT DENSITY: 10 / 20 [A/mm^2]

OPTIMIZED VARIABLES:

dx1,dy1,dyoke,wc,dc

- The set of optimized vaariables is chosen in order to always obtain a feasible geometry

OPTIMIZED FUNCTION:

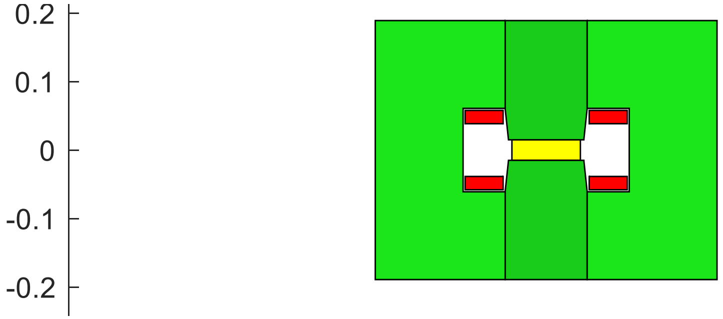
total magnetic energy ([J])

CONSTRAINTS:

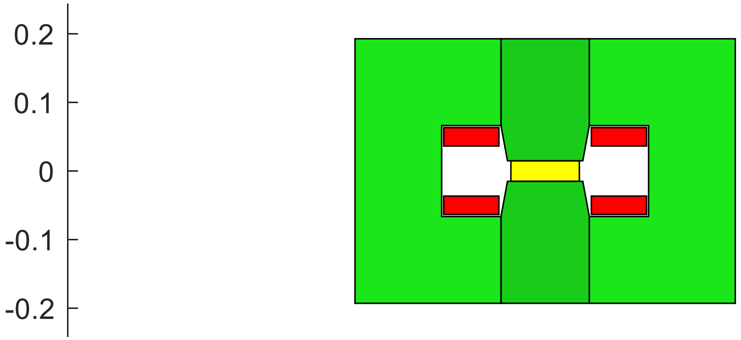
- B0y $\geq$ 1.8 [T]

B0y: vertical component of the magnetic flux density field in the central point of the gap

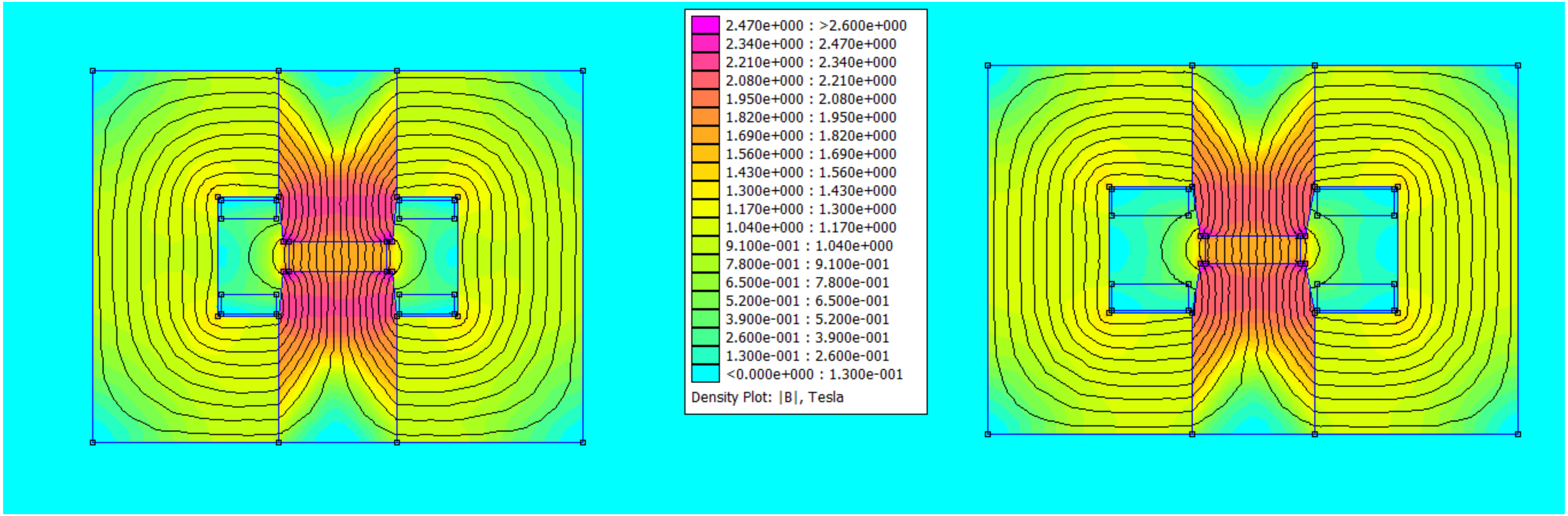
H-type magnet: field maps



$J = 20\ \mathrm{A/mm^2}$



$J = 10\ \mathrm{A/mm^2}$

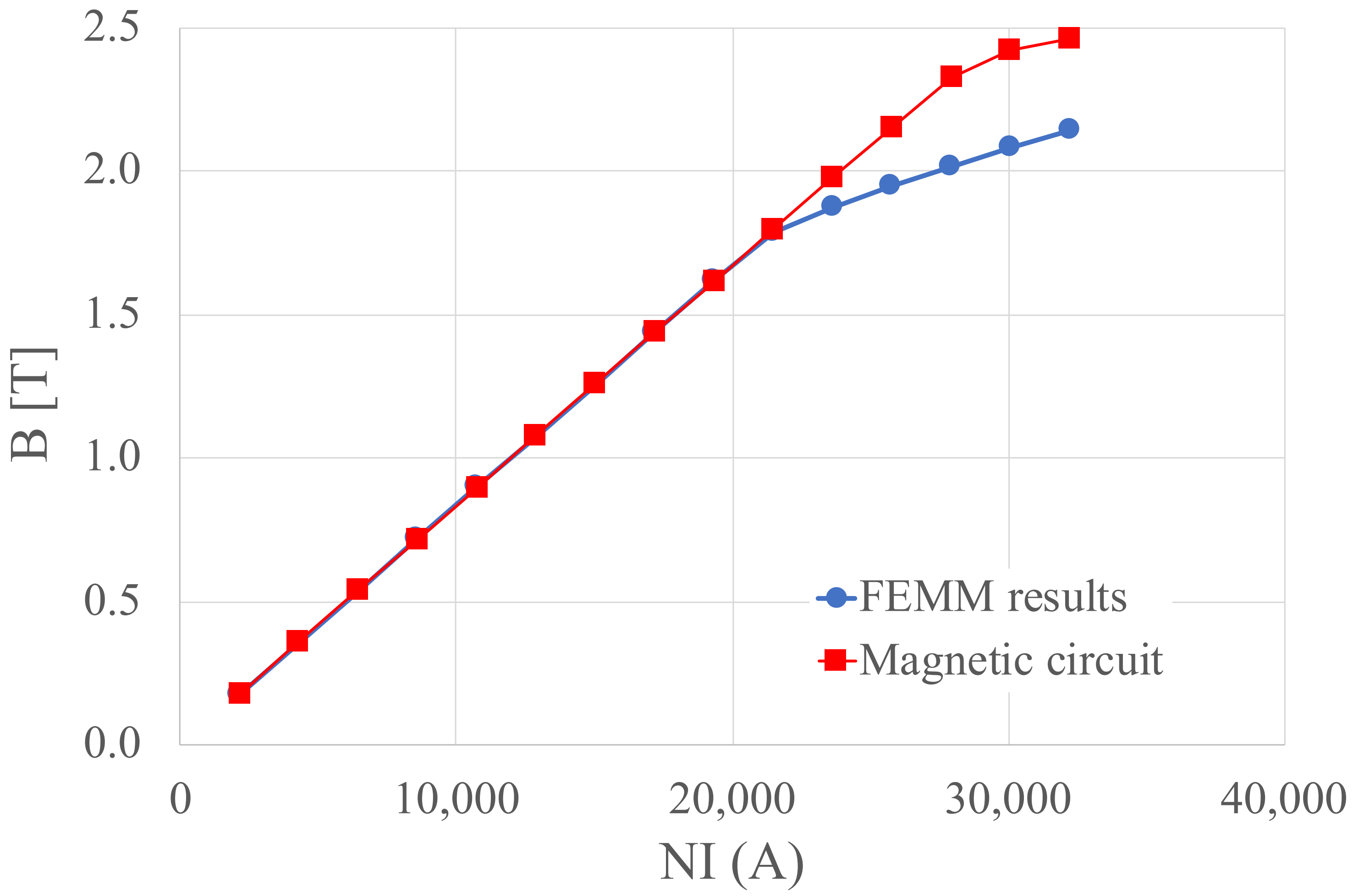


Comparing 2D FEM results with the equivalent magnetic circuit

- The results of the FEMM model and of the equivalent non-linear magnetic circuit are in **very good agreement before saturation**

- A **discrepancy** between the two models is observed **above saturation**

- Improvements of the magnetic circuit have to be implemented to reduce this discrepancy



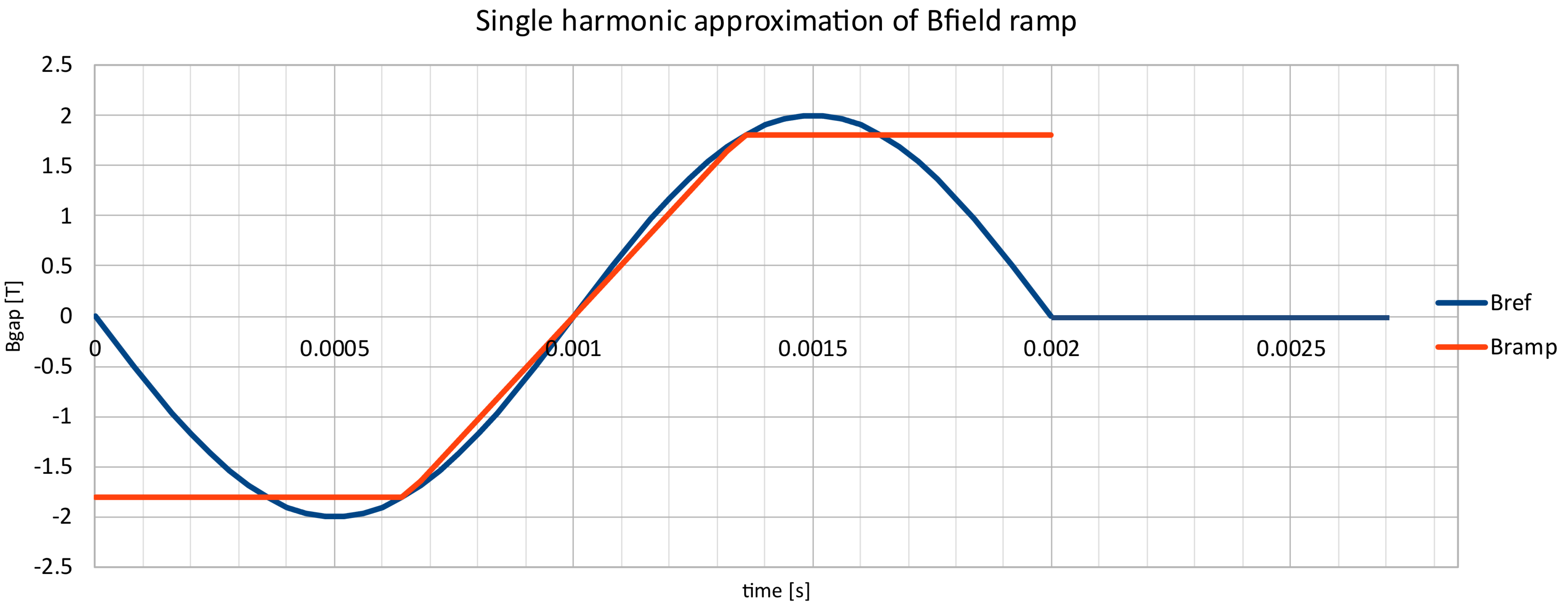
Field in the middle of the good field region vs NI

FEMM model assumptions in AC regime

- It is not possible to analyze a time transient with FEMM. To have a rough estimate of the losses in one cycle of operation, an **AC regime with 500 Hz frequency** (period = 2 ms) is considered. The losses over one cycle are then calculated.
- Non-linear hysteretic materials (Supermendur and M-22 steel) are **linearized and a hysteresis lag ϑ** is considered between the phasors of H and B.
- The hysteresis lag ϑ is computed by **fitting the experimental data** on the losses measured on a toroidal sample with a dedicated FEMM model
- For Supermendur a hysteresis loss of 236 [J/(m^3 cycle)] is considered for a cycle with B_{max}= 2 T
- For M-22 steel a total loss of 520 [J/(m^3 cycle)] is considered for a cycle at 60 Hz and B_{max} = 1.5 T

Design current cycle

- In the first 2 ms of each operation cycle (100 ms) it is assumed that the current varies as a sinus with a period of 2 ms. In the remaining 98 ms it remains constant at 0 kA. To obtain a ramp from -1.8 T to +1.8 T, the **field is approximated with a sinusoid** having a peak of 2 T.



Minimization of the stored magnetic energy

- The optimization problem is solved by means of the routine *fmincon* in a **Matlab environment**.
- Three possible optimization algorithms can be used to perform computations, namely SQP (Sequential Quadratic Programming), Interior-point and active-set.
- The magnetic energy (objective function) and the magnetic flux density field in the centre of the free gap are calculated by means of a model of the magnet implemented in the software **FEMM**
- The problem is solved either in **DC conditions** or **AC conditions** during the optimization process
- The FEMM model is called at each iteration by the Matlab optimization routine and returns the values of the magnetic field in the centre of the air gap of the magnet and of the total magnetic energy

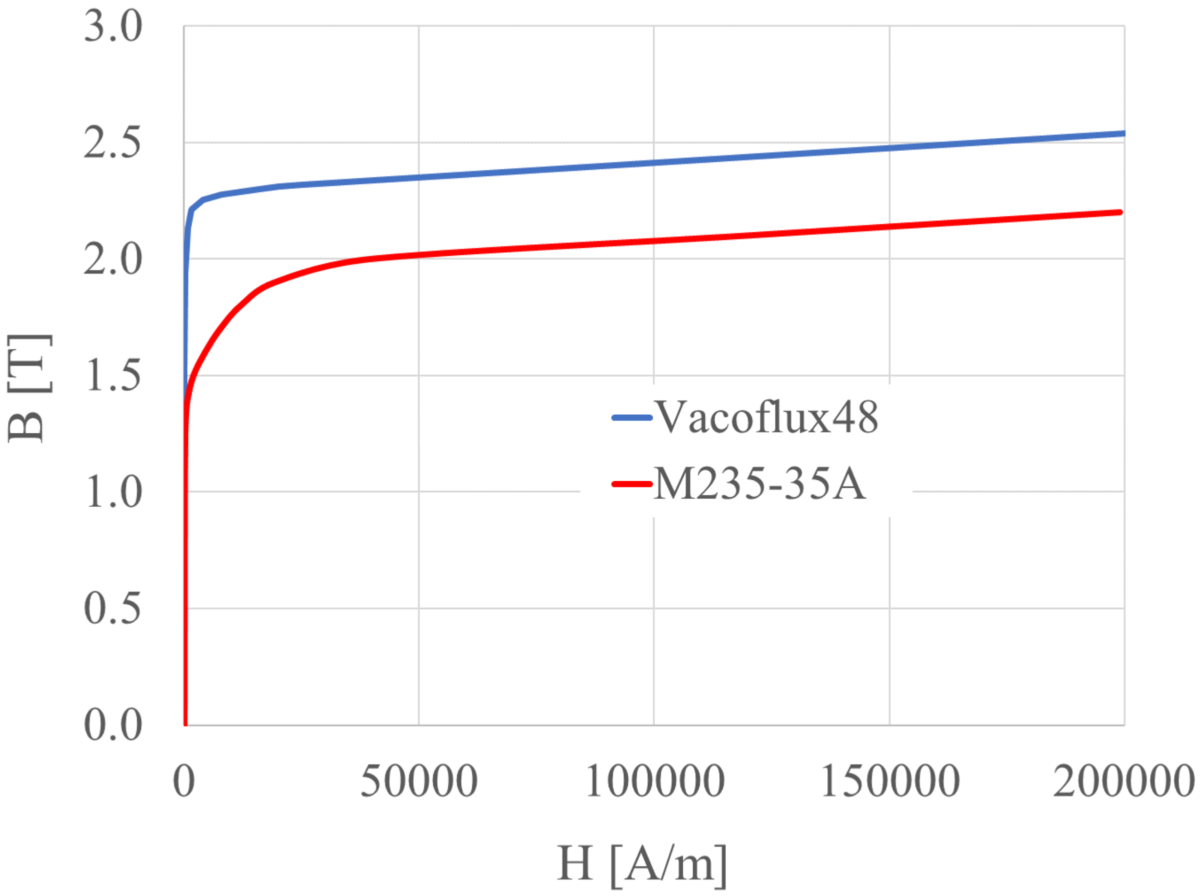
Comparison of the analyzed configurations (J = 20 A/mm^2)

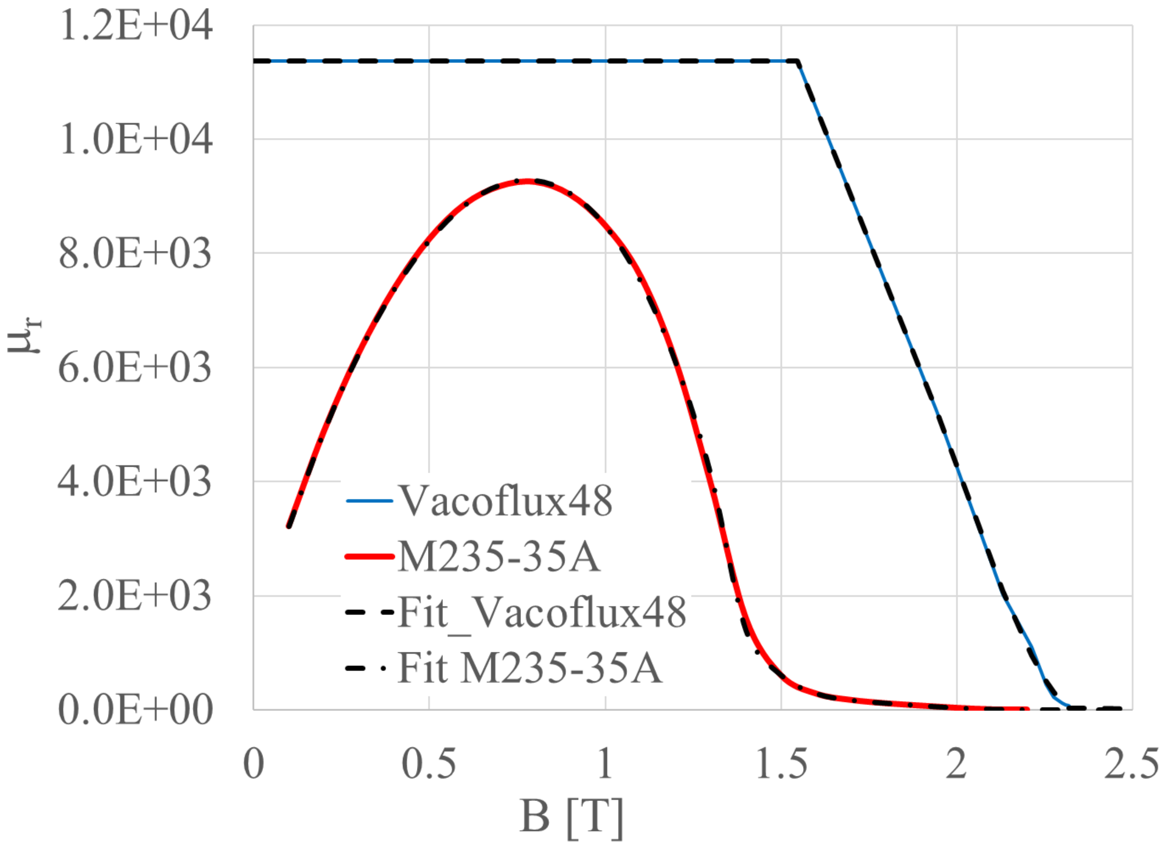
* Maximum current in AC was reduced with respect to dc regime to keep the field at the 2 T peak (linearization not precise)

Geometry (Jc = 20 A/mm^2)	**HG**	**WF1**	**WF1M**	**WF2**	**HM**	**WF3**
Results in dc regime						
δ_B (B0y = 1.8 T)	3.61e-02	4.47e-04	1.53e-02	3.95e-02	3.27e-02	2.52e-02
Supermendur volume [dm^3/m]	48.2	48.7	42.9	84.6	41.3	74.0
M22 steel volume [dm^3/m]	107.3	288.4	71.0	165.9	128.5	202.4
Copper volume [dm^3/m]	5.63	4.30	4.33	5.13	4.30	4.31
Total magnetic energy [kJ/m]	5.77	6.46	6.05	5.44	5.74	5.36
Results in ac regime (f=500Hz)						
Imax (B0y = 2 T) [kA]	23.2*	47.7	48.1	23.7*	23.9	15.9
Vmax (B0y = 2 T) [kV/m]	1.74	0.71	0.95	1.48	1.86	2.34
Real power (MW/m)	0.203	0.517	0.242	0.511	0.222	0.603
Reactive power (MVAR/m)	20.2	17.0	22.8	17.5	22.4	18.7
Total loss [J/(m cycle)]	406.4	1034.9	483.2	1021.7	422.9	1205.2
Copper losses	258.3	984.5	359.8	858.5	294.8	1137.5
Iron losses	148.1	50.4	123.4	163.2	128.1	67.7

Magnetic circuit model of the H-type Magnet: material properties

- Two commercial ferromagnetic materials were selected for the poles and the other parts of the magnetic circuit, namely **Vacoflux-48 and M235-35A steel**





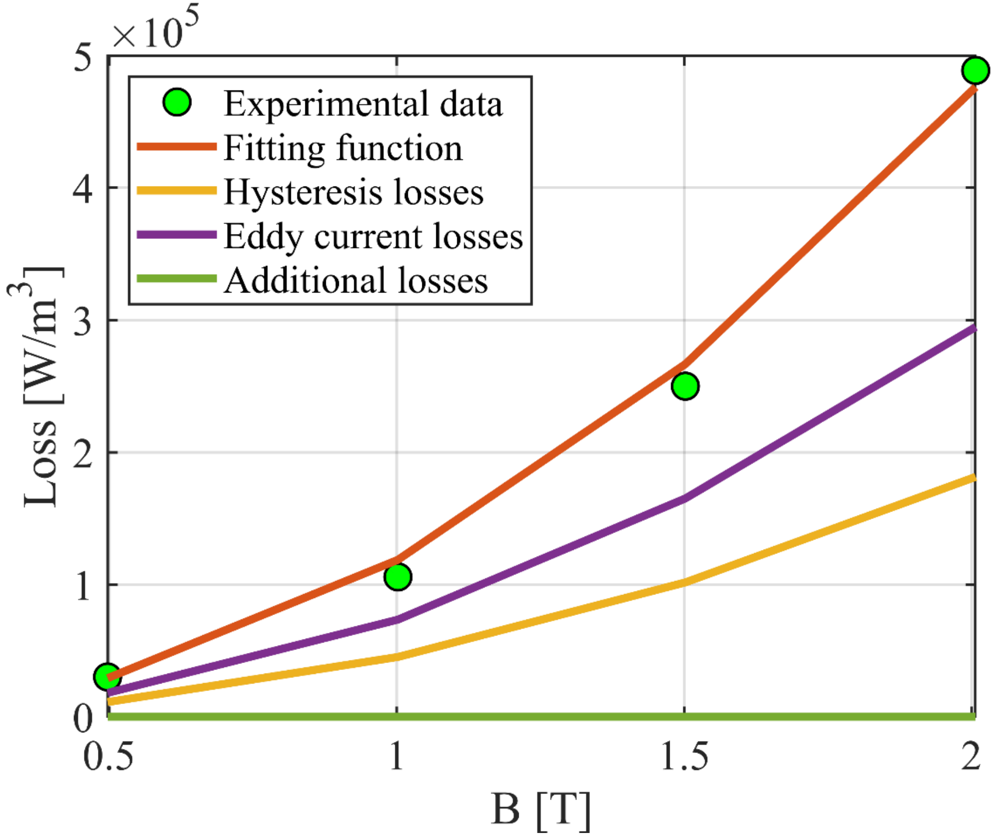
- The **magnetic permeability** was fitted via 4th and 5th order **polynomials** for M235-35A and with a 4th order polynomial for the Vacoflux48

Magnetic circuit model of the H-type Magnet: losses

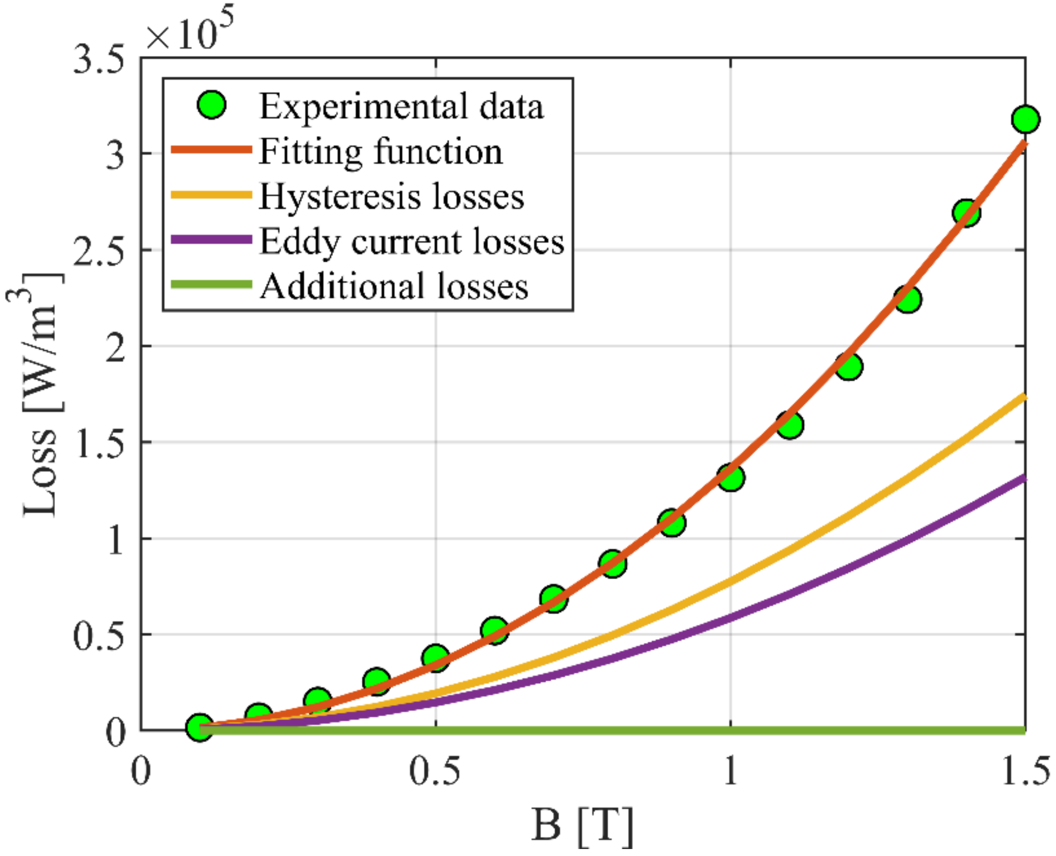
- The losses in the two selected ferromagnetic materials were **fitted by an analytical formula** to retrieve the values of the k_{hyst}, k_{eddy}, and k_{addit} parameters.

$$P_{Fe} = \left(K_{hyst} \cdot f \cdot B^2 + K_{eddy} \cdot f^2 \cdot B^2 + K_{addit} \cdot f^{1.5} \cdot B^{1.5}\right)$$

Vacoflux48 f = 400 Hz

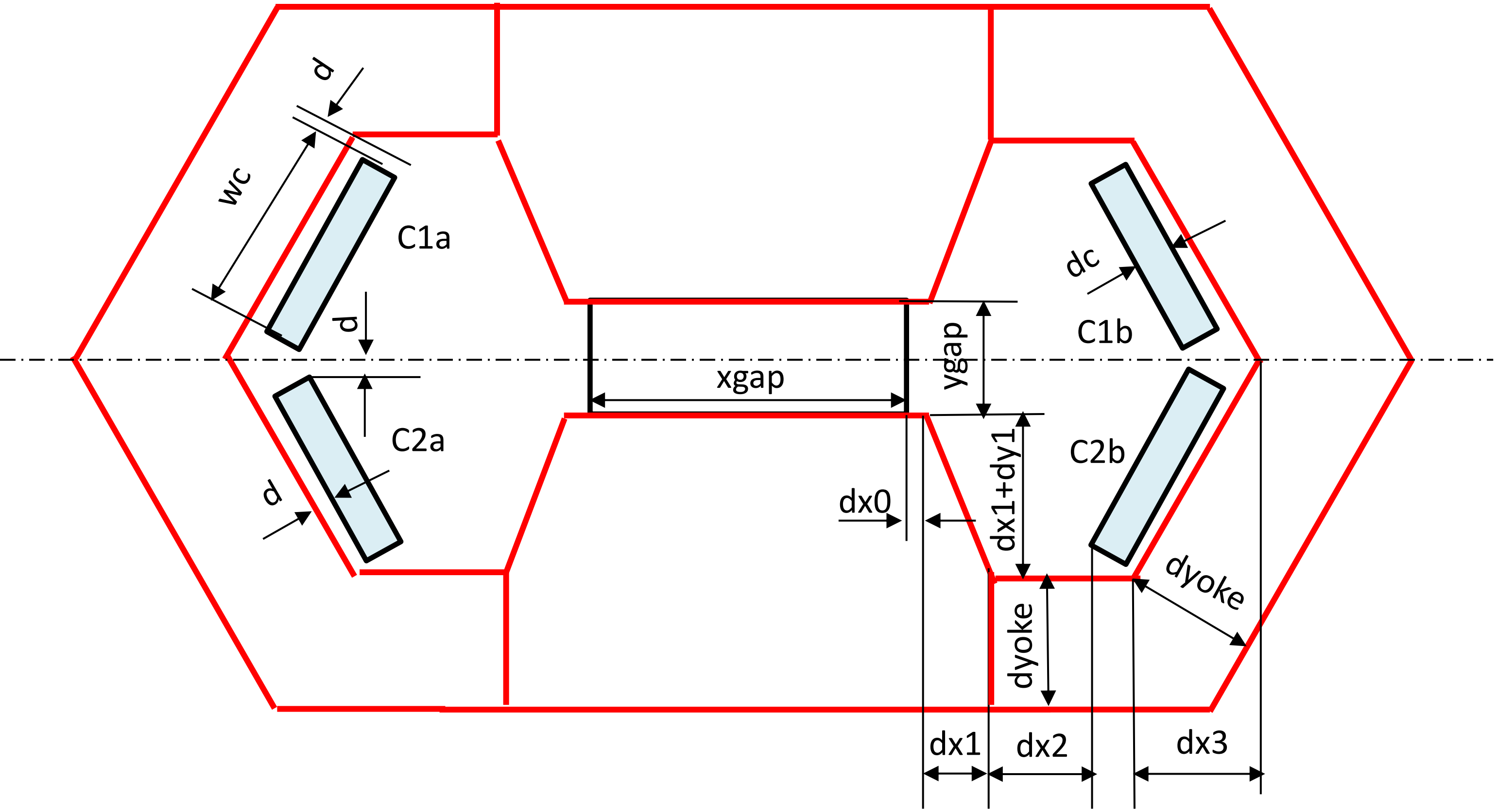


M235-35A at f = 400 Hz



Hourglass magnet: geometry

HG (Hourglass) magnet geometry



GEOMETRICAL DATA:

- xgap = 100 [mm]
- ygap = 30 [mm]
- dx0 = 5 [mm]
- d = 3 [mm]

MATERIAL DATA:

- Supermendur in poles
- M-22 steel in yoke

UNIFORM CURRENT DENSITY: 10 / 20 [A/mm^2]

OPTIMIZED VARIABLES:

dx1,dx2,dx3,dy1,dyoke,χ (dc/wc)

- The set of optimized vaariables is chosen in order to avoid intepenetration of solids

OPTIMIZED FUNCTION:

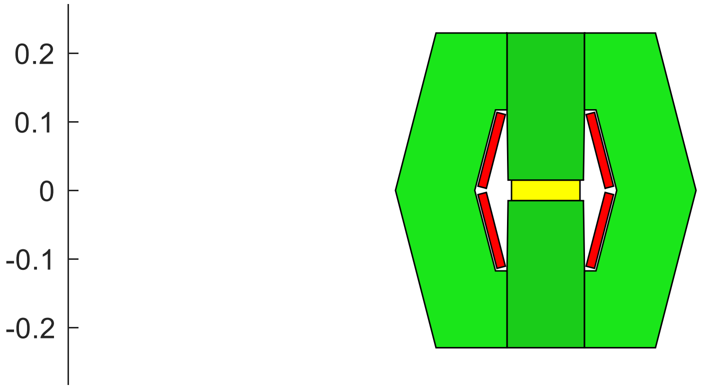
total magnetic energy ([J])

CONSTRAINTS:

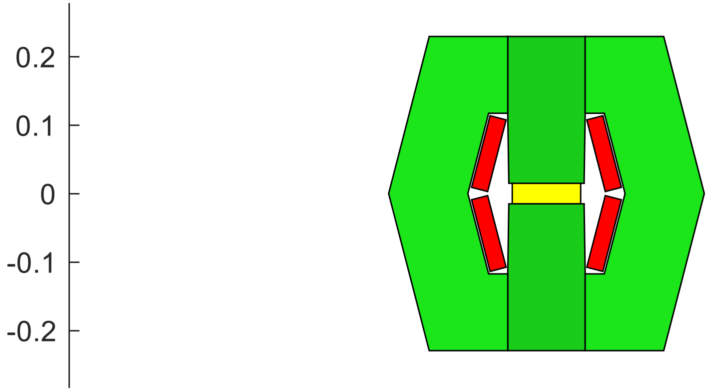
- B0y $\geq$ 1.8 [T]

B0y: vertical component of the magnetic flux density field in the central point of the gap

Hourglass magnet: field maps



J = 20 A/mm^2



J = 10 A/mm^2