ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

# Resistive magnets design studies

Marco Breschi[1], Rebecca Miceli[1], Pier Luigi Ribani[1], Camilla Bartoli[1], Luca Bottura[2], Fulvio Boattini[2]

[1]Alma Mater Studiorum – Università di Bologna, Italy
[2]CERN, Geneva, Switzerland

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# *Outline*

- Resistive dipole magnets specifications
- Design methodology
- DC optimization of the three analyzed magnet configurations

    - Windowframe magnet with 1, 2, 3 coils
    - 'Hourglass' magnet from the US study
    - H-type magnet

- AC optimization of the H-type configuration
- Development of a non-linear magnetic circuit model of the H-type magnet

# *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) Magnetic field homogeneity within $10 \times$ **$10^{-4}$** in the good field region (**30 mm * 100 mm**)

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

    4) Limit the **magnetic stored energy** (crucial design specification to limit the supplied power)

    5) Limit the **total losses (iron + copper)**

# Design methodology

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

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

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

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

$\boldsymbol{x}_{min}, \boldsymbol{x}_{max}$ = 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**: $B_{ref} - B_{0,y}(x) \le 0$ ($B_{ref}$=1.8 T)

# *Minimization problem solution*

- The 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 **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

# 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 $\delta_B$:

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

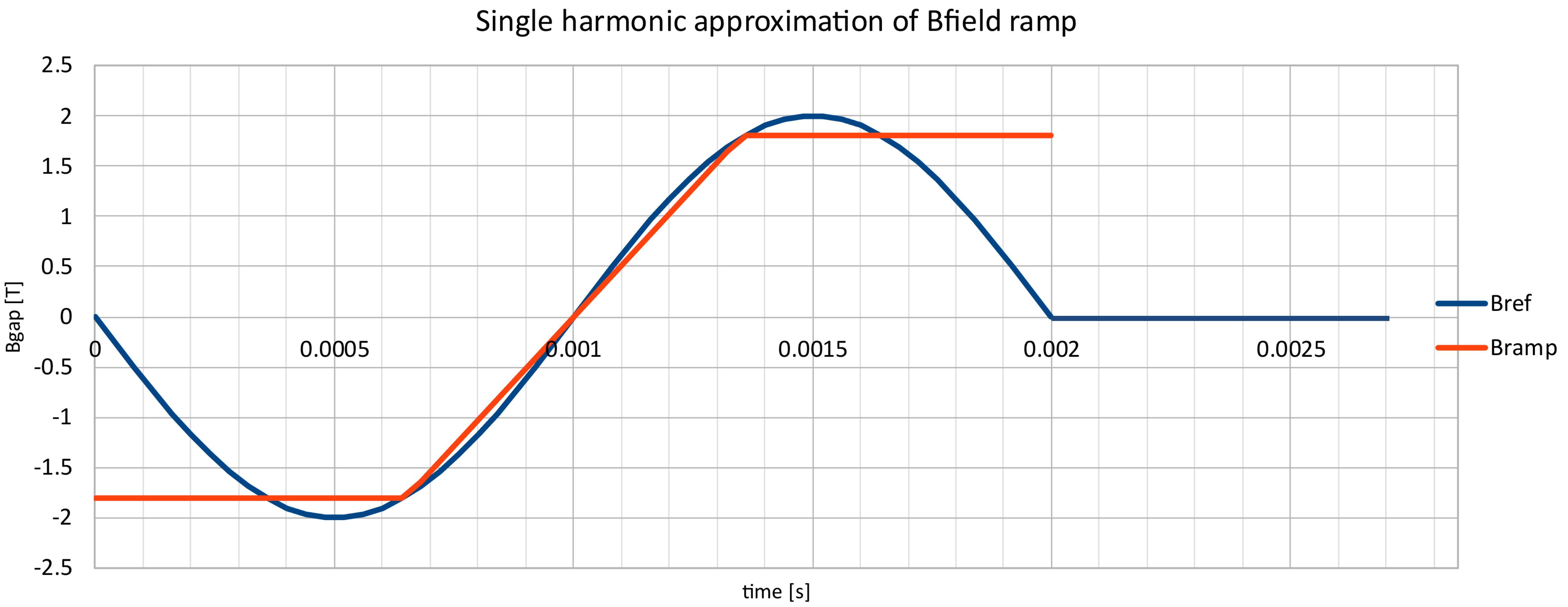
where:

- $A_{gap}$ 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

# 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.

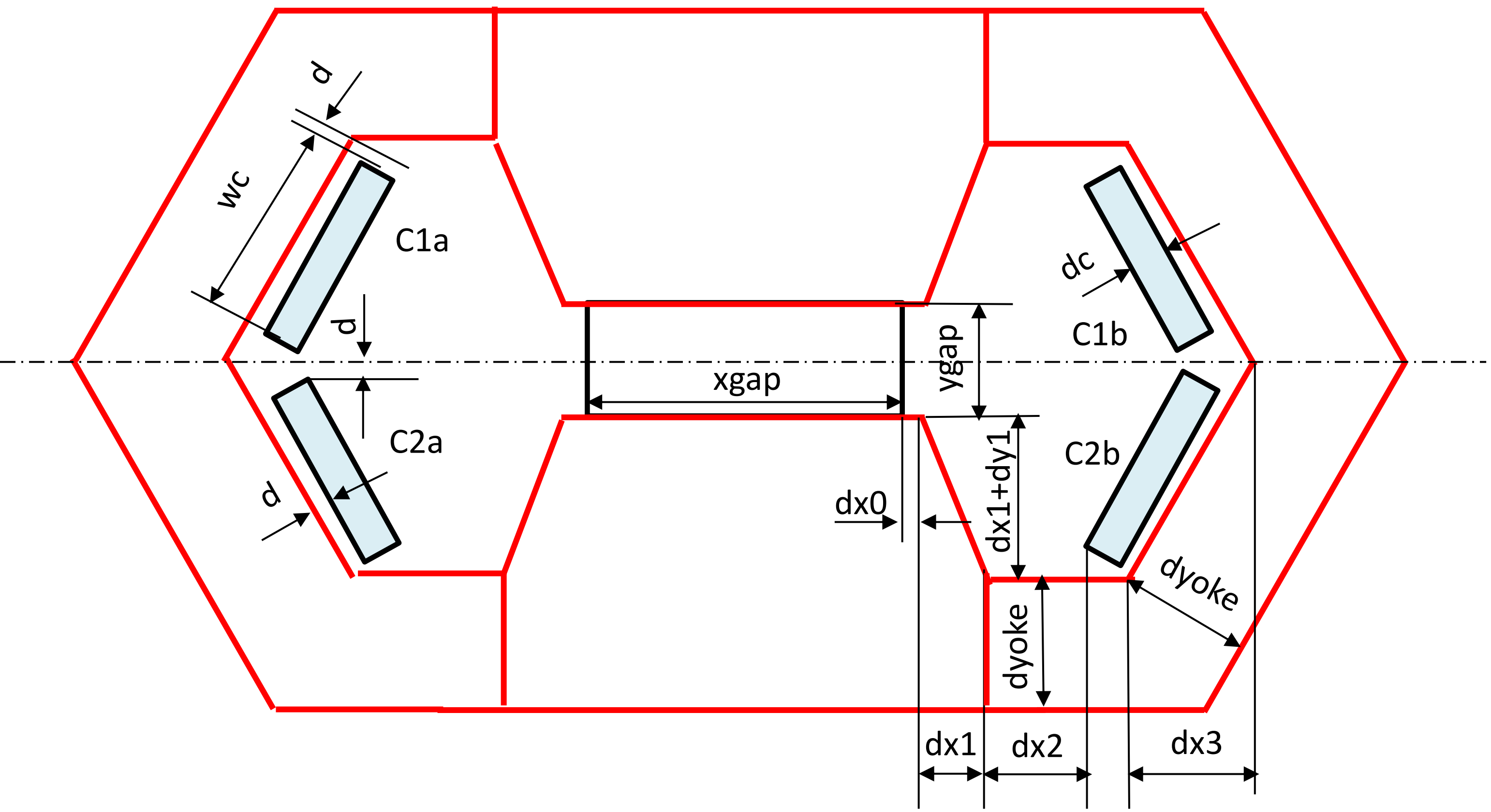


# FEMM model assumptions in AC regime

- 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 $\vartheta$** is considered between the phasors of H and B.
- The hysteresis lag $\vartheta$ 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
- The optimizations were performed in DC conditions on different magnetic configurations

# 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,$\chi$ (dc/wc)

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

**OPTIMIZED FUNCTION**:

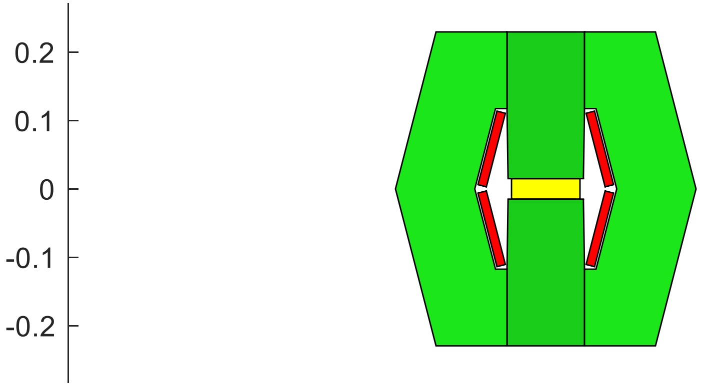
total magnetic energy ([J])

**CONSTRAINTS:**

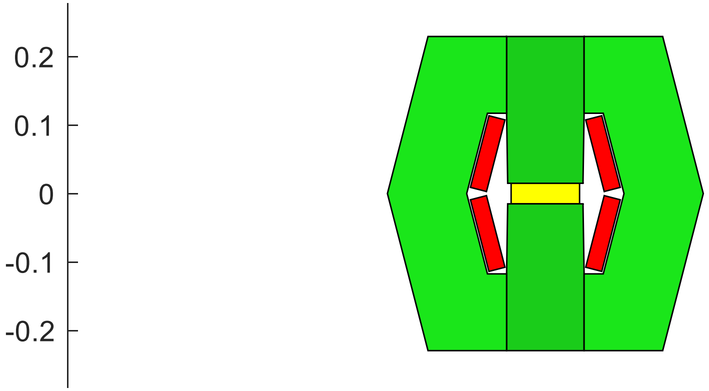
- B0y $\geq$ 1.8 [T]

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

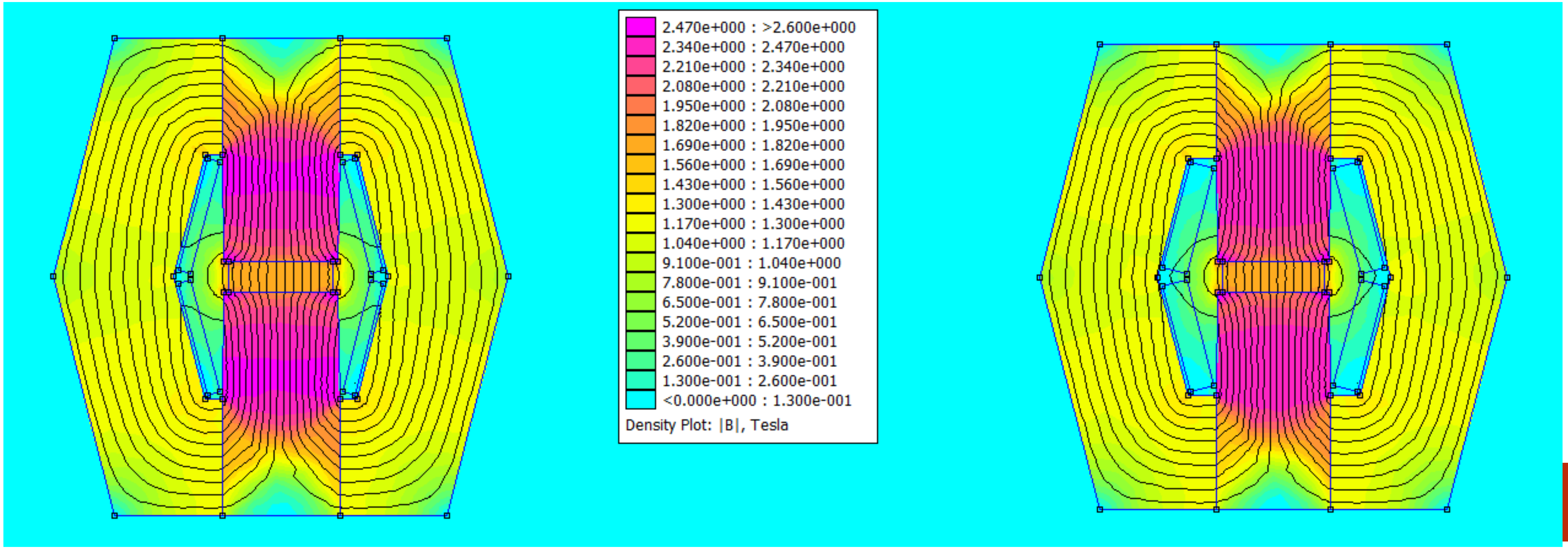
# *Hourglass magnet: field maps*




J = 20 A/mm²

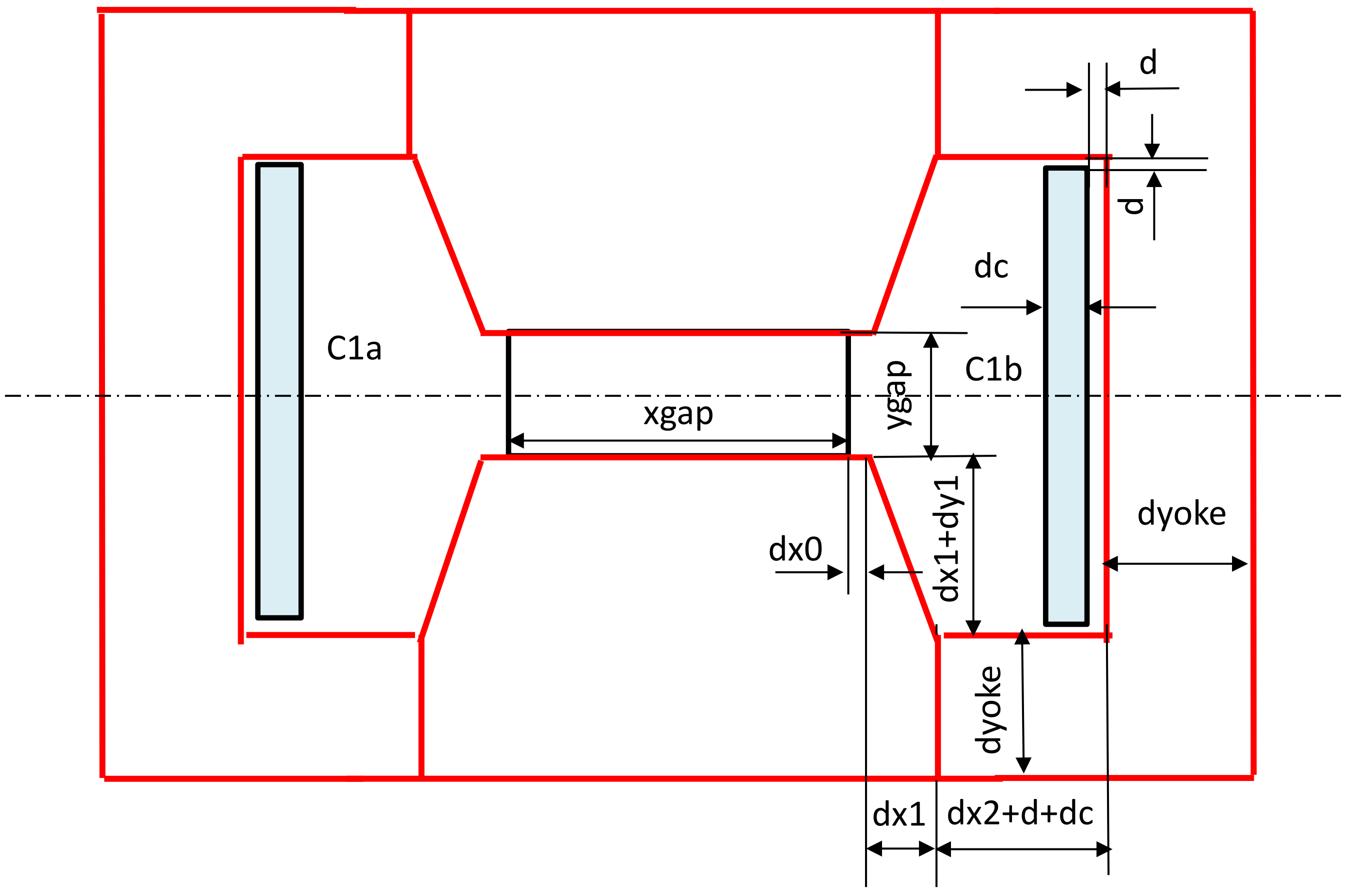



J = 10 A/mm²



# *Window Frame magnet with 1 coil: geometry*

WF1 (Window Frame with 1 coil) geometry

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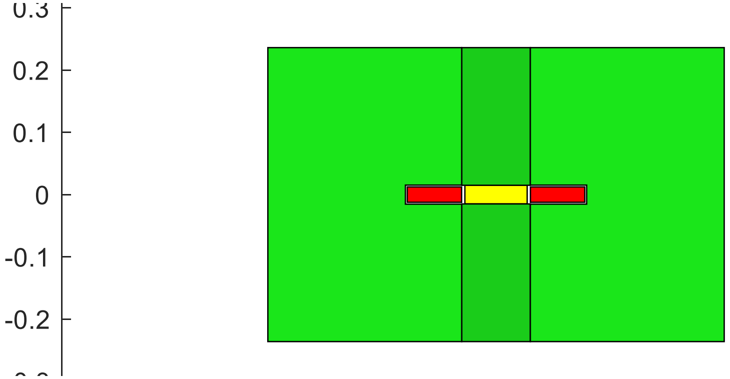
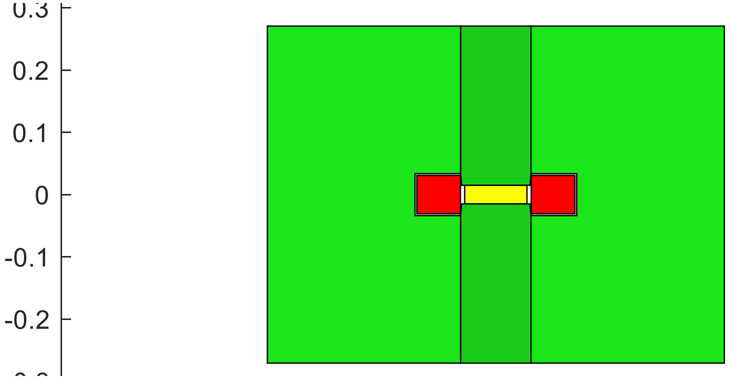
- B0y ≥ 1.8 [T]

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

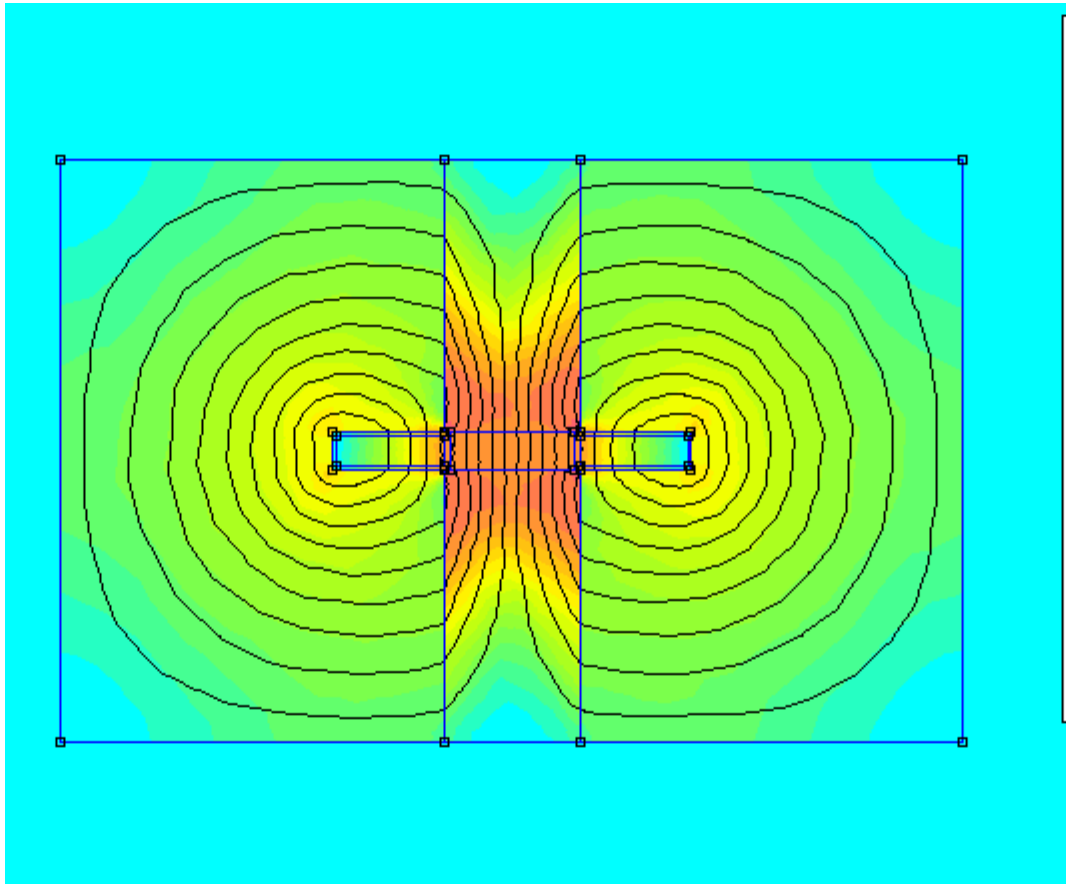
# *Window Frame magnet with 1 coil: field maps*

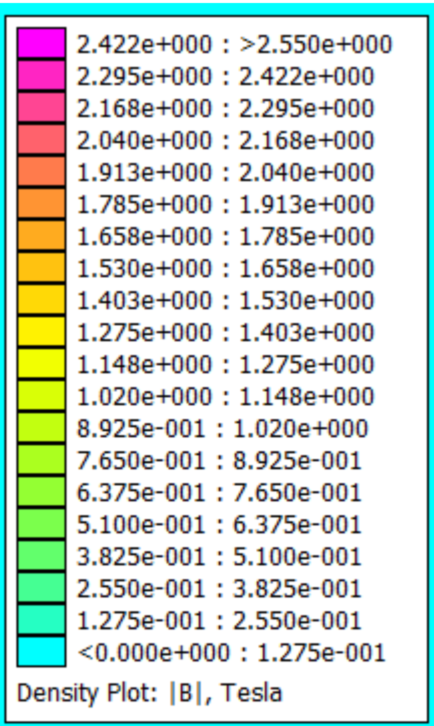


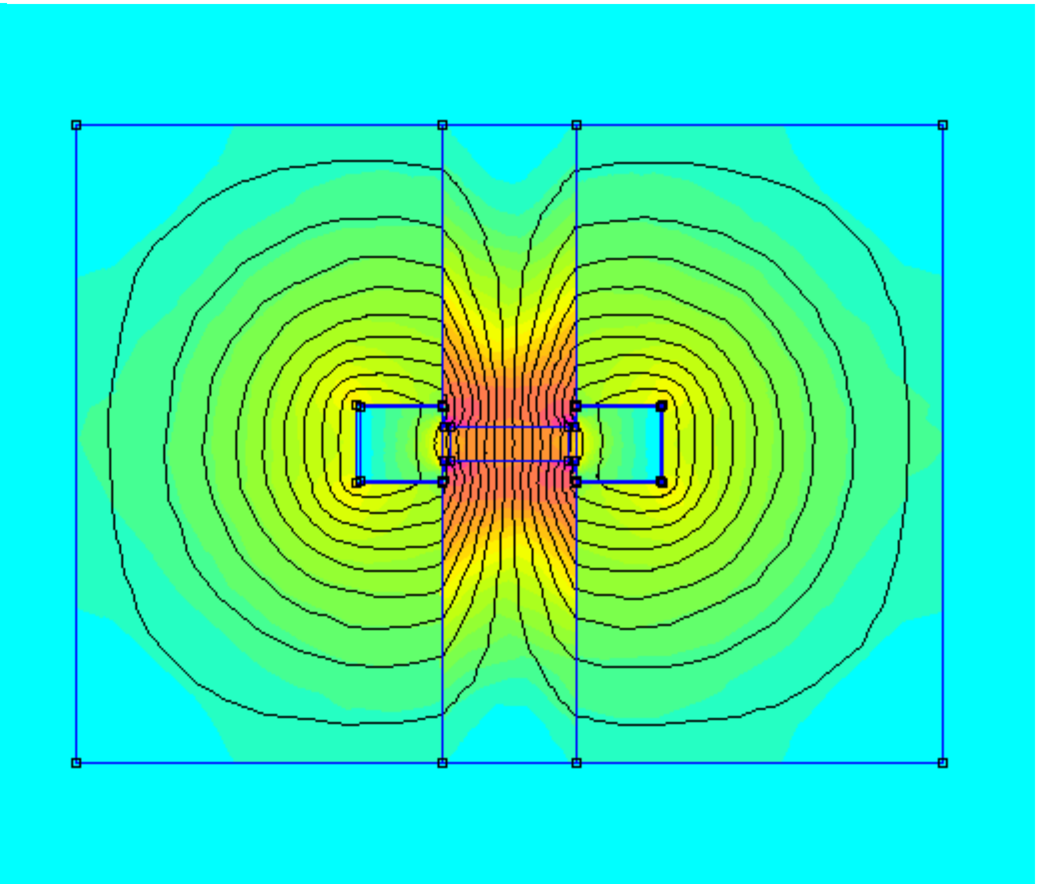

J = 20 A/mm²



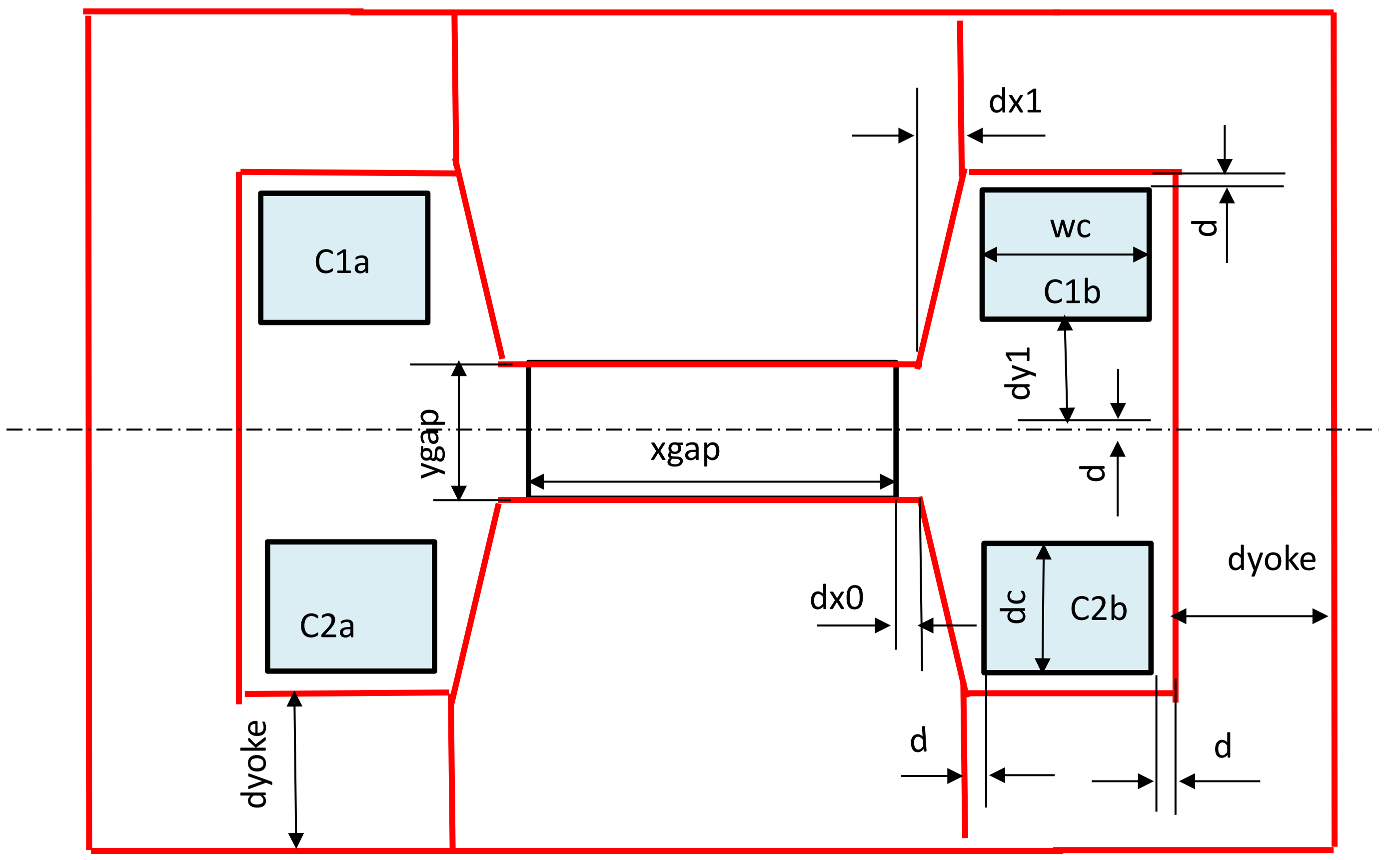

J = 10 A/mm²





# *H-type magnet: geometry*




**GEOMETRICAL DATA:**

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dx1,dy1,dyoke,wc,dc

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

**OPTIMIZED FUNCTION**:

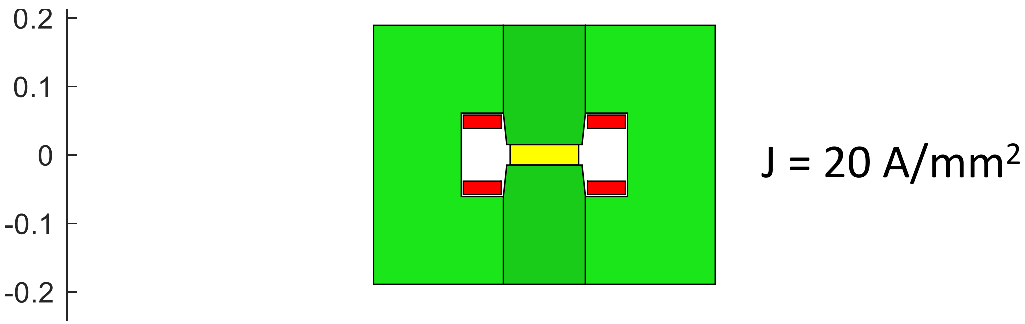
total magnetic energy ([J])

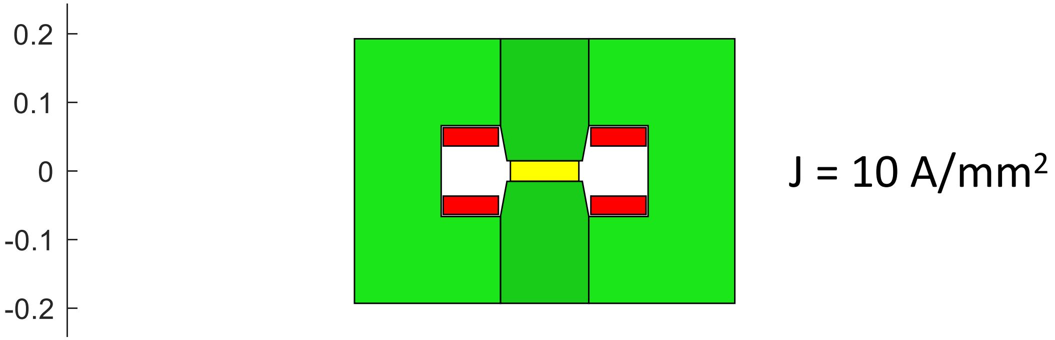
**CONSTRAINTS:**

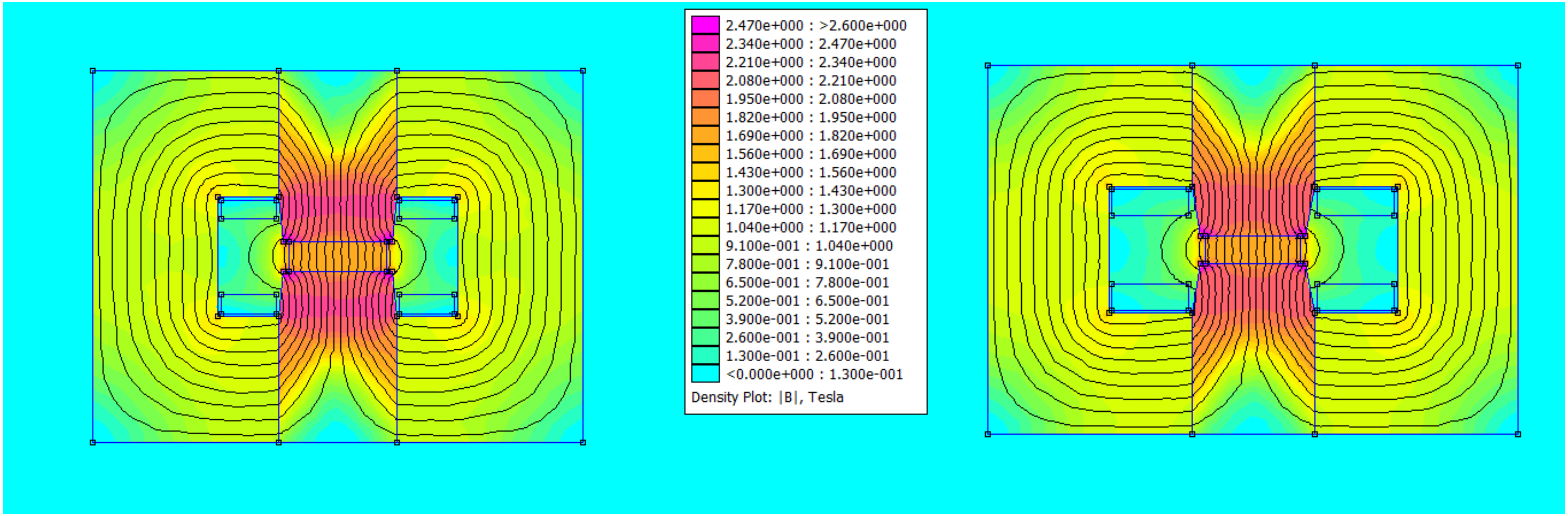
- $B0y \geq 1.8$ [T]

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

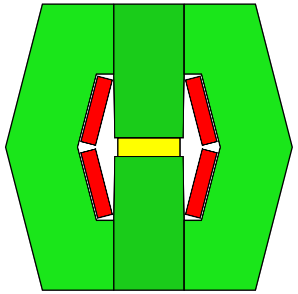
# *H-type magnet: field maps*



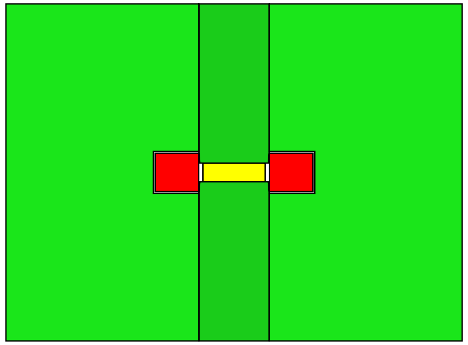



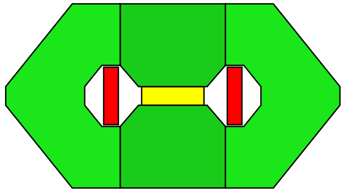
# *Comparison of the optimized geometries*



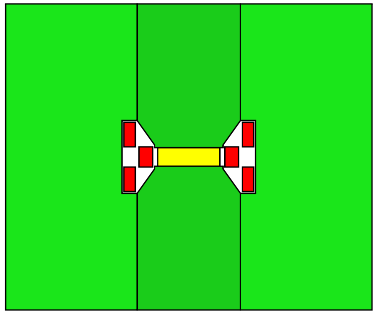
**HG (J=10 A/$mm^2$): Emag = 5.71** [kJ/m]



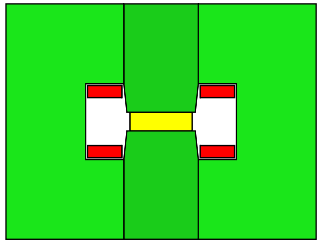
**WF1: (J=10 A/$mm^2$ Emag = 5.37** [kJ/m]



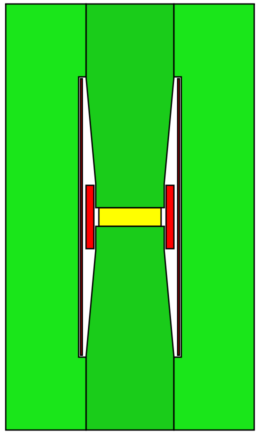
**WF1M: (J=20 A/$mm^2$ Emag = 6.05** [kJ/m]



**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**

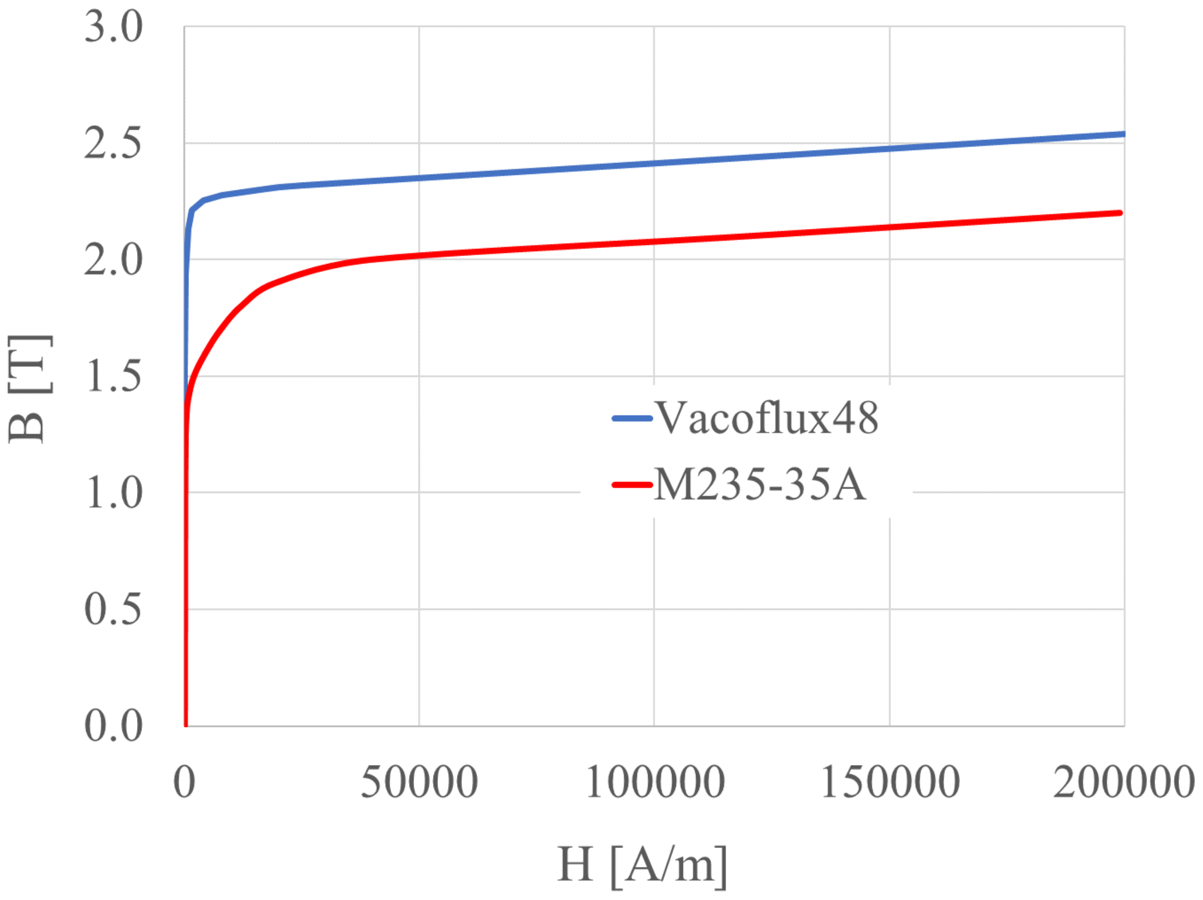
# Comparison of the analyzed configurations ($J = 20\ A/mm^2$)

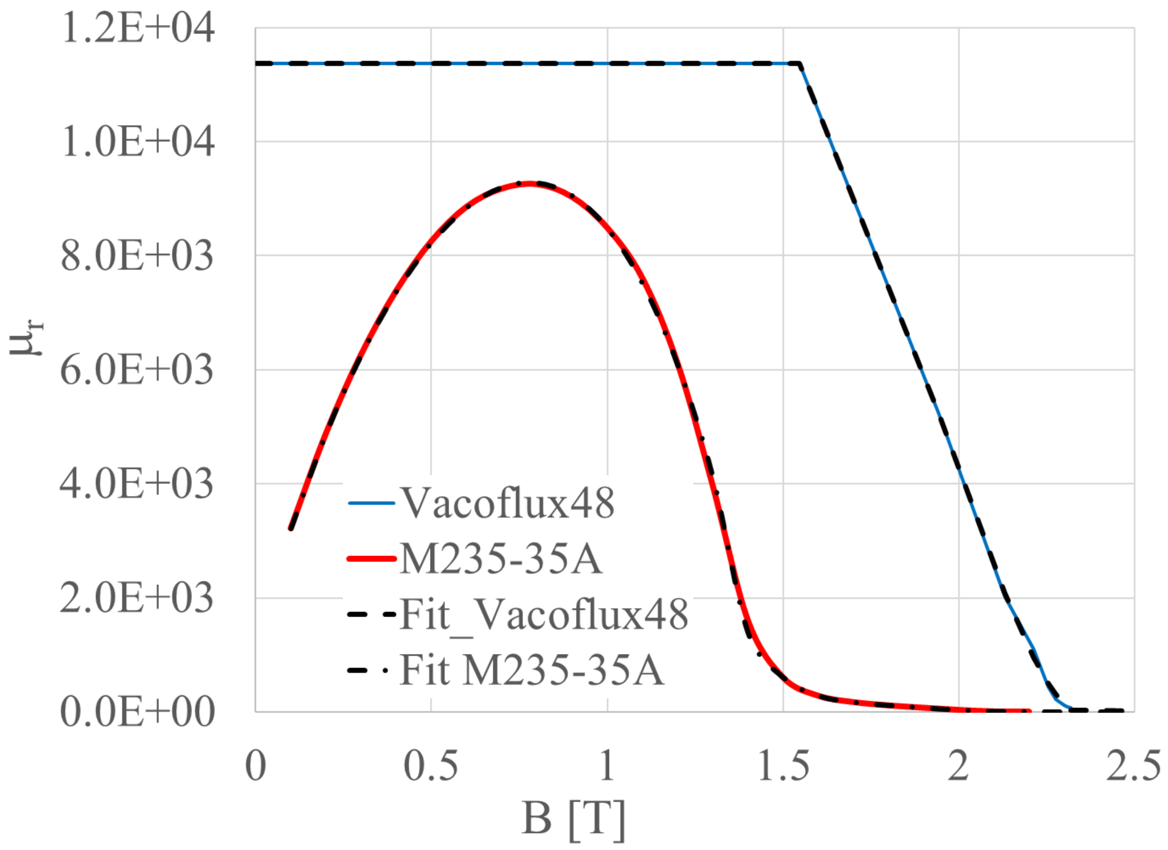
* Maximum current in AC was reduced with respect to dc regime to keep the field at the 2 T peak (linearization not precise)

| Geometry (Jc = 20 $A/mm^2$) | HG | WF1 | WF1M | WF2 | HM | WF3 |
|---|---|---|---|---|---|---|
| **Results in dc regime** | | | | | | |
| $\delta_B$ (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)]<br>Copper losses<br>Iron losses | 406.4<br>258.3<br>148.1 | 1034.9<br>984.5<br>50.4 | 483.2<br>359.8<br>123.4 | 1021.7<br>858.5<br>163.2 | 422.9<br>294.8<br>128.1 | 1205.2<br>1137.5<br>67.7 |

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

- Further studies were performed by selecting two commercial materials for the magnetic poles and the lateral columns of the magnetic circuit, namely **Vacoflux-48 and M235-35A steel**




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

# Optimization of the H-magnet with Vacoflux48 and M235-35A

| Optimized quantity | **Magnetic energy** | **Reactive power** | **Active Power** |
|---|---|---|---|
| Vacoflux48 volume [$dm^3/m$] | 41.8 | 41.23 | 41.23 |
| M235-35A volume [$dm^3/m$] | 129.6 | 128.3 | 128.3 |
| Copper volume [$dm^3/m$] | 4.35 | 4.306 | 4.306 |
| **Results in dc regime** (Jc = 20 $A/mm^2$) | | | |
| $\delta_B$ (B0y = 1.8 T) | 3.38e-02 | 3.29e-2 | 3.29e-2 |
| Total magnetic energy [kJ/m] | 5.75 | 5.66 | 5.66 |
| **Results in ac regime** (B0ymax=2T, f=500 Hz) | | | |
| Imax (B0y = 2 T) [kA] | 24.18 | 23.92 | 23.92 |
| Vmax (B0y = 2 T) [kV/m] | 1.886 | 1.865 | 1.865 |
| Real power (MW/m) | 0.1993 | 0.1946 | 0.1940 |
| Reactive power (MVAR/m) | 22.81 | 22.30 | 22.31 |
| Total loss [J/(m cycle)]<br>Copper losses<br>Iron losses | 398.7<br>306.5<br>92.20 | 387.93<br>297.4<br>90.55 | 387.93<br>297.4<br>90.55 |

- The magnetic energy **optimization in DC** with Vacoflux-48 and M235-35A leads to a solution which is very close to that found with Supermendur and M22 steel
- The **optimization in AC conditions** of either **reactive or active power** give practically the same solution
- Both solutions of the **AC optimization** are very close to that found with the **DC optimization**

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# *Development of a simplified model of the H-type 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 **$\phi$ vs I characteristics of the magnet**

  2) Magnetic energy stored in the magnet

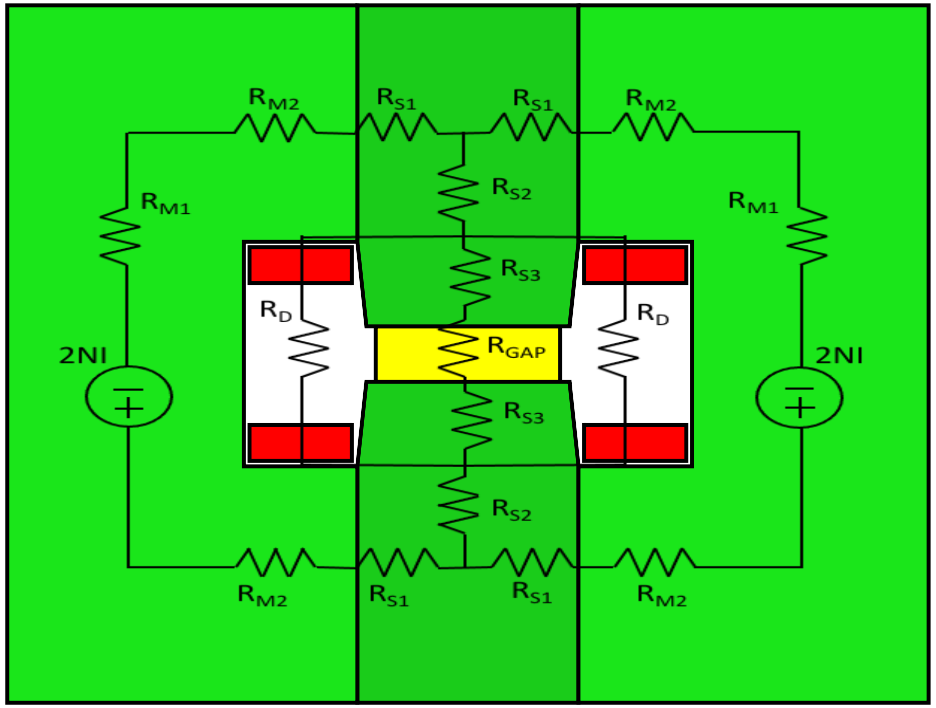
  3) Losses in the iron and copper (possibly through analytical formulae)

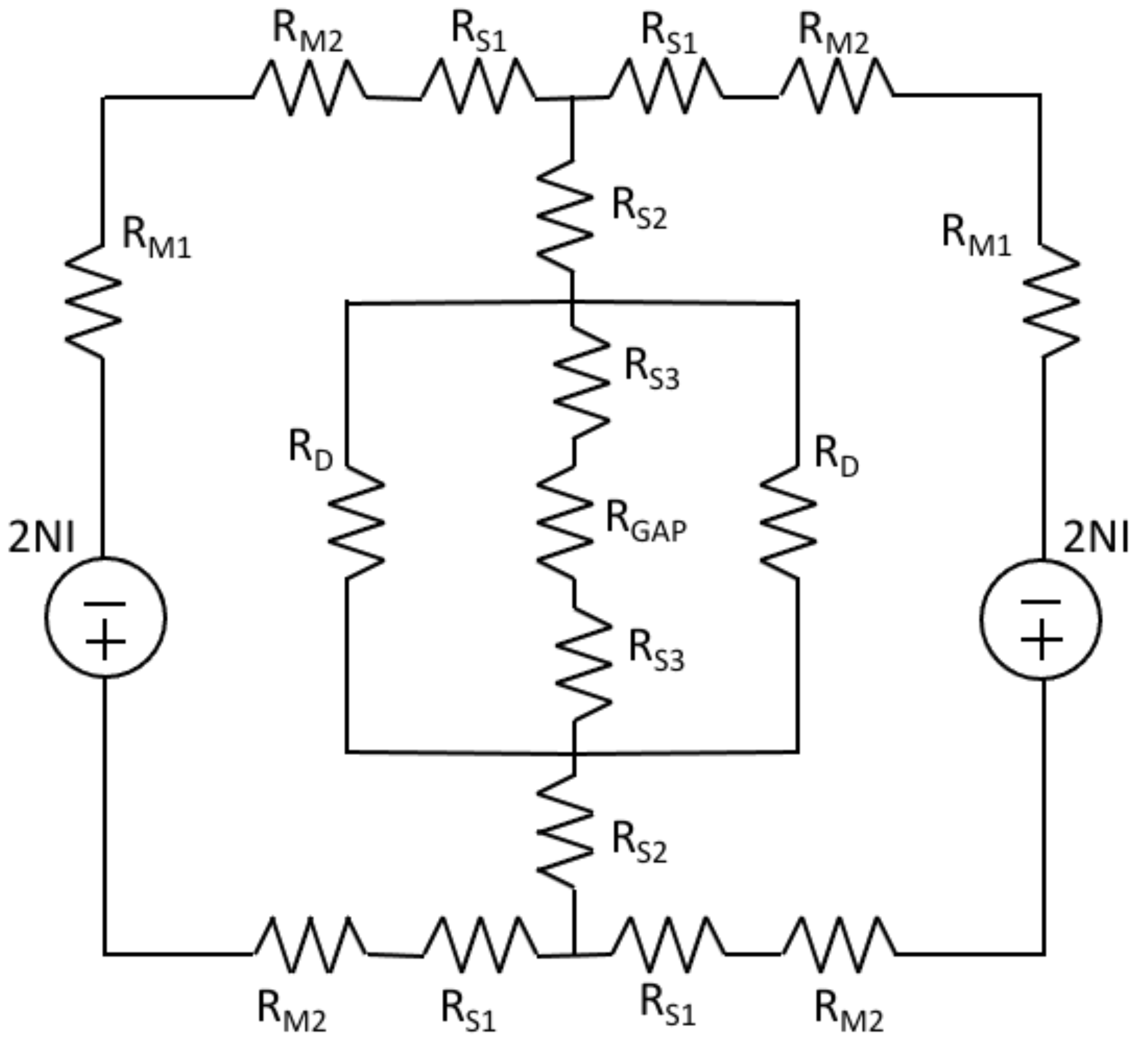
  4) Average magnetic field in the midplane of the good field region vs winding current

# Magnetic circuit model of the H-type Magnet

- An **equivalent lumped elements circuit model** of the H-type magnet is under development

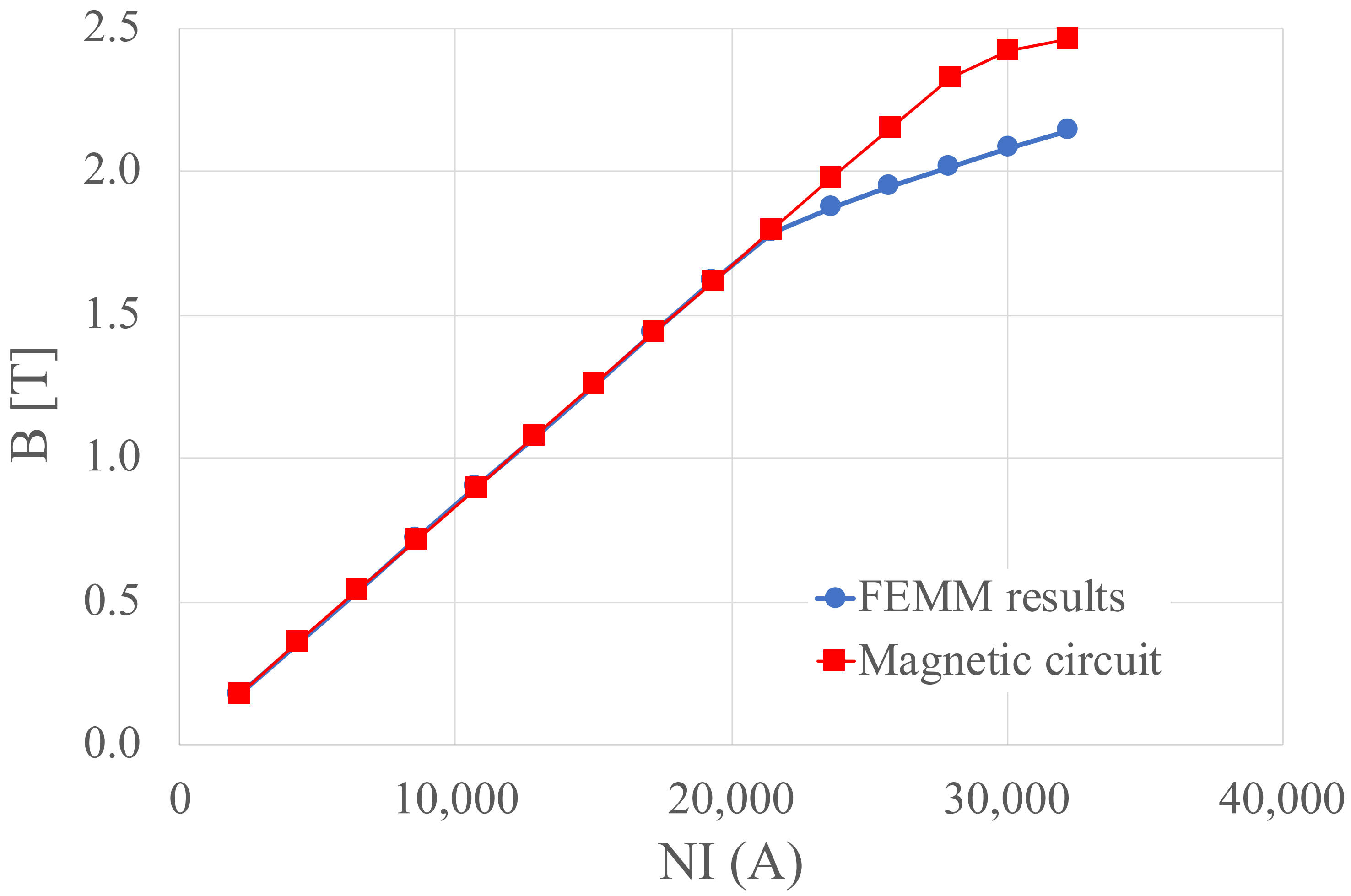
- The **non-linear reluctances** depend on the value of the magnetic flux density: $R\ (B) = l\ /\ \mu\ (B)\ S$



# 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



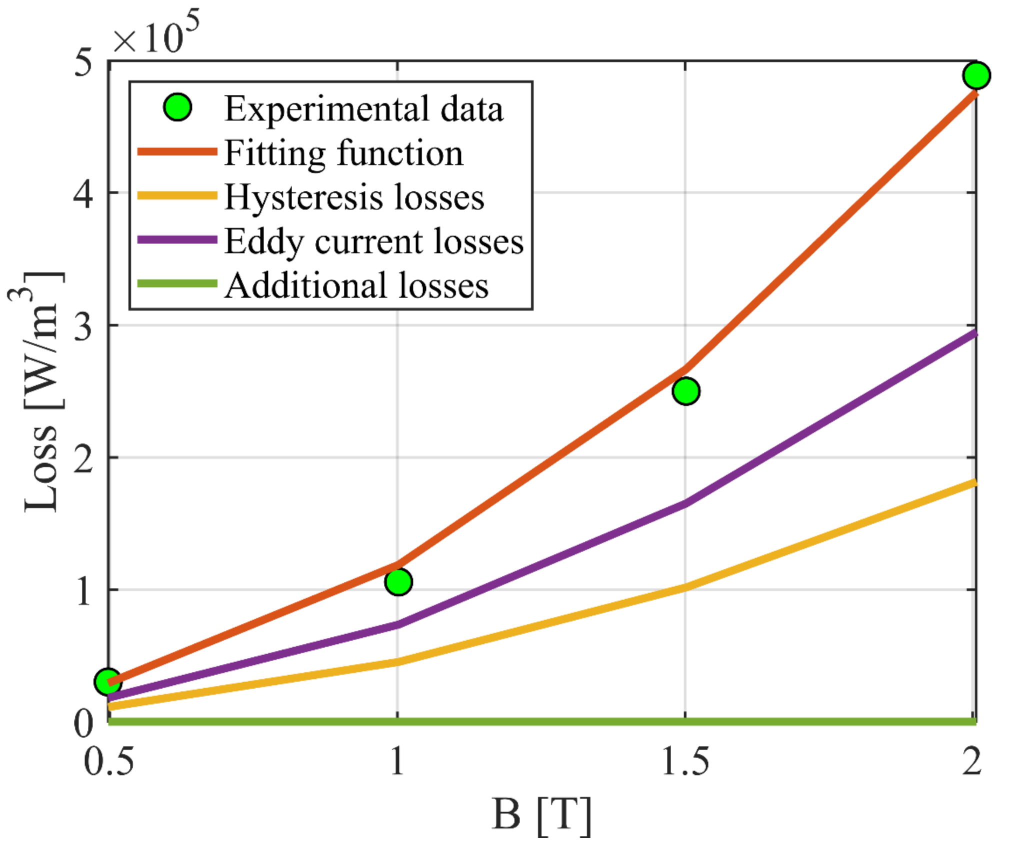

**Field in the middle of the good field region vs NI**

# *Analytical computation of the iron losses*

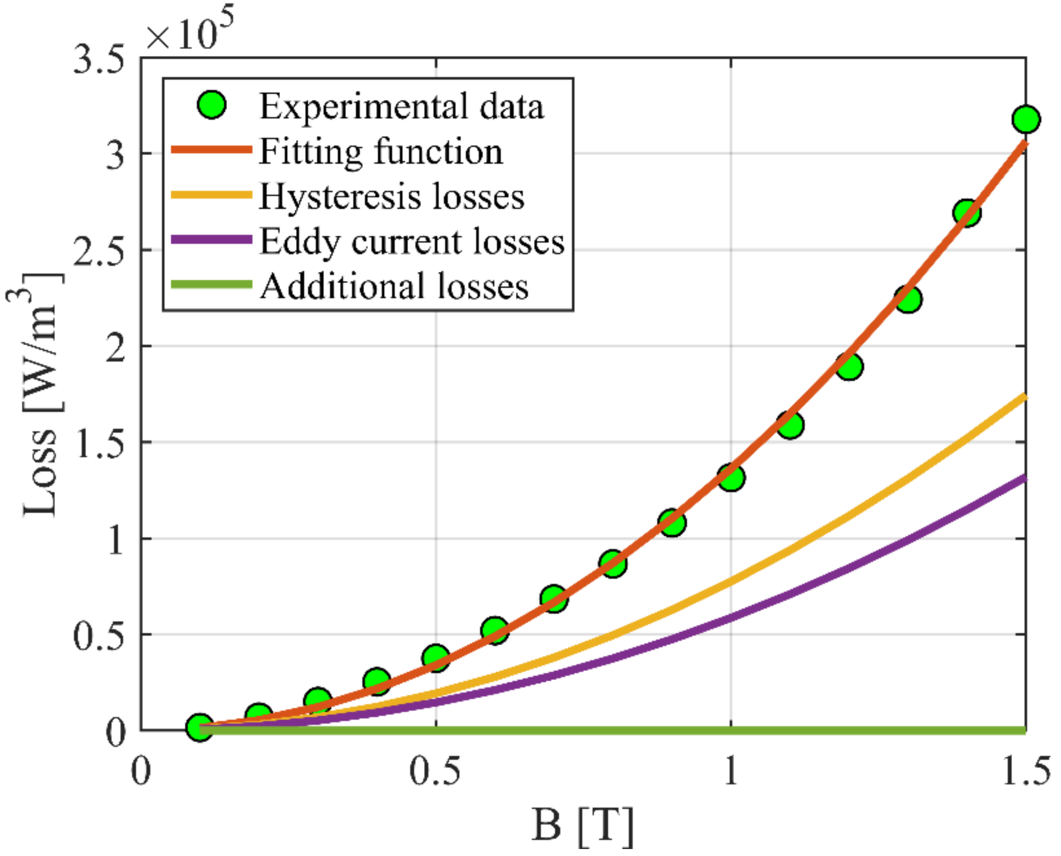
- Available experimental data on losses in the two selected commercial materials were **fitted by an analytical formula,** thus retrieving the values of the parameters $k_{hyst}$, $k_{eddy}$, and $k_{addit}$.

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

**Vacoflux48 f = 400 Hz**




**M235-35A at f = 400 Hz**



# Summary

- An optimization was applied in DC conditions on **three magnet configurations** keeping the **same current density and minimizing the stored energy** of the magnet

- All configurations **reach the desired magnetic field in the gap**, which is set as a constraint of the optimization

- 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

- The solutions obtained with AC optimization of active and reactive power are almost coincident with that found via DC optimization of the magnetic energy

- A **non-linear magnetic circuit model** was developed to describe the H-type magnet, finding good agreement with the 2D FEM model up to 1.8 T (discrepancy between 1.8 T and 2.0 T)

- An **analytical formula for the losses in ferromagnetic materials** was applied to fit the experimental results obtained on two selected ferromagnetic materials

# *Future activities*

- Further 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)
- **Improvement of the magnetic circuit model of the H-type magnet** to achieve a better agreement with the 2D FEM model above saturation
- Implementation of **analytical formulae for the losses in the copper conductor** and validation with the 2D FEM results
- **Reduction of the copper losses** by segmentation of the conductor
- Implementation of a **thermal model of the magnet** including heat exchange with a coolant
- Computation of the **force distribution in the magnet**, to be used as an input for mechanical models

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**Thank you for your kind attention !**

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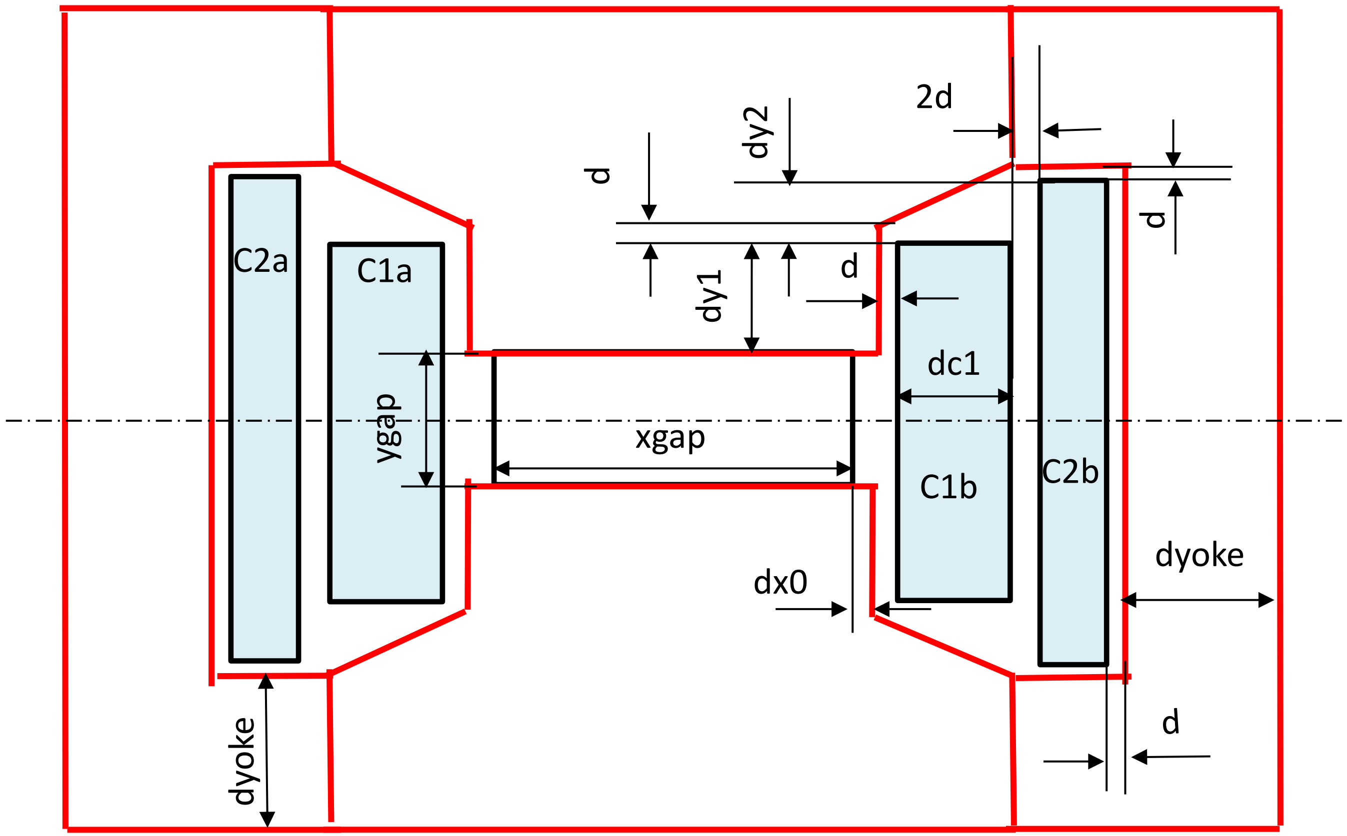
marco.breschi@unibo.it

# *Window frame magnet with 2 coils: geometry*

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**OPTIMIZED FUNCTION**:
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**CONSTRAINTS:**
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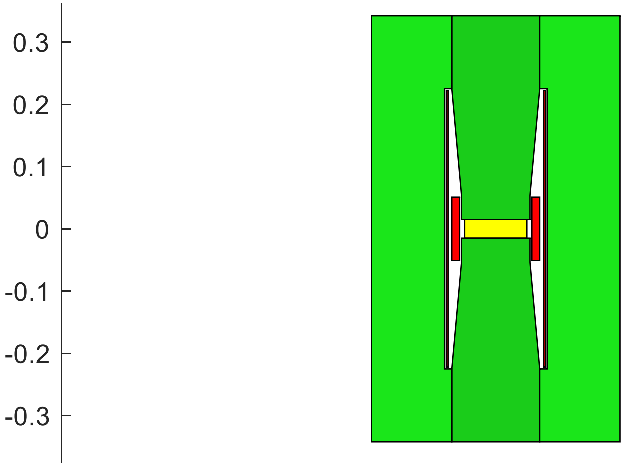
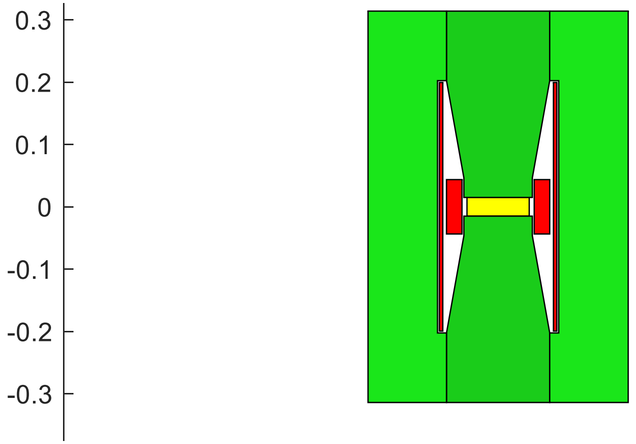
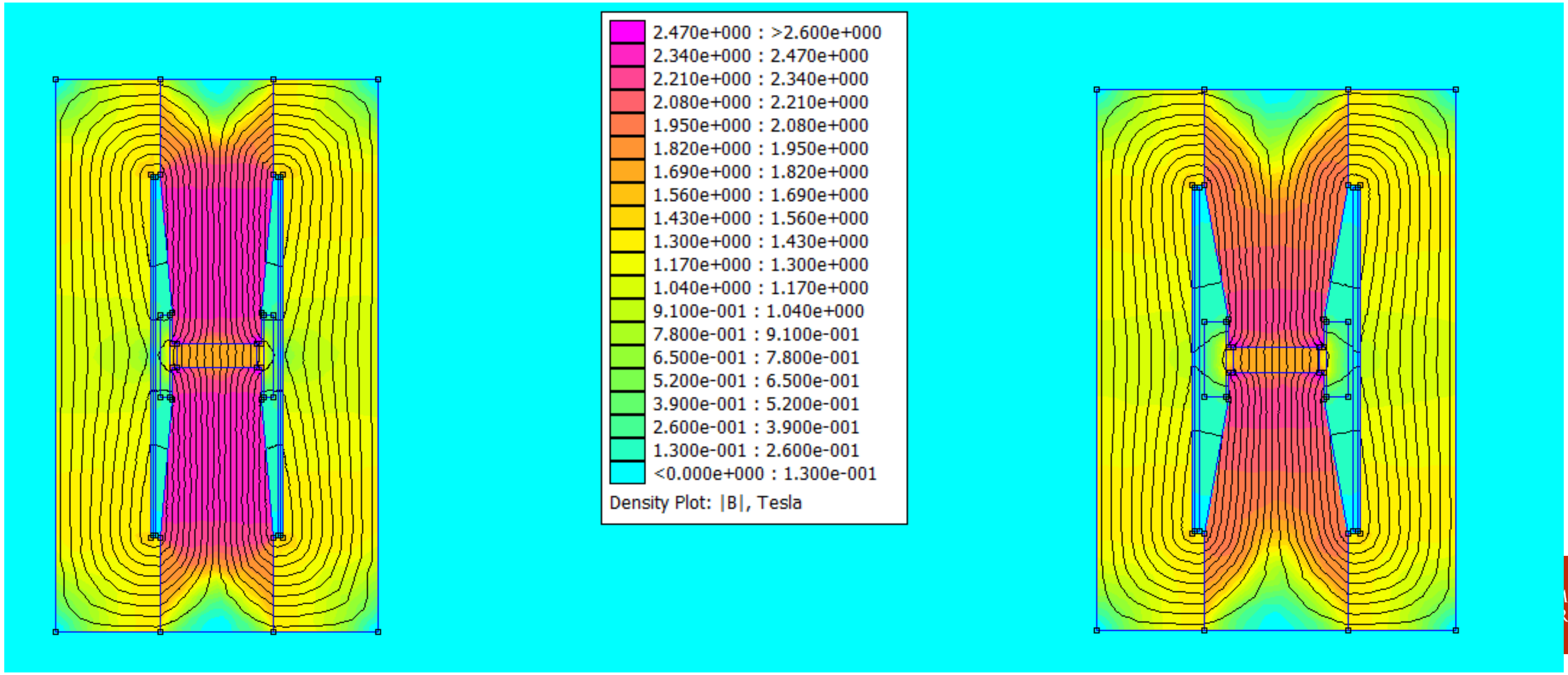
# *Window frame magnet with 2 coils: field maps*



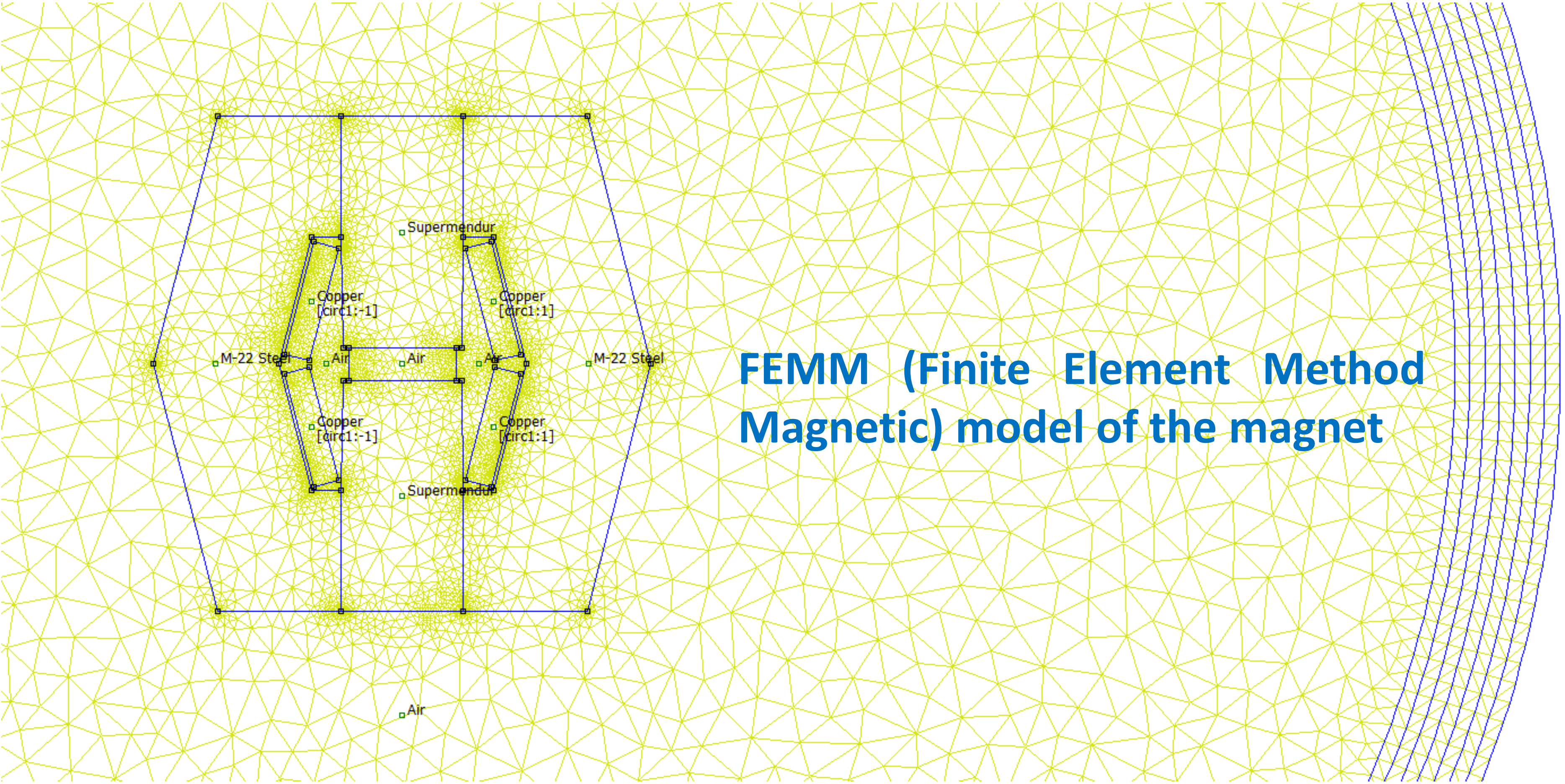
J = 20 A/mm$^2$



J = 10 A/mm$^2$



# FEMM model assumptions (1/2)

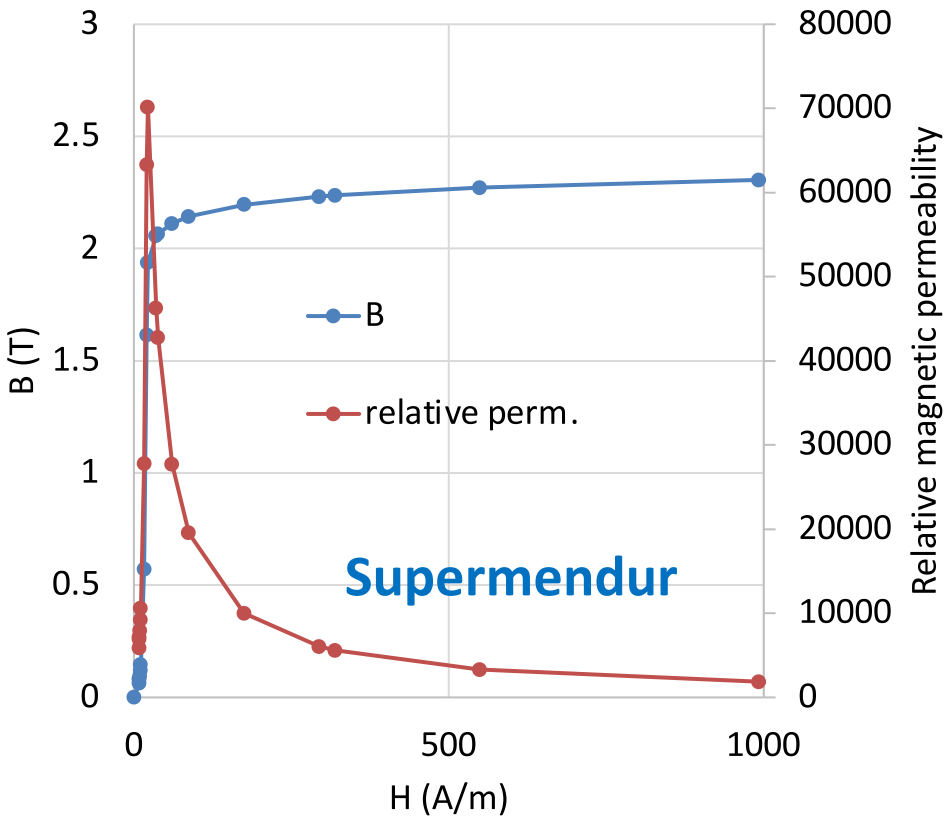


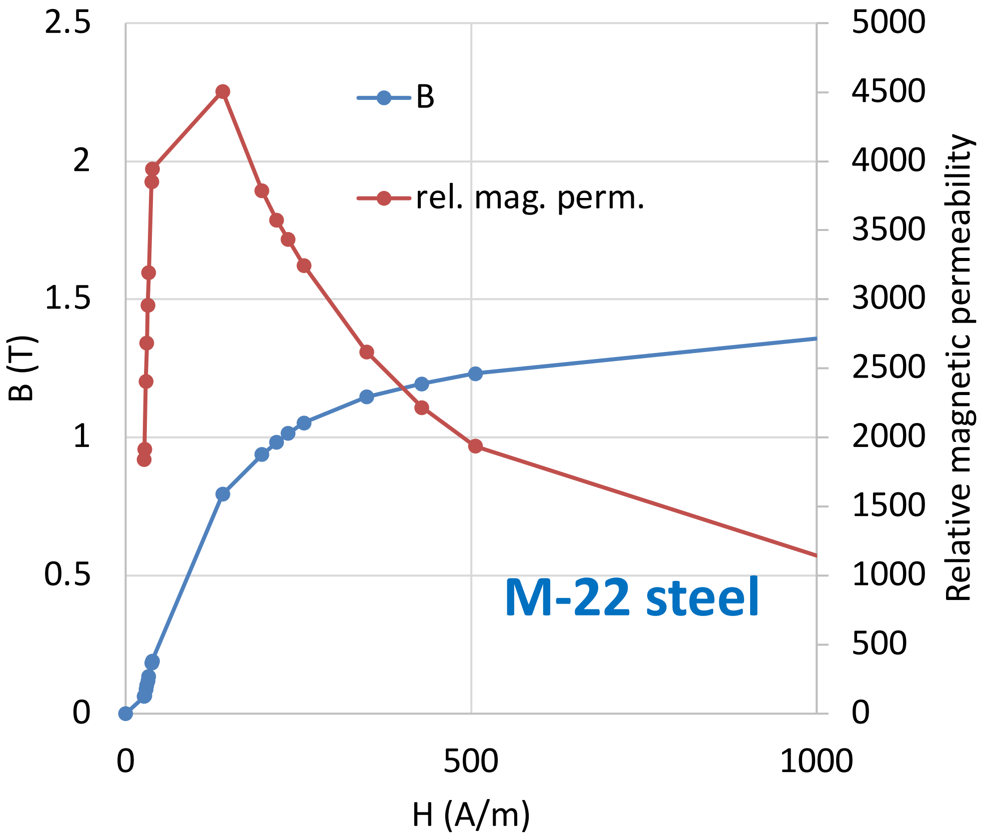

**FEMM (Finite Element Method Magnetic) model of the magnet**

- All coils are **series connected and the current density is fixed**: for each studied geometrical configuration two values of the current density were considered: 10 A/mm$^2$ and 20 A/mm$^2$

# *FEMM model assumptions* (2/2)

- The magnetic structure of the system is divided in two parts made of different materials
- The poles which surround the free gap, where the magnetic flux density field is high (> 1.8 T), are made of **Supermendur** material (from FEMM material library) with a remanence larger than 1.8 T
- The yokes are made of **M-22 steel** (from FEMM material library) with a much lower remanence



# *FEMM model assumptions in AC regime* *(2/2)*

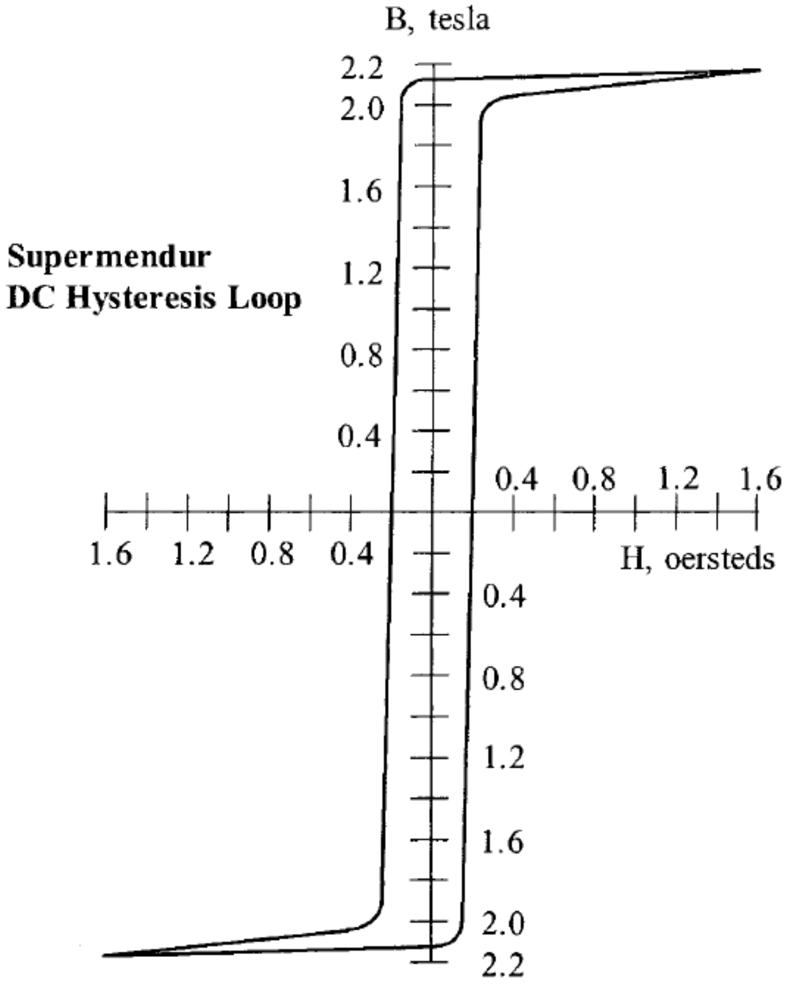



**Figure 2-4.** Supermendur B-H Loop: 49% Fe 49% Co 2% V.

Reference: TRANSFORMER AND INDUCTOR DESIGN HANDBOOK *Third Edition, Revised and Expanded* COLONEL WM. T. MCLYMAN, 2004

Reference for losses in M-22 steel:
SELECTION OF ELECTRICAL STEELS FOR Magnetic Cores
**AK Steel Corporation,** West Chester, OH 45069
www.aksteel.com