Resistive magnets design studies

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Outline

- Resistive dipole magnets specifications
- Analysis methodology
- Results of the three analyzed magnet configurations
    - Windowframe magnet
    - H-type magnet
    - ‘Hourglass’ magnet from the US study
- Comparison of the three configurations
- Summary and perspectives

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**)

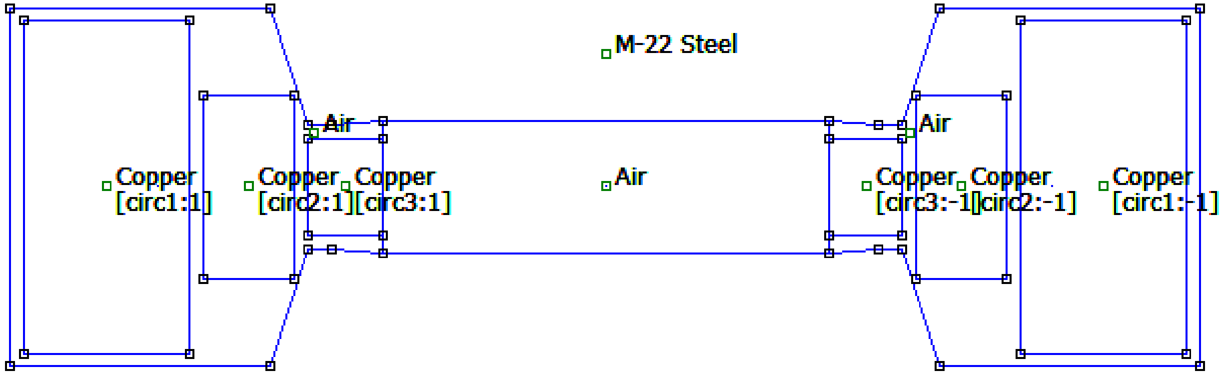
  3) Ramps from □B_{max} to $+B_{max}$ in **1 ms.** The objective for the value of B_{max} is 2.0 T

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

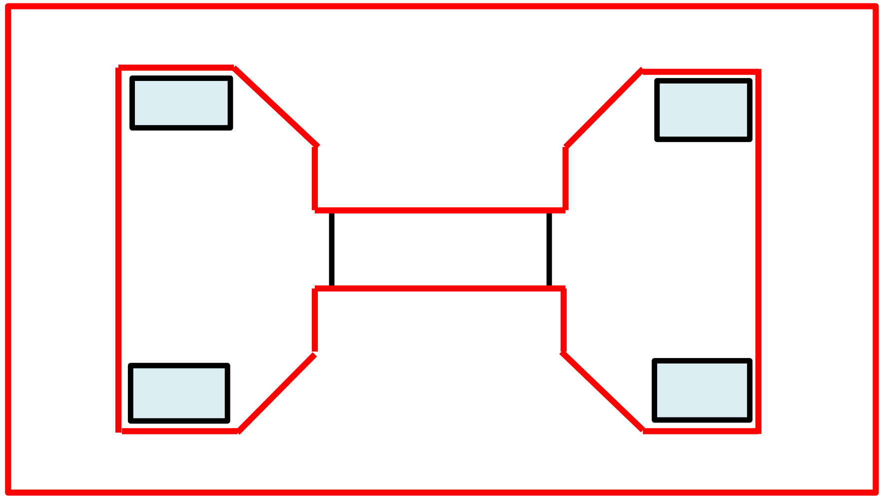
  5) Limit the **total losses (iron + copper)**

Analysed magnet configurations

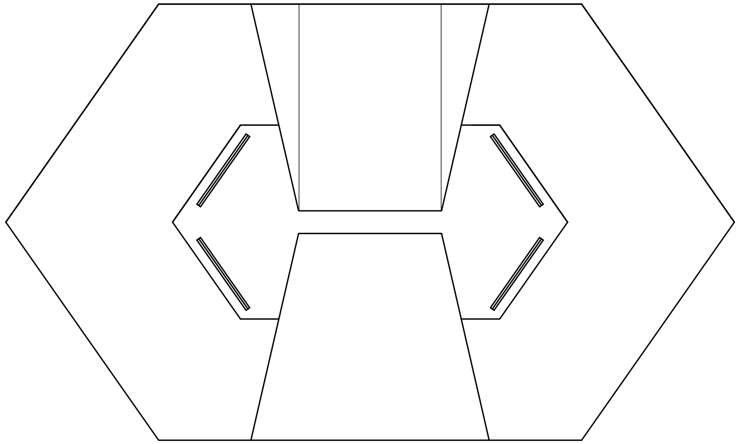
- In this preliminary study 3 main configurations are analyzed: **Windowframe magnet, H magnet, Hourglass magnet** (from the US study)



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.

Study methodology: DC optimization

- The analysis is performed both in **DC and AC conditions,** in the frame of a 2D electromagnetic software (FEMM).
- A first optimization is performed in DC conditions, aimed at improving the field homogeneity in the good field region. The **objective function** to be optimized is the following:

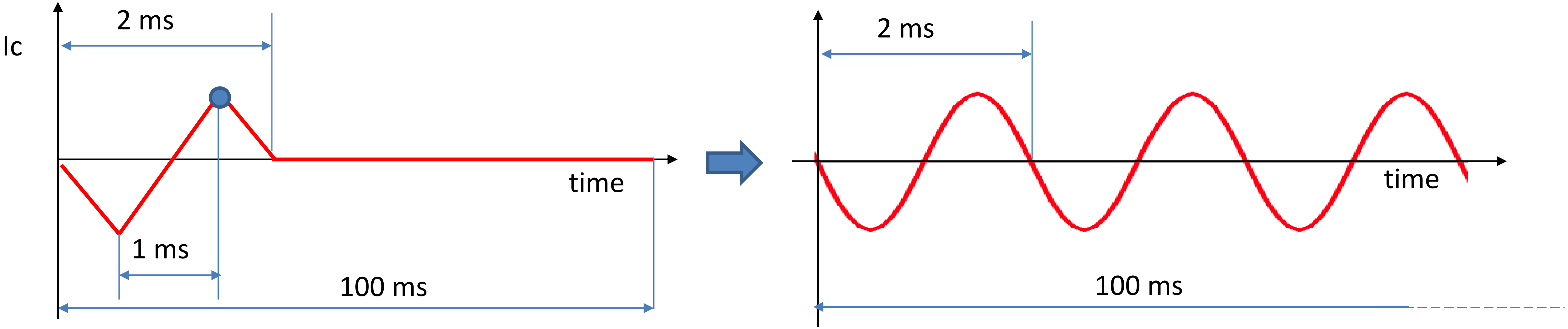
$$Field\ goodness = \frac{1}{B_{des}} \sqrt{\frac{1}{A_{gap}} \iint_{A_{gap}} \{[By(x,y) - Bdes]^2 + [Bx(x,y)]^2\}\, dA_{gap}}$$

where B_{des} is the design value of the magnetic field in the center of the gap.

- The optimization is performed by using the MATLAB optimization toolbox and is based on the **interior point method** (function *fmincon*).
- The variables of the optimization are **geometric parameters**, while the current density is kept fixed
- Convergence is reached when the relative variation of all components of the vector of unknowns is less than 10^{-10}. The **typical number of iterations** to reach convergence is **100**.

Study methodology: AC analysis

- The **design current profile** consists of a ramp from $-B_{max}$ to $+B_{max}$ in 1 ms. It is foreseen that this current profile will be provided by the power supply through the superposition of sinusoidal waves.



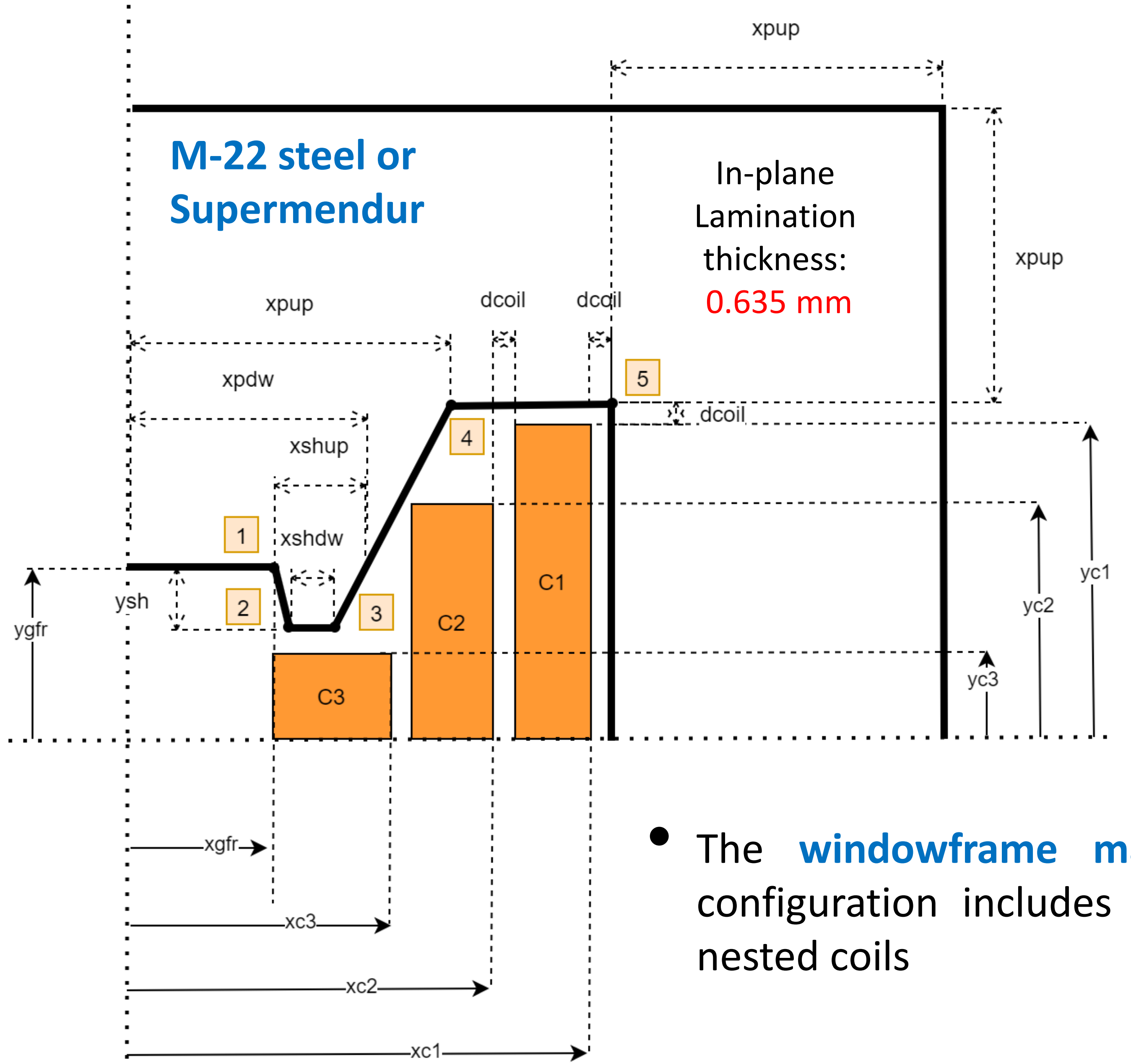
- The study in AC conditions starts from the geometric parameters defined in the DC optimization. The AC study is performed in the frequency domain: the coil currents are assumed **sinusoidal,** with a frequency of 500 Hz.

- Two approximations are made with the AC study:

  1) the **linear ramp** is approximated as a **sinusoid**

  2) the AC stationary conditions are assumed, which differ from the pulse followed by a standby time.

Windowframe magnet: geometry

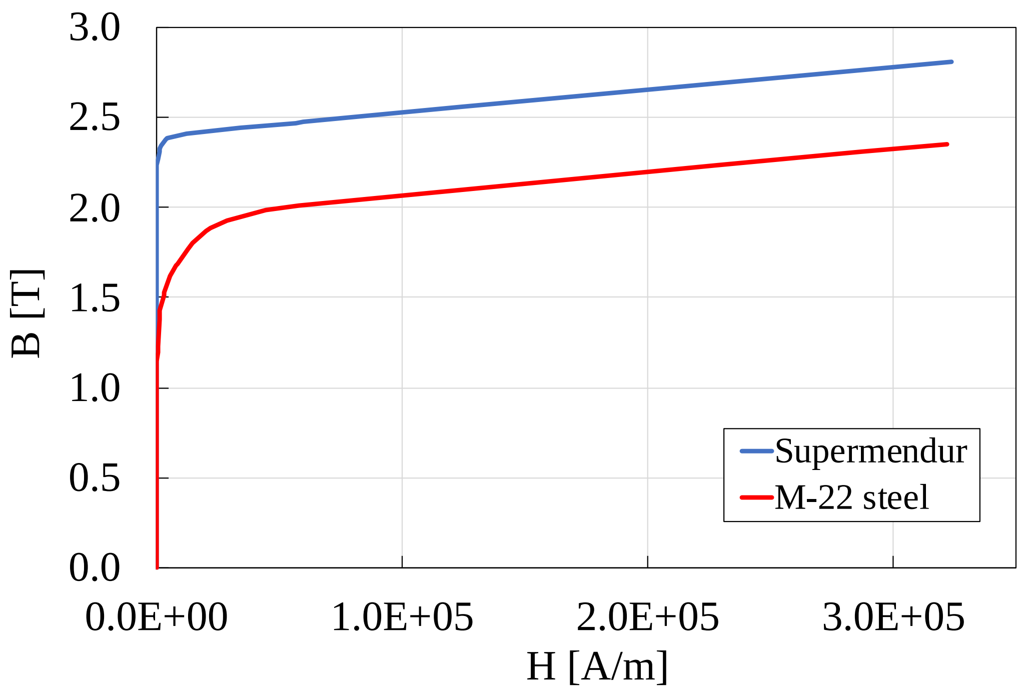


Parameters:

1. Curatio = 0.8
2. ygap = 0.03 [m]
3. xgap = 0.1 [m]
4. xgfr = xgap/2
5. ygfr = ygap/2
6. dcoil = 0.003 [m]

Optimized variables (M-22 steel):

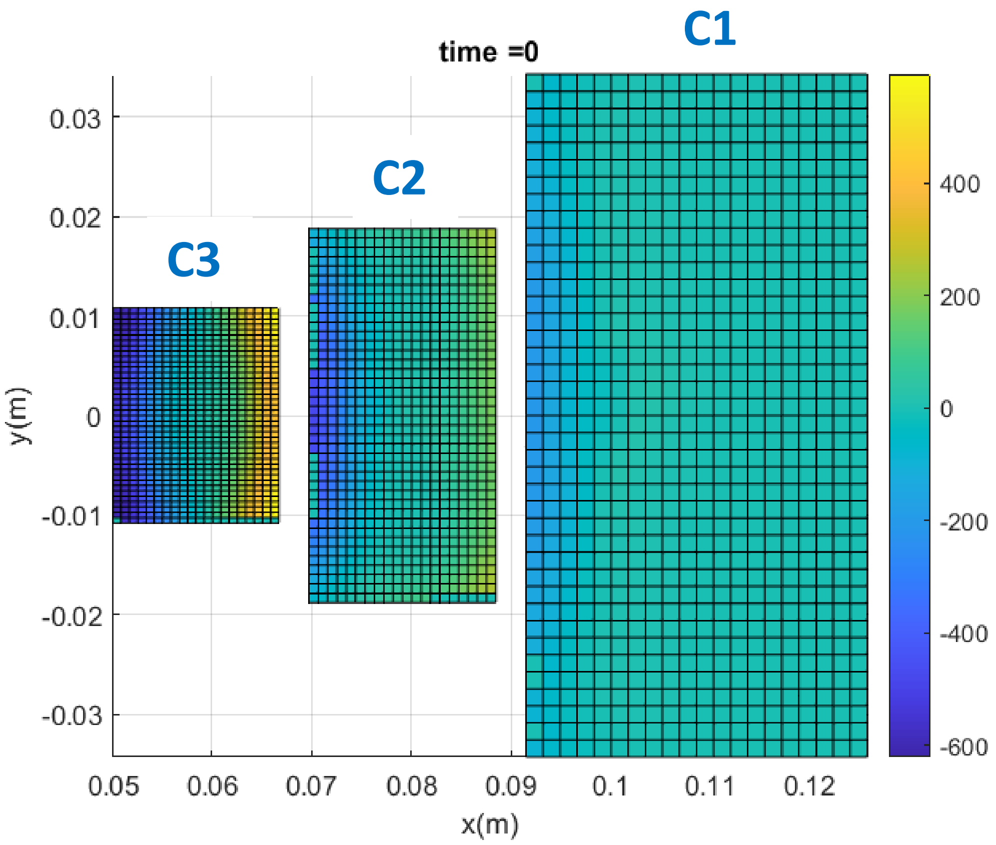
1. Ic1 = 35000 A
2. Ic2 = 10500 A
3. Ic3 = 4500 A
4. ysh = 0.0012 [m]
5. xshup = 0.0167[m]
6. xshratio = xshup/xshdown = 0.3

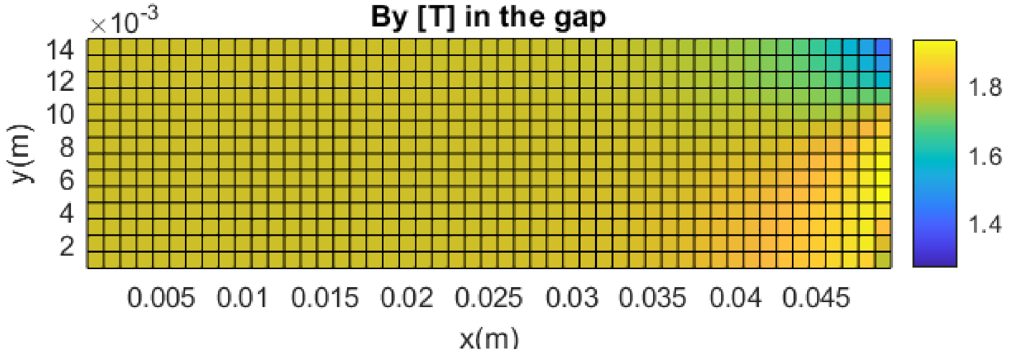


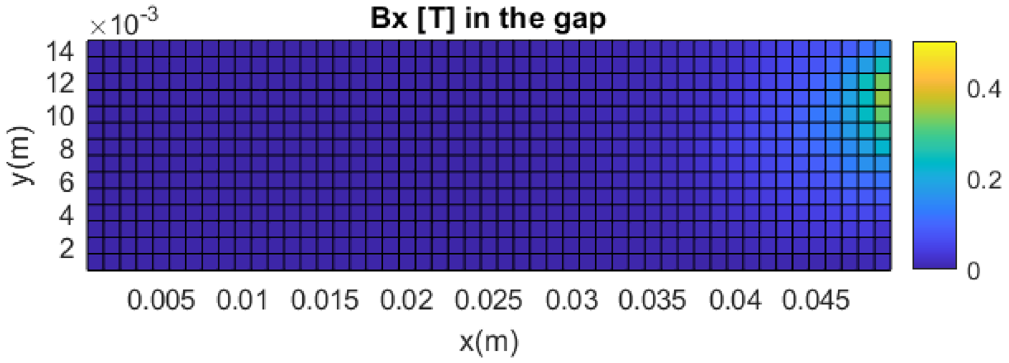
- The **windowframe magnet** configuration includes three nested coils

Windowframe magnet: results with Supermendur in AC

- With Supermendur, having a **high saturation field,** a good agreement is found between the computed DC field (1.77 T) and AC field (1.76 T)



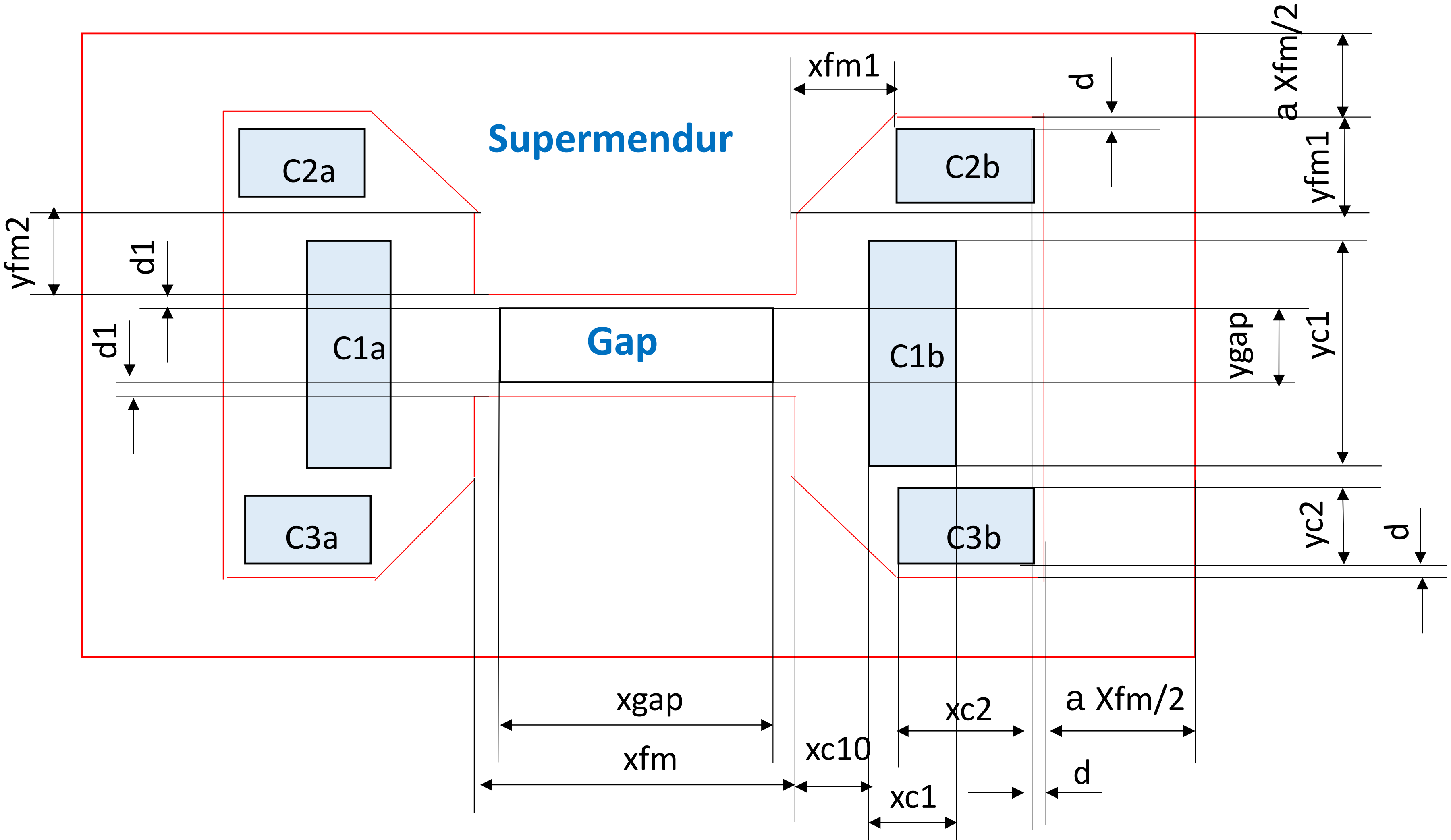




- The use of the Supermendur allows a reduction of the iron losses from **64 kW/m to 18 kW/m** with respect to M-22 steel

H magnet 3-coils configuration: geometry

- In order to reduce the **current distribution non-uniformity**, and the mutual induction coupling between different coils, a different configuration was analyzed.



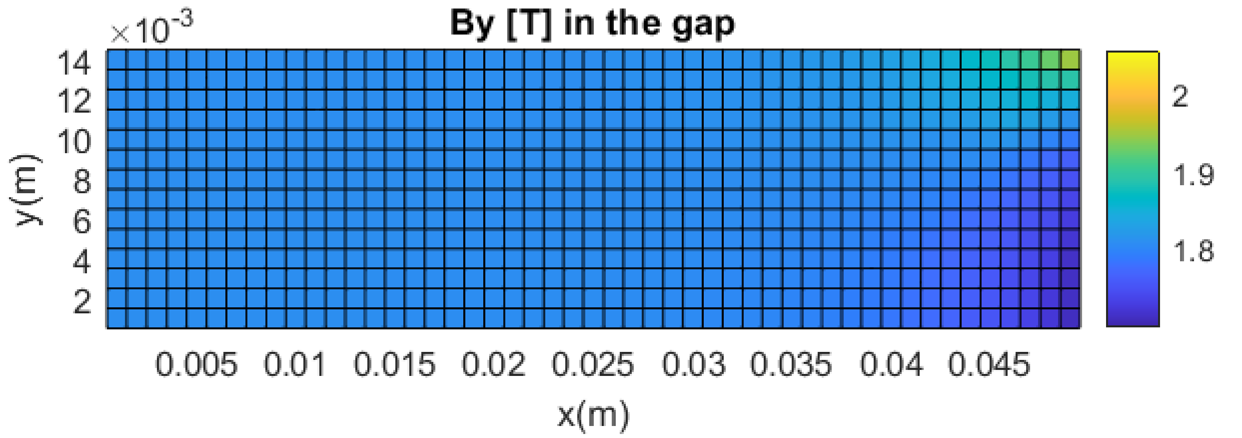
Parameters:

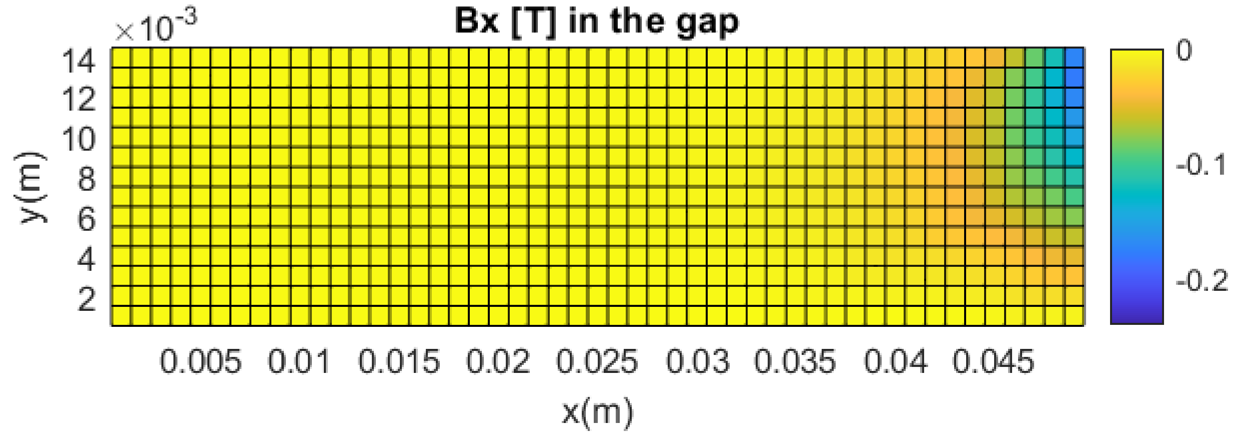
1. xgap = 100 mm
2. ygap = 30 mm
3. d = 3 mm
4. $\alpha = 1.3$
5. Jc = 12 A/mm^2

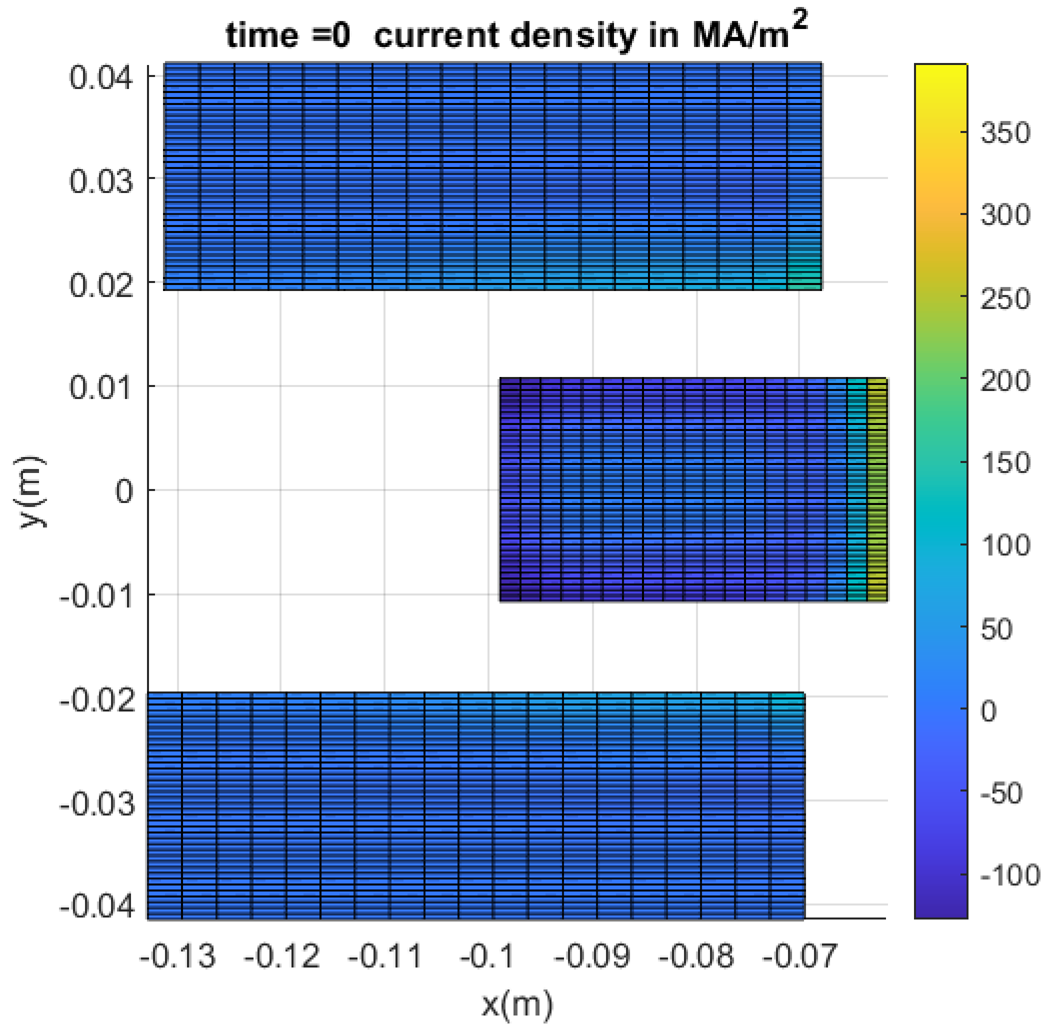
Optimized variables:

1. xfm
2. xfm1
3. yfm1
4. yfm2
5. xc10
6. xc1
7. yc1
8. xc2
9. yc2 (xc3 = xc2, yc3 = yc2)

H magnet 3-coils configuration: results in AC

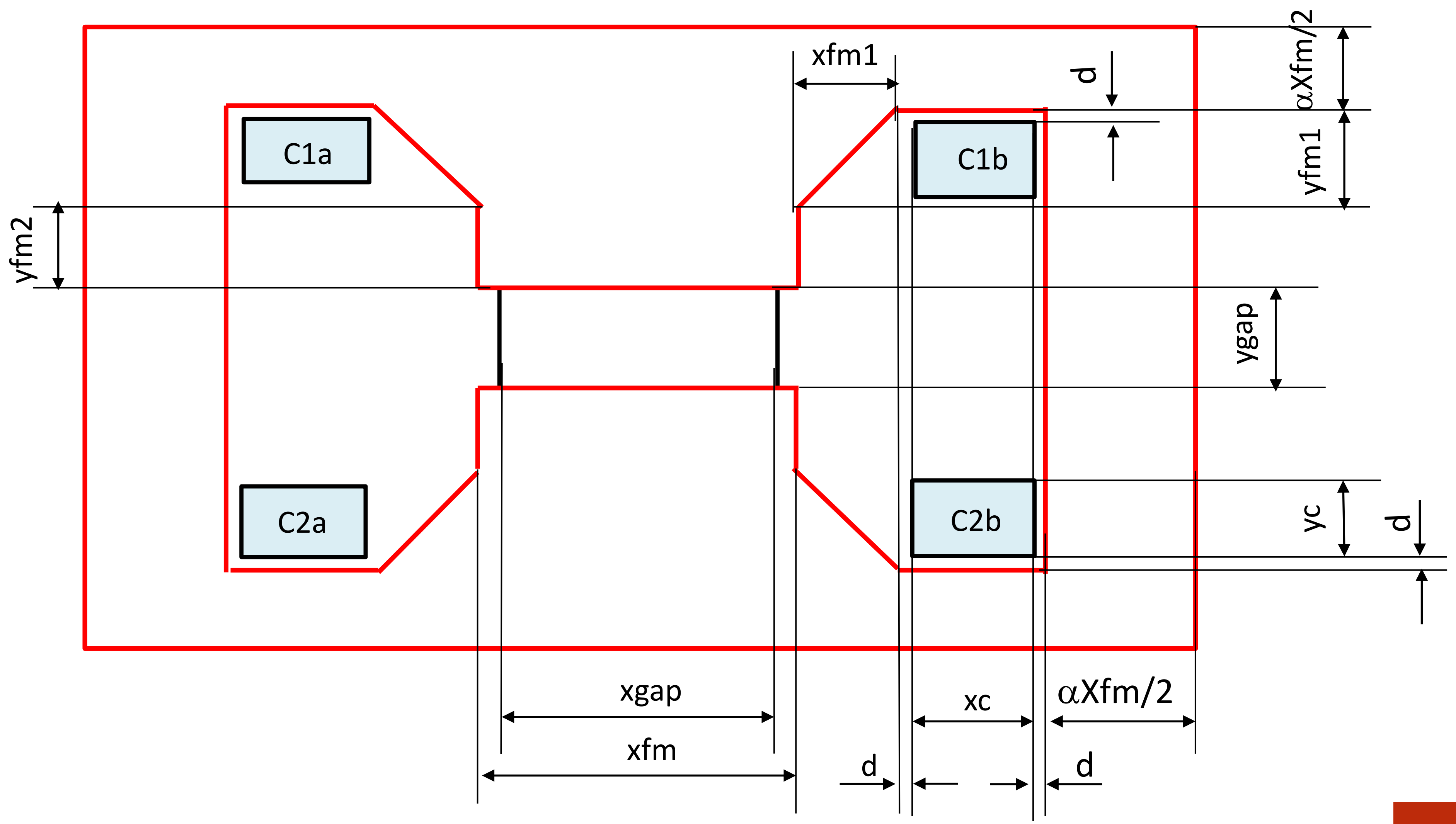






- The current distribution is **more uniform** than in the windowframe magnet, which leads to lower losses in the copper
- A significant non-uniformity is still found in the **central coil,** which suggests its elimination

H magnet 2-coils configuration: geometry



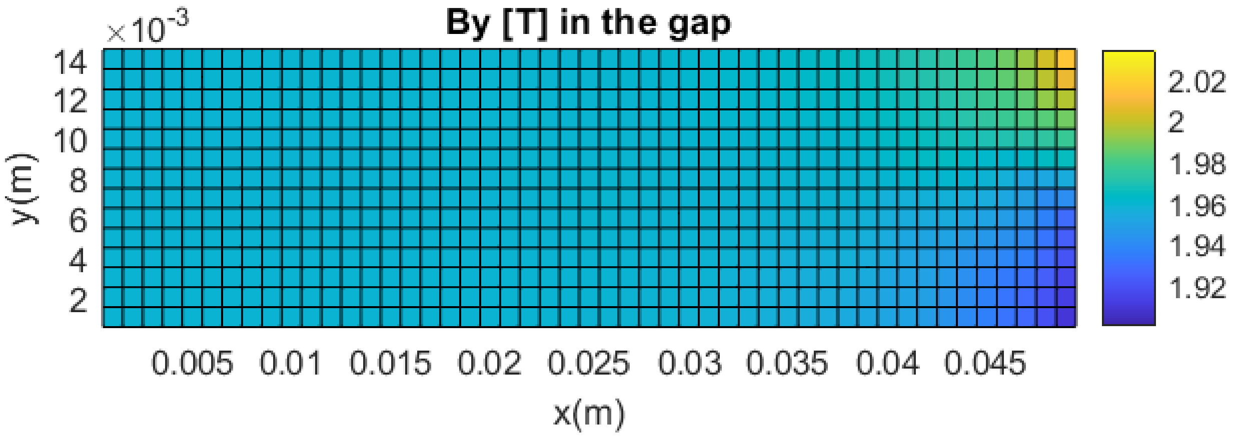
Parameters:

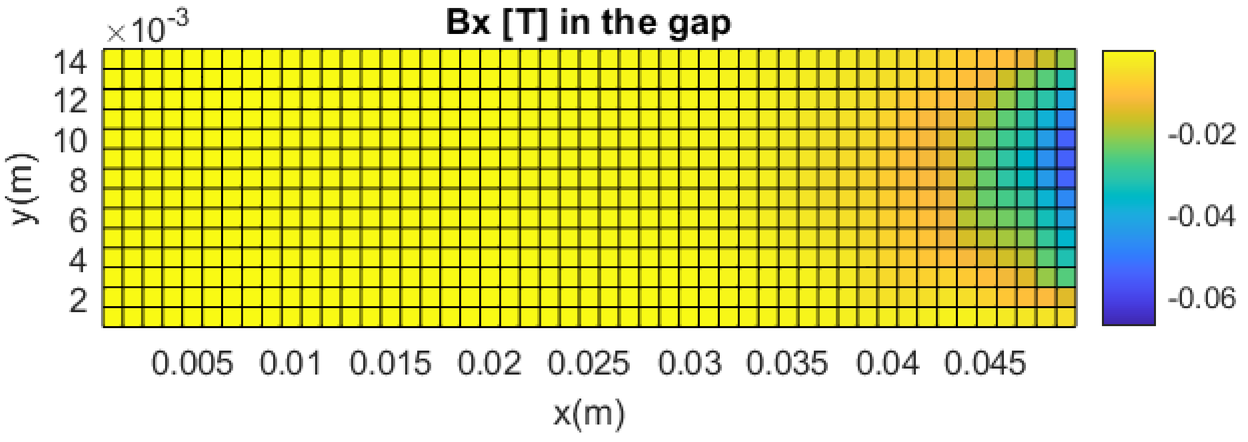
1. xgap
2. ygap
3. d
4. α
5. Jc

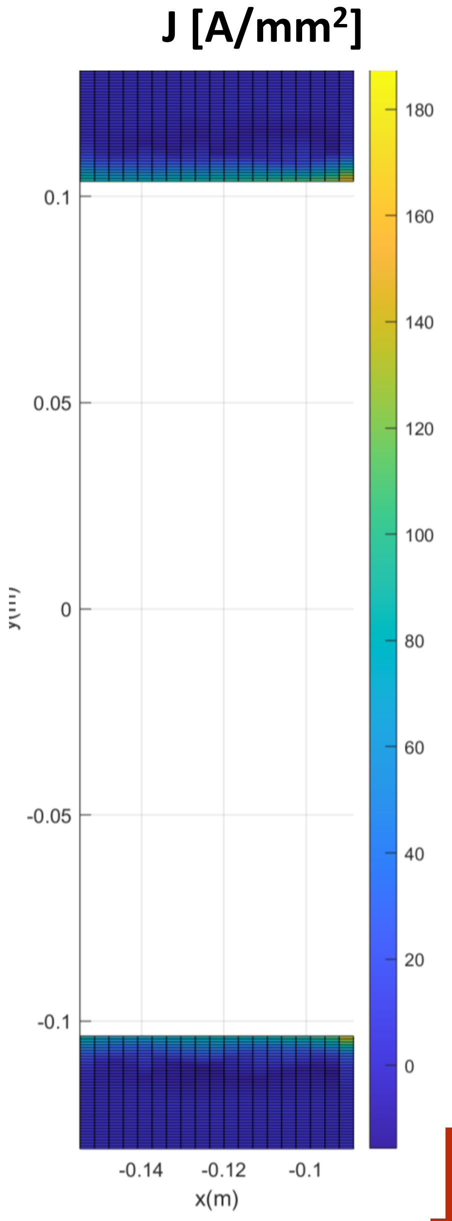
Optimized variables:

1. xfm
2. xfm1
3. yfm1
4. yfm2
5. xc
6. yc

H-Type magnet 2-coils configuration: results in AC



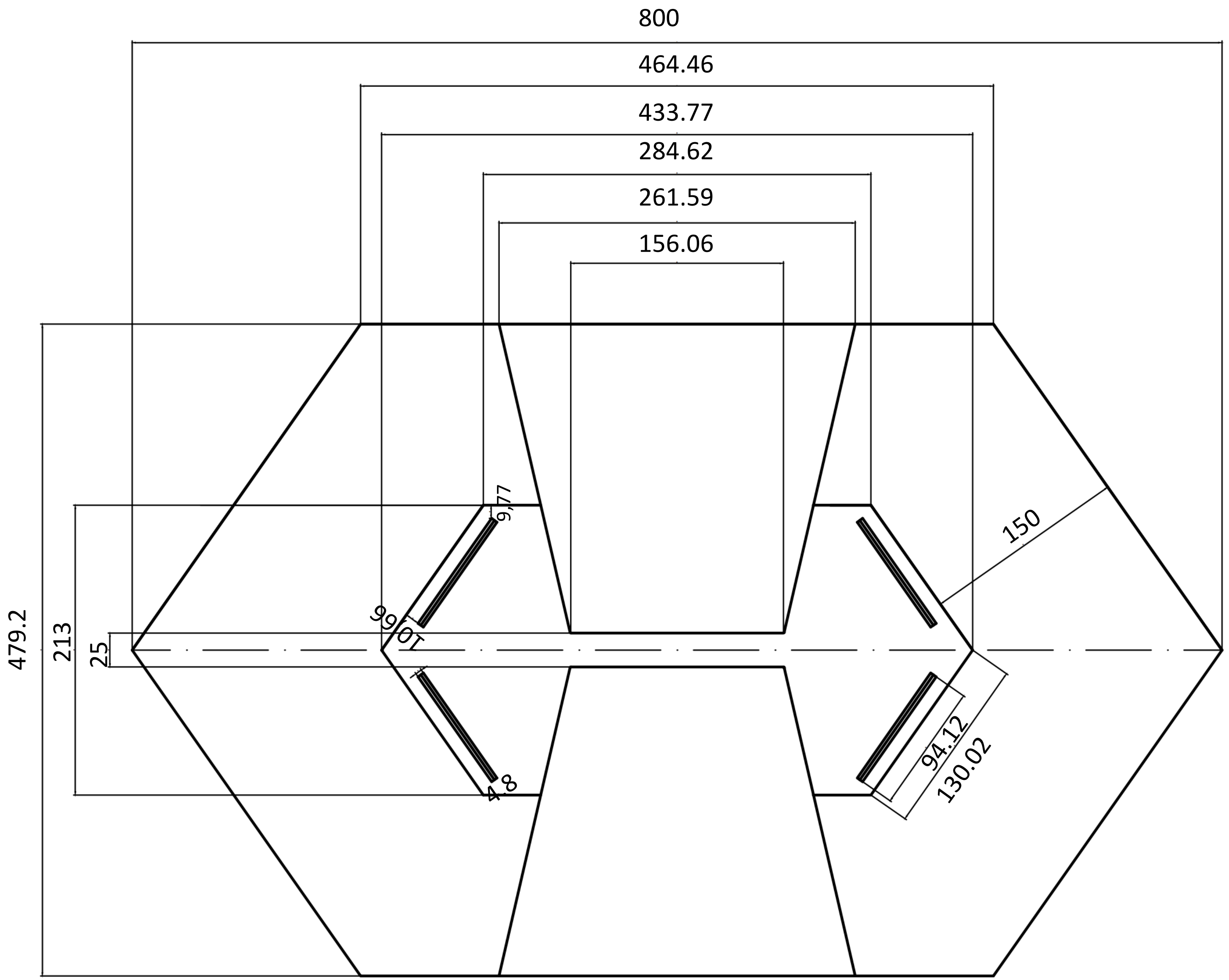




- A **more uniform current distribution** is obtained than in the configuration with 3 coils

- The results reported in this plot correspond to a current density set to **12 A/mm²** in the DC optimization
- Only the total transport current is kept fixed in the AC analysis

Hourglass magnet configuration: geometry

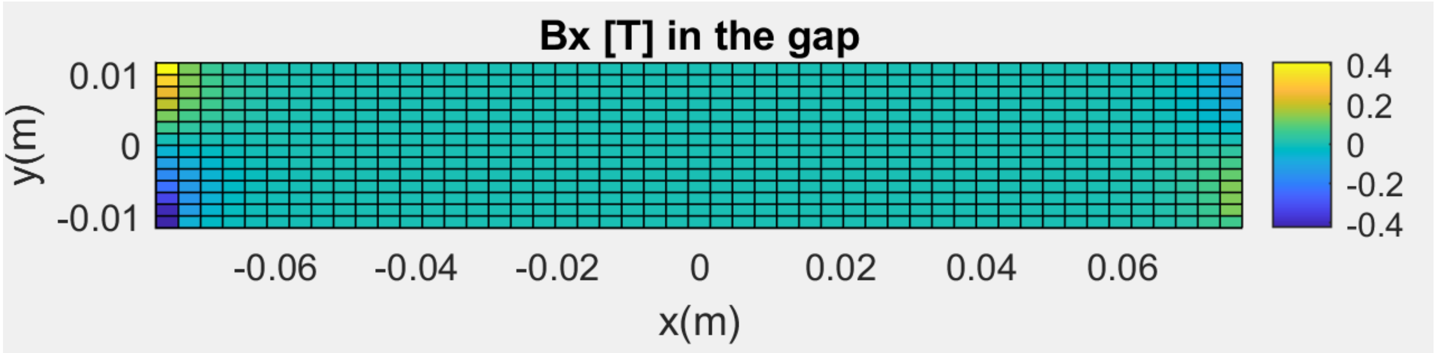


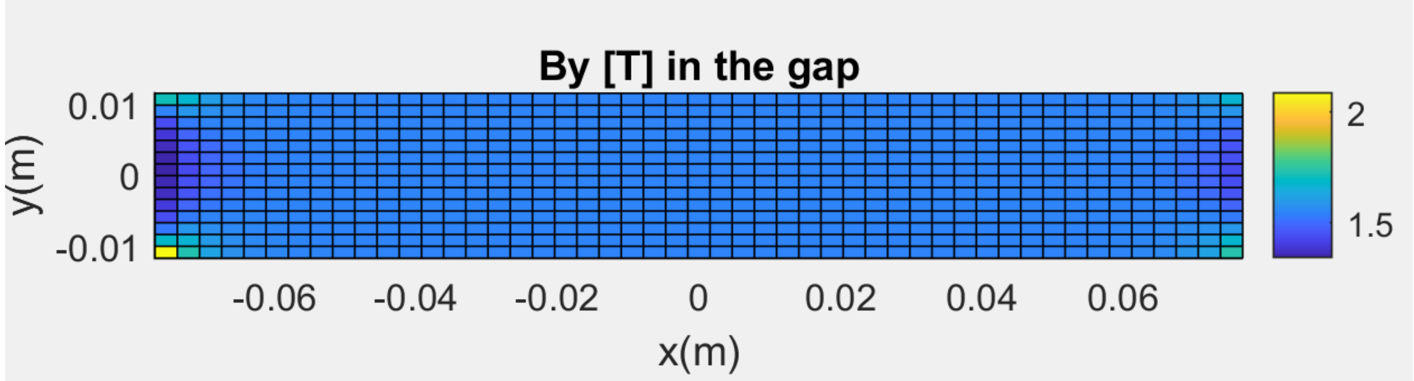
- In this analysis the same magnet dimensions adopted in the **US Muon Collider design study** have been considered

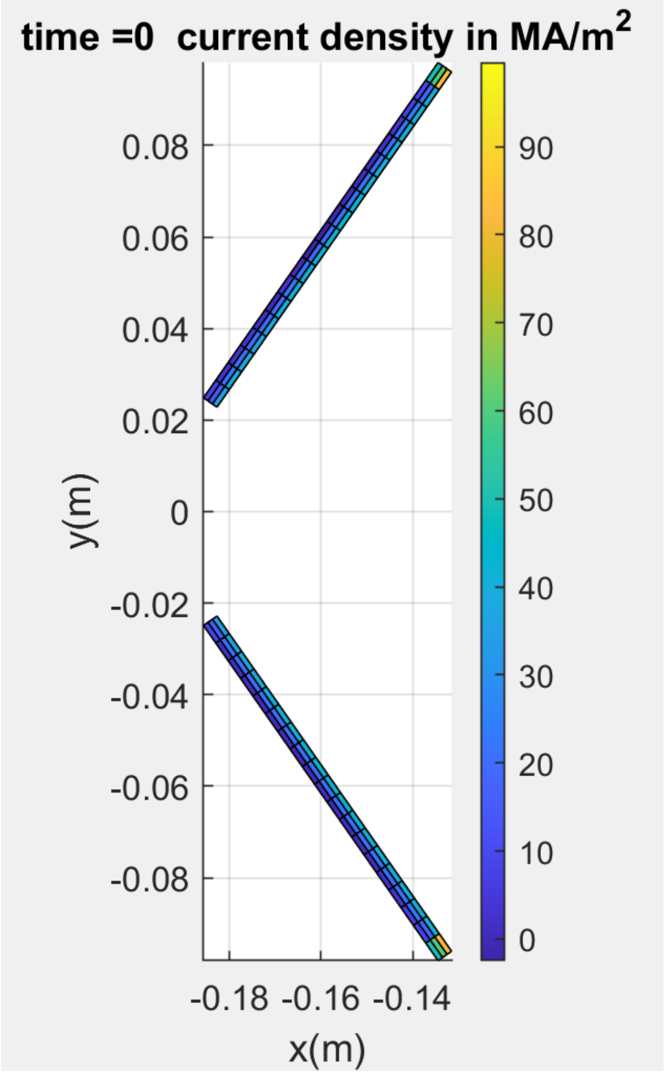
- Differently from the present configuration, the gap height is set to **25 mm instead of 30 mm**, while the gap length is set to **157 mm instead of 100 mm**

- **No further optimization** is applied to this configuration, as it results from the US study; in this analysis the coils are not subdivided into separate current sheets

Hourglass magnet configuration: results in AC







- **Current density** and **magnetic flux density** in the gap calculated in a.c. regime with f = 500 Hz, with Supermendur in the iron yoke
- A **very uniform current distribution** is found, except for the edges of the two coils

Comparison of the three analyzed configurations

- The **'hourglass' magnet** from the US study exhibits the **lowest real power (losses) and low reactive power**
- The windowframe magnet exhibits the **lowest reactive power**
- The H-magnets exhibit **lower copper losses** than the windowframe magnet

	Active power [kW/m]	Reactive power [MVar/m]	Gap energy [J/m]	Energy in air (no gap) [J/m]	Energy in coils [J/m]	Losses in iron [kW/m]
Windowframe magnet	1236	14.0	3697	668	1485	18
H magnet - 3 coils	356	16.3	3814	1305	552	26
H magnet - 2 coils	182	19.9	3875	3140	142	111
Hourglass magnet	149	15.7	3821	1165	7	122

Summary and perspectives

- A **tool for the optimized analysis** of resistive magnets for the Muon Collider accelerator has been developed
- The **assumptions of this tool** will be carefully checked through other computation methods not requiring the AC approximation
- Three different configurations have been analyzed, namely the **windowframe magnet, the H type magnet** and **the 'hourglass' configuration** resulting from the US design study
- The '**hourglass' configuration** exhibits **low real and reactive power**, which indicates it already reached a very good level of optimization
- Further **optimization** will be applied to the newly proposed designs

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Thank you for your kind attention !

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Windowframe magnet: M-22 steel vs Supermendur

M-22 steel

Ic1max = 35.0 kA
Vc1max = 789 V/m
Fluxmax = 0.25 Wb/m
Real Power = 1.35 MW/m
Reactive Power = 13.7 MVar/m
Cu losses = 110.6 kW/m

Ic2max = 10.5 kA
Vc2max = 759 V/m
Fluxmax = 0.24 Wb/m
Real Power = 0.33 MW/m
Reactive Power = 3.96 MVAr/m
Cu losses = 501.6 kW/m

Ic3max = 4.5 kA
Vc3max = 680 V/m
Fluxmax = 0.26 Wb/m
Real Power = 0.057 MW/m
Reactive Power = 1.53 MVAr/m
Cu losses = 1068.8 kW/m

Fe loss = 64 kW/m

Supermendur

Ic1max = 29.8 [kA]
Vc1max = 676 [V/m]
Fluxmax = 0.22 [Wb/m]
Real Power = 0.97 [MW/m]
Reactive Power = 10.0 [MVar/m]
Cu losses = 89.2 [kW/m]

Ic2max = 8.9 [kA]
Vc2max = 648 [V/m]
Fluxmax = 0.21 [Wb/m]
Real Power = 0.23 [MW/m]
Reactive Power = 2.88 [MVAr/m]
Cu losses = 371.8 [kW/m]

Ic3max = 3.8 [kA]
Vc3max = 580 [V/m]
Fluxmax = 0.22 [Wb/m]
Real Power = 0.038 [MW/m]
Reactive Power = 1.11 [MVAr/m]
Cu losses = 757.3 [kW/m]

Fe loss = 18 [kW/m]

H-Type magnet 2-coils configuration: results in AC

Nominal current density = 12 MA/m^2

Ic1max = 23.5 [kA]
Vc1max = 1118 [V/m]
Fluxmax = 0.356 [Wb/m]
Real Power = 0.1006 [MW/m]
Reactive Power = 13.134 [Mvar/m]
Resistive loss = 45.104 [kW/m]

Ic2max = 23.5 [kA]
Vc2max = 1118 [V/m]
Fluxmax = 0.356 [Wb/m]
Real Power = 0.1006 [MW/m]
Reactive Power = 13.134 [MVAr/m]
Resistive loss = 45.104 [kW/m]

Fe loss = 111.009 [kW/m]
field energy in the gap = 2.292 [kJ/m]
field energy in iron = 40.6 [J/m]
field energy in air-in = 1.838 [kJ/m]
field energy in coil 1 [J/m] = 5.0 [J/m]
field energy in coil 2 [J/m] = 5.0 [J/m]

Nominal current density = 10 MA/m^2

Ic1max = 22.7 [kA]
Vc1max = 1064 [V/m]
Fluxmax = 0.339 [Wb/m]
Real Power = 0.0904 [MW/m]
Reactive Power = 12.107 [Mvar/m]
Resistive loss = 42.714 [kW/m]

Ic2max = 22.7 [kA]
Vc2max = 1064 [V/m]
Fluxmax = 0.339 [Wb/m]
Real Power = 0.0904 [MW/m]
Reactive Power = 12.107 [MVAr/m]
Resistive loss = 42.714 [kW/m]

Fe loss = 95.434 [kW/m]
field energy in the gap = 2.153 [kJ/m]
field energy in iron = 40.6 [J/m]
field energy in air-in = 1.659 [kJ/m]
field energy in coil 1 [J/m] = 4.7 [J/m]
field energy in coil 2 [J/m] = 4.7 [J/m]

Comparison of the three analyzed configurations

- The **'hourglass' magnet** from the US study exhibits the **lowest real power**
- Among the newly developed designs, the windowframe magnet exhibits the **lowest value of reactive power**
- Due to a **more uniform current distribution,** the H-magnets exhibit lower copper losses than the windowframe magnet

Windowframe magnet	Real power [kW/m]	Reactive power [MVar/m]	Gap energy [J/m]	Energy in air (no gap) [J/m]	Energy in coils [J/m]	Losses in iron [kW/m]
Coil1	966.0	10.0	3697	668	1485	18
Coil2	232.0	2.9				
Coil3	38.0	1.1				
Total	1236.0	14.0				
H magnet 3-coils						
Coil1	62.4	3.6	3814	1305	552	26
Coil2	146.6	6.4				
Coil3	146.6	6.4				
Total	355.6	16.3				
H magnet 2-coils						
Coil1	90.9	10.0	3875	3140	142	111
Coil2	90.9	10.0				
Total	181.8	19.9				
Hourglass magnet						
Coil1	74.5	7.9	3821	1165	7	122
Coil2	74.5	7.9				
Total	149.1	15.7				