Magnetically Coupled Actuator (MCA) Planar magnet topologies investigation and simulation for the LHC wire-scanner

Magnetic Coupling for the LHC Linear Wire Scanners – review

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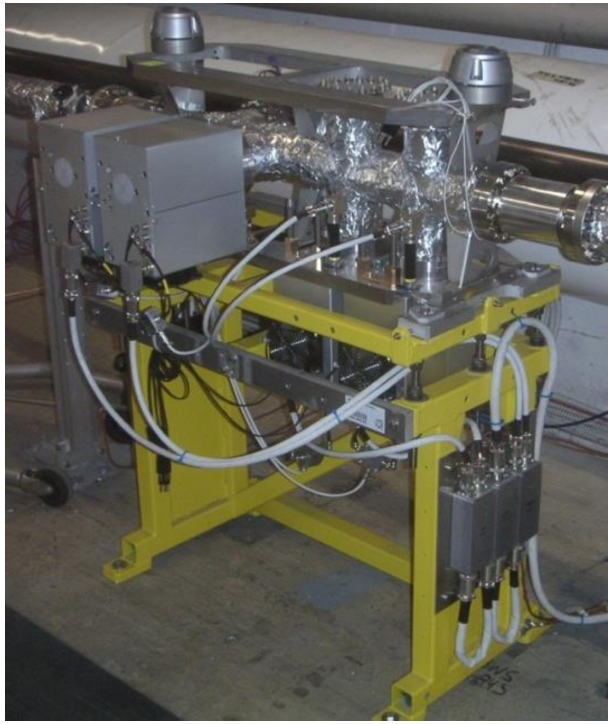
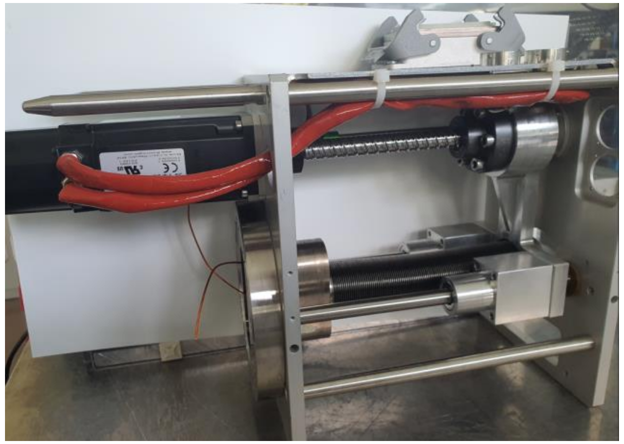
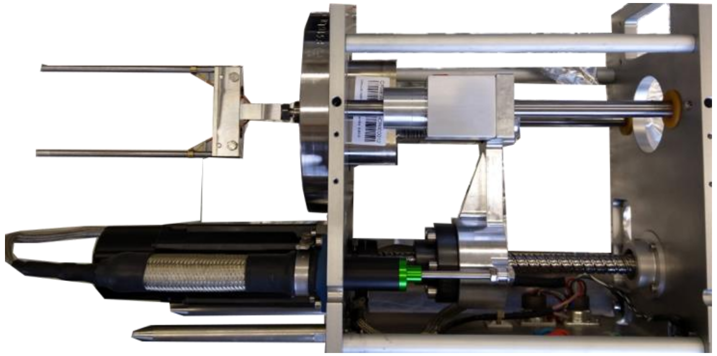
06.06.2024

Magnetically Coupled Actuator (MCA) investigation for the LHC wire scanners

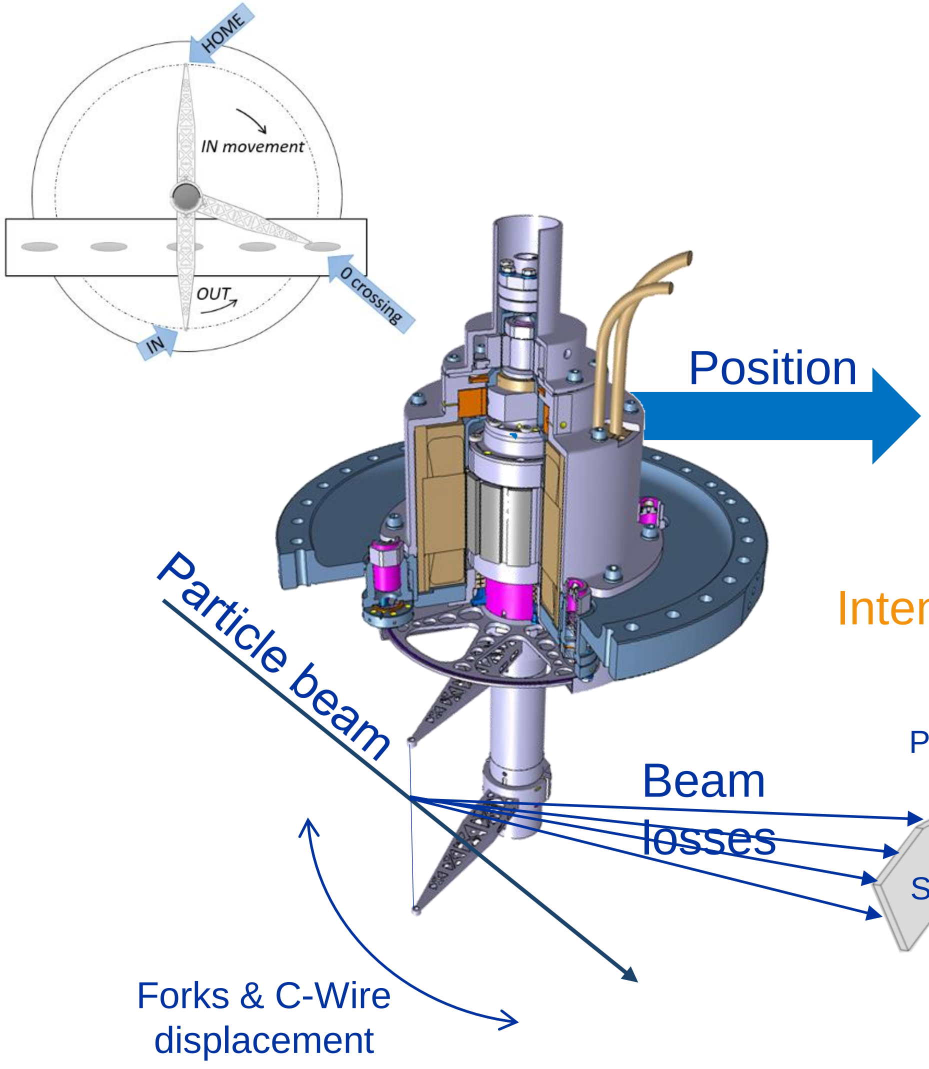
- **Wire scanner introduction**
- **Magnetic system integration**
- **Magnets topologies presentation and benchmarking**
- **Optimization of most promising topologies**
- **Summary and outlook**



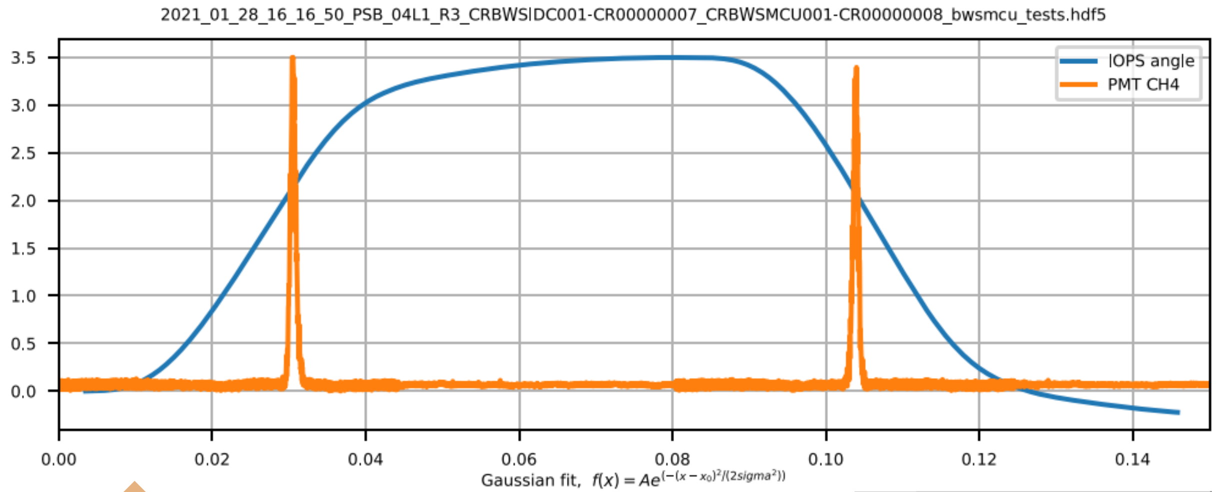




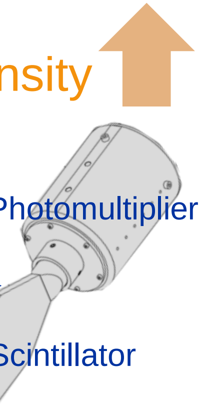
Beam wire scanner principle

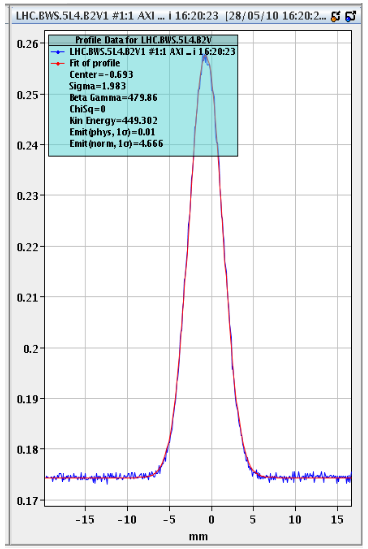


Position



Intensity

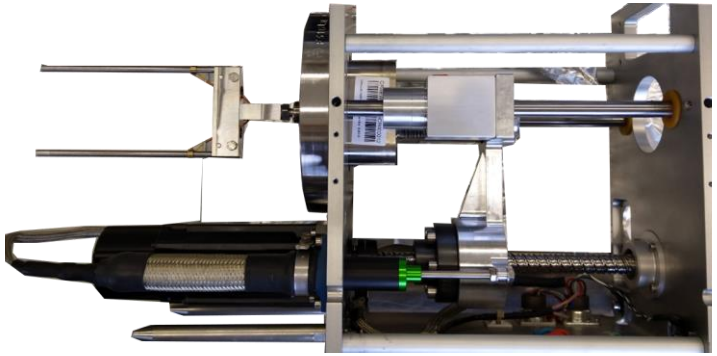




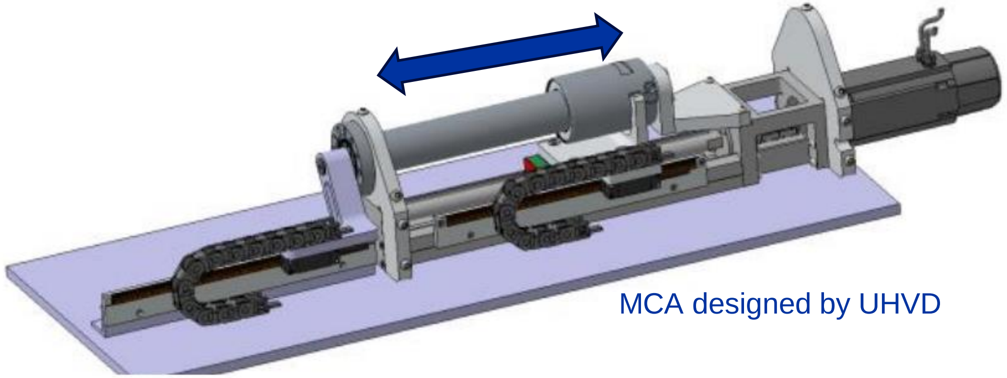
Profile Data for LHC.BWS.5L4.B2V
LHC.BWS.5L4.B2V1 #1:1 AXI ... i 16:20:23
Fit of profile
Center=-0.693
Sigma=1.983
Beta Gamma=479.86
ChiSq=0
Kin Energy=449.302
Emit(phys, 1σ)=0.01
Emit(norm, 1σ)=4.666

Beam Transversal Profile (OP app)

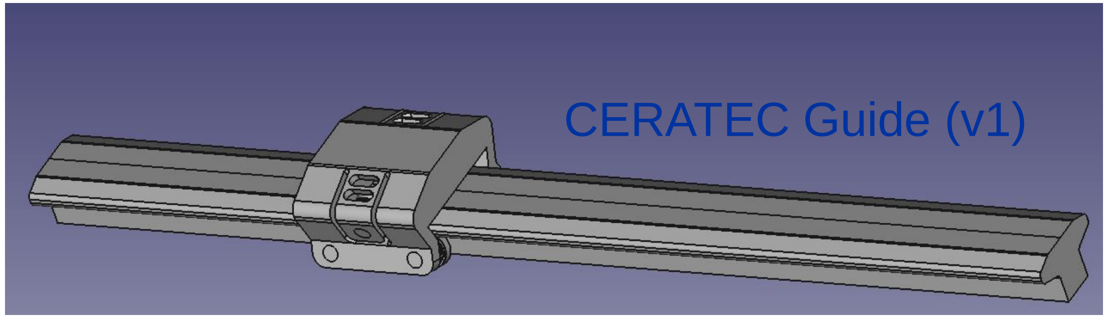
Motivation for a design with MCA



- **Lifetime & reliability limitation of the current design**
  - Bellows / vacuum forces, long arm, etc..
- **Look into passive magnetic system to avoid using position sensor in vacuum**
- **Commercial tubular MCA coupling limitations:**
  - requires large space on one side of the beam line
  - forks fixation fare from c-wires (cantilever).
- **Maximum available force (UHVD design): 90N**
- **Linear guide being investigated to be placed just below the forks (from CERATEC)**

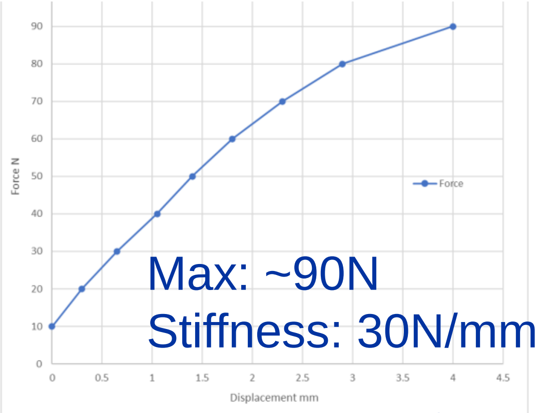


MCA designed by UHVD



CERATEC Guide (v1)

=> Integrate MCA on the CERATEC moving part



Max: ~90N
Stiffness: 30N/mm

Courtesy of UHVD

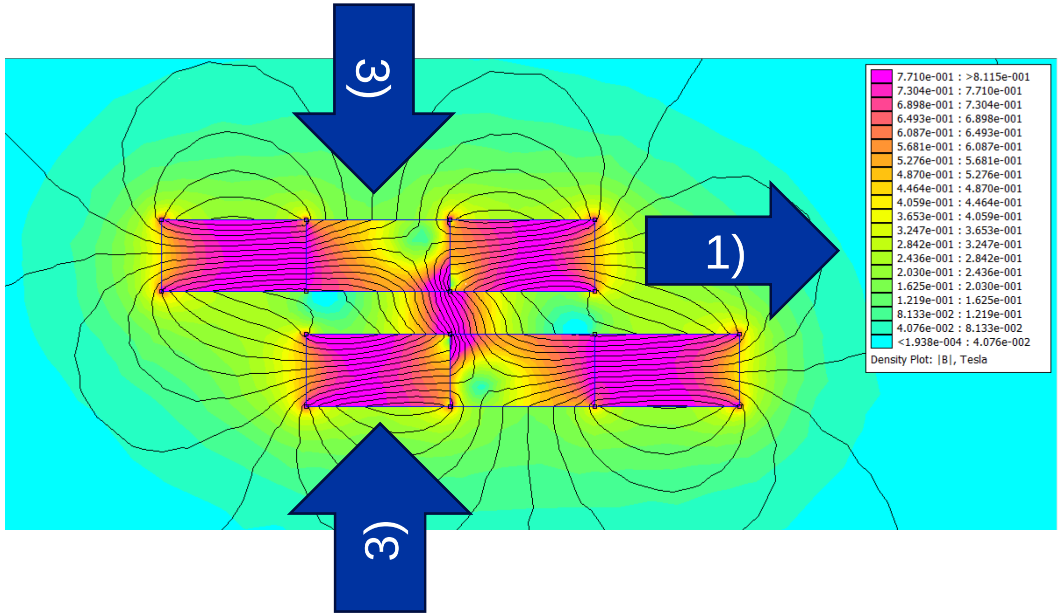
Investigation goals

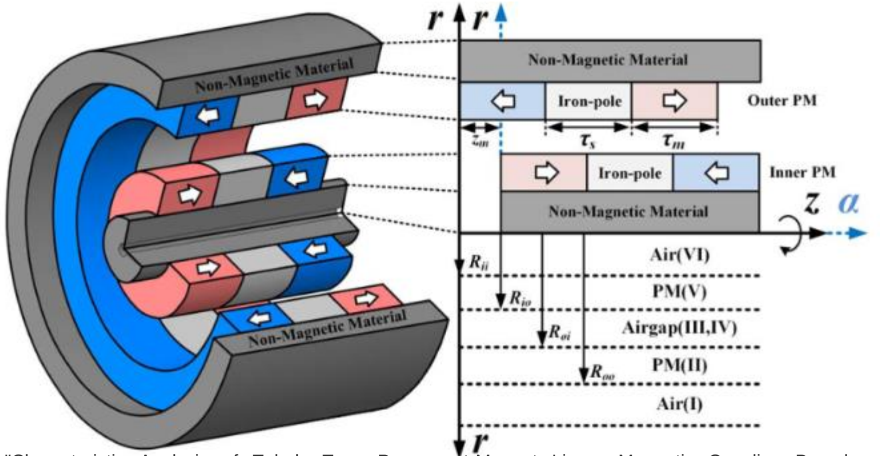
- Evaluate few topologies of magnets arrangements within the available space

- Simulate the performance using a FEA tool

- Optimize MCA parameters:
  1) <u>Generated force</u>
  => longitudinal force moving the inner part
  2) <u>Stiffness</u>
  => force generated per length difference between inner and outer part of the MCA
  3) <u>Attraction force</u>
  => force between inner and outer part of the MCA (stressing magnets holding structures)
  4) <u>force ratio</u>
  between generated force 1) / attraction force 3)

- Suggest a prototype strategy

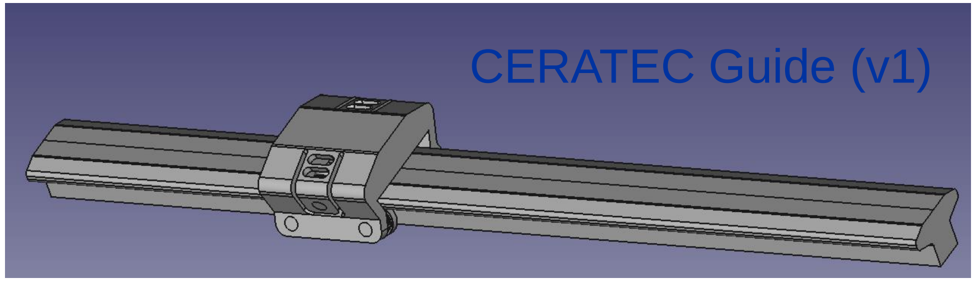


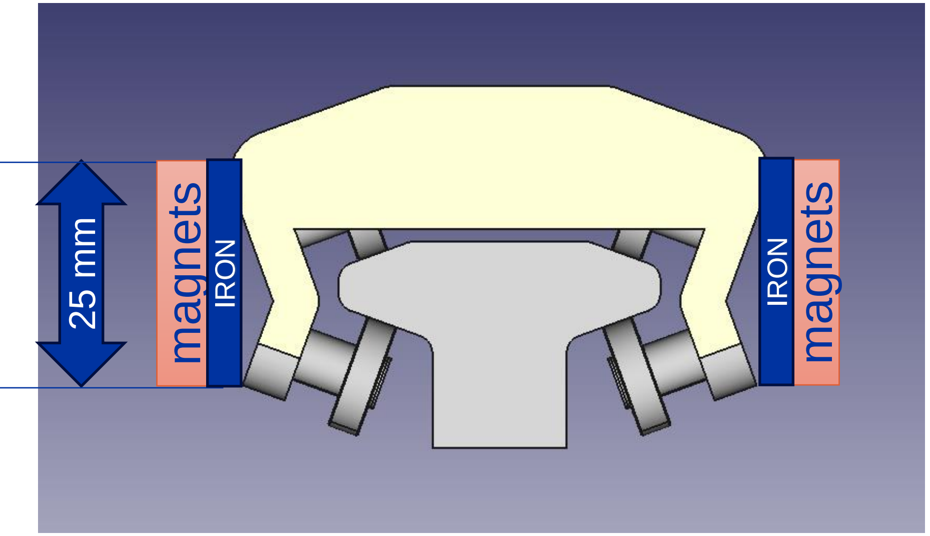


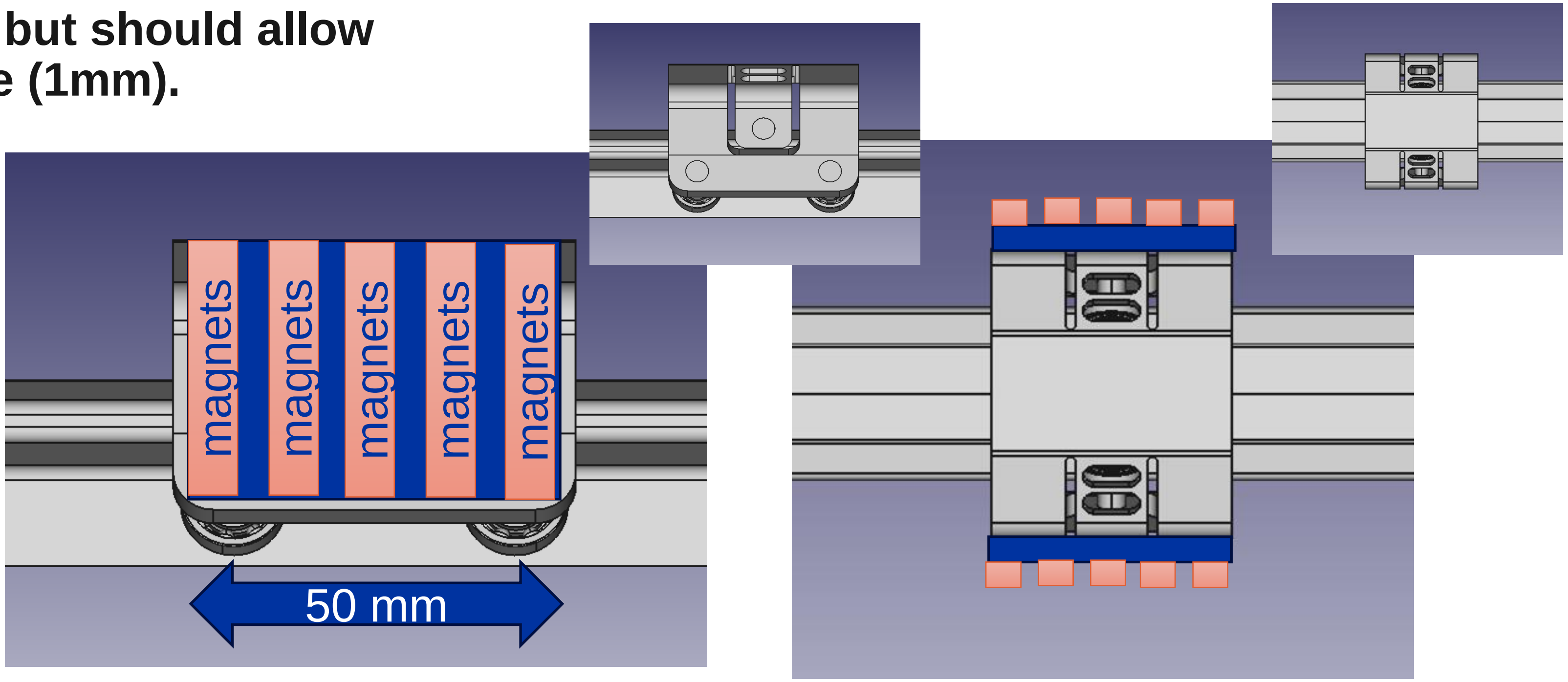
"Characteristic Analysis of Tubular-Type Permanent-Magnet Linear Magnetic Coupling Based on Analytical Magnetic Field Calculations," in IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1-5, June 2016, Art no. 0604605, doi: 10.1109/TASC.2016.2544948.

Magnetic system integration

- **Available surface on the side of the rail is about 25x50mm on each sides**
- **Preferably place the MCA on both sides of the mover to balance the forces applied on the mover/rail**
- **Thickness of the MCA to be optimized to limit weight**
- **Airgap should be preferably small but should allow integration of a vacuum membrane (1mm).**





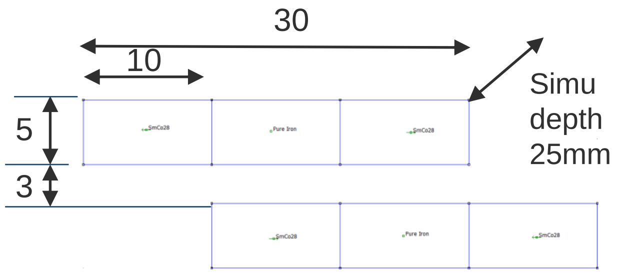


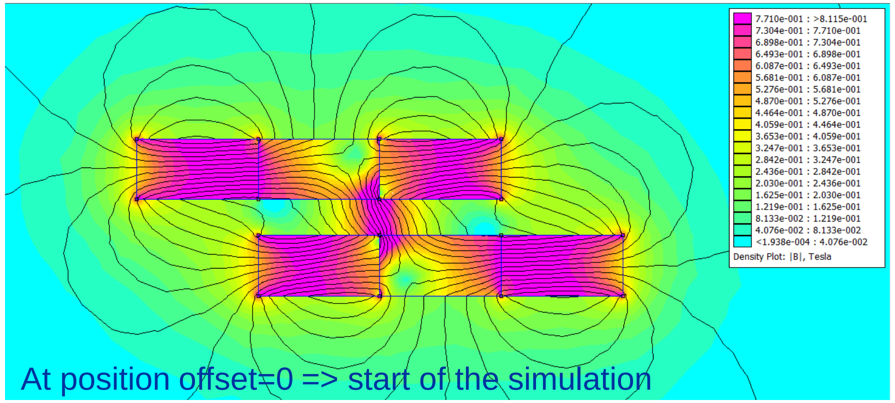
FEA simulation principle

Magnets on both sides – longitudinally magnetized wrt displacement

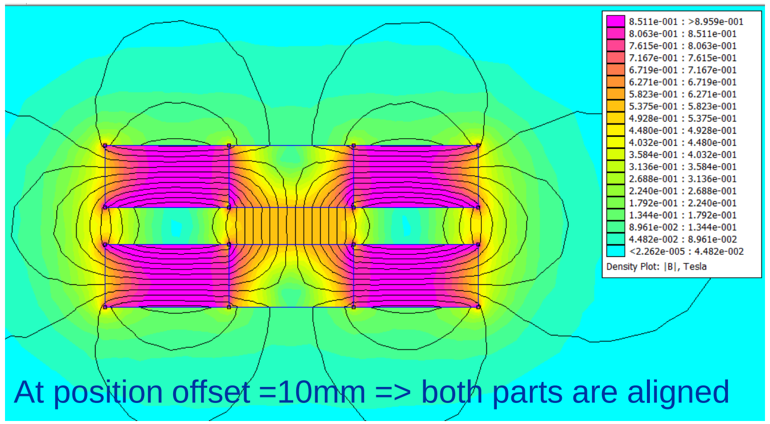
Topology 1 – same arrangement as with UHVD tubular design

Geometry (mm)



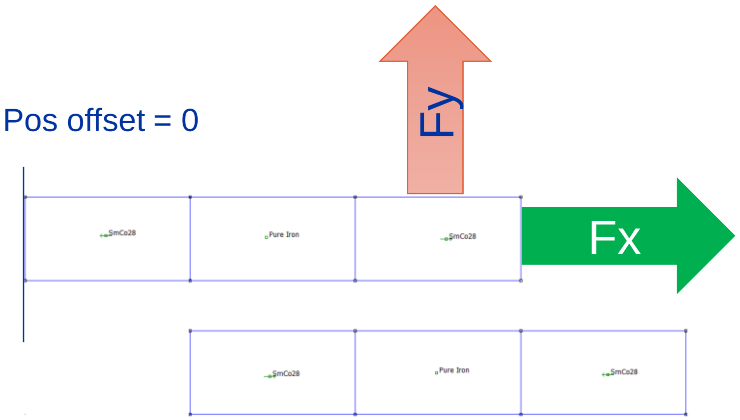


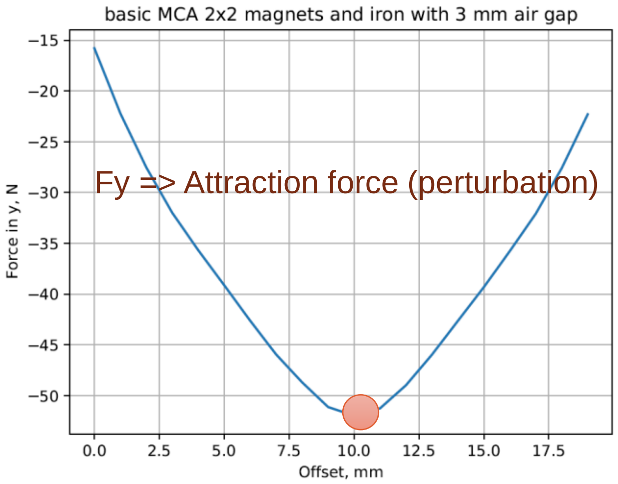
At position offset=0 => start of the simulation



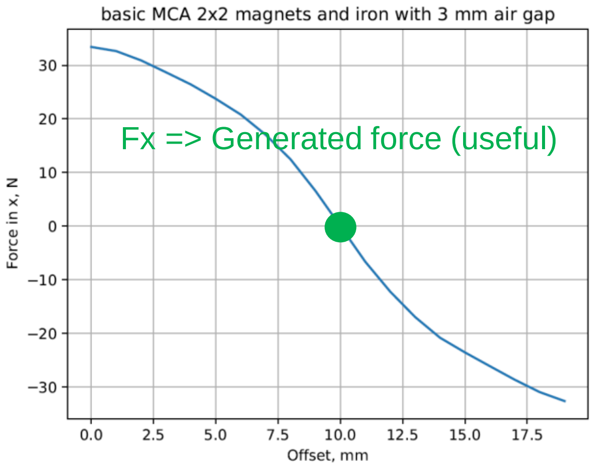
At position offset =10mm => both parts are aligned

Pos offset = 0





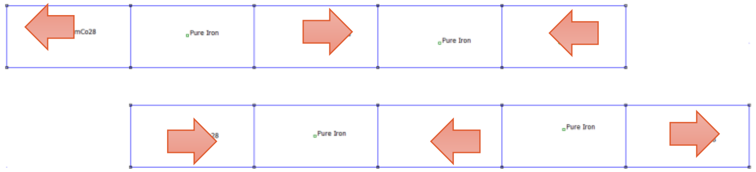
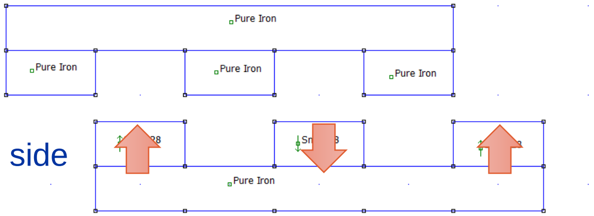
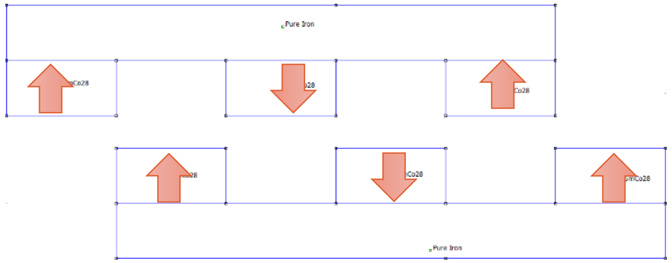
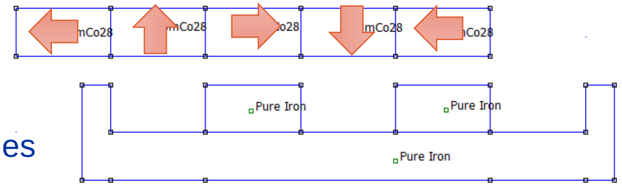
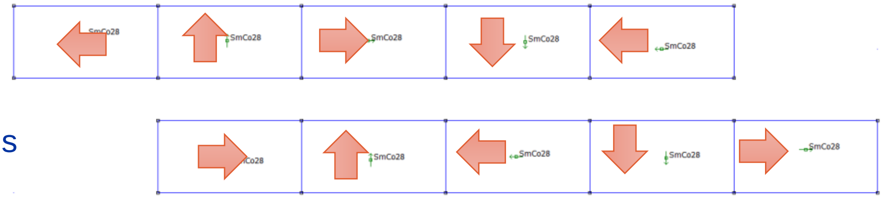
Fy => Attraction force (perturbation)



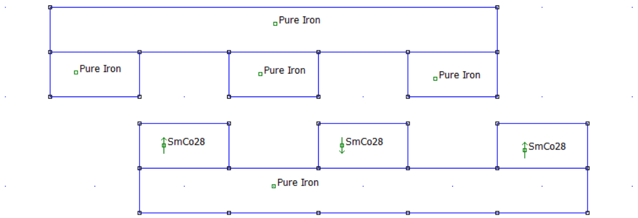
Fx => Generated force (useful)

Magnetic system topologies investigation

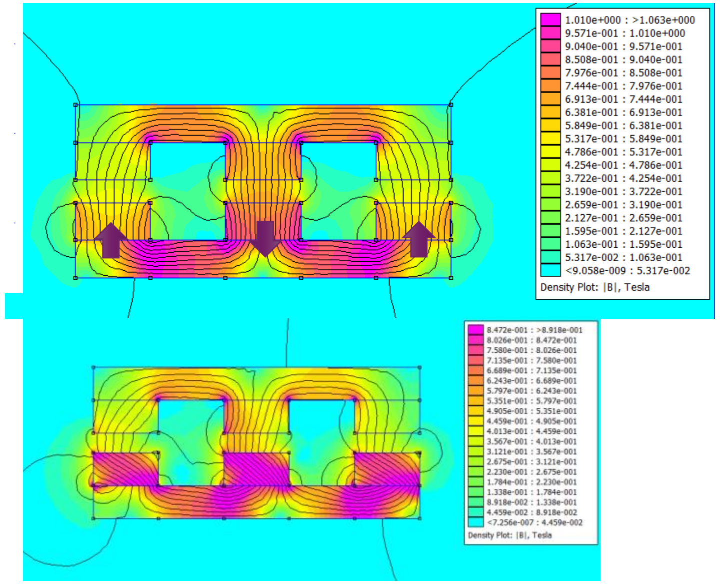
Geometries are using the same magnets size (10x5mm SmCo28)
Ferromagnetic material is pure Iron

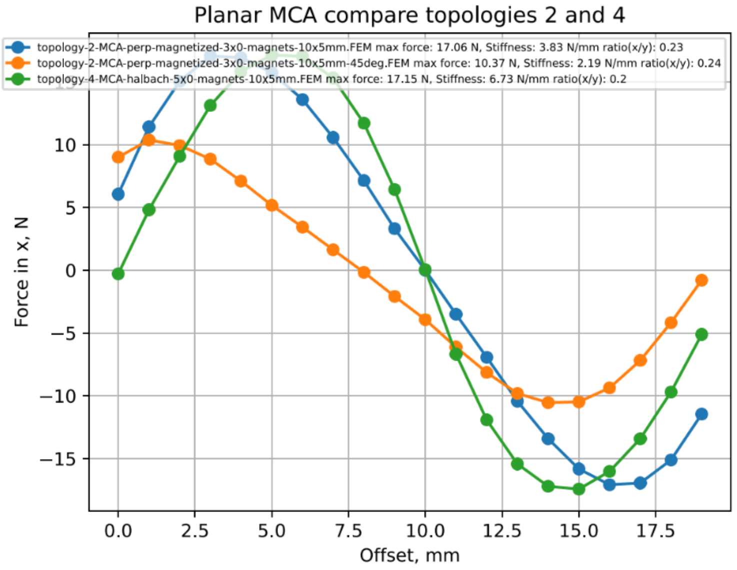
	No magnets in vacuum (Group 1)	Magnets in vacuum (Group 2)
Longitudinal magnetized		**Topology 1** longitudinally magnetized (6 mag.) 
Perpendicular magnetized	**Topology 2** perpendicularly magnetized with magnets on one side (3 mag.) 	**Topology 3** perpendicularly magnetized with magnets on both sides (6 mag.) 
Halbach array magnetized	**Topology 4** halbach array with magnets on one sides (5 mag.) 	**Topology 5** halbach array with magnets on both sides (10 mag.) 

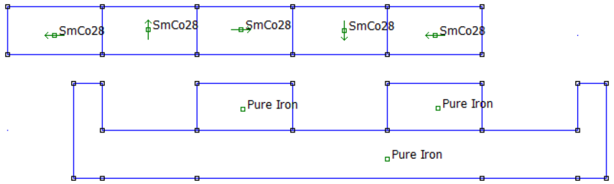
MCA Topologies with in-air magnets only



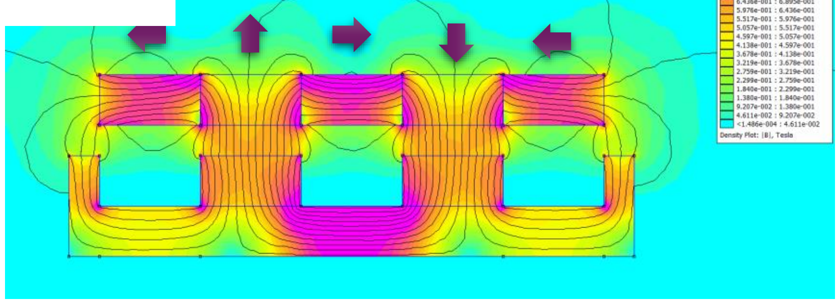
Topology 2
perpendicularly magnetized
with magnets on one side
(3 mag.)

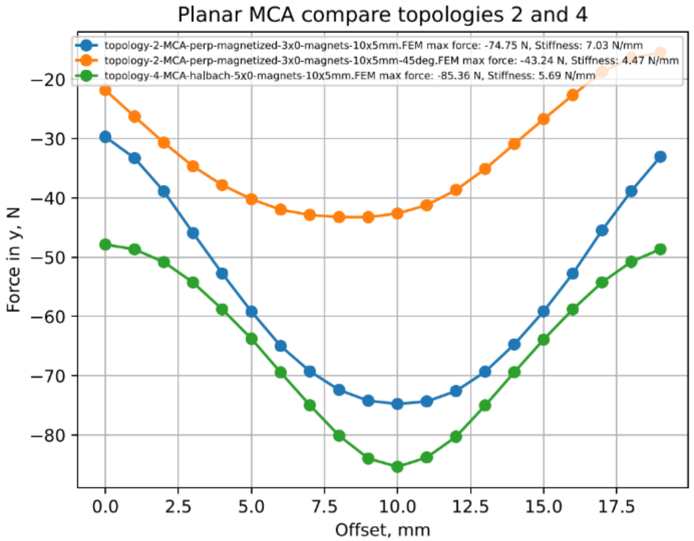






Topology 4
halbach array
with magnets on one sides
(5 mag.)

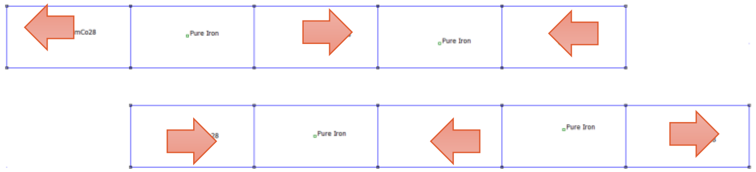




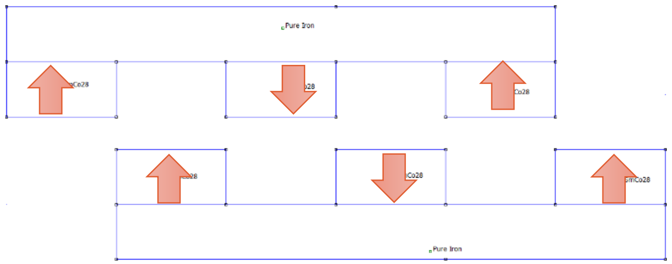
MCA Topologies with in-vacuum magnets

(25x10x5mm magnets)

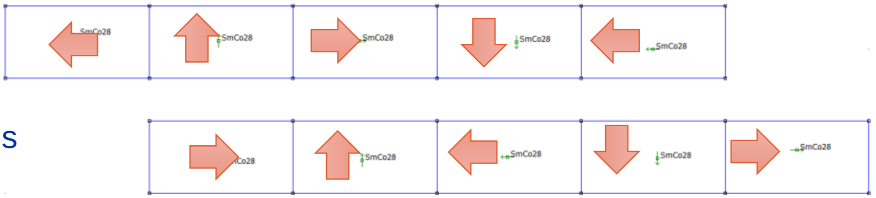
Topology 1
longitudinally magnetized
(6 mag.)

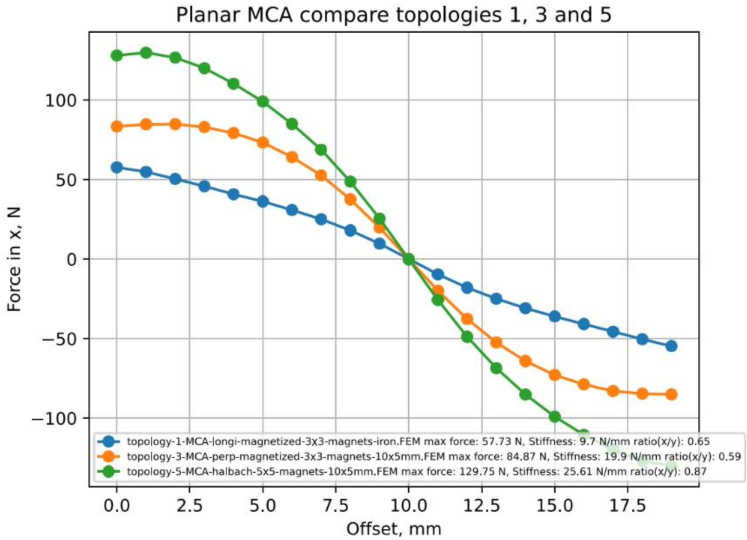


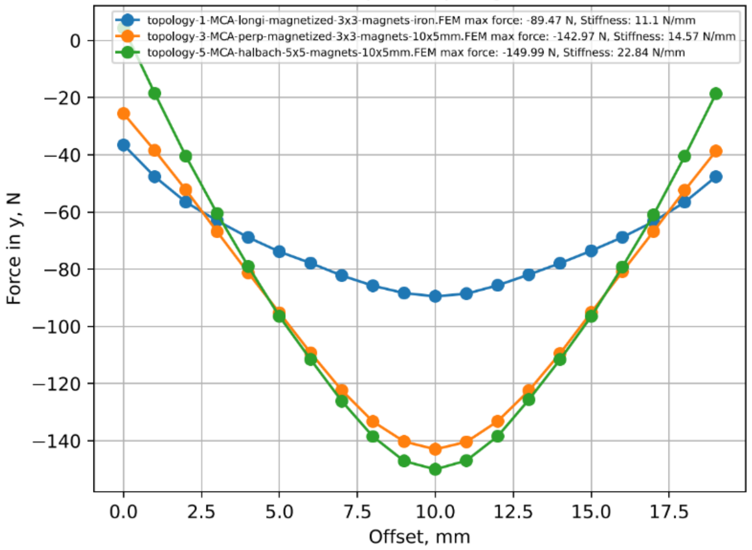
Topology 3
perpendicularly magnetized
with magnets on both sides
(6 mag.)



Topology 5
halbach array
with magnets on both sides
(10 mag.)







MCA topologies comparison

Same magnets size (but not the same number of magnets)

Topology # (as per this doc)	In-vac magnets	# Magnets	Magnets orientation (with respect to the linear motion)	pro	cons	Force X (N)	Stiffness	Force Y (N)	Ratio (x/y)
1	Yes	6	longitudinally	known tech (UHVD) good force and ratio (x/y)	Low stiffness	58	9.7	89	0.65
2	No	3	perpendicularly	No magnets in vacuum	Low useful force low x/y ratio	17	3.8	75	0.23
3	Yes	6	perpendicularly	High force and stiffness	Lower force and ratio (x/y) compared to #5 *	85	19.9	143	0.59
4	No	5	Halbach array	No magnets in vacuum	Low useful force low x/y ratio Assembly Repulsion forces	17	6.7	85	0.2
5	Yes	10	Halbach array	High force and stiffness	Assembly # magnets Repulsion forces field leakages**	115	25.6	150	0.87

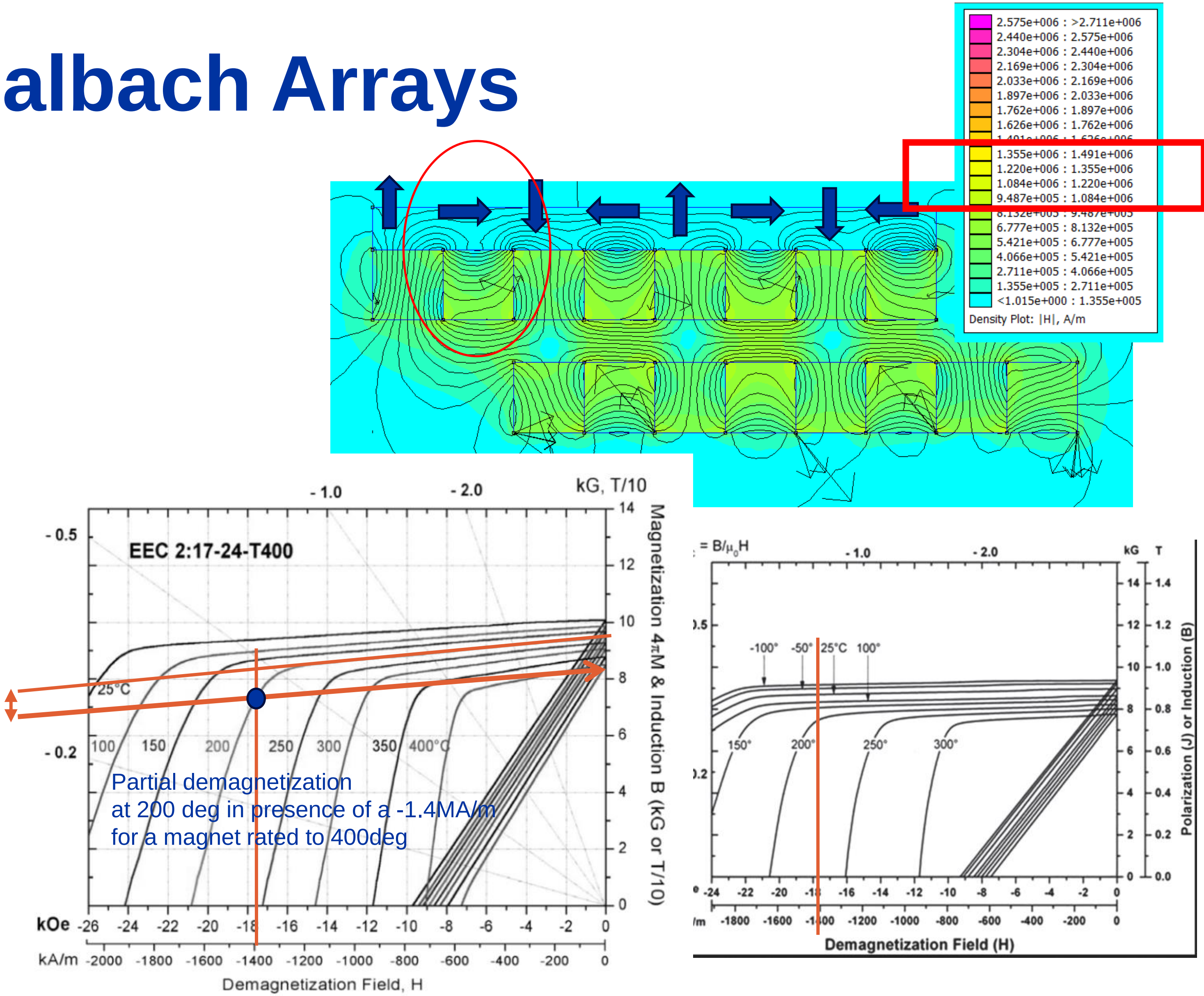
* before optimization of the geometry
** before shielding

Negative Aspects of Halbach Arrays

The benefit is increased performance, but this benefit comes at a cost of increased difficulty in manufacturing.

Another disadvantage is that the magnets are arranged in a direct or quasi-direct repelling condition. This means that magnets in the same array are acting to demagnetize their neighbouring magnets. With a high coercivity alloy, this may not be an issue, unless elevated temperatures are required in the application – as the operating temperature increases, a magnet is more susceptible to demagnetizing, and the neighbourin magnet demagnetization is exacerbated.

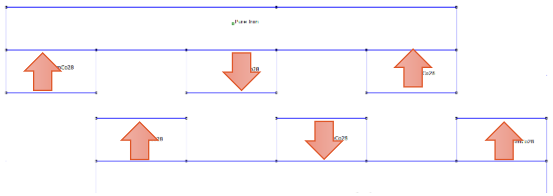
https://www.duramag.com/techtalk/halbach-arrays/benefits-and-drawbacks-to-using-halbach-arrays/



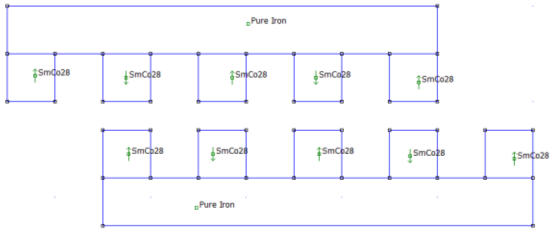
Partial demagnetization
at 200 deg in presence of a -1.4MA/m
for a magnet rated to 400deg

https://www.researchgate.net/publication/3065907_Thermal_Stability_and_Performance_Data_for_SmCo_217_High-Temperature_Magnets_on_PPM_Focusing_Structures/figures?lo=1
https://cpb.iphy.ac.cn/article/2019/1969/cpb_28_1_017501.html

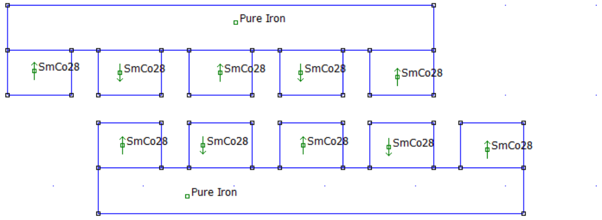
Magnet size opt (Topology 3)



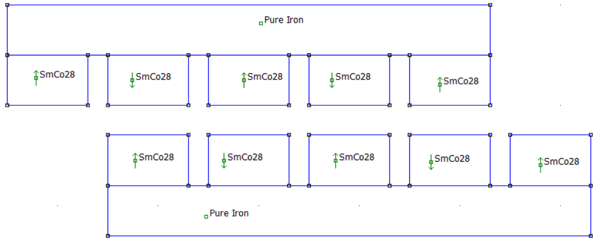
10x5mm magnets



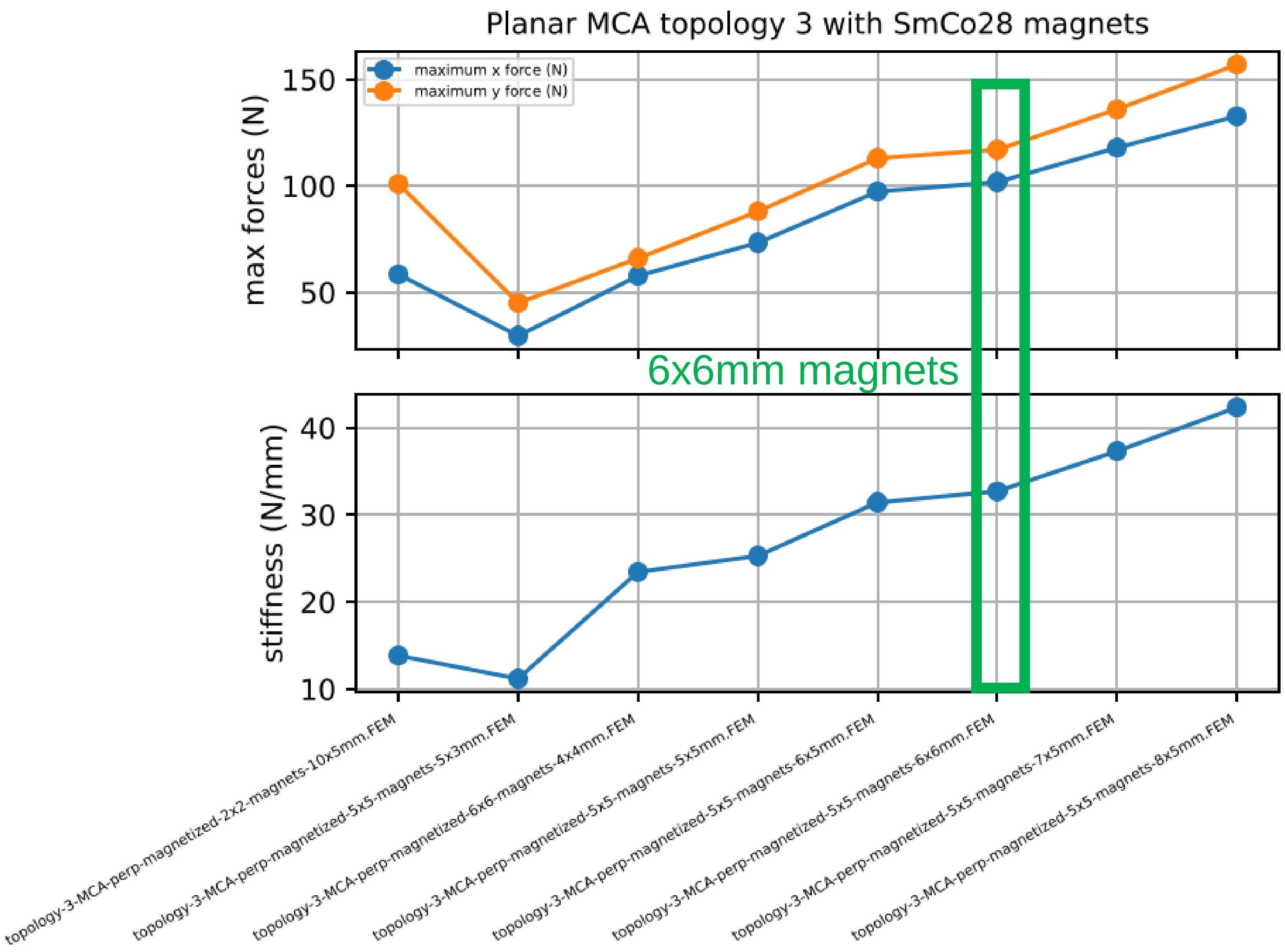
5x5mm magnets



7x5mm magnets

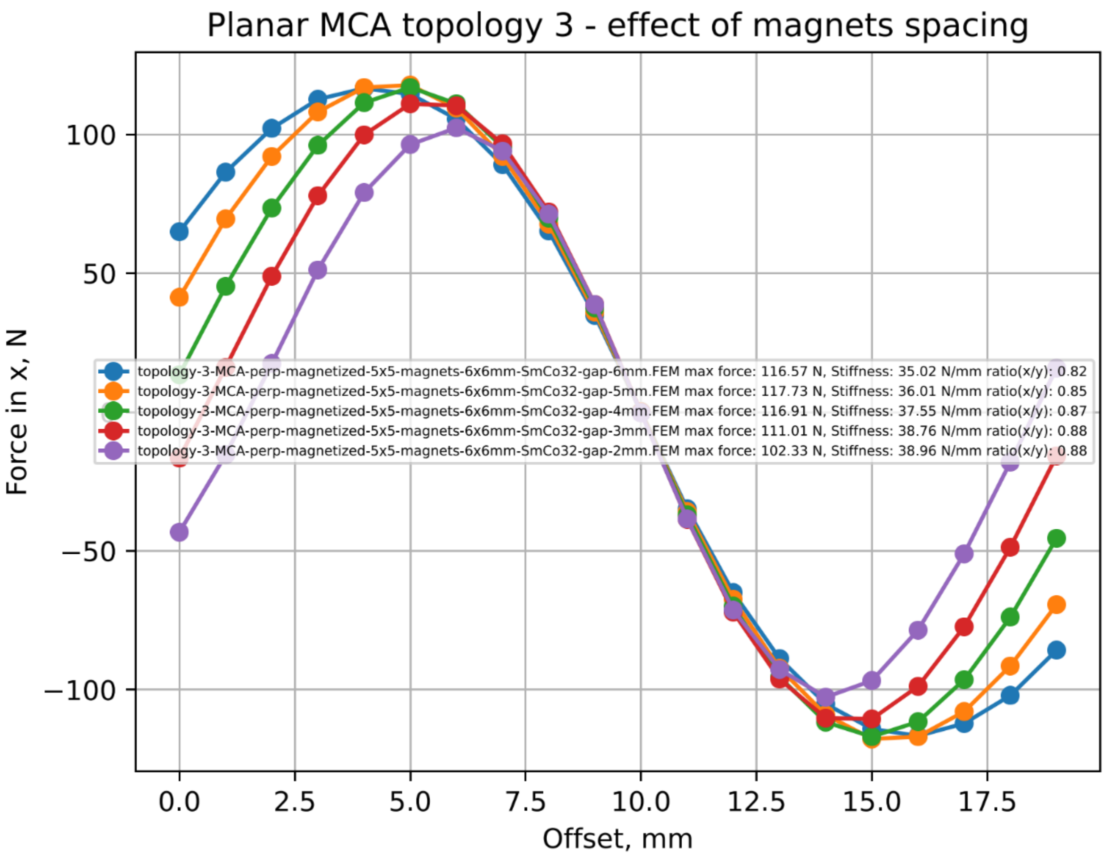


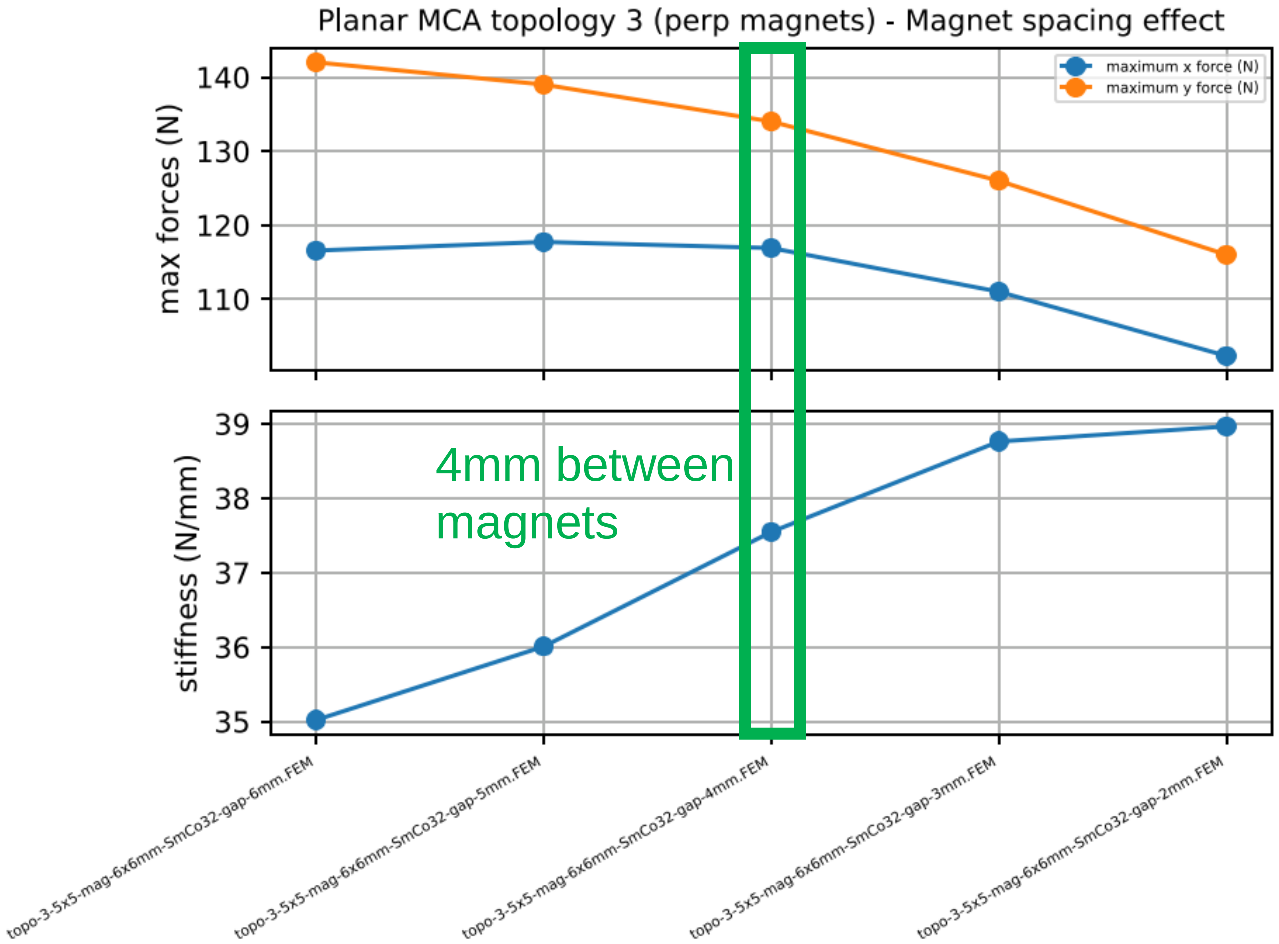
8x5mm magnets



6x6mm magnets

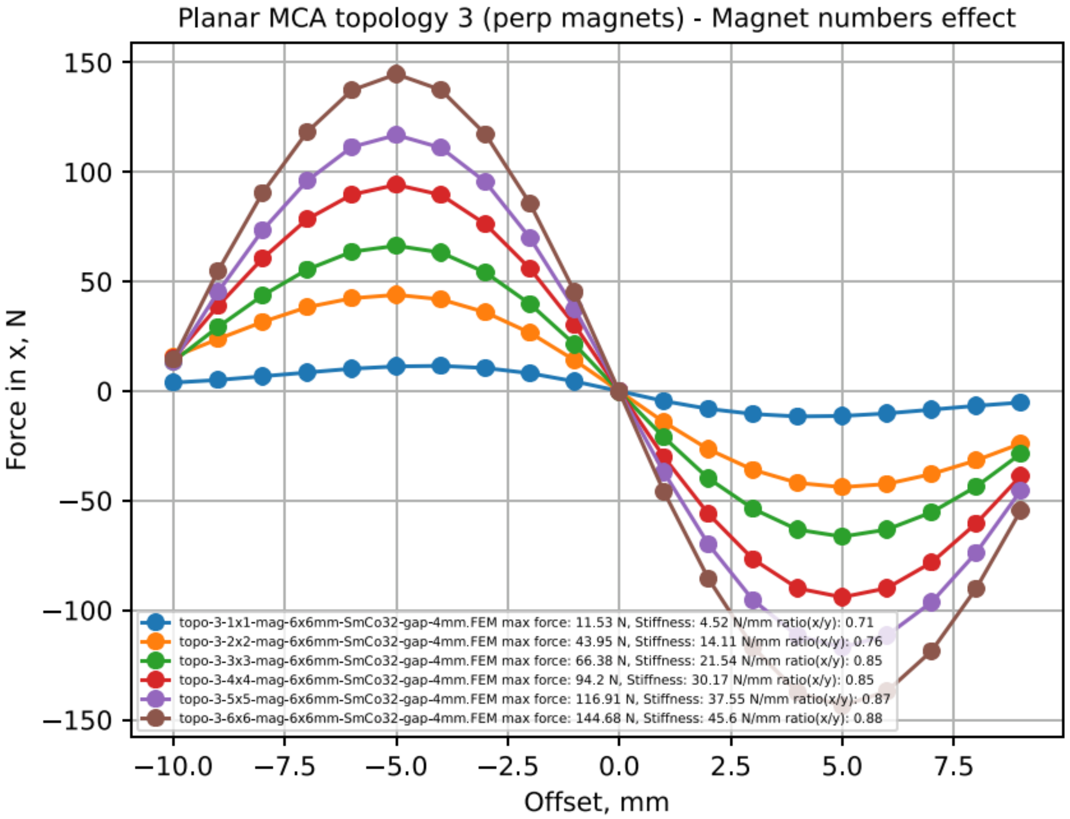
Distance between magnets opt (Topology 3)

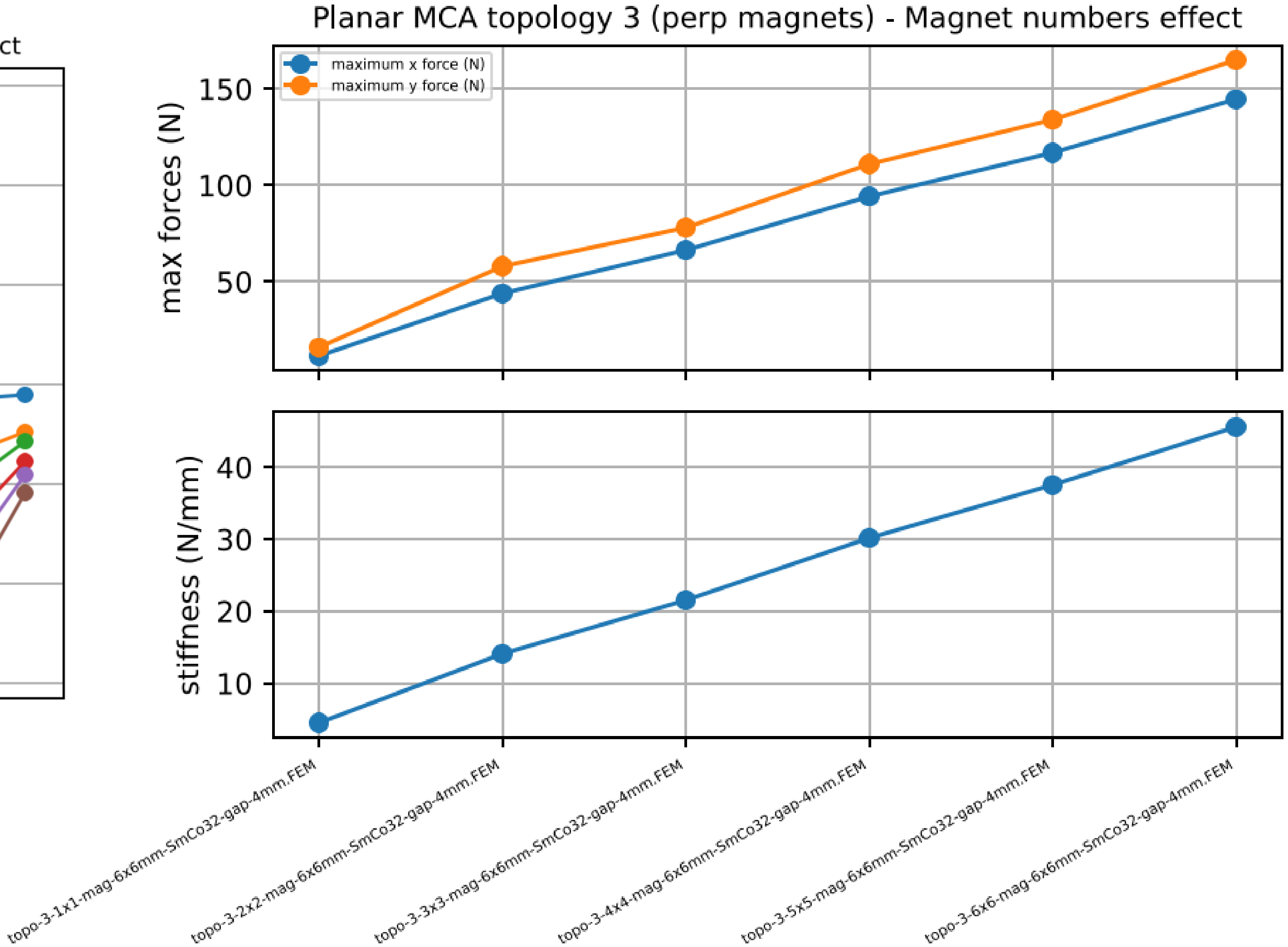




4mm between magnets

Number of magnets (Topology 3)





Summary and outlook 1/2

- **5 magnet arrangement topologies for the planar Magnetic coupled actuator has been investigated using a FEA tool called FEMM.**

- **Installing this system on both sides of rail mover available space (2x 56x25mm active areas), the sum of the perpendicular force will be ~0**

- **Options without magnets in vacuum have low useful force ~17N**

- **Options with magnets in vacuum have good performance (Topology 1, 3, 5)**

- **The topology 3 (perpendicular orientation of the magnets)**
  provides the best compromise between performance, manufacturing and flexibility.

- **By setting the number of magnets,**
  stiffness and max force can be set in 6 steps, if MCA on both sides:
  9 N/mm to 90 N/mm stiffness
  23 N to 289 N maximum force

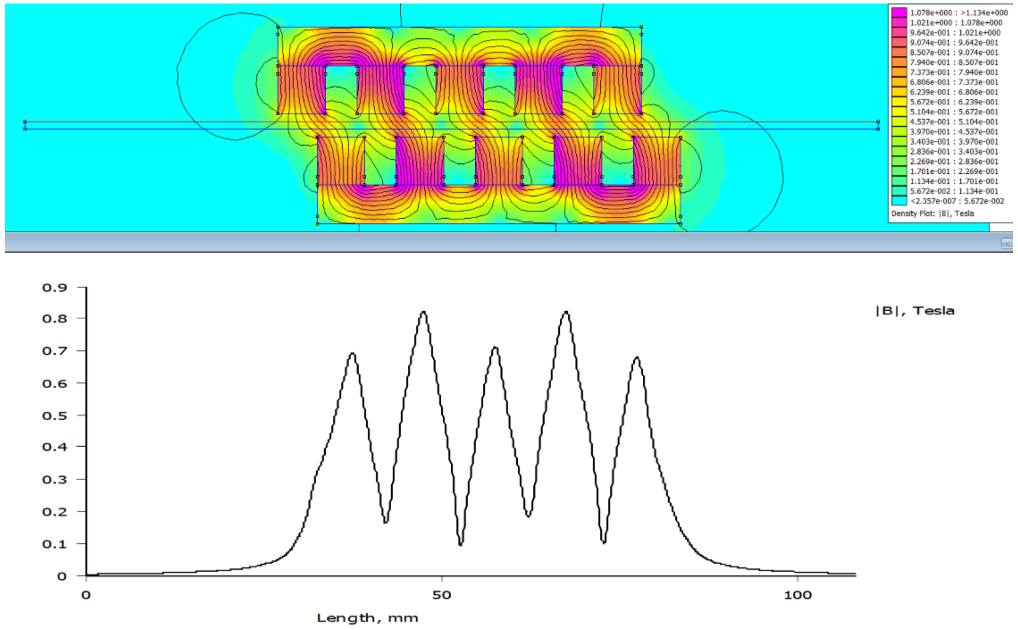
- **Reference system (UHVD)**
  30 N/mm stiffness
  90N maximum force

Summary and outlook 2/2

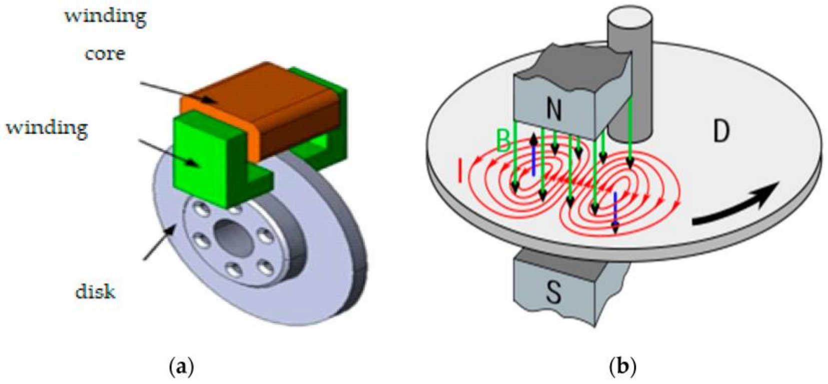
- **Evaluate Eddy currents in the vacuum membrane due to the magnetic flux variation induced by the magnet's motions**

- **Evaluate magnet ends leakages and how to shield it**

- **Experimental test of the selected geometry to benchmark simulation**



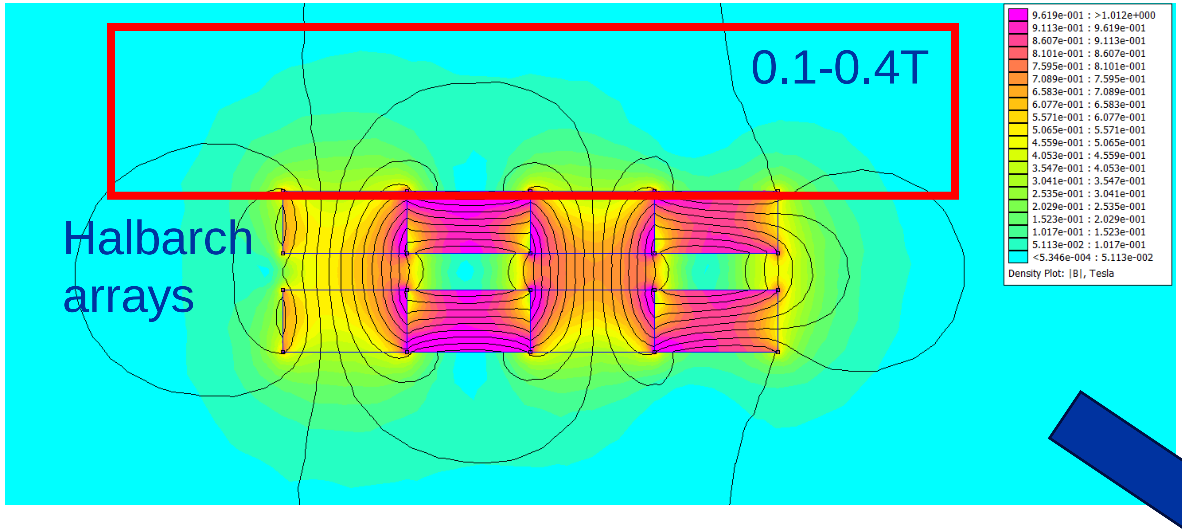
Air gap magnetic flux density



Application of Multiple Unipolar Axial Eddy Current Brakes for Lightweight Electric Vehicle Braking

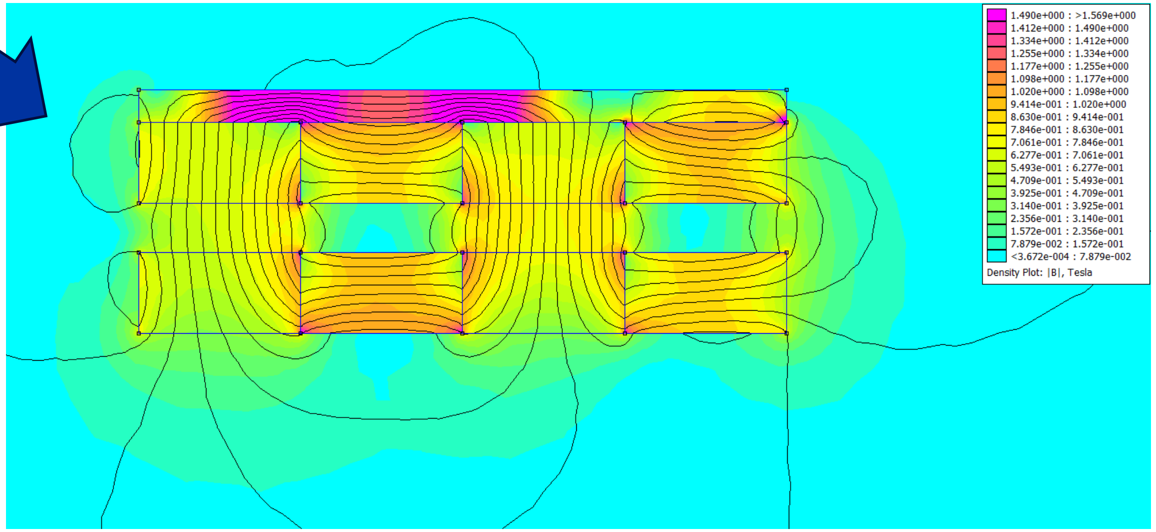
https://www.mdpi.com/2076-3417/10/13/4659 home.cern

Topology 5 (Halbach array) leakages



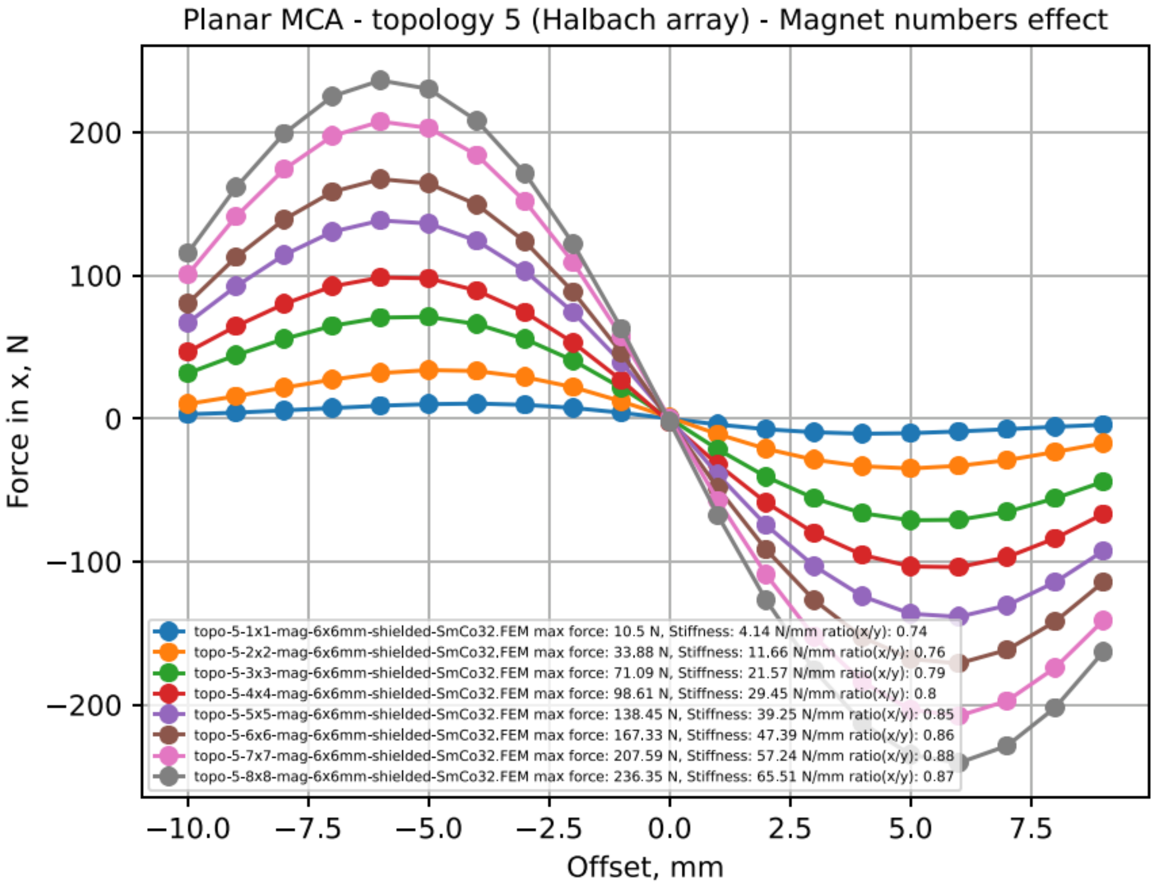
0.1-0.4T

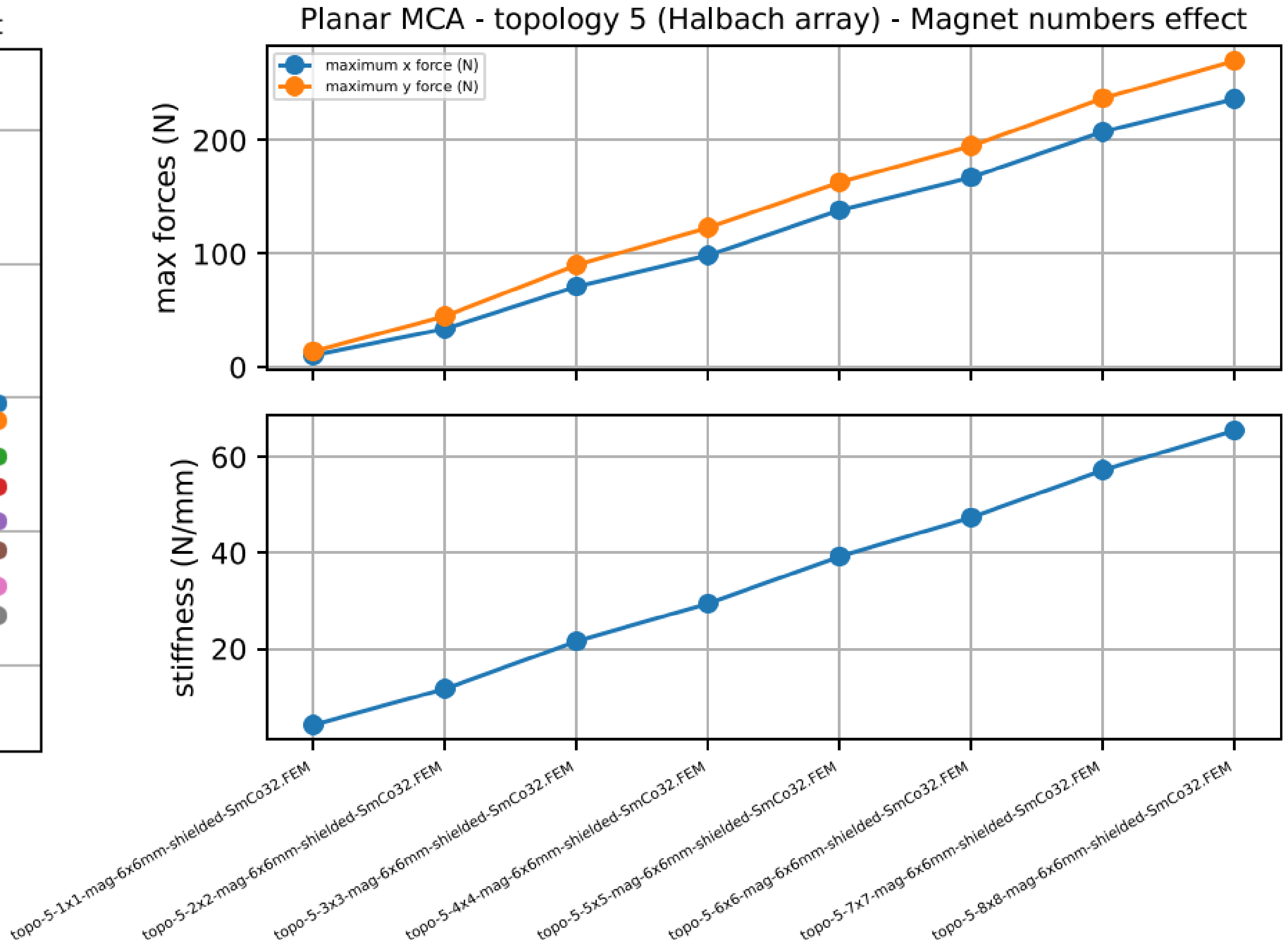
Halbarch arrays



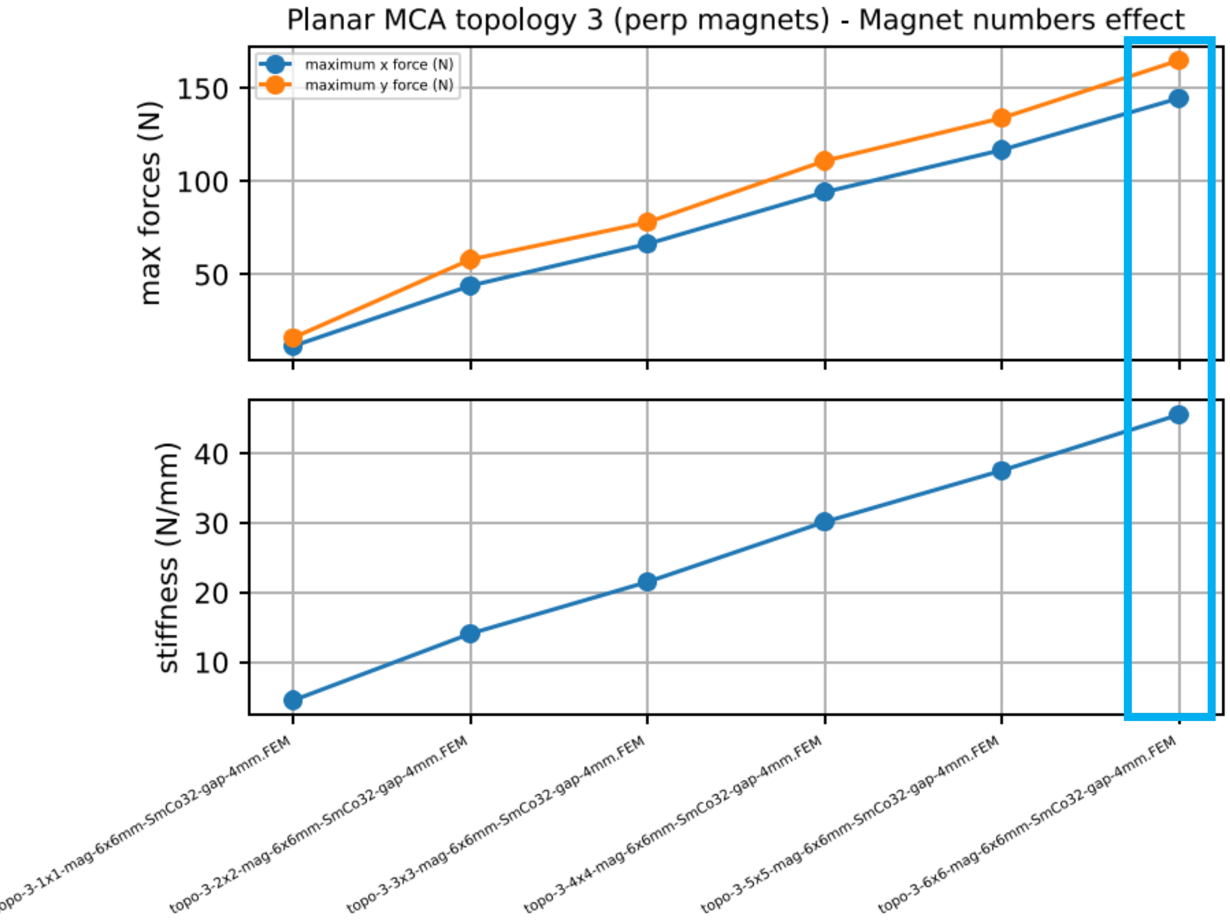
2mm shielding =>
- lower the leakage drastically
- 1.5T into the Iron ~ a little high better to have 3mm
- Small effect of the x force

Number of magnets (Topology 5)



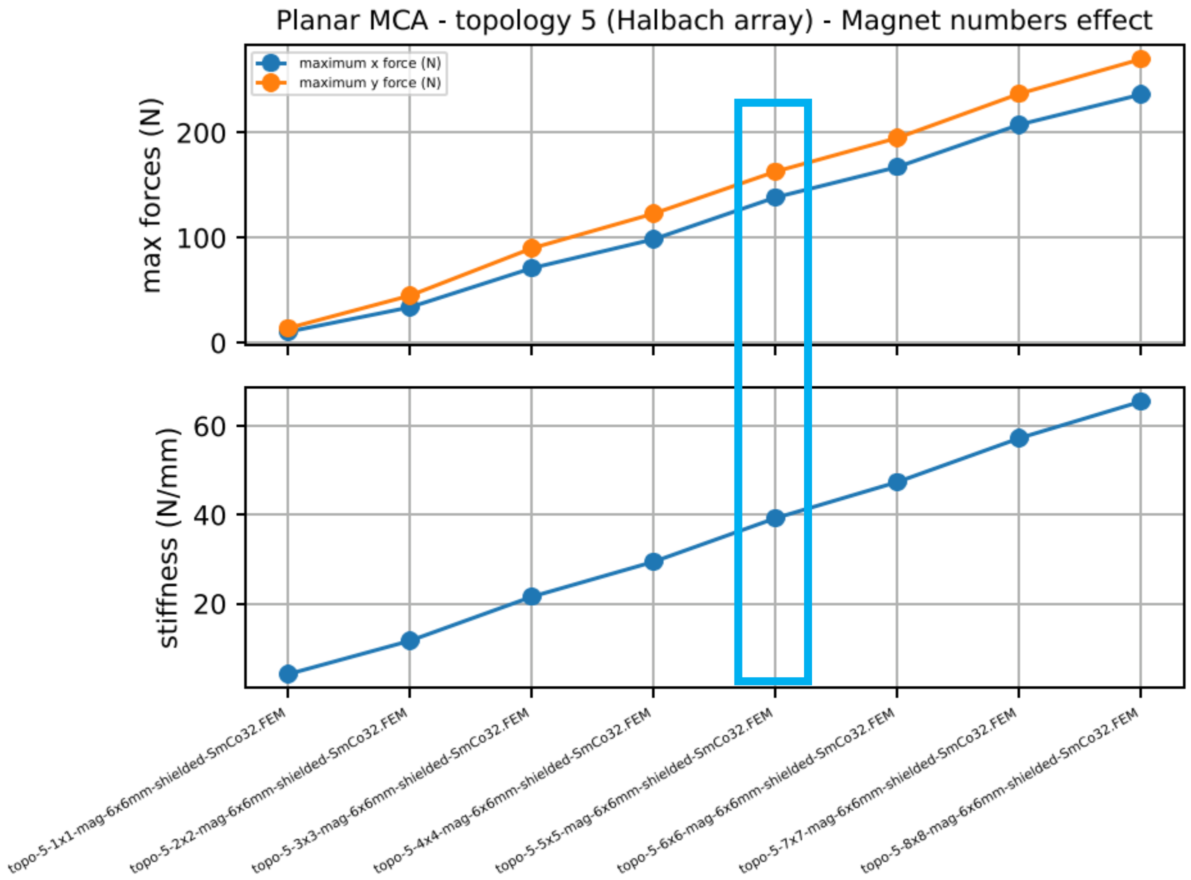


Performance comparison (Topo 3 / 5)



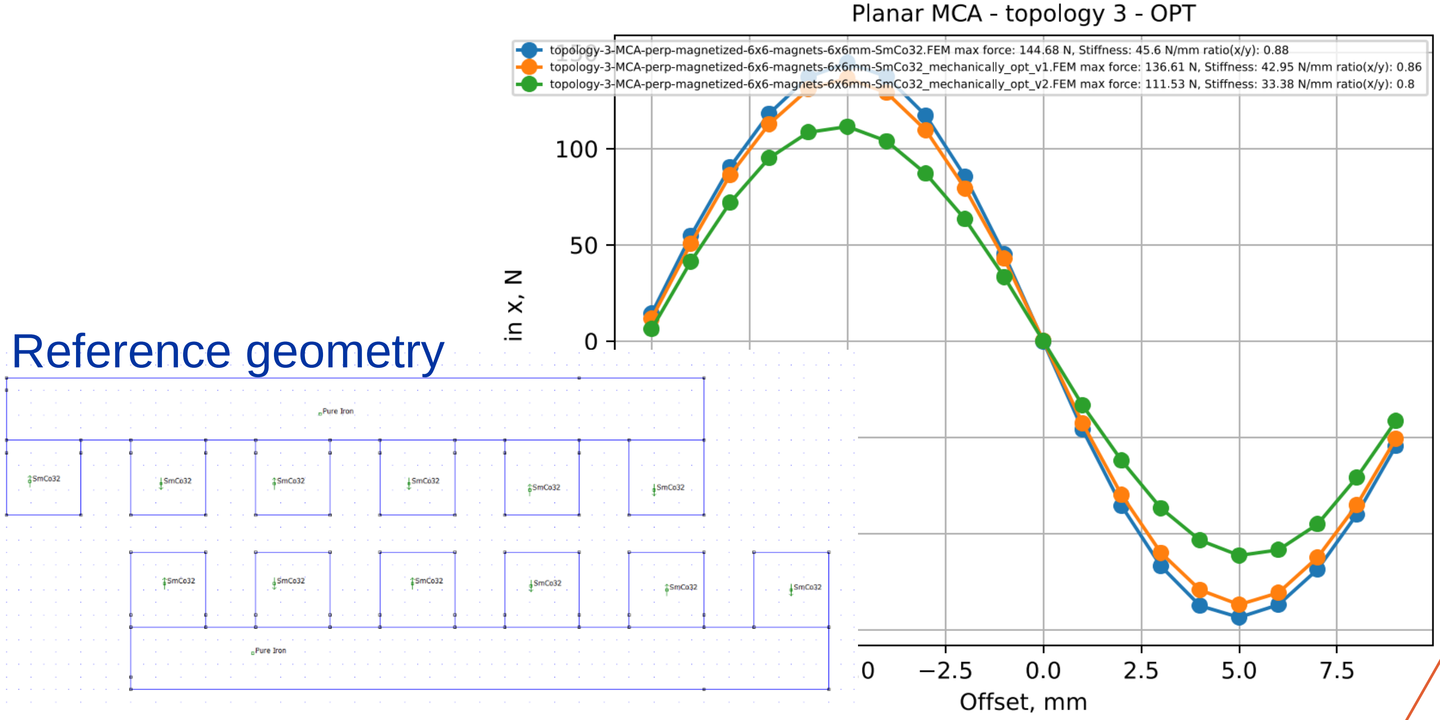
Planar MCA topology 3 (perp magnets) - Magnet numbers effect

144N max



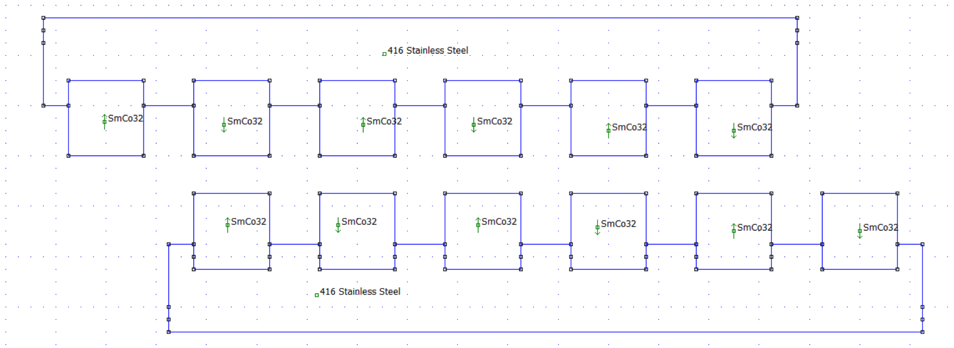
Planar MCA - topology 5 (Halbach array) - Magnet numbers effect

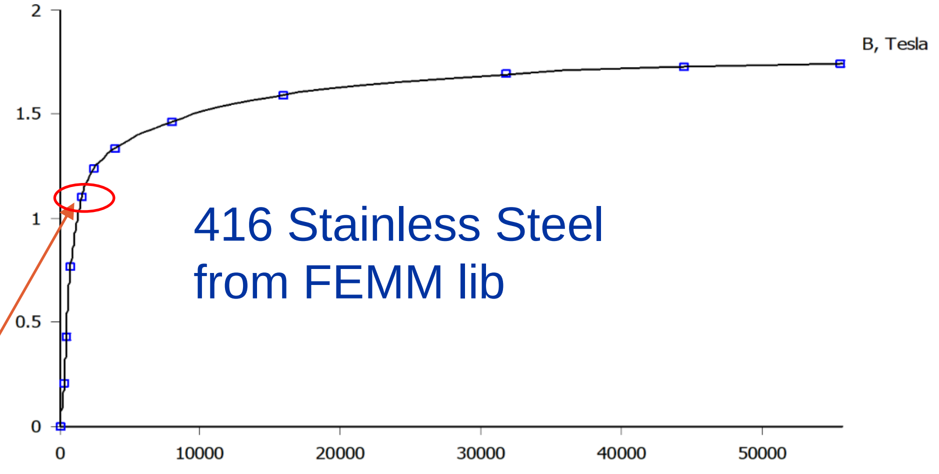
Post meeting optimization of the geometry (to target manufacturing)



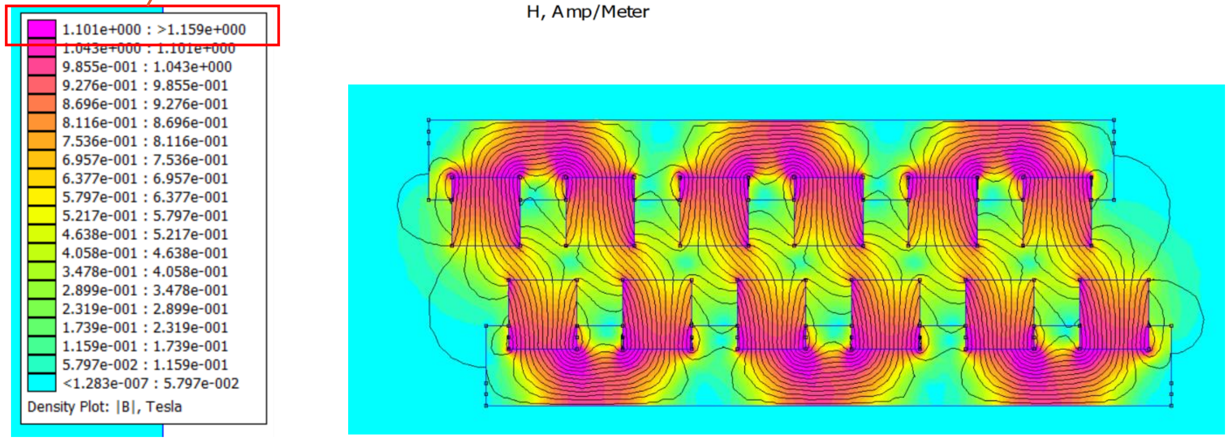
Reference geometry

“Opt v1” (2mm slot + 416 Stainless Steel) loss of few % of perf => ok
“Opt v2” (4mm slot + 416 Stainless Steel) loss of perf significant => not ok…

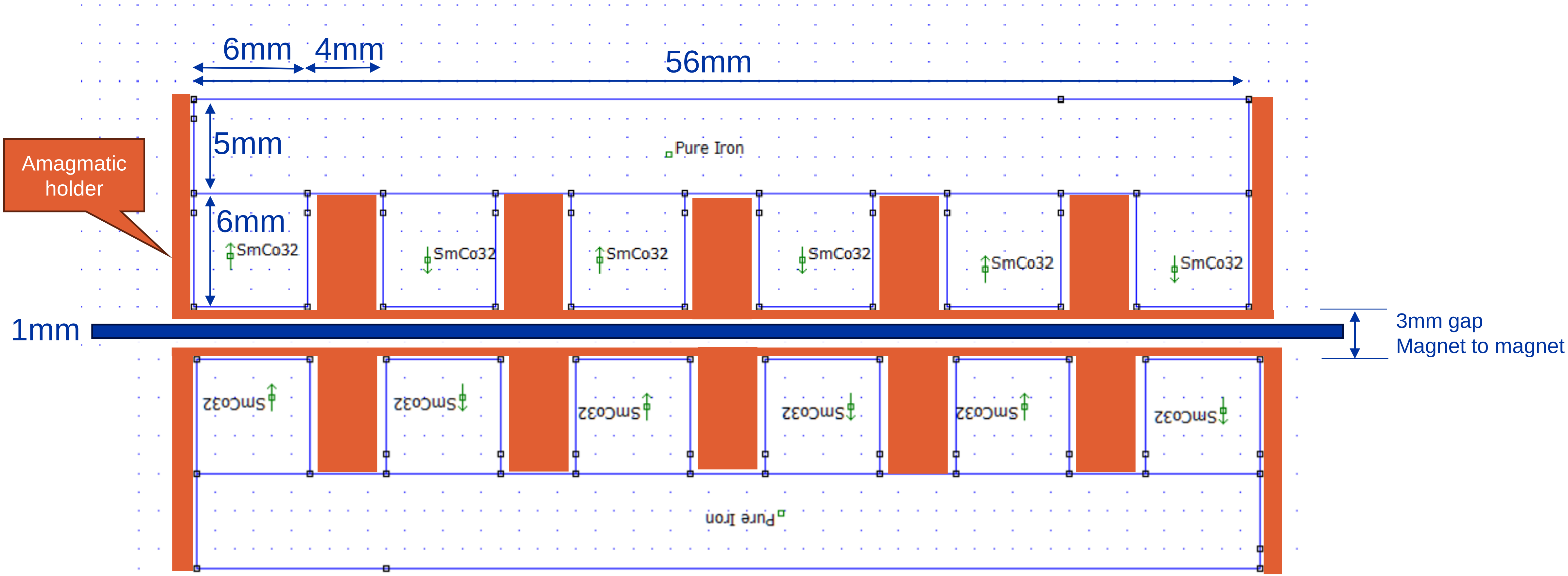




416 Stainless Steel
from FEMM lib

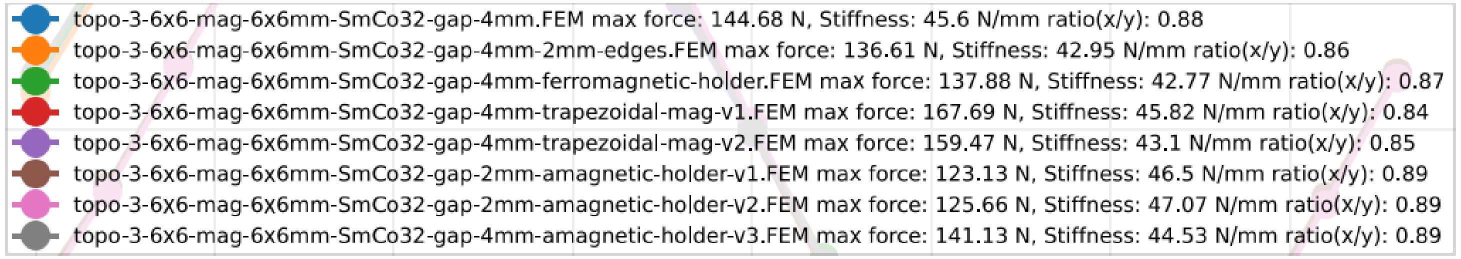


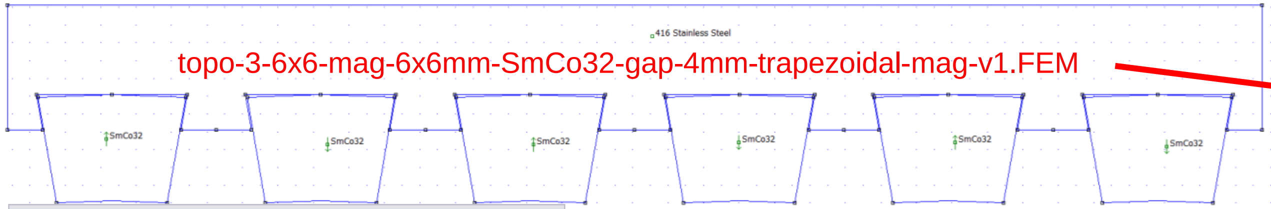
Topology 3: MCA design proposal



If the holder can be open easily for the prototype,
we can test different MCA stiffness/max force by adding or removing magnets in the spaces

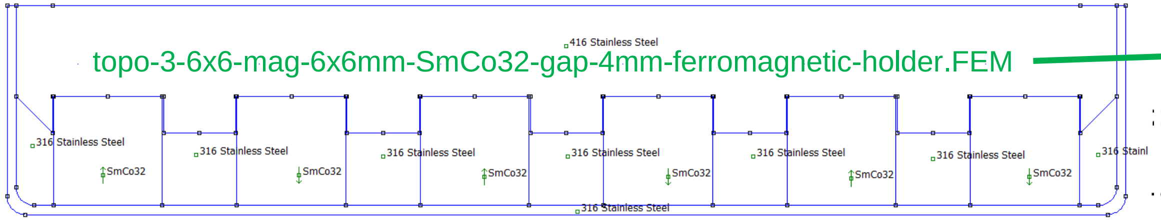
Generated force Fx (Horizontal plane)



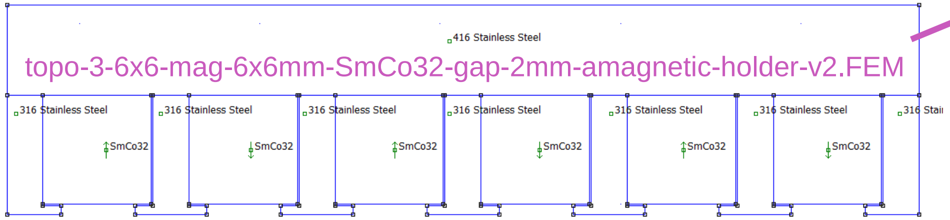


topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-trapezoidal-mag-v1.FEM

*trapezoidal magnets - size > 6x6mm

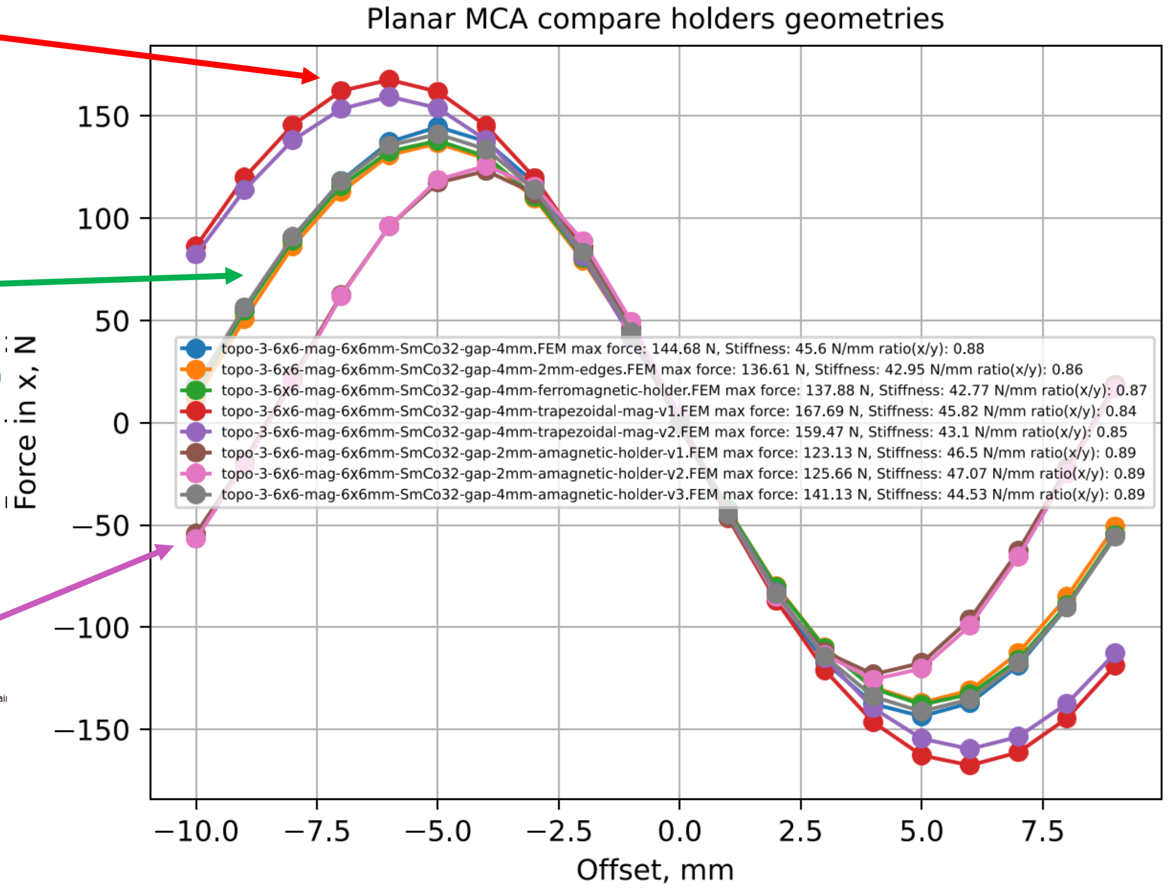


topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-ferromagnetic-holder.FEM

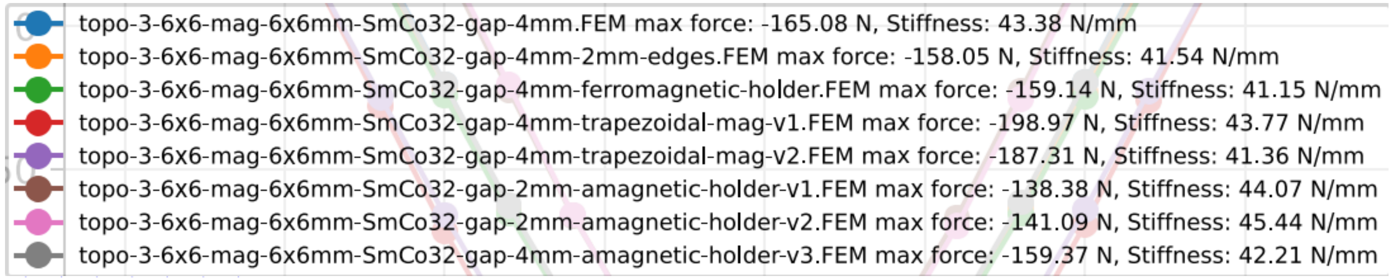


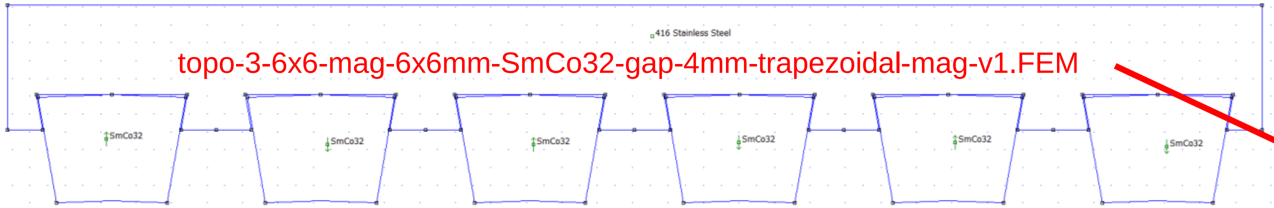
topo-3-6x6-mag-6x6mm-SmCo32-gap-2mm-amagnetic-holder-v2.FEM

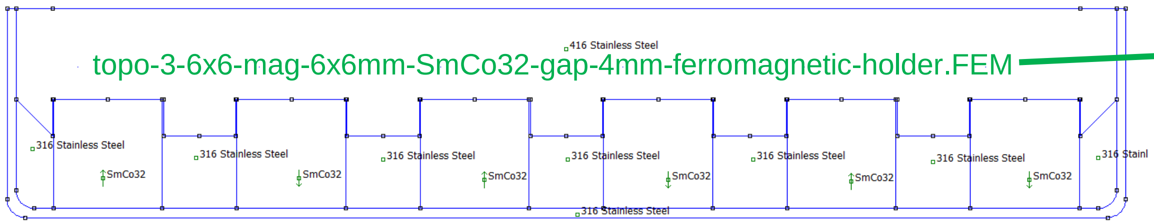
*Amagnetic holder - gap between magnets = 2mm

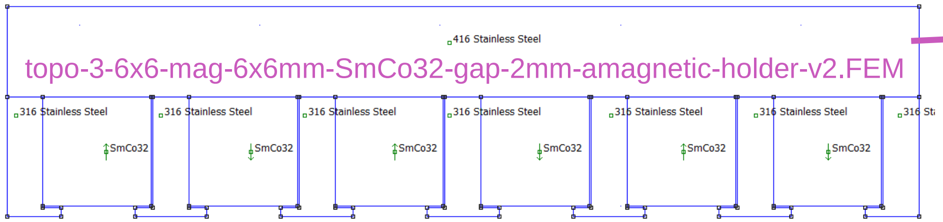


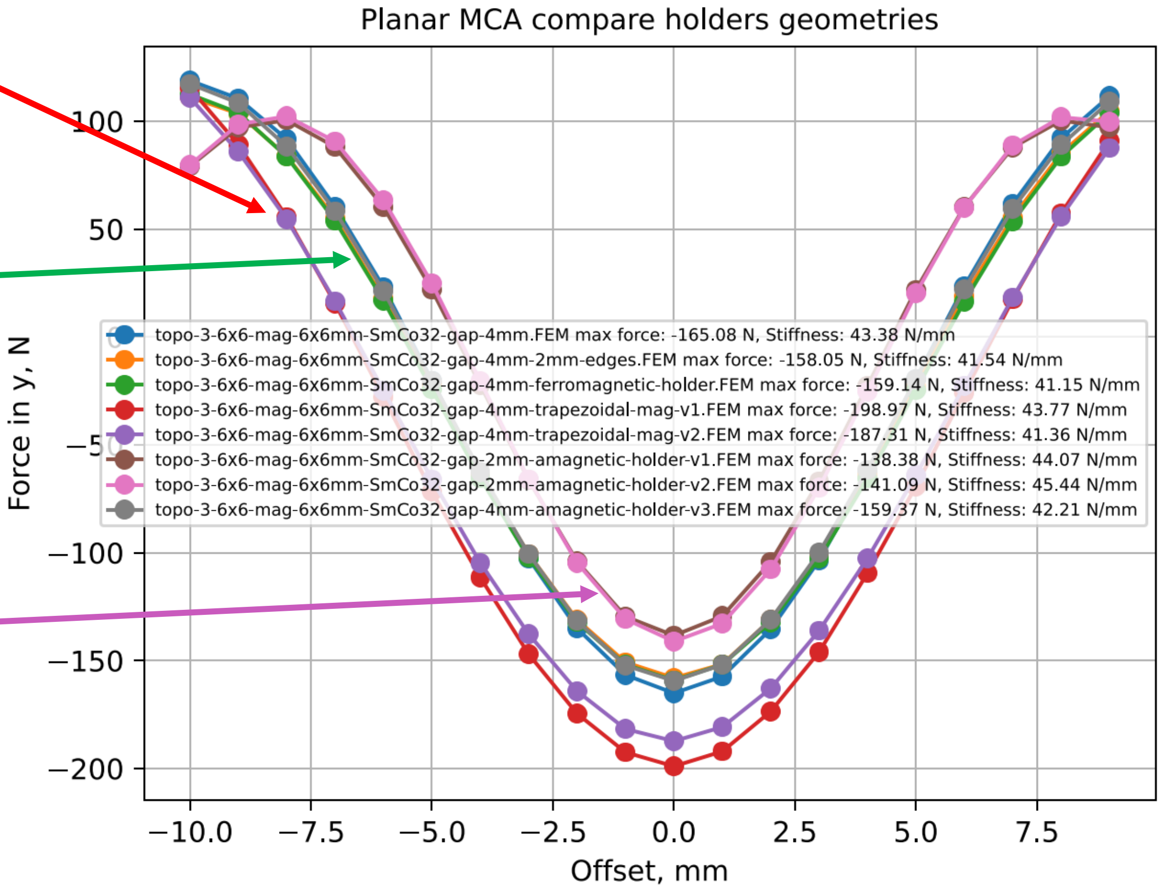
Generated force Fy (Vertical plane)


- ● topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm.FEM max force: -165.08 N, Stiffness: 43.38 N/mm
- ● topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-2mm-edges.FEM max force: -158.05 N, Stiffness: 41.54 N/mm
- ● topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-ferromagnetic-holder.FEM max force: -159.14 N, Stiffness: 41.15 N/mm
- ● topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-trapezoidal-mag-v1.FEM max force: -198.97 N, Stiffness: 43.77 N/mm
- ● topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-trapezoidal-mag-v2.FEM max force: -187.31 N, Stiffness: 41.36 N/mm
- ● topo-3-6x6-mag-6x6mm-SmCo32-gap-2mm-amagnetic-holder-v1.FEM max force: -138.38 N, Stiffness: 44.07 N/mm
- ● topo-3-6x6-mag-6x6mm-SmCo32-gap-2mm-amagnetic-holder-v2.FEM max force: -141.09 N, Stiffness: 45.44 N/mm
- ● topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-amagnetic-holder-v3.FEM max force: -159.37 N, Stiffness: 42.21 N/mm


topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-trapezoidal-mag-v1.FEM


topo-3-6x6-mag-6x6mm-SmCo32-gap-4mm-ferromagnetic-holder.FEM


topo-3-6x6-mag-6x6mm-SmCo32-gap-2mm-amagnetic-holder-v2.FEM



Influence of the air gap to the generated force in Fx (Horizontal plane) at 4mm displacement