Preliminary Electromagnetic and Mechanical Design of a Cosθ Dipole for the Muon Collider Project

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The Muon Collider

IMCC (International Muon Collider Collaboration) aims at studying the feasibility of a **10 km**, **10 TeV** center of mass energy Muon Collider.

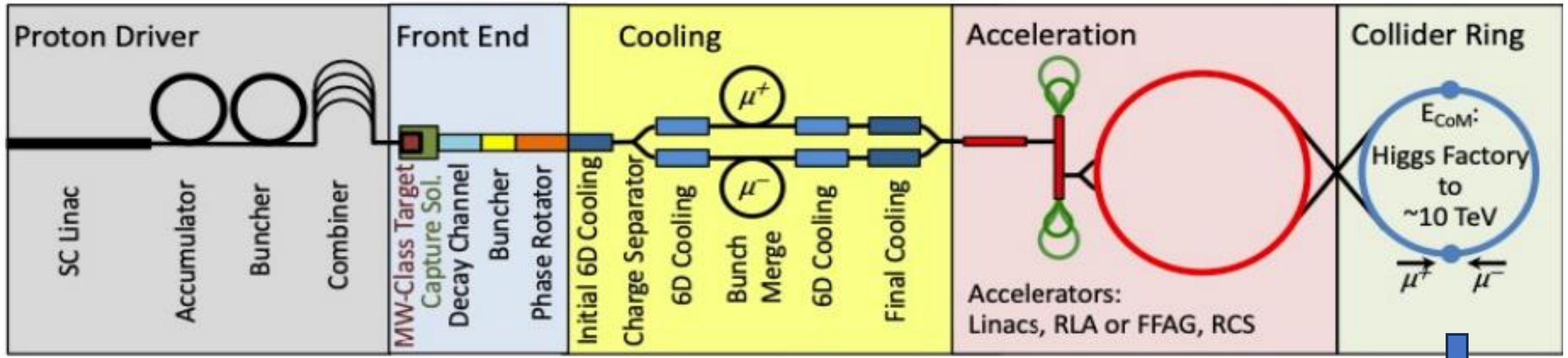
Why a Muon Collider?

$m_\mu \approx 200\, m_e$

μ = elementary particle

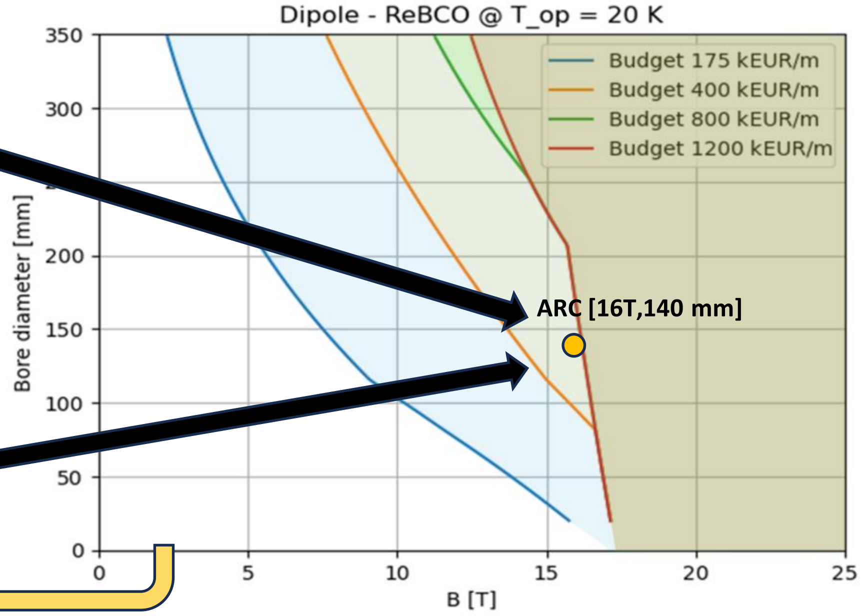
10^9 times less radiation loss

all COM energy available for the collision



Collider ring dipole magnets:

- **Highest field** possible to have a compact ring.
- **Large aperture dipoles** for shielding against beam induced heat.



(See D. Novelli ID 3LPo2H-05)

Motivation & Magnet Requirements

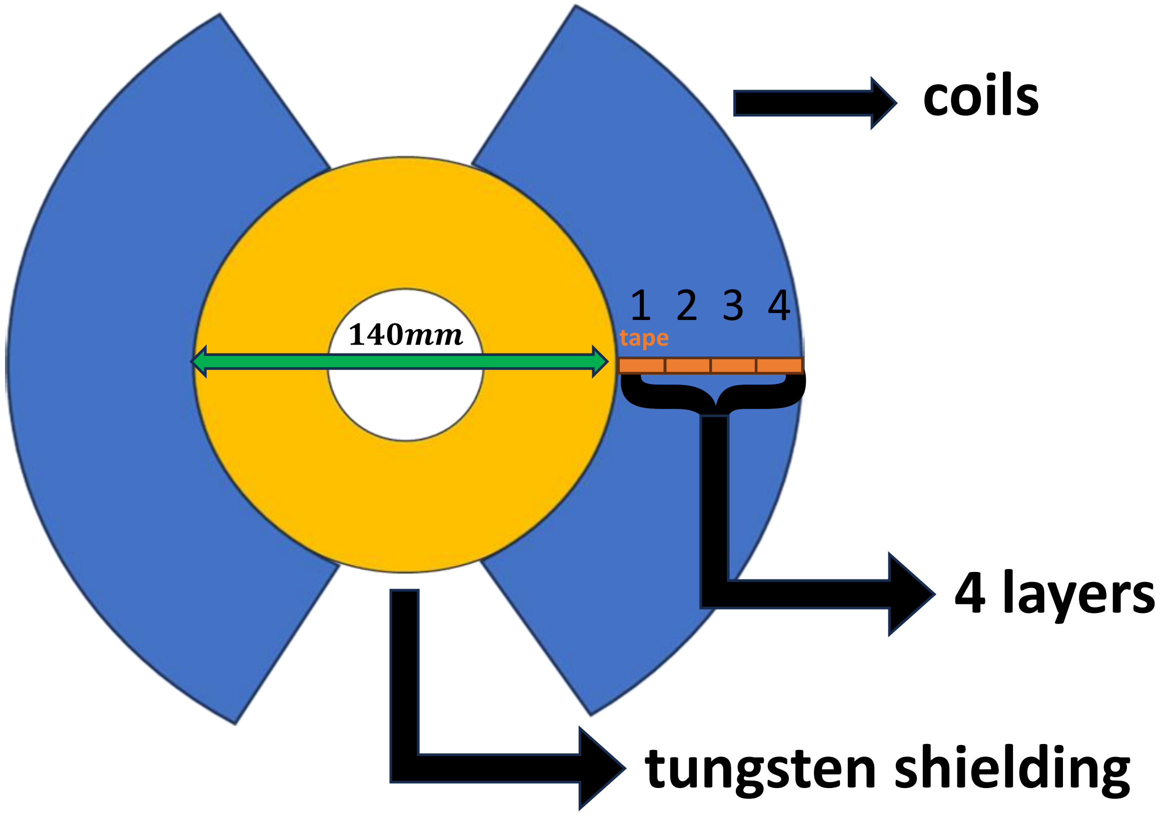
Motivation

A preliminary **electromagnetic** and **mechanical** study of $\cos\vartheta$ dipole magnet taking into account **non-uniform** current distribution.

REQUIREMENTS

- $bore\ aperture = 140\ mm$
- B_d = 16 T
- $T_{op} = 20\ K$
- $\Delta T_{marg} = 2.5\ K$

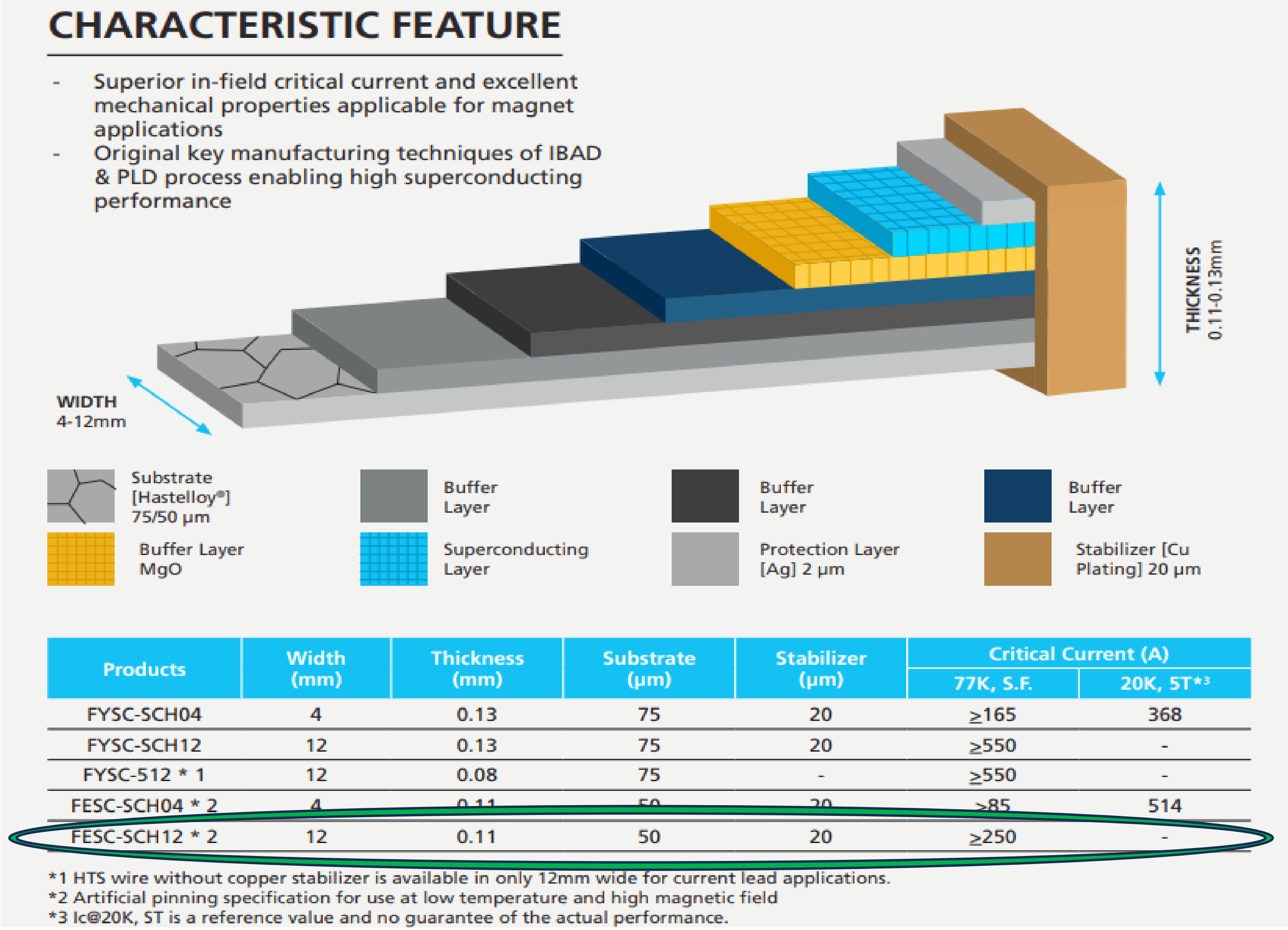
$\}$ **HTS techonology is needed!**



Cable: Double tape

Tape: REBCO (12 mm) Fujikura FESC tape

Tape & Cable



CHARACTERISTIC FEATURE

- Superior in-field critical current and excellent mechanical properties applicable for magnet applications
- Original key manufacturing techniques of IBAD & PLD process enabling high superconducting performance

Substrate [Hastelloy®] 75/50 µm	Buffer Layer	Buffer Layer	Buffer Layer
Buffer Layer MgO	Superconducting Layer	Protection Layer [Ag] 2 µm	Stabilizer [Cu Plating] 20 µm

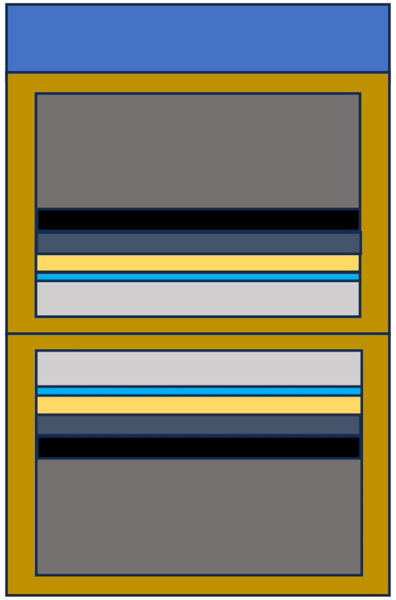
Products	Width (mm)	Thickness (mm)	Substrate (µm)	Stabilizer (µm)	Critical Current (A)	
					77K, S.F.	20K, 5T*3
FYSC-SCH04	4	0.13	75	20	≥165	368
FYSC-SCH12	12	0.13	75	20	≥550	-
FYSC-512 * 1	12	0.08	75	-	≥550	-
FESC-SCH04 * 2	4	0.11	50	20	≥85	514
FESC-SCH12 * 2	12	0.11	50	20	≥250	-

*1 HTS wire without copper stabilizer is available in only 12mm wide for current lead applications.
*2 Artificial pinning specification for use at low temperature and high magnetic field
*3 Ic@20K, ST is a reference value and no guarantee of the actual performance.

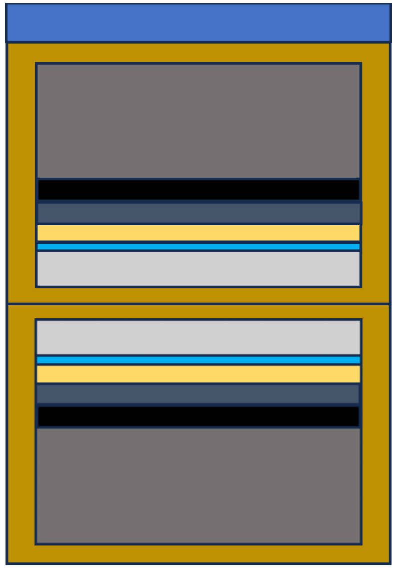
double tape & metal-insulated cable, co-wounded with:

- 50 μm thick **SS tape** (layers 1-2)
- 25 μm thick **SS tape** (layers 3-4)

Cable in layers 1-2



Cable in layers 3-4



HTS vs LTS technology

(See T.Salmi ID 1LPo1I-04)

Advantages

- Higher B_{c2} → Magnet can reach higher field without quenching.
- Higher I_c → More compact magnets.
- Higher T_c → higher T_{op} thus reducing the refrigeration cost.

Disadvantages

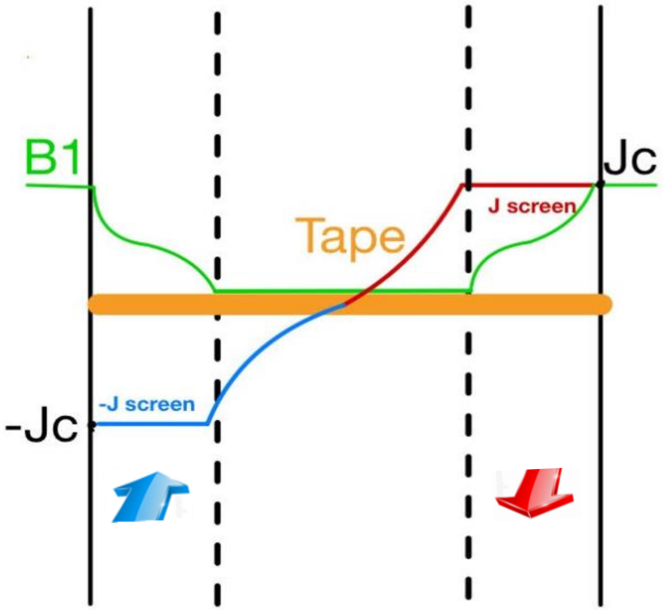
- Challenging quench protection
- More expensive than LTS
- Wide width of REBCO tapes (12mm) + No twisted/transposed tapes

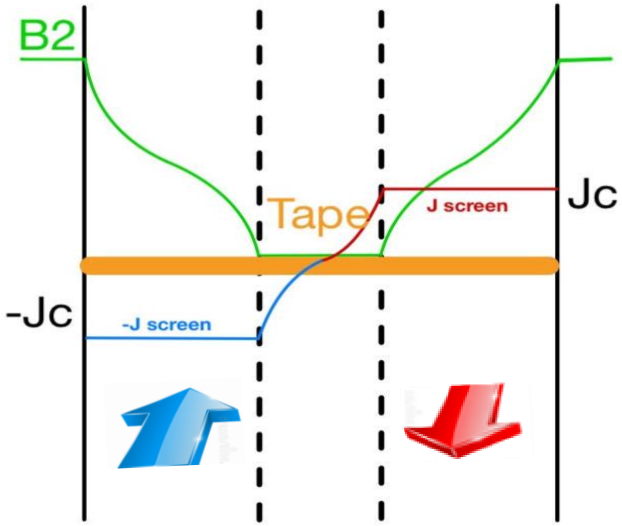
Higher magnetization w.r.t. LTS cables, leading to **higher losses** and threatening the **field quality**.

Current distribution inside tapes must be taken into account!

J distribution according to Brandt Model (1)

When the tape is immersed in a magnetic field region, a screening current (I_{screen}) originates inside it to cancel the inner perpendicular field, starting from the edges.





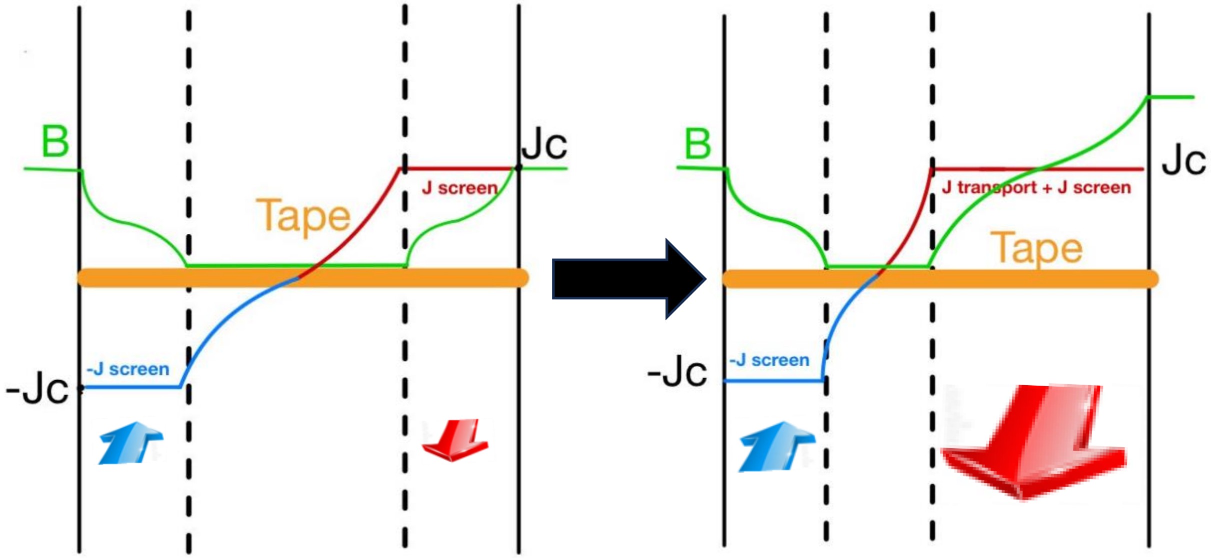
As the field increases, I_{screen} penetrates towards the center of the tape.

J distribution according to Brandt Model (2)

If a transport current I_t flows along the tape, we need to distinguish between 2 scenarios:

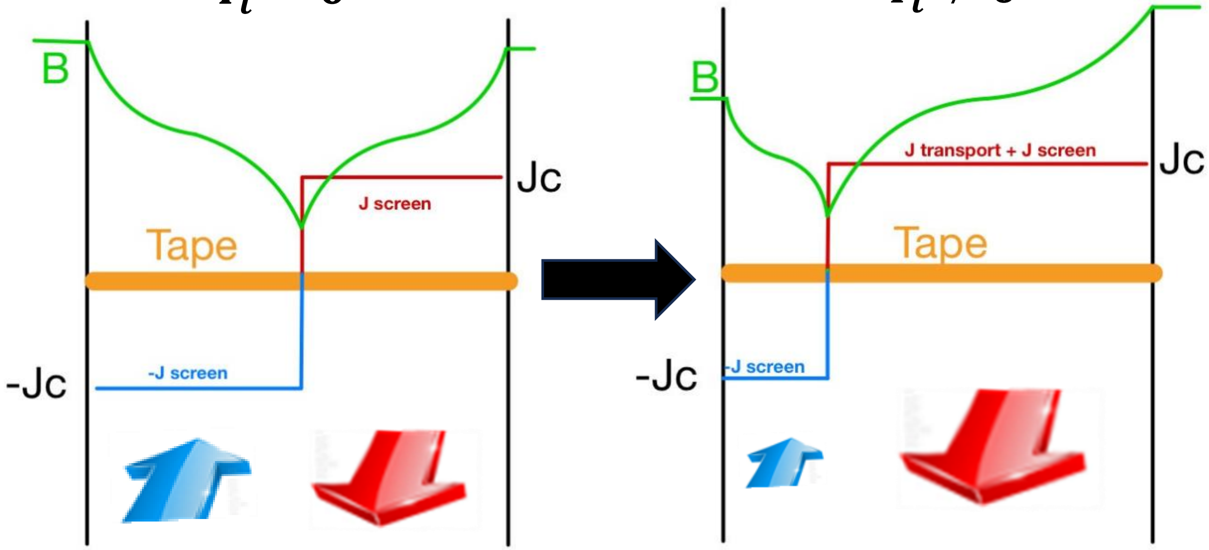
A) If I_{screen} has not yet fully penetrated inside the tape, then I_t will distribute in the region not yet Saturated.

$I_t = 0$ $\qquad$ $I_t \neq 0$



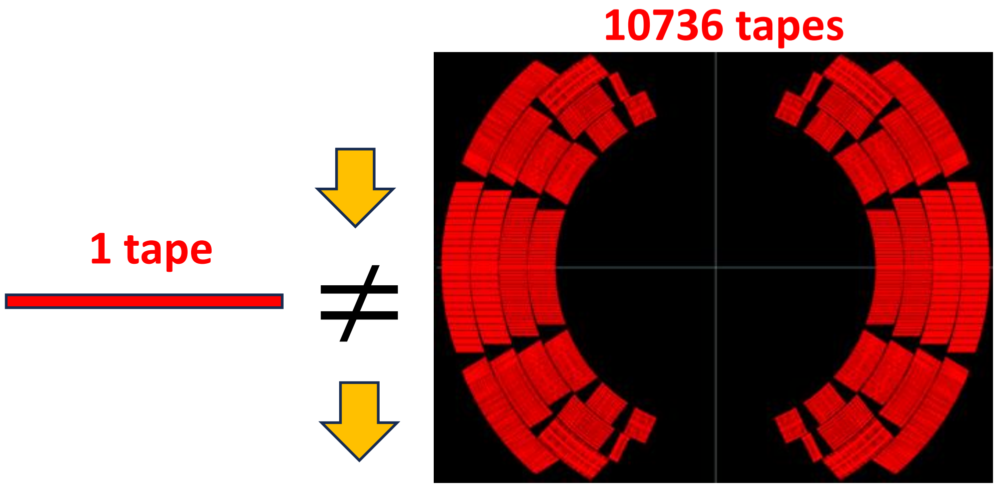
B) If I_{screen} has fully penetrated , then I_t will distribute in the central region of the tape by pushing I_{screen} towards the edges thus reducing I_{screen} .

$I_t = 0$ $\qquad$ $I_t \neq 0$



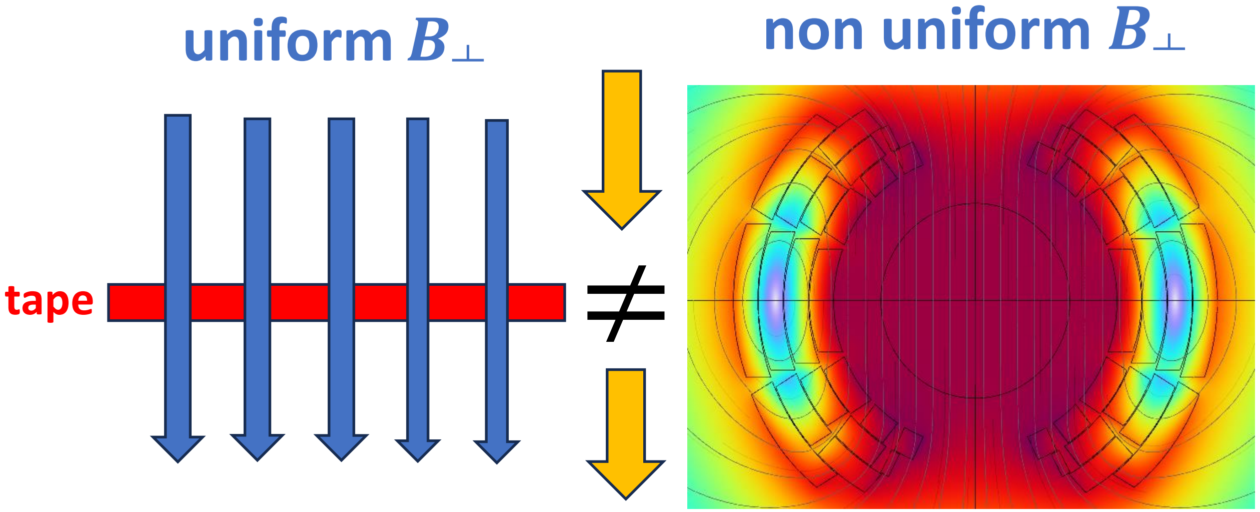
Limitations of the model and Mitigations adopted

- The model considers only a single tape, whereas the dipole magnet is made of thousands of tapes.



- Iterative solution was performed to consider how each tape is affected by the current distribution of the others.

- The model assumes a single value of $\boldsymbol{B}_{\perp}$ in which the tape is immersed.



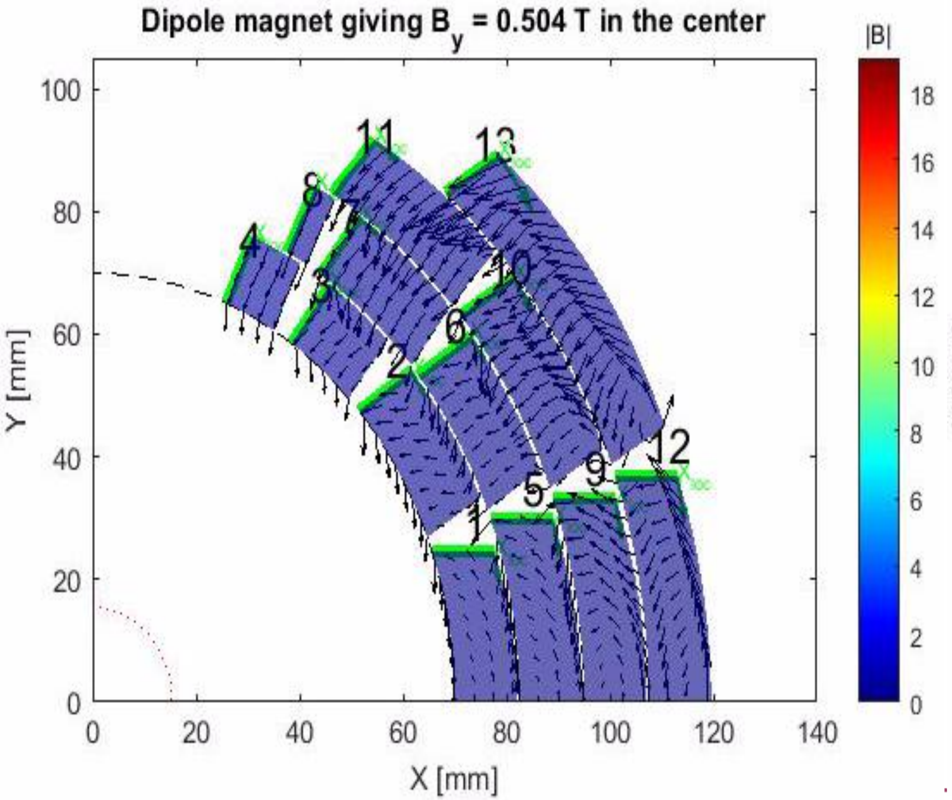
- $\boldsymbol{B}_{\perp}$ averaged along each tape is taken as the uniform field in which the tape is immersed.

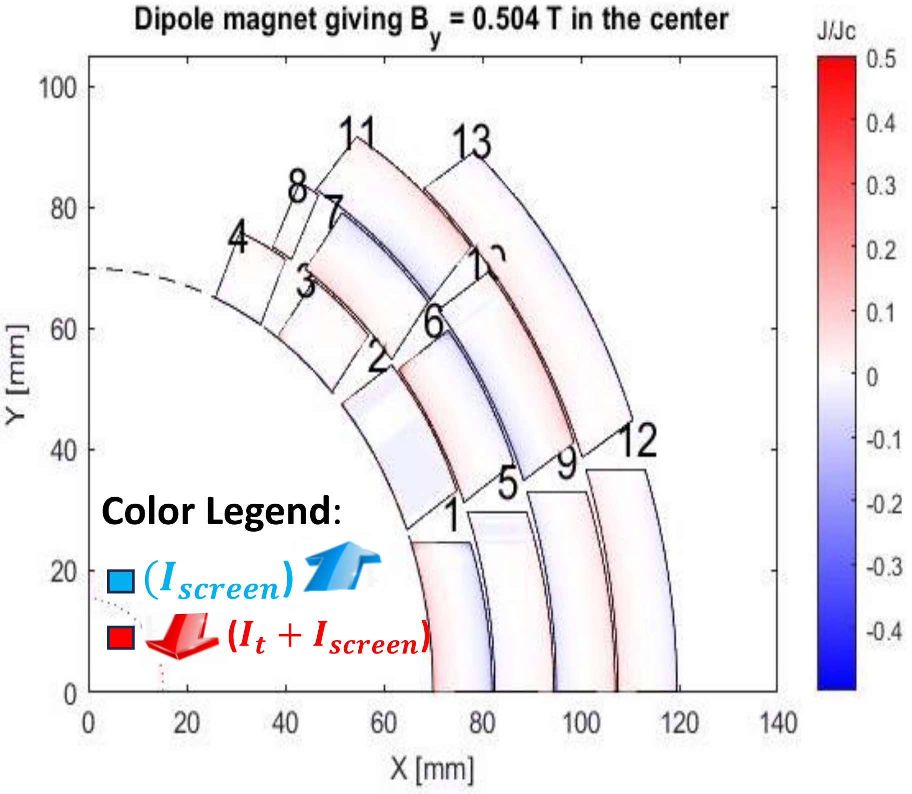
ELECTROMAGNETIC STUDY

Field & Current distribution

B_d (T)	$d\ (mm)$	T_{op} (K)	I_{nom} (A)	$Energy$ (kJ/m)	$Inductance$ (mH/m)
16	140	20	1702	4927	3402

Field quality (I_{nom})		
$I = 1702$ A	b_3	b_5
J unif	0.05	1.2
J non-unif	5	2

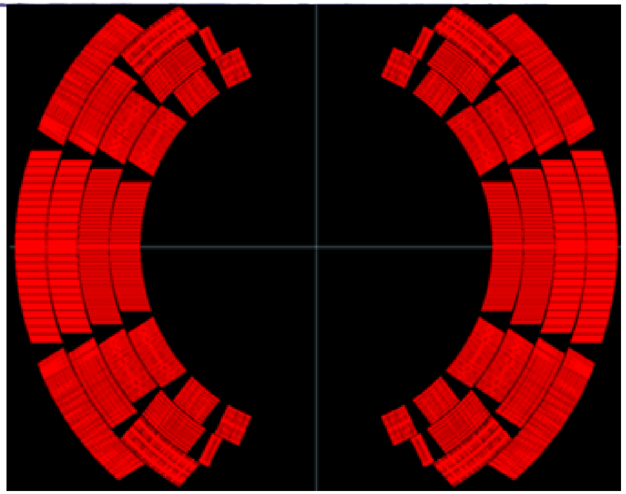


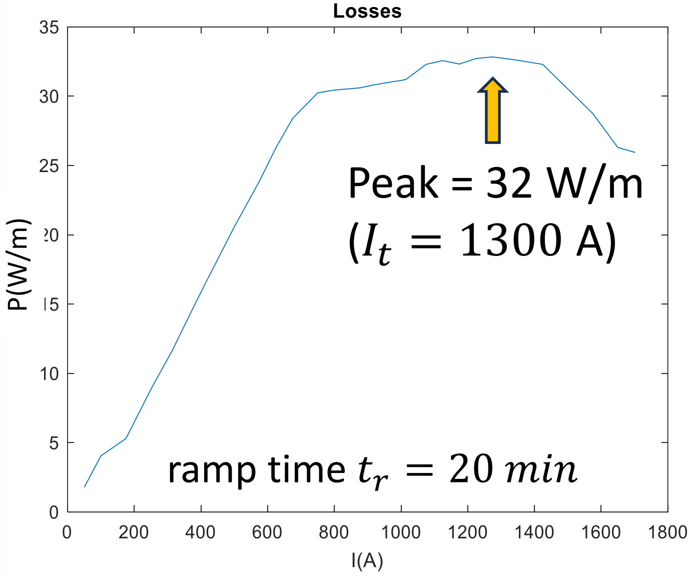


Color Legend:

🟦 (I_{screen})

🟥 $(I_t + I_{screen})$



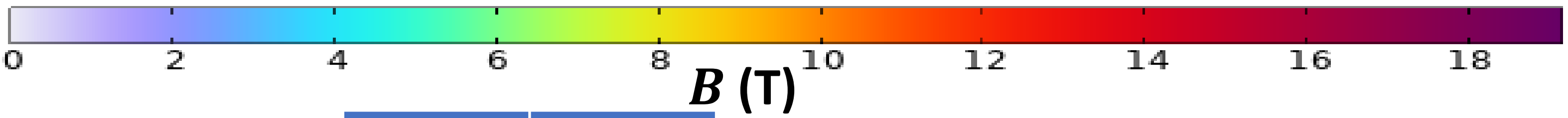


Peak = 32 W/m ($I_t = 1300$ A)

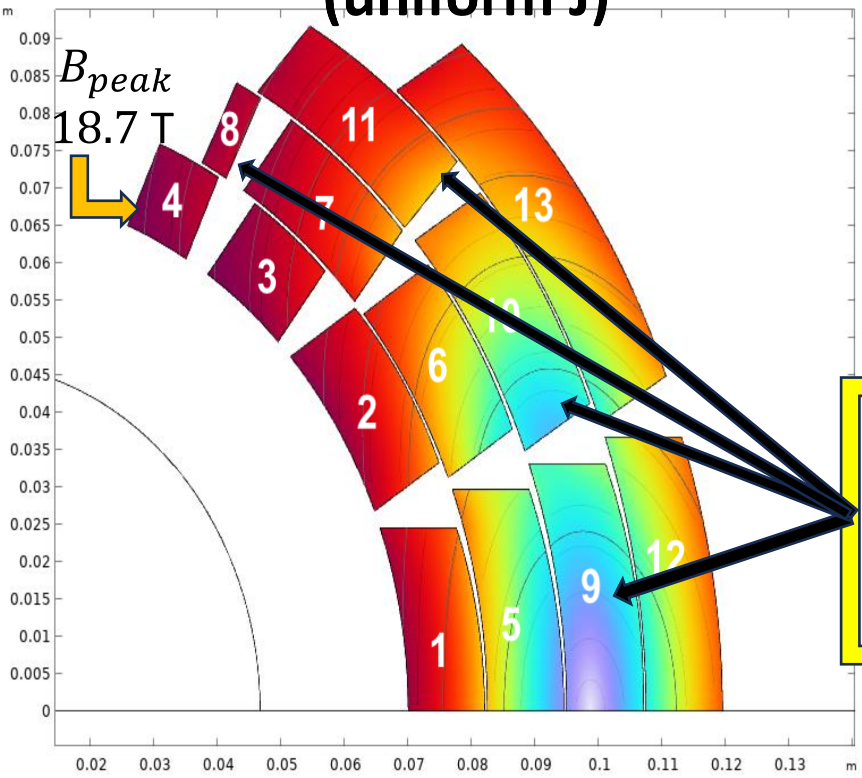
ramp time $t_r = 20\ min$

Electromagnetic Study

Margin

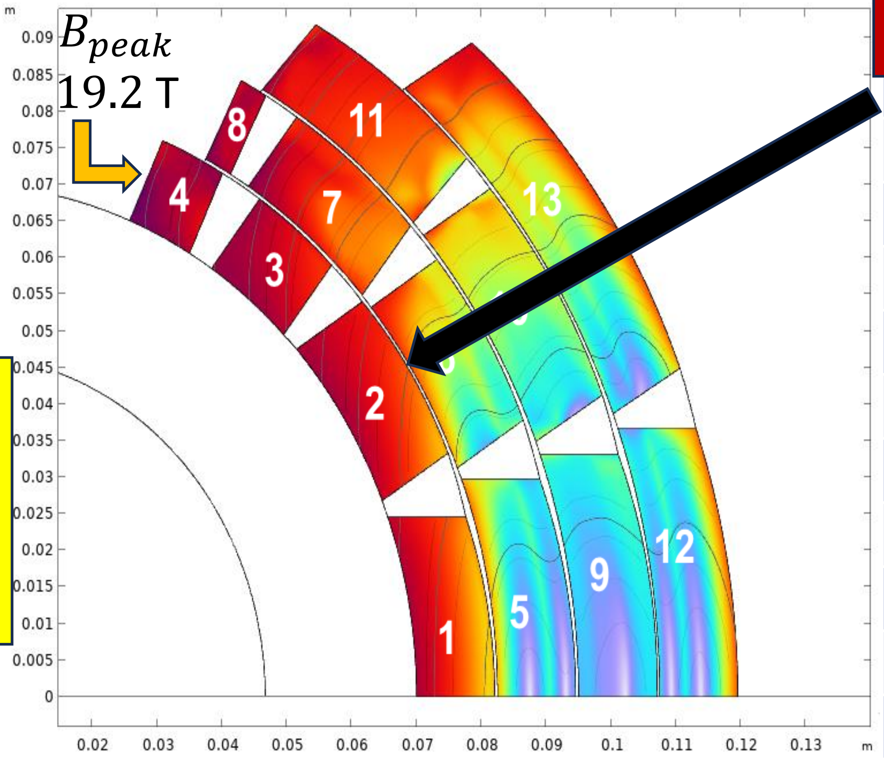


No screening current (uniform J)



Block n.	Margin (%)
1	8.6
2	1.5
3	11.6
4	33.5
5	32.8
6	29.4
7	36.2
8	72.7
9	71
10	69.8
11	66.5
12	34.8
13	30.9

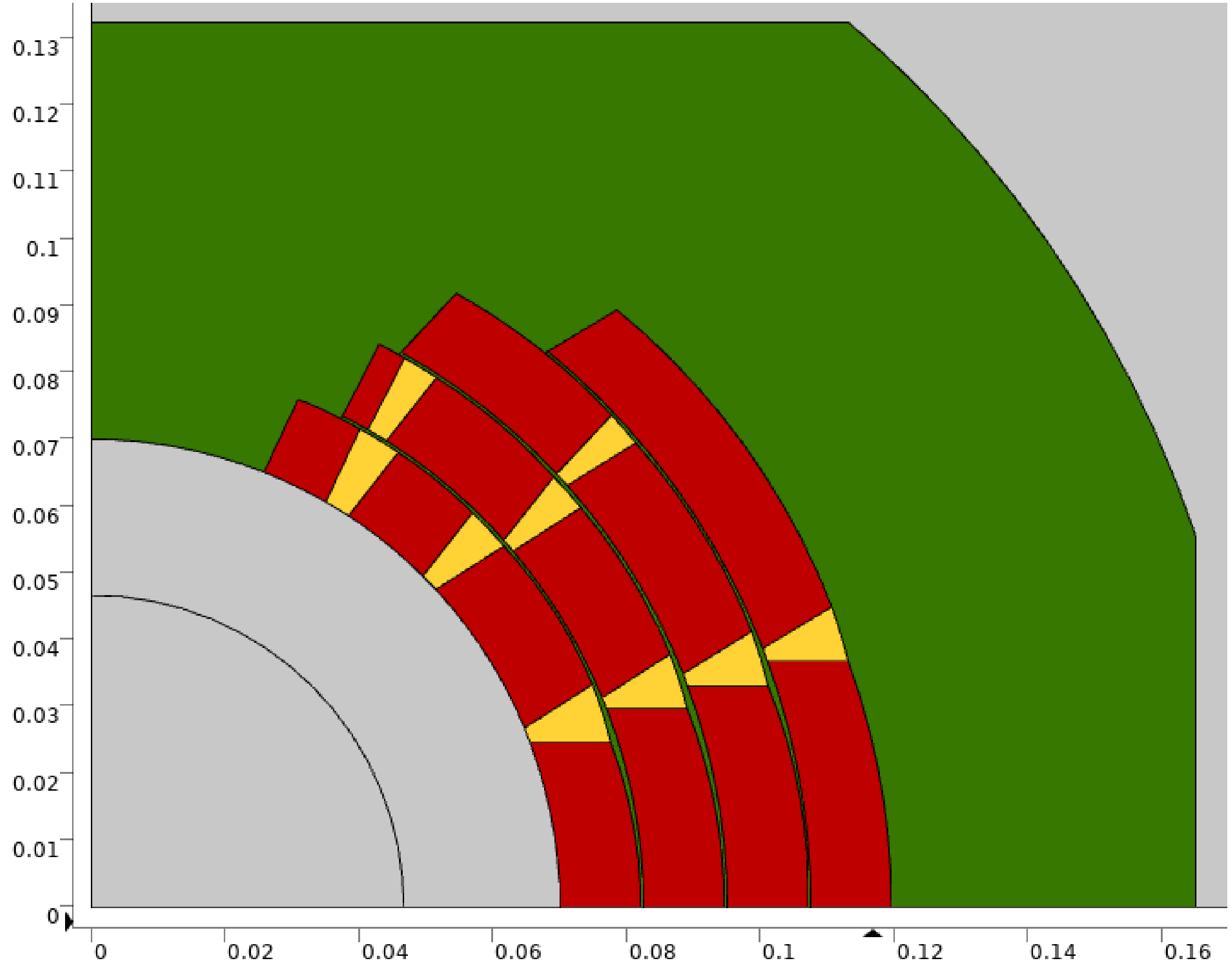
Screening current (non uniform J)



Block n.	Margin (%)
1	9.9
2	3.9
3	14.2
4	59
5	64.3
6	61
7	61.4
8	72.4
9	67.5
10	66.5
11	65.2
12	63.7
13	60.3

Mechanical Study

Assumptions



- 2 different mechanical studies:

  1) Bounded layers

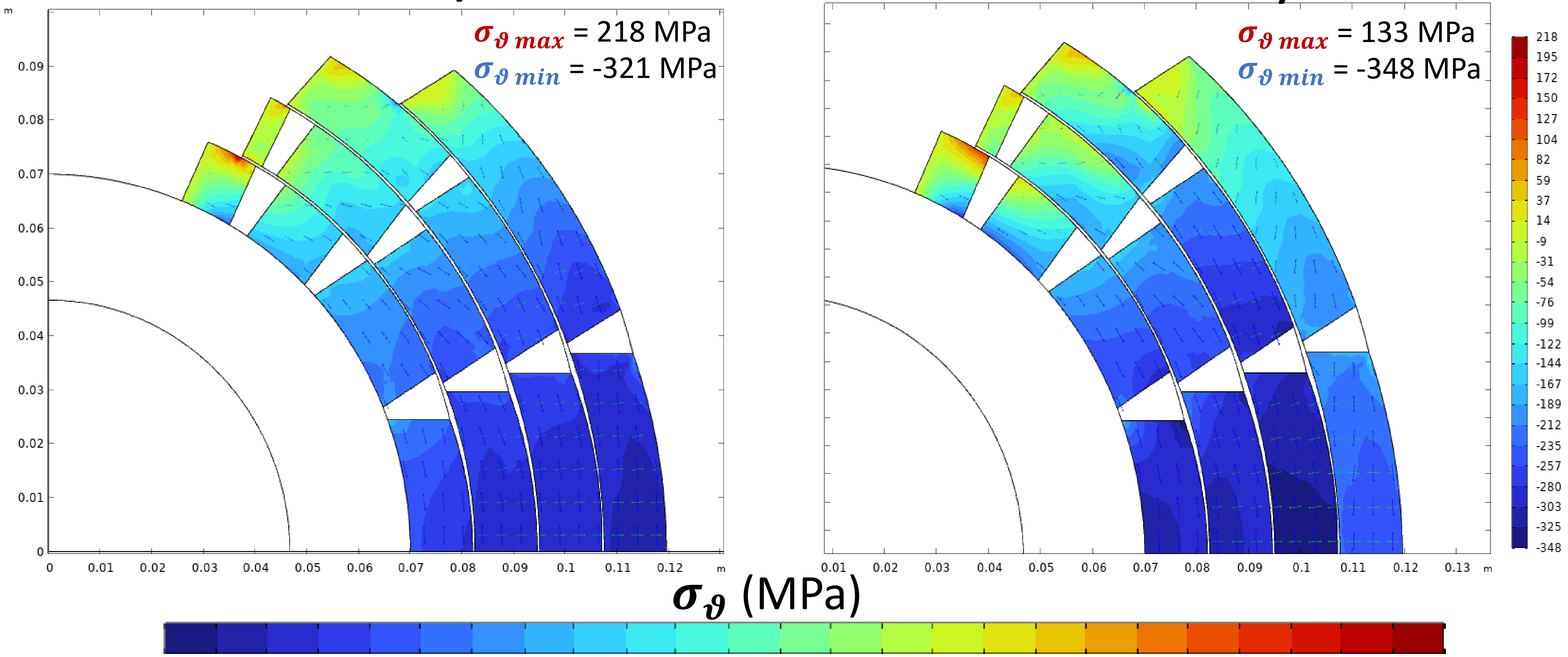
  2) Frictionless layers (with separation)

- Infinitely rigid collar
- Frictionless contact between collar and layers
- Young modulus of layers E=174 GPa
- Wedges material → copper

Mechanical Study

Azimuthal stress σ_ϑ

Bounded layers **Frictionless layers**



Bounded layers: $\sigma_{\vartheta\,max}$ = 218 MPa, $\sigma_{\vartheta\,min}$ = -321 MPa

Frictionless layers: $\sigma_{\vartheta\,max}$ = 133 MPa, $\sigma_{\vartheta\,min}$ = -348 MPa

σ_ϑ (MPa)

Conclusion & Perspectives

- A **cosϑ dipole magnet** entirely designed with HTS technology needs to account for non-uniform J distribution.

- The non-uniform J distribution calculation based on Brandt model allowed to evaluate the **losses** taking place during the ramping time and how **field quality** is affected by magnetization.

- For the moment, the **margin** requirement of 2.5 K is not fulfilled in the first layer. However:

  1. High margin in outer layers.
  2. Iron contribution.

- The **tensile stress** at the top of the magnet must be cancelled, whereas the **compressive stress** on the midplane needs to be compensated/reduced by **appropriate structures** (**stress management** could be a valid solution).

- **Further improvement of code** for current distribution evaluation will be performed to obtain more accurate results. **Mechanical study will be further developed** to find appropriate solutions to assure mechanical stability.

Next Steps

- Computational time **optimization** of the analytical code and **improvement** of the Brandt Model:
  a) J distribution inside a tape immersed in **non-uniform B**.
  b) Not only first magnetization study.

- **Validation** with a fem software (e.g. COMSOL) starting from a simple cosθ geometry (sector coil 60°) and considering "H" formulation.

- Further validation with more complex geometries using "T-A" or "J-A" formulations (**coil homogenization** to reduce computational time).

Thank you

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Backup Slides

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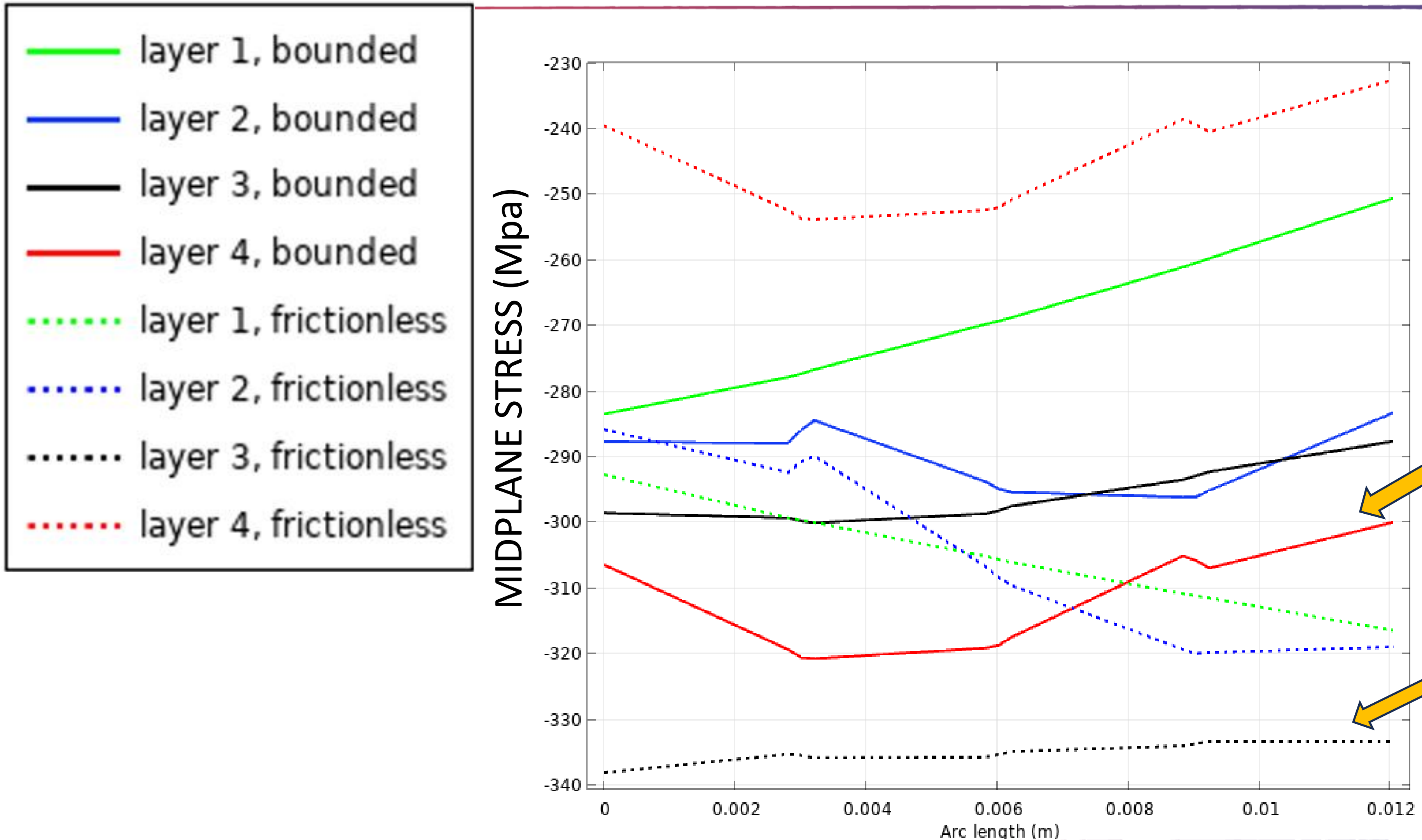
Mechanical Study

Stress on Midplane & Deformation



Difference on midplane stress between bounded and frictionless layers:

- Maximum compressive stress in layer 4 in case of bounded layers.
- Maximum compressive stress in **layer 3** in case of frictionless layers.

Field Quality
Limit of the model

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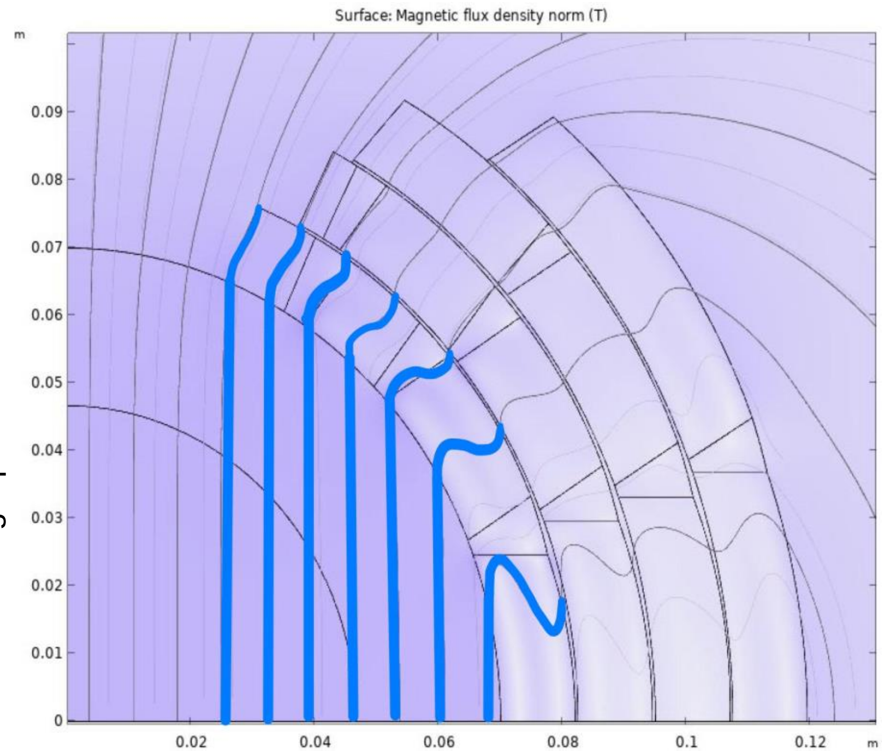
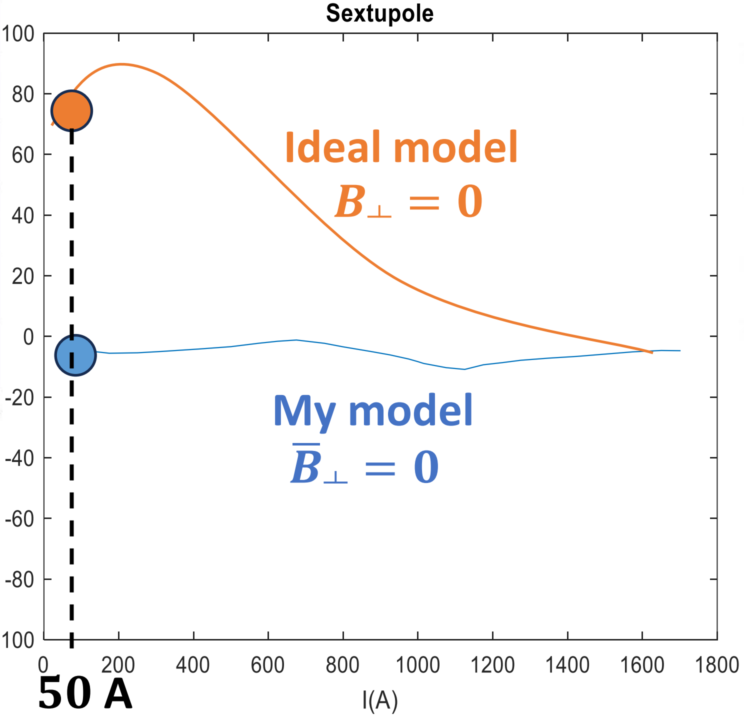
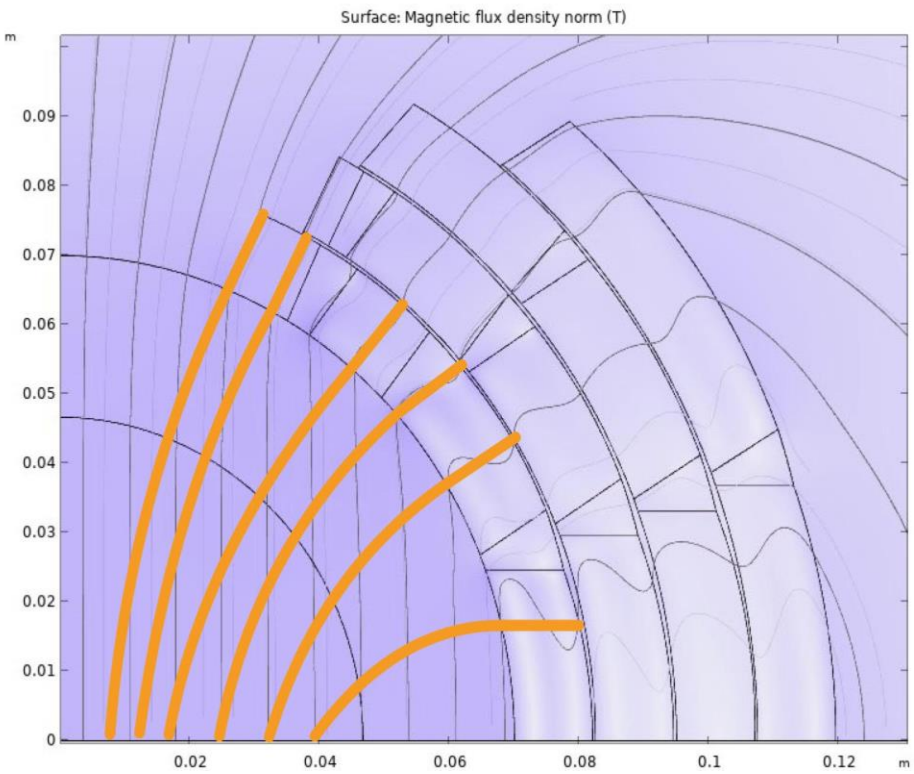


Non Uniform J

$I = 50$ A

$$b_3$$





My model

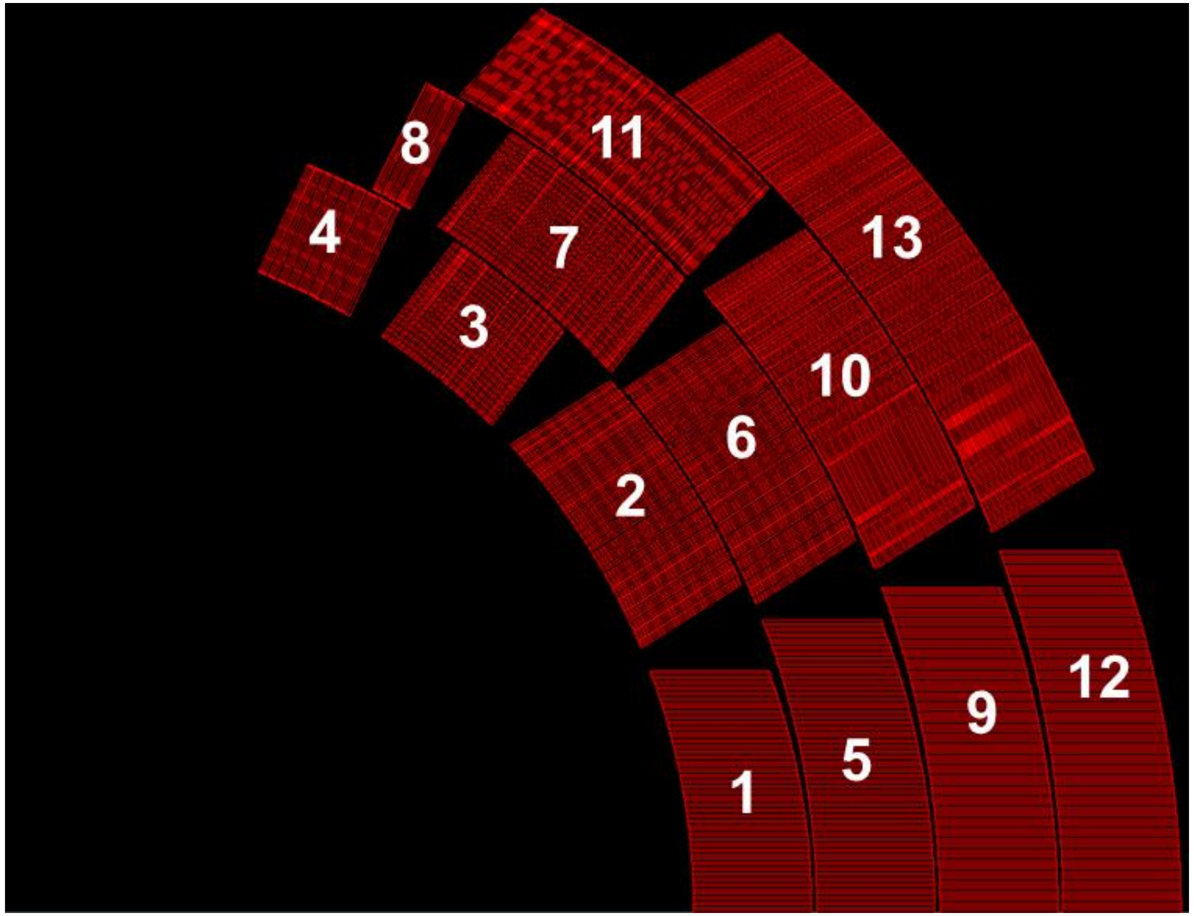
Inside tape → $\bar{B}_\perp = 0$

Ideal model

Inside tape → $B_\perp = 0$

tape quantity and cost

- Total tape quantity = $10.736\ Km/m$ → Total cost of tape = $6441.6\ €/m$

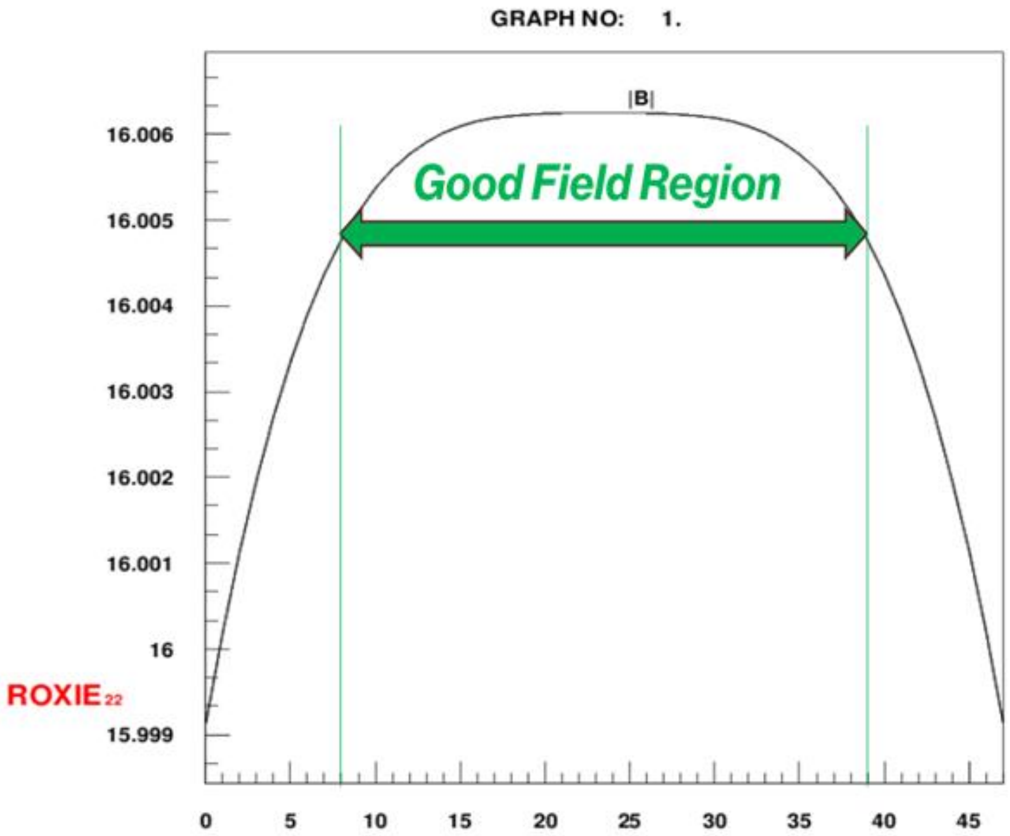


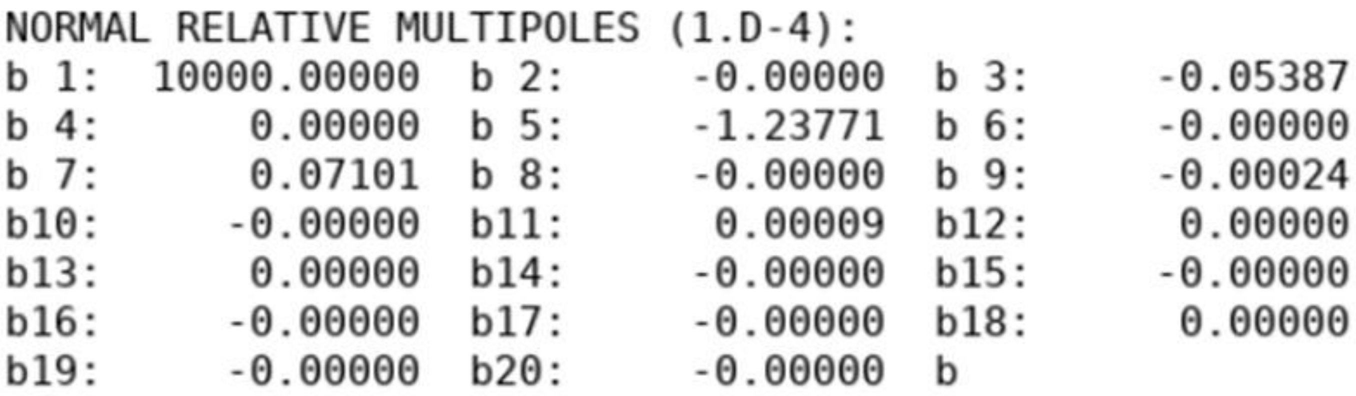
Block n.	Cable length (per meter)
1	**182**
2	**182**
3	**106**
4	**76**
5	**220**
6	**190**
7	**170**
8	**32**
9	**270**

Block n.	Cable length (per meter)
10	**270**
11	**240**
12	**300**
13	**446**

Layer n.	Cable length (per meter)
1	**546**
2	**612**
3	**780**
4	**746**

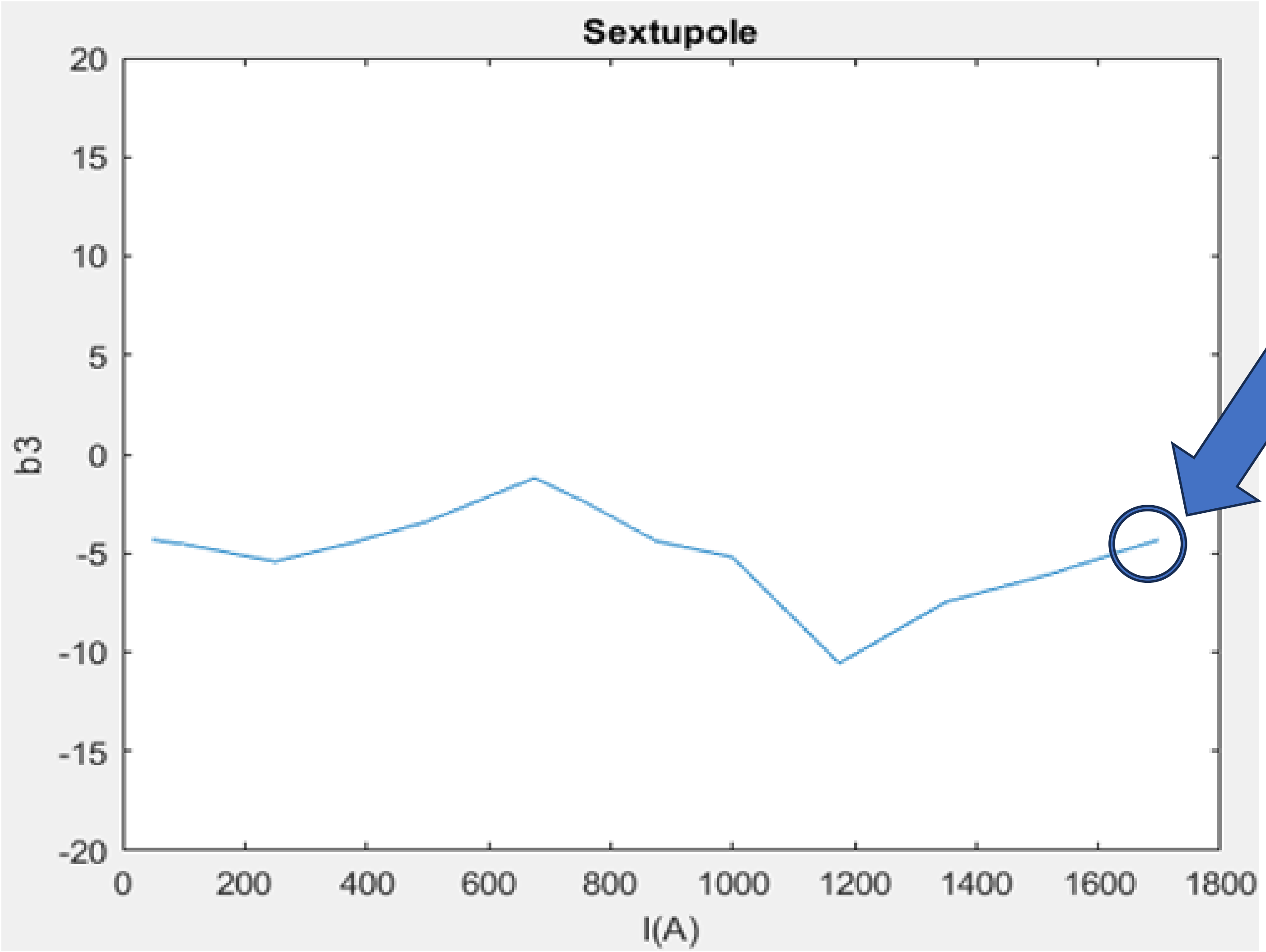
Field quality
uniform nominal current





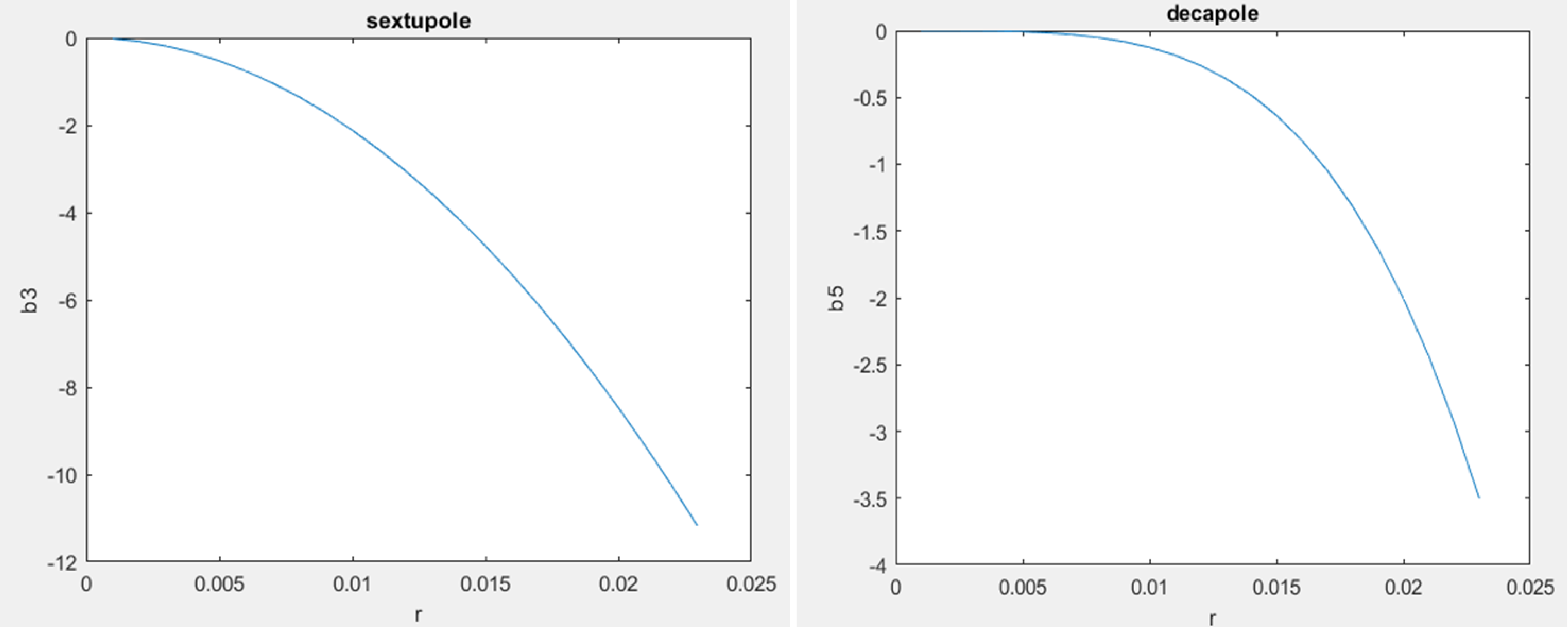
```
NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:   10000.00000  b 2:      -0.00000  b 3:      -0.05387
b 4:       0.00000  b 5:      -1.23771  b 6:      -0.00000
b 7:       0.07101  b 8:      -0.00000  b 9:      -0.00024
b10:      -0.00000  b11:       0.00009  b12:       0.00000
b13:       0.00000  b14:      -0.00000  b15:      -0.00000
b16:      -0.00000  b17:      -0.00000  b18:       0.00000
b19:      -0.00000  b20:      -0.00000  b
```

Field quality at non uniform current



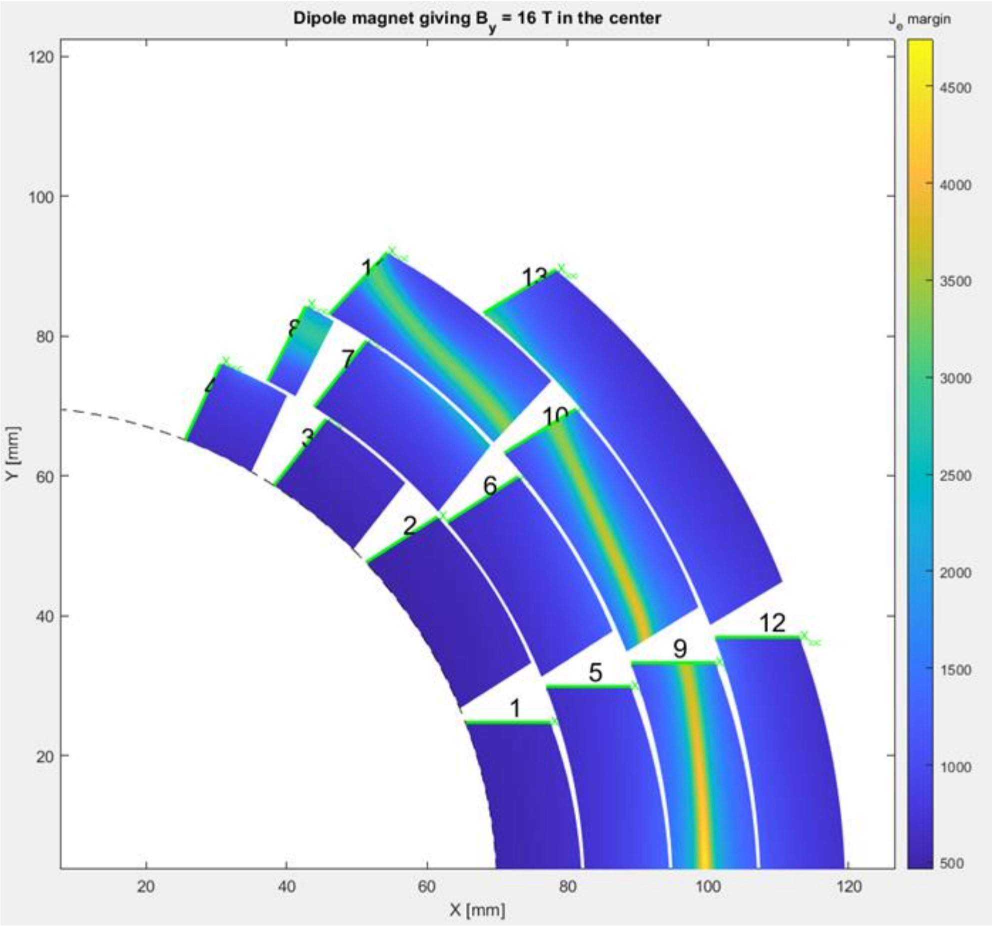
b3 (I_{nom}) = -5

Field quality
non uniform nominal current

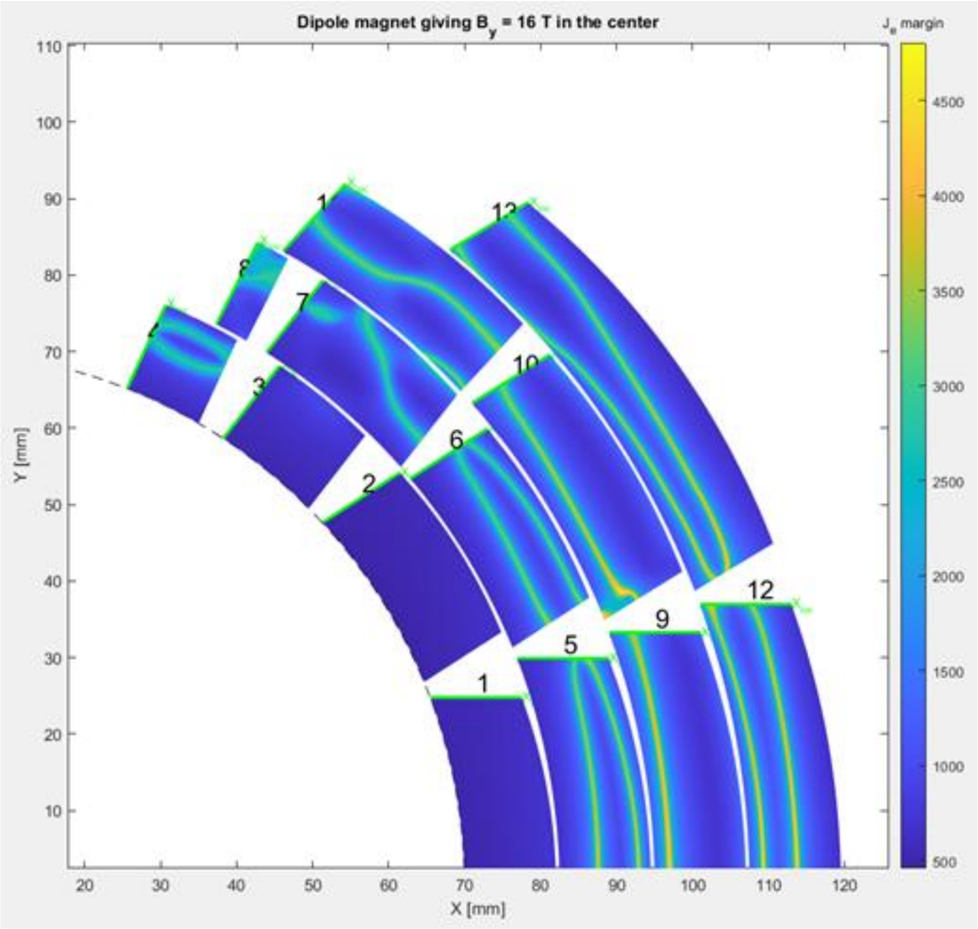


Margin

J uniform

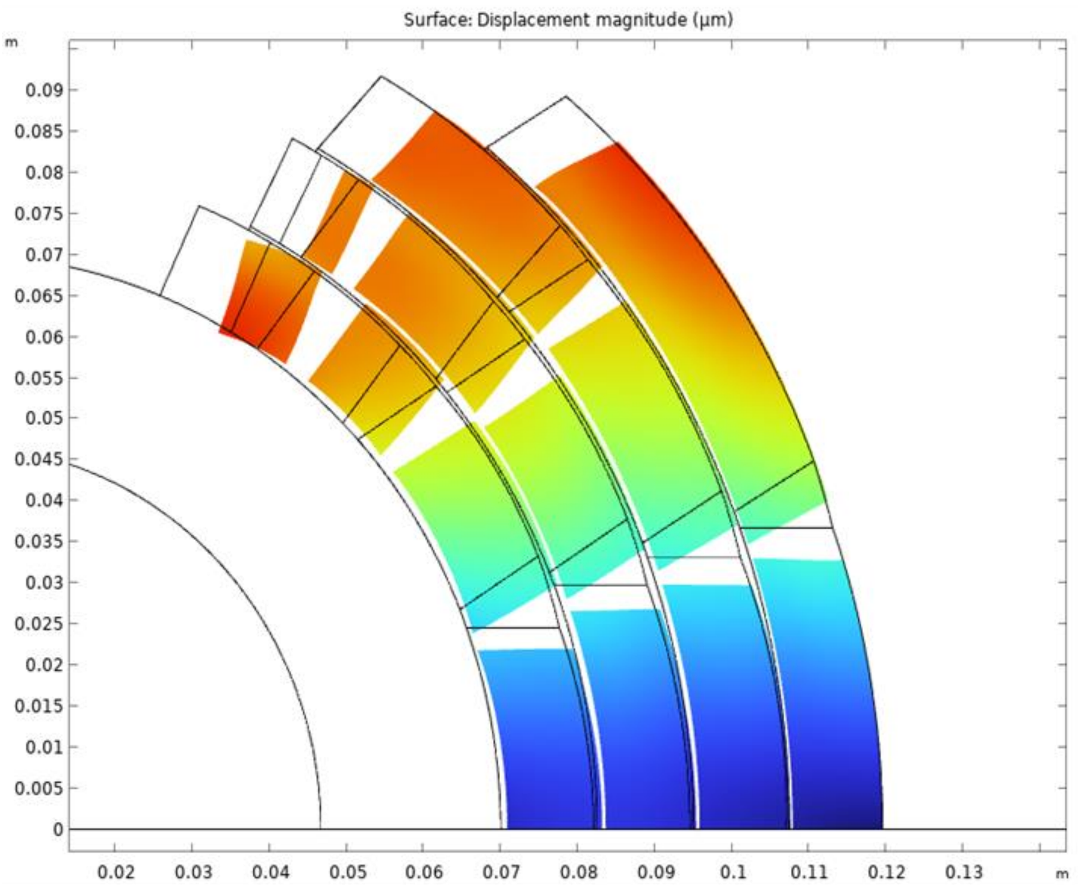


J non uniform

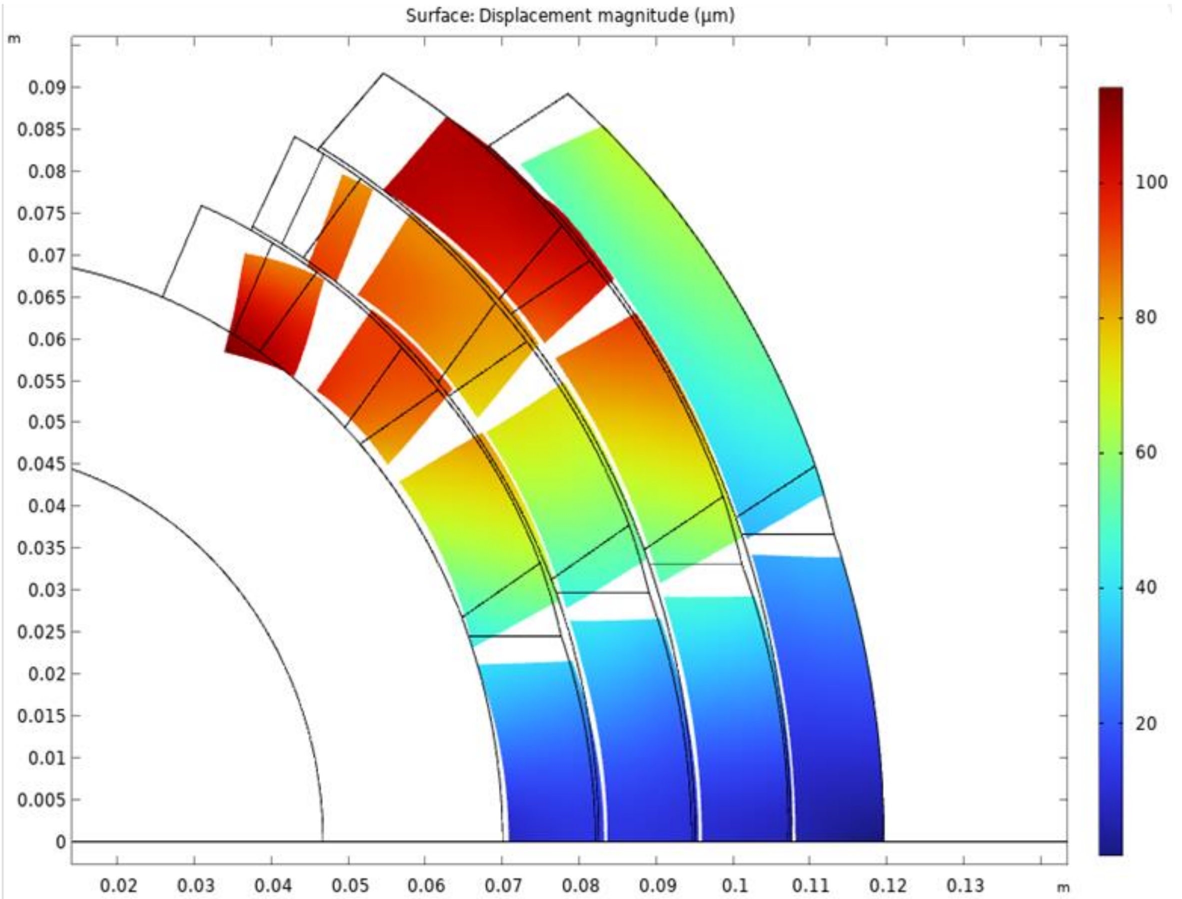


Deformation

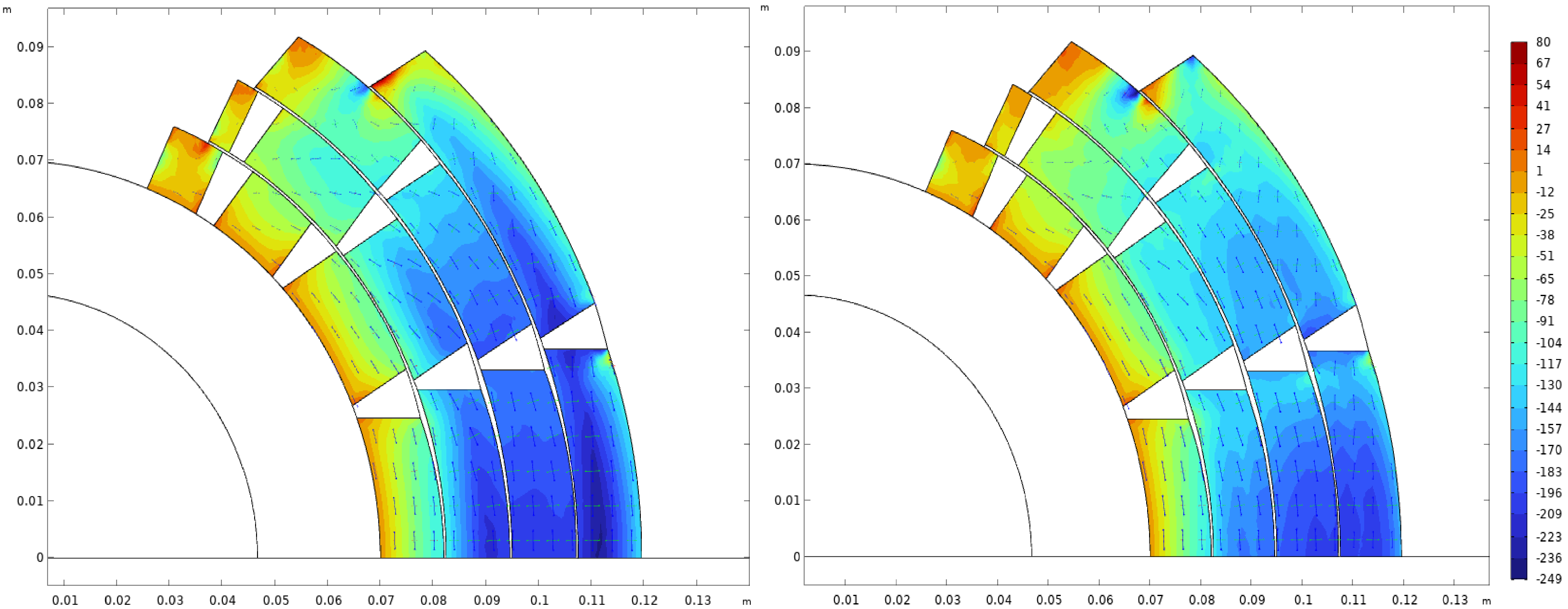
J uniform



J non uniform



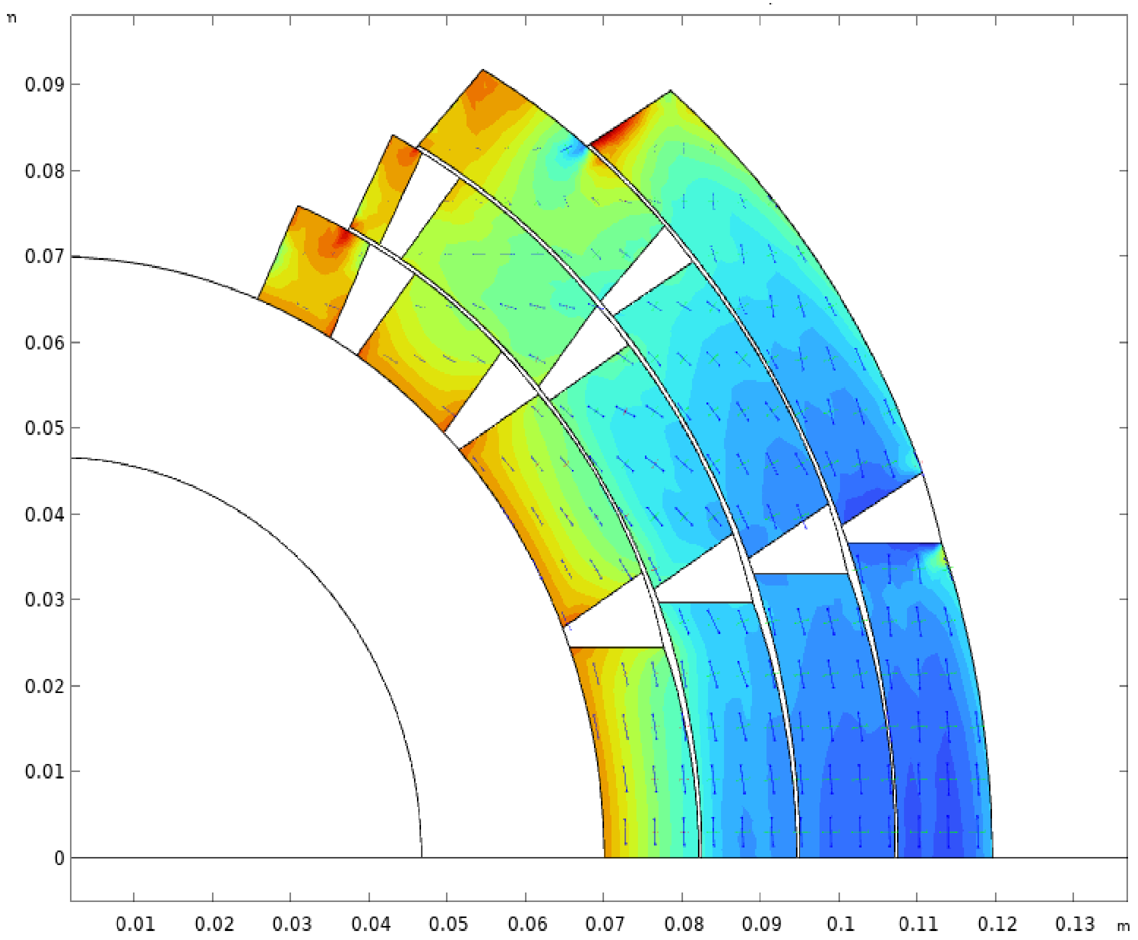
Radial stress


J uniform

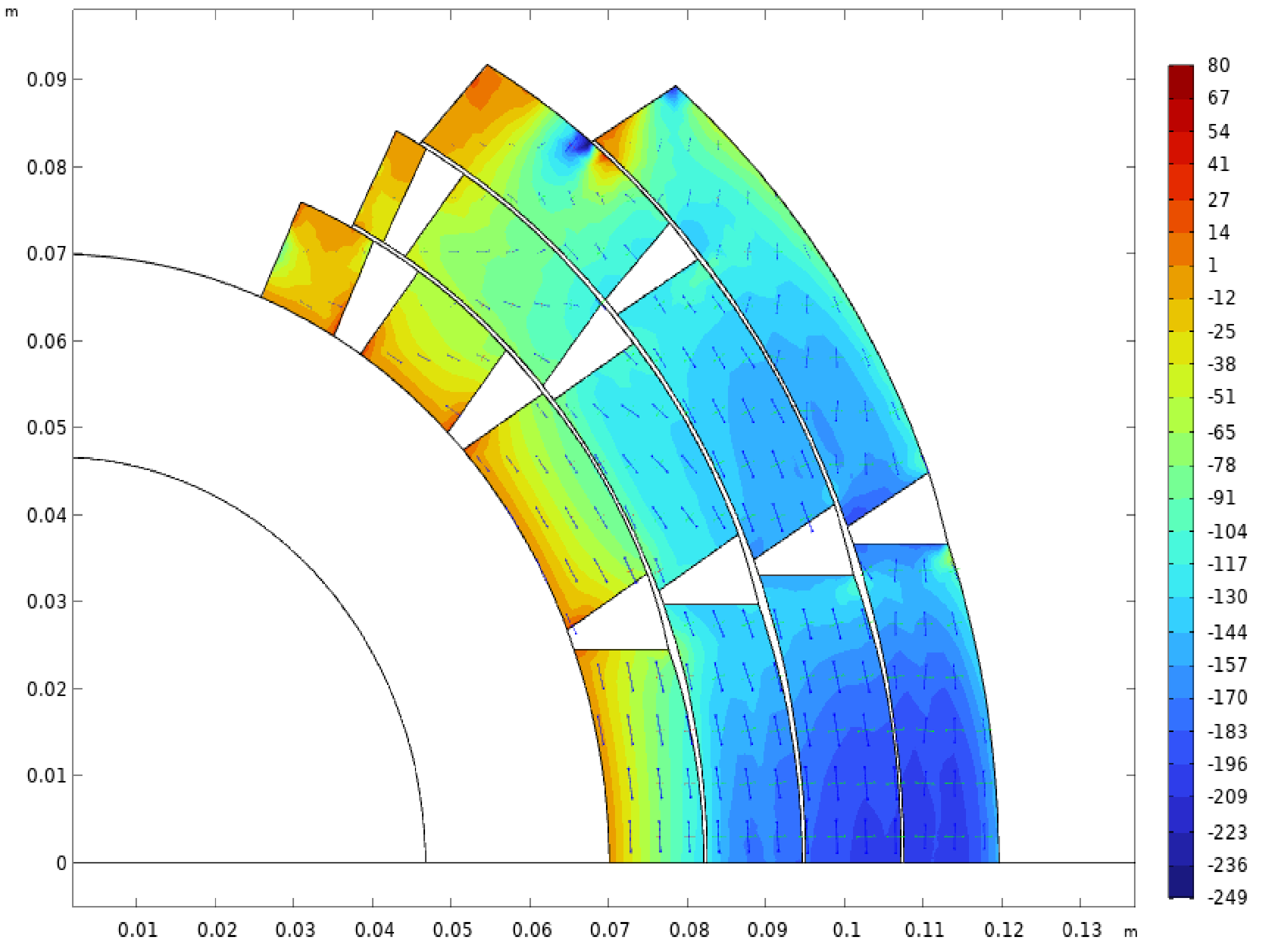
J non uniform

Radial stress

Bounded layers

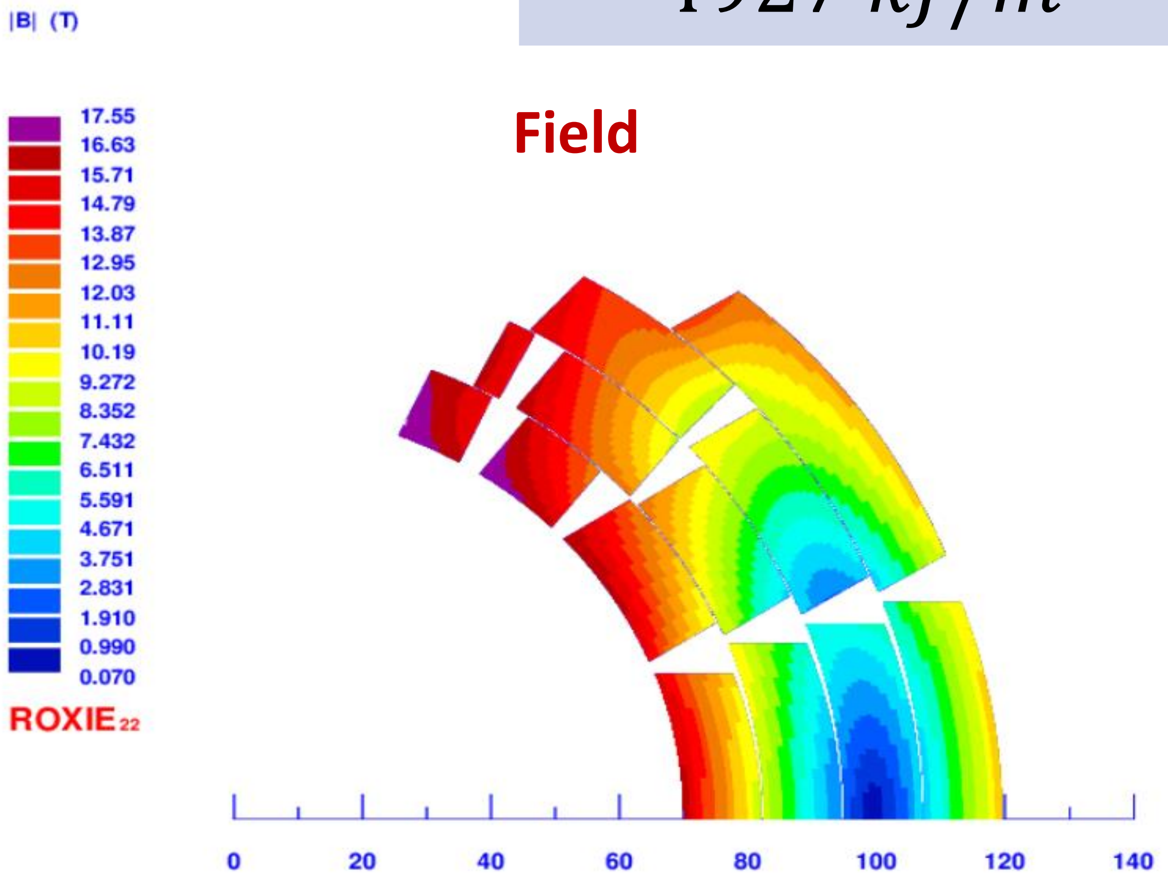


Unbounded layers

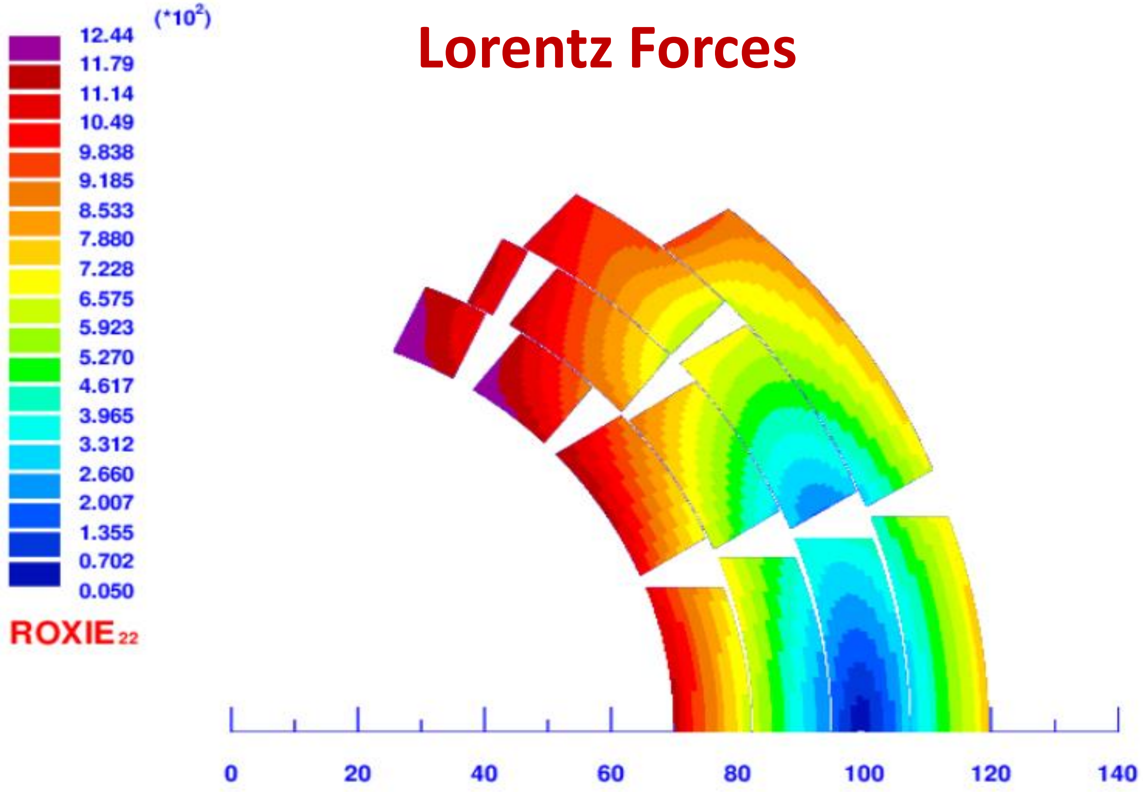


Field & Forces
(J uniform)

Stored Energy	Self Inductance
$4927\ kJ/m$	$3402\ mH/m$



Field



Lorentz Forces

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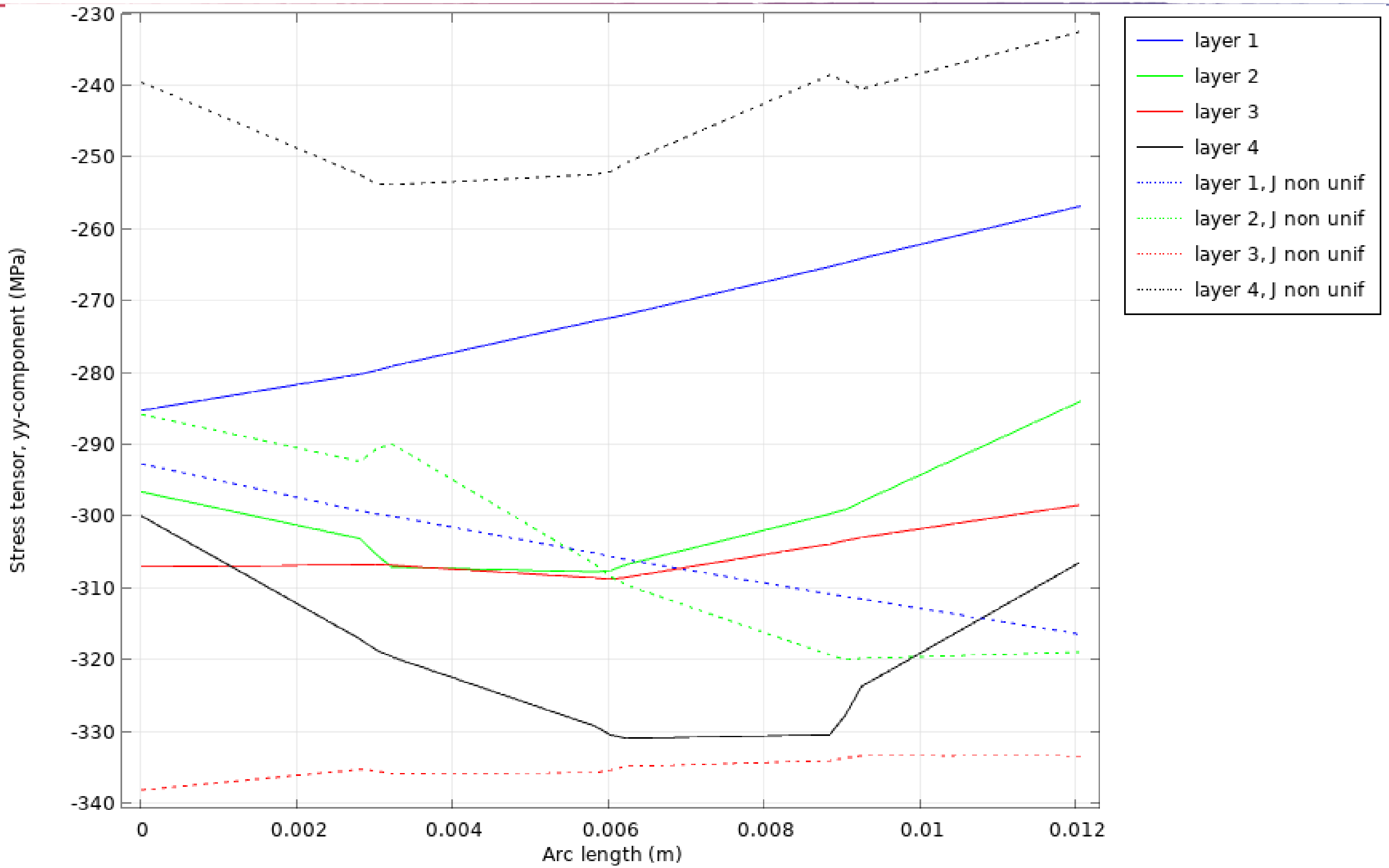
Stress on Midplane



heat intercept

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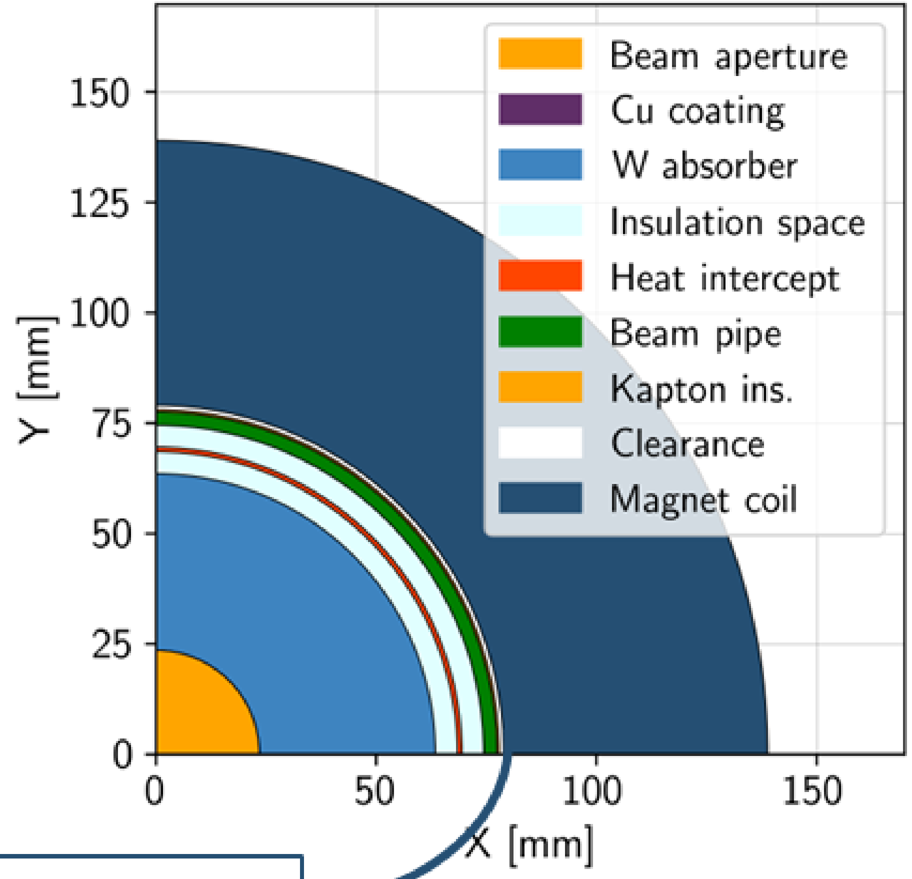
Beam aperture (5σ)	23.5 mm radius
Cu layer beam screen	0.01 mm thick
Tungsten absorber	40 mm thick
Insulation space	5 mm thick
Heat intercept	1 mm thick
Insulation space	5 mm thick
Beam pipe	3 mm thick
Kapton insulation	0.5 mm thick
Clearance	1 mm thick
Coil pack*	(60 mm thick)

*thickness TBD, placeholder



Coil aperture 158 mm