Combined Function Magnets

Workshop at LASA

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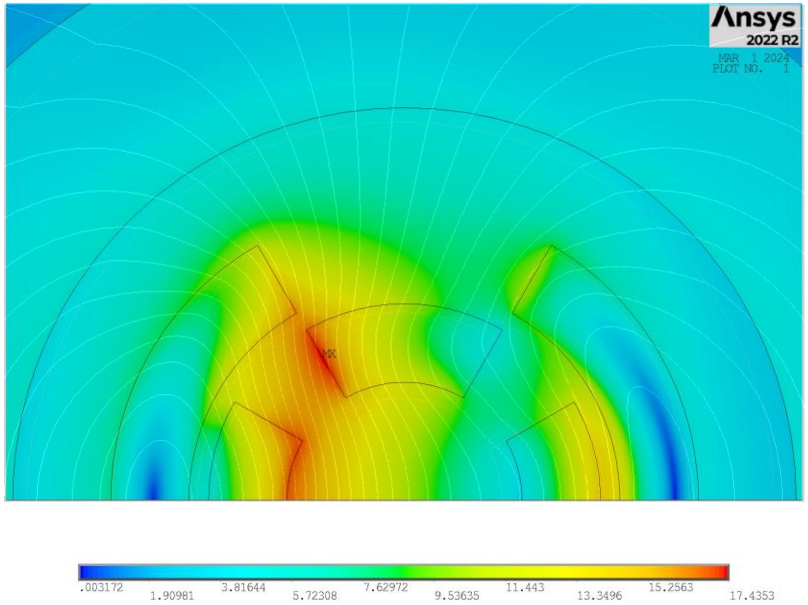
Nested Configurations



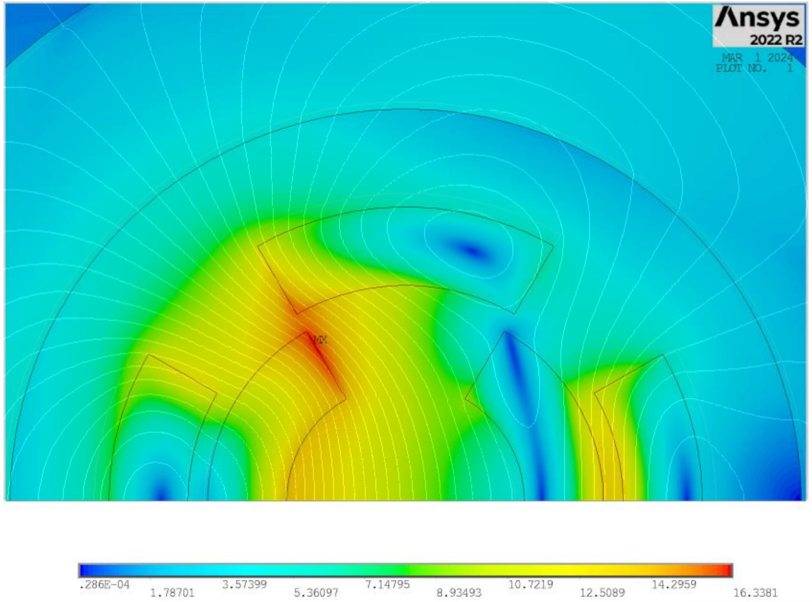
Quad into dipole:

(ReBCO @20 K)

$J = 3.5 \cdot 10^8 A/m^2$

$B \sim 11.7\ T$

$G \sim 143.3$ T/m



Dipole into quad:

(ReBCO @20 K)

$J = 3.5 \cdot 10^8 A/m^2$

$B \sim 12.4\ T$

$G \sim 90.4$ T/m

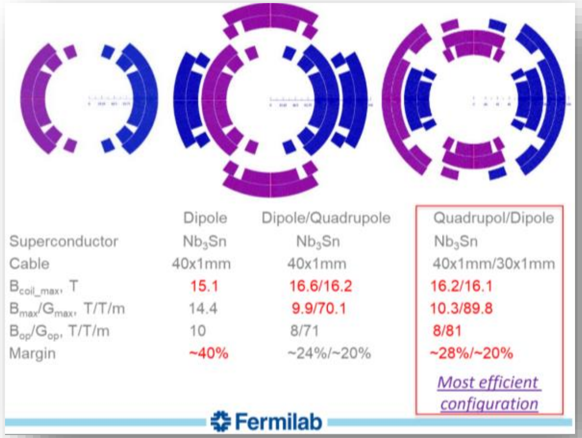
Arc:

- Combined function magnets: B1, **B1+B2** and **B1+B3**
- B ≈ 8…16 T; G ≈ 320 T/m; G' ≈ 7100 T/m^2
- Aperture ≈ 160 mm

Final focus:

- Combined function magnets: B1, B2, **B1+B2** , **B1+B3**
- B ≈ 4…16 T; G ≈ 100…300 T/m; G' ≈ 12000 T/m^2
- Aperture ≈ 120…300 mm

The quadrupole into dipole configuration is the most efficient one, in accordance with US-MAP. Additionally, for combined function magnets in the muon collider, quadrupoles are generally required to be stronger than dipoles.



	Dipole	Dipole/Quadrupole	Quadrupol/Dipole
Superconductor	Nb_3Sn	Nb_3Sn	Nb_3Sn
Cable	40x1mm	40x1mm	40x1mm/30x1mm
B_{coil_max}, T	15.1	16.6/16.2	16.2/16.1
B_{max}/G_{max}, T/T/m	14.4	9.9/70.1	10.3/89.8
B_{op}/G_{op}, T/T/m	10	8/71	8/81
Margin	~40%	~24%/~20%	~28%/~20%
			Most efficient configuration

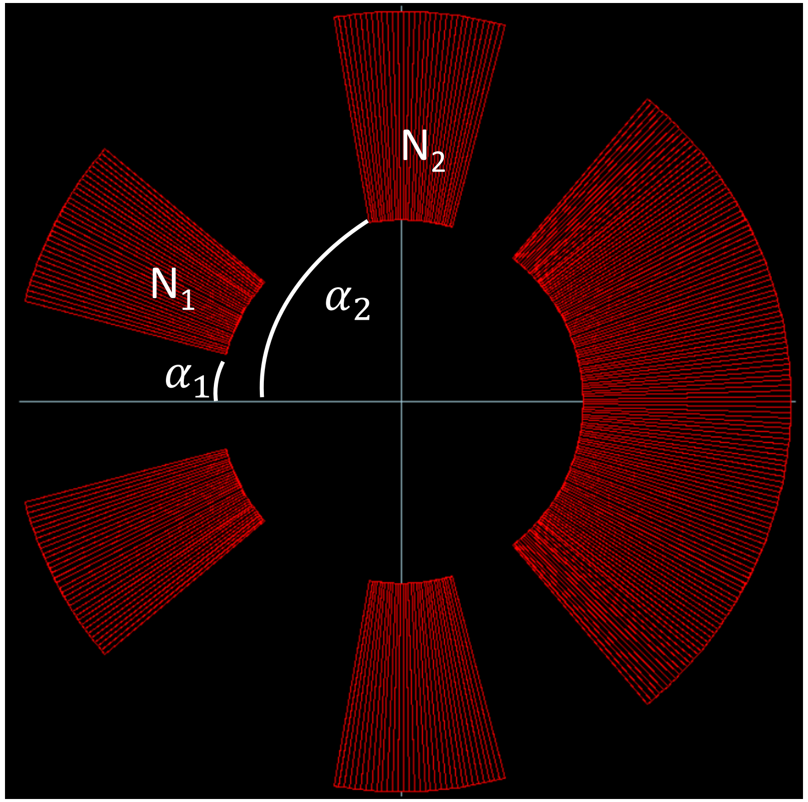
Asymmetric Dipole

Block Data 2D

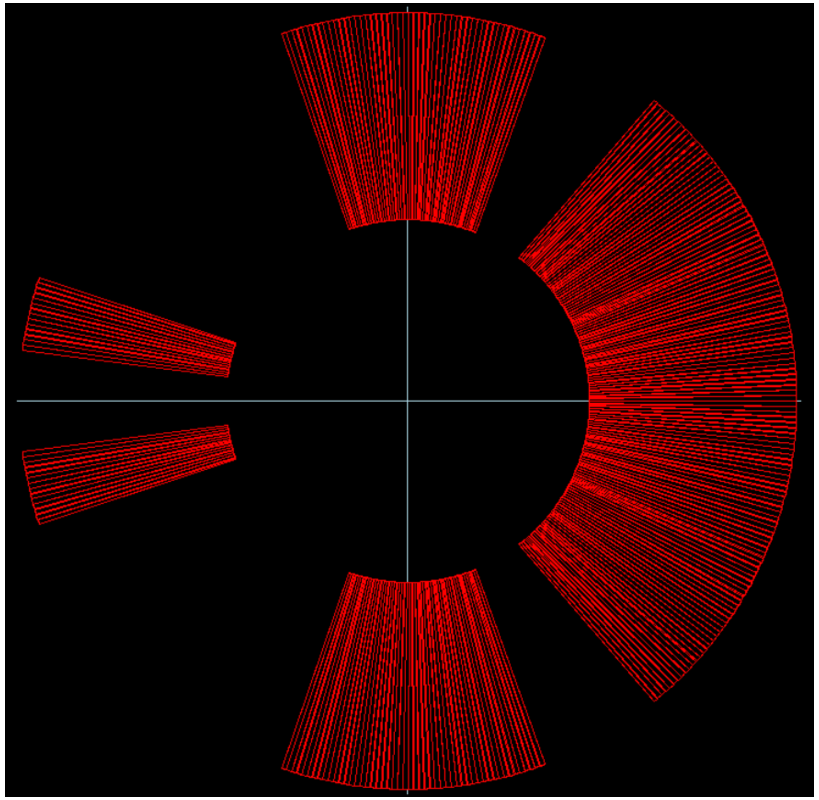
No	Type	NCab	X	Y	\u03b1	Current	Cable name	N1	N2	Imag	Turn
1	Cos	64	70	0	0	48800	REBCO	1	15	0	0
2	Cos	14	70	7.5	7.5	-48800	REBCO	1	15	1	180
3	Cos	50	70	71	71	-48800	REBCO	1	15	1	180

As first approx. I used the same cable assumption of L. Alfonso.

Optimization of α_1, α_2, N_1 and N_2 with ROXIE by maximizing $B_2(@\ R_{ref} = 50\ mm)$ with a weight of 1 and B_1 with a weight of 0.5



ROXIE optimization



$$B = 13\ T$$
$$G = 140\ T/m$$
$$Ratio = 0.5$$

$$Ratio = \frac{B_2@R_{ref}}{B1}$$

Starting from the experience of T.Ogitsu:
https://indico.cern.ch/event/1043242/contributions/4448798/attachments/2279860/3873498/MCM20210712SCFM.pdf

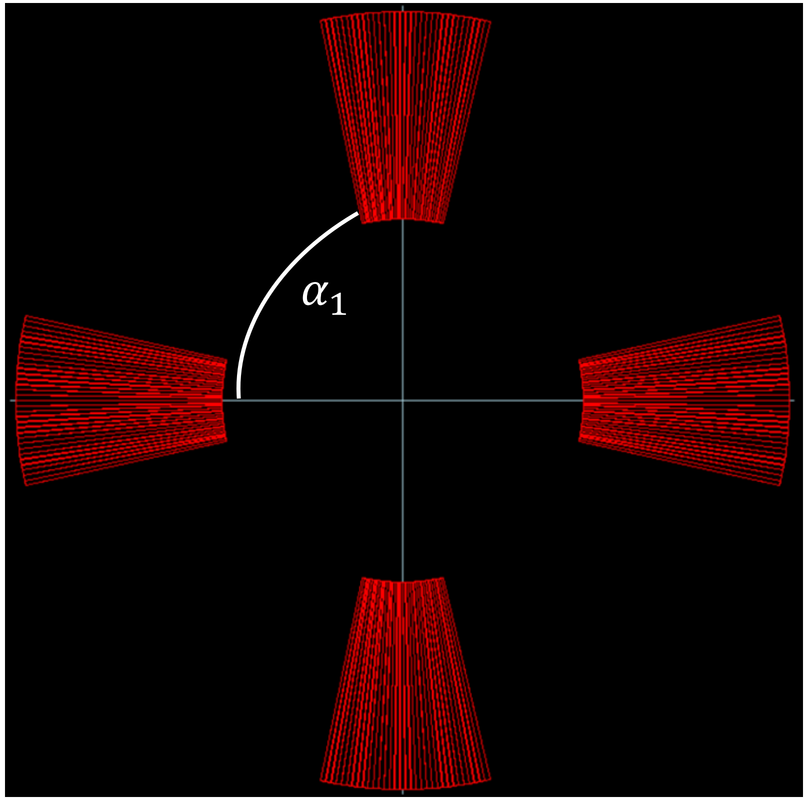
Asymmetric Quadrupole

Block Data 2D

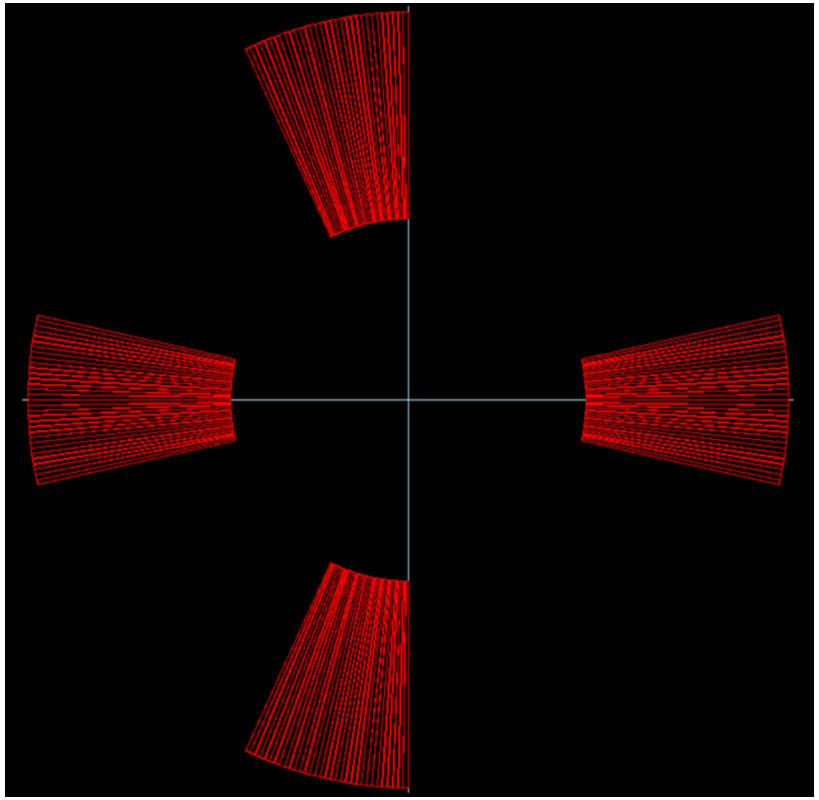
No	Type	NCab	X	Y	\u03b1	Current	Cable name	N1	N2	Imag	Turn
1	Cos	16	70	0	0	24400	REBCO	1	15	0	0
2	Cos	16	70	0	0	24400	REBCO	1	15	1	180
3	Cos	32	70	89.975	89.975	-48800	REBCO	1	15	0	0

As first approx. I used the same cable assumption of L. Alfonso.

Optimization of α_1 with ROXIE by maximizing $B_2(@\ R_{ref} = 50\ mm)$ with a weight of 0.5 and B_1 with a weight of 1



ROXIE optimization

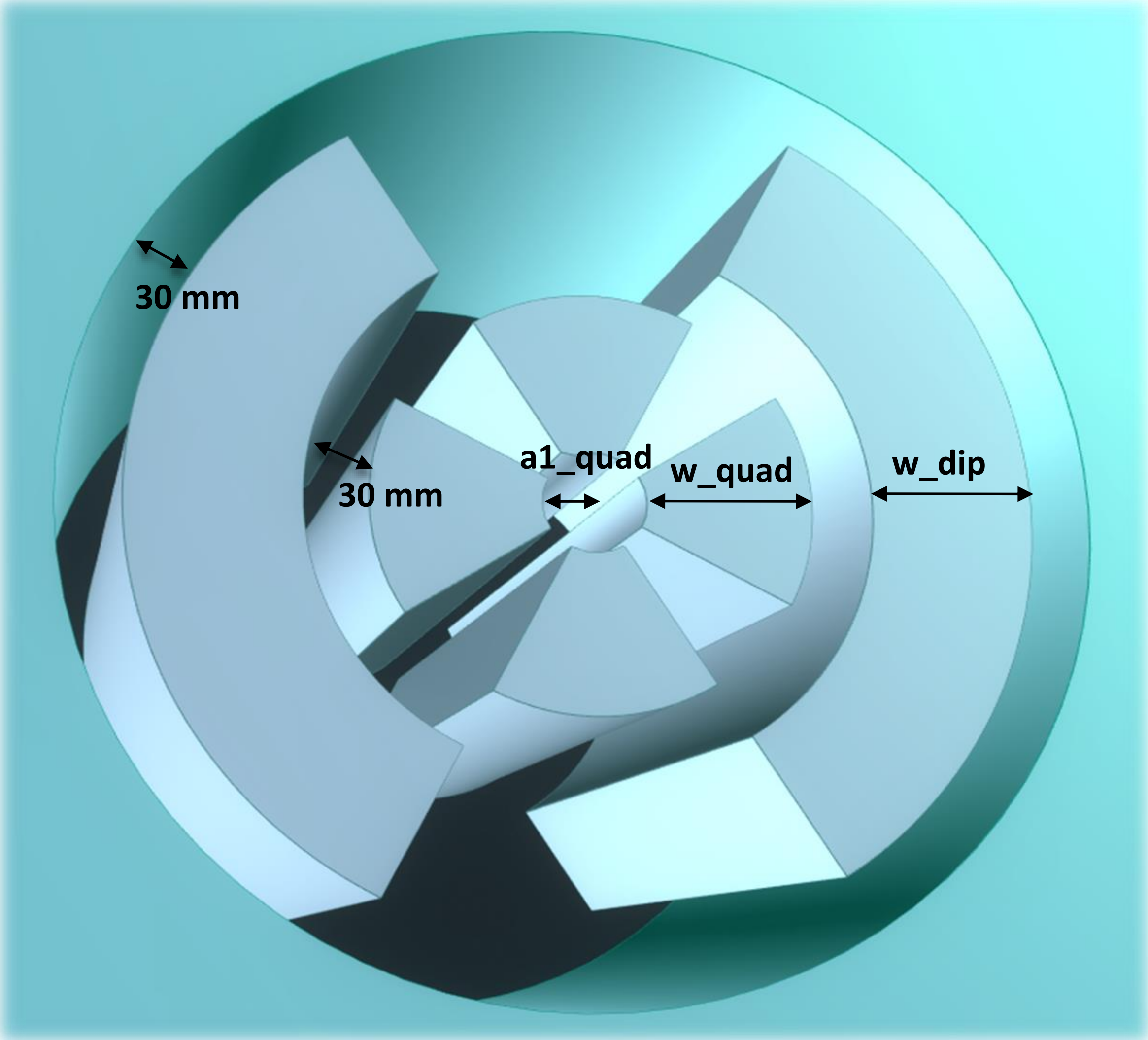


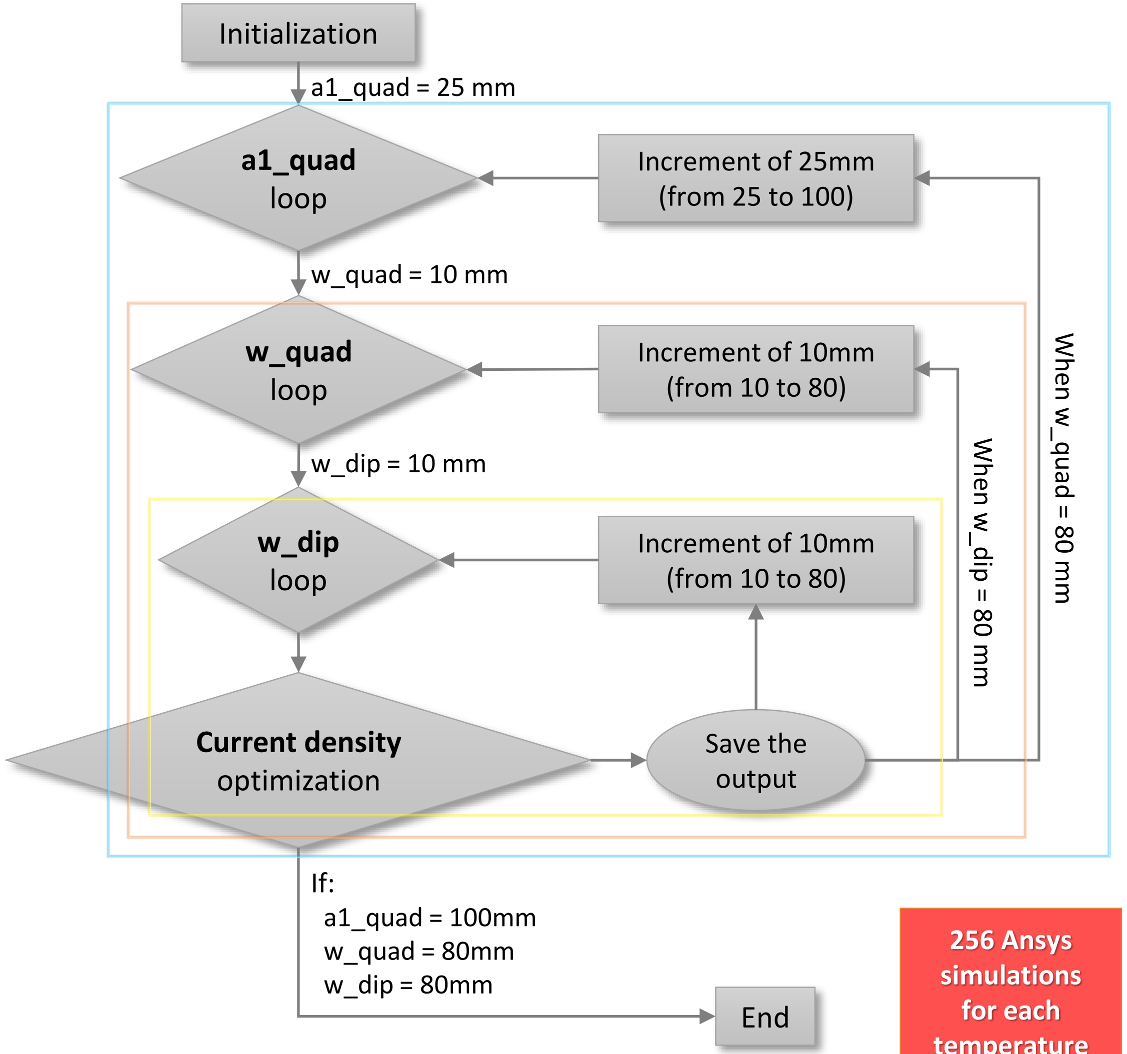
$$B = 4\ \mathrm{T}$$
$$G = 80\ \mathrm{T/m}$$
$$\mathrm{Ratio} = 0.2$$

$$\mathrm{Ratio} = \frac{\mathrm{B1}}{\mathrm{B_2@R_{ref}}}$$

By also allowing the number of conductors to vary, it becomes again an asymmetric dipole.

Python-Ansys Interface

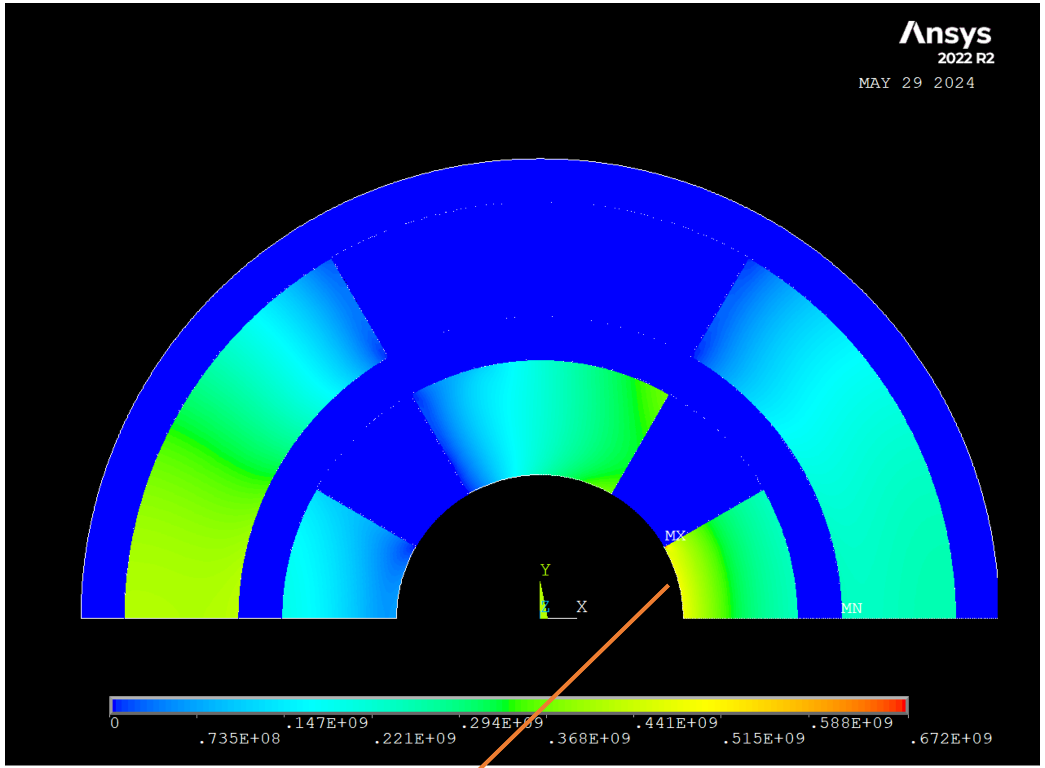




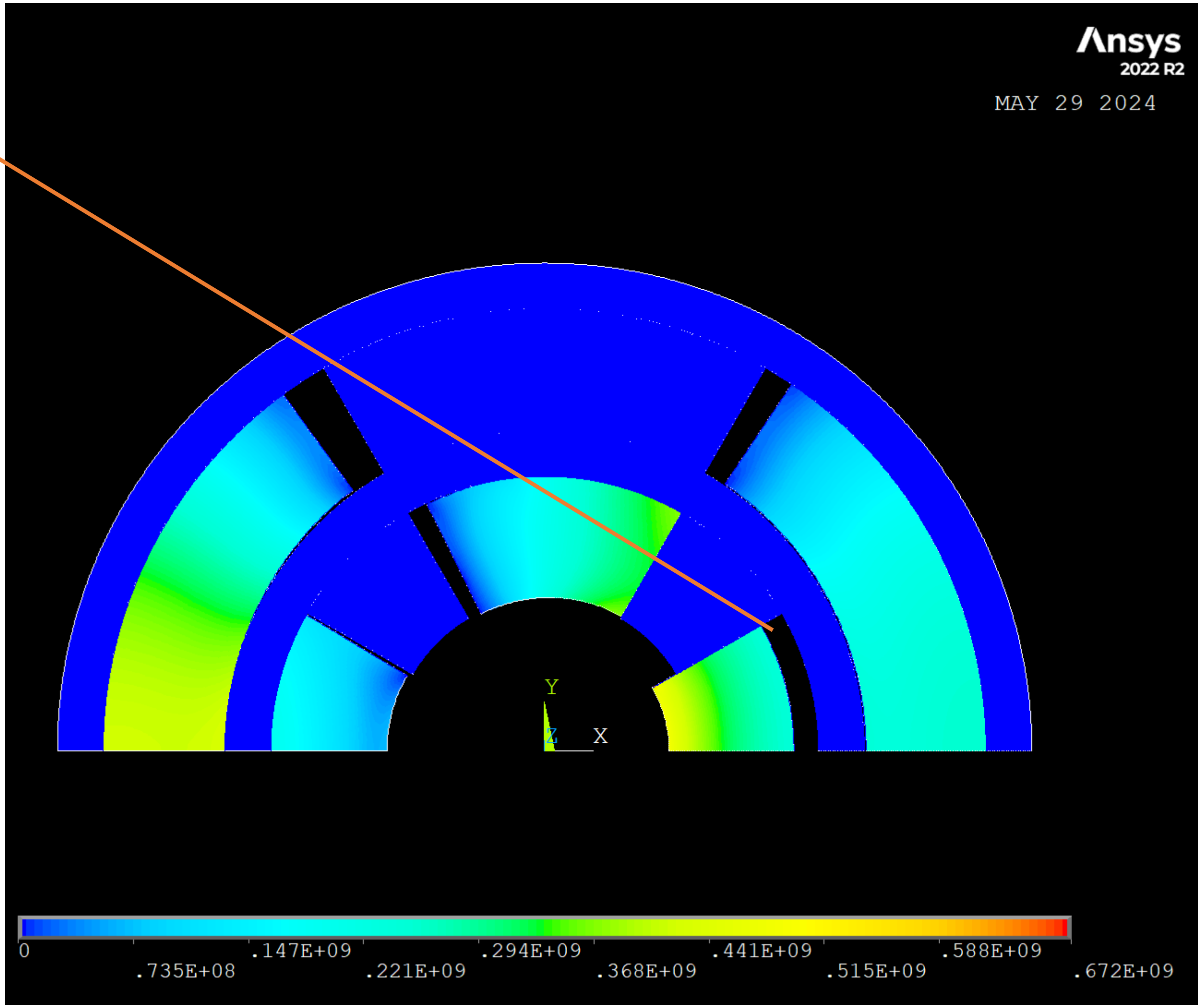
256 Ansys simulations for each temperature

Stress Issue

- Zoom-in on the displacements shows that this sector of the quadrupole moves inward

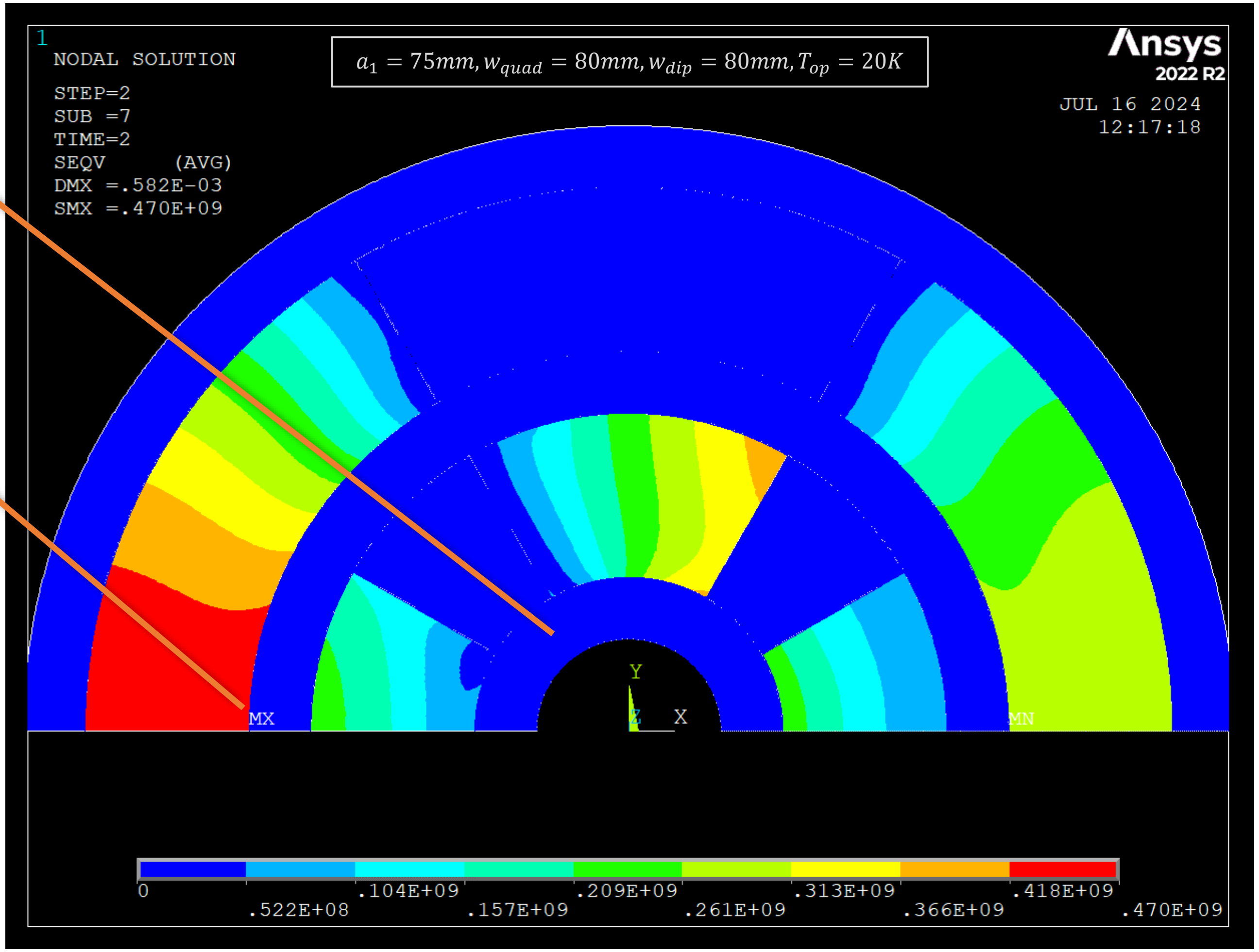


The Von Mises peak stress is on the inner part of the coil

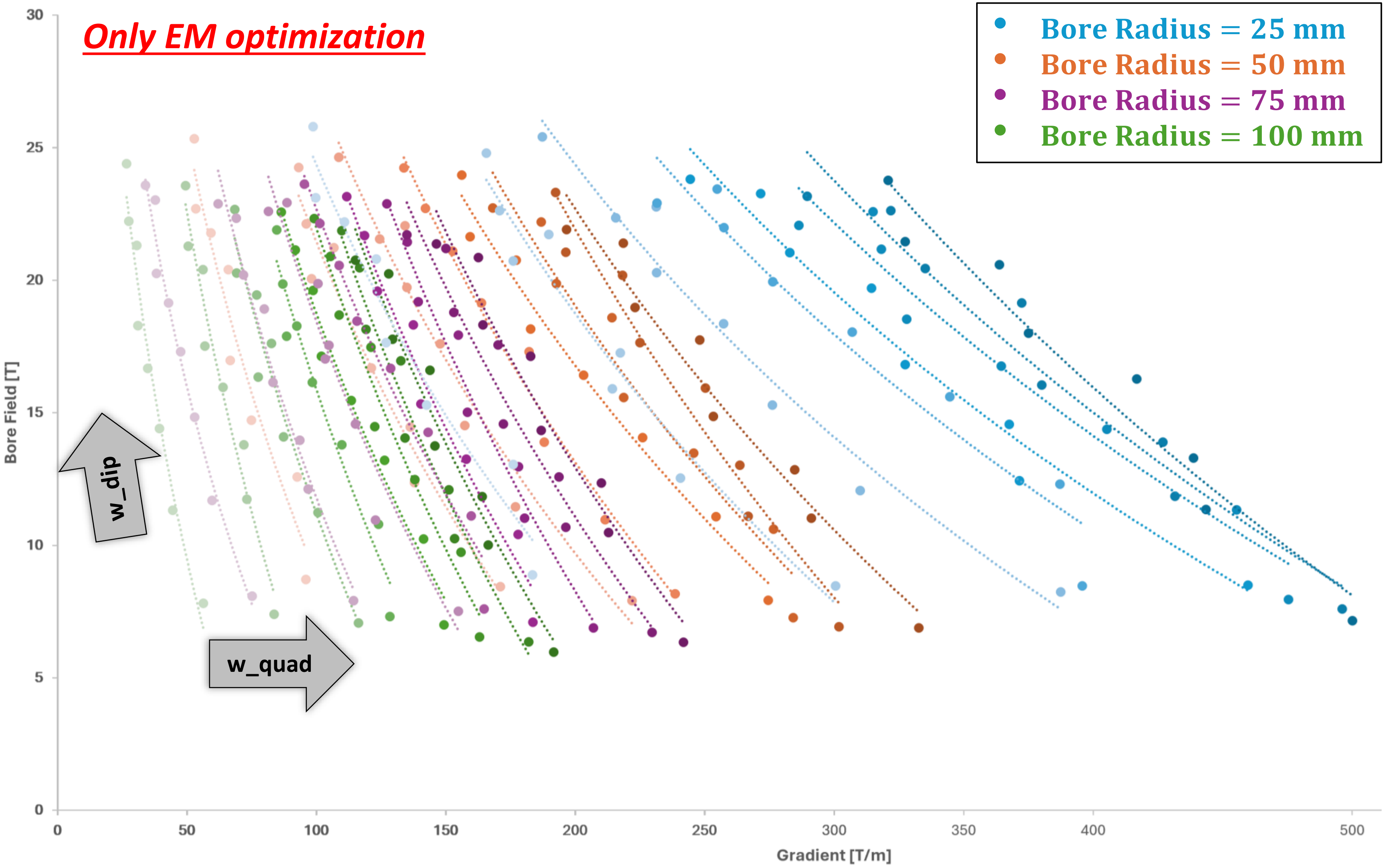


Stress Issue

- To address the issue, we insert an infinitely rigid internal structure to enable the study of stress behavior in the coils.
- Now the peak stress, in the same configuration discussed so far, is on the dipole in compression on the midplane (by changing the parameters, the maximum could be shifted).
- Now that we have a stress distribution in the coils, we can run the code and add a column with the peak stress to the data.
- With all information we will try to create B-G plots for the combined.



B-G plot at 4.5K



Current density optimization (10%)

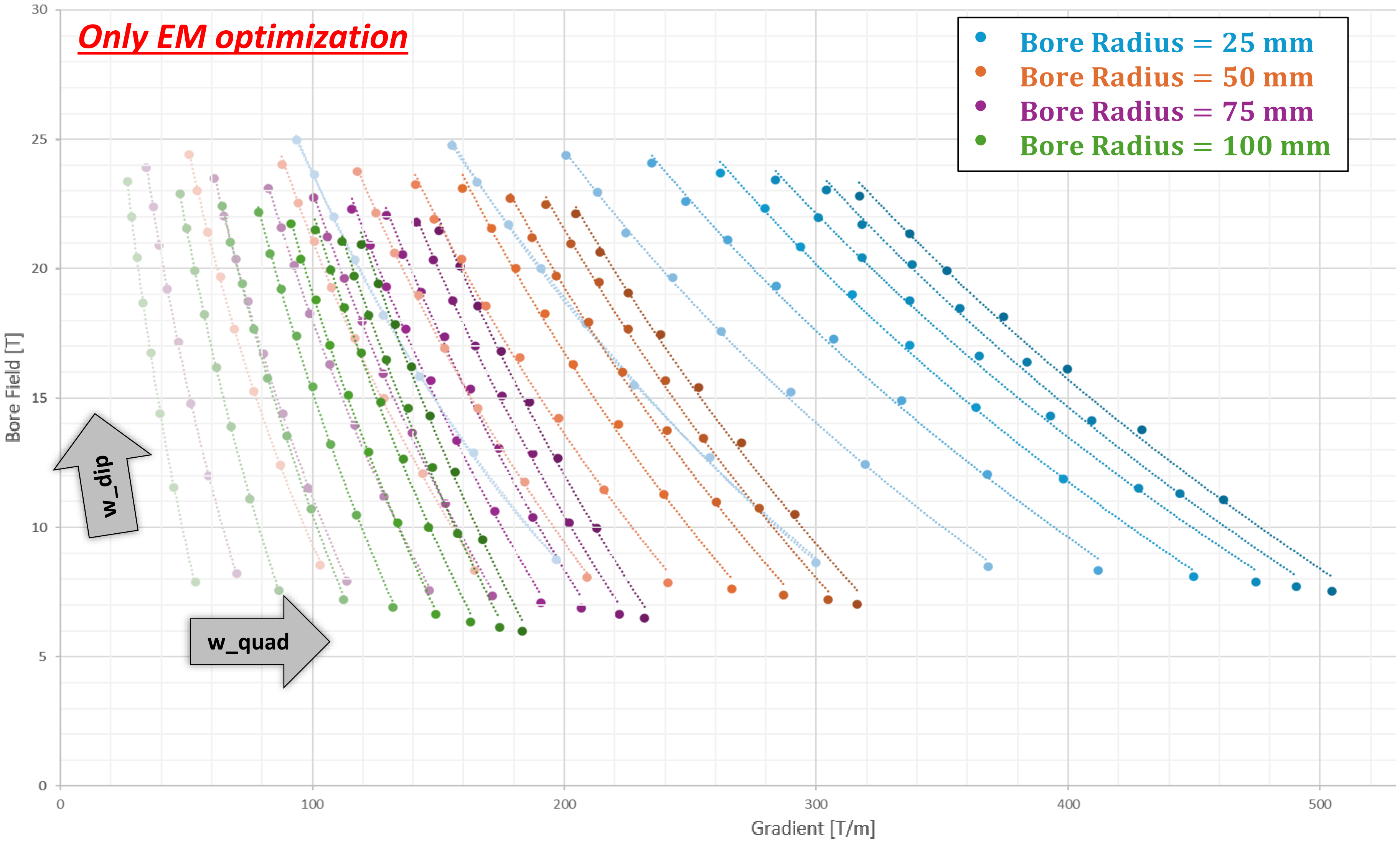
Optimize J_quad and J_dip to be close to the critical current density:

....
while not (0.9 < f < 1.1):
.....
*→ ANSYS input (a1, w_quad, **J_quad**, w_dip, **J_dip**)*
Run ANSYS
ANSYS output →
*f = J_c (B_peak) / **J***
*if f > 1: **J**=**J***1.1*
*else: **J** = **J***0.9*
.....
.....

the optimization acts on J_quad and J_dip with corrections of 10%, and the cycle closes when either J_quad or J_dip is within 10% of J_c

What if we performed a 1% optimization ?

B-G plot at 4.5K



Current density
Optimization (1%)

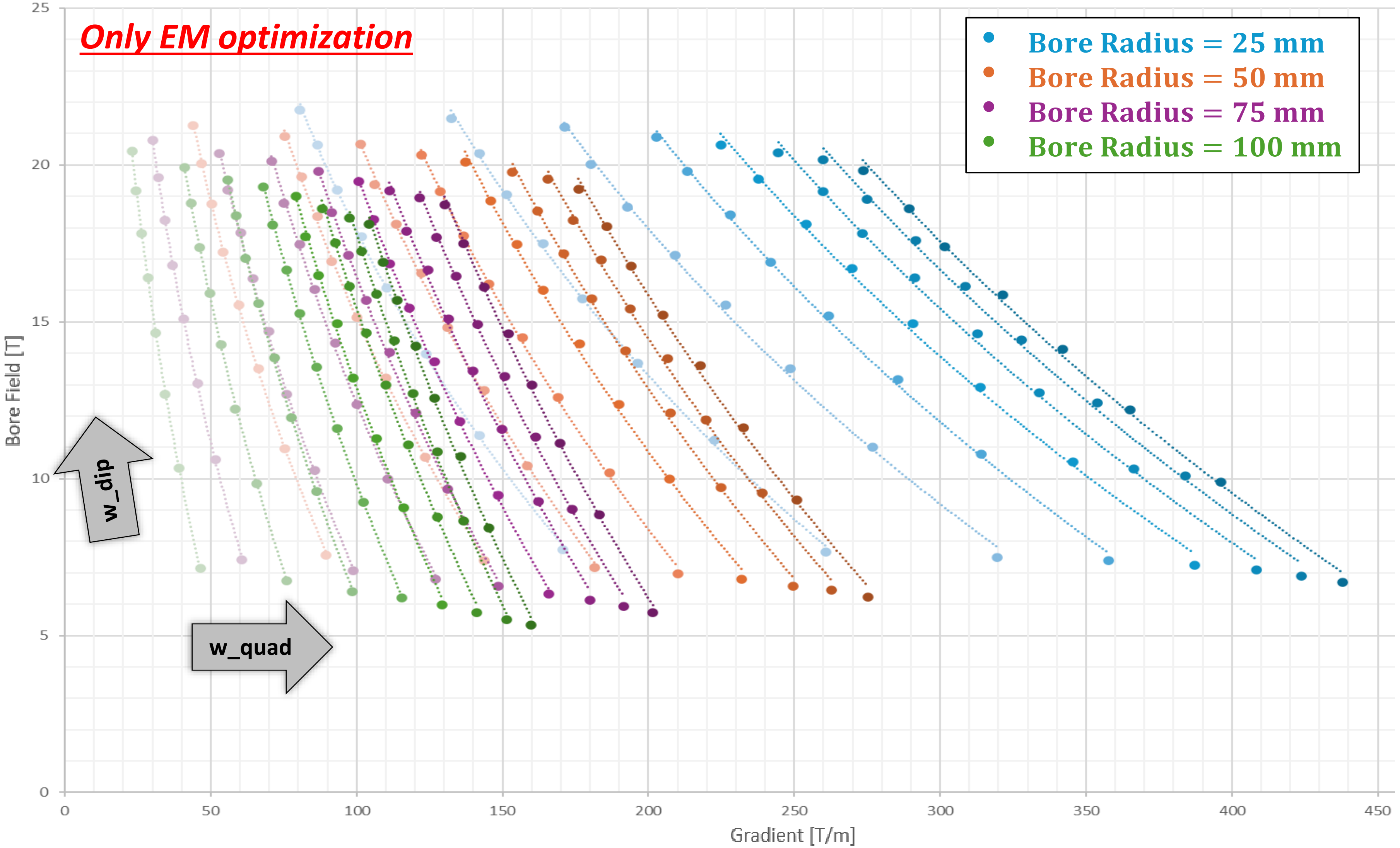
Optimize J_quad and J_dip to be close to the critical current density:

....
while not (0.99 < f < 1.01):
.....
*→ ANSYS input (a1, w_quad, **J_quad**, w_dip, **J_dip**)*
Run ANSYS
ANSYS output →
*f = J_c (B_peak) / **J***
*if f > 1: **J**=**J***1.01*
*else: **J** = **J***0.99*
.....
.....

the optimization acts on J_quad and J_dip with corrections of 1%,
and the cycle closes when either J_quad or J_dip is within 1% of J_c

This optimization requires more computational effort, but the result is more understandable graphs.

B-G plot at 10K



Current density
Optimization (1%)

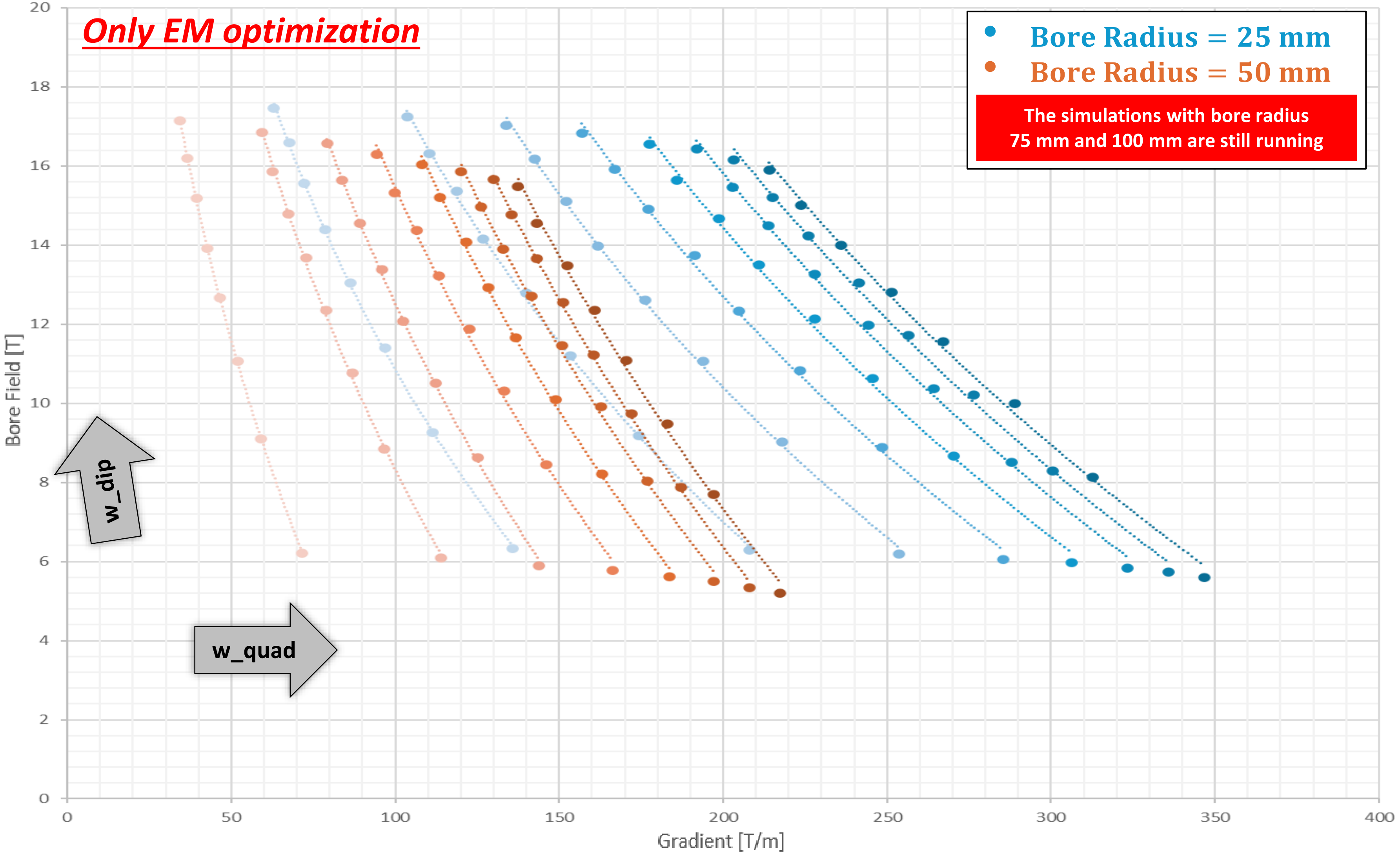
Optimize J_quad and J_dip to be close to the critical current density:

```
....
while not ( 0.99 < f < 1.01 ):
    .....
    → ANSYS input (a1, w_quad, J_quad, w_dip, J_dip)
    Run ANSYS
    ANSYS output →
    f = J_c (B_peak) / J
    if f > 1: J=J*1.01
    else: J = J*0.99
    .....
.....
```

the optimization acts on J_quad and J_dip with corrections of 1%, and the cycle closes when either J_quad or J_dip is within 1% of J_c

This optimization requires more computational effort, but the result is more understandable graphs.

B-G plot at 20K



Current density
Optimization (1%)

Optimize J_quad and J_dip to be close to the critical current density:

```
....
while not ( 0.99 < f < 1.01 ):
    .....
    → ANSYS input (a1, w_quad, J_quad, w_dip, J_dip)
    Run ANSYS
    ANSYS output →
    f = J_c (B_peak) / J
    if f > 1: J=J*1.01
    else: J = J*0.99
    .....
.....
```

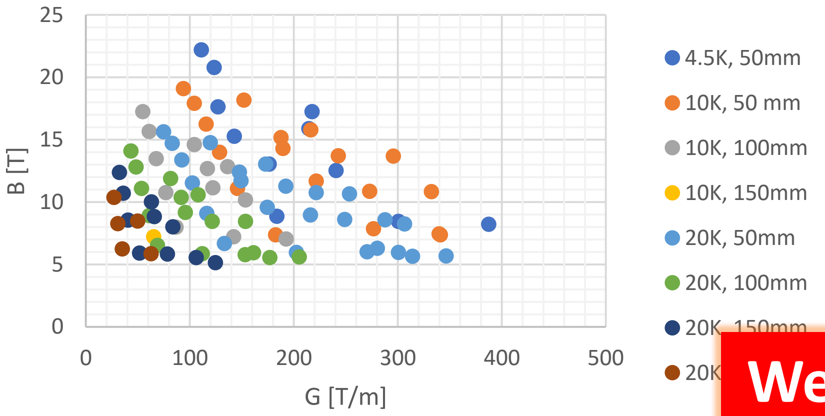
the optimization acts on J_quad and J_dip with corrections of 1%, and the cycle closes when either J_quad or J_dip is within 1% of J_c

This optimization requires more computational effort, but the result is more understandable graphs.

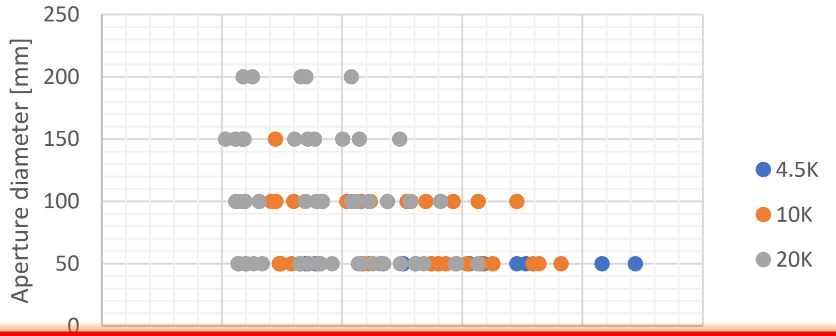
Stress and Cost considerations

Manually excluding the points that exceed the cost (400 kEUR/m) and the stress (400 MPa) limits

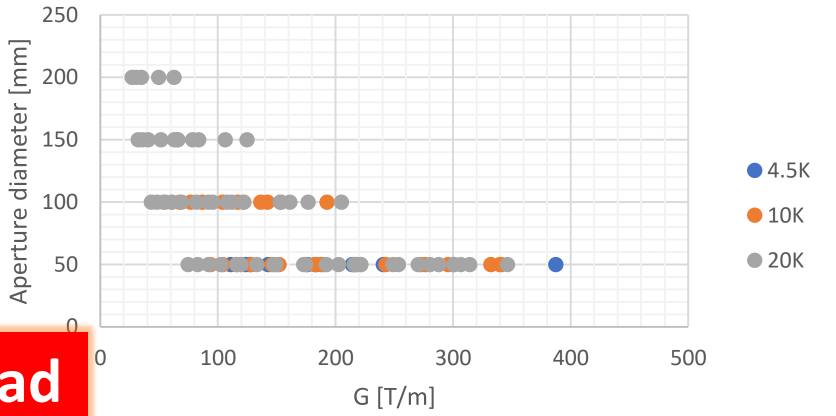
B vs G – Cost and Stress limits



A vs B – Cost and Stress limits

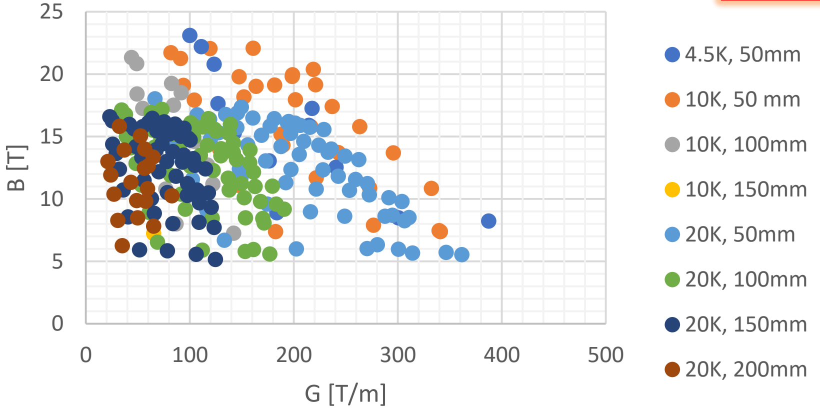


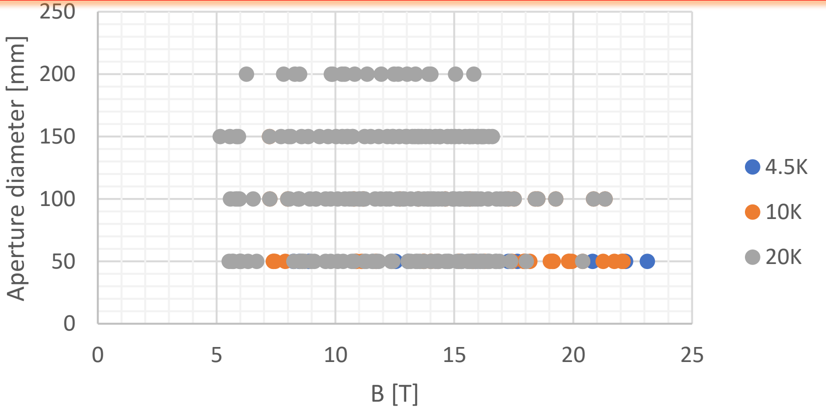
A vs G – Cost and Stress limits



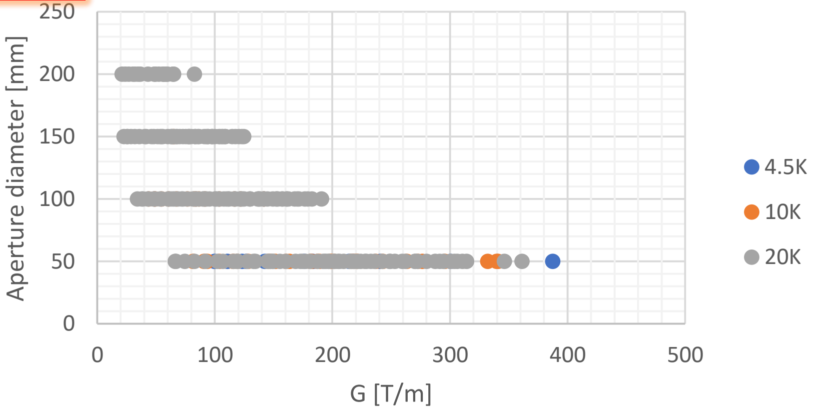
We should optimize the stress instead of excluding the points manually

B vs G – only Stress limit

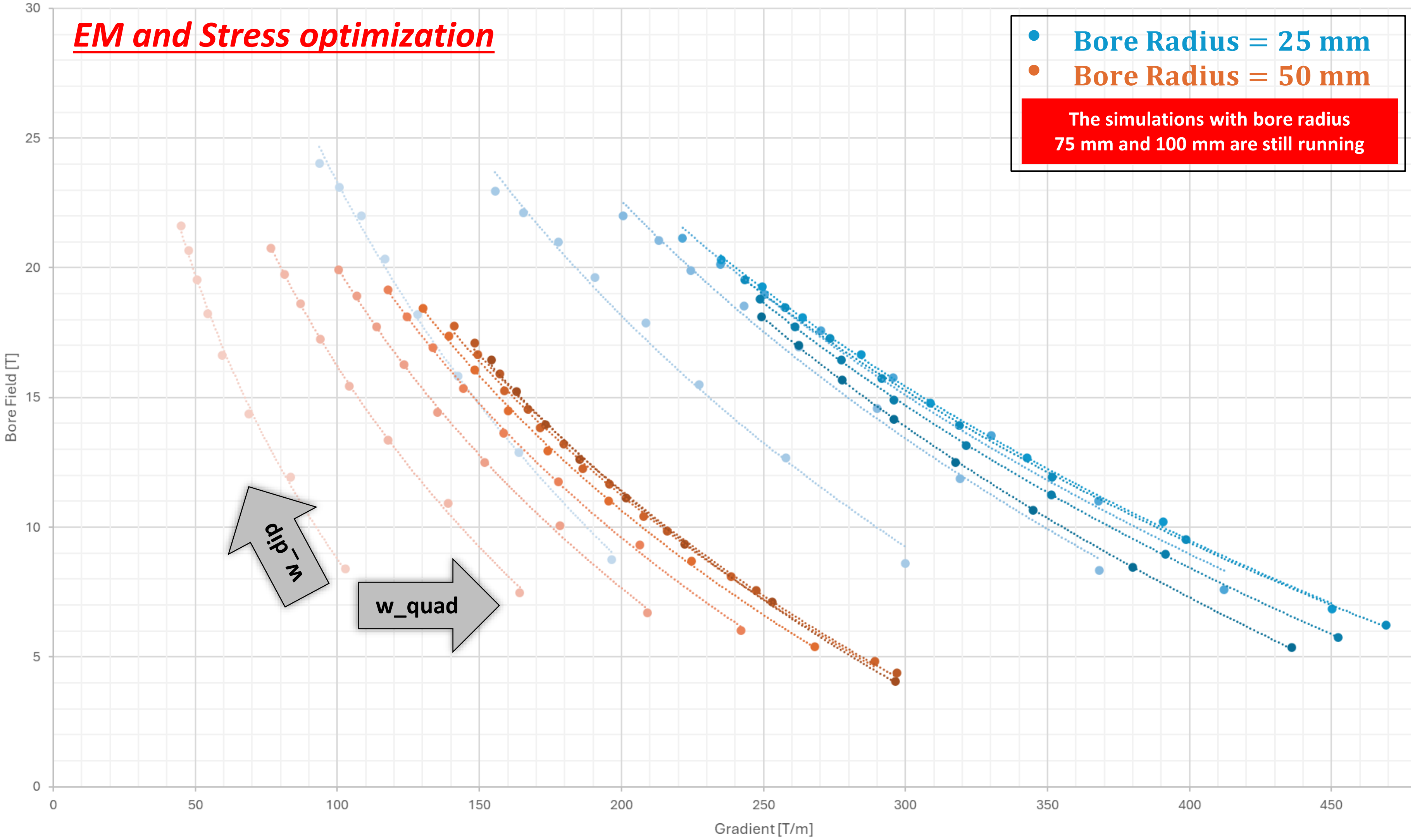




A vs G – only Stress limit



B-G plot at 4.5K



Midplane pressure optimization

Optimize (decrease) J_quad and J_dip to not exceed the maximum stress (400 MPa)

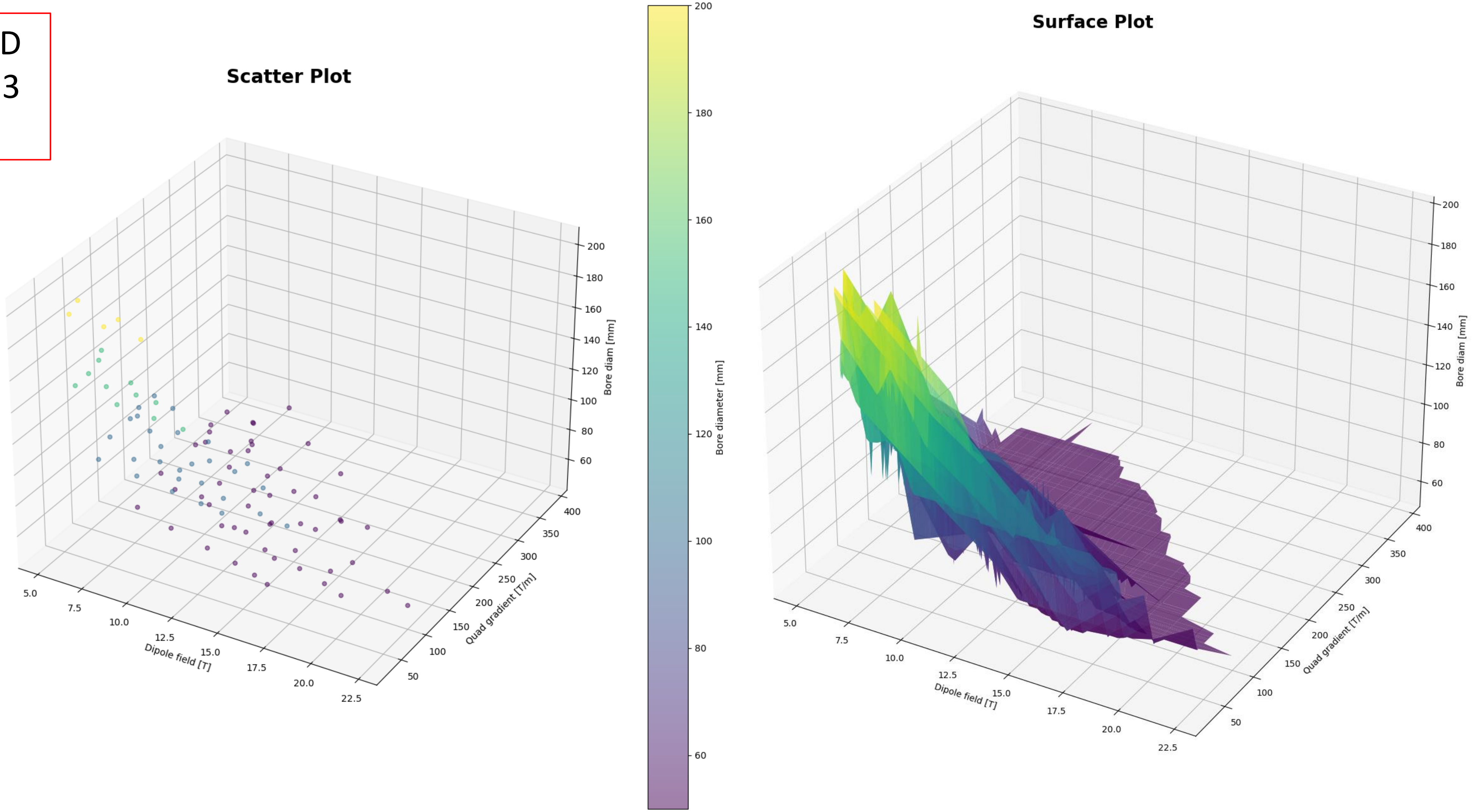
.....
while not (0.99 < f < 1.01):
.....
read the J from 1% optimization
*→ ANSYS input (a1, w_quad, **J_quad**, w_dip, **J_dip**)*
Run ANSYS
ANSYS output →
if stress > 400:
f = 400/stress
J=J*√*f*
.....
.....

the optimization acts on J_quad and J_dip with quadratic dependence of J on stress, and the cycle closes when the stress is below 400 MPa on both the dipole and the quadrupole.

Limitations on cost are still missing

3D plot

Is it useful to have a 3D representation of the 3 planes of interest?



Conclusions

- Do we exclude the asymmetric configuration a priori? We have seen the cos-theta, but what about the CCT? The nested configuration may be best for the B-G plot, allowing B2 values greater than B1, but to study specific configurations the asymmetric might be better.

- We inserted an internal support to solve the problem of the coil wanting to enter the aperture. I assumed an internal support with infinitely rigid structure, so the thickness does not matter for the code, but it is relevant to the results. How thick do we consider the inner support?

- The code throws simulations with w from 10 to 80 mm (step 10mm), bore diameter from 50 to 200 (step 50mm). How can we make the graphs more accessible? Could it be useful to add points with w from 1 to 10 mm in 1mm steps? Add aperture points?

- Now I'm considering roebel cable, 150 MPa as Young module of the ReBCO tape, etc. Should I align with the dipole design considerations? What about the protection of these kind of magnets?

- Is it possible to interface the new plots with the old A-B plots? It might be useful to have a relationship between the new work with the old work. Is there a way to analytically assess if we are on the right path with the combined?

- Should we start focusing on a specific configuration? If so, nested or asymmetric?

THANK YOU FOR YOUR ATTENTION

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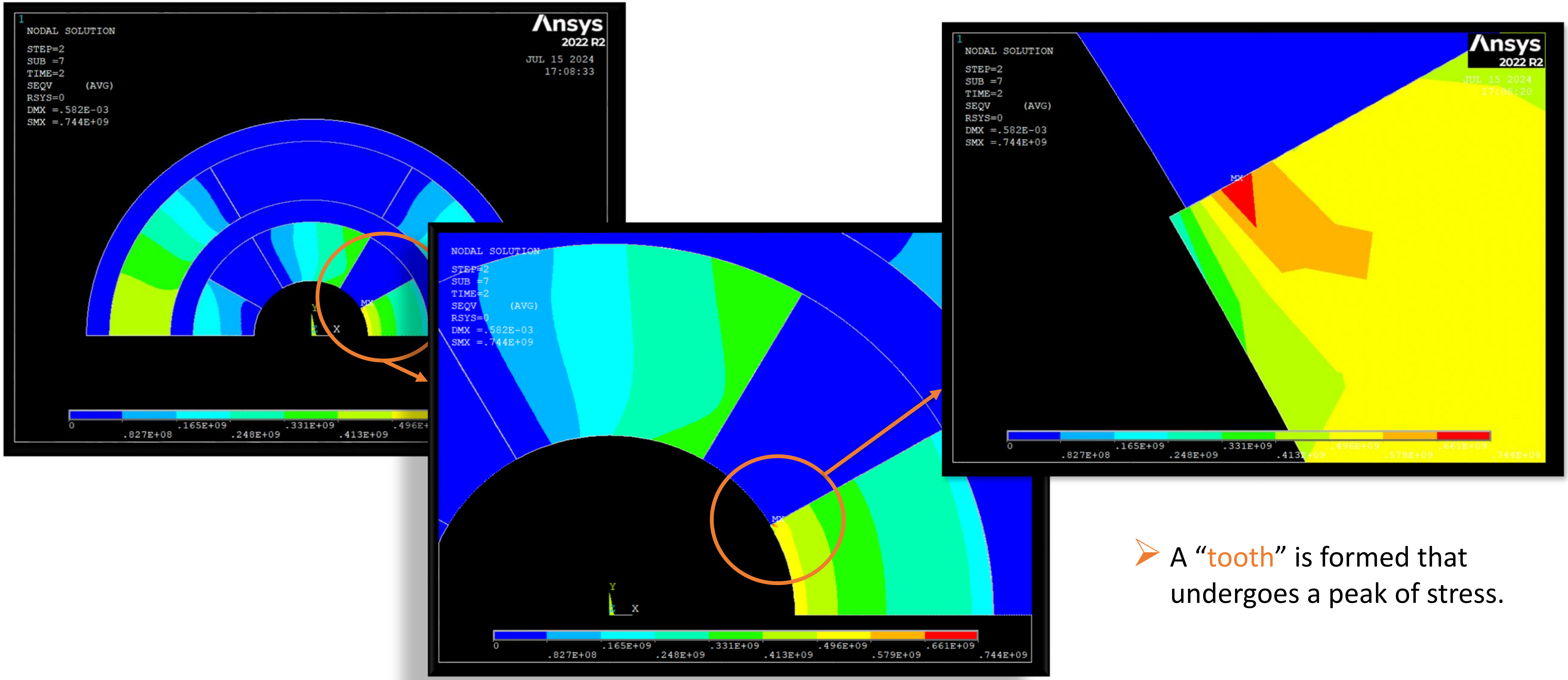
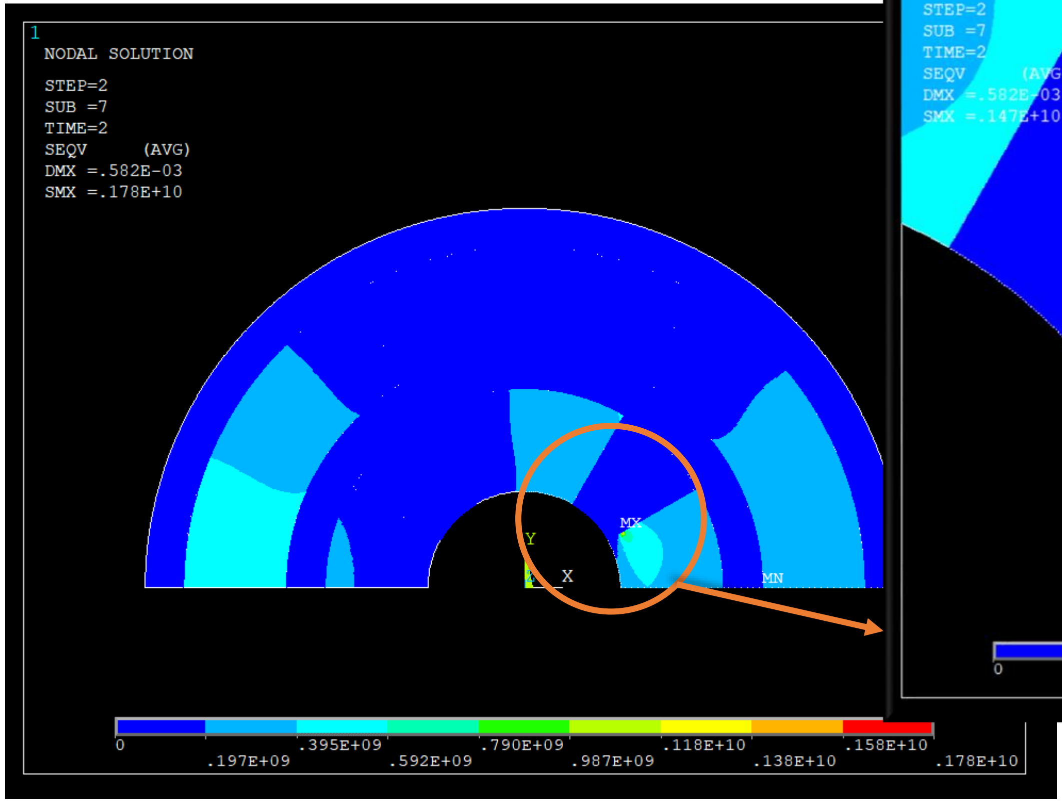
Stress Issue

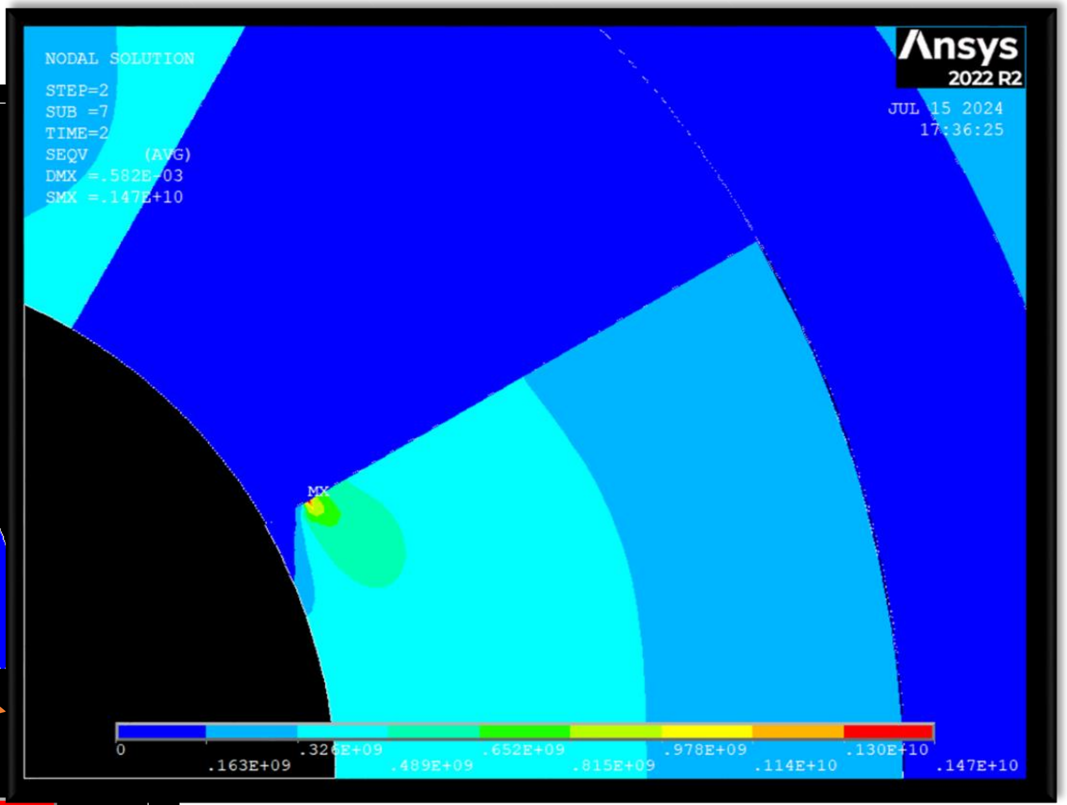


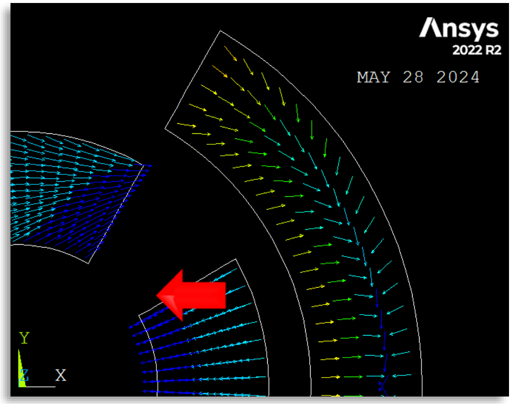
- A "tooth" is formed that undergoes a peak of stress.

Stress Issue

- If we manually remove the "tooth," it moves to the first zone not excluded.

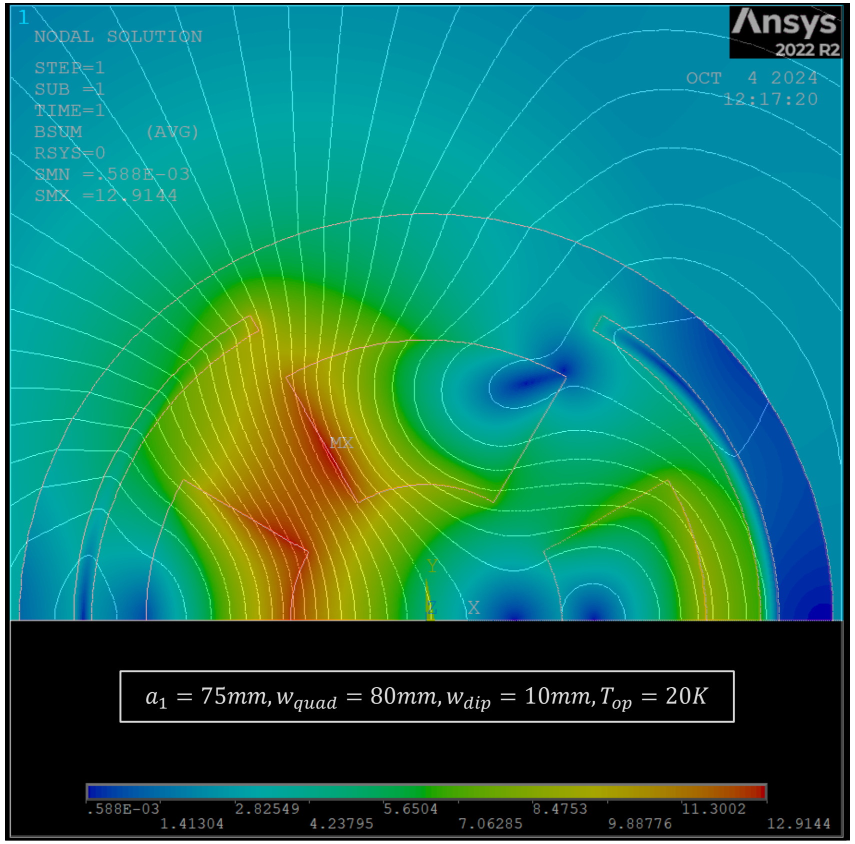


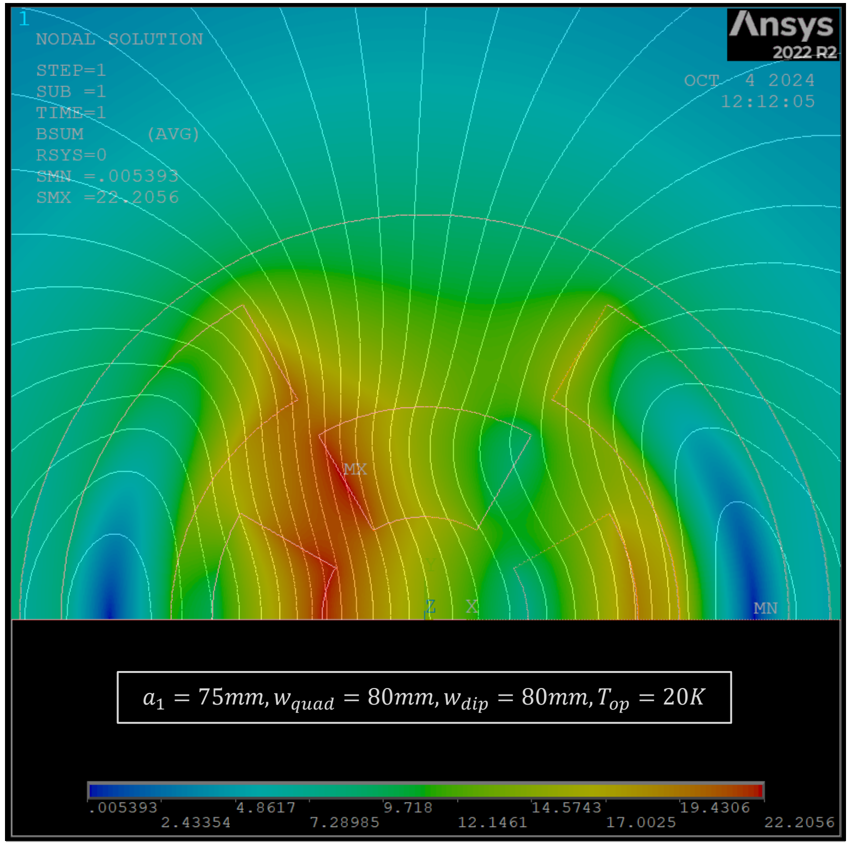


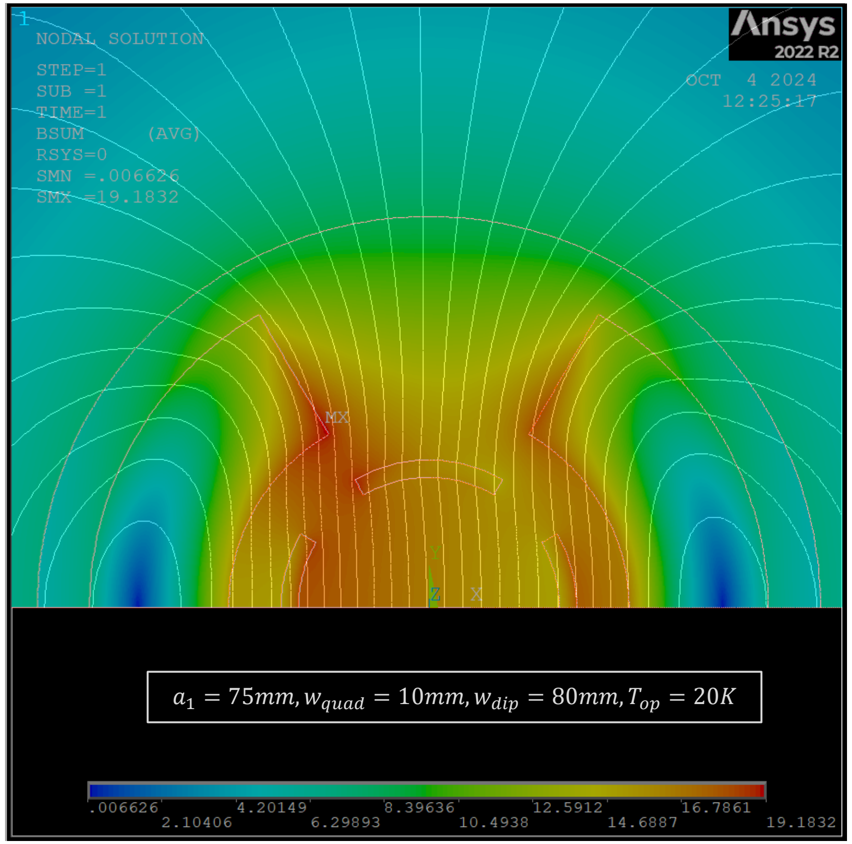


- This is due to the fact that wedges are infinitely rigid, and the coil wants to move inside.

Bsum + plf2d


Ansys
2022 R2
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
BSUM (AVG)
RSYS=0
SMN =.588E-03
SMX =12.9144
OCT 4 2024
12:17:20
MX
$a_1 = 75mm, w_{quad} = 80mm, w_{dip} = 10mm, T_{op} = 20K$
.588E-03 1.41304 2.82549 4.23795 5.6504 7.06285 8.4753 9.88776 11.3002 12.9144


Ansys
2022 R2
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
BSUM (AVG)
RSYS=0
SMN =.005393
SMX =22.2056
OCT 4 2024
12:12:05
MX
MN
$a_1 = 75mm, w_{quad} = 80mm, w_{dip} = 80mm, T_{op} = 20K$
.005393 2.43354 4.8617 7.28985 9.718 12.1461 14.5743 17.0025 19.4306 22.2056


Ansys
2022 R2
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
BSUM (AVG)
RSYS=0
SMN =.006626
SMX =19.1832
OCT 4 2024
12:25:17
MX
$a_1 = 75mm, w_{quad} = 10mm, w_{dip} = 80mm, T_{op} = 20K$
.006626 2.10406 4.20149 6.29893 8.39636 10.4938 12.5912 14.6887 16.7861 19.1832