Performance Limits of Combined Function Magnets

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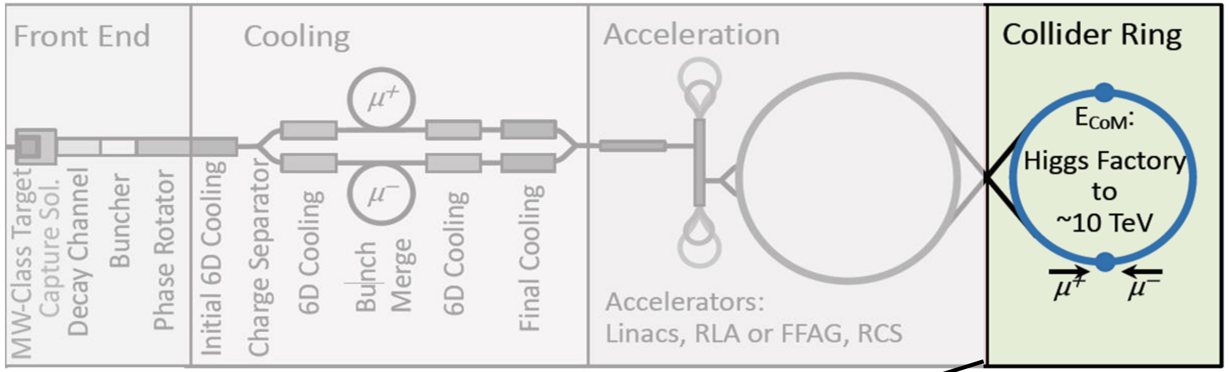
9 December 2024

Collider Magnets Requirements

Main stages of a muon collider complex



Need for high fields in large apertures

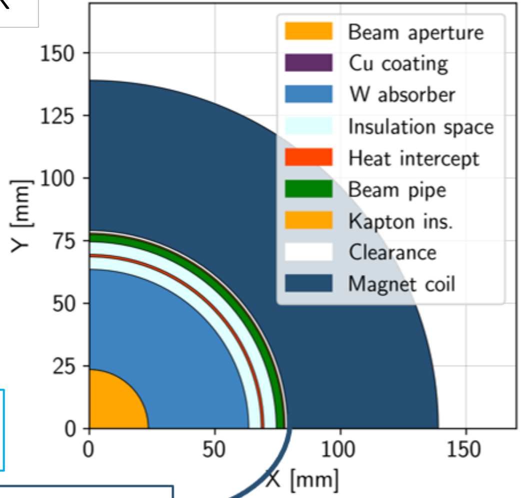
Dipole Radial Build

Assuming 10 TeV machine and coil at 4.5 K

- 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

Courtesy of Patricia Borges de Sousa
https://indico.cern.ch/event/1250075/contributions/5357594/



Coil aperture 158 mm

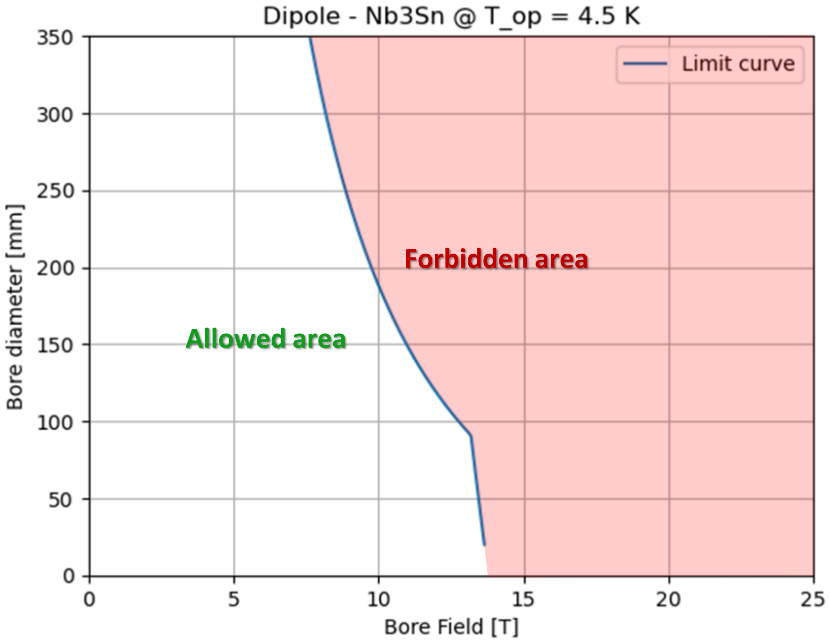
	2 cm	3 cm	4 cm
Beam aperture (radius)	23.5 mm	23.5 mm	23.5 mm
Outer shielding radius	43.5 mm	53.5 mm	63.5 mm
Inner coil aperture (radius)	59 mm	69 mm	79 mm
Power penetrating tungsten absorber	19.1 W/m (3.8%)	8.2 W/m (1.6%)	4.1 W/m (0.8%)
Peak power density in coils	6.5 mW/cm^3	2.1 mW/cm^3	0.7 mW/cm^3
Peak dose in Kapton (5/10 years)	56/112 MGy	18/36 MGy	7/14 MGy
Peak dose in coils (5/10 years)	45/90 MGy	15/30 MGy	5/10 MGy
Peak DPA in coils (5/10 years)	$8/16\times10^{-5}$ DPA	$6/12\times10^{-5}$ DPA	$5/10\times10^{-5}$ DPA

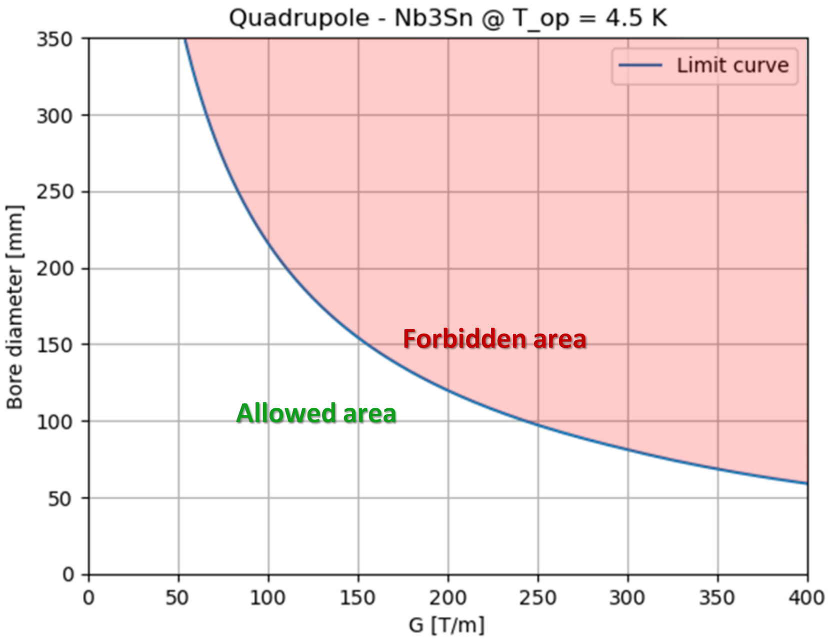
Courtesy of Anton Lechner

4 cm W_{abs} @ T < 20 K (P < 5 W/m)
→ 158 mm magnet aperture

3 cm W_{abs} @ T = 20 K (P < 10 W/m)
→ 138 mm magnet aperture

A-B Plots for Nb_3Sn





- A-B plots show the **performance limits** as a function of aperture diameter (A) and bore field (B) or gradient (G).
- Starting the design of a magnet **in the forbidden area** means already knowing from analytical approximations that one or more **technological limits** in the construction of superconducting magnets **will be exceeded**.
- Starting the design of a magnet **in the allowed area** but close to the limit curves does not mean that the magnet is easy to manufacture; rather, it indicates that **with progress in R&D**, it could become **feasible**.

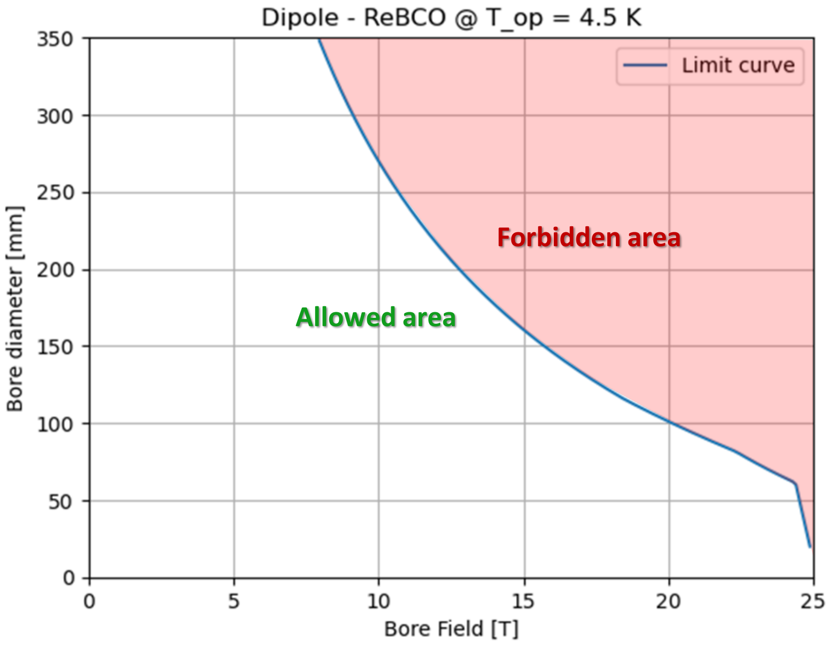
- Budget: 400 kEUR/m for each magnet.
- SC cost: 700 EUR/kg (aspirational, same cost as ITER procurement).
- These plots apply to both ARC and FF.
- Operating temperature: 4.5 K
  → tungsten shield with a radius of 4 cm.

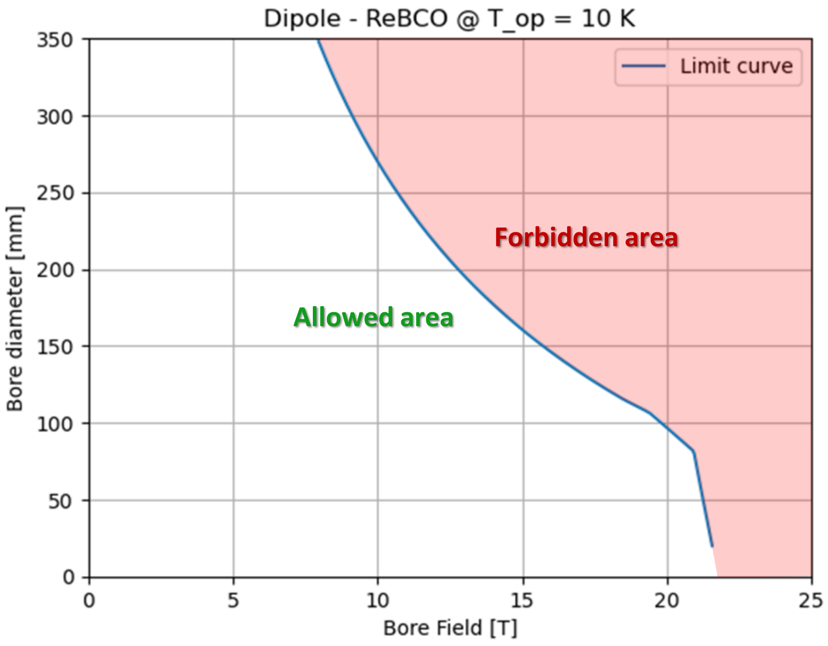
The **Limit curve** includes:

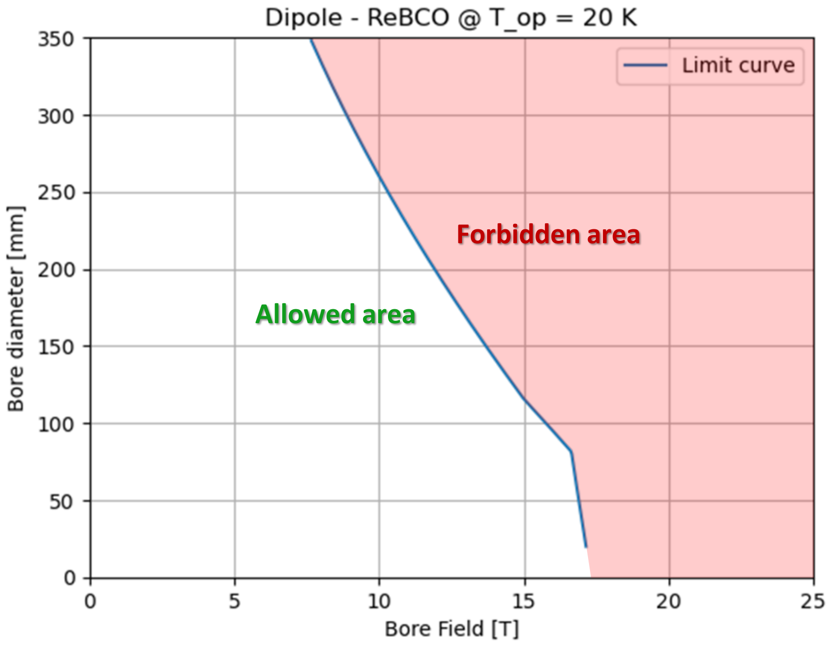
- Cost model: including coils, iron, structures and labour
- Protection: maximum hotspot temperature of 350K
- Margin: FCC cable target performance for the Jc fit
- Maximum midplane stress: 150 MPa

Nb_3Sn is not considered for the 10 TeV as it falls short of the required performance.
It may be an option for the 3TeV.

HTS ARC Dipoles A-B Plots







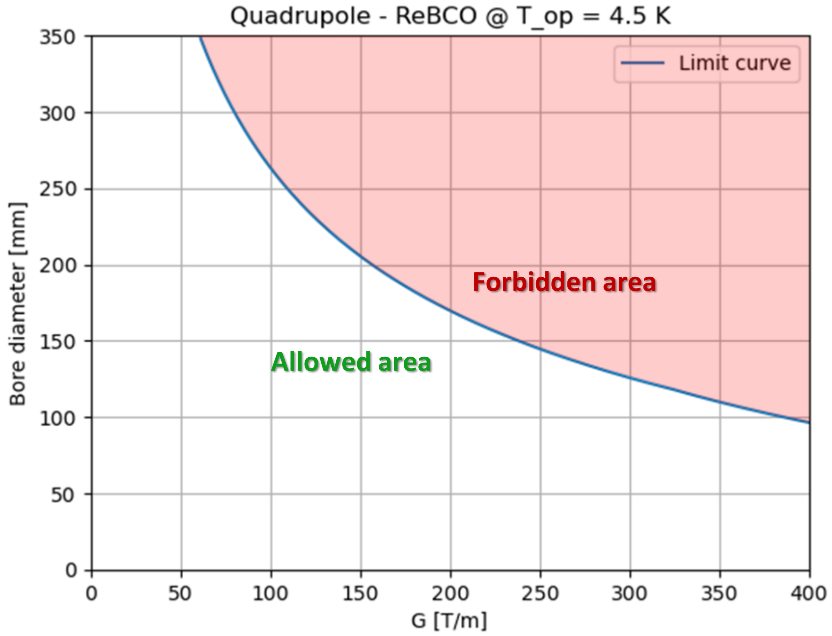
- Operating temperature: 4.5 K
  → tungsten shield with a radius of 4 cm
- Operating temperature: 10 K
  → tungsten shield with a radius of 4 cm
- Operating temperature: 20 K
  → tungsten shield with a radius of 3 cm

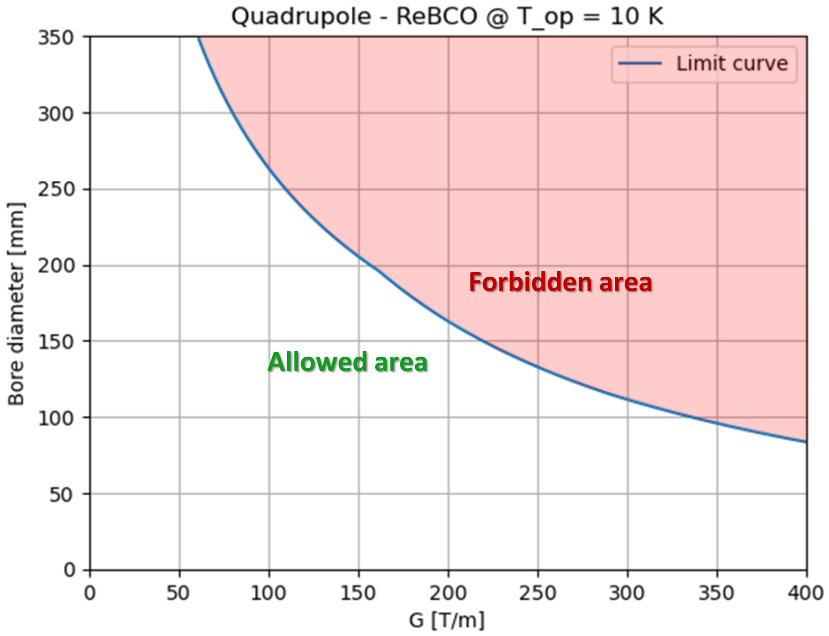
- Budget: 400 kEUR/m for each magnet.
- SC cost: 2500 EUR/kg (aspirational value).
- These plots apply to ARC dipoles.

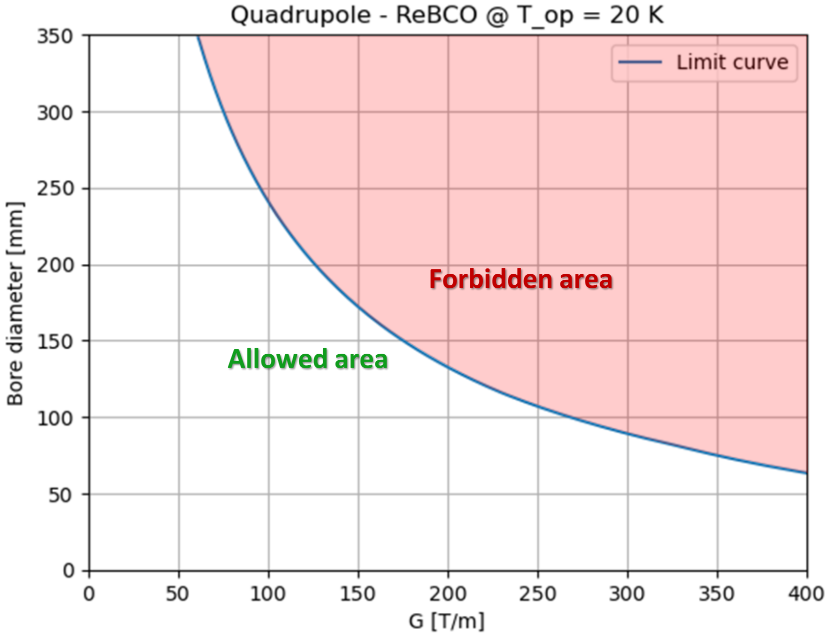
The **Limit curve** includes:
- Cost model: including coils, iron, structures and labour
- Protection: Non-insulated or Metal-insulated cable
- Margin: Fujikura FESC AP Tape for the Jc fit
- Maximum midplane stress: 400 MPa

ReBCO is considered the baseline for 10 TeV.

HTS ARC Quads A-G Plots







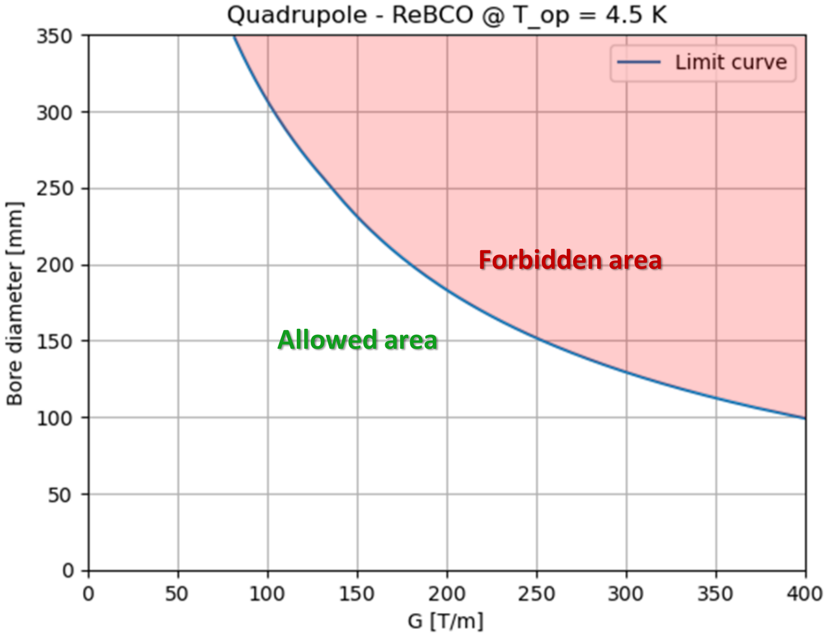
- Operating temperature: 4.5 K
  → tungsten shield with a radius of 4 cm
- Operating temperature: 10 K
  → tungsten shield with a radius of 4 cm
- Operating temperature: 20 K
  → tungsten shield with a radius of 3 cm

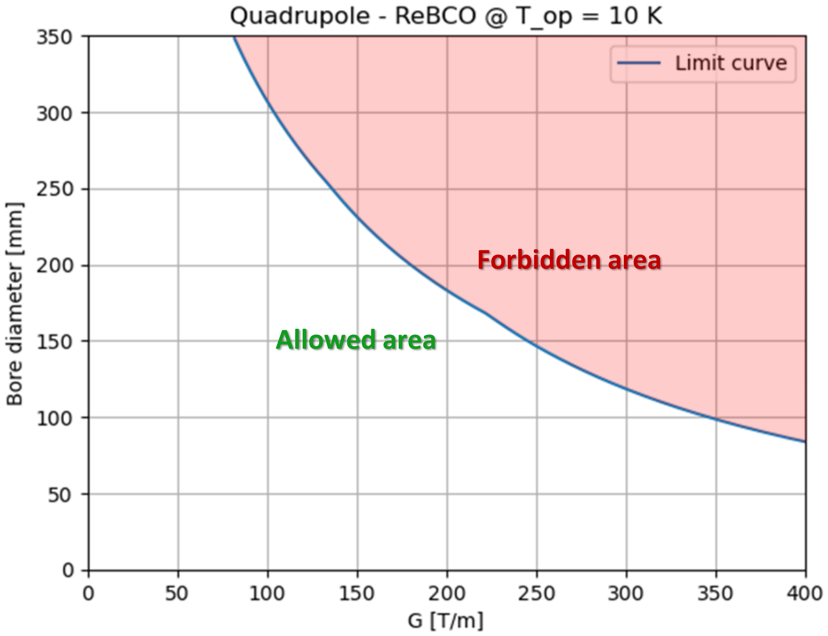
- Budget: 400 kEUR/m for each magnet.
- SC cost: 2500 EUR/kg (aspirational value).
- These plots apply to ARC quadrupoles.

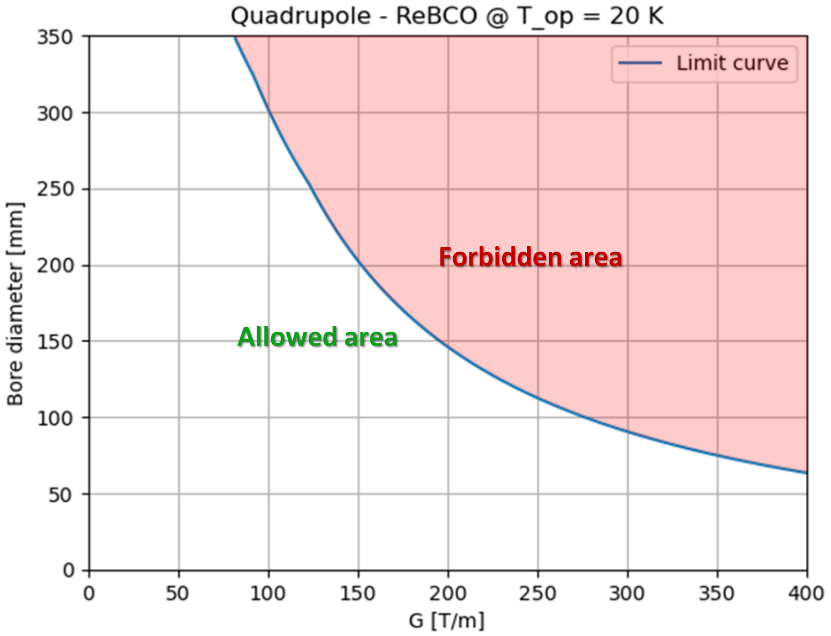
The **Limit curve** includes:
- Cost model: including coils, iron, structures and labour
- Protection: Non-insulated or Metal-insulated cable
- Margin: Fujikura FESC AP Tape for the Jc fit
- Maximum midplane stress: 400 MPa

ReBCO is considered the baseline for 10 TeV.

HTS FF Quads A-G Plots







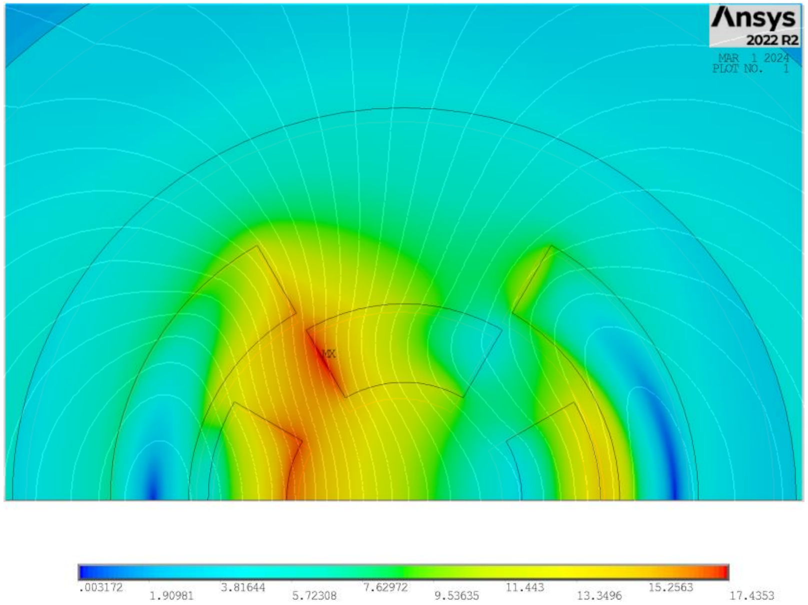
- Operating temperature: 4.5 K
  → tungsten shield with a radius of 4 cm
- Operating temperature: 10 K
  → tungsten shield with a radius of 4 cm
- Operating temperature: 20 K
  → tungsten shield with a radius of 3 cm

- Budget: 800 kEUR/m for each magnet.
- SC cost: 2500 EUR/kg (aspirational value).
- These plots apply to FF quadrupoles.

The **Limit curve** includes:
- Cost model: including coils, iron, structures and labour
- Protection: Non-insulated or Metal-insulated cable
- Margin: Fujikura FESC AP Tape for the Jc fit
- Maximum midplane stress: 400 MPa

ReBCO is considered the baseline for 10 TeV.

COMBINED: NESTED CONFIGURATION



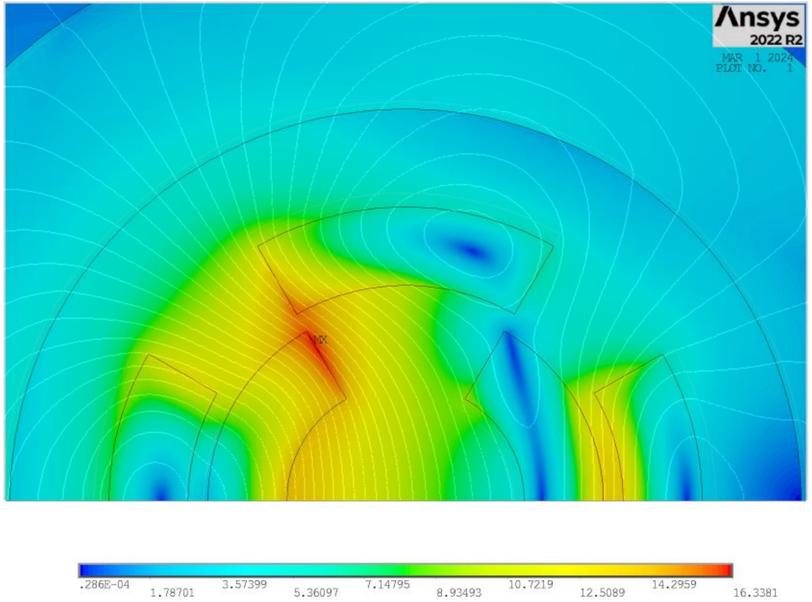
Quad into dipole:

(ReBCO @20 K)

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

$B \sim 11.7\ T$

$G \sim 143.3\ \mathrm{T/m}$



Dipole into quad:

(ReBCO @20 K)

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

$B \sim 12.4\ T$

$G \sim 90.4\ \mathrm{T/m}$

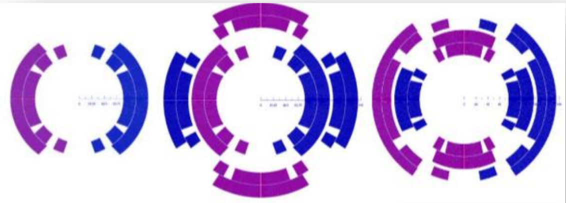
Arc:

- 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.

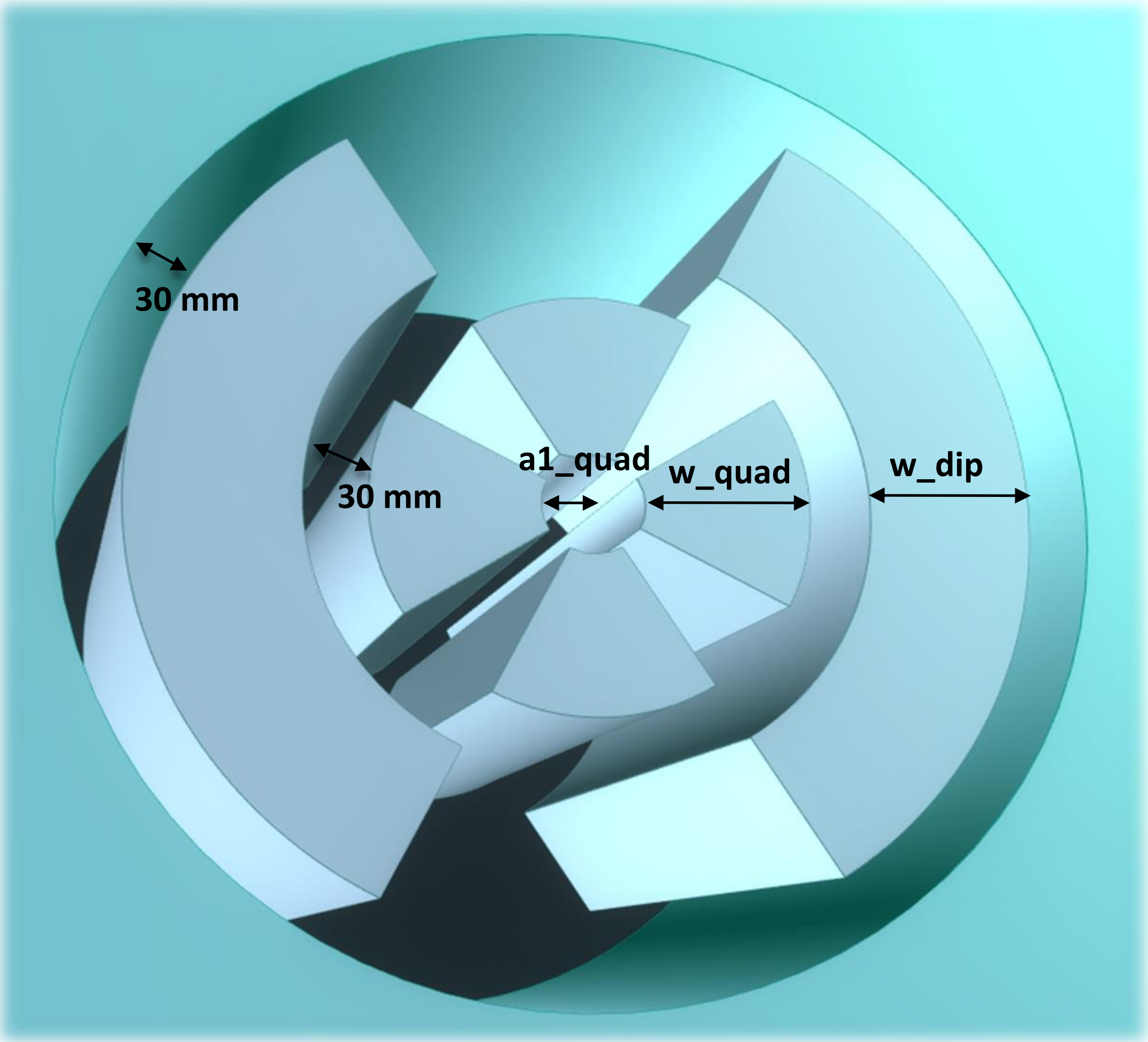


	Dipole	Dipole/Quadrupole	Quadrupol/Dipole
Superconductor	Nb_3Sn	Nb_3Sn	Nb_3Sn
Cable	40x1mm	40x1mm	40x1mm/30x1mm
B_{coil_max}, T	15.1	16.6/16.2	16.2/16.1
B_{max}/G_{max}, T/T/m	14.4	9.9/70.1	10.3/89.8
B_{op}/G_{op}, T/T/m	10	8/71	8/81
Margin	~40%	~24%/~20%	~28%/~20%

Most efficient configuration

Fermilab

PYTHON-ANSYS INTERFACE

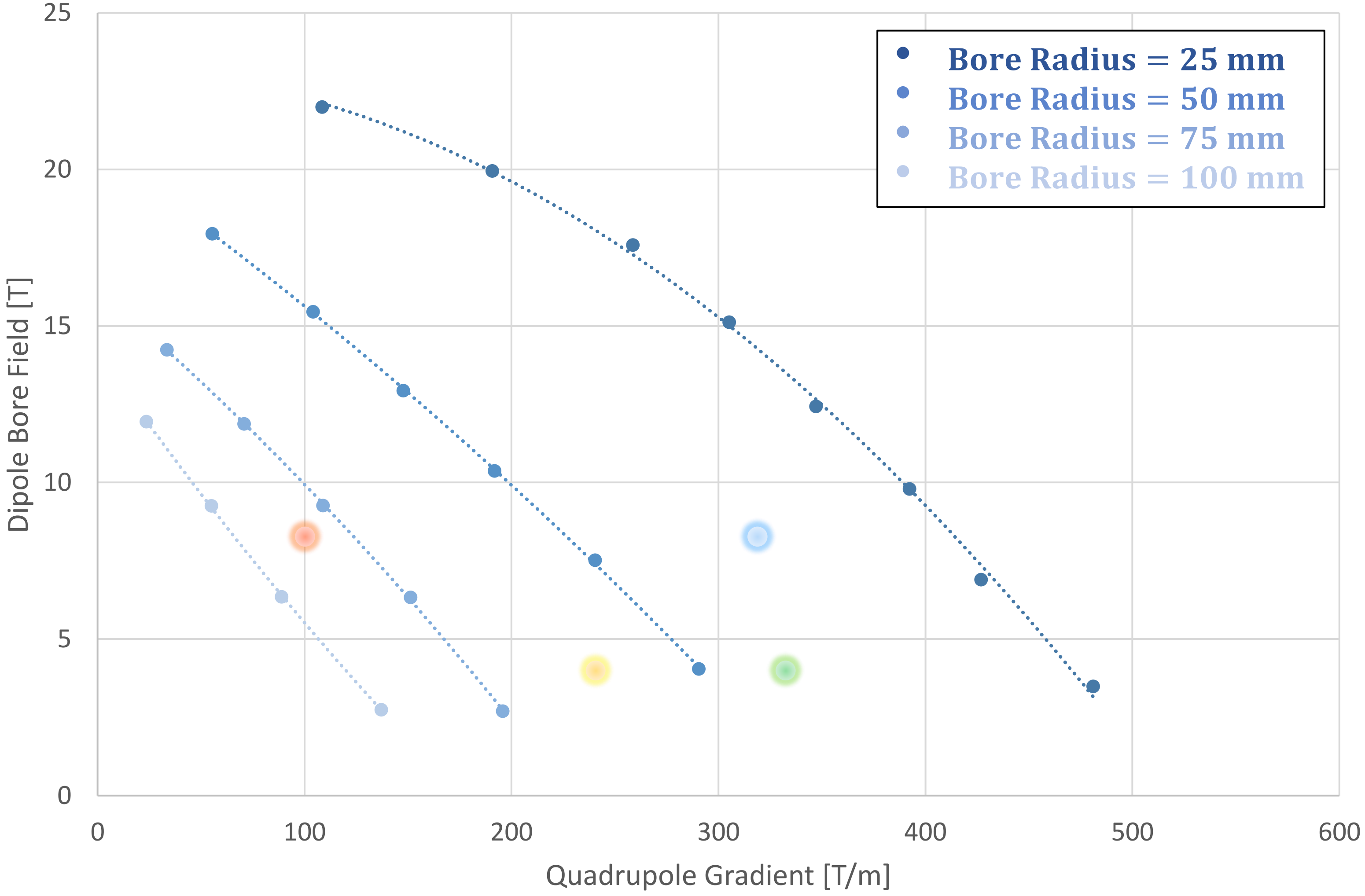


- A **Python-ANSYS interface** was developed to run FEM configurations capable of providing the electromagnetic performance of various designs.

- Loops were implemented by varying the temperature, a1_quad and w_quad. For each fixed value, the maximum w_dip was calculated using a **cost model**, and an optimization code for electromagnetic performance was executed. This code aimed to maximize the current density while staying within **stress and margin limits.**

- As anticipated, the performance limits for combined function magnets are significantly more stringent compared to those for dipoles and quadrupoles individually. **Extending the curves along the axes reveals the boundaries defined by the A-B and A-G plots**.

FINAL B-G PLOT AT T = 4.5 K



From v0.7:

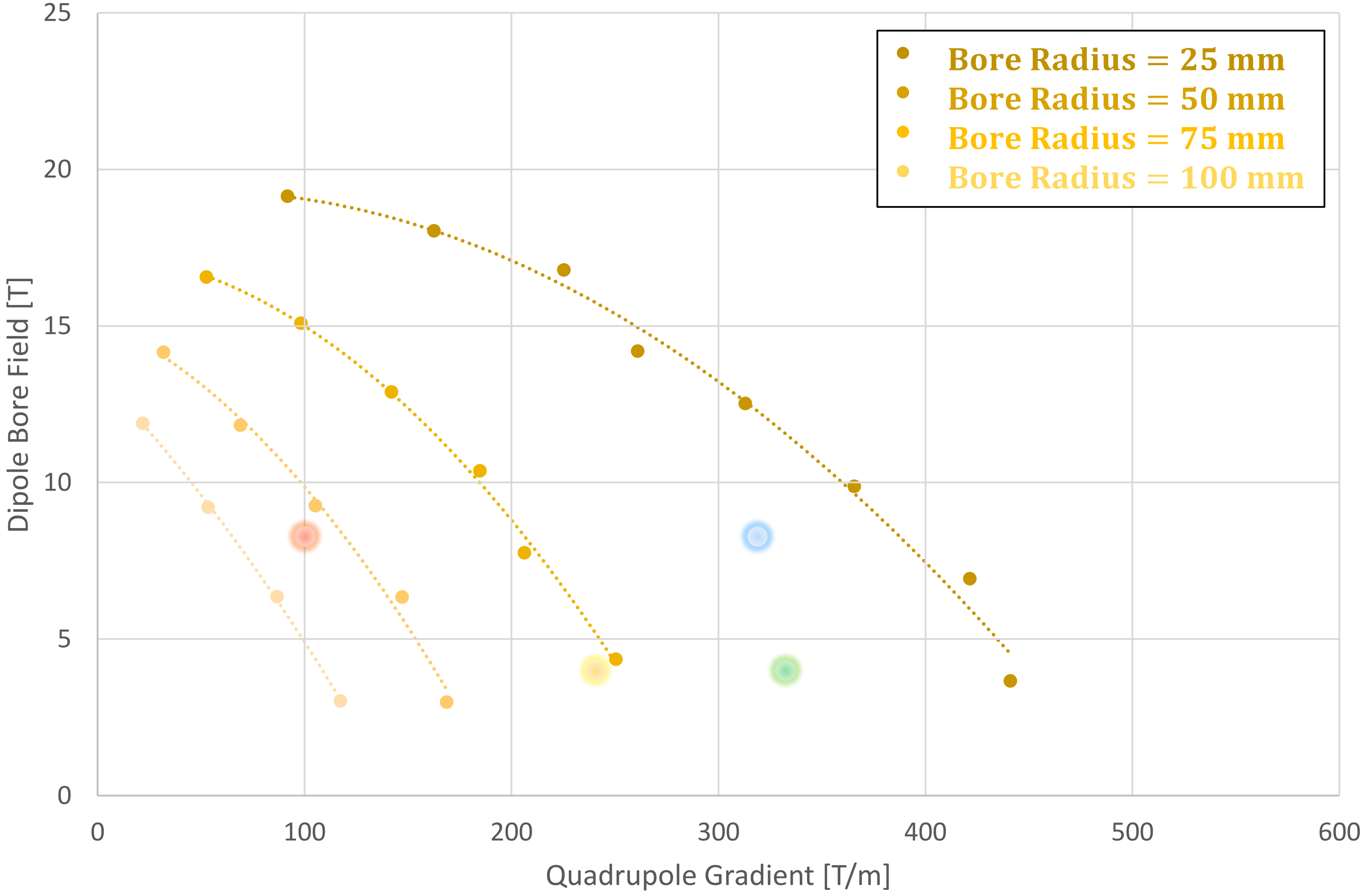
- 8 T, 100 T/m, 140 mm of radius
- 8 T, 320 T/m, 50 mm of radius
- 4 T, 240 T/m, 70 mm of radius
- 4 T, 330 T/m, 50 mm of radius

Courtesy of Kyriacos Skoufaris
https://indico.cern.ch/event/1351046/

Maximum budget = 400 kEUR/m
Labour = 20 kEUR/m
Iron and Structures = 60 kEUR/m
↓
Budget for the SC = 320 kEUR/m

The radial build might change: a solution needs to be studied to address the issue of the quadrupole moving inward.

FINAL B-G PLOT AT T = 10 K



From v0.7:

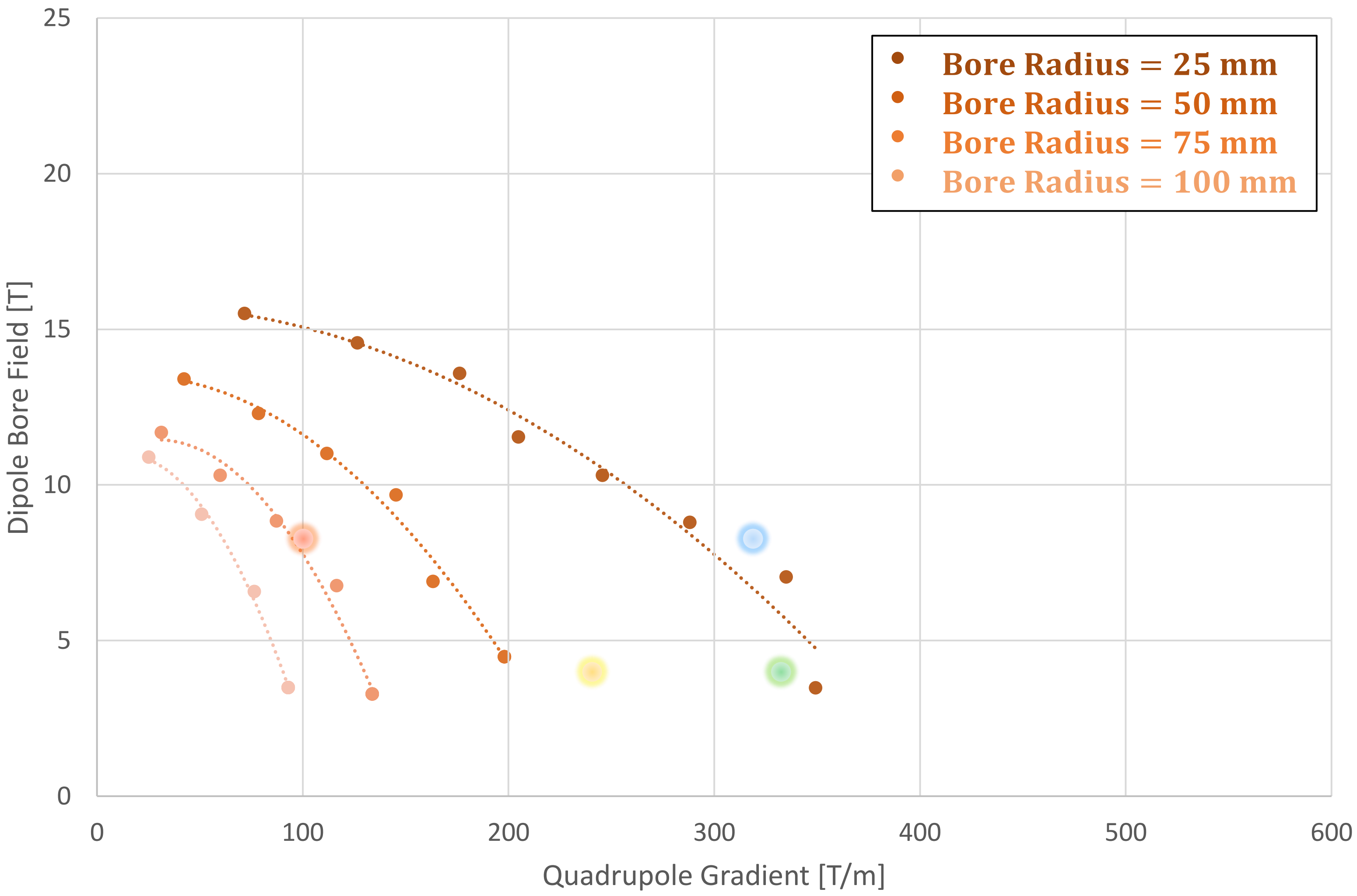
- 8 T, 100 T/m, 140 mm of radius
- 8 T, 320 T/m, 50 mm of radius
- 4 T, 240 T/m, 70 mm of radius
- 4 T, 330 T/m, 50 mm of radius

Courtesy of Kyriacos Skoufaris
https://indico.cern.ch/event/1351046/

Maximum budget = 400 kEUR/m
Labour = 20 kEUR/m
Iron and Structures = 60 kEUR/m
↓
Budget for the SC = 320 kEUR/m

The radial build might change: a solution needs to be studied to address the issue of the quadrupole moving inward.

FINAL B-G PLOT AT T = 20 K



From v0.7:

- 8 T, 100 T/m, 140 mm of radius
- 8 T, 320 T/m, 50 mm of radius
- 4 T, 240 T/m, 70 mm of radius
- 4 T, 330 T/m, 50 mm of radius

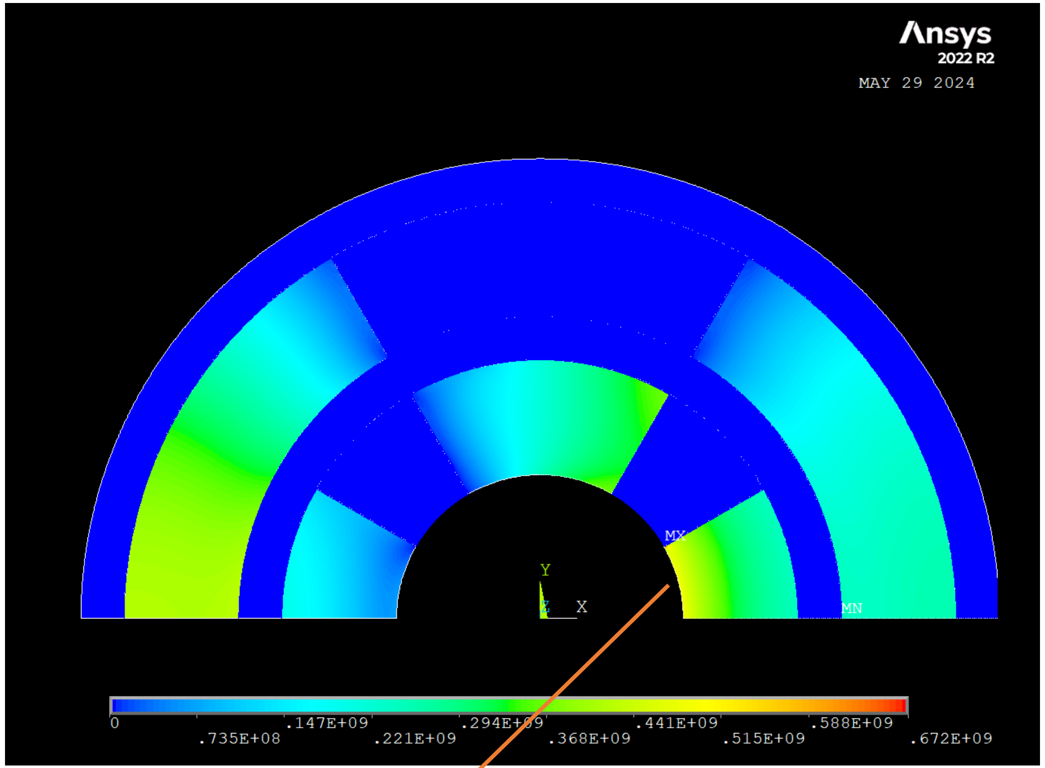
Courtesy of Kyriacos Skoufaris
https://indico.cern.ch/event/1351046/

Maximum budget = 400 kEUR/m
Labour = 20 kEUR/m
Iron and Structures = 60 kEUR/m
↓
Budget for the SC = 320 kEUR/m

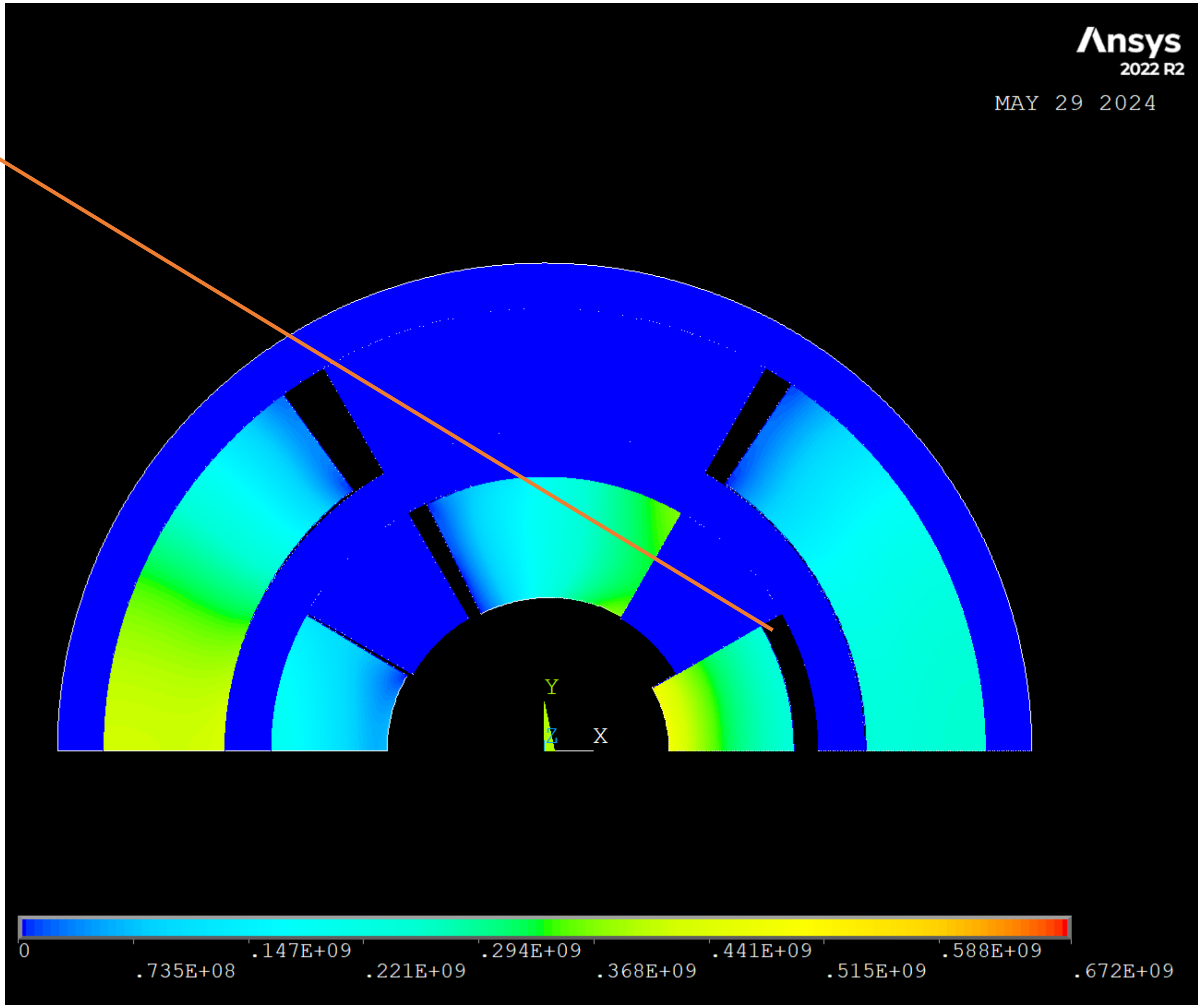
The radial build might change: a solution needs to be studied to address the issue of the quadrupole moving inward.

Stress Issue

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

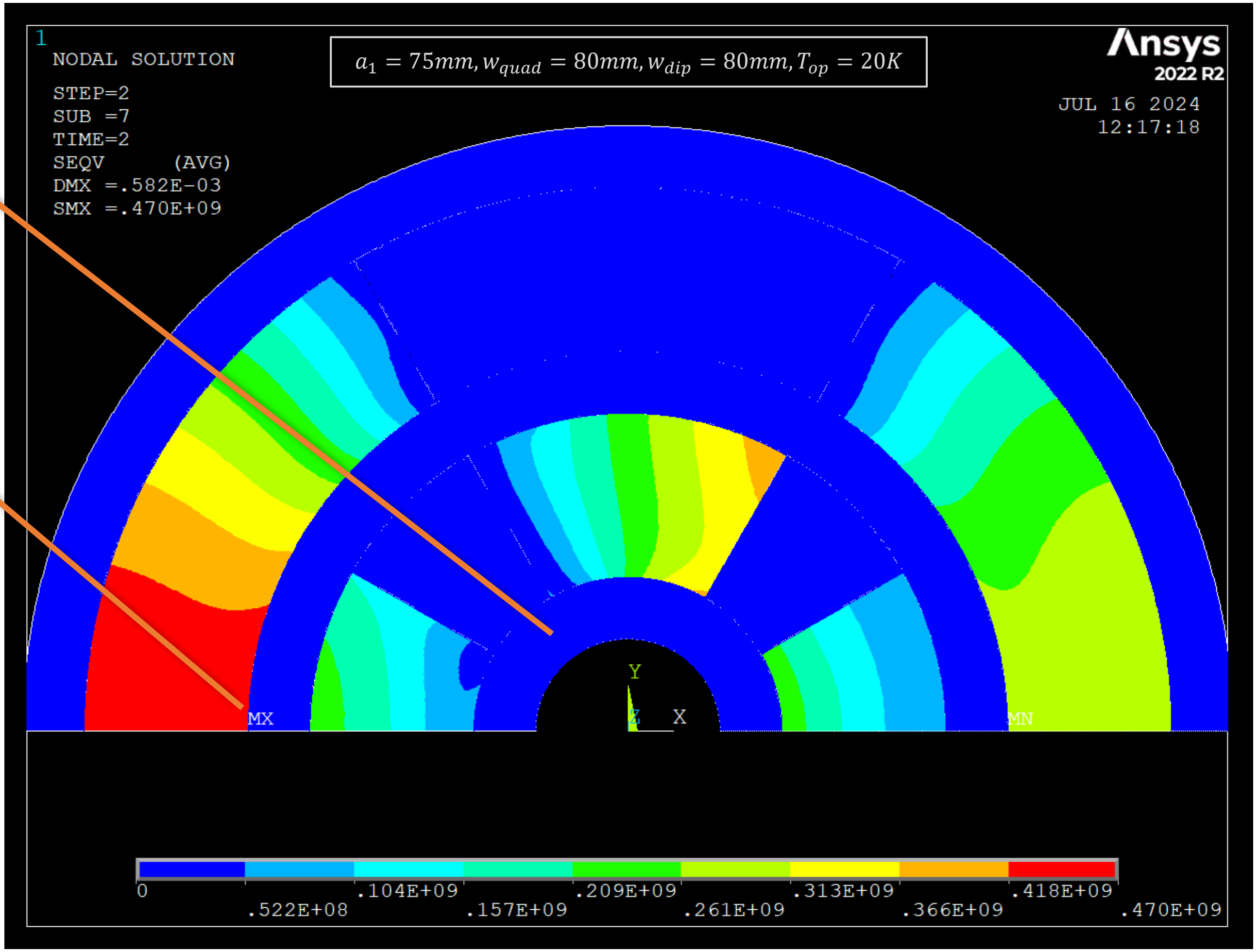


The Von Mises peak stress is on the inner part of the coil



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.



CONCUSIONS

- As the **A-B plots** for dipoles and the **A-G plots** for quadrupoles were presented, the performance of combined function superconducting magnets was analyzed in various configurations, leading to the development of **B-G plots**.

- In the **cost model**, the same limitations discussed for the arc magnets were assumed.

- The study will continue to address the **issue of stress** (one of the quadrupole coils moves into the aperture), in collaboration with the cryogenic and energy deposition groups, and to develop a potential **quench protection system**, while further exploring innovative approaches such as non-insulated and metal-insulated coils.

- **The presented B-G plots should be considered as the best representation of the EM performance of combined function magnets.** Consequently, target designs can be identified in collaboration with beam optics.

THANK YOU FOR YOUR ATTENTION

D. Novelli[1,2], L. Alfonso[2], A. Bersani[2], L. Bottura[5], B. Caiffi[2], S. Farinon[2], F. Mariani[1], S. Mariotto[3] , A. Pampaloni[2], T. Salmi[4]

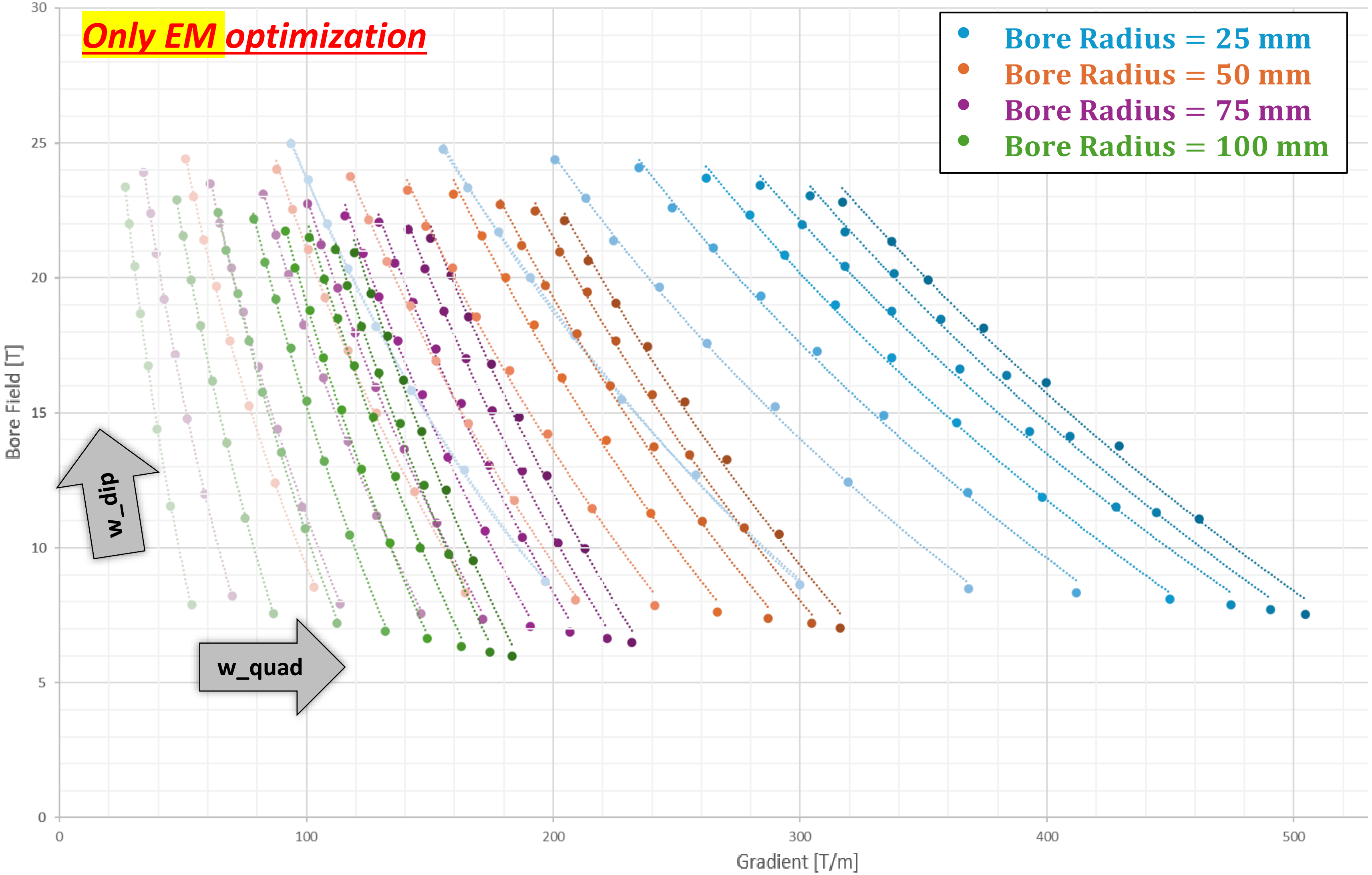
[1]Sapienza University of Rome, [2]INFN – Genoa , [3]INFN and University of Milan

[4]Tampere University, [5]CERN

9 December 2024

BACKUP SLIDES

EM. 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*
.....
.....

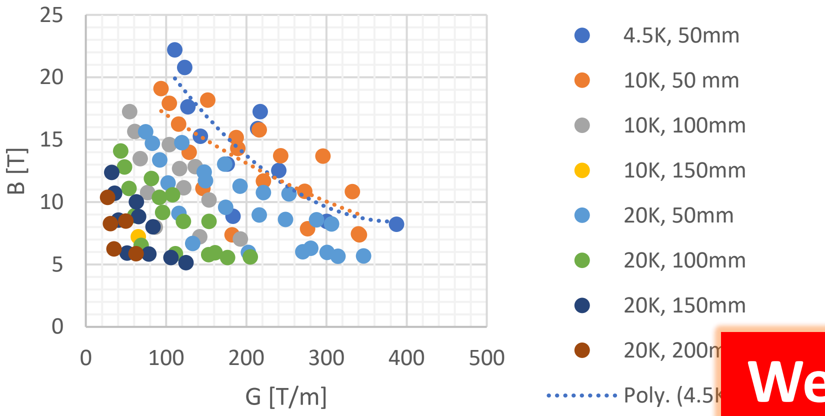
the optimization acts on J_quad and J_dip with corrections of 1%, and the cycle closes when either J_quad or J_dip is within 1% of J_c

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

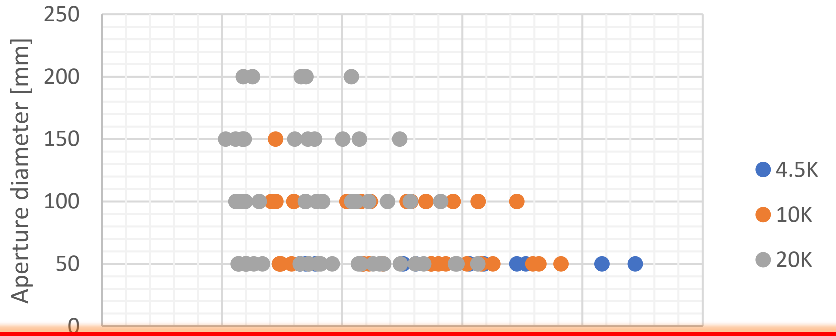
Stress and Cost considerations

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

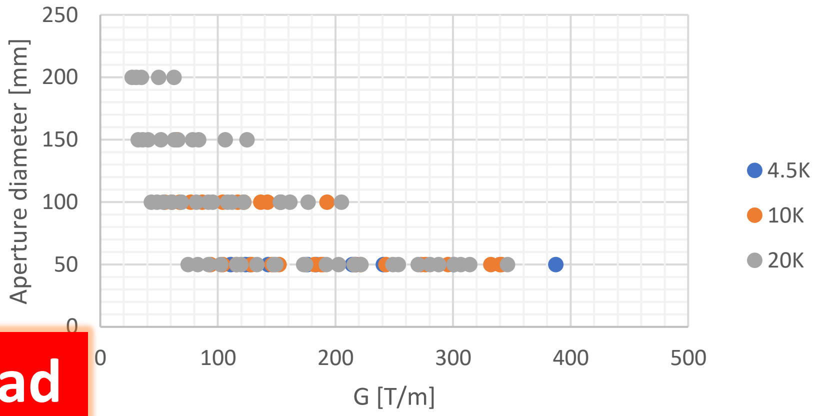
B vs G – Cost and Stress limits



A vs B – Cost and Stress limits

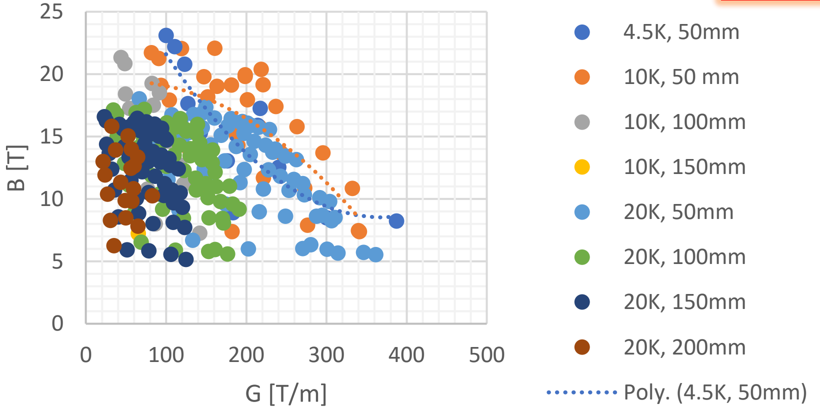


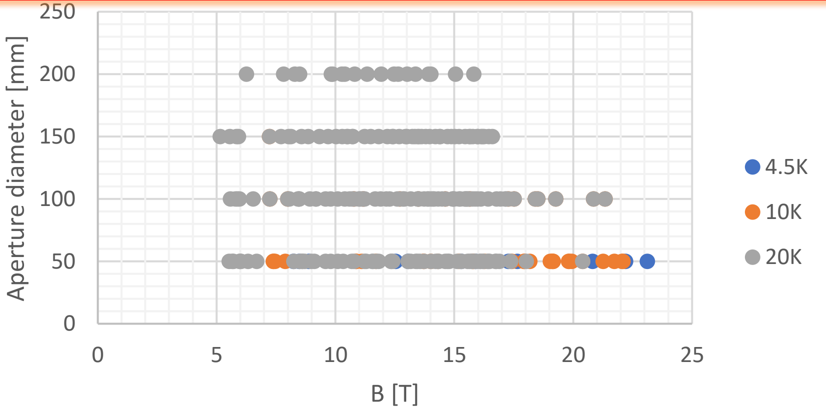
A vs G – Cost and Stress limits



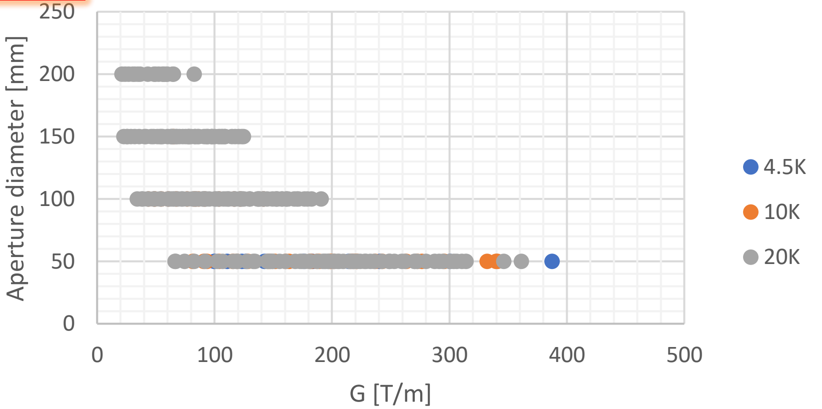
We should optimize the stress instead of excluding the points manually

B vs G – only Stress limit



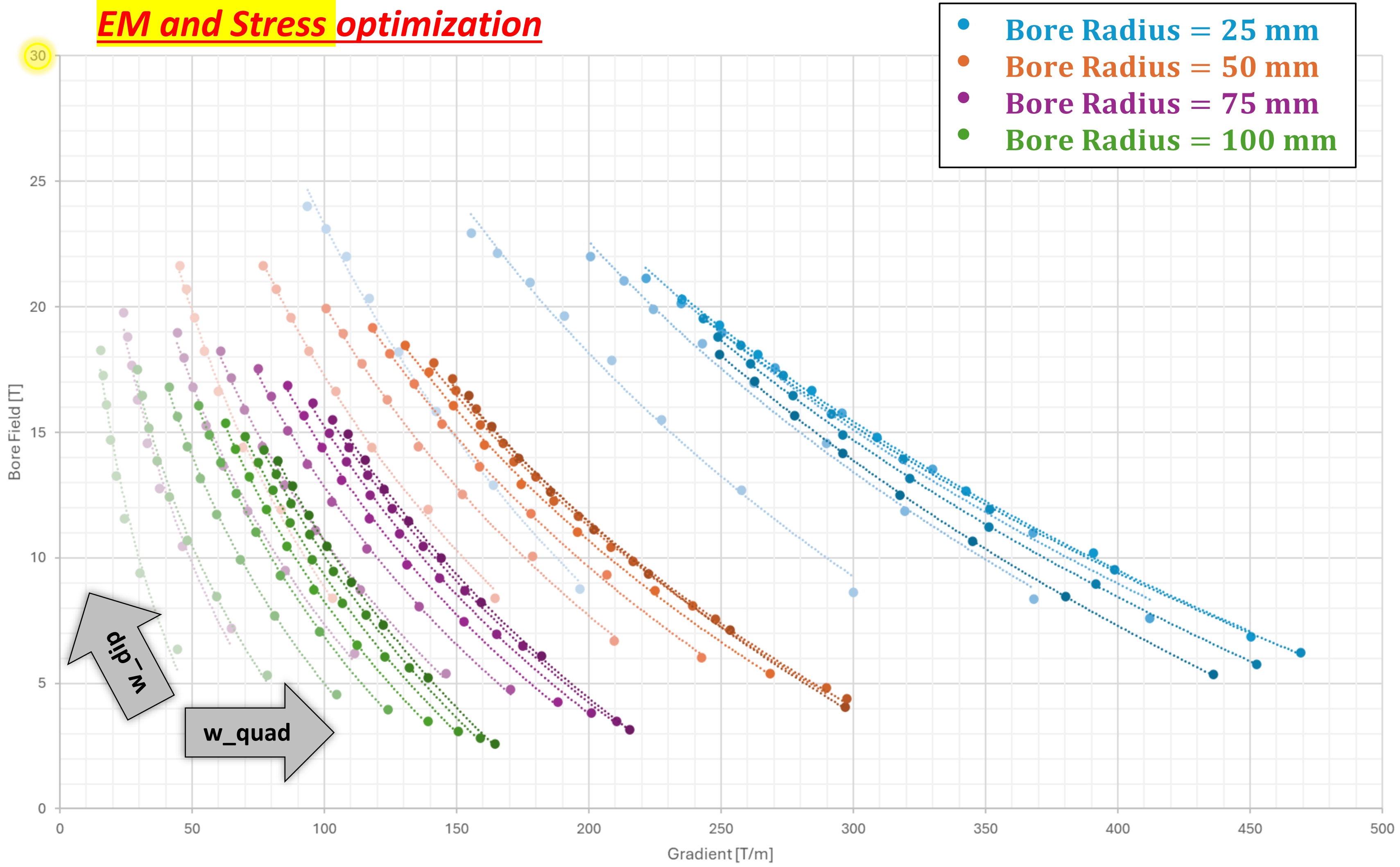


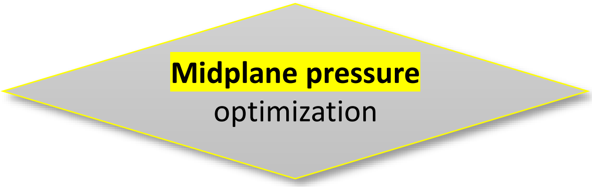
A vs G – only Stress limit



EM. And Stress B-G plot at 4.5K

EM and Stress optimization





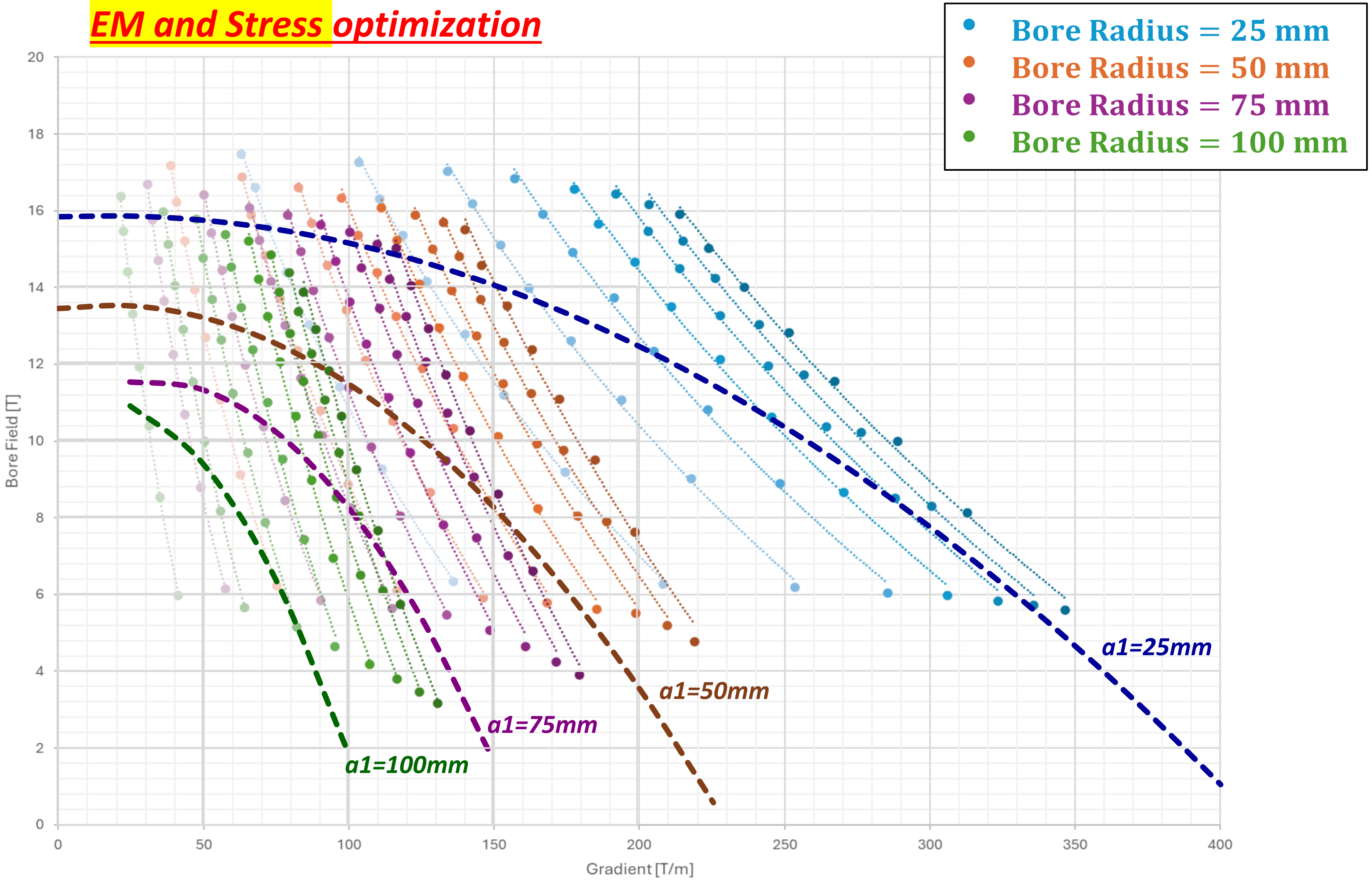
Optimize (decrease) J_quad and J_dip to not exceed the maximum stress (400 MPa)

```
.....
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

FINAL B-G PLOT AT 20K



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