PERFORMANCE LIMITS OF COMBINED FUNCTION MAGNETS

***mmWG*, 20 February 2025**

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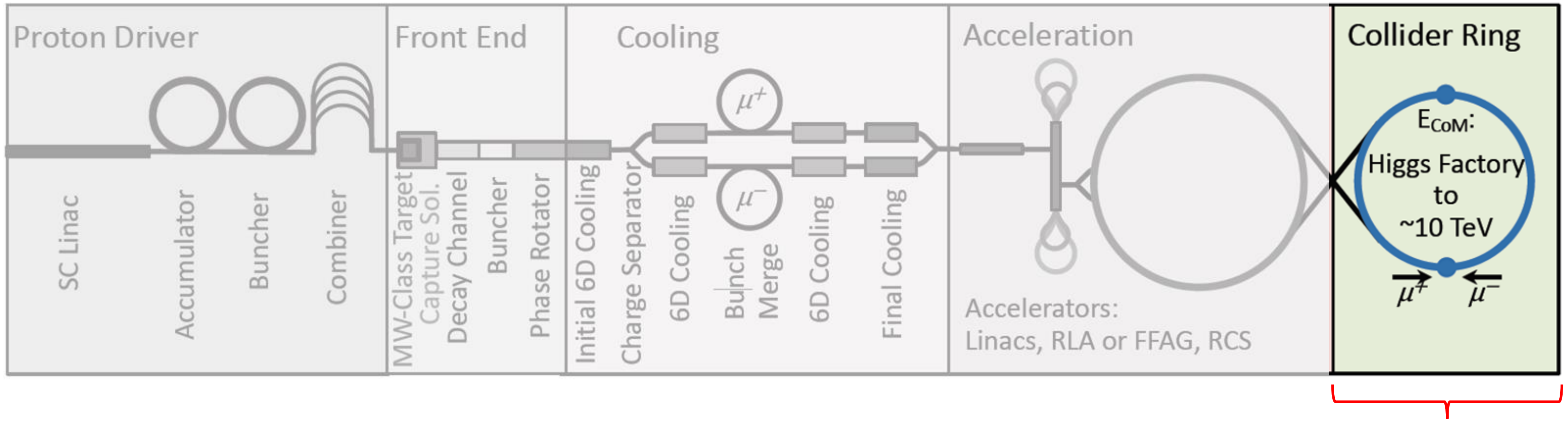
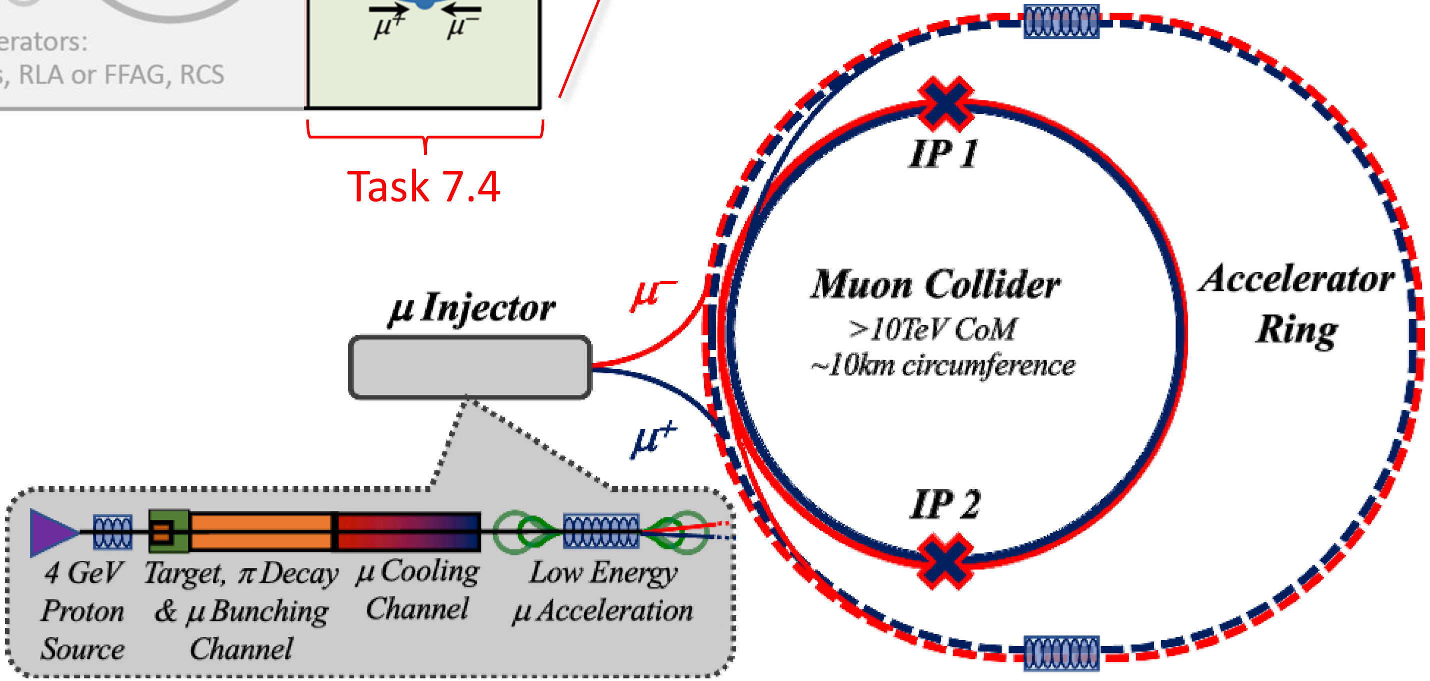
OVERVIEW

Main stages of a muon collider complex



Magnets:

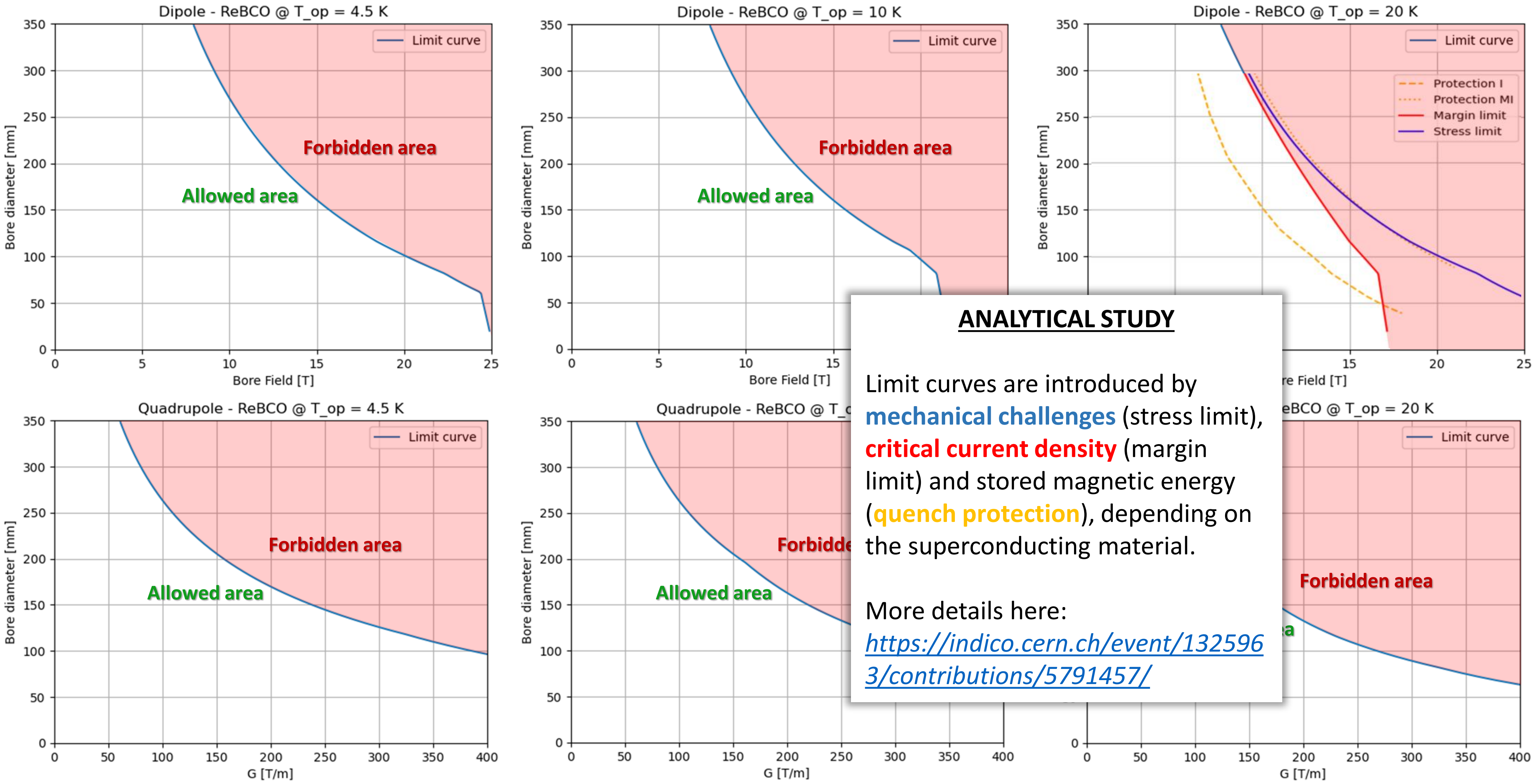
- Dipoles
- Quadrupoles
- Sextupoles
- **Combined Dip+Quad**
- **Combined Dip+Sext**



Purpose:

- Evaluate realistic performance targets for the collider magnets, in close collaboration with studies of beam physics, cryogenics, and energy storage.
- Produce a credible and affordable design study (contain costs, energy efficiency, sustainable operation).

HTS ARC A-B AND A-G PLOTS



ANALYTICAL STUDY

Limit curves are introduced by **mechanical challenges** (stress limit), **critical current density** (margin limit) and stored magnetic energy (**quench protection**), depending on the superconducting material.

More details here: https://indico.cern.ch/event/1325963/contributions/5791457/

Main assumptions:

– Budget: 400 kEUR/m for each magnet.

– These plots apply to ARC magnets. For the IR quadrupoles, a double budget is assumed.

– SC cost: 2500 EUR/kg (aspirational value).

– Max. coil width: 80 mm

– Max. stress: 400 MPa

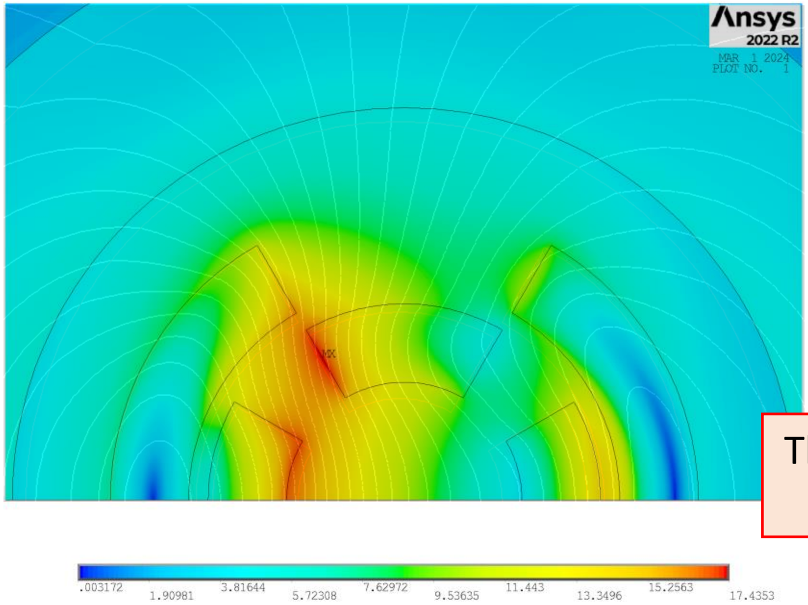
– Protection: MI or NI

– Tungsten screen: 3 cm at 20K, increasing to 4 cm if below 20K.

– HTS as baseline for the 10 TeV, NbTi and Nb_3Sn as options for the 3 TeV.

– Filling factor = 0.011

COMBINED: NESTED CONFIGURATION



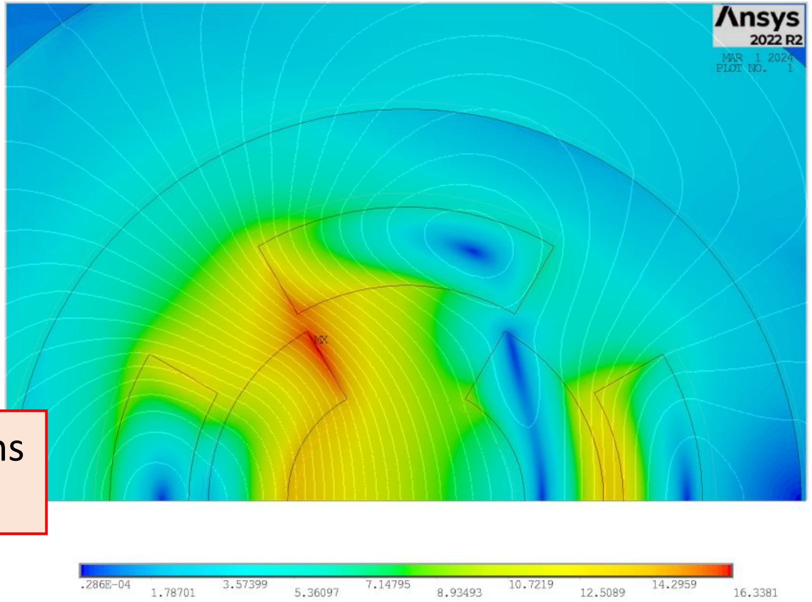
Quad into dipole:

(ReBCO @20 K)

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

$B \sim 11.7\ T$

$G \sim 143.3$ 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

These two configurations are NOT realistic.

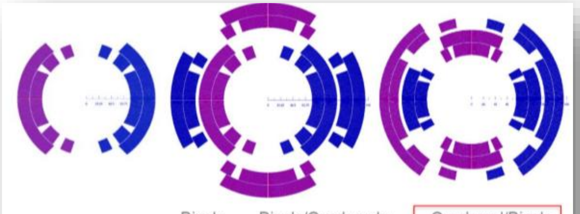
Arc:

- 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.

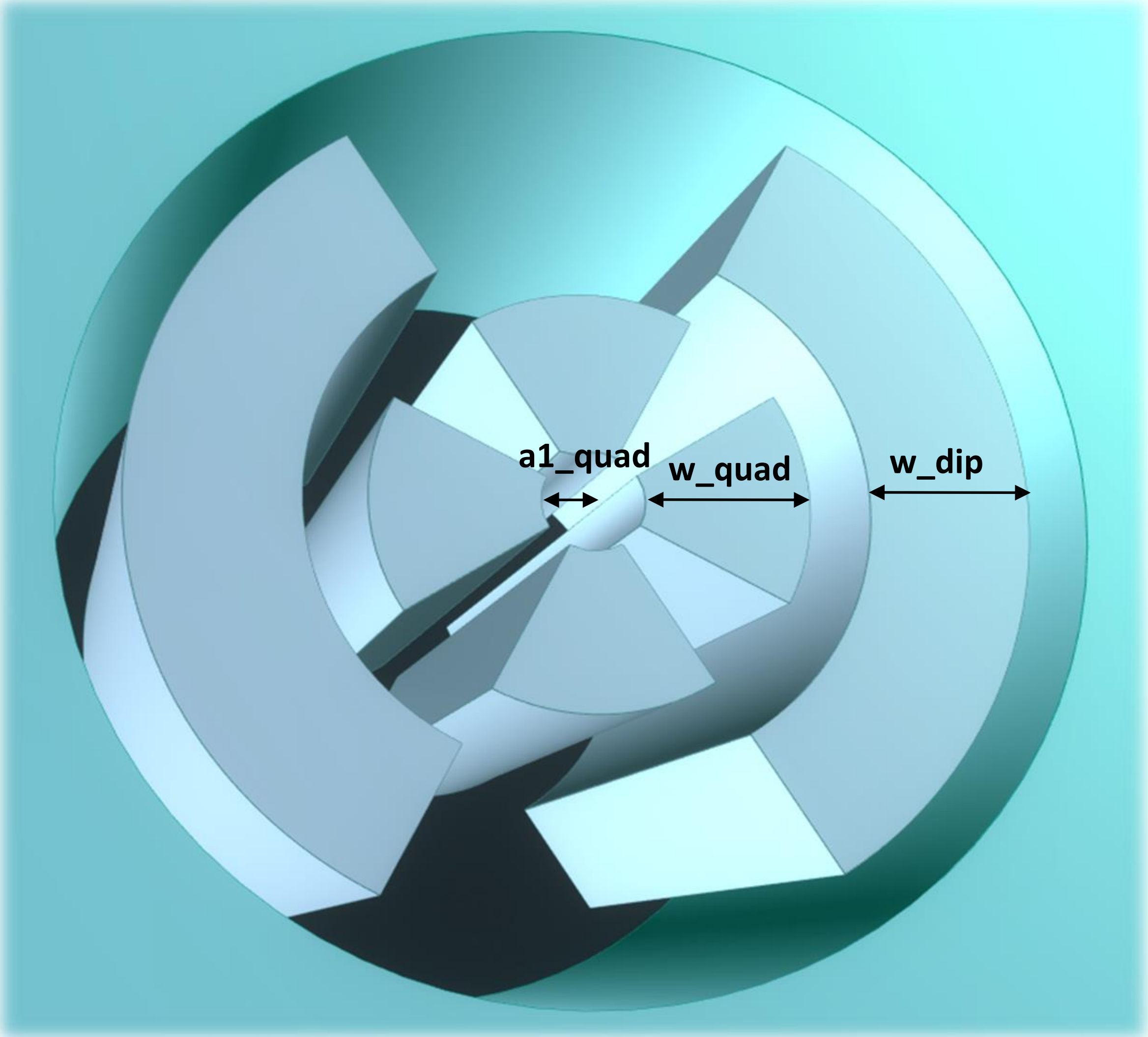


	Dipole	Dipole/Quadrupole	Quadrupol/Dipole
Superconductor	Nb_3Sn	Nb_3Sn	Nb_3Sn
Cable	40x1mm	40x1mm	40x1mm/30x1mm
B_{coil_max}, T	15.1	16.6/16.2	16.2/16.1
B_{max}/G_{max}, T/T/m	14.4	9.9/70.1	10.3/89.8
B_{op}/G_{op}, T/T/m	10	8/71	8/81
Margin	~40%	~24%/~20%	~28%/~20%

Most efficient configuration

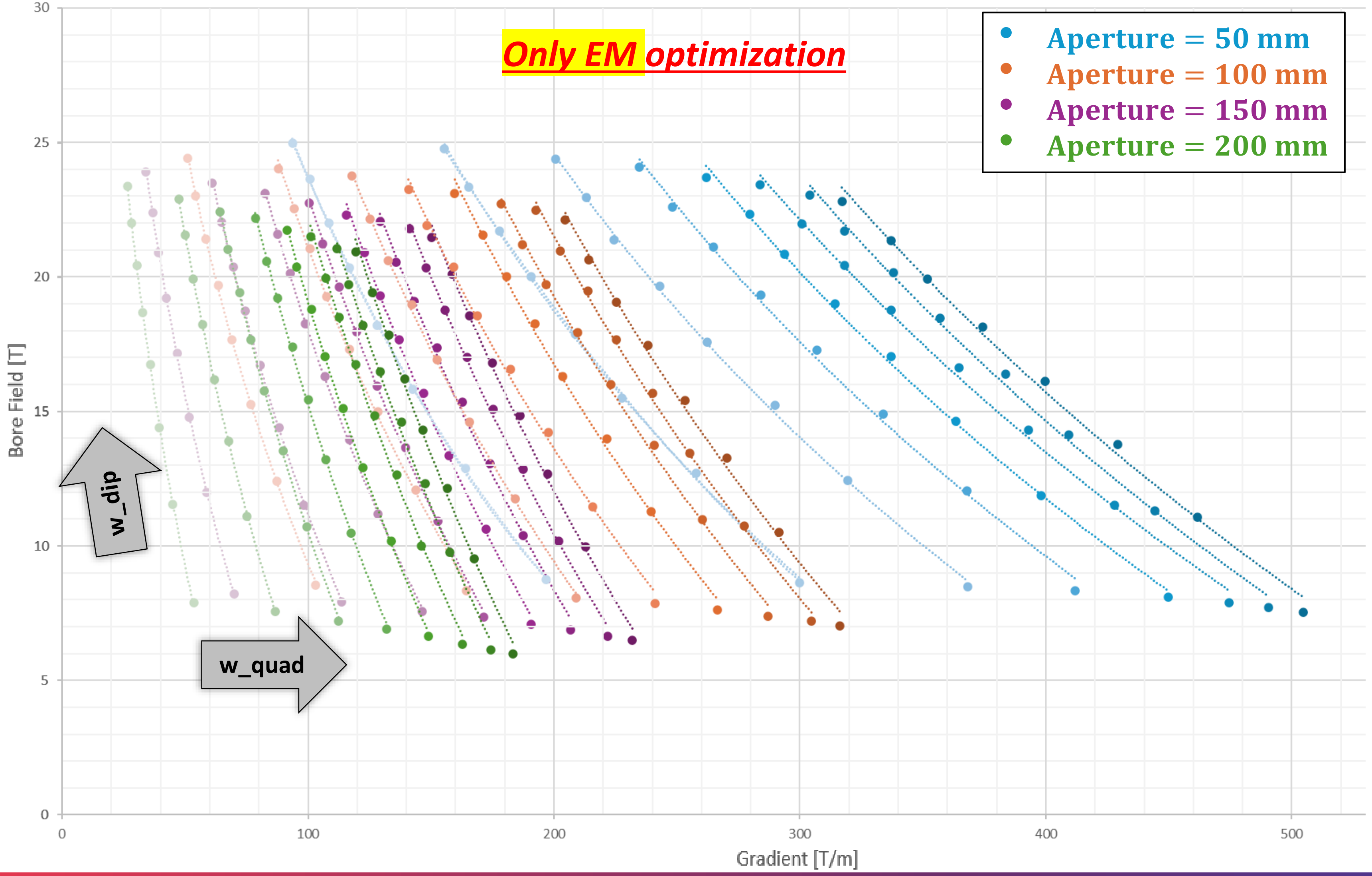
Fermilab

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**.

METHOD: B-G PLOT AT 4.5K



Current density
Optimization (1%)

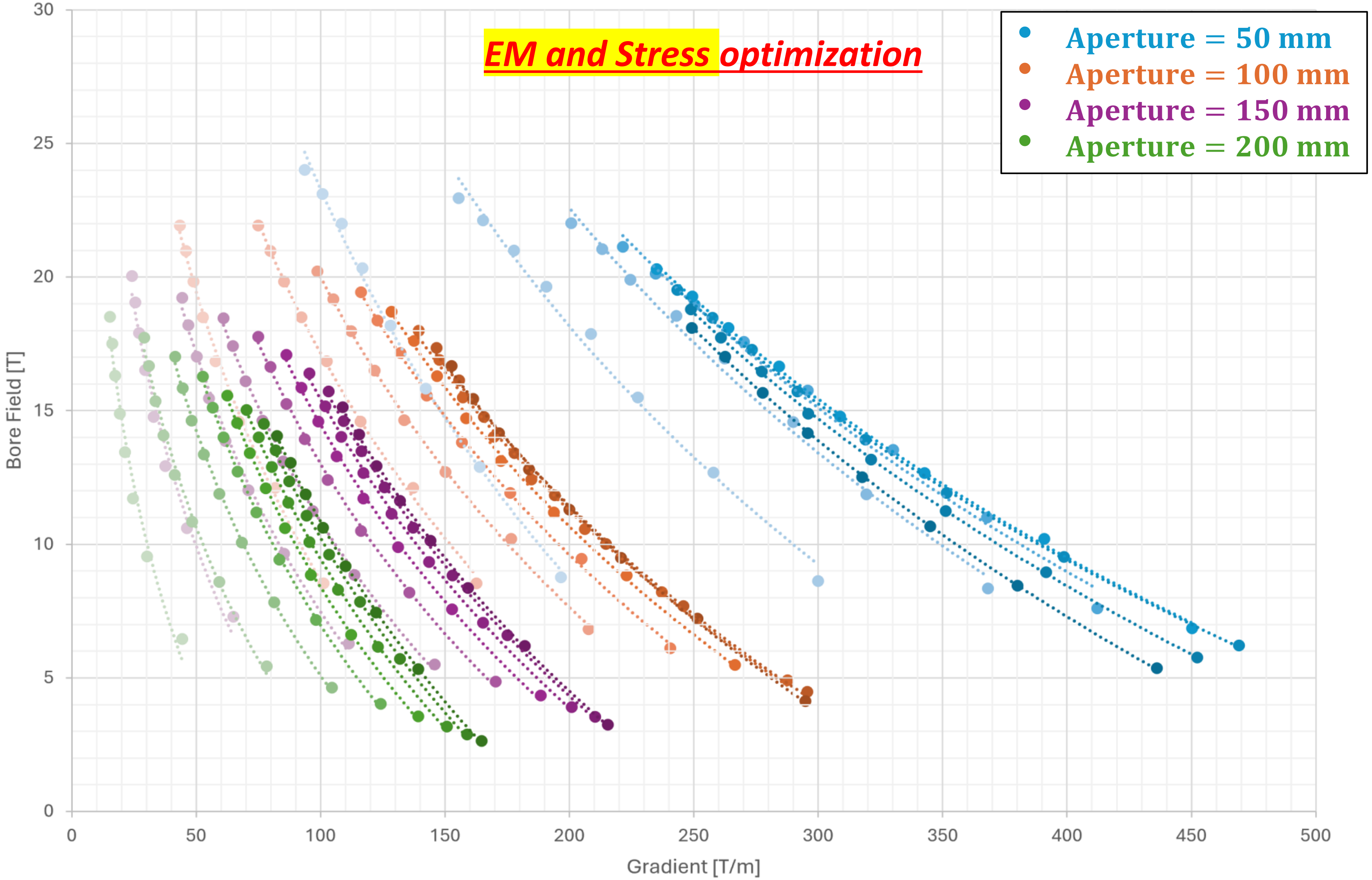
Optimize J_quad and J_dip to be close to the critical current density:

```
....
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

Limitations on stress and cost are still missing

METHOD: B-G PLOT AT 4.5K



Midplane pressure
Optimization (1%)

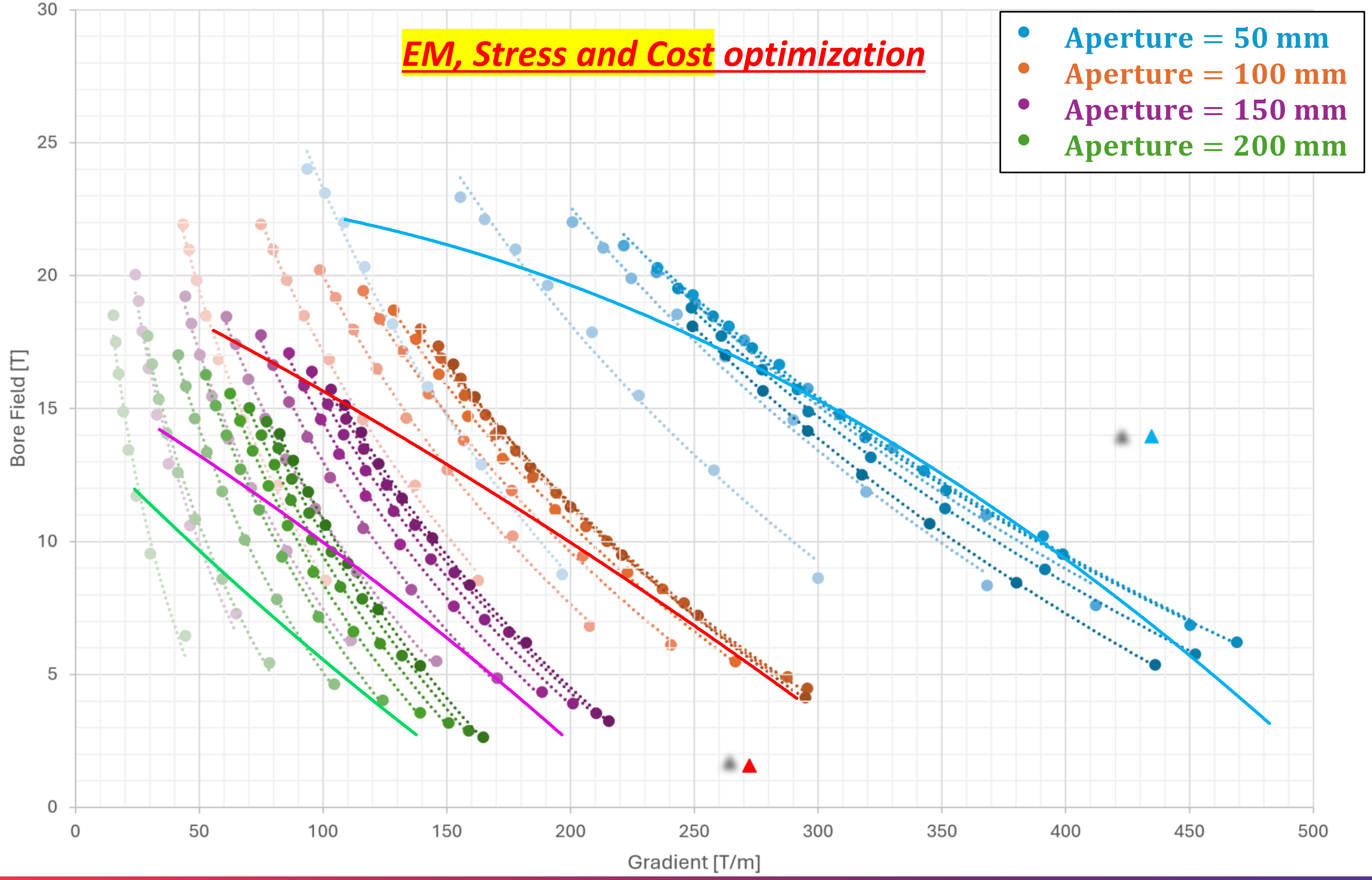
Optimize (decrease) J_quad and J_dip to not exceed the maximum stress (400 MPa)

```
.....
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.

Limitation on cost is still missing

METHOD: B-G PLOT AT 4.5K



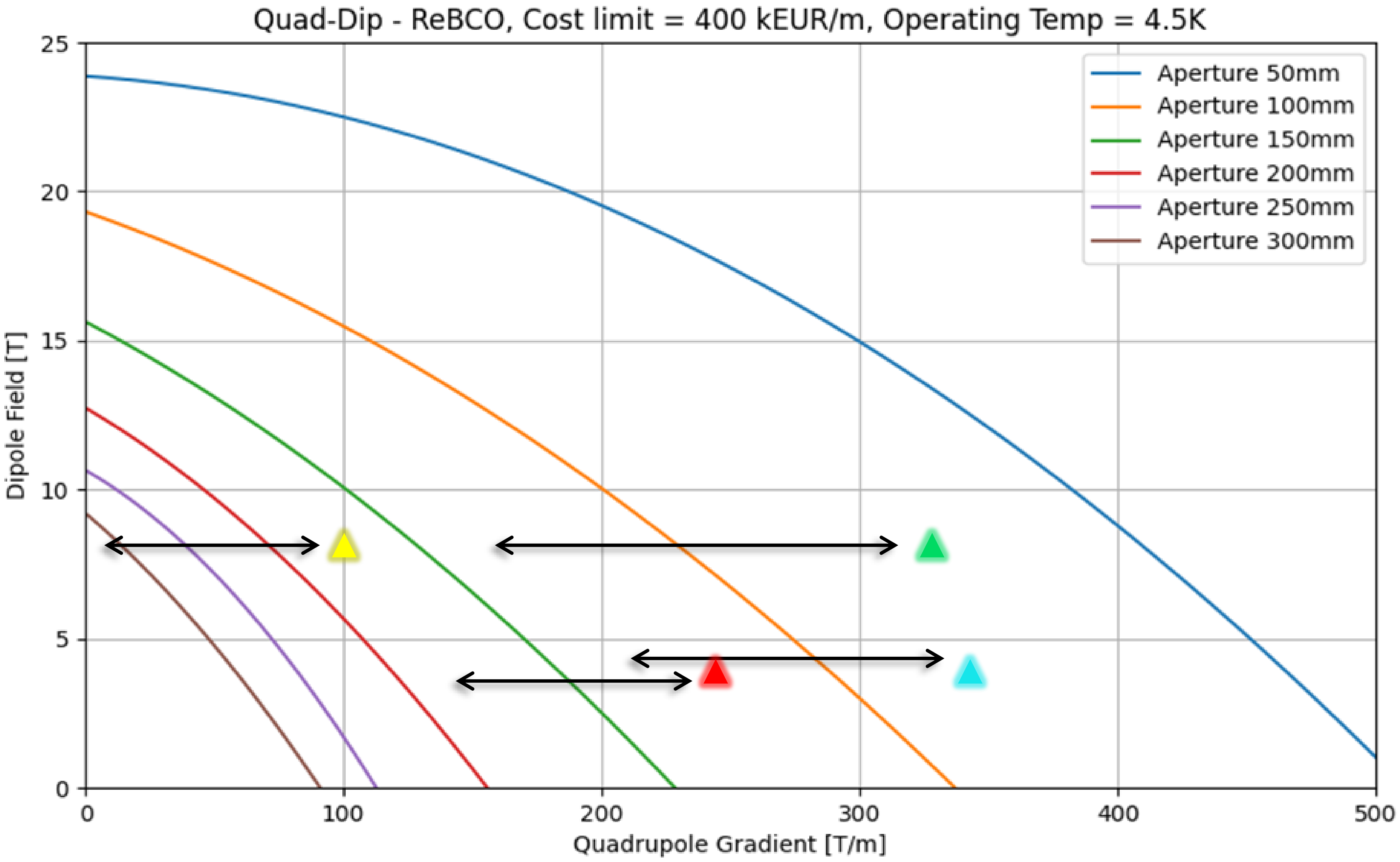
The dipole coil width (w_dip) can be computed if the aperture radius (a1_quad) and the quadrupole coil width (w_quad) are known.

```
.....
for a1_quad in range(25,151,25):
    .....
    for w_quad in range(10, 81, 10):
        w_dip = round(cost_model(a1_quad,w_quad),0)
        .....
    .....
.....
```

The cost value for the structures and iron is taken from HL-LHC, while the cost of the superconducting material (ReBCO) is based on the aspirational value of 2500 EUR/kg.

The cost model saves one point for each curve with the same aperture.

RESULTS: B-G PLOT AT 4.5K



From v0.7:

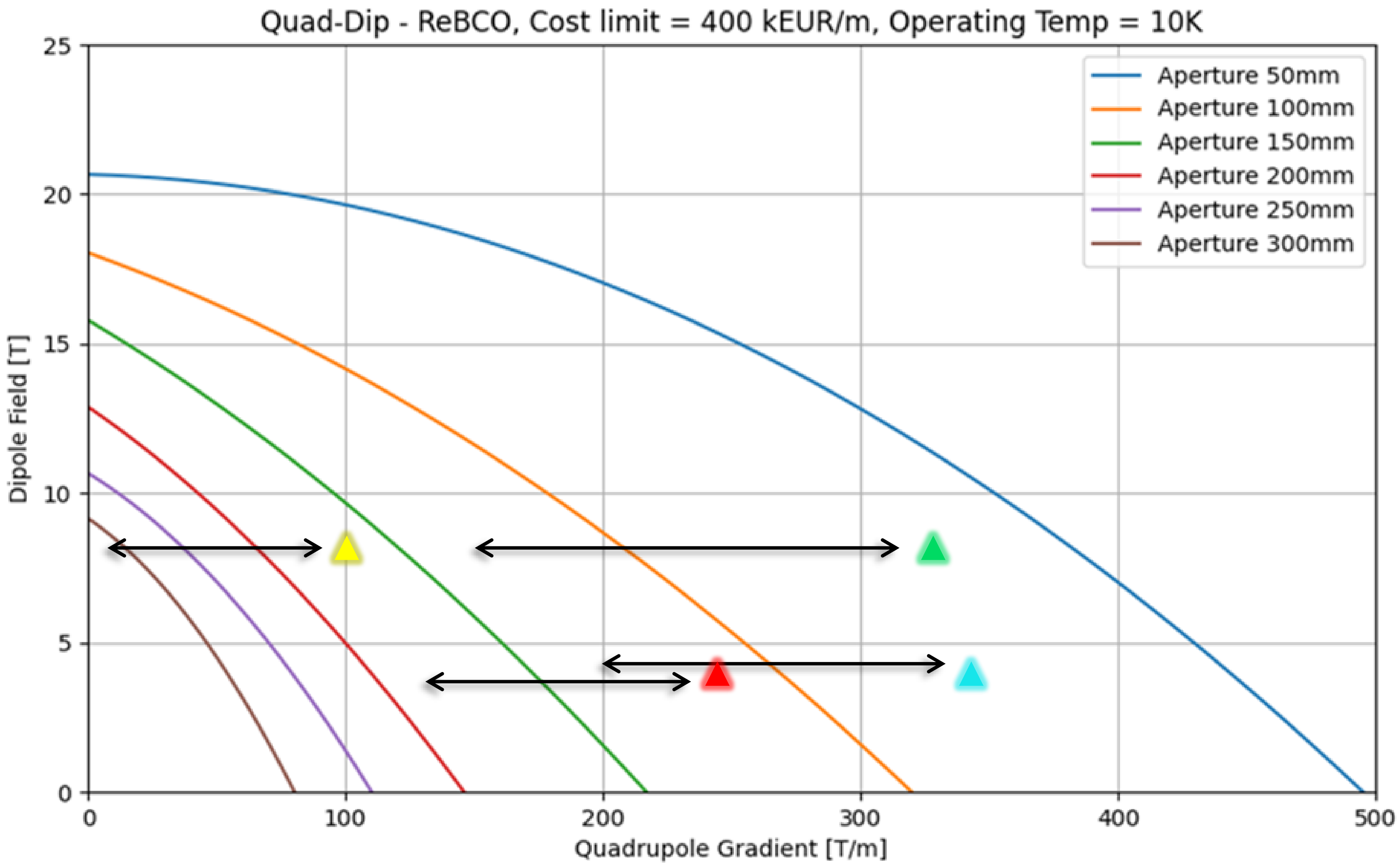
- ▲ 8 T, 100 T/m, aperture of 310 mm (FF)
- ▲ 8 T, 320 T/m, aperture of 130 mm (ARC)
- ▲ 4 T, 240 T/m, aperture of 170 mm (Corr.)
- ▲ 4 T, 330 T/m, aperture of 130 mm (Corr.)

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.

RESULTS: B-G PLOT AT 10K



From v0.7:

- 8 T, 100 T/m, aperture of 310 mm (FF)
- 8 T, 320 T/m, aperture of 130 mm (ARC)
- 4 T, 240 T/m, aperture of 170 mm (Corr.)
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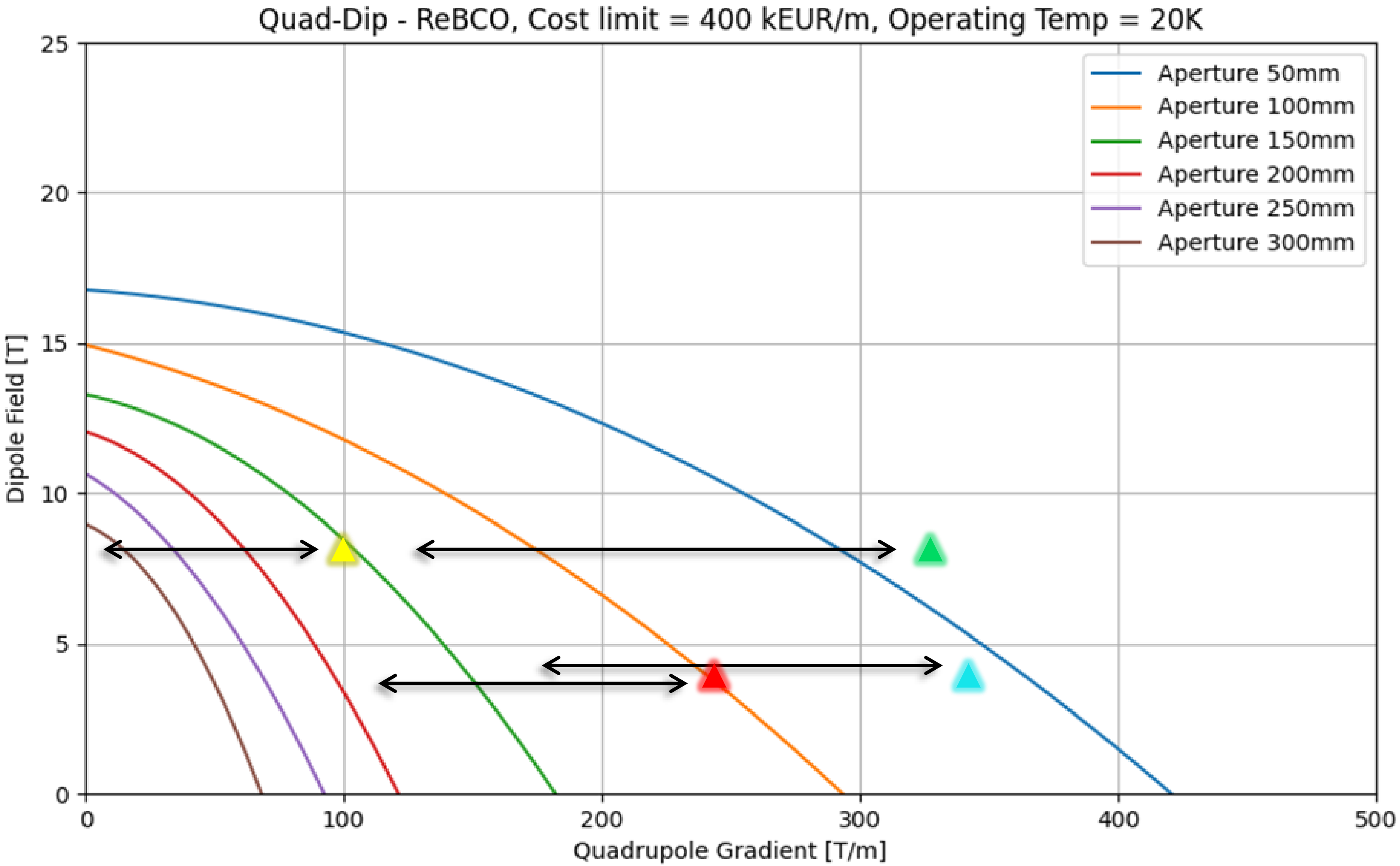
↓
Budget for the SC = 320 kEUR/m

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

RESULTS: B-G PLOT AT 20K



From v0.7:

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- 8 T, 320 T/m, aperture of 130 mm (ARC)
- 4 T, 240 T/m, aperture of 170 mm (Corr.)
- 4 T, 330 T/m, aperture of 130 mm (Corr.)

Courtesy of Kyriacos Skoufaris
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Maximum budget = 400 kEUR/m
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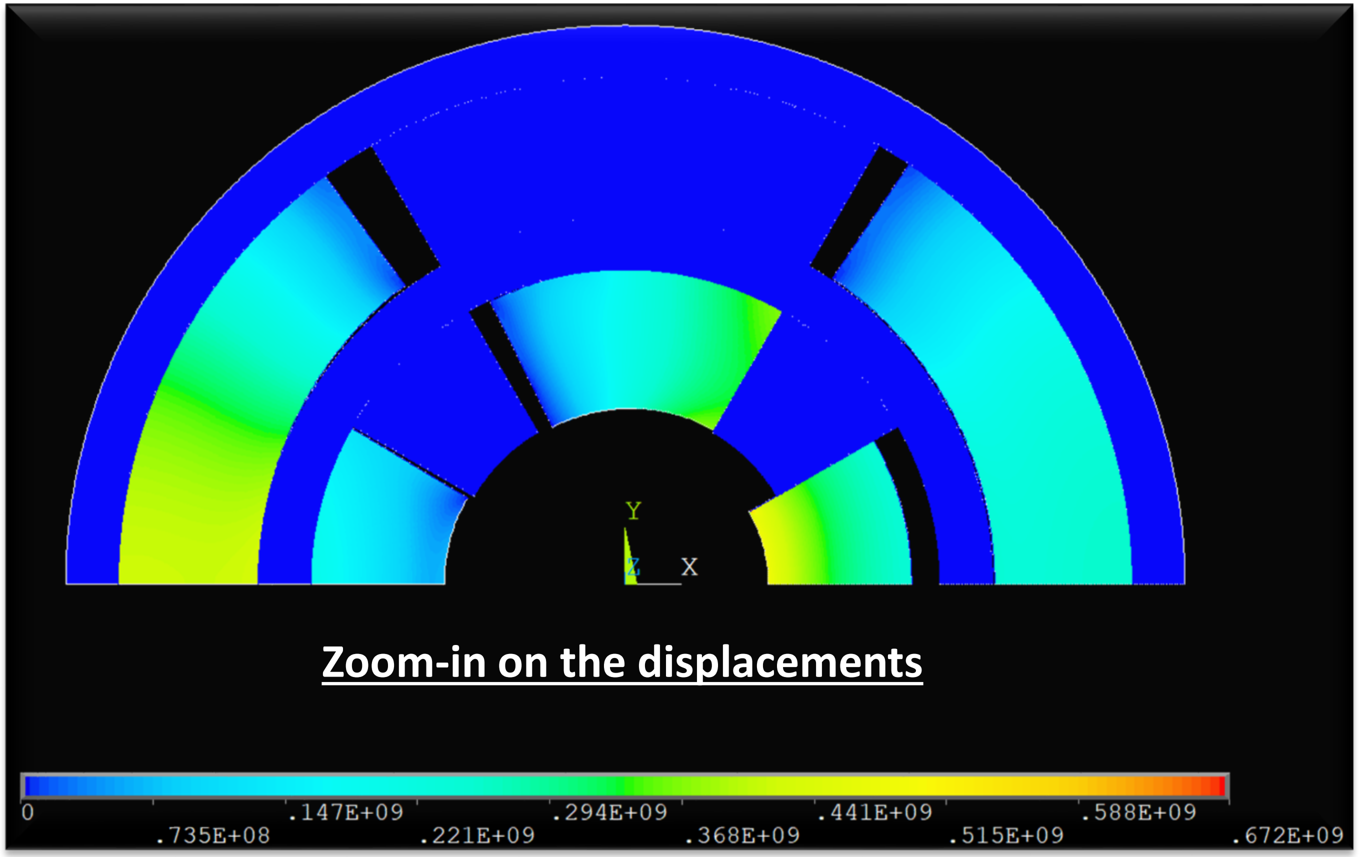
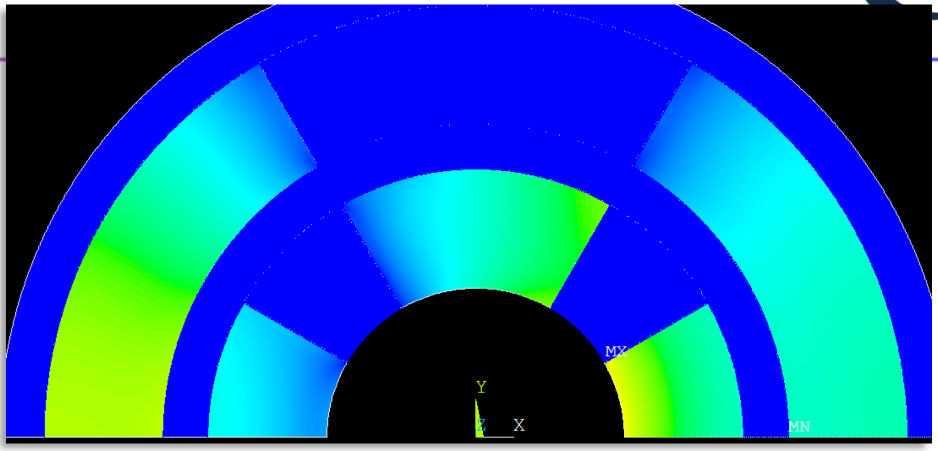
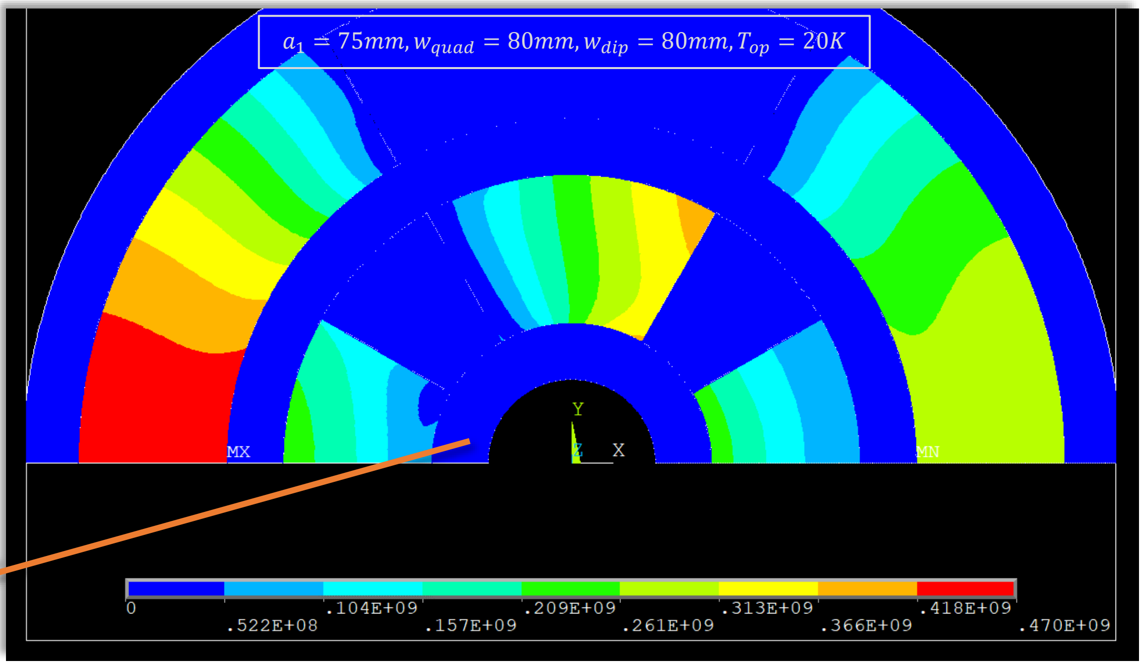
↓
Budget for the SC = 320 kEUR/m

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

Stress Issue

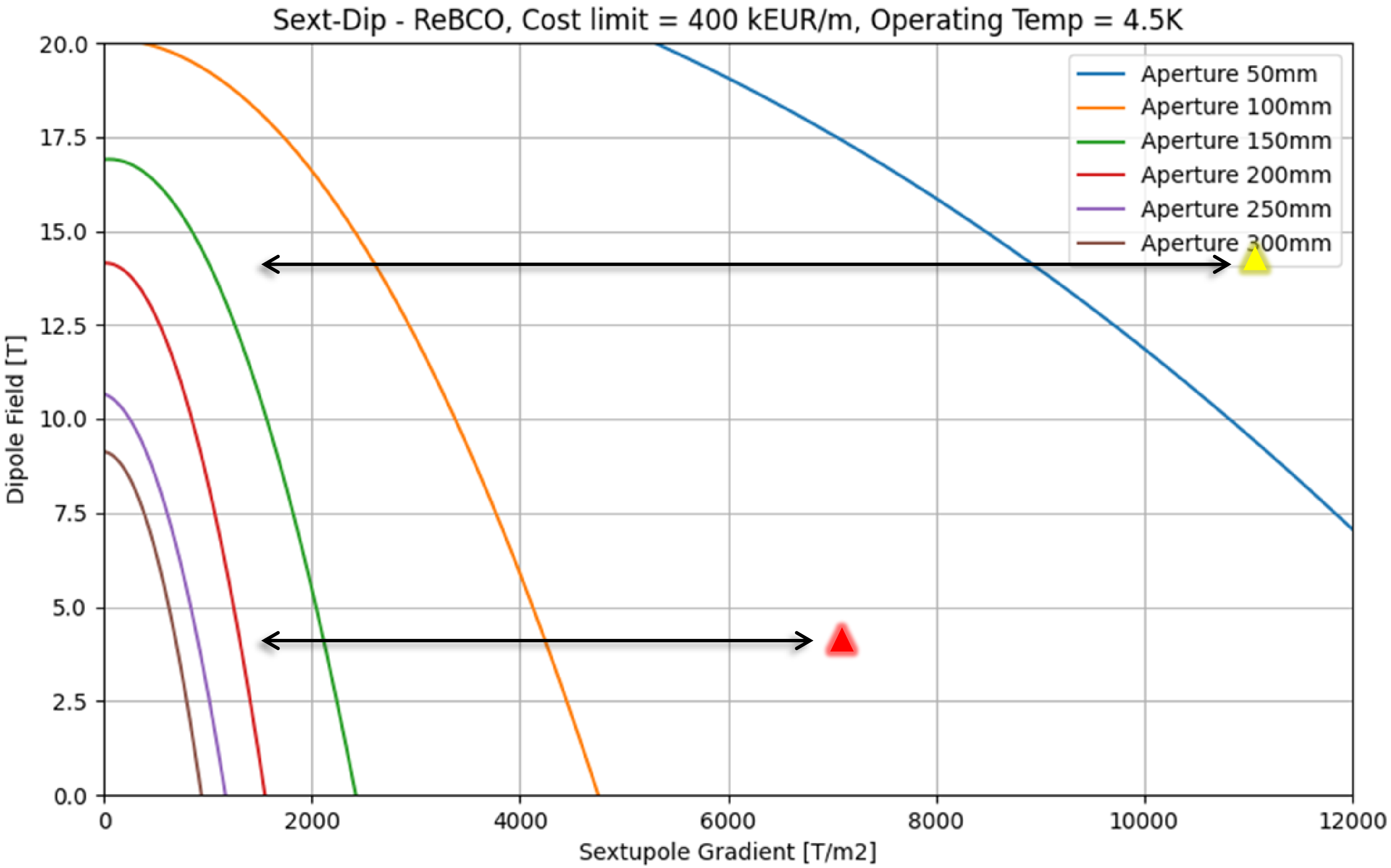






To address the issue, we insert an infinitely rigid internal structure to enable the study of stress behavior in the coils.

RESULTS: B-G2 PLOT AT 4.5K



The same method used for B-G plots is applied to B-G2 plots.

From v0.7:

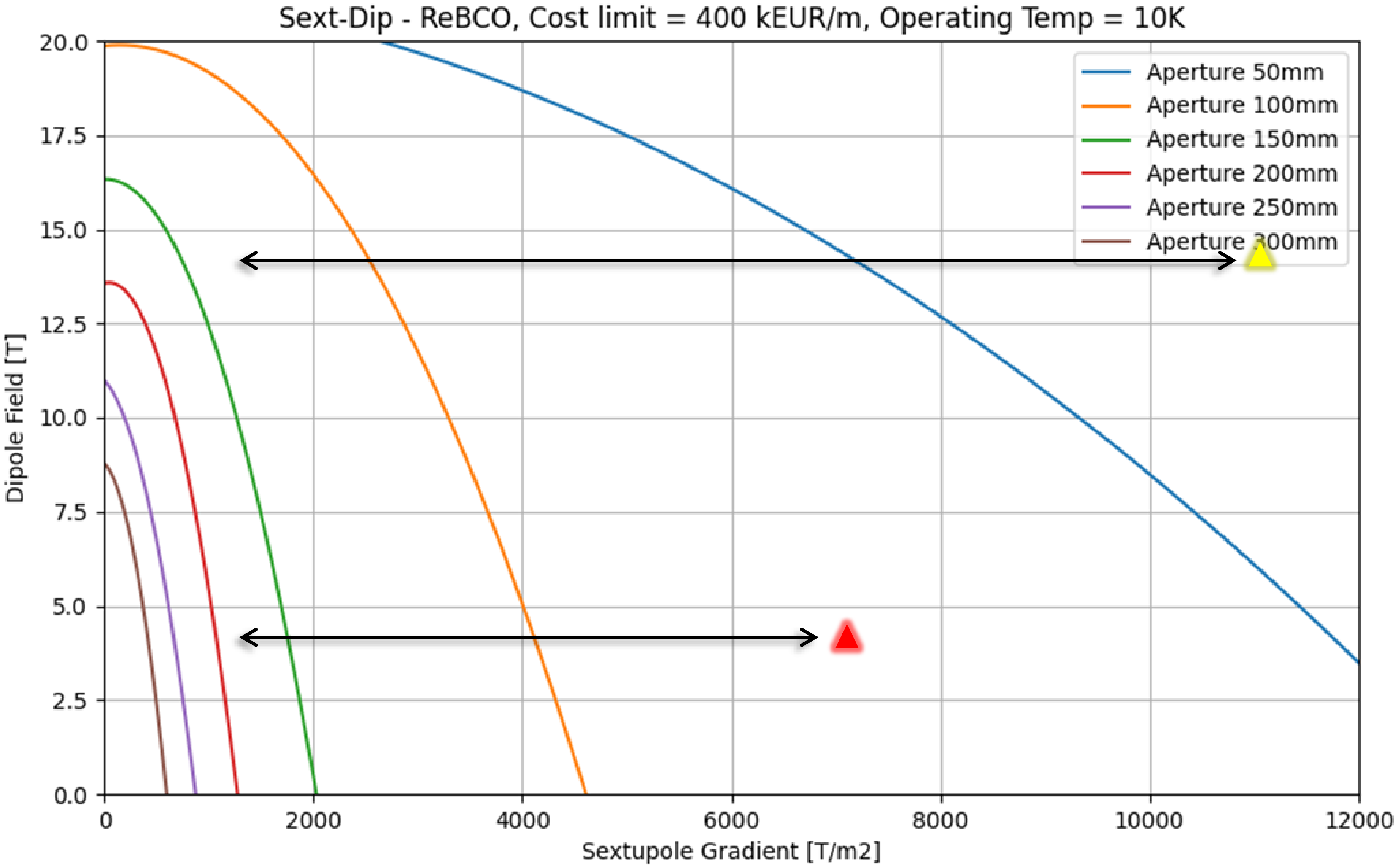
▲ 14 T, 7100 T/m2, aperture of 130 mm (ARC)

▲ 4 T, 11555 T/m2, aperture of 170 mm (Corr.)

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

RESULTS: B-G2 PLOT AT 10K



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Maximum budget = 400 kEUR/m
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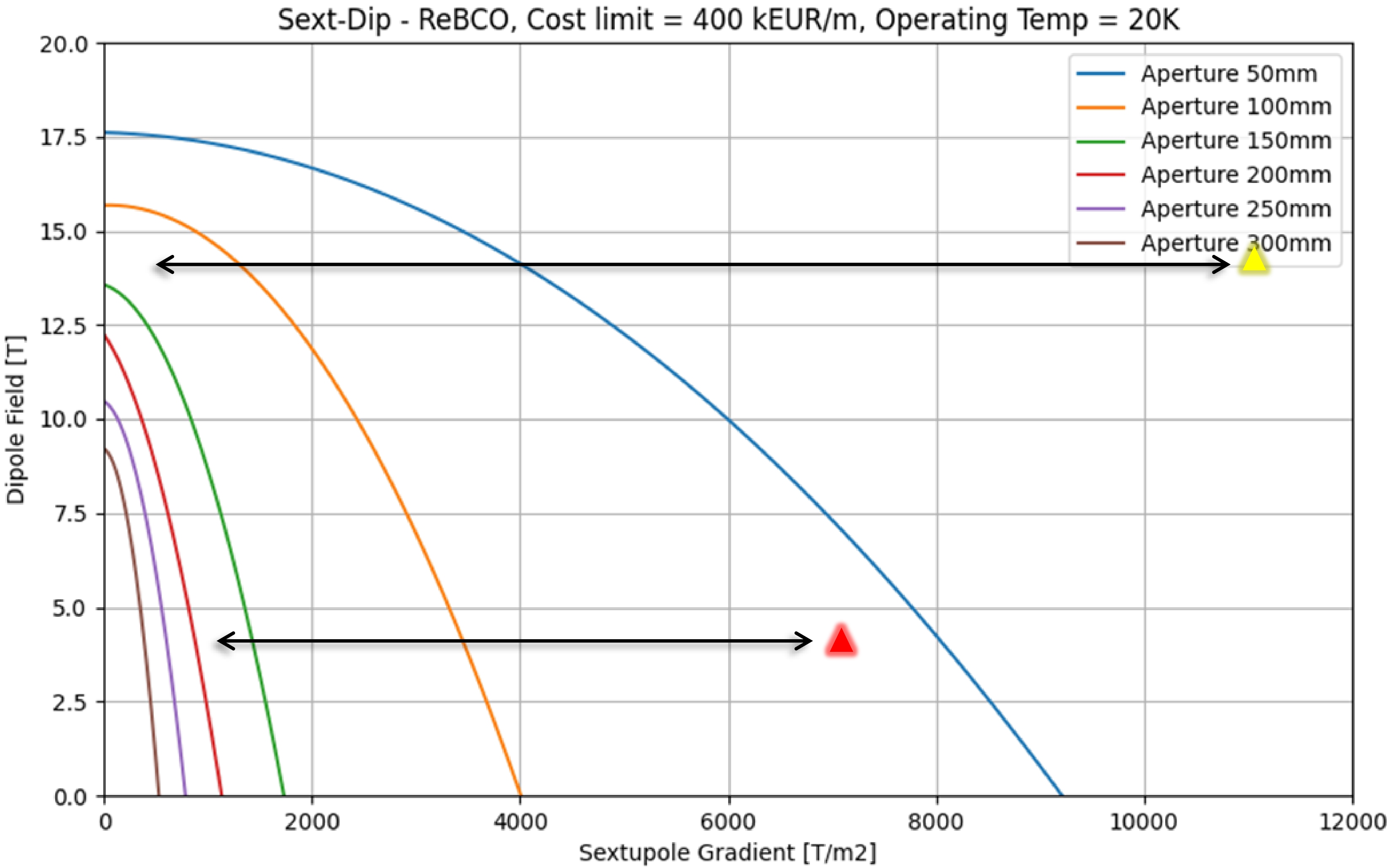
↓
Budget for the SC = 320 kEUR/m

RESULTS: B-G2 PLOT AT 20K



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↓
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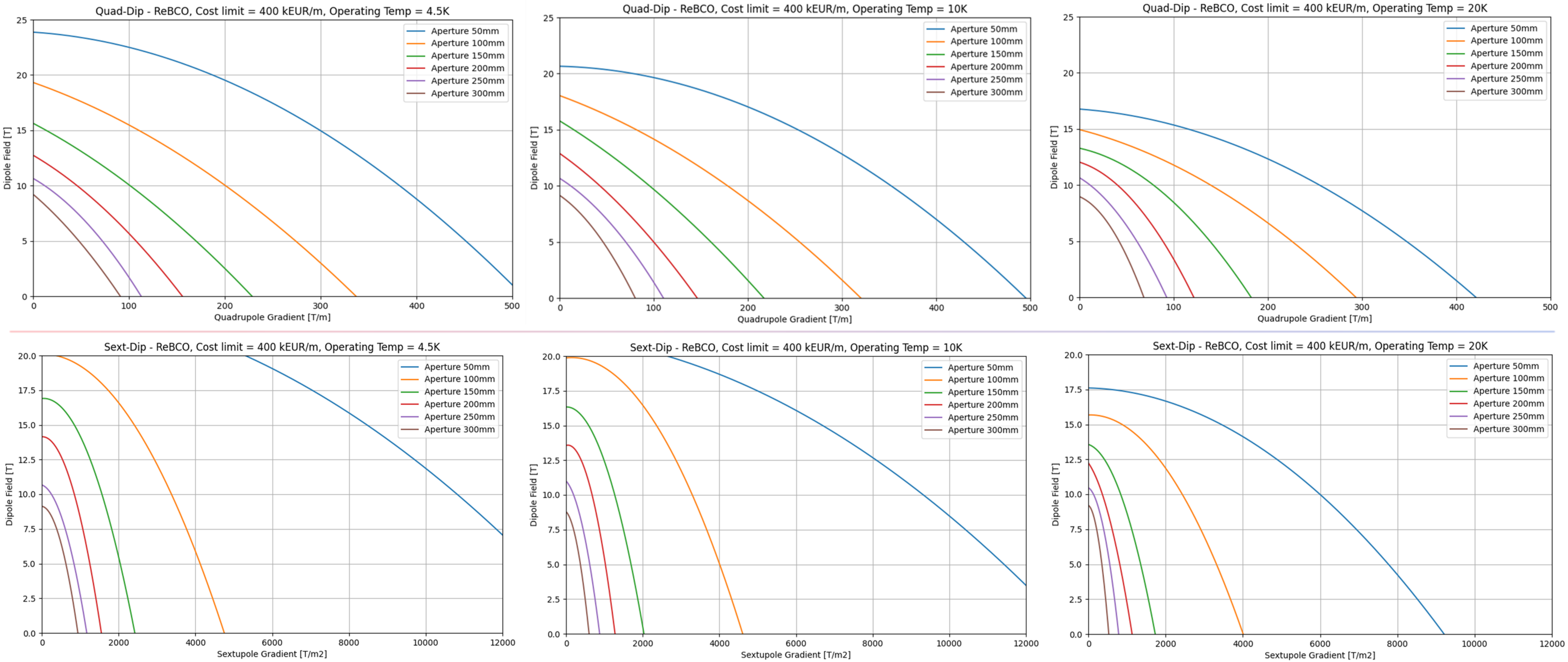
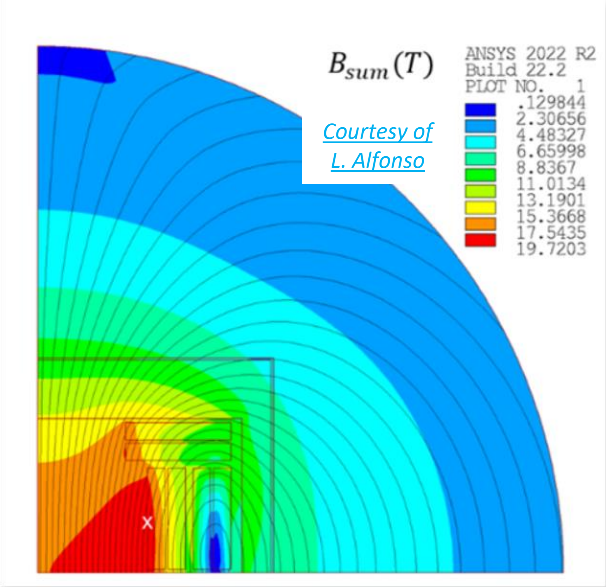
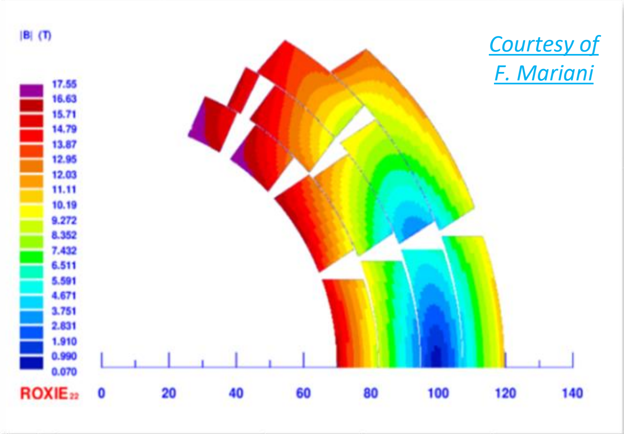
SUMMARY OF FINAL RESULTS



CONCLUSIONS

- The A-B, A-G, B-G, and B-G2 plots are provided and discussed, using both analytical and FEM approaches, representing the starting point to define possible beam optics that are also acceptable from a technological point of view.





- The allowed phase spaces do not imply that the magnet is feasible, but rather that it is possible to start studying a specific design for that magnet. In this regard, in line with this work, we are studying a specific cos-theta and block coil design for the main arc dipoles.

- Following the same approach, we will begin to study the specific design of a combined function magnet (starting with the arc quad-dip magnet) and will integrate quench protection into the limit curves.

THANK YOU FOR YOUR ATTENTION

mmWG, 20 February 2025

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