Collider magnets study

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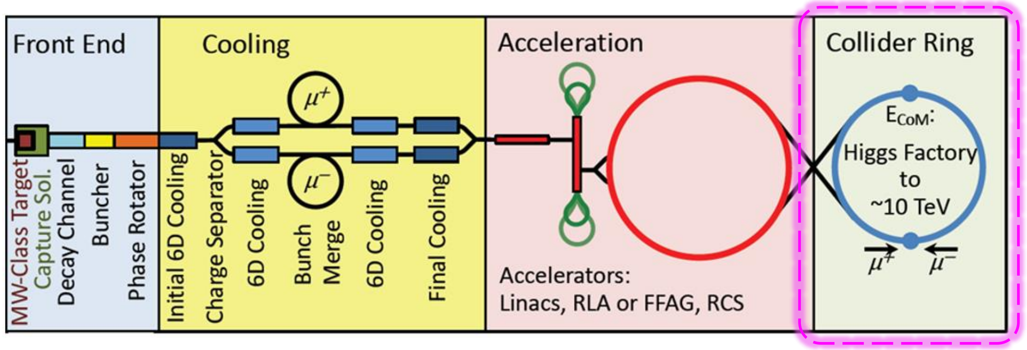
Collider Magnets Requirements



Main bending dipoles:

10 TeV collider (10 km ring):

- 15T /150 mm (REBCO, hybrid)
- 5 m length
- 1200 magnets

3 TeV collider (5 km ring):

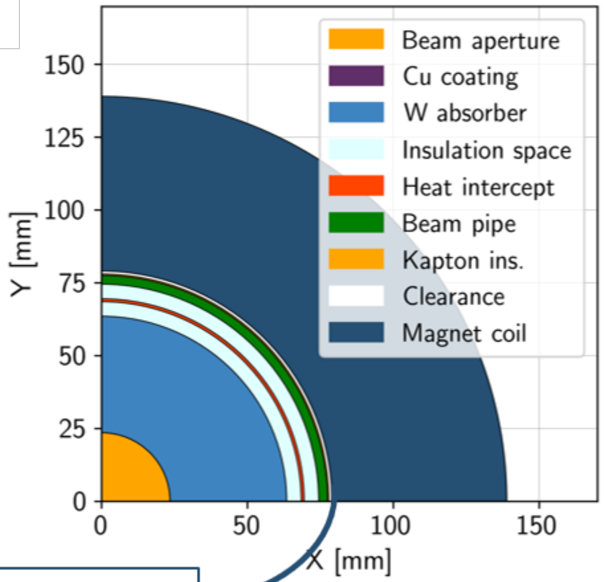
- 11T/150 mm (Nb_3Sn)
- 5 m length
- 600 magnets

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

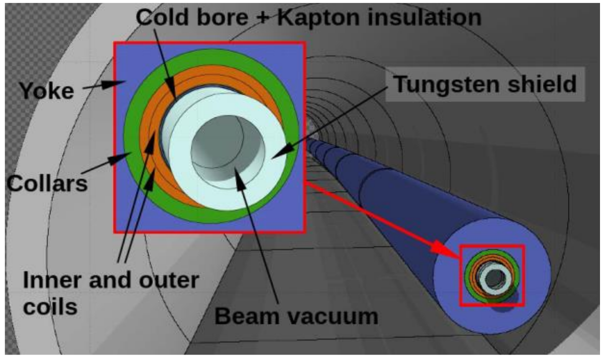
Courtesy of Patricia Borges de Sousa
https://indico.cern.ch/event/1250075/contributions/5357594/



Coil aperture 158 mm

with HTS @20K the absorber can be 30 mm thick:
coil aperture 138 mm

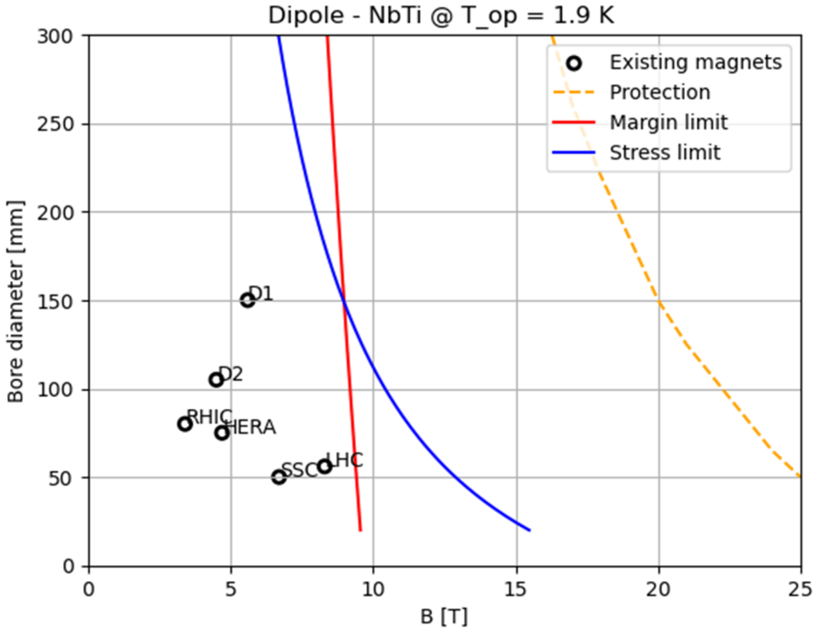
Courtesy of A.Lechner

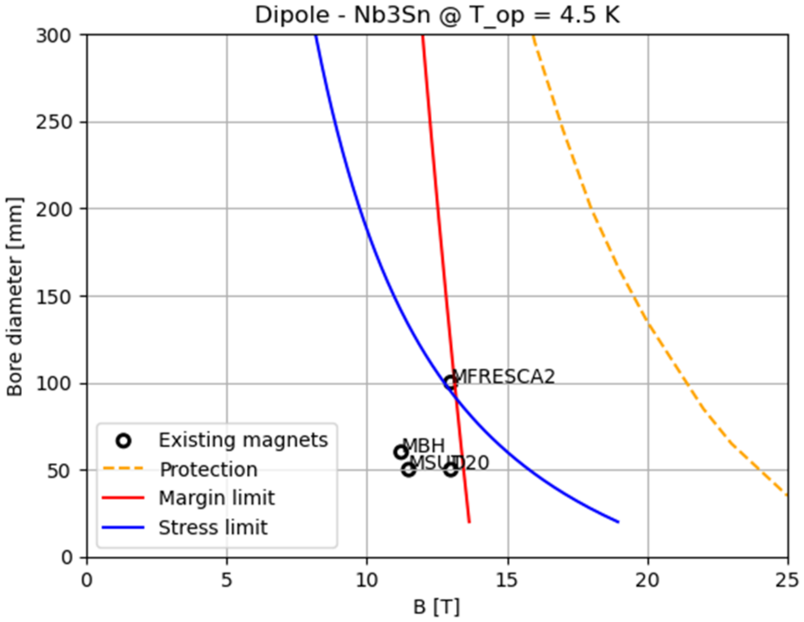


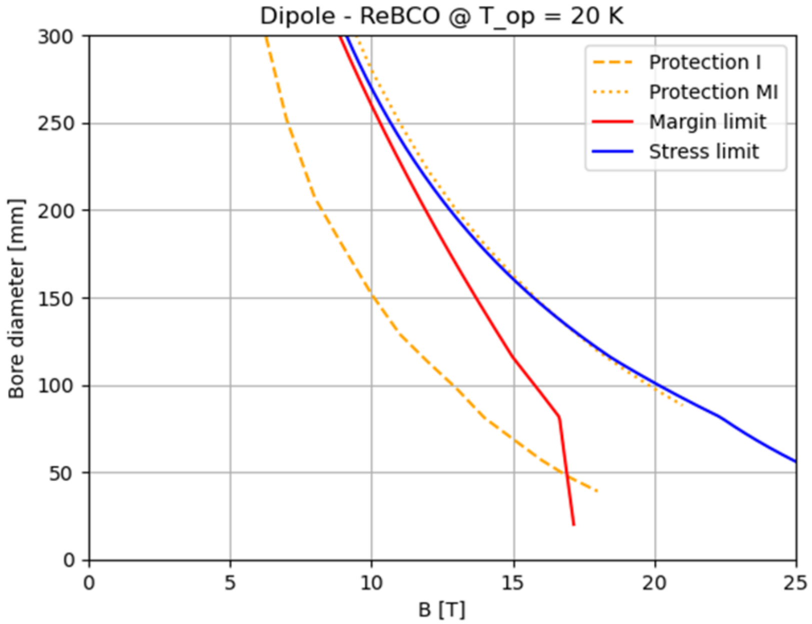
! **Need for high fields in large apertures**

INTRODUCTION

- We perform plots that can show the allowed area between aperture diameter (A) and bore field (B).
- We consider 3 materials: two LTS (NbTi and Nb_3Sn) and one HTS (ReBCO) at different operating temperatures.
- A Python code is used to implement the analytic formulas, for a cos-theta magnets in sector coil approximation (α is 60° for the dipole and 30° for the quadrupole), which provide the limit curves shown below.
- Limit curves, introduced by stress, margin and protection, are discussed in presentations.





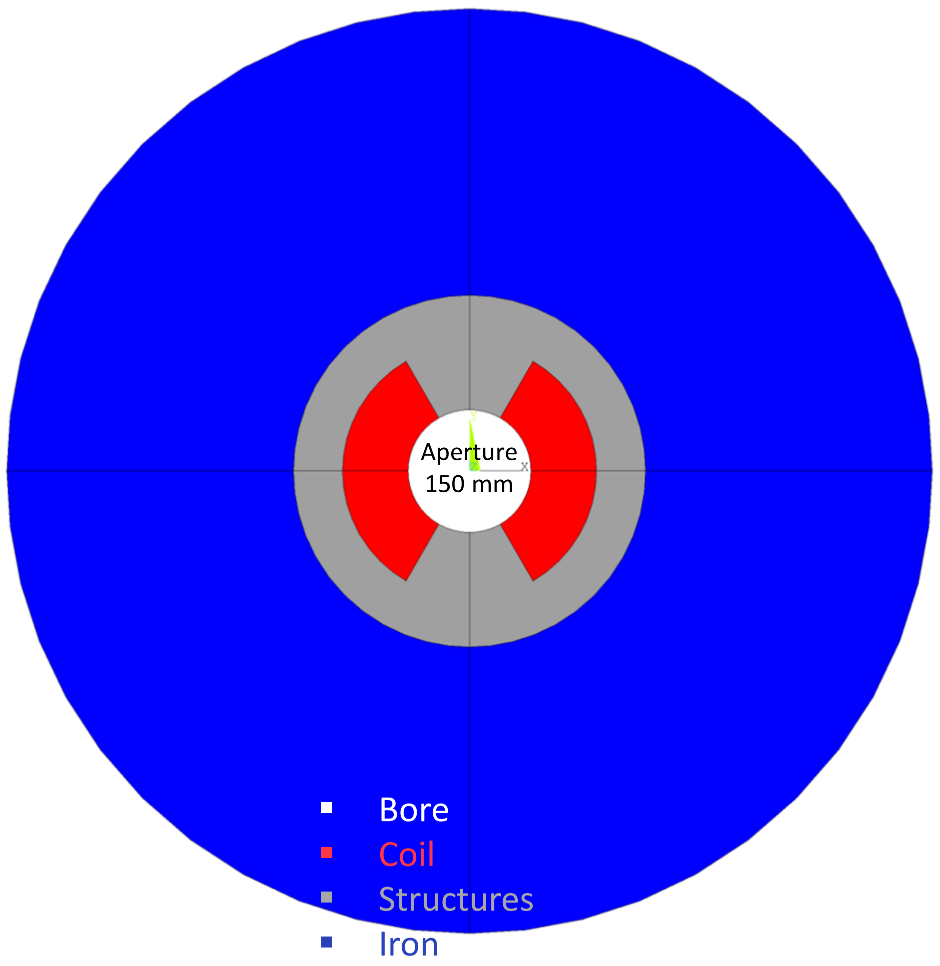


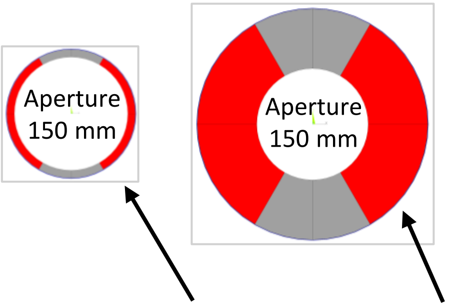
COST MODEL

Total cost of the magnet = 400 kEUR/m (FCC-hh 175 kEUR/m [ref])

Cost of the labour = 20 kEUR/m (LHC)

Example diagram with bore aperture set at 150 mm.





Coil width: $10\ mm \leq w_c \leq 80\ mm$
$\rho_{coil} = 8000\ kg/m^3$

Structures: $w_s \leq 60\ mm$
SS cost: 10 EUR/kg (HL-LHC)
$\rho_{SS} = 7800\ kg/m^3$

Iron yoke: $w_i \leq 350\ mm$
Fe cost: 8 EUR/kg (HL-LHC)
$\rho_{Fe} = 7800\ kg/m^3$

The assumptions made for the cost model are very important !

- Higher cost ⇒ Thinner coil
  - ⇒ Higher current density
    - ⇒ Problem with quench protection
    - ⇒ Work close to the critical surface (margin limit)
  - ⇒ Higher pressure on midplane ⇒ Stress limitations

Materials	SC cost [EUR/kg]	Aspirational SC cost [EUR/kg]
NbTi	330	330 (today value)
Nb_3Sn	2000	700 (FCC target)
ReBCO	8000	2500 (realistic projection)

The maximum total cost of the magnet is the same for all materials.

Cost Model

$$C_{Magnet} = C_{tot} - C_{labour} = \sum_k C_k \rho_k A_k \quad \text{where} \quad k = \text{coil, structures, iron}$$

$$A_{coil} = \frac{2\pi}{3}(a_2^2 - a_1^2) \qquad A_{Structures} = \pi(a_3^2 - a_2^2)$$
$$A_{iron} = \pi(a_4^2 - a_3^2)$$

$$a_2 = a_1 + w_{coil}$$
$$a_3 = a_2 + w_s$$
$$a_4 = a_3 + w_i$$

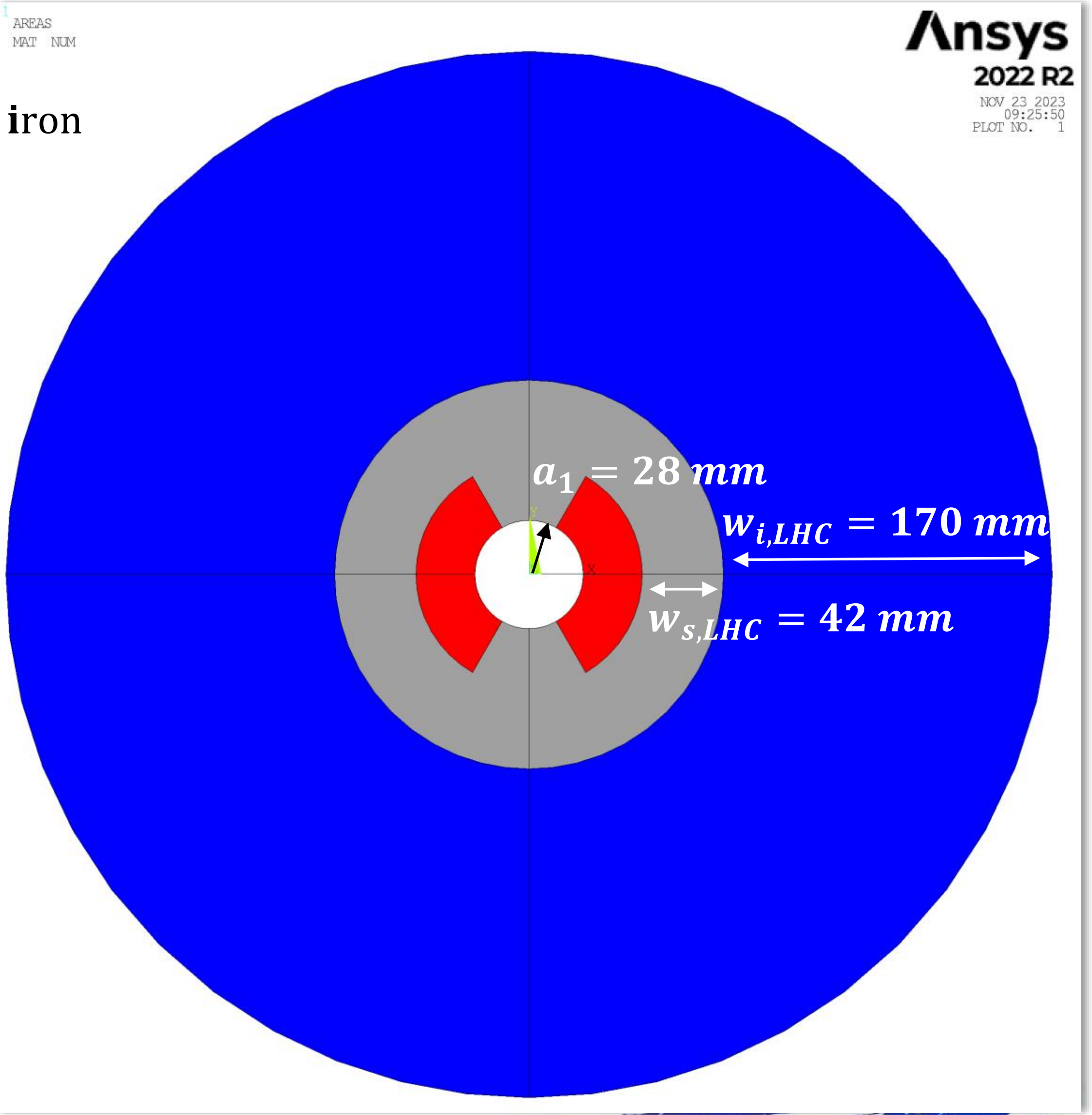
The cost of the magnets is function of:

$$C_{Magnet}(a_1, w_c, w_s, w_i)$$

$$w_s = w_{s,LHC} \cdot \frac{a_1}{a_{1,LHC}}$$

$$w_i = w_{i,LHC} \cdot \frac{a_1}{a_{1,LHC}}$$

Using the main LHC dipoles as a reference



We can express the total cost of the magnets as a function of only two variables: the internal radius and the coil width.

$$C_{Magnet}(a_1, w_c) \rightarrow w_c(a_1, C_{Magnet})$$

Stress Limit

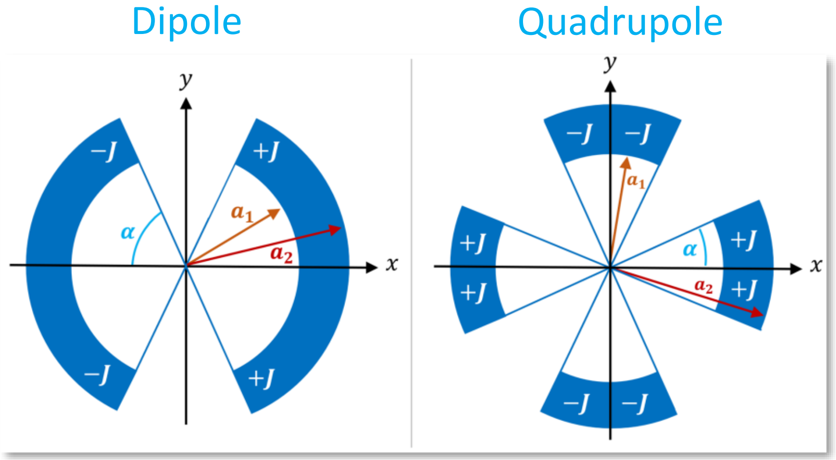
Starting point

Constants → $\boldsymbol{\sigma_{max}}$ as a function of the material, $\boldsymbol{\alpha}$ of the sector coil.

- NbTi = 100 MPa
- Nb_3Sn = 150 MPa
- ReBCO = 400 MPa

- Dip = 60°
- Quad = 30°

Variables → For each aperture radius $\mathbf{a_1}$, $\mathbf{w_{coil}}$ can be calculated from the cost model.



Reference: https://doi.org/10.15161/oar.it/143359

Dipole

At the first order of approximation, the **midplane pressure** is:

$$P_\theta = \frac{2\mu_0 sin\alpha\,(cos\alpha - 1)\,J^2}{\pi w}\left(-\frac{2}{3}\frac{a_2^3 - a_1^3}{3} - \frac{a_1^3}{3}\ln\left(\frac{a_2}{a_1}\right) + \frac{a_2^3 - a_1^2 a_2}{2}\right)$$

For fixed P_θ, the **current density** can be computed:

$$P_\theta = \sigma_{max}/1.5 \quad \Longrightarrow \quad J\,(\sigma_{max}\,, a_1\,, w)$$

Quadrupole

At the first order of approximation, the **midplane pressure** is:

$$P_\theta = \frac{2\mu_0 sin2\alpha\,(cos2\alpha - 1)\,J^2}{\pi w}\left(\frac{7}{12}\frac{a_2^3 - a_1^3}{3} - \frac{a_1^3}{3}\ln\left(\frac{a_2}{a_1}\right) + \frac{a_1^4 - a_1^3 a_2}{4a_2}\right)$$

For fixed P_θ, the **current density** can be computed:

$$P_\theta = \sigma_{max}/1.5 \quad \Longrightarrow \quad J\,(\sigma_{max}\,, a_1\,, w)$$

It is difficult to consider the true stress on the magnet as it depends on the geometry of the magnet.
Therefore we use this value to convert $P_{\theta,max}$ into σ_{max}

STRESS LIMIT

STARTING POINT

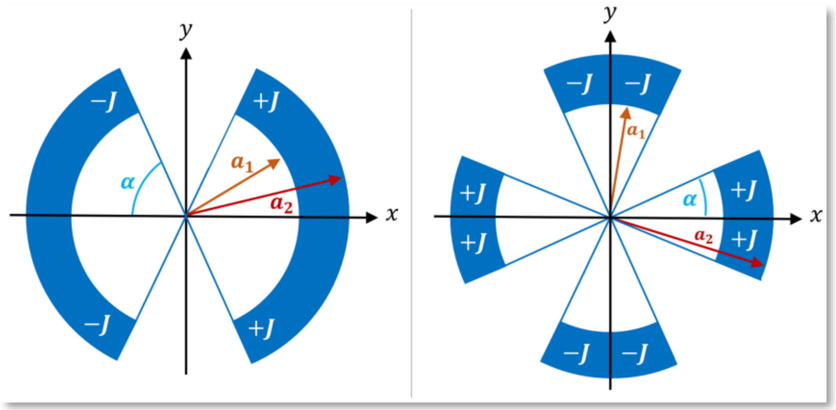
Constants → $\boldsymbol{\sigma_{max}}$ as a function of the material, $\boldsymbol{\alpha}$ of the sector coil.

- NbTi = 100 MPa
- Nb_3Sn = 150 MPa
- ReBCO = 400 MPa

- Dip = 60°
- Quad = 30°

Variables → For each aperture radius $\mathbf{a_1}$, $\mathbf{w_{coil}}$ can be calculated from the cost model.

Dipole Quadrupole



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DIPOLE

At the first order of approximation, the **midplane pressure** is:

$$P_\theta = \frac{2\mu_0 sin\alpha\,(cos\alpha - 1)\,J^2}{\pi w}\left(-\frac{2}{3}\frac{a_2^3 - a_1^3}{3} - \frac{a_1^3}{3}\ln\left(\frac{a_2}{a_1}\right) + \frac{a_2^3 - a_1^2 a_2}{2}\right)$$

For fixed P_θ, the **current density** can be computed:

$$P_\theta = \sigma_{max}/1.5 \quad \Longrightarrow \quad J\,(\sigma_{max}\,, a_1\,, w)$$

Then, through the analytic formulas, the **magnetic field** in the bore is:

$$B\,(w, J\,) = \frac{2\mu_0\,J}{\pi}\; w\; sin\alpha$$

QUADRUPOLE

At the first order of approximation, the **midplane pressure** is:

$$P_\theta = \frac{2\mu_0 sin2\alpha\,(cos2\alpha - 1)\,J^2}{\pi w}\left(\frac{7}{12}\frac{a_2^3 - a_1^3}{3} - \frac{a_1^3}{3}\ln\left(\frac{a_2}{a_1}\right) + \frac{a_1^4 - a_1^3 a_2}{4a_2}\right)$$

For fixed P_θ, the **current density** can be computed:

$$P_\theta = \sigma_{max}/1.5 \quad \Longrightarrow \quad J\,(\sigma_{max}\,, a_1\,, w)$$

Then, through the analytic formulas, the **gradient** is:

$$G\,(w, J\,) = \frac{2\mu_0\,J}{\pi}\ln\left(\frac{a_2}{a_1}\right)\; sin2\alpha$$

MARGIN LIMITATIONS

STARTING POINT

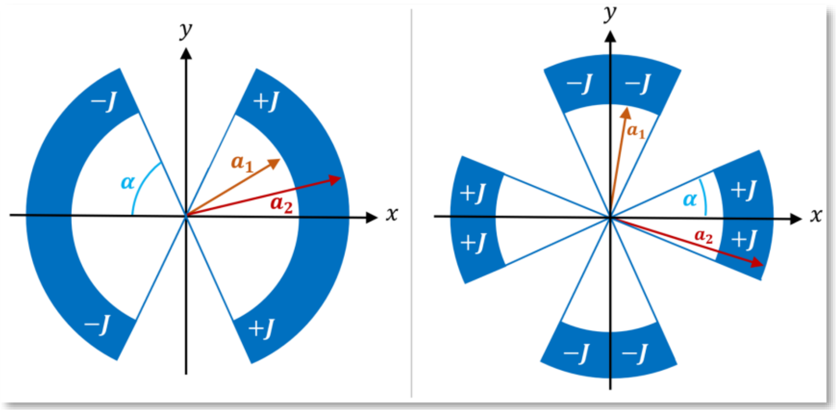
Constants → $T_{op} + T_{margin}$ as a function of the material, α of the sector coil.

- NbTi: 1.9K + 2K (LHC)
- Nb_3Sn: 4.5K + 2.5K (HL-LHC)
- ReBCO: 20K + 2.5K

- Dip = 60°
- Quad = 30°

Variables → For each aperture radius $\mathbf{a_1}$, $\mathbf{w_{coil}}$ can be calculated from the cost model.

Dipole Quadrupole



DIPOLE

Through the load line formula, the **current density** is proportional to the coil width *w* and the peak magnetic field *B*:

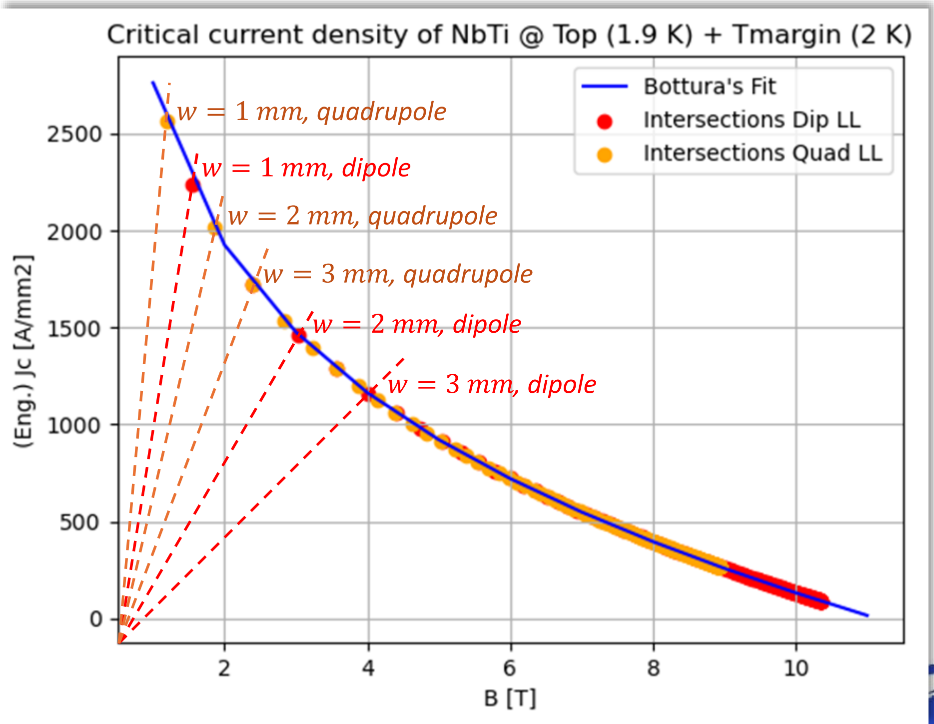
$$J = \frac{\pi B}{2\mu_0 w \sin\alpha}$$

The intersection between J_0 and the fit of the **critical current density** J_c

$$J(B) - J_c(B,T) = 0$$

gives us a pair of J_{max} and B_{peak} values on the critical curve.

Using the **peaking factor**, convert the peak field B_{peak} into the **bore field**.

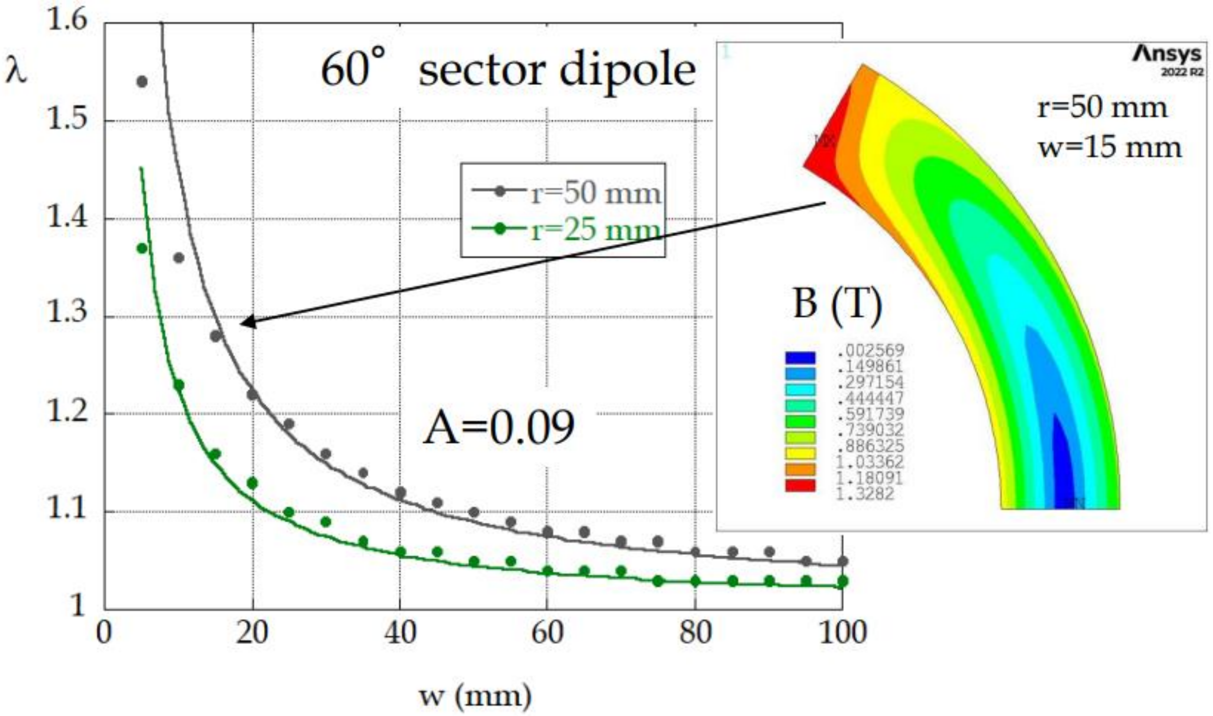


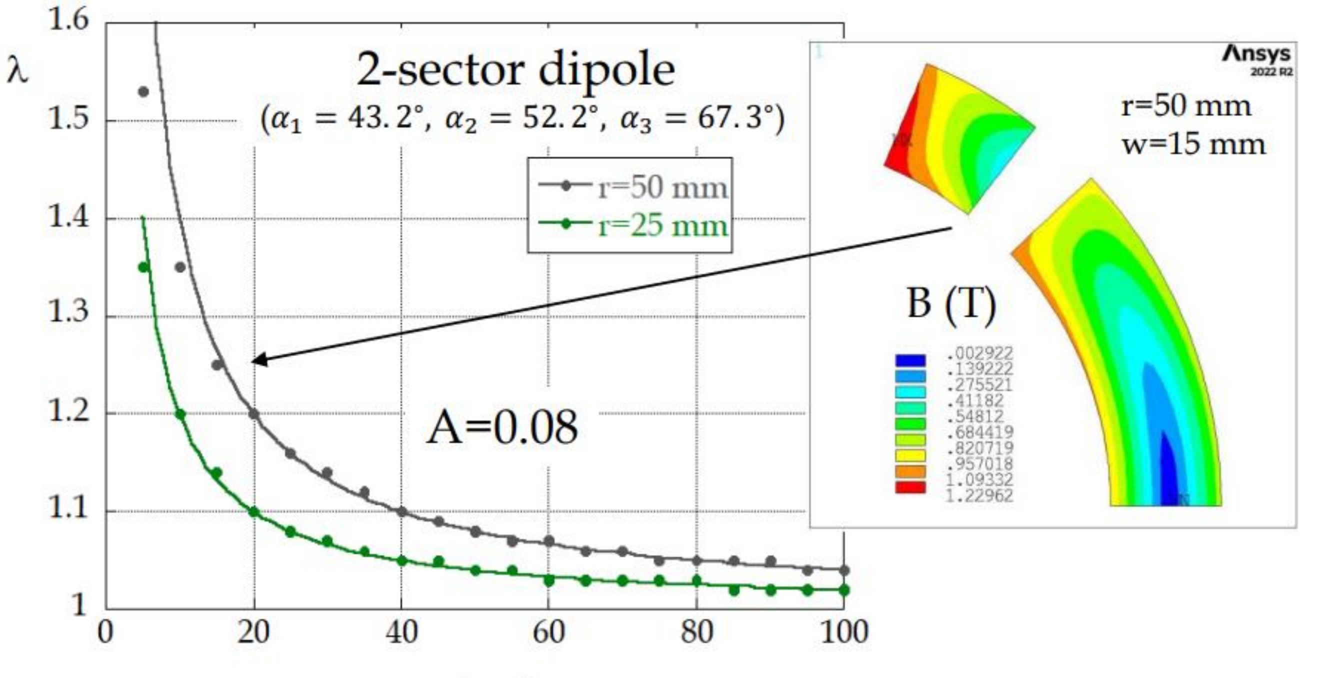
PEAKING FACTOR

We need a peaking factor to switch between peak field and bore field for the sector dipole.

The ratio between peak field and bore field follows the hyperbolic fit: $\lambda(w, r) \sim 1 + A \cdot \frac{r}{w}$
where *r* is the aperture radius ad *w* is the coil width of the sector coil

$$B_{peak}/B_{bore} = \lambda$$





Stefania Farinon, CAS – November 2023

MARGIN LIMITATIONS

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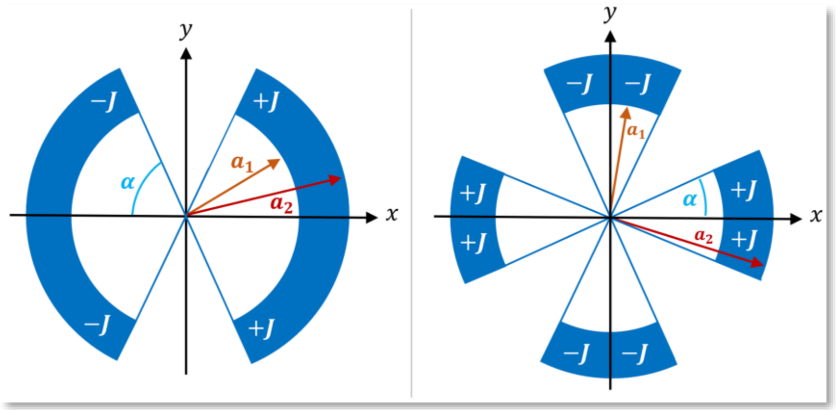
Dipole Quadrupole



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DIPOLE

Through the load line formula, the **current density** is proportional to the coil width *w* and the peak magnetic field *B*:

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The intersection between J and the fit of the **critical current density** J_c

$$J(B) - J_c(B,T) = 0$$

gives us a pair of J_{max} and B_{peak} values on the critical curve.

Using the **peaking factor**, convert the peak field B_{peak} into the **bore field**.

QUADRUPOLE

Through the load line formula, the **current density** is proportional to the coil width *w* and the magnetic field *B* in a_1:

$$J = \frac{\pi B}{2\mu_0 a_1 \ln\left(\frac{a_2}{a_1}\right) \sin\alpha}$$

The intersection between J and the fit of the **critical current density** J_c

$$J - J_c = 0$$

gives us a pair of J_{max} and B_{peak} values on the critical curve.

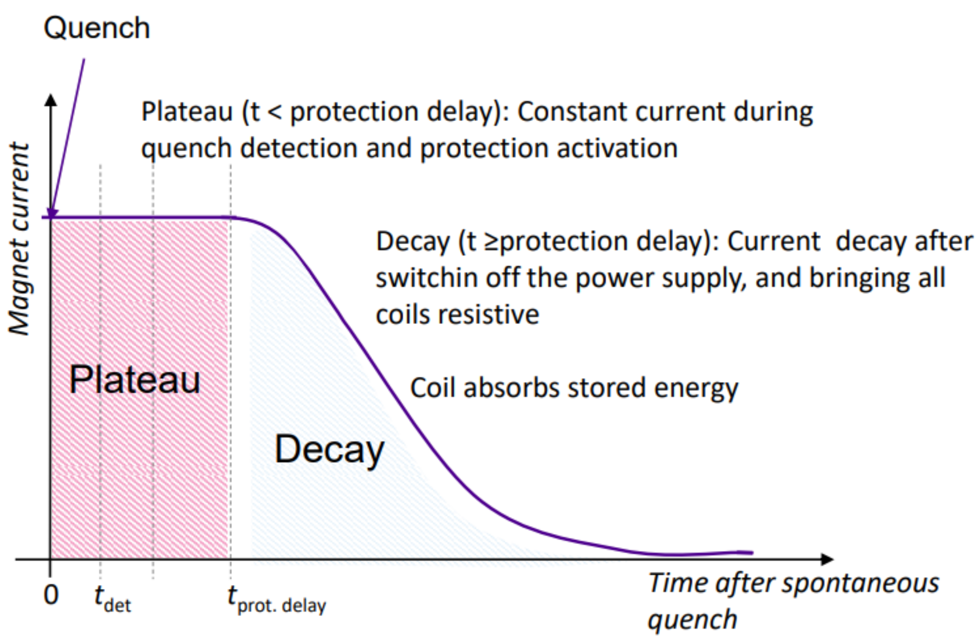
The gradient is calculated as: $G = B / a_1$

PROTECTION CONSTRAINT

(COURTESY OF TIINA SALMI – HTTPS://INDICO.CERN.CH/EVENT/1240045/)

Summary of steps:

1. Current density vs. dipole field
2. Maximum energy density vs. current density
3. Aperture vs. stored energy density
4. Aperture vs. bore field, assuming constant coil cross-section (as limited by conductor cost)



- **NbTi**, hotspot temperature limit 350 K:

  Low conductor cost allows large coil and low current density → protection does not limit design

- **Nb_3Sn**, hotspot temperature limit 350 K:

  Higher cost starts to limit the coil size and force higher current density → protection may become a limitation

- **ReBCO**, hotspot temperature limit 200 K:

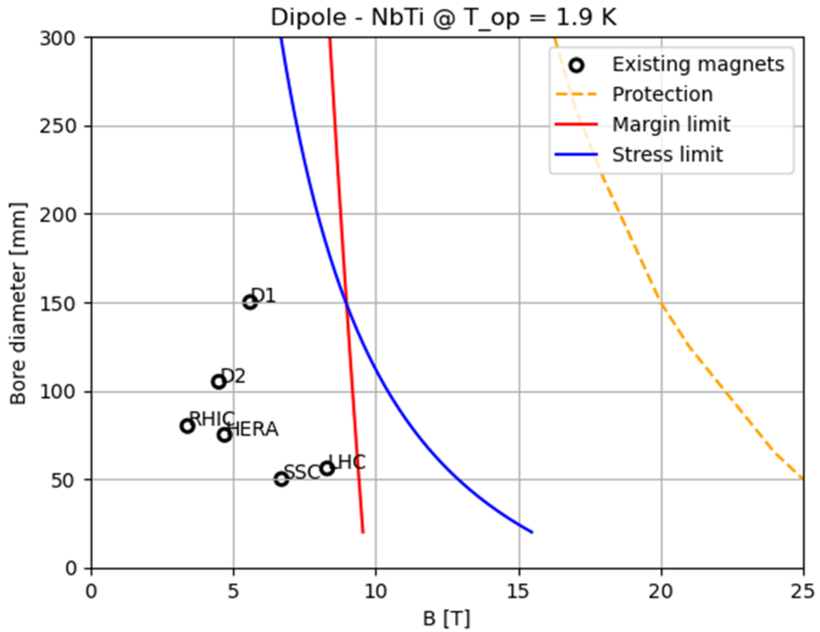
  High cost requires small coil and very high current density → Protection will be a limiting factor

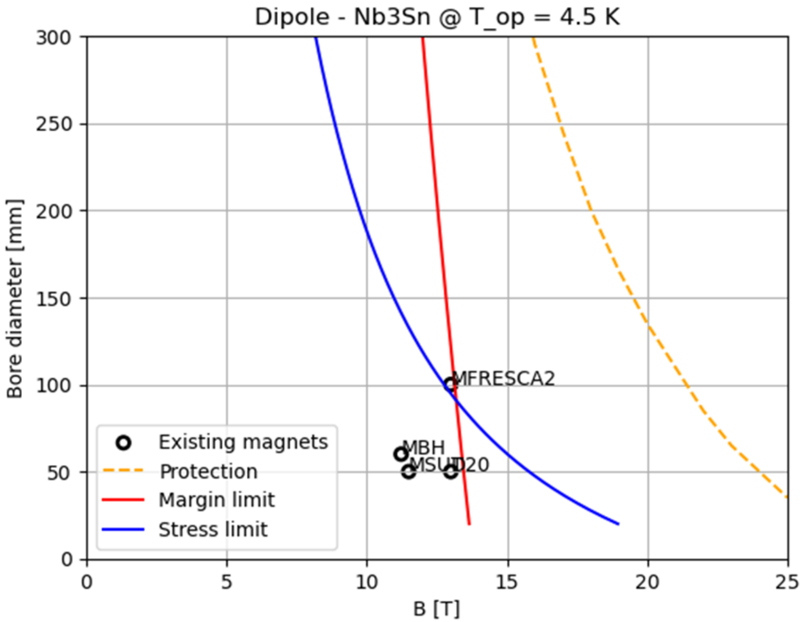
  - **Need to devise alternative protection schemes!**

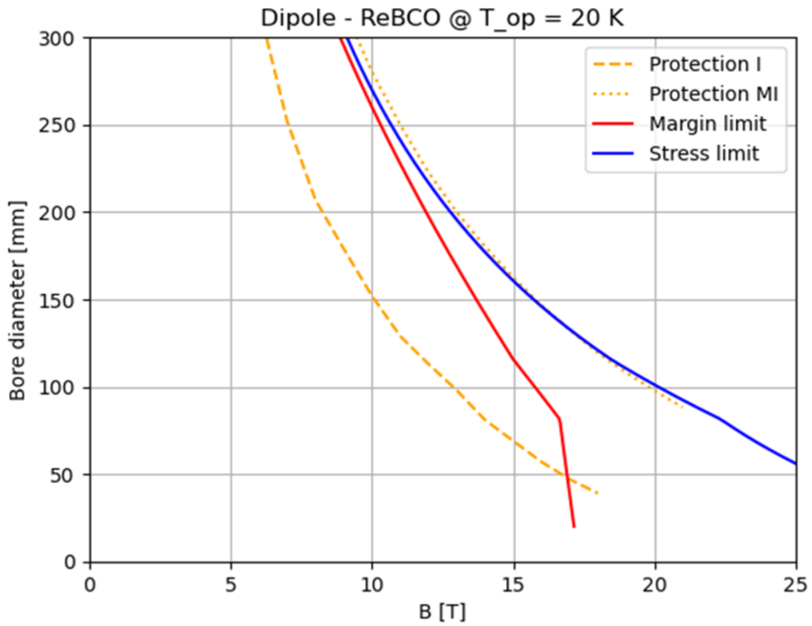
    → Non-Insulated and Metal-Insulated coils

In all cases we assume 40 ms protection delay between original quench and quench protection system efficiency.

DIPOLE A-B PLOTS







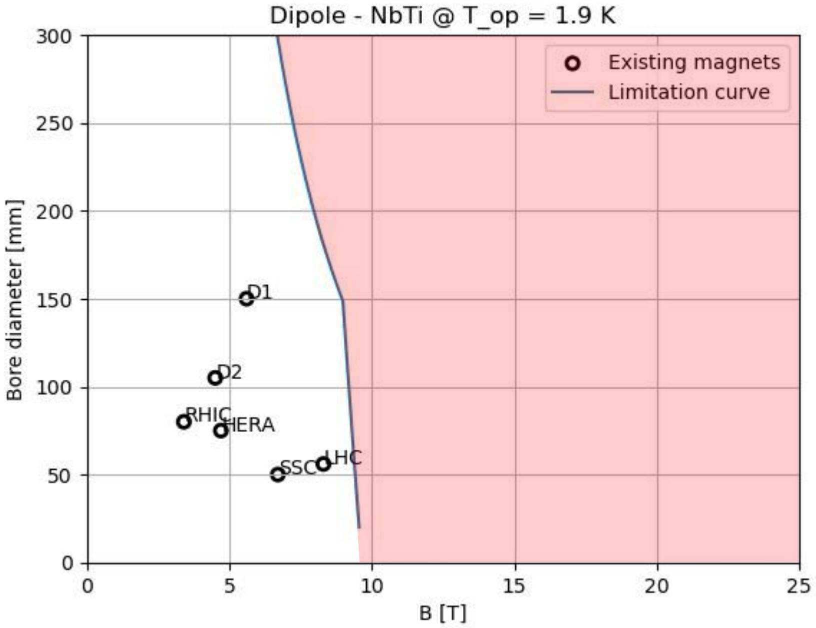
- NbTi is intrinsically limited by the J_c which doesn't allow to reach high field

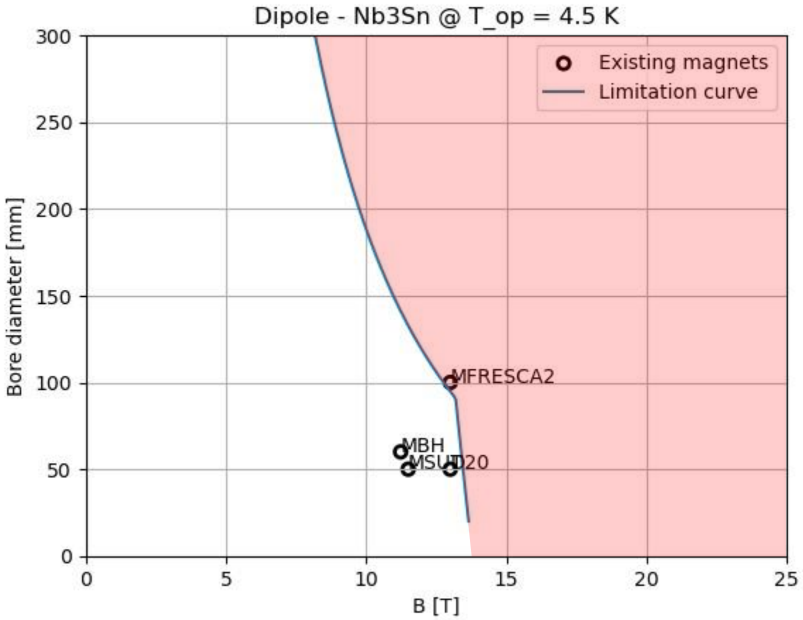
- Nb_3Sn is limited by peak stress and operating margin

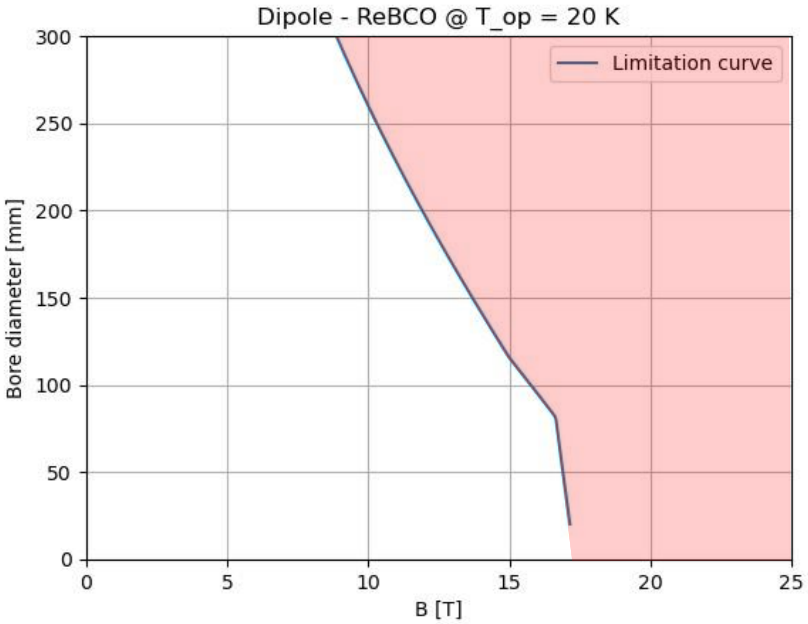
- HTS is strongly limited by protection!
  - Need to devise alternative protection schemes: Non-Insulated and Metal-Insulated coils

(courtesy of Tiina Salmi)

DIPOLE A-B PLOTS



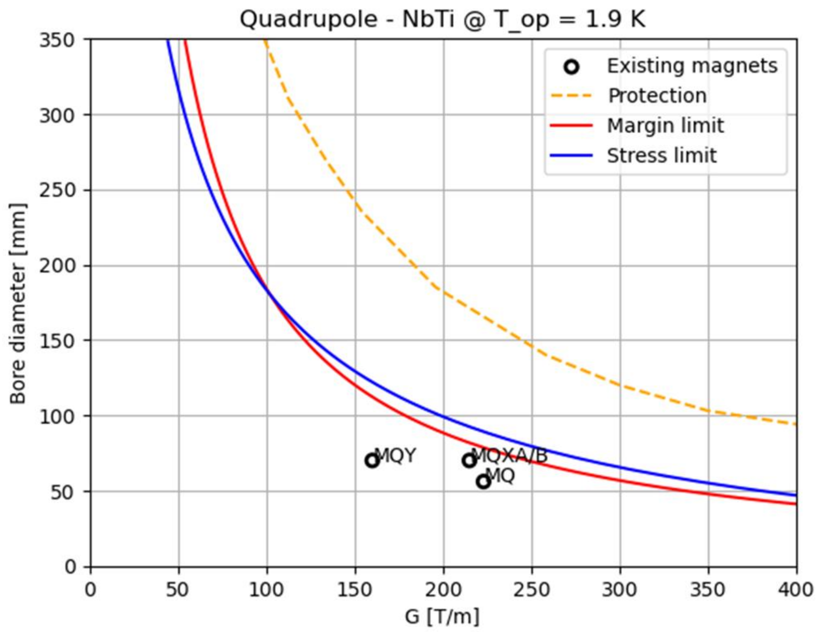


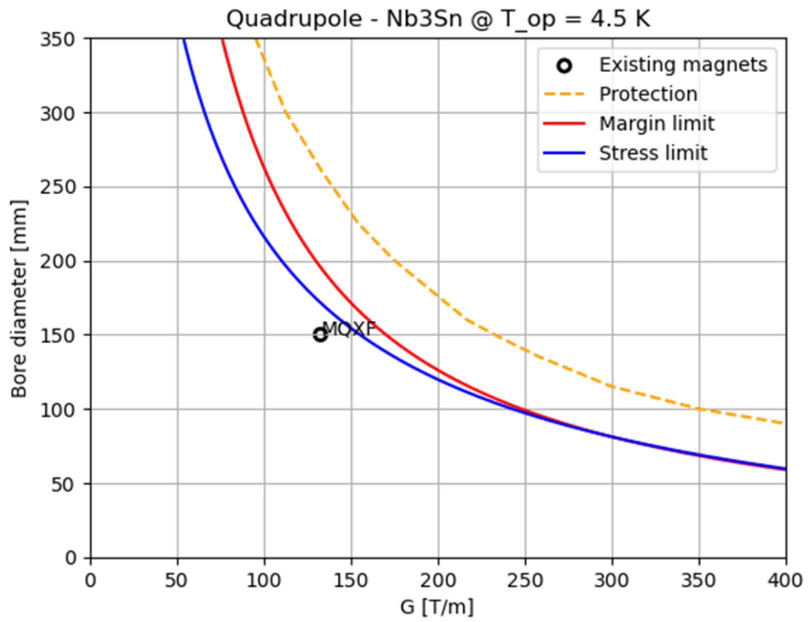


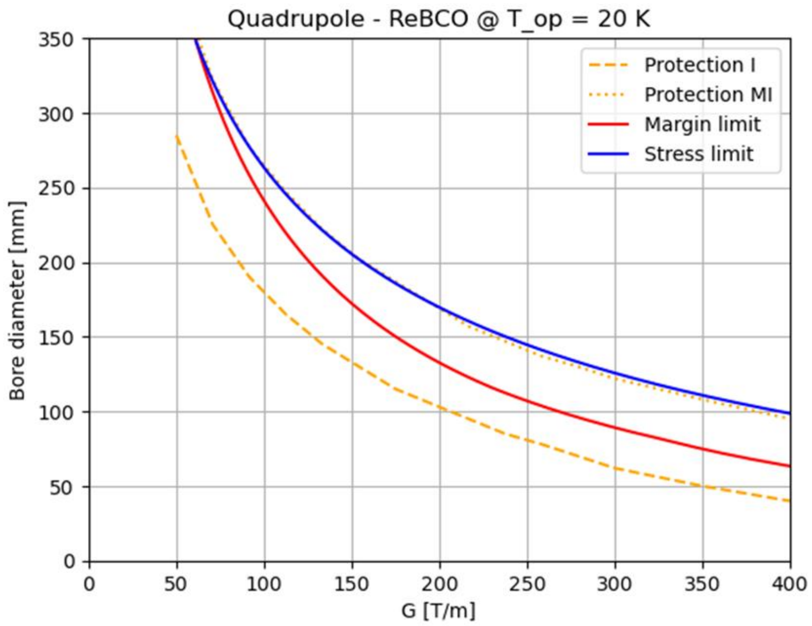
- NbTi is intrinsically limited by the J_c which doesn't allow to reach high field
- Nb_3Sn is limited by peak stress and operating margin
- HTS is mainly limited by cost production

- The allowed area is in white; the prohibited area is in red.

QUADRUPOLE A-B PLOTS

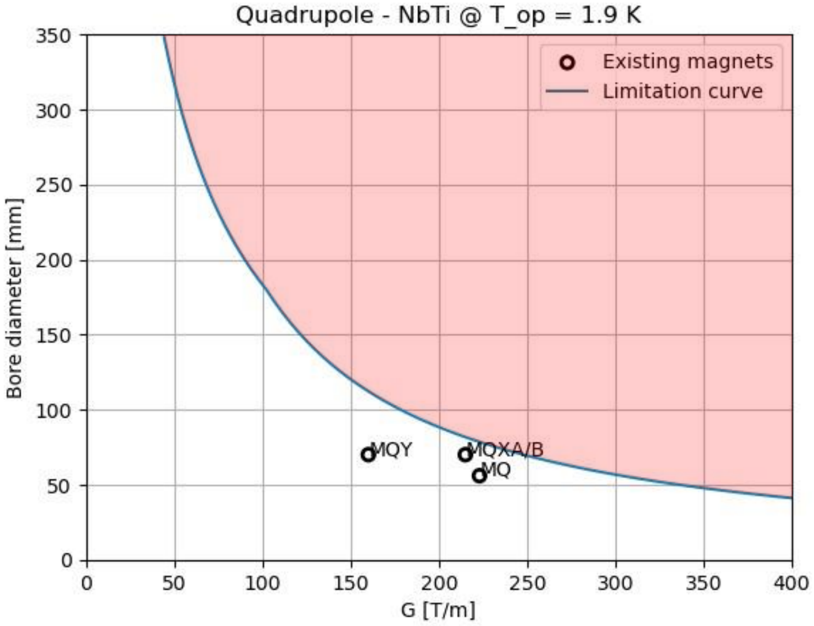


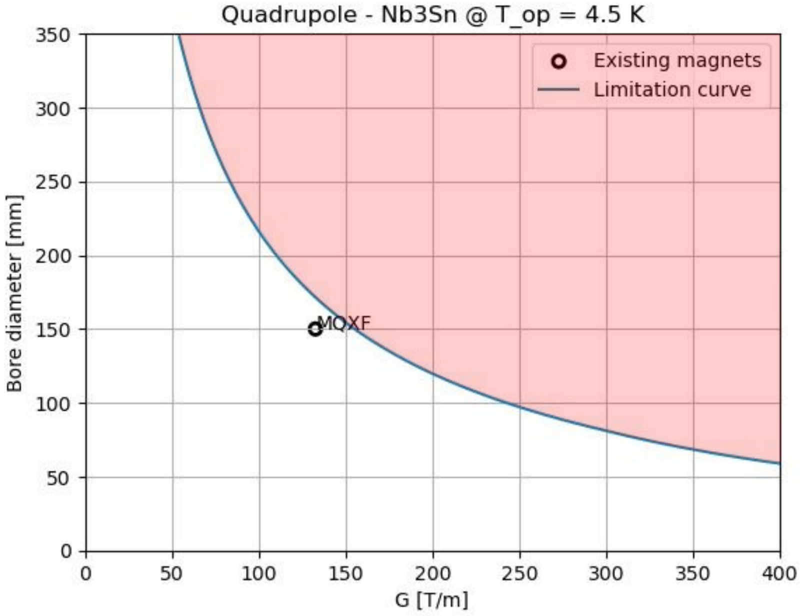


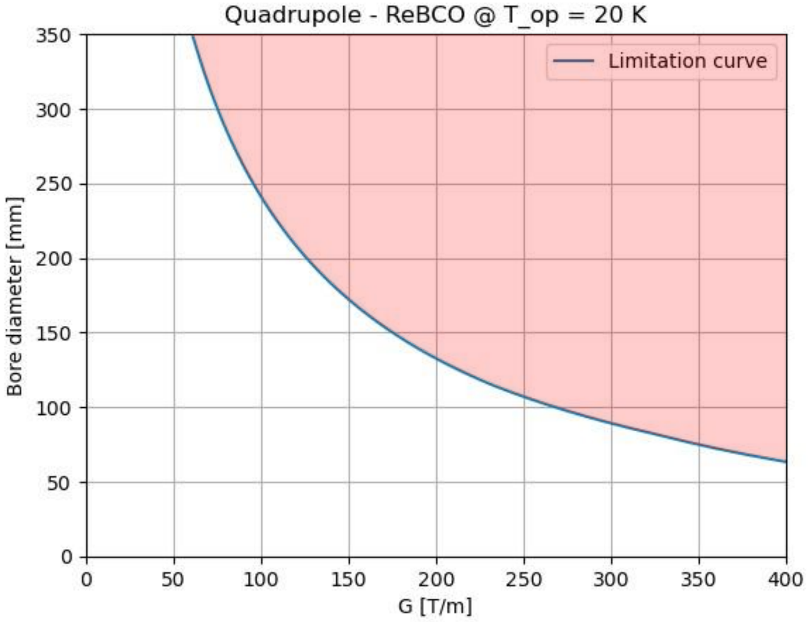


- NbTi is intrinsically limited by the J_c
- Nb_3Sn is limited by peak stress and operating margin
- HTS is mainly limited by cost production and protection. Working @20K the margin curve is also a limiting factor.

QUADRUPOLE A-B PLOTS







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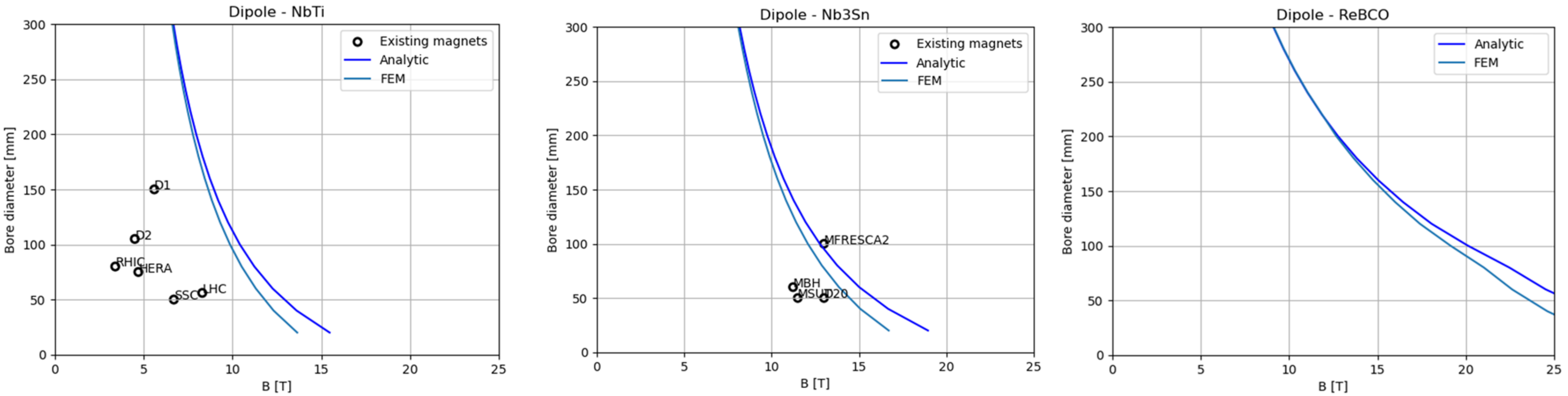
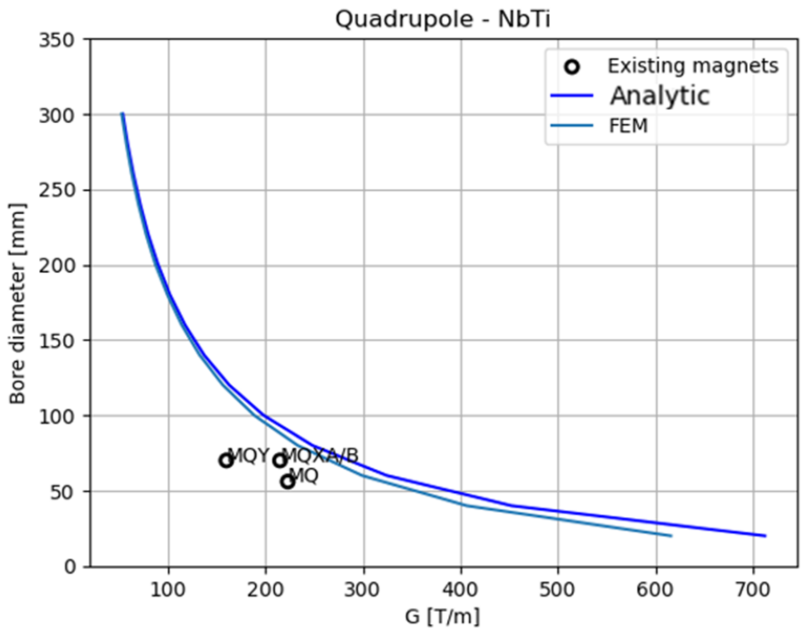
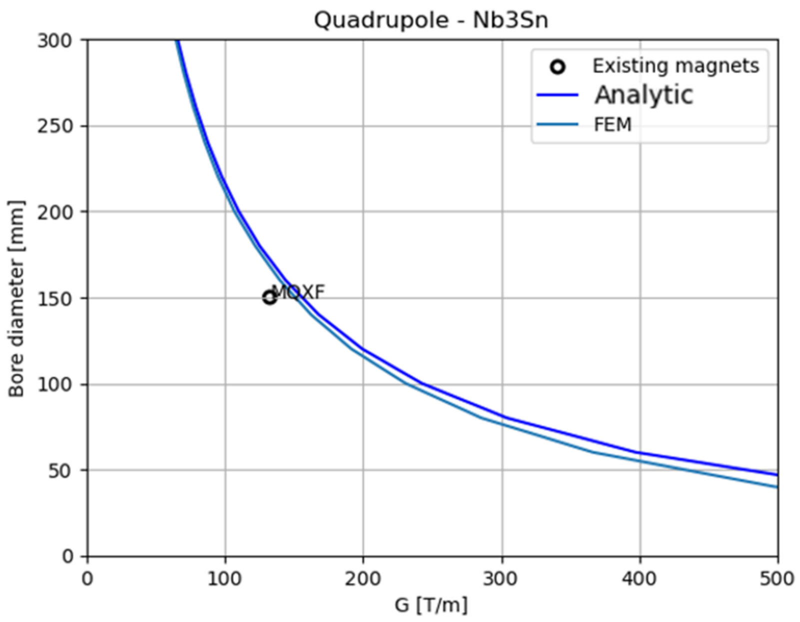
FEM Crosscheck

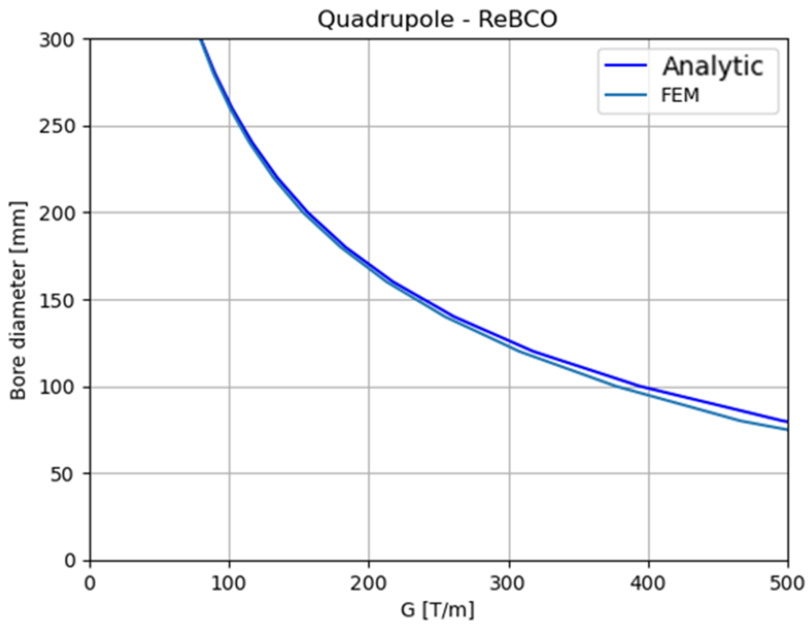


- We implemented a FEM model for a sector **dipole** in ANSYS.
- We implemented a **Python** code able to work with **Ansys** software to run FEM simulations with the same inputs as the analytical study.
- In the comparison, the FEM curves are always more restricting than the analytical ones since they take the maximum pressure on the midplane instead of an average over the coil width.

FEM CROSSCHECK







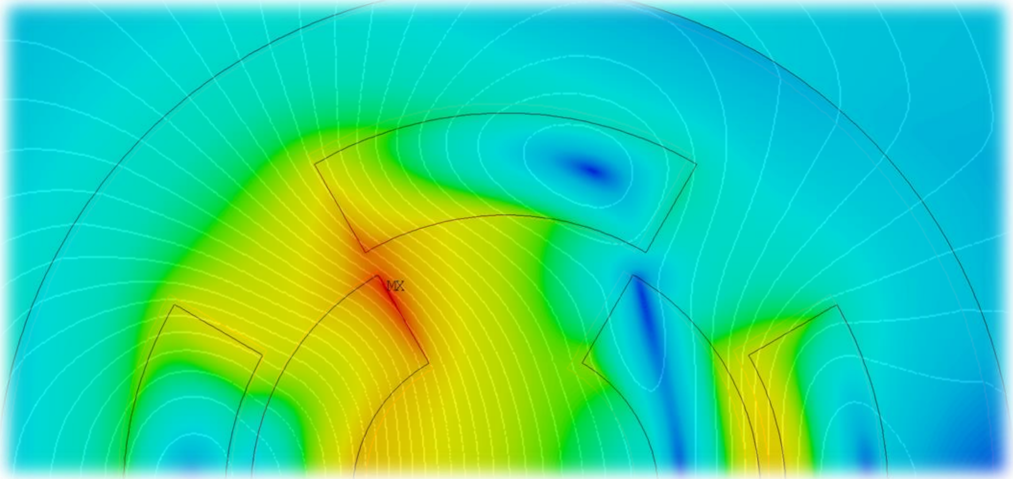
- We implemented a FEM model for a sector **quadrupole** in ANSYS.
- We implemented a **Python** code able to work with **Ansys** software to run FEM simulations with the same inputs as the analytical study.
- In the comparison, the FEM curves are always more restricting than the analytical ones since they take the maximum pressure on the midplane instead of an average over the coil width.

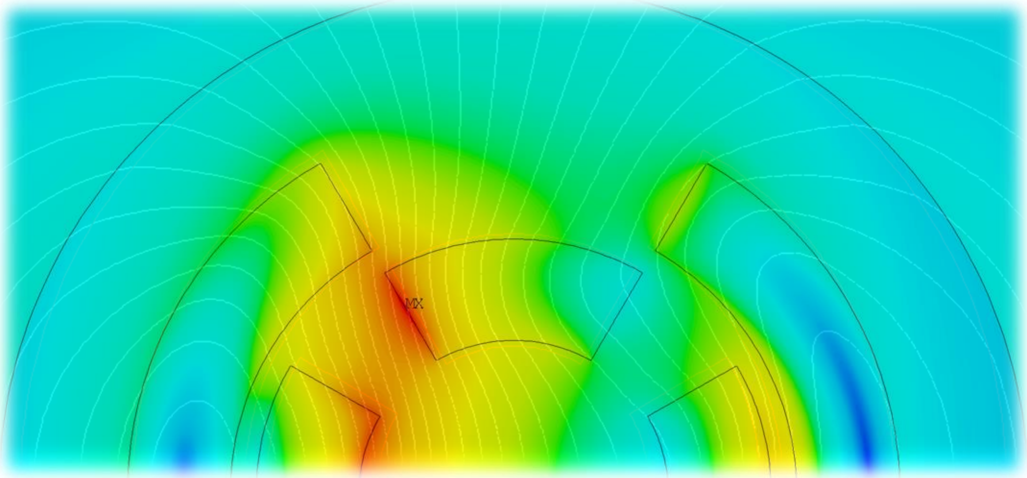
CONCLUSIONS

- The allowed magnet aperture (A) - magnetic field (B) phase spaces are provided and discussed, representing the starting point to define possible beam optics which are also acceptable from a technological point of view.

- We will develop preliminary electromagnetic and mechanical designs for possible 10 TeV and 3 TeV muon collider ring magnets.

- To solve the problem of neutrino flux in straight sections, we have just started a study on nested combined function magnets.





Thank you for your attention