Development of superconducting magnets for the future Muon Collider

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Why a Muon Collider?

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IMCC (Internation Muon Collider Collaboration) aims at studying the feasibility of a 10 km, 10 TeV center of mass energy **Muon Collider**, as indicated by the European Strategy for Particle Physics.

The Muon Collider is a very promising post-LHC high physics facility:

- μ 200 times heavier than electron (m_μ =105.7 MeV/c^2 ,m_e=0.511 MeV/c^2) → 10^9 times less radiation loss.
- μ elementary particle: all COM energy available for the collision, contrary to hadron machines.

BUT μ decays in 2.2 μs in rest frame:

- must be produced, accelerated and collided ASAP
- decay products must be shielded to avoid damage to the machine or radiation

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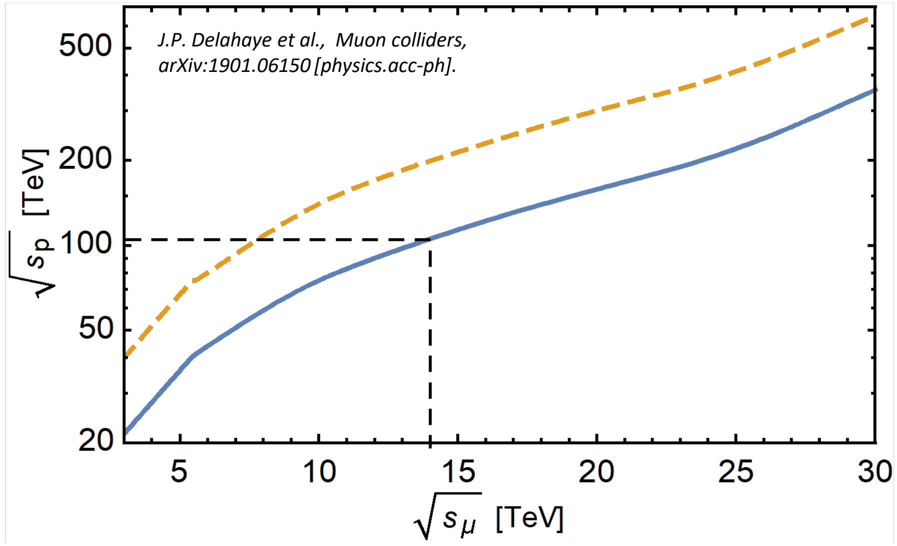

Physics?

Muon collisions in the range of 14 TeV have comparable discovery potential to hadron (proton) collisions in the range of 100 TeV

- - - Comparable Feynman amplitudes for the muon and the proton production processes.

—— A factor of ten enhancement of the proton production amplitude squared, possibly due to QCD production, is considered.

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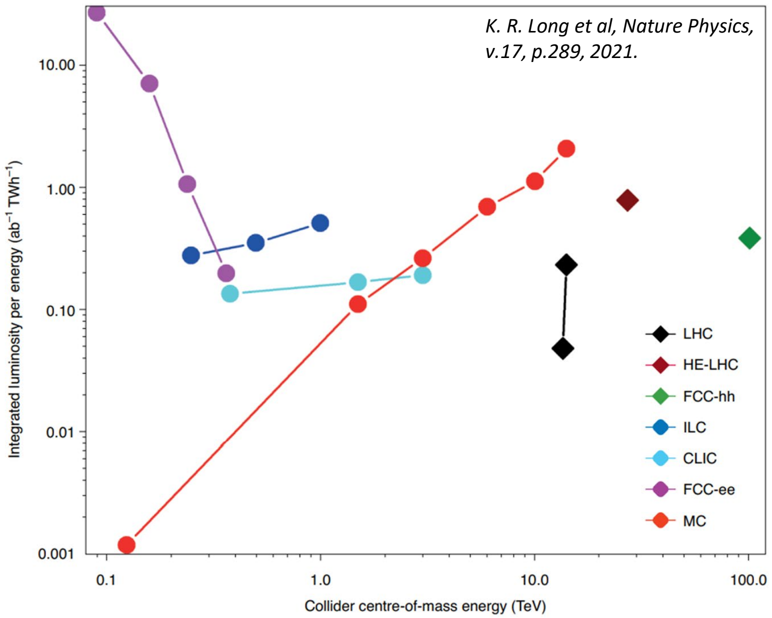
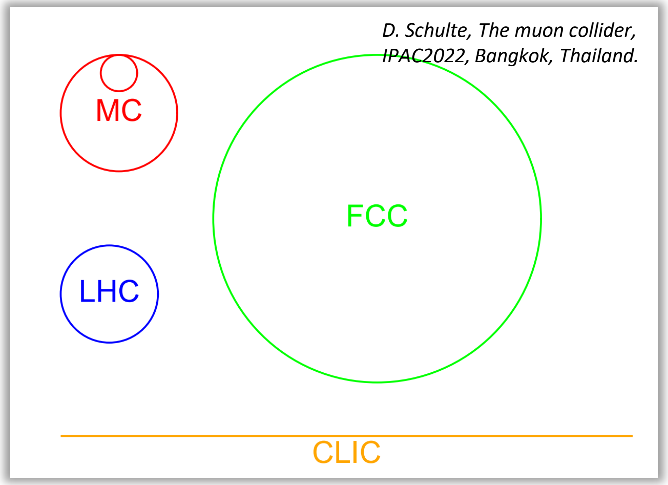


Sustainability?

A 10 TeV muon collider
can provide the highest integrated luminosity
per unit of energy consumption.

Collider size comparison



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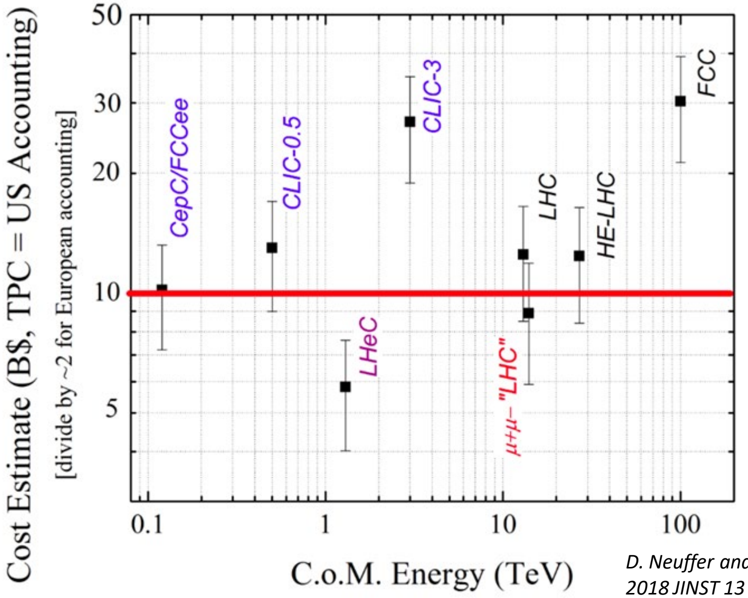


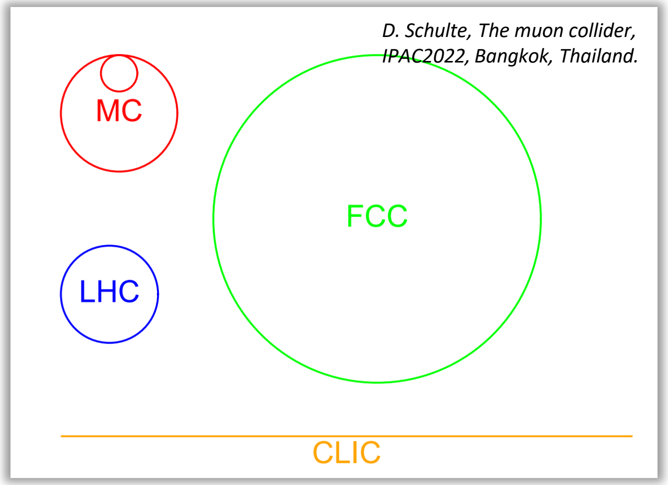
D. Neuffer and V. Shiltsev 2018 JINST 13 T10003

Affordability?

Its size is competitive because it is compact.

A 10 TeV muon collider making use of the LHC infrastructure could be the most cost-effective energy frontier collider

Collider size comparison



D. Schulte, The muon collider, IPAC2022, Bangkok, Thailand.

The Muon Collider Complex

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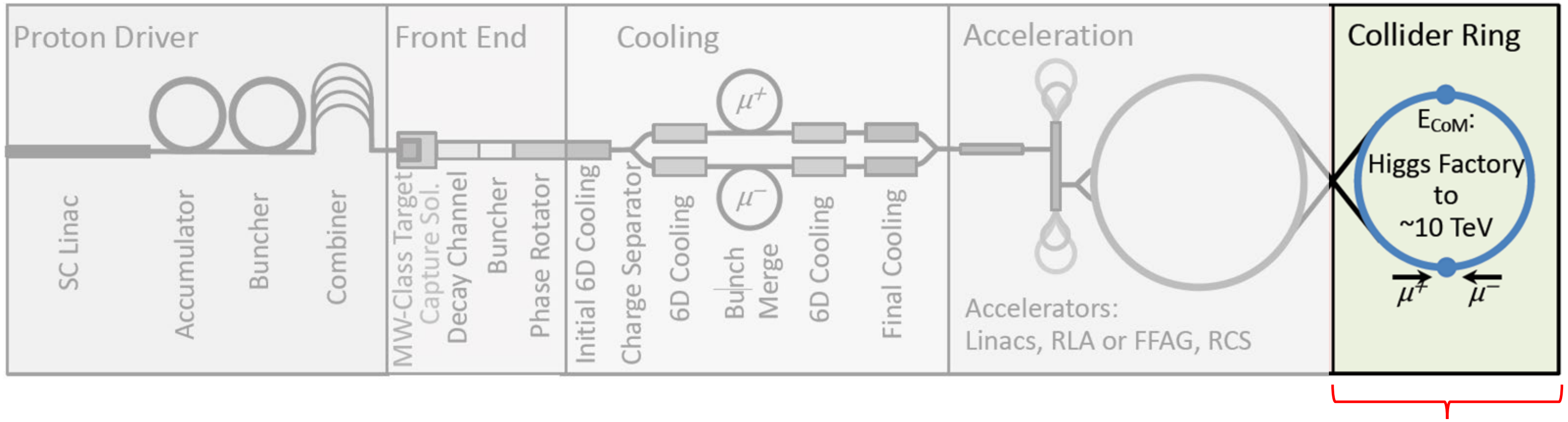
Main stages of a muon collider complex

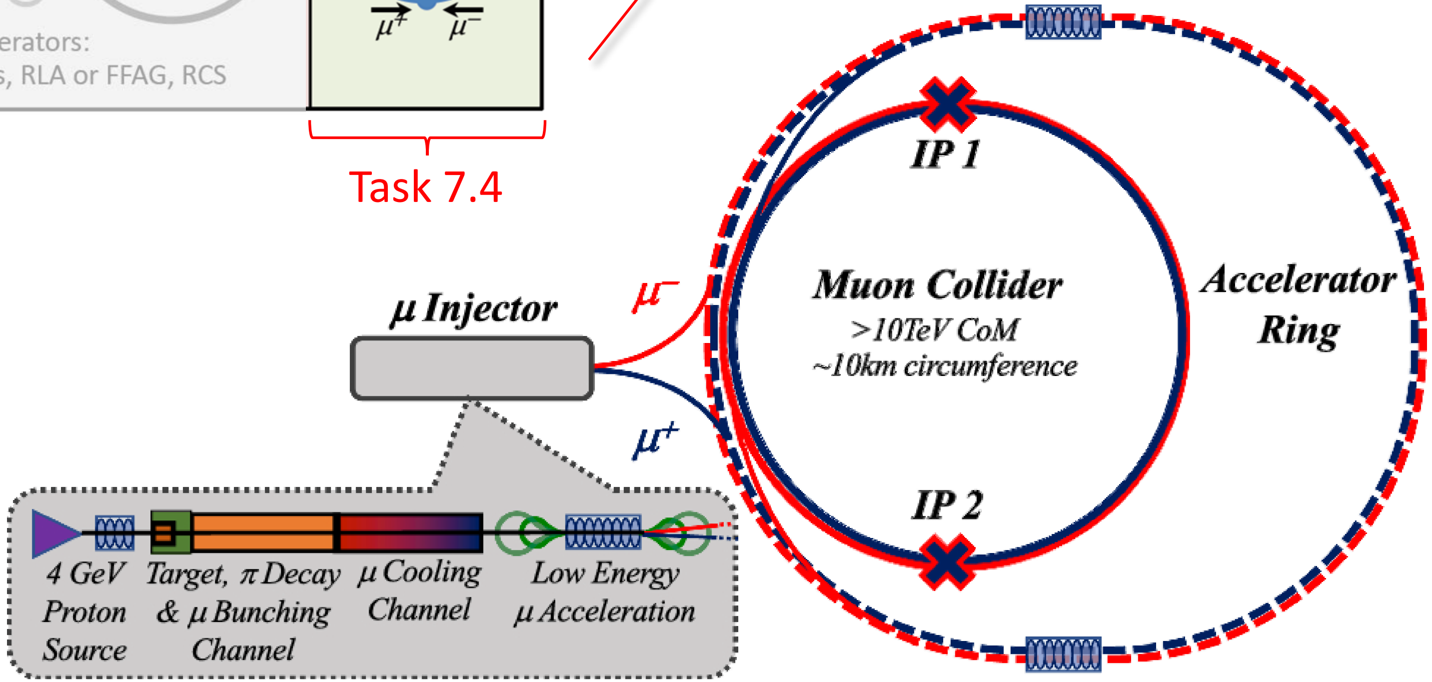


Magnets:

- **Dipoles**
- **Quadrupoles**
- Sextupoles

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).



Collider Magnets Requirements

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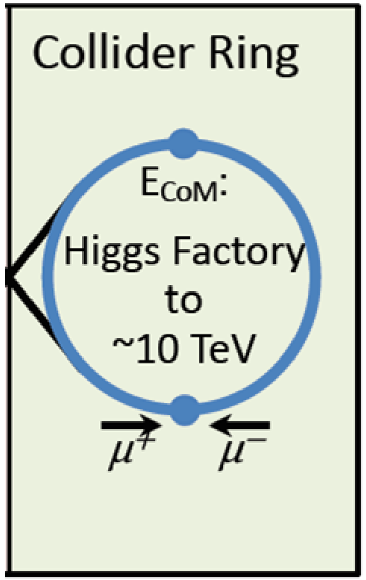
3 TeV collider (5 km ring):

- Close to state of the art
- ~11T/150mm (Nb_3Sn)
- 600 magnets, 5 m length
- Operating temperature: 4.5 K

10+ TeV collider (10 km ring):

- HTS magnets, R&D is required
- ~15T/150mm (ReBCO, hybrid)
- 1200 magnets, 5 m length
- Operating temperature: 4.5…20 K

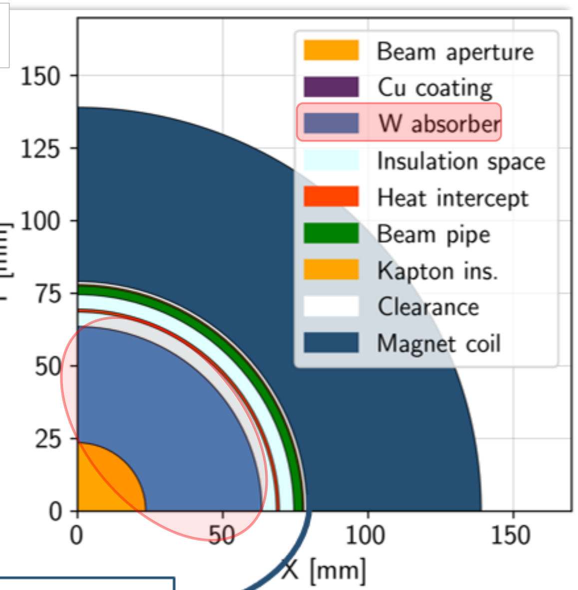


Assuming 10 TeV machine and coil at 4.5 K

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/



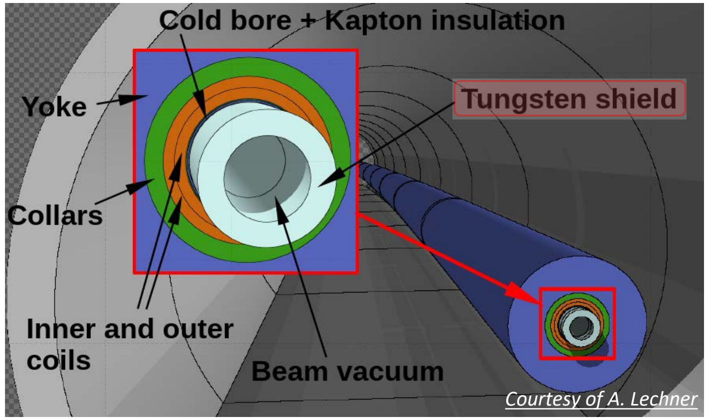
Coil aperture 158 mm

with HTS @20K the absorber can be thinner

- **High field** dipoles to minimize collider ring size and maximize luminosity.
- Beam loss protection

High-energy electrons and positrons arising from muon decay and striking the collider ring magnets can cause radiation damage and unwanted heat load.

- Shielding
- **Large aperture**



Courtesy of A. Lechner

Collider Magnets Requirements

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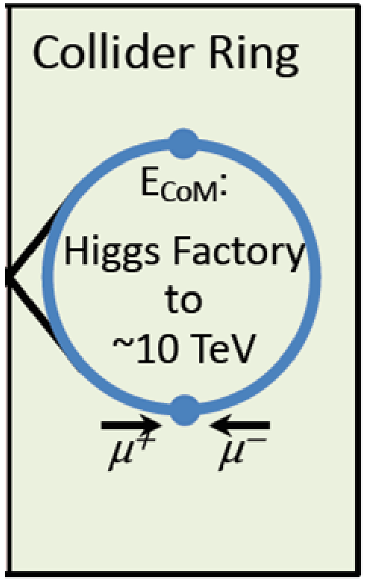


Arc:

- 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:

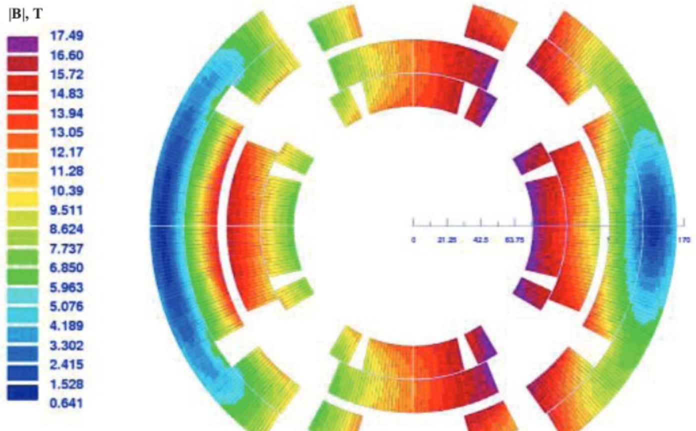
- Combined function magnets: B1, B2, B1+B2, B1+B3
- B ≈ 4…16 T; G ≈ 100…300 T/m; G’ ≈ 12000 T/m^2
- Aperture ≈ 150…330 mm

- ➢ **High field** dipoles to minimize collider ring size and maximize luminosity.
- ➢ Beam loss protection

High-energy electrons and positrons arising from muon decay and striking the collider ring magnets can cause radiation damage and unwanted heat load.

Difficult to define a single magnet specification

- ➢ Shielding
- ➢ **Large aperture**



V.V. Kashikhin et al.

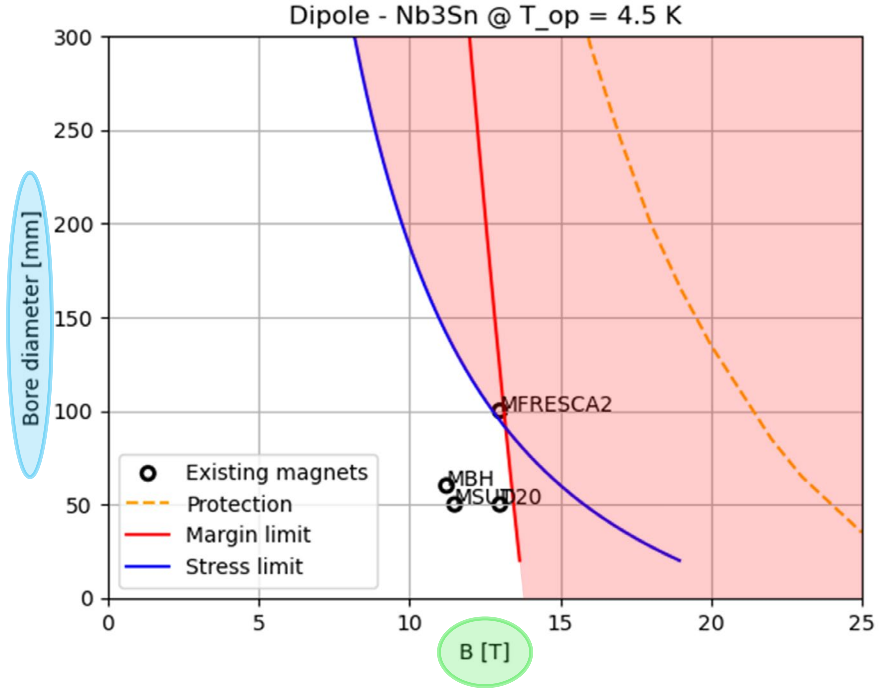
Introduction to A-B plots

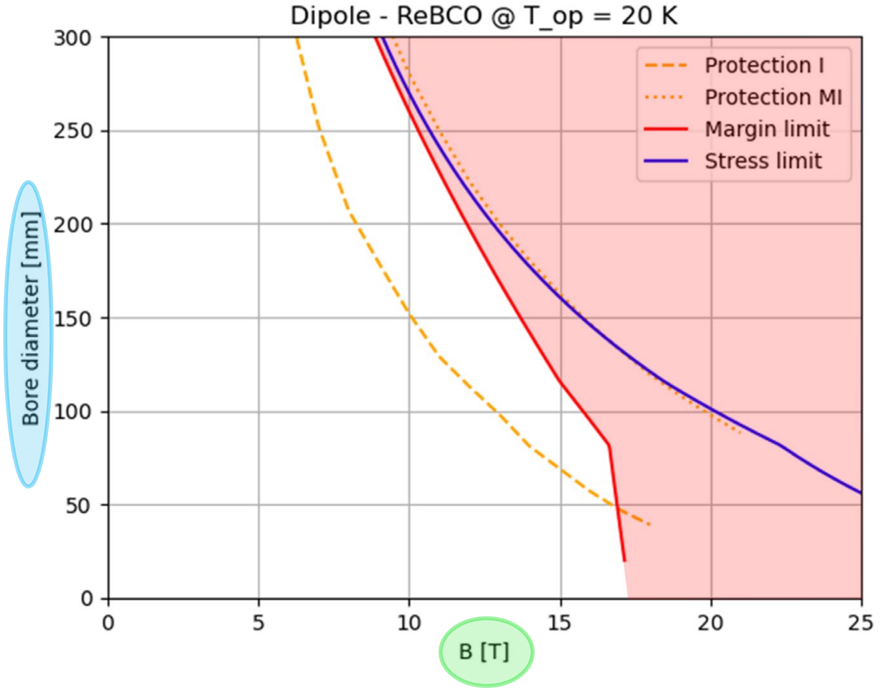
Need for high fields in large apertures

- We perform plots that can show the allowed area between aperture diameter (A) and bore field (B).

✓ Innovative approach, useful for interfacing the needs of beam dynamics with the technological limits (of today and the near future) related to superconducting magnets.

✓ Immediate feedback capable of analyzing many possible configurations in a single plot



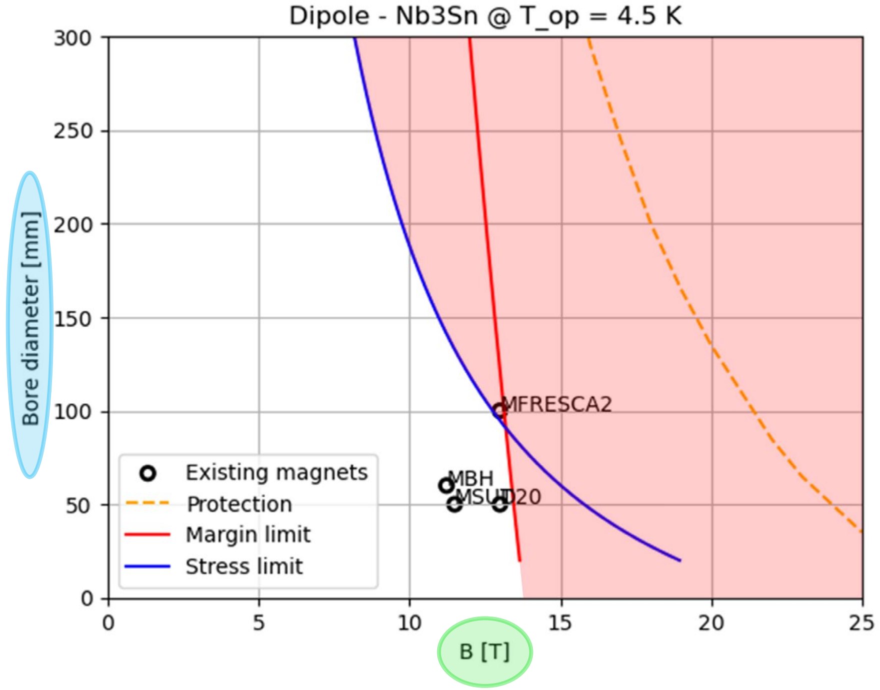


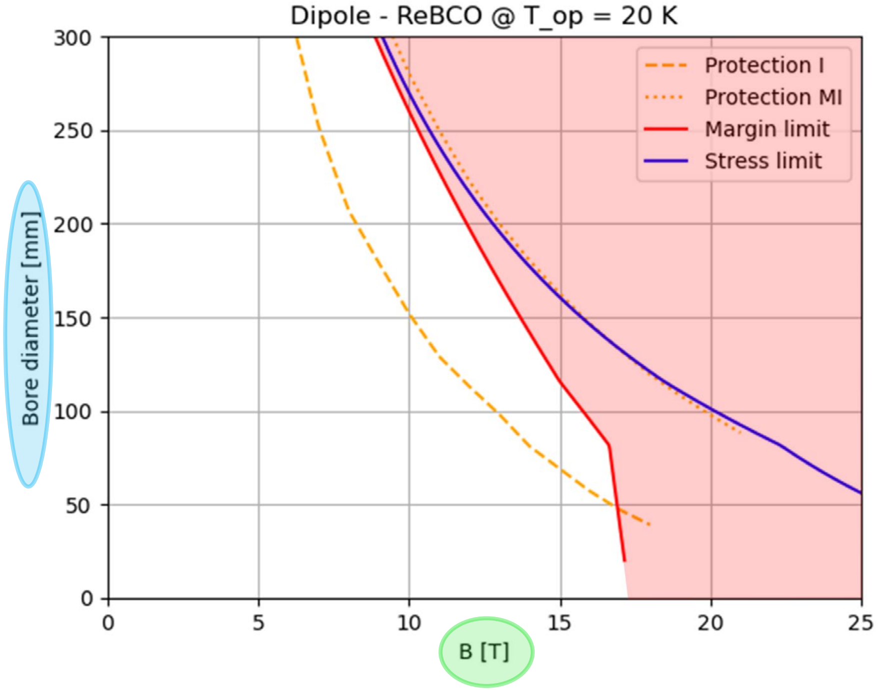
Introduction to A-B plots

Need for high fields in large apertures

- We perform plots that can show the allowed area between aperture diameter (A) and bore field (B).
- We consider Nb_3Sn for the 3 TeV machine and HTS (ReBCO) for the 10 TeV collider.

- 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.



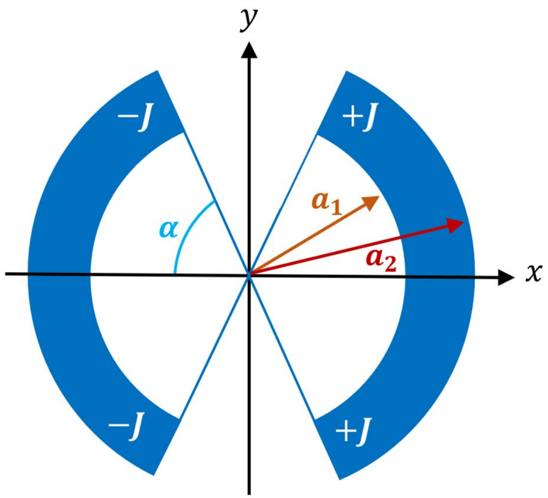


Method and Assumptions

- A Python code is used to implement the **analytic formulas** for the cos-theta magnets in **sector coil** approximation.

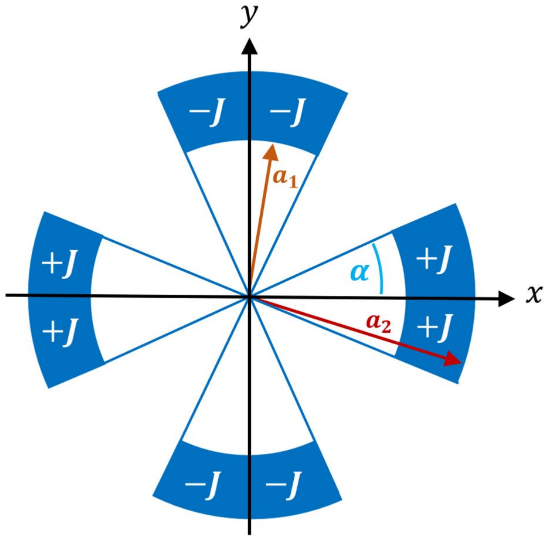
(α is 60° for the dipole and 30° for the quadrupole)

Dipole



$$B(w,J) = \frac{2\mu_0 J(a_2 - a_1) sin\alpha}{\pi}$$

Quadrupole



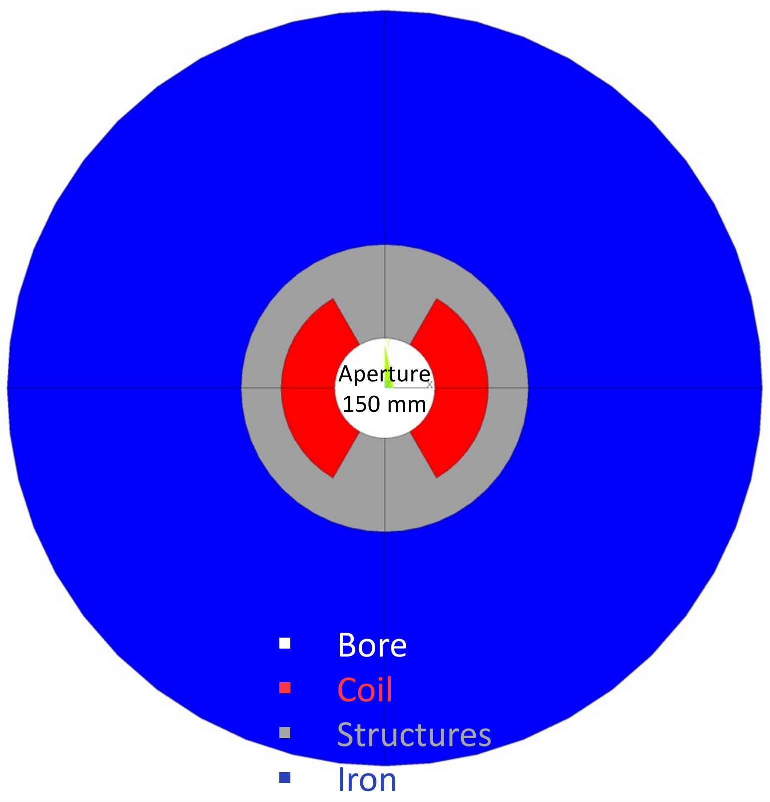
$$G(w,J) = \frac{2\mu_0 J}{\pi} \ln\left(\frac{a_2}{a_1}\right) \sin(2\alpha)$$

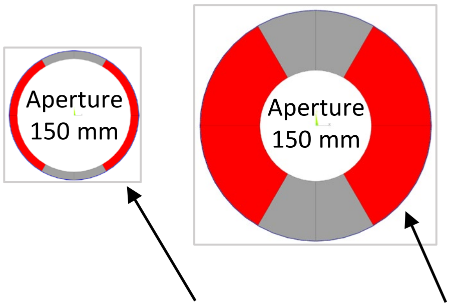
$(w = coil\ width)$

Method and Assumptions

- A Python code is used to implement the **analytic formulas** for the cos-theta magnets in **sector coil** approximation.
- **Cost model**: by setting an upper limit to the cost of the magnet, the maximum coil width can be calculated for each aperture, taking into account the other components.

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)
$\rho_{Fe} = 7800\ kg/m^3$

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

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

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

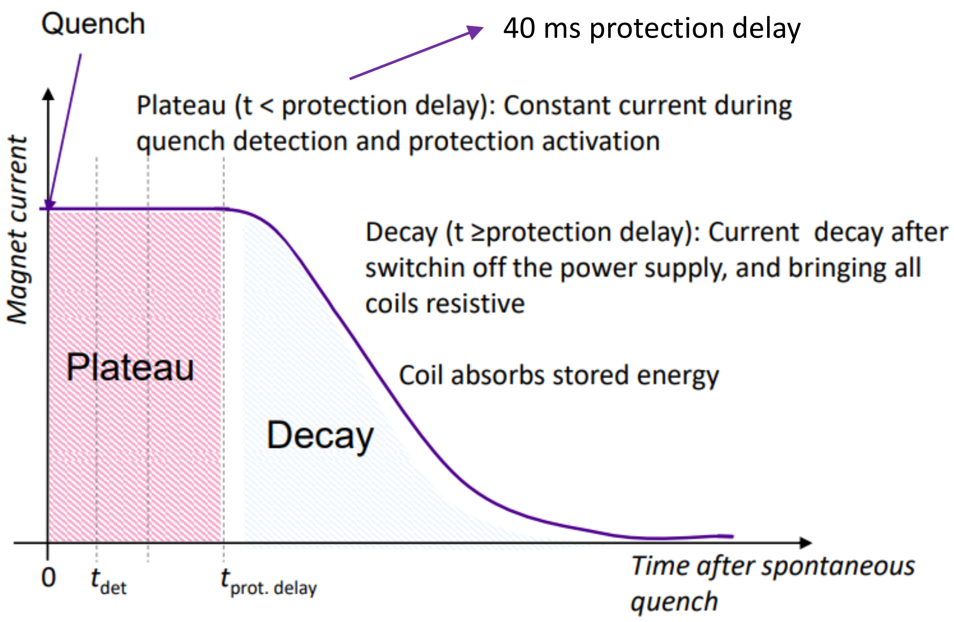
* 7€/kAm, FCC target 5€/kAm

** 50 €/kAm: 1/3 of today prize (150€/kAm)
Also based on projection of ref
A. Molodyk and C. Larbalestier, Science, 2023

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

Method and Assumptions

- A Python code is used to implement the **analytic formulas** for the cos-theta magnets in **sector coil** approximation.
- **Cost model**: by setting an upper limit to the cost of the magnet, the maximum coil width can be calculated for each aperture, taking into account the other components.
- The **protection scheme** consists in QH (or CLIQ) for classical insulated coils, limiting the hotspot temperature and the stored energy in the coils.

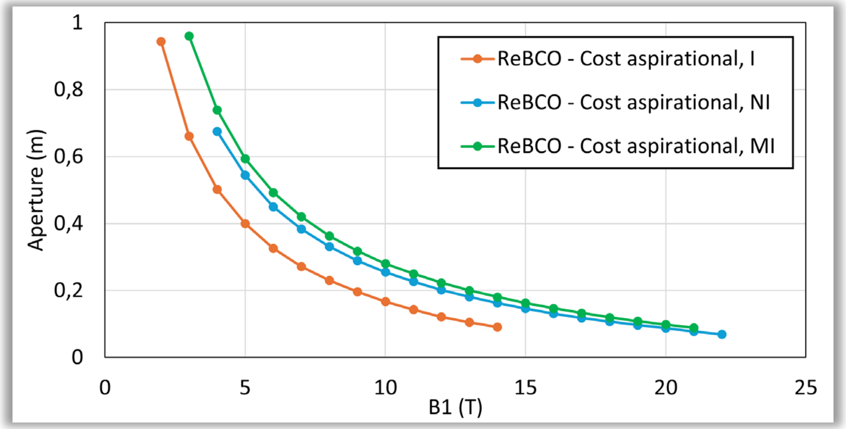


Materials	Hotspot T [K]
Nb_3Sn	350
ReBCO	200

Courtesy of Tiina Salmi
https://indico.cern.ch/event/1240045/
Tampere University

For the ReBCO, 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



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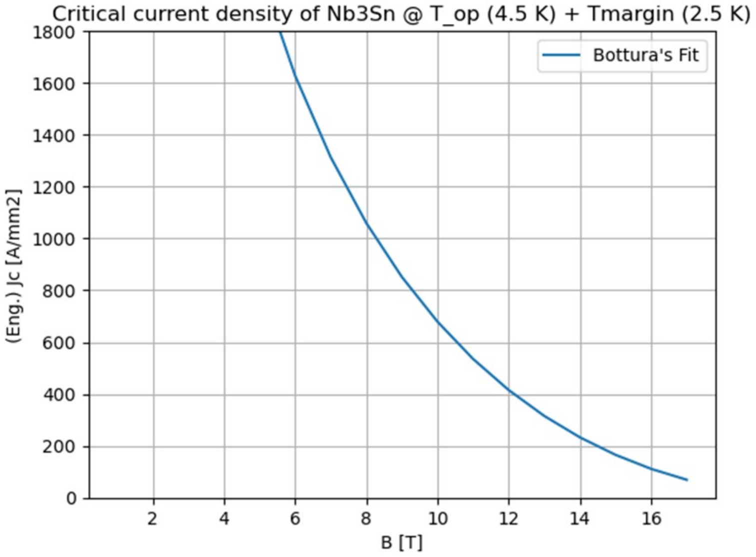
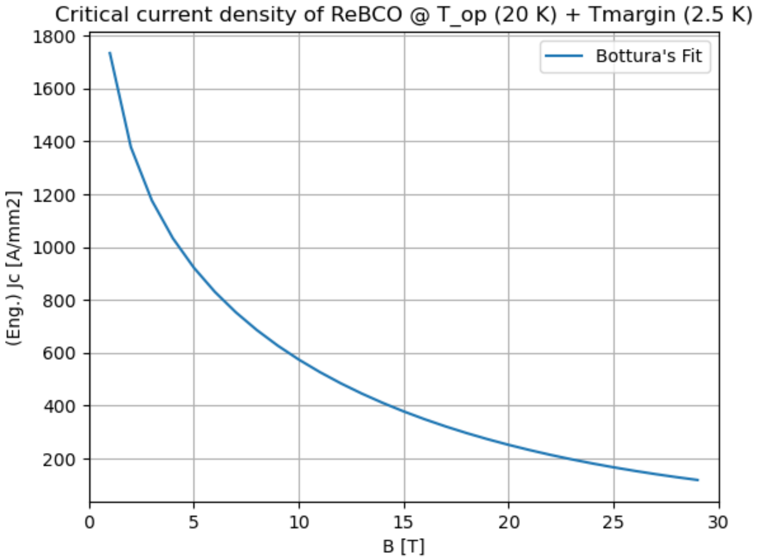
- The **margin limit** is the limit due to the SC material itself, starting from the Bottura's fit for the critical current density.





Materials	Operating T [K]	T margin [K]
Nb_3Sn	4.5	2.5 (HL-LHC)
ReBCO	20	2.5

J_c refers to:

- Nb_3Sn: FCC cable target performance
- ReBCO: Fujikura FESC-AP tape

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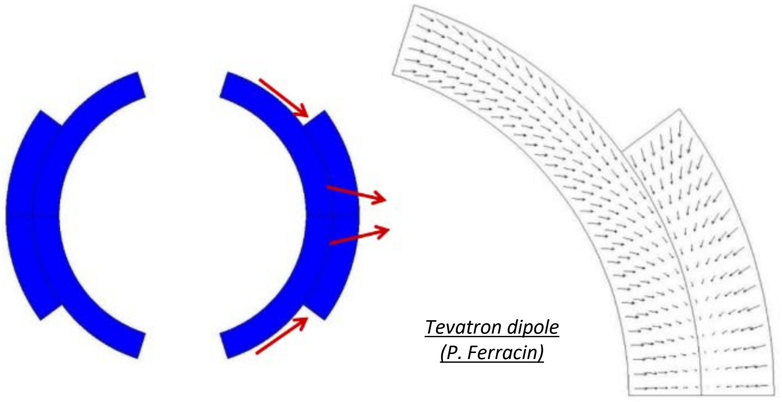
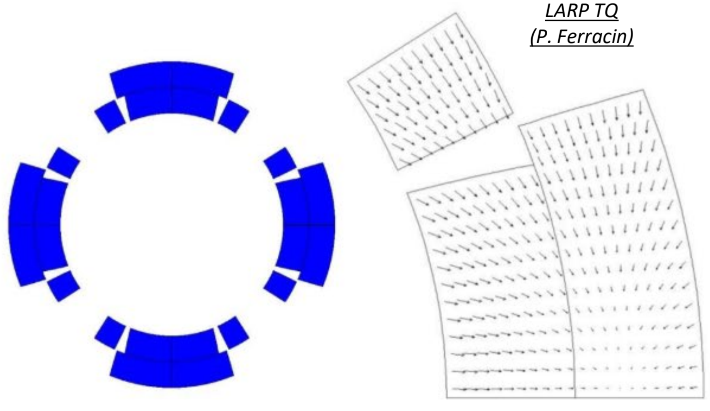
- The **protection scheme** consists in QH (or CLIQ) for classical insulated coils, limiting the hotspot temperature and the stored energy in the coils.
- The **margin limit** is the limit due to the SC material itself, starting from the Bottura's fit for the critical current density.
- The **stress limit** considers the maximum mechanical stress we can have on the coils, starting from the analytical formula for the midplane pressure of cos-theta magnet in sector coil approx. *(Reference: https://doi.org/10.15161/oar.it/143359)*

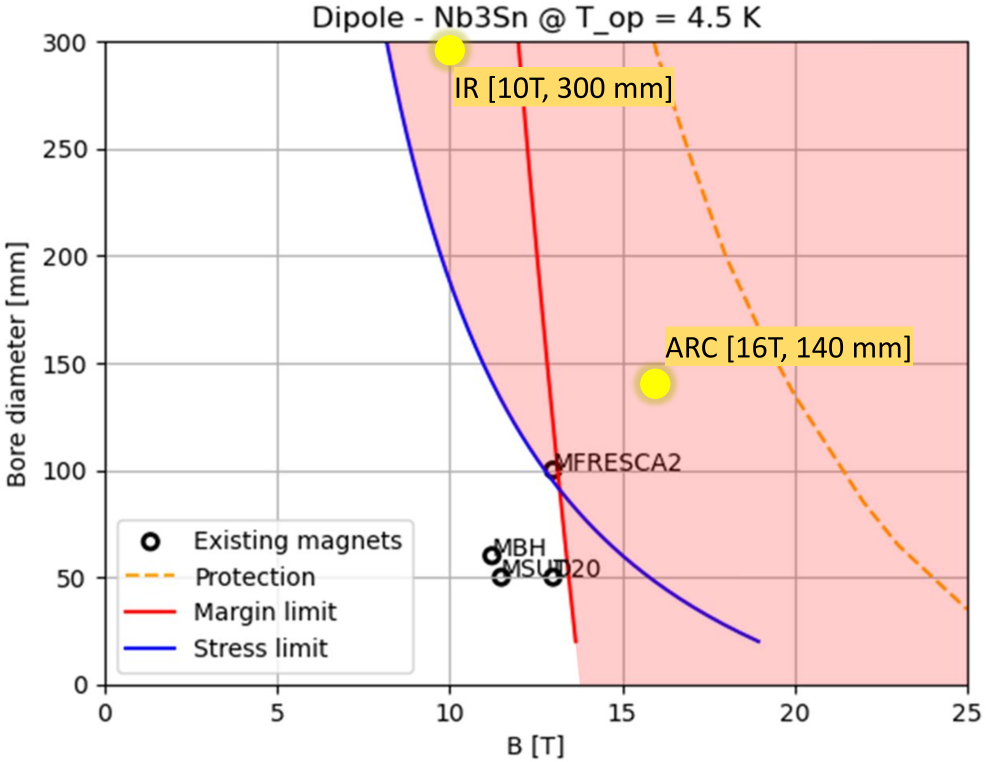
Materials	Peak Stress [MPa]
Nb_3Sn	150
ReBCO	400

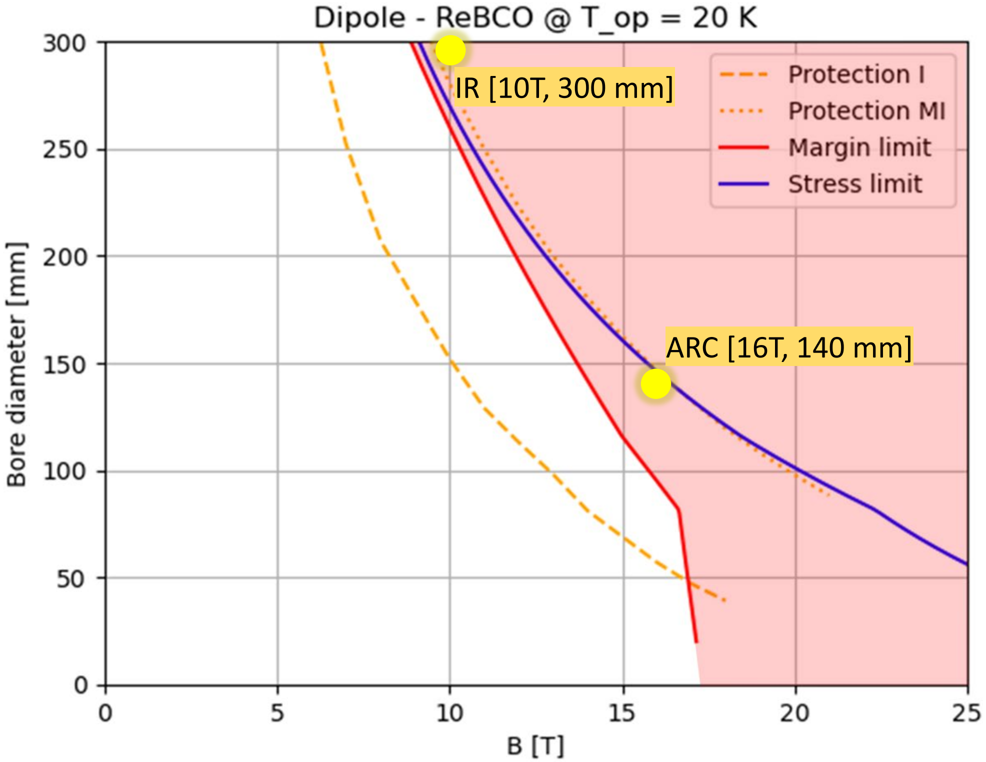
Currently, only stresses generated by Lorentz forces are considered.





Dipole A-B Plots

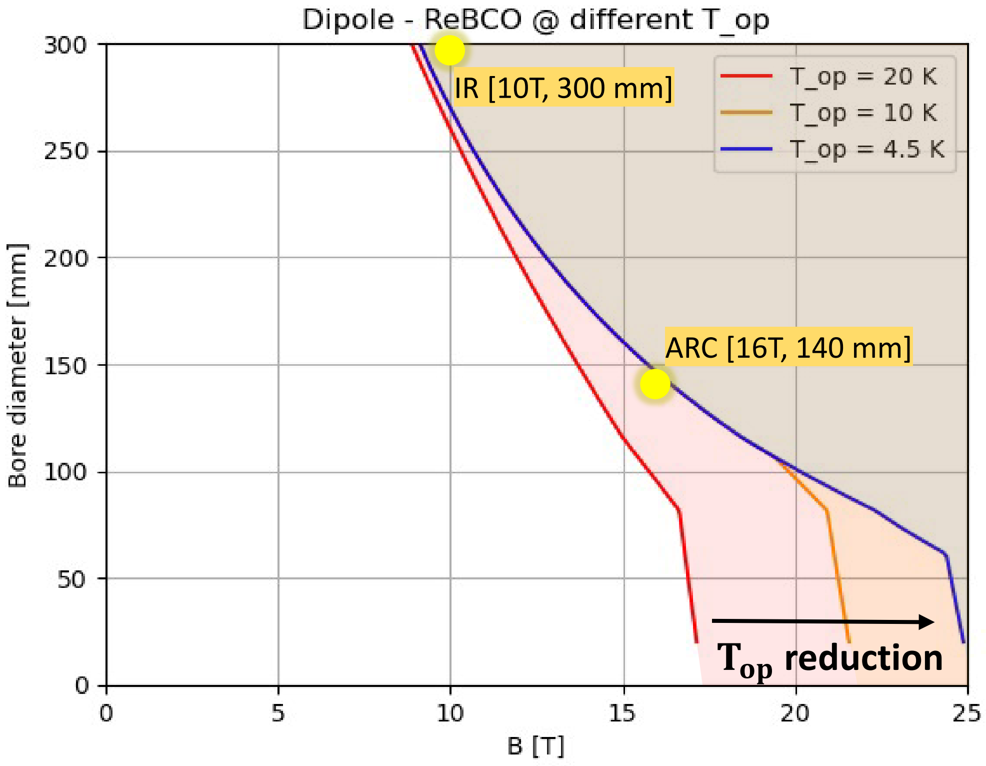


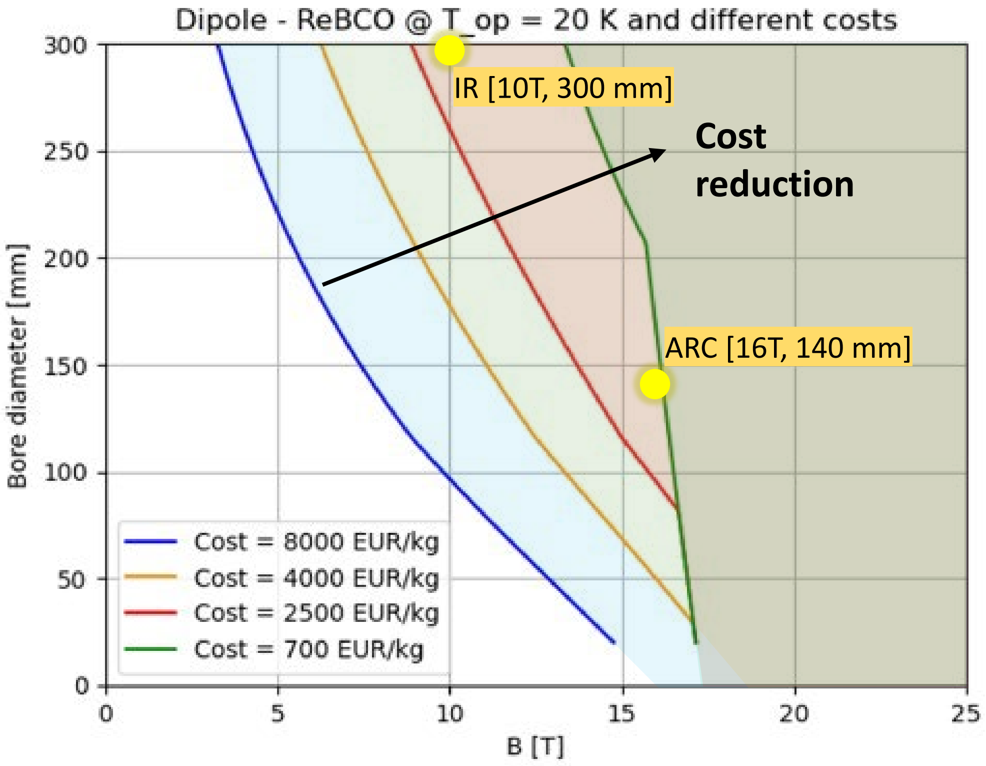


Nb_3Sn falls short of required performance because of **operating margin** and peak stress (at affordable cost !)

HTS falls short of required performance with classical insulated coils. Assuming MI or NI magnets, the **protection** limit becomes comparable with the other limits.

HTS dipole A-B Plots



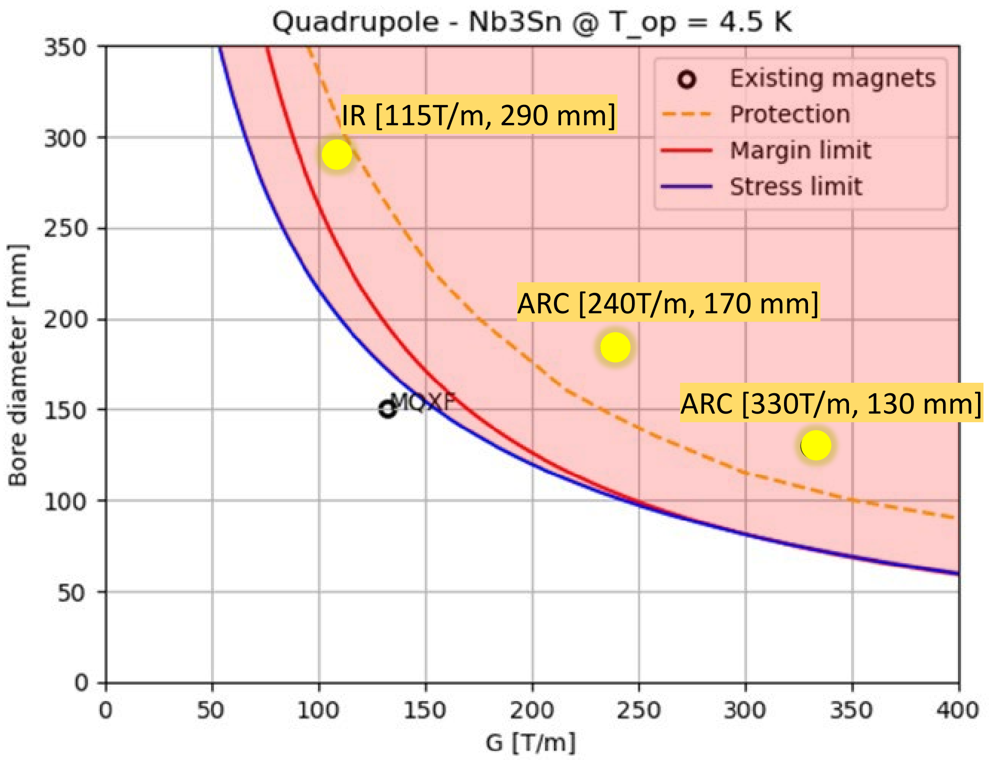


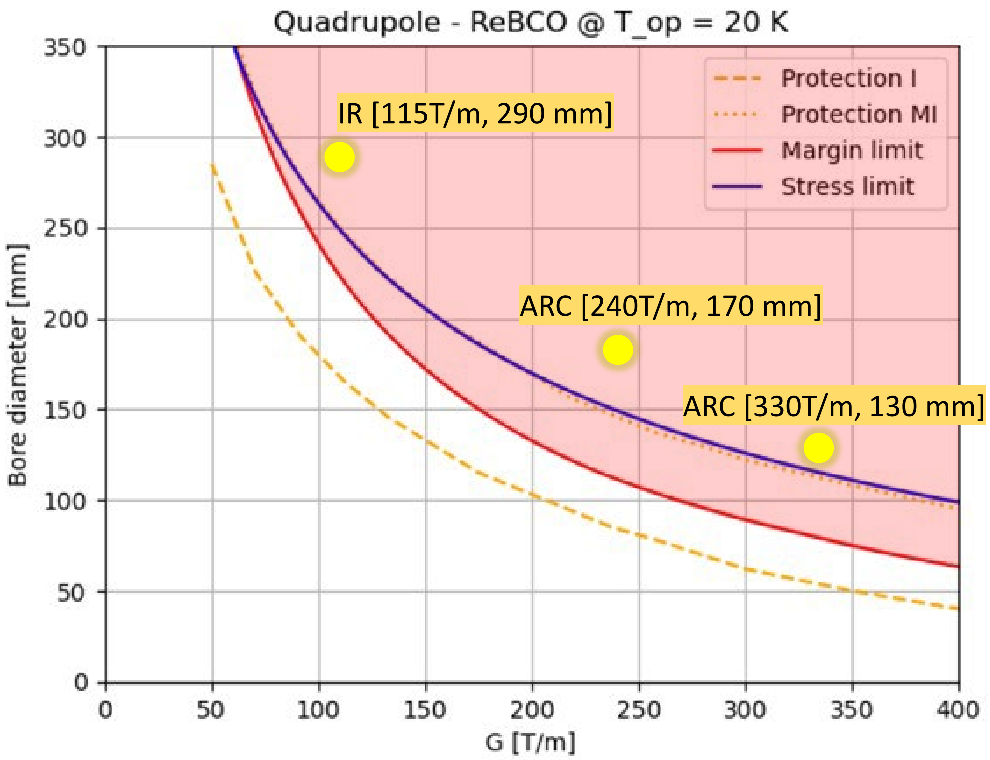
A reduction of operating temperature will result in wider design A-B range

The curves shown in the plots are the limit curves, i.e., for each aperture value the strictest limit is taken, excluding the limit for insulated magnets.

A reduction of HTS cost will result in wider design A-B range

Quadrupole A-B Plots

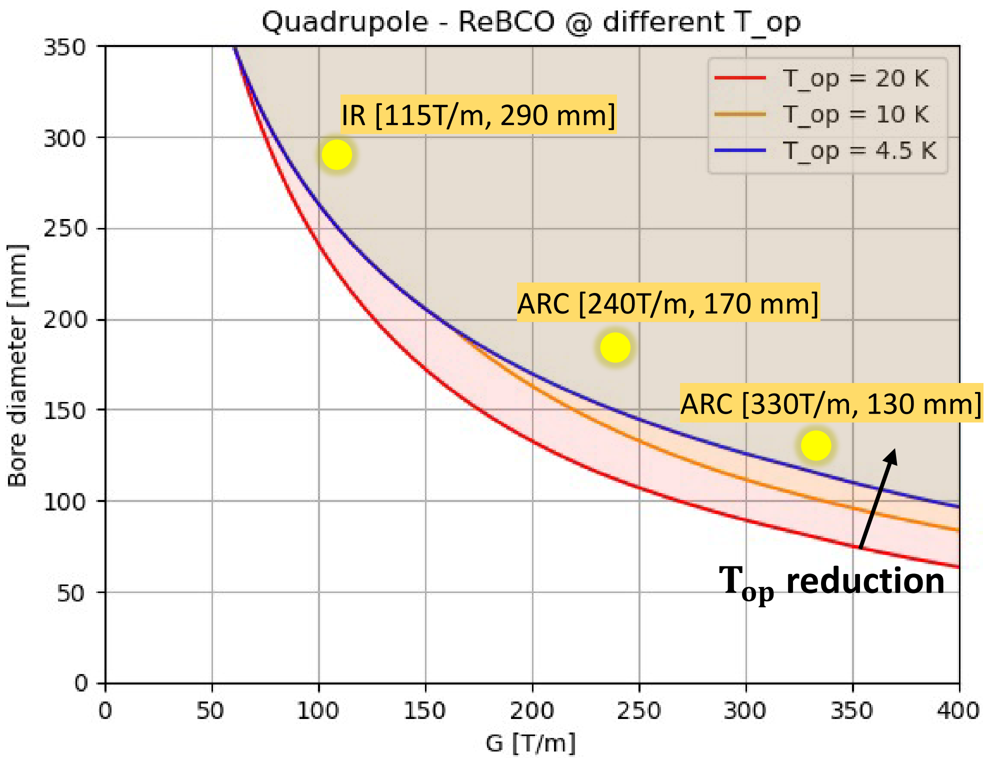


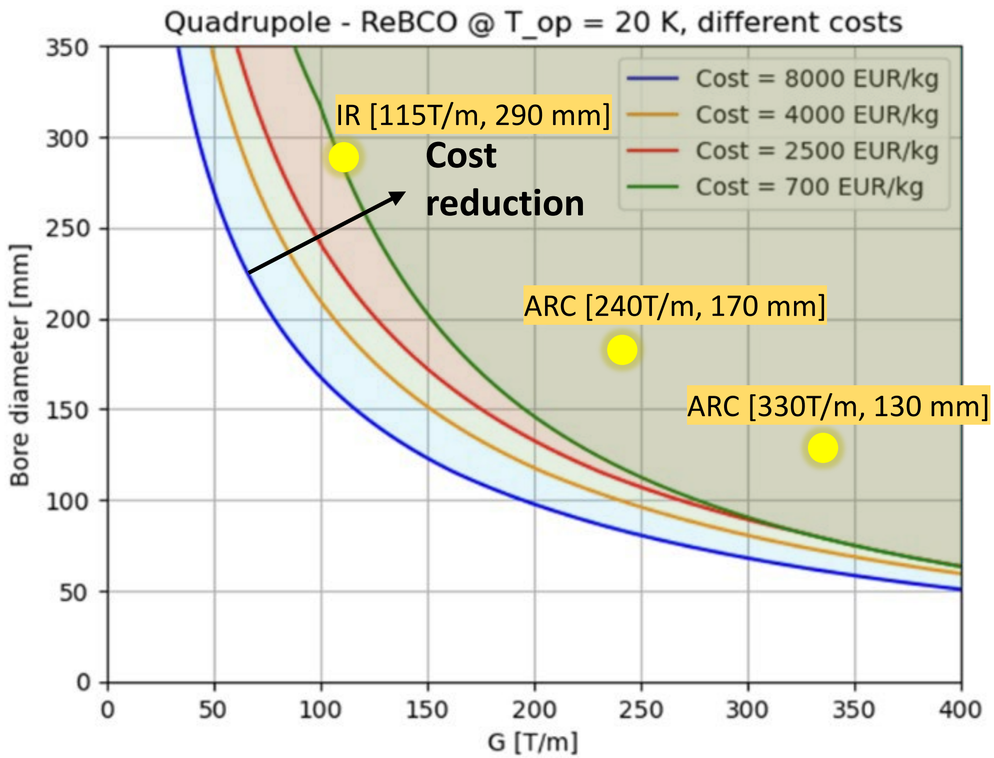


- Nb_3Sn is limited by peak stress and operating margin

- HTS is mainly limited by cost production and protection. Working @20K the margin curve is also a limiting factor.

HTS quadrupole A-B Plots





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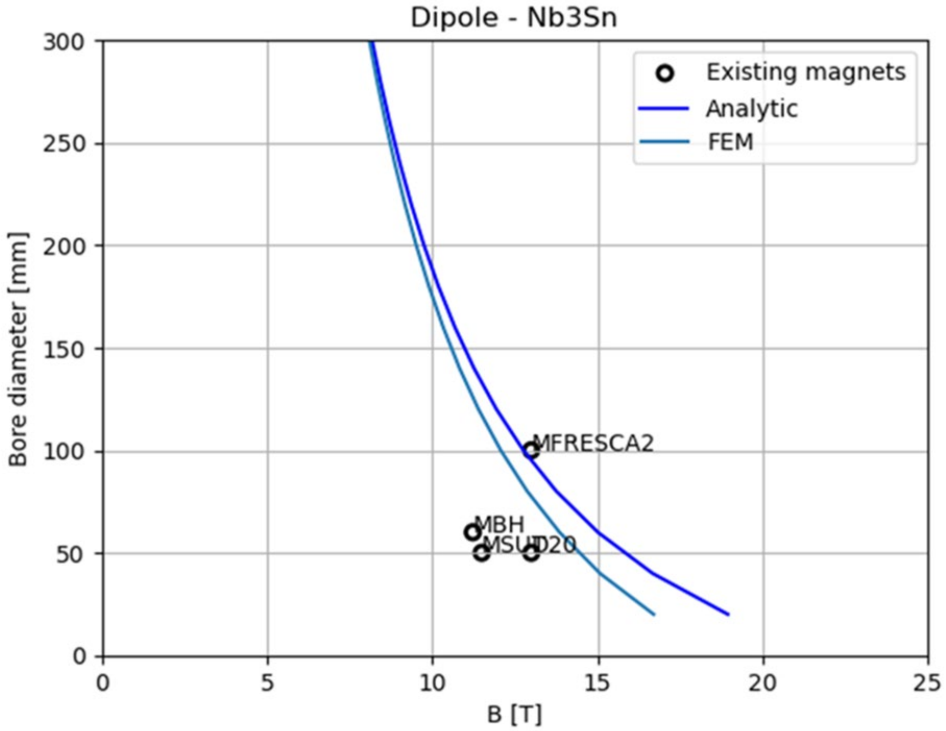
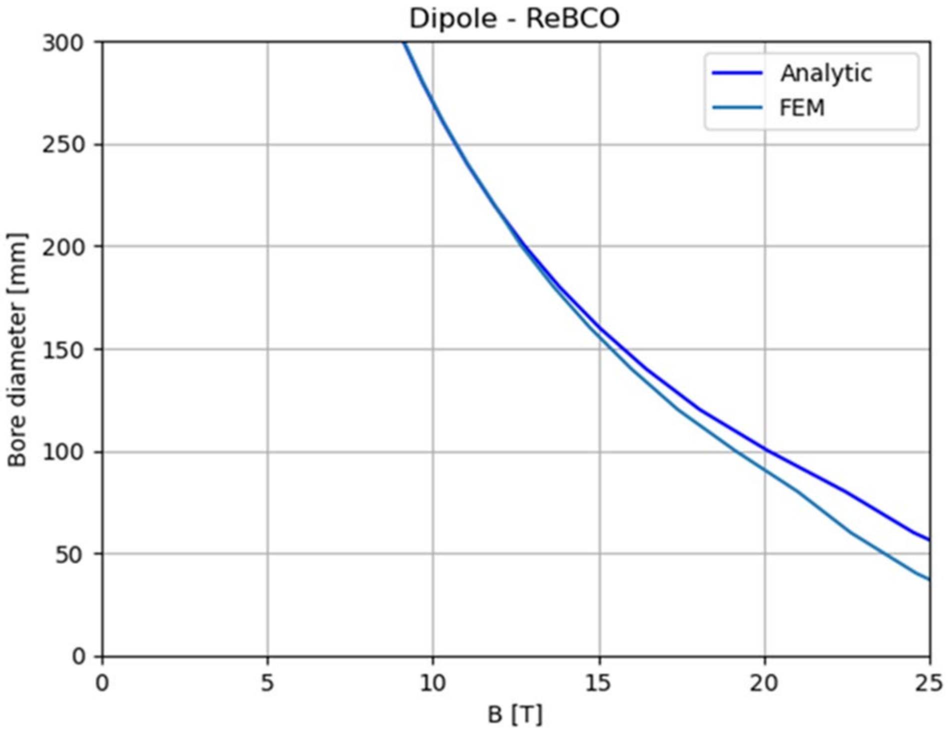
FEM Crosscheck for Stress Curves





- 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.

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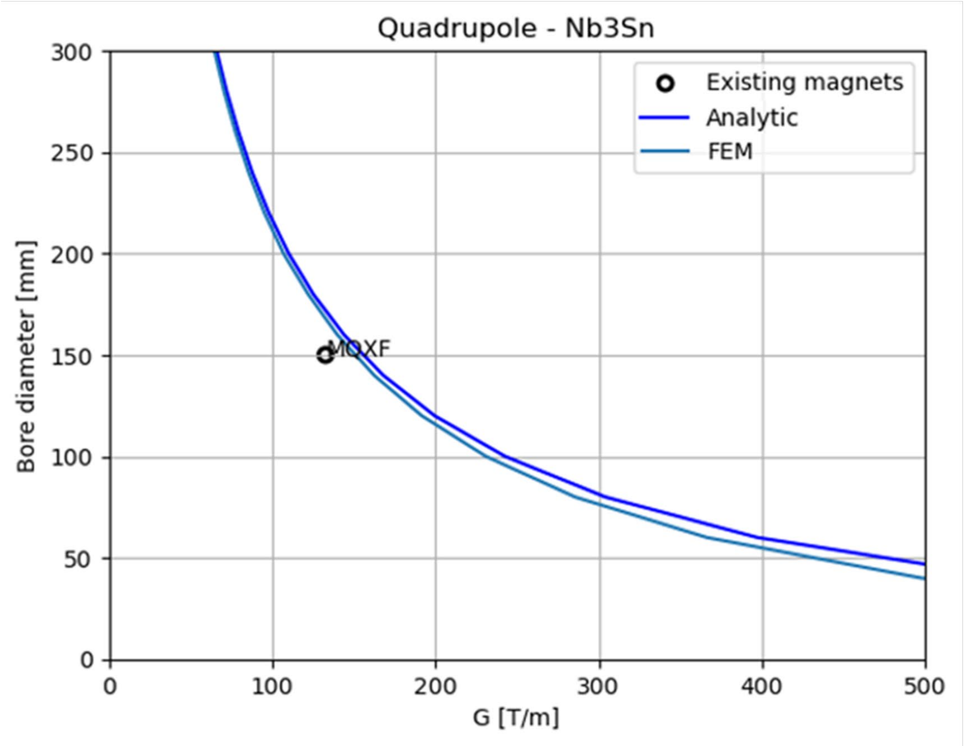
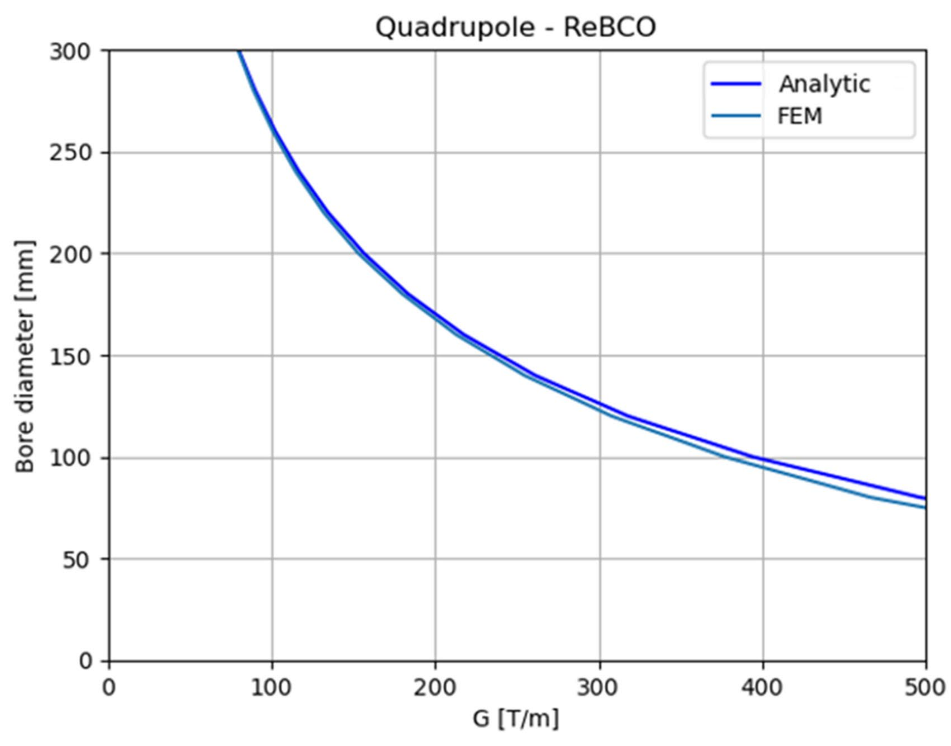




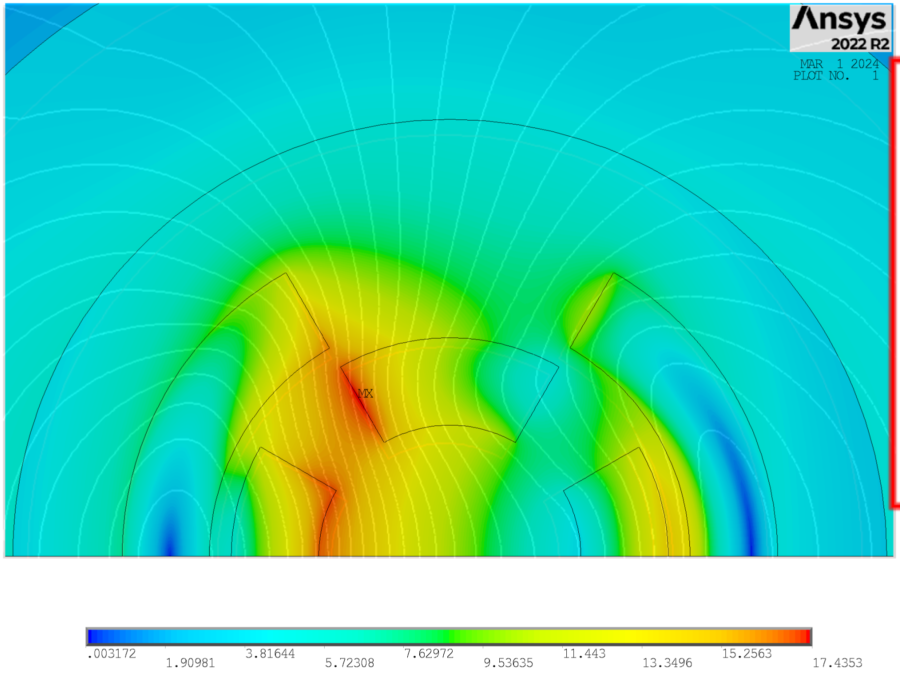
- We implemented a FEM model for a sector **quadrupole** in ANSYS.
- We implemented a **Python** code able to work with **Ansys** software to run FEM simulations with the same inputs as the analytical study.
- In the comparison, the FEM curves are always more restricting than the analytical ones since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

Combined Function Magnet

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

Preliminary results obtained with ANSYS in a sector coil approximation



Quad into dipole:

(ReBCO @20 K)

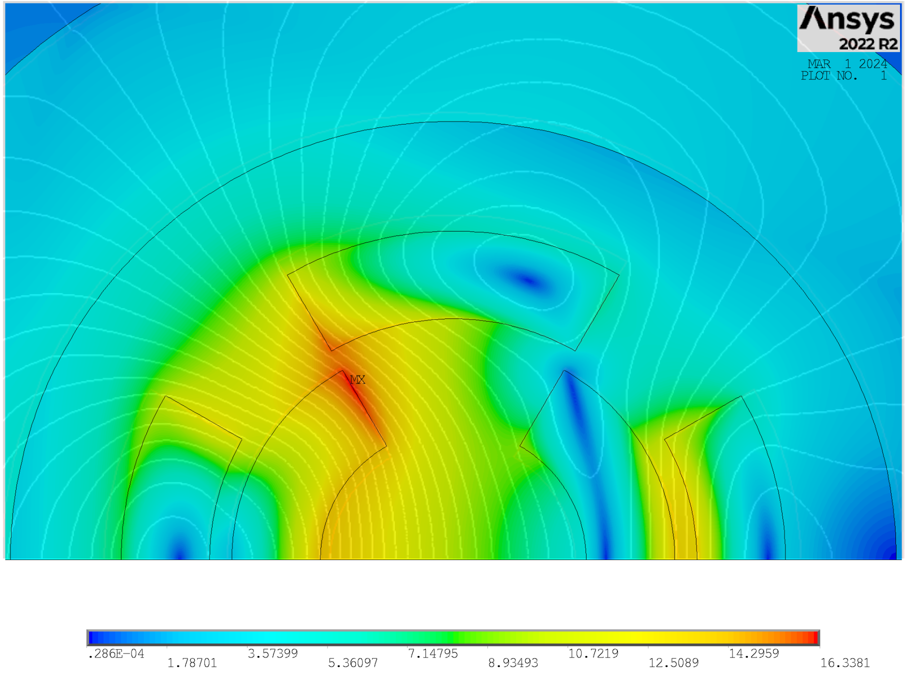
$J = 3.5 \cdot 10^8 A/m^2$

$B \sim 11.7\ T$

$G \sim 143.3$ T/m

$r_{aperture} = 70\ mm$

$w_{coil} = 80\ mm$



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

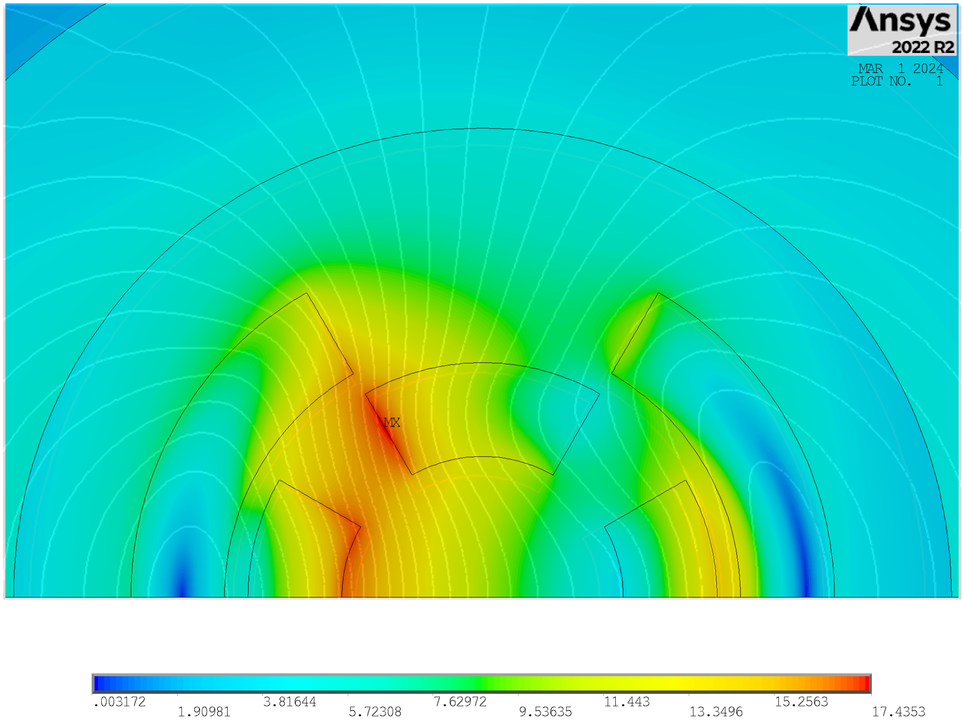
$r_{aperture} = 70\ mm$

$w_{coil} = 80\ mm$

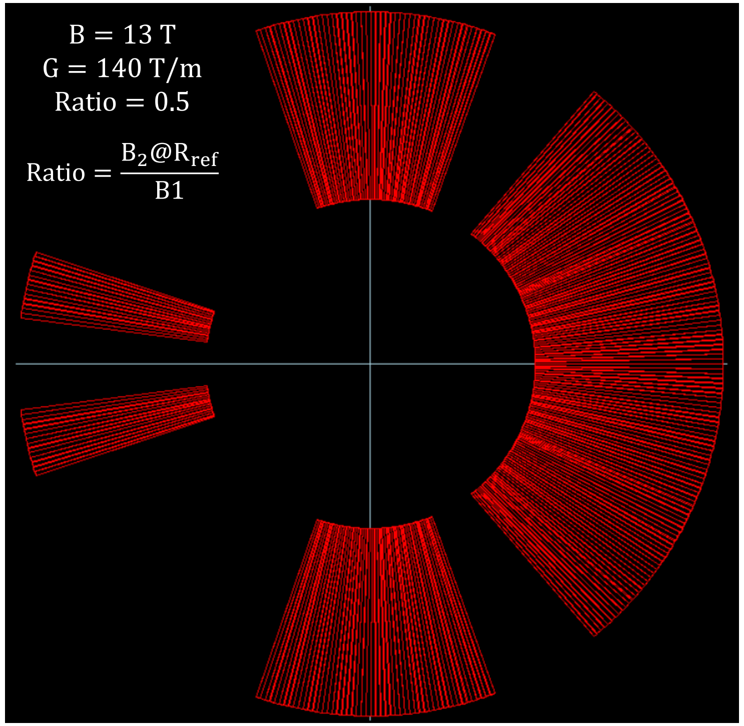
Quadrupole inside dipole is more efficient, in agreement with *US-MAP [ref]*

Combined Function Magnet

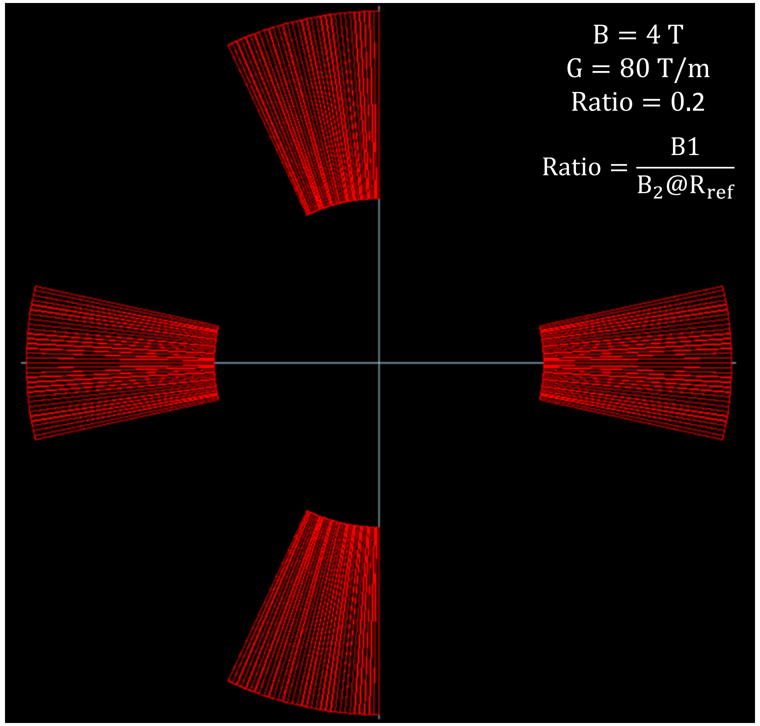
Nested: Quad into dipole



Asymmetric Dipole



Asymmetric Quadrupole



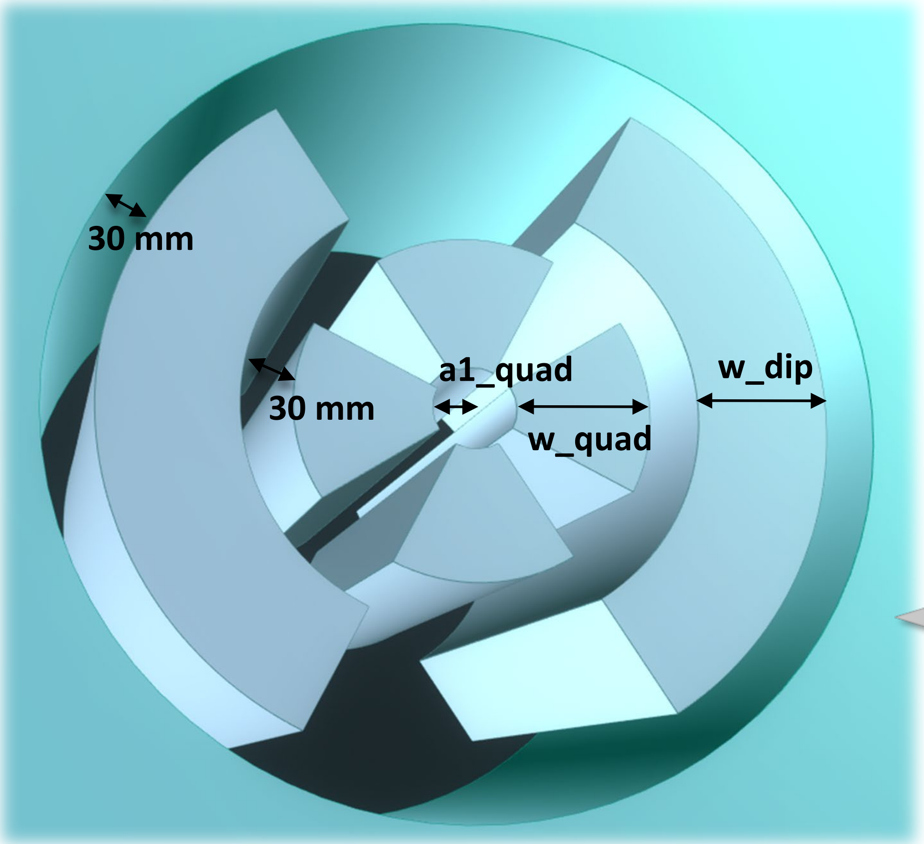
B and G are not independent and the feasibility of windability still to be studied

Quadrupole inside dipole is the primary choice for the combined functions of the muon collider

Combined Function Magnet

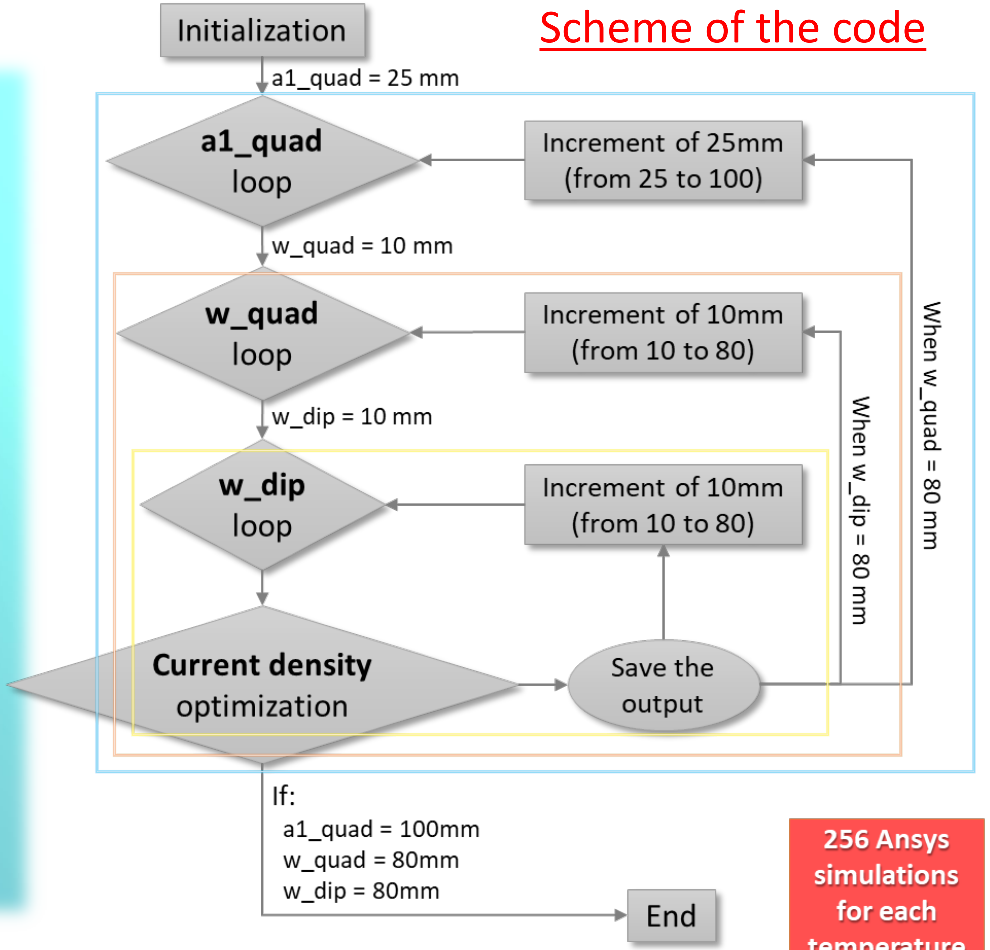
What's next? We would like to produce B-G plots in order to provide the allowed area for the combined function magnets

- **Python-Ansys Interface**



Graphical representation

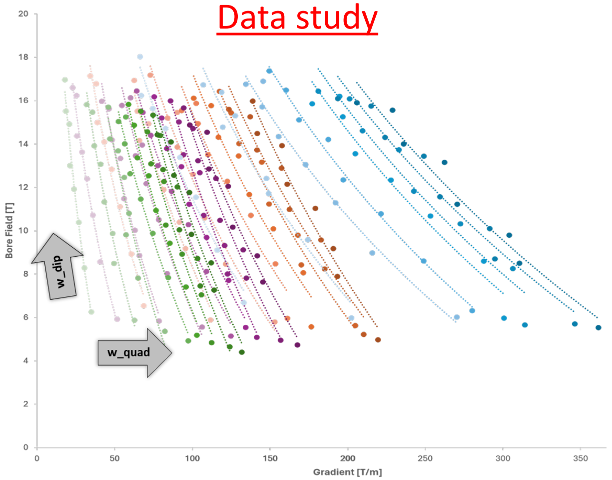
Scheme of the code



256 Ansys simulations for each temperature

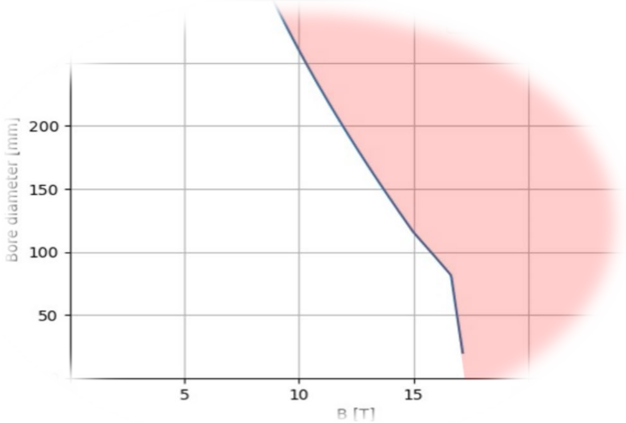
Data saving

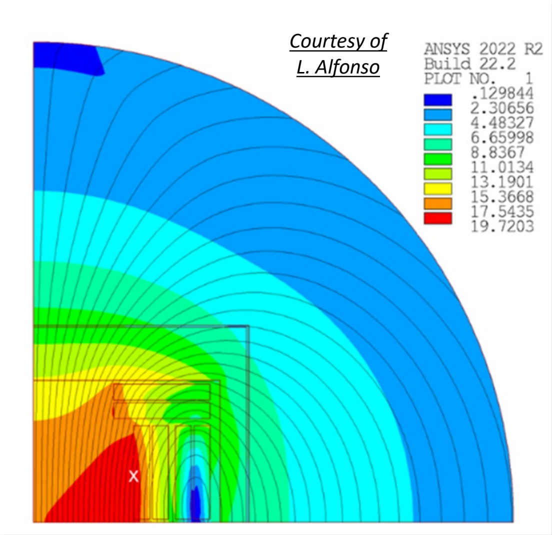
Data study

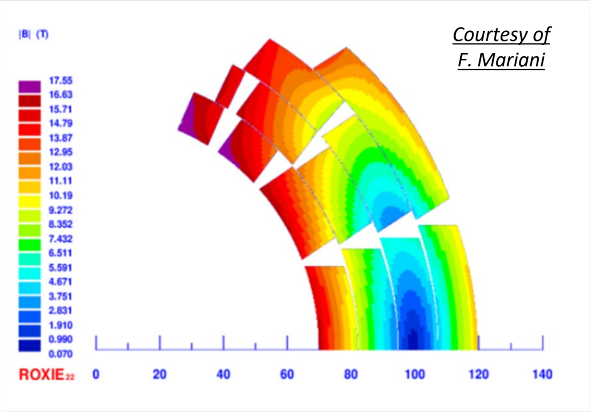


Conclusions

➢ 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.



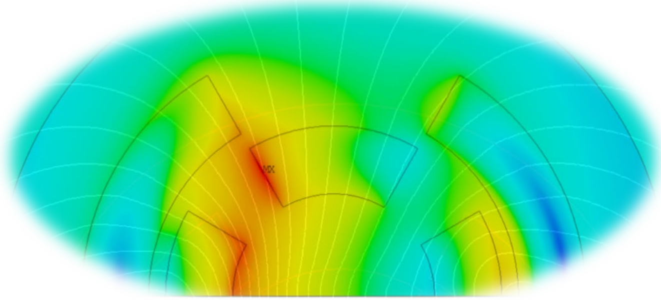




➢ Thanks to the A-B plots, we were able to identify a target design, allowing us to begin studying specific designs.

In particular, we are exploring a cos-theta design and a block coil design.

➢ To address the issue of neutrino flux in the straight sections, combined function magnets must be used in the Muon Collider. In this regard, we are working to identify realistic target designs from a technological point of view.



Thank you for your attention

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Ph.D. in Accelerator Physics – XXXVIII cycle

24 October 2024