Magnet Technologies for Final Focusing Region

IMCC and MuCol MDI workshop 2024

S. Mariotto[1,2], D.Novelli[3,4], A. Bersani[3], B. Caiffi[3], A. Pampaloni[3]
F. Mariani[4], L. Alfonso[3], S. Farinon[3], T. Salmi[5], L. Bottura[6]

[1]University Of Milan, [2]INFN-Milano, [3]INFN-Genova, [4]La Sapienza-Rome, [5]University of Tampere, [6]CERN

Outline

Requirements for the magnet design

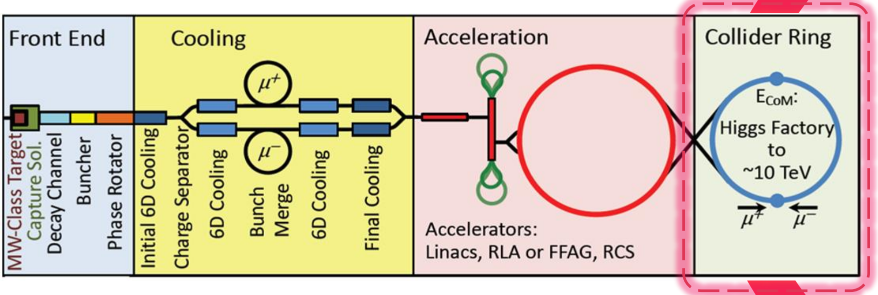
Assumptions and technology parameters

Magnet performances

1. Dipoles
2. Quadrupoles

Conclusions

Introduction



Superconducting Magnet Technology Drivers

- Beam Dynamic Requirements
- Heat Load on Conductor
- Magnet Cooling Options
- Superconductor technology performances
- Magnet Mechanical/Thermal Stability
- Cost of the magnet

Introduction

Scope of this presentation:

- **Feedback** on magnet performances and feasible working points for the next design iteration
- Trigger of **discussion** on which **assumptions and requirements** are critical or not

More on the following presentations:

Wednesday 13th March 2024 - 30/7-018 - Kjell Johnsen Auditorium (CERN)

- *"Collider Magnets Study"* - D. Novelli, 09:40-10:00, https://indi.to/5kwCc
- *"Magnet plan – collider"* - B. Caiffi,11:10-11:30, https://indi.to/nm6NN

Thursday 14th March 2024 - 30/7-018 - Kjell Johnsen Auditorium (CERN)

- "*Magnet Limitations for Muon Collider Rings" – D. Novelli,* 10:30 - 11:00, https://indi.to/MXn2q

Friday 15th March 2024 - 503/1-001 - Council Chamber (CERN)

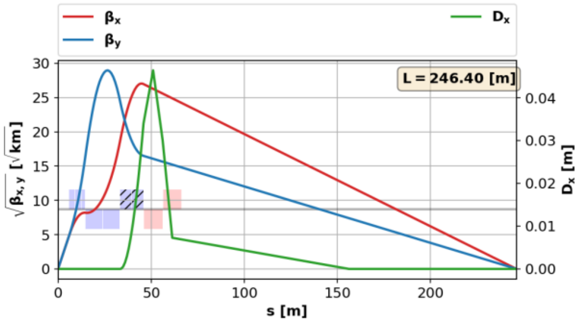
- "*Highlight 1*", D. Novelli, 09:40-10:00, https://indi.to/MvDMZ

Requirements for the IR Magnets

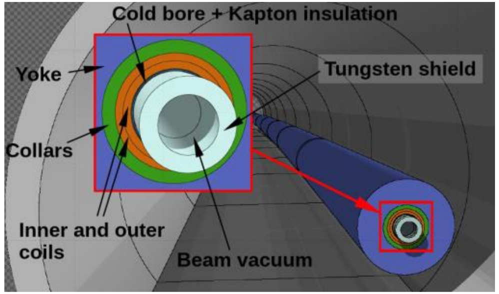
Courtesy of Kyriacos Skoufaris
https://indico.cern.ch/event/1351046/contributions/5687387

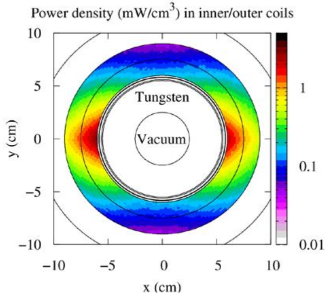
V0.7 Work in Progress

Magnet Type	Performance	Shielding Outer Diameter $2 \cdot (5\sigma + 4[cm])$	Coil Inner Diameter
Quadrupole	$G_1 \approx \pm 300\ T/m$	120 mm	151 mm
Quadrupole	$G_1 \approx \pm 110\ T/m$	300 mm	331 mm
Dipole/Quad	$B_d \approx 8\ T, G_1 \approx \pm 100\ T/m$	280 mm	311 mm
Dipole	$B_d \approx 16\ T$	120 mm	158 mm



Courtesy of Anton Lechner
https://indico.cern.ch/event/1183573/contributions/4972215

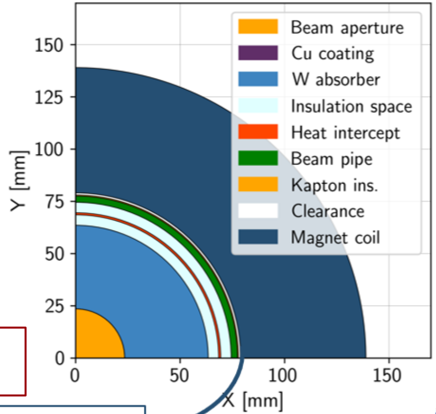




• Beam aperture (5σ)	23.5 mm radius
• Cu layer beam screen	0.01 mm thick
• Tungsten absorber	40 mm thick
• Insulation space	5 mm thick
• Heat intercept	1 mm thick
• Insulation space	5 mm thick
• Beam pipe	3 mm thick
• Kapton insulation	0.5 mm thick
• Clearance	1 mm thick
• Coil pack*	(60 mm thick)

*thickness TBD, placeholder

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



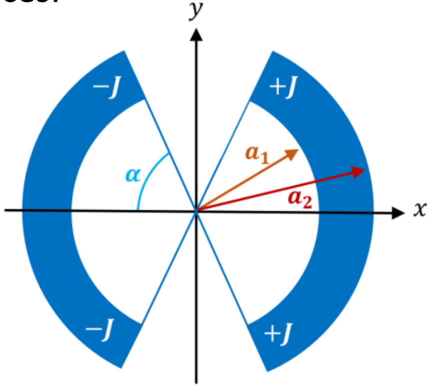
Coil aperture 158 mm

General Assumption

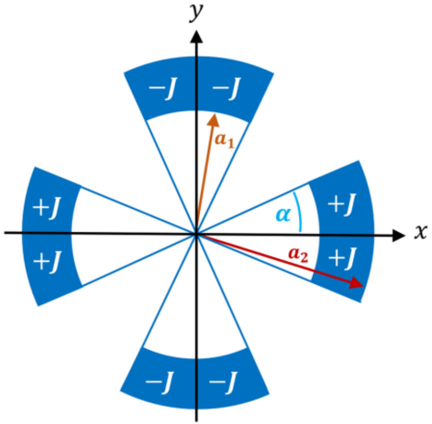
Analytical evaluation of dipole and quadrupole performances:
simplified design in section coil approximation:
(α is 60° for the dipole and 30° for the quadrupole)

Material	Temperature	Configuration
$NbTi$	$1.9\ K$	3 TeV
Nb_3Sn	$4.5\ K$	3-10 TeV
$ReBCO$	$4.5\ K$ $20\ K$	10 TeV

Dipole



Quadrupole



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

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

$(w = coil\ width)$

Scope of the analysis

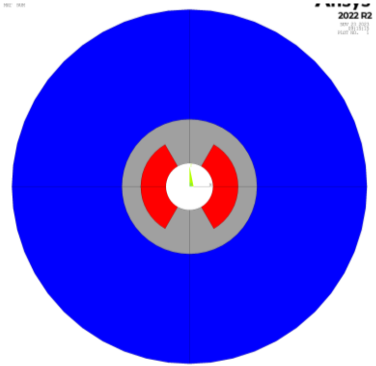
Plots of the Magnet Aperture (A) – Bore Field (B) phase space allowed region

Limitations:

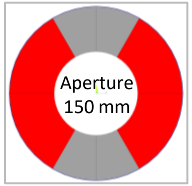
Cost → **Margin** → **Stress** → **Protection**

Cost and Performances

Limitation of magnet performance fixed by total magnet cost: 400 kEUR/m (~Twice FCC-hh value [1])



- Bore
- Coil
- Structures
- Iron



Magnet cross-section design: **optimization process**

Separation of total magnet cost:

1. Cost of the labour = 40 kEUR/m (derived from FCC)
2. Cost of material = 380 kEUR/m

Physical limitation on magnet dimensions:

a) Coil width: $10\ mm \leq w_c \leq 80\ mm$

b) Structures: $w_s \leq 60\ mm$ (SS cost: 10 EUR/kg (HL-LHC))

c) Iron yoke: $w_i \leq 350\ mm$ (Fe cost: 8 EUR/kg (HL-LHC))

Material	Projection	Cost Superconductor
NbTi	Value @ 2016	330 EUR/kg
Nb_3Sn	Value @ 2016	2000 EUR/kg
	Aspirational Value (FCC Target)	700 EUR/kg
ReBCO	Today Value	8000 EUR/kg
	Aspirational Value (Projection @ 2040)	2500 EUR/kg

Cost model assumptions affects magnet dimensions

$R_{bore}, w_{coil}, w_{iron}, w_{struct}$

Beam Dynamic | Radiation Load | Cryogenic

- Maximum Magnetic Field: B[T]
- Maximum Magnet Aperture: A[mm]

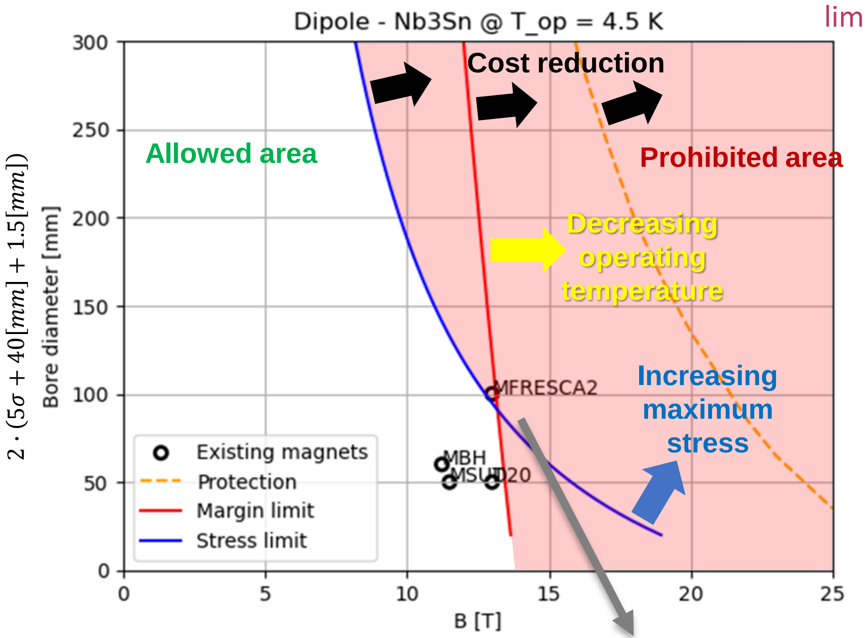
A-B Plots

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.

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

The **protection limit** consists in QH (or CLIQ) for classical insulated coils, limiting the hotspot temperature and the stored energy in the coils.

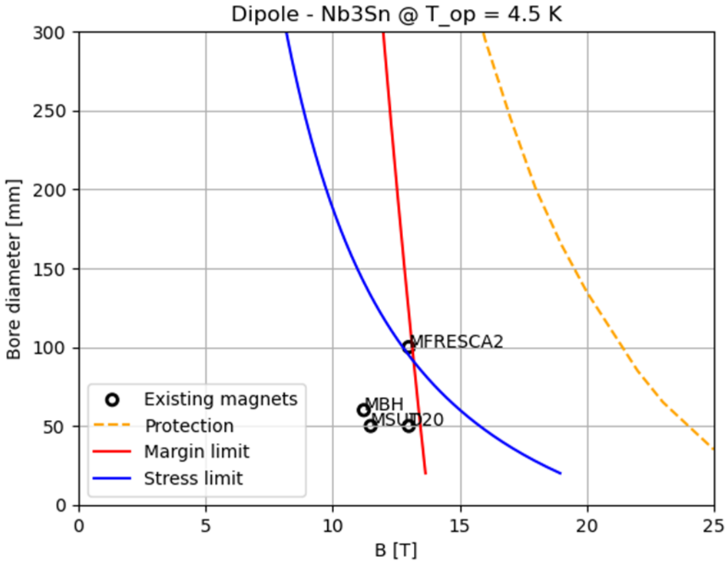
(courtesy of Tiina Salmi)

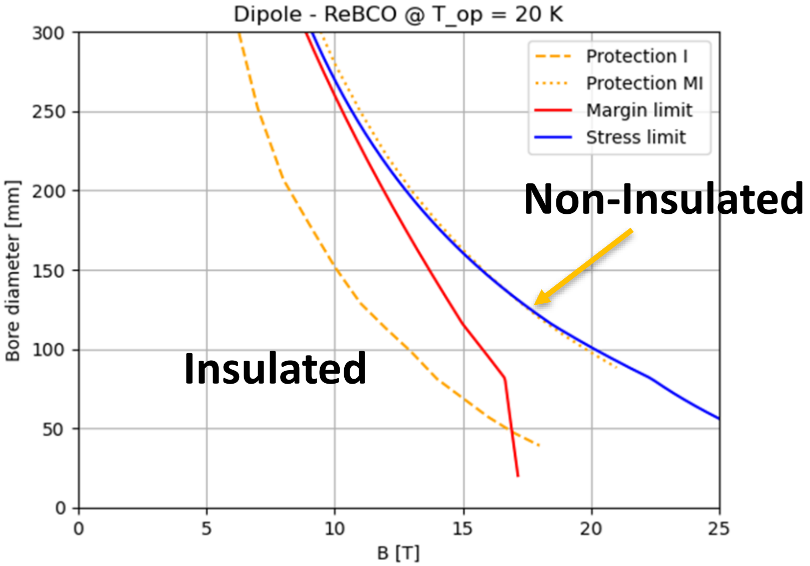


- With more budget (or cheaper SC), the allowed region increase.
- By reducing the operating temperature (or the temperature margin), the limitation due to the margin is weaker.
- By increasing the maximum allowable stress, the limitation due to the margin is weaker.

The limit changes: in this case, before the intersection, the stricter limit is the stress while after it is the margin.

Dipole Performances





Stronger Limitations: **Stress and Margin**

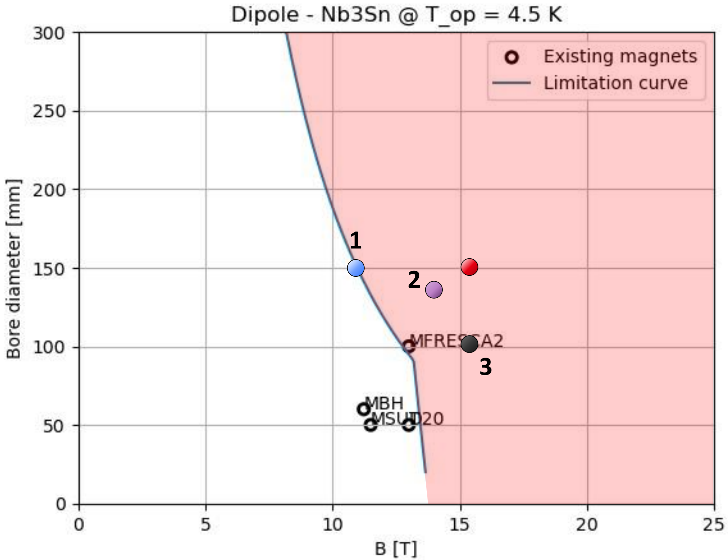
- Quench protection not a problem

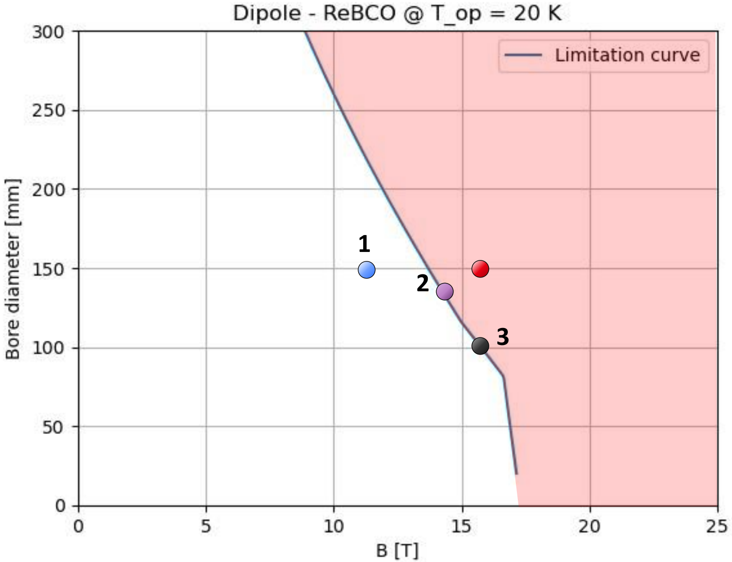
Performances compatible with 3 TeV ARC

ReBCO HTS design strongly limited by protection!

- Need to devise **alternative protection schemes**: **Non-Insulated** and **Metal-Insulated** coils
- Need of an R&D development program

Possible Variations



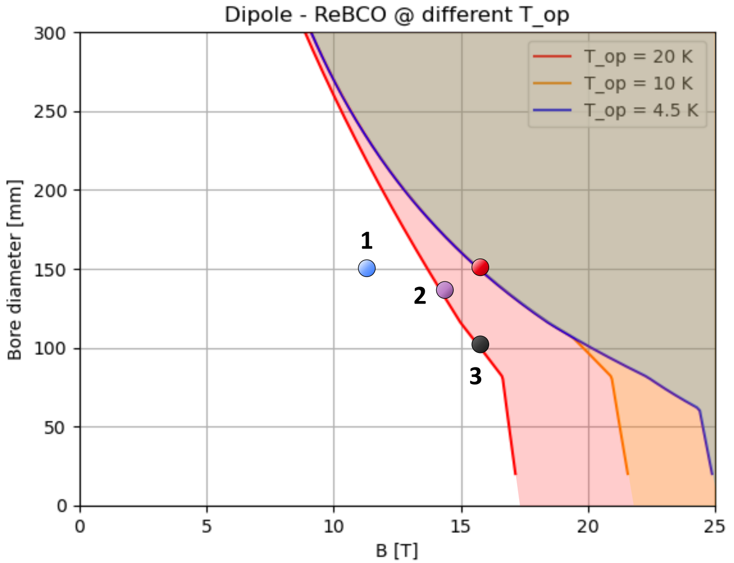


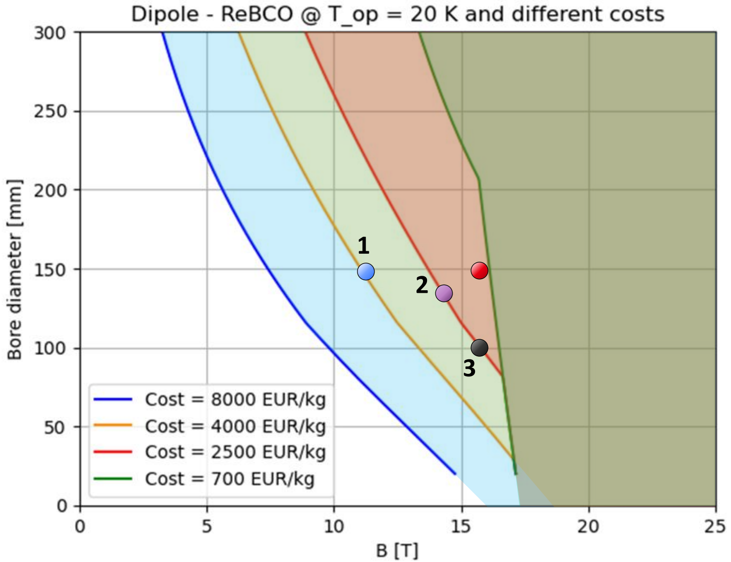
	Field	Shielding Outer Diameter $2 \cdot (5\sigma + 4[cm])$	Coil Inner Diameter
Baseline	$B_d \approx 16\,T$	127 mm	158 mm
1	$B_d \approx 11\,T$	119 mm	150 mm (3 TeV ARC)
2	$B_d \approx 14\,T$	109 mm	140 mm
3	$B_d \approx 16\,T$	69 mm	100 mm

Three possible configurations considered:

1. **Magnetic Field: Nb_3Sn** Variation (11 T/150 mm)
2. **Mixed Solution: ReBCO** (14 T, 140 mm)
3. **Shield/beam** reduction: **ReBCO** (16 T, 100 mm)

Assumptions Dependance





ARC Dipoles Heat Load

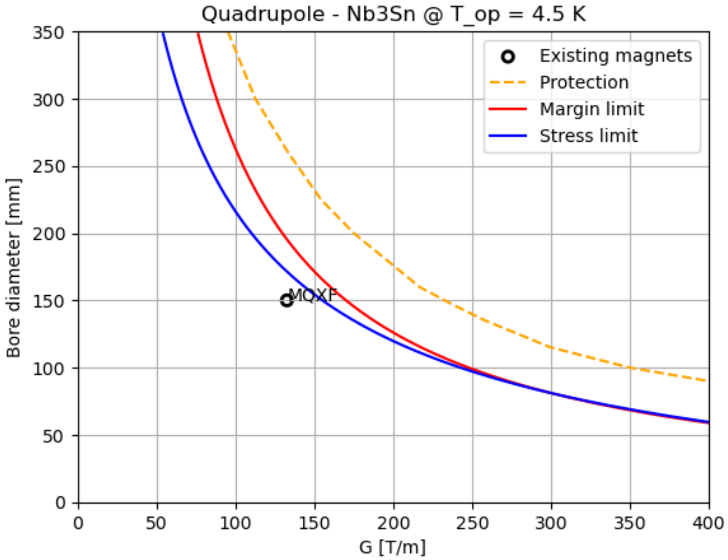
	2 cm	3 cm	4 cm
Beam aperture (radius)	23.5 mm	23.5 mm	23.5 mm
Outer shielding radius	43.5 mm	53.5 mm	63.5 mm
Inner coil aperture (radius)	59 mm	69 mm	79 mm
Power penetrating tungsten absorber	19.1 W/m (3.8%)	8.2 W/m (1.6%)	4.1 W/m (0.8%)
Peak power density in coils	6.5 mW/cm^3	2.1 mW/cm^3	0.7 mW/cm^3
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

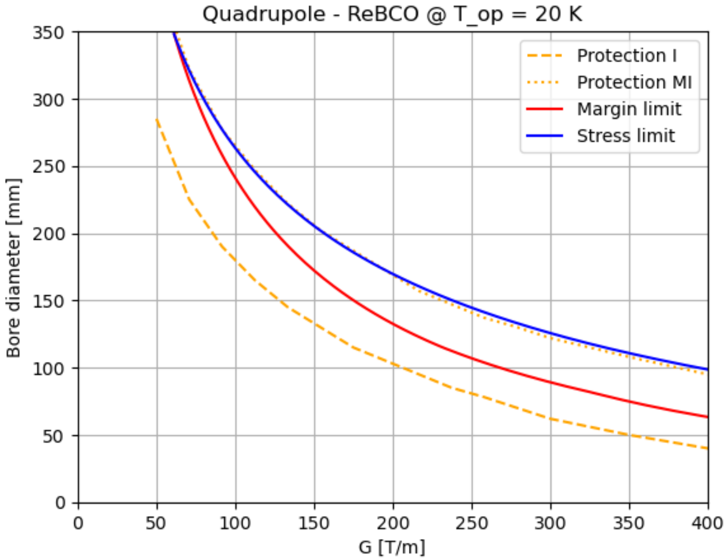
Courtesy of A. Lechner

Currently, tungsten **shielding at 40 mm** thickness.

1. **FROM ARC Evaluation**: **shielding @ 30 mm** and T=20 K ReBCO feasible from cooling calculation estimation enabling working point **2 but not 3**
2. **Temperature reduction** could be exploited (less magnets) but needed to be check with **cooling**

Quadrupole Performances





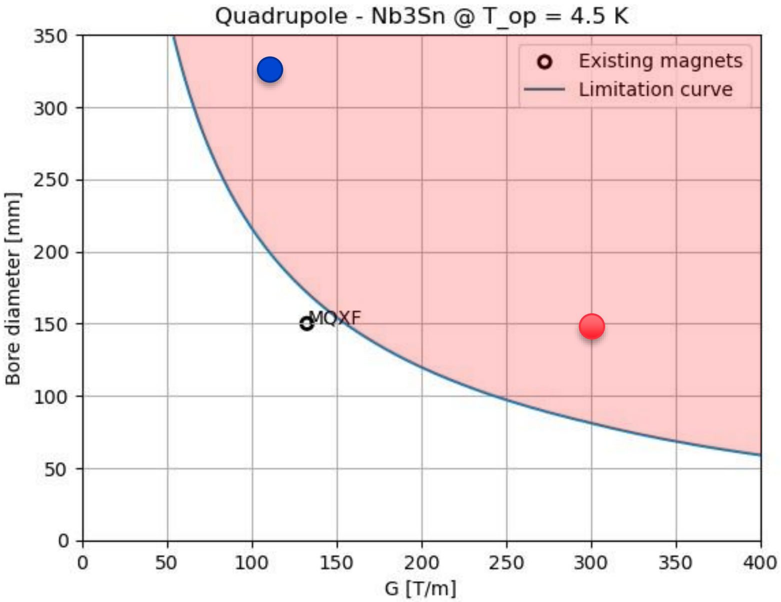
Stronger Limitations: **Stress and Margin**

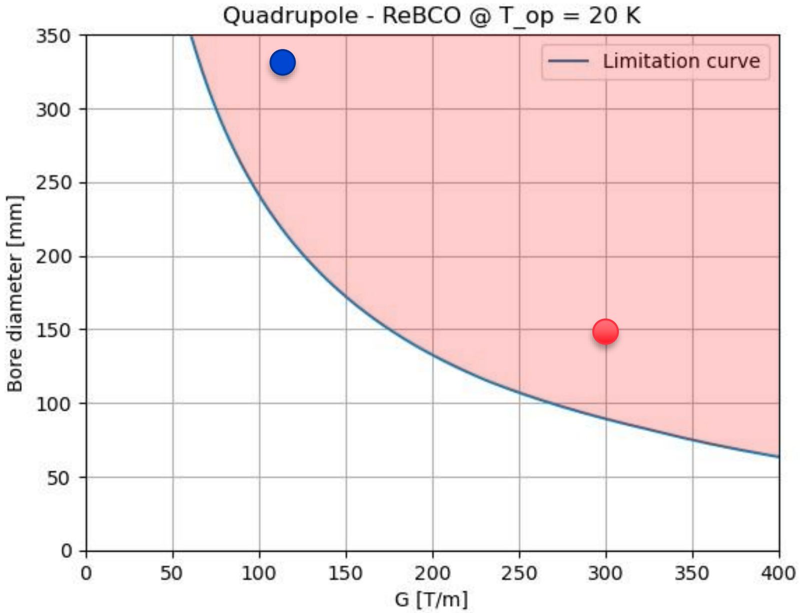
- Quench protection not a problem
- **HL-LHC MQXF** quadrupole work @ 1.9 [K] and has lower cost ($/m) than what we considered.

Same consideration on magnet quench protection done for the dipole configuration

- **Alternative Protection Scheme required**

Possible Variations

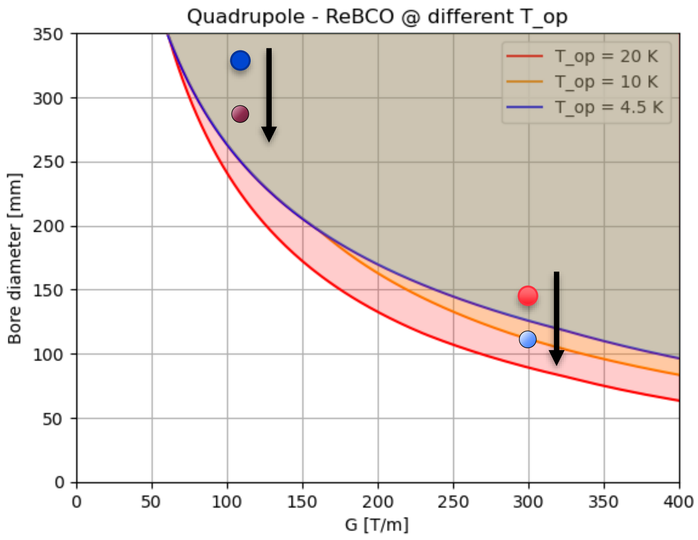


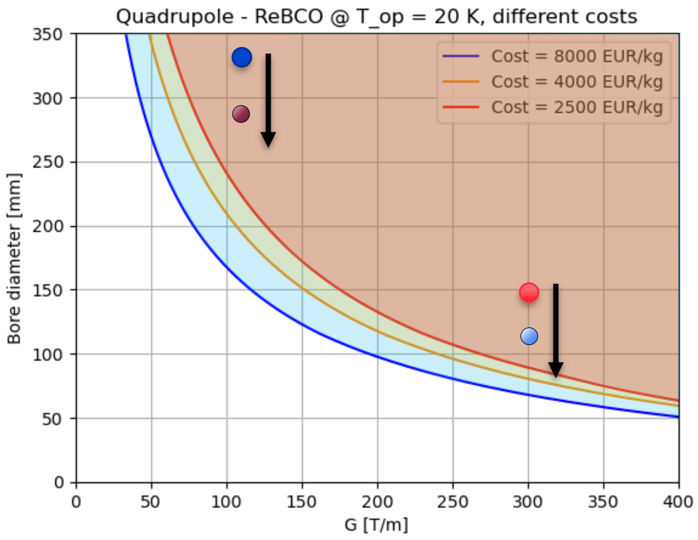


	Performance	Shielding Outer Diameter $2 \cdot (5\sigma + 4[cm])$	Coil Inner Diameter
Baseline	$G_1 \approx \pm 300\ T/m$	120 mm	151 mm
	$G_1 \approx \pm 110\ T/m$	300 mm	331 mm

- Both Baseline design are within prohibited region: ReBCO @ T=20 K performances slightly better than Nb3Sn @ T=4.5 K.
- **Iteration on required aperture and gradient**

Assumptions Dependance





Possible solutions: combination or **lower temperature** of operation and **higher magnet cost**
(very few magnets, separated cooling solution)

Example: ReBCO @ T≈10 K / W≈ 2 cm ?

	Performance	Shielding Outer Diameter	Coil Inner Diameter
1	$G_1 \approx \pm 300\ T/m$	80 mm (W @ 2 cm)	111 mm
2	$G_1 \approx \pm 110\ T/m$	260 mm (W @ 2 cm)	291 mm

Conclusions

Evaluation of the performance target for the collider ring magnets of the Interaction Region (IR)

- Maximum performances limited by **cost, mechanics, and protection**.
- Different configurations are compared using the magnet aperture (A) - field (B) plot
- Results are **heavily dependent** on **assumptions considered**

Dipoles performances

1. Nb_3Sn @ (T=4.5 K, B= 11T) suitable for ARC magnets also compatible with IR dipole
2. ReBCO @ (T=20 K, **B=14 T, ϕ =140 mm**) already suitable with cooling and tungsten **shielding reduced to 3 [cm]** for the ARC magnets. Need to be checked also for IR.

Quadrupoles performances: **HTS** could enable high gradient and aperture
Better **high gradient** but reduce coil diameter: **shielding thickness** @ 2 [cm] and **T=10 K**???

NEXT STEPS: **Combined function magnets**

- Move toward more detailed magnet configurations → **FEM**
- **Looking forward** to have **iteration** on performance and requirements

MUON Collider Collaboration

INFN

Thank you for the attention