International Muon Collider Collaboration
MuCol
CCA2025
International Workshop on Coated Conductors for Applications
CERN | March 11-13, 2025
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HTS magnets for the Muon Collider Ring

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Funded by the European Union

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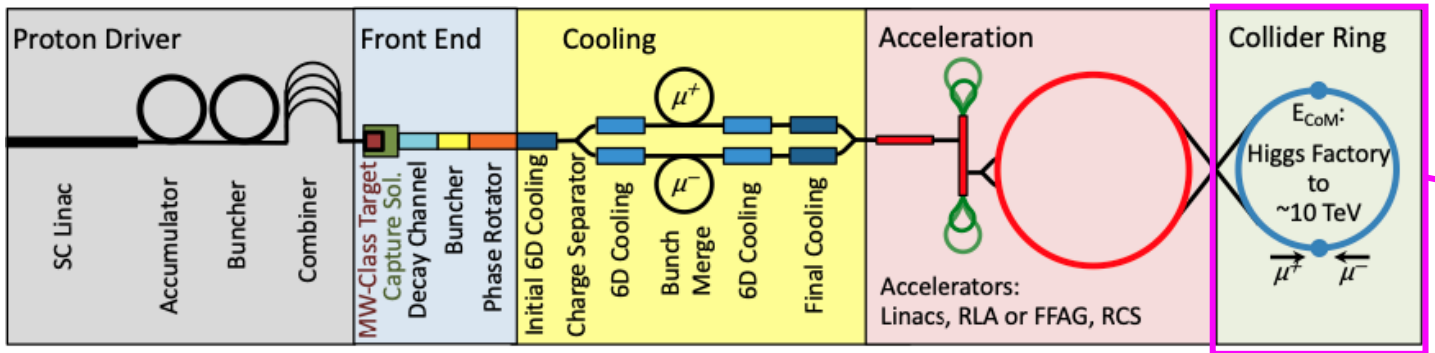
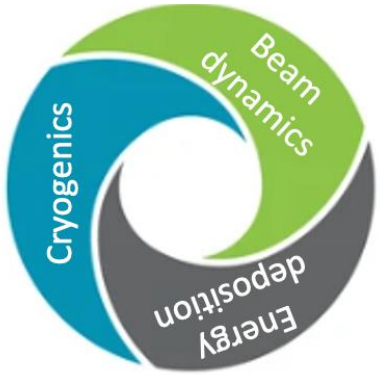
The Muon Collider Complex

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 and supported by European Grant Agreement N° 101094300.

μ decays in 2.2 μs in rest frame:

- must be produced, cooled, accelerated and collided ASAP
- decay products must be shielded to avoid damage to the machine or radiation
- Straight sections must be minimized to avoid collimated neutrino flux





Optimization and definition of magnets requirements is a multi-disciplinary tasks, involving cryogenics, beam dynamics, energy deposition and magnet engineering

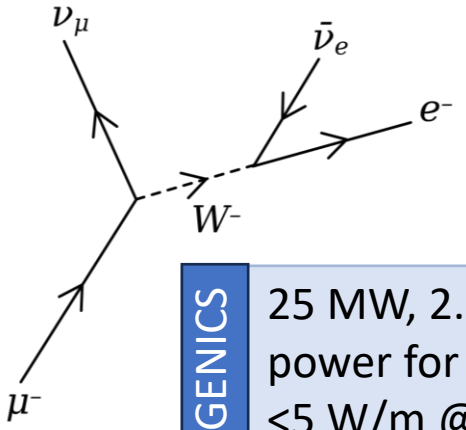
10 km collider ring with 10 TeV center of mass energy (also a 3TeV E_{COM} is being considered as a staged option)

Collider magnets: B_d ~ 16-20T in 150 mm bore:

- Highest field possible to have a compact ring
- Large dipoles and quadrupoles (150 mm bore diameter) for shielding against heat (500 W/m) and radiation loads
- Combined function (dipole + quadrupole & dipole+sextupole) to avoid straight sections and minimize neutrino hazard

Magnets for the Collider Ring: cryogenics and energy deposition

Muon decay



- Neutrinos carry 65% of E_μ → radiation hazard outside the accelerators → straight sections must be minimized
- Electrons carry ~35% of E_μ (**500 W/m** for 10 TeV collider →high-Z shield needed to limit the energy deposited inside the magnets

CRYOGENICS

25 MW, 2.5 kW/m : target cryogenics power for the collider ring
<5 W/m @ 4.5 K (LTS, He cooling)
<10 W/m @ 20K (HTS, H2 possible)

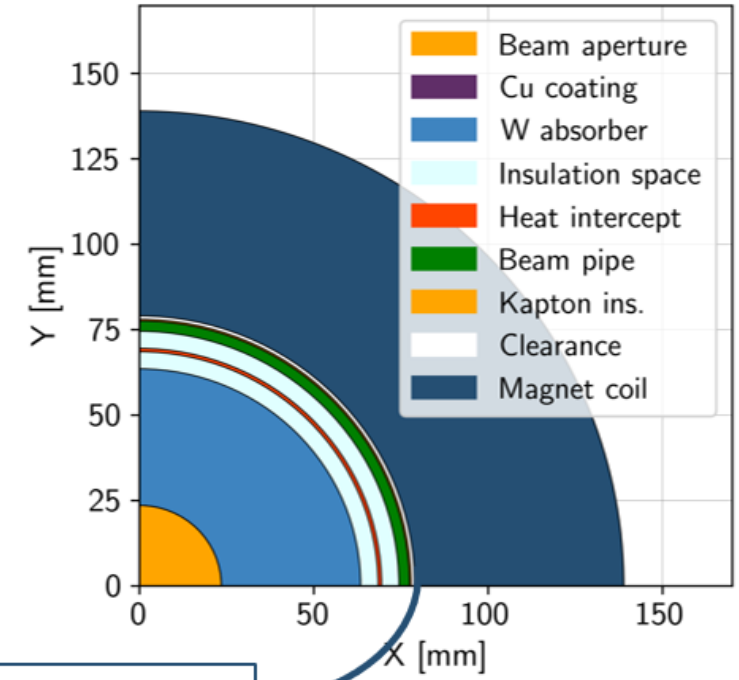
	2 cm	3 cm	4 cm
Beam aperture (radius)	23.5 mm	23.5 mm	23.5 mm
Outer shielding radius	43.5 mm	53.5 mm	63.5 mm
Inner coil aperture (radius)	59 mm	69 mm	79 mm
Power penetrating tungsten absorber	19.1 W/m (3.8%)	8.2 W/m (1.6%)	4.1 W/m (0.8%)
Peak power density in coils	6.5 mW/cm^3	2.1 mW/cm^3	0.7 mW/cm^3
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
"Radiation shielding studies for superconducting magnets in multi-TeV muon colliders" IPAC24

Radial Build

- Beam aperture (5σ) — 23.5 mm radius
- Cu layer beam screen — 0.01 mm thick
- Tungsten absorber — 20-40 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 138-158 mm

Magnets for the Collider Ring: Beam Dynamics

BEAM DYNAMICS

- 10 km collider ring
- Maximum 10 m long magnet
- Maximum field of 16 T for dipoles and 20 T for combined-function magnets
- 30 cm drift for interconnection

ARC[1]

Dipole:

B_d=16 T in 138 mm bore aperture

Combined magnets:

B_d=8 T, G1=+-320 T/m bore in 130 mm bore aperture

Chromatic correction & Matching

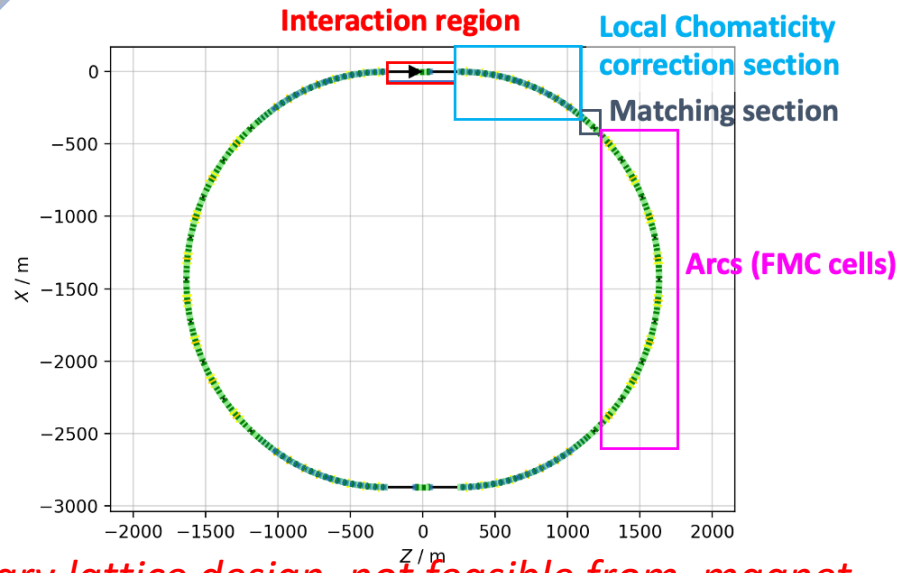
Dipole[1]:

B_d=16 T in 138 mm bore aperture

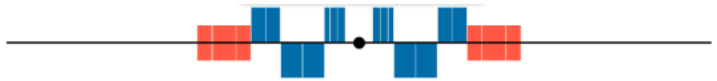
Combined magnets:

B_d=4 T, G1=+-240 T/m in 170 mm bore aperture

B_d=4 T, G2=+-330 T/m in 130 mm bore aperture



Interaction region[2]



Name	L [m]	Magnet aperture diameter [mm]	B[T]
IB2	6	320	8.1
IB1	10	320	9.7
IB3	6	320	8.1
Name	**L [m]**	**Magnet aperture diameter [mm]**	**G [T/m]**
IQF2	6	280	85.2
IQF2_1	6	266	85.2
IQD1	9	290	-115.4
IQD1_1	9	290	-115.4
IQF1B	2	204	205.1
IQF1A	3	172	241.8
IQF1	3	140	302.2

***DISCLAIMER**: Tentative and very preliminary lattice design, not feasible from magnet technology point of view*

Courtesy of Christian Carli, Kyriacos Skoufaris , Marion Vanwelde and D. Calzolari

[1] K. Skoufaris et al. https://indico.cern.ch/event/1351046/contributions/5687387/attachments/2758663/4803779/Current_Magnets_Requirements_for_Muon_Collider_Lattice_v0.7.pdf

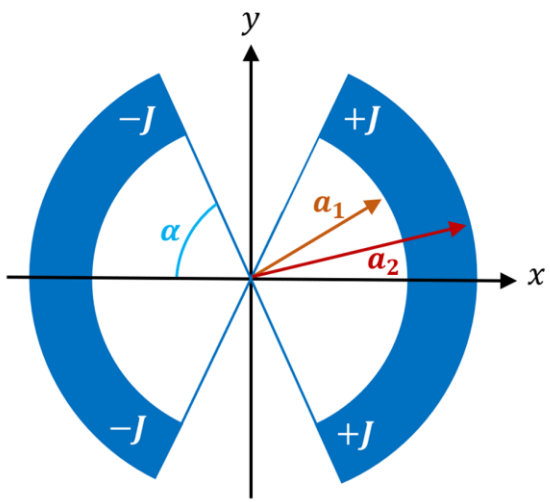
[2] M. Vanwelde et al., `` Status of the 10 TeV center-of-mass collider lattice and IR design'', IMCC Detector and MDI workshop 2024 https://indico.cern.ch/event/1402725

[3] D. Calzolari et al. https://indico.cern.ch/event/1402725/contributions/6013056/attachments/2883747/5054157/MDI_workshop_magnet_load.pdf

Accessible Phase Space

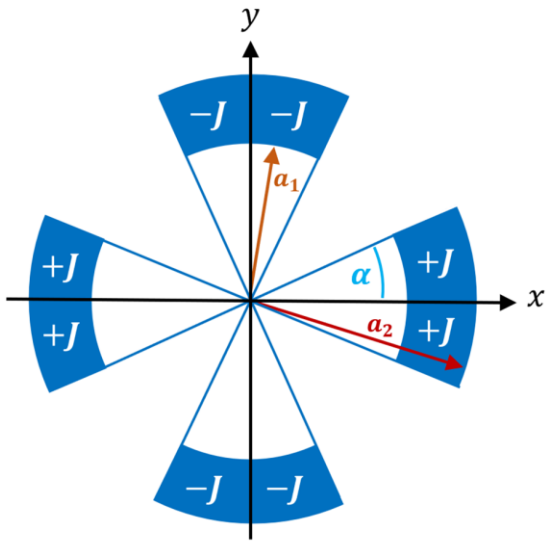
Several magnets are necessary for the lattice → **a dedicated FEM study for each not possible at this stage!**
We developed a semi-analytic tool to assess the feasibility and quickly provide a feedback to beam dynamics, energy deposition and cryogenics teams. Focus on HTS ReBCO, but LTS NbTi and Nb3Sn analysed for comparison.

Dipole



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

Quadrupole



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

$(\ w = coil\ width\ )$

Courtesy of Daniel Novelli

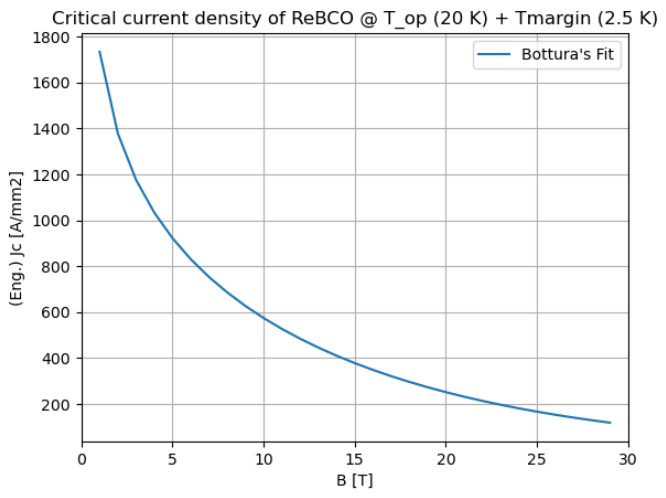
Method and assumptions:

- Given the ***magnet aperture a_1***, B and G can be found as a function of J (engineering current density) and w (coil width)
- **J** and **w** are chosen to maximize B and G, fulfilling realistic limits on:

1. MARGIN ON THE LOAD LINE
2. COST
3. PROTECTION
4. STRESS

Constraints on the Accessible Phase Space

MARGIN ON THE LOAD LINE



Materials	T_{op} [K]	T margin [K]
NbTi	1.9	2 (LHC)
Nb_3Sn	4.5	2.5 (HL-LHC)
ReBCO	20	2.5 *

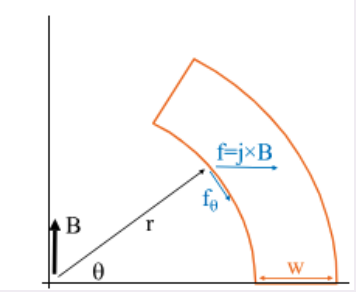
* Margin given by the stability of the cryogenic system

J_c refers to:

- NbTi: LHC cable performance
- Nb_3Sn: FCC cable target performance
- ReBCO: Fujikura FESC12-AP tape[1]

STRESS

Material	σ_{max}[MPa]
NbTi	100
Nb3Sn	150
ReBCO	400[1]



E Todesco *et al* 2021 *Supercond. Sci. Technol.* **34** 053001

Midplane pressure (1st order approximation):

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

DIPOLE

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

QUADRUPOLE

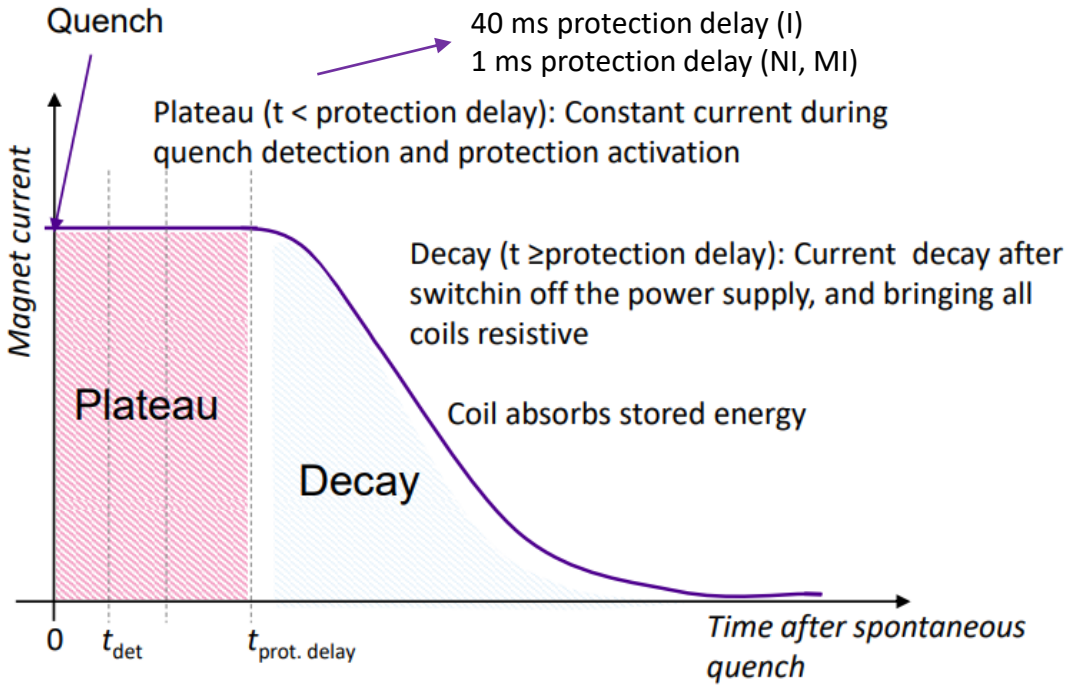
$$P_\theta = \frac{2\mu_0 sin2\alpha\,(cos2\alpha - 1)\,J^2}{\pi w}\left(\frac{7}{12}\frac{a_2^3 - a_1^3}{3} - \frac{a_1^3}{3}\ln\left(\frac{a_2}{a_1}\right) + \frac{a_1^4 - a_1^3 a_2}{4a_2}\right)$$

Maximum Stress $\sigma_{max} \propto P_\theta \implies J\,(\sigma_{max}, a_1, w)$ [2]

[1] https://www.fujikura.co.uk/netalogue/pdfs/Fujikura%20Superconductor%20Guide.pdf

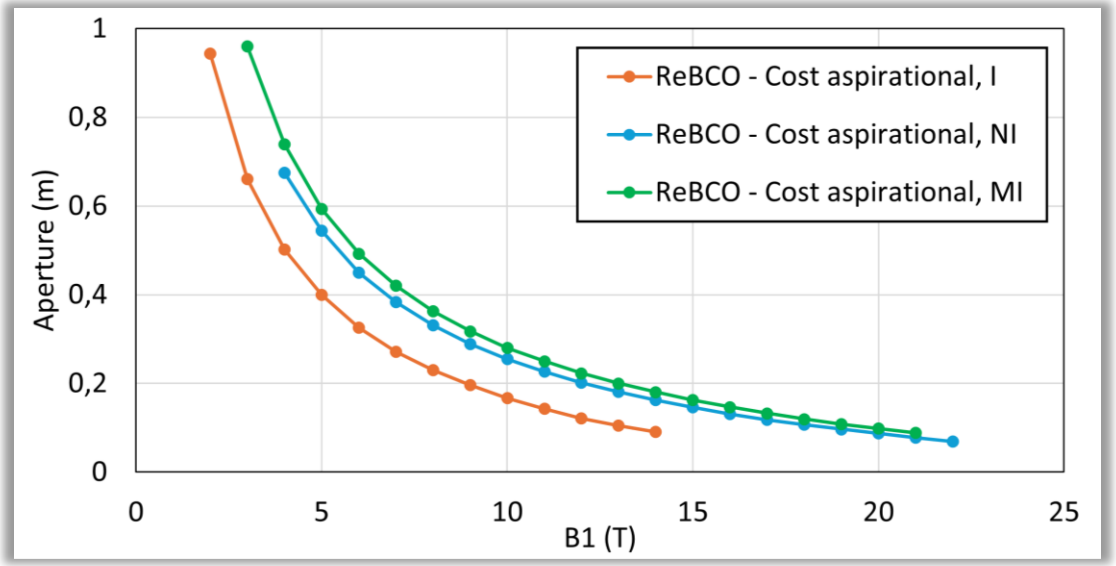
[2] E Todesco *et al* 2021 *Supercond. Sci. Technol.* **34** 053001**DOI** 10.1088/1361-6668/abdba4

Constraints on the Accessible Phase Space: Protection



Materials	Hotspot T [K]*
NbTi	350
Nb_3Sn	350
ReBCO	200

*Adiabatic approximation (cooling not taken into account)



Courtesy of Tiina Salmi

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

Cost Model

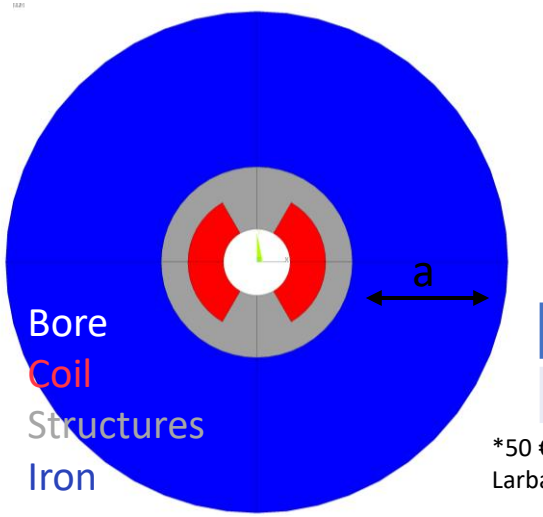
Cost estimate performed on a simplified geometry with a **sector coil** dipole and iron and steel structures modelled as circular crowns.

$C_{tot} = 400$ kEUR/m *(FCC-hh 175 kEUR/m)*

$C_{assembly} = 40$ kEUR/m *(as FCC, 2xLHC)*

$C_{mat} = \sum_i C_i \ \rho_i \ A_i$

where $i = \text{coil, structures, iron}$



14T /140 mm (REBCO)

R_{bore}= 70 mm ($5\sigma + shield$@20K)
w_{coil}= 58 mm (max cost)
w_{struct}= 30 mm (as FalconD [1])
w_{iron}= 300 mm (B_{fringe}<0.1 T)

€/kg iron	€/kg struct	€/kg conductor *
8	10	2500

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

Material	*Cost*
SS	10 EUR/kg
Iron	8 EUR/kg
NbTi	330 EUR/kg
Nb_3Sn today (*aspirational value*)	2000 EUR/kg (700 EUR/kg)
ReBCO today (*aspirational value*)	8000 EUR/kg (2500 EUR/kg)

D2 HL-LHC as benchmark

Escalated price in 2016

The right value in 2016 vs FCC target

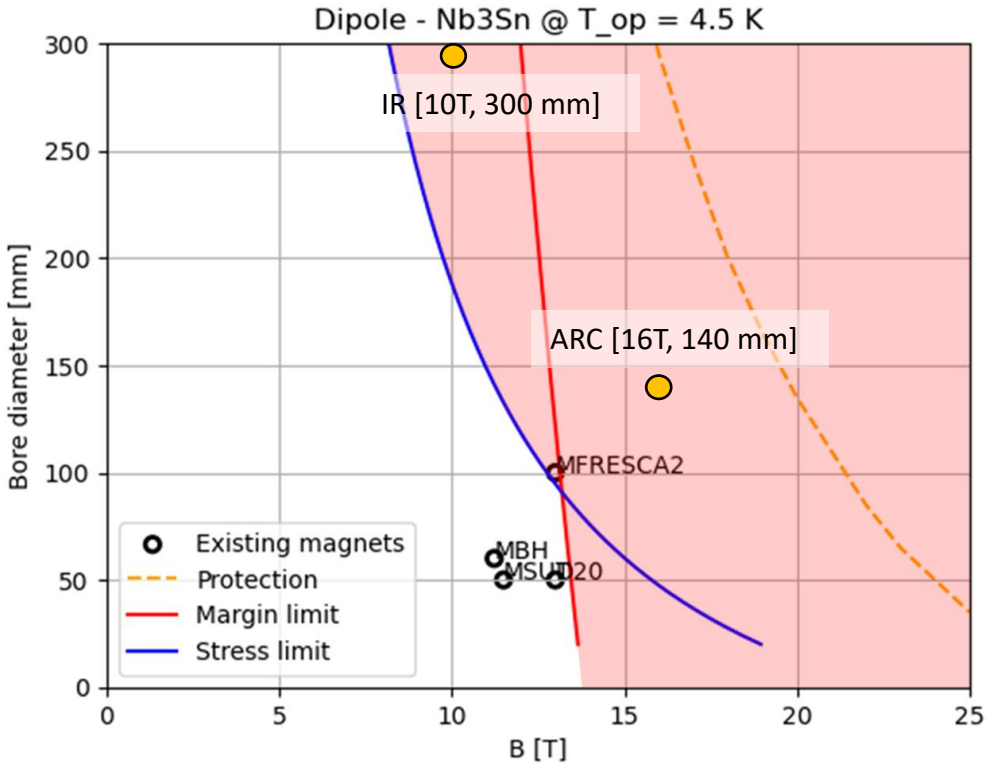
The value of today (2023) vs realistic projection for the next years

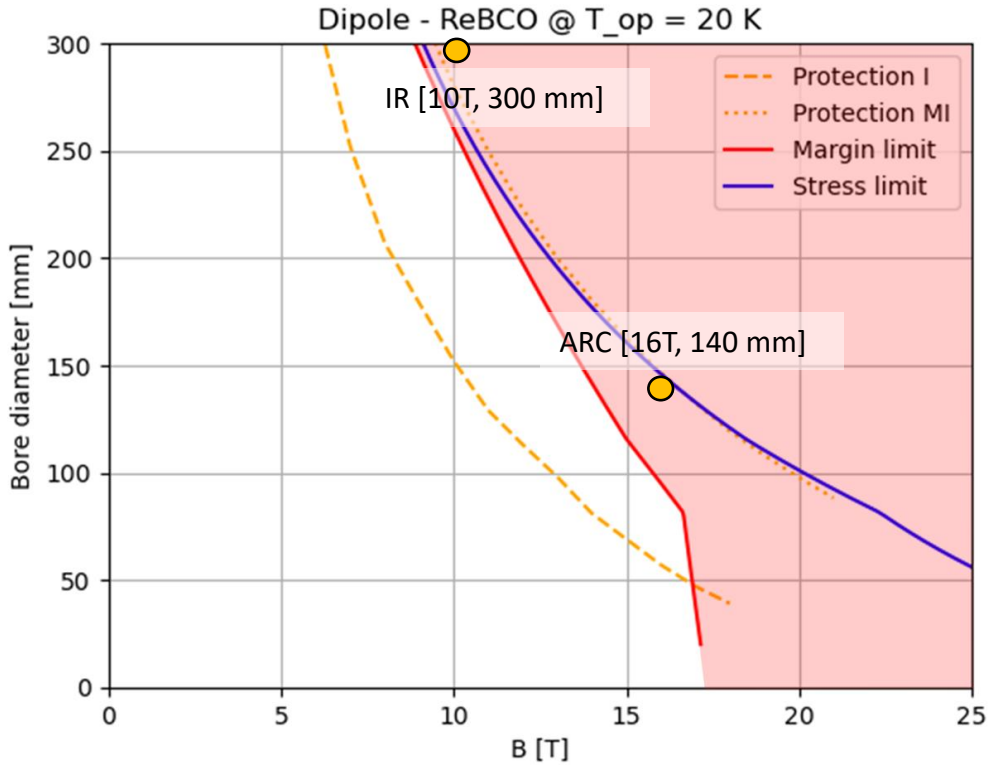
Iron [Kg/m]	Structure [kg/m]	Coil [kg/m]
4512	209	121
Iron cost [k€/m]	Structure cost [k€/m]	Coil cost [k€/m]
36	2.1	304

Tot. Material k€/m	56	14%
Tot. Assembly k€/m	40	10%
Tot. Conductor k€/m	304	76%
Tot. Cost k€/m	400	

1.5 m long demonstrator ~6M€

AB-plots for dipoles





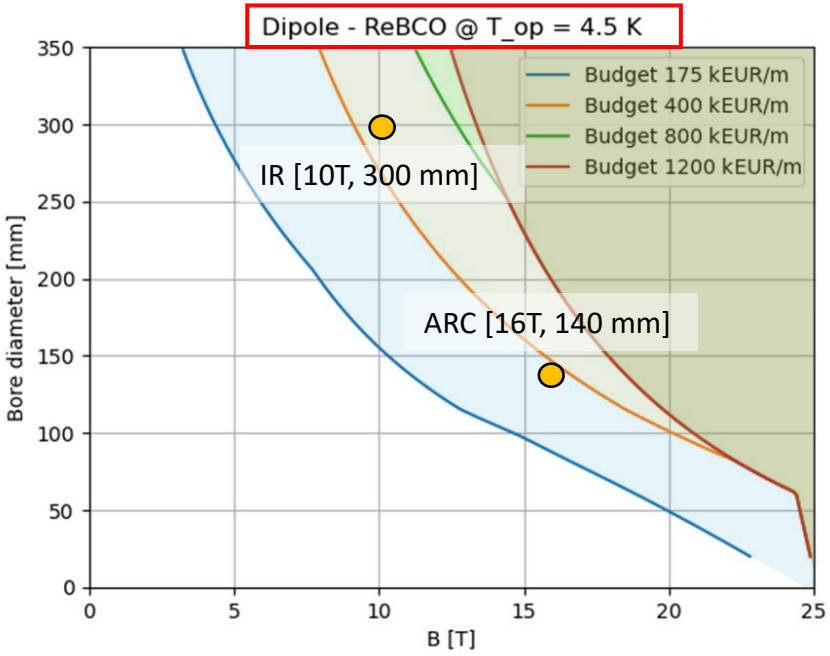
Nb_3Sn falls short of required performance because of **operating margin** and peak stress for B >14 T

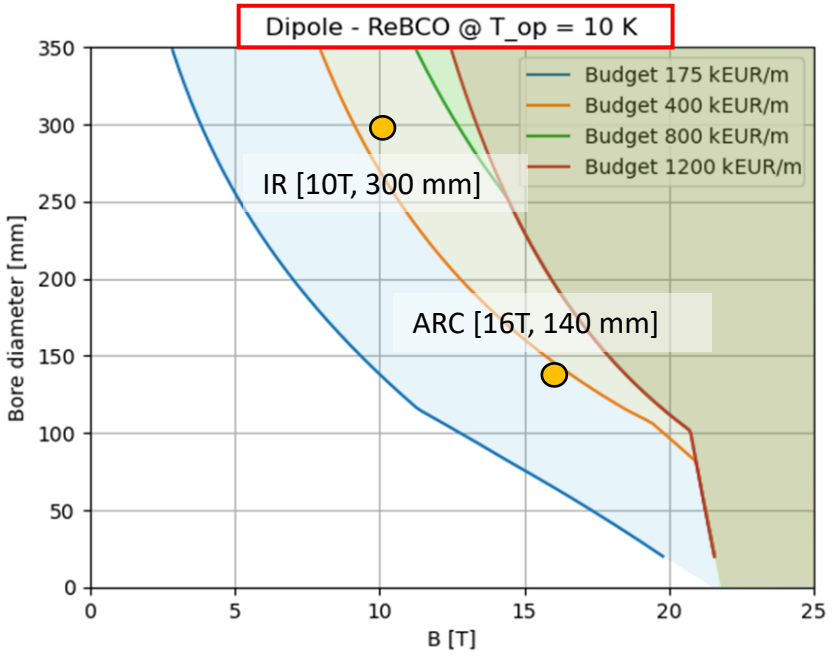
Cost and **protection** are the main limitation for ReBCO. Metal insulated (MI) or Not Insulated (NI) coils must be used.

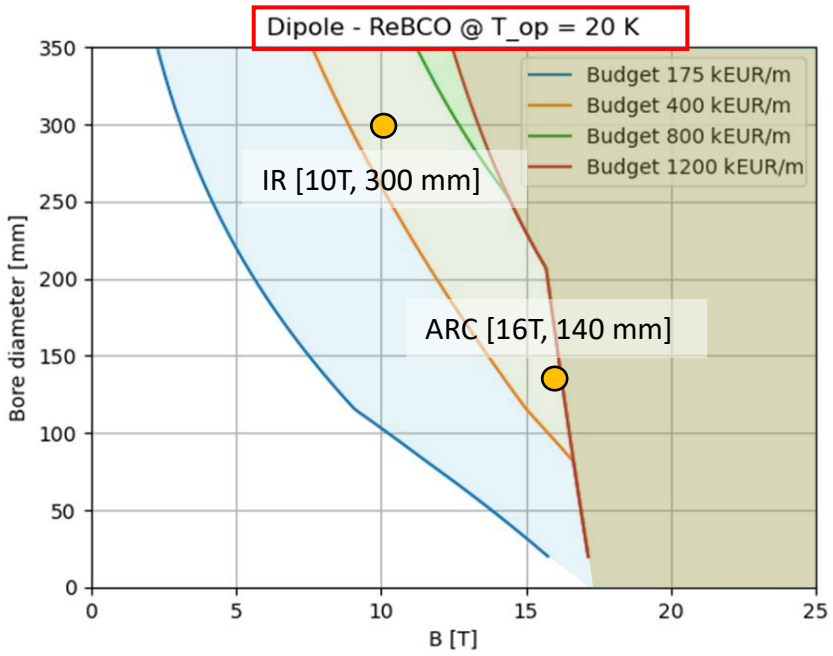
Current lattice requirements falls in the forbidden A-B area, more iterations are needed

Courtesy of D. Novelli

AB-plots for dipoles







- ReBCO today's prize ~ 8000 EUR/kg
- Aspirational price 2500 EUR/kg (factor 3 reduction, same assumption as FCC)
- Target budget: 175 kEUR/m (as FCC)
- Higher budget can be possible (Lring=10 km)

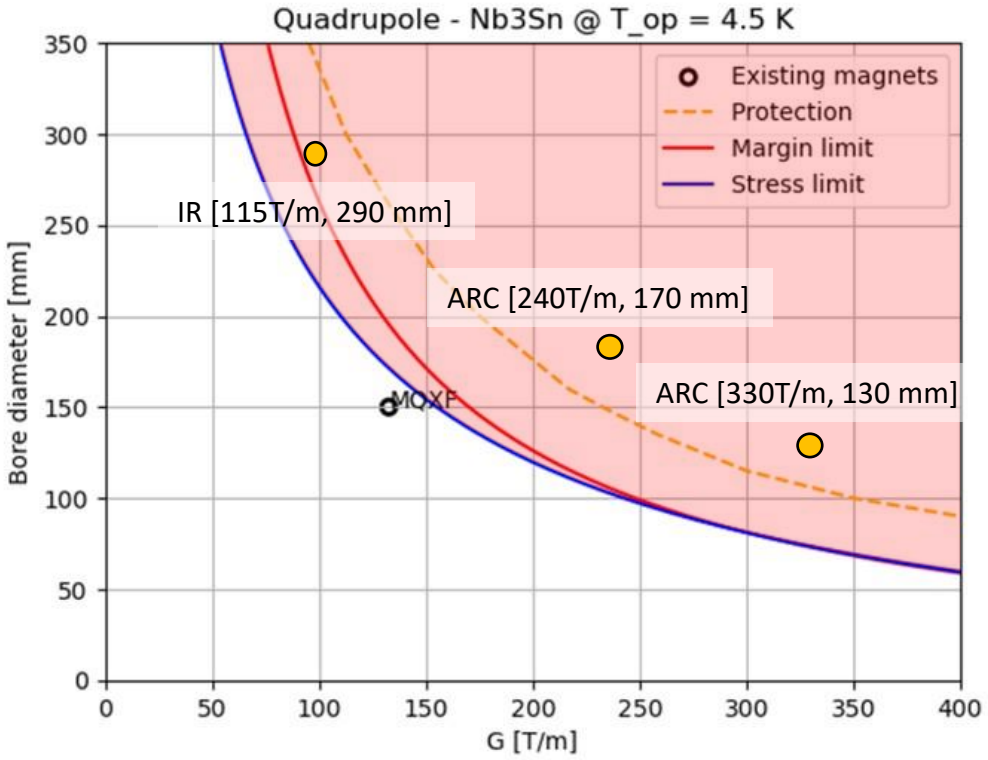
Increasing budget, lattice requirements in the permitted region (dedicated FEM studied needed to confirm)

Summary of technical assumptions:

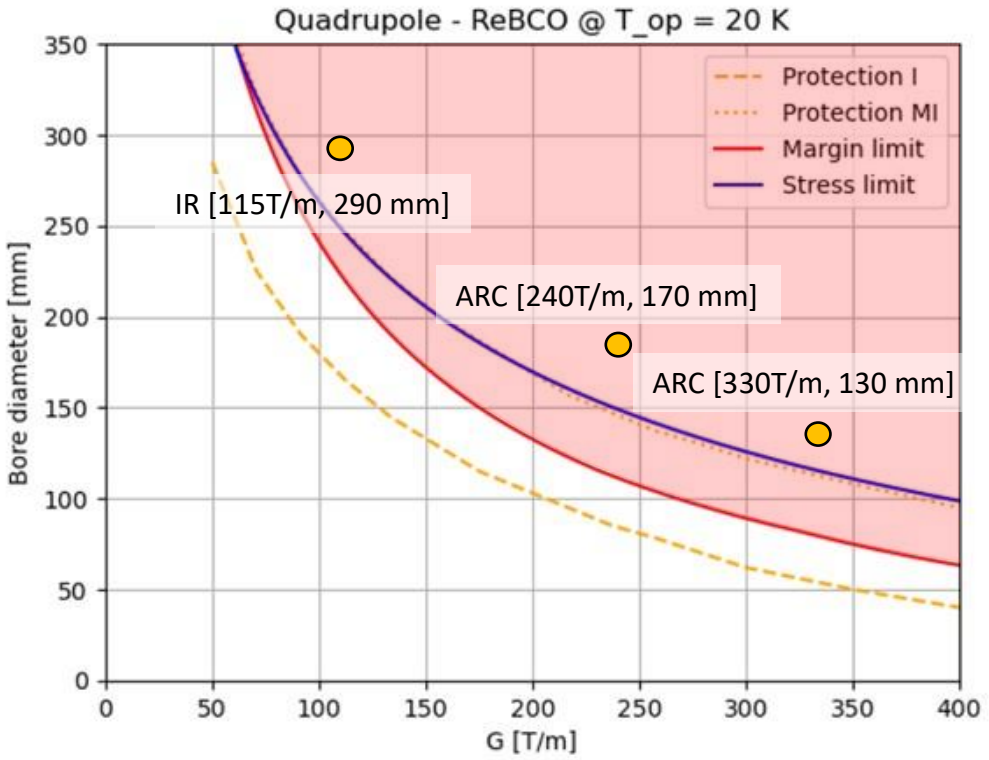
- Single sector coil
- Maximum allowed stress: 400 MPa
- Fujikura Tape, Roebel cable
- Non-insulated or Metal-insulated cable

Courtesy of D. Novelli

AG-plots for quadrupoles



- Nb_3Sn is limited by **peak stress** and **operating margin**

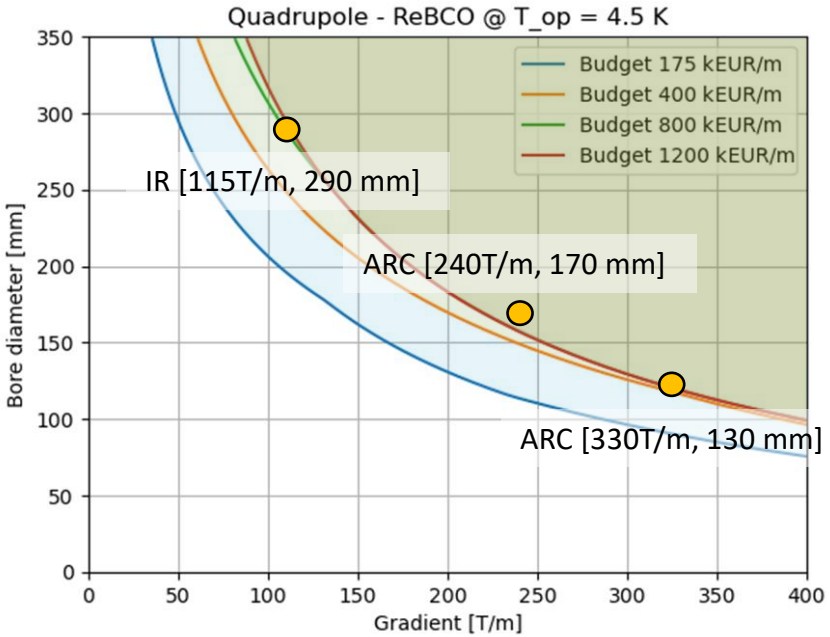


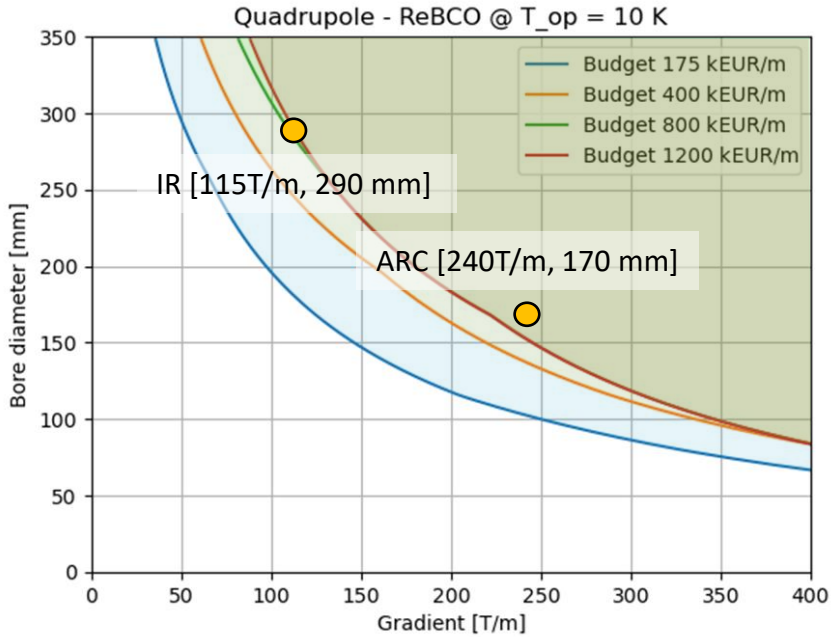
- HTS is mainly limited by **cost** production and **protection**. Working @20K the margin curve is also a limiting factor.

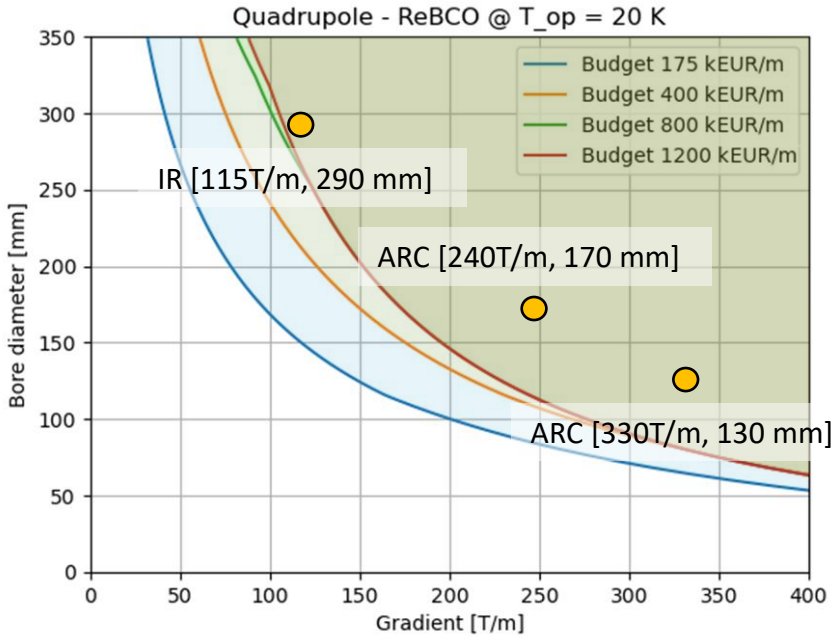
Courtesy of D. Novelli

Current lattice requirements falls in the forbidden A-B area, more iterations are needed

AG-plots for quadrupoles







- ReBCO today's prize ~ 8000 EUR/kg
- Aspirational price 2500 EUR/kg (factor 3 reduction, same assumption as FCC)
- Target budget: 175 kEUR/m (as FCC)
- Higher budget can be possible (Lring=10 km)

Increasing budget, lattice requirements still not feasible. Only at 4.5 K we approach the upper limit, though still to be verified with ad hoc FEM simulations. More iterations with beam dynamics needed!

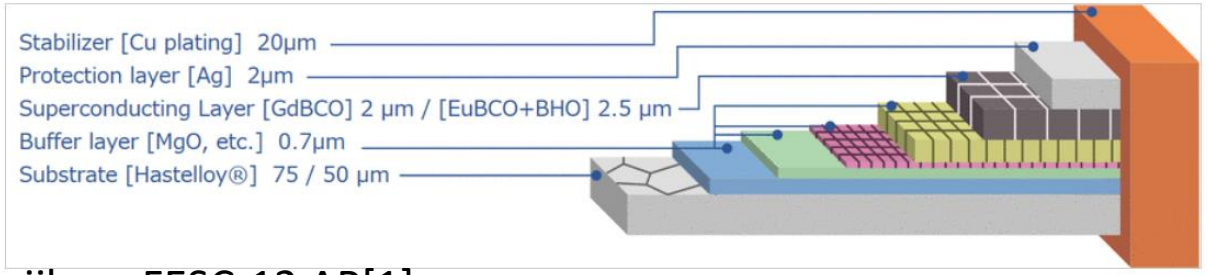
Summary of technical assumptions:

- Single sector coil
- Maximum allowed stress: 400 MPa
- Fujikura Tape, Roebel cable
- Non-insulated or Metal-insulated cable

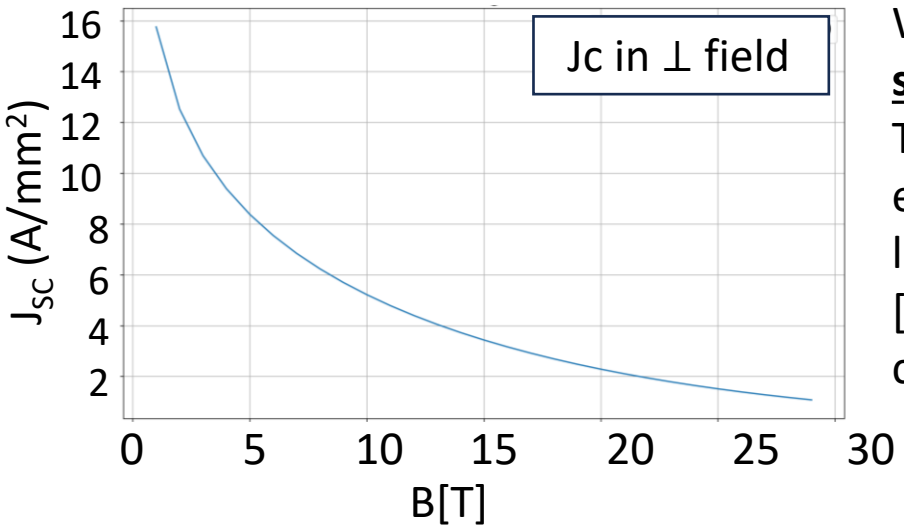
Courtesy of D. Novelli

Cable choice considerations

REBCO TAPE



Fujikura FESC-12 AP[1]

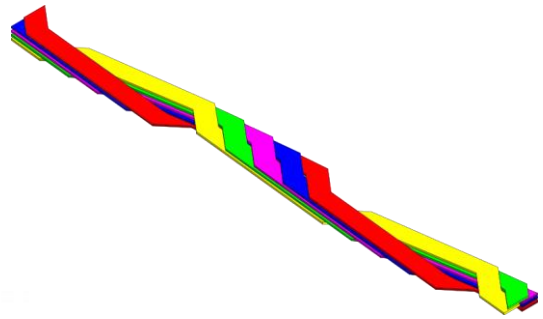


We want to use **not twisted stacked tapes cable.**
Twist and transposition not effective in reducing the AC losses for coated conductors [2], while increasing cost and complexity

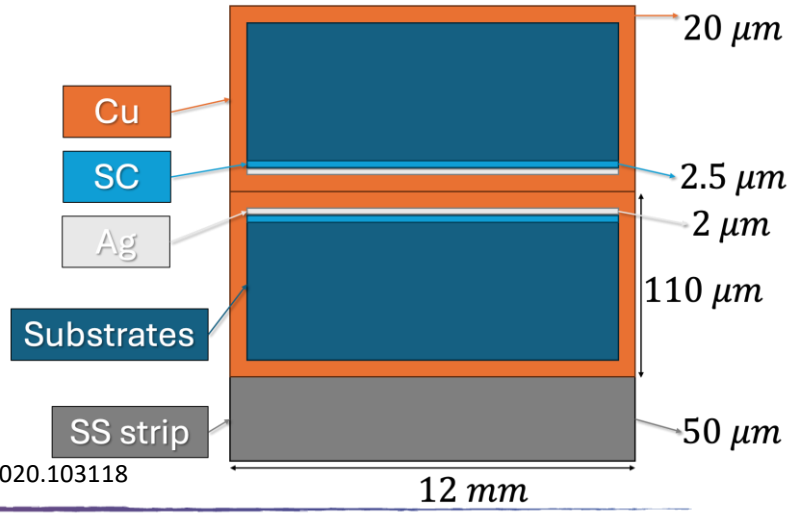
REBCO CABLES:

CORC®

ROEBEL



2 tapes co-wounded with 50 μm thick SS layer

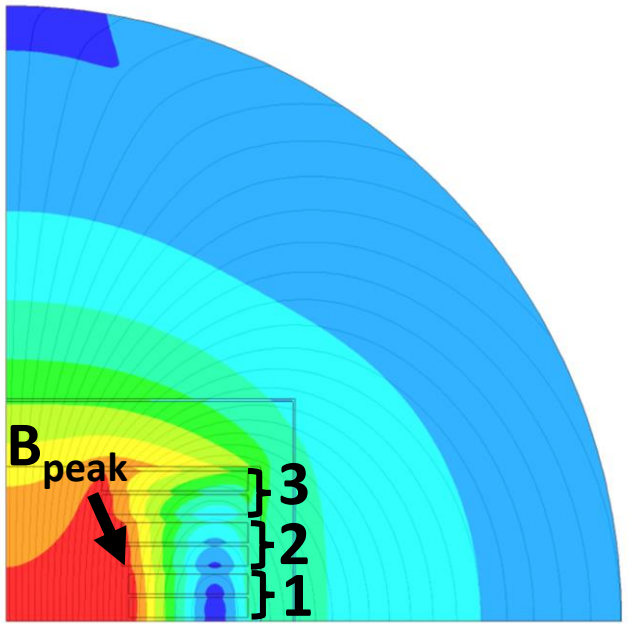


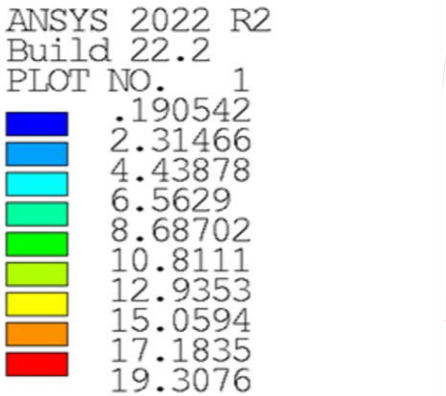
[1] https://www.fujikura.co.uk/netalogue/pdfs/Fujikura%20Superconductor%20Guide.pdf
[2] D. Uglietti at al. "Non-twisted stacks of coated conductors for magnets: Analysis of inductance and AC losses" https://doi.org/10.1016/j.cryogenics.2020.103118

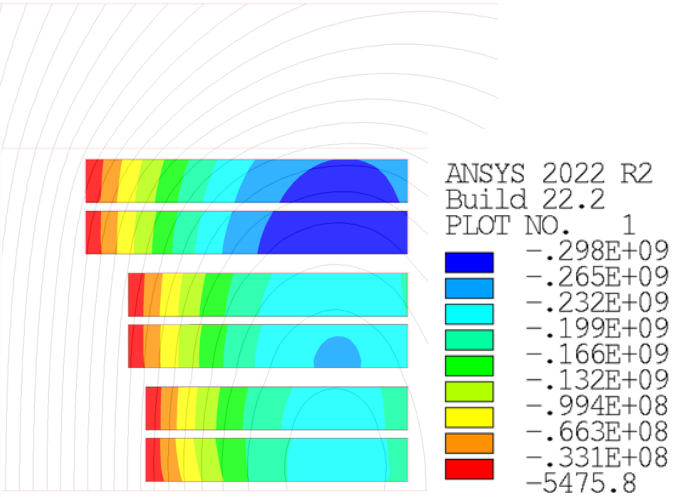
Preliminary discussion on block – coil design

- 6 blocks (10680 tapes in ¼ of the magnet), racetracks with flared ends
- B_{bore}=17.5 T, B_{peak}=19.3 T
- σ_{III}=- 298 MPa (infinitely rigid structure approximation)
- $Q = 356.1 \frac{kJ}{m}$ (Bean model, full penetration)

	Cond 1	Cond 2	Cond 3
B_{peak}[T]	19.25	19.31	19.02
J_{op}[A/mm²]	443.8	443.8	443.8



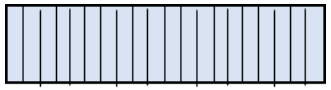


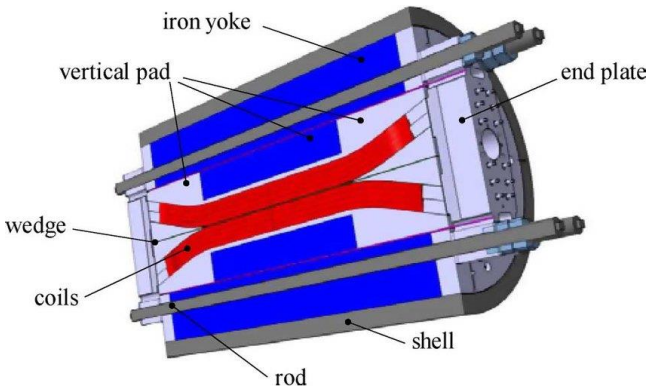


σ_X^{MAX}= -298 MPa (5th layer)

σ_Y^{MAX}= -53 MPa (1st layer)

Stacked cable





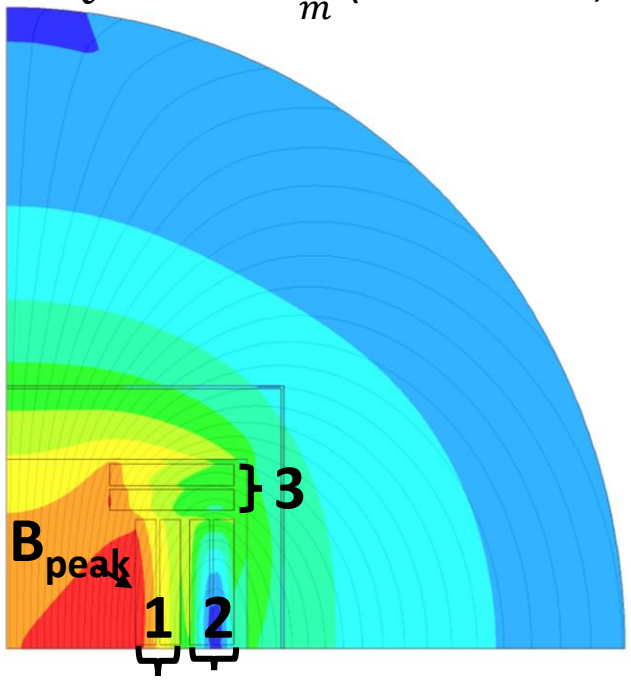
Courtesy of Luca Alfonso

PRELIMINARY!

Preliminary discussion on block – coil design

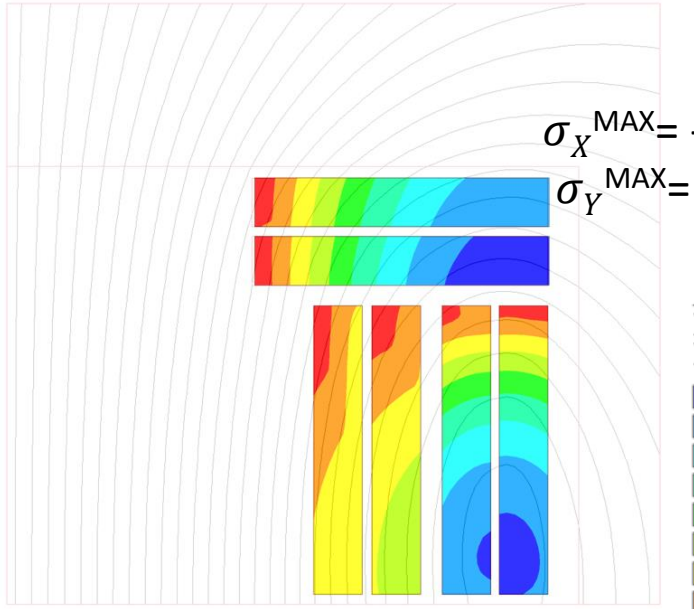
- 6 blocks (12704 tapes in ¼ of the magnet), 4 stacked vertically & 2 racetracks (no flared ends needed)
- B_{bore}= 17.5 T, B_{peak}=19.7 T, I_{op}=2481 A
- σ_{III}=- 238 MPa (infinitely rigid structure approximation)
- $Q = 652 \quad \frac{kJ}{m}$ (Bean model, full penetration)

	Cond 1	Cond 2	Cond 3
B_{peak}[T]	19.25	19.31	19.02
J_{op}[A/mm²]	386	766	386

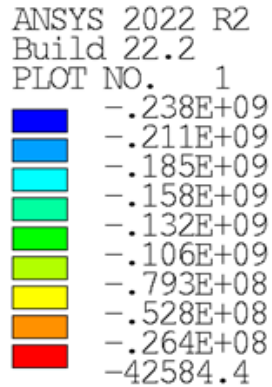


Courtesy of Luca Alfonso

PRELIMINARY!

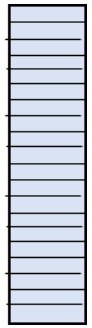


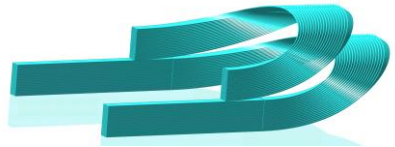
σ_X^{MAX}= -238 MPa
σ_Y^{MAX}= -47 MPa

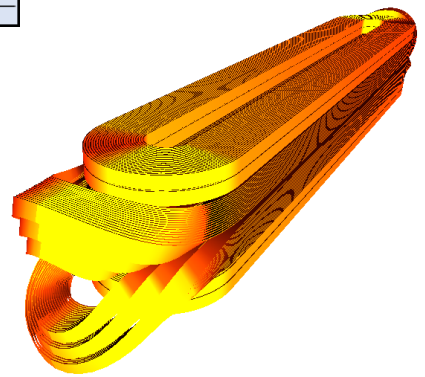


σ_X^{MAX}= -80 MPa
σ_Y^{MAX}= -218 MPa

Stacked cable





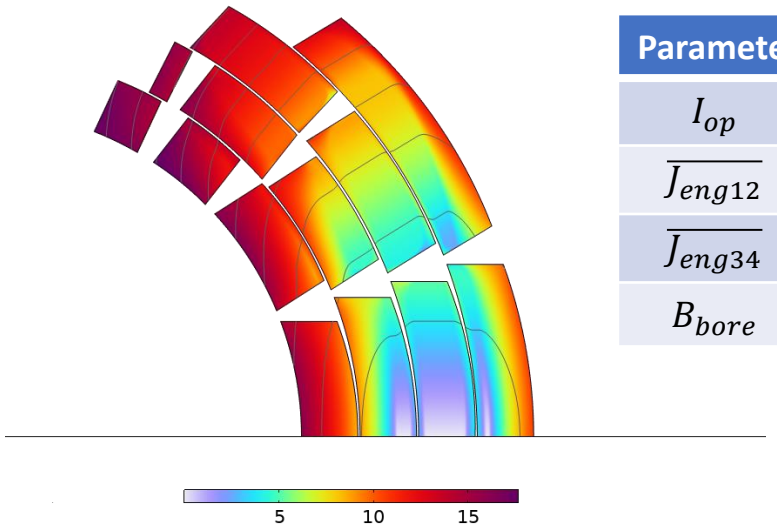


Preliminary discussion on cos – theta design

- 13 blocks in 4 layers, N_{tapes}: 10736 in ¼ of the model
- B_{bore}= 16 T (margin 8 K), B_{peak}=17.7 T (still no iron, design to be homogenized)
- σ_θ=- 320 MPa (infinitely rigid structure approximation)
- $Q = 36\ \frac{kJ}{m}$ (Brandt model)

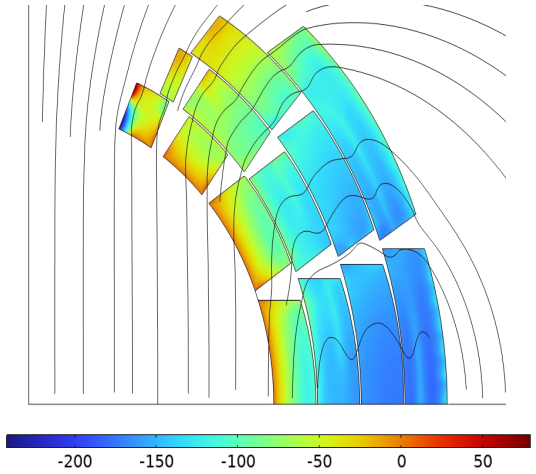
Parameter	Value	U.M.
σ_{r_max}	-241	MPa
σ_{ϑ_max}	-320	MPa

Field map [T]

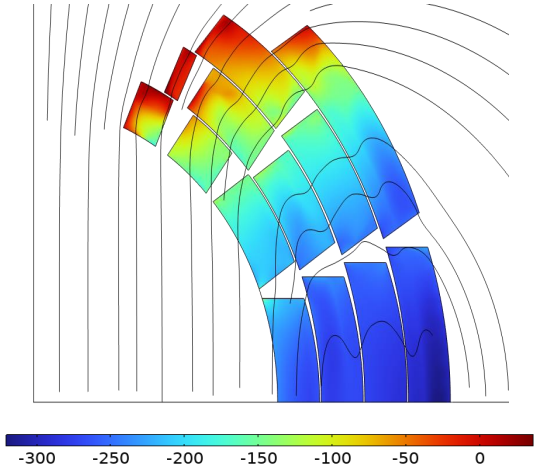


Parameter	Value	U.M.
I_{op}	1702	A
$\overline{J_{eng12}}$	525	A/mm^2
$\overline{J_{eng34}}$	579	A/mm^2
B_{bore}	16	T

Radial Stress (MPa)



Azimuthal Stress (MPa)



Courtesy of Francesco Mariani

PRELIMINARY!

Conclusions and final remarks

- Using an innovative approach, we have established **upper limits for the target performance** of the Muon Collider storage ring magnets. These limits are derived from sector coil approximation and analytical estimates, incorporating the most critical constraints related to **stress**, **protection**, **margin on the load line** and **cost**.
- From this analysis, we conclude that **HTS REBCO** is the only viable candidate capable of meeting the extremely demanding requirements.
- These performance limits should be considered as **guidelines** rather than absolute constraints, as actual engineering designs may require additional safety margins and optimization windows
- Despite that, the latest **lattice design requirements** are far beyond any improvements and optimization window that can be optimistically assumed within the next 20 years and **must be revised**
- Currently, **conceptual design** efforts for arc dipoles are ongoing, based on **cos-theta** and **«hybrid» block coil** layout and focused on the optimization of the mechanics and the e.m. aspects
- To produce credible conceptual designs for HTS ReBCO accelerator magnets **we need experimental** data from measurements of mechanical properties, critical current density assessments, feasibility studies on protection systems, winding tests

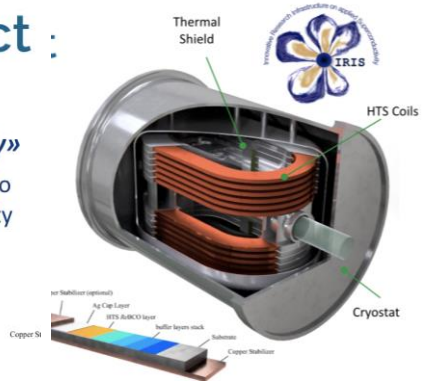
Mock-up activities are essential to validate these concepts!

Synergies

10 T HTS Dipole for IRIS project :

New development project (PNRR-IRIS) 2022-2025
«Innovative Research Infrastructure on applied Superconductivity»

- Improvement of **6 national research laboratories and university labs** to perform cutting-edge technology research activity on superconductivity



Parameter	Unit	Value
Central field	tesla	10
Free bore dimensions	mm	70
Magnet length	mm	1000
Good field region uniformity	N/A	1.5%
Operating temperature	K	20
Minimum op. temper. for test	K	10
Maximum current	A	<1000

Courtesy of M. Statera, C.Santini, S. Sorti, L. Balconi, L. Rossi

HFM program INFN 10 T dipole demonstrator

	B centre	Aperture diameter[1]	T_{op}	Straight section	Tape quality[2]	Max. Unit Length	Target J_{Cu}
Common	10 T	50 mm	20 K	700 mm	FFJ 2021	200 m	800 A/mm²

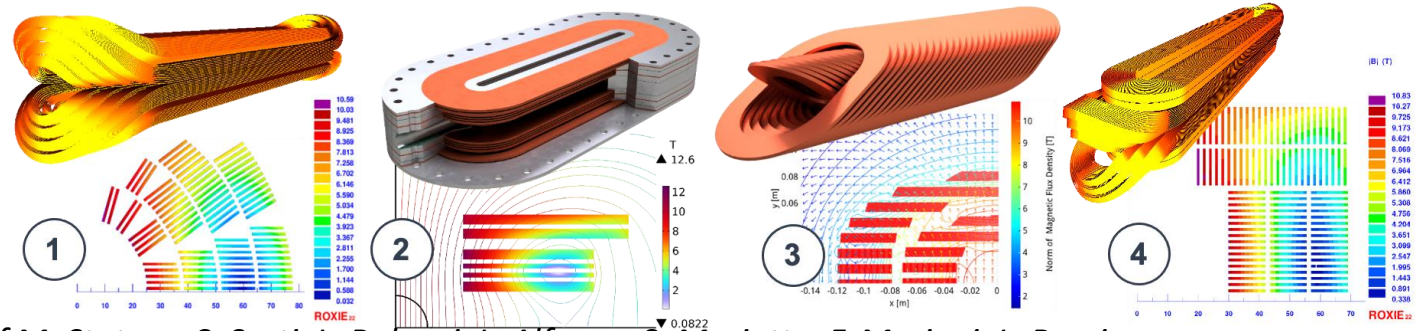
	#	Coil geometry	L of tape (km) 12-mm *equivalent*	I_{op} (A)	I×n	i= I/I_c (%)	ΔT (K) *margin*	Loadline Margin (%)	Field q. $(10^{-4})^3$
Configurations	1	Cos-Theta	3.9	9230	1.5 MA	68.5	10	22	<1
	2	Racetrack	7.3	3330	3.4 MA	67	10	22	<20
	3	Pancake CCT	5.5	1440	2.1 MA	69	10	23	100
	4	Hybrid	4.5	9170	1.8 MA	58	10	18	<10

Courtesy of M. Statera, xxx

Shared R&D Focus Areas :

- HTS Tape & Cable Development
- Electrical & Mechanical Characterization
- Analytical & Finite Element Modeling

- **HFM Program:** High-field, small-aperture, ramped HTS dipoles
- **Muon Collider:** High-field, large-aperture, steady-state magnets



Courtesy of M. Statera, S. Sorti, L. Balconi, L. Alfonso, S. Mariotto, F. Mariani, L. Rossi

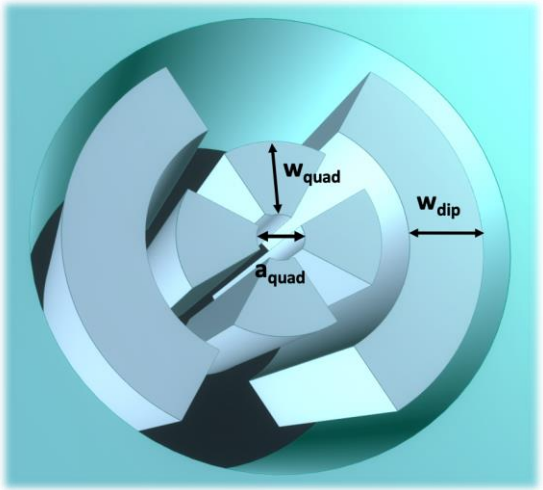
Thank you

Funded by the European Union

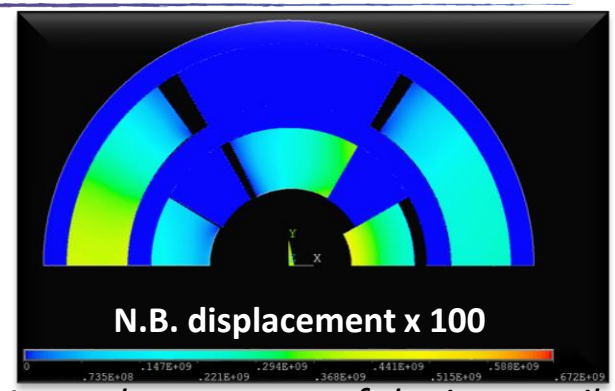
Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

Back-up slides

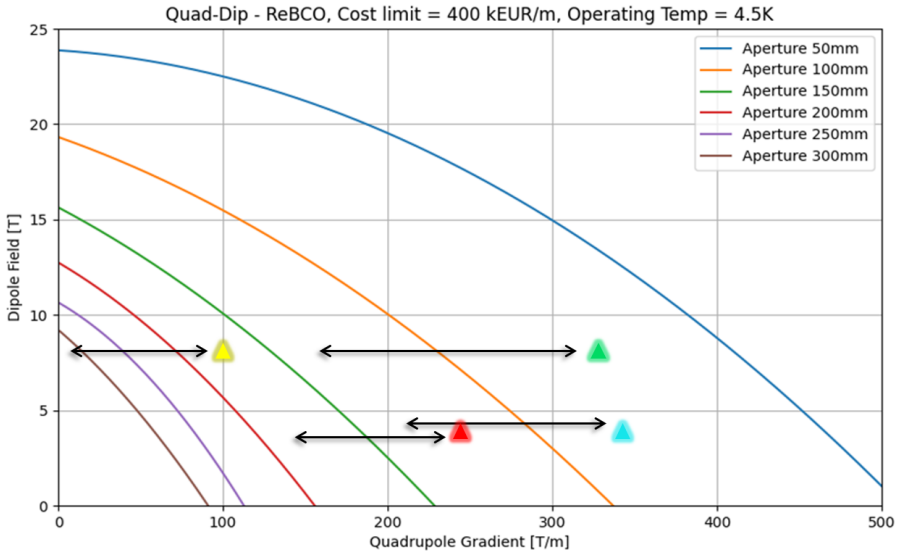
BG-plots for combined function magnets

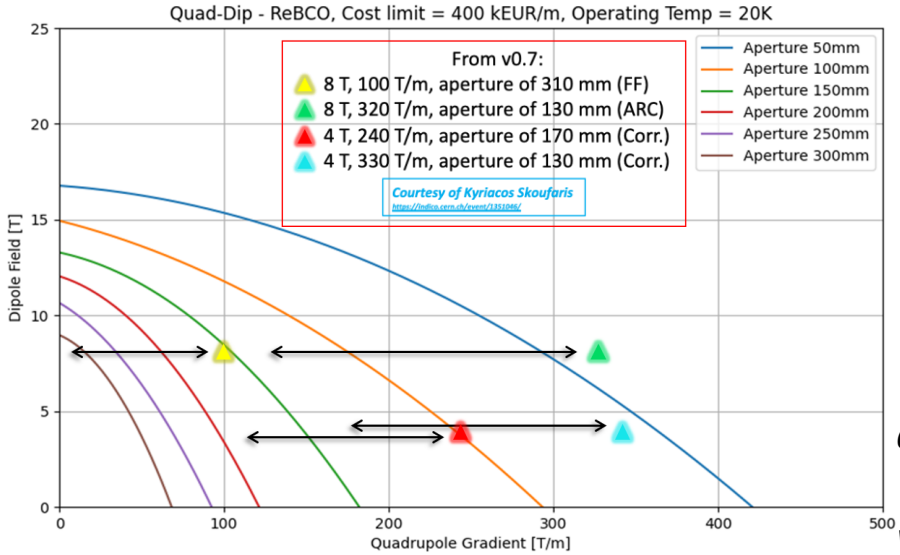


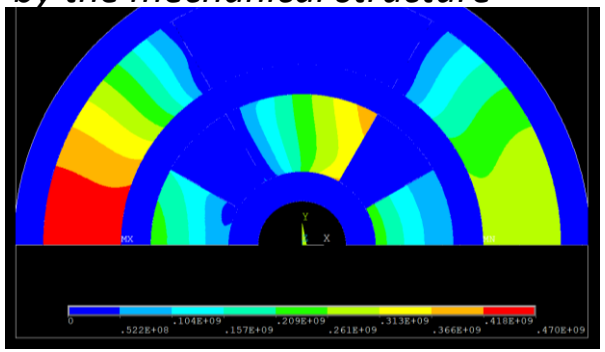
- Nested configuration with quadrupole (inside) + dipole (outside), sector coil approximation
- **Python-ANSYS interface** to run FEM configurations capable of providing the electromagnetic performance of various designs. Optimization parameter: a_{quad}, w_{quad}, w_{dip}
- Constraints on stress, margin on the loadline and cost as in the AB-plots and AG plots. Protection still to be implemented



Inward movement of the inner coil (quadrupole) -> must be intercept by the mechanical structure



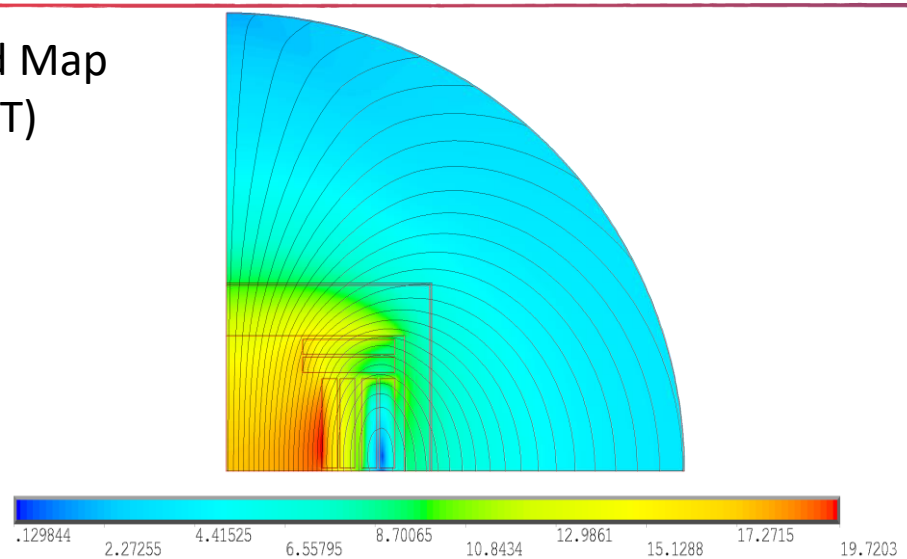




An inner infinite rigid structure was assumed in this simplified calculation. More realistic solution will be studied when a specific design will be decided

Courtesy of D. Novelli

Field Map
(T)



Parameter	Value	U.M.
I_{op}	2481	A
J_{eng13}	386	A/mm^2
J_{eng2}	766	A/mm^2
B_{bore}	17.5	T

Parameter	Value	U.M.
B_{peak1}	19.7	T
$Margin$	2.5	K
E	7575	kJ/m
L	2461	mH/m

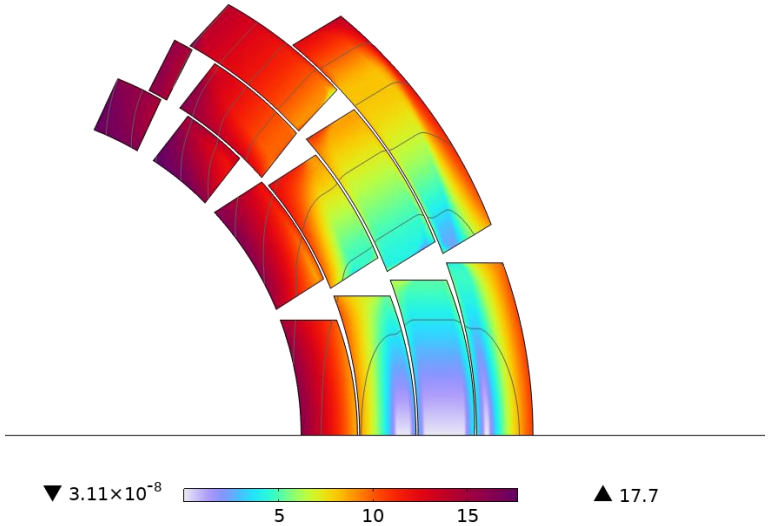
Total Tapes	Value	U.M.
$Ntapes$	12704 [1]	–

AC losses	Value	U.M.
Q_{sat}	651.6 [2]	kJ/m

[1] Value referred to a quarter of the cross section

[2] Value referred to the entire cross section

Field Map
(T)



Parameter	Value	U.M.
I_{op}	1702	A
$\overline{J_{eng12}}$	525	A/mm^2
$\overline{J_{eng34}}$	579	A/mm^2
B_{bore}	16	T

Parameter	Value	U.M.
B_{peak1}	17.7	T
$Margin$	8	K
E	4927	kJ/m
L	3402	mH/m

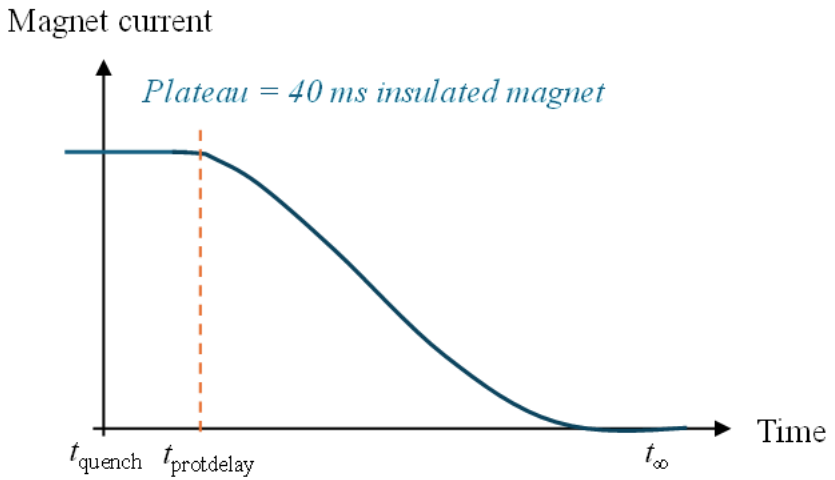
Total Tapes	Value	U.M.
$Ntapes$	10736 [1]	–

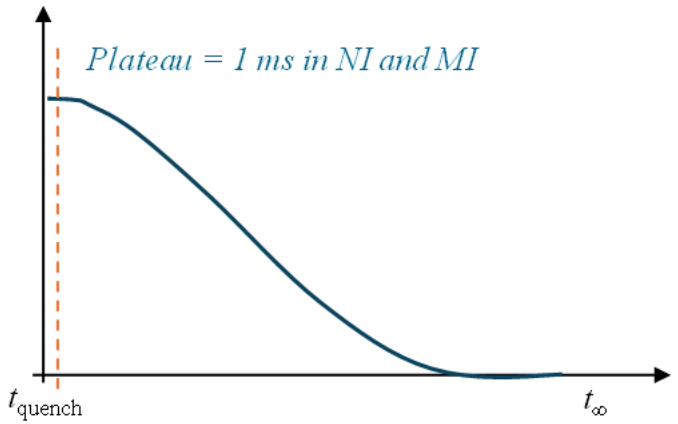
AC losses	Value	U.M.
Q_{tot}	36 [2]	kJ/m

[1] Value referred to a quarter of the cross section

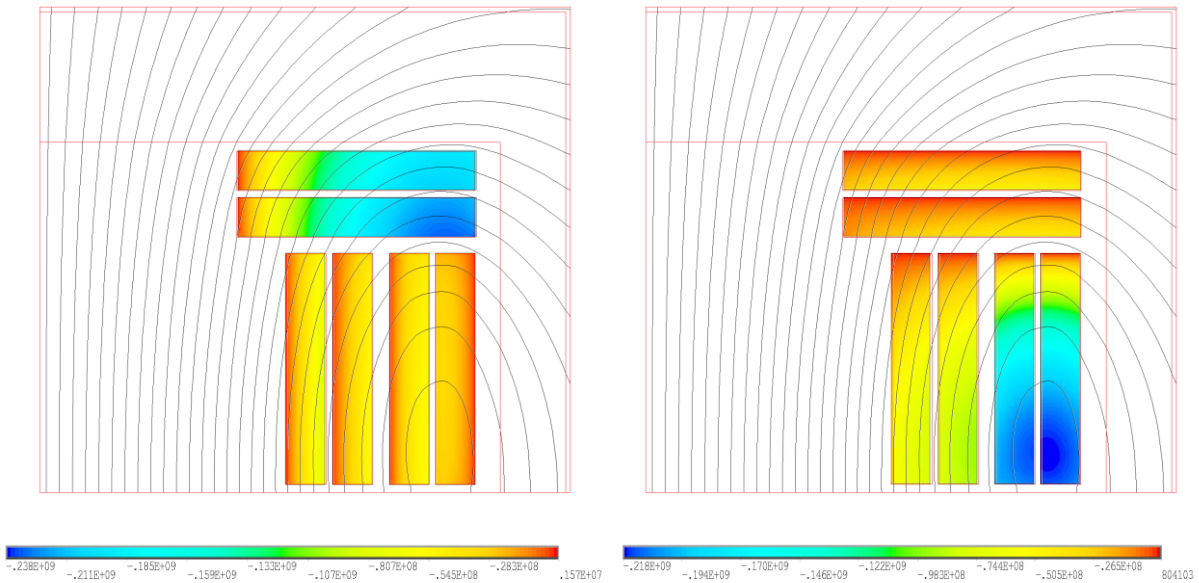
[2] Value referred to the entire cross section

Adiabatic hot spot temperature calculation





X Stress (Pa)

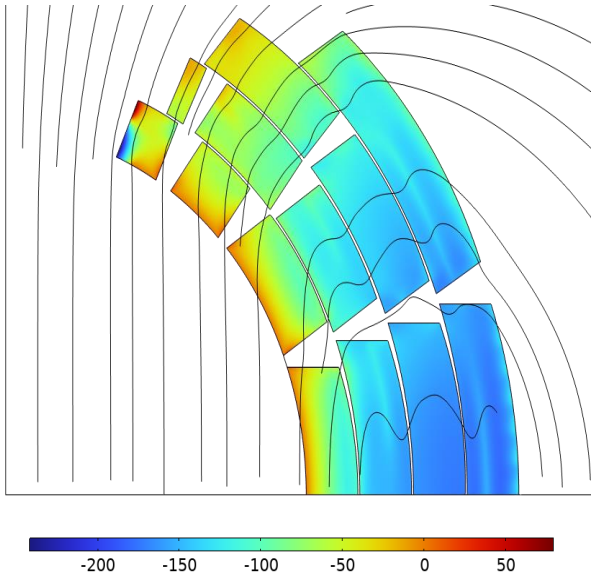


Parameter	Value	U.M.
σ_{x_max}	-238	MPa

Y Stress (Pa)

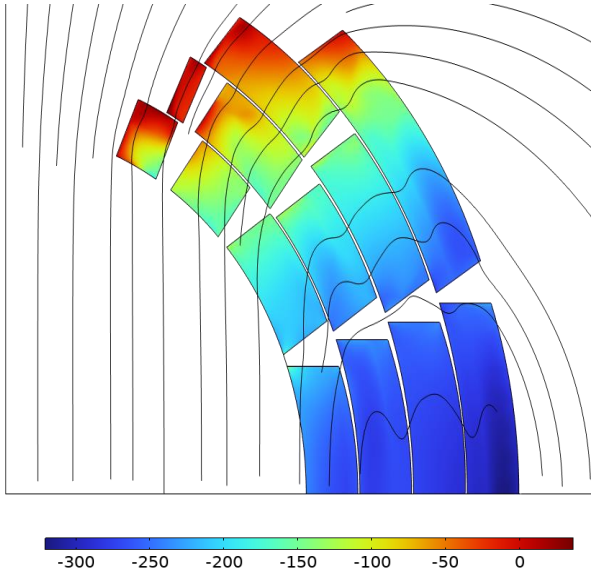
Parameter	Value	U.M.
σ_{y_max}	-218	MPa

Radial Stress (MPa)



Parameter	Value	U.M.
σ_{r_max}	-241	MPa
σ_{ϑ_max}	-320	MPa

Azimuthal Stress (MPa)



Parameter	Value	U.M.
σ_{ϑ_max}	-320	MPa