ASC 24 SALT LAKE CITY
SEPTEMBER 1 - 6
SALT PALACE CONVENTION CENTER

Challenges and Perspectives of the Muon Collider Ring Superconducting Magnets

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[6] Tampere University

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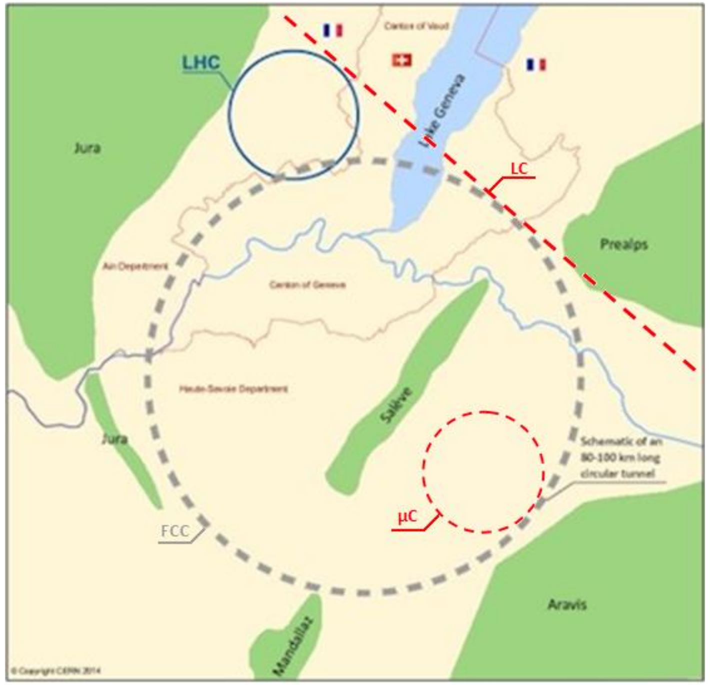
Why a Muon Collider?

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



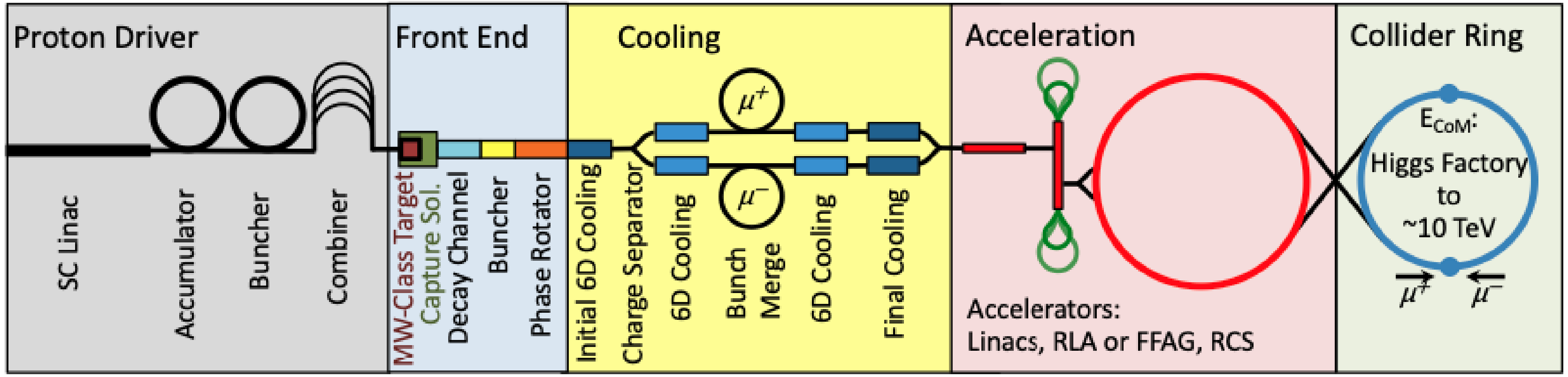
BUT μ decays in 2.2 μs in rest frame:

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

Muon Collider compared to **FCC-hh**:

- Requires less energy (10 TeV)
- requires a smaller circumference (10 km)
- Less expensive
- Consumes less energy

The Muon Collider Complex



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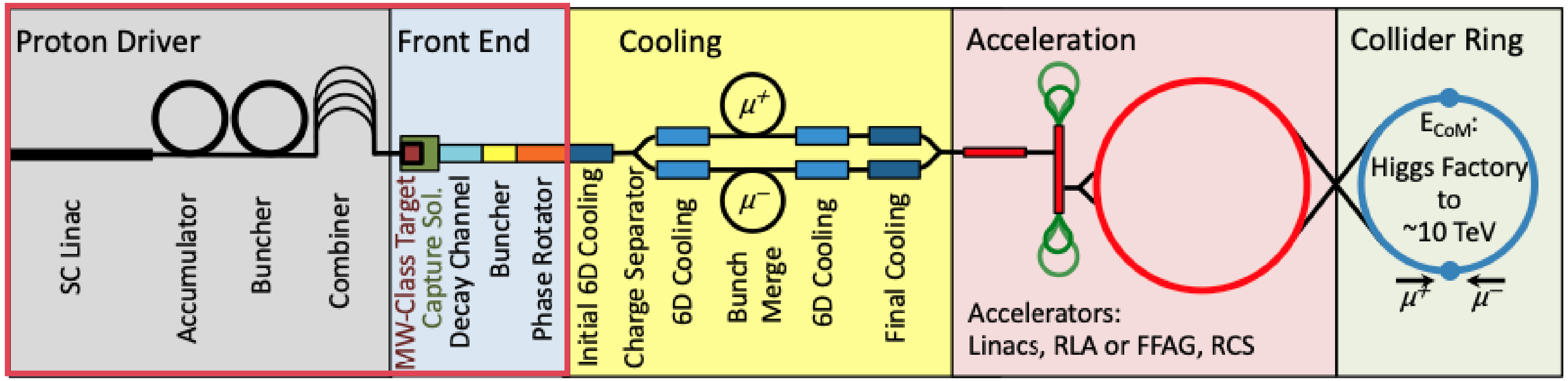

4 GeV protons hit solid target, producing pions that decay into muons

Target solenoid: ~20 T in 150 mm bore
High-field and large aperture target solenoid with heavy shielding to withstand heat (100 kW/m) and radiation loads
Baseline: NC (5 T in 150 mm bore) +
LTS (15 T in 2400 mm bore)
Advance option: HTS+LTS

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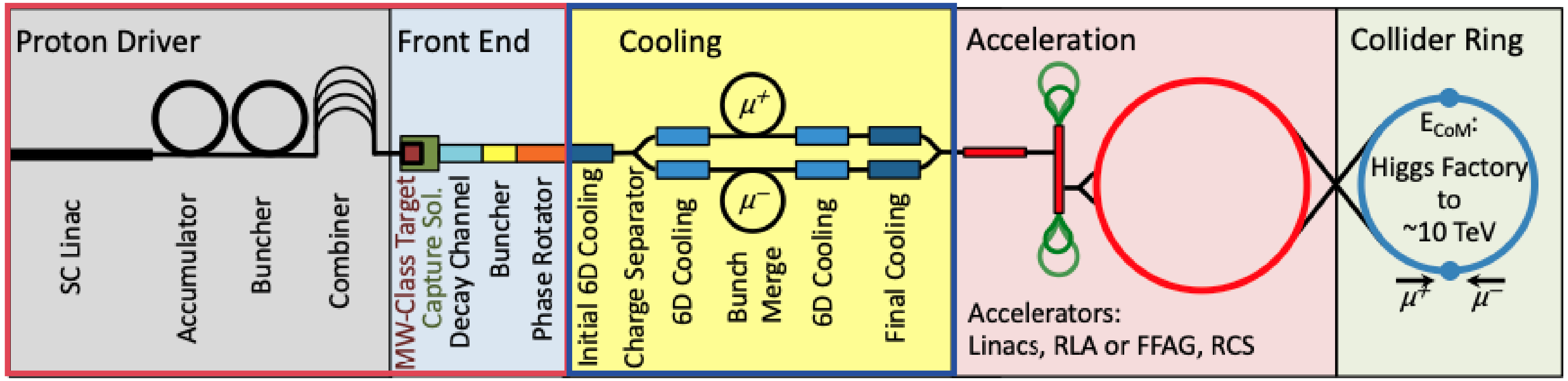

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Cooling channel: H moderators + RFs in a solenoidal B field

Cooling solenoids: Ultra high field solenoid 40… 60 T in 50 mm solenoid
Baseline: LTS with HTS insert

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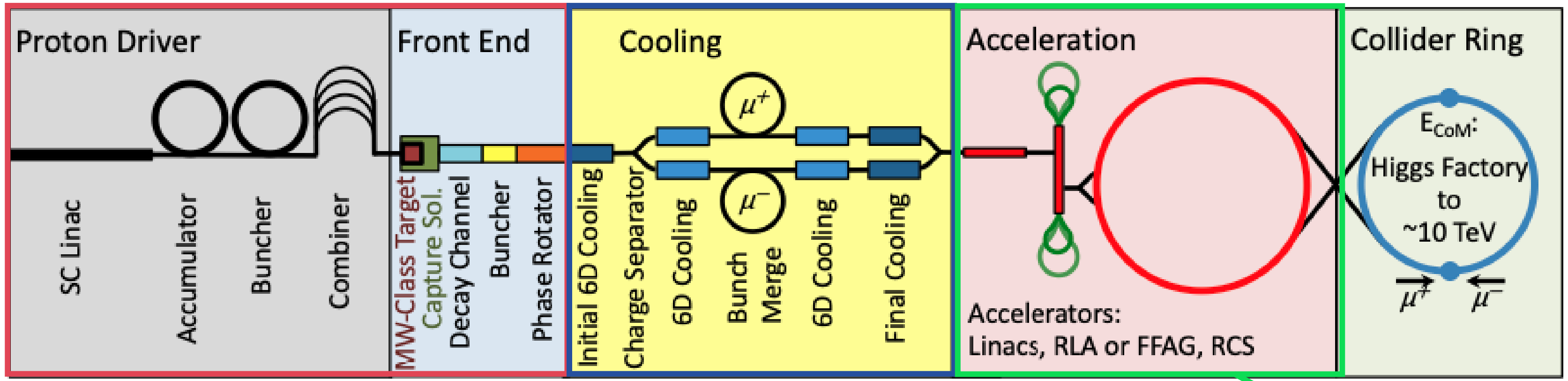

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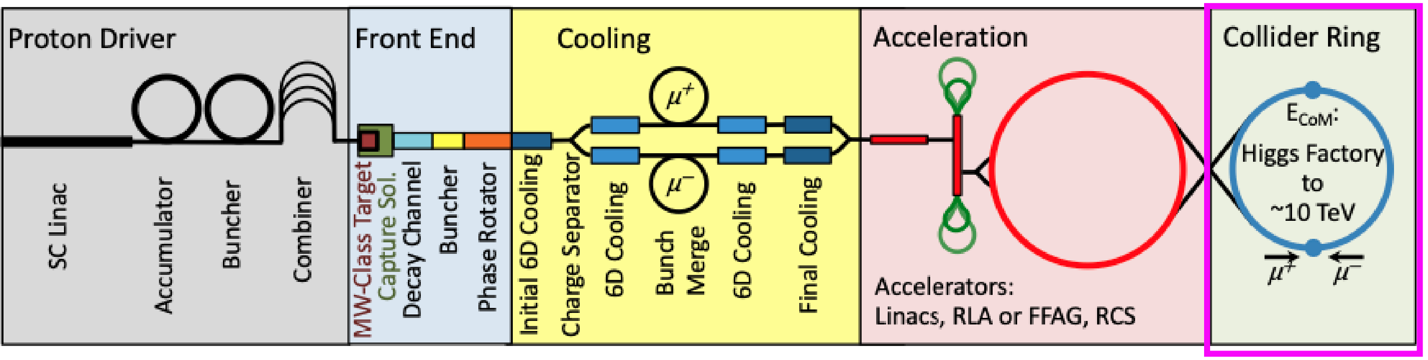
Baseline: LTS with HTS insert

Accelerator complex, take the beams from 100 GeV to the multi-TeV energy required

Accelerator magnets:
Combination of DC SC magnets (10 T) and AC resistive magnets (± 2T, 400 Hz, ~ GW of peak power to be managed) 80x40 mm
Baseline: NC fast ramped magnets + static SC magnets

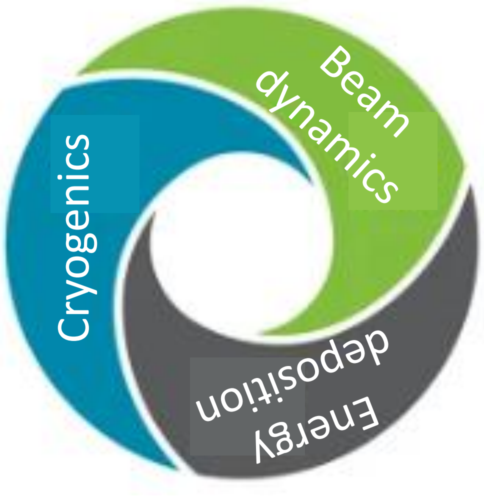
The Muon Collider Complex



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: $B_d \sim$ 16-20T in 150 mm bore:

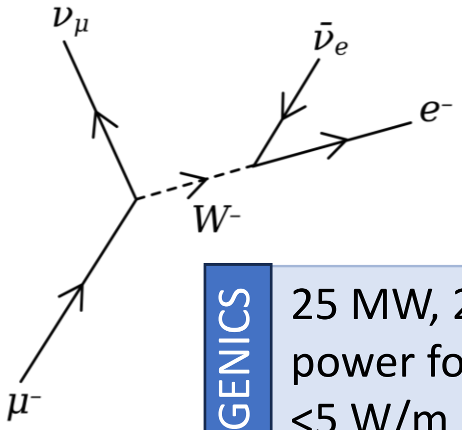
- Highest field possible to have a compact ring
- Open midplane or large dipoles and quadrupoles (150 mm bore diameter) for shielding against heat (500 W/m) and radiation loads
- Combined function (dipole + quadrupole) to avoid straight sections and minimize neutrino hazard



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

Magnets for the Collider Ring: cryogenics and energy deposition

Muon decay



- Neutrinos carry 65% of E $_\mu$ → radiation hazard outside the accelerators → straight sections must be minimized
- Electrons carry ~35% of E$_\mu$ (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

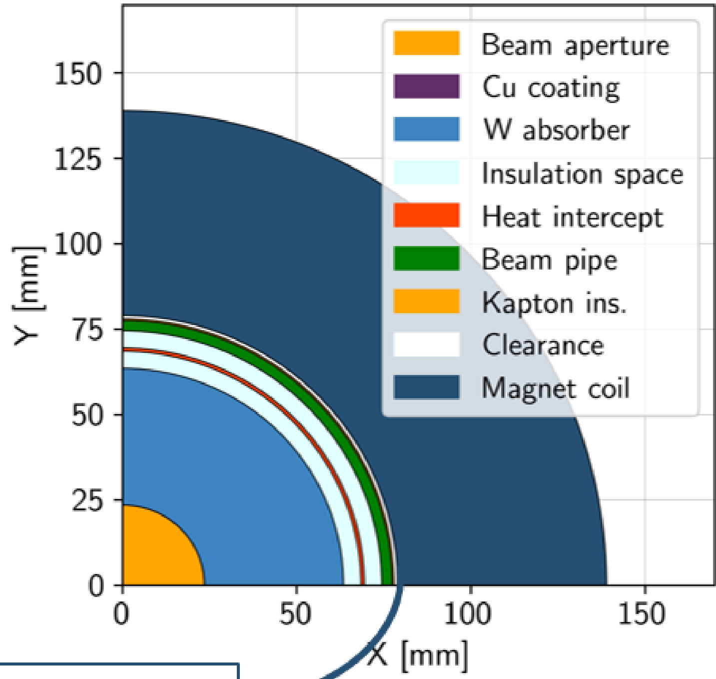
Radial Build

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

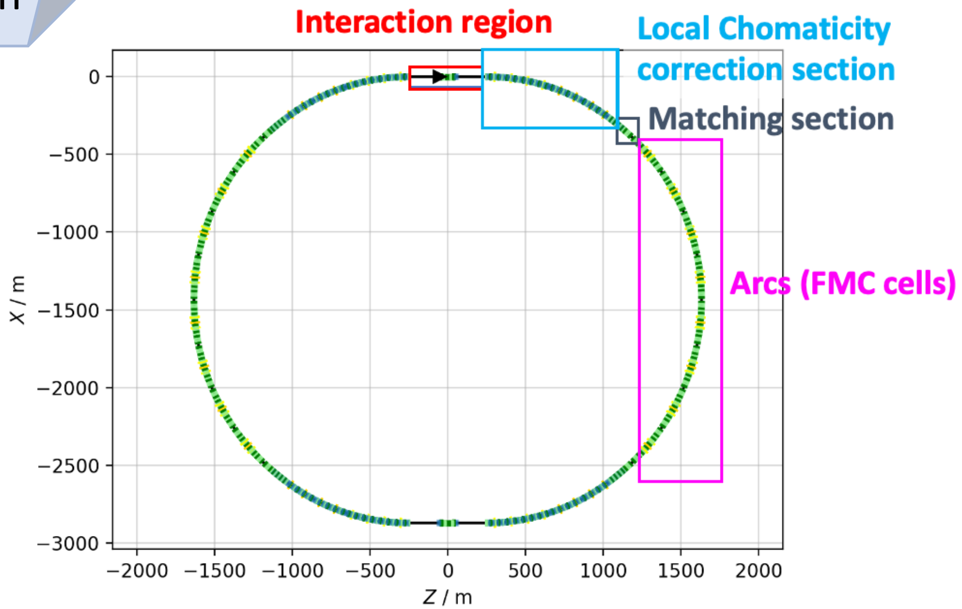
Dipole[1]:

B_d=16 T in 138 mm bore aperture

Combined magnets:

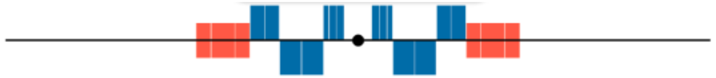
B_d=4 T, G1=+-240 T/m in 170 mm bore aperture

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



Courtesy of Christian Carli, Kyriacos Skoufaris , Marion Vanwelde

Interaction region[2]



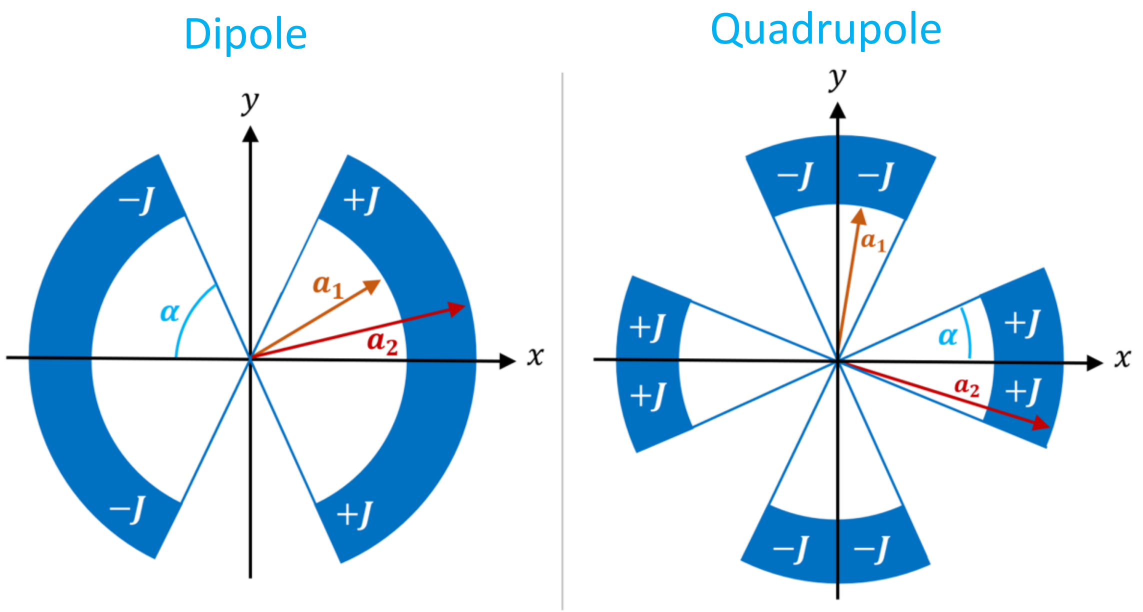
Name	L [m]	Magnet aperture diameter [mm]	B[T]
IB2	6	320	8.1
IB1	10	320	-9.7
IB3	6	320	8.1
Name	**L [m]**	**Magnet aperture diameter [mm]**	**G [T/m]**
IQF2	6	280	85.2
IQF2_1	6	266	85.2
IQD1	9	290	-115.4
IQD1_1	9	290	-115.4
IQF1B	2	204	205.1
IQF1A	3	172	241.8
IQF1	3	140	302.2

[1] K. Skoufaris et al. ``Update on collider optics design'', IMCC Annual Collaboration Meeting 2024 https://indico.cern.ch/event/1325963

[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

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. Nb3Sn (LTS) and REBCO (HTS) are considered.



Dipole

Quadrupole

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

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

$(w = coil\ width)$

Courtesy of Daniel Novelli

Method and assumptions:

- Given the ***magnet aperture*** $\boldsymbol{a_1}$, 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:

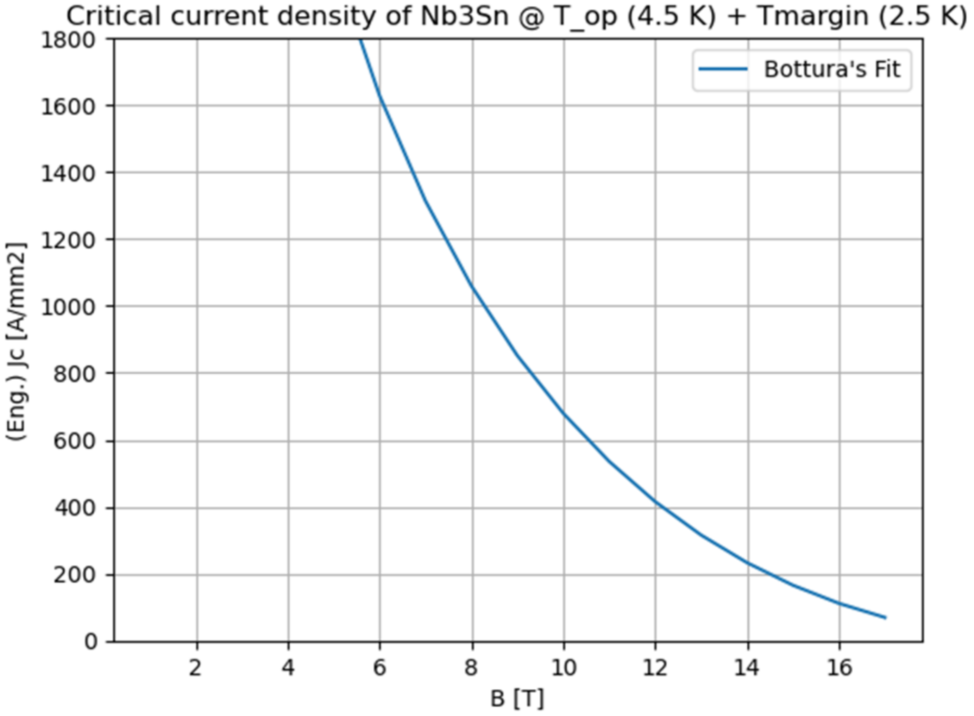
1. MARGIN ON THE LOAD LINE
2. COST
3. PROTECTION
4. STRESS

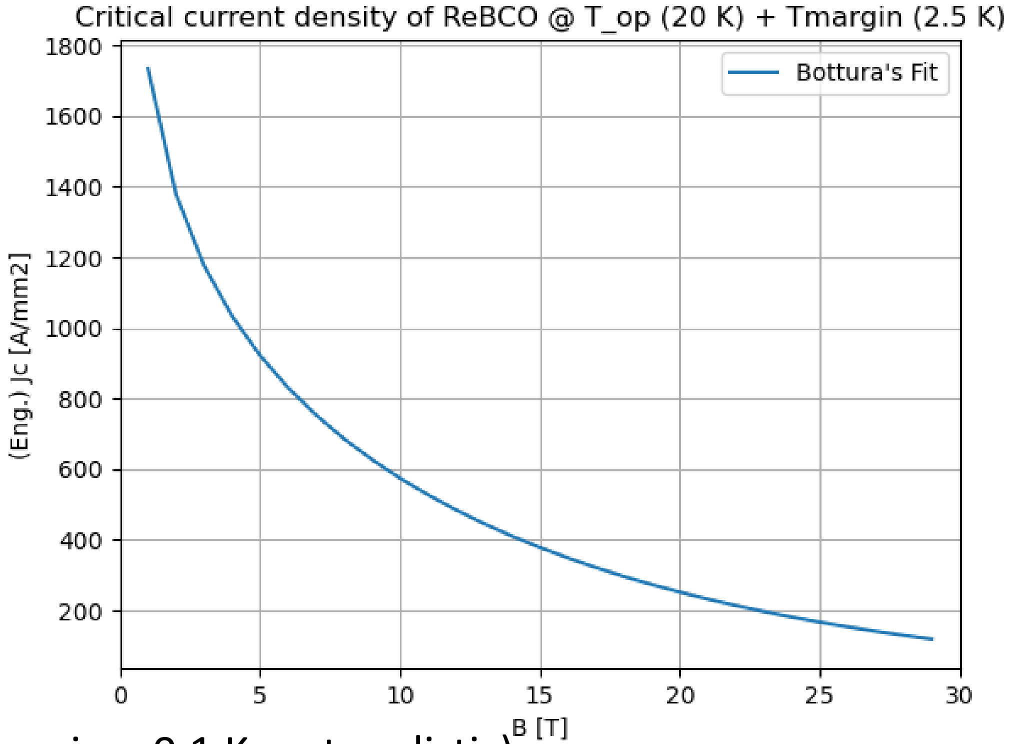
Margin on the Load Line

J_c refers to:

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

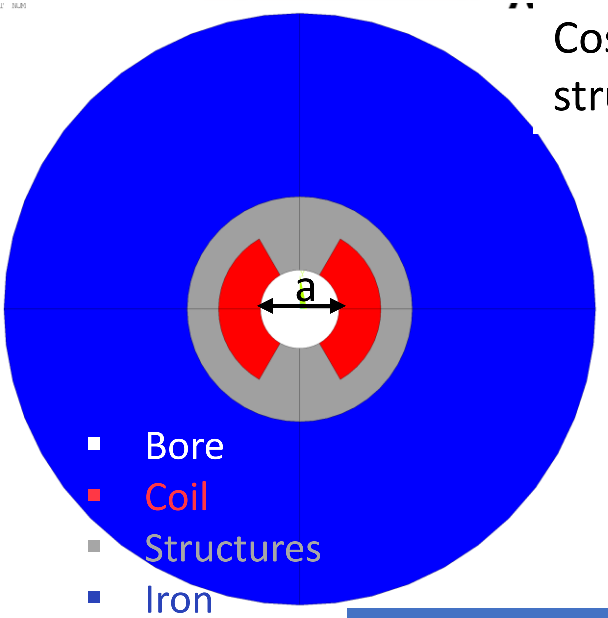
Materials	Operating T [K]	T margin [K]
Nb_3Sn	4.5	2.5 (HL-LHC)
ReBCO	20	2.5 *


Critical current density of Nb3Sn @ T_op (4.5 K) + Tmargin (2.5 K)


Critical current density of ReBCO @ T_op (20 K) + Tmargin (2.5 K)

* Margin given by the stability of the cryogenic system (enthalpy margin ~0.1 K, not realistic)

Cost Model



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

$$C_{tot} = 400\ \mathrm{kEUR/m}$$ *(*FCC-hh 175 kEUR/m [ref]*)*

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

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

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

$$\begin{cases} \rho_{coil} = 8000\ kg/m^3 \\ \rho_{Strucutres} = \rho_{iron} = 7800\ kg/m^3 \end{cases}$$

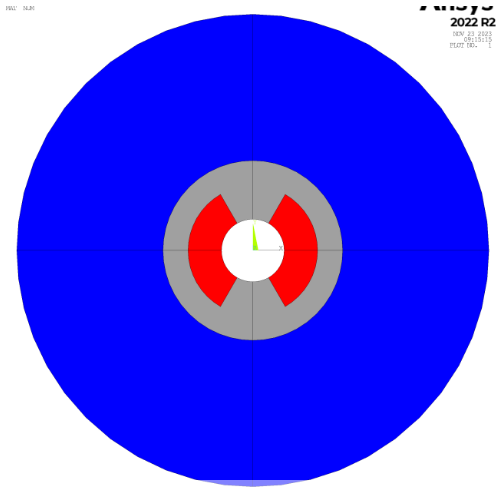
$$\begin{cases} C_{Structures} = 10\ EUR/kg & \text{(D2 HL-LHC as benchmark)} \\ C_{iron} = 8\ EUR/kg & \text{(D2 HL-LHC as benchmark)} \end{cases}$$

$$\begin{cases} A_{coil} = \frac{2}{3}\pi\left(w_{coil}^2 + w_{coil}\ a\right) = f(a, w_{coil}) \\ A_{iron}(w_{iron}) = f_3(a, w_{coil}) \\ A_{structure}(w_{structure}) = f_2(a, w_{coil}) \end{cases}$$

Material	C_{SC}	
NbTi	330 EUR/kg	*Escalated price in 2016*
Nb_3Sn	2000 EUR/kg	*The right value in 2016*
aspirational value	700 EUR/kg	*Corresponds to the FCC target*
ReBCO	8000 EUR/kg	*The value of today (2023)*
aspirational value	2500 EUR/kg	*A realistic projection for the next years*

Cost Model

15T /138 mm (REBCO)



€/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

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**	

Tot. Material = (C_{iron}+ C_{struct})*f_{struct}

f_{struct} = 1.5

200 k€/magnet (~2FTE)

R_{bore}= 69 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)

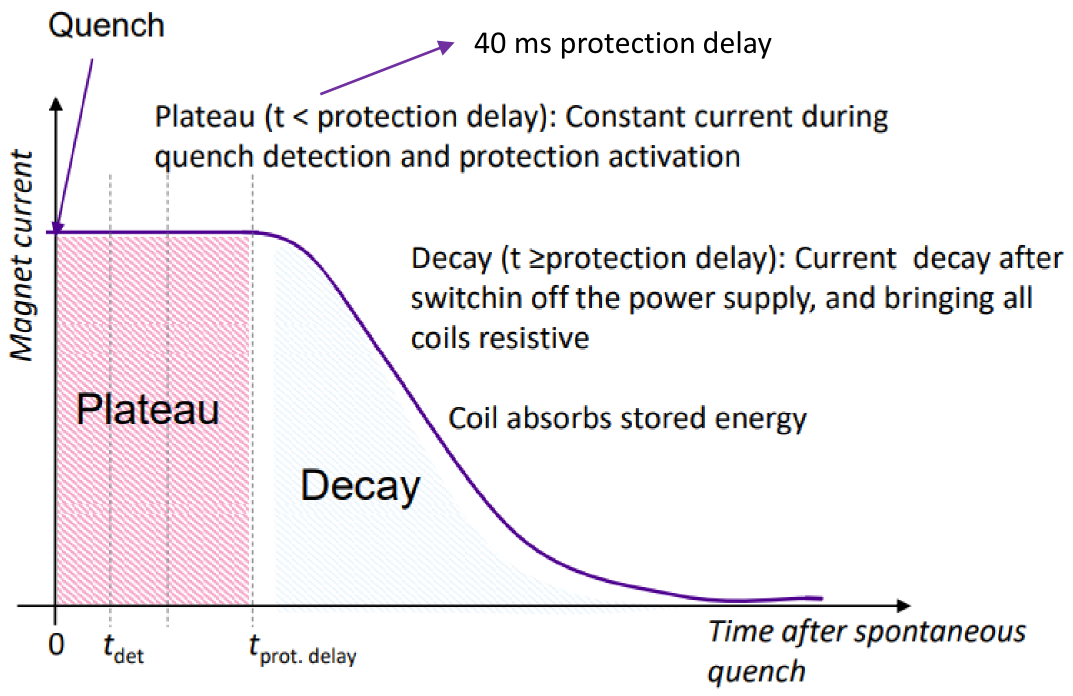
Coordination, design and follow-up: 4 FTE x 4 years= 16 FTE-years (1.6 MEur)

1.5 m long demonstrator ~6M€

Disclaimer: cryostat, specific tooling, W absorber not taken into account

[1] 10.1109/TASC.2023.3241832

Protection

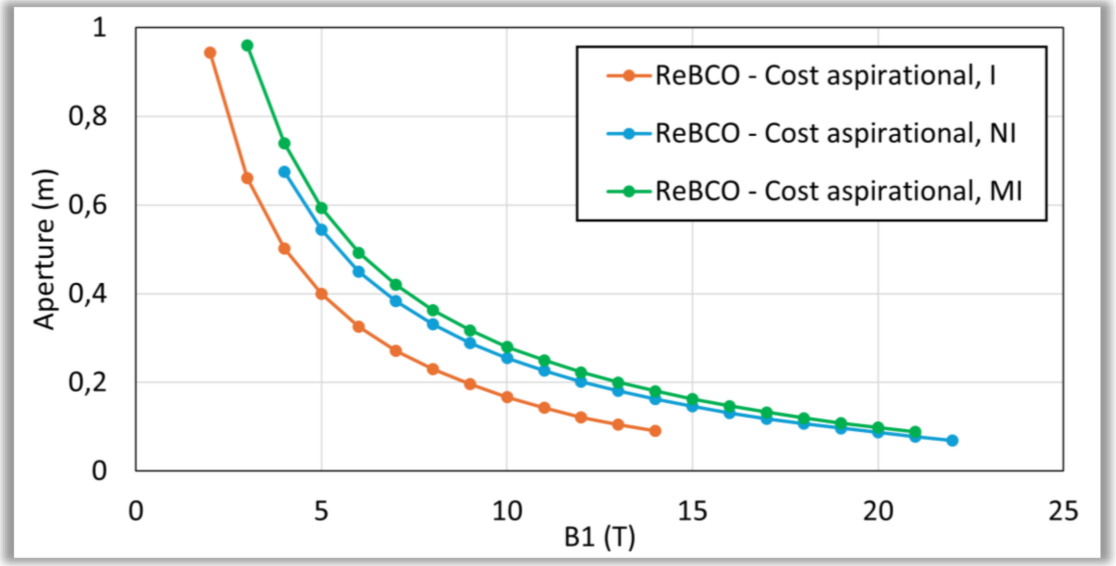


Plateau (t < protection delay): Constant current during quench detection and protection activation

Decay (t ≥protection delay): Current decay after switchin off the power supply, and bringing all coils resistive

Coil absorbs stored energy

Materials	Hotspot T [K]
Nb_3Sn	350
ReBCO	200



Courtesy of Tiina Salmi
See "Analytical estimation of quench protection limits in insulated, non-insulated, and metal-insulated ReBCO accelerator dipoles and quadrupoles " 1LPo1I-04

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

Stress

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

Midplane pressure (1st order approximation):

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

DIPOLE

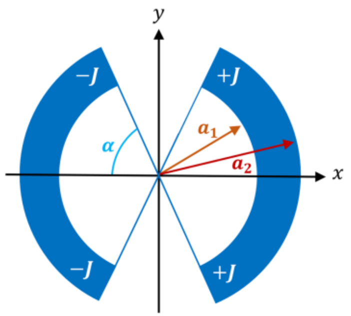
$$P_\theta = \frac{2\mu_0 sin\alpha\ (cos\alpha - 1)\ J^2}{\pi w}\left(-\frac{2}{3}\frac{a_2^3 - a_1^3}{3} - \frac{a_1^3}{3}\ln\left(\frac{a_2}{a_1}\right) + \frac{a_2^3 - a_1^2 a_2}{2}\right)$$

QUADRUPOLE

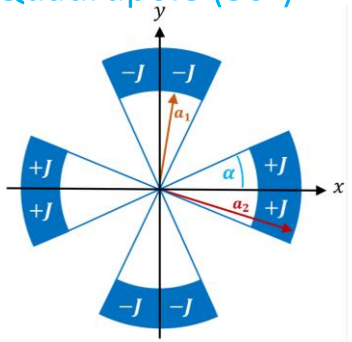
$$P_\theta = \frac{2\mu_0 sin2\alpha\ (cos2\alpha - 1)\ J^2}{\pi w}\left(\frac{7}{12}\frac{a_2^3 - a_1^3}{3} - \frac{a_1^3}{3}\ln\left(\frac{a_2}{a_1}\right) + \frac{a_1^4 - a_1^3 a_2}{4a_2}\right)$$

Maximum Stress $\boxed{P_\theta = \sigma_{max}/1.5 \quad \Longrightarrow \quad J\,(\sigma_{max}\,, a_1\,, w)}$ 1.5 : empirical factor

Dipole (60°)



Quadrupole (30°)



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

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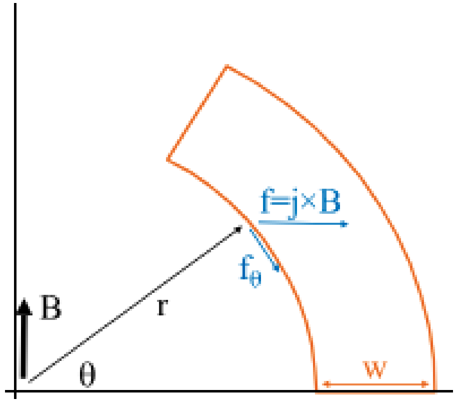
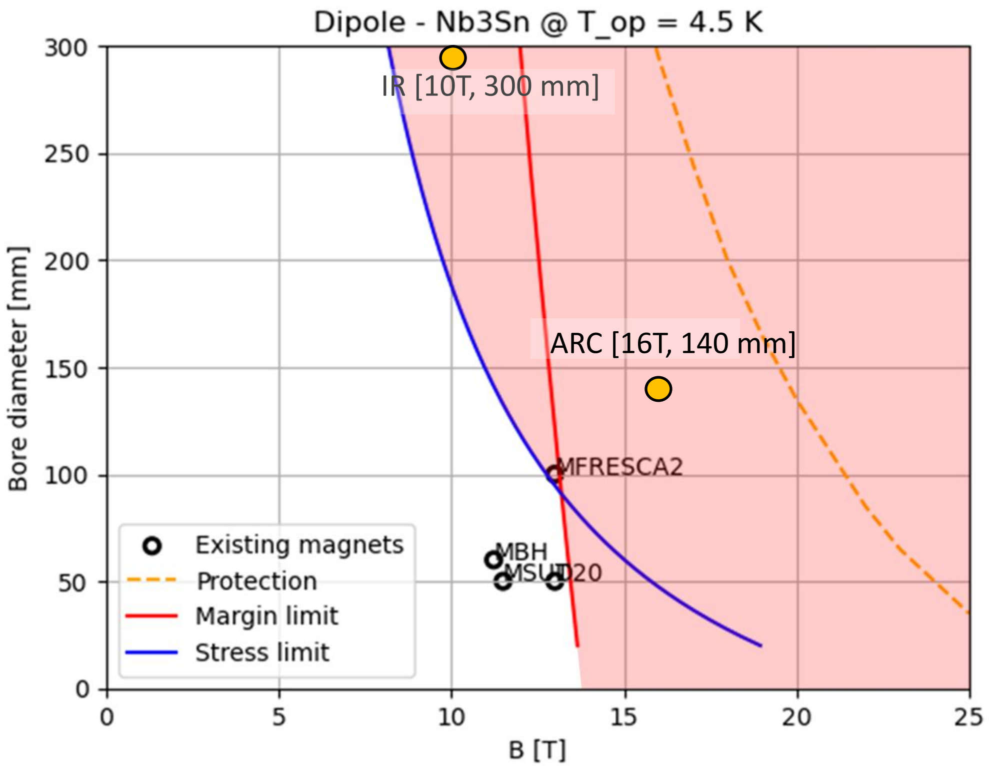
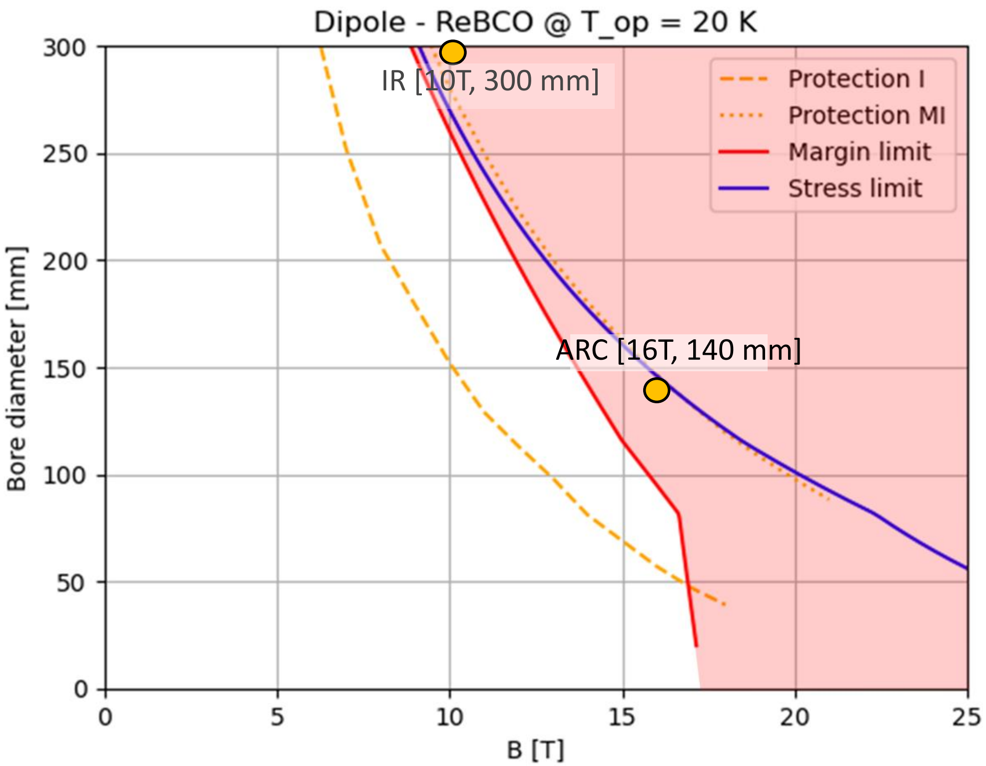
$(\,w = coil\ width\,)$



Courtesy of D. Novelli,
See «A new approach to analytical and numerical analysis of dipole an
quadrupole performance limits for a Muon Collider, 3LPo2H-05

AB-plot for dipoles





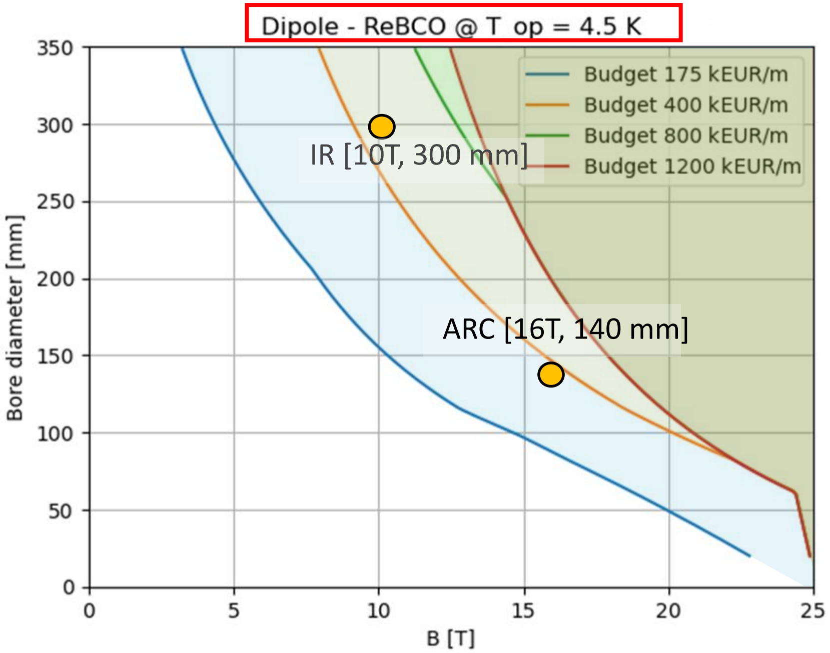
Nb_3Sn falls short of required performance because of **operating margin** and peak stress for B >14 T

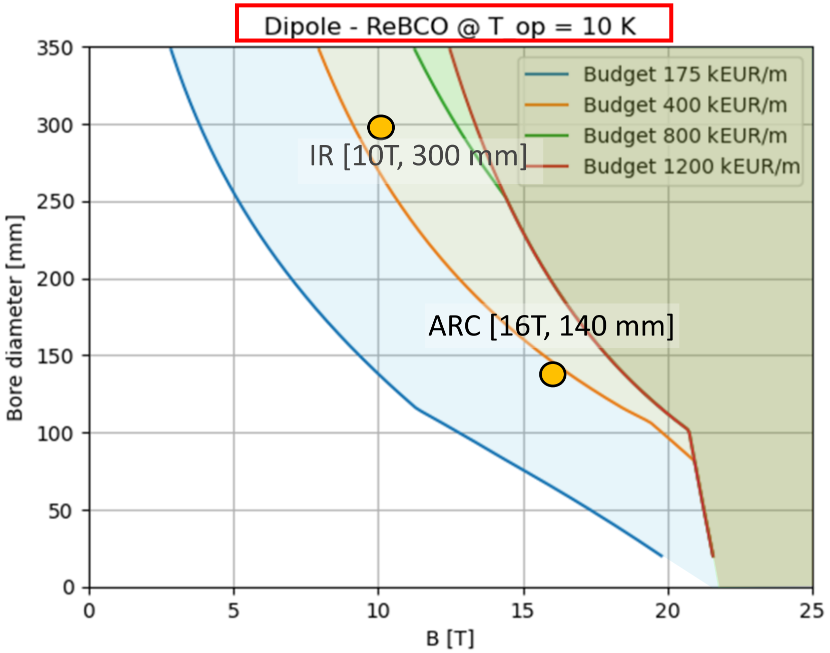
Cost and **protection** are the main limitation for ReBCO. Metal insulated (MI) or Not Insulated (NI) coils must be used.

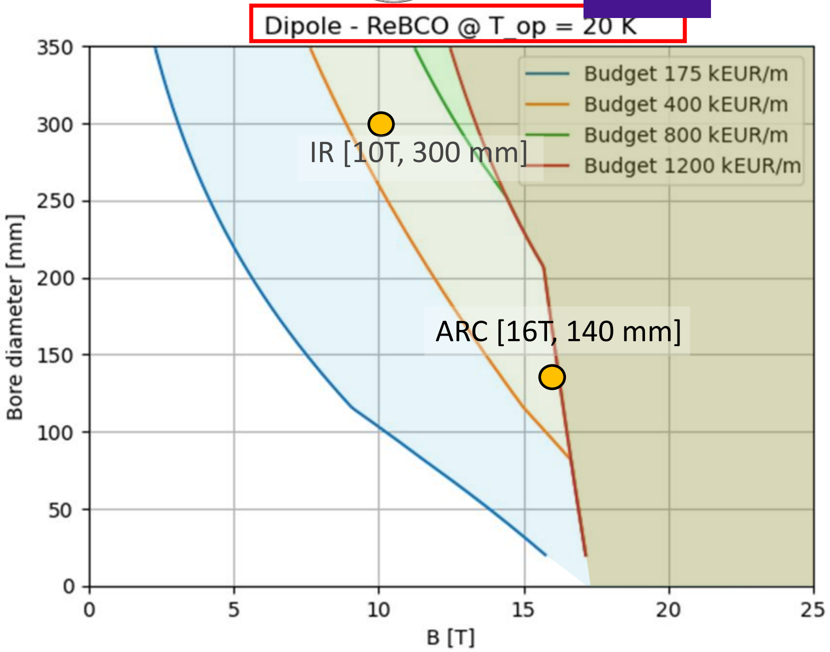
Current lattice requirements falls in the forbidden A-B area, more iterations are needed

Courtesy of D. Novelli,
See «A new approach to analytical and numerical analysis of dipole and quadrupole performance limits for a Muon Collider, 3LPo2H-05

AB-plot 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)

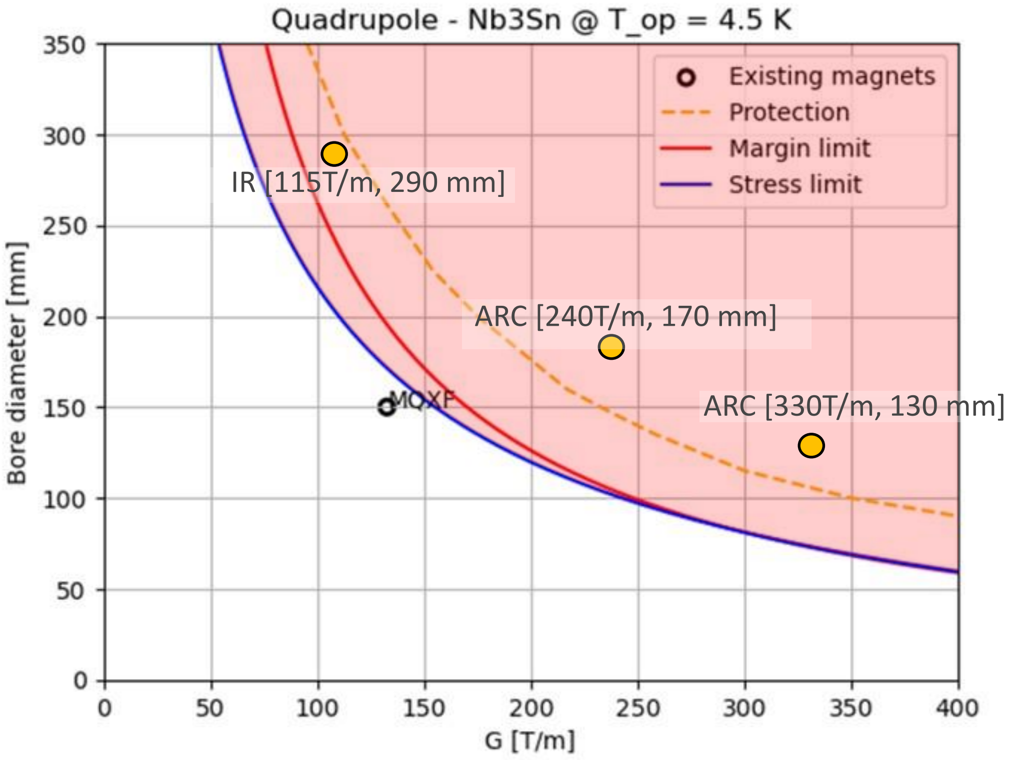
Increasing budget, lattice requirements in the permitted region (dedicated FEM studied needed to confirm)

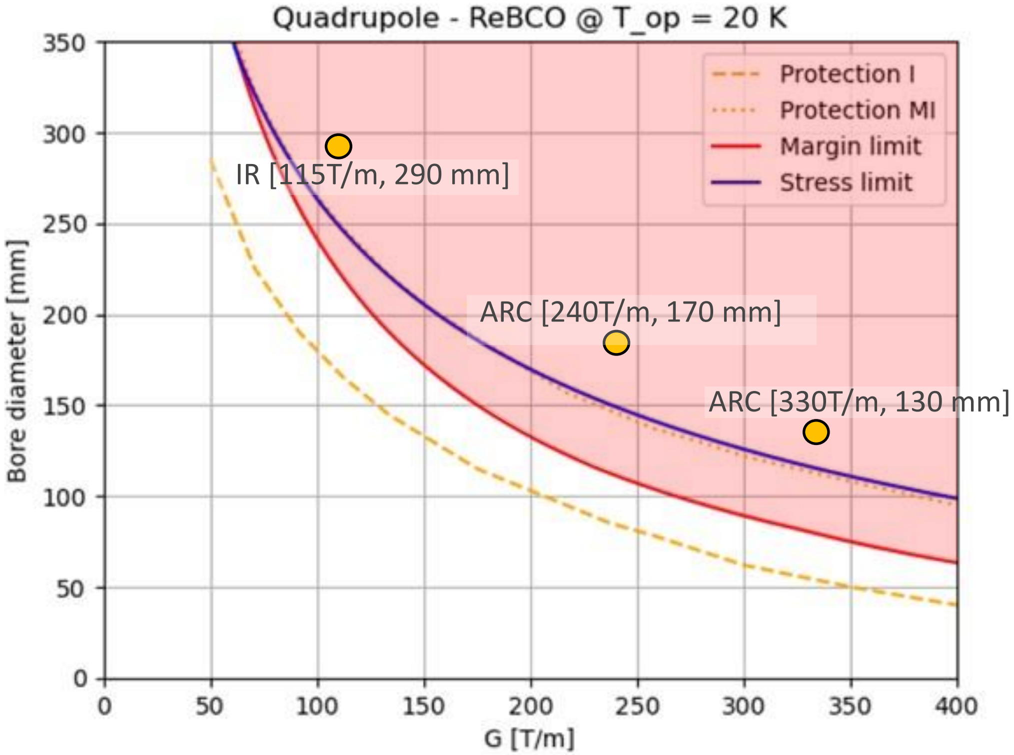
Summary of technical assumptions:

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

Courtesy of D. Novelli

AB-plot for quadrupoles





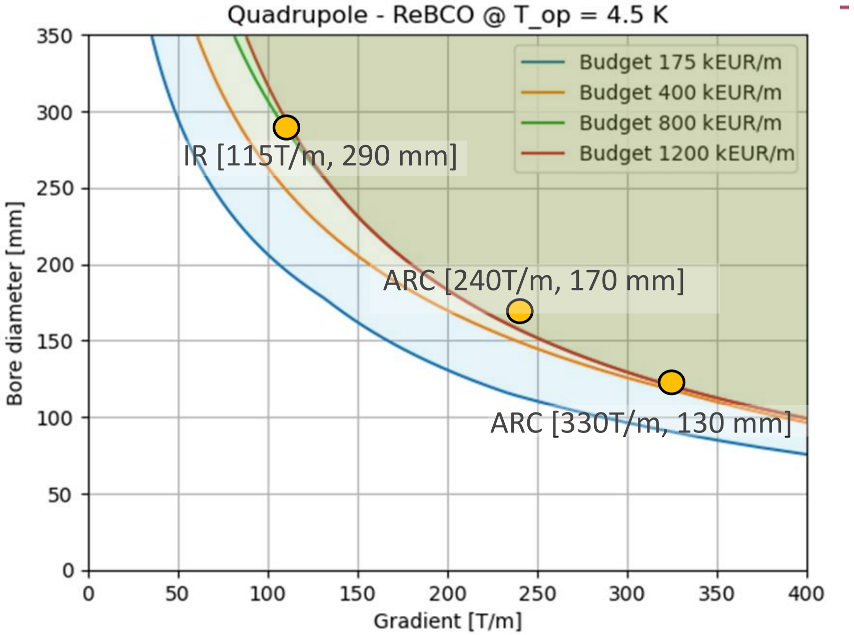
- Nb_3Sn is limited by **peak stress** and **operating margin**

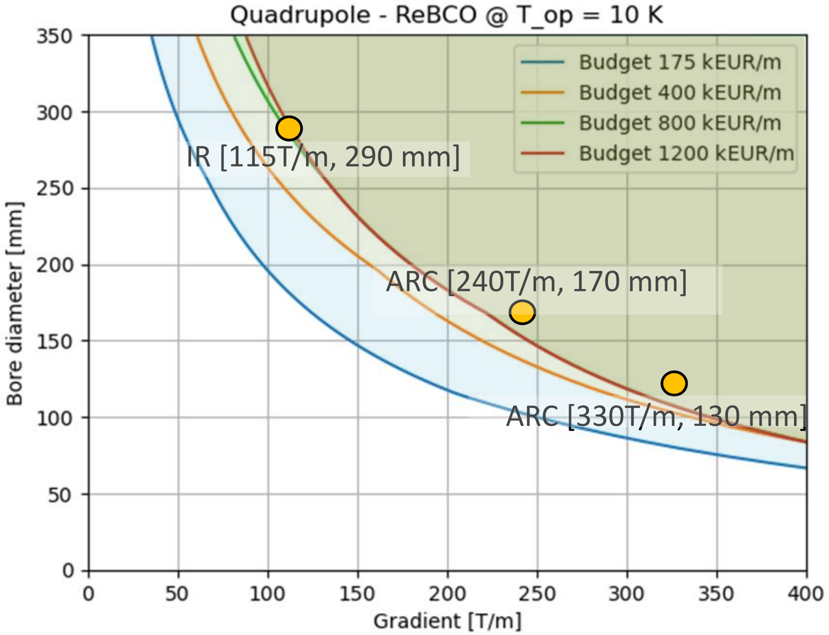
- HTS is mainly limited by **cost** production and **protection**. Working @20K the margin curve is also a limiting factor.

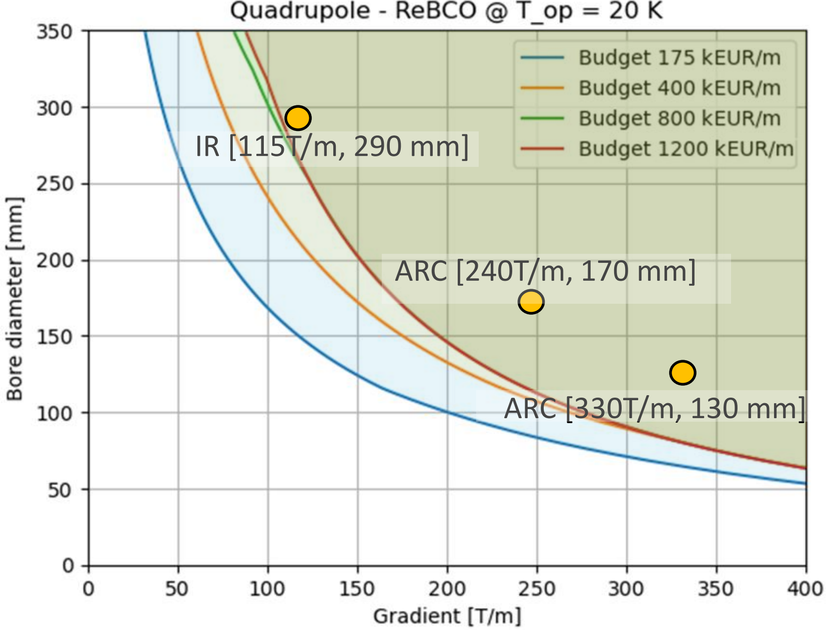
Courtesy of D. Novelli

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

AB-plot for quadrupoles


Quadrupole - ReBCO @ T_op = 4.5 K


Quadrupole - ReBCO @ T_op = 10 K


Quadrupole - ReBCO @ T_op = 20 K

- 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!

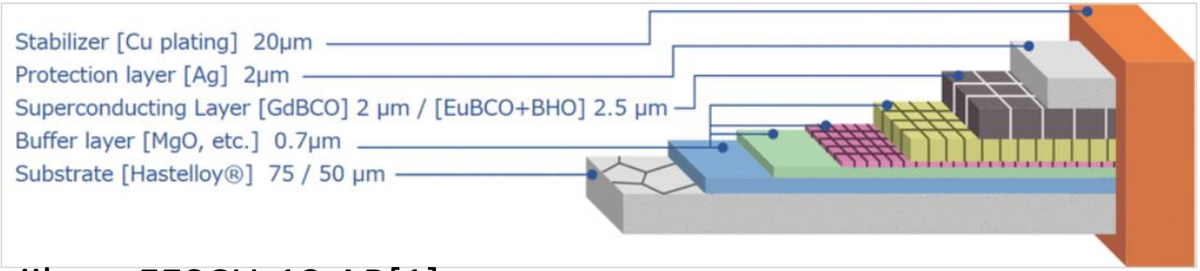
Summary of technical assumptions:

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

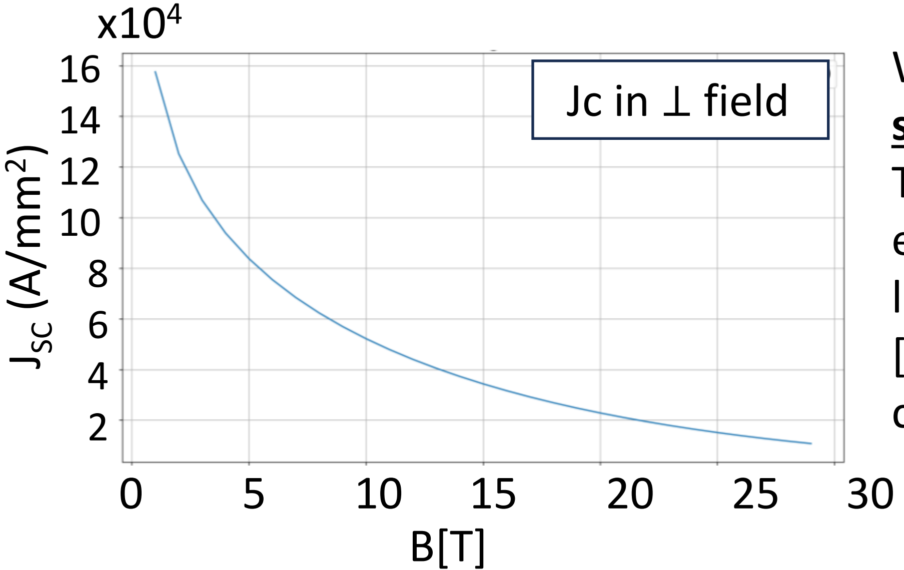
Courtesy of D. Novelli

Cable choice considerations

REBCO TAPE



Fujikura FESCH-12 AP[1]



We want to use **not twisted stacked tapes cable.**

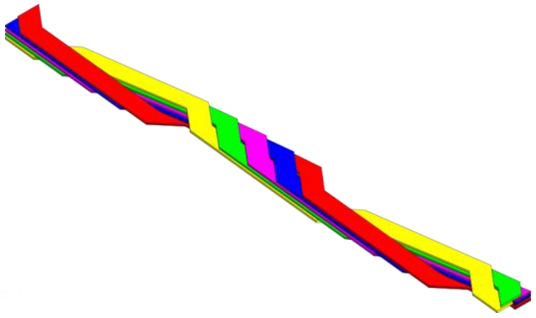
Twist and transposition not effective in reducing the AC losses for coated conductors [2], while increasing cost and complexity

For the analytic evaluation, J_{sc} ⊥ was used to be conservative

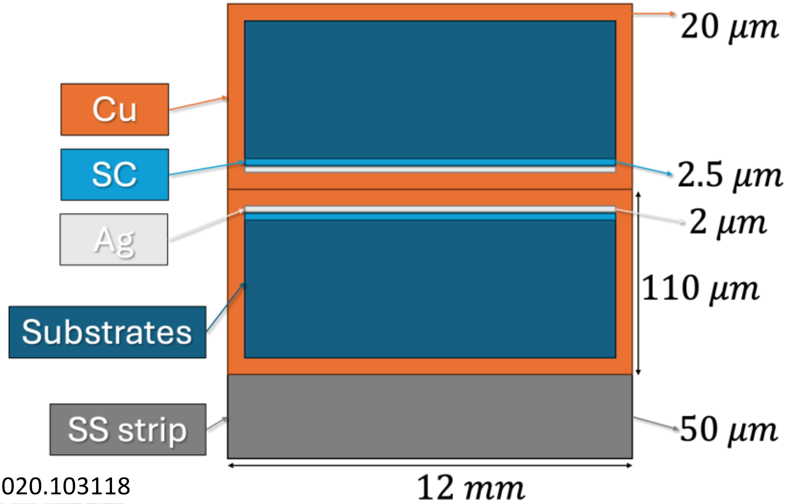
REBCO CABLES:

CORC®

ROEBEL



2 tapes co-wounded with 50 μm thick SS layer



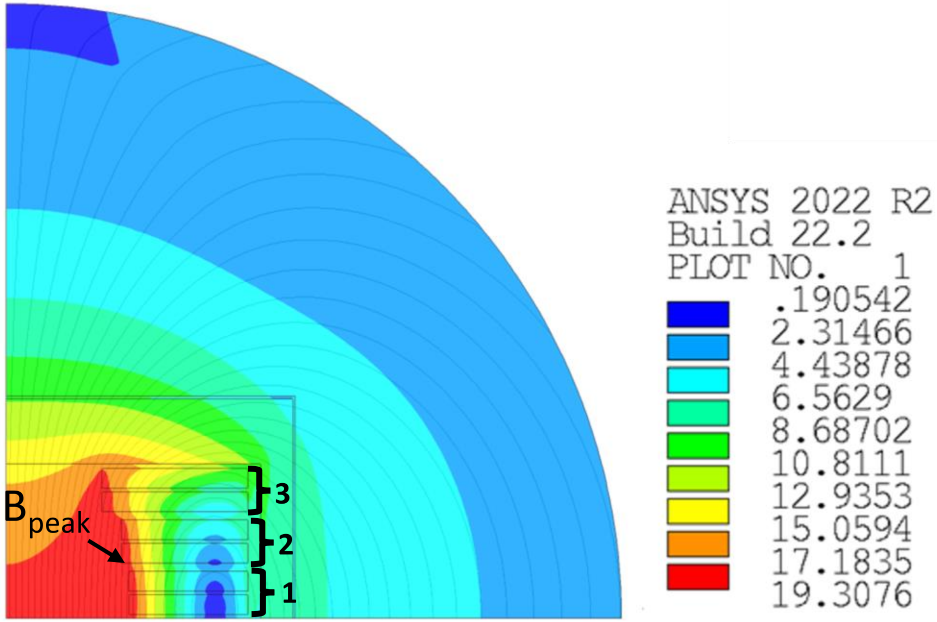
[1] https://www.fujikura.co.uk/netalogue/pdfs/Fujikura%20Superconductor%20Guide.pdf

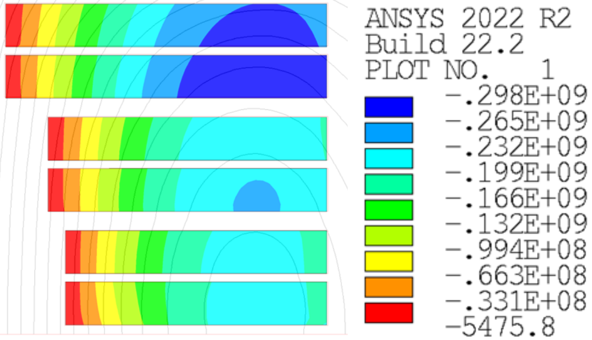
[2] D. Uglietti at al. "Non-twisted stacks of coated conductors for magnets: Analysis of inductance and AC losses" https://doi.org/10.1016/j.cryogenics.2020.103118

Preliminary discussion on block –coil design

- 6 blocks (135,135,144,144,166,166 turns), 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, no transport current)

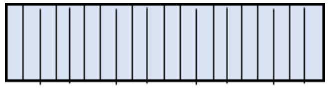
	Cond 1	Cond 2	Cond 3
B_{peak}[T]	19.25	19.31	19.02
J_{op}[A/mm^2]	443.8	443.8	443.8

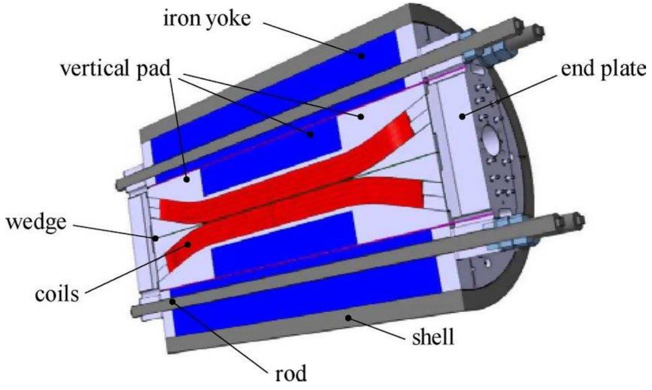




$\sigma_X{}^{MAX}$= -298 MPa (5th layer)
$\sigma_Y{}^{MAX}$= -53 MPa (1st layer)

Stacked cable



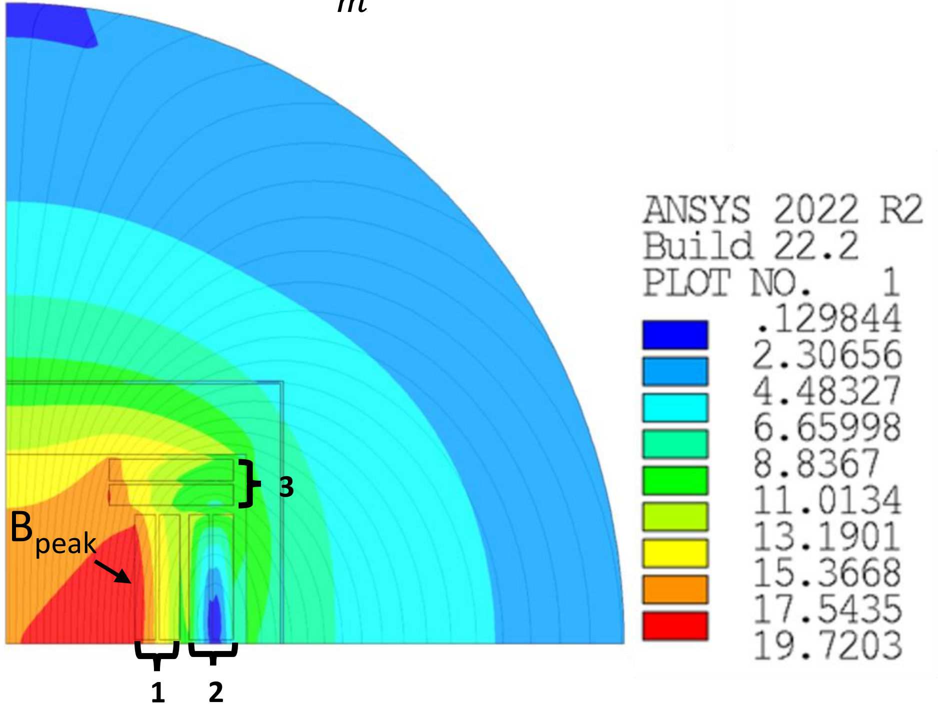


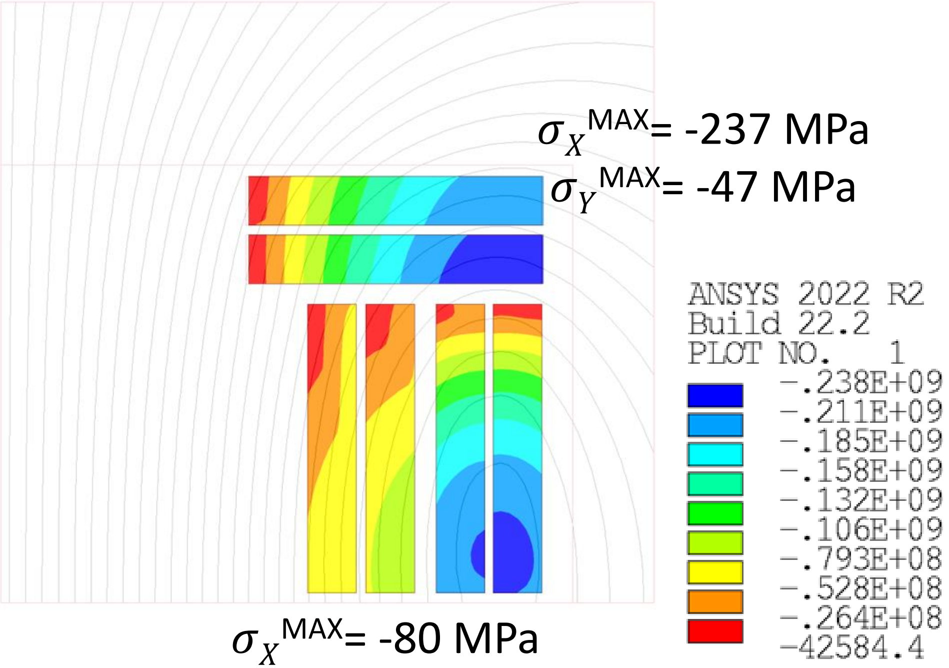
Courtesy of Luca Alfonso
See “Preliminary Design of a Block-Coil Magnet for the Muon Collider Ring”
4LPo1I-01

Preliminary discussion on block –coil design

- 6 blocks (131,131,262,262,135,135 turns), 4 stacked vertically & 2 racetracks (no flared ends needed)
- B_{bore}= 17.5 T, B_{peak}=19.7 T
- σ_{III}=- 238 MPa (infinitely rigid structure approximation)
- $Q = 527.5 \frac{kJ}{m}$ (Bean model, full penetration, no transport current)

	Cond 1	Cond 2	Cond 3
B_{peak}[T]	19.25	19.31	19.02
J_{op}[A/mm^2]	382.9	765.9	382.9

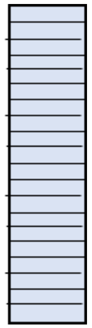


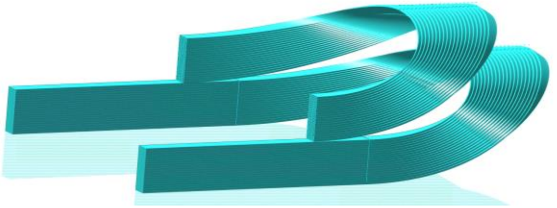


σ_X^{MAX}= -237 MPa
σ_Y^{MAX}= -47 MPa

σ_X^{MAX}= -80 MPa
σ_Y^{MAX}= -213 MPa

Stacked cable

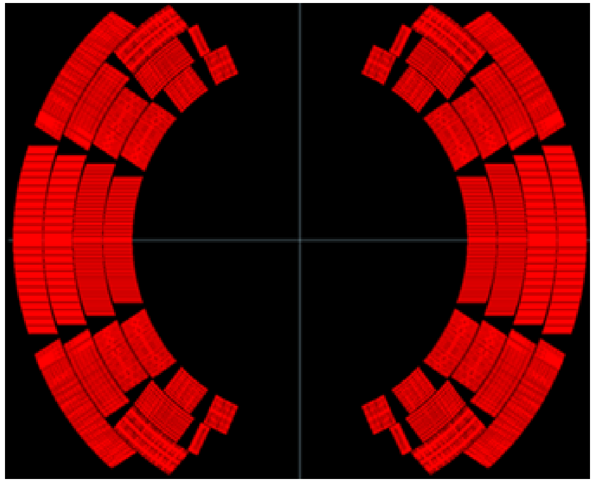




Courtesy of Luca Alfonso

See "Preliminary Design of a Block-Coil Magnet for the Muon Collider Ring" 4LPo1I-01

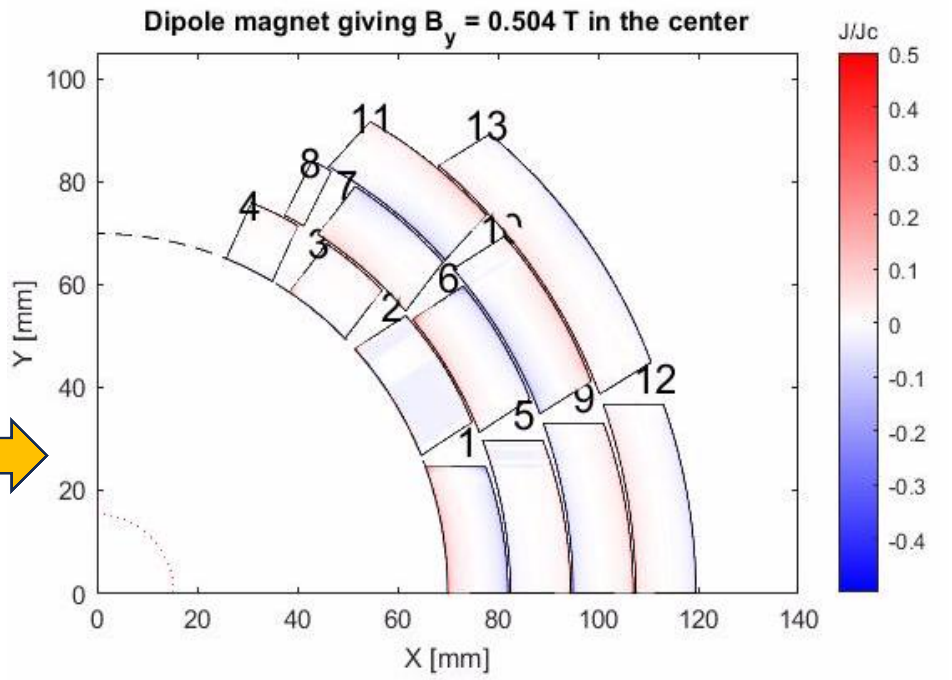
Preliminary discussion on cos-theta design

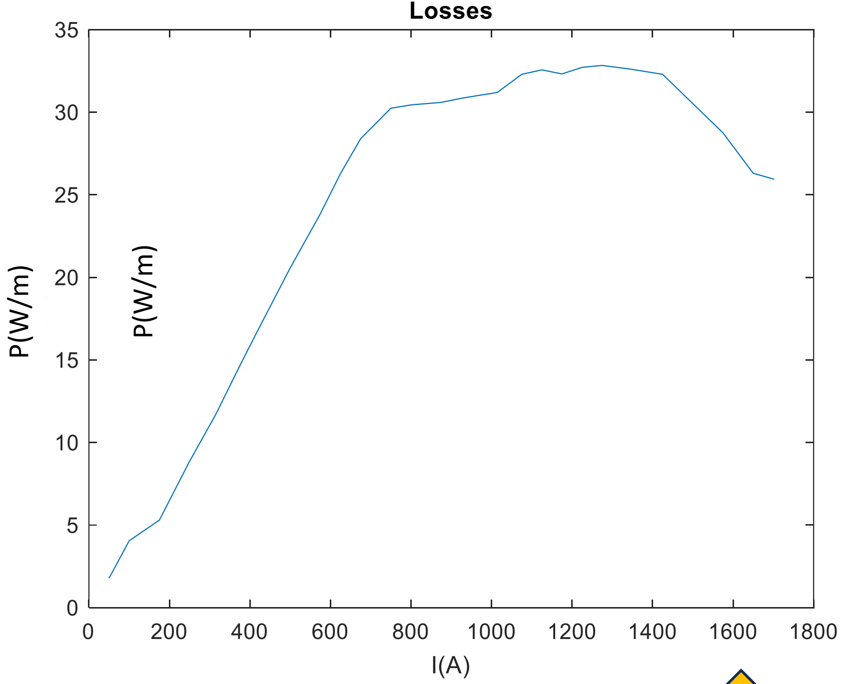


4 layers, 13 blocks

B_d (T)	B_{peak} (T)	$d\ (mm)$	T_{op} (K)	I_{nom} (A)	$Energy$ (kJ/m)	$Inductance$ (mH/m)
16	19.2	140	20	1702	4927	3402

Current density during energization

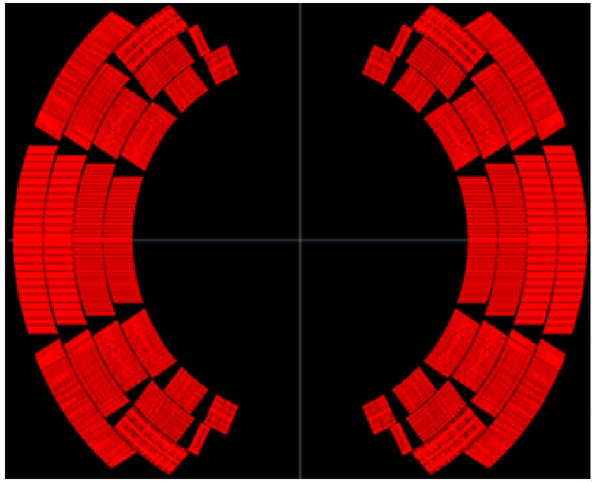




Losses during energization

Courtesy of Francesco Mariani
See "Preliminary Electromagnetic and Mechanical Design of a Cos-theta Dipole for the Muon Collider Project." 1LOr2E-06

Preliminary discussion on cos-theta design

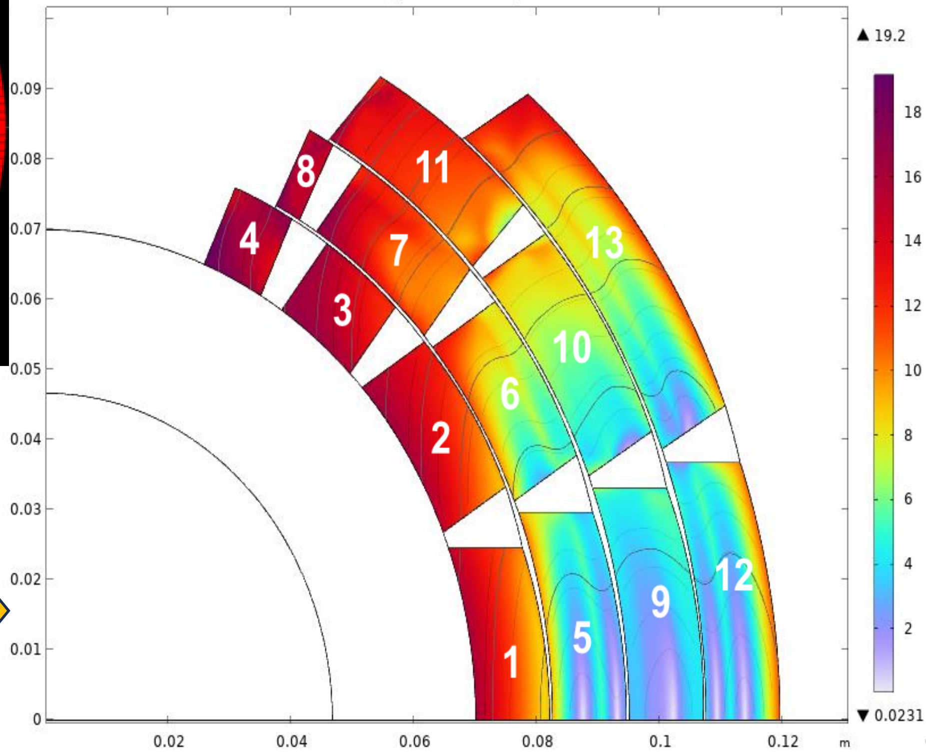


4 layers, 13 blocks

Field map at nominal non-uniform current density

Field map B

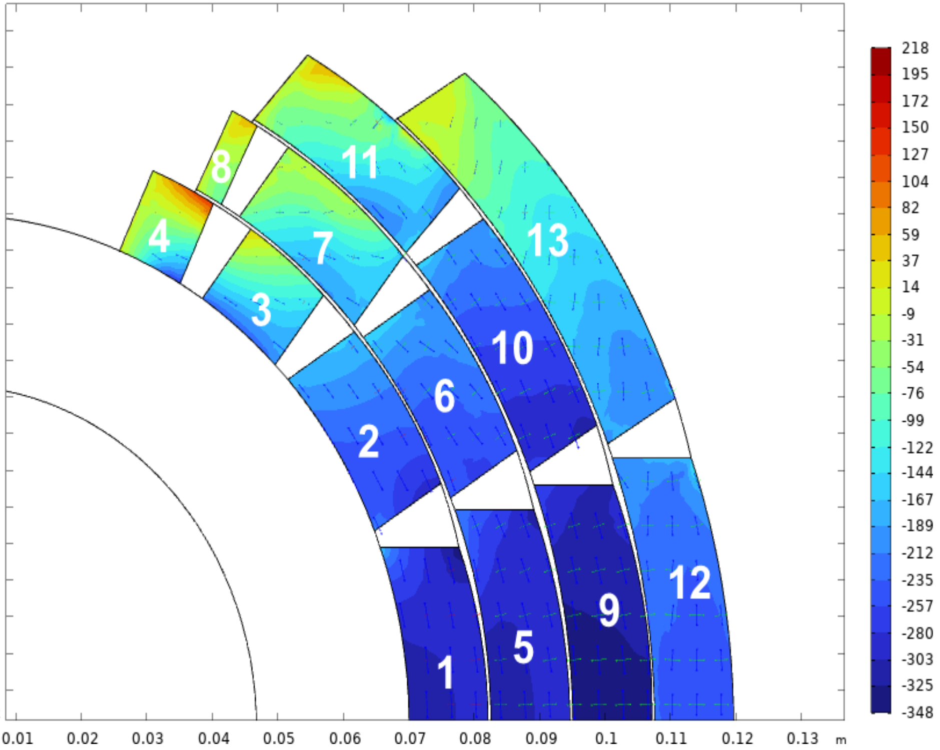
Surface: Magnetic flux density norm (T)



$B_{peak} = 19.2$ T

Azimuthal stress σ_ϑ

Surface: Stress tensor, azimuthal stress (MPa) Principal stress



σ_ϑ max (highest tension) = 218 MPa

σ_ϑ min (highest compression) = -348 MPa

Courtesy of Francesco Mariani

See "Preliminary Electromagnetic and Mechanical Design of a Cos-theta Dipole for the Muon Collider Project." 1LOr2E-06

What’s next

- Finalization of lattice requirements and identification of the most challenging magnets
- Conceptual design of ARC dipole and combined function magnets and IR quadrupole, focusing on:
  - ➢ Mechanics
  - ➢ Margin
  - ➢ AC losses and magnetization
  - ➢ Protection
- Open points
  - ➢ Windability of ReBCO tape
  - ➢ Dipole: cosθ, block coil?
  - ➢ Combined function: nested, asymmetric?

R&D priorities

ReBCO cable

- ❖ Improve reproducibility and uniformity in batch length beyond 1 km
- ❖ Optimization of industrial HTS tape mechanical and thermal properties
- ❖ Characterization of magnetization behaviour and minimization of AC losses
- ❖ Development of novel technique of control of the inter-turn resistance to use Metal Insulated or Not Insulated Coil

Synergies

12 T Nb_3Sn Dipole FalconD

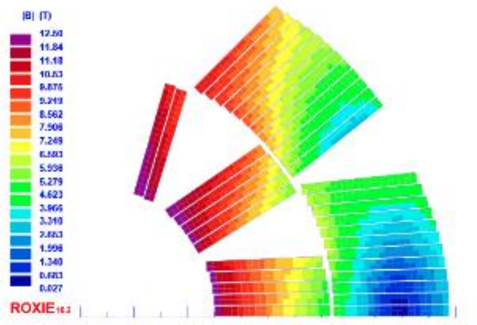
Nb_3Sn is a viable solution for the 3 TeV collider (11 T in 160 mm aperture)

S. Farinon, M. Sorbi

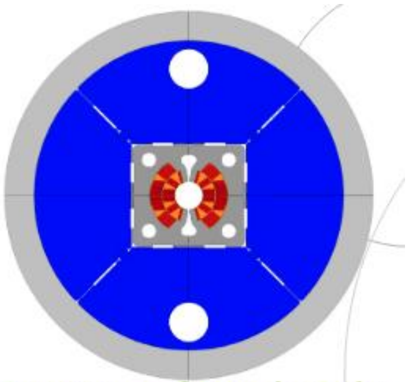
INFN (Istituto Nazionale di Fisica Nucleare) is currently building a Nb3Sn 12 T demonstrator, in collaboration with ASG industry

For more info about FALCOND:

4LOr2E-03	Massimo Sorbi
1LPo1G-04	Nicola Sala



Courtesy of Riccardo Valente



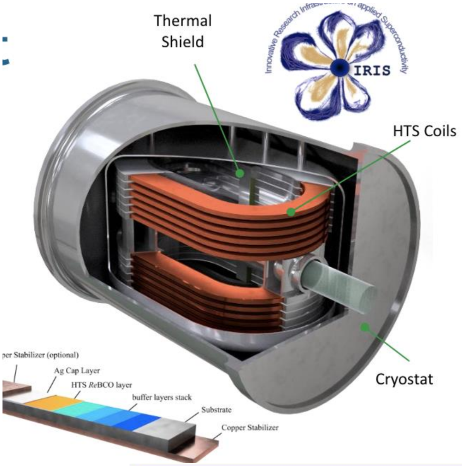
Courtesy of Nicola Sala

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, S. Sorti, S. Maffezzoli, L. Balconi

For more info about ESMA:

3LOr1B-01	Lucio Rossi
5LOr1A-06	Stefano Sorti

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Ministero dell'Università e della Ricerca
Italiadomani

Conclusions

- SC magnets for the Muon Collider ring are particularly challenging: **high field** and **large aperture** are needed, as well as combined dipole and quadrupoles to mitigate neutrino radiation hazard
- The design of such magnets require the cooperative effort of magnet experts together with **beam dynamics**, **cryogenics** and **energy deposition** groups
- To provide fast feedback, we produced design chart with **maximum aperture (A) vs bore field (B)** considering the constrains on operating margin, peak stress, protection and cost through analytical evaluation assuming a sector coil geometry. A-B plots were produced for NbTi, Nb3Sn and ReBCO, the latter at different **T_{op}** and **budget**.
- Some of the current lattice requirements fall short of the feasible parameters phase space, so more iterations are needed
- When the lattice will be defined, the **conceptual design** for the arc dipole and combine function will be finalized, including all the relevant e.m., machinal and protection aspects

Thank you

International
MUON Collider
Collaboration

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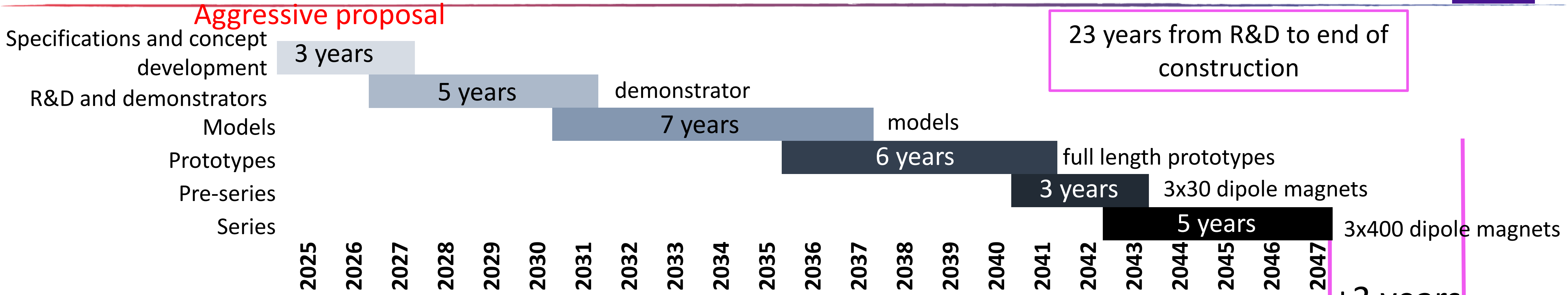
Backup Slides

Funded by
the European Union

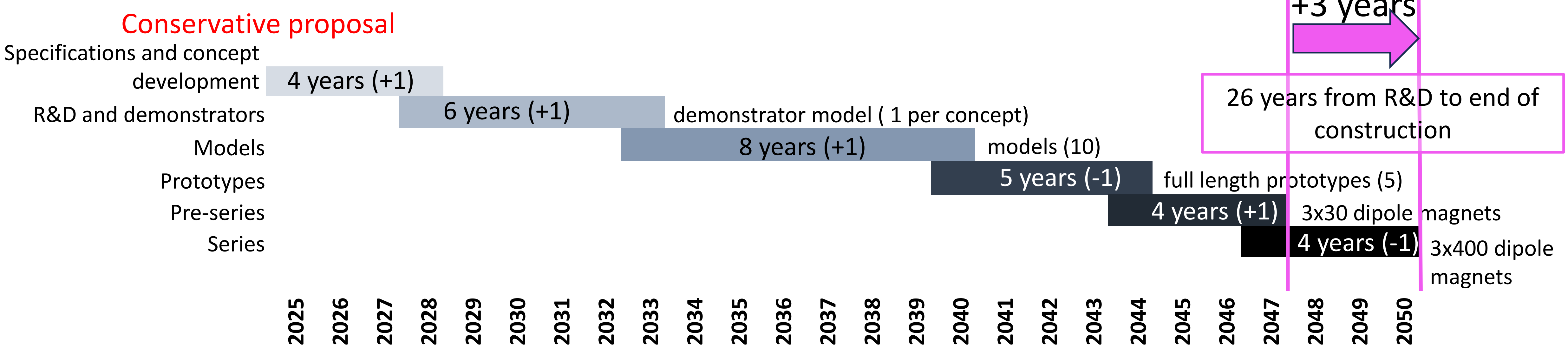
Tentative time schedule



Aggressive proposal

Phase	Duration	Output
Specifications and concept development	3 years	
R&D and demonstrators	5 years	demonstrator
Models	7 years	models
Prototypes	6 years	full length prototypes
Pre-series	3 years	3x30 dipole magnets
Series	5 years	3x400 dipole magnets

23 years from R&D to end of construction



Conservative proposal

Phase	Duration	Output
Specifications and concept development	4 years (+1)	
R&D and demonstrators	6 years (+1)	demonstrator model (1 per concept)
Models	8 years (+1)	models (10)
Prototypes	5 years (-1)	full length prototypes (5)
Pre-series	4 years (+1)	3x30 dipole magnets
Series	4 years (-1)	3x400 dipole magnets

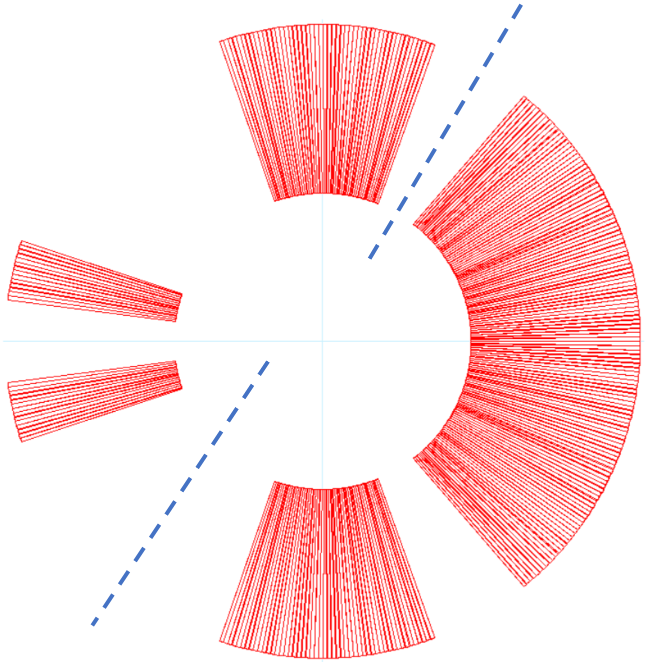
+3 years

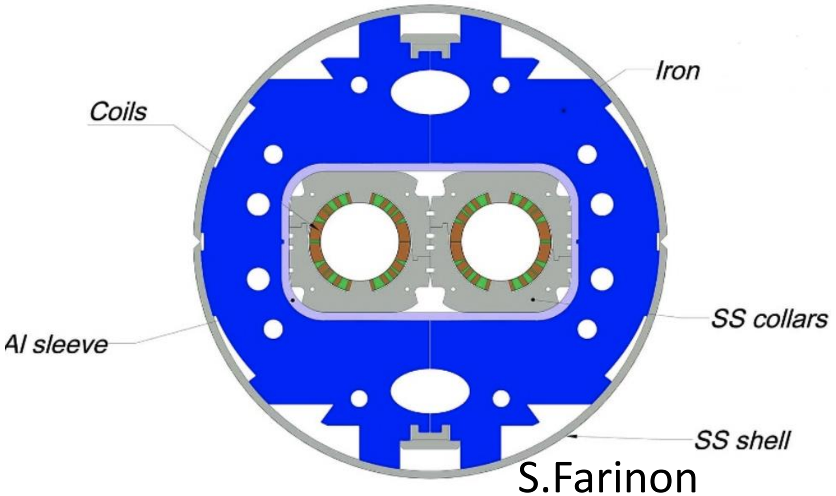
26 years from R&D to end of construction

More emphasis on demonstrator and short model phase (REBCO or hybrid solutions still to be studied)

Preliminary discussion on combined function magnets

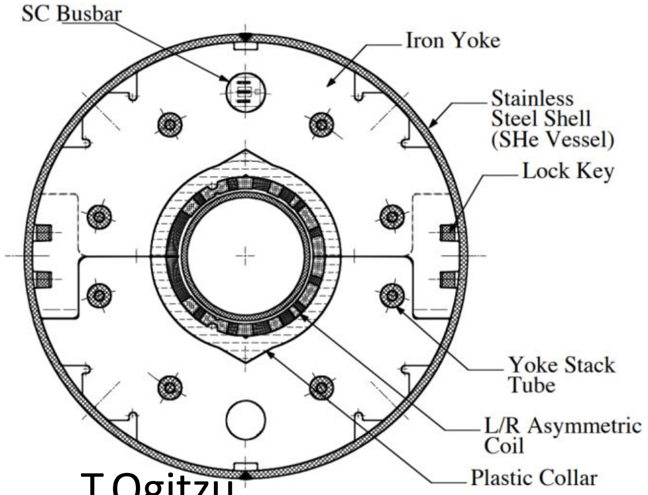
Asymmetric design





S.Farinon

Hi-Lumi LHC separation-recombination dipole [1]
~200 units of b2 (2% of B_0)



T.Ogitzu

Combined function magnets for J-PARC [2]
~3600 units of b2 (36% of B_0)

- Sector coil, optimized with Roxie (very preliminary)
- tilted winding axis (r_{min}=17°, corresponding to 20 mm spacer width)
- B = 13T , G = 140 T/m , r_{ref} = 2/3 $r_{aperture}$=47 mm → B_2=6.5 T

~ 5000 units of b2 (50% of B_0)
Not realistic, upper limit estimate

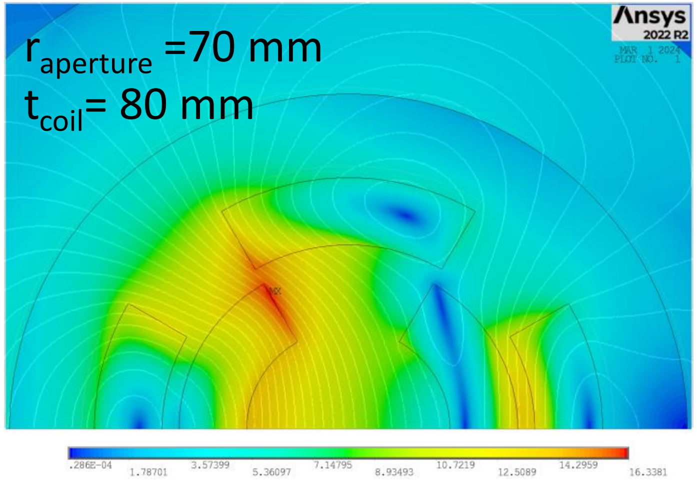
- ➢ B and G are not independent
- ➢ Feasibility of windability and mechanical structure still to be studied

[1] E Todesco *et al* 2021 *Supercond. Sci. Technol.* **34** 053001
[2] T Ogitzu et al 2005 *IEEE Trans Appl Supercond*. **15**, 1175

See D.Novelli

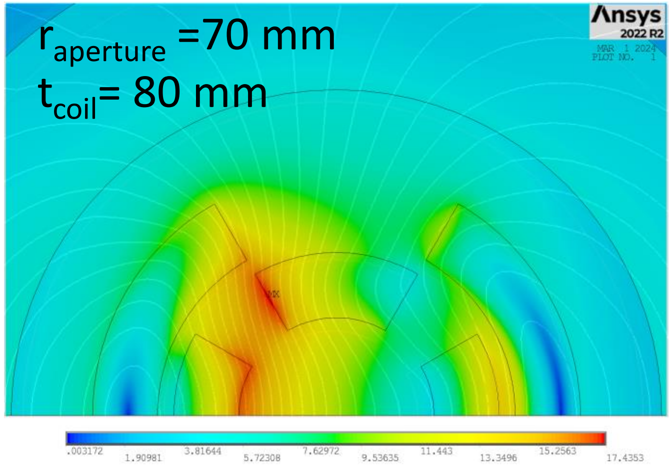
Preliminary discussion on combined function magnets

Nested coil design



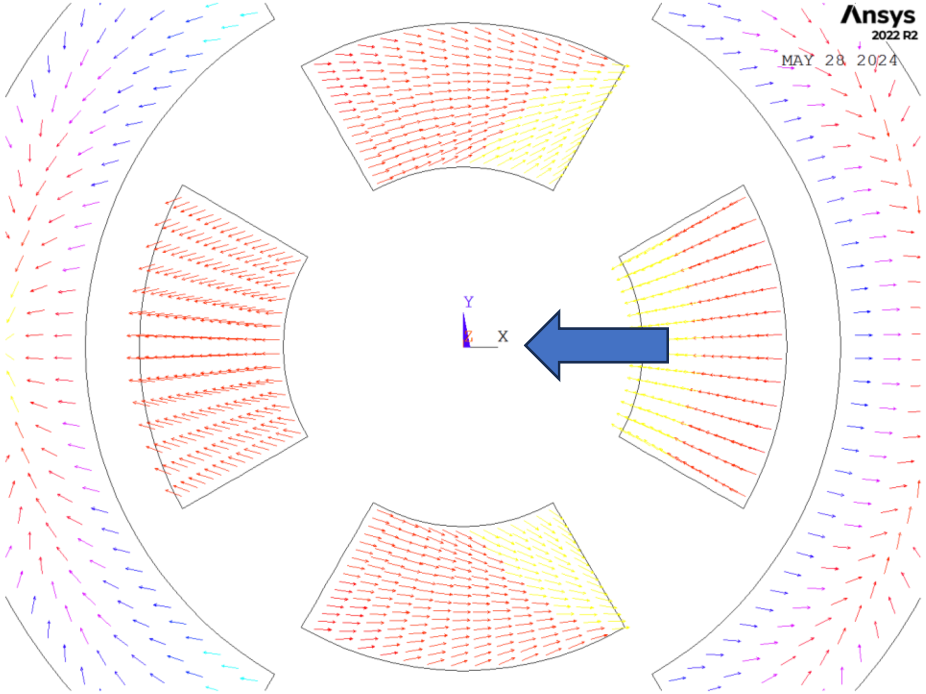
$r_{aperture}$ =70 mm
t_{coil}= 80 mm

B = 11.7 T
G = 143.3 T/m
B_{peak} = 17.5 T



$r_{aperture}$ =70 mm
t_{coil}= 80 mm

B= 12.4
G= 90.4 T/m
B_{peak}= 16.3 T



- Lorentz forces pushed quadrupole coil inward: internal mechanical structure needed (as also stated in [4] by

See D. Novelli

- Very preliminary results obtained with ANSYS in sector coil approximation
- Quadrupole inside dipole more efficient (in agreement with [3] by V. Kashikhin)

[3] V.Kashikhin et al. “High-FieldCombined-Function Magnets for a 1.5-1.5 TeV Muon Collider StorageRing,” in Proc. 12th Int. Particle Acc. Conf., pp. 3587–3589, JACoWPublishing, Geneva, Switzerland
[4]