Dipole magnet designs for the Muon Collider

S. Mariotto[1,2], L. Alfonso[3], A. Bersani[3], B. Caiffi[3], S. Farinon[3],

F. Mariani[2,4], D. Novelli[3,4] , A. Pampaloni[3], T. Salmi[5] , L. Bottura[6]

[1]University of Milan, [2]INFN – Milan, [3]INFN – Genoa, [4]Sapienza University of Rome, [5]Tampere University, [6]CERN

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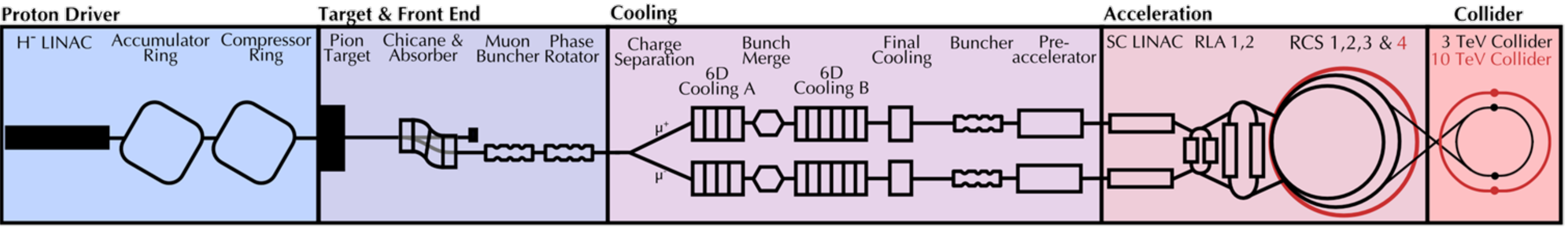
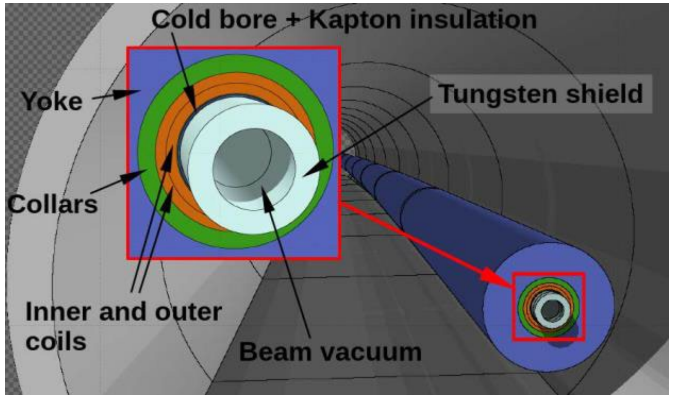
COLLIDER RING MAGNETS





Task 7.4 Collider Ring Magnets (INFN)

Motivation:

1. **Analyze realistic technical design options** for the development of superconducting magnets for the 10 TeV Muon Collider main ring

2. **Identify technical challenges** limiting magnet performance and **propose innovative technologies** to be further developed in the R&D phase following the ongoing feasibility study.

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

- Highest field possible to minimize ring
- Open midplane or large aperture (150 mm bore diameter) for shielding against heat (500 W/m) and radiation loads
- Combined function (dipole + quadrupole) to minimize neutrino hazard

INTERACTION WITH OTHER WPs

International UON Collider Collaboration

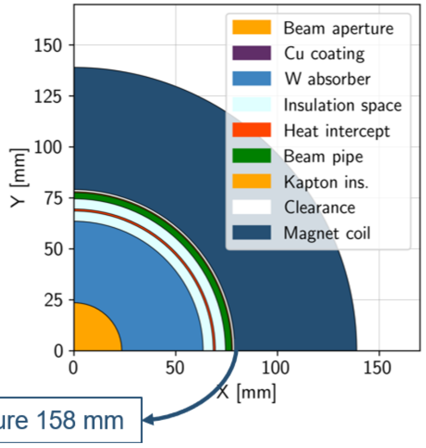
Courtesy of Patricia Borges de Sousa
https://indico.cern.ch/event/1250075/contributions/5357594/

Collection of requirement and constraints coming from other WP studies to select most challenging magnet configuration for technical design study:

1. **Beam Lattice design:**
   - Magnet type / Field / Aperture
2. **Cryogenic studies:**
   - Operating Temperature, Thermal Insulation thickness
3. **Radiation heat loading/degradation**
   - Shielding thickness, Radiation heat load, radiation dose

- 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



Radial build

	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 – IPAC24 Conference
https://cds.cern.ch/record/2912945

N.B bore_{magnet}= beam aperture (23.5 mm) + [Cu layer beam screen,+ Insulation space & heat intercept + beam pipe + Kapton insulation + clearence] (15.5 mm) + W_{abs} (30-40 mm)

ARC Magnet Shielding assumption:

- **T_{op} < 10 K:**

W_{abs} = 4 cm (P<5 W/m) / 160 mm aperture

- **T_{op} = 20 K:**

W_{abs} =3 cm (P<10 W/m) / 140 mm aperture

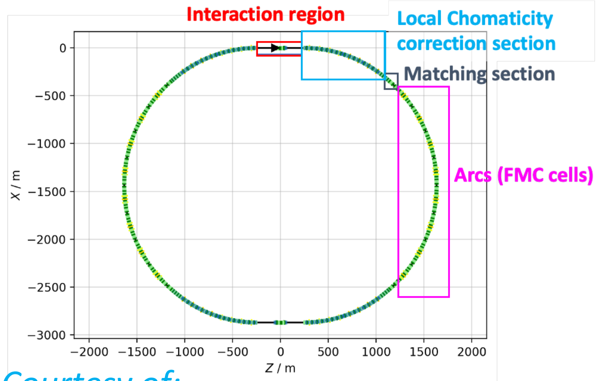
Different Magnet Options: Specs from Beam Optic Studies

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

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^2 in 130 mm bore aperture

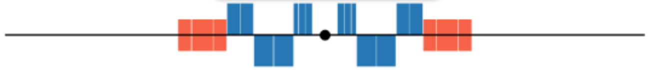


Courtesy of:
C. Carli, K.Skoufaris , M. Vanwelde

[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

Interaction region[2]



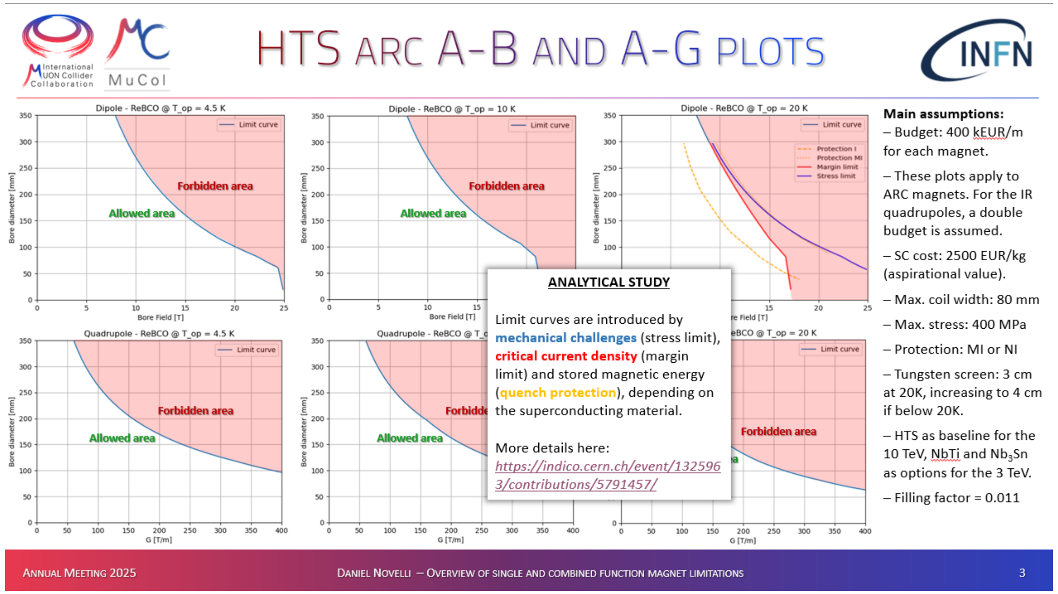
Name	L [m]	Magnet aperture diameter [mm]	B[T]
IB2	6	320	8.1
IB1	10	320	-9.7
IB3	6	320	8.1
Name	**L [m]**	**Magnet aperture diameter [mm]**	**G [T/m]**
IQF2	6	280	85.2
IQF2_1	6	266	85.2
IQD1	9	290	-115.4
IQD1_1	9	290	-115.4
IQF1B	2	204	205.1
IQF1A	3	172	241.8
IQF1	3	140	302.2

Several magnet types are necessary for the collider lattice:
Dedicated FEM study for each configuration NOT POSSIBLE

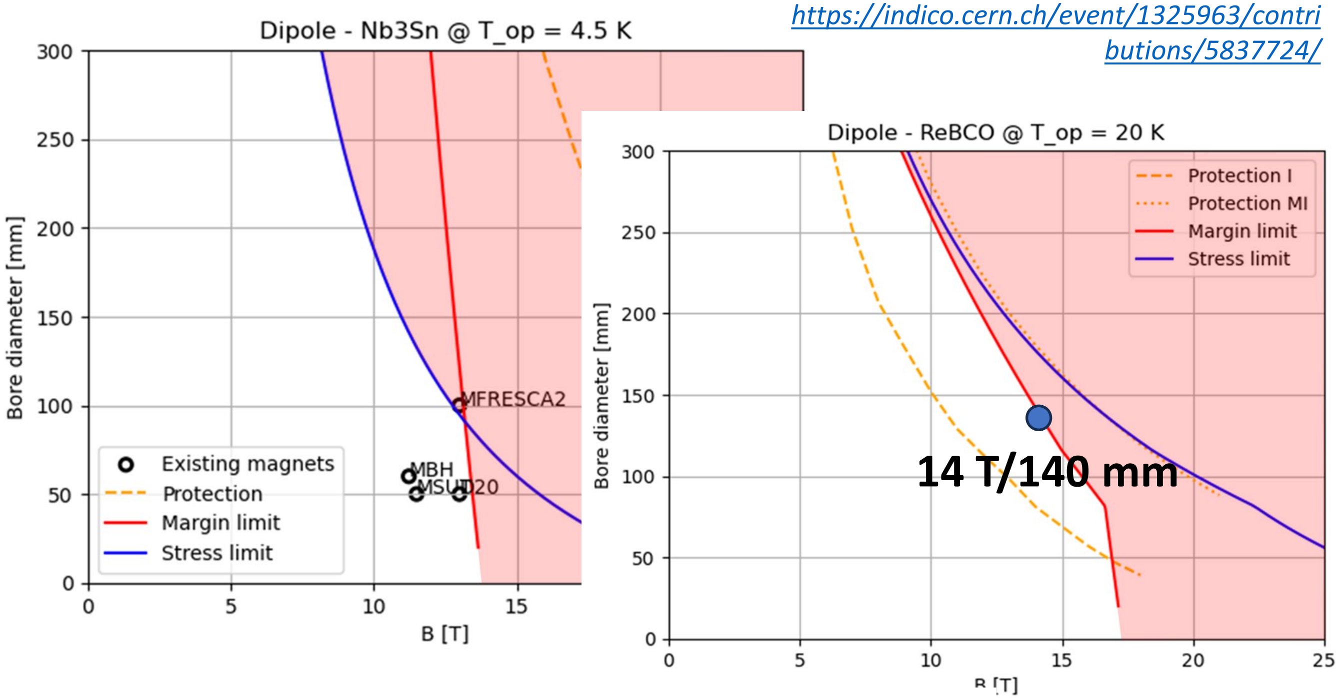
→ **Analytical tool** to evaluate space parameters Field/Aperture

Working Point for FEM Models

Courtesy of D. Novelli @ IMCC-2025
https://indico.desy.de/event/45968/contributions/186264/



Courtesy of D. Novelli @ IMCC-2024
https://indico.cern.ch/event/1325963/contributions/5837724/



Selection of interesting design configuration using A-B plots for the ARC DIPOLE collider magnets in parallel with phase space exploration

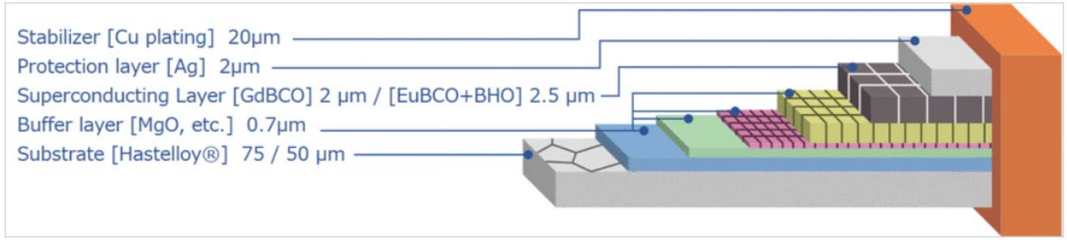
Main outcome from Analytical exploration:

- **Nb_3Sn** limited by **operating margin** and Peak stress for B >14 T
- **HTS (ReBCO) limited by Cost** and **protection**.
  - Metal insulated (MI) or Not Insulated (NI) coils must be used.

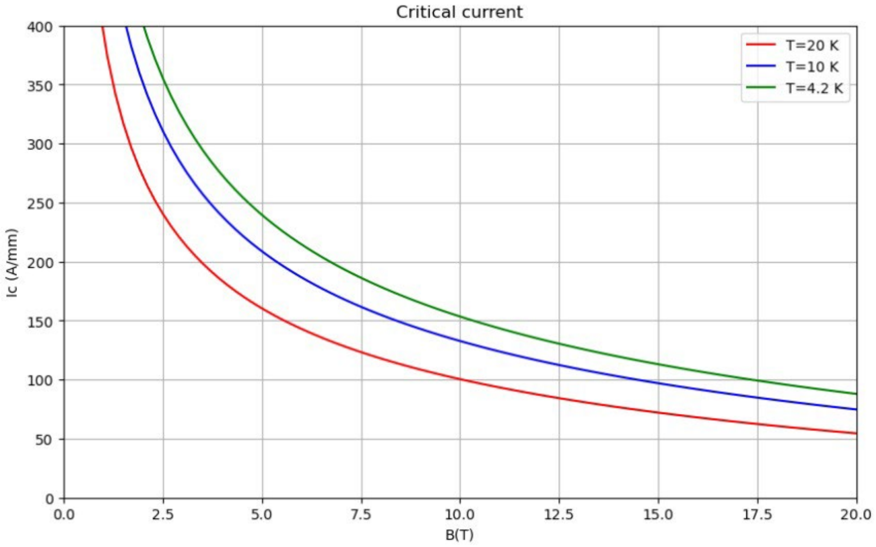
FEM DESIGN
High Field Large Bore
HTS Dipoles

HTS Cable Assumptions

Fujikura FESCH-12 AP tape [1]

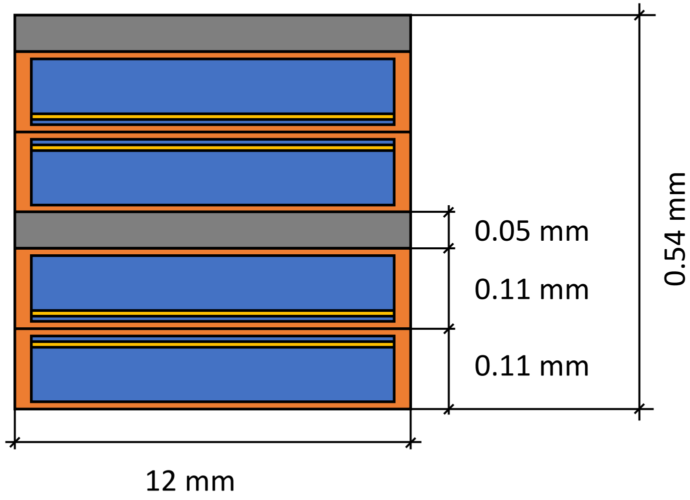


[1] https://www.fujikura.co.uk/netalogue/pdfs/Fujikura%20Superconductor%20Guide.pdf
[2] D. Uglietti at al. "Non-twisted stacks of coated conductors for magnets: Analysis of inductance and AC losses" https://doi.org/10.1016/j.cryogenics.2020.103118



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

2 tapes co-wounded with 50 μm thick SS layer (x2)



Maximum allowable stresses (only tape without metal layer):

- X-direction: $\sigma_{MAX} = -100$ MPa
- Y-direction: $\sigma_{MAX} = -400$ MPa
- XY-direction: $\sigma_{MAX} > 19$ MPa

ELECTROMAGNETIC DESIGN: BLOCK-COIL LAYOUT

Development of two Different magnet design: **Block-Coil vs Cos-theta layout**

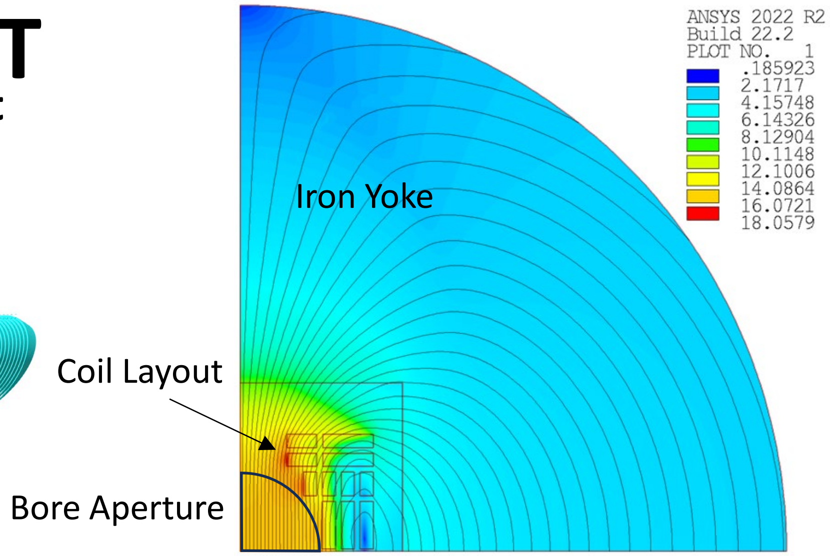
Block-coil advantages:

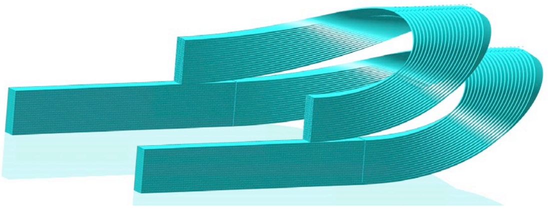
- **Cable configuration suitable to coil geometry winding**
- Better Lorentz forces stress management

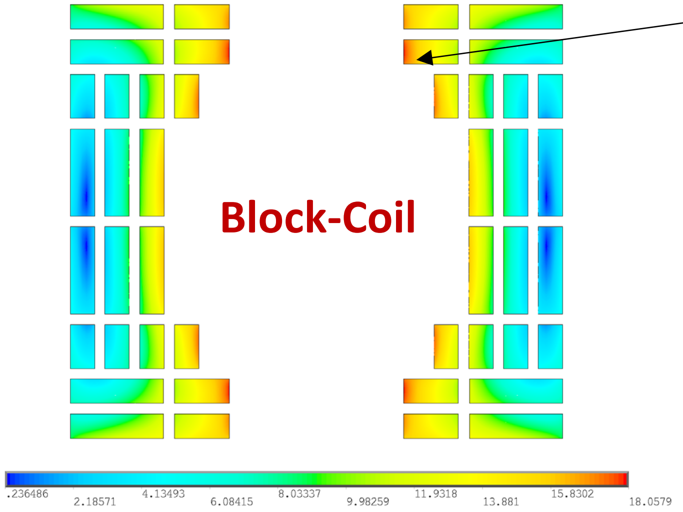
Disadvantages:

- Field quality optimization more difficult

Magnetic Field Maps (T)







$B_{peak} = 18.06$ T

Parameter	Value	U.M.
I_{OP}	3515	A
J_{ENG}	542	A/mm²
J_{COPPER}	1820	A/mm²
B_1	16	T
B_{PEAK}	18.06	T
T_{OP}	20	K

Parameter	Value	U.M.
ΔT_{MARGIN}	2.5±1%	K
Aperture	140	mm
E_{STORED}/V	0.3	J/mm³
E_{STORED}/L	5.3[1]	MJ/m
L	853[1]	mH/m

Harmonics[1]	Value
B3	0.16
b5	-0.36
b7	0.02
Conductor Quantity	
N_{tapes}	10720

Courtesy of L. Alfonso @ IMCC-2025
https://indico.desy.de/event/45968/contributions/185355/

[1]HTS persistent current effect **NOT considered**

ELECTROMAGNETIC DESIGN: $cos(\theta)$ LAYOUT

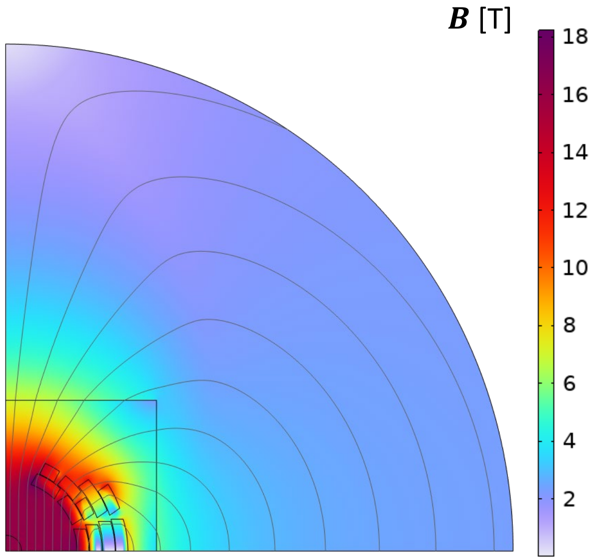
Development of two Different magnet design: **Block-Coil vs Cos-theta layout**

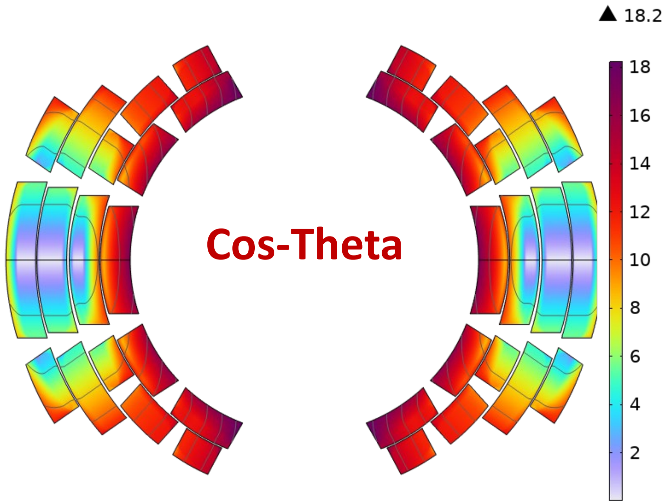
Costheta Advantages

- **Minimization of conductor quantity** in coil cross-section
- **Better field quality optimization** (here considering also HTS persistent current)

Costheta Disadvantages

- Stress management (layer supports still to be implemented)





Parameter	Value	U.M.
I_{OP}	3700	A
J_{ENG}	571	A/mm^2
J_{COPPER}	1916	A/mm^2
B_1	16	T
B_{PEAK}	18.2	T
T_{OP}	20	K

Parameter	Value	U.M.
ΔT_{MARGIN}	2.5±1%	K
Aperture	140	mm
E_{STORED}/V	0.29	J/mm^3
E_{STORED}/L	3.9	MJ/m
L	534	mH/m

Harmonics[1]	Value
b3	4
b5	-5
b7	-2
Conductor Quantity	
N_{tapes}	8272

Courtesy of F. Mariani @ IMCC-2025
https://indico.desy.de/event/45968/contributions/185356/

[1]HTS persistent current effect **considered**

PERSISTENT CURRENT MODELS

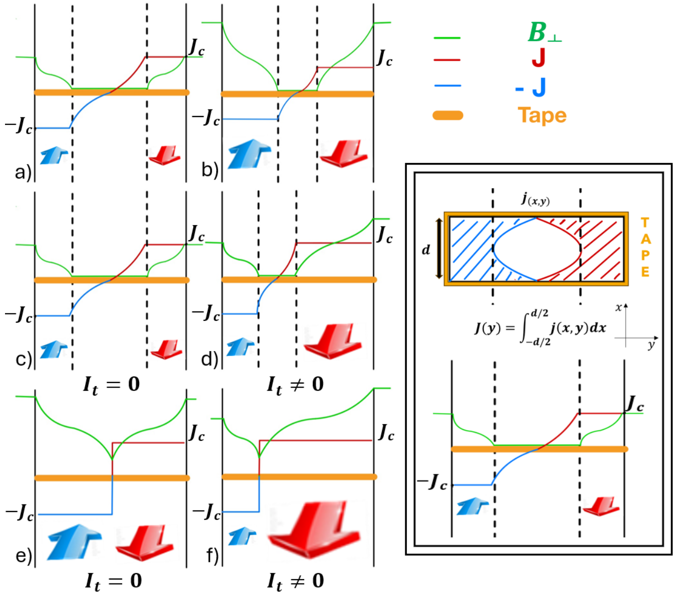
Courtesy of F. Mariani @ IMCC-2025
https://indico.desy.de/event/45968/contributions/185356/

Development of electromagnetic modelling for **FAST** persistent current simulation in HTS magnet cross-section:

- Tape orientation optimization
- Induced peak lorentz forces on conductor estimation

Analytical Model in MATLAB (Brandt) or FEM Model (COMSOL)

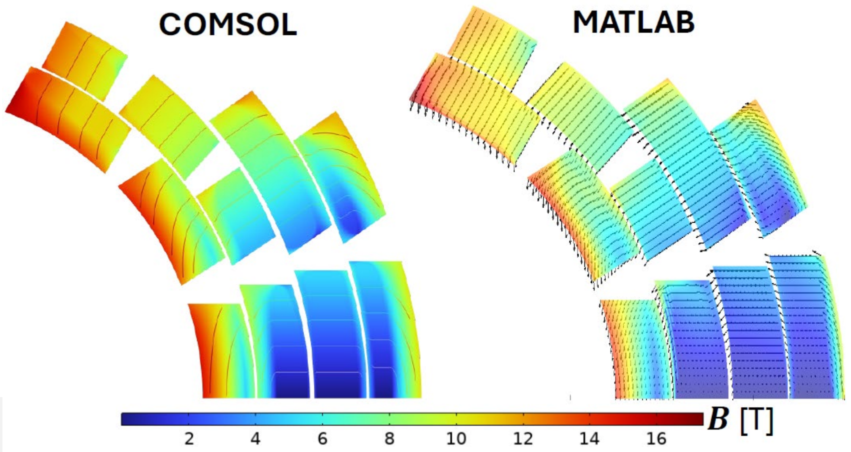
- **Compatible results on hysteretic losses**

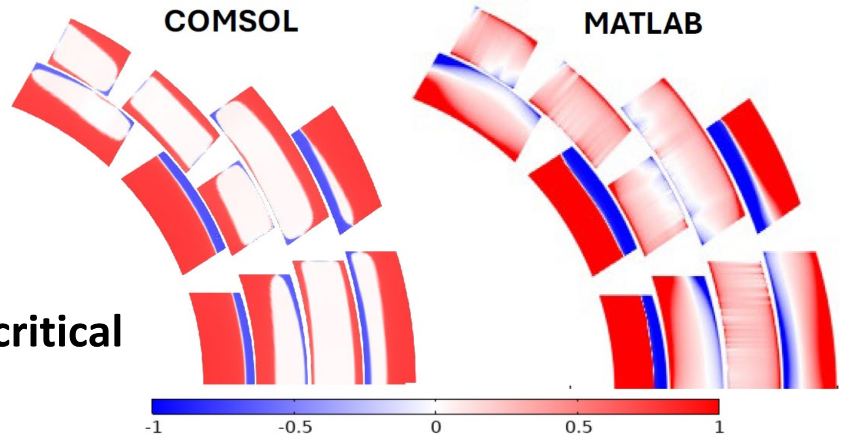


Losses Calculation	COMSOL	MATLAB
Q_{hyst}	22.5	22

Harmonic	COMSOL	MATLAB
b3	3	4
b5	-7	-0.2
b7	-3	-0.05

Harmonic content **strongly affected** by **critical current saturation** in tape cross-section

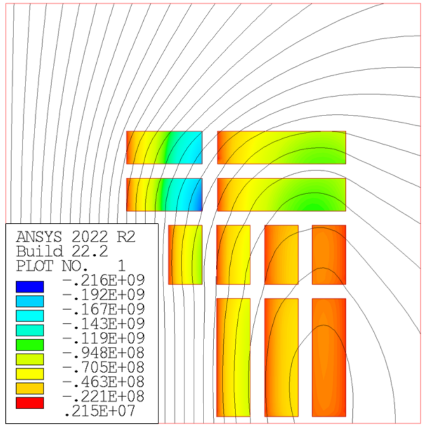




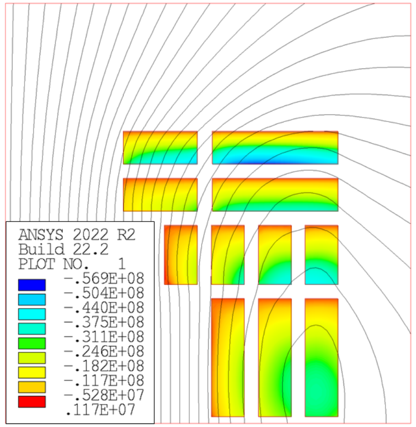
Mechanical Design

Uniform current distribution

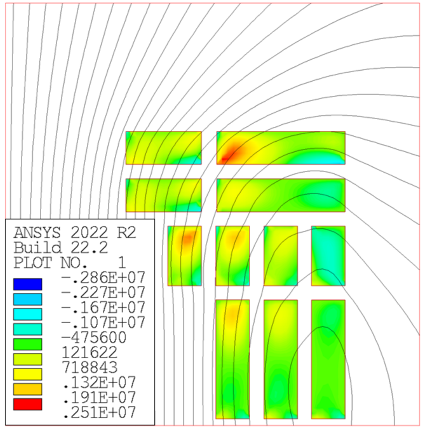
Horizontal x-stress (Pa)



Vertical y-stress (Pa)



Shear xy-stress (Pa)



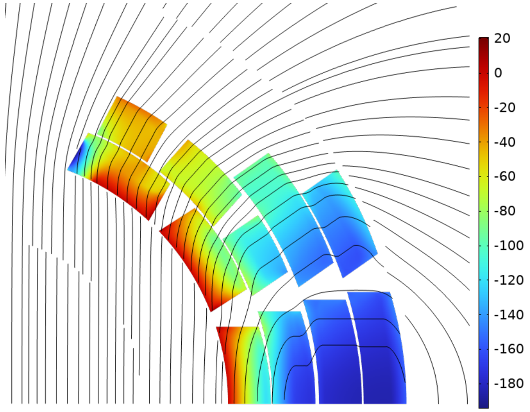
Parameter	Value	U.M.
σ_{X_MAX}	-216	MPa
σ_{Y_MAX}	-56.9	MPa
$\lvert\sigma_{XY\_MAX}\rvert$	2.86	MPa

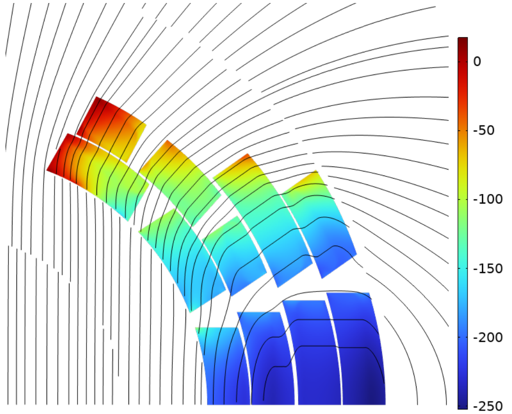
Block-coil stress values are below the maximum allowable limits

Assumptions considered for coil modeling:

- Homogenized coils surrounded by an **infinitely rigid** structure in frictionless contact to avoid peak stress and intercept forces
- Maximum **allowable stresses**:
  - ∥ tape face: σ_{max} = -100 MPa
  - ⊥ tape face: σ_{max} = - 400 MPa

Non-uniform current distribution due to magnetization





E_{COIL} = 174 Gpa [1], ν_{COIL} = 0.3

Parameter	Value	U.M.
$\sigma_{r_{MAX}}$	-194	MPa
$\sigma_{\theta_{MAX}}$	-252	MPa

[1] Barth, Christian & Mondonico, G & Senatore, C. (2015). Superconductor Science and Technology. 28. 045011. DOI: 10.1088/0953-2048/28/4/045011.

Cost Estimation Check

Same Cost Model previously used for the evaluation of entire collider magnet total cost

- Modified cost model presented at IMCC (see B. Caiffi talk) still to be implemented in the evaluation
- Compatible results with analytical prediction and scaling
- Costheta magnet evaluation to be updated after stress management optimization

Cost Assumption (C)

Material	Value	U.M.
ReBCO tape	2500	€/kg
Stainless Steel	10	€/kg
Iron	8	€/kg
Labor	20000	€/m

Density Assumption (ρ)

Material	Value	U.M.
ReBCO tape	8000	kg/m³
Stainless Steel	7800	kg/m³
Iron	7800	kg/m³

Cost Estimation: $C = (\sum A_n \cdot C_n \cdot \rho_n) + C_{LABOR} \qquad (€/m)$

Block Coil Design		
Material	Value	U.M.
ReBCO tape	281	k€/m
Stainless Steel	17	k€/m
Iron	43	k€/m
Labor	20	k€/m
Total Cost	361	k€/m

Costheta Design		
Material	Value	U.M.
REBCO tape	217	k€/m
Stainless Steel	17	k€/m
Iron	43	k€/m
Labor	20	k€/m
Total Cost	297	k€/m

Field Free Magnetic Length

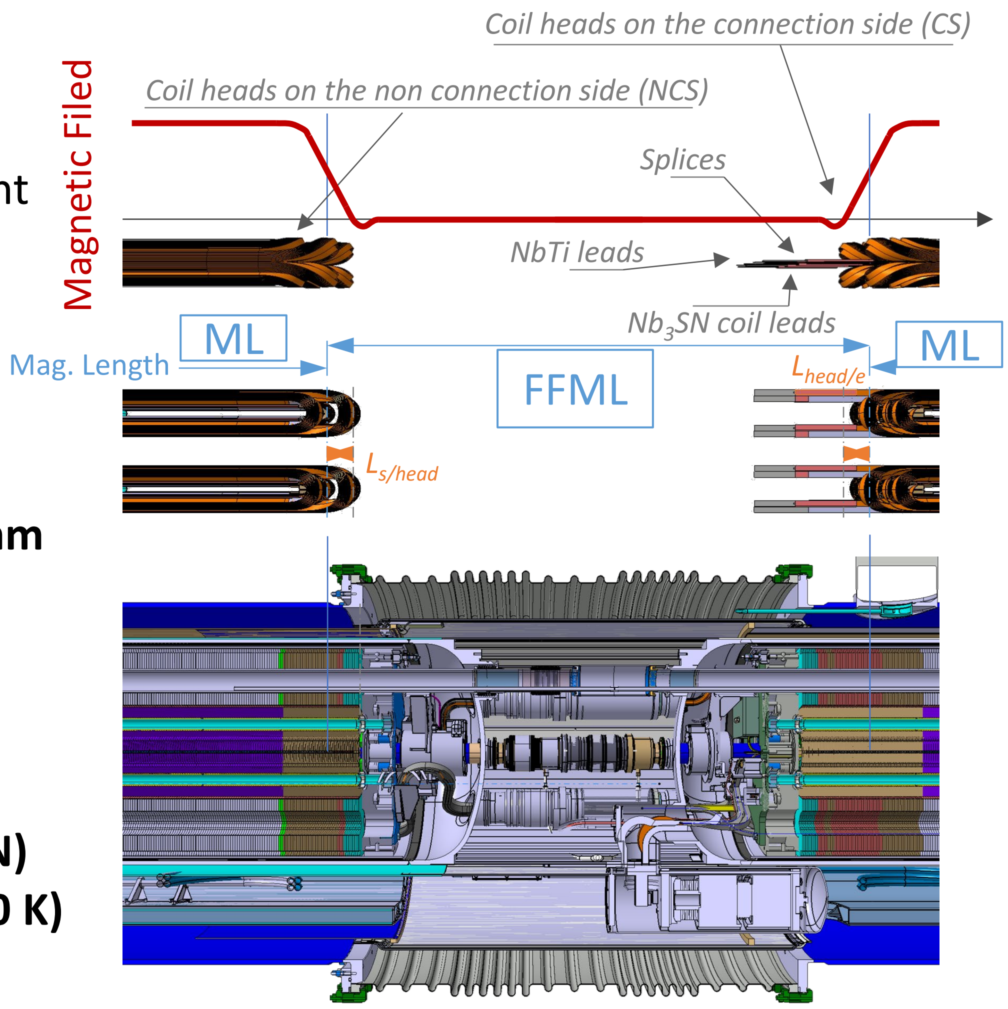
Recap from H. Prin [presentation](#) @ mmWG 13th June 2024:
Collection of superconducting magnet connection between two different cryostat and within the same cryostat interface.

1. LHC MB (NbTi, 1.9 K) **1200/1300 mm (LHC $L_{d\text{-}d}$=1.36 m)**
    - Coil Length - Magnetic Length = **236 mm**
    - CSpoolpiece corrector: **176 mm**
    - Magnet End Plate/Cold mass: **226.5 mm**
2. MQXFa/b for the HL-LHC project (Nb3Sn, 1.9 K) Q2A/Q2B **L= 2090 mm**
    - Coil Length - Magnetic Length = **109 mm**
    - CSpoolpiece corrector: **NA**
    - Magnet End Plate/Cold mass: **228 mm**

Possible method to minimize FFML

- **Compact Coil ends (difficult for HTS/200mm typical value for Nb_3SN)**
- **Reduction of cold mass head equipment (for example with T_{op} = 20 K)**

$$\Delta L = -100/300\ \text{mm} \qquad L_{FFML} > 1000/1200\ \text{mm}$$

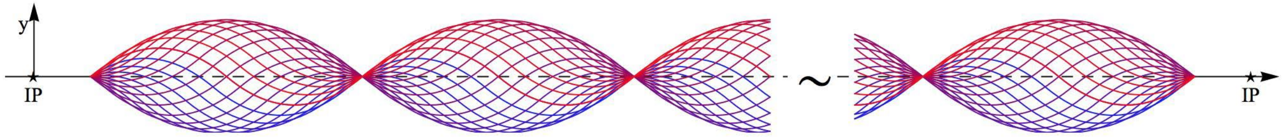


[E. Todesco, "Optimizing the filling factor in high energy colliders"](#)
[P. Ferracin, MQXF Design Overview - HL-LHC/LARP Review](#)

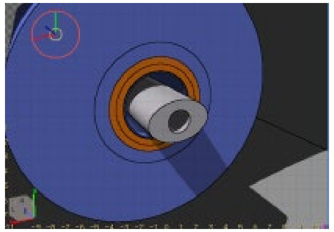
MUON BEAM WOBBLING

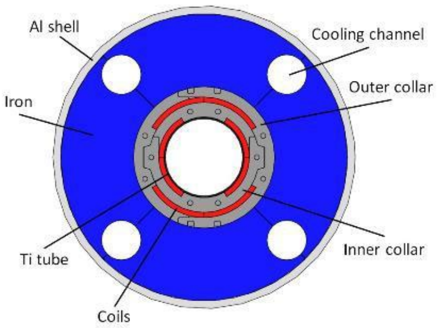
Possible implementation of horizontal field (FOR DISCUSSION)

REQUIREMENTS:
- $B \sim 0.67\ T$ for 100 m period and ± 25 mm
- Tunable horizontal dipole field



1. **External Steering Magnet** outside of the main dipole/combined function magnet
   - Integrated strength: ± 8.375 Tm
   - Easier implementation and tunability
   - **Additional length** between the magnet
2. **Magnet handling with additional coil** (horizontal dipolar field)
   - Already implemented in **HL-LHC MCBXF** (**Ciemat**)
     - 150 mm aperture magnet (2.1 T Vertical – 2.1 T Horizontal field)
     - **Main issue**: **TORQUE 147 kNm/m**
       - **EXAMPLE: 16 T vertical – 0.67 T horizontal → 350 kNm/m**
     - **Difficult for 3 combined function magnets (HD-Q-VD)**
3. **Fixed magnet position with additional coil**
   - **Larger bore aperture/inner elliptical tungsten layout (horizontal thickness >vertical thickness)**





Courtesy of F. Toral

CONCLUSIONS

- **Finite element models** for large aperture high field **HTS dipoles** have been started and are being presently developed to address **technological challenges** to be solved during the R&D phase of superconducting magnet development
- Analytical/FEM models for **persistent current simulation** already implemented for **costheta** magnet layout used to address HTS dynamic effects during magnet operation and evaluate impact on **field quality and losses**
- **Stress management** design must be further studied including peak stress at conductor level
  - **Block coil** design more suitable for stress management configuration
  - **Costheta** magnet layout to be implemented
- **Field free magnetic length > 1 m** are like to be considered depending on connection scheme
- Additional horizontal field in collider magnet to be further developed
  - Separate magnet layout / nested solution

Thank you for the attention

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