First Considerations on the Electromagnetic and Mechanical Design of a Block-Coil Dipole for the Muon Collider Ring

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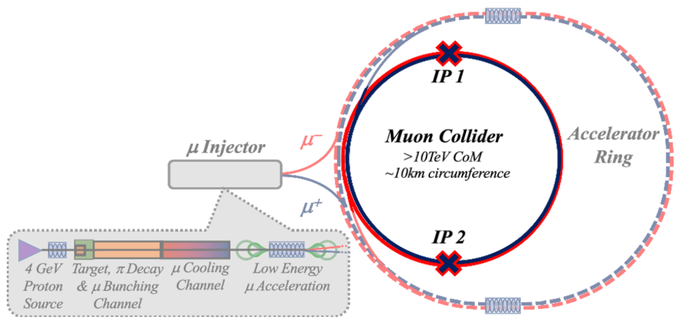
Introduction



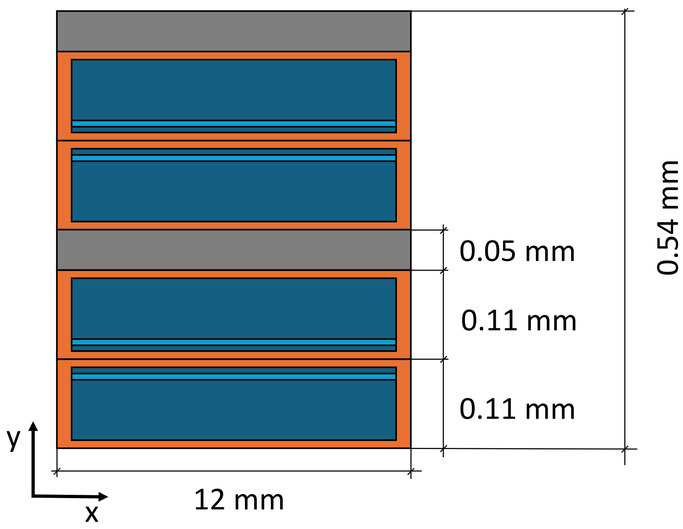
Goal:
Feasibility study and new technological solutions for an innovative muon accelerator of a 10-km-long collider ring with a center-of-mass energy of 10 TeV.

Main Challenges:
- Short lifetime of muons (2.2 μs at rest)
- Production and cooling processes
- Shielding for muon decay
- High field magnets with large aperture and ambitious quench protection

Main Magnet Requirements

- HTS technology
- T_{OP} = 20 K
- ΔT_{MARGIN} = 2.5 K
- B_1 = 16 T
- Ø= 140 mm
- b_n<1 unit

Cable Assumptions



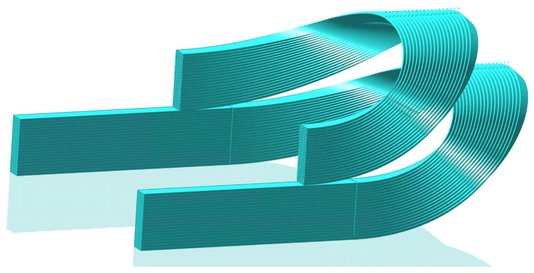
$$R_{Cu/SC} = \frac{A_{Cu}}{A_{SC}} = 16.15$$

$$f_f = \frac{A_{SC}}{A_{tot}} = 0.018$$

- Not twisted **stacked** tapes cable
  - ➢ 2 ReBCO tapes co-wounded with SS layer (x2)
- Maximum **allowable stresses** (only tape without metal layer):
  - ➢ X-direction: σ_{MAX} = -100 MPa
  - ➢ Y-direction: σ_{MAX} = -400 MPa
  - ➢ XY-direction: σ_{MAX} > 19 MPa

Innovative Ends Winding Design

Main Mechanical Disadvantages:
- ReBCO = ceramic material → extremely **brittle**
  - ➢ Crack with a tensile strain about 0.6 %
    - ↳ Permanent degradation of its current-carrying capability
- **Delamination**
- Tape cable can be bent BUT only with **limited flexibility**

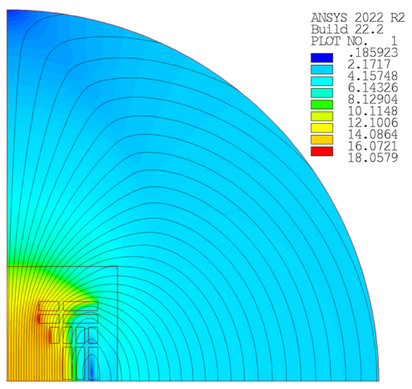


- Possible winding technique: flared-ends
- Winding in the **easy-way** direction, i.e. along the broad face of the tape
- **Assembly tests** required

Electromagnetic Optimization

- Sensitivity study using as free parameters the number of turns and the blocks positions
- Analytical harmonics calculation **neglecting magnetization** effects (current redistribution)
- Use of **Roxie** software

Magnetic Field Maps (T)



Harmonic	Value
b1	10000
b3	0.16402
b5	-0.36534
b7	0.01796
b9	0.00008

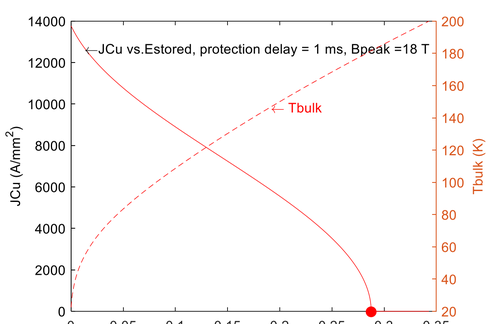
Parameter	Value	U.M.
I_{OP}	3515	A
J_{ENG}	542	A/mm²
J_{COPPER}	1820	A/mm²
B_1	16	T
B_{PEAK}	18.06	T
T_{OP}	20	K

Parameter	Value	U.M.
ΔT_{MARGIN}	2.5±1%	K
E_{STORED}/V	0.3	J/mm³
E_{STORED}/L	5.3[1]	MJ/m
L	853[1]	mH/m
N_{TAPES}	10720[1]	-

[1] Value referred to the entire cross-section

Quench Protection Analysis

- Estimation of maximum Stored Energy Density through analytical calculation



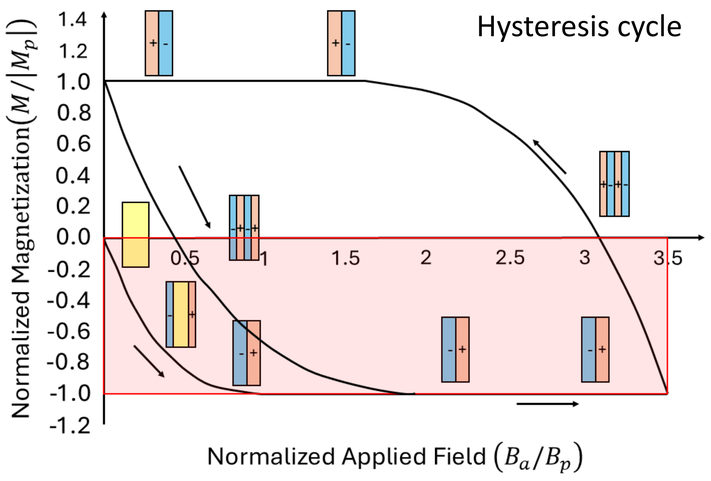
Main assumptions:
- B_{PEAK} = 18 T
- T_{MAX} = 200 K
- t_{DELAY}[2] = 1 ms

[2] Time at constant current before the entire magnet quenches and energy dissipates uniformly

Maximum Stored Energy Density < ~0.28 J/mm³

Estimation of the Hysteretic Losses

- **Bean's critical state model**
- Slab geometry
- Assumption of complete **tape saturation**



- **Overestimation** of the hysteretic losses in the ramping phase (red rectangle area) → worst-case scenario
- Estimation through magnetization calculation:
  - ➢ $\vec{M} = \frac{\vec{m}}{V} = -\frac{1}{2V}\int \vec{r} \times \vec{J}(B)\, dV \qquad \left(\frac{A}{m}\right)$
- Hysteretic losses **without** the effects of the transport current:
  - ➢ $Q_{sat} = M\overline{B}A = \frac{1}{4}J_C\overline{B}w_{SC}^2 t_{sc} \qquad \left(\frac{J}{m}\right)$
- Hysteretic losses **with** the effects of the transport current:
  - ➢ $Q_{sat} = M\overline{B}A = \frac{1}{4}J_C\overline{B}w_{SC}^2 t_{sc}\left(\left(\frac{J_t}{J_c}\right)^2 + 1\right) \qquad \left(\frac{J}{m}\right)$

where: w_{SC}= width of SC layer J_t= transport current density
t_{SC}= thickness of SC layer

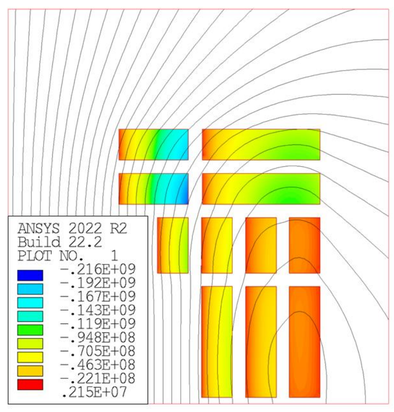
Parameter	J_T=0	$J_T \neq 0$	U.M.
Q_{SAT}	388[1]	482[1]	kJ/m
ΔQ_{SAT}	~20		%

[1] Value referred to the entire cross-section

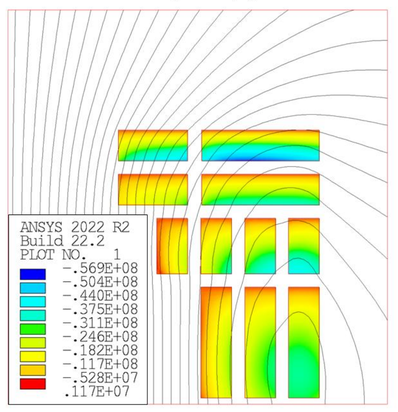
Preliminary Mechanical Calculation

- Homogenized coils surrounded by an **infinitely rigid** structure
- Standard type contacts **frictionless** between pancakes and structure
- Use of **FEM** software ANSYS
- From electromagnetic FEM analysis:
  - ➢ F_x = 15.16 MN/m
  - ➢ F_y = -7.63 MN/m
- E_{COIL} = 174[3] GPa and ν_{COIL} = 0.3

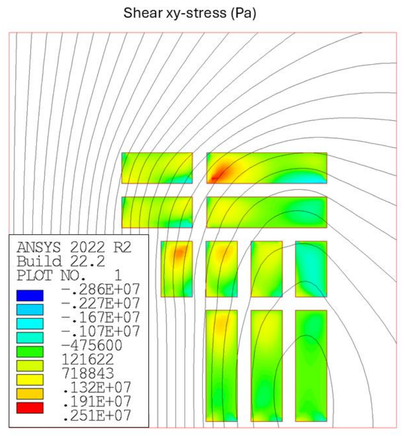
Horizontal x-stress (Pa)



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

All current stress values are **below** the maximum allowable limits

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

Estimation of Magnet Cost

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

Cost Results

Material	Value	U.M.
ReBCO tape	281[1]	k€/m
Stainless Steel	17[1]	k€/m
Iron	43[1]	k€/m
Labor	20[1]	k€/m
Total Cost	361[1]	k€/m

[1] Value referred to the entire cross-section

Conclusions

These preliminary results show that the magnet meets all the performance requirements and operates within the mechanical limits of ReBCO tapes.

Next steps
- Conduct assembly tests using a winding machine to validate mechanically the new end winding concept
- Study in more detail the mechanics

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