International MUON Collider Collaboration

A Superconducting Detector Magnet for the Muon Collider

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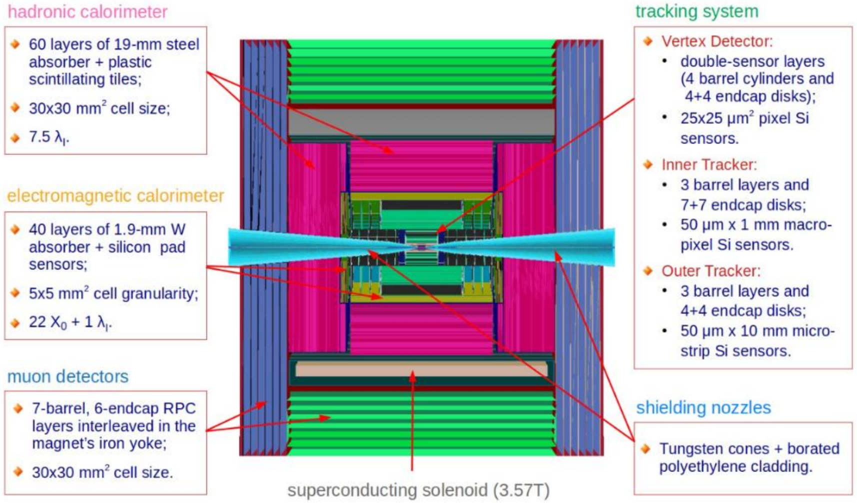
Introduction

- First look at a Muon Collider detector magnet design: Properties, stray field, conductor, stability, mechanics, quench protection
- Cost estimate
- Challenges: Technical, organizational, conductor availability
- HTS-based R&D

CLIC-like Solenoid Concept without Return Yoke



Proposed Muon Collider layout [1]

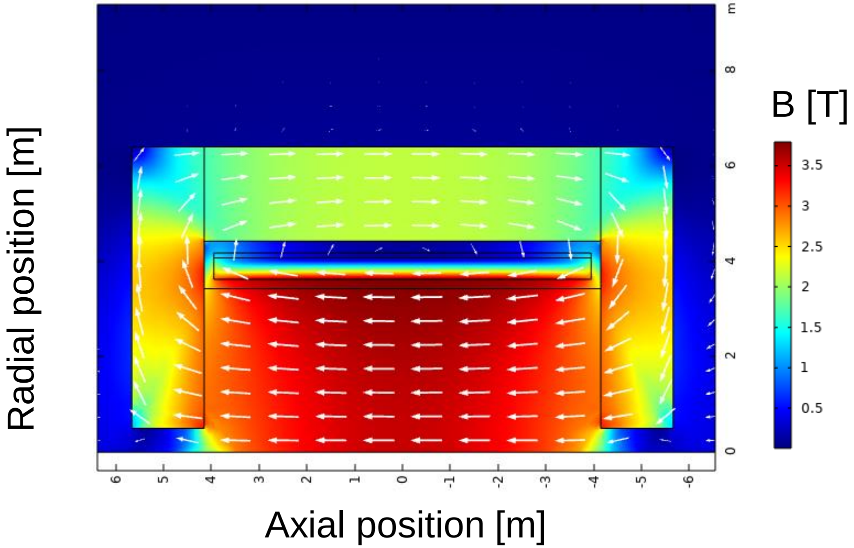
Property	Value
Magnetic field at IP [T]	3.6
Cold mass length [m]	7.89
Free bore diameter [m]	6.85

Field and layout, [2]

- Following [1], here considered: CLIC-like Superconducting Solenoid [2], with 3.6 T at the interaction point

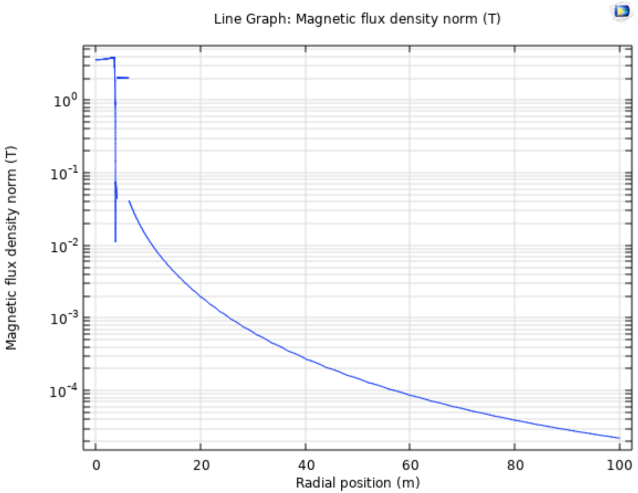
Magnet Properties

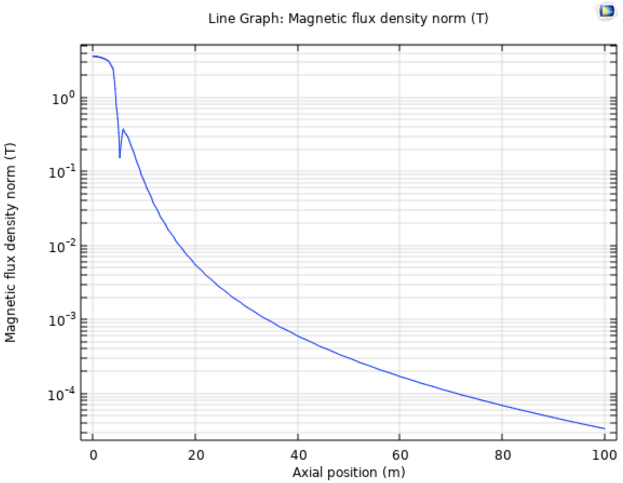
Property	Value
Operating current [kA]	19.5
Stored magnetic energy [GJ]	1.8
Inductance [H]	9.4
Cold mass volume [m³]	53
Cold mass weight [t]	155
Energy density [kJ/kg]	11.6
Windings (layers x turns-per-layer)	4 x 320
Conductor length [km]	36

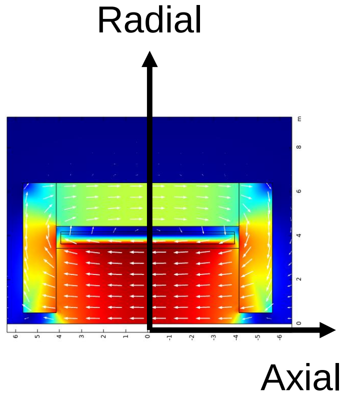


- 3.6 T at IP and with return yoke → 1.8 GJ stored magnetic energy
- For reference, Compact Muon Solenoid has stored energy of 2.6 GJ

Magnetic Stray Field



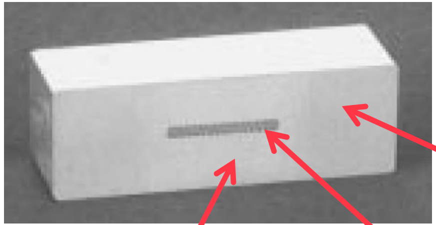




Conductor Considerations (1/2)

- CMS design philosophy: The conductor and mandrel support the Lorentz forces together
- Aluminium-based conductor is cost-effective and gives favourable mechanical, electrical, and thermal properties
- Nb-Ti: Affordable and robust work-horse superconductor
- Two “Standard” options for combining good electrical, thermal, and mechanical properties
  - CMS-like conductor [3]: Pure aluminium conductor with welded-on aluminium-alloy reinforcements
  - ATLAS CS-like conductor [4]: Nickel-doped aluminium
- **An important consideration is manufacturing availability (more on this later)**

CMS conductor

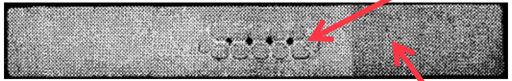


Al-alloy reinforcement (E-beam welded)

Pure aluminium

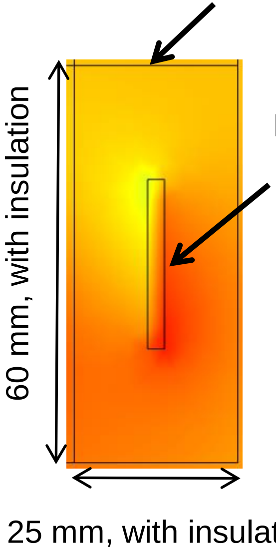
Rutherford cable comprising Nb-Ti/Cu strands

ATLAS CS conductor

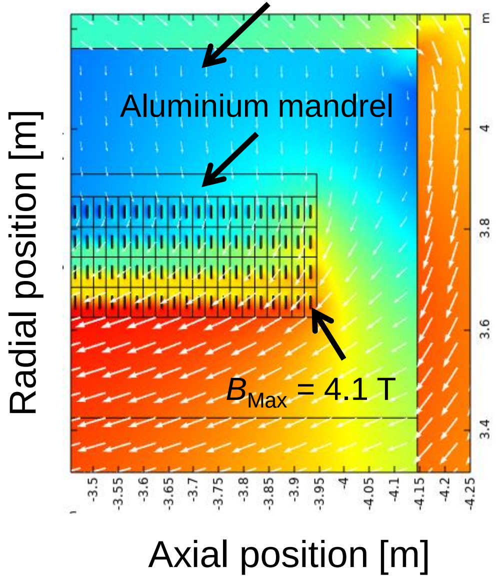


Nickel-doped aluminium

Conductor Considerations (2/2)



Proposed conductor

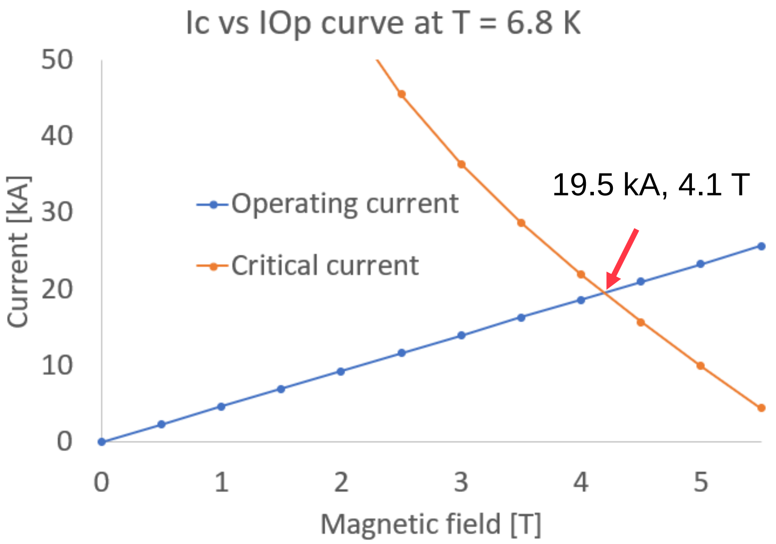


Field map with peak field

Composition	Vol. Fraction
Either (1) Nicked-doped aluminum or (2) pure aluminum + aluminum alloy	90%
Copper	2.2%
Nb-Ti	2.2%
Insulation	5.6%

- Volumetric density: 2860 kg/m^3
- Operating current: 19.5 kA → Current density: 13.2 A/mm^2

Conductor Stability

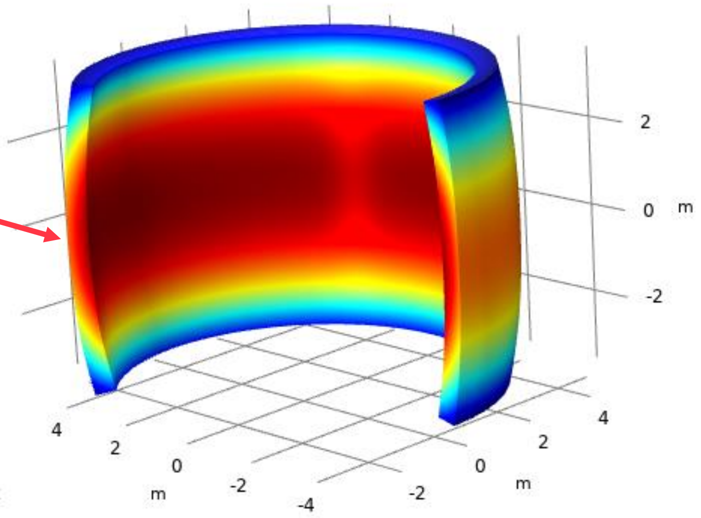


- Peak field on the conductor at nominal current (19.5 kA) = 4.1 T
- With: 32 x 1.6 mm Nb-Ti/Cu strands (50% Cu): Current sharing temperature = 6.8 K
- Operating temperature: 4.5 K
- Margin: 2.3 K → OK
- **The magnet is thus compatible with 'standard' aluminium-stabilized Rutherford cable technology**

Mechanics

Peak Von Mises stress:
94 MPa

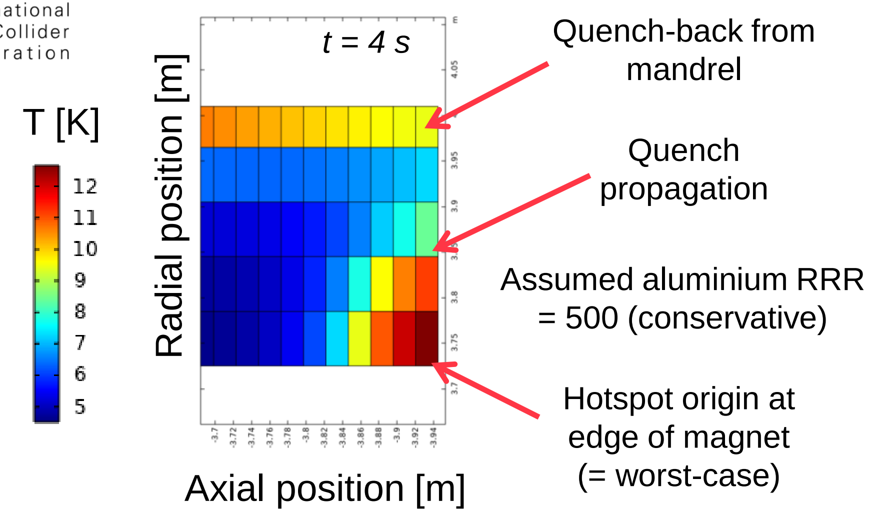
Peak tensile strain:
0.13%



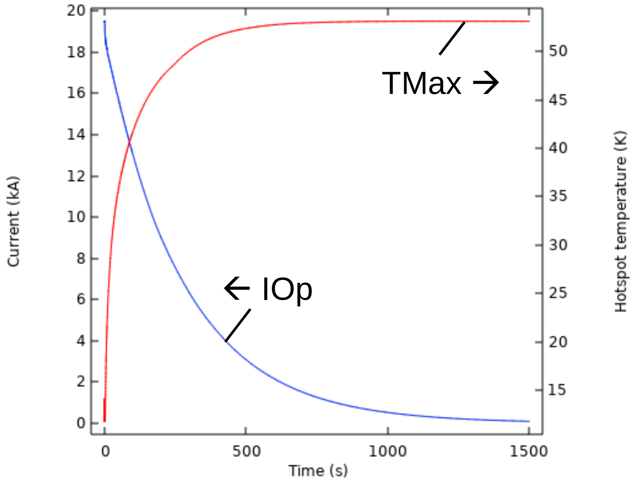
Simulation: Stress and strain at nominal current

- The energy density (= Stored magnet energy / cold mass) = 11.6 kJ/kg (same as CMS)
- At nominal current: 94 MPa maximum von Mises stress, and 0.13% tensile strain (not considering bending strain)
- All looks reasonable

Quench Protection



FEM-based quench simulation: Temperature development during quench



Simulation: Magnet protected with energy extraction

- Quench protection choices: Energy extraction, quench heaters, or combination
- Here considered: Energy extraction after 2 s, with 0.03 mΩ dump resistor (like CMS)
- Gives hotspot temperature of 53 K with correct quench protection, and 149 K for complete absence of quench protection (= failure scenario)

Cost Estimate

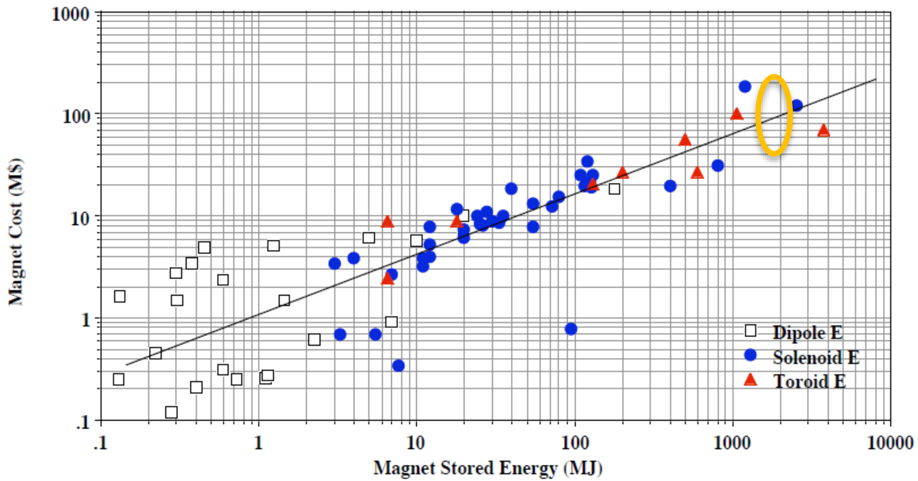


Fig. 2. Superconducting magnet costs (M$) versus stored energy (MJ) for solenoid magnets (closed circles), dipole and Quadruple magnets (open squares) and toroid magnets (closed triangles). The line is a plot of equation 1, which can used to calculate the cost of all magnets.

- Stored magnet energy: 1.8 GJ
- First-order cost estimate based on historical trends [5]: ~80-100 MCHF (2008, not corrected for inflation)

Challenges for the Future

- **Technical challenge: The solenoid properties are similar to those of the Compact Muon Solenoid, so there is a recipe to be followed**

- Organizational challenges (Based on ATLAS and CMS magnet development)
  - There is a 8 – 10 year period between finalization of the design and commissioning of the magnet → **Superconducting detector magnets have to be planned on a time-scale of 15-20 years**
  - Superconducting detector magnets of this scale are developed with strong support of multiple institutes, and tens of people will be working on it for a period of many years → **High-level coordination is a must**
  - Associated cost is on the order of 80-100 MCHF (first estimate)
  - One-of-a-kind magnet that must work without problems, so **technology demonstrators are needed to check aspects of the design** before the design is finalized

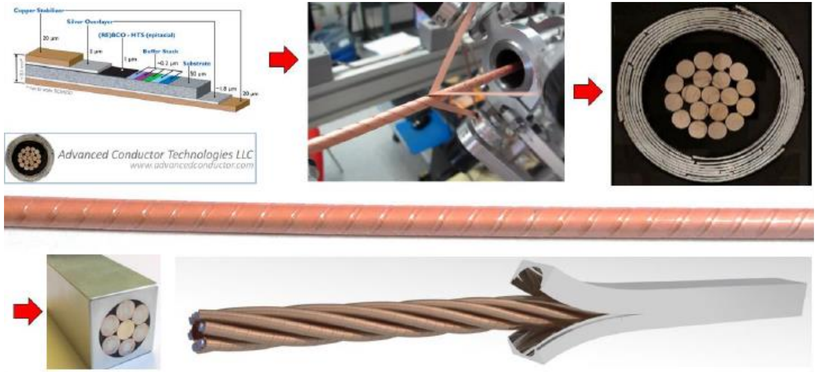
- Conductor challenge: Unlike some tens of years ago, **presently qualified suppliers of aluminium-stabilized conductors are hard to come by**

High-Temperature-Superconductor R&D

- The Nb-Ti superconductor, a low-temperature-superconductor (LTS), is affordable and robust, but requires a low operating temperature (4.5 K)

- High-temperature-superconductors (ReBCO / BSCCO) are (currently) more expensive than Nb-Ti in terms of upfront cost, but allow operation at elevated temperatures (30-40 K), for significant cryogenics cost savings

- Therefore: HTS-based superconducting detector magnet conductor research in anticipation of the future (for example: CORC-CIC in recent years), for coils and for busbars



Example of HTS-based conductor:
CORC-CIC conductor

Summary

- A first look at the superconducting detector solenoid for the Muon Collider
  - Similar to Compact Muon Solenoid, so there is a recipe to follow
  - Conductor matrix options: Nickel-doped aluminium or pure aluminium + aluminium-alloy reinforcements
  - No major showstoppers identified in terms of quench protection and mechanics

- Organizational challenges:
  - Superconducting detector magnet of this size requires a long-term (15-20 years) schedule and support from multiple institutes
  - This magnet will not be cheap, even though detector magnets are designed to be as affordable as possible
  - Demonstrators are needed to check various aspects of the design before a design can be finalized

- Conductor challenge: Currently, no qualified suppliers of aluminium-stabilized conductors in industry

- Consideration of HTS-based detector magnets for potential future cost savings

References

[1]. D. Lucchesi et al., 1st Muon Community Meeting, (2021).
[2]. A. Gaddi et al., International Workshop on Future Linear Colliders, (2012).
[3]. B. Blau et al., IEEE Trans. on Appl. Supercond. 12, p. 345 (2002).
[4]. A. Yamamoto et al., IEEE Trans. on Appl. Supercond. 9, p. 852 (1999)
[5]. M. A. Green et al., IEEE Trans. on Appl. Supercond. 18, (2008).

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Thank you
for attention