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The 3.6 T CLIC-like superconducting solenoid 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
- What does a detector magnet of this size cost?
- CMS Solenoid development history
- Aluminum-stabilized Nb-Ti conductor availability
- Conductor technology alternatives
- Summary

CLIC-like Solenoid Concept

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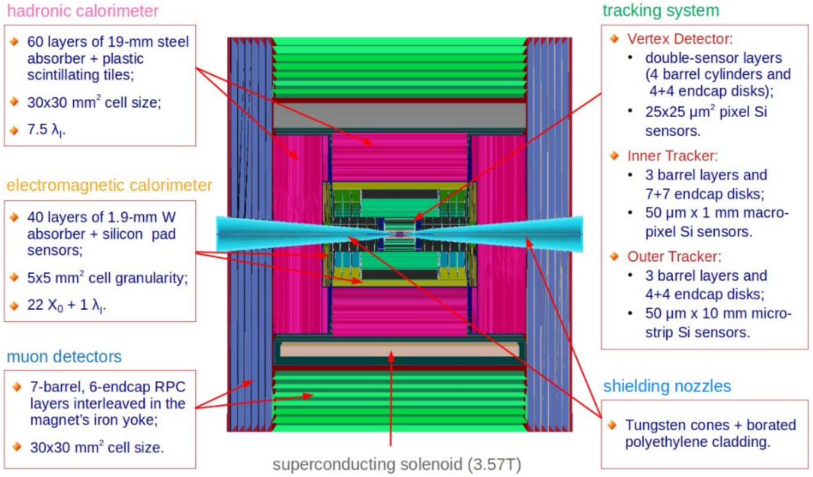


Proposed Muon Collider layout [1]

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

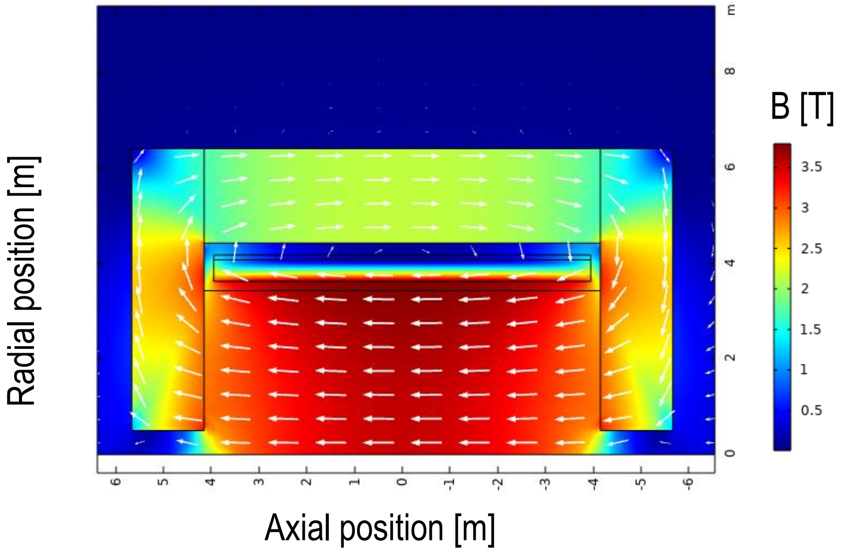
Field and layout, [2]

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

[1]. D. Lucchesi et al., 1st Muon Community Meeting, (2021).
[2]. A. Gaddi et al., International Workshop on Future Linear Colliders, (2012).

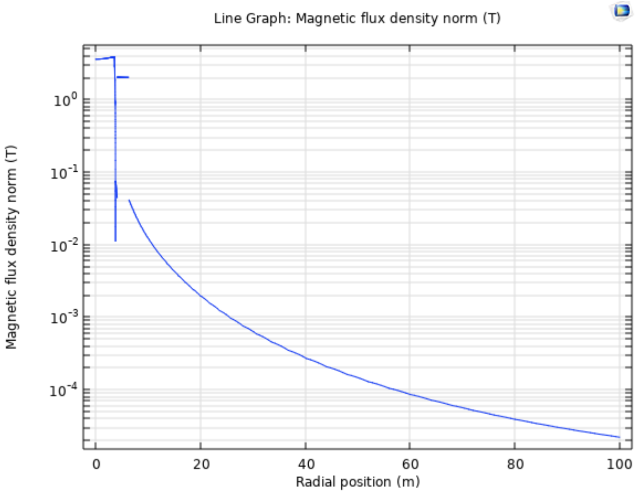
Magnet Properties

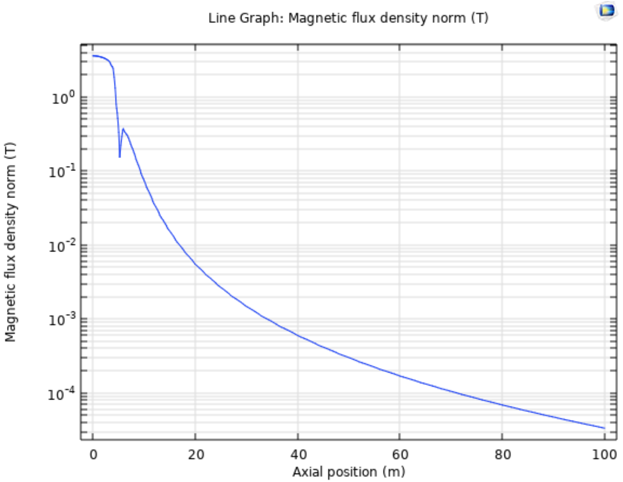
Property	Value
Operating current [kA]	19.5
Stored magnetic energy [GJ]	1.8
Inductance [H]	9.4
Cold mass volume [m^3]	53
Cold mass weight [t]	155
Energy density [kJ/kg]	11.6
Windings (layers x turns-per-layer)	4 x 320
Conductor length [km]	36

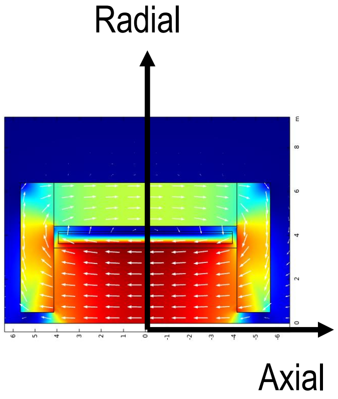


- 3.6 T at IP and with return yoke → 1.8 GJ stored magnetic energy
- For reference, Compact Muon Solenoid has stored energy of 2.4 GJ

Magnetic Stray Field





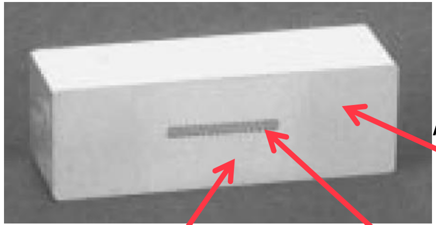


The stray magnetic field may be optimized through optimization of the yoke geometry if needed

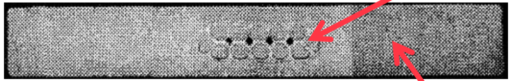
Conductor Considerations (1/2)

- CMS design philosophy: The conductor carries a significant fraction (~80%) of the Lorentz forces
- Aluminium-based conductors are cost-effective and give favourable mechanical, electrical, and thermal properties
- Nb-Ti: Affordable and robust work-horse superconductor, available in long lengths from multiple vendors
- Two proven aluminum-stabilized Nb-Ti conductor variants 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

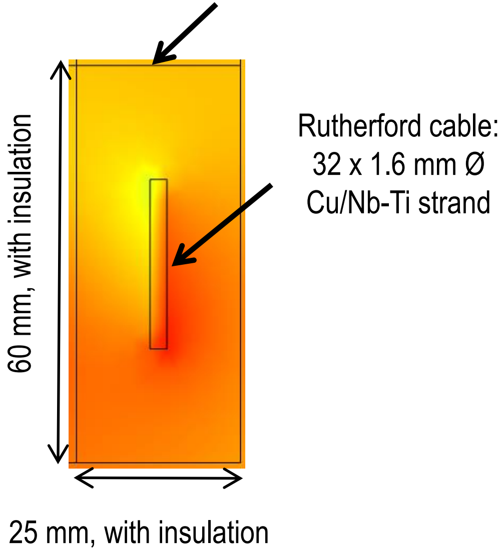


ATLAS CS conductor

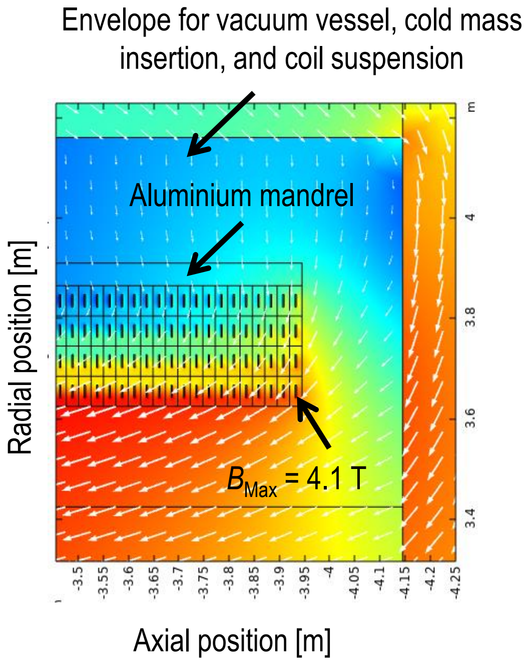


[3]. B. Blau et al., IEEE Trans. on Appl. Supercond. 12, p. 345 (2002).
[4]. A. Yamamoto et al., IEEE Trans. on Appl. Supercond. 9, p. 852 (1999)

Conductor Considerations (2/2)



Possible conductor layout

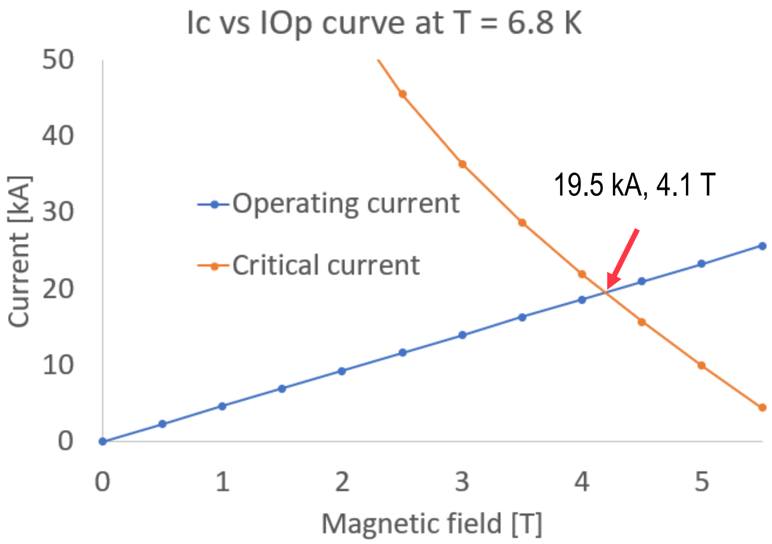


Field map with peak field

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

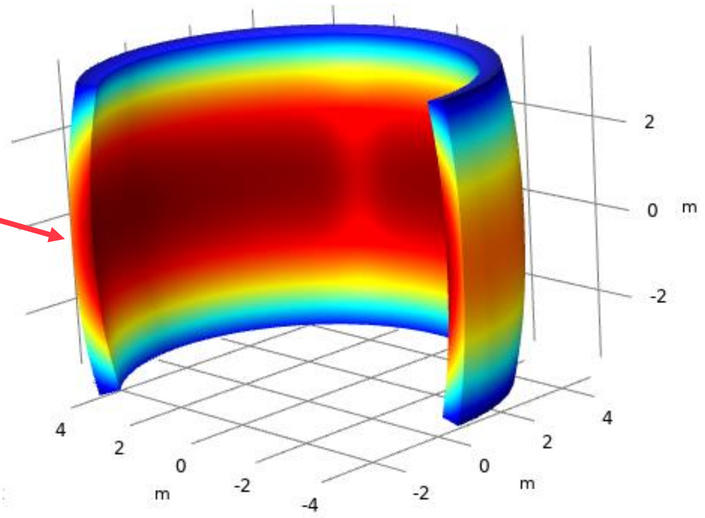


- Peak field on the conductor at nominal current (19.5 kA) = 4.1 T
- With: 32 x 1.6 mm Nb-Ti/Cu strands (50% Cu): Current sharing temperature = 6.8 K
- Operating temperature: 4.5 K
- Temperature margin between current-sharing and operating temperature: 2.3 K → OK
- **The magnet is thus compatible with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

Mechanics

Peak Von Mises stress:
94 MPa

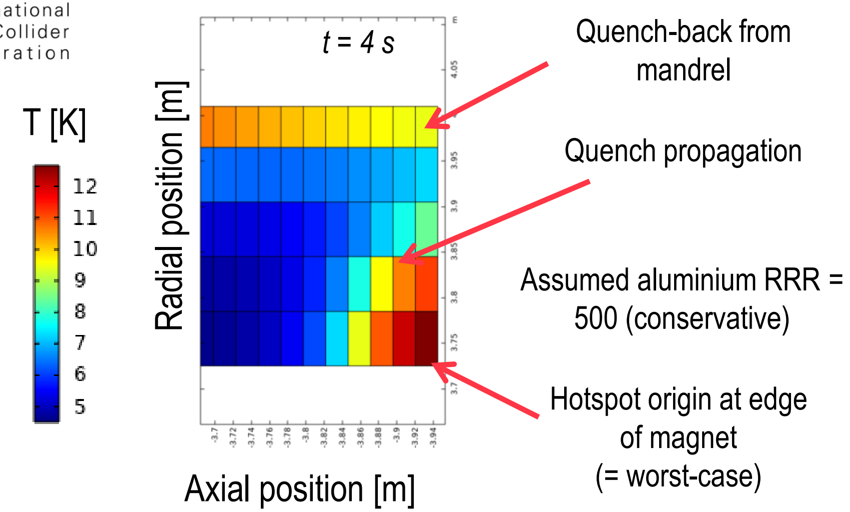
Peak tensile strain:
0.13%



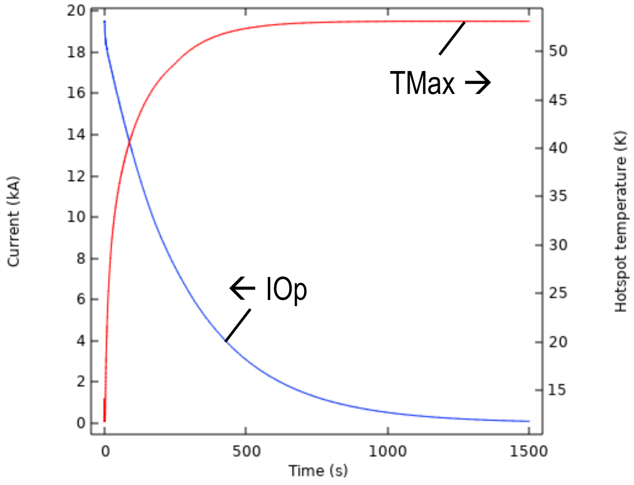
Simulation: Stress and strain at nominal current

- 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 applied to conductor due to powering of the coil

Quench Protection



FEM-based quench simulation: Temperature development during quench



Simulation: Magnet protected with energy extraction

- Quench protection 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)

What does a detector magnet of this size cost?

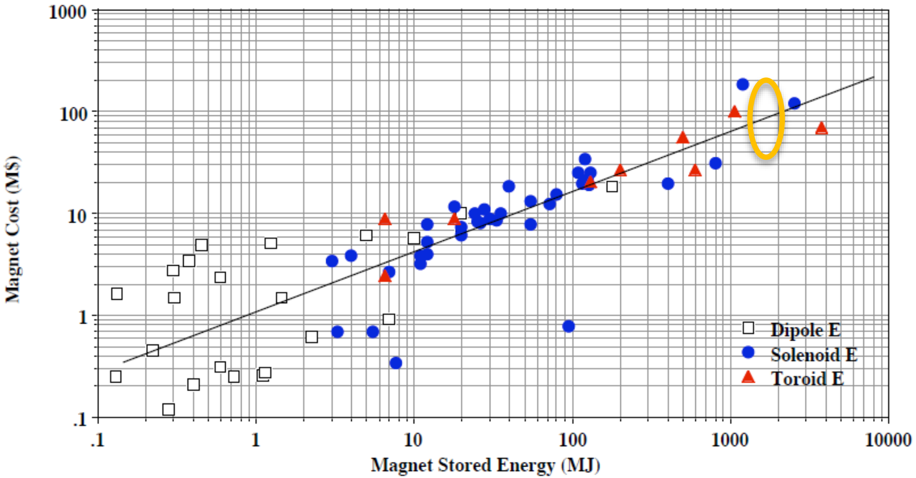


Fig. 2. Superconducting magnet costs (M$) versus stored energy (MJ) for solenoid magnets (closed circles), dipole and Quadruple magnets (open squares) and toroid magnets (closed triangles). The line is a plot of equation 1, which can used to calculate the cost of all magnets.

[5]. M. A. Green et al., IEEE Trans. on Appl. Supercond. 18, (2008).

- Stored magnetic energy: 1.8 GJ
- First-order cost estimate based on historical trends for building [5]: ~90 MCHF (2008, not corrected for inflation)
- This includes the magnet and associated systems, but not cryogenics, the design effort, nor the cost of commissioning

CMS Solenoid development history

The superconducting detector magnet considered for the Muon Collider is very similar to the CMS solenoid, albeit a bit smaller (CMS: 2.4 GJ, Muon Collider: 1.8 GJ)

- Technical challenge: The solenoid properties are similar to and a bit smaller than the Compact Muon Solenoid, so there is a recipe to be followed
- Organizational challenges (Based on ATLAS and CMS magnet development)
  - ATLAS and CMS: 16 years between the finalization of a conceptual design to the finalization of commissioning
  - Realized with strong support by multiple international institutes (9 in case of ATLAS, 7 in case of CMS)
  - 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: Very large magnet that requires a specific conductor, and conductor technology availability is a concern for future superconducting detector magnets

Aluminum-stabilized Nb-Ti conductor technology availability

Superconducting Detector Magnet Workshop, 12/8/22 (https://indico.cern.ch/event/1162992/)

Aluminum-stabilized Nb-Ti = historical go-to conductor (also see slide 6):

- The SDMW workshop was organized in 2022 by CERN and KEK, joined by global institutes and industry. Important conclusion: Commercial availability of this conductor type discontinued since a few years
- On-going effort by Chinese institute and industry to re-establish reliable commercial long length production
- Organized at CERN with KEK support: Interdepartmental workgroup with steering committee (since March 2023), investigating how commercial availability of aluminum-stabilized Nb-Ti conductor may be re-established

Conductor technology alternatives

(featuring some personal opinions)

Aluminum-stabilized Nb-Ti conductor advantages/disadvantages:

- Nb-Ti strands are cost-effective, mechanically extremely resilient, and widely available.
- Nb-Ti gives sufficient magnetic field range for typical superconducting detector magnet applications: Comfortably up to 4 T in aluminum-stabilized conduction-cooled superconducting detector magnets
- Aluminum is lightweight, transparent, good for quench protection, stability, and mechanics
- Well-understood and extensively proven technology, has been in use for 50 years
- **It requires low operating temperature (4.5 K) and commercial availability is presently unclear**

(Aluminum-stabilized) MgB2 conductor technology advantages/disadvantages:

- **More expensive than aluminum-stabilized Nb-Ti, requires development for use in superconducting detector magnets, less mechanically robust than Nb-Ti, currently only allows a limited magnetic field range (probably not suited for 4 T)**
- Useful for superconducting busbars
- Allows operation at higher temperatures, and benefits from technology developments through the HL-LHC Superconducting Link project

Aluminum-stabilized High Temperature Superconducting (ReBCO / Bi-22223) conductor advantages/disadvantages:

- **More expensive than aluminum-stabilized Nb-Ti, not yet available in long lengths, not yet fully understood, less mechanically robust than Nb-Ti**
- High-purity aluminum-stabilization is not needed, although aluminum is still required to carry the current during a quench
- Useful for superconducting busbars
- Enables operation at much higher temperatures and magnetic fields

Summary

- A first look at the superconducting detector solenoid for the Muon Collider: A similar but slightly smaller variant of the Compact Muon Solenoid → There is a recipe to follow.
- Organizational challenges:
  - Long-term commitment needed, with strong support from multiple institutes (ATLAS/CMS: 16 years between finalization of conceptual design and commissioning, strong support from up to 9 institutes).
  - Magnet and associated systems will not be cheap, even though detector magnets are designed to be as affordable as possible.
  - Demonstrators needed to check various aspects of the design before a design can be finalized
- Aluminum-stabilized Nb-Ti conductor challenge:
  - Availability of Aluminum-stabilized Nb-Ti conductor technology a concern, although there are on-going efforts to address this issue
  - This magnet requires a very large conductor with excellent mechanical properties
- Potential alternatives to aluminum-stabilized Nb-Ti conductor technology do exist, but substantial development and associated support would be needed if used for this magnet.

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Thank you
for attention