R&D on superconducting detector magnets for a future Higgs factory

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Introduction: CERN EP Magnet Working Group

- Within CERN, EP Magnet working group comprises members from several groups within CERN EP Department

- Main responsibility: Maintenance, operation, and troubleshooting of (superconducting) detector magnets, such as ATLAS, CMS, Morpurgo dipole, M1, Vertex magnets, etc.

- In addition, since few years, participation in technology development for (superconducting) detector magnets through CERN EP R&D WP8

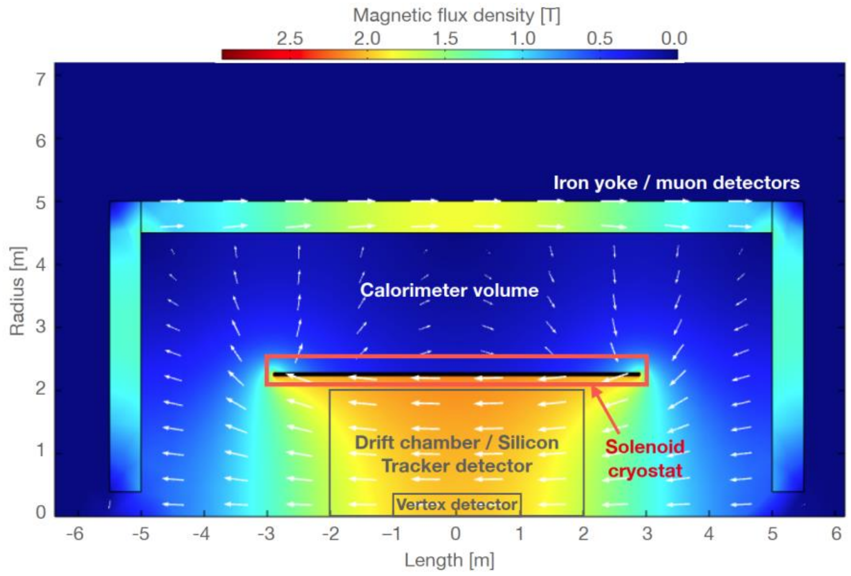
- Support for superconducting detector magnet projects, such as BabyIAXO, Alice-3, AMS-100, FCC-hh, FCC-ee, Muon collider, NA60+, etc.

Introduction: Contributions to FCC-ee superconducting detector magnets

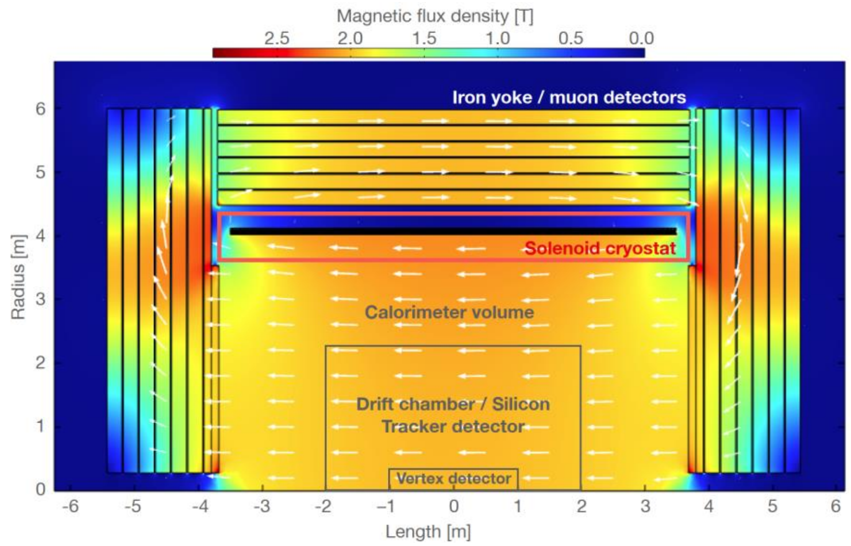
In recent years, conceptual design studies of superconducting detector magnets for the FCC-ee “IDEA” and “CLD” detector concepts [1-5] (not the main focus of this talk).

- IDEA detector magnet: 2 T ultra-transparent solenoid, featuring full magnetic shielding through a return yoke, where particles must traverse the solenoid and vacuum vessel before reaching the calorimter

- CLD detector magnet: 2 T larger solenoid inside yoke featuring partial magnetic shielding



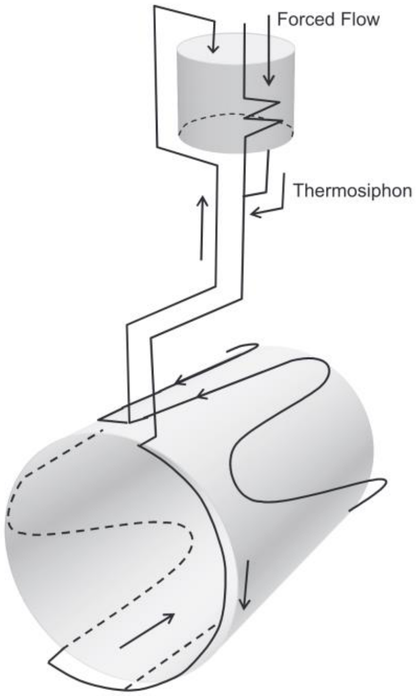
FCC-ee IDEA concept

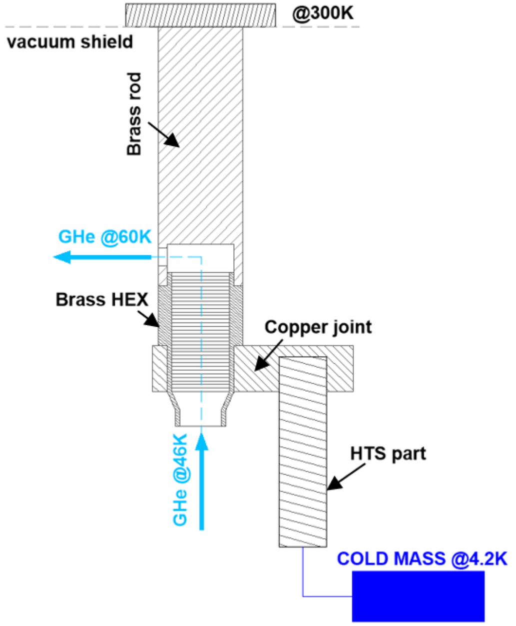


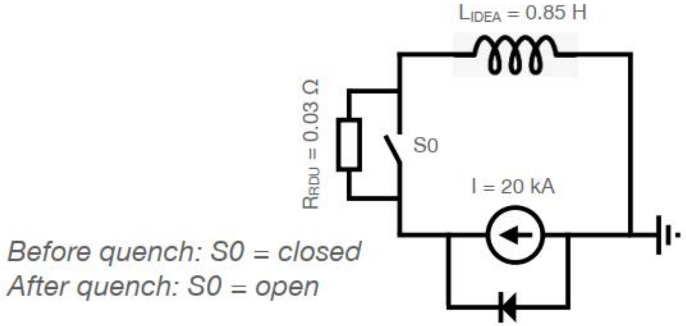
FCC-ee CLD concept

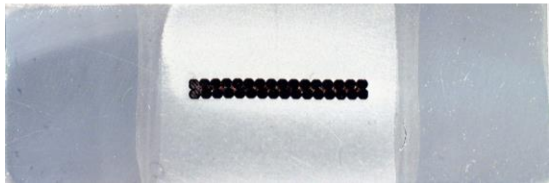
What technology developments are useful, needed, critical for future superconducting detector magnets?

- Cryogenics
- Quench detection and protection
- Vacuum vessel technology
- Conductor technology







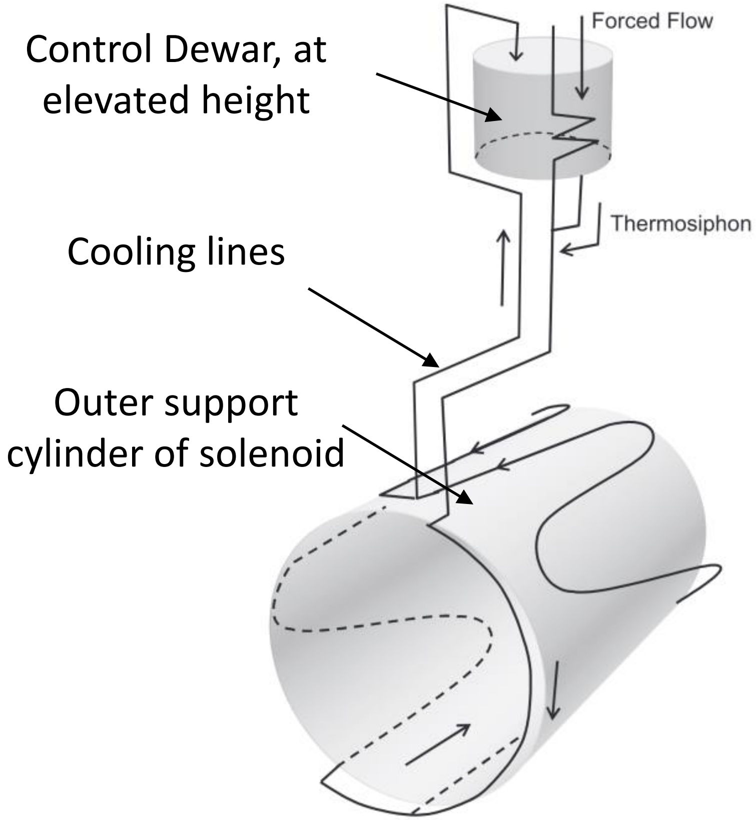


“Standard” Cryogenic solution

“Standard” cryogenic solution for cooling superconducting detector magnets, including for FCC-ee

- Liquid helium accumulated in control Dewar, located at elevated height, fed with liquid helium from external cryogenic plant
- External cryogenic plant also provides forced-flow gaseous helium cooling at ~50 K to maintain thermal shield temperature.
- Cooling lines between Control Dewar and cold mass, for circulation of mixture of liquid and gaseous helium
- **Gravity-powered thermosyphon circulation: Minimal losses, no pump needed, circulation keeps going even in case of power cut**

Convenient, well-understood, reliable, and historically widely demonstrated solution for cooling superconducting detector magnets



Control Dewar, at elevated height

Cooling lines

Outer support cylinder of solenoid

Liquid-helium Thermosiphon of ATLAS Central Solenoid [6] (very similar to CMS)

Magnet power consumption numbers (ATLAS example)

ATLAS Magnets (Comprising Central Solenoid, Barrel Toroid, 2x End-cap Toroid, cryogenic needs [7]:

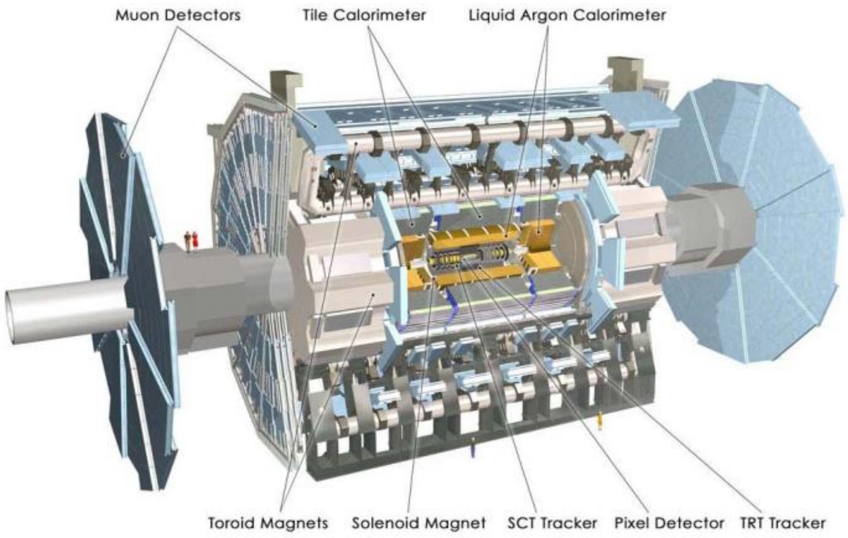
- 2400 m^2 of cold mass area, 140 kA of current carried by current leads (connecting 4.5 K to room temperature)
- 20 kW cooling power at ~50 K for maintaining thermal shield temperature
- 3 kW cooling power at 4.5 K for maintaining cold mass temperature
- 3 kW cooling power at 4.5 K for maintaining bottom of current leads at 4.5 K
- Cryogenics main power consumer at 2.9 MW (~90% of total for magnet system)

Nb-Ti-based superconducting detector magnets, **energy-efficiency from a capital perspective:**

- Officially acknowledged ATLAS magnet cost in 2007: 159 MCHF
- Typical cost of commercial solar/wind electricity production: ~1 CHF/Watt [8,9]
- This implies: Capital investment to cover electricity consumption of cryogenics: ~3 MCHF, **less than 2% of overall magnet cost**

→ **For large superconducting detector magnets: Expensive, despite being designed as-cheap-as-possible, and magnet power consumption looks reasonable given upfront cost.**

→ Important to limit power consumption where possible, **provided it does not substantially increase the overall cost of the magnet system**



ATLAS Detector including superconducting magnets

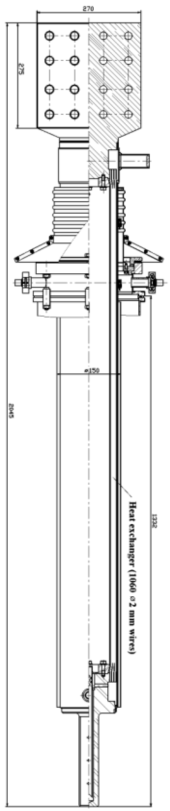
Solar/wind power generation

Novel cryogenic technology development: HTS-based current leads

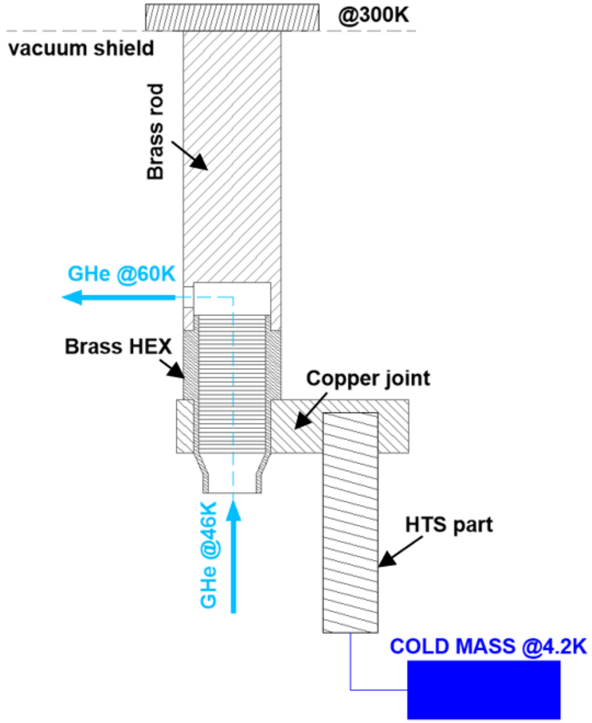
Conventional current leads for superconducting detector magnets:

- Current leads: Needed to connect magnets at 4.5 K to room-temperature power converters
- Conventional solution [10]: Liquid helium evaporates inside cooling leads to provide cooling power → About third of total magnet power consumption dedicated to maintaining current lead temperature
- Novel solution, similar to what was applied in LHC [11]:
    - >99% of current lead heat load intercepted at ~50 K
    - 4.5 K to 50 K section comprises stainless steel shunted with high-temperature superconducting tapes
    - Resulting in minimal heat load at 4.5 K

Expectation with novel solution: 10x reduction in power consumption needed for maintaining the current lead temperature → Currently under investigation, in context of CERN EP R&D WP8



ATLAS Toroid current leads [5]



Concept of an HTS-based current lead (Courtesy W. Gluchowska)

Novel cryogenic technology development: Cryocoolers for superconducting detector magnets

Conventional cryogenic plant:

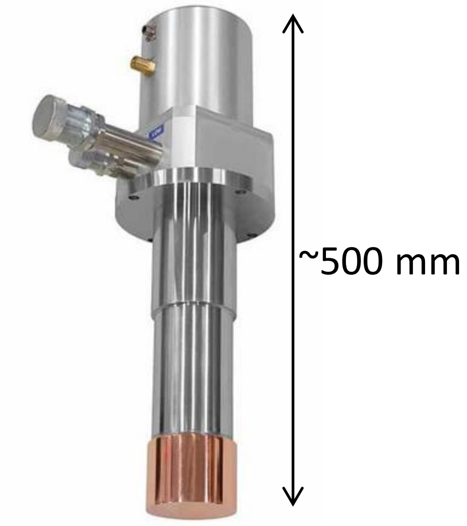
- Relatively high efficiency, in terms of cooling power at 4.5 K vs electricity consumption at 300 K
- Large installation, featuring long transfer lines (adds to heat load and relatively large amount of helium needed)

Cryo-coolers:

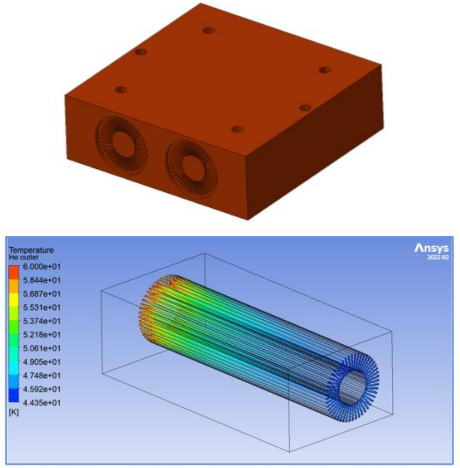
- Currently, modest cooling power and lower cryogenic efficiency compared to large plants, although higher-efficiency commercially available cryocoolers are expected this year and the next
- Compact and modular, contributing to enhanced reliability and redundancy
- Low-maintenance, closed-circuit without liquid helium → **Only modest amount of helium needed, important given future helium availability constraints and rising price of helium**
- Allows for localized liquefaction (less overall heat load), and compatible with thermosiphon cooling
- Localized helium gas circulation for thermal-shield cooling

Currently under development in context of CERN EP R&D:

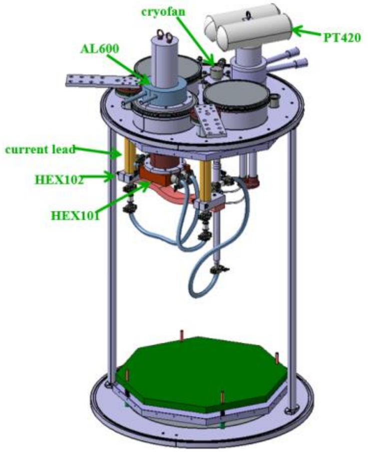
- Cryocooler-to-helium heat exchangers, local helium liquefaction + thermosyphon, HTS-based current leads, demonstrator setup
- Part of the BabyIAXO magnet design



Example of a commercially-available cryo-cooler cold-head, to be connected to an external compressor [12,13]



Cryo-cooler-to-helium-gas heat exchanger, under development in context of CERN EP R&D WP8 (Courtesy W. Gluchowska)



Demonstrator setup, featuring cryo-coolers, cryofan, heat exchangers, HTS-based current leads (CERN EP WP8, Courtesy W. Gluchowska)

Quench detection and protection

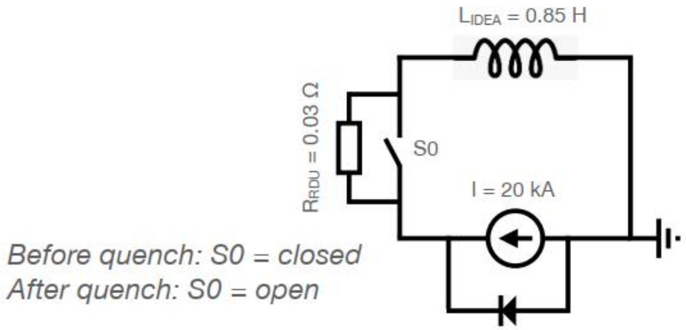
Quench detection and protection of conventional aluminum-stabilized Nb-Ti superconducting detector magnets:

- Quench detection through continuous redundant voltage measurements and inductive balancing
- Quench protection through energy extraction (i.e. external dump resistor) or quench heaters
- Well-understood and works well

Quench detection and protection of future High-Temperature-Superconductor-based superconducting detector magnets:

- More challenging detection, as quench propagation velocity is very low
- More challenging protection, given that inducing a large normal-zone throughout the cold mass is extremely difficult
- Nevertheless, concepts do exist to tackle both quench detection and protection, suitable for both Low and High-Temperature Superconductor for example [14] → Under investigation in CERN EP R&D WP8 through demonstration with demonstrator coil

→ For conventional aluminum-stabilized Nb-Ti superconducting detector magnets, quench detection and protection is available and well-understood



Quench protection of superconducting detector magnet for FCC-ee IDEA concept [1]

Ultra-transparent vacuum vessel technology

Of interest for ultra-transparent magnets (such as for FCC-ee IDEA detector): Ultra-transparent vacuum vessel

- Solenoid for IDEA concept: Particles must traverse solenoid before reaching calorimeter → Transparent cold mass and vacuum vessel needed.
- Major challenge: Outer vacuum vessel wall, exposed to bucking
- For highest transparency:
  - Smart structures such as honey-combs, to increase effective thickness and resilience against buckling
  - Smart materials, such as carbon-based materials
- Under investigation in context of CERN EP R&D Work-package 4

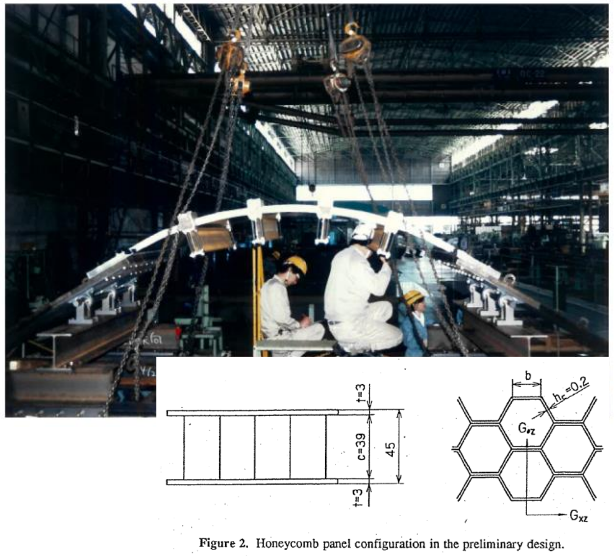
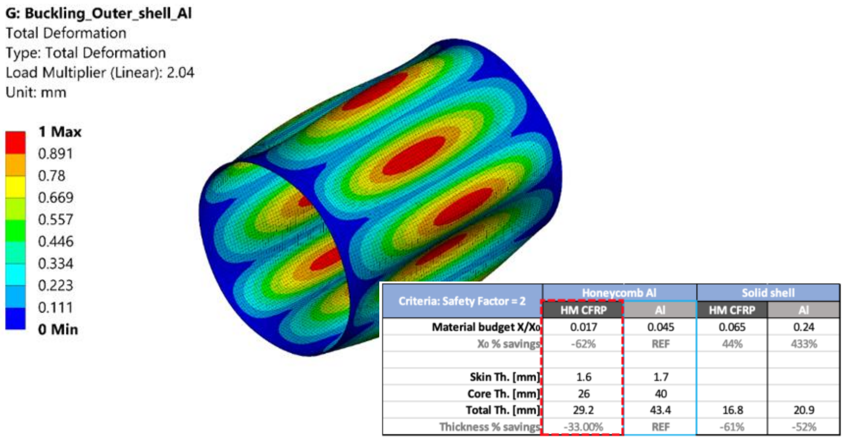


Figure 2. Honeycomb panel configuration in the preliminary design.

Aluminum-based honey-comb vacuum-vessel technology, as demonstrated previously at KEK (Courtesy A. Yamamoto)



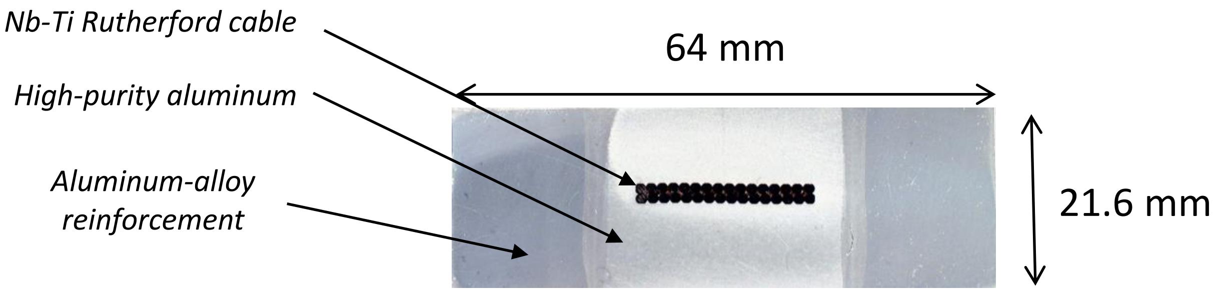
Criteria: Safety Factor = 2	Honeycomb Al		Solid shell	
	HM CFRP	Al	HM CFRP	Al
Material budget X/X_0	0.017	0.045	0.065	0.24
X_0 % savings	-62%	REF	44%	433%
Skin Th. [mm]	1.6	1.7		
Core Th. [mm]	26	40		
Total Th. [mm]	29.2	43.4	16.8	20.9
Thickness % savings	-33.00%	REF	-61%	-52%

Transparency comparison of different materials for FCC-ee IDEA Solenoid (Courtesy M. Barba [15])

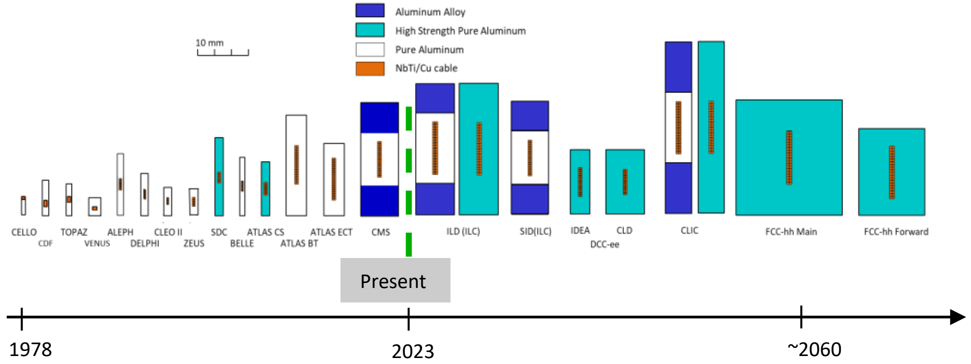
Out-of-autoclave process (Courtesy M. Barba [15])

Critical need for future superconducting detector magnets: Conductor (1/3)

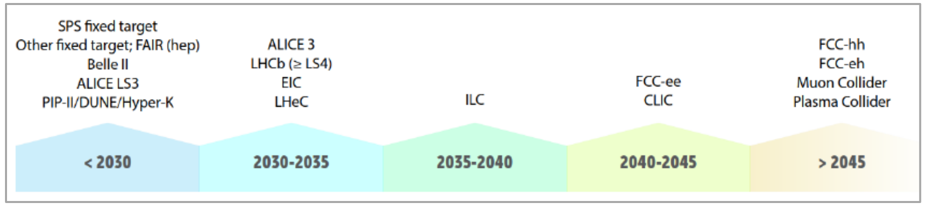
- Superconducting detector magnets require unique conductor technology, owing to their very large stored magnetic energy
- Historically proven solution: Aluminum-stabilized niobium-titanium conductor
    - Superconducting Nb-Ti carries current during nominal operation, and aluminum provides stability and mechanical reinforcement and temporarily carries current in case of a quench
    - Aluminum stabilization: Cost-effective, robust, well-understood and proven over 50 years, with excellent thermal, electrical, and (in case of aluminum-alloy) mechanical properties for a given weight
    - Niobium-titanium superconductor: Most widely used superconductor, cheap, widely available, comfortably allows up to ~4-5 T (covers most detector needs), mechanically extremely resilient compared to other superconductors



Cross-section of the CMS conductor
Courtesy: The CMS collaboration



Aluminum-stabilized Nb-Ti conductors over 100 years (Courtesy A. Yamamoto [16])



Future proposed particle physics experiments being studied: from LDG Accelerator R&D Report, CERN 2022-001

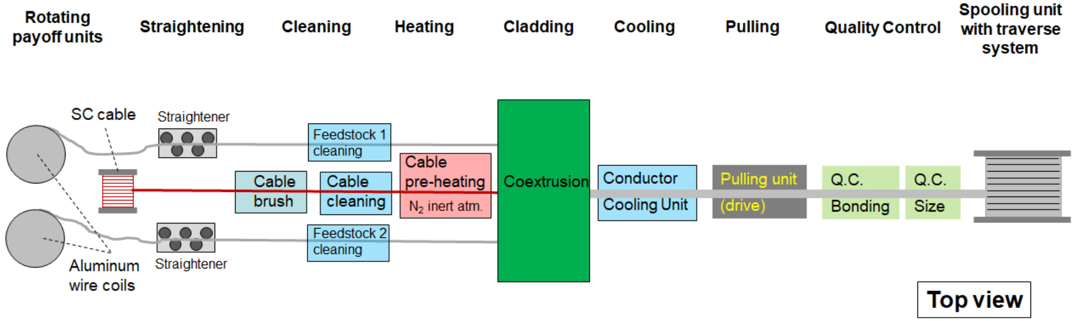
Critical need for future superconducting detector magnets: Conductor (2/3)

- Superconducting Detector Magnet Workshop (2022, co-organized by CERN and KEK):
  - Aluminum-stabilized conductor was a topic of key interest
  - Workshop included world-wide representatives from institutes and industry
  - Findings: On-going R&D effort at IHEP with Chinese industry, but **no commercial availability since a few years**

- Following this: Since 2023, organization of inter-departmental working group and associated steering committee at CERN supported by KEK expertise, for the purpose of re-establishing availability in context of CERN EP R&D

- Plans [17]:
  - Currently on-going: Effort to collaborate with industry using existing facilities on re-establishing conductor technology, which includes co-extrusion process and cold-working facility
  - Future options, depending on budget availability: Setup of a dedicated facility in industry or at institute

Superconducting Detector Magnet Workshop, held at CERN in 2022 (indico.cern.ch/event/sdmw)



Co-extrusion process needed for aluminum-stabilized Nb-Ti conductor production (Courtesy B. Cure [17])

Critical need for future superconducting detector magnets: Conductor (3/3)

Some possible conductor long-term alternatives (not exhaustive):

- Aluminum-stabilized niobium-titanium:
  - **Proven over 50 years, affordable, well-understood, with sufficient magnetic field range to cover typical superconducting detector magnets, mechanically extremely resilient**
  - Requires low temperature operation (5 K), and currently not commercially available
  - On-going effort to re-establish availability through CERN EP R&D WP8

- Aluminum-stabilized Magnesium-diboride:
  - Of interest for superconducting busbars and magnets
  - Demonstrated for superconducting busbars, through LHC Hi-lumi superconducting link project
  - Would allow operation at elevated temperatures (10-20 K), albeit with limited magnetic field range
  - Likely more expensive than niobium-titanium, and requires development
  - On-going effort at INFN Genoa to investigate feasibility for proposed Alice-3 solenoid

- Aluminum-stabilized high-temperature superconducting (HTS) conductor (ReBCO / Bi-2223)
  - Of interest for superconducting busbars and magnets
  - Would allow operation over wide temperature range (4-77 K) and wide magnetic field range, significantly beyond the limits of niobium-titanium
  - Likely more expensive than niobium-titanium, and requires development
  - On-going effort within CERN EP R&D WP8 to fabricate short-length prototype conductors

Summary: R&D of superconducting detector magnet technologies for future Higgs factory

- Cryogenics
  - Existing cryogenic solutions work well, although helium price and availability is a concern
  - Investigations within context of CERN EP R&D WP8:
    - Cryo-coolers and associated technologies
    - HTS-based high-efficiency current-leads to reduce cryogenic power requirement for superconducting detector magnets

- Quench detection and protection
  - Existing technology works well for conventional superconducting detector magnets
  - Within context of EP R&D WP8: Novel method for quench detection and protection for both low- and high-temperature superconducting magnets under investigation

- Ultra-transparent vacuum vessel technology:
  - Effort within EP R&D WP4 to optimize transparency through smart geometries (such as honey-comb structure) and novel materials (carbon-based vacuum-vessel wall)

- Conductor technology for superconducting detector magnets
  - Commercial availability of work-horse aluminum-stabilized Nb-Ti conductor has been an issue in recent years, therefore an inter-departmental effort at CERN with KEK support was organized to see how availability may be re-established
  - Other conductor types may be of interest as well, although there are presently no obvious fully developed, just-as-good, and commercially-available candidates (that I know of)

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