R&D for Future Detector Magnets

Herman ten Kate

1. Charge
2. Reference designs

3-7. Flavor of detector magnets for CLIC/ILC, FCC, Muon C

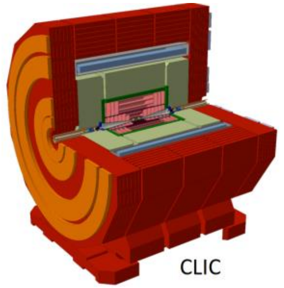
8. Examples non-colliding beam experiments, axions searches
9. Main R&D issues
10. Conclusion

ECFA Detector R&D Roadmap Symposium of Task Force 8 Integration, March 31, 2021

1. Charge - Questions to answer

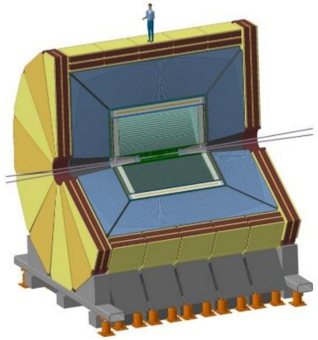
✓ **How do the detector magnets of the future look like?**

✓ **And what is the R&D needed to achieve this?**



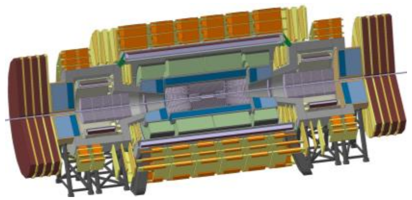
Classification:

- Detector magnets for colliders (HL-LHC, FCC, CLIC, ILC, Muon C., ….)
- Detector magnets for no-colliding beam experiments (e.g. axions)
- Magnet layout: solenoid (e.g. CMS), toroid (e.g. ATLAS), dipoles (e.g. LHCb)



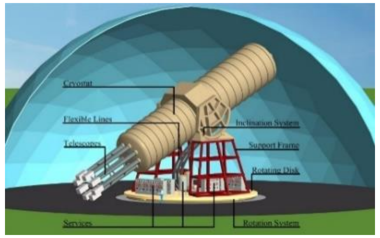
Collider type of detectors:

- No quest for ATLAS style toroids (motivation gone) in large detectors, thus solenoids



2 types we distinguish:

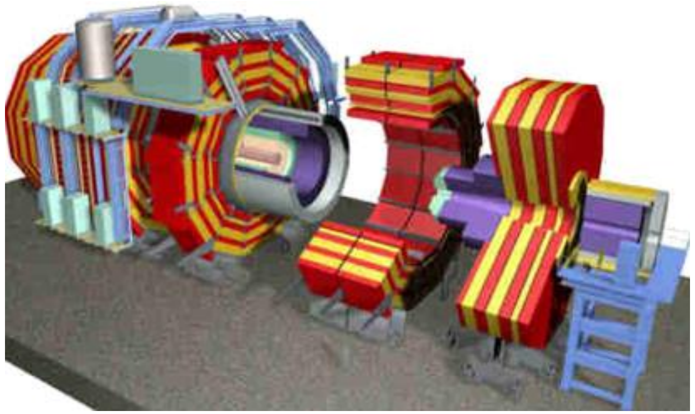
- <u>in front of calorimeter (directly around the tracker)</u> (ATLAS style, radiation thin)
- or <u>behind</u> the calorimeter(CMS style, classical).

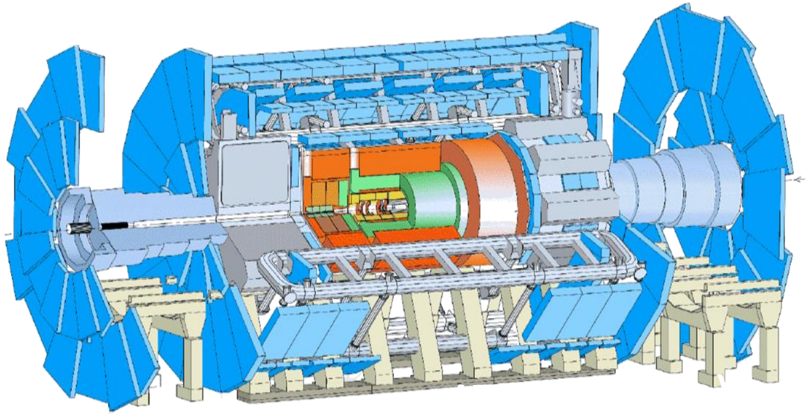


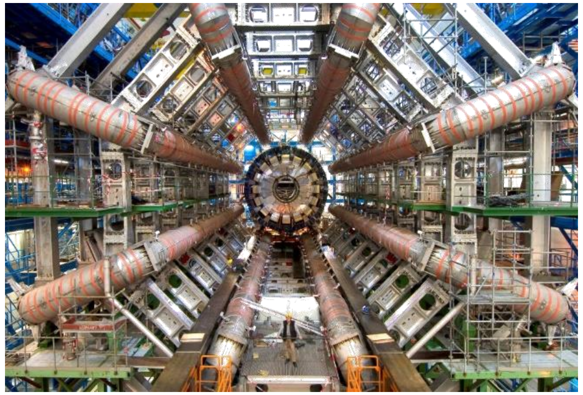
Disclaimer: there are too many details, focus here is on global values & main issues.

2.1 Reference designs: CMS (outside cal) and ATLAS (inside cal)

- Everybody is using 2 respected solenoids as references: CMS (behind) and ATLAS (in front)







Solenoid 3.8 T at 19 kA
6 m bore x 12.5 m long
2.3 GJ

Solenoid 2 T at 7.8 kA
2.4 m bore x 5.3 m long
39 MJ

2.2 Solenoid inside or outside calorimeter

Motivation:

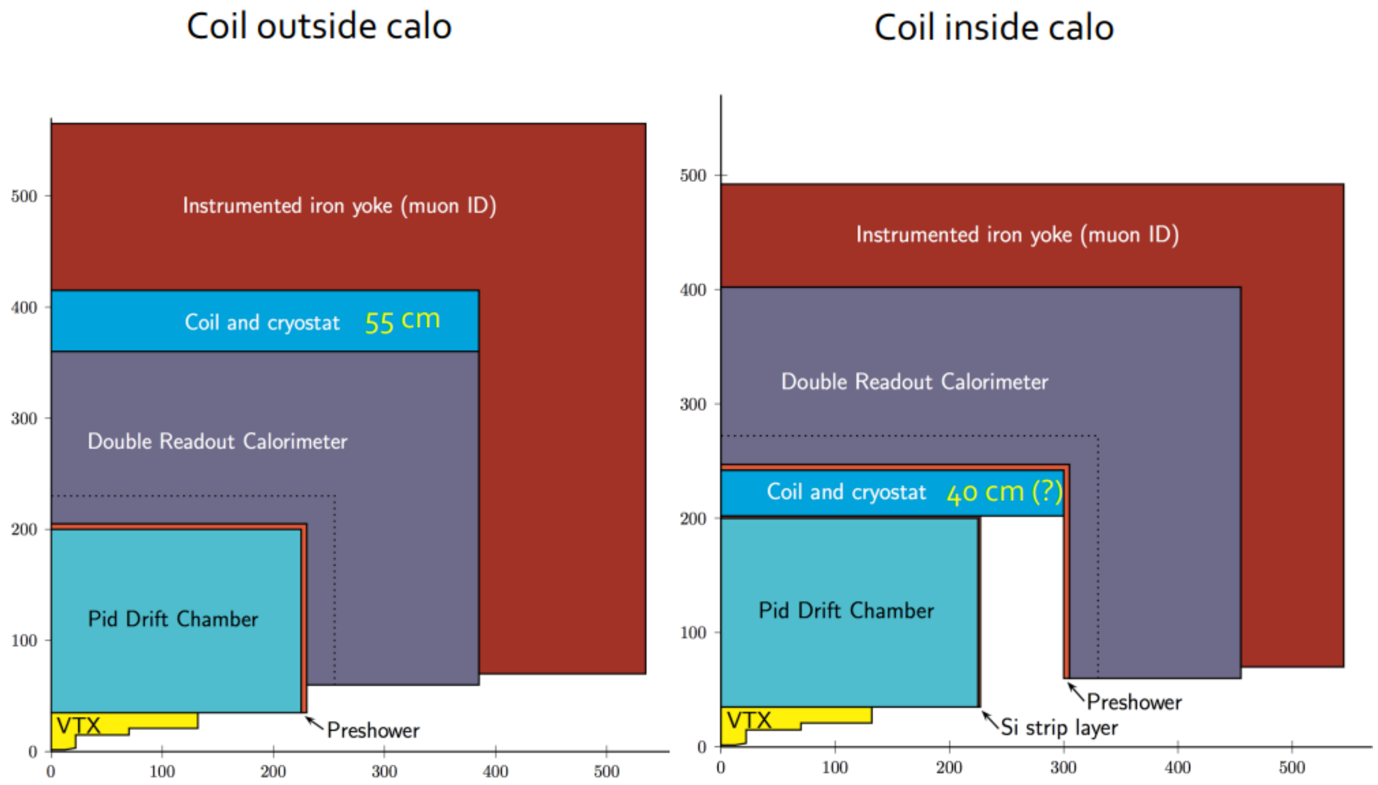
- Magnetic field is only required in the tracker + muon chambers, but most stored magnetic energy (some 80%) is wasted in the calorimeter space!

Obvious savings when coil is positioned inside, in this FCCee case:

- **Factor ≈ 4 in stored energy**
- **Factor ≈ 2 in cost!**

Similar or even more gain in other designs.

But design and construction are not obvious and **require R&D and a demonstrator.**



*Solenoid **outside** or **inside** calorimeter?*

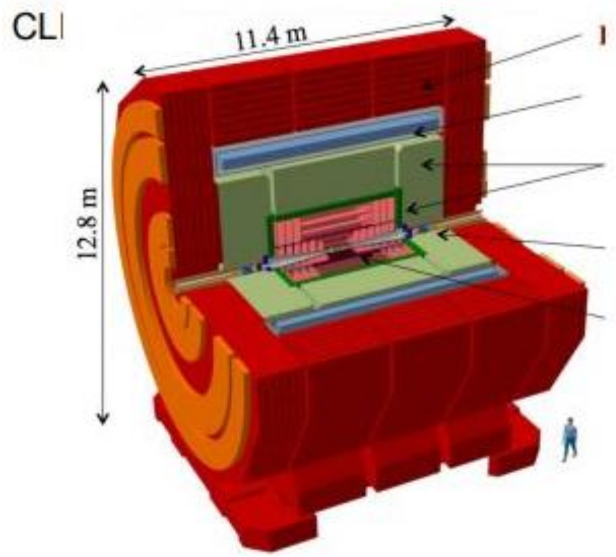
Requirement: $X_0 < 1$

3. CLIC/LC Detector Magnets

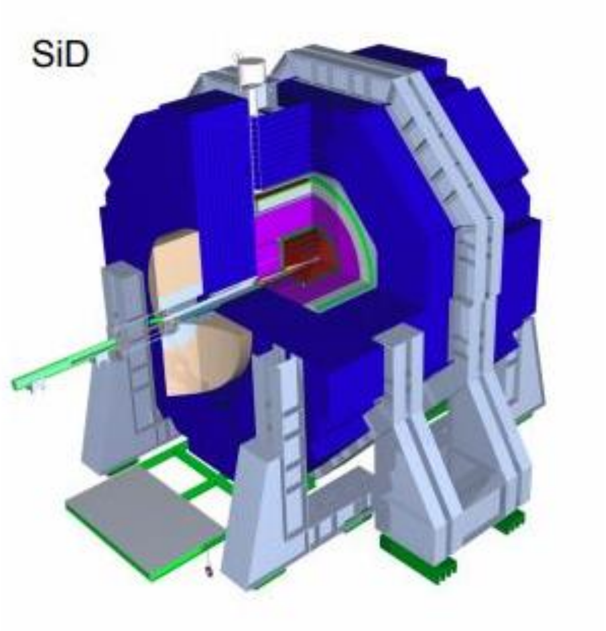
Conventional "CMS based scaled" solenoids behind the calorimeters

"Initial Design period 2008-2011, fine tuning since then:

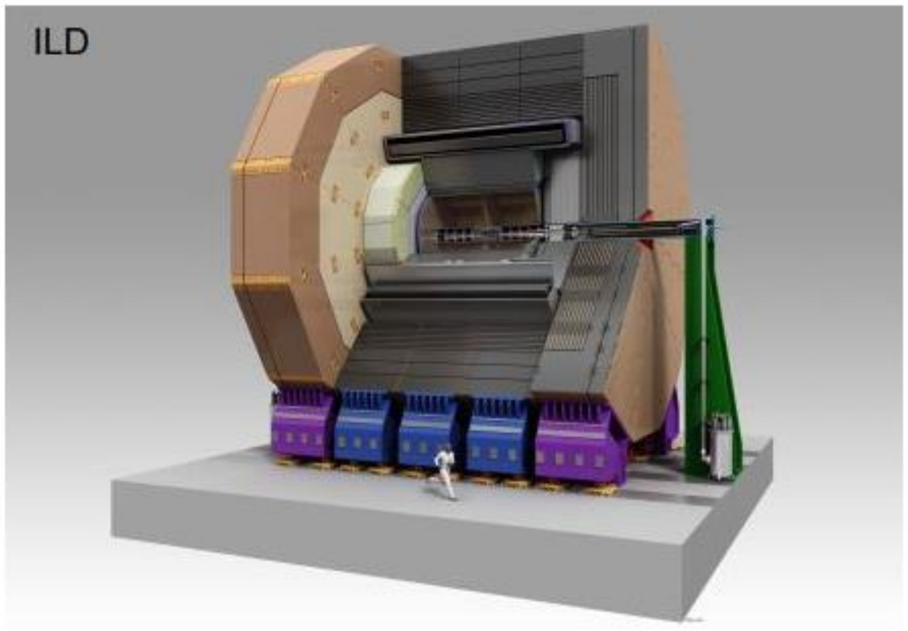
- 4 and 5 T SiD and ILD variants published in CDR 2011, various updates released
- CLIC-ILD 4 T in a 7 m free bore, 8 m long; SiD 5T in 5 m bore and 6 m long.



B= 4T



B= 5T

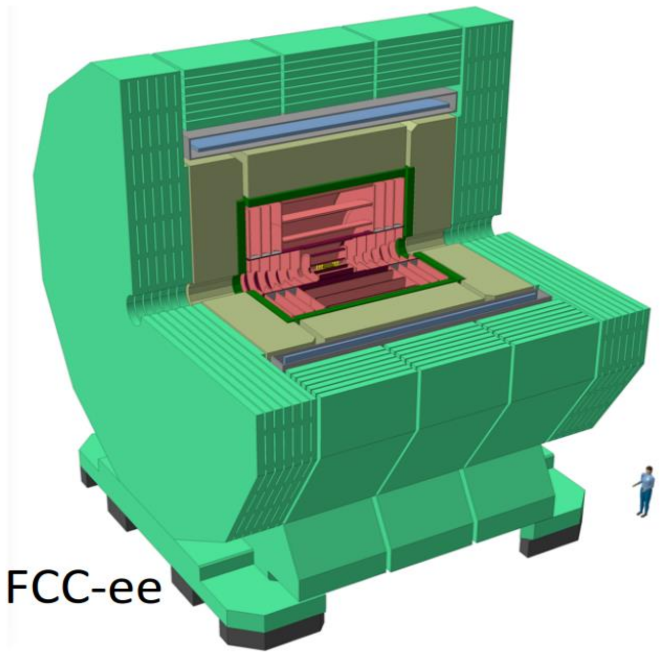


B= 3.5T

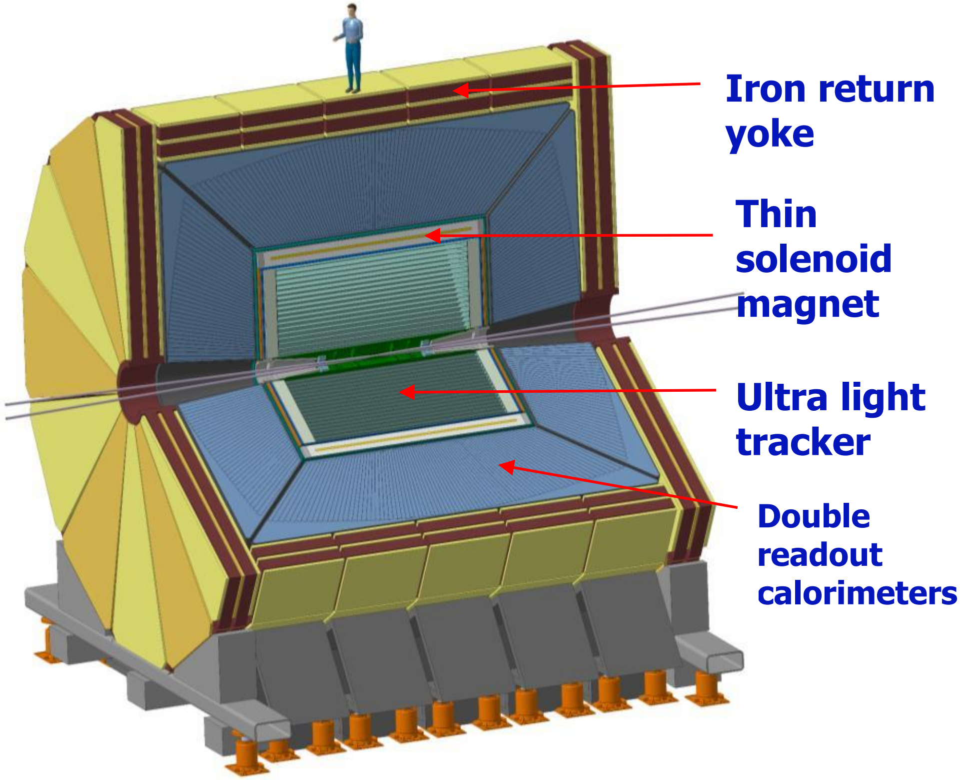
4.1 FCC-ee Detector magnets

For FCC-ee two main detector designs are proposed:

- a conventional 2 T solenoid outside the calorimeter, essentially a down-scaled CLIC design,
- a challenging 2 T solenoid "ultra-thin & transparent" around the tracker, an "ATLAS solenoid style magnet", but slightly larger and mechanically much stronger.

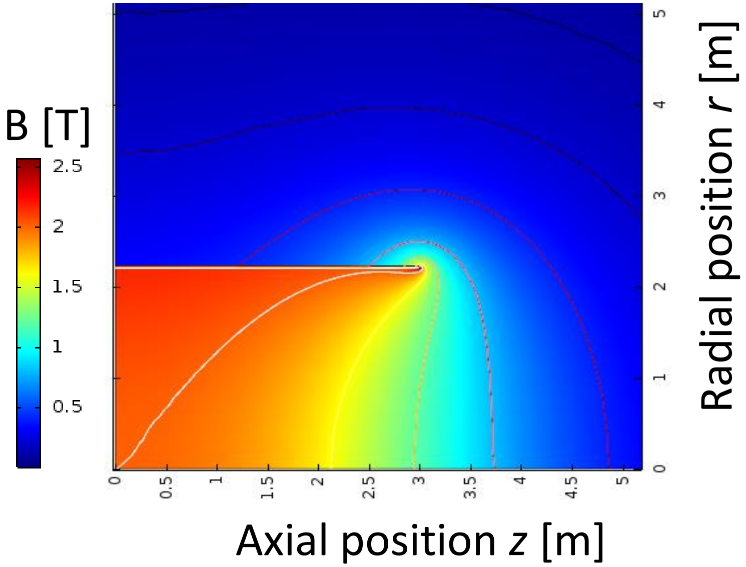


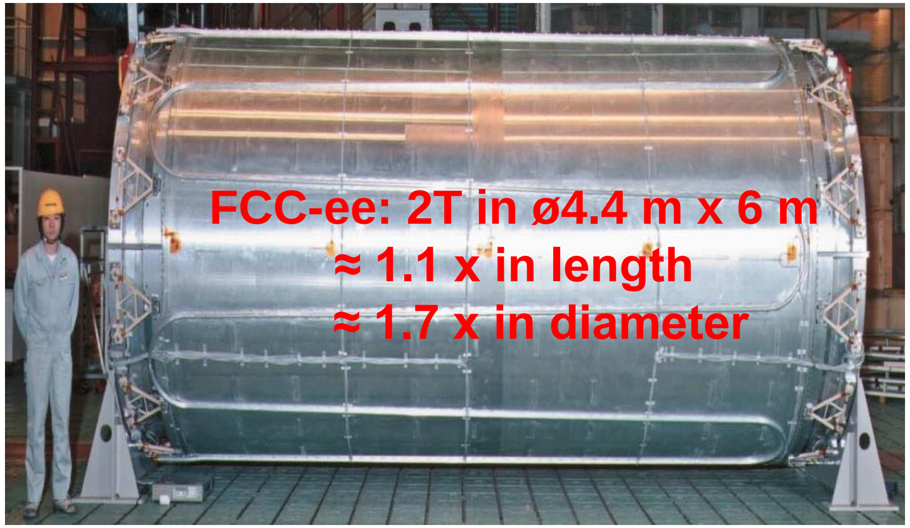
CLIC style downscaled 2T solenoid



***IDEA detector**, innovative thin 2T solenoid around tracker*

4.2 FCC-ee - 2T "thin" solenoid inside HCAL





A thin high YS conductor based solenoid, ATLAS-like

- Coil composition: mainly aluminum (77 vol.%) + copper (5 vol.%) + NbTi (5 vol.%) + glass/resin/dielectric film (13 vol.%)

Radiation thickness, e.g. :

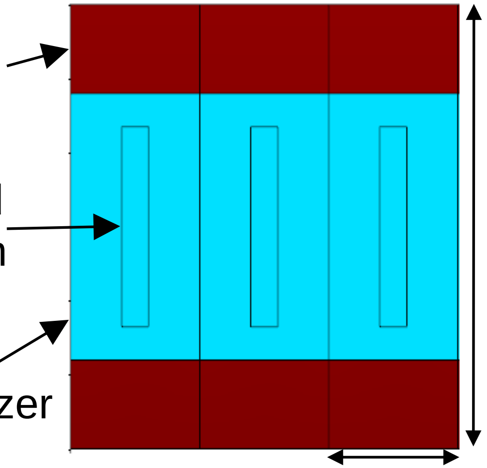
- Cold mass: $X_0 = 0.46$, $\lambda = 0.09$
- Vacuum vessel (25 mm Al): $X_0 = 0.28$
- **Preliminary design shows that it is achievable, total $X_0 = 0.8<1$!**

Property	Value
Magnetic field in center [T]	**2**
Free bore diameter [m]	4
Stored energy [MJ]	**170**
Cold mass [t]	8
Cold mass inner radius [m]	2.2
Cold mass thickness [m]	0.03
Cold mass length [m]	6

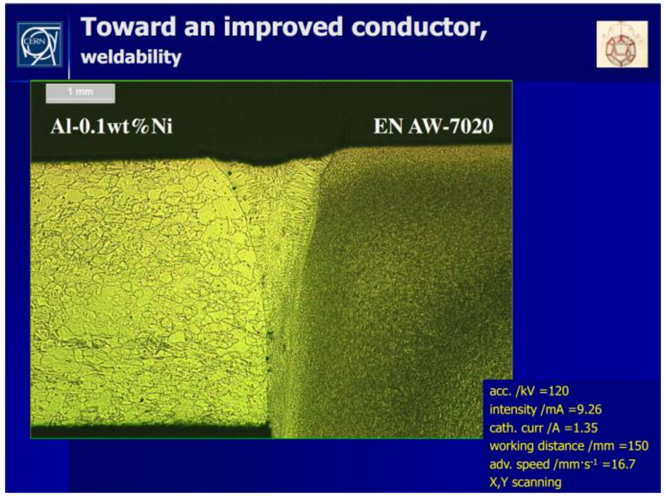
4.3 Thin coil R&D on Conductor – Reinforcement option

Conductor:

- A strengthened CMS-like conductor
- NbTi/Cu Rutherford cable, Al 0.1%Ni stabilizer, welded Al-7xxx alloy bar reinforcements
- 20 kA operating current, 0.85 H self-inductance
- 6.5 K current sharing temperature (at 3.2 T peak)
- 2.0 K temperature margin at 4.5 K cooling
- 100 MPa combined Yield Strength of Al-Ni + NbTi core + G10 insulation
- **280 MPa local peak stress**
- 1 layer coil, 595 turns, conductor length 8.3 km
- **Energy over mass density: about 24 kJ/kg.**



Conductor axial thickness: 10 mm (including insulation)

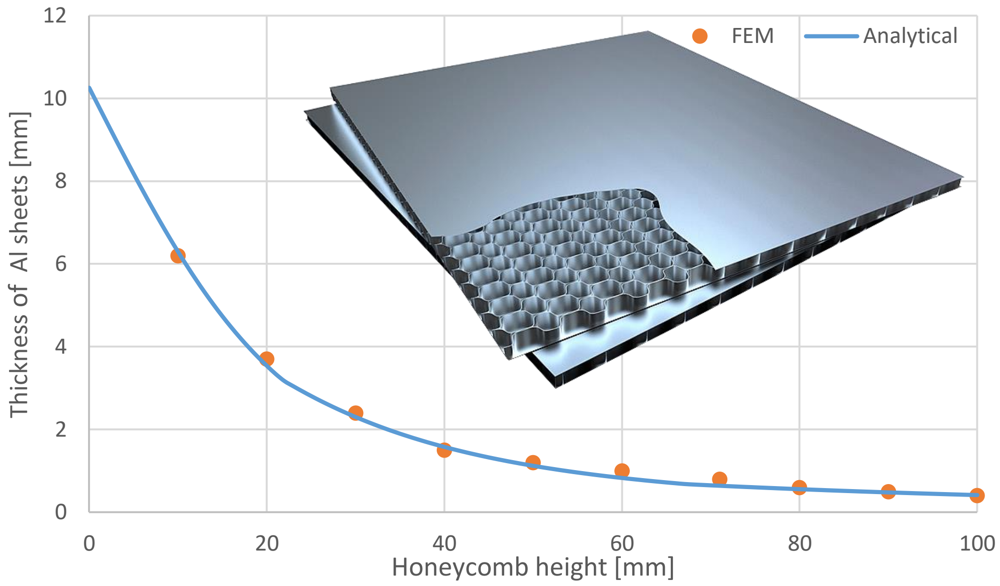


EB welded reinforcement, Sgobba

4.4 Thin cryostat R&D - Use honeycomb-like plate

Option for the cryostat outer vessel: use honeycomb plate or isogrid like sandwich panels.

- Drastic effective thickness reduction possible by using two separated plates with filling structure in between



When comparing 4 solutions, honeycomb delivers the best minimum radiation thickness!

Comparison of outer shell solutions and effect on radiation length

	Uniform plate	Corrugated plate	Reinforcement rings	Honeycomb
Plate thickness [mm]	**20.5**	7.0	4.3	**3.5**
Radiation length [X_0]	**0.23**	0.11 (mean)	0.05 (1.0)	**0.04**
Height	**20.5**	57	92	**44**

Reference

5.1 LHeC --> FCC-eh - Detector magnet and e-beam dipole

Beams in interaction region: e + p1 + p2, also heavy ions

Solenoid Detector Magnet integrated with dipole magnets:

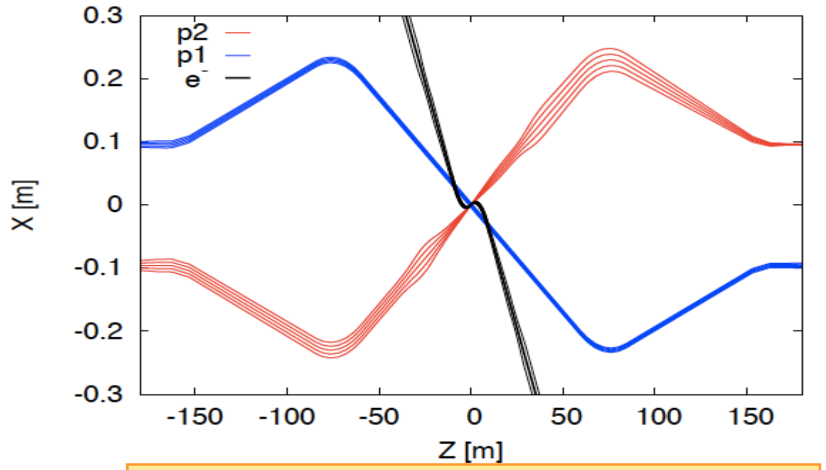
- to guide the e-beam in and out
- for making electrons to collide head-on with proton beam
- to safely extract the distorted electron beam.

Design: Detector Solenoid making 3.5 T

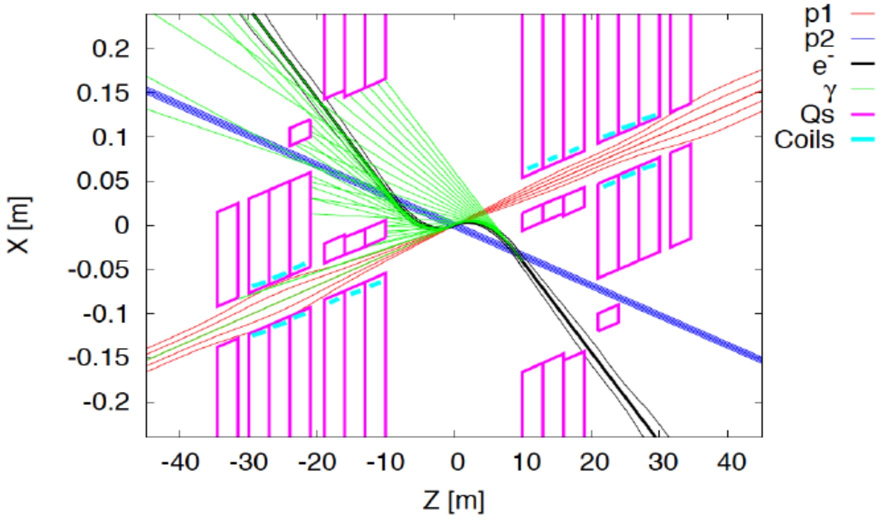
2 dipole magnets making some 1 Tm (LHeC)

0.3 T transverse field along 2 x 9 m (LHeC)

- Initial Design 2009-2014 when LHeC was an LHC+ project.
- Since 2014 incorporated in FCCeh effort.
- 3.5 T detector magnet in few variants, in combination with dipoles.

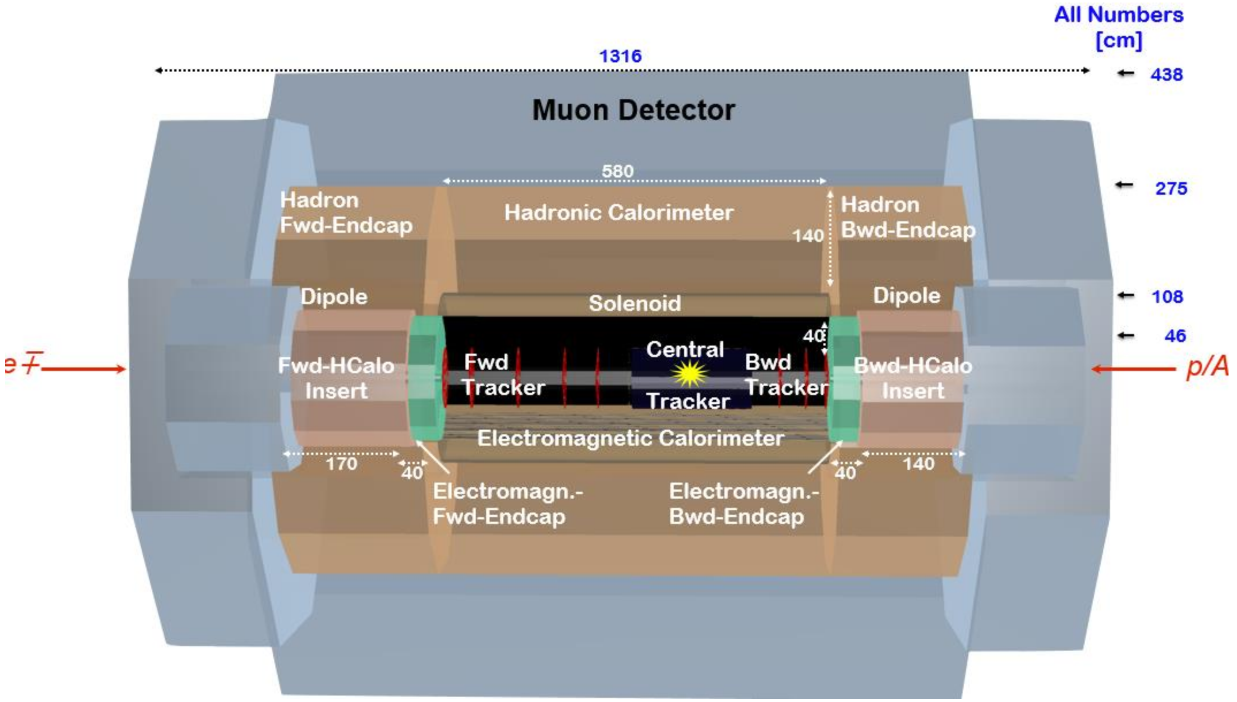


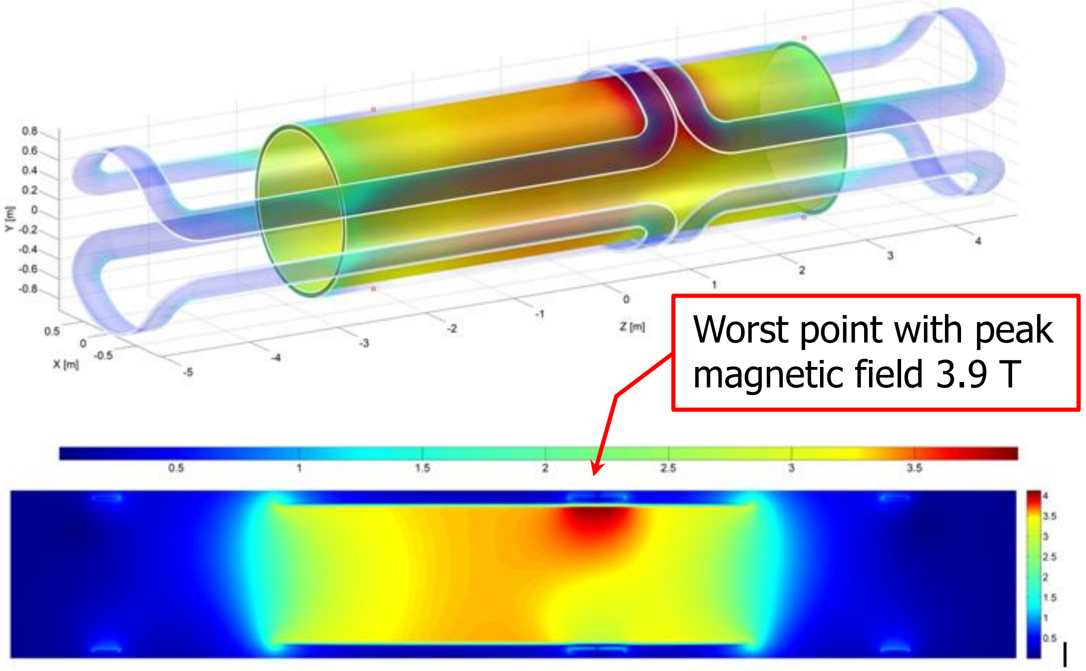
LHeC: 3 beams, head-on collisions



0.3T dipole field to allow head-on collision

5.2 LHeC --> FCCeh - Detector Magnet layout (CDR baseline)

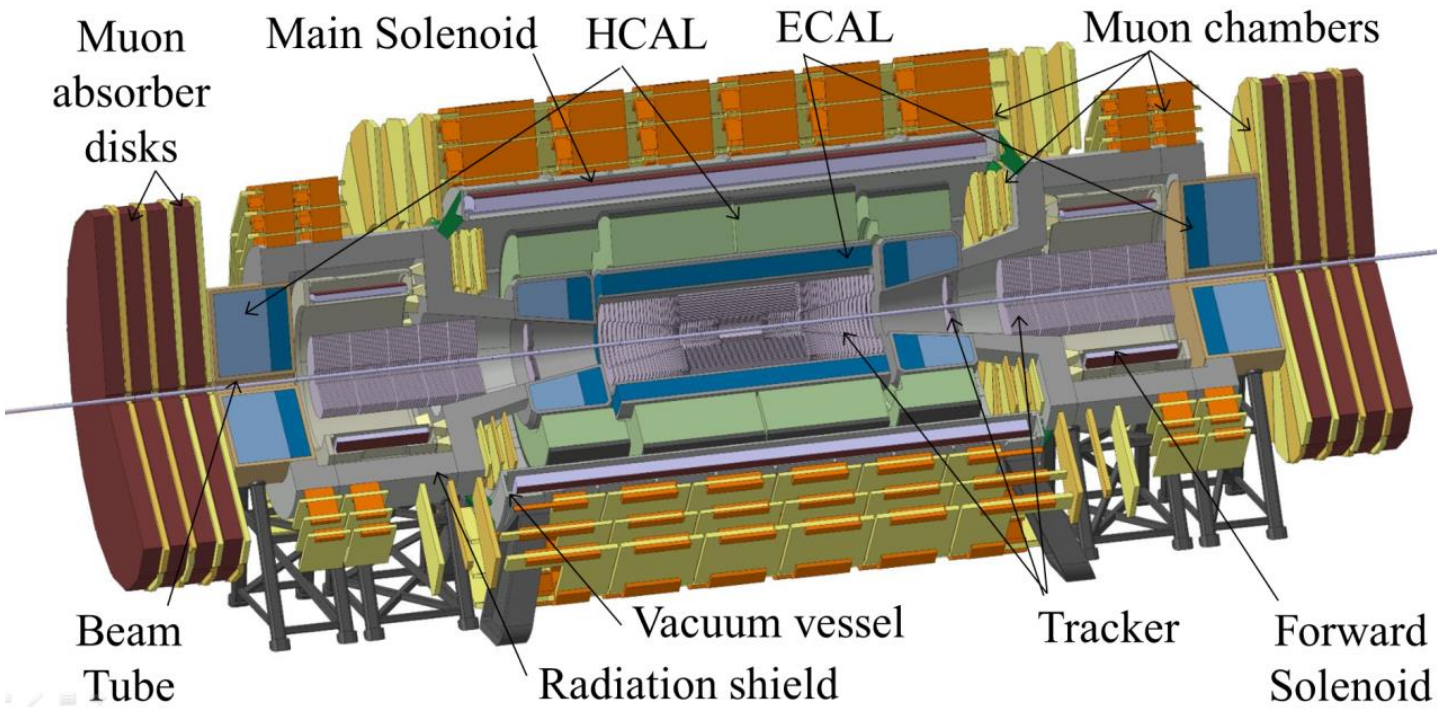




- Design concept: relies on present technology for detectors magnets but hybrid with dipole.
- **3.5 T Solenoid & 2 Dipoles** in same cryostat around EMC, muon tagging chambers in outer layer.
- **New: solenoid and dipoles have a common support cylinder in a single cryostat**; free bore of 1.8 m; extending along the detector with a length of 10 m.

- **From LHeC towards FCC eh:** Increasing system bore (1.8 to 2.6m) and length (5.7 to 9.2m)

6.1 FCC-hh detector baseline



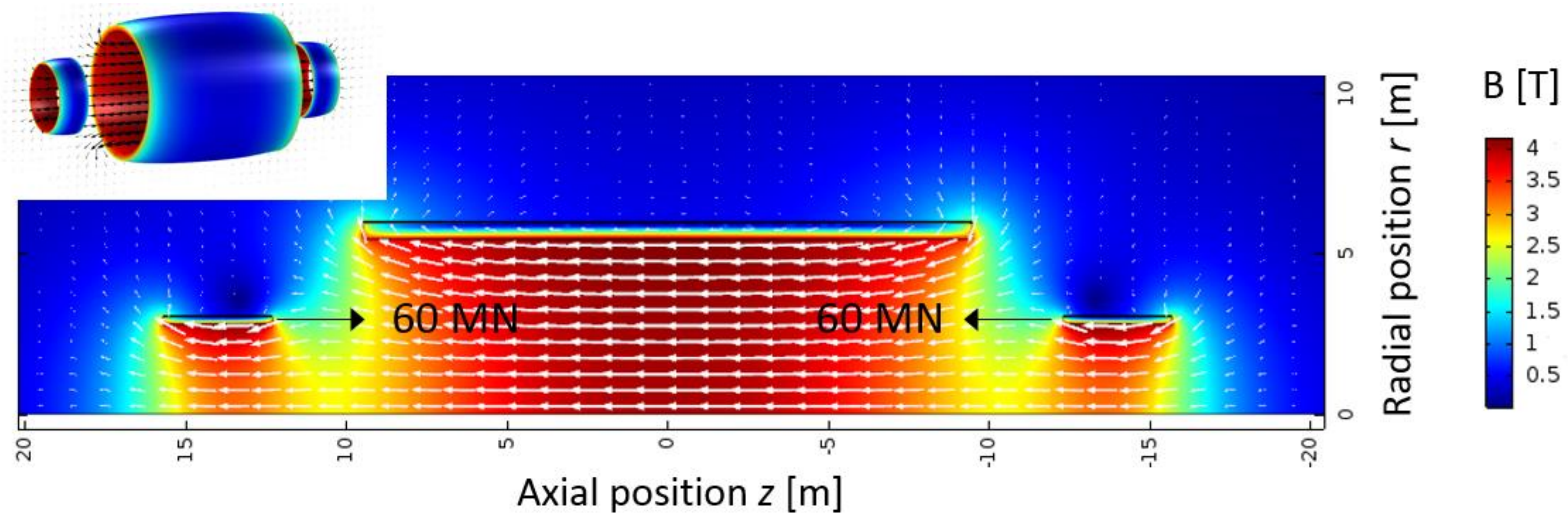
Main solenoid:

- Trackers and calorimeters inside bore, supported by the bore tube
- Muon chambers (for tagging) as outer layer in barrel region

Forward Solenoids (or optionally forward dipoles):

- Tracker inside solenoid
- Forward calorimeters after forward solenoids
- Enclosed by radiation shield
- Muon station behind

6.2 Baseline - 4T/10m Solenoid with 4T Forward Solenoids

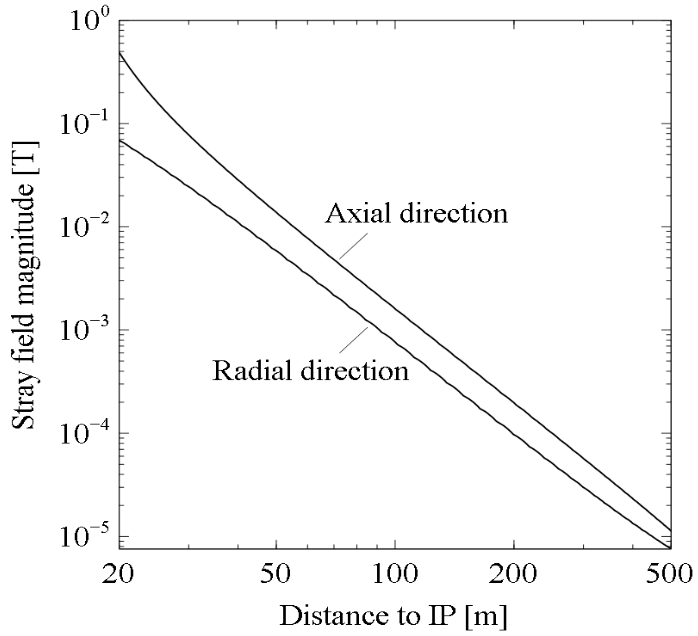


Concept:

- 4 T in 10 m free bore of main solenoid, 32 m overall length.
- No iron yoke, no magnetic shielding since 300 m underground.
- 60 MN net force on forward solenoids handled by axial tie rods.

Result:

- **Stored energy: 14 GJ**
- Lowest degree of complexity from a cold-mass perspective.
- But: with significant stray field to be accepted and coped with.



6.3 Option for FCC-hh - Ultra-thin & “transparent” 3-4T Solenoid

Motivation for this R&D:

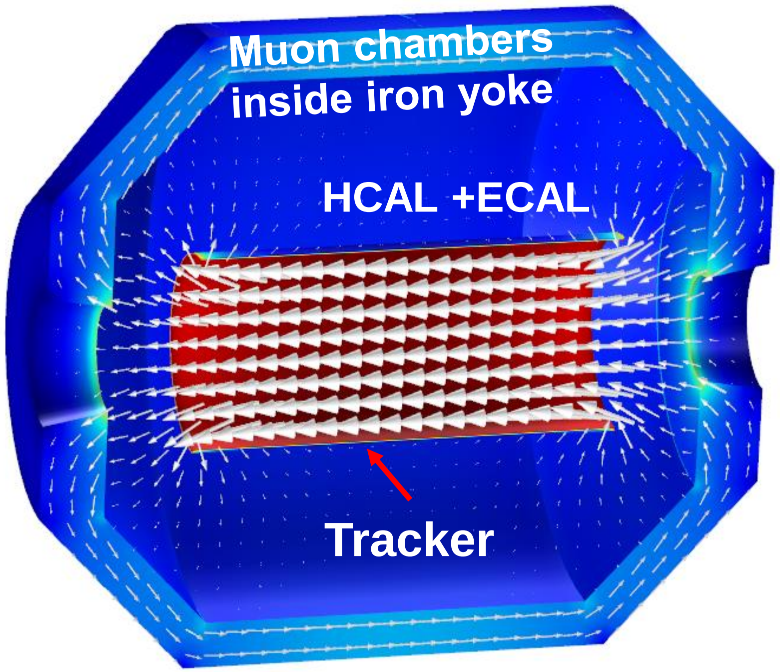
Also for FCC-hh it makes sense to put the solenoid inside the calorimeter provided the coil can be made “radiation thin”.

Solution: use concept of the 2T ATLAS Solenoid, but for 3 to 4 T.

Generate magnetic field on tracker & muon chambers only
---> **16x lower stored energy (and thus cost, roughly ½).**

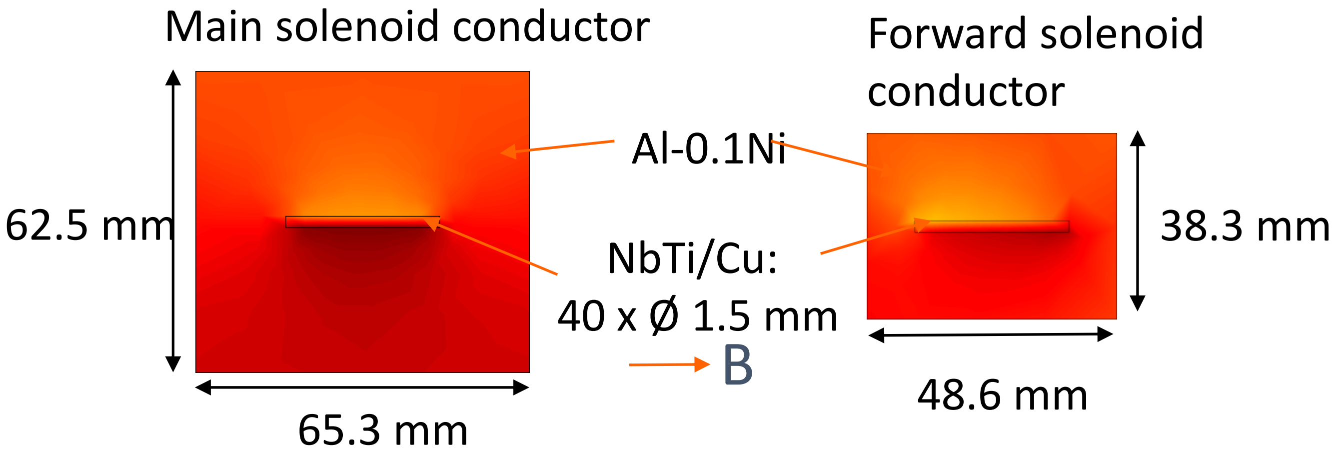
Use a light iron yoke (6 kt) for returning flux
- Provides magnetic flux for muon tagging
- And magnetic shielding
- And Lorentz Force decoupling with forward detector magnets

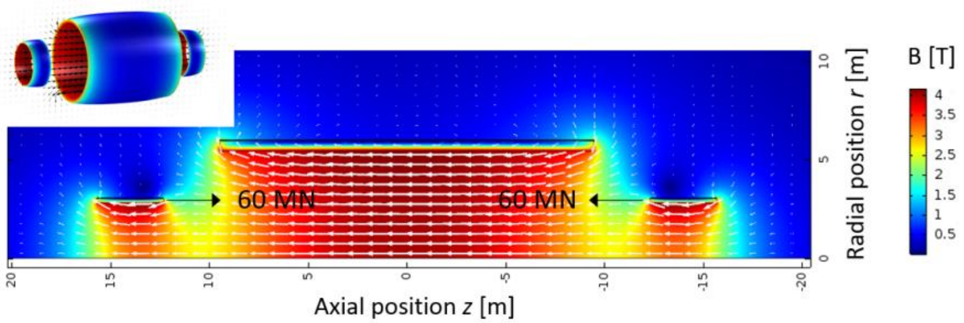
But: particles go through solenoid before reaching calorimeters
- **Thin solenoid required for minimal interference**
- **Very high-strength conductor needed.**



Property	4 m bore, ECAL out
Field in center [T]	4
Stored energy [GJ]	0.87
Iron mass [kt]	6
Muon FI at η = 0 [Tm]	1.2

6.4 Superconductor for in 4T/10m baseline design solenoids





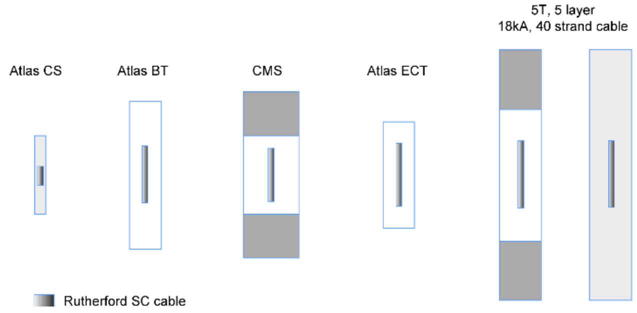
	Main Solenoid	Forward Solenoid
Current [kA]	30	30
Self-inductance [H]	28	0.9
Layers x turns	8 x 290	6 x 70
Conductor length [km]	83	2 x 7.7
Bending strain [%]	0.57	0.68

We need a next generation of Aluminum-stabilized Rutherford cable conductors for 30-40 kA:

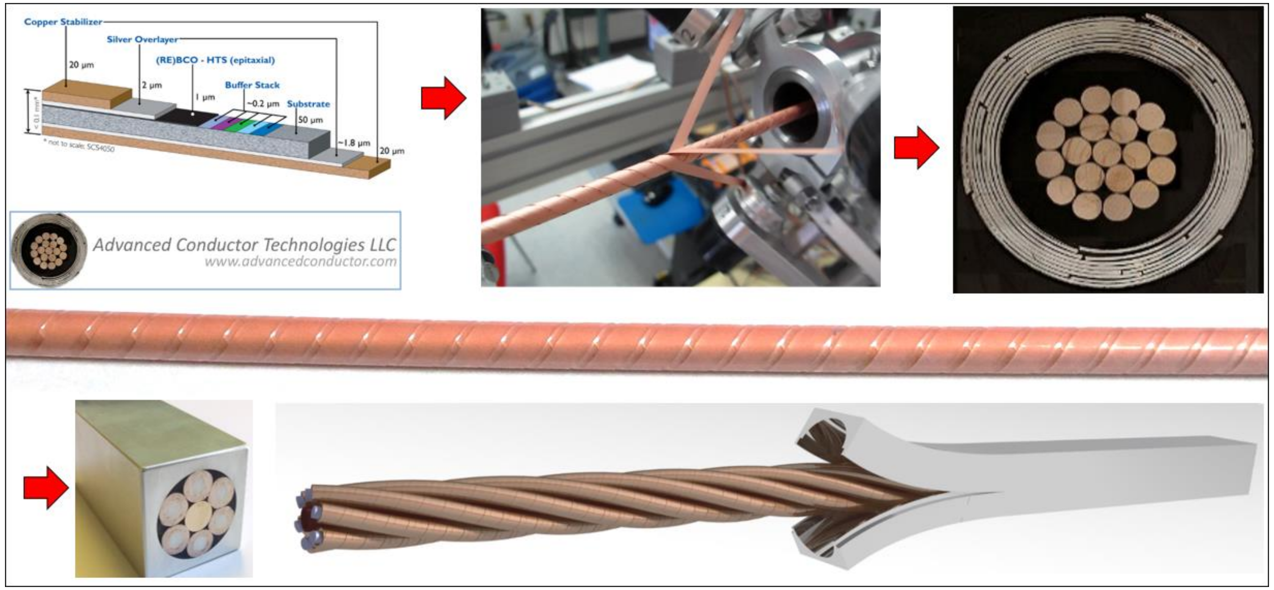
- Peak field on conductor 4.5 T
- Current sharing temperature 6.45 K
- 1.95 K temperature margin when operating at T_{op} = 4.5 K
- Nickel-doped Aluminum (≥0.1 wt.%): combines good electrical properties (RRR=600) with mechanical properties (146 MPa conductor yield strength [1]), Peak stress 100 MPa.
- **Super-Conductors are key to success of any sc magnet, it deserves the highest priority!**

6.5 Detector Magnet Conductor R&D in general

- We see higher field, wider bore detector magnets require "stronger" and larger size super-conductors.
- **R&D is needed to reinforce Al stabilized conductors.**
- Also on long term, demonstrating ReBCO HTS conductors for coils, and current leads is essential to get rid of He and allow 30-40K.
- **Super-conductor development needs a boost and resources!**



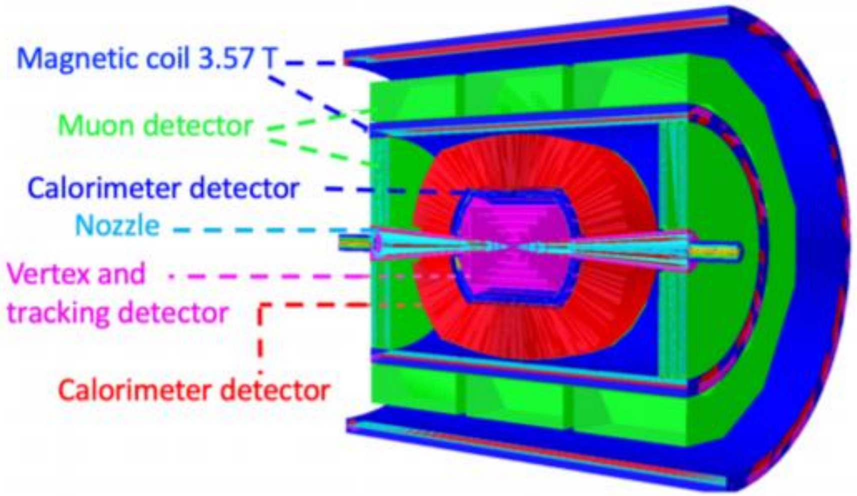
Trial extrusion of reinforced Al stabilized superconductors



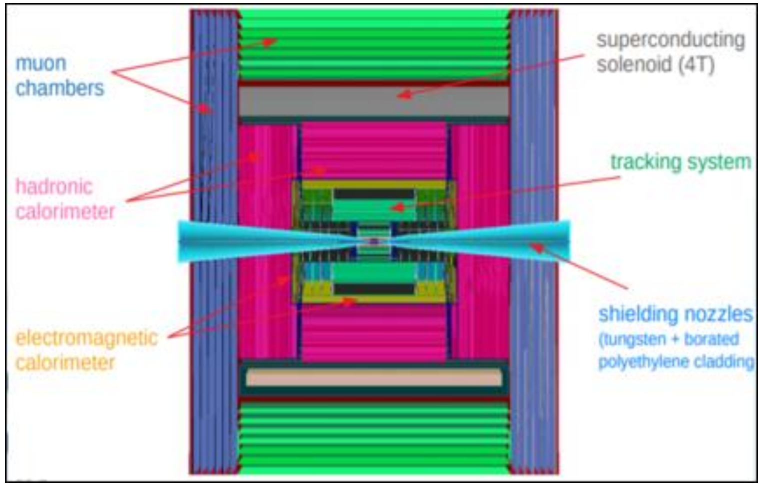
New generation ReBCO HTS conductors for detectors.

7. Detector magnets for Muon Collider

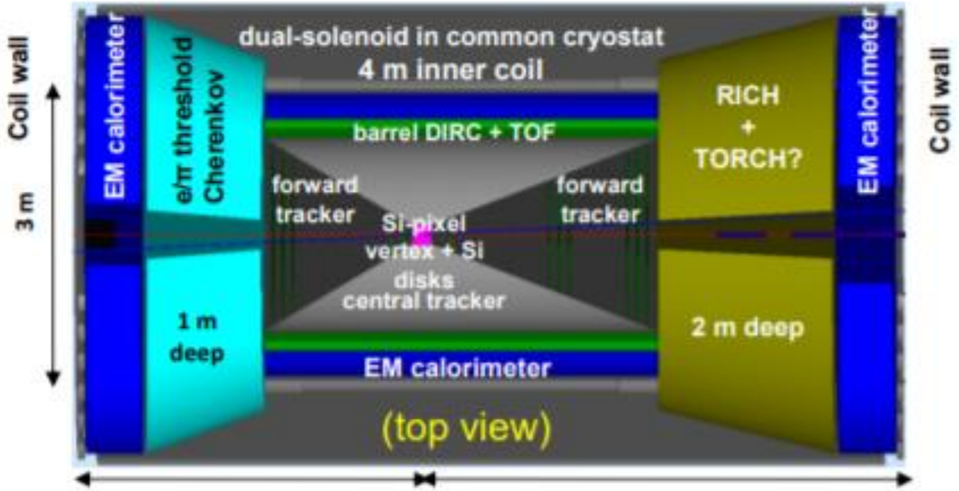
- Magnets for Muon Collider detectors are ee⁺-like, 3 – 4 T solenoids of similar size.
- Also **Dual Solenoids are proposed** (active shielding, no iron yoke) for Muon collider and eRHIC as well.
- **Dual Solenoids need R&D for this size not yet demonstrated.**



Muon Collider: Dual Solenoid for 3.6 T.



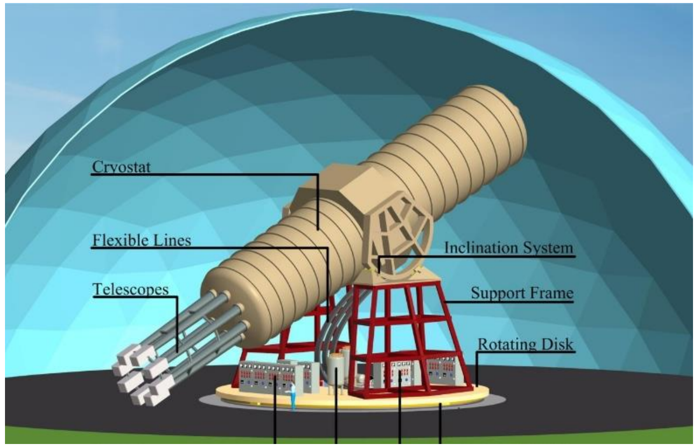
Muon Collider : CLIC based 4 T Solenoid.

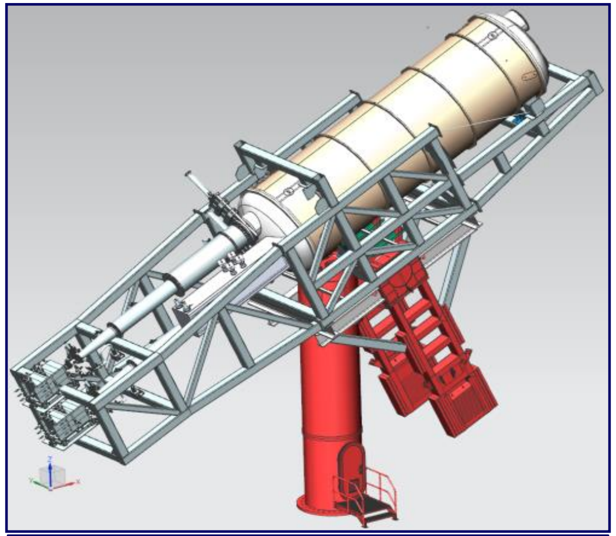


Dual Solenoid design for 3 T, 4 m bore, 8 m long for eRHIC.

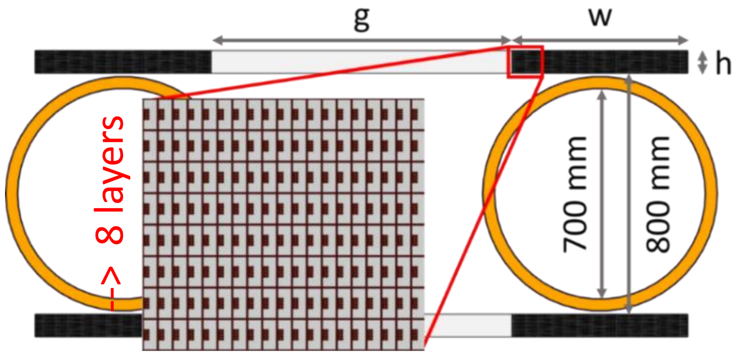
8.1 Unique magnets in a no-beam experiment - (baby) IAXO

- **I**nternational **Ax**ions **O**bservatory (>>300xCAST), a 22 m long 8-coils Toroid with 2.5T user field for seeking solar axions and more, novel design inspired by ATLAS toroids.
- BabyIAXO, a near term intermediate step, a short twin-tube version of IAXO, comprising two 10-m long racetrack coils, 17 ton cold mass, stand-alone operated with cryocoolers at 4.5 K.
- Conceptual design completed, construction in preparation, installation at DESY in the next few years.

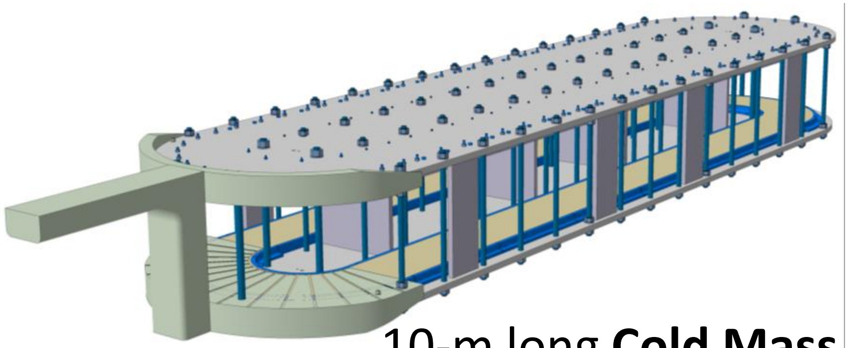




BabyIAXO on drive system installed at DESY



---> 130 turns



10-m long **Cold Mass**

8.2 Other examples of axion detectors

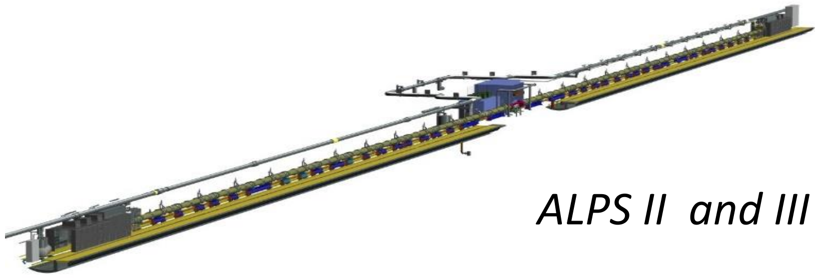
No new detector magnet R&D, but making use of magnets developed for collider projects:

- **OSQAR, PVLAS, STAX, ALPS, JURA**: strings of 2 to 20 accelerator dipole magnets taken from completed (HERA), running (LHC+) or future (FCC) projects.
- **Haloscopes**, axion search in high field solenoids (like in Grenoble hybrid).

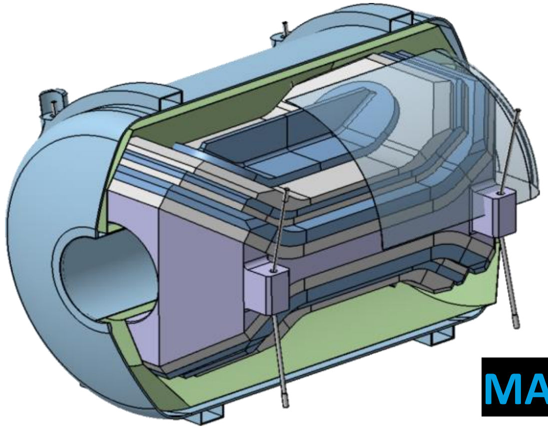
A challenging magnet requiring extensive R&D:

- **MadMAX:** a new 9 T, 1.3 m wide bore dipole magnet, under conceptual design and engineering.

Haloscope, Axion search using Hybrid Magnet at Grenoble	Magnet expertise
LSW-OSQAR+ , Axion search	Up to some 20 units 8T LHC Dipole Magnets if possible depending on LHC operations and availability, Cryogenics and Powering
LSW-ALPS-III, Axion and WISP search	About 20 units 15-16T FCC type Dipole Magnets, add on to pre-series
LSW-STAX, Axion search	2 units 11 T short model Dipole Magnets in 2 cryostats, Cryogenics and Powering
PVLAS	1 high field LHC+ Dipole Magnet, Cryogenics and Powering



ALPS II and III



MADMAX

9. Main R&D issues summary

1. Super-conductor development is crucial, every magnet project starts with this on the critical path:
    - High-yield strength Al stabilized conductors enabling radiation thin solenoids (Xo<1) of 2-3 T;
    - Larger size Al stabilized conductors for larger scale wide bore 4 to 5 T magnets;
    - ReBCO high temperature superconductor based high current conductors for magnets operating at 30-40 K on cryocoolers, also for busbars and for current leads;
    - Cable-in-Conduit like conductors and cooling technique specific for detector magnets.
2. Thin solenoid cold mass development for transparent solenoids, high YS designs.
3. Radiation transparent solenoid cryostats, honeycomb-like Al, fibre-in-resins based or hybrids.
4. Dual (twin) Solenoid designs to get shielding, magnetize muon detectors and avoid heavy iron yoke.
5. Study of scaling issues for enabling solenoids providing 5 T in 7 to 10 m bores.
6. R&D for non-colliding beam experiment magnets, e.g. axions (and more), demonstrators.
7. Quench protection, energy extraction, high-voltage designs for high energy/mass density coils.

10. Conclusion

- Requirements for future detector magnets were reviewed in order to formulate common global R&D targets.
- Many magnets are scaled up versions of CMS (3.8T in 6m bore), with larger bore of up to 7.5 m (FCCee/CIC/LC). This scaling is significant, requires R&D in particular in the development of larger and stronger conductors.
- Very challenging designs are proposed for FCC-hh 4T/10m and the ultra- light and transparent variants for both 2T FCC-ee and 3-4T FCC-hh. Again this requires R&D, specifically, but not only, on developing proper conductors, and for both a demonstrator to mitigate the risks.
- For non-colliding beam experiments, like for axions, examples were presented of unique and challenging magnets to be built.
- Global R&D issues for future detector magnet were identified and listed. These will be further detailed and put on a time line to enable timely readiness.