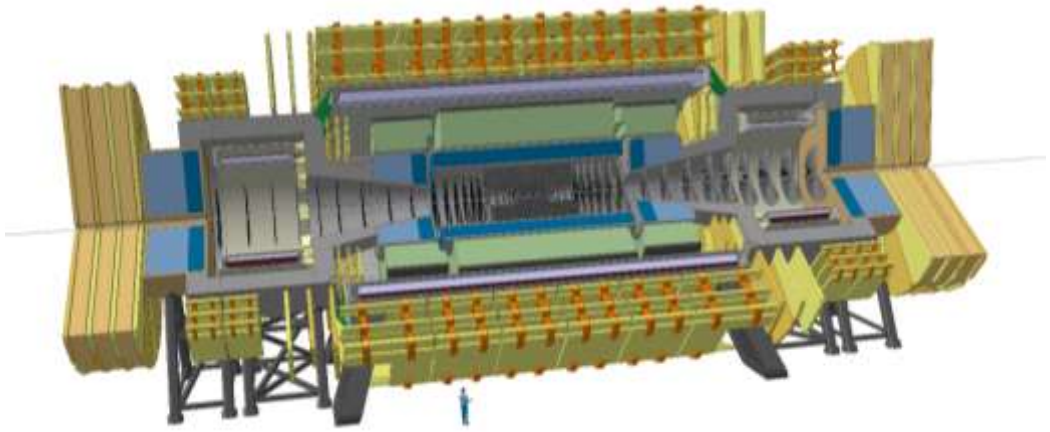
Detector Magnets for the Future Circular Collider



Herman ten Kate

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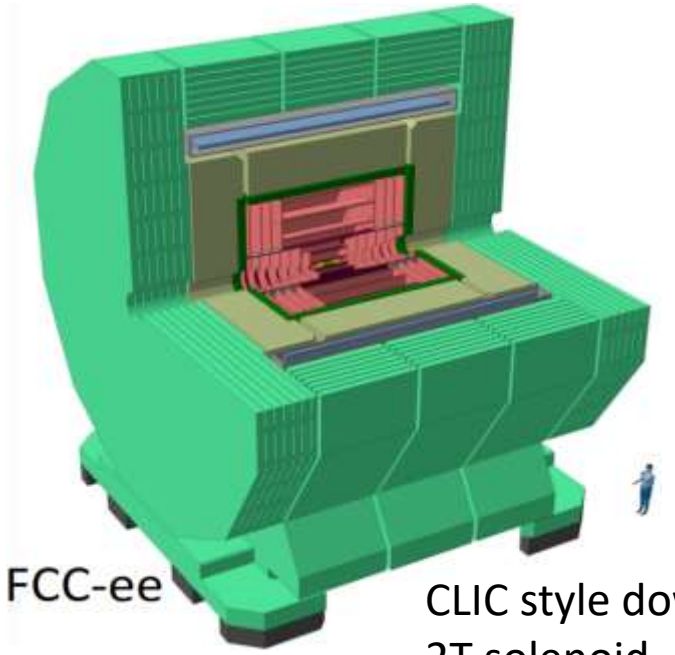
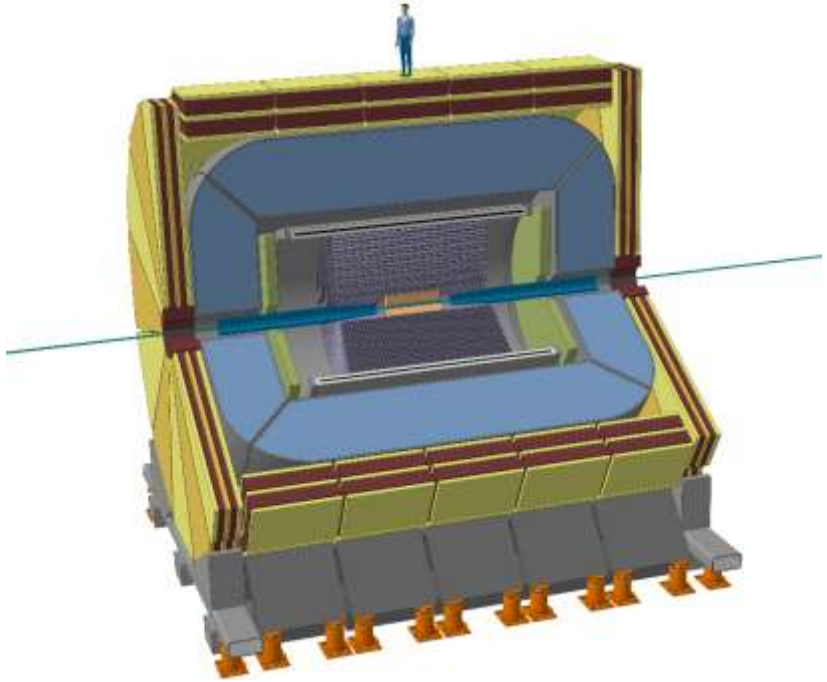
1. Magnets for FCC-electron-positron collisions detector

For FCC-ee two detector designs are proposed:

- **a conventional 2T solenoid around the calorimeter**, essentially a downscaled CLIC design, not further presented here,
- **a challenging 2T solenoid "ultra-thin & transparent" around the tracker**, proposed by the magnet team and accepted as baseline.



CLIC style downscaled 2T solenoid



IDEA detector, innovative thin solenoid around tracker

Solenoid inside or outside calorimeter

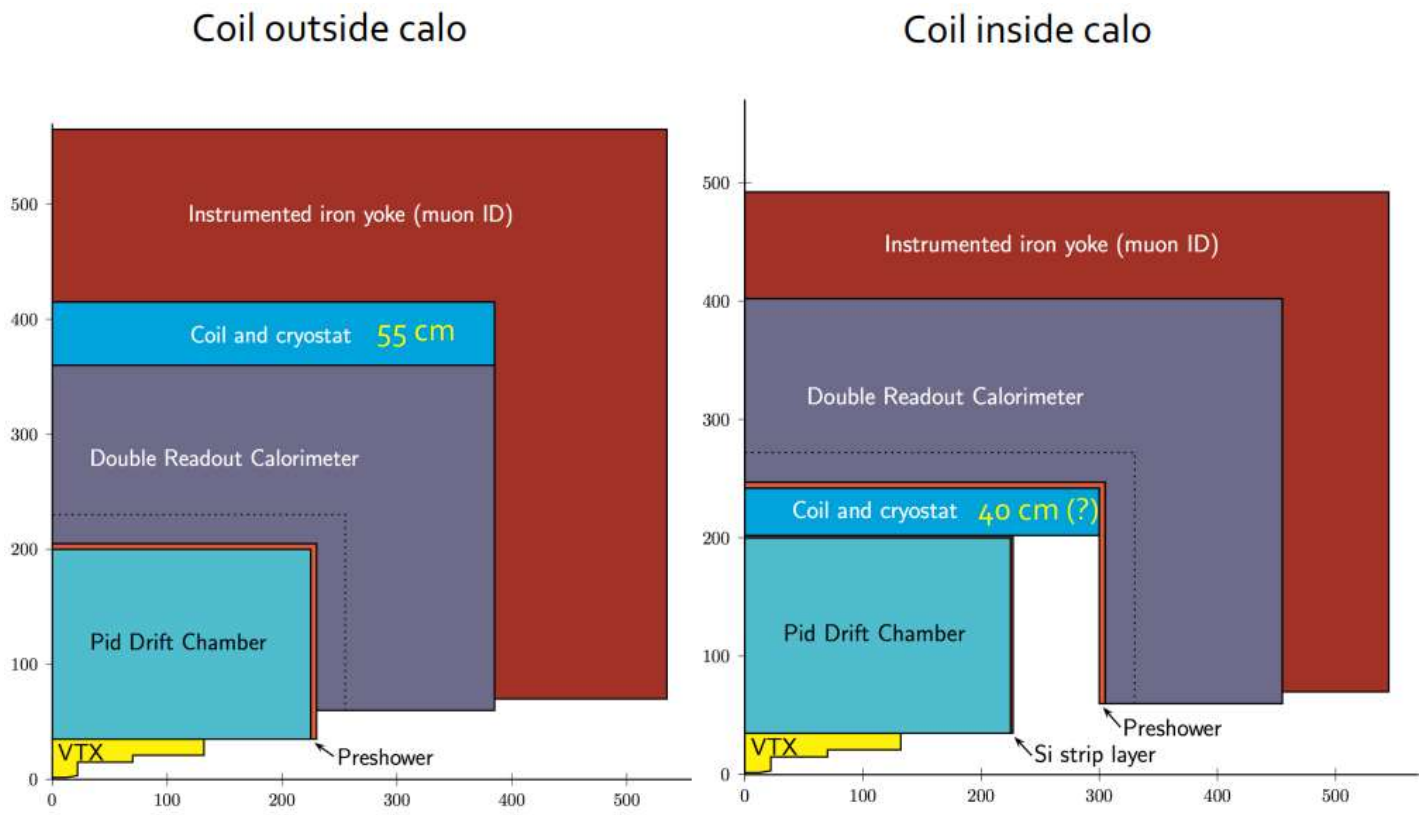
Motivation:

- 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:

- **Factor ≈ 4.2 in stored energy**
- **Factor ≈ 2.1 in cost!**

But design is not obvious and requires R&D and a demonstrator.



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

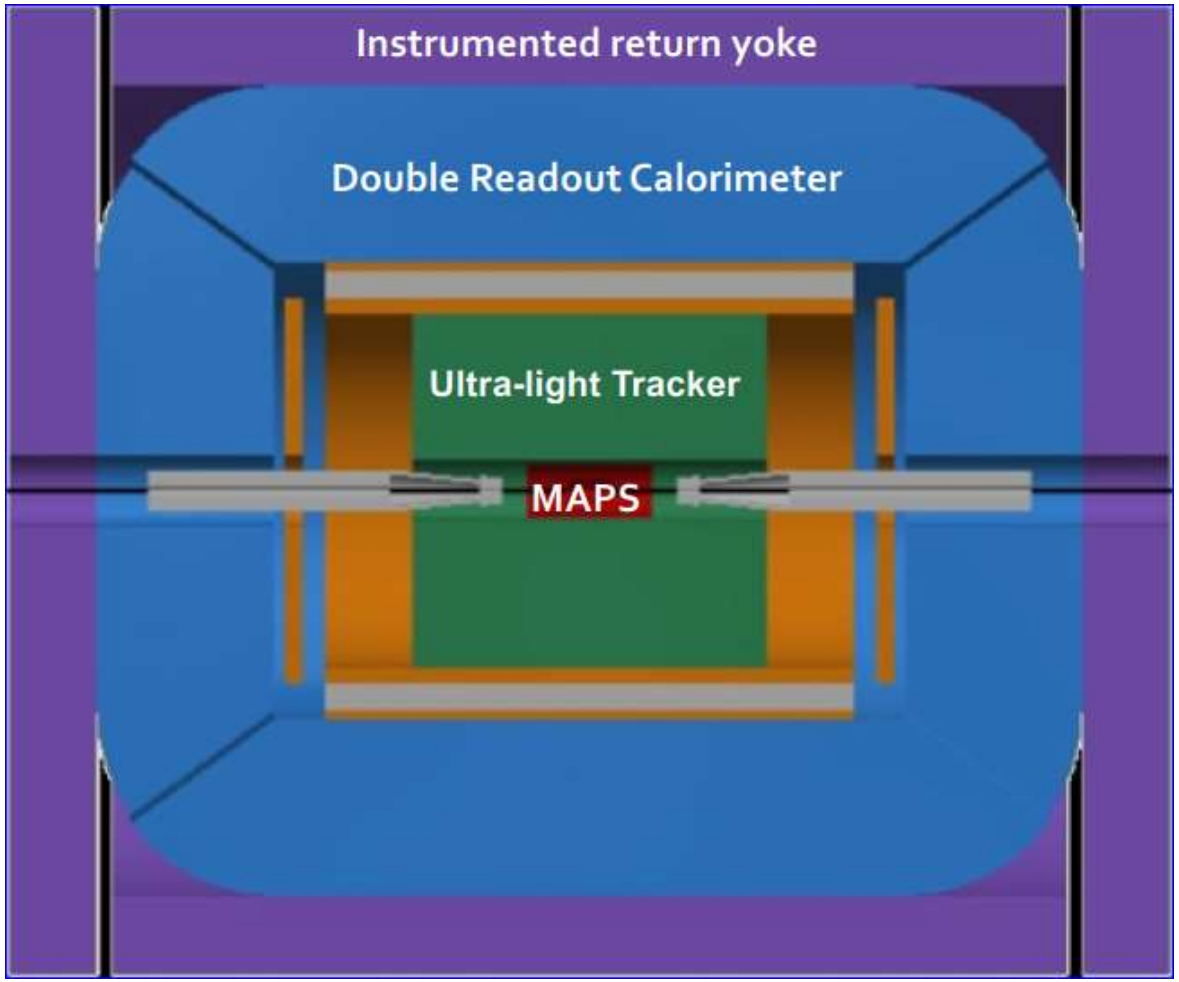
Solenoid for "ultra-thin" IDEA detector

Requirements:

- 2 T in thin Solenoid with radiation length $X_0 < 1$ in radial direction!
- Radial envelope < 300 mm.
- Magnetized iron for muon detection.

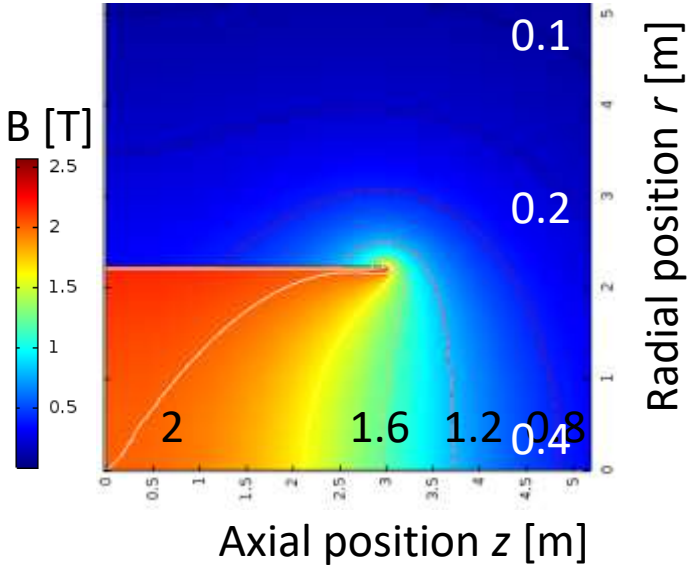
Strategy:

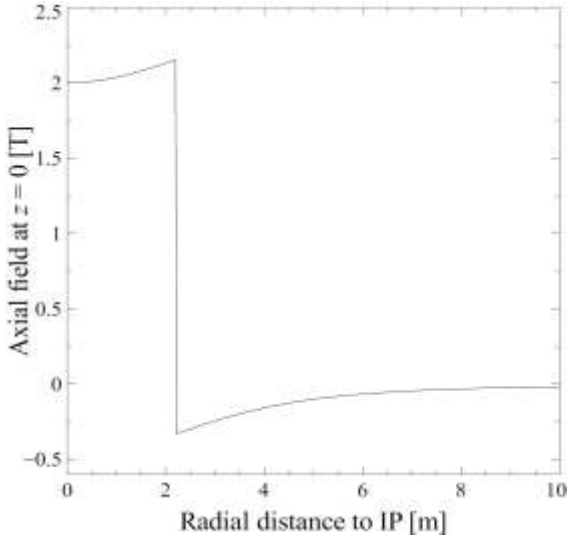
- Reduce thickness of cold mass.
- Reduce thickness of cryostat.
- Magnetic flux return by a light return yoke.

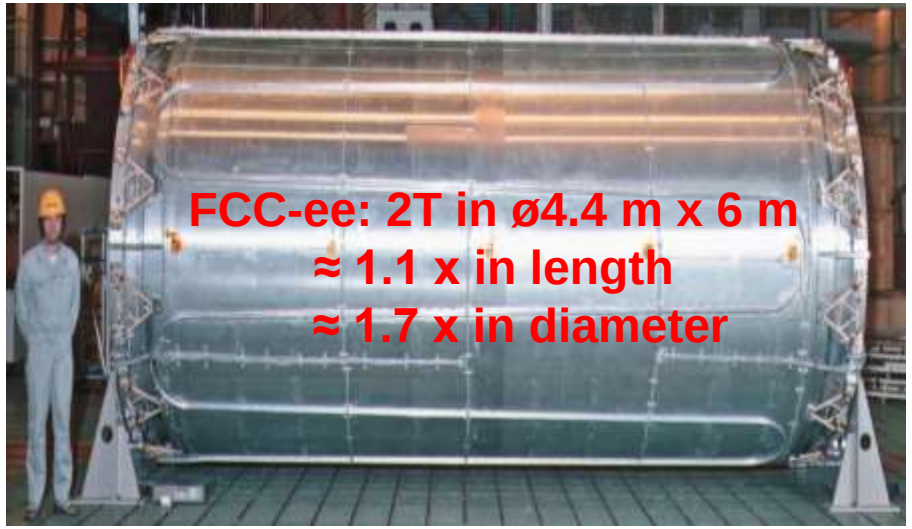


IDEA detector (***I***nternational ***D***etector ***E***lectron ***A***ccelerators), an innovative thin solenoid around tracker

FCC-ee 2T "thin" solenoid inside HCAL







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

- 5mT stray field in radial direction at 15 m, in axial direction at 20 m
- Coil composition: mainly aluminum (77 vol.%) + copper (5 vol.%) + NbTi (5 vol.%) + glass/resin/dielectric film (13 vol.%).

Radiation thickness:

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

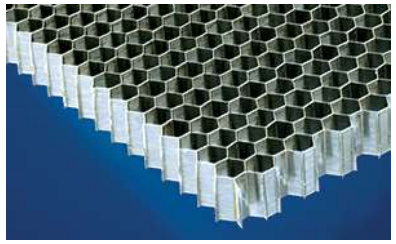
R&D for a Thin & Transparent Solenoid

Crucial technologies to be developed:

- High YS Super-Conductor allowing self-supporting coil windings.
- Maximum energy extraction at quench to minimize cold mass hot spot temperature.

- New ultra-light cryostat design following two routes:
  - high level of thermal insulation and mechanical support through metal foil sealed glass spheres or permaglass under vacuum (not presented here).
  - lightest possible metallic-vacuum cryostat using honeycomb structures or corrugated plate-sandwich panels.

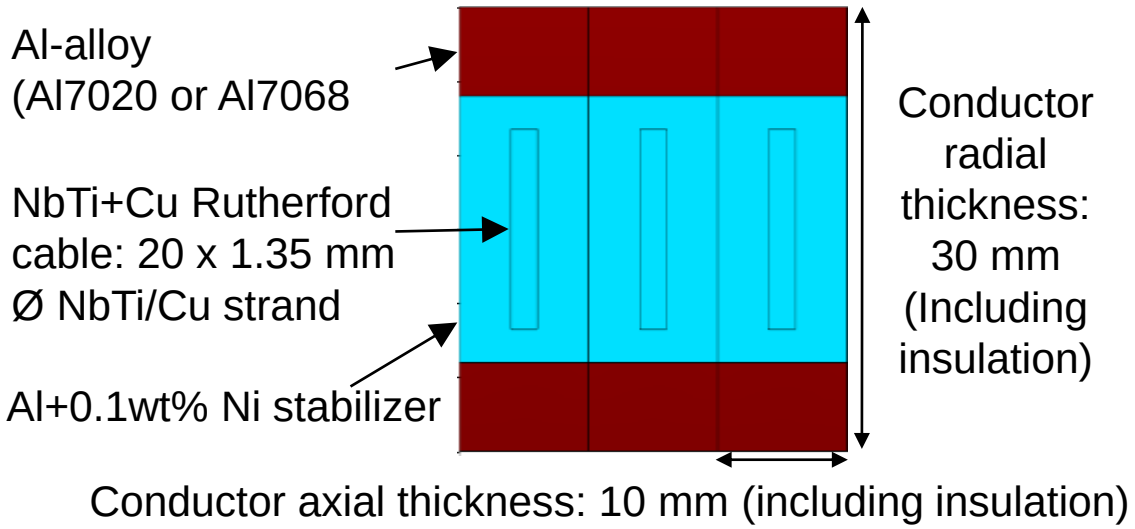
1st design shows that it is feasible; would be a breakthrough towards lighter and smaller detector magnets, and significant cost saving.

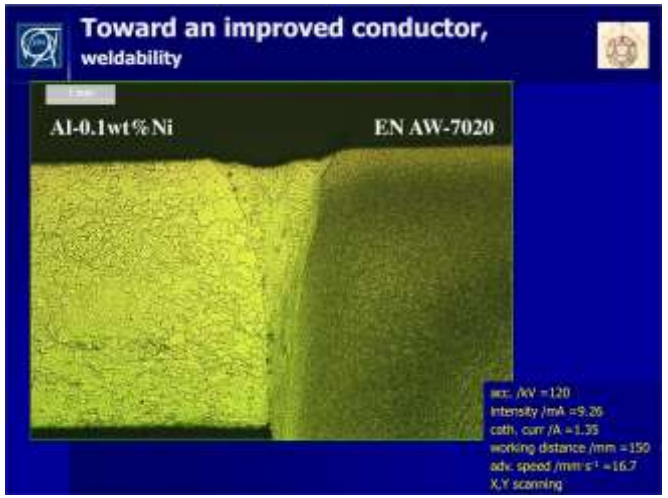


R&D on Conductor – Reinforced conductor

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: 24 kJ/kg.



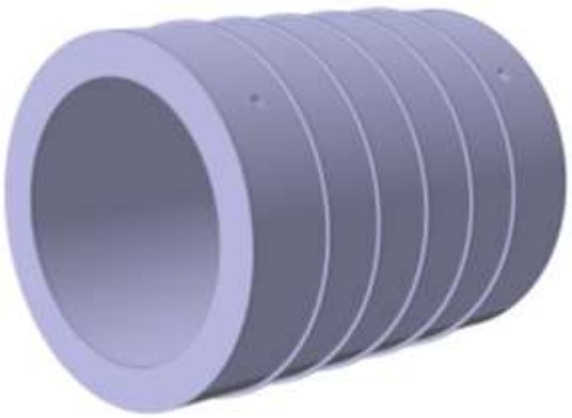


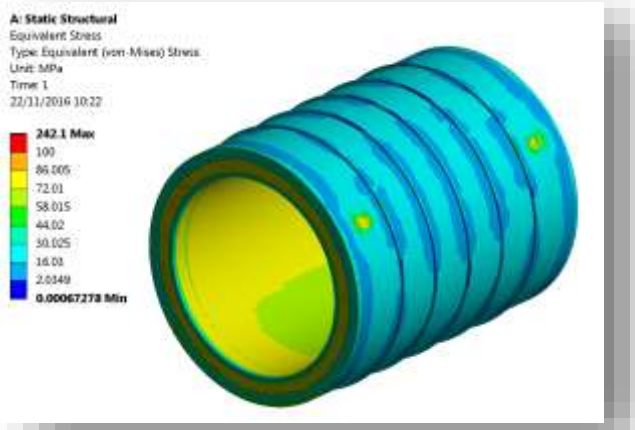
EB welded reinforcement, Sgobba [2010]

R&D on Cryostat – Using thin reinforced outer shell

Main features:

- CAL is supporting the cryostat
- Cold mass supports to end flanges
- Solid plate inner shell
- Outer shell reinforcement rings to prevent buckling
- Material Al 5083-O





	Loads
Tracker mass [t]	4
External pressure [MPa]	0.1
Self mass [t]	7
Cold mass + rods thermal shrinkage [kN]*	215

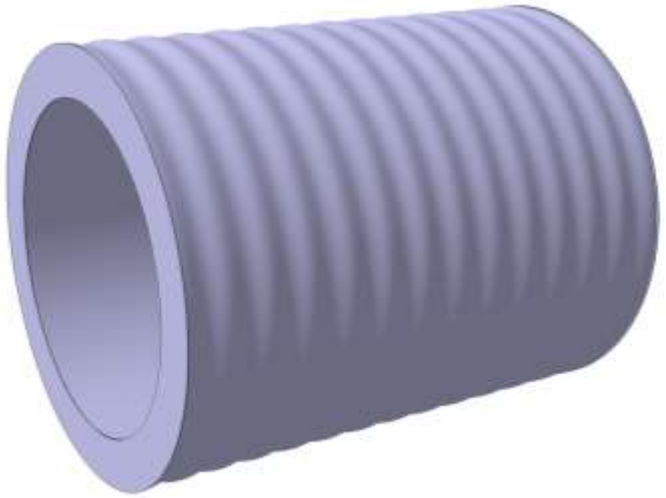
* Initial estimate is 3 times the weight of the cold mass

	Inner shell	Outer shell	Flanges
Material	Al 5083-O	Al 5083-O	Al 5083-O
Thickness [mm]	3	15*	12
Min thickness [mm]	3	13	12
Max thickness [mm]	3	73	12
Shield thickness [mm]	3	3	3
Volume [t]	0.5	1.7	2 x 0.13
Mass [t]	1.4	5.2	2 x 0.4
Total mass [t]	7.4		
Stress limits	According to EN 13458		

Cryostat option – Corrugated outer shell plate

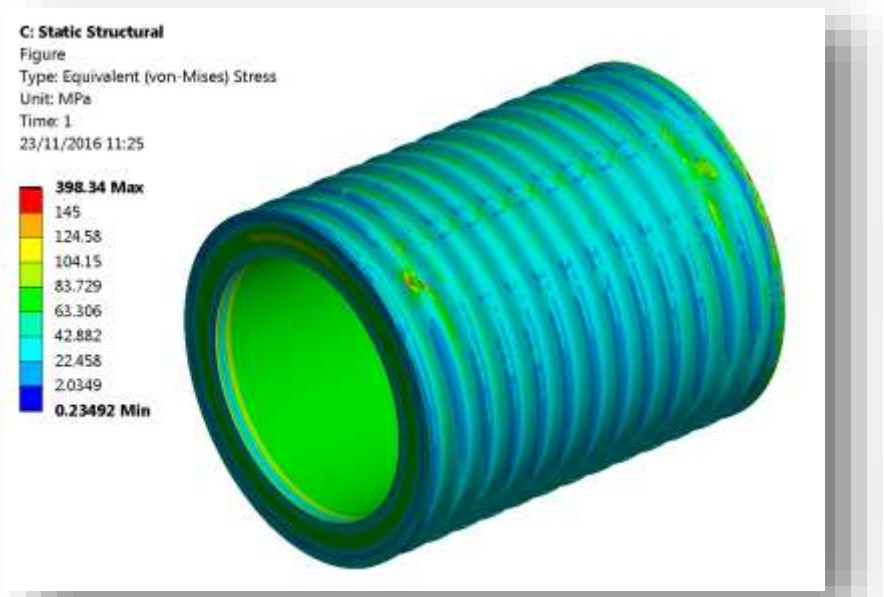
Option for the external shell, use corrugated plate:

- More uniform thickness seen by particles
- Thickness of outer shell is very dependent on the period and amplitude of the corrugation
- Flat flanges may not be suitable in this case



	External shell	Flanges
Material	Al 5083-O	Al 5083-O
Thickness [mm]	**9**	15
Sin Amplitude [mm]	**50**	-
Wave period [mm]	500	-
Volume [t] [1]	1.4	2 x 0.16
Mass [t] [1]	3.8	2 x 0.5
Mass cryostat [t] [1]	6.2	

[1] Including thermal shield [2] EN13456 standard

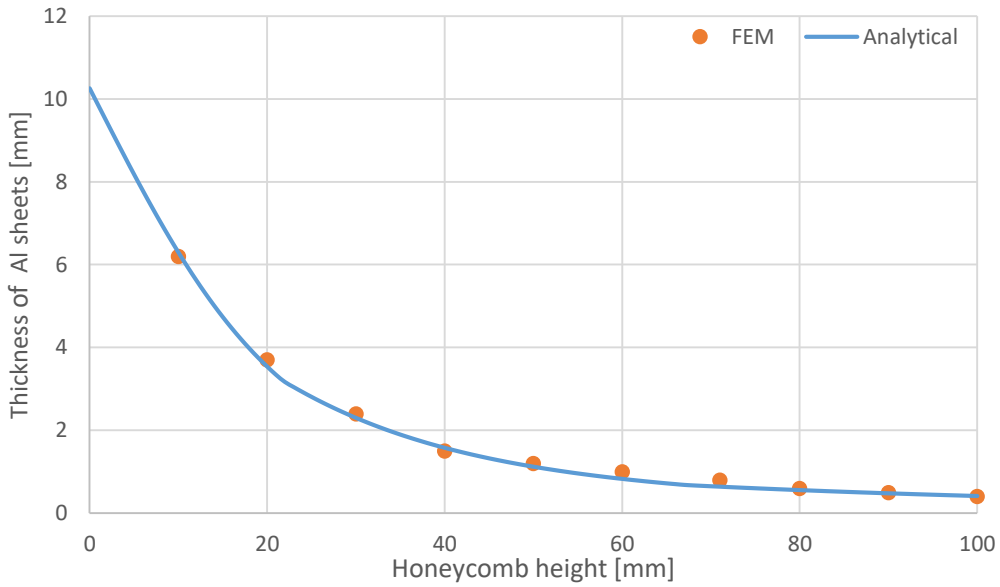


Best cryostat option – Use honeycomb-like plate

Option for the external shell, use honeycomb plate or sandwich panels:

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

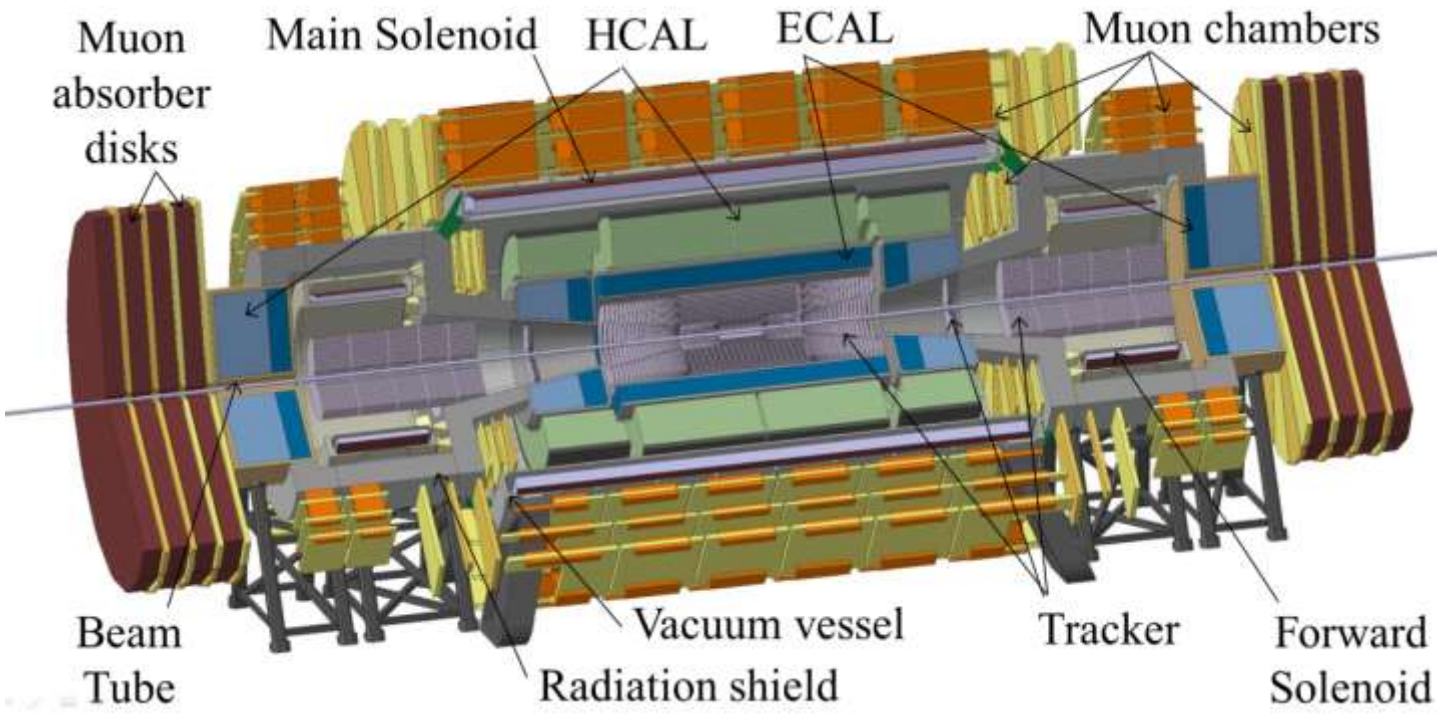
When comparing the 4 solutions, honeycomb delivers the best minimum radiation thickness!



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**

2. FCC-proton-proton collisions Detector - Baseline



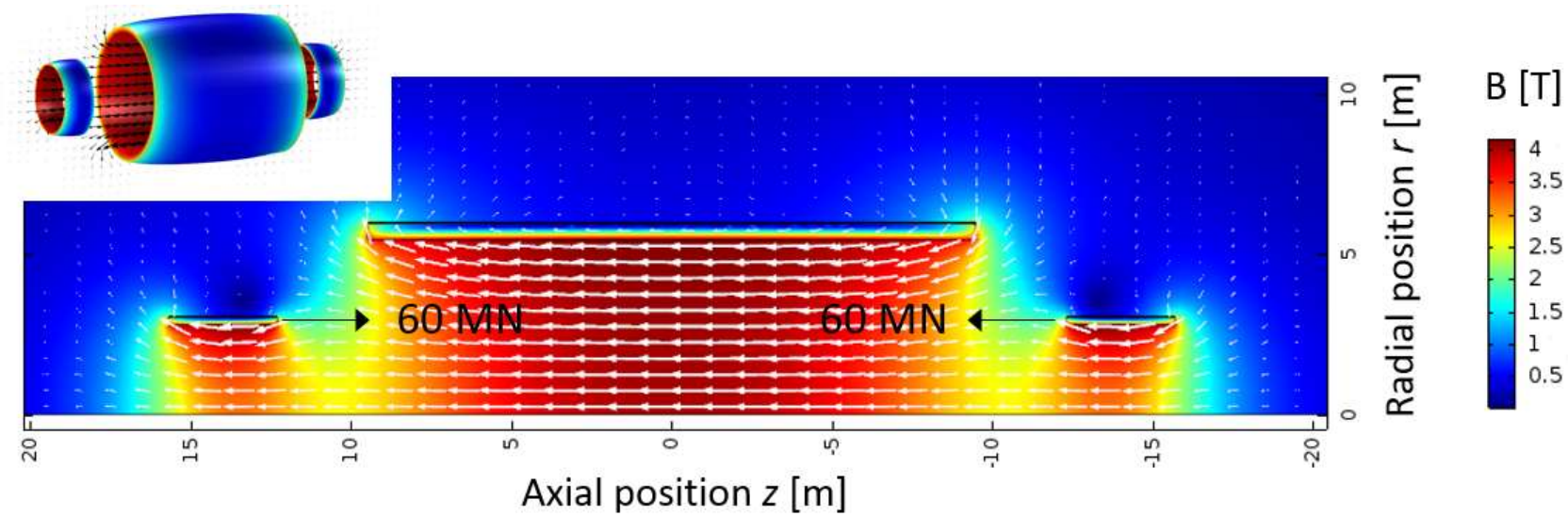
Main solenoid:

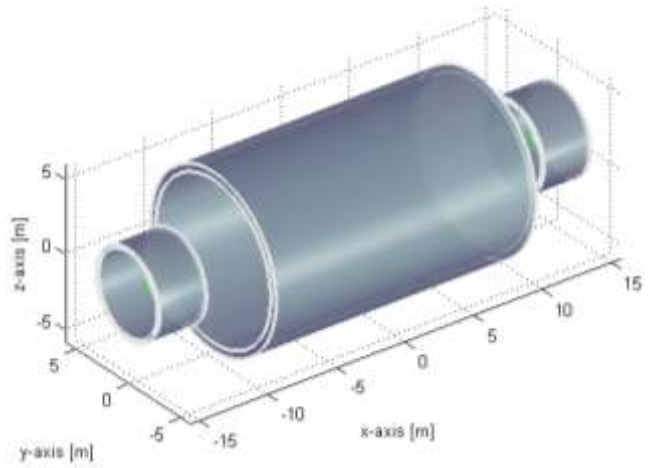
- Trackers and calorimeters inside bore, supported by the bore tube
- Muon chambers (for tagging) as outer layer in barrel region

Forward Solenoids (forward dipole is an option):

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

4T/10m-bore Solenoid with 4T Forward Solenoids - baseline



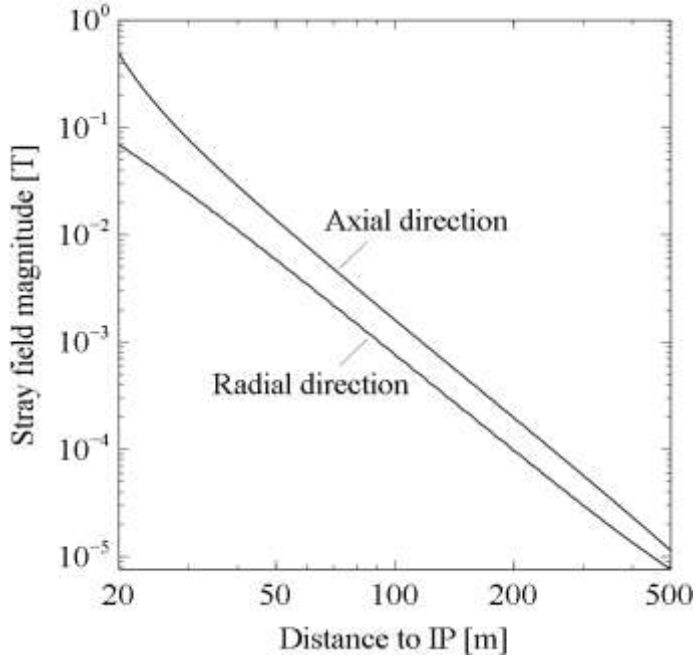


Concept:

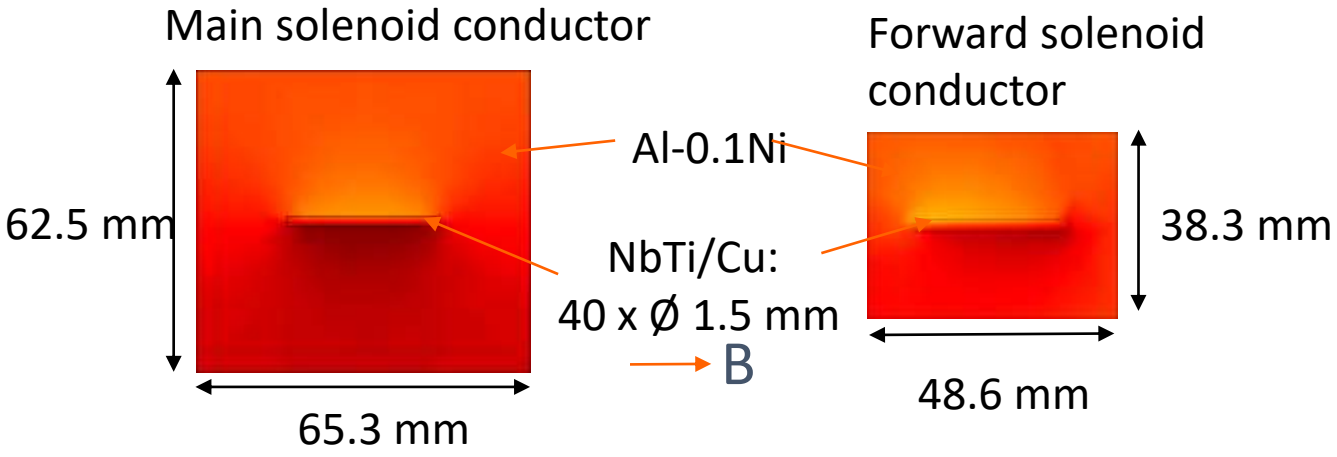
- 4 T in 10 m free bore
- Magnetic shielding not required
- 60 MN net force on forward solenoids handled by axial tie rods

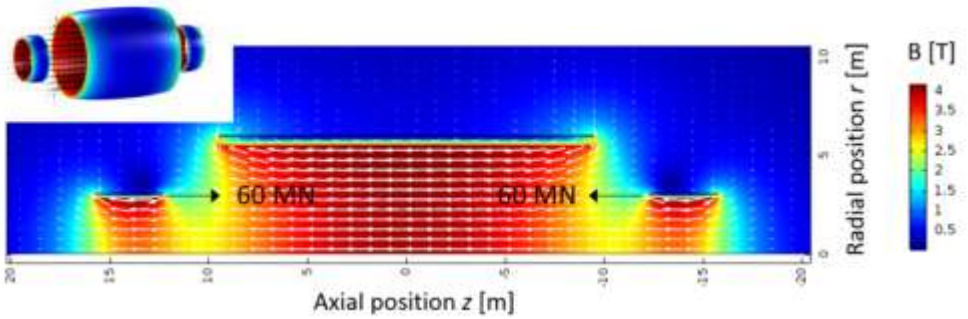
Result:

- **Stored energy: 14 GJ, energy density 12 kJ/kg**
- Main solenoid cold mass 1070 t, forward solenoids 48 t
- Lowest degree of complexity from a cold-mass perspective
- But with significant stray field to be coped with



Super-Conductor for in 4T/10m baseline design solenoids



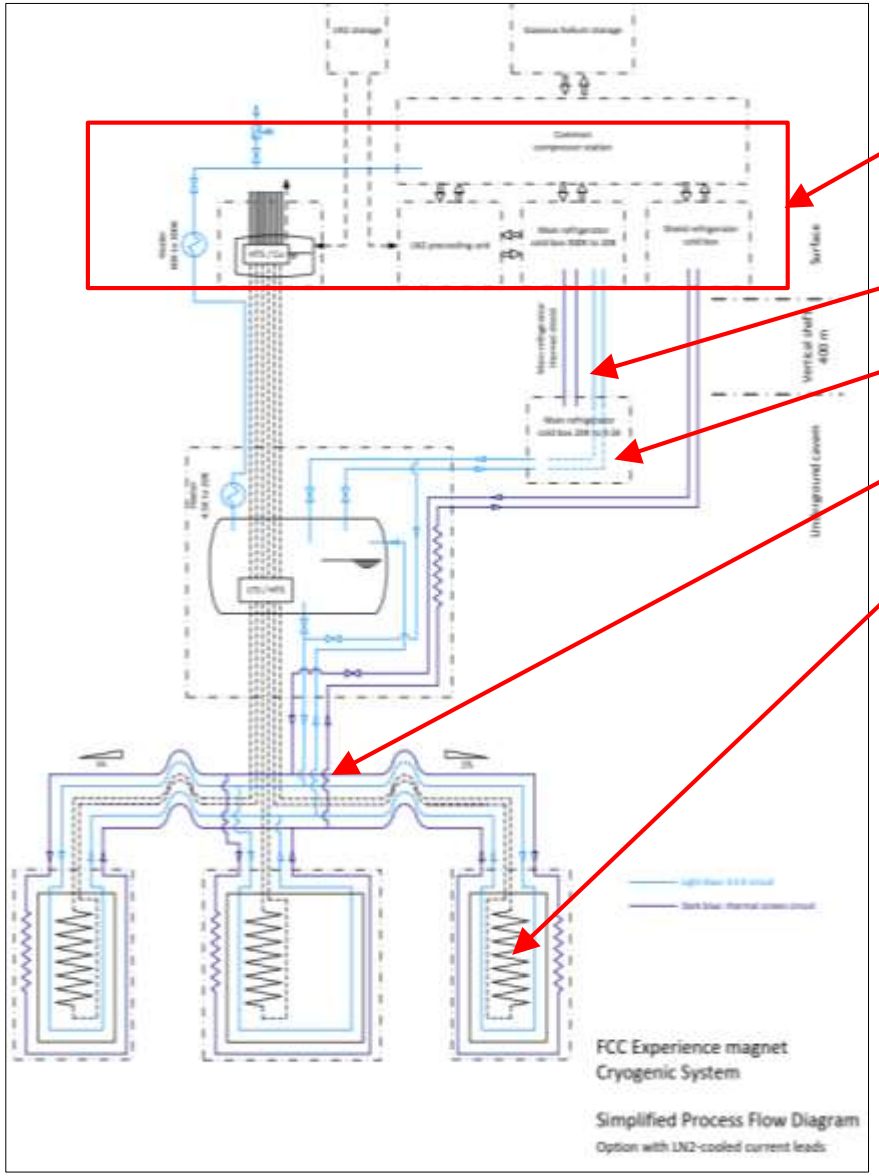


	Main Solenoid	Forward Solenoid
Current [kA]	30	30
Self-inductance [H]	28	0.9
Layers x turns	8 x 290	6 x 70
Conductor length [km]	83	2 x 7.7
Bending strain [%]	0.57	0.68

Next generation Aluminum-stabilized Rutherford 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, deserves the highest priority!**

Cryogenics, Powering and Controls



Main Cryogenics equipment is on surface, not underground

- Intervention on critical installations on surface including Main & Shield refrigerators
- Sending high pressure (20 bar) helium gas down the shaft
- In cavern JT unit producing LiHe and filling dewars
- Distribution of liquid over the main and forward systems
- All coils are conduction cooled using thermosyphon He circulation through pipe work on cold masses
- One cold box (shown) or three cold boxes (baseline), for the main and each of the forward magnets

Power converters and diode/dump are on surface

- feeding the coils through SC link down the ≈350m shaft

Control and safety systems (MCS and MSS) on surface

Conclusion

- **Baseline Designs for the detector magnet systems for FCC ee$^+$, and FCC hh were developed and detailed in CDR chapters.**

- FCC-ee IDEA detector: a conceptual design of a 2T/4m free bore / 6m long Solenoid surrounding the tracker was developed, a design using 300 mm radial space and 1 X_0 radiation length is doable.

- FCC-hh: a 4 T Main Solenoid, 10 m bore, 20 m long, complemented by two Forward Solenoids, 3.2 T center field in a 5 m bore, 4 m long. Also the option of using forward dipole magnets was developed.

- Cryogenics based on using MR+SR on surface, with 20b/20K into cavern, JT-liquefying in cavern into dewar and thermo-siphon cooling of cold masses.

- **No show stoppers identified**, **but a serious R&D program is required** on reinforced superconductors and ultra-transparent cold masses and cryostats.