Ultra-light 2T/4m bore Detector Solenoid for FCCee

- the Solenoid in the IDEA detector -

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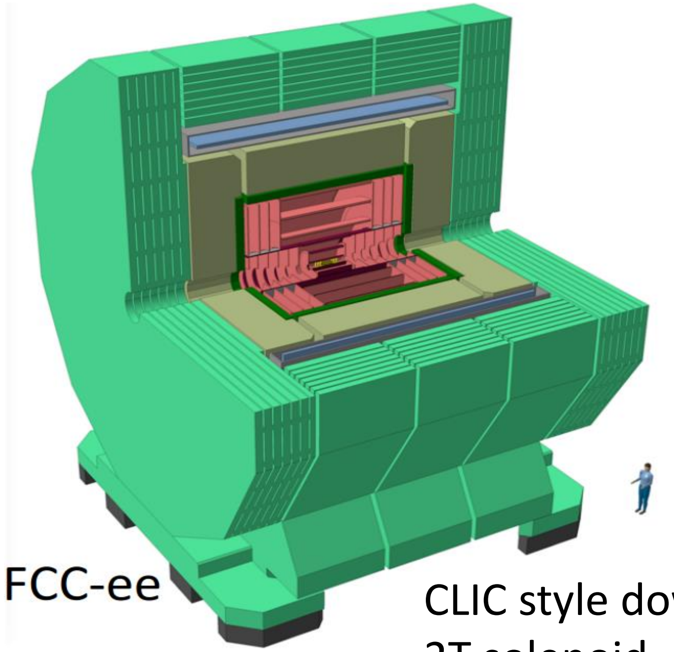
for the FCC detector magnets design team

1. Motivation
2. 2T IDEA Solenoid
   - Conductor, coil windings, Quench protection
3. Cryostat
   - Optimized conventional, Honeycomb-like
4. Conclusion

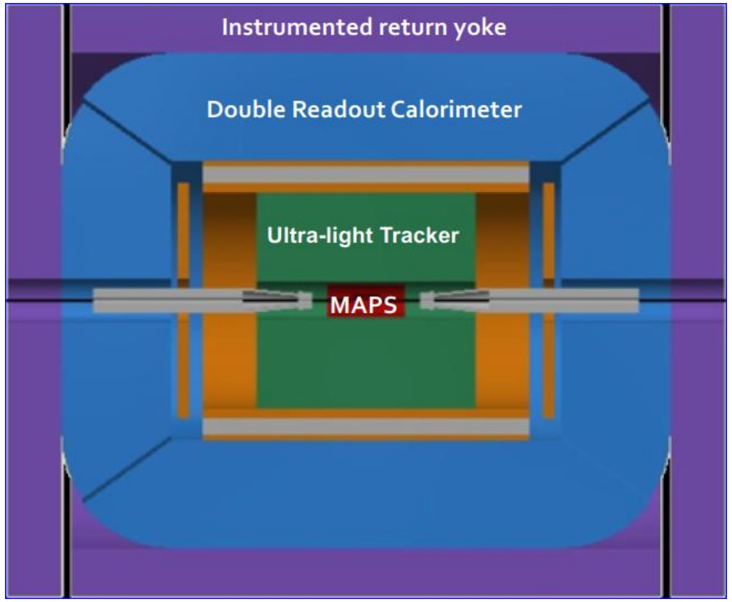
1. Detector magnets for FCC-ee

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

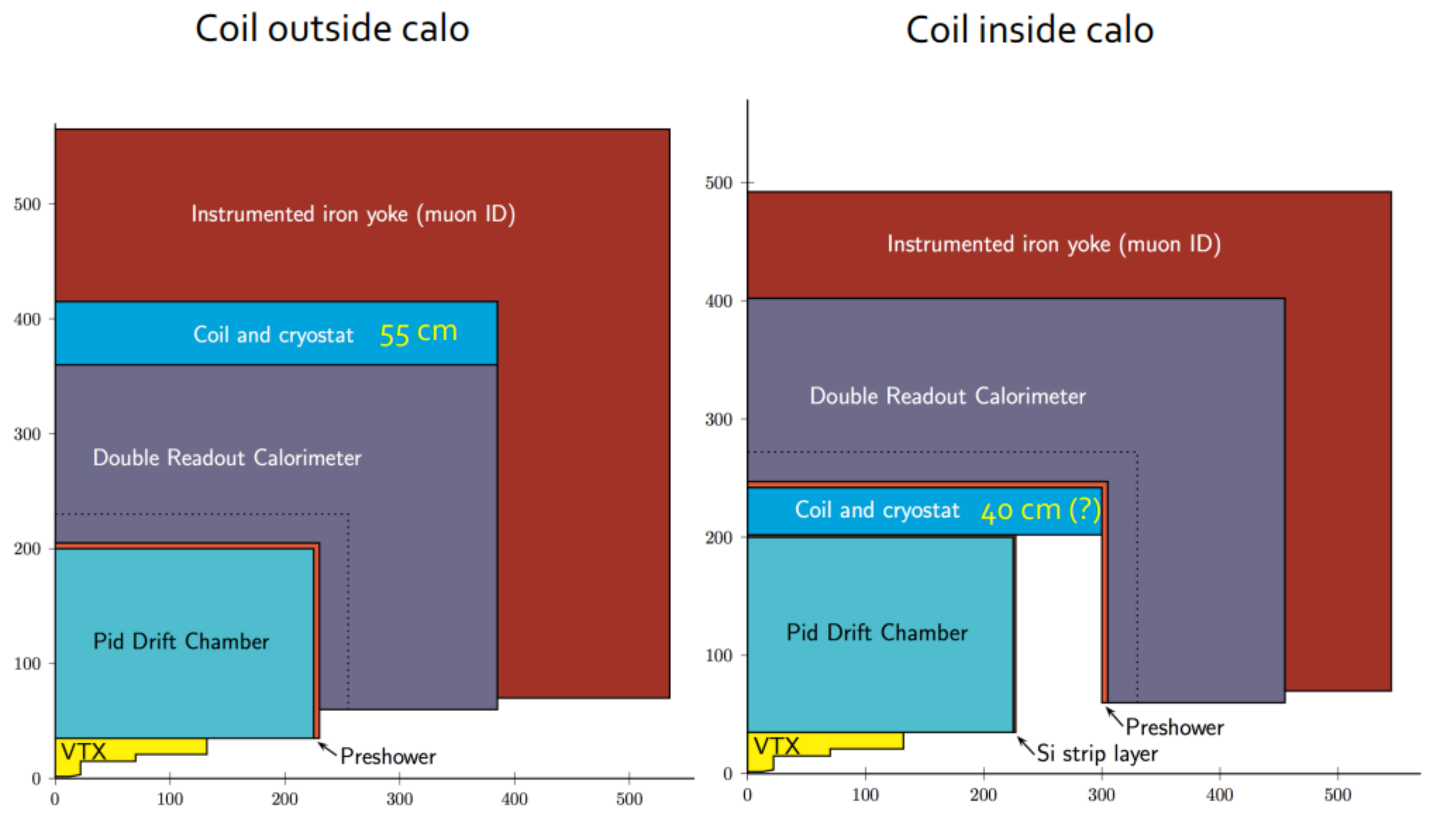
Motivation:

- 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?

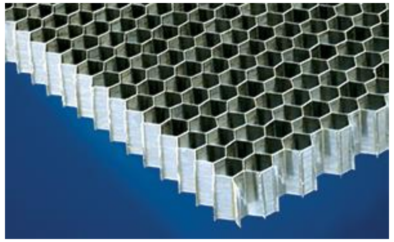
Thin & Transparent Solenoid Development

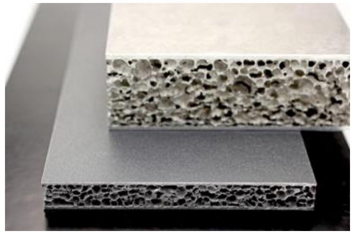
Crucial technologies to be developed:

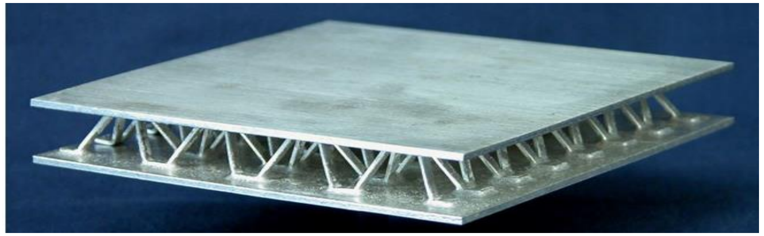
- High YS Super-Conductor allowing self-supporting cold mass
- Maximum energy extraction at quench to minimize cold mass hot spot temperature

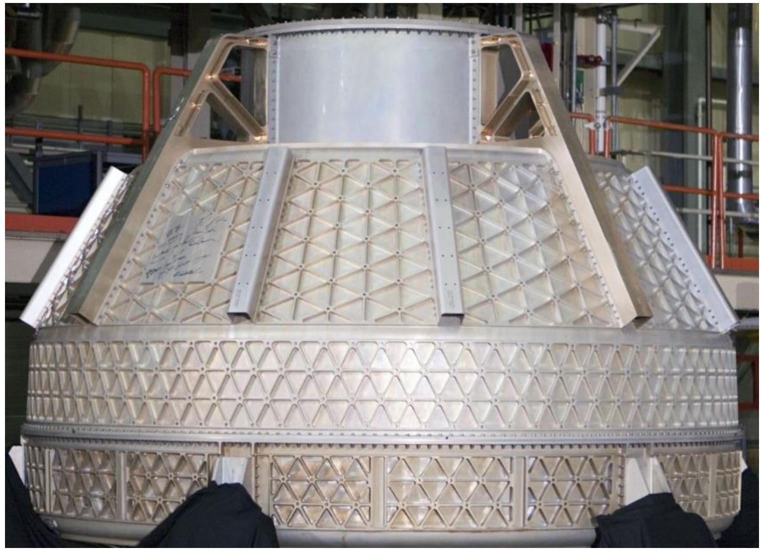
- New ultra-light cryostat design following two routes:
  - high level of thermal insulation and mechanical support through metal foil sealed glass spheres or permaglass under vacuum (not presented here)
  - lightest possible metallic-vacuum cryostat using honeycomb structures or corrugated plate-sandwich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

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









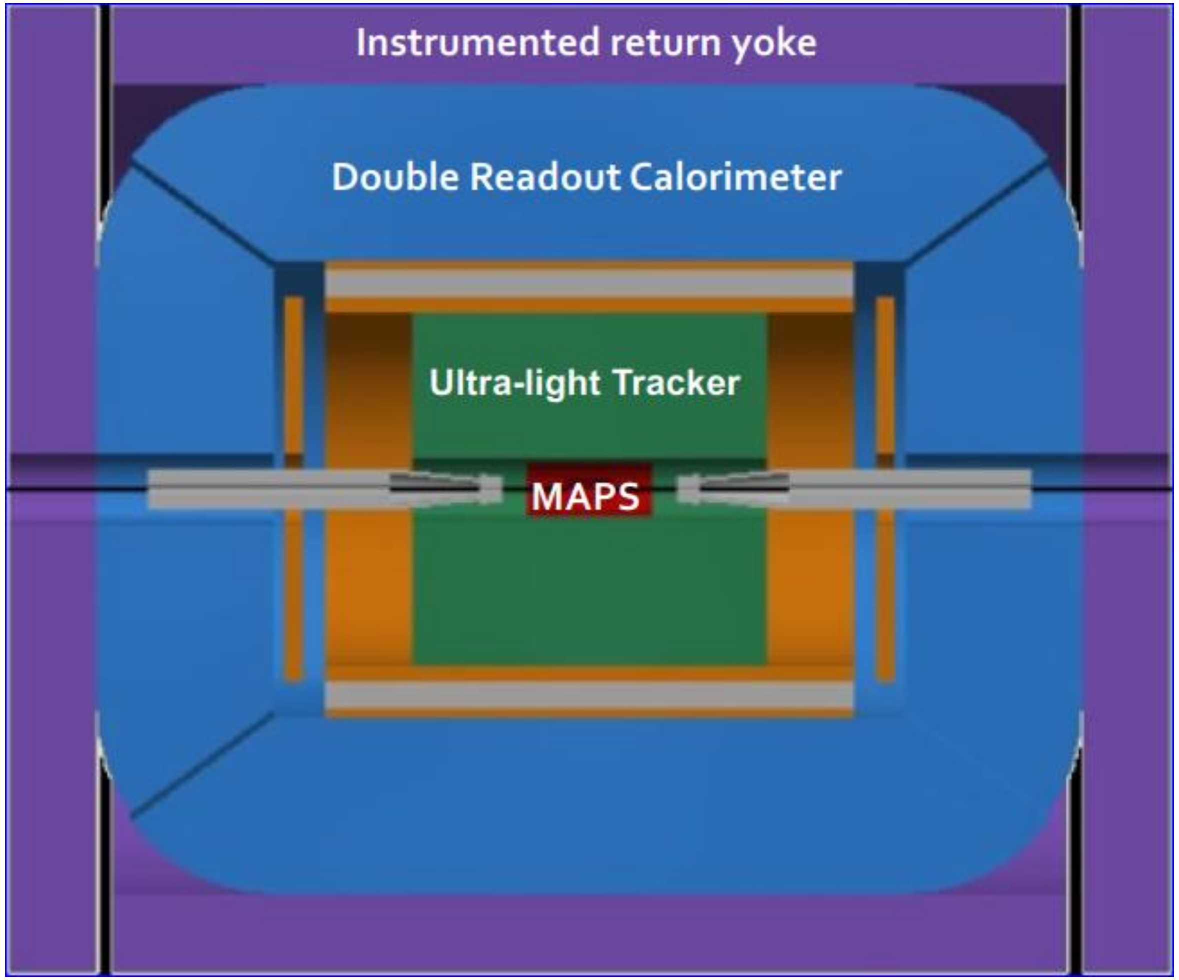
2. Solenoid for IDEA detector

Requirements:

- 2T 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

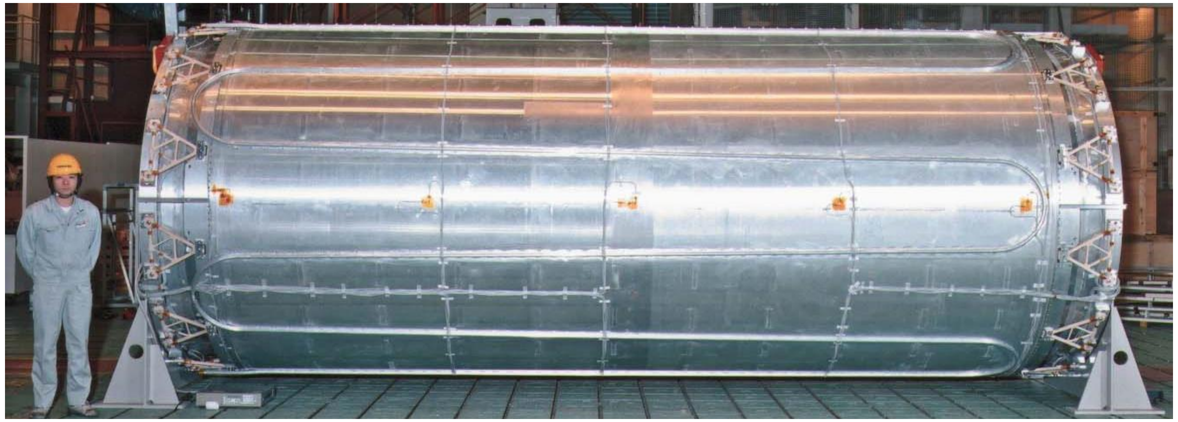


IDEA detector (International Detector Electron Accelerators), innovative thin solenoid around tracker

Scaling from ATLAS Solenoid to FCC-ee IDEA Solenoid

ATLAS Solenoid:

2T in ø2.51 m x 5.4 m



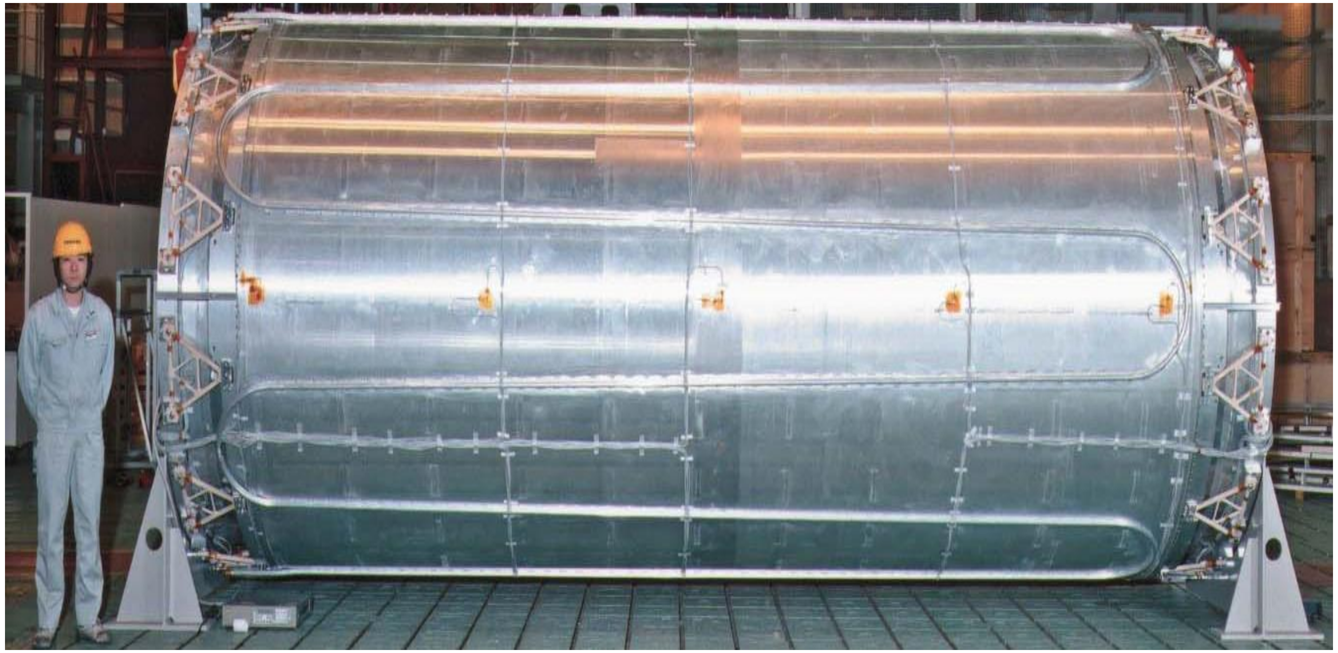
IDEA Solenoid:

2T in ø4.4 m x 6

≈ 1.1 x in length

and

≈ 1.8 x in diameter



2 T "light & thin" solenoid inside Calorimeter

Self-supporting single layer coil

- high yield strength conductor fully bonded
- thin Al support cylinder for conduction cooling

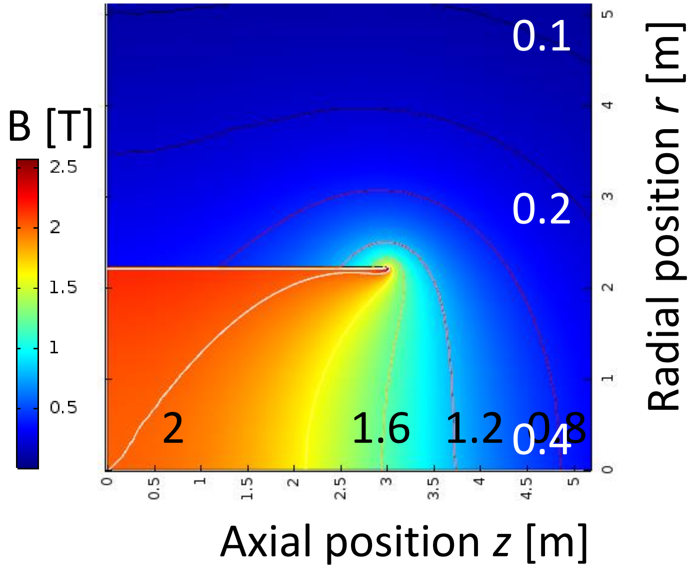
Coil composition:

- Aluminum (77 vol.%)
- NbTi (5 vol.%) / copper (5 vol.%)
- glass/resin/dielectric film (13 vol.%)

Radiation thickness:

- Cold mass: X_0 = 0.46, λ = 0.09
- Cryostat (25 mm Al): X_0 = 0.28, λ = 0.07

1st design shows that achievable is a total X_0 = 0.74 < 1 (at η = 0)



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

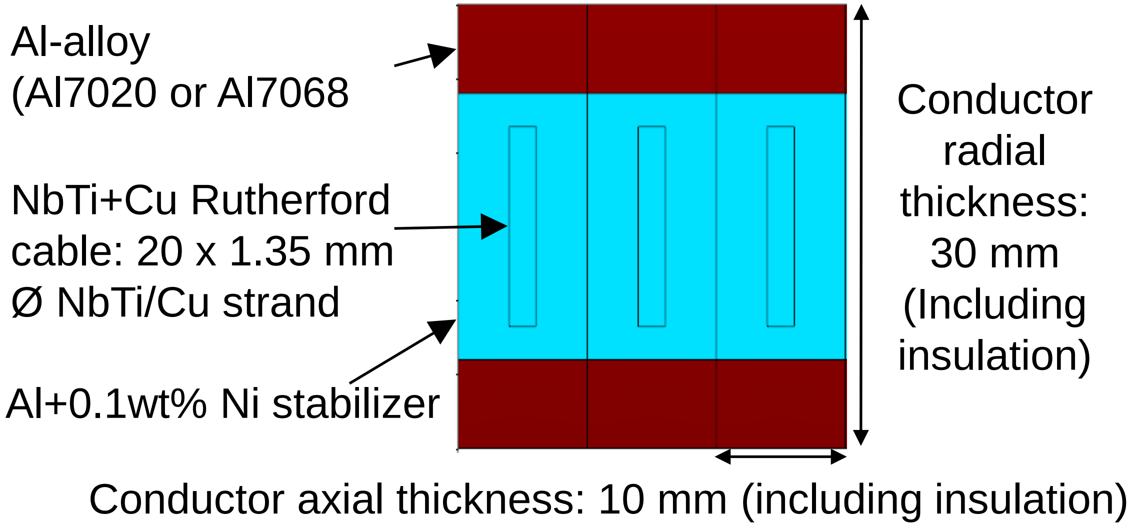
Conductor & Windings

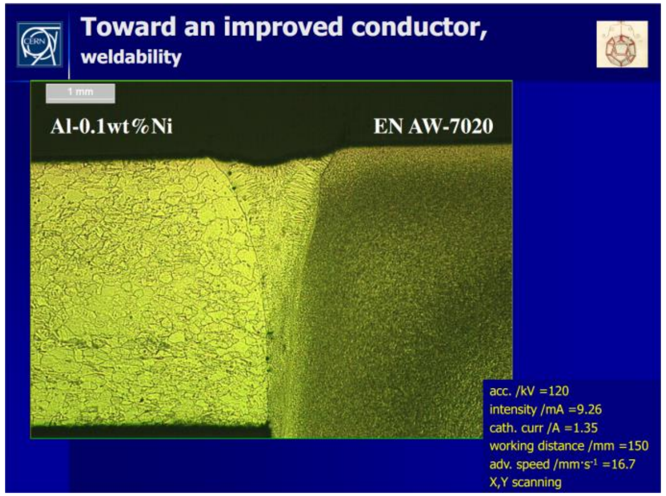
Conductor:

- 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

Winding scheme:

- 1 layer coil, 595 turns, conductor length 8.3 km
- Energy over mass density: 24 kJ/kg





EB welded reinforcement, Sgobba [2010]

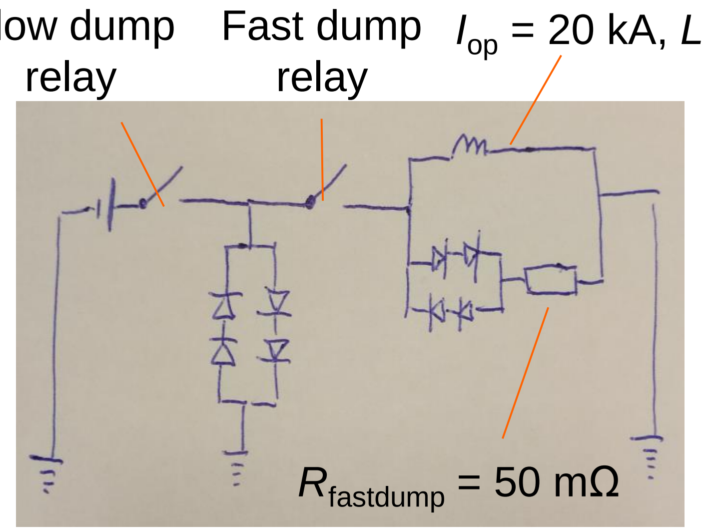
Quench Protection and Hot-spot temperature

Quench protection:

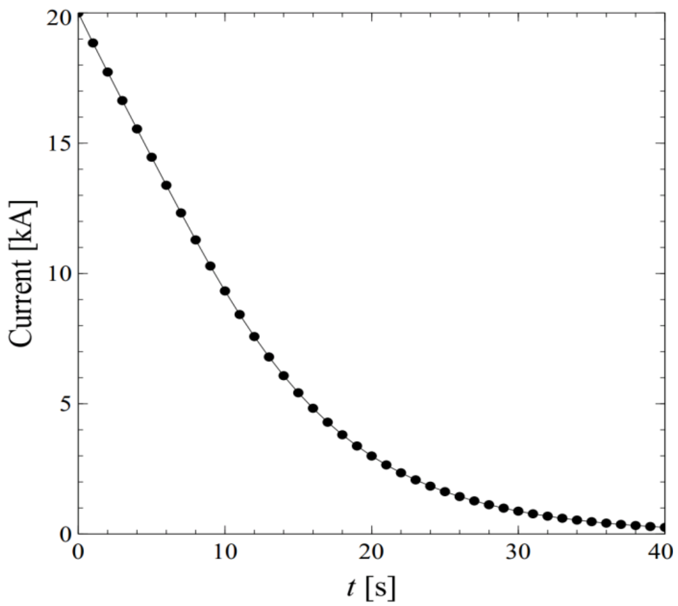
- Relies on high percentage of extraction to reduce cold mass enthalpy
- And relies on quench heaters
- 1000 V peak extraction voltage accepted to yield 76% extraction
- Required conductor RRR> 400
- Normal quench scenario:

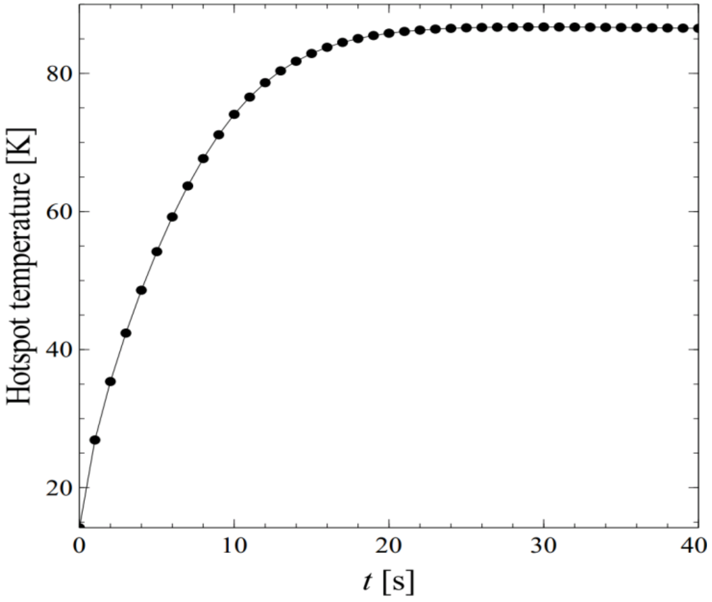
  $T_{hotspot} < 100$ K

- Extreme fault scenario hot spot can be improved by using axial quench propagation strips.



Scenario	Hot spot temperature [K]
Regular	87
Malfunctioning heaters	150
Malfunctioning extraction	118

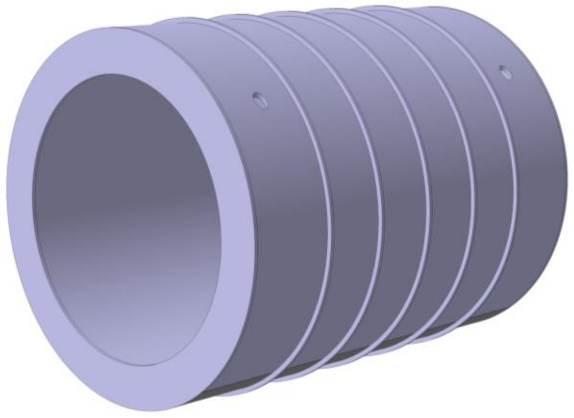


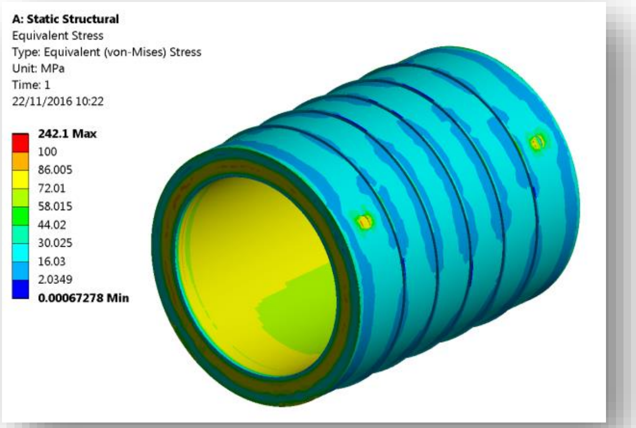


3. Cryostat – using thin reinforced outer shell

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

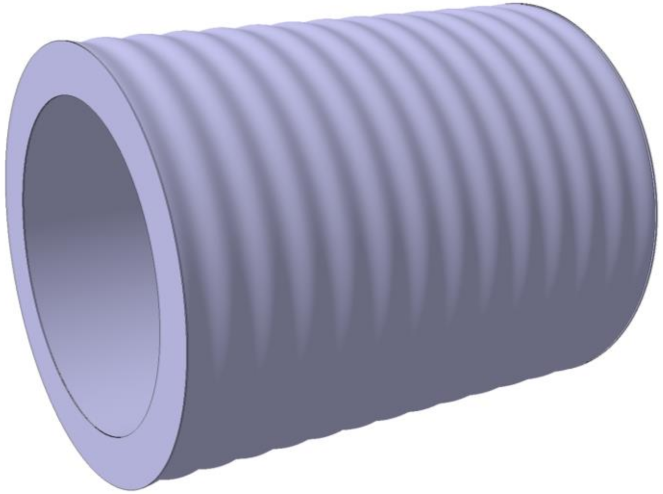
* Initial estimate is 3 times the weight of the cold mass

	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

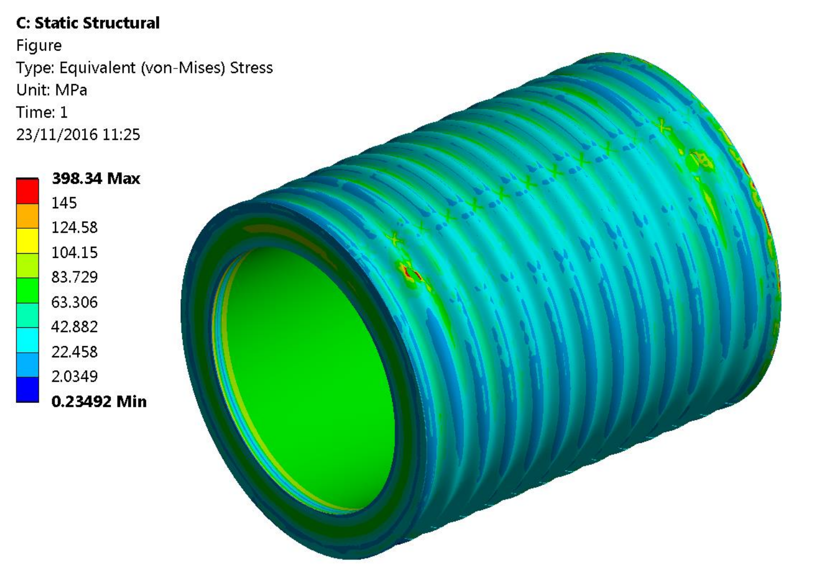
Option for the external shell, use corrugated plate:

- 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

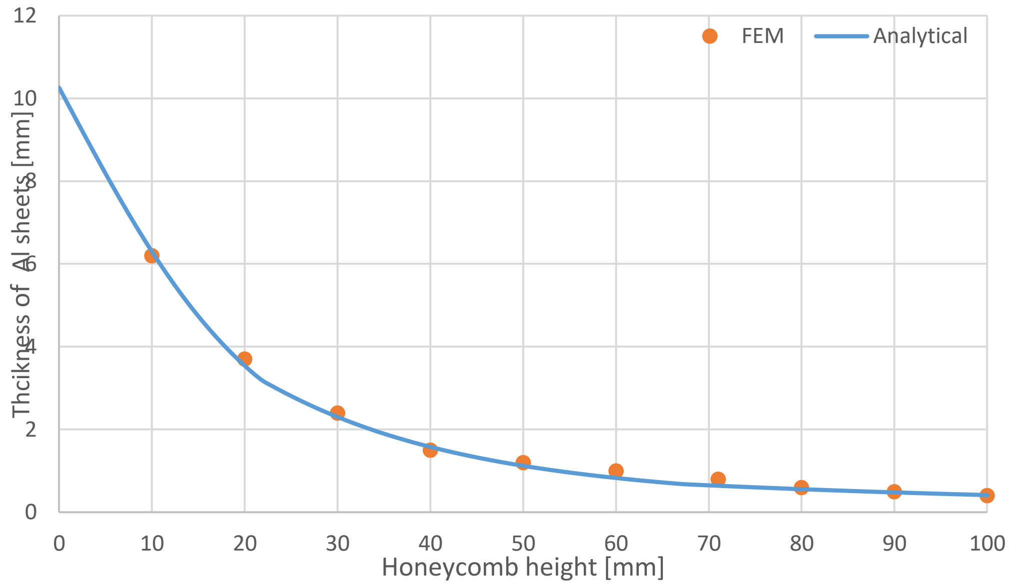


Cryostat option – use honeycomb-like plate

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 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**
# support rings			6	-
# corrugations		30	-	-

Conclusion

- For the FCCee IDEA detector, a conceptual design of a 2T / 4m free bore / 6m long Solenoid surrounding the tracker was developed
- The acceptance of the solenoid depends on the radial space the cryostat needs and effective Al thickness of the total radial build
- A design using 300 mm radial space and 1 Xo radiation length is doable
- Further, aggressive design may lead to another 20% reduction but requiring thickness-reducing engineering driving all sizes to minimum values
- This may also lead to important innovations in thin-coil technology with spin-off to other magnet projects.