FCC-ee 2T/4m thin solenoid

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1. Introduction
2. Example 2T/2.5m ATLAS Solenoid inside ECAL
3. 2T - 4m free bore FCC-ee Solenoid
4. Radial thickness
5. Conclusion

1. Designs presented so far

In previous meetings we responded to 3 requests and 1st designs were presented accordingly

1.2 Introduction, detector magnet requirements

A first more serious discussion took place November 1 with Gigi Rolandi & Alain Blondel, leading to requests for 1st designs of three detector magnet systems:

Request 1: Solenoid around EHCAL

2 T / 6.6 m free bore & 8 m length

Questions:
- shielding? answer = No!
  (not needed 350m below surface, same for the 4T FCC-hh detectors)
- Coil thickness
- Services, cryostat & chimney
- Rough cost estimate

Request 2: Solenoid inside EHCAL

2 T / 4 m free bore & 6 m length

Questions:
- shielding? answer = No!
- Coil thickness, radiation length
- Services, cryostat & chimney
- Rough cost estimate
- Extra cost for 5 m bore
- Extra cost for 8 m length

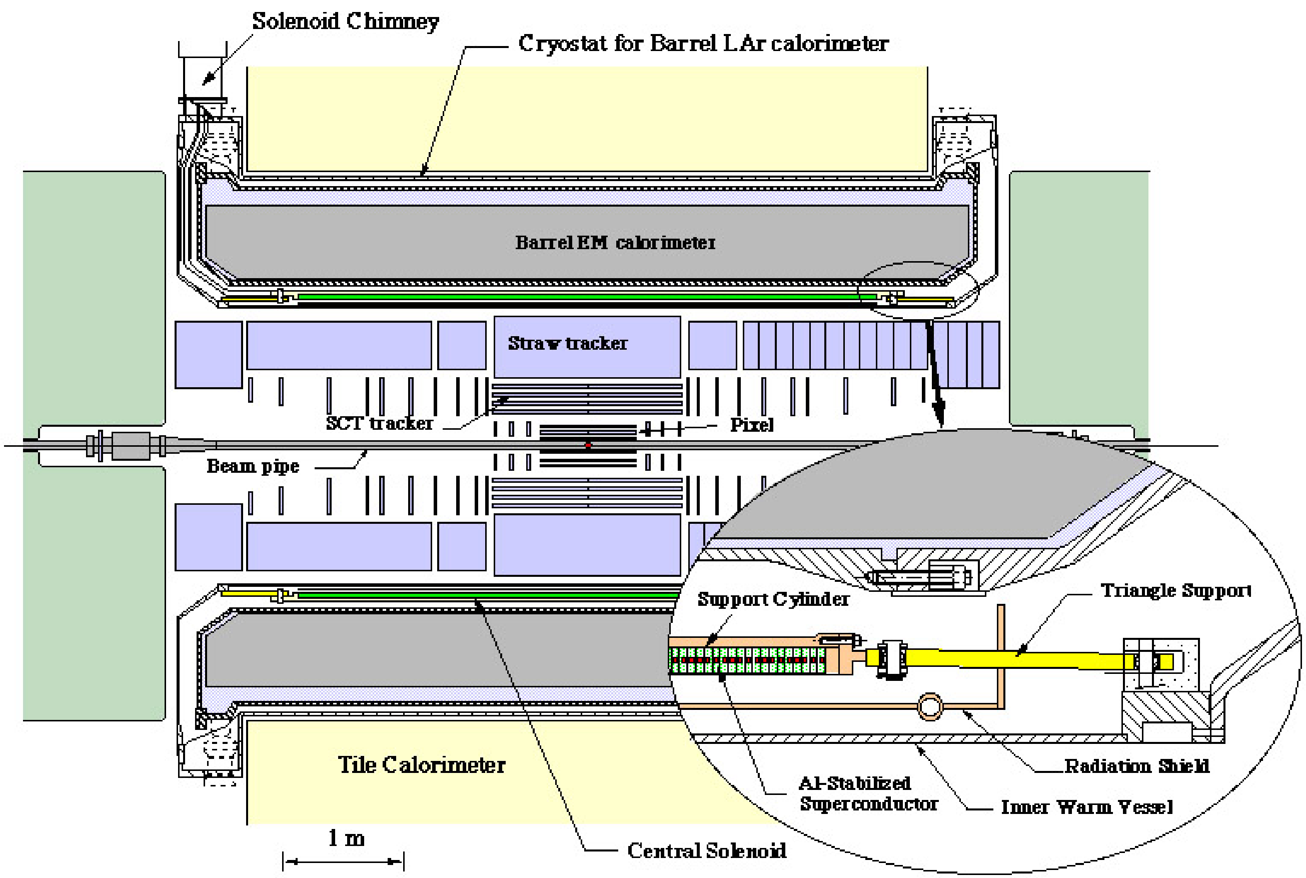
Request 3: huge low-field wide Solenoid
- Very wide bore Solenoid
- 0.5 T / 16 m free bore and 16 m length

Based on these 3 cases we made 1st conceptual designs of these solenoids including their cryostats.

3

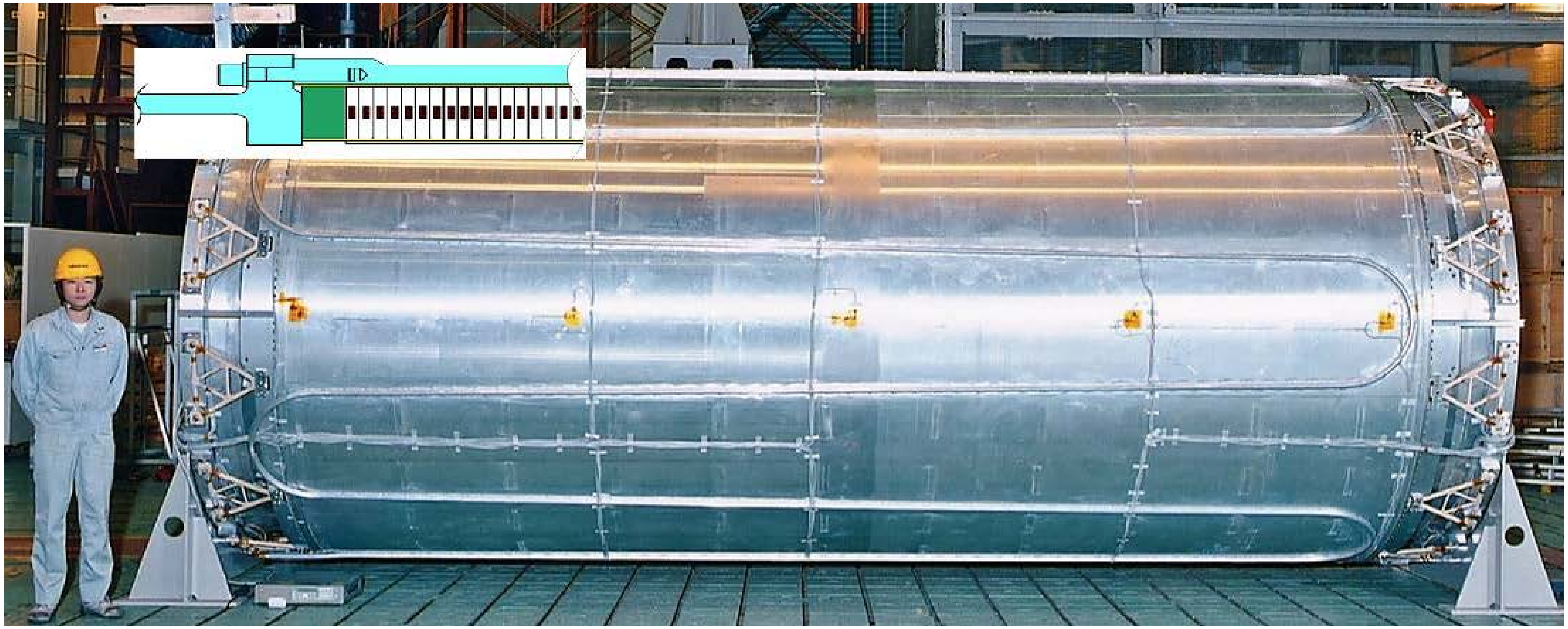
- The 2T/6.6m free bore version is a standard design perfectly feasible.
- The 2T/4m free bore “ultra-light” design is non-standard and requires significant R&D in order to confirm all material thicknesses and feasible spacing between the parts in the radial structure.
- **Next the issues with the radial structure will be explained, and easy and more aggressive goals set.**

2.1 Example 2T “thin” ATLAS Solenoid 2T in ECAL Cryostat



- In ATLAS Solenoid in Cryostat of ECAL (2 vessel & rad shield wall less)
- If not combined, but stand alone, the solenoid effective radiation thickness is determined by the summation of all material between the cryostat’s inner and outer radii.

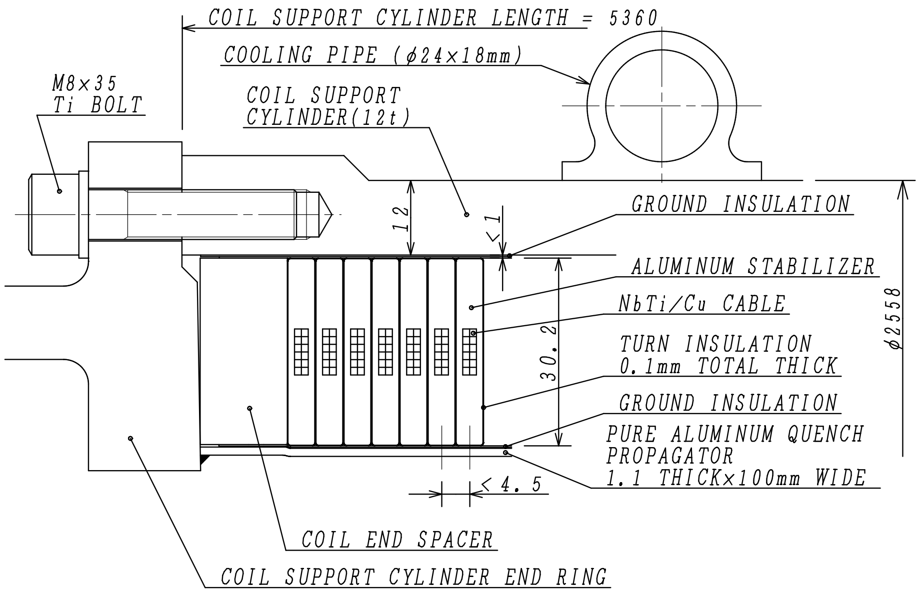
2.2 Example 2T ATLAS Solenoid

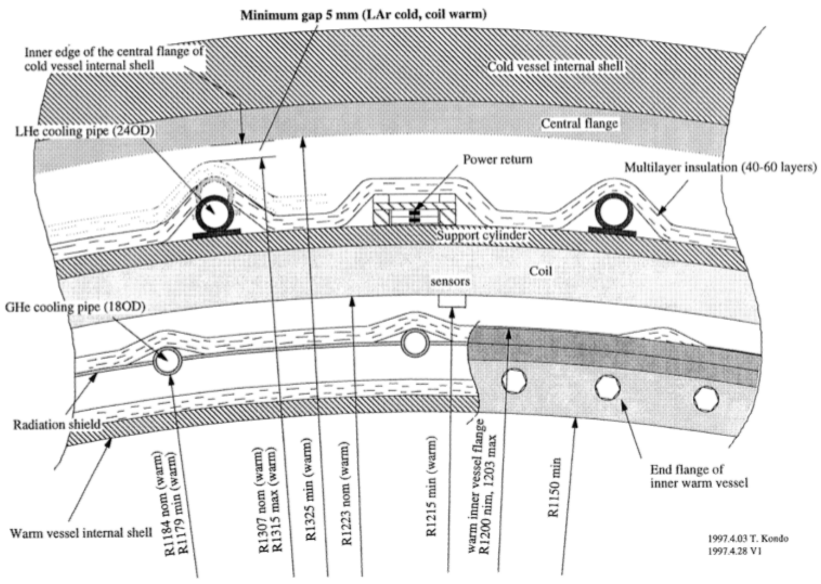


2.3 Example dimensions 2T ATLAS Solenoid

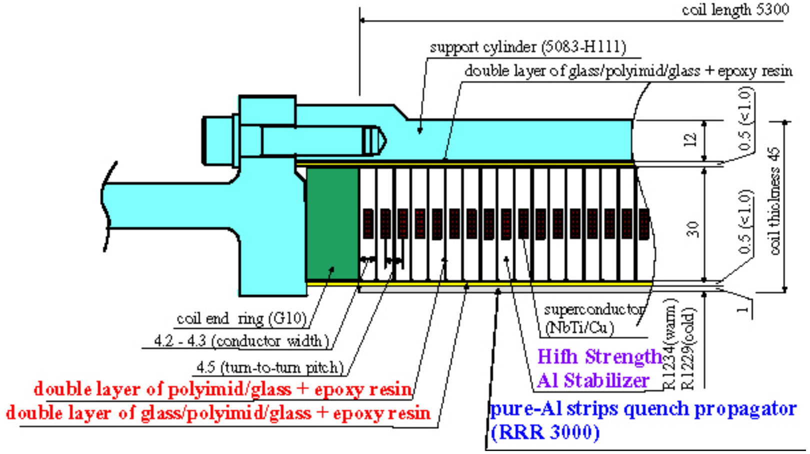
ATLAS Solenoid Design

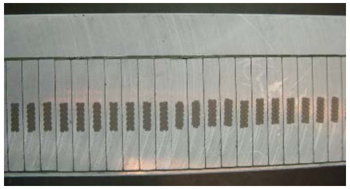
- Single layer coil internally wound in a 12 mm thick support cylinder
- Cold mass thickness based on 90 MPa maximum (2 T & 2.5 m diameter)
- Relatively thick cooling pipes (24 mm)





2.4. Example 2T ATLAS Solenoid





3.9 Radiation and interaction lengths

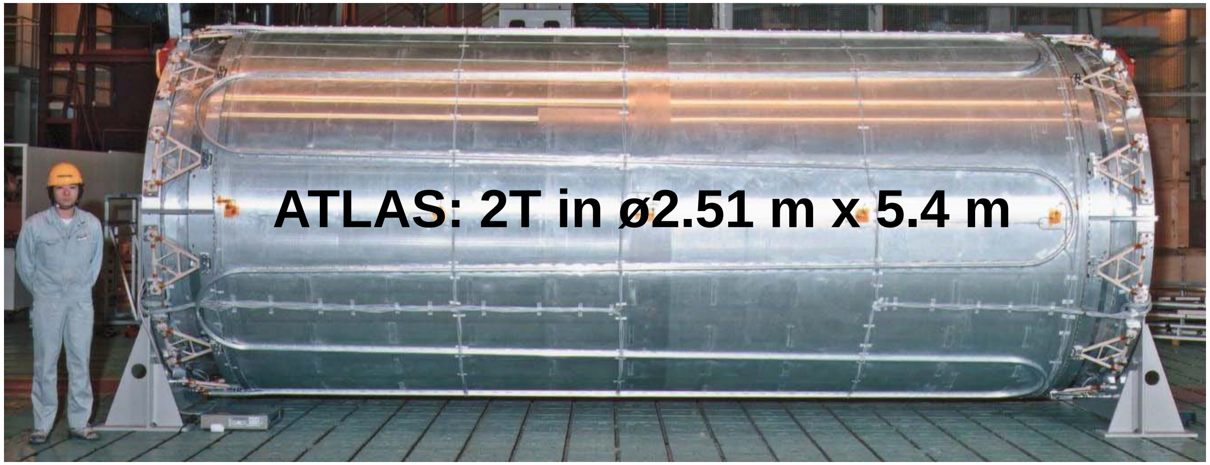
Table 3-7 shows the summary of radiation thickness X_0 and interaction length thickness λ_I for particles penetrating normal to the coil and cryostat.

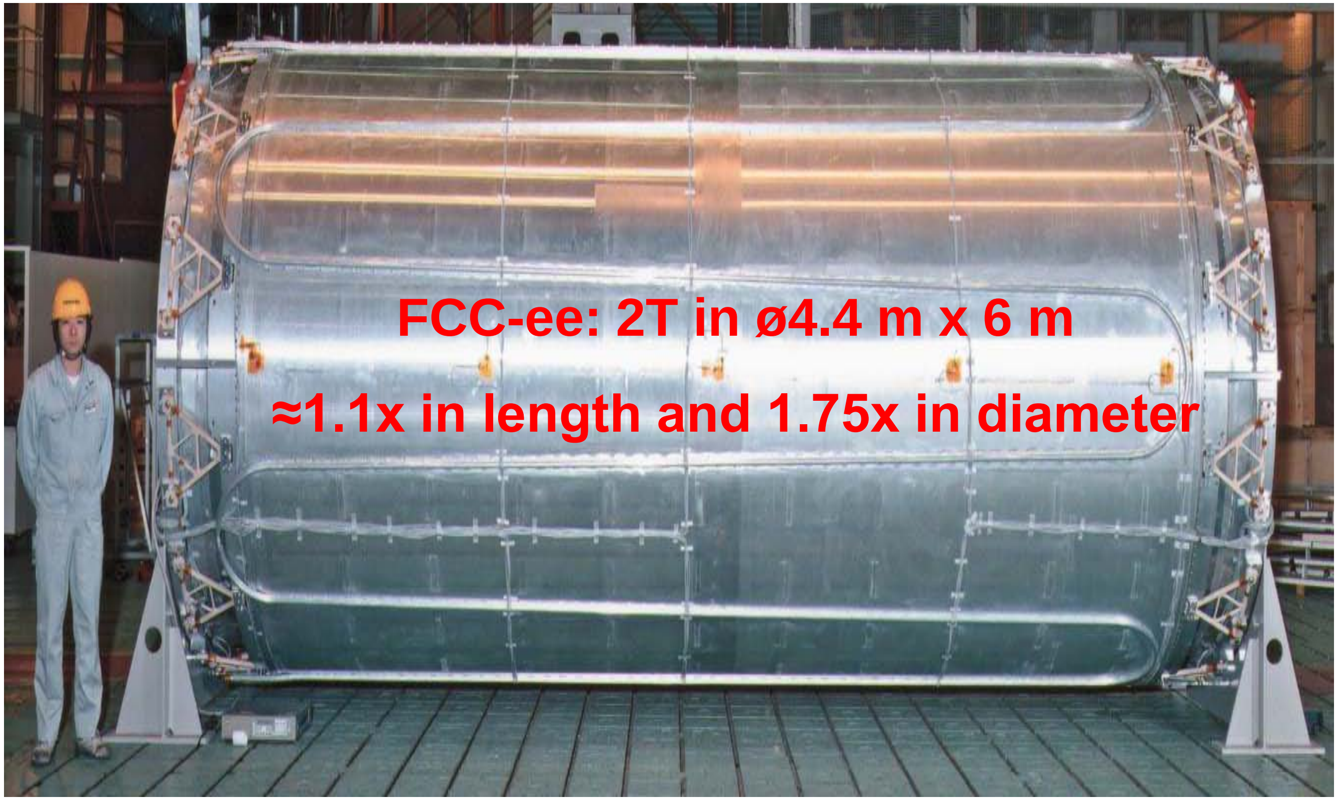
Table 3-7 Composition of the coil including the LAr wall

material	effective thickness	X_0	λ_I
Al stabilizer (30 x 4.3)	25.4 mm	0.285	0.068
NbTi/Cu (12 strands)	3.1 mm	0.194	0.021
GFRP	3 mm	0.017	0.007
Al strip	1 mm	0.011	0.003
support cylinder	12 mm	0.135	0.032
coil subtotal		0.642	0.131
multi-layer insulation	2 mm	0.005	0.005
thermal shield	2 mm	0.022	0.005
grand total for magnet part		0.669	0.141

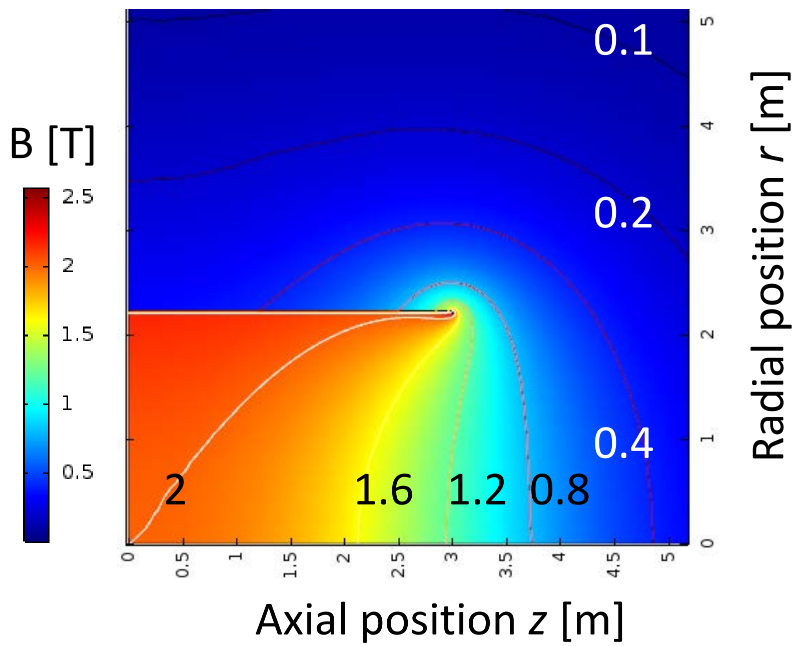
- **Contributions to the radiation thickness of the constituents**

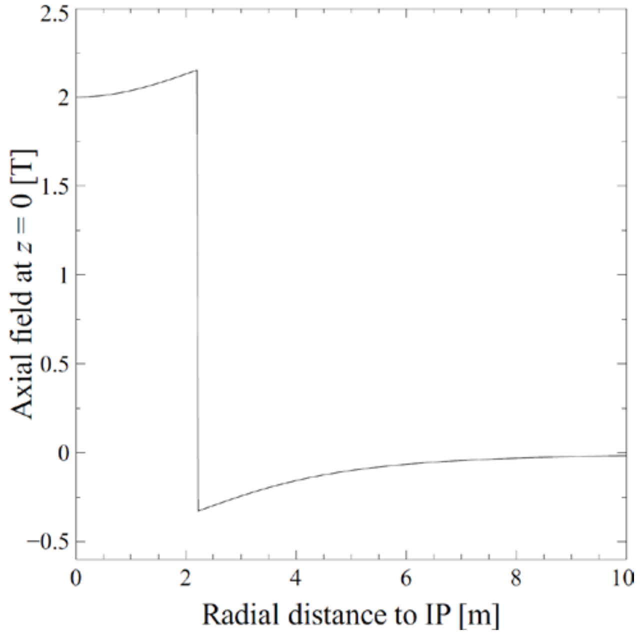
2.5 Scaling from ATLAS to FCC-ee





3.1 2T "light & thin" solenoid inside HCAL





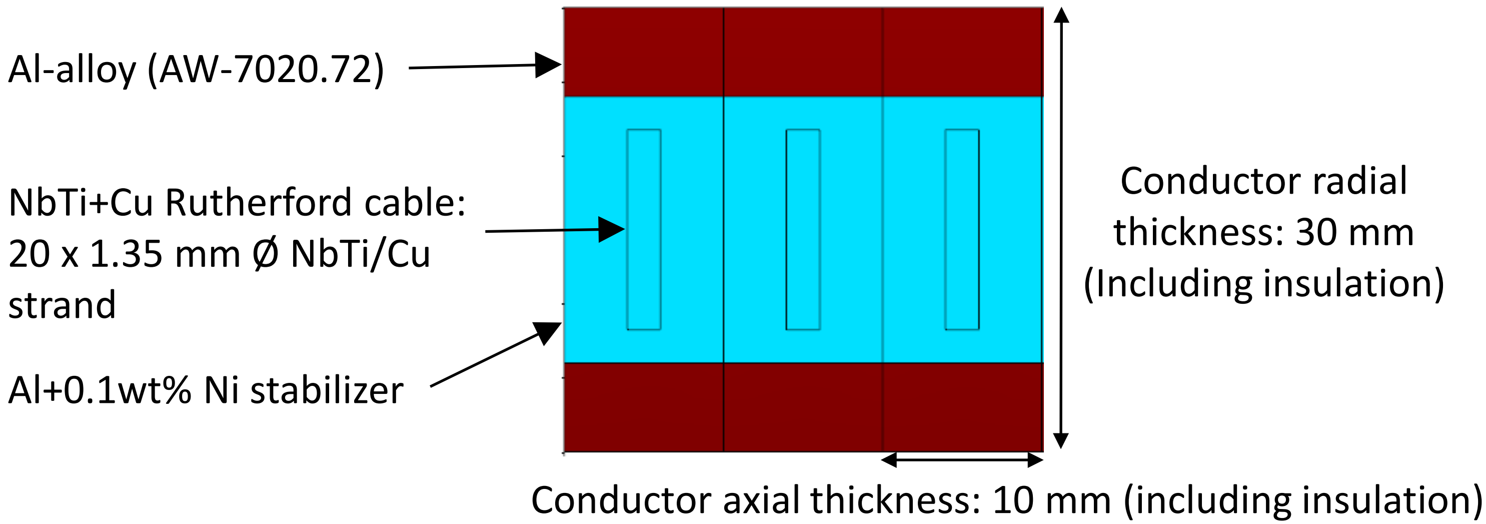
- Stray field (5 mT boundary): in radial direction 15 m, in axial direction, 20 m
- Composition: mainly aluminum (77 vol.%) + copper (5 vol.%) + NbTi (5 vol.%) + G10 (13 vol.%)

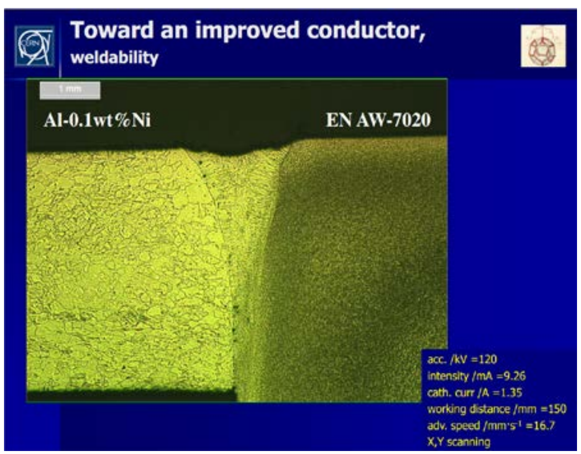
Radiation thickness:

- Cold mass: $X_0 = 0.46$, $\lambda = 0.09$
- Vacuum vessel (25 mm Al): $X_0 = 0.28$, $\lambda = 0.07$
- **Total: $X_0 = 0.74$, $\lambda = 0.16$ (at $\eta = 0$)**

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

3.2 Conductor & Winding scheme



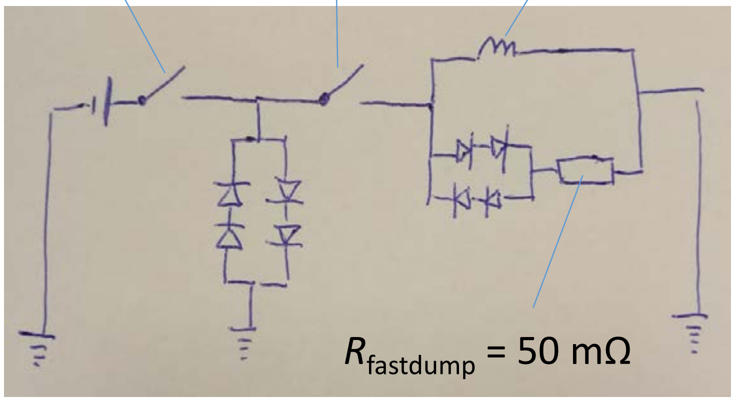


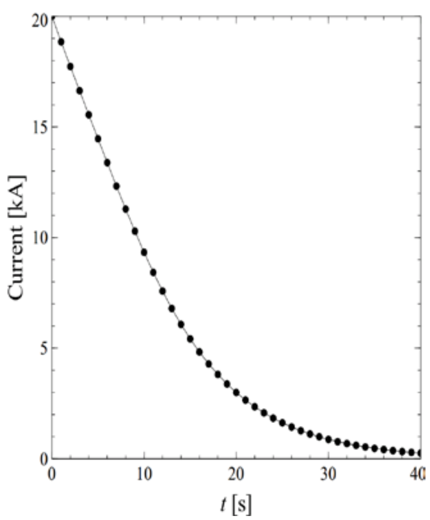
Sgobba [2010]

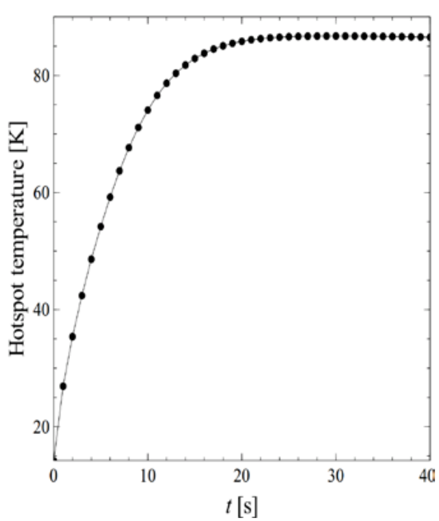
Conductor is a NbTi/Cu Rutherford cable + Al-Ni stabilization + Al-alloy reinforcement.

- Operating current: 20 kA, self-inductance: 0.85 H
- Current sharing temperature at peak field (3.2 T): 6.5 K
- Combined Yield Strength of Al-Ni + NbTi core + G10 insulation assumed at 100 MPa (conservative estimate)
- Local peak stress: 280 MPa
- Energy density: 24 kJ/kg (ambitious, research needed)
- Winding scheme: 1 layer with 595 turns, 8.3 km.

3.3 Quench Protection







Scenario	Peak hot spot temperature [K]
Regular	87
Malfunctioning heaters	150
Malfunctioning extraction	118
Malfunctioning heaters+extraction	> 500

Quench protection:

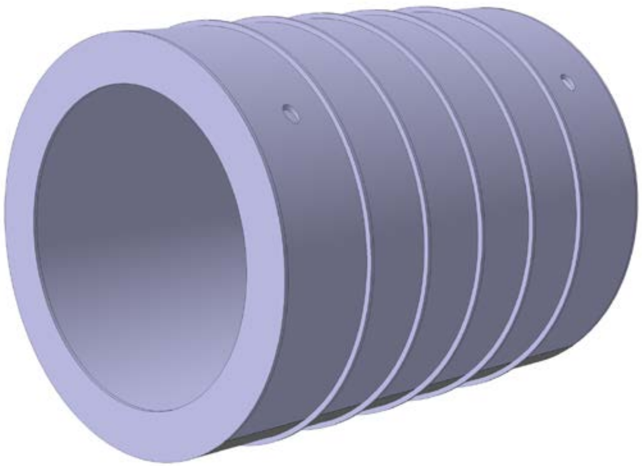
- Relies on extraction & quench heaters
- 1000 V peak extraction voltage gives 76% extraction
- Assumed conductor RRR: 400
- Regular quench scenario:

  $T_{hotspot} < 100$ K
- Most extreme fault scenario may be improved with axial quench propagation strips.

3.4 Cryostat for 2T/4m Solenoid inside ECAL

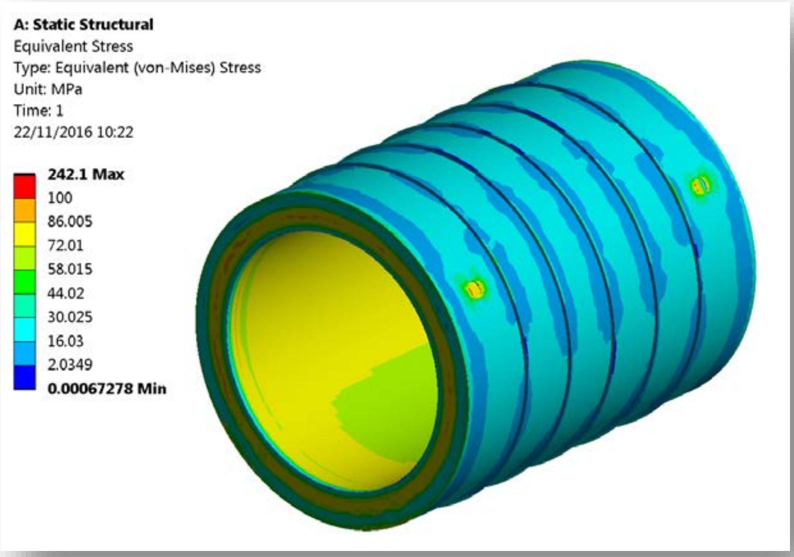
Main features:

- HCAL is used as support for the cryostat
- Local outer shell reinforcements to prevent buckling
- Cold mass supported by rods at the ends of the cryostat
- Material used is Al 5083-O



	Loads
Tracker weight [t]	4
External pressure [MPa]	0.101
Self weight [t]	5.7
Cold mass weight + rods thermal shrinkage [kN] *	215

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



3.5 Cryostat for 2T/4m Solenoid inside HCAL

	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
Al thermal 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		

Inner shell:

- Membrane stress
  - $fm = 74MPa < \frac{2}{3}Sy$
- Membrane Stress + Bending stress
  - $fm + fb = 74 < Sy$

Flat flange:

- Membrane stress
  - $fm = 2MPa < \frac{2}{3}Sy$
- Bending stress
  - $fb = 77MPa < \frac{2}{3}Sy$
- Membrane Stress + Bending stress
  - $fm + fb = 79 < Sy$

Can be further optimized by moving to a dished head

Outer shell:

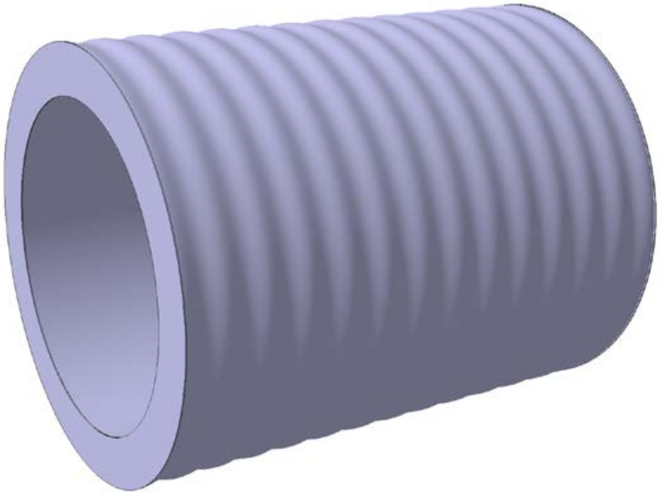
- Longitudinal compressive stress
  - $f = 8MPa < 0.73 \times \Delta \times Sy = 10Mpa$
  - **Except for localized stress**
- Buckling factor > 2
  - **Non-linear analysis may help to reduce outer shell thickness**
- Membrane stress
  - $fm = 16MPa < \frac{2}{3}Sy$
- Bending stress
  - $fb = 9MPa < \frac{2}{3}Sy$
- Membrane Stress + Bending stress
  - $fm + fb = 25 < Sy$

3.6 Cryostat for 2T/4m Solenoid inside HCal

Alternatively for the external shell corrugated plate may be used:

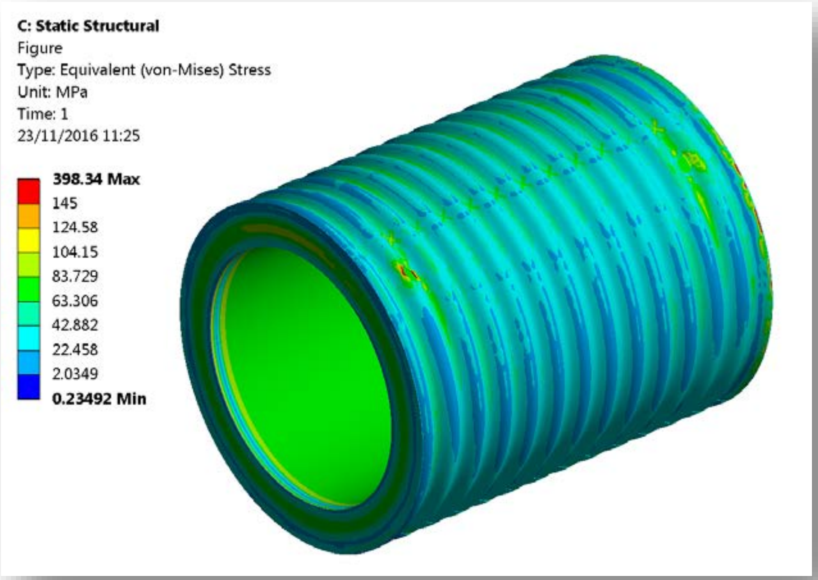
- More uniform thickness seen by particles
- Thickness of outer shell is very dependent on the period and amplitude of the corrugation
- Flat flanges may not be suitable in this case

EN13458 standard was used



	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	

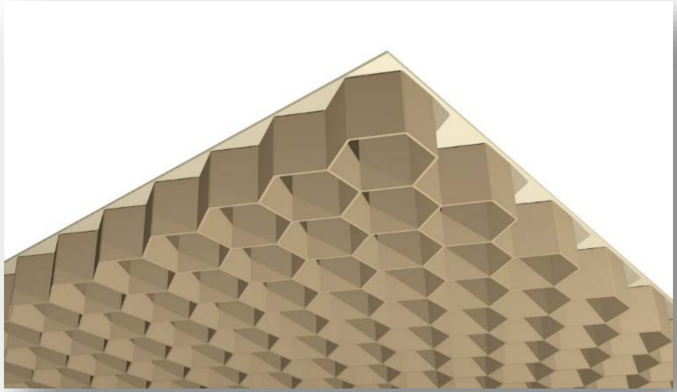
[1] Including thermal shield

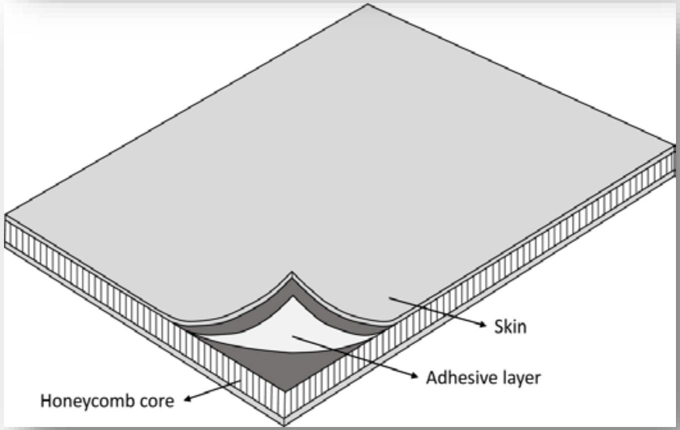


3.7 Cryostat for Solenoid inside HCAL

Since radiation length is critical and shall be minimized, options may be:

- New composite materials to further reduce the outer shell effective thickness
- Plate flexural strength is related to the thickness of the plate, "regardless" of the amount of material in the center
- Composite plates have more materials in their composition than just aluminum
- Use of these materials needs to be validated and code-approved
- Thickness of material seen by particles is highly non-uniform.





We started an FCC funded R&D project for developing this ultra-thin solenoid following 2 routes:

- Study of Al stabilized 20 kA class conductors that can accept 250 MPa (1PhD)
- Study of light & strong materials for minimizing cryostat material thickness (1PhD)

4.1 Radial Structure Thickness (all data preliminary)

FCC ultra thin cryostat and solenoid (not combined with ECAL) (all dimensions indicative only)								
Radial thickness (all sizes in mm)	**R&D Aggressive design**				**Presently Doable design**			
	thickness	radius	%		thickness	radius	%	
Inner radius free bore		2000	Al fill-factor	Al thickness		2000	Al fill-factor	Al thickness
Inner wall thickness	3	2003	100	3	5	2005	100	5
Gap to inner shield	20	2023	0	0	30	2035	0	0
Shield MLI 30 layers	10	2033	1	0.1	12	2047	10	1.2
Inner shield thickness	3	2036	100	3	5	2052	100	5
Cooling pipes on inner shield	16	2052	30	4.8	18	2070	30	5.4
Gap to cold mass MLI	20	2072	0	0	30	2100	0	0
Cold mass MLI	1	2073	1	0.01	1	2101	10	0.1
Cold mass windings thickness	21	2094	100	21	21	2122	100	21
Cold mass support cylinder	12	2106	100	12	24	2146	100	24
Cold mass thickness piping/leads	15	2121	30	4.5	20	2166	30	6
Cold mass MLI	10	2131	1	0.1	10	2176	10	1
Gap to outer shield	20	2151	0	0	30	2206	0	0
Outer shield thickness	3	2154	100	3	5	2211	100	5
Cooling pipes on outer shield	16	2170	30	4.8	18	2229	30	5.4
MLI on shield thickness	10	2180	1	0.1	12	2241	10	1.2
Gap to outer wall	20	2200	0	0	30	2271	0	0
Outer wall thickness	13	2213	100	13	20	2291	100	20
Outer radius cryostat wall		2213				2291		
Total radial build	213			69	291			100

When analyzing the radial build, with ATLAS Solenoid as a good reference, we can define doable and aggressive goals for the future.

- With todays constructions, a radial build of 300 mm would be fine including an effective Al thickness of 100 mm (all to be confirmed by more in-depth structural analysis).
- A very aggressive design taking away bulk material and gaps wherever possible, may lead to some 210 mm radial build and some 70 mm Al thickness.

5. Conclusion

- A 2T / 4m free bore Solenoid surrounding the 4 m diameter tracker is proposed as a challenging design.
- The acceptance of this solenoid depends on the radial space the cryostat needs and the effective Al thickness of the total radial build.
- Doable looks a design with 300 mm space and 100 mm Al thickness.
- A very aggressive design may lead to some 210 mm and 70 mm Al thickness, though this case explicitly requires thickness-reducing engineering driving all dimensions to minimum values.
- For the extremely thin version an R&D project has started lasting 4 years.
- The ultra-thin solenoid is a very attractive solution and there is time to develop it.
- It also may lead to innovations in thin-coils technology with spin-off to other magnet projects.
- Work in progress…..