FCC-ee, first look at detector magnet concepts

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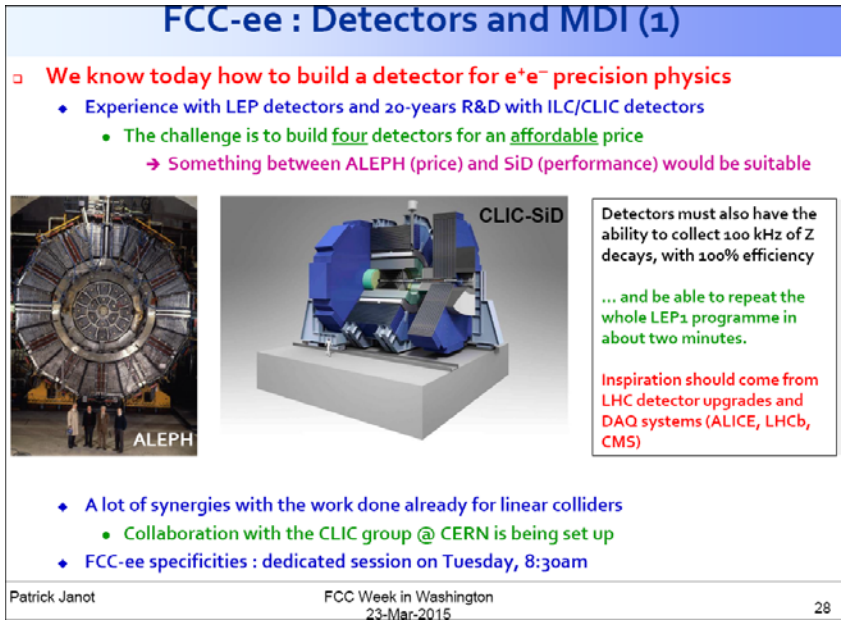
1. Introduction & detector requirements
2. 2T superconducting solenoid around HCAL
3. 2T superconducting solenoid inside HCAL
4. Very large 0.5 T normal conducting solenoid
5. Cryostat designs for the 2T magnets
6. Conclusion

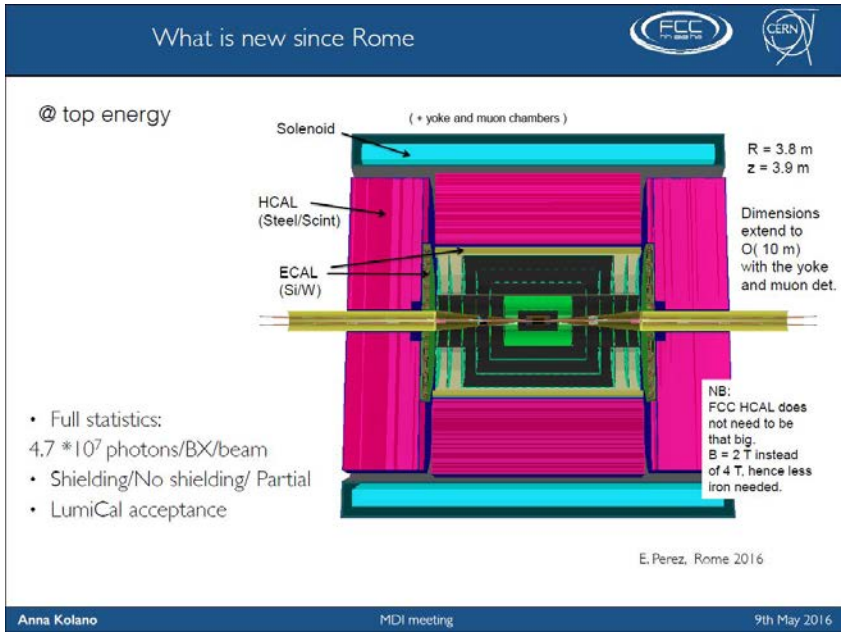
1.1 Introduction, detector magnet requirements



FCC meeting Washington May 2015:

No specs mentioned, not accurate dimensions not magnetic field, just:

- We know how to build…
- Challenge is affordable price



FCC meeting Rome May 2016:

1st sketch of a detector shown:

- Solenoid around EHCAL
- 2 T is sufficient
- ~ 7.6 m diameter
- ~ 7.8 m length
- Shielding needed ?

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:

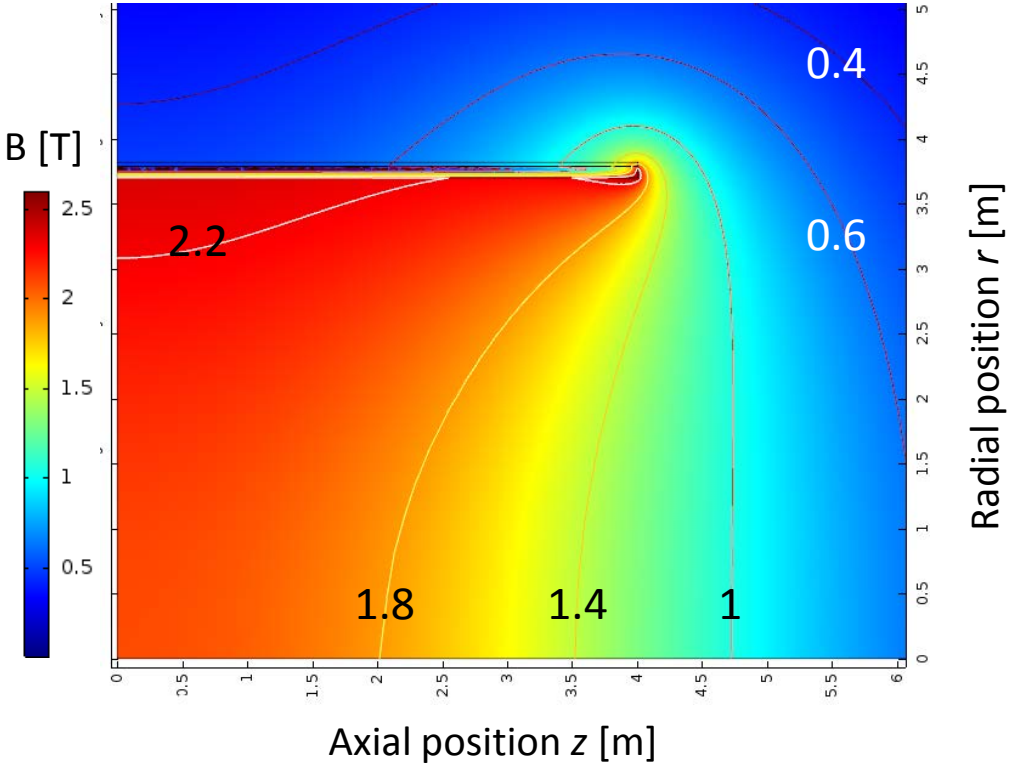
- shielding? answer = No!
- Coil thickness, radiation length
- Services, cryostat & chimney
- Rough cost estimate
- Extra cost for 5 m bore
- Extra cost for 8 m length

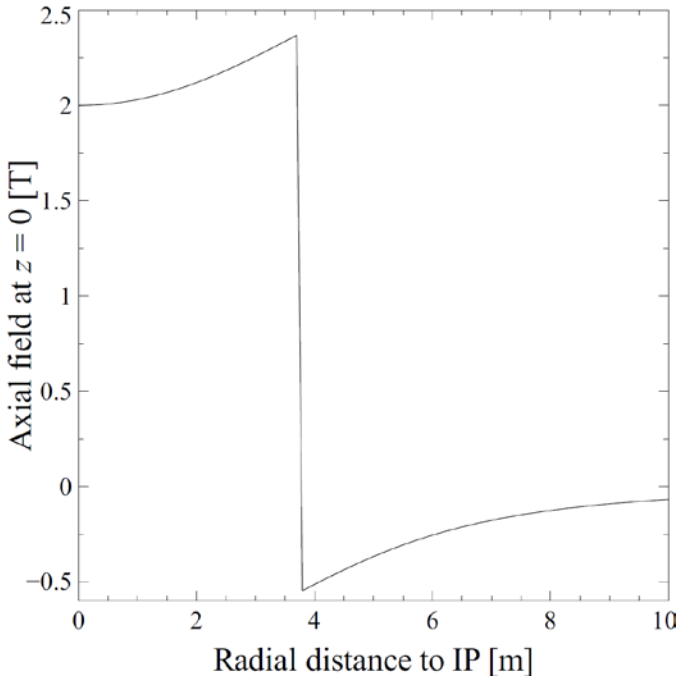
Request 3: huge low-field wide Solenoid

- 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.

2.1 Detector concept 1: 2T Solenoid around HCAL

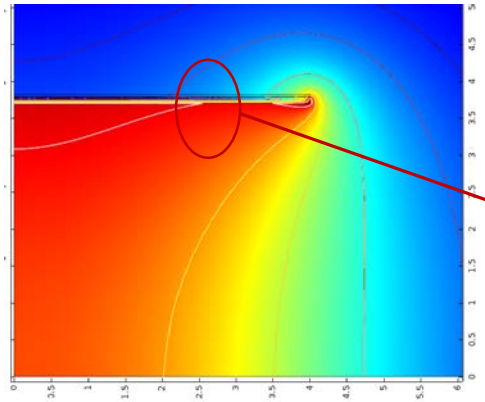


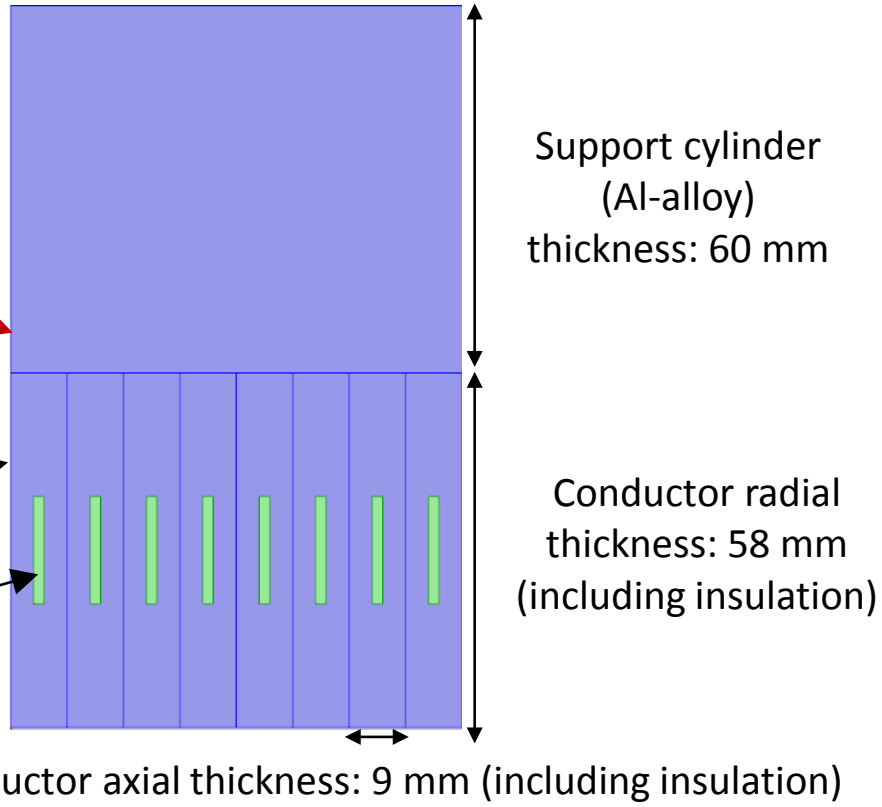


- Stray field (5 mT boundary): in radial direction 25 m, in axial direction, 31 m
- Energy density: 12.2 kJ/kg

Property	Value
Magnetic field in center [T]	2
Free bore diameter [m]	6.6
Stored energy [MJ]	730
Cold mass [t]	60
Cold mass inner radius [m]	3.7
Cold mass thickness [m]	0.118
Cold mass length [m]	8

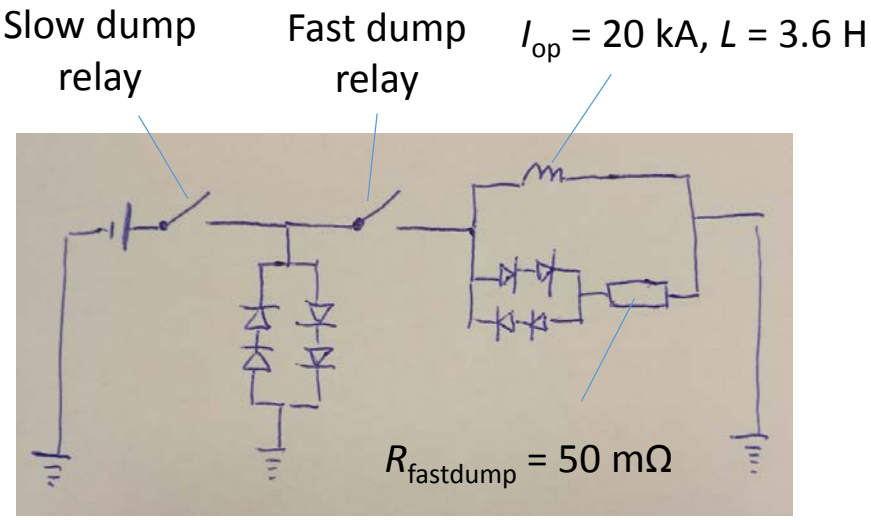
2.2 Detector concept 1: Conductor & Winding scheme



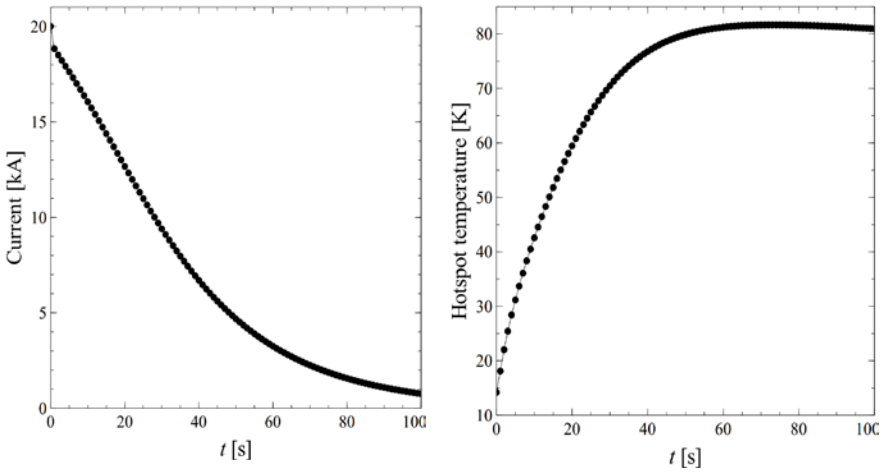


- Operating current: 20 kA, self-inductance: 3.6 H
- Based on ATLAS central solenoid conductor: NbTi Rutherford cable + Al-Ni stabilizer
- Local peak stress: 89 MPa
- Rutherford cable: 32 x 1.1 mm Ø NbTi/Cu strand. T_{cs} at peak field (3.5 T): 6.5 K
- Winding scheme: 1 layer with 870 turns, 20 km

2.3 Detector concept 1: Quench Protection



Scenario	Peak hotspot temperature [K]
Regular	82
Malfunctioning heaters	82
Malfunctioning extraction	122
Malfunctioning heaters+extraction	400

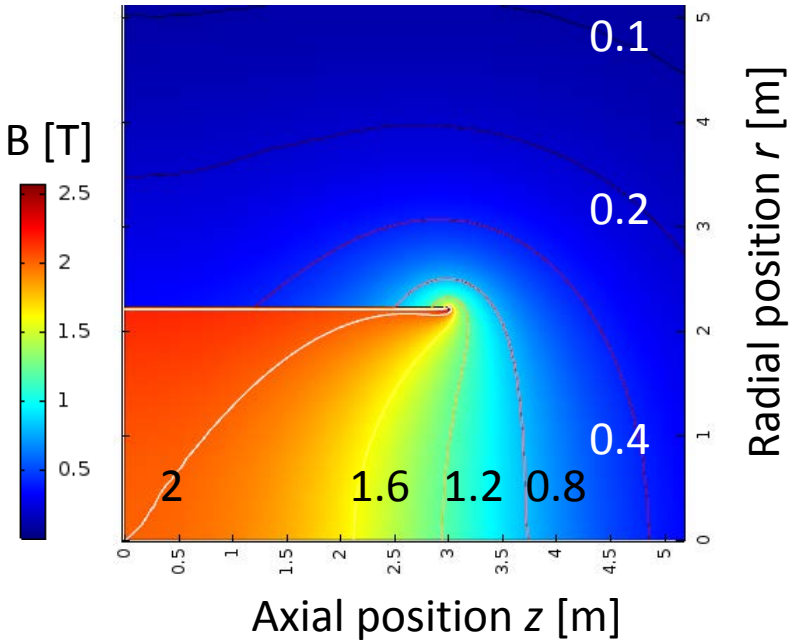


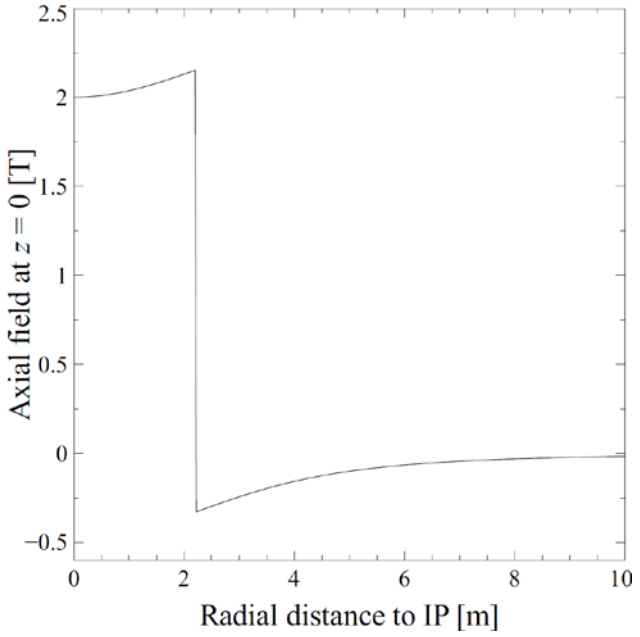
Quench protection:

- Relies on extraction + quench heaters
- 1000 V peak extraction voltage gives 53% extraction
- Assumed conductor RRR: 400
- Regular quench scenario:

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

3.1 Detector concept 2: 2T "light & thin" solenoid inside HCAL





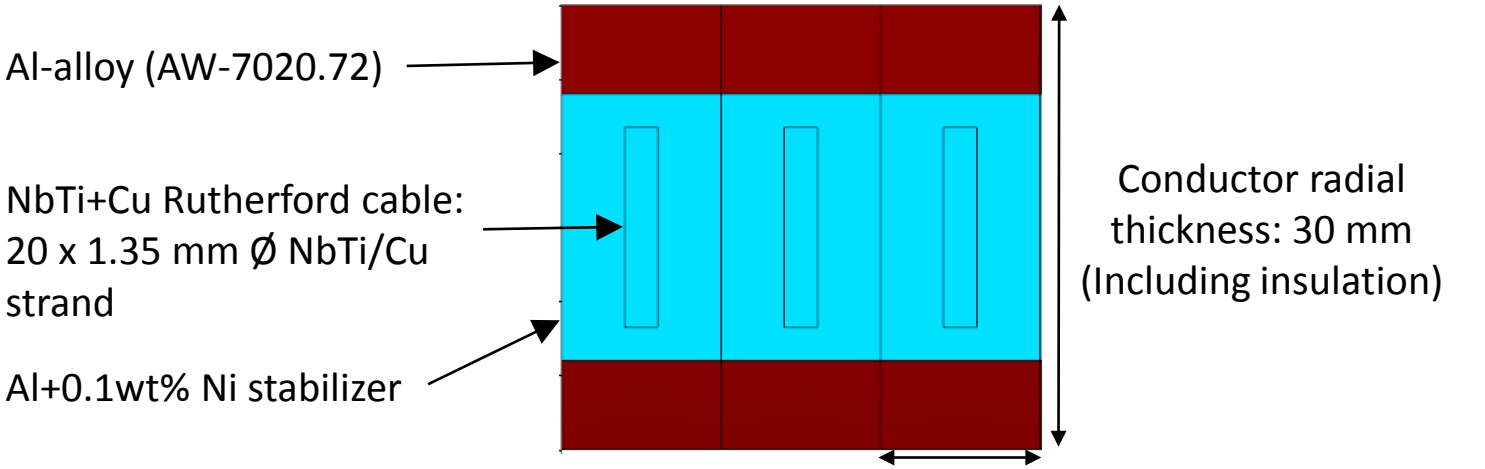
- Stray field (5 mT boundary): in radial direction 15 m, in axial direction, 20 m
- Composition: mainly aluminum (77 vol.%) + copper (5 vol.%) + NbTi (5 vol.%) + G10 (13 vol.%)

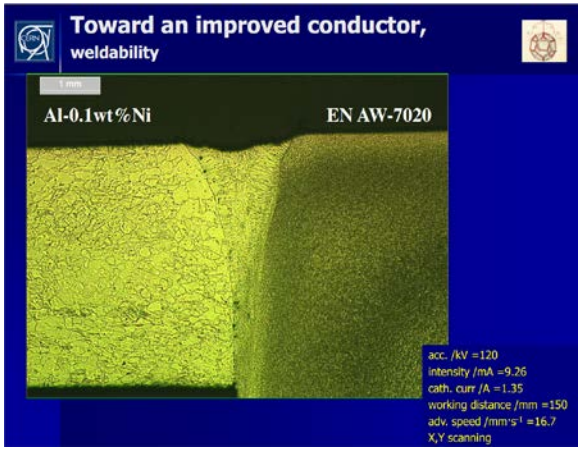
Radiation thickness:

- 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 Detector concept 2: Conductor & Winding scheme



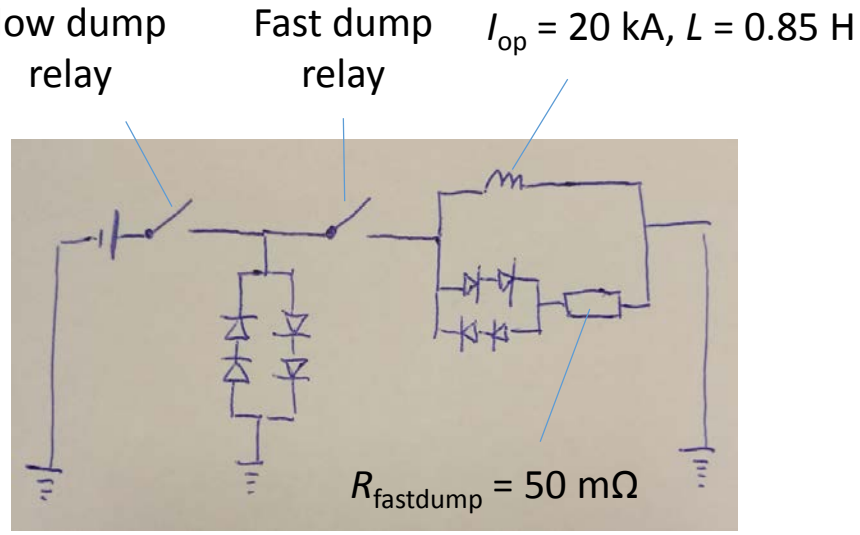


Sgobba [2010]

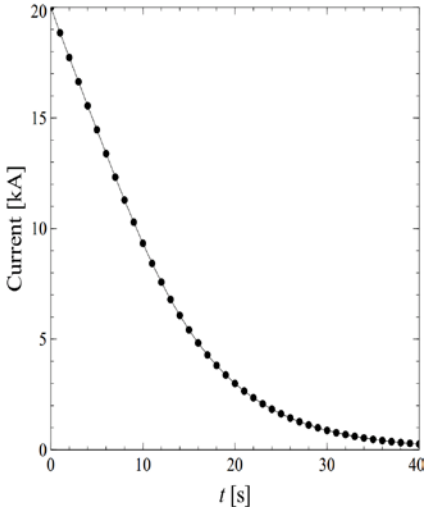
Conductor is a NbTi/Cu Rutherford cable + Al-Ni stabilization + Al-alloy reinforcement.

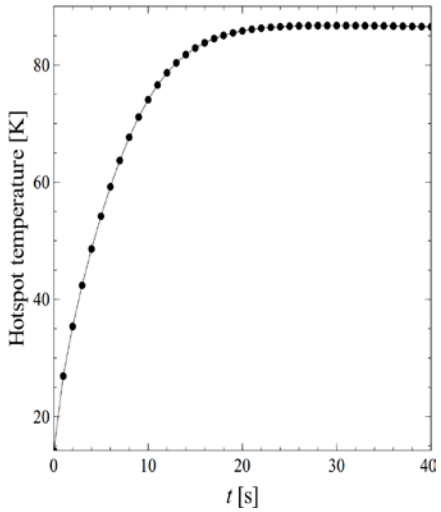
- Operating current: 20 kA, self-inductance: 0.85 H
- Current sharing temperature at peak field (3.2 T): 6.5 K
- Combined Yield Strength of Al-Ni + NbTi core + G10 insulation assumed at 100 MPa (conservative estimate)
- Local peak stress: 280 MPa
- Energy density: 24 kJ/kg (Ambitious, research needed)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

3.3 Detector concept 2: Quench Protection



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



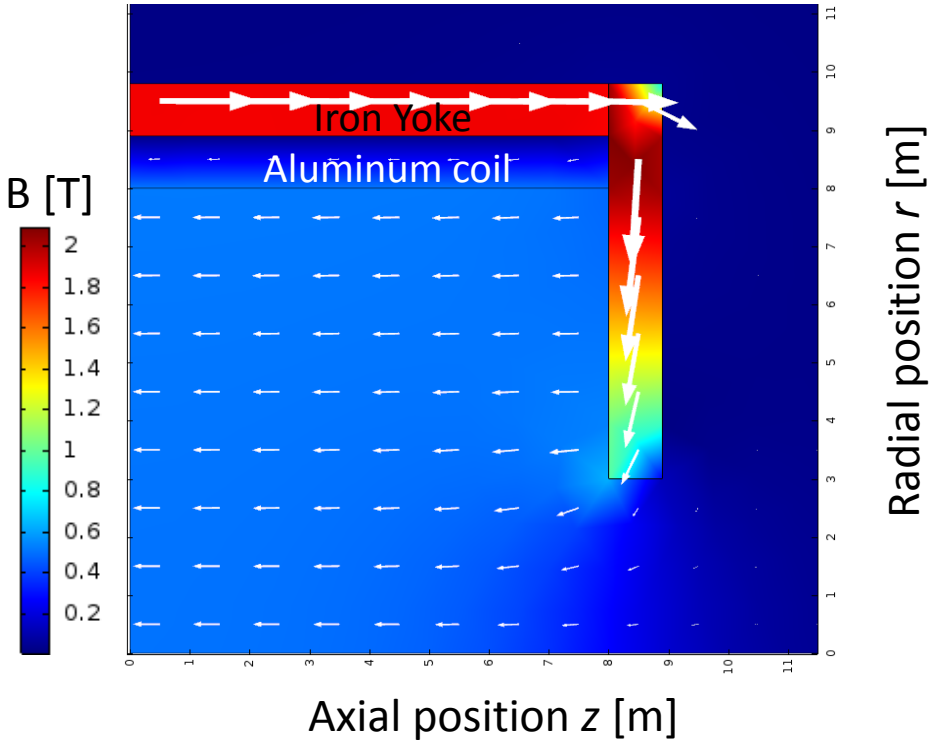


Quench protection:

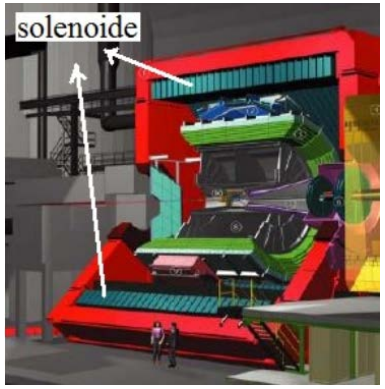
- Relies on extraction & quench heaters
- 1000 V peak extraction voltage gives 76% extraction
- Assumed conductor RRR: 400
- Regular quench scenario:

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

4.1 Detector concept 3: 0.5T very large normal conducting Solenoid



Property	Value
Magnetic field in center [T]	0.50
Free bore diameter [m]	16
Coil length [m]	16
Aluminum mass [kt]	1.75
Iron mass [kt]	10.5
Assumed coil thickness [m]	0.9
Stored energy [MJ]	370
Operating current [kA]	30.5
Inductance [H]	0.8
Number of coil turns	220
Ohmic power loss [MW]	5.4

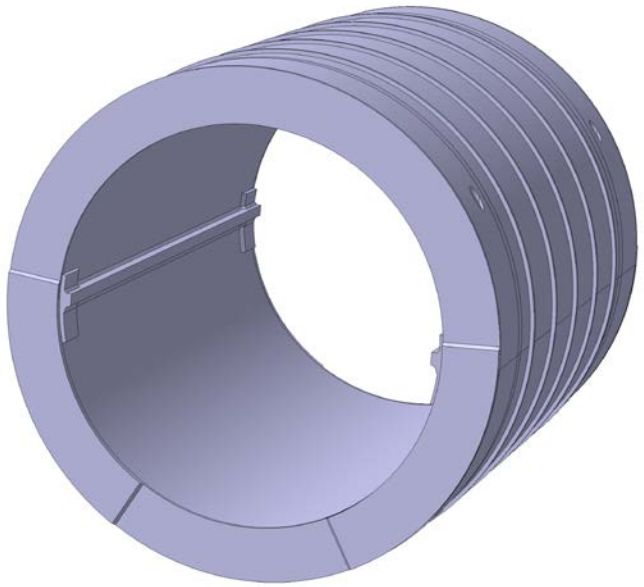


- Scaled-up version of the L3 Alice solenoid
- Conductor dimensions: 900 (radial) x 62 mm (axial); Current: 30.5 kA
- Aluminum conductor occupies 85% of total coil space → 220 turns
- $P \propto 1/th_{Coil}$: Thickness: 0.9 m → Ohmic power loss: 5.4 MW
- Yoke contribution 0.13T + uniformity, without iron yoke: 0.37 T
- Estimated power consumption of cryo-plant for superconducting coil: 2 MW, likely to be more expensive than warm magnet + water cooling

5.1 Cryostat designs : Cryostat for 2T/6.6m Solenoid around HCAL

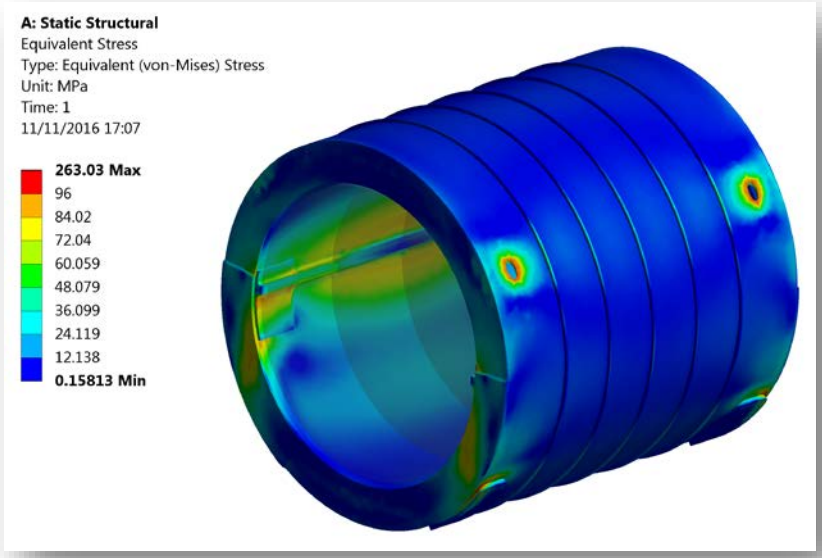
Cryostat main features:

- Rails inside the bore to slide-in the HCAL
- 4 feet under the bottom half shell close to the end flanges
- Local end flange reinforcements to transfer the HCAL weight to the floor
- Local outer shell reinforcements to prevent buckling, while minimizing minimum shell thickness.



	Loads	
HCAL weight [kt]	1.6	
External pressure [MPa]	0.101	
Self weight [t] (Al / Steel)	76	127
Cold mass weight + rods thermal shrinkage [kN] *	1765	

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



5.2 Cryostat designs: Cryostat for 3^/6.6m solenoid around HCal

Material thickness, volume, mass and stress for Al-alloy and steel versions:

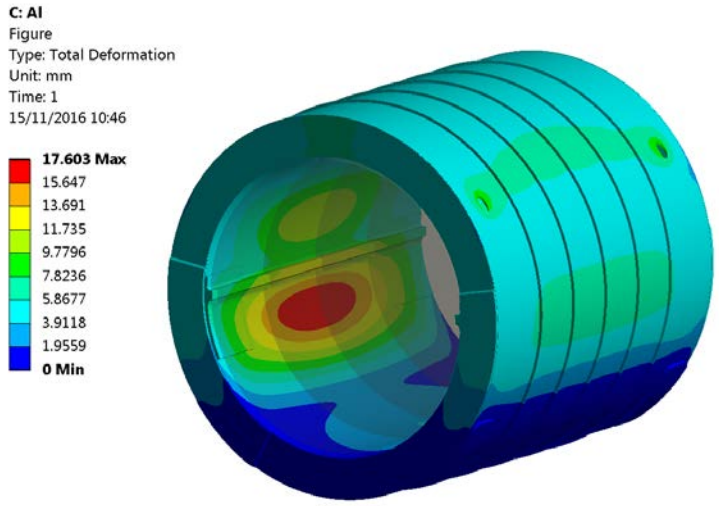
	Aluminum alloy version			Steel version		
	Inner shell	Outer shell	Flanges	Inner shell	Outer shell	Flanges
Thickness [mm] [1]	80	50	53	50	24	26
Min. thickness [mm]	70	45	25	40	20	20
Max. thickness [mm]	140	115	70	120	90	30
Aluminum thermal shield thickness [mm]	5.0	5.0	5.0	5.0	5.0	5.0
Volume [t] [2]	15	12	2 x 1.0	10	6.4	2 x 0.73
Mass [t] [2]	42	34	2 x 2.7	75	45	2 x 5.4
Total mass [t]	81			130		
Max. allowable stress [MPa]	100			140		
Min. buckling factor	5			5		

[1] Average value including reinforcements
[2] Thermal shield and cryostat

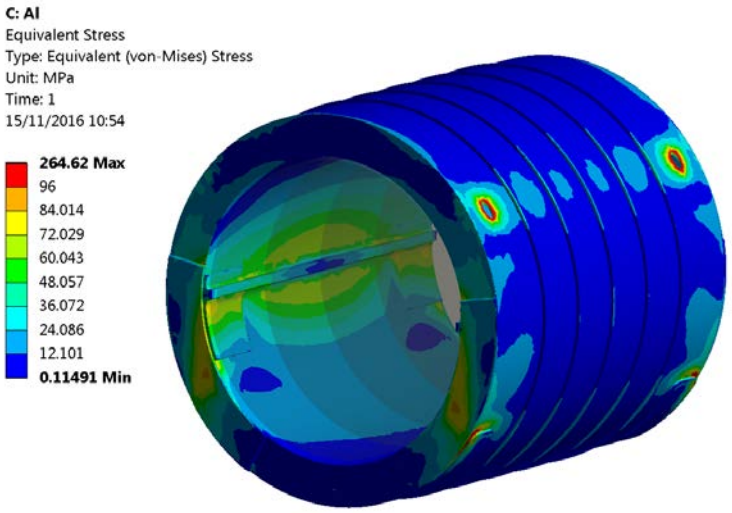
5.3 Cryostat designs : Cryostat for solenoid inside HCal

Aluminum version

Deformation

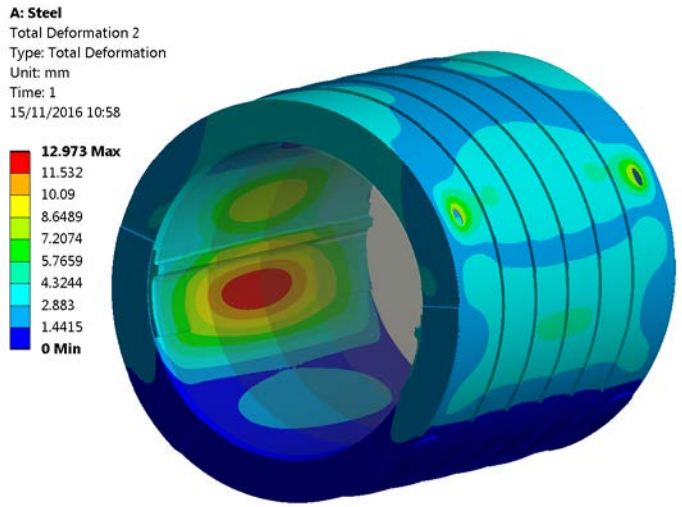


Stress

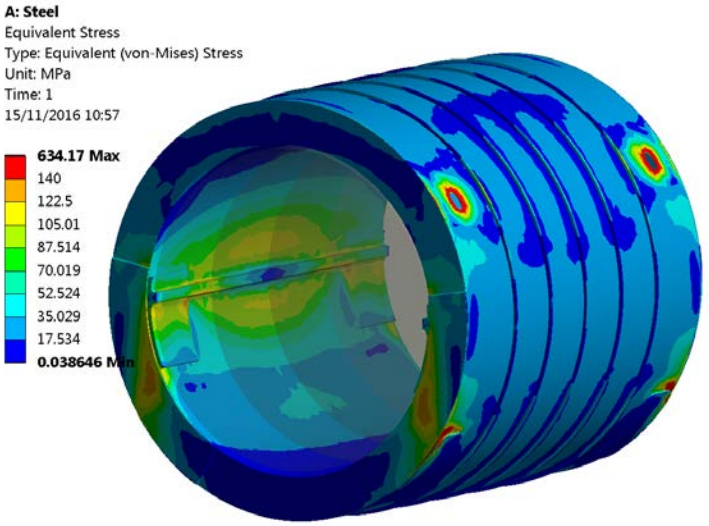


Stainless Steel version

Deformation



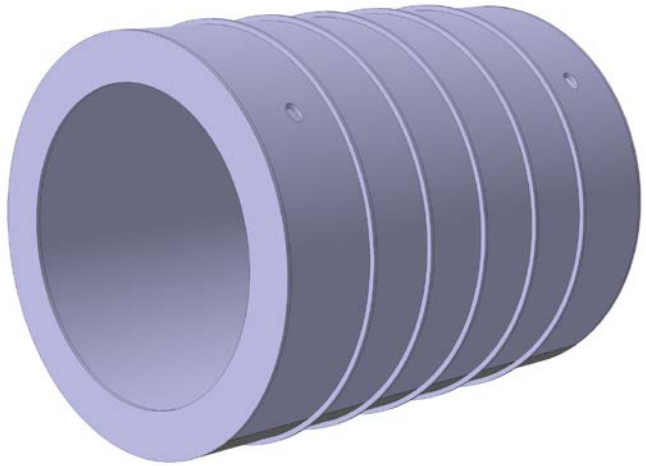
Stress



5.4 Cryostat designs: Cryostat for 2T/4m Solenoid inside ECAL

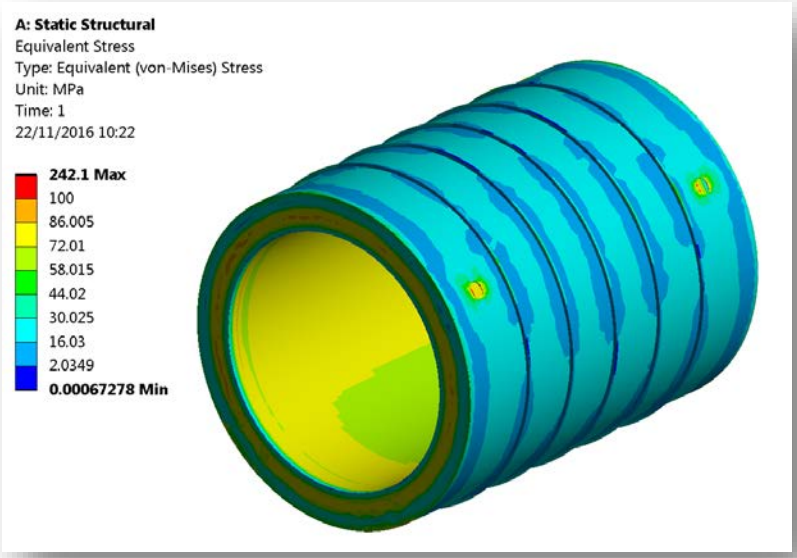
Main features:

- 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



5.5 Cryostat designs: Cryostat for 2T 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:

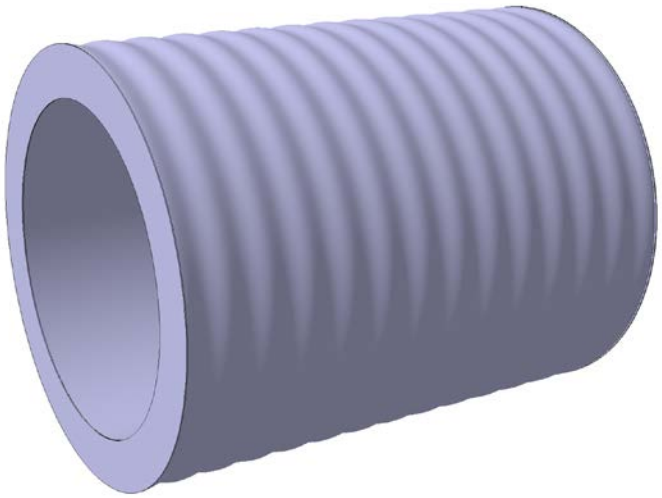
- Longitudinal compressive stress
  - $f = 8MPa < 0.73 \times \Delta \times Sy = 10Mpa$
  - **Except for localized stress**
- Buckling factor > 2
  - **Non-linear analysis may help to reduce outer shell thickness**
- Membrane stress
  - $fm = 16MPa < \frac{2}{3}Sy$
- Bending stress
  - $fb = 9MPa < \frac{2}{3}Sy$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

5.6 Cryostat designs: Cryostat for 2T Solenoid inside HCal

Alternatively for the external shell corrugated plate can be used:

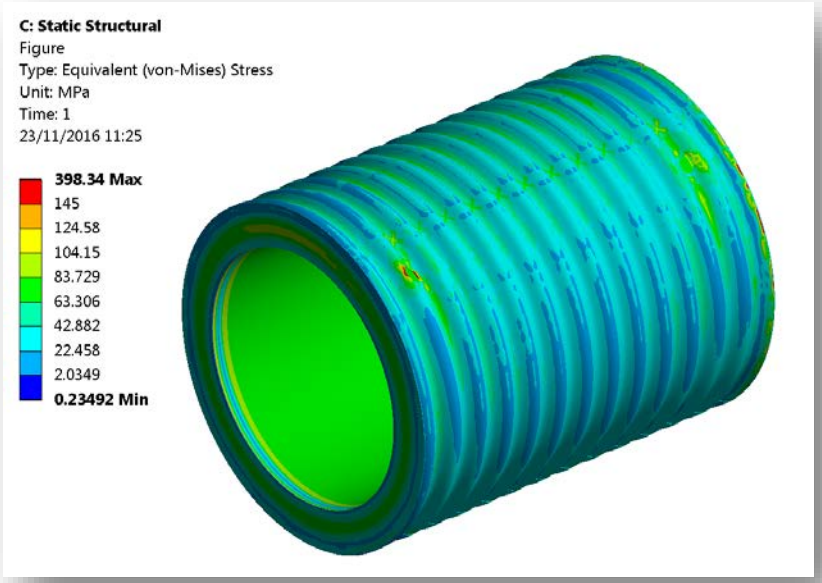
- More homogeneous thickness seen by particles
- Thickness of outer shell is very dependent on the period and amplitude of the corrugation
- **Flat flanges may not be suitable in this case**

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	

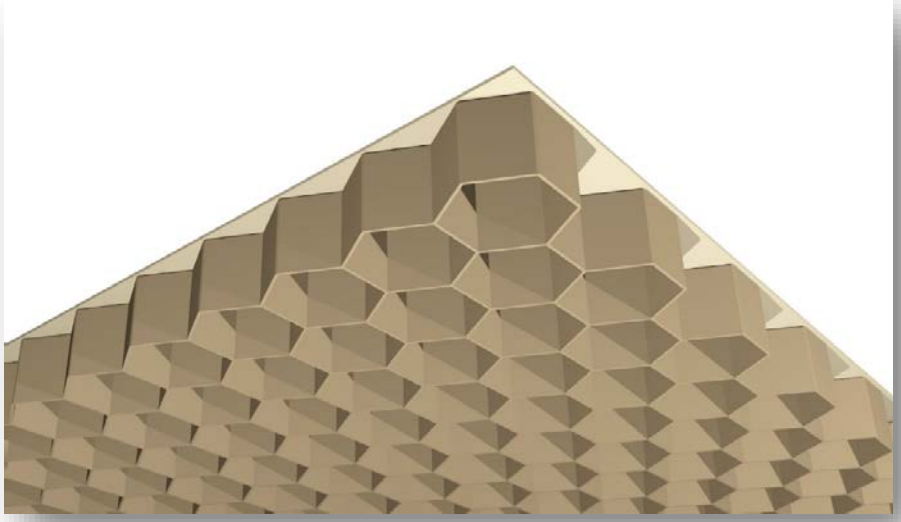
[1] Including thermal shield

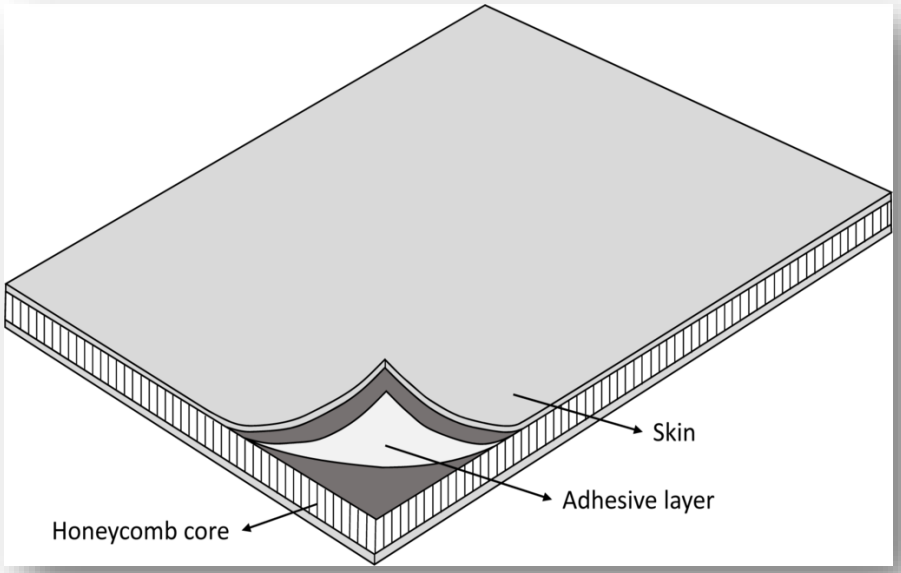


5.7 Cryostat designs: Cryostat for Solenoid inside HCAL

Since radiation length is critical and shall be minimized, an option is:

- New composite materials can be used to further reduce the outer shell effective thickness
- The 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
- The use of these materials needs to be validated
- Thickness of material seen by particles is highly inhomogeneous.





6. Cost estimate (disclaimer: 1st guess, very rough!)

Cost of the solenoid system incl. services, very rough estimate only, use with care !

Case	B [T]	Free Bore [m]	Length [m]	Cost (MCHF) ± 10%
1 (outside EHCAL)	2	6.6	8	≈ 45
2a (inside EHCAL) 2b (1m extra bore) 2c (2 m longer)	2	4 5 (+1) 4	6 6 8 (+2)	≈ 25 + 5 + 6
3 (very wide bore)	0.5	16	16	≈ 80 (nc) - 120 (sc.) + ≈ 45 for iron

- Case 2 is lowest cost, making field only where needed, directly around the tracker. 1m more bore or 2m more length (+30%) cost about 20% extra.
- Case 1 is obviously more expensive.
- Case 3 is most expensive and cost very much depends on technology used.
  - More study needed to get more accurate estimate.
  - Iron Yoke cost roughly 45 MCHF (≈ 4.5 CHF/kg all in).

6. Conclusion

Based on very first magnetic field & size requirements, 3 conceptual designs were presented for both cold mass and cryostat:

For detector number 1:

- A conservative 2 T solenoid surrounding the 6.6 m diameter Calorimeter.
- A challenging 2 T solenoid surrounding the 4 m diameter tracker only.

For detector number 2:

- A 0.5T /16m wide bore solenoid, normal conducting, ALICE-alike.

- ❖ All these designs are certainly doable, though the 2T/4m system requires some attention due to the required minimum radial material build.
- ❖ Cost wise the 2T/4m system looks favorable.
- ❖ Magnetic shielding of the magnets is not required when installed in caverns 300-400m below surface as field is less than pacemaker limit everywhere.
- ❖ **Next: study these designs presented and give feedback for next iteration!**
- ❖ **Decide on baseline designs for CDR asap**